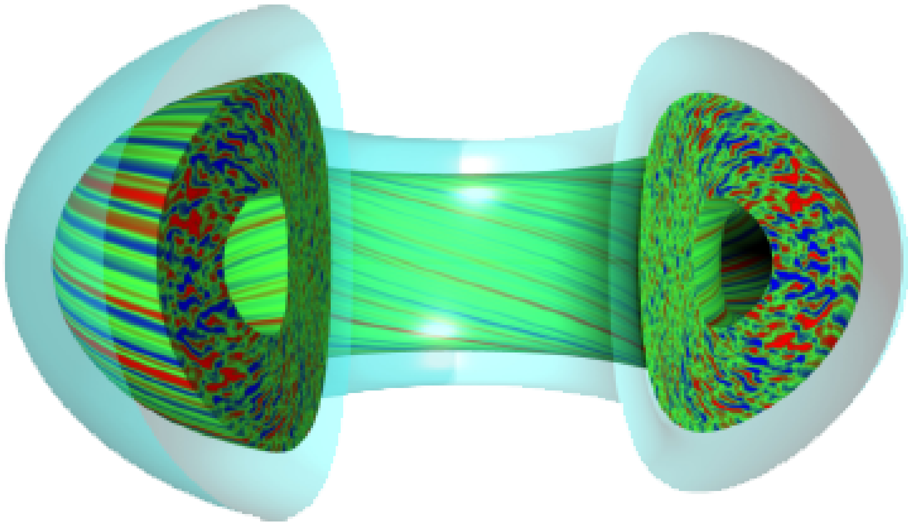
4th IAEA Technical Meeting on Fusion Data Processing, Validation and Analysis



Report of Contributions

https://conferences.iaea.org/e/251

Contribution ID: **2** Type: **Regular Oral**

FAST CHARACTERIZATION OF PLASMA STATES IN W7-X WITH PERMUTATION ENTROPY

Tuesday, November 30, 2021 12:00 PM (15 minutes)

Permutation entropy (PE) is an information-theoretic complexity measure; it is a single number that represents the information rate to derive the ordinal properties of a time series. In sliding window analysis of a single information channel, a change of PE can indicate a bifurcation of the system state. The method is robust and fast. Therefore, the PE approach is applied on large data sets of highly-sampled plasma data in an automated procedure. The paper reports on the identification of confinement changes by PE in W7-X plasmas revealed in a bulk data survey. Once transitions were detected, spectrogram analyses validated the PE findings.

In order to identify temporal changes of a systems state from a time series, PE quantifies the degree of randomness (resp. disorder, unpredictability) of the ordering of time series data. The complexity of a system measured through PE is determined through the probability distributions of ordinal patterns in consecutive data (taken on a time comb with a delay time ⊠D). The calculation of PE is computationally fast since it is based on sorting algorithms rather than distance calculations. Moreover, this approach allows the extraction of robust dynamic properties because PE is invariant for all mappings preserving the order of the data of the time series. PE has been successfully implemented in different science branches e.g. medicine (detection of epileptic electroencephalogram) and economics (characterizing complexity changes in stock market). The widespread applications provide evidence that the method is attractive for in-situ monitoring purposes. Data from hot plasmas are usually processed applying corrections and calibrations. PE is directly applicable provided any analysis step preserves the ordering of the data. In order to use signals for characterizing and forecasting plasma states, PE has advantages from being both computationally fast and robust against noise.

The specific case for applying PE is the analysis of multi-variate, highly sampled time series from an electron cyclotron emission radiometer. Spatio-temporal changes of the plasma states were detected from emissivity changes resulting in significant alterations of the PE in individual channels of the radiometer. While visual inspection of the (noisy) data allows one to conclude on state changes, the time to identify the bifurcation is much reduced when automated analyses with PE were conducted. This acceleration in the processing time allowed us to analyse a large amount of data and to detect systematically changes in the plasma state in a set of experiments. As a result of the systematic survey conducted with PE analysis on a 32-channel-ECE radiometer, the detection of a spontaneous transition to high core-electron temperatures (Te). The bulk processing was employed to investigate the existence and parameter dependencies such as different heating power and density. The reason for the sensitivity of PE was identified (a posteriori) to go along with the occurrence of low frequency emissivity fluctuations, which cease when Te increases in the transition. The identification of spontaneous plasma transition periods was validated by spectrogram analysis.

These results suggest that a complexity measure such as PE is a method to support in-situ monitoring of plasma parameters and for novelty detection in plasma data. PE is therefore proposed as a method for big-data-processing of plasma data. Moreover, the acceleration in processing time offers implementations of plasma-state-detection that provides results fast enough to induce control actions even during the experiment.

Country or International Organisation

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Session Classification: Tuesday 30 Nov

Track Classification: Data Analysis for Fusion Reactor

Contribution ID: **3** Type: **Regular Oral**

Adaptive and transfer learning for disruption classification and prevention on ASDEX-Upgrade and JET

Wednesday, December 1, 2021 12:25 PM (15 minutes)

In metallic devices, the occurrence of disruptions is particularly difficult to predict because of the nonlinear interactions between various effects, such as neoclassical convection of impurities, centrifugal forces, rotation, profile hollowness and MHD modes, just to name a few. While efforts to develop physics based plasma simulators are continuing, data driven predictors, based on machine learning, remain an important fall back solution. In the perspective of contributing to the safe operation of new large Tokamaks, being able to transfer experience from one device to another would be very beneficial. The paper describes a procedure to deploy predictors trained on one device at the beginning of the operation of a different one. The proposed tools have been tested by training them using AUG data and then deploying them on JET data of the first campaigns with the new ITER Like Wall. The obtained results are very encouraging. After a transition learning phase, in which in any case the performances remain sufficiently high, the predictors manage to meet the ITER requirements for mitigation in terms of both success rate and false alarms. Promising improvements have also been achieved for prevention, using in particular information about the radiation profiles.

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Session Classification: Wednesday 1 Dec

Track Classification: Real time prediction of off-normal events, with particular attention to disruption and predictive maintenance

Contribution ID: **4** Type: **Invited Oral**

OPEN WORLD LEARNING: A NEW PARADIGM FOR DISRUPTION PREDICTION

Wednesday, December 1, 2021 12:00 PM (25 minutes)

Disruption predictors based on traditional machine learning have been very successful in present day devices but have shown some fundamental limitations in the perspective of the next generation of Tokomaks, such as ITER and DEMO. In particular, even the most performing require an unrealistic number of examples to learn, tend to become obsolete very quickly and cannot easily cope with new problems. These drawbacks can all be traced back to the type of training adopted: closed world training. In the contribution, it is shown how the new approach of open world training can solve or at least significantly alleviate the aforementioned issues. Adaptive techniques, based on ensembles of classifiers, allow following the changes in the experimental programmes and the evolution in the nature of the disruptions. Exploiting unsupervised clustering, new predictors can autonomously detect the need for the definition of new disruption types, not yet seen in the past. All the solutions can be implemented from scratch, meaning that the predictors can start operating with just one example of disruptive and one of safe discharge. The proposed techniques would obviously be particularly valuable at the beginning of the operation of new devices, when experience is limited and not many example are available.

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Session Classification: Wednesday 1 Dec

Track Classification: Real time prediction of off-normal events, with particular attention to disruption and predictive maintenance

Contribution ID: **5** Type: **Invited Oral**

OBSERVATIONAL CAUSALITY DETECTION FOR TIME SERIES: FROM THEORY TO PRACTICE

Thursday, December 2, 2021 1:55 PM (25 minutes)

Causality is a crucial aspect of human understanding and therefore one would expect that it would play a major role in science and particularly in statistical inference. On the contrary, traditional statistical and machine learning tools cannot distinguish between correlation and causality. This lack of discrimination capability can have catastrophic consequences for both understanding and control, particularly in the investigation of complex systems. The field of so called observational causality detection is devoted to refining techniques for the extraction of causal information directly from data. In this contribution, a conceptual framework, based on the concept of intervention, is provided to substantiate the statement that correlation is not causality. An operational definition of causality is also introduced. The conversion of such a conceptual framework into mathematical criteria applicable to times series is covered in detail. The proposed tools can be classified into two major categories: those based on the analysis of the system dynamics in phase space (such as Convergent Cross Mapping and Recurrence Plots) and those relying on the statically and information theoretic properties of the data (such as transfer Entropy and Conditional Mutual Information). The potential of these techniques for the analysis of fusion data, in particular synchronisation experiments, is introduced and discussed.

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Session Classification: Thursday 2 Dec

Track Classification: Causality Detection in Time Series

Contribution ID: **6** Type: **Regular Oral**

Near real-time streaming analysis of big fusiondata

Friday, December 3, 2021 1:50 PM (15 minutes)

While experiments on fusion plasmas produce high-dimensional data time series with ever increasing magnitude and velocity, turn-around times for analysis of this data have not kept up. For example, many data analysis tasks are often performed in a manual, ad-hoc manner some time after an experiment. In this article we introduce the DELTA framework that facilitates near real-time streaming analysis of big and fast fusion data. By streaming measurement data from fusion experiments to a high-performance compute center, DELTA allows computationally expensive data analysis tasks to be performed in between plasma pulses. This article describe the modular and expandable software architecture of DELTA and present performance benchmarks of individual components as well as of an example workflows. Focusing on a streaming analysis workflow where ECEi data measured at KSTAR on NERSC's supercomputer we routinely observe data transfer rates of about 500 Megabyte per second.
At NERSC, a demanding turbulence analysis workflow effectively utilizes multiple nodes and graphical processing units and executes in under 5 minutes. We further discuss how DELTA uses modern database systems and container orchestration services to provide web-based real-time data visualization. For the case of ECEi data we demonstrate how data visualizations can be augmented with outputs from machine learning models.
By providing session leaders and physics operators results of higher order data analysis using live visualizations may make more informed decisions on how to configure the machine for the next shot.

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Session Classification: Friday 3 Dec

Track Classification: Big data

Contribution ID: **7** Type: **Invited Oral**

Error estimation in filament measurements using a synthetic probe

Thursday, December 2, 2021 3:05 PM (25 minutes)

Plasma filaments –or blobs –are large, coherent structures in the Scrape-Off-Layer (SOL) of fusion devices which can significantly contribute to heat and particle transport out of the plasma. Electric probe arrangements are a standard tool for investigating plasma filaments in the SOL of magnetic fusion experiments. In the Wendelstein 7-X (W7-X) stellarator, recent work has characterized plasma filaments using reciprocating electric probes and provided a comparison of filament scaling to simulated filaments, showing remarkable agreement. The paper further utilizes such simulations to assess uncertainties inherent to probe measurements by introducing a synthetic probe diagnostic into the simulation. It is determined that filament diameters, and to a smaller degree radial filament velocities, are inherently underestimated in experiment when a filament is not centered on the probe tip. Filament velocity measurements are also sensitive to the alignment of the probes relative to the poloidal direction and the distance between pins. Floating potential pins which are spaced too far apart will underestimate filament velocity, whereas pins which are closely-spaced can overestimate the filament velocity. The sensitivity of the floating potential measurements – from which radial velocity is extracted – to temperature fluctuations is discussed. These investigations apply to measurements of filaments by electric probes in tokamaks as well and may serve as guidance for interpreting probe data and designing probe arrays.

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Session Classification: Thursday 2 Dec

Track Classification: Synthetic Diagnostics, Integration, Verification and Validation

Contribution ID: **8** Type: **Invited Oral**

Toward Automatic Wall Protection of Magnetic Fusion Reactors based on Infrared Monitoring

Wednesday, December 1, 2021 2:15 PM (25 minutes)

Tokamak wall protection systems are becoming a key asset for fusion machine operation, as internal plasma facing components (main wall, divertor) have evolved to high-tech actively cooled metallic walls. Tokamak (and Stellerator) walls are the thermal power sink, transfer 10-100 MW to the cooling system and heat up to temperatures of 1000-2000 K during plasma operation. These protection components are among the hottest high-tech industrial components operating in steady state, along with aircraft engine turbine blades and industrial furnaces. Operation incidents or unstable plasma events may cause abnormal hot spots on the wall, which can evolve to a component damage with potential consequences on machine availability. Wall protection systems use real-time infrared (IR) monitoring of the wall temperature, visible imaging systems, data streams relevant to the thermal event classification and expert knowledge. An active wall monitoring system uses real-time analysis of video streams, capable of recognizing known temperature patterns (strike lines, heat losses, especially from additional heating systems, uncooled or deteriorating components) as well as new thermal events, which might be significant for operational safety. The large amount of data is processed through computer vision, pattern recognition algorithms and advanced classification and management tools.
At WEST, CEA's tungsten steady state tokamak, an active wall monitoring system is being developed and progressively put in service [1]. Activities in the field of IR video data processing encompass the:
• Use of artificial intelligence and machine learning techniques for relevant event detection and classification processes,
• Development of a database of thermal events on fusion devices walls. This database is a rationalized ground truth description capturing experts knowledge,
• Computerized tools providing expert assistance for thermal event capture, annotation and analysis,
• Automatized data pipeline and client oriented applications,
• Research toward finding efficient algorithms for detection, classification and expertise, and real-time processing of the vast amount of data.
The progressive set up of the video data pipeline unveils three technical challenges:
• The challenge of having to serve multiple clients with different expectations and requirements: plasma operation agents focusing on standard events and requiring real-time reaction, wall maintenance clients needing long term monitoring and data accuracy, experimentalists striving to capture and process rare and potentially new events.
• The challenge of constituting an extensive, coherent and consistent cross machine database: wall health monitoring and wall incident language is still strongly device-dependent. The fusion communities have to converge toward common approaches and languages, especially in view of the upcoming ITER operation with international experimental teams.
• The challenge of data quantity and complexity: IR video data quantity is abundant (> TB per campaign) and still requires processing with time series from other diagnostic data for reaching a good expertise of the thermal events.
The challenges are described in the paper, along with the WEST team action path toward overcoming them.

[1] WEST operation with real time feed back control based on wall component temperature toward machine protection in a steady state, tungsten environment, Fusion Engineering and Design 165 (2021) 112223, R. Mitteau et Al.

Country or International Organisation

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Session Classification: Wednesday 1 Dec

Track Classification: Image Processing

Contribution ID: **9** Type: **Regular Oral**

Deep Learning and Image Processing for the Automated Analysis of Thermal Events on the First Wall and Divertor of Fusion Reactors

Wednesday, December 1, 2021 2:40 PM (15 minutes)

The analysis of thermal events on the components of fusion reactors is of major importance, both from a machine protection and from a science standpoints. This analysis, which can be conducted using infrared cameras placed inside the reactor [1], ought to be transferred from human operators to automatized processes because of the quantity of data involved and the need for real-time analysis. Hence, there is a need for an automated pipeline able to detect and classify thermal events, either for feedback control of the injected power during plasma operation, or for later analysis. The paper presents a multi-stage algorithm which aims at detecting, tracking and classifying thermal events automatically using thermal imaging of the inside of the fusion reactor as well as other relevant signals.

The first stage of the pipeline is the detection of the hot spots in infrared images: it is carried out, one frame at a time, by the Cascade R-CNN algorithm [2], implemented using PyTorch by Facebook AI in Detectron2 [3]. The inference speed reaches 30fps on a high-end laptop equipped with a GPU, making this approach compatible with real-time monitoring. Once the hot spots detection has been performed in each image, thermal events are inferred by matching and tracking the hot spots in time, using the real-time tracking algorithm SORT [4].

The second stage of the pipeline is the classification of the detected thermal events according to a defined ontology. This step is crucial since it will dictate the response of the feedback system, that will react based on the criticality of the classified event. The classifier relies on the detected thermal events (from the first stage of the pipeline) as well as on signals from other diagnostics, such as the plasma current or the power injected in the reactor.

The model is trained, validated and tested using a database of 1325 manually annotated thermal events from a divertor-facing infrared camera of the WEST fusion reactor, a tokamak located in Cadarache, France, right next to ITER. The first stage of the model (the detection) reaches a mean average precision mAP@50% of 84.3% on the test set. Other criteria quantifying the performance of the pipeline are introduced in the paper. These encouraging results motivate the creation of another database of manually annotated thermal events from different types of cameras (wide-angle, antennas…), and show the potential for a real-time wall monitoring system, able to automatically detect and classify thermal events and to trigger feedbacks during plasma operation (for instance by reducing the power injected by an antenna if a local overheating has been detected).

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[2] Z. Cai and N. Vasconcelos, "Cascade R-CNN: High Quality Object Detection and Instance Segmentation,"24 6 2019.
[3] Y. Wu, A. Kirillov, F. Massa, W.-Y. Lo and R. Girshick, Detectron2, 2019.
[4] A. Bewley, Z. Ge, L. Ott, F. Ramos and B. Upcroft, "Simple online and realtime tracking,"in 2016 IEEE International Conference on Image Processing (ICIP), 2016.

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Session Classification: Wednesday 1 Dec

Track Classification: Image Processing

Contribution ID: **10** Type: **Regular Oral**

Implementation and validation of swept density reflektometry to integrated data analysis at ASDEX Upgrade

Friday, December 3, 2021 12:55 PM (15 minutes)

Integrated Data Analysis (IDA) allows to infer plasma quantities like electron density using heterogeneous data sources. Essential is forward modelling with physically reasonable models to the data space for probabilistic evaluation. The paper presents the progress in extending the set of AUG's diagnostics for electron density profile inference by a microwave reflectometry system.
For swept density reflectometry a FM-CW signal is directed radially into the plasma where it interacts and is eventually reflected when the plasma density exceeds the frequency-dependent cut-off frequency of the probing wave. The returning wave is mixed with a reference wave and the beating signal is observed using a square law detector. The determination of density profiles from the beating signal is an ill-posed inverse problem, classically solved by an Abel inversion.
An efficient semi-analytical forward model is presented, which allows IDA to overcome problems associated with the classic determination of cut-off locations via Abel inversion. Instead of using a hard coded initialisation for densities below the first measured cut-off density, other diagnostics like the lithium beam are used to inform the shape of this part of the profile.
Error propagation of uncertainties in the density profile is inbuilt in the Bayesian approach. This is essential, as each evaluated chirp frequency and the associated group delay (derivative of the collected frequency wrt chirp frequency) is an integrated measure of the entire density profile up to the reflection point. This allows reliable estimation of the uncertainty in the gradient, which is an important input for modelling codes.
Also, by using forward modelling the frequencies measured twice, due to overlapping bands, can be fully included. At the same time a gap in the group delay - e.g. due to poor SNR or a missing band - does not prevent inferring the profile at higher cut-off densities. Missing data simply increases the uncertainty for densities beyond the gap. In addition the inferred density model is unequivocal, so that no ambiguities in the density profile can arise. Abel inversion provides the cut-off position as function of cut-off density, which is not necessarily monotonic.
As IDA uses various diagnostics to infer the density profile, systematic disagreements between them are revealed and can be studied to improve the understanding of the diagnostics and their modelling. A set of plasma conditions is presented, for which agreement and also disagreement between reflectometry and other diagnostics is observed. The differences are discussed and set into context of the remaining limitations of the currently used forward model.

Country or International Organisation

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Session Classification: Friday 3 Dec

Track Classification: Integrated Data Analysis

Contribution ID: **12** Type: **Short Talks**

REAL-TIME DISRUPTION PREDICTION IN THE PLASMA CONTROL SYSTEM OF HL-2A BASED ON DEEP LEARNING

Wednesday, December 1, 2021 1:25 PM (10 minutes)

A real-time disruption predictor based on deep learning method is implemented into the Plasma Control System (PCS) of HL-2A. This upgrade consists of four parts:
1. The Data Acquisition System (DAS) of HL-2A is updated to provide real-time signals to PCS
2. The disruption prediction algorithm proposed in reference 1 is adjusted to reach a higher calculation speed.
3. The PCS, which is developed with C++ language, will call python interpreter and use TFLite framework to execute the disruption prediction algorithm, which is developed with python language and in Tensorflow framework.
The PCS is connected to the Massive Gas Injection (MGI) system to send disruption alarms.
The input signal list of disruption predictor is quite different from the one mentioned in reference 1 because many signals in the original version can't be obtained in real time. In the real-time disruption predictor, only two kinds of data sources are used. Firstly, raw signals are collected from each diagnostic system by hard connect the PCS acquisition card and the diagnostic systems. Secondly, some feedback control signals and preset signals are provided by PCS.
As for the algorithm, 2 main adjustments are made on top of the version in reference 1. Most convolutional layers are replaced by recurrent layers to avoid redundant calculation. Input signals with high sample rates are down sampled by neural networks. Figure 1 shows the structure of model used in this research. These adjustments can reduce the algorithm's calculation time from 17ms per slice to 2ms per slice.
Besides, further acceleration can be realized by TFLite framework, which can automatically implement a series of optimizations, such as quantization, to speed up the execution of deep learning models. By utilizing TFLite framework, the calculation time can be reduced from 2ms per slice to 0.3ms per slice.
Using C++ language to call python interpreter is a pretty good way to connect the PCS and disruption predictor. The cross language calling only brings a delay of several microseconds and can minimize the influence on the two connected parts.
Figure 2 gives the flowchart of disruption prediction module in PCS. The input signals are collected by PCS and then fed into the model by cross language calling between C++ and python. The output of algorithm will be sent back to PCS. Finally the PCS will decide whether or not to send a disruption alarm to MGI system. The disruption prediction module is tested in a simulated real-time environment to predict disruptions in Shot Nos. 35000-37000 in HL-2A. The result shows that all the calculation can be finished within 1ms. The accuracy of the algorithm is evaluated by Area Under receiver-operator characteristic Curve (AUC) and the result is 0.925.
Figure 1. Structure of the deep learning model.
Figure 2. Flowchart of disruption prediction module in PCS

Reference

1. Z. Yang, et al, Nucl. Fusion 60 (2020) 016017

Country or International Organisation

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Session Classification: Wednesday 1 Dec

Track Classification: Real time prediction of off-normal events, with particular attention to disruption and predictive maintenance

Contribution ID: **13** Type: **Regular Oral**

Mori-Zwanzig projection operator method as a statistical correlation analysis of time-series data

Monday, November 29, 2021 3:30 PM (15 minutes)

Mori-Zwanzig projection operator method as a statistical correlation analysis of time-series data

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Mori-Zwanzig projection operator method is a mathematical method developed in non-equilibrium statistical physics 1. A key is a decomposition of a time propagator by the Dyson decomposition, where the time propagator is split into the projected and complementary parts based on a definition of a projection operator 2. Using the Mori's linear projection on initial values 1 as the projection operator, we have developed a statistical correlation analysis method for two time-series ensemble data in a statistically steady state [3]. Based on the method, the analyzed time series data $f(t)$ is split into a correlated (Markov and memory) part and an uncorrelated part $r(t)$ with regard to the variable of interest $u(t)$. The uncorrelated part $r(t)$ is characterized by the no statistical correlation with the initial value $u(0)$, namely, $\langle r(t)u(0)\rangle = 0$, where the angle brackets denote the ensemble average. There is a relation between the memory function and the uncorrelated term, known as a generalized fluctuation-dissipation theorem of the second kind.

In this presentation, we will explain the formulation of the projection operator method, the validity range of the method, and the procedure to apply the method to analyze two time-series ensemble data as a practical data analysis tool. As an example, we have analyzed the nonlinear excitation and damping of zonal flows in Hasegawa-Wakatani resistive drift wave turbulence [4]. We found that Reynolds stress of turbulence on zonal flows acts not only a stochastic forcing but also damping via the correlation with the memory term.

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Session Classification: Monday 29 Nov

Track Classification: Data analysis preparation for ITER and Software Tools for ITER diagnostics

Contribution ID: **14** Type: **Invited Oral**

Deep learning for fast Bayesian inference of plasma diagnostic models

Thursday, December 2, 2021 12:00 PM (25 minutes)

Bayesian inference provides the ideal framework for modelling complex systems made of multiple heterogeneous measurements. Independent generative models of plasma diagnostic measurements can be implemented in a modular way and used to carry out Bayesian inference within a single consistent Bayesian model which relates few common plasma parameters to different kinds of observations. Unfortunately, it is often the case that for complex models, carrying out Bayesian inference with traditional algorithms such as MCMC can require long omputational times. The paper proposes a framework to train deep neural networks to approximate Bayesian inference in order to accelerate it: results conducted on experimental data collected at the Wendelstein 7-X experiment with a multi-line-of-sight X-ray imaging diagnostic and a single line-of-sight spectrometer, and at the JET tokamak with a He-beam diagnostic are promising. An acceleration up to 6 order of magnitude is achieved when the trained artificial neural network is valuated on experimental data to infer plasma parameters such as electron and ion temperature, the plasma effective ion charge, and the edge electron density. One main novelty of such approach is the following: the training data are generated from the Bayesian model that is the target of the fast approximation by sampling from the prescribed joint probability distribution. In particular, the neural network can be trained to infer plasma parameters from the observations, the joint probability distribution value conditioned on the observations, or it can be trained to approximate the posterior distribution of the parameters. Also, uncertainties on the neural network output can be calculated with MC dropout, a variational Bayesian inference approach to the network learning problem. The suggested approach is general, in the sense that it can be carried out on any given Bayesian model. In order to facilitate the automation of the implementation of the method described, it is particularly useful to have one common interface to different plasma physics models: in our case, this is provided by the Minerva Bayesian modeling framework which prescribes a modular environment to express Bayesian models of different kinds. In this way, traditional Bayesian inference can be accelerated, and, on the long term, fast surrogate Bayesian models can be used in possible real time applications which require fast evaluation of experimental data together with appropriate uncertainty calibration. The application described in the paper will provide present and future nuclear fusion experiments with novel chances of automation in experiment planning, execution and diagnosis.

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Session Classification: Thursday 2 Dec

Track Classification: Inverse Problems

Contribution ID: **16** Type: **Regular Oral**

REAL-TIME INFERENCING AND CONTROL FOR FAST PLASMA DYNAMICS WITH BEAM EMISSION SPECTROSCOPY AT DIII-D

Wednesday, December 1, 2021 12:40 PM (15 minutes)

High bandwidth fluctuation diagnostics capture the fast plasma dynamics of drift wave turbulence and Alfven/MHD instabilities on μs timescales. Fluctuation diagnostics coupled with high throughput compute accelerators, such as field programmable gate arrays (FPGAs), introduce new capabilities for real-time characterization, prediction, and control of fast plasma dynamics. Real-time applications of interest include the onset of edge-localized modes (ELMs), turbulence characterization, pedestal characterization, confinement mode transitions and sustainment, and Alfven/MHD mode activity. Following an "edge ML"strategy, machine learning (ML) inference models are deployed on compute accelerators at the diagnostic sensor to ingest the real-time data stream. The models generate reduced signals that target specific physics applications, and the reduced signals are available for real-time plasma control.

The paper reports on a new initiative to implement edge ML capabilities for real-time ELM onset prediction, turbulence characterization, and confinement mode control using the 2D beam emission spectroscopy (BES) diagnostic system at DIII-D. The 64-channel, 1 MHz 2D BES system at DIII-D captures plasma density perturbations from turbulence and instabilities. Edge ML models transform 10-100 μs data histories from the real-time data stream to a low dimension feature space that services multiple prediction and classification tasks. The feature space is derived from 3D convolution kernels (2D in space, 1D in time) and "colour"channels that correspond to spatial and time derivatives in the input data block. The autoencoder will additionally facilitate the real-time assessment of unseen data to be in or out of the training data distribution. The models will be implemented on FPGAs that buffer the real-time data stream and execute model evaluations with latencies on the order of 10 μs. In practice, achieving low latency, high throughput evaluation on an FPGA imposes constraints on the model architecture. The feature space for present models can predict the explosive onset of ELM events (Figure 1a) with reliable forecasts up to 100 μs, and the predictive capability indicates that precursors for the onset of ELM events are present in the data. Strategies to increase the forecast horizon include bootstrapping the ELM onset prediction model from short prediction horizon with high accuracy to longer prediction. Current work is focused on developing a feature space that jointly captures the explosive growth of ELM events and the spatial-temporal patterns of small-amplitude turbulence (Figure 1b). A real-time turbulence classifier will identify the confinement regime including L-mode, H-mode, and enhanced confinement regimes like the wide-pedestal quiescent H-mode at DIII-D. Real-time signals for turbulence activity can facilitate the plasma control system learning to achieve and sustain enhanced confinement regimes. Closely related to the spatial-temporal patterns of turbulence are flow shear patterns (Figure 1c) and the radial electric field (Er) profile. The Er profile is a critical factor for turbulence dynamics and the edge transport barrier, so an additional classification task can be the real-time characterization of Er profile dynamics on 10-100 μs timescales.

Supported by US DOE Grant No. DE-SC0021157, DE-FG02-08ER54999, and DE-FC02-04ER54698.

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Session Classification: Wednesday 1 Dec

Track Classification: Real time prediction of off-normal events, with particular attention to disruption and predictive maintenance

Contribution ID: **17** Type: **Regular Oral**

ASSESSING PHASE AND AMPLITUDE INFLUENCE IN SYNCHRONIZATION EXPERIMENTS

Thursday, December 2, 2021 2:20 PM (15 minutes)

The next generation of Tokamaks and the future reactor will be operated relying much more on feedback control than present day machines. The control of macroscopic instabilities, such as Sawteeth and ELMs, will be essential. In this perspective, various pacing experiments have been indeed successfully carried out in many devices in the framework of scenario optimisation. Unfortunately, many details of their interactions with the plasma remain poorly understood, in particular the assessment of the relative importance of phase and amplitude in frequency synchronization. A data analysis methodology for investigating the details of pacing experiments is described in detail. The technique is based on the wavelet decomposition of the signals and information theoretic indicators, to determine the actual form of the interactions. In both JET and AUG coherent results have been obtained. The main effect, in both ELMs pacing with pellets and sawteeth synchronization with ICRH modulation, is due to the influence of the amplitude of the external perturbations. Some evidence of phase synchronization has been found, which could show the direction of future optimization of the interventions.

Acknowledgment. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Session Classification: Thursday 2 Dec

Track Classification: Causality Detection in Time Series

Contribution ID: **19** Type: **Short Talks**

Experimental data analysis and Proposal validation of EAST tokamak based on machine learning approach

Friday, December 3, 2021 3:05 PM (10 minutes)

A suggestion tool for experimental data analysis and tokamak proposal validation was developed using machine learning methods. The bidirectional LSTM neural network model was used, and experimental data from Experimental Advanced Superconducting Tokamak (EAST) campaign 2010-2020 discharges were used as the model training data set. Compared to our previous works (Chenguang Wan et al 2021 Nucl. Fusion **61** 066015), the present work reproduces the discharge evolution process through more key diagnostic signals, including the electron density n_e, store energy W_{mhd}, loop voltage V_{loop}, actual plasma current I_p, normalized beta β_n, toroidal beta β_t, beta poloidal β_p, elongation at plasma boundary κ, internal inductance l_i, q at magnetic axis q_0, and q at 95% flux surface q_{95}. The similarity of electron density n_e and loop voltage V_{loop} is improved by 1%, and 5%. The average similarity of all the selected key diagnostic signals between modeling results and the experimental data are greater than 90%, except for the V_{loop} and q_0. The model has two main application scenarios: After tokamak discharge experiment, the model gives an estimate of the diagnostic signals based on the actual actuator signals. When the actual value of the diagnostic signals is close to the estimated value it means that the discharge is normal, and vice versa it means that the discharge is abnormal or a new discharge mode occurs. Before the tokamak discharge experiment, the proposal designer sets the values of the actuator signals, and the model has the promising for giving the estimated values of the diagnostic signals to assist in checking the reasonableness of the tokamak experimental proposal.

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Session Classification: Friday 3 Dec

Track Classification: Big data

Contribution ID: **20** Type: **Short Talks**

Predicting locked-mode disruptions with explainable deep learning on MHD spectrograms

Wednesday, December 1, 2021 1:35 PM (10 minutes)

The locked mode amplitude is one of the most commonly used signals for disruption prediction in tokamaks. On the JET baseline scenario, our results suggest that the simple application of a threshold on that signal yields a disruption predictor with more than 95% accuracy. It is well-known that mode locking is one of the main disruption causes at JET; however, it is often too late to avoid a disruption by the time it is detected. In this work, we apply deep learning on MHD spectrograms to predict the locked mode itself and to identify the MHD behaviour that typically precedes mode locking. Specifically, we apply a Convolutional Neural Network (CNN) on a sliding window over the MHD spectrogram to predict whether the locked mode amplitude will exceed a given threshold. In addition, we use Class Activation Mapping (CAM) to highlight the regions in the spectrogram that the model considers to be the most important to arrive at a certain prediction. The results suggest that the interruption of the n=1 mode activity followed by the resurgence of a mode at the q=2 surface are strong indicators that mode locking is about to occur, which is consistent with the literature. Since we are predicting the locked mode, and not the disruption itself, the model is unable to predict all types of disruptions; however, for those that have a locked mode signature, the model can predict them well before the rise in the locked mode amplitude. The use of explainability techniques also suggests that the model can be useful, as an interpretable machine learning tool, to support the analysis of MHD activity.

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Session Classification: Wednesday 1 Dec

Track Classification: Real time prediction of off-normal events, with particular attention to disruption and predictive maintenance

Contribution ID: **21** Type: **Regular Oral**

APPLICATION OF TOMOGRAPHY METHODS IN EAST LINE-INTEGRATED X-RAY RADIATION DIAGNOSTICS

Thursday, December 2, 2021 12:25 PM (15 minutes)

In tokamaks, most diagnostics systems have a relatively small aperture, which limits the availability of only line-integrated measurements. The measurement represents line-integrated emissivity through the approximated line-of-sights (LOS), determined by pin-hole positions. By combining line-integrated measurements, tomography can reconstruct the two-dimensional (2D) distributions of physical quantities in a poloidal cross-section. Reconstruction of a space-resolved image or profile of a plasma quantity using tomography technology has been considered on many fusion devices. Typical tomography problems involve the existence, uniqueness, and process stability of the solution, and are ill-posed. In practice, the data analysis is challenging due to the insufficient coverage of LOS and errors on the measured data, the reconstruction done by any method will have uncertainties. In this work, a brief overview of several tomography technologies, including tokamak flux coordinate based Abel and Fourier-Bessel methods, and L-curve Phillips–Tikhonov, Maximum Entropy, constrained optimization (improved minimum Fisher information) methods for EAST multiple line-integrated measurement diagnostics, such as SXR, AXUV and Gas Electron Multiplier (GEM) camera, is present. Singular Value Decomposition (SVD) technology is commonly employed to obtain the perturbation signal or to remove noise for 2-D tomographic pattern. In particular, a method that introduces a Bayesian probability theory based Gaussian process tomography (GPT) technique has been developed to reconstruct the SXR emissivity distribution. It has certain advantages in uncertainty analysis and overcomes typical tomographic problems by considering a probabilistic approach. This method has already been implemented in the SXR or AXUV systems on multiple fusion devices, such as HL-2A, WEST and EAST. In theory, it can be extended to any line-integrated measurement diagnostic system. An additional advantage of this method is non-iterative and nonparametric, which can realize fast calculation and provide the possibility for real-time application (8 ms for a 50 × 50 pixels grid on a recent PC with MATLAB, the presently used algorithm minimum Fisher information easily reaches execution times up to seconds). Latest preliminary tests on SXR data using various designs of convolutional neural networks suggest the potential towards real-time reconstruction of impurity density profiles. Real-time application (~1ms for 75× 50 pixels grid output) of VGG-CNN method based on Pytorch framework (Python language) with strong GPU acceleration for EAST 92 channels SXR tomography has been carried out. The primary tomography of VGG-CNN shows good agreement to the Fourier-Bessel reconstruction regrading both equilibrium SXR emission and MHD-perturbed SXR emission. Besides of those much efforts in tomographic reconstruction been made for EAST line-integrated diagnostic, the numerical code output based forward modelling also have been developed for solving some special cases. Since each fusion device has been equipped with abundant of diagnostic systems, it is always necessary to explore new methods to effectively process the measurements in order to further understand the physical mechanism of plasma.

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Session Classification: Thursday 2 Dec

Track Classification: Inverse Problems

Contribution ID: **22** Type: **Regular Oral**

Data Forcasting of Gyro-Landau Extended Fluid Code Using Neural Networks

Wednesday, December 1, 2021 4:05 PM (15 minutes)

By means of shortening the execution cost of Gyro-Landau Extended Fluid Code (ExFC), a recurrent neural network (RNN) based surrogate model has been raised to forecast data on the next time step using initial values given by ExFC. The model has been structured as a sequence-to-sequence model which implemented with the well-known Gated Recurrent Unit (GRU) with a residual connection. By using a bucket Min-Max feature scaling technique, a training set is established with the values of all training samples almost equally distributed in [0,1] section. After training, the loss on the training set reaches the order of 10ˆ(-5), while the loss on validation set remains an order higher than that on the training set, implying some overfitting. The prediction given by the model matches considerably well with the original data, where the total relative error of about 10%. Hence the model is capable of fast evaluation of flux and transport level for parameter sweeping during the simulation. On the other hand, in current prediction model performance, turbulent structures have been flattened comparing to the original result, which presumably arises from the lack of potential data during the training of the neural network. A further detailed investigation is still ongoing by means of fully demonstrated turbulence structure.

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Session Classification: Wednesday 1 Dec

Track Classification: Deep Learning

Contribution ID: **23** Type: **Regular Oral**

BAYESIAN PROBABILISTIC DATA ANALYSIS PLATFORM R&D ON HL-2A

Tuesday, November 30, 2021 2:30 PM (15 minutes)

Magnetic confinement fusion experiments generate large quantities of complex data. At a basic level, the data reflects the state of the machine and plasma, enabling a safe and reliable operation of the device, i.e. well within the design limits of the machine and compatible with the scientific goals of the experiment. Depending on the requirements, different analysis techniques are needed to extract as much useful information as possible from the raw data. Bayesian inference is used in many scientific areas as a conceptually well-founded data analysis framework. On HL-2A tokamak, a Bayesian probability theory-based data analysis platform has been initiatively developed, which applied on electron temperature and density profiles inference by using a set of diagnostic systems, including electron cyclotron emission, Thomson scattering, reflectometry and interferometry. In this paper, we will give a brief introduction of recent progress of data analysis platform R&D. The first integrated data analysis application on HL-2A experiment will also be discussed.

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Session Classification: Tuesday 30 Nov

Track Classification: Applications of probabilistic inference and statistics

Contribution ID: **24** Type: **Regular Oral**

IMPROVEMENTS IN EFFICIENCY OF GYROKINETIC SIMULATION RUNS WITH CONVOLUTIONAL NEURAL NETWORK MODELS ANALYZING NONLINEAR SATURATION PROCESSES

Tuesday, November 30, 2021 1:20 PM (15 minutes)

Gyrokinetic codes are the essential tools to predict and understand turbulent transport in magnetically confined fusion plasmas. They calculate the time evolution of the perturbed distribution function in the five-dimensional phase space. It often takes more than a few days to finish their runs and an enormous amount of calculation data is generated per run. When such codes are used to estimate turbulent fluxes, one checks a turbulent saturation state, where the amplitudes of the turbulent fluxes remain almost constant. Since the calculation data produced in the linearly and nonlinearly growing phases sitting prior to the saturation phase are usually not used for turbulent transport analyses, the shorter the growing phase is, the more efficiently the simulations can be carried out. However, there was no way to forecast when the saturation phase starts, i.e. the saturation time, before the simulation is executed or at an early stage of the simulation. In the paper, a new method that forecasts the saturation time is introduced by adopting a machine-learning approach.
When the perturbed distribution function f in the five-dimensional phase space is represented as a combination of two-dimensional images, e.g. $f(k_x, k_y)$ in the wavenumber space, it is visualized that the pattern of the images changes in time showing the saturation process in the linearly and nonlinearly growing phases. In the paper, the images have been generated by the gyrokinetic code GKV to extract the features of the patterns from such images, a convolutional neural network (CNN) model has been constructed, which predicts the simulation time corresponding to the image. The first CNN model was trained based on the GKV calculation for the JT-60U plasma, where turbulence is driven by both the ion temperature gradient (ITG) mode and the trapped electron mode (TEM). About 3,000 images of the amplitude of f in the (k_x, k_y) space were generated from the calculation, and they were split into training, validation and test data. Using the data, transfer learning and fine tuning have been performed with a pre-trained state-of-the-art CNN model EfficientNet to predict the simulation time from the image. The trained model can predict the simulation time of the test data with a high coefficient of determination, $R^2 = 0.9949$.
To apply the method to various nonlinear calculations, three CNN models have been prepared, trained by the data of GKV simulations for Cyclone base case (CBC)-like parameter sets. In addition to the simulation with the original CBC case, where turbulence is driven by both ITG mode and TEM, the two cases with density and temperature gradients artificially changed to selectively develop ITG mode and TEM, individually have been prepared for training. Focusing on the fact that the nonlinear growth in the simulation depends on the dominant instability, the numerically low-cost linear calculation is first performed to identify the dominant instability for the case in which a nonlinear calculation is going to be performed. Then, one can choose the best model out of three to better predict the simulation time. When the three CNN models are applied to the aforementioned JT-60U case, it is found that the CNN trained by the data of the original CBC parameters has the best prediction accuracy. The practical use of the models is as follows: Several runs are launched with different initial conditions. After running the simulations for a while, say six hours after the start, an $f(k_x, k_y)$ image is processed for each case, which is fed into the CNN model. The case predicted to finish the fastest is kept running and the others are terminated. This procedure makes it possible to get the result as fast as possible with minimum computational resources.

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Session Classification: Tuesday 30 Nov

Track Classification: Uncertainty Propagation of Experimental Data in Modelling Codes

Contribution ID: **25** Type: **Regular Oral**

DETECTING CAUSAL RELATIONS BETWEEN TIME SERIES WITH NEURAL NETWROKS

Thursday, December 2, 2021 2:35 PM (15 minutes)

In fusion devices, as in many other experiments, time series are the typical form of the signals produced by the measuring systems. The detection of causality between time series is therefore of great interest, since it can give a unique contribution to the understanding, modelling, and prediction of phenomena still not fully understood. However, detecting and quantifying the causal influence between complex signals remains a difficult task, not solved yet in full generality. This contribution presents a new causality detection method based on Time Delay Neural Networks (TDNNs). The architecture of TDNNs is sufficiently flexible to allow predicting one time series, on the basis of its past and the past of others. With suitable statistical indicators, it is possible to detect and quantify the mutual influence between signals. Some of the most common and critical systems will be analyzed in this work, and the great performances and competitive advantages of this new method will be discussed. The proposed approach has also been tested varying the noise of the signals and the number of data to perform the analysis, in order to provide a comprehensive assessment of the limits and potentialities of TDNNs.

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Session Classification: Thursday 2 Dec

Track Classification: Causality Detection in Time Series

Contribution ID: **27** Type: **Short Talks**

Machine learning models for real-time inference of plasma dynamics using the 2-dimensional beam emission spectroscopy system at DIII-D

Wednesday, December 1, 2021 4:20 PM (10 minutes)

Multi-channel fluctuation diagnostics capture the spatial patterns of high-bandwidth plasma dynamics. The paper reports on an effort to develop machine learning (ML) models for the real-time identification of edge-localized-mode (ELM) events and the turbulence properties of confinement regimes using the 2-dimensional Beam Emission Spectroscopy (BES) system at DIII-D. The 64-channel BES system captures plasma density perturbations at a 1 MHz frame rate. The "edge ML" models will be deployed on high-throughput hardware such as a Field Programmable Gate Array (FPGA) accelerator for integration in the real-time plasma control system (PCS). The models will generate reduced signals that correspond to ELM activity and turbulence dynamics, and the real-time PCS will learn to avoid ELM regimes and to achieve and sustain advanced confinement regimes such as the wide pedestal QH-mode.
The ELM onset dataset contains about 400 hand-labelled ELM events each consisting of about 4-8 millisecond time series data from all the 64 BES channels. Before model training, about 15% of the total ELM events are kept for cross-validation and 10% of them are reserved as previously unseen (test) data. The remaining data is used for training various machine learning models ranging from logistic regression to deep convolutional neural networks. The entire training and cross-validation workflow makes use of time series data truncated beyond 75 μs after the leading edge of the active ELM in each ELM event. Instead of sequential training on the time series, the input data windows, and their corresponding labels, are sampled at random from the ELM events. This whole data pre-processing and training pipeline is repeated for different values of label lookaheads from 10-100 μs to assess the predictive power of the trained models in context of predicting ELM onset and turbulence activity. The model performance on the test data is analyzed using metrics like precision, recall, F1-score and area under the receiver operating characteristics curve (ROC curve) showing the variation of True Positive Rate (TPR) with False Positive Rate (FPR). The model robustness is also assessed using custom metrics such as macro predictions in which the entire time series is divided into the regions of pre-active ELM (region on the left of the first vertical line in the left figure), and active ELM (region between two vertical lines) and model predictions are analyzed in each of the regions separately which are then combined. Various feature engineering techniques based on the max and average pooling or the output feature map from a convolutional neural network are also employed and tested against classical machine learning algorithms such as logistic regression, random forests and gradient boosting. As compared to the baseline results of around 0.83 using classical machine learning algorithms, deep convolutional neural networks yield an AUC-ROC score of about 0.92 on the test data (right figure). Preliminary results also indicate that deep convolutional models can predict ELM onset up to 100 μs in advance using data windows as small as 16 μs. The predictive performance suggests that ELM precursors can be identified and detected in high-bandwidth data streams for ELM onset warning. The paper also explores other data pre-processing techniques like spatial and time gradients as color channels and different neural network architectures such as autoencoders to perform multiple classification and forecasting tasks like ELM prediction, LH transition forecasting, and control for enhanced confinement regimes such as the wide pedestal QH-mode. Autoencoders can help to compress the spatial-temporal information from the input data windows in a low-dimension feature space which can be used for

self-supervised feature engineering with unlabelled datasets.
Supported by US DOE Grant No. DE-SC0021157, DE-FG02-08ER54999, and DE-FC02-04ER54698.

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Session Classification: Wednesday 1 Dec

Track Classification: Deep Learning

Contribution ID: **28** Type: **Regular Oral**

CATALOGUING OF ITER SIMULATIONS USING SIMDB

Monday, November 29, 2021 4:00 PM (15 minutes)

ITER already has a catalogue of around 2000 simulations stored in IMAS format. This catalogue will grow much larger as we approach the initial operational phase of the experiment. Alongside the simulation data are other catalogues including ITER machine description. To make this data useful to the community requires making it FAIR (findable, accessible, interoperable, and reusable). The interoperable goal is handled by making the data available via the IMAS access library but to achieve the other FAIR goals requires handling of the data, it's provenance and associated metadata, and making all these searchable.

To make the ITER data catalogues FAIR and maintainable into future operations the SimDB simulation cataloguing tool was developed. This tool consists of a command line interface, remote data servers and web-based dashboard and allows simulations to be ingested, tagged with additional metadata, pushed to remote storage, and made searchable via REST API queries or web-based searching. The existing ITER simulations have been ingested using SimDB and made available via the SimDB CLI and web dashboard.

The paper details the implementation of SimDB, the associated dashboard and querying tools, and the current state of the ITER data catalogue.

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Session Classification: Monday 29 Nov

Track Classification: Data analysis preparation for ITER and Software Tools for ITER diagnostics

Contribution ID: **30** Type: **Regular Oral**

Utilising cloud resources to perform Monte-Carlo based UQ of fusion simulations

Tuesday, November 30, 2021 1:35 PM (15 minutes)

UTILISING CLOUD RESOURCES TO PERFORM MONTE-CARLO BASED UNCERTAINTY QUANTIFICATION OF FUSION SIMULATIONS

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Abstract

The increased availability of academic and affordable public cloud compute resources provides an opportunity for cheap and easy deployment of large ensembles of simulations onto remote clusters, subject to the caveat that the simulations do not require specific HPC infrastructures. An obvious target use case of such an ensemble is for the propagation of aleatory uncertainties through simulation codes. By sampling from known distributions of uncertain input parameters one can build distributions of outputs of interest, thus providing quantification of the output uncertainty. The ability to quantify the uncertainties on key parameters output from simulations will be a vital ingredient both in optimising plasma scenarios and in de-risking the design of future reactors. UKAEA has developed a framework, VVeb.UQ, which enables the deployment of ensembles of containerised user codes onto cloud resources for performing Monte-Carlo based uncertainty quantification. The framework is built on top of Docker and can exploit either the DAKOTA framework 1 or the VECMA toolkit 2 for parameter sampling. It uses PROMINENCE [3] to handle deployment opportunistically across all available resources. The framework can be interacted with via a simple web interface or a command line REST API.

Some preliminary studies have been undertaken using the framework to look at uncertainties around fusion relevant codes. Equilibrium reconstruction is a foundational component of many fusion workflows, so an attempt has been made to quantify the uncertainties on equilibria reconstructed using the EFIT++ equilibrium code [4] due to uncertainties on input magnetics and MSE data on MAST. In addition to this, work has been conducted using the JOREK non-linear MHD code [5] regarding the prediction of large-scale plasma instabilities.

Future work will focus on expanding the number of codes coupled to framework as well as on the development of more dynamic workflows where outputs are recovered, and further runs are

submitted automatically based on the results. This would enable the training of surrogate models, including the use of sequential design schemes, and the use of optimisation tools built into frameworks like DAKOTA.

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Session Classification: Tuesday 30 Nov

Track Classification: Uncertainty Propagation of Experimental Data in Modelling Codes

Contribution ID: **31** Type: **Regular Oral**

Integrated Data Analysis: Status and Prospects for Future Fusion Devices

Friday, December 3, 2021 12:00 PM (15 minutes)

Present and future fusion devices have to analyse a huge amount of measurements coming from many diagnostic systems. The information obtained from these measurements are and will be used for machine control and safety as well as physics studies. Integrated Data Analysis (IDA) in the framework of Bayesian probability theory provides a concept to analyse a coherent combination of measured data from heterogeneous diagnostics including their statistical and systematic uncertainties and to combine them with modelling information to optimize information available for plasma operation and physics studies. Different techniques for measuring the same subset of physical parameters provide complementary and redundant data for, e.g., improving the reliability of physical parameters, increasing the spatial and temporal resolution of profiles, allowing for new analysis approaches based on diagnostics interdependencies, resolving data inconsistencies, and for reducing the ambiguity of parameters to be estimated without employing non-physical constraints.

Nowadays ample experience exist from applying IDA at various fusion devices, such as W7-AS, ASDEX Upgrade, JET, W7-X, TJ-II, and MST RFP, and for estimating various sets of physical parameters. Based on this experience and due to the conceptional clearly defined Bayesian approach an open-source IDA toolbox, written in python and designed to be modular and flexible to be used at present and next generation fusion devices is presently under development. A summary of the IDA ingredients, the status of the newly developed IDA platform, the linkage with the ITER:IMAS data base and recent applications will be presented.

Country or International Organisation

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Session Classification: Friday 3 Dec

Track Classification: Integrated Data Analysis

Contribution ID: **32** Type: **Regular Oral**

CONDITIONAL RECURRENT PLOTS AND TRANSFER ENTROPY FOR OBSERVATIONAL CAUSALITY DETECTION

Thursday, December 2, 2021 2:50 PM (15 minutes)

In many fields of the natural sciences, from biology to physics, information tools are acquiring more and more importance. For the analysis of information transfer between time series in particular, the use of the transfer entropy is spreading. A typical application is synchronization experiments, which involve coupled quantities, a "target"and a "source", with quasi-periodic behaviours. On the other hand, in complex systems very rarely a couple of quantities can be really considered fully isolated and immune from other influences. It is therefore important to consider not only the legacy of their past, but also the possible effects of additional factors. In order to tackle this problem, an advanced application of the recurrence plots, called Conditional Recurrence plots, has been developed. The innovative technique is corroborated by the application of the conditional transfer entropy. Preliminary results from experimental data of sawteeth pacing with radio frequency are very encouraging. Being quasi periodic, sawteeth occurs naturally and, especially in H mode plasmas, the effectiveness of the pacing with radiofrequency heating can be difficult to establish. The proposed data analysis procedure is aimed at better isolating the confounding factors, like natural sawteeth, providing both a more accurate quantification of the pacing efficiency and a deeper insight into the physical processes involved, thanks to a better understanding of the relevant causal relations.

Country or International Organisation

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Session Classification: Thursday 2 Dec

Track Classification: Causality Detection in Time Series

Contribution ID: **33** Type: **Short Talks**

A Preliminary Study on Experimental Data Analysis System and Breakdown Prediction Based on Neural Networks for EAST-NBI

Monday, November 29, 2021 5:10 PM (10 minutes)

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The mismatch of the operating parameters of the NBI (Neutral Beam Injector) ion source of the nuclear fusion experimental device will lead to the instability of the plasma in NBI ion source, and maybe cause breakdown in the ion source, which will limit the operation of the NBI long pulse and high power. At present, the main method to mitigate the equipment failure caused by the breakdown of the ion source is to add a snubber on the transmission line. However, a snubber can only mitigate the damage to the high-voltage power supply caused by the breakdown event to a certain extent, and the breakdown event damages the ion source itself and the electromagnetic interference caused by the breakdown event to other equipment, which are unavoidable. To stabilize the plasma in the NBI ion source of EAST (Experimental and Advanced Superconducting Tokamak), data from multiple rounds of experiments along with a priori information obtained from a predictive plasma model are used. For the problem of poor accuracy of the existing key-values extraction algorithms for experimental data, the OPTICS (Ordering Point To Identify the Cluster Structure) algorithm is used to improve the accuracy of the experimental data extraction, and provide a reference for the failure analysis during the experimental operation. A method based on SOM (Self-Organizing feature Map) and BP (Back Propagation) neural networks is adopted. By training historical data, the pulse width of the NBI ion source beam extraction process is estimated under given parameters to adjust the operating parameters. However, for some shots with normal parameters but breakdown events actually occurred, some distortions were observed in the diagnostic signals several milliseconds before the breakdown event. Using the method based on machine learning, some breakdown events have been successfully predicted. Although the success rate is not encouraging, it also provides a new method for the safe operation of the ion source. In the future, more efficient algorithms will be developed to apply to the breakdown prediction of CFETR-NNBI or other NBI facilities.

Country or International Organisation

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Session Classification: Monday 29 Nov

Track Classification: Data analysis preparation for ITER and Software Tools for ITER diagnostics

Contribution ID: **34** Type: **Short Talks**

WEST DATA PROCESSING WORKFLOW AND STATISTICAL ANALYSIS

Friday, December 3, 2021 1:40 PM (10 minutes)

WEST (tungsten –W–Experimental Steady-state Tokamak) is a device specialized for long pulse operation in a tungsten environment. Its main purpose is to study the plasma-wall interactions in a metallic environment and to be a test bed for ITER plasma facing components [1-3]. Between 40 and 50 diagnostics help to characterize WEST plasmas. The acquisition systems produce a large heterogeneous amount of data and we made a significant effort to unify data storage and to improve data access and traceability. To this end, we are using IMAS (Integrated Modelling and Analysis Suite) infrastructure to manage WEST experimental data [4]. The data processing workflow or plasma reconstruction chain allows for the integration of information coming from several diagnostics and the production of relevant data for scientific and operational purposes.

From the IMAS data processing workflow, we build a reduced database suited for validation, statistical analysis and machine learning algorithms. Three WEST experimental campaigns are included with a total of 2000 plasma pulses. This database is composed of two parts: the first one contains statistical moments describing quasi-steady states reached by the plasma (6000 quasi-steady states for more than 700 quantities); the second contains the same number of quantities but evolving in time (for example quantities as: averaged temperatures, densities, equilibrium parameters, etc.). The quasi-steady states are detected automatically, avoiding any bias that can appear when a human selection is made. The definition of a quasi-steady state is explicitly given to the detection algorithm by the user. The same definition is applied to all time signals and the algorithm extracts the quasi-steady states under the same assumptions. For example in WEST, a quasi-steady state is defined as a time interval of a minimum length of 0.3 seconds where both, plasma current and total power vary less than 5% (we call them quasi-steady because only these two signals are imposed to be slowly varying). On the other hand, the second part of the reduced database includes the time evolution. To illustrate the benefits of using this reduced two-fold database we present two analysis performed recently. The first one is the L-mode confinement time analysis in WEST and the comparison with an international tokamak database [5]. The second is the identification of two plasma confinement regimes: a good confinement regime characterized by a central electron temperature above 2.5 keV and a degraded confinement regime with electron temperatures below 2 keV (identification done using the first part of the reduced database). Thanks to the second part of the reduced database we are able to identify the main parameters driving this bifurcation (the precursors to the plasma regime separation). The main parameters found are: the lower hybrid (LH) power to plasma density ratio, the LH antenna reflection coefficient and the radial outer gap (equatorial distance between the LH antennas and the plasma separatrix). This identification done, we are able to make recommendations to WEST operational team on how to avoid the degraded confinement regime.

To summarize, from data processing using ITER relevant IMAS infrastructure we obtain a reduced database, in our case stationary states together with temporal data. The data structured as such allows to tackle different questions efficiently contributing to improve tokamak scientific analysis and operations.

1 J. Bucalossi et al. 2021, Nucl. Fusion in press https://doi.org/10.1088/1741-4326/ac2525

2 J. Bucalossi et al. 2014, Fusion Eng. Des. 89 907912

[3] C. Bourdelle et al. 2015, Nucl. Fusion 55 063017

[4] F. Imbeaux et al. 2015, Nucl. Fusion 55 123006

[5] V. Ostuni et al. 24th Transport and Confinement Topical Group Meeting IPP Garching, June 29 - July 3, 2020

Country or International Organisation

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Session Classification: Friday 3 Dec

Track Classification: Integrated Data Analysis

Contribution ID: **35** Type: **Regular Oral**

PERFORMANCE ANALYSIS OF THE CENTROID METHOD PREDICTOR IN THE JET REAL TIME NETWORK

Wednesday, December 1, 2021 12:55 PM (15 minutes)

Recently, a linear disruption predictor was installed in the JET real-time network for mitigation purposes. From a mathematical point of view, the predictor is based on computing centroids of disruptive examples and non-disruptive examples in a two-dimensional space. This is the reason of calling it centroid method (CM). It uses a single signal: the mode lock normalised to the plasma current. The predictor is not based on thresholds to trigger alarms but on the differences of amplitudes between consecutive samples. The article analyses its results for the range of discharges 94152 – 97137 (June 2019 –March 2020), in particular, discharges of both baseline scenario and hybrid scenario. The article presents a comparison between the CM predictor and several different disruption detection systems on board PETRA in the JET real time network. PETRA reads in real time data to produce different types of 'events', which are then fed into the Real Time Protection System (RTPS) for JET during a discharge. The comparison takes into account the conditions to trigger the disruption mitigation valve (DMV): plasma current ≥ 2 MA and plasma total energy ≥ 5 MJ. For baseline scenario, the CM predictor detected a total of 83.87% disruptions prior to the normalized mode lock (NRMLOCA) event detector and detections were made 61.8 ms before NRMLOCA detector on average. In case of normalized combined loop voltage (NRMCMBLV) event detector, the CM predictor detected 87% disruptions prior to NRMCMBLV detector with an average 61.5 ms early detection. The event detector based on short range time derivative of plasma current (SHRTDIDT) was bettered by the CM predictor for 90% of disruptions with an average 64 ms early detection. The CM predictor outperformed long range time derivative of plasma current (LONGDIDT) based event detector for 94% of detected disruptions and did so with an average early warning time of 60 ms. In case of hybrid scenario discharges, the trend is followed for all the event detectors attached to the disruption mitigation alarms 1 and 2, although the average time of early detection for CM predictor reduces to tens of ms. Against NRMLOCA detector, CM predictor detected 80% of disruptions beforehand with an average improvement of detection time by 9 ms. The NRMCMBLV detector was bettered by CM predictor for 70% of detected disruptions and the average gain on detection time was deduced to be 118 ms. The LONGDIDT and SHRTDIDT detectors were also found lagging behind the CM predictor by an average 9.5 ms for 80% of detected disruptions.

Country or International Organisation

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Session Classification: Wednesday 1 Dec

Track Classification: Real time prediction of off-normal events, with particular attention to disruption and predictive maintenance

Contribution ID: **36** Type: **Regular Oral**

PLASMA CONFINEMENT MODE CLASSIFICATION USING A SEQUENCE-TO-SEQUENCE NEURAL NETWORK WITH ATTENTION

Wednesday, December 1, 2021 3:35 PM (15 minutes)

During a typical fusion experiment, the plasma can have several different confinement modes. At the TCV tokamak, it is typically classified as being in either Low(L), Dithering(D) or High(H) confinement mode. All plasma discharges, during the initial ramp-up phase, begin in L mode. By applying sufficient heating power, the plasma spontaneously transitions into H mode (typically at TCV this process lasts approximately 1 ms). This new mode is termed High confinement because, once it is reached, one can observe significantly reduced transport of particles and energy from the plasma to the surrounding vessel walls. In some cases the transition from L to H mode does not happen directly, but rather the plasma oscillates rapidly between the two confinement regimes. In this case, the plasma is considered to be in a Dithering mode.

Many studies have been done on the physical factors behind the transition between L and H mode, but the phenomenon is still not completely understood. Furthermore, there is no simple set of rules that can be used to determine the plasma mode given the values of signal time series data during a fusion experiment. Nevertheless, most of the time, there are highly salient patterns in these measured signals that can be used by domain experts to determine the plasma mode with high confidence.

The process of manually labelling experimental data can be quite cumbersome in many cases, particularly when one wishes to conduct large studies and analyse many shots. For that reason, work has been put into developing tools capable of automating the task of detecting different plasma confinement modes. In particular, in the past few years, research has been done on using machine learning and, more recently, deep learning for this task. Those algorithms are particularly suitable for dealing with challenges of extracting patterns from high-dimensional time series data collected during fusion experiments.

Previous work with deep learning methods, particularly convolutional long short-term memory networks (conv-LSTMs), indicates that they are a suitable approach for this task. Nevertheless, those models are sensitive to noise in the temporal alignment of labels, and are limited to making individual decisions taking into account only the input data at a given timestep and the past data. The paper presents an architecture for a sequence-to-sequence neural network model with attention which solves both of those issues. Using a carefully calibrated dataset, the paper compares the performance of a conv-LSTM with that of its proposed sequence-to-sequence model, and shows two results: one, that the conv-LSTM approach can be improved upon with new data; two, that the sequence-to-sequence model can improve the results even further, achieving excellent scores on both train and test data.

Country or International Organisation

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Session Classification: Wednesday 1 Dec

Track Classification: Deep Learning

Contribution ID: **39** Type: **Short Talks**

PROVENANCE IN FUSION: APPLYING THE W3C-PROV MODEL TO FUSION DATA

Friday, December 3, 2021 3:15 PM (10 minutes)

With a growing emphasis on open data, and a drive to improve the interoperability of fusion data, a holistic and standardised approach to data provenance is required. Modern and emerging research methods that handle large data sets will require that metadata, including provenance, can be handled similarly and programmatically, regardless of their source. The FAIR data principles outline guidance for improving data quality and machine-actionability, featuring provenance as a key measure of how reusable data are. Well described provenance also increases the level of trust that users can have in the data, encouraging the wider use of it in studies. The W3C-PROV model provides a way of describing provenance that is both human and machine-readable. As part of the work carried out by the FAIR4fusion project, an approach to the curation of provenance for fusion data is presented. The challenges and areas for development are discussed, with examples including data from the Mega-Amp Spherical Tokamak (MAST) in the UK, and WEST in France. WEST data is provided as Interface Data Structures (IDS) –the format developed for ITER data – demonstrating a potential for fusion data to be united and distributed under a common ontology, with provenance described according a globally-recognised standard.

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Session Classification: Friday 3 Dec

Track Classification: Big data

Contribution ID: **40** Type: **Invited Oral**

ANALYSIS OF ELECTRON CYCLOTRON EMISSION MEASUREMENTS WITH RADIATION TRANSPORT MODELING IN PRESENT AND FUTURE FUSION DEVICES

Friday, December 3, 2021 12:30 PM (25 minutes)

The electron cyclotron emission (ECE) diagnostic is a well-established and robust instrument for the localized measurement of the electron temperature T_e. It measures the microwave spectrum radiated by the plasma. The measured microwave intensity can be calibrated to directly deliver T_e. The location of the measurement is determined by finding the position on the line of sight at which the measured frequency equals one of the harmonics of the cyclotron frequency.
While this simple analysis works well for the core of plasmas in current fusion devices, it is too inaccurate for the pedestal region of current H-mode plasmas, and the much hotter plasmas in future machines like ITER, SPARC, and DEMO in general. Under these circumstances, the kinetic broadening of the ECE due to the relativistic mass increase and the Doppler shift can no longer be neglected and radiation transport effects need to be included in the interpretation of the ECE measurements. This also inhibits the direct inference of T_e, as the measurements are no longer localized, and the T_e information is entangled with the electron density. This challenge can be overcome by combining integrated data analysis[1] with a radiation transport code like ECRad[2]. With this approach complex, ECE spectra measured at the ASDEX Upgrade tokamak can be well understood. This contribution will demonstrate this for the edge of H-mode plasmas, high-temperature, low-density scenarios with conditions for ECE similar to ITER, oblique ECE measurements, and harmonic overlap. In addition, we will highlight the importance of radiation transport modeling for future machines by discussing predictive ECE spectra for ITER and SPARC[3].

1 R. Fischer et al Fusion science and technology 2010 Oct 1;58(2): 675-84.
2 S. S. Denk et al. Computer Physics Communications 253 (2020): 107175.
[3] A. J. Creely et al. Journal of Plasma Physics 86.5 (2020).

Country or International Organisation

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Session Classification: Friday 3 Dec

Track Classification: Integrated Data Analysis

Contribution ID: **41** Type: **Short Talks**

Full life-cycle provenance of physical modules repositories for integrated modeling and analysis workflow

Friday, December 3, 2021 3:25 PM (10 minutes)

"Data provenance" is critical to establishing repeatable and integrated modeling and analysis workflow (e.g. IMAS). Most of the physical modules in the workflow are published in source code. The configuration parameters and compilation environment during the module construction process can affect their output. The provenance information generated by traditional workflow management tools only documents the process of data generation, and lacks records of the construction process of the modules that generated the data. In the present work, a tool chain for the full life-cycle management of the physical module repository is developed. A common module specification is defined that contains the data interface to the physical module, as well as the description of the program coding, building, deploying, executing, and retiring process. The full life-cycle of physical modules, from source code to workflow actors, is automatically managed and documented through CI/CD tools.

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Session Classification: Friday 3 Dec

Track Classification: Big data

Contribution ID: **42** Type: **Regular Oral**

Design of a soft-X ray imaging system and tomography analysis based on Bayesian principle

Thursday, December 2, 2021 12:40 PM (15 minutes)

It is reported about the prior analysis in design and tomography analysis of soft X-ray (SXR) diagnostic on Keda Torus eXperiment (KTX). The tomographic KTX aims at studying three dimensional effect in reversed field pinch with high plasma current, particularly in quasi-single-helicity (QSH) states. In order to reflect the experimental constraints and QSH configuration, the Bayesian experimental design (BED) has been chosen to design the view distribution of the probes. This method can optimize the camera location and emission view angle, aiming at maximizing the gain information in future QSH states equilibrium. The Bayesian tomography method is used to do the following data analysis of SXR. It provides an assessment of reconstruction accuracy of SXR and the uncertainty in the reconstruction from errors can be analyzed by the Bayesian probability theory. The Bayesian principle makes prior and quantified analysis in SXR tomographic and it is expected to be extended to other diagnostics in advanced fusion devices such as ITER.

Country or International Organisation

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Session Classification: Thursday 2 Dec

Track Classification: Inverse Problems

Contribution ID: **44** Type: **Short Talks**

AN EXAMPLE FOR COMPLEMENTARITY BETWEEN PLASMA PHYSICS AND DATA-DRIVEN RESEARCH

Tuesday, November 30, 2021 3:45 PM (10 minutes)

An example for complementarity between plasma physic and data-driven research will be reported. It is the application of the information criterion (either Akaike or Bayesian) in the field of the statistics to the data obtained in the fusion research. A particular example described in the paper is the trials being conducted by utilizing the thermal diffusivity database in the Large Helical Device (LHD), Japan. The paper will reveal that the information criterion can be a powerful tool to unravel complicated entangled phenomena in fusion plasmas, from a viewpoint different from plasma physics. By efficiently extracting the information contained in the data, which could not always be achieved only by the variables of interest based on plasma physics (physicist's view), the convincingness supported by plasma physics and/or new discoveries and awareness from the perspective of the data-driven approach can be achieved. By considering complementarity between plasma physics and data-driven approach, fusion research should be qualitatively strengthened.

Country or International Organisation

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Session Classification: Tuesday 30 Nov

Track Classification: Applications of probabilistic inference and statistics

Contribution ID: **45** Type: **Regular Oral**

FUSION CLOUD –Open Science Platform for Fusion Research in Japan –

Friday, December 3, 2021 2:05 PM (15 minutes)

"Fusion Cloud"is a new concept to realize an interdisciplinary data analysis platform primarily based on fusion experiments and numerical modeling data across academic institutions and universities in Japan. Not only for the next-generation fusion experiment's diagnostics and operations, such as in ITER and JT-60SA, but also for enabling the fusion demo reactor designs, some standard platform will be highly expected on which the integrated data processing, validation, analysis and model calculations would be performed. The Integrated Modeling and Analysis Suite (IMAS) is a well-known activity to develop a cluster of necessary software toward the ITER era.

The Fusion Virtual Laboratory (FVL) was the Japanese inter-university remote collaboration platform over several fusion experiments, whose data linkage has been established through the dedicated virtual private network named SNET. To date, the LHD-SNET unified data storage has been storing approximately 3 peta-bytes (PB) of fusion experimental data collected from LHD and other university experiments remotely via SNET. The distributed data acquisition, archiving, and analysis systems constitute an integrated data system infrastructure that transparently links multiple fusion experiments via high-speed long-distance academic network SINET. The latest technologies for fusion experiments, the LABCOM high-bandwidth real-time streaming data acquisition and the AutoAna/EG data processing and analysis automation by data synchronization triggers, have been newly developed and the effectiveness has been practically demonstrated in LHD-SNET.

Both in terms of research data management (RDM) and open science (OS), digital data properties generated by LHD and SNET experiments are considered to be open by means of assigning global persistent identifiers, such as DOI (Digital Object Identifier), to enable universal access by the public and enhance the opportunities for reuse and re-evaluation. It will also help researchers to directly refer and cite the data object they used in publication and presentation. With considering the FAIR (Findable, Accessible, Interoperable and Reusable) data principles, more specific platform designs are developed underway.

The Fusion Science Information Centre is also a new project of QST (ITER Japan Domestic Agency), which aims to unify the Fusion Science Data Centre (DC), the Computation Simulation Centre (CSC) and the Remote Experimentation Centre (REC) to realize a hybrid platform for fusion data analysis and computation. The NIFS institutional repository is already operated on the JAIRO Cloud open-access repository platform, a part of the Gakunin RDM of National Institute for Informatics (NII). "Fusion Cloud"will challenge the integration of the relevant platforms and also the established system technologies developed in LHD and SNET toward the next-generation fusion research activities.

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Session Classification: Friday 3 Dec

Track Classification: Big data

Contribution ID: **46** Type: **Regular Oral**

Development of Data Assimilation System for Control of Toroidal Plasmas

Tuesday, November 30, 2021 2:45 PM (15 minutes)

ASTI, a data assimilation system for integrated simulation of fusion plasma, is being developed to analyze, predict, and control the fusion plasma behavior. ASTI employs the ensemble Kalman filter (EnKF) and smoother (EnKS) as data assimilation methods. The integrated transport simulation code for helical fusion plasmas, TASK3D, is employed as the system model in the data assimilation framework. In this study, a control method for fusion toroidal plasmas using data assimilation techniques has been developed and implemented in ASTI. The heating input parameters are estimated sequentially by assimilating the target states of plasma into the integrated simulation. Furthermore, the simulation model parameters with uncertainties are optimized to enhance simulation accuracy by sequentially assimilating the observation results. The implemented control method keeps the prediction performance of the employed simulation model and adjusts the heating input parameters to achieve the target state. To investigate the effectiveness of the control method, ASTI is applied to control the simulated LHD plasma by the integrated simulation code, TASK3D, assuming the appropriate transport models.

Country or International Organisation

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Session Classification: Tuesday 30 Nov

Track Classification: Applications of probabilistic inference and statistics

Contribution ID: **47** Type: **Regular Oral**

NON-PARAMETRIC INFERENCE OF IMPURITY TRANSPORT COEFFICIENTS IN THE ASDEX UPGRADE TOKAMAK.

Tuesday, November 30, 2021 1:50 PM (15 minutes)

Controlling impurity ions is a critical requirement for a fusion reactor. Impurity accumulation in the core region dilutes fuel and radiates away power through line emission and enhanced Bremsstrahlung. However, a proper amount of impurity is likely to be required in the edge region in order to mitigate the heat load on the plasma facing components.
The transport properties of impurity ions are often experimentally characterized by using a diffusion coefficient D and a convection velocity v. Since the realistic experimental setups usually necessitate the determination of D and v under ill-posed conditions, rigorous comparisons between simulations and experiments cannot be made without addressing the model selection and uncertainty estimation problems. To this end, the Bayesian formalism has been applied to the impurity transport studies in recent years.
In this contribution, a non-parametric inference of impurity transport coefficients by using charge exchange recombination spectroscopy measurements of Ne X, Ne VIII, O VIII, and C VI lines is presented for the first time. Due to their close atomic numbers, neon, oxygen and carbon impurity ions are assumed to have the same diffusion coefficient D and convection velocity v. In order to reduce a large computational cost, which a non-parametric approach typically entails, an analytical steady state solution for impurity profiles for given background plasma parameters and transport coefficients is derived. Since the ratio of v to D only describes the equilibrated profile of the sum of all impurity charge states, steady-state measurements can still decouple D and v if different charge states are simultaneously observed. A non-parametric analysis framework based on the Bayesian probability theory is formulated, and transport coefficient measurements for a Type III ELMy H-mode plasma at ASDEX Upgrade are conducted. The charge exchange reactions with the background neutrals, which are known to affect the impurity charge state balance, are taken into account by introducing additional free parameters. Unlike spline functions, the non-parametric inference does not reduce the degrees of freedom for representing spatial profiles. Thus, all solutions that are consistent with the measurements and the prescribed smoothing conditions can be calculated. D ~30 m/s^2 and v ~ 120 m/s are inferred right inside the pedestal top.

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Session Classification: Tuesday 30 Nov

Track Classification: Uncertainty Propagation of Experimental Data in Modelling Codes

Contribution ID: **48**   Type: **Short Talks**

Making MAST Open Data FAIR Compiant

Friday, December 3, 2021 3:35 PM (10 minutes)

MAST data has been "open"following UK Research Institute guidelines since the end of its 36 month embargo period, with all data now available. This data is available on request through a web interface and is built around maintaining control over who can access the data and for what purpose, in order to provide support to users making use of the data and ensuring it is used for valid research purposes. To achieve this, users need to register for each file from each shot in which they have an interest; a time-consuming process but one that helps maintain a knowledge of who has access to the data and ensure that appropriate credit is given in any publications.

While this was originally seen as being a model for making data open, the landscape has changed with the introduction of FAIR concepts, cloud computing and storage and the desire to maximise the impact of government funded research by making data more easily available to researchers within and outside the community. The paper presents the work currently undertaken in the adoption of FAIR principles for MAST data and making it available to a wider range of users through APIs which can be addressed programmatically. This includes the use to standard top level schemas, clear data licensing, integrating the Summary Interface Data Structure as scientific metadata and the use of persistent identifiers to make data more easily citable. Experiments with integrating the new open MAST data with the FAIR4Fusion Data Portal are described in addition to the open file formats adopted which make data accessible both by the community through IMAS and by providing tools to access data by non-fusion users.

Country or International Organisation

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Session Classification: Friday 3 Dec

Track Classification: Big data

Contribution ID: **49** Type: **Regular Oral**

tofu: an open-source python library for synthetic diagnostics, data analysis and inversions for fusion

Monday, November 29, 2021 4:30 PM (15 minutes)

The fusion community and ITER need reliable software tools to be included in data reconstructions and validation chains. One way to provide such tools is via open-source solutions developed using industry-standard quality processes like version-control, continuous integration, unit testing etc. Such open-source libraries, are usually developed jointly by communities of developers and users, and they are a response of the scientific communities to the more general replication crisis observed in many fields. For published results to be replicable and verifiable, the numerical tools must be transparent, version-controlled and freely accessible. Some already successful example exist in other communities, like the Astropy library for astrophysicists, the Numpy, Scipy and Matplotlib libraries for data scientists in general. The fusion community is relatively new to this way of working and despite a few notable exceptions, like the PlasmaPy library, there are only relatively few such open-source widespread tools for fusion.
Tofu is an attempt at providing the fusion community with one such tool, a specialized, transparent, free and community-driven python library for synthetic diagnostics, data analysis and inversions for fusion devices. It is relevant for diagnostics measuring light emitted by the plasma in wavelength ranges for which the plasma is transparent, like visible cameras, bolometers, soft and hard x-ray detectors and x-ray crystal spectrometers.
It is object-oriented, hosted on a public repository on Github and licensed with a very permissive MIT license. It can be used to easily:
• model a tokamak geometry using a quasi-axisymmetric approach (axisymmetric by parts)
• model 1d or 2d cameras as sets of lines of sight easily placed around the tokamak geometry, ray-tracing tools automatically compute the extent of rays in the chosen geometry
• model a spherically curved crystal for a 2D X-ray imaging spectrometer
• used the modelled cameras to compute synthetic data from an arbitrary user-provided emissivity function
• display specialized interactive plots to explore diagnostics geometry and experimental or synthetic data
• create a 2D mesh of the plasma cross-section to compute a geometry matrix for inversions
Furthermore it is natively compatible with IMAS, from/to which it read/write data (geometric data or experimental / synthetic data), and can integrate in a high-quality data reconstruction chain based on IMAS. It also provides ready-made interfaces to communicate with other open tools like Inkscape (for drawing an arbitrary tokamak geometry) openadas and the nist database (for spectral data).
The paper introduces tofu to the larger fusion community by:
• Introducing the methods and good practices behind its development and discussing how and why they are necessary for ensuring, on the long term, that data validation and reconstruction chains in which tofu is, or can be, inserted are robust, reproducible and transparent.
• presenting some of its key functionalities for synthetic diagnostics
• presenting an example of application for ITER, that will be easily replicable (the version of tofu used and the corresponding code lines will be provided)

Country or International Organisation

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Session Classification: Monday 29 Nov

Track Classification: Data analysis preparation for ITER and Software Tools for ITER diagnostics

Contribution ID: **50** Type: **Regular Oral**

Anisotropic diffusion as a proxy model for the estimation of heat-loads on plasma-facing components

Thursday, December 2, 2021 3:45 PM (15 minutes)

When preparing the operation of a magnetic confinement fusion device, estimating the heat-load distribution on plasma-facing components expected during operation presents a critical issue. Due to the relevance of this problem, most magnetic confinement fusion laboratories can be expected to develop their own device-specific approaches to predict this heat-load distribution.

This contribution gives an overview over (some of) the current strategies employed at the Wendelstein 7-X stellarator to predict heat-load distributions on the divertor. Its main focus is on an anisotropic diffusion model developed as a middle ground between the fast calculation speed of diffusive field-line tracing and the high physical accuracy obtained by solving the Braginskii equations in the plasma edge.

To facilitate the visualization of the heat-load distributions, as well as the comparison to experimental measurements, a novel synthetic camera based approach to heat-load density estimation was developed. This method can compute the heat-load density from Monte Carlo point clouds on arbitrary geometries without being limited by the triangle density of the mesh. Such an approach has the advantage of requiring very little human interaction during preparation, and being able to handle difficult (e.g. complex and non-manifold) geometries.

Comparisons with IR camera measurements indicate that the improvement gained from anisotropic diffusion over diffusive field-line tracing is worth the added computational cost in many cases. Unsurprisingly, it does not reach the level of accuracy provided by full edge transport simulations (which do, however, require substantially more computational resources and human interaction).

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Country or International Organisation

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Session Classification: Thursday 2 Dec

Track Classification: Synthetic Diagnostics, Integration, Verification and Validation

Contribution ID: **51** Type: **Regular Oral**

Progress in the Application of Machine Learning and Artificial Intelligence To Enhance EFIT Equilibrium Reconstruction for Fusion Data Analysis and Real-Time Applications

Thursday, December 2, 2021 12:55 PM (15 minutes)

Recent progress in harnessing novel machine learning (ML) / artificial intelligence (AI) algorithms to enhance EFIT equilibrium reconstruction for fusion data analysis and real-time applications is presented. This includes development of a ML-enhanced Bayesian framework to automate and maximize information from measurements and Model-Order-Reduction (MOR)-based ML models to efficiently guide the search of solution vector. A device-independent portable core equilibrium solver has been created to ease adaptation of ML enhanced reconstruction algorithms. An EFIT database comprising of DIII-D magnetic, motional Stark effect (MSE), and kinetic reconstruction data is being generated for developments of EFIT-MOR surrogate models to speed up the search of solution vector. A parallel Python framework is used to construct input and output vectors for communication with the equilibrium database and training of EFIT-MOR surrogate models. Approaches to improve portability between the OpenMP and GPU EFIT versions are being explored on Linux GPU clusters and the new NERSC Perlmutter to create a performance-portable GPU implementation for further optimization of ML/AI based reconstruction algorithms. Other progress includes development of a Gaussian-Process Bayesian framework to improve processing of input data, and construction of a 3D perturbed equilibrium database from toroidal full MHD linear response modeling with the MARS-F MHD code for developments of 3D-MOR surrogate models.
Work supported by US DOE under DE-SC0021203, DE-SC0021380, and DE-FC02-04ER54698.

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Session Classification: Thursday 2 Dec

Track Classification: Inverse Problems

Contribution ID: **52** Type: **Regular Oral**

STATUS, PROSPECTS, AND BENCHMARKING OF THE MINERVA BAYESIAN MODELING FRAMEWORK AT WENDELSTEIN 7-X

Thursday, December 2, 2021 3:30 PM (15 minutes)

Over the last years, Bayesian Analysis became a standard method in plasma physics for a common plasma parameter profile determination and mathematical correct error analysis [1-3], evaluating data measured by various diagnostics.
This paper gives an overview of established as well as recently deployed physics models within the Minerva Bayesian analysis framework 2 for a wide range of different diagnostics operated at Wendelstein 7-X, such as two X-ray imaging spectrometers (XICS) [4], a charge exchange recombination spectroscopy diagnostic (CXRS) [5], an X-ray tomography system (XMCTS) [6,7], a Thomson scattering (TS) [8], an electron cyclotron emission (ECE) [9], and an effective charge measurement (Zeff) [10] diagnostic.
Upon individual examples, benchmarking of evaluated plasma parameters in cross comparison for different diagnostics, e.g. Te , Ti , and nAr observed with XICS, CXRS, and TS will be discussed as well as prospects for the application of artificial neural networks for fast data analysis of complex physics models.

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Session Classification: Thursday 2 Dec

Track Classification: Synthetic Diagnostics, Integration, Verification and Validation

Contribution ID: **53** Type: **Invited Oral**

FAST INTEGRATED MODELLING USING A NEURAL NETWORK SURROGATE MODEL FOR TURBULENT TRANSPORT

Tuesday, November 30, 2021 12:55 PM (25 minutes)

Tractable and accurate prediction of tokamak plasma temperature, density and rotation profiles is vital for interpretation and preparation of current-day fusion experiments, optimization of plasma scenarios, and designing future devices. Predictions can be made using so-called integrated modelling suites, a collection of codes describing different physical processes integrated together to create a "virtual tokamak". The complexity of theory-based models, vital for accuracy, is often the computational bottleneck, leading to up to weeks of simulation time for a single scenario in extreme cases. This means a significant speed-up is needed to enable use cases like inter-shot predict-first optimization and large scale optimization exercises. In this work, a neural network regression of the quasilinear gyrokinetic turbulent transport model QuaLiKiz is used to accelerate by orders of magnitude the prediction of transport fluxes.

The QuaLiKiz [1, 2] model has been verified against its non-linear counterparts in wide regimes. Combined with the JINTRAC integrated modelling suite [3] it has provided validated prediction of JET and AUG scenarios, with 1s of plasma evolution predicted in ~24 hours using ~10 cores [4, 5]. Previous work presented the QLKNN-hyper-10D model, a feed-forward neural network model trained on a database consisting of 300 million QuaLiKiz flux calculations over an rectilinear grid of dimensionless input parameters [6, 7]. This model can be evaluated under a millisecond, sufficient for real-time turbulent transport prediction. When used as a drop-in replacement for QuaLiKiz this results in simulation times of mere minutes while still being able to reproduce kinetic profiles within 1%-15% compared to the original QuaLiKiz model. In this work various extensions to the QLKNN family of models are presented. Firstly, the QLKNN-hyper methodology is extended with a new dataset consisting of 3 billion calculations, increasing the input dimensionality of the model with scans over the impurity density gradient. Combined with the addition of impurity fluxes to the output dimensions, this enables large scale studies on impurity transport, fuelling, and impurity seeding. Secondly, a QLKNN model trained on a database based on experimental JET data, QLKNN-jetexp-15D [8], is presented. By reducing the input subspace, a larger number of input dimensions is feasible, leading to more accurate predictions with a far smaller dataset, but limited to dimensionless parameters similar to JET. Several examples within the JINTRAC suite are shown. Thirdly, the QLKNN model has been integrated in the control oriented plasma simulator RAPTOR [9, 10]. The availability of analytic Jacobians of the input-output mapping of QLKNN enables its direct application in implicit solver schemes for fast PDE evolution, as well as for trajectory optimization and stationary-state solvers. An optimization of the ECCD deposition profile in ITER hybrid scenario's is shown using these techniques [11]. Finally, all QLKNN models capture known physical features of tokamak turbulence, such as sharp instability thresholds common to all transport channels. Previous work includes these features by a physics-based cost function. However, superior regression results can be obtained by including the physical constraints directly into the neural network architecture, of which examples are shown.

The QLKNN family of models allow for simulations based on first-principle, within a fraction of simulation time. This opens the pathway for accurate and tractable full-device tokamak simulation, a longstanding challenge in the fusion
simulation community.

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Session Classification: Tuesday 30 Nov

Track Classification: Uncertainty Propagation of Experimental Data in Modelling Codes

Contribution ID: **54** Type: **Regular Oral**

DEVELOPMENT OF INVERSE THERMOGRAPHY METHODS BASED ON INFRARED SYNTHETIC DIAGNOSTIC

Thursday, December 2, 2021 1:10 PM (15 minutes)

Infrared (IR) thermography system is a key diagnostic in fusion devices to monitor the Plasma Facing Components. Nevertheless, both the qualitative and quantitative analysis (i.e. the hot spot detection and the surface temperature measurement) are challenging due to the presence of disturbance phenomena as variable emissivity and multiple reflections in fully metallic environment. To do so, a synthetic diagnostic approach has been developed to assess accurately the abovementioned effects. Such synthetic diagnostic is an indispensable tool both for predicting and better understanding the wall heat loads but this is also the basis from which a general inverse model can be established for filtering reflections and getting more reliable surface temperature. IR synthetic diagnostic (i.e. forward model) and inverse methodology are two programs developed in parallel as they are benchmarked on existing devices as WEST and W7x.

IR synthetic diagnostic is based on Monte Carlo Ray Tracing (RT) codes coupled with the 3D field line tracing and thermal calculations. The accurate prediction of the measurements will depend on the capability of modelling all physical processes involved in the measurements, i.e.: (1) the plasma heat loads deposit and the resulting surface temperature of in-vessel components for different plasma scenarios (2) the radiative properties of materials (reflectance and emission model) managing photon-wall interactions (3) the production of synthetic images including camera and optical model. Several efforts have been made to consolidate the chain of calculations. First, on a theoretical point of view, physical models have been improved (e.g. the development of reduced and robust thermal model based on the Modal Identification Method). Moreover some parameters have been adjusted through the use of experimental data e.g. the fitting of Bidirectional Reflectivity Distribution Function from measurements performed on tungsten samples or the automatic adjustment of camera model from an experimental image. Applied on WEST and W7x devices, IR synthetic diagnostic made it possible to prove the multiple reflections features in the experimental images.

A first inverse model has been also established using an analytical reduced-model of radiative transfer assuming diffuse surfaces. A first proof of concept applied on WEST has shown that the temperature profile on the divertor can be estimated with an accuracy better than 30% on colder target at 90℃ and better than 6% on peak temperature, which is a clear improvement compared to usual methods considering blackbody (BB) or pure emitter or yet with simple correction of reflected flux assuming uniform radiative black-body environment, as shown in figure below. Further improvements are under going to consider specular surfaces in the same time as it is investigated deep-learning neural network trained from synthetic data sets derived from forward models (RT codes or reduced-model).

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Session Classification: Thursday 2 Dec

Track Classification: Inverse Problems

Contribution ID: **55** Type: **Regular Oral**

TOWARDS IMPLEMENTING THE FAIR4FUSION OPEN DATA BLUEPRINT

Friday, December 3, 2021 2:20 PM (15 minutes)

TOWARDS IMPLEMENTING THE FAIR4FUSION OPEN DATA BLUEPRINT

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Abstract
The Euratom project "Fair4Fusion"aims to explore ways of addressing part of the Fusion community requirements regarding the accessibility and fair access to the fusion data. One of the main outputs of the project is a blueprint of the architecture that combines various elements in a way that simplifies discoverability and access to data. There are a number of elements from physical data storage, through communication channels, means of authorization and authentication to user focused interfaces - both based on Web UI and publicly available APIs. Some of these elements have been implemented as reference implementation. The paper presents these reference implementations - Demonstrator 1 (also known as Catalog QT 2) and Demonstrator 2 (exploring scalability and flexible searchability of time series for Fusion research).

These two demonstrators have different aims and therefore respond to different aspects of the blueprint. While Demonstrator focuses mostly on data acquisition, data presentation and validation of various means of exposing IMAS based data, Demonstrator 2 explores alternative technologies and approaches, especially in exploiting containerisation for adding flexibility and scalability to large-scale time-series searching and in workflow-based data transformation and analysis. Computational experiments were defined as compositions of containers, where each container provided an elementary tool for data transformation. The main advantage of defining an experiment as a transform-process-transform pipeline is the separation of DTW tool itself and steps being executed.

The paper presents design and implementation decision of the aforementioned demonstrators and discusses their position with respect to the further-reaching Fair4Fusion Open Data blueprint. It also showcases how loosely coupled components can be made to behave in concert, based on Docker-based technologies and on the composition of various containers.

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Session Classification: Friday 3 Dec

Track Classification: Big data

Contribution ID: **56** Type: **Regular Oral**

A Bayesian model of filamentary dynamics in MAST

Tuesday, November 30, 2021 3:00 PM (15 minutes)

A novel approach using Bayesian inference has been implemented using the Bayesian Framework Minerva to interpret the filamentary dynamics measured by a Langmuir probe fixed to a reciprocating assembly on MAST. The model describes the system as a superposition of time-displaced filaments and a fixed background component. Each filament is parameterised in terms of a characteristic rise and fall time and maximum amplitude centred on local maxima in the measured data time-series. A distinctive feature of the approach is that no minimum threshold is set for the existence of filaments. Furthermore, the model uncertainty is provided as an additional free parameter. It is observed that whereas large amplitude filaments are well characterised in terms
of rise times, smaller amplitude filaments are often unconstrained by the data and are limited by the details of the prior. Based on these findings, a new definition for the plasma filaments is proposed based on the uncertainty in the filament rise times. The remaining filaments together with the constant background component forms a new time-dependent signal referred to as the computed background fluctuation signal (shown in the figure below). The characteristics of these signals (for the plasma filaments and for the background fluctuations) are reported in terms of their
spatial variation as the probe moves through the SOL and into the core plasma.

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Session Classification: Tuesday 30 Nov

Track Classification: Applications of probabilistic inference and statistics

Contribution ID: **57** Type: **Regular Oral**

DEVELOPMENT OF A FAIR BASED APPROACH TO DATA MANAGEMENT AND SHARING WITHIN EUROFUSION

Friday, December 3, 2021 2:35 PM (15 minutes)

The European fusion research activities have over the last decades generated a vast and varied set of data. Even if a survey of the generated data is restricted to EUROFusion, the implementation of the fusion research programme under the EU Horizon 2020 framework programme, the volume and diversity of the data that need to be catalogued and reviewed make the task of organizing and making the data available very challenging. Nevertheless, there are strong scientific drivers as well as incentives and mandates from national research agencies suggesting that a more coherent approach to data dissemination and sharing would be very necessary for the fusion research community. In anticipation of stricter requirements on data management for the EUROfusion implementation within the 2021-2025 EURATOM programme both policies and technical implementations to facilitate a partial transition to open and FAIR (Findable, Accessible, Interoperable, and Reusable) data sharing are being developed within the continued European activities, guided by the principle "as open as possible, as closed as necessary".
Here, the progress and status of the work done in two related activities are reported: a) the EUROfusion Open Data Working Group and b) the Fair for Fusion project (funded under EURATOM). Together they cover the necessary and needed policy and technological elements to formulate a data management plan and propose a corresponding implementation plan. Restrictions on the scope of data being made available are being addressed, policies related to data access, data validation and embargo periods are discussed and the technical solutions proposed in relation to metadata description, persistent identifiers, data ingestion, and data access and exchange formats (IMAS based) as well as authentication and authorization are being motivated.
The proposed infrastructure has been developed based on several use cases covering both experimental and modelling data from different user perspectives: active, researchers, managers, and the general public. The researchers'point of view had a strong focus on multidevice access and the ability to do both searches on global quantities for the full range of supported devices and to make bespoke data collections based on a range of criteria covering both single and multiple devices. The proposed infrastructure lends itself well to data centric analytics work and these aspects are introduced and discussed in view of prototypes and demonstrators that have been designed

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Session Classification: Friday 3 Dec

Track Classification: Big data

Contribution ID: **59** Type: **Short Talks**

RESEARCHES ON THE RECONSTRUCTION ALGORITHM OF ELECTRON DENSITY PROFILES BASED ON MACHINE LEARNING TECHNIQUES

Thursday, December 2, 2021 1:35 PM (10 minutes)

The measuring conditions in Magnetic Confinement Fusion (MCF) devices are complex. Original diagnostic data of interferometer systems could be unreliable due to electromagnetic interference, mechanical vibration, and hardware failures. Obtaining accurate density profiles, which are reconstructed without the influence of incorrect data, are beneficial to the reliable feedback control of density and the stable long-pulse operation of fusion devices. In this project, machine learning techniques are introduced into the reconstruction of electron density profiles using the diagnostic data from the interferometer systems in EAST tokamak. This new algorithm could identify and sort correct and incorrect data in millisecond. Then the electron density profiles are calculated using the correct interferometer data and magnetic surfaces data. In this profile reconstruction algorithm, accurate density profiles are calculated without the influence of incorrect data, which is beneficial for the control system to obtain accurate distribution information of electron density. Meanwhile, this algorithm is robustness to the vacancy values in the input dataset. After identifying and removing incorrect data, globally optimal solutions could be solved out using residual correct data. This algorithm has a good application prospect in fusion data processing, and can be employed in the profile reconstruction of other diagnostic systems, which measure the line-integrated parameters of plasma in fusion devices.

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Session Classification: Thursday 2 Dec

Track Classification: Inverse Problems

Contribution ID: **60** Type: **Short Talks**

Update of the architecture for the implementation of the fusion FAIR data framework.

Monday, November 29, 2021 5:00 PM (10 minutes)

Currently, largely for historical reasons, almost all fusion experiments are using their own tools to manage and store measured and processed data as well as their own ontology. Thus, very similar functionalities (data storage, data access, data model documentation, cataloguing and browsing of metadata) are often provided differently depending on experiment. The overall objective of the Fair4Fusion project is to demonstrate the impact of making experimental data from fusion devices more easily findable and accessible. The main focus towards achieving this goal is to improve FAIRness of the fusion data to make scientific analysis interoperable across multiple fusion experiments. Fair4Fusion (F4F) is proposing a blueprint report that aims for a long term architecture for Fusion Open Data Framework implementation.
The proposed solution assume the use of the ITER Integrated Modelling & Analysis Suite (IMAS) Data Dictionary as a standard ontology for making data and metadata interoperable across the various EU experiments. The resulting architecture of the system consists of 3 main building blocks, namely Metadata Ingests, Central Fair4Fusion Services related to metadata and Search and Access Services as part of user facing. The paper presents an update on the blueprint developed in the last months. Besides updated technical architecture including the diagrams for important flows of operations, the analysis and license recommendations have been added. The recommendation, following the example of other major European projects, and EU guidelines, and after consulting with legal experts of labs involved in F4F is to use CC-BY-NC-SA license. The Blueprint is summarized with the roadmap of the implementation as well as technical and non-technical recommendations to implement FAIR and/or open data platform for fusion community.

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Session Classification: Monday 29 Nov

Track Classification: Data analysis preparation for ITER and Software Tools for ITER diagnostics

Contribution ID: **61** Type: **Regular Oral**

COMPARISON OF UNSUPERVISED METHODS TO DETERMINE COMMON PATTERNS IN THE TERMINATION PHASE OF DISRUPTIVE DISCHARGES IN JET

Wednesday, December 1, 2021 1:10 PM (15 minutes)

The general model of learning from data assumes that the examples are drawn independently from a fixed but unknown probability distribution function (PDF). In any system that generates a continuous data flow (data streaming setting), the PDF may change as the data are streaming. It is important to note that the new PDF is also unknown. Such changes in the data may convey interesting time-dependent information and knowledge and, in general, the changes can be seen as anomalies in the system evolution. There are methods that detect the changes in the data although the exact form of the PDFs remains unknown. The recognition of anomalies is used in the article to find common patterns in the termination phase of disruptive discharges. Two different techniques for anomaly detection are used: exchangeability test and unsupervised event detection and classification. Once anomalies are determined, the temporal segments between consecutive anomalies are classified in an unsupervised way and the different classes, obtained in the classification process, define the common patterns. The temporal evolution of the patterns close to the disruption will allow distinguishing the types of disruptions. The detection of anomalies has been applied to 78 disruptive discharges of JET corresponding to the C38 campaign. The discharges belong to shots of both the ITER baseline scenario (53 shots) and the ITER hybrid scenario (25 shots). The discharges are analysed from plasma breakdown to plasma extinction, looking for anomalies. Of course, not all anomalies are related to disruptions (for example switch on/off of plasma heating, gas puffing or changes in radiation patterns). Criteria have been established to identify anomalies related to disruptions. The two techniques mentioned above, which are founded on completely different mathematical principles, provide similar results in parameter spaces of dimension 22 (datasets of 22 plasma quantities). Both techniques require the optimisation of several parameters that will be discussed together with the common patterns found (about 5).

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Session Classification: Wednesday 1 Dec

Track Classification: Real time prediction of off-normal events, with particular attention to disruption and predictive maintenance

Contribution ID: **63** Type: **Short Talks**

An advanced plasma current tomography based on Bayesian inference and neural networks

Thursday, December 2, 2021 1:45 PM (10 minutes)

Recently, an advanced plasma current tomography has been constructed on EAST, which combines Bayesian probability theory and neural networks. It is different from the previous current tomography using CAR prior. Here, CAR prior is replaced with Advanced Squared Exponential kernel function (ASE) prior. It can solve the deficiencies on CAR prior, where the calculated core current is lower than the reference current and the uncertainty becomes serious after adding the error in the diagnostics. ASE prior developed from Squared Exponential kernel function (SE) by combining reference discharge. ASE prior adopts non-stationary hyperparameter and introduces the profile of current into hyperparameter, which can make the shape of current more flexible in space. In order to provide a suitable reference discharge, a neural network model has also been trained.

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Session Classification: Thursday 2 Dec

Track Classification: Inverse Problems

Contribution ID: **64** Type: **Short Talks**

DISRUPTION PREDICTION WITH DEEP HYBRID NEURAL NETWORK FEATURE EXTRACTOR DESIGNED SPECIFIC FOR TOKAMAK ON J-TEXT

Wednesday, December 1, 2021 4:30 PM (10 minutes)

Despite the rapid development in machine learning based disruption prediction, predicting disruptions across different tokamaks is still a great obstacle to overcome. Furthermore, ITER-like tokamaks can hardly tolerate disruptions at a large scale, which makes it very hard for current data-driven method to obtain an acceptable result. A machine learning method capable of transfering a disruption prediction model trained on one tokamak to another is required to solve the problem. The key is a model containing a feature extractor able to extract common disruption precursor traces in tokamak diagnostic data and a transferable disruption classifier. Currently, most deep learning based disruption prediction methods refer to neural network structure from some state-of-the-art computer vision models. However, the problem is that those networks are designed to extract image features, resulting in strong inductive bias on image data. On the other hand, tokamak diagnosis produce high dimensional heterogeneous time series data, which is very different from images. Based on the concerns above, the paper presents a deep "hybrid" neural network that is designed specifically for extracting disruption precursor features from common diagnosis on tokamaks, providing a promising foundation for transferable models.
The "hybrid"deep neural network feature extractor is designed according to the understanding of currently known precursors of disruption and their representations in common tokamak diagnosis. Both temporal and spatial features are considered. Different network structures are used to handle different features. Thus, strong inductive bias on tokamak diagnosis data is introduced to the model. The paper presents the evolution of the neural network feature extractor and its comparison against general deep neural networks, as well as a physics based feature extraction with a traditional machine learning method. At last, possible use cases in transfer a prediction model of the feature extractor are presented.

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Session Classification: Wednesday 1 Dec

Track Classification: Deep Learning

Contribution ID: **65** Type: **Short Talks**

Scalable Bayesian inference with model based machine learning

Wednesday, December 1, 2021 4:40 PM (10 minutes)

At large nuclear fusion experiments, plasma discharges are assessed through measurements collected with several diagnostic devices. Each instrument collects data generated in different physics processes: a consistent and efficient exploitation of the information contained in each different data source regarding a few common plasma parameters can be achieved with Bayesian inference. In Bayesian inference, a model of the physics processes generating the observations is prescribed. Such a model consists of physical assumptions and the quantification of the uncertainties with probability distributions regarding the model parameters prior to any observation and the predictive process. The former are described with a prior distribution, whereas the latter with a likelihood function. The product of these two distributions is known as the joint probability distribution of the model, which provides a comprehensive view of the distribution of the parameters and the observations which can be generated with the Bayesian model. The Minerva Bayesian modelling framework offers a modular environment where physics models of measuring devices and corresponding uncertainties can be implemented computationally as Bayesian models such that inference can be carried out on the available experimental observations. Conventional Bayesian inference algorithms such as Markov Chain Monte Carlo for sampling from the posterior distribution of the model parameters and Maximum A Posterior for point estimates of the most likely values are typically robust but slow, especially for computationally expensive forward models. Ideally, it would be desirable to have the soundness and integrity of Bayesian modelling and inference with the efficiency of fast machine learning algorithms, which modern artificial neural networks have demonstrated in different domains of science. This can be achieved by training neural networks on data sampled from a Bayesian model joint probability distribution. Networks trained on such data can learn to approximate different aspects of Bayesian inference: they can learn to reconstruct the model parameters given the observations, the observations given the model parameters and the posterior probability distribution values. Each one of these tasks has its own applicability in the acceleration of the Bayesian inference process. MAP point estimates, MCMC sampling and direct posterior sampling can be estimated with a properly trained neural network model in time scales of hundreds to thousands of microseconds. In principle, this allows to develop "real time"tools based on reliable Bayesian inference results. Moreover, the neural network predictions can also be adorned with uncertainties, calibrated in a Bayesian fashion, without introducing significant time delays. Finally, by leveraging on a common computational implementation of different Bayesian models within the Minerva modelling framework, it is possible to produce fast and approximate machine learning based representation of any model in an automatic fashion, independently of its specific features and implementation details. This method could therefore be thought as a general approach to make Bayesian inference a fast, scalable, and versatile modelling tool.

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Session Classification: Wednesday 1 Dec

Track Classification: Deep Learning

Contribution ID: **66** Type: **Short Talks**

DISRUPTION PREDICTION BASED ON PHYSICAL FEATURE EXTRACTION IN J-TEXT AND EAST

Wednesday, December 1, 2021 1:55 PM (10 minutes)

Disruption prediction has made rapid progress in recent years especially deep learning-based methods. Most of the current deep learning method use the raw or slightly progressed diagnostic data as the inputs. As deep learning is an end-to-end machine learning method, it requires little feature engineering. It can extract features from data if given enough. However, the diagnostic systems in different tokamak devices is not necessarily measured the same physical information. Even in the different period of the same device, the diagnostic systems also can be changed. We can hardly control the feature extracted by the deep learning model. This leads to the model performing well on the device it is trained on but perform poorly on new device. Also, there is no easy way to transfer a deep learning disruption predictor to new tokamaks. Moreover, the interpretability on these deep learning models is not very good as most results are in lower level raw signal space and has little physics meaning. In order to develop a cross machine disruption method, we need to build a portable model and use the model to derive new understanding about the cause of disruption.
In this work, we developed a set of physical feature algorithms. They can extract features from the diagnostic data in J-TEXT and EAST based on the understanding of MHD instabilities and disruption physics. These extracted features are used as the inputs of some traditional data-driven algorithms to build a disruption prediction model. Machine learning algorithms has been set up to train the disruption predict model by using these kinds of extracted physical features as inputs in J-TEXT and EAST. The model not just out performed our deep learning model but it also has much higher portability in cross machine test. This can serve as a foundation of the future cross machine disruption prediction model. Further model interpretation on J-TEXT and EAST prediction model can be carried out to deepen understanding of disruption mechanism as the input features of the models have clear physics meanings.

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Session Classification: Wednesday 1 Dec

Track Classification: Real time prediction of off-normal events, with particular attention to disruption and predictive maintenance

Contribution ID: **67** Type: **Regular Oral**

IMAS - INTEGRATED WORKFLOW FOR ENERGETIC PARTICLE STABILITY

Friday, December 3, 2021 1:25 PM (15 minutes)

Previous analyses show that various Alfven Eigenmodes (AEs) can be partially unstable in ITER: energetic particles (EPs), such as fusion-born alpha-particles or neutral beam ions are energetic enough to resonantly interact with these weakly damped plasma waves. Due to the sensitivity of the AEs'properties on the background kinetic profiles, an automated analysis method is required to study their stability that does not rely upon prior knowledge of the linear mode spectrum, as is the case for most reduced models for EP transport.

In the paper, the first automated time-dependent workflow for energetic particles stability analysis within the Integrated Modelling & Analysis Suite (IMAS) (Python-based) is presented. The workflow orchestrates the retrieval and storage of Interface Data Structures (IDSs) as well as their passing between the physics actors involved: the equilibrium code HELENA and the linear gyro-kinetic stability code LIGKA. In order to demonstrate the capabilities of the workflow, 4 scenarios were chosen from the many available in the ITER - IMAS database. Two of them are time-independent (given by the ASTRA transport code) and two are time-dependent (given by METIS). Both Pre-Fusion Power Operation (PFPO) hydrogen plasmas and Q=10 D-T scenarios are investigated. An analysis of the linear mode properties such as frequency, damping rates and mode structures of various modes present in this scenario is performed to verify and validate various parts of the workflow. A hierarchy of models (analytical, local, global) is employed in sequence, and the results of each model are stored in the IMAS database for documentation and comparison. Fig. 1 shows an example of a series of time-dependent local runs for the two branches (m=21 and 22) of an n=20 TAE: the most unstable phases are expected during ramp-up and ramp-down due to reduced damping during these phases. With the help of the workflow, the calculations can be performed in an automatic way, with controlled input and output in order to ensure reproducibility and consistency. Presently, the WF is also ported to different architectures and various experiments (TCV, ASDEX-Upgrade).

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Session Classification: Friday 3 Dec

Track Classification: Integrated Data Analysis

Contribution ID: **68** Type: **Regular Oral**

Synthetic diagnostics tools for identification of the L-H transition in ITER PFPO campaigns

Friday, December 3, 2021 1:10 PM (15 minutes)

This paper summarizes the development of software tools to detect the approach to the L-H transition in ITER PFPO (Pre-Fusion Power Operation) scenarios. In particular, it describes to what extent the physical phenomena associated with the L-H transition can be characterized using the set of diagnostics available in PFPO. The H-mode is associated with the development of an edge transport barrier, which guarantees higher temperatures and densities at the plasma core with strong gradients at the edge. At the same time as the confinement improves, the power distribution on the first wall and divertor targets changes. These effects can be detected by temperature and density diagnostics, as well as by diagnostics of energy deposition on the plasma facing components. The list of relevant ITER diagnostic systems includes microwave diagnostics (reflectometry, refractometry, ECE), interferometry, spectroscopic diagnostics, thermography, bolometry and Langmuir probes.

Before the start of ITER operation and the availability of experimental data, synthetic diagnostics can be used to simulate measurements given the plasma parameters from predictive simulations and the configuration of each diagnostic system. Synthetic diagnostics can be used to support diagnostic design by modelling their performance in various scenarios, to support the development of controllers, and for physics studies such as in this paper. The assessment of the L-H transition detection uses advanced core and edge transport solvers like ASTRA, JINTRAC and SOLPS-ITER. The simulation results and the machine descriptions are unified within the IMAS (Integrated Modelling and Analysis Suite) framework and the synthetic diagnostics are adapted to use standard Interface Data Structures (IDSs) for data exchange. The paper will cover the development and application of the ITER synthetic diagnostics workflow, including components like DIP_TIP (interferometry), CASPER (spectroscopy) and ECRad (ECE).

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Session Classification: Friday 3 Dec

Track Classification: Integrated Data Analysis

Contribution ID: **69** Type: **Regular Oral**

Offline automated model predictive control of SOLPS-ITER plasma edge simulations

Tuesday, November 30, 2021 12:15 PM (15 minutes)

Reduced models of SOLPS-ITER plasma edge simulations are deployed in the time-dependent model predictive control of upstream and downstream divertor conditions. Virtual main ion and impurity gas puffs actuate the simulated tokamak boundary based on predictions obtained from the dynamic mode decomposition (DMD) and the Sparse Identification of Nonlinear Dynamics (SINDy) data-driven techniques. Equations governing the time evolution of the plasma state are extracted from an expansive database of transport runs configured to the DIII-D experiment and mediated by actuation sequences probing system response. An automated algorithm is developed to scan a running series of simulation data that enables training and testing of reduced models capable of a prediction horizon within a cross-validated error threshold. With the computationally inexpensive DMD and SINDy procedures, an offline evaluation of model predictive control of the expensive SOLPS-ITER code is presented. The optimal actuation sequence required to produce a target trajectory, subject to physical constraints on the input and output signals, is determined for static and variable setpoints. Baseline feedforward control with gas puff actuators has been found to agree well with the dynamics of the upstream separatrix density and modifications to DMD and SINDy have allowed adequate control of the noisy downstream divertor target temperature. The data-driven approach to model predictive control described in the paper is being implemented as a module that can be utilized within SOLPS-ITER in an online manner for performing simulations. In addition, the results are being validated against analytic and empirical correlations of key observables from experiments for application to future device designs.

Work supported by US DOE under contract numbers DE-AC05-00OR22725 and DE-FC02-04ER54698.

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Session Classification: Tuesday 30 Nov

Track Classification: Data Analysis for Fusion Reactor

Contribution ID: **70** Type: **Short Talks**

Informed Sampling of the Plasma Hyperspace for Digital Twinning

Tuesday, November 30, 2021 12:45 PM (10 minutes)

Digital twins capable of predicting plasma evolution ahead of plasma progression within a Tokamak is a crucial tool required for real-time plasma intervention and control. Considering speed and scale required, quite often these have to be purely data conditioned models as opposed to being physics conditioned, making data selection a vital component of model efficacy. However, as we move to the exascale regime, the amount of data generated tends to choke the data pipelines, introducing latency to the model. It might also be the case that some of the data available might be redundant and creating imbalances within the training dataset. In this work we demonstrate a machine learning pipeline that maps out in hyperspace the distributions of the plasma behaviours within a specific campaign. The embedding created through dimensionality reduction within the pipeline is then used as the sampling space for the training dataset for a Convolutional LSTM that maps the control signals to diagnostic signals in a sequential manner. We primarily experiment with MAST data with the control signals being plasma current, toroidal magnetic field, plasma shape, gas fuelling and auxiliary heating. The diagnostics of interest are the core density and temperature as measured by the Thomson scattering diagnostic. With initial focus on a single experimental campaign (M7), we demonstrate that our predictive model trained on all available data is capable of achieving a mean squared error of 0.0285. However, our pipeline demonstrates that by using a distance based informed sampling method to gather only 10 percent of the dataset we can achieve a comparable mean squared error of 0.0293.

We further demonstrate the robustness of the pipeline by extending the model to operate within the space of the M9 campaign in addition to the M7 campaign. Our work shows that a predictive model trained on all of the available data across both campaigns achieves a mean squared error of 0.0279, while the one sampled using the knowledge garnered from the cluster representations (mapped individually across each campaign) achieves an L2 error of 0.0282, while only relying on 10 percent of the dataset. We also engage with standard continual learning practices such as elastic weight consolidation and deep generative replay to move the model across various campaign data and cross reference against our pipeline.

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Session Classification: Tuesday 30 Nov

Track Classification: Data Analysis for Fusion Reactor

Contribution ID: **71** Type: **Regular Oral**

DEVELOPMENT OF THE ITER SYNTHETIC REFLECTOMETRY DIAGNOSTIC

Thursday, December 2, 2021 4:00 PM (15 minutes)

Reflectometry will be used in ITER to measure the electron density profile and to provide key information of the density fluctuations. There are two reflectometry systems, one at the high magnetic field side (HFS) and one at the low field side (LFS).

The synthetic diagnostic (SD) for both reflectometry systems is being developed, with a goal of modelling the reflected signals for ITER baseline discharges. The estimation of the core and edge density profile will be simulated using the HFS and the LFS SD reflectometers, correspondingly. The paper describes a structure of the SD reflectometry, which consists of blocks, representing different parts of the real diagnostic scheme. There are modules that include simulation of a microwave source, a single side band modulator, frequency multipliers, a transmission line, an IQ detector, analog-to-digital converters, antenna, augmented along with a plasma-wave interaction modelling and the data processing.

The tasks of the reflectometry synthetic diagnostics involve evaluation of optimum measurement parameters and techniques for different plasma scenarios, development & optimization of data analysis algorithms and simulation of data reconstruction incorporated to the ITER modelling database (IMAS). Results of this work will contribute to the optimization of reflectometry systems measurement capabilities, which is important for ITER plasma control and operation, as well as for physics study.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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Session Classification: Thursday 2 Dec

Track Classification: Synthetic Diagnostics, Integration, Verification and Validation

Contribution ID: **73** Type: **Regular Oral**

Normalizing flows for likelihood-free inference with fusion simulations

Tuesday, November 30, 2021 3:15 PM (15 minutes)

Fluid based scrape-off layer transport codes such as UEDGE are heavily utilized in tokamak analysis and design, but typically require user-specified anomalous transport coefficients to match experiment. Determining uniqueness of these parameters and the uncertainties in them to match experiments can provide valuable insights to fusion scientists. We leverage recent work in the area of likelihood-free inference ("simulation-based inference") to train a neural network which enables accurate statistical inference of the anomalous transport coefficients given experimental plasma profile input. UEDGE is treated as a black-box simulator, and run multiple times with anomalous transport coefficients sampled from priors, and the neural network is trained on these simulations to emulate the posterior. The neural network is trained as a normalizing flow model for density estimation, allowing it to accurately represent complicated, high-dimensional distribution functions. We discuss important implementation details such as the use of summary statistics and the number of simulations needed for good results. We also discuss the future possibilities for use of amortized models which train on a wide range of simulations and enable fast statistical inference for results during experiments.

This work is funded through the SciDAC program by the U.S. Department of Energy, Office of Fusion Energy Science and Office of Advanced Scientific Computing Research under contract No. DE-AC02-09CH11466 with Princeton University f

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Session Classification: Tuesday 30 Nov

Track Classification: Applications of probabilistic inference and statistics

Contribution ID: **74** Type: **Regular Oral**

Single Gaussian process method for profile fitting in arbitrary tokamak regimes

Tuesday, November 30, 2021 12:30 PM (15 minutes)

Gaussian Process Regression (GPR) is a Bayesian method for inferring profiles based on input data. The technique is increasing in popularity in the fusion community due to its many advantages over traditional fitting techniques including intrinsic uncertainty quantification and robustness to overfitting. Most fusion researchers to date have utilized a different GPR kernel for each tokamak regime. This requires a Machine Learning (or simpler) method to first predict the regime, choose the right kernel for that regime, and then use that kernel. The disadvantage of this method is that it requires an additional step, and it is unclear how well it will behave if the plasma enters a new, unexpected regime. We summarize our work developing a general kernel for all regimes (including radially-varying hyperparameters via a non-stationary change-point kernel), utilizing heavy-tailed likelihood distributions to automatically handle data outliers, and using GPFlow 1 for full Bayesian inference via Markov chain Monte Carlo to sample hyperparameter distributions. We present a single GPR method that is robust across many different tokamak regimes and a wide range of data inputs and quality.

1 GPFlow: A Gaussian process library using TensorFlow. Journal of Machine Learning Research. 2017.

Work supported by US DOE under DE-SC0021203, DE-SC0021380, and DE-FC02-04ER54698.

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Session Classification: Tuesday 30 Nov

Track Classification: Data Analysis for Fusion Reactor

Contribution ID: **76** Type: **Regular Oral**

Energy confinement scaling with machine size in the updated ITPA global H-mode confinement database

Tuesday, November 30, 2021 3:30 PM (15 minutes)

The well-known IPB98 scaling law for the energy confinement in tokamak H-mode plasmas has recently been revised. A considerably larger data set was used for estimating the scaling, including data from devices with fully metallic walls (JET and ASDEX Upgrade). In order to facilitate comparison with IPB98, the new scaling was estimated using a simple power-law model. Like its predecessor, the new ITPA20-IL scaling can be used as a benchmark for experiments, for setting boundary conditions in modelling codes and for extrapolation to ITER-like devices. Particular attention was paid to establishing practically useful uncertainty estimates on the scaling parameters and predictions, in order to account for model uncertainty. Considering these error estimates, the dependence of the confinement time on several predictor variables turns out to be rather weak. Nevertheless, one key difference with the '98 scaling is the significantly weaker dependence on machine size, from quadratic to slightly stronger than linear. The present work is aimed at clarifying the cause for this weaker size scaling. To do this, the influence on the size scaling is investigated by analysing the data points that were added to the most recent iteration of the database. In particular, we explore the effect specific regions of the operational space have on the scaling.

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Session Classification: Tuesday 30 Nov

Track Classification: Applications of probabilistic inference and statistics

Contribution ID: **77** Type: **Regular Oral**

Reduced transport model development informed by machine learning tools

Wednesday, December 1, 2021 3:50 PM (15 minutes)

The TGLF model is a quasi-linear model of transport driven by gyrokinetic turbulence. A reduced velocity space moment linear eigensolver is used, which is calibrated to first principles linear calculations. The saturation rule for the intensity of the fluctuations is fit to 3D spectra of nonlinear gyrokinetic simulations with the CGYRO code. TGLF is never fit to experiment so that it can be used to test the gyrokinetic theory over large datasets and predict plasma profiles with a transport code. A new approach to testing TGLF flux predictions (not plasma profile predictions) with a very large database of DIII-D discharges, which have been curated to remove cases where gyrokinetic transport should not apply, has been completed. This database contains experimental profiles and power balance analyses, and was generated using automated workflows within the Python based data analysis suite OMFIT. A novel way to identify the experimental input parameters that are associated with the largest differences between TGLF energy fluxes and experimental power balance fluxes will be reported here. This identification will help direct the choice of nonlinear gyrokinetic turbulence simulations to perform with the CGYRO code to improve the fidelity of TGLF to CGYRO or to confirm disagreement of gyrokinetics with experiment. As a first step, the TGLF model for the intensity spectrum is multiplied with a hypothetical correction factor that is sensitive to the overall shape of the intensity spectrum and computed by a neural network trained on the experimental database. Symbolic regression tools find the main elements of this correction factor. This process resulted in a power law form with plasma parameters that typically are associated with trapped electron mode turbulence. These identified plasma parameters will be used to direct new CGYRO gyrokinetic database simulations to efficiently cover the least accurately covered operational space of present and future devices.

Country or International Organisation

United States of America

Affiliation

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Presenter: NEISER, Tom F. (General Atomics)

Session Classification: Wednesday 1 Dec

Track Classification: Deep Learning

Contribution ID: **78** Type: **Invited Oral**

Bayesian Inference of Experimental Particle Transport in Tokamak Plasmas

Tuesday, November 30, 2021 2:05 PM (25 minutes)

Impurity and neutral particles play a critical role in tokamak core-edge integration. This motivates close examination of state-of-the-art transport models and comparison of their predictions with experiments using modern computational statistics tools. Here we present a High Performance Computing (HPC) framework for fully-Bayesian inferences of particle diffusion and convection profiles and its application to both Alcator C-Mod and DIII-D plasmas without ELMs. Our inferences make use of the new Aurora package (https://aurora-fusion.readthedocs.io/en/latest/), developed to permit 1.5D forward modeling of impurity transport using new high-fidelity open-source code. Aurora simulations of Laser Blow-Off (LBO) injections of Ca, Al, and F are used to illustrate discrepancies between experimental inferences and theoretical modeling with neoclassical (NEO) and turbulent (TGLF, CGYRO) codes in cases where flat or hollow impurity profiles are observed in experiments. These C-Mod and DIII-D inferences leverage a number of new spectroscopic analysis and statistical techniques, including forward-modeling of the entire Ca K-alpha spectrum, simulation of multiple atomic species, and use of non-separable priors. Extensive modeling capabilities have been made public via the OMFIT framework (https://omfit.io/index.html).

This material is based upon work supported by the Department of Energy under Award Numbers DE-SC0014264, DE-FC02-04ER54698, DE-SC0007880.

Country or International Organisation

United States of America

Affiliation

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Presenter: SCIORTINO, Francesco (MIT)

Session Classification: Tuesday 30 Nov

Track Classification: Applications of probabilistic inference and statistics

Contribution ID: **79** Type: **Invited Oral**

EMPIRICAL MODELING OF KINETIC PROFILE SHAPES USING NEURAL NETWORKS

Wednesday, December 1, 2021 3:10 PM (25 minutes)

Between-shots and real-time actuator trajectory planning will be critical to achieving high performance scenarios and reliable, disruption-free operation in present-day tokamaks, ITER, and future fusion reactors. Such tools require models that are both accurate enough to facilitate useful decision making and fast enough to enable optimization algorithms to meet between-shots and real-time deadlines. Both problems can be addressed with machine learning approaches. First, well-validated physics models can be used to train surrogate models that maintain high-fidelity at reduced computational complexity. For quantities that are not accurately modeled by available physics modules, machine learning can applied to available experimental databases to create fast empirical models. Combining the two approaches allows for predictive scenario modeling using high-fidelity physics models where available, and empirical models where necessary, with real-time relevant execution times.

The paper reports on a new empirical model for predicting kinetic profile shapes in tokamaks using neural networks. The model has been trained and tested on measured profiles from experimental discharges. Models have been developed for NSTX-U and NSTX electron pressure and density, as well as DIII-D electron/ion pressure/density and toroidal rotation. By projecting profiles onto empirically derived basis functions, the model is able to efficiently and accurately reproduce profile shapes. It has been found that the profile shapes can be quite accurately predicted with only scalar parameters as input, using no detailed source information or time history. This simplifies the profile prediction problem to specification of plasma current, boundary shaping descriptors, and prediction of volume averages of energy, density, and momentum. The latter can be modeled with a confinement scaling or other empirical models. A large database of profiles from the operation of NSTX has been used to test performance as a function of available data. It is found that the model learns quickly and shows promise for use in guiding exploration of operating space. The rapid execution time of the model is well suited to the planned applications, including optimization during scenario development activities, and real-time plasma control. A potential application of the model to real-time profile estimation is demonstrated.

Country or International Organisation

United States of America

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Session Classification: Wednesday 1 Dec

Track Classification: Deep Learning

Contribution ID: **80** Type: **Regular Oral**

SPATIO-TEMPORAL DETECTION AND TRACKING OF THERMAL EVENTS ON THE PLASMA FACING COMPONENTS OF WENDELSTEIN 7-X

Wednesday, December 1, 2021 2:55 PM (15 minutes)

In steady-state fusion devices like Wendelstein 7-X (W7-X), the active control of heat loads is mandatory to attain long-plasma operation. An intelligent feedback control system that mitigates the risk of overheating is required to avoid a premature plasma termination by the safety system. To keep the plasma within the safe operational limits of the plasma facing components, the feedback control system must be informed of the ongoing thermal events and their evolution in time. Then it can take effectives countermeasures to prevent the thermal events from reaching a critical point. These countermeasures may include reducing the heating power, changing the strike-line position or inducing detachment. With reaction times of the order of a hundred milliseconds, a fully automated real-time image analysis algorithm is required.

In this work, we present a spatio-temporal algorithm to detect, classify and track the thermal events observed by the thermography diagnostic on the plasma facing components of W7-X. The system detects and distinguishes between strike-lines and isolated hot spots as well as leading edges. The segmentation of the strike-line is specially challenging at W7-X. As a 3-dimensional helically-shaped stellarator equipped with 10 island divertors, the strike-lines have a complex heat load distribution with a high-dynamic range. The use of morphological tools and, in particular, the use of the Max-tree transform allow us to segment the thermal events in a hierarchical way preserving the inclusion relationship between different events, like hot spots and leading edges embedded in the strike-line structure. The thermal events are segmented for each frame and tracked over time in order to forecast their temporal evolution and to evaluate their risk. To this end, a spatio-temporal graph is built and spatio-temporal connected components are used to track the thermal events across the sequence frames. The spatio-temporal components in the graph are used to label the events in the sequence preserving temporal coherence and minimizing discontinuities, solving splits and merges. Spatio-temporal descriptors are then generated for each event to assess their risk.

The algorithm was tested offline on the infrared data acquired during the last operation phase OP1.2 and the results are presented here. Further work will follow to accelerate the code with GPUs to reach real-time processing and be ready to protect the water-cooled plasma facing components in the forthcoming operation phase OP2.

Country or International Organisation

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Session Classification: Wednesday 1 Dec

Track Classification: Image Processing

Contribution ID: **81** Type: **Regular Oral**

DATA-DRIVEN DISCOVERY APPROACH TO TACKLE TURBULENCE IN FUSION PLASMA

Friday, December 3, 2021 2:50 PM (15 minutes)

DATA-DRIVEN DISCOVERY APPROACH TO TACKLE TURBULENCE IN FUSION PLASMA

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Abstract

The identification of turbulence sources could prove to be advantageous for a deeper understanding of dynamics in magnetic confinement in fusion devices. The aim of this work is to obtain a database from reflectometry (a technique based on the radar principle) raw signals, ready to be analyzed with the purpose of investigating turbulence behavior and its dynamics.

A systematic study, based on data from the Tore Supra tokamak, has been carried out as part of a PhD (Yan Sun's work) in order to extract general trends according to a set of parameters (from thousands of parameters to eleven associated with the frequency spectrum decomposition). The spectrum decomposition follows models as Generalized Gaussian function and Lorenztian function and there are 4 components: Carrier component, Low frequency fluctuations, Broadband turbulence and the noise. However, despite the significant parameter reduction, this systematic study has some limitations as the assumption of stationary turbulence and the setting of the component frequency threshold and range in advance.

This study is born out of the necessity of removing the ad-hoc frequency range of the components, overcoming these stationary issues and thereby enabling a description of the energy exchange among of the different components in a context of non-stationary turbulence.

The main idea is to combine the approach of signal processing with artificial intelligence: the continuous wavelet transform has proven to be efficient in providing a decomposition of signal at different scales over time. The time-scale representation (image) produced enables the visualization of some patterns evolving with the time. These patterns are present on a range of defined scales, avoiding setting the frequency range in advance; the convolutional auto-encoder neural network is responsible for taking these produced images for automatic identification of every pattern. This automatic process is based on threshold learning, with a large quantity of signals.

This current study aims to remove smartly the identified patterns in order to get a "clean-up" frequency spectrum, making it possible to focus only on the Broadband turbulence component, more precisely on its internal structure and dynamics.

This intelligent process has the potential to make a turbulence source(s) identification (frequency ranges) and their interplay in real-time, so this can be applied to data from the West tokamak in

the near future.

Country or International Organisation

France

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Presenter: Mr SALAZAR, Luigui

Session Classification: Friday 3 Dec

Track Classification: Big data

Contribution ID: **82** Type: **Regular Oral**

Bringing Anomalous Transport Models to the TRANSP Code as IMAS Components

Monday, November 29, 2021 4:45 PM (15 minutes)

The ITER Integrated Modeling and Analysis Suite (IMAS) is utilized in this research to develop a generalized approach to transport model implementation in the TRANSP code 1. Similar to the efforts in the European Transport Simulator (ETS) 2, the transport models in TRANSP will communicate with all other components through the Interface Data Structures (IDSs) that are defined in the IMAS Data Model. The Multi-Mode Model (MMM) v8.2 [3] for anomalous transport has been selected for testing and initial implementation of the new interface to IDSs. The *core_profiles* and *equilibrium* IDSs are used to initialize the model, and the *core_transport* and *gyrokinetic* IDSs are used for the model output. Using these three IDSs, the MMM v8.2 model communicates with other relevant modules such as the equilibrium and transport solvers. In this work, we also demonstrate how to utilize the new IMAS interface for the stability analysis of experimental data and for the neural network development for MMM v8.2. For these tasks, the experimental data and kinetic equilibrium reconstructions come from the OMAS interface in OMFIT [4], which is connected to several experimental databases. This capability provides an opportunity to test the IMAS interface for anomalous transport models using the experimental data from several tokamaks until direct IMAS plugins for these tokamaks are developed. The experimental data are being saved in a local IMAS database and retrieved by a standalone MMM v8.2 driver program. The stability analysis of experimental data and neural network model development can be substantially accelerated with this workflow.

1. J. Ongena, M. Evrard, D. McCune, Numerical Transport Codes, in the Proceedings of the Third Carolus Magnus Summer School on Plasma Physics, (Spa, Belgium, Sept 1997), as published in Transactions of Fusion Technology, March, 1998, **33** No. 2T, pp. 181-191.
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4. O. Meneghini, S.P. Smith, L.L. Lao, O. Izacard, Q. Ren, J.M. Park, J. Candy, Z. Wang, C.J. Luna, V.A. Izzo, B.A. Grierson, P.B. Snyder, C. Holland, J. Penna, G. Lu, P. Raum, A. McCubbin, D.M. Orlov, E.A. Belli, N.M. Ferraro, R. Prater, T.H. Osborne, A.D. Turnbull, G.M. Staebler, and the AToM Team [Integrated Modeling Applications of Tokamak Experiments with OMFIT] Nuclear Fusion **55** (2015) 083008.

Country or International Organisation

United States of America

Affiliation

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Presenter: PANKIN, Alexei (Princeton Plasma Physics Laboratory)

Session Classification: Monday 29 Nov

Track Classification: Data analysis preparation for ITER and Software Tools for ITER diagnostics

Contribution ID: **83** Type: **Regular Oral**

DEVELOPMENT OF SYNTHETIC DIAGNOSTICS FOR ITER

Friday, December 3, 2021 12:15 PM (15 minutes)

The development of Synthetic Diagnostics for ITER is essential to optimise the design of the diagnostics, to develop the necessary control algorithms utilising them, and to perform specific physics studies, including integrated data analysis, for each phase of the ITER Research Plan. The work will involve the standardised approach of the Integrated and Modelling & Analysis Suite (IMAS) with the Plasma Control System Simulation Platform (PCSSP) focused on controlling the plasma behaviour and optimising its performance: the signals sent by the diagnostics provide the necessary information to the PCSSP for adjusting the instructions sent to the actuators (heating and current drive, fuelling, etc.) to keep the plasma stable according to the scenario as defined in the pulse schedule.
Developing synthetic diagnostics using the standard IMAS Data Model ensures portability and a more flexible use within different workflows, as well as supporting better traceability and reproducibility of the data generated, providing a robust modelling procedure. Requirements on the performance of each model depends on its application. For example, for dedicated physics studies, physics fidelity and accuracy is favoured, while for the use of models in faster-than-real-time transport suites, computation speed is an essential factor. Various synthetic diagnostic models are available fulfilling the criteria for specific applications, but all have a common requirement: in order to be exploitable within the IMAS/PCSSP platform, they have to follow the IMAS standard, i.e. they have to exchange Interface Data Structures (IDSs) exclusively as input and output. This way, they can take their input from the Scenario and Machine Description databases and provide their output into an IDS specific to the type of the diagnostic, facilitating the comparison and coupling between models.
Using the IMAS standard has permitted the development of a workflow that can generate synthetic diagnostic data from ITER scenario simulations and which encompasses all the various synthetic diagnostic models currently available, providing generality and modularity. A specific example with models for visible spectroscopy is described, in which a single code called CASPER (for CAmera and SPectrocopy Emission Ray-tracer) provides light spectra for all synthetic diagnostic models downstream (Charge Exchange Recombination Spectroscopy, Visible Spectroscopy Reference System, H-alpha, Divertor Impurity Monitor etc.)
Several other Synthetic Diagnostics are already available in IMAS. Examples will be shown of IMAS models developed for Interferometry, Refractometry, Bolometry, Neutron flux monitors, and Visible Spectroscopy. The workflow for Synthetic Diagnostics, still under development, will also be presented. It is based on the same concept as the IMAS H&CD workflow, with a possibility to define different and dynamic time bases for each synthetic diagnostic model independently. Each code propagates its own bundle of IDSs to avoid conflicts when different models require the same input IDS type with different data (e.g. different detector geometries). Mergers are defined to save a unique IDS as output, containing the synthetic signals from the various models.
The development of synthetic diagnostics is a coordinated activity with contributors from across the ITER Members. The strategy for this development within the various phases of the ITER Research Plan will be shown. Ultimately, these models will be combined in an integrated approach to data analysis to deliver a robust interpretation of ITER experimental data.

Country or International Organisation

France

Affiliation

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Session Classification: Friday 3 Dec

Track Classification: Synthetic Diagnostics, Integration, Verification and Validation

Contribution ID: **86** Type: **not specified**

Round table Discussion

Hosted by D. Mazon

Session Classification: Monday 6 Dec

Contribution ID: **87** Type: **not specified**

Conference Closure; Hosted by Sehila Gonzalez

Monday, December 6, 2021 2:30 PM (10 minutes)

Contribution ID: **88** Type: **not specified**

Introduction to IMAS

Monday, November 29, 2021 12:10 PM (1 hour)

Presenter: PINCHES, S.

Session Classification: Monday 29 Nov

Contribution ID: **89** Type: **not specified**

Introduction to Scientific Machine Learning and Deep Learning

Monday, November 29, 2021 1:30 PM (1 hour)

Presenter: CHURCHILL, M.

Session Classification: Monday 29 Nov

Contribution ID: **90** Type: **not specified**

Introduction to Bayesian methods and their use in fusion data analysis

Monday, November 29, 2021 2:30 PM (1 hour)

Presenter: VERDOOLAEGE, G.

Session Classification: Monday 29 Nov

Contribution ID: **91** Type: **Tutorial**

Demonstration of the FAIR4Fusion Data Discovery and Access Portal

Monday, November 29, 2021 1:10 PM (20 minutes)

Country or International Organisation

Affiliation

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Presenter: DE WITT, Shaun (UKAEA)

Session Classification: Monday 29 Nov

Contribution ID: **92** Type: **Invited Oral**

Introductions to Digital Twin and Knowledge Graph Applications at Zhejiang Lab

Monday, December 6, 2021 12:00 PM (30 minutes)

Country or International Organisation

Affiliation

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Presenter: JIA, W. (Zhejiang LAB)

Session Classification: Monday 6 Dec

Contribution ID: **93** Type: **Invited Oral**

UNSUPERVISED LEARNING FOR LATENT DATA ANALYSIS USING SOURCE SEPARATION

Monday, December 6, 2021 12:30 PM (30 minutes)

Country or International Organisation

Affiliation

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Session Classification: Monday 6 Dec

Contribution ID: **94** Type: **Regular Oral**

CLASSIFYING AND LOCATING ALFVÉN EIGENMODES IN TOKAMAK PLASMAS BASED ON A HIGH RESOLUTION ECE DIAGNOSTIC AT DIII-D USING DEEP NEURAL NETWORKS AND IMAGE PROCESSING TECHNIQUES

Monday, November 29, 2021 3:45 PM (15 minutes)

Physics understanding of fusion plasmas has made significant advances, but further progress towards steady-state operation is challenged by a host of kinetic and MHD instabilities. Alfvén eigenmodes (AE) are a class of mixed kinetic and MHD instabilities that are important to identify and control because they can reduce confinement and potentially damage machine components. In the present work, we utilize an expert-labeled database of DIII-D discharges and use (deep) recurrent neural networks such as reservoir computing networks (RCN) to classify five types of AE modes, namely, BAE, EAE, LFM, RSAE and TAE. To deploy the model on a high-throughput FPGA accelerator for integration in the real-time plasma control system, we consider a data processing pipeline with minimum complexity. We trained a simple yet effective RCN on 40 raw ECE diagnostic channels down-sampled from 500 kHz to only 2 kHz. Our experiments show that such a model achieves a true positive rate of 91% with a false positive rate of only 7%. Moreover, as a preliminary step towards locating Alfvén eigenmodes spatially inside the plasma, we focus on processing the ECE spectrograms, which naturally have high levels of noise. State-of-the-art deep learning techniques for enhancing the images need to see both noisy and clean versions of the data during the training, which is not feasible in the current application. To alleviate this issue, we first employ a pipeline of existing image processing techniques to partially denoise the spectrogram. The output of this pipeline is then considered as a target for autoencoders to further enhance the spectrograms. These enhanced images are used to develop spatio-temporal data-driven models in a real-time control strategy for detecting shape and location of instabilities inside the plasma.

Country or International Organisation

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Session Classification: Monday 29 Nov

Track Classification: Data analysis preparation for ITER and Software Tools for ITER diagnostics