Introduction and content

- yesterday’s session motivates this session
- division between “disruption avoidance/prevention” and “disruption prediction” is artificial
- 10 invited talks + 10 oral talks; all excellent (clear and interesting) contributions; this summary cannot replace watching/reading contributions
- some threads behind summary; summary index
- summary
Scenario development

Plasma control

Theory, Modeling, extrapolating

Data analysis, ML tools, statistics, physics

Disruption avoidance/prevention
Prediction (A&P)
DMS trigger generation
Evolving disruption A&P needs

existing device \rightarrow \text{ITER half } I_p \text{ and } B_t \rightarrow \text{ITER high } I_p \rightarrow \text{DEMO and FPP)

- e.g. allow/plan disruptions;
- experiment and expand PCS;
- training NN on one device w dimensioned variables for device protection;
- data analysis and education;
- complex PCS with several layers of decisions/competences
- few diagnostics survive neutron environment;
- no disruptions allowed \rightarrow \text{scenario must be controllable and stable (existence?)};
- stripped-down PCS and device
ITER scenario development, plasma control, physics

F. Turco. Scenario optimization and instability monitoring to reach Q=10 ITER mission without disruptions

Plasma control, disruption avoidance, scenario development, data analysis

D. Humphreys. Design of the ITER PCS for disruption prevention and mitigation

A. Pau. Off-normal event-detection and NTM-control for integrated disruption avoidance and scenario control

J. Barr. Control solutions supporting disruption free operation on DIII-D and EAST

M. Maraschek. Prevention of the H-mode density limit by various heating schemes through control of the plasma state space

Scenario development towards DEMO and FPP

F. Janky. Controlling a burning plasma in the DEMO tokamak away from disruptive events

L. Zakharov. Does a tokamak have a chance to avoid disruptions?

Data analysis, methods and tools, physics

Steven Sabbagh. Progress on tokamak disruption event characterization

E. Kolemen. RT prediction and avoidance of fusion plasma instabilities using feedback control

C. Rea. Interpretable data-driven disruption predictors to trigger avoidance and mitigation actuators on different tokamaks

J. Zhu. A hybrid deep learning architecture for general disruption prediction across tokamaks

K. Montes. Accelerating disruption database studies with semi-supervised learning

M. Fontana. Real-time applications of ECE interferometry for disruption avoidance in JET

D.R. Ferreira. Identifying disruption precursors by anomaly detection on bolometer tomography

M.J. Choi. 2D Te patterns of various disruptive events

R. Nies. RF current condensation with self-consistent ray-tracing and application to ITER

A. Reiman. Magnetic island suppression and disruption avoidance via RF current condensation

A. Murari. Investigating the physics of the tokamak operational boundaries using ML tools

M. Gelfusa. On the potential of adaptive predictors and their transfer between different devices for both mitigation and prevention of disruptions

E. Aymerich. Continuous update of machine learning disruption prediction and prevention models at JET
ITER scenario development, plasma control, physics
F. Turco et al., Scenario optimization and instability monitoring to reach the Q=10 ITER mission without disruptions

- More than a decade dedicated to IBS (Q=10) development
- IBS DIII-D scenario matches most of target parameters, $q_{95} \sim 3$ and $q=2$ @ $\rho=0.8$; many discharges suffer of growth of 2,1 mode (no NTM, no beta dependence) followed by disruption: why?
- equilibrium/current profile reconstruction show well at $q=2$; found that steeper well has high probability of generating 2,1 (figure)
- mostly inductive and bootstrap current → NI drive and ECCD (low $T_e$ and $j_{CD}$) are ineffective
- modification of ramp-up (*slower* $I_p$ *ramp*, *later* heating, *lower* $T_{e,ped}$, *modest* gas flow) allows for passively stable scenario (next slide)
More in talk: MHD spectroscopy; preview of effect of shaping on current density and stability
Plasma control, disruption avoidance, scenario development, data analysis
D. Humphreys et al., Design of the ITER plasma control system for disruption prevention and mitigation

- The ITER PCS plays a central role in preventing and managing ITER disruptions.

- Key PCS functions for disruption management include:
  - Shot validation through control simulation verification: mitigate human error
  - Robust control algorithms: tolerate expected noise/disturbances
  - Proximity control: prevent approach to disruptive states, continuously minimize risk
  - Effective Exception Handling: respond to system faults to avoid disruptive states
  - FRTS Forecasting and effective predictors: avoid potential disruptive states
  - DMS triggering (maybe) and effective mitigation scenarios: mitigate effects

- Novel elements needed for ITER PCS are now subject of active research:
  - Proximity control, controllability assessment/prediction, disruption risk assessment
  - ITPA Joint Activity between IOS and MDC TG’s: disruption-free operation

(see description of Exception Handling in Dave’s slides)
Exception Handling and Control is Possible Only If Predictors Are Designed to Provide Information in Actionable Form

1. **Must predict SPECIFIC pre-disruptive phenomena to enable control action:**
   - VDE, radiation limit, n≠0 MHD stability/controllability, TM-stability profile state, system fault, etc...
   - “Disruptions” aren’t a single thing to predict!!!! They’re the end result of many different risky phenomena which should THEMSELVES be predicted individually… (possible exception is a final “Disruption Alarm”)

2. **Must provide a CONTINUOUS variable that quantifies proximity (& can GENERATE triggers):**
   - Vertical Controllability metric: e.g. ΔZmax; Tearing mode stability metric: Turco J-well depth
   - Formal “Hazard” probability, quantified risk metric

3. **Must be REAL-TIME CALCULABLE (control is real-time by definition…)**

4. **Must be linked to SPECIFIC CONTROL ACTIONS and provide SUFFICIENT LEAD TIME**
   - Predictor interpretability: must provide information on source of prediction and implied control action

5. **Must be EXTRAPOLABLE to new device (ITER) control solution prior to operation:**
   - ITER control requirement: must validate shot prior to execution…
   - COULD allow iterative improvement over time…
• **A. Pau et al.,** Off-normal event-detection and NTM-control for integrated disruption avoidance and scenario control

• Generic Framework for PCS must easily accommodate new algorithms for PCS evolving tasks

• different task simultaneously, need for actuator sharing, actuator management

• particularly true for off-normal event handling

• event detection and characterization, e.g. NTM rotating amplitude, frequency

• long tradition of NTM and beta RT integrated control

• off-normal events can be detected with data-driven algorithms (pre-disr states w high edge oder core radiation, GTM →)
How to determine “free” coefficients of MRE in Real-Time

Real-time adaption of MRE coefficients
- coefficient adaptation based on tracing of $w(t)$ evolution;
- At each time $t_m$ the simulation of $w(t)$ in $[t_m-t_m, t_m]$ is compared with RT measurements ($t_m$ is of the order of the resistive time scale ~50ms)

"Adapt $a_2$" case predicts very well $rt-w(t)$
Comprehensive disruption prevention must cover the full range of control regimes

Control Regimes:

1. Continuous Prevention:
   - Stable scenarios
   - Regulate stability vs performance
   - Mode Suppression
   - Should prevent 99%+ of disruptions!

2. Asynchronous Avoidance:
   - Perturbative mode response, state-change
   - Temporarily de-rate scenario, then return
   - Should need to prevent < 0.9% disruptions!

3. Emergency Avoidance:
   - Rapid Controlled shutdown:
     - Large piggyback study on DIII-D
     - < 0.09% of disruptions!
   - Mitigation should be the last resort:
     - Has side-effects
     - < 0.01% of disruptions!
A new proximity-to-instability control architecture has been developed for DIII-D and EAST in FY 2020

**Stability estimators:**
- Stability *metrics* &
- Stability *limits*
- Error bars!

**Target modification:**
- Problem focused
- Maps stability to plasma target mod's

**Integration:**
- D3D PCS Architecture:
  - Integrate with actuator algorithms
- Future (missing) piece: actuator authority
Transitioning to limited topology for emergency shutdown dramatically reduces LM disruption risk on DIII-D

- After LM is detected, shape modification immediately applied:
  - Continuing diverted (SN): 19% reach $I_N < 0.3$ (ITER req.), 26% $I_N < 0.5$
  - Transitioning to limited (from SN): 53% reach $I_N < 0.3$ (ITER req.), 74% $I_N < 0.5$
- Despite common use and improvements, ITER must achieve better
  - Synergy with multiple prevention tools likely required: ECH, RMP spin-up strategies (many)

Focus on LM disruptions:

![Graphs showing Limited Shutdown and Diverted Shutdown](chart)

**Limited Shutdown:**
- After LM detected
- $N = 18$
- $I_N = I_D / aB_I$

**Diverted Shutdown:**
- After LM detected
- $N = 31$
- $I_N = I_D / aB_I$
M. Maraschek et al., Prevention of the H-mode density limit by various heating schemes through control of the plasma state … space

- Learning to control H mode high density scenario close to HDL: it can end in a disruption

- precursors: continuous increase of $P_{\text{rad}}$, $li$, confinement deterioration $\rightarrow$ MARFE $\rightarrow$ HL transition $\rightarrow$ MHD modes, LM (figure left)

- plasma state evolution can be followed on H-$f_{\text{crit}}$ space (figure right); green points indicate confinement degradation start; H-L transition boundary in read; possible actuators: gas valves, aux heating (effect depends on type)

- possible actuators: gas flux reduction, particle confinement reduction, additional heating, …

- empirical boundary for D in $H_{\text{ITER-98P}(y,\theta,2)} - n_e/n_{e,\text{scal}}$ plasma-state

- normalized 2D distance $d$:
  - $d > 0$, safe region
  - $d \leq 0$, danger zone
M. Maraschek (continue)

- Control by heating = maintain plasma in green region (figure left); different heating systems have different effect

- if N2 added to plasma, different plasma trajectory and MARFE formation conditions observed

- this calls for different sensors, control algorithms and plasma state definition
M. Maraschek (continue)

- Similar exp.s carried on on TCV; exception handling and use of 2 actuators

**Controller with 2 actuators, NBI and gas flux, and hierarchical reaction at TCV**

- Low danger for $E_{d,\text{ne\_lim}}$ and still no danger for $E_{\text{act\_lim}}$

- Normal scenario:
  - NBI and gas valve are controlled by the feedforward tasks
  - $DA_{\text{power\_nor}}$ asks for linearly increasing power
  - $DA_{\text{gas\_nor}}$ reduces the gas flux
Scenario development towards DEMO and FPP
F. Janky et al., Kinetic control of a tokamak burning plasma away from disruptive events

- **EU DEMO 2019 standard ELMy H-mode scenario requirements**: no disruptions and required electric power

- **PCS requirements**: continuous plasma magnetic and kinetic control (ramp up and down, flattop, L-H-L transition); plasma parameters anomaly is detected (Prad, li and ne); control of unexpected events (ufo, loss of actuator) or shut-down w/o disruption

- Simulations are required to design PCS and scenario

- **Fenix** – tokamak flight simulator for physics and control studies – is used for AUG and DEMO

<table>
<thead>
<tr>
<th>R</th>
<th>8.94 [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2.883 [m]</td>
</tr>
<tr>
<td>B_t</td>
<td>5.744 [T]</td>
</tr>
<tr>
<td>k</td>
<td>1.73</td>
</tr>
<tr>
<td>$\delta$</td>
<td>0.341</td>
</tr>
<tr>
<td>$I_p$</td>
<td>18.21 [MA]</td>
</tr>
<tr>
<td>V</td>
<td>2500 [m³]</td>
</tr>
<tr>
<td>$T_{id}$</td>
<td>30 - 40 [keV]</td>
</tr>
<tr>
<td>$n_{id}$</td>
<td>1e20 [m⁻³]</td>
</tr>
<tr>
<td>$P_{ fus }$</td>
<td>2 [GW]</td>
</tr>
<tr>
<td>$P_{ el }$</td>
<td>500 [MW]</td>
</tr>
<tr>
<td>$P_{ ul }$</td>
<td>130 [MW]</td>
</tr>
</tbody>
</table>

- **A tokamak flight-simulator [1,2,3]**
  - Plasma model - ASTRA (1-D transport) [4]
  - SPIDER (2-D coil current and equilibrium solver) [5]
  - models
    - Edge
    - Sawtooth
    - L-H
    - pedestal
    - SOL/divertor particle balance and exhaust model [6]
  - control system model (MATLAB/Simulink)
  - actuators and diagnostics

<table>
<thead>
<tr>
<th>Control quantity</th>
<th>Operational limits</th>
<th>DEMO Diagnostics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma (edge) density</td>
<td>density limit</td>
<td>Reflectometry IR polarimetry/interferometry Plasma radiation</td>
</tr>
<tr>
<td>Plasma radiation, impurity mixture, $Z_{ef}$</td>
<td>radiation limit LH threshold</td>
<td>Spectroscopy-radiation meas. $U_{loop}$</td>
</tr>
<tr>
<td>Fusion power</td>
<td>wall loads (FW and div.) LH threshold</td>
<td>Neutron diagnostics FW/blanket and div. power (for calibration only)</td>
</tr>
<tr>
<td>Divertor detachment and heat flux control</td>
<td>divertor wall loads LH threshold</td>
<td>Spectroscopy-radiation meas. Thermography Divertor thermo-currents Reflectometry, ECE</td>
</tr>
</tbody>
</table>
Causes for disruptions in DEMO

- During different phases of the discharge:
  - ramp-up: breakdown, variation of internal inductance, Li (avoid vertical displacement event - VDE), L-H transition
  - flat-top: burn control, detachment, keep the plasma inside limits
  - ramp-down: Li control (avoid VDE), H-L transition

- During the flat top phase:
  - Sawteeth: core events, not dramatic per se, but can trigger NTMs
  - Impurity accumulation: not dramatic in a low-collisionality hot plasma
  - NTMs: need to be controlled or pre-emptively avoided
  - Pedestal events: ELMs (ELM-free scenario or very small), radiation anomalies
  - Density limit: keep density below limits at pedestal top AND separatrix
  - Loss of detachment: avoid divertor damage

- Technical issues:
  - Failure of actuators: need redundancy as much as possible
  - Failure of diagnostics: strategy to detect it and stop plasma safely

Unexpected radiation from W influx

- Tungsten influx for from 1e19 to 2.2e19 particles/seconds (3 mg, 6 mg, 6 mg, 6.6 mg)
- E.g. Tungsten flake falling from the upper tiles or erosion from divertor
- Separatrix power controlled by Xe puff from “top” Psep (ref) = 160 MW

- Heuristic finding 6.6 mg
  - W puff at the separatrix (model)
  - No rocking effect
- Technical and control aspects to avoid disruptions
  - Pipes length
  - Diagnostic latencies
  - Control of pumping speed and pumping impurities is not possible
  - Stop injecting xenon is slow

Controlled tungsten radiation event with ECRH

- Tungsten influx for from 1e19 to 50e19 particles/seconds (3 mg to 6.6 mg, 3 mg to 15 mg)

  1) Psep controlled only from “top”
     - Xe puff, Psep target = 160 MW
     - Max 6 mg of tungsten

  2) Psep control as 1) plus
     - Xe puff, Psep target = 160 MW
     - Max ECRH power = 100 MW
     - ECRH @ r98 0.8 (close NTM location)
     - Psep target = 140 [MW]
     - Max 9 mg of tungsten
     - Surviving ~ 50% bigger tungsten influx

Current density and T_e profile tungsten case analysis

- Comparison of two cases with and without ECRH control
  - 6.6 mg vs 9 mg of tungsten
  - 0.6 MW ECRH vs 50 MW of ECRH at r98 = 0.8 if Psep < 140 MW
  - Psep controlled with xenon puff if Psep > 160 MW in both cases
  - Psep = 130 MW
  - Psep = P_th + P_rad – dW/dt
  - In foreseen Psep diagnostic there is missing plasma thermal stored energy derivative term
  - It is advantage for control
Does tokamak have a chance to avoid disruptions?

Leonid Zakharov

- 62 years with no Q_{DT} = 1 and 58 years with no clue for disruption avoidance indicates a fundamental flaw in the approach, including confinement and stability.
- Recognized by Igor Tamm in 1951 the main reason of problems is the 60-years old high recycling regime.
- In contrast, the realistic 50% recycling regime (PDT=26 MW at PNBI=4 MW, Q_{DT}=6.4 for 3 T, 3 MA JET)

  (a) leads to the “best possible confinement”, which is determined by particle diffusion
  (b) automatically has high plasma edge temperature \( \sim 16 \text{ keV} \) determined by ENBI=120 keV,
  (c) suppresses to negligence the thermal conduction in energy losses
  (d) replaces PSI by interaction of individual 16 – 20 keV particles with liquid lithium

With two the most dirty parts of tokamak physics gone
the tokamak regime becomes predictable, while plasma controllable.
Everything is simplified.

In addition it
(e) leads to the best core stability: no sawteeth, no NTM triggering, no ELMs, \( q > 1 \) corresponds to the second
stability of ballooning modes,
(f) high \( T_e \) and finite current density are consistent with free boundary stability (S. Medvedev 2003)

High performance and stability of tokamak plasma can be achieved only by rejection
of high recycling regime with its PSI and 20 eV at the W surface
and by development of 24/7-Flowing Liquid Lithium technology for 50% recycling divertor.
Otherwise, tokamaks (e.g., JET) are ready for burning and stable plasma.

Leonid Zakharov suggests a low recycling tokamak. Recycling is controlled to low level by Li PFCs.
It is anticipated that this plasma would be free of MHD, turbulence and disruptions.

Are there turbulence calculations, MHD analysis and Tritium balance calculations in support of these theses? → discussion session
Data analysis, methods and tools, physics
S. Sabbagh et al., Progress on tokamak disruption event characterization and forecasting research and expansion to real-time application

- DECAF code: suite of routines to study pre-disruption phase (and not only)
- Originally inspired by deVries' JET disruption classification
- Routine functions
  - access to data of several devices (AUG, KSTAR, MAST-U, NSTX-U)
  - database assembly and analysis
  - event and event chain identification
  - evaluation of disruption forecasting and performance
  - use of ML tools for event analysis and building models
  - MHD mode analysis
  - stability analysis
  - rt application on KSTAR
Expanding DECAF approach provides a new paradigm for disruption avoidance research

- Multi-device, integrated approach to disruption prediction and avoidance that meets disruption predictor requirement metrics
  - Physics-based “event chain” yields key understanding of evolution toward disruptions needed for confident extrapolation of forecasting, control
  - Present performance on large \(10^4\) databases: 91.2\% w/ only 5 Events
  - Full multi-machine databases used (full databases needed!)
  - Innovative use of machine learning started (event analysis, pred. models)
  - Physics analysis, experiments run to understand, create, validate models

- DECAF producing early warning disruption forecasts
  - On \textit{transport timescales}: \textit{guide disruption avoidance by profile control}

- Continuing development
  - Improve DECAF forecasting performance run on large database analysis
  - Continue / expand disruption forecasting performance analysis (\textit{ITER})
  - Implement DECAF disruption forecasting models in real-time (\textit{KSTAR})
E. Kolemen et al., Real-time prediction and avoidance of fusion plasmas instabilities using feedback control

PORTFOLIO approach to disruption avoidance

• Automated plasma equilibrium from diagnostic
  • automatic kinetic equilibrium reconstruction (CAKE kinetic EFIT) workflow robustly generates quality equilibria; RT Thomson + MSE and RT CER constrains current and pressure profiles → RT version running on DIII-D = basis for stability analysis

• Tearing and disruption prediction
  • STRIDE: RT calculation of deltaW for ideal stability calculation; STRIDE GPU implementation under development, projected to achieve 20 ms calculation time
  • STRIDE: Delta prime calculation, < 100 ms (CPU only); planned to incorporate into real time
  • Physics + ML: “Tearibility” predicting TM onset; it may allow prevention

• ML control for disruption avoidance
  • Using NN profile predictor for control: given plasma state and actuator inputs, predict future state and energy confinement

• RT adapting ML prediction and control
  • Reservoir computing network: a recurrent NN with random and sparsely connected early layers (can process temporal information, much faster and easier training procedure than DNN)
Big Updates for 2020: For the people who know our research already

1. **ML-based plasma evolution predictor/controller running on DIII-D**
2. **Real-time kinetic EFIT is functional and being tested on DIII-D**
3. **Keras2c ➜ Automatic NN to PCS code conversion functional**
4. **Real-time δW running at ~200 ms at DIII-D: Offline tests projecting to ~20 ms is using GPU, RT-Δ’ in development**
5. **Dynamic Mode Decomposition gives good plasma evolution models**
6. **Big Highlight: RT-Adaptive ML proof-of-concept shown using reservoir learning. So fast ~20 ms that for ML profile predictor/controller, we can update the ML online as new data comes in**
Interpretable ML models (DPRF) for disruption prediction useful resources to identify in real-time stability boundaries

- PCS feedforward exp with early rapid shutdown, MGI, and ECH.
- Assessed peaking factors as relevant metrics in DIII-D ITER baseline scenario

Access to disruptivity drivers in real-time: monitoring of unstable plasma features.

- Disruptivity as general proximity of current plasma state to unstable ops space.
- Feature contributions mapped onto controllable plasma parameters to regulate stability.
Data-driven predictors to be adopted as last line of defense for disruption mitigation but...

- When interpretable, can be combined with control algorithms to detect disruption precursors and employed in avoidance schemes → Rea, Barr et al.
- Frameworks exist to extract plasma future survival → Tinguely et al. or instantaneous hazard (as probability generator) for instabilities → Olofsson et al.
- DPRF provides explainable predictions – tested on C-Mod, EAST, DIII-D:
  - Works as real-time scenario detector (DIII-D, EAST).
  - To be integrated with proximity controller for continuous avoidance (DIII-D).
- Analogous efforts ongoing at international facilities:
  - J. Lee and J. Kim @ KSTAR
  - T. Yokoyama @ JT-60U;
  - A. Pau and others @ JET, TCV, AUG;
  - G. Dong et al. @ DIII-D.
- Ongoing work to design predictor for ITER:
  - Few ITER disruptions might still be needed to design effective data-driven solutions. → J.X. Zhu et al.
    → J. Kates-Harbeck et al.
Deep Learning extracts general representations of disruptive behavior across devices

J.X. Zhu et al. “A new Deep Learning architecture for general disruption prediction across tokamaks”, this meeting

- Numerical experiments with aggregated DIII-D, C-Mod, and EAST data show DL learns disruptive characteristics: **device-independent knowledge**.

- Non disruptive data results **device-specific**, not improving performances.

- **Limited disruptive** data from target device still needed for prediction, as well as all available **non-disruptive** data.
Data analysis, methods and tools, physics: Event identification
Algorithms able to recognize events can contribute to progress in disruption avoidance.

preparation of input for data-driven/ML algorithms is tedious.

**label spreading** allows to learn identifying event with few examples (*but proper variables*)

requires samples *(time sequences of proper signals)* some of which classified; application uses only 1-5% of samples with classified labels; performance increases as labels are added.

algorithm infers classes of unclassified samples; success with H-L transition, initially rotating LM, core radiative collapses (figures show examples of events, left, and H-L event study, right).
M. Fontana et al., Real-time applications of electron cyclotron emission interferometry for disruption avoidance at JET

- JET ECE X-mode interferometer delivers $T_e$ in RT
- $T_e$ profile correlated with disruption occurrence (proxy for current profile); fast current ramp and impurity accumulation $\rightarrow$ hollow current profile $\rightarrow$ 2,1 TM, LM $\rightarrow$ disruption
- RT monitoring of $T_e$ profile, peaking and edge gradient
  - $P_1 = (T_{\text{core}} - T_{\text{edge}})/T_{\text{edge}}$ (control) $\rightarrow$ $P_1 > 1$ $\rightarrow$ safe termination
  - $P_1 < -0.1$ for $>20$ ms in [3 5.5] s $\rightarrow$ Soft stop
  - gradlog($T_e$) indicate edge cooling
- Future: combine with radiation measurements (uncorrelated? Added information?)
• Impurity accumulation and core radiation, strong edge cooling w marfe, radiation collapse can precede disruptions

• can be detected e.g. fast tomographic method + ML methods for anomaly detection

• method speed matters in RT

• question to PCS: which information would be more useful for control?
Data analysis, methods and tools, physics: locked mode phase
Minjun J. Choi et al., 2D Te patterns of various disruptive events and retardation of turbulence-associated disruption with non-resonant magnetic field

- Disruptions are caused by growth of MHD instabilities
- KSTAR has 3 ECEI (2D) systems at two toroidal positions, 2 cm and 1 micros resolution
- Observations of various disruptive events: sawtooth crash, tearing and interchange mode, king+tearing+interchange, cold bubbles, ballooning fingers, turbulence-modes-NRMP interaction
- Figures below: sudden expansion of island during LM phase

- Physics understanding + application: TQ onset, LM phase duration (dwelling), mode structure evolution during LM are not known ↔ ITER low rotation and DMS trigger generation

- Discharge condition
  - \( B_T = 2.0 \) T, \( I_p = 0.6 \) MA, \( q_{95} = 4.0 \), NBI ~ 2.6 MW, L-mode limiter plasma

- Tearing mode growth → Mode locking → Locked mode disruption

- \( \frac{\langle T_e \rangle - \langle T_e \rangle_{Ref}}{\langle T_e \rangle_{Ref}} \) images provide a relative \( T_e \) change against the Ref period @ \( t = 1.925 \) s

- Tearing mode growth → Mode locking → Locked mode disruption by a sudden expansion of the locked island
A. Reiman et al., Electron-cyclotron current drive stabilization of large islands could play an important role in reducing disruption frequency in ITER. RF current condensation can facilitate this.

- Disruptions are preceded by large MHD modes, which lock wall (deVries et al.)
- Most large islands arises from off-normal events other than NTMs (*NTM control is not enough*)
- Fast ramp-down w LM can trigger disruption
- Need to investigate use of ECCD to stabilize large islands: **nonlinear effects can facilitate suppression**
- Sensitivity to current drive and power deposition to small Te changes can give rise to “**current condensation**” and increased stabilization efficiency
- RF current condensation motivates reevaluation of lower hybrid CD for stabilizing islands
- Simulation for use in ITER
- Need experimental study
R. Nies et al., RF current condensation with self-consistent ray-tracing and application to ITER

Island evolution equations

Generalised Rutherford Equation

\[
0.8 \frac{\delta \theta}{\delta r} = \left( \frac{\delta \theta}{\delta r} \right)_{\text{Classical}}^{(1,2)} + 2m \left( \frac{w_{\text{in}}}{w} \right)^3 \cos(\phi - \phi_{\text{B}}) + 3 \frac{\delta w_{\text{in}}}{\delta r} \frac{2}{3w^3} \frac{3a^2 w^2}{4n_{\text{bg}}^2} \left( \frac{w_{\text{in}}}{w} \right)^2 \text{Current drive}\]

Equation of angular motion

\[
\frac{\delta \phi}{\delta r} = \frac{m(\Omega - \Omega_{\text{m}}) - \alpha}{\tau_{\text{H}}} \left[ \frac{w}{a} \right]^3 \frac{C_1}{m(a \tau_{\text{H}})^2 + 1} + \frac{m^2}{256} \left( \frac{w_{\text{in}}}{w} \right)^2 \text{Current field / RMP}\]

Advantages of LM stabilisation: dynamical (fast locking ⇒ rotating island stabilisation is hard + \( w_{\text{lock}} \) is small) and geometrical (higher stabilisation efficiency, less sensitive to misalignment and broadening).

Stabilisation of small LMs is efficient (lower EC power) and robust (no problem with large \( w_{\text{seed}} \), detection threshold).

A lot of attention on rotating island stabilisation, comparatively little for locked modes [4, 5, 12]. Let us correct that.

A. Murari et al., Investigating the physics of the tokamak operation boundaries using machine learning tools

- Critical introduction on past and future use of ML tools for disruption P&A.

- Revisiting pre-TQ LM amplitude. Formula → (P. de Vries et al.) does not perform well: why?
  \[ B_{ML}(r_c) = c \cdot I_p^{a_I} \cdot a^{aa} \cdot q_{95}^{aq} \cdot li(3)^{a_{li}} \cdot \rho_c^{a_o} \]

- Method: probabilistic SVM (→ right figure) + symbolic regression via genetic programming

- Variables are informative but physics interpretation? ↔ ITER low rotation and DMS trigger generation

\[
\begin{align*}
\text{LM} &= 0.475 - 0.017 \cdot y^{0.95} - 0.014 \cdot x^{1.00} \\
&\quad \text{(no power law)}
\end{align*}
\]

\[
\begin{align*}
x &= li[H] \\
y &= q_{95} \\
z &= LM[mT]
\end{align*}
\]

<table>
<thead>
<tr>
<th>Success Rate</th>
<th>Tardy</th>
<th>Missed</th>
<th>False</th>
<th>Mean [ms]</th>
<th>Std [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>51.85 %</td>
<td>26.67 %</td>
<td>21.48 %</td>
<td>1.96 %</td>
<td>184</td>
<td>349</td>
</tr>
<tr>
<td>(70/135)</td>
<td>(36/135)</td>
<td>(29/135)</td>
<td>(1000/1020)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Method</th>
<th>Success Rate</th>
<th>Missed</th>
<th>Early</th>
<th>Tardy</th>
<th>False</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVM and SR via GP</td>
<td>91.7%</td>
<td>1.2%</td>
<td>0%</td>
<td>7.1%</td>
<td>2.3%</td>
</tr>
<tr>
<td></td>
<td>(156/170)</td>
<td>(2/170)</td>
<td>(0/170)</td>
<td>(12/170)</td>
<td>(23/987)</td>
</tr>
</tbody>
</table>
Data analysis, methods and tools, physics: learning whole operational space
M. Gelfusa et al., On the potential of adaptive predictors and their transfer between different devices for both mitigation and prevention of disruptions

- She uses methods of adaptive learning and has been quite successful in predicting ILW JET disruptions after training on ASDEX Upgrade. Good fall-back solution for ITER.

- Types of adaptation: trajectory learning during discharge; updates of training set (error in output or obsolete sample) and modification of decision functions between discharges

- Different decision functions are run in parallel and one with best (?) results generates alarm

- Variables used →

---

### Results on JET for mitigation

AUG predictors have been applied directly to JET shots without any manipulation (except the time translation)

Different colours indicate different decision functions. $L_{MA}$ normalised locked mode amplitude, $L_{STD}$ locked mode std deviation, $li$ internal inductance

<table>
<thead>
<tr>
<th>JET</th>
<th>Success rate</th>
<th>Missed</th>
<th>Early</th>
<th>Tardy</th>
<th>False</th>
<th>Mean [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{MA}$, $L_{STD}$, li</td>
<td>98.14% (421/429)</td>
<td>1.4% (6/429)</td>
<td>0% (0/429)</td>
<td>0.47% (2/429)</td>
<td>1.9% (38/1998)</td>
<td>278.3</td>
</tr>
</tbody>
</table>
E. Aymeric et al., Continuous update of machine learning disruption prediction and prevention models at JET

- GTM (generative topographic map) is used to 2D-map non-disruptive and pre-disruption phases of JET discharges
- Evolving operational space suggests updating of maps (done, fig.s below); large fraction of recent disruptions are preceded by impurity accumulation; pre-disruption phase chosen automatically → continuous update
- Variables: $T_{e,pf}$, $n_{e,pf}$, $\text{Rad}_{pf-CVA}$, $\text{Rad}_{pf-XDIV}$, $li$, PFRAC
- Possible use in PCS to trigger JET DMS? Suitable for avoidance? Extrapolation to other devices?

[1]: A.Pau et al., Nucl. Fusion 2019, 106017 (22pp)
Discussion follows