Max-Planck-Institut für Plasmaphysik

Integrated Data Analysis: Status and Prospects for Future Fusion Devices

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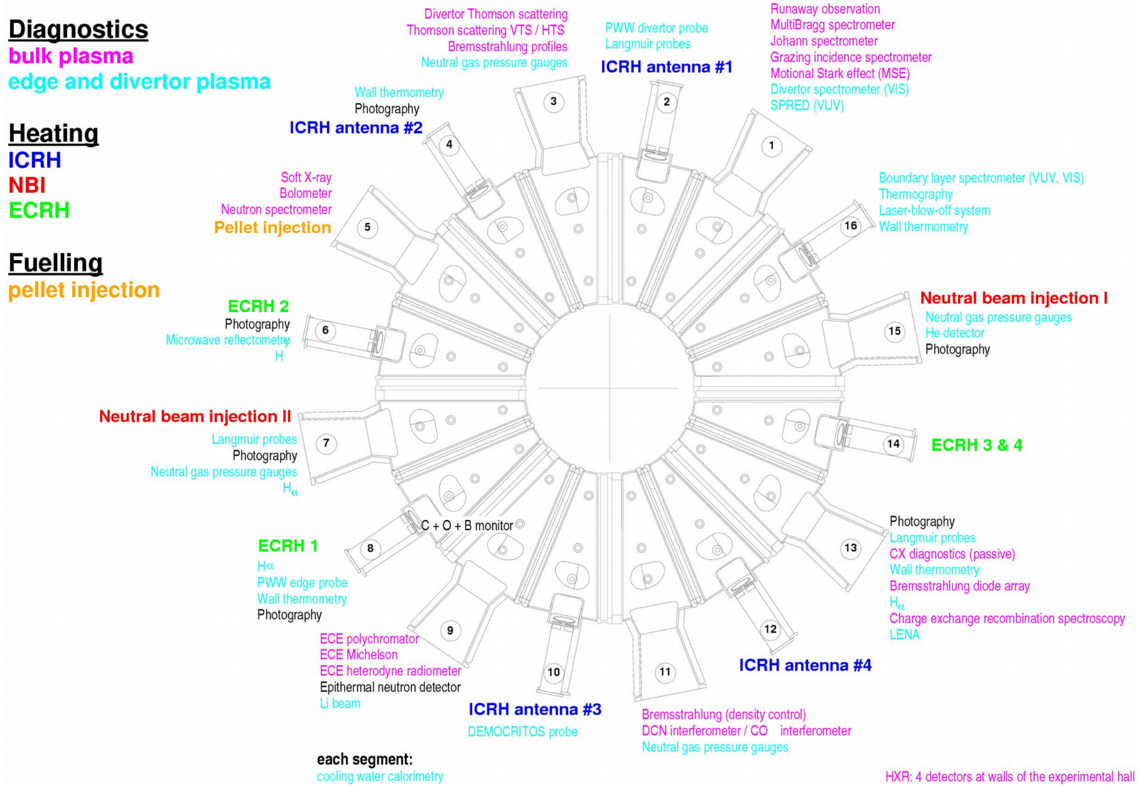
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European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

IDA for Nuclear Fusion

Different measurement techniques for the same quantities → redundant and complementary data

Coherent combination of measurements from different diagnostics



Goal:

- ➢ replace combination of results from individual diagnostics
- ➢ with combination of measured data
  - → one-step analysis of pooled data

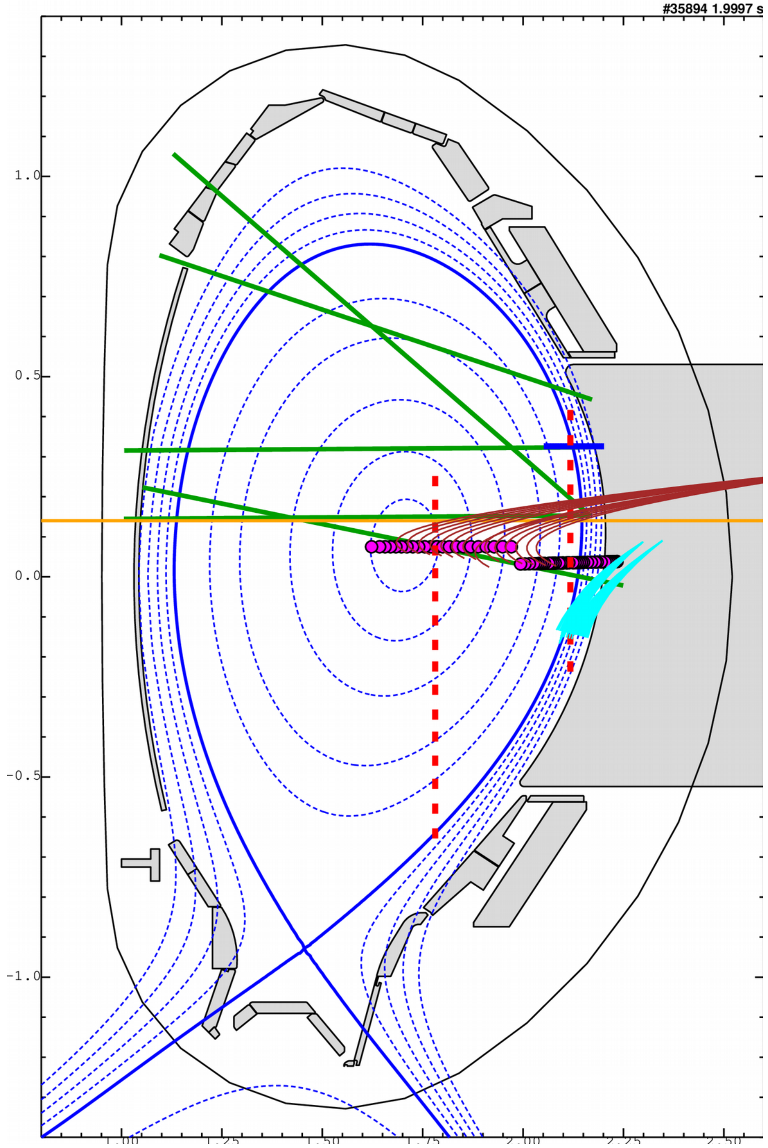
IDA at ASDEX Upgrade

multi-diagnostic profile reconstruction: n_e , T_e

- Lithium beam impact excitation spectroscopy (LIB)
  collisional radiative model → n_e (T_e)
- Interferometry measurements (DCN) → n_e
- Electron cyclotron emission (ECE)
  ECRad: Electron cyclotron radiation transport → T_e (n_e)
- Thomson scattering (TS) → n_e , T_e
- Reflectometry → n_e
- Beam emission spectroscopy → n_e (Z_{eff})
- Thermal Helium beam spectroscopy → n_e , T_e

- Equilibrium reconstructions for diagnostics mapping
  (*IDE*: Grad-Shafranov equation coupled with current diffusion equation)

A lot of dependencies and uncertainties:
We need a probabilistic approach!



IDA for Nuclear Fusion

Goal: combination of measured data → one-step analysis of pooled data
→ within a probabilistic approach

Result: probability distribution of parameters of interest incl. all dependencies (set of diagnostics)

- improved workflow (avoid iteration of various diagnostic analyses)
- improved parameter reliability (more data)
- (self-)consistent result (cumbersome otherwise)
- forward modeling only (no backward inversion techniques; noise fitting?, numerical stability?)
- unified error interpretation (Bayesian: uncertainty quantification and error propagation)
- additional physical information easily integrated (works simultaneously on different data/diagnostics)
- synergistic effects (not easily obtained with individual diagnostics)
- identify and resolve inconsistencies (nuisance parameters)
- probabilistic data and result validation (non-linear dependencies)
- automated analysis chain (huge amount of data from steady state devices)

Further Applications of IDA

W7-AS: n_e , T_e : TS, interferometry, soft X-ray

ASDEX UG: n_e , T_e : TS, interferometry, ECE, …
Z_{eff} : bremsstrahlung spectra
T_i , v_{rot} : CXRS
equilibrium: Grad-Shafranov, current diffusion, many diagnostics

W7-X: non-Maxwellian electron energy distribution function: visible emission spectrum
n_e , $T_{e/i}$, impurity densities, flows: TS, X-ray imaging
n_e , T_e : TS, interferometry, helium beam
Z_{eff} : bremsstrahlung spectra

MST RFP: T_e : TS, soft X-ray
Z_{eff} : soft X-ray, CXRS

TJ-II: n_e , T_e : TS, interferometry, reflectometry, Helium beam

JET: n_e : LIB
n_e , T_e : LIDAR, interferometry
fast-ion distributions : velocity-space tomography of fast-ion D-alpha spectroscopy, collective TS, gamma-ray and neutron emission spectrometry, and neutral particle analyzers.

R. Fischer et al., PPCF, 45, 1095-1111 (2003)
R. Fischer et al., FST, 58, 675-684 (2010)
S.K. Rathgeber et al., PPCF, 52, 095008 (2010)
R. Fischer et al., FST, 76, 879-893 (2020)
R. Fischer et al., NF, 59, 056010 (2019)

D. Dodt et al., J. Phys. D: Appl. Phys., 41:205207, 2008.
A. Langenberg et al., RSI, 90(6), 063505 (2019)
S. Kwak et al., arXiv:2103.07582, 2021
S. Kwak et al., RSI, 92:043505 (2021)

L. M. Reusch et al., RSI, 85:11D844, 2014.
M.E. Galante et al., NF, 55:123016, 2015.

B. Ph. van Milligen, et al., RSI 82, 073503 (2011)

D. Dodt, et al., P-2.148, EPS 2009
O. Ford, et al., P-2.150, EPS 2009
M. Salewski et al., FST 74:23–36, 2018.

IDA Basic Implementation for ITER, ...

Integrated Data Analysis for ITER: basic implementation in python

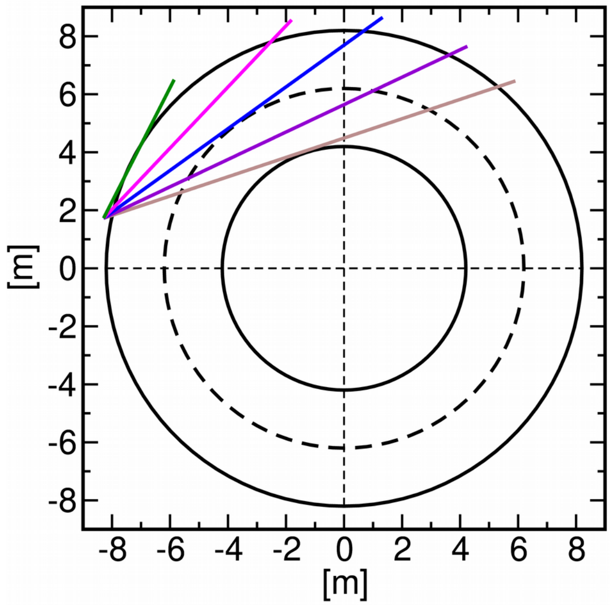
- ITPA on Diagnostics: IDAV SWG (since 2020, R. Fischer, K. Fujii, S. Pinches)
- open source license
- (working) implementation on https://git.iter.org (A. Bock, S. Denk, D. Stieglitz)
  - being completely modular
  - to be compatible with any fusion device (ITER:IMAS, ...)
  - diagnostics: Thomson scattering, ECE and interferometry, ...
  - likelihoods (data uncertainty): Gaussian, Cauchy (outlier robust), …
  - multi-fidelity forward models / synthetic diagnostics
    - ECE: $T_{rad} = T_e$ vs radiation transport modeling $T_{rad}(T_e, n_e)$
  - flexible parameterisation of, e.g., profiles: splines, GPR, ...
  - priors: smoothness, positivity, physical modeling, ...
  - results and their uncertainties:
    - MAP solution: minimize(method='Nelder-Mead'), …
    - MCMC sampling methods

```
├── run_ida_sample.py
└── lib
    ├── core
    │   ├── likelihoods
    │   ├── priors
    │   ├── variables
    │   ├── optimizers
    │   └── IDA
    ├── forward models
    │   └── ECRad
    └── diagnostics
        ├── base
        ├── AUG
        │   ├── ECE
        │   ├── INTF
        │   └── TS
        ├── ITER
        ├── DIII-D
        ├── WEST
        └── JT-60SA
```

IDA at ITER: TIP forward model and IMAS

- artificial diagnostics: Thomson scattering and ECE

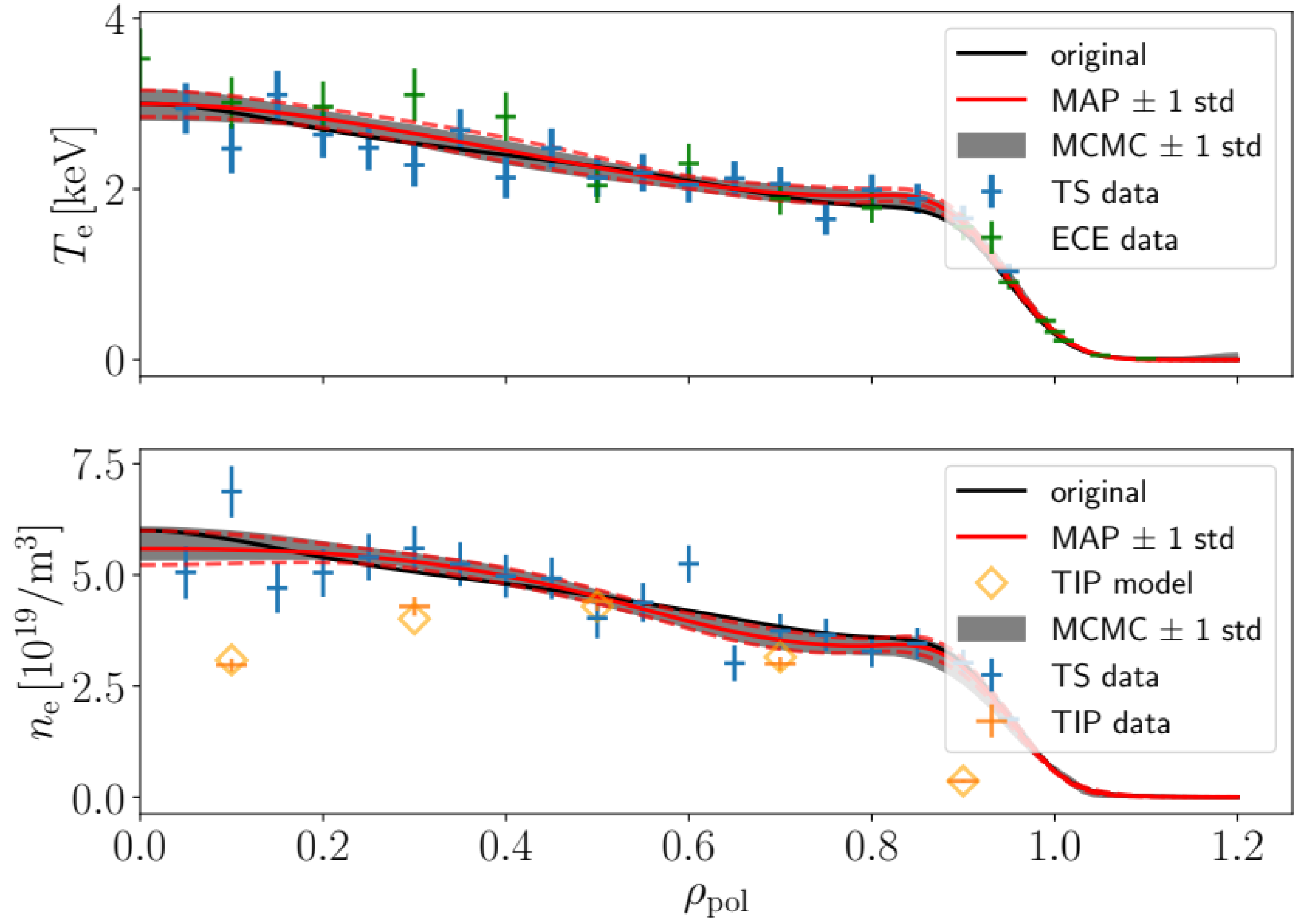
- 1st ITER diagnostic: Toroidal Interferometer Polarimeter (TIP)
  - * available from PFPO-1
  - * 5 LOS, 0.1 ms
  - * core and edge n_e profiles
  - → forward model in python (ITER git)
  - → IMAS: read Interface Data Structures (IDS):
    - TIP geometry (interferometer_md)
    - ITER equilibrium (equilibrium)
    - optional: core profiles (core_profiles)
  - → equilibrium mapping (r,z) → rhopol (to be provided by ITER)



ITER toroidal (R_0=6.2m, a=2m)

ITER: Profile test example

ITER IDA n_e and T_e profile and uncertainty estimation



(T_e, n_e) → TS data (10% noise)

(T_e) → ECE data (10% noise)

(n_e) → Interferometry data (5% noise)

- profile estimation
  - maximum-a-posteriori (MAP)
  - MCMC mean
- profile uncertainty
  - MAP Laplace approx.
  - MCMC standard deviation
    - → exploring full pdf
    - → asymmetric error bars

IDA for ITER: Next steps

- write results to IMAS (profiles, uncertainties, data residuals, …)

  → check/define for appropriate Interface Data Structures (IDS)
- multi-fidelity forward models, e.g., ECRad (S. Denk, A. Medvedeva)
- add further ITER profile diagnostics as available (T_e, n_e, T_i, n_i, Z_{eff}, …)
- define/collect code parameters in parameter-file

  → diagnostics, forward models, likelihood, priors, temporal and spatial resolution/averaging, …

  → use YAML (more user friendly then XML)
- compatibility with IMAS workflow for synthetic diagnostics (M. Schneider, A. Medvedeva)

needed: accelerate ITER SD forward models to be iterated within the IDA loop

→ Initialization of static variables	(geometries)	init_static()
→ Initialization of dynamic variables	(equilibrium)	init_dynamic()
→ Innermost IDA loop: Evaluation of synthetic diagnostic signal		evaluate()

IDA for JT-60SA: Status, plan and goal

Present status: (WP SA-SE.CM.OP.04-T001)

"2021: Requirement capture and specifications for the adaptation of the modular IDA python code to JT-60SA diagnostics, starting with commissioning diagnostics."

H. Tojo (QST), K. Fujii (Kyoto Univ.), R. Fischer (IPP), D. Stieglitz (IPP), G. Falchetto (CEA)

Plan (to be agreed):

1) start with commissioning diagnostics (PO-1):
   - interferometry → n_e
   - soft-X ray → $T_e(n_e, Z_{eff})$
   - visible spectroscopy → $Z_{eff}(n_e, T_e)$
2) augment with PO-2 synthetic diagnostics:
   - Thomson scattering → n_e, T_e
   - ECE → $T_e(n_e)$

Goal: IDA for physics exploitation in 2024

Benefits of IDA approach:

1) same IDA as for ITER
2) mutual development for various devices
3) mutual development for similar diagnostics

4) diagnostics inter-dependencies resolved
5) probabilistic parameter space exploration (MCMC)
   → to characterize diagnostics to be commissioned
6) unified uncertainty quantification of data and parameters
7) addtl. information: positivity (n_e, T_e), Z_{eff}>=1, modeling, ...
8) (nuisance) parameters, e.g. calibration and uncertainty
9) easily to be augmented with further diagnostics...

Summary: IDA for Nuclear Fusion

Bring together different diagnostics/diagnosticians/theoreticians with redundant/complementary/modeling data

- modular IDA python package
- ITER workflow: interferometry (TIP), TS, ECE
- IMAS (IDS, forward models)

IDAV SWG: Nuclear Fusion Paper, Chapter 10

Special issue in Nuclear Fusion:

ITPA contributions to ITER and burning plasma diagnostics

Chapter 10

“Integrated Data Analysis and Validation”

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M. Salewski,
M. Schneider,
D. Stieglitz

submitted to ITPA TG Diagnostics

1. Introduction	(overview of applications worldwide)
2. Integrated Data Analysis	(comparison with conventional approaches)
2.1. Bayesian probability theory	(concept)
2.2. Forward models	(multi-fidelity: from RT to offline)
2.3. Uncertainty quantification	
2.3.1. Uncertainties in measured data	(statistical, systematic)
2.3.2. Uncertainties in physics models	(calibration, atomic data, nuisance parameters)
2.3.3. Uncertainties in estimated quantities	(various methods)
2.4 Likelihoods	(Gaussian, outlier tolerant Cauchy)
2.5. Prior information	(smoothness, positivity, …, physical modeling)
2.6. Parameterization	(spline, GPR, ...)
2.7. Methods for parameter and uncertainty estimation	(MAP, MCMC)
2.8. Validation	(treatment of inconsistent/degrading data/diagnostics, outlier detection)
2.9. Numerical implementation	(new IDA-ITER python code)
3. IMAS	
4. Examples	
4.1. Synergistic effect	
4.2. Profile reconstruction	
4.3. Equilibrium reconstruction	
4.4. Integrated data analysis by velocity-space tomography	
5. Summary	