Models and Workflows for Heating and Current Drive and Synthetic Diagnostics in the IMAS Integrated Modelling Framework

PPPL seminar, 7 February 2022

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Outline

- The ITER mission goals and Research Plan
- The IMAS Integrated Analysis and Modelling Suite
- Synthetic Diagnostics in IMAS
- Workflows and Bayesian technique platforms
- H&CD models and workflow in IMAS
- Summary

Suggestions on how PPPL can contribute in the clouds!

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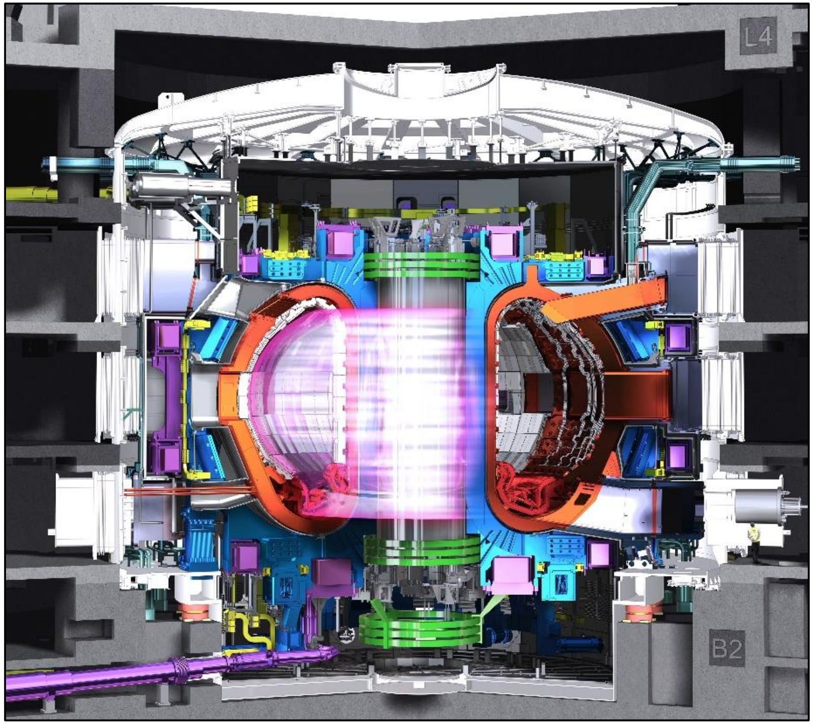
ITER mission goals

ITER shall demonstrate the scientific and technological feasibility of fusion energy:

- Pulsed operation:
  $Q \geq 10$ for burn of 300-500 s, with inductively driven current.
  → Baseline scenario 15 MA / 5.3 T.

- Long pulse operation:
  $Q \sim 5$ for long pulses up to 1000 s, supported by non-inductive current drive.
  → Hybrid scenario ~ 12.5 MA / 5.3 T.



- Steady-state operation:
  $Q \sim 5$ for long pulses up to 3000 s, with fully non-inductive current drive
  → Steady-state scenario ~ 10 MA / 5.3 T.

H&CD systems and diagnostics in the ITER Research Plan

Link to ITR-18-003


ITER TECHNICAL REPORT

ITER Research Plan within the Staged Approach (Level III – Provisional Version)

- The ITER Research Plan defines the strategy to achieve its mission goals throughout the scientific and technical exploitation of the tokamak and its ancillary systems.
- It will unfold in four stages:

First Plasma

18 months **FP**

H plasmas

ECH - 6.7 MW

Integrated commissioning of tokamak core components

↓

Basic set of diagnostics (magnetics, breakdown, investment protection, density)

Pre-Fusion Power Operation 1 and 2

18 months **PFPO-1**

H, ^{4}He plasmas

ECH - 20 (+10) MW

- Main plant systems commissioning
- $P_{L\text{-}H}$ determination

↓

Extra diagnostic subset for measurements of plasma parameters & control

21 months **PFPO-2**

H, ^{4}He plasmas

ECH, ICRH, NBI 73 (+10) MW

- Raise current and power
- Increase pulse duration

↓

Nearly complete set of diagnostics

Fusion Power Operation

16m periods **FPO**

D, DT plasmas

ECH, ICRH, NBI + fusion 73 (+10) MW + 100 MW

- Q=10
- Long pulse operation
- Burning plasmas

↓

Complete set of diagnostics including DT fusion products

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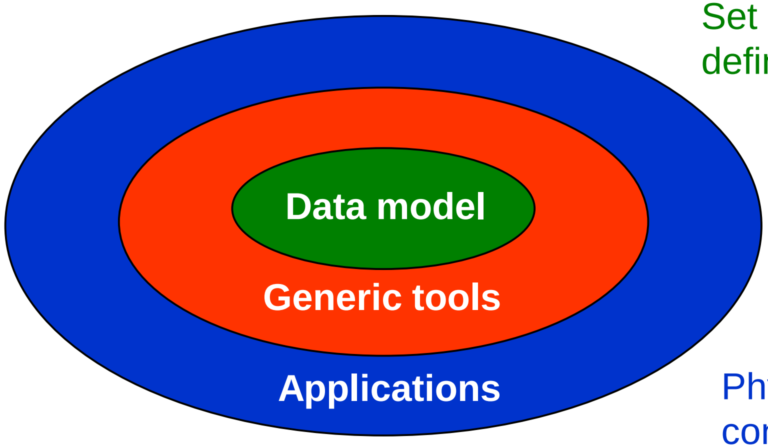
The ITER Integrated Modelling & Analysis Suite (IMAS)

- IMAS is the collection of physics software that will be used to support ITER operations and research as defined in the ITER Integrated Modelling Programme
- It uses standard Interface Data Structures (IDS):
  - For access to experimental and simulated data defined in collaboration with ITER Members
  - For exchanging data between components in an integrated modelling environment
- It is suitable for any fusion device
- It will contain components enabling high physics-fidelity predictive simulations of ITER plasmas
- It will be used for ITER data processing and analysis



Set of machine-independent IDSs defining the IMAS standard

Functions for data access, storage, manipulation, visualization

Physics codes, physics workflows, control algorithms

Databases
Scenarios
Machine Descr.
Atomic data

Doc & support
Tutorials
Web documentation
Tracker system

The IMAS Data Dictionary

- Core
- Edge
- Electro-Magnetics
- Physics phenomena
- Fuelling
- H&CD
- Other plant systems
- Diagnostics
- Data management

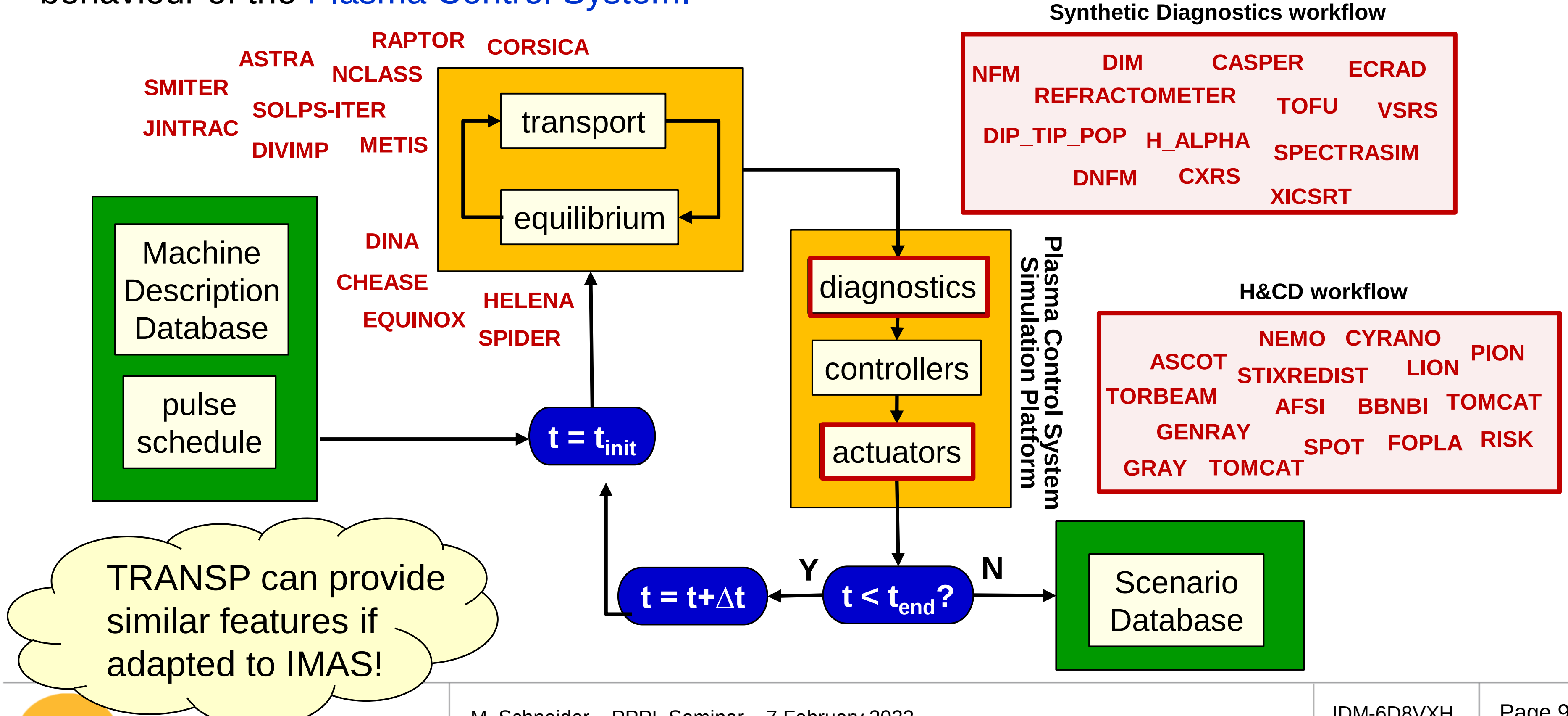
charge_exchange
edge_profiles
bremsstrahlung_visible
edge_sources
gas_injection
magnetics
edge_transport
pellets
mhd ntms
spectrometer_mass
disruption radiation
spectrometer_visible
turbulence mhd_linear
ec_launchers
gyrokinetics sawteeth
waves ic_antennas
distribution_sources
lh_antennas
spectrometer_uv
core_transport
distributions
nbi
bolometer pf_active
core_sources
core_profiles
wall soft_x_rays
langmuir_probes
core_instant_changes
cryostat
tf
hard_x_rays
pf_passive
mse interferometer
polarimeter
equilibrium
iron_core
barometry
em_coupling
reflectometer_profile
camera_visible
coils_non_axisymmetric
camera_ir
thomson_scattering
spectrometer_x_ray_crystal
ece calorimetry neutron_diagnostic

dataset_description
summary
transport_solver_numerics
numerics
temporary
dataset_fair
controllers
pulse_schedule
amns_data
sdn

The dictionary evolves with the development of the IM platform.

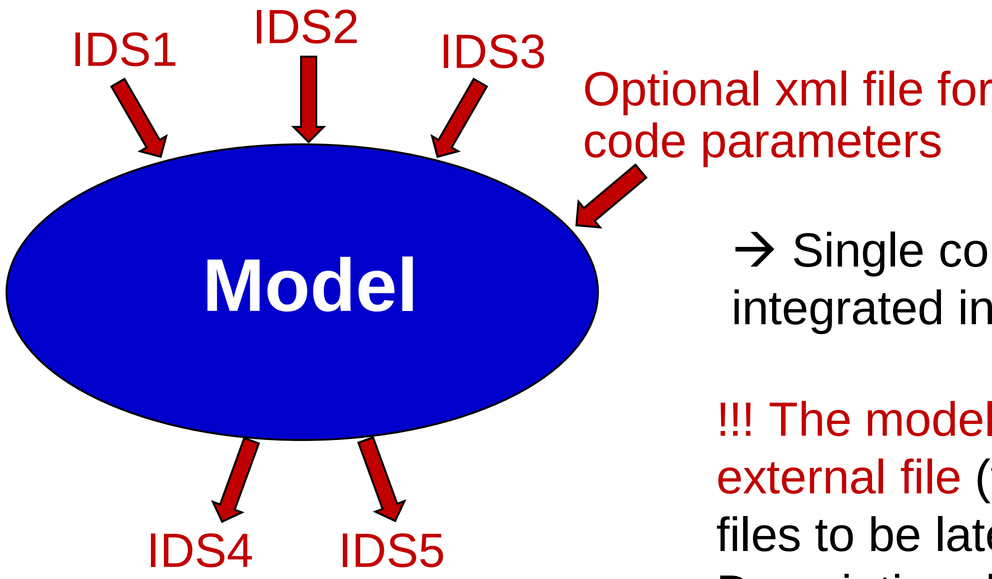
Towards a high-fidelity plasma simulator

- IMAS will contain a plasma simulator that integrates free-boundary evolution, core-edge-SOL transport, divertor physics and PFC models to allow high fidelity physics simulations.
- Diagnostic and actuator models will be used together with control algorithms to simulate the behaviour of the Plasma Control System.



Criteria for models to be in IMAS

- An IMAS model exchanges IDSs exclusively + an optional xml code parameter file:



TRANSP and its modules to use IDSs as input and output

→ Single component that can be integrated into the IMAS framework.

!!! The model should not depend on any other external file (for now we use centralised CAD files to be later included in the Machine Description database)

```
ids4,ids5 = model(ids1,ids2,ids3,xml_codeparam)
```

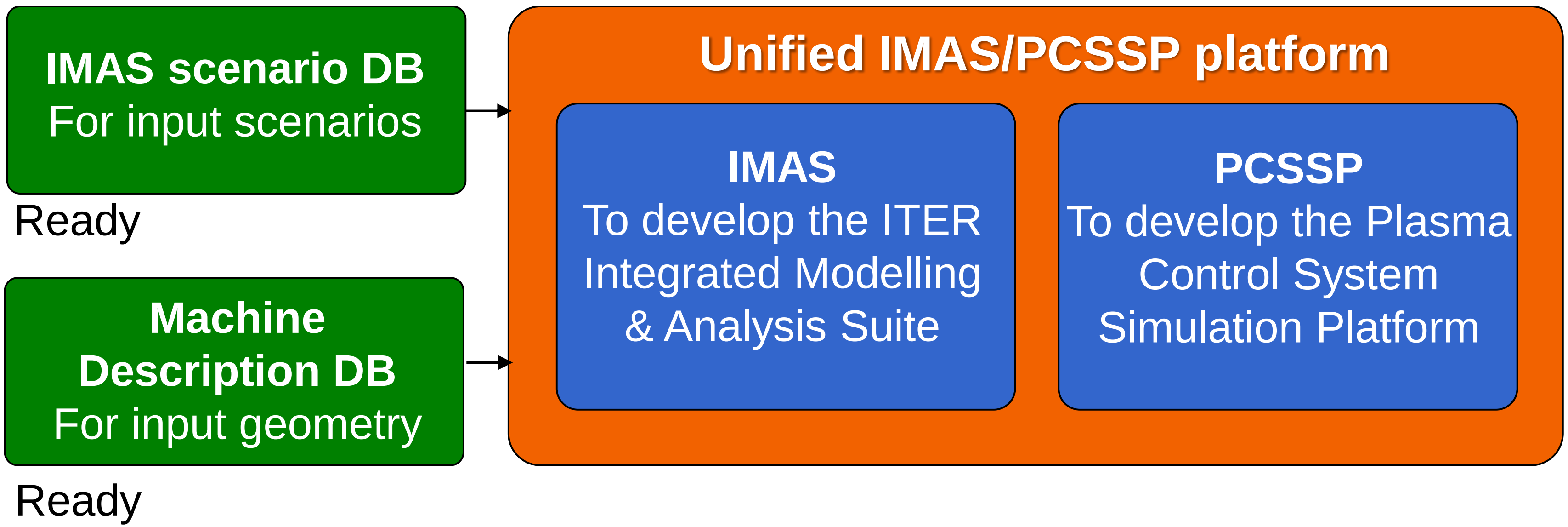
- Associated development:
  - Extension of the IMAS Data Dictionary (some IDSs are too basic or not existing)
  - Population of the Machine Description DB with the geometry of ITER diagnostics

PPPL possible contributions

- TRANSP physics components should exchange IDSs without any layer of data conversion or translation
- To help with planning, it would be good to communicate the schedule for creating new IMAS actors, e.g.:
  - TORAY-GA, GENRAY, CQL3D, MMM, GLF23, TGLF, NEO already extracted
  - TEQ, ISOLVER and reduced SOL model will be extracted

... All these components to be made IMAS-compliant

Models in IMAS

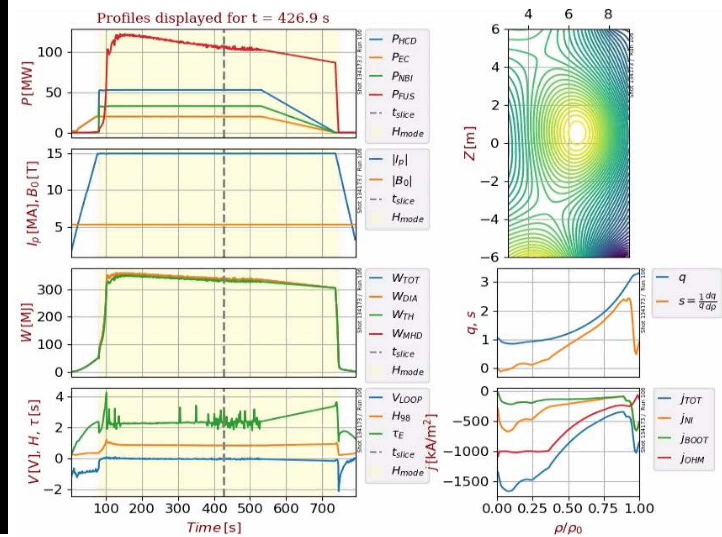


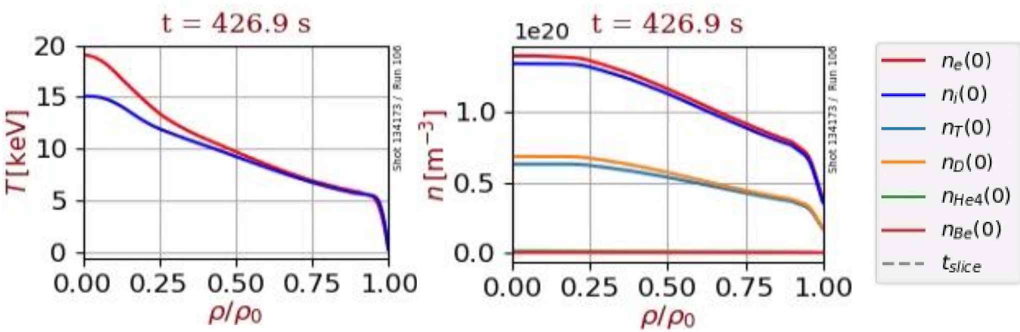
IMAS scenario database

- ~1800 simulations for core and/or edge scenarios, among which 680 are active

```
----> Default call equivalent to:
      scenario_summary -c shot,run,database,ref_name,ip,b0,fuelling,confinement,workflow
------------------------------------------------------------------------------------------------------------------------------
Pulse    Run  Database  Reference                                     Ip[MA]  B0[T]  Fuelling  Confinement      Workflow
------------------------------------------------------------------------------------------------------------------------------
100001   2    ITER      ITER-full-field-H                              -15.0   -5.3   H         L-mode           METIS
100002   1    ITER      ITER-half-field-H                              -7.5    -2.65  H         L-mode           METIS
100003   1    ITER      ITER-third-field-H                             -5.0    -1.8   H         L-H-L            METIS
100007   1    ITER      ITER-intermediate-3T-H                         -8.5    -3.0   H         L-H-L            METIS
100008   1    ITER      ITER-intermediate-3.3T-H                       -9.5    -3.3   H         L-H-L            METIS
100009   1    ITER      ITER-intermediate-4.5T-H                       -12.5   -4.5   H         L-mode           METIS
100013   1    ITER      ITER-PFPO1-1.8T-H                              -5.0    -1.8   H         L-H-L            METIS
100014   2    ITER      ITER-PFPO2-1.8T-H-0.5*n_GW-NBI_530keV_9.4MW    -5.0    -1.8   H         L-H-L            METIS
100015   1    ITER      ITER-PFPO2-1.8T-H-0.9*n_GW-NBI_745keV_22.3MW   -5.0    -1.8   H         L-H-L            METIS
100501   3    ITER      ITER-nonactive-H                               -7.5    -2.65  H         L-H-L            CORSICA
100502   3    ITER      ITER-nonactive-H                               -7.5    -2.65  H         L-H dithering    CORSICA
100503   3    ITER      ITER-nonactive-H                               -7.5    -2.65  H         L                CORSICA
100504   3    ITER      ITER-nonactive-H                               -9.6    -3.25  H         L                CORSICA
100505   3    ITER      ITER-nonactive-H                               -12.7   -4.7   H         L                CORSICA
100506   3    ITER      ITER-nonactive-H                               -15.0   -5.3   H         L                CORSICA
100507   3    ITER      ITER-nonactive-H                               -5.0    -1.77  H         L-H-L            CORSICA
101000   50   ITER      PFPO-2 tf=tE,2NBI,highTped,postST              -7.5    -2.65  H         H-mode           ASTRA
101001   50   ITER      PFPO-2 tf=tE,2NBI,highTped,preST               -7.5    -2.65  H         H-mode           ASTRA
101002   50   ITER      PFPO-2 tf=tE,2NBI,lowTped,postST               -7.5    -2.65  H         H-mode           ASTRA
101003   50   ITER      PFPO-2 tf=tE,2NBI,lowTped,preST                -7.5    -2.65  H         H-mode           ASTRA
101004   60   ITER      PFPO-2 tf=2tE,2NBI                             -7.5    -2.65  H         H-mode           ASTRA
101005   60   ITER      PFPO-2 tf=tE,2NBI                              -7.5    -2.65  H         H-mode           ASTRA
101006   60   ITER      PFPO-2 tf=0.5tE,2NBI                           -7.5    -2.65  H         H-mode           ASTRA
101007   40   ITER      PFPO-2 H-5MA-20EC-10NBI Pr=0.3(tF/tE=2)        -5.0    -1.8   H         H-mode           ASTRA
101007   41   ITER      PFPO-2 H-5MA-20EC-10NBI Pr=0.3(tF/tE=1)        -5.0    -1.8   H         H-mode           ASTRA
101007   42   ITER      PFPO-2 H-5MA-20EC-10NBI Pr=0.3(tF/tE=0.65)     -5.0    -1.8   H         H-mode           ASTRA
```

DINA-JINTRAC free boundary core-edge ITER DT scenario 15 MA / 5.3 T





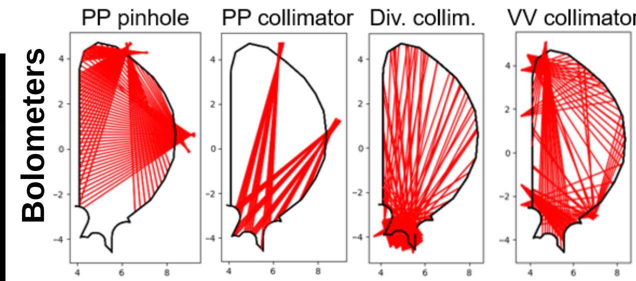
Tools are available to list and visualise IMAS scenarios

Predictive TRANSP modelling of ITER discharges

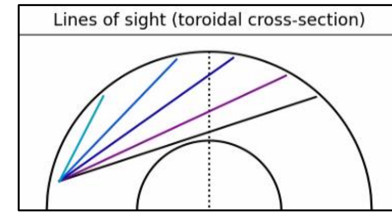
IMAS Machine Description database

- Machine Description available for H&CD systems, many diagnostics, wall, magnetics and coils:

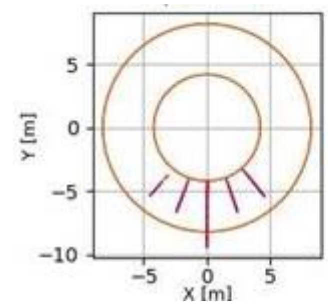
```
---> Default call equivalent to:
     md_summary -c pbs,ids,description
-----------------------------------------------------------------------------------------------------------------------------------------------
PBS             IDS                            DESCRIPTION                                                                                         SHOT/RUN
-----------------------------------------------------------------------------------------------------------------------------------------------
PBS-11          pf_active                      PF/CS Coil System, TF busbars (equivalent) and Virtual Coils                                        111001/3
PBS-11          tf                             TF Coil System                                                                                      111002/1
PBS-11          coils_non_axisymmetric         Ex-Vessel Coils (EVC) Systems (CC)                                                                  111003/1
PBS-15          coils_non_axisymmetric         In-Vessel Coils (IVC) Systems (ELM)                                                                 115001/1
PBS-15          coils_non_axisymmetric         In-Vessel Coils (IVC) Systems (ELM periodic)                                                        115002/1
PBS-15          coils_non_axisymmetric         In-Vessel Coils (IVC) Systems (VS)                                                                  115003/1
PBS-15          pf_passive                     Vacuum Vessel (VV), Triangular Support (TS) and Divertor Inboard Rails (DIR) from IDM               115004/1
PBS-15          pf_passive                     Vacuum Vessel (VV), Triangular Support (TS) and Divertor Inboard Rails (DIR) from DINA              115005/2
PBS-55.D1       bolometer                      PP pinholes and collim., Div. collim., VV collim. (550 channels)                                    150401/2
PBS-55.E5       spectrometer_x_ray_crystal     Core X-Ray Spectrometer (XRCS)                                                                      150505/2
PBS-55.EC       spectrometer_visible           Charge Exchange Recombination Spectroscopy (CXRS) Edge                                              150512/2
PBS-55.E1       spectrometer_visible           Charge Exchange Recombination Spectroscopy (CXRS) Core                                              150501/2
PBS-55.EF       spectrometer_visible           Charge Exchange Recombination Spectroscopy (CXRS) Pedestal                                          150515/2
PBS-52          ec_launchers                   Electron Cyclotron (EC) launchers                                                                   120000/1
PBS-55.F1       ece                            Electron Cyclotron Emission (ECE) - Radial O-mode                                                   150601/1
PBS-55.F1       ece                            Electron Cyclotron Emission (ECE) - Radial X-mode                                                   150601/2
PBS-55.F1       ece                            Electron Cyclotron Emission (ECE) - Oblique O-mode                                                  150601/3
PBS-55.F1       ece                            Electron Cyclotron Emission (ECE) - Oblique X-mode                                                  150601/4
PBS-51          ic_antennas                    Ion Cyclotron (IC) antennas                                                                         110000/1
PBS-55.C5       interferometer                 Toroidal Interfero-Polarimeter (TIP)                                                                150305/2
PBS-55.FA       interferometer                 Density Interfero-Polarimeter (DIP)                                                                 150610/2
PBS-55.A*       magnetics                      AD,AE,AF,AH,AI,A3,A4,A5,A6,AA,AB,AJ,AL,A9,AC,AG,AP magnetic systems                                 150100/3
PBS-53          nbi                            Heating Neutral Beams (HNB) - H beams 870 keV - off-off                                             130000/1201
PBS-53          nbi                            Heating Neutral Beams (HNB) - H beams 870 keV - off-on                                              130000/1301
PBS-53          nbi                            Heating Neutral Beams (HNB) - H beams 870 keV - on-on                                               130000/1501
PBS-53          nbi                            Heating Neutral Beams (HNB) - D beams 1 MeV - off-off                                               130000/2201
PBS-53          nbi                            Heating Neutral Beams (HNB) - D beams 1 MeV - off-on                                                130000/2301
PBS-53          nbi                            Heating Neutral Beams (HNB) - D beams 1 MeV - on-on                                                 130000/2501
PBS-53          nbi                            Diagnostic Neutral Beam (DNB) - on-axis                                                             130000/3202
PBS-53          nbi                            Diagnostic Neutral Beam (DNB) - off-axis                                                            130000/3102
PBS-55.C6       polarimeter                    Poloidal Polarimeter (POP)                                                                          150306/2
PBS-55.F9.40    refractometer                  Sub-system refractometer of HFS reflectometer                                                       150609/401
PBS-55.E6       spectrometer_visible           Visible Spectroscopy Reference System (VSRS) - PFPO and beyond                                      150506/3
PBS-55.E6       spectrometer_visible           Visible Spectroscopy Reference System (VSRS) - First Plasma                                         150506/101
PBS-55.E2       camera_visible                 H-alpha - First Plasma                                                                              150502/101
PBS-16          wall                           First wall and divertor geometry for PFPO and FPO phases                                            116000/2
PBS-16.FC       wall                           First Plasma Protection Components (FPPC)                                                           116612/1
PBS-16          pf_passive                     Blanket Module Panel (BMP)                                                                          116001/1
-----------------------------------------------------------------------------------------------------------------------------------------------
```

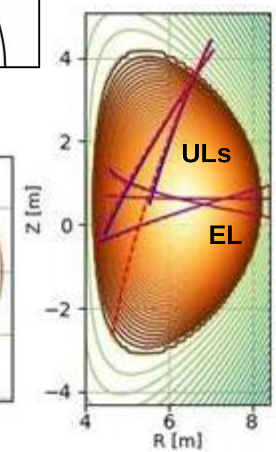


Toroidal Interfero-Polarimeter



EC launchers





- The MD database provides the geometry of the plant systems to be used as input of simulation codes.

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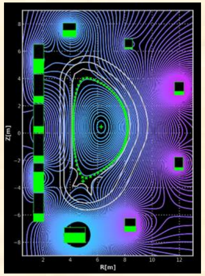
SD models presented here could be used within the TRANSP suite to support the validation of the models

Development and/or IMAS-adpation of SD models available/developed in PPPL

ITER (Synthetic) Diagnostics

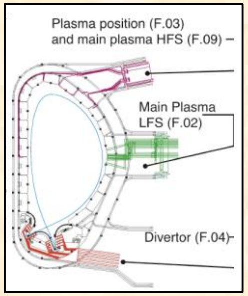
Magnetic Diagnostics

Determination of plasma equilibrium, current and stored energy, control of plasma shape and position



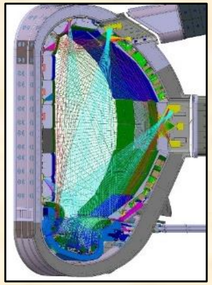
Microwave Diagnostics

Determination of the plasma position, through measurements in the main plasma and divertor **DIP, ECRad, REFI, refractometer**



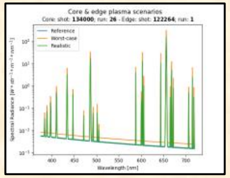
Bolometric Systems

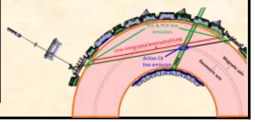
Determination of the spatial distribution of the radiated power in the plasma and divertor using tomographic reconstruction **TOFU_bolo**



Spectroscopic Instruments and NPA Systems

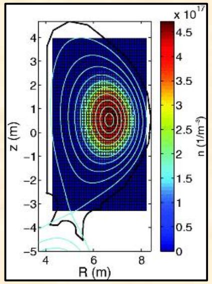
Determination of plasma composition, density, particle fluxes, ion temperature, fuelling ratio, plasma rotation, current density; **CASPER, CXRS, XICSRT**





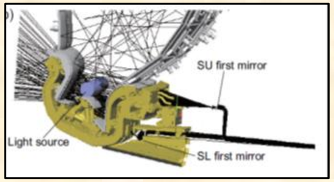
Neutron and Fusion Products Diagnostics

Measurement of fusion power, fusion products and fast ion losses **DNFM, NFM**



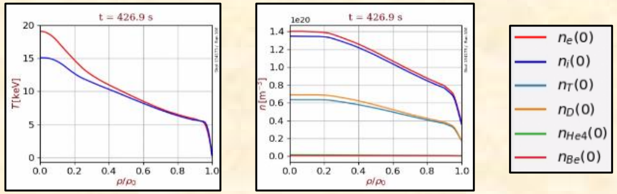
Plasma-Facing and Operational Diagnostics

Assist the machine protection and operation, especially the main chamber and divertor state (temperature, pressure, erosion, dust and tritium monitoring)



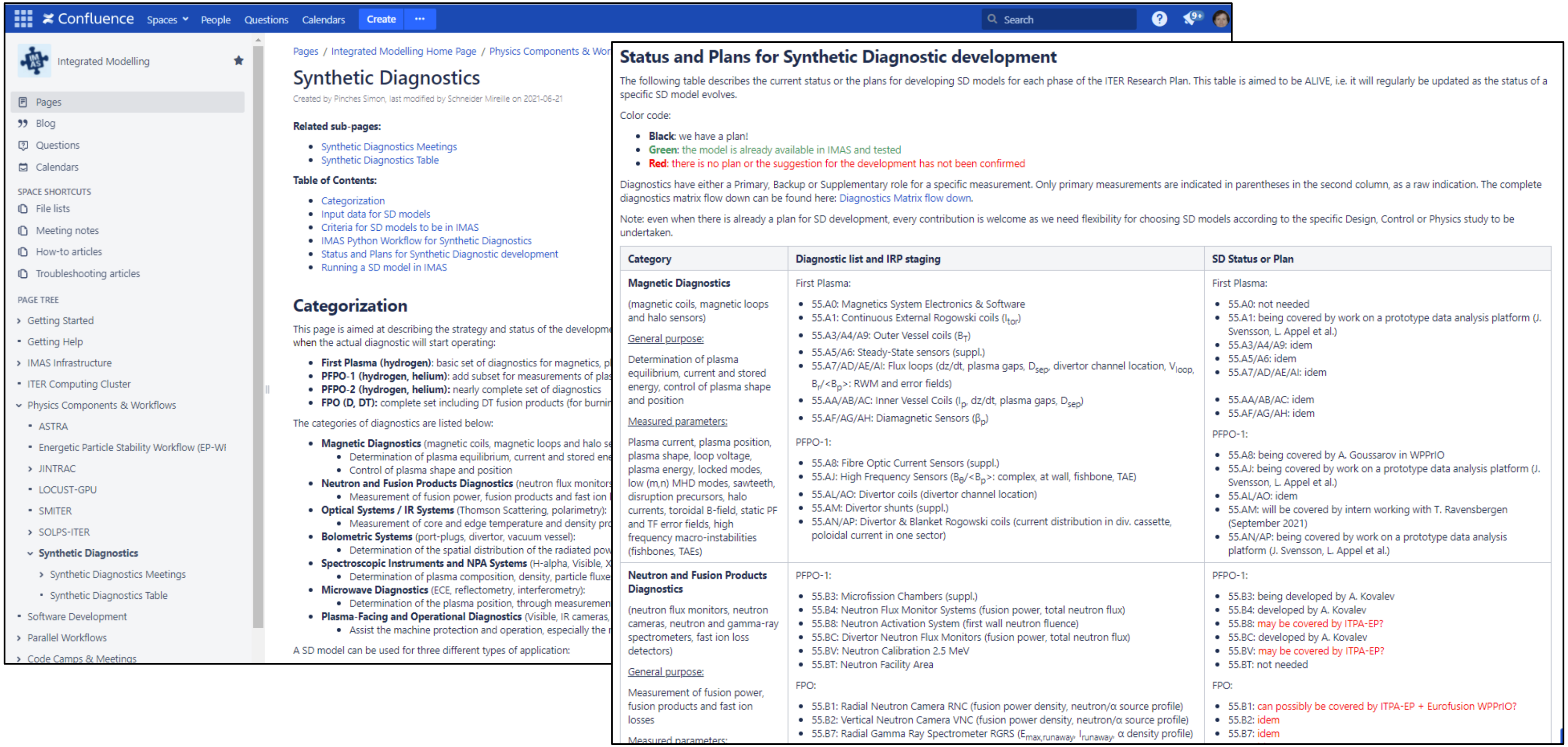
Optical Systems / IR Systems

Measurement of core and edge temperature and density profiles; **TIP, POP**



Central information on SD development for ITER

- The webpage showing the status of the SD development for ITER is here: https://confluence.iter.org/display/IMP/Synthetic+Diagnostics



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Meeting notes
How-to articles
Troubleshooting articles

PAGE TREE
Getting Started
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IMAS Infrastructure
ITER Computing Cluster
Physics Components & Workflows
ASTRA
Energetic Particle Stability Workflow (EP-WI
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Synthetic Diagnostics

Created by Pinches Simon, last modified by Schneider Mireille on 2021-06-21

Related sub-pages:

- Synthetic Diagnostics Meetings
- Synthetic Diagnostics Table

Table of Contents:

Categorization

This page is aimed at describing the strategy and status of the developme
when the actual diagnostic will start operating:

- **First Plasma (hydrogen)**: basic set of diagnostics for magnetics, p
- **PFPO-1 (hydrogen, helium)**: add subset for measurements of plas
- **PFPO-2 (hydrogen, helium)**: nearly complete set of diagnostics
- **FPO (D, DT)**: complete set including DT fusion products (for burnir

The categories of diagnostics are listed below:

- **Magnetic Diagnostics** (magnetic coils, magnetic loops and halo se
  - Determination of plasma equilibrium, current and stored ene
  - Control of plasma shape and position
- **Neutron and Fusion Products Diagnostics** (neutron flux monitors
  - Measurement of fusion power, fusion products and fast ion l
- **Optical Systems / IR Systems** (Thomson Scattering, polarimetry):
  - Measurement of core and edge temperature and density pro
- **Bolometric Systems** (port-plugs, divertor, vacuum vessel):
  - Determination of the spatial distribution of the radiated pow
- **Spectroscopic Instruments and NPA Systems** (H-alpha, Visible, X
  - Determination of plasma composition, density, particle fluxe
- **Microwave Diagnostics** (ECE, reflectometry, interferometry):
  - Determination of the plasma position, through measuremen
- **Plasma-Facing and Operational Diagnostics** (Visible, IR cameras,
  - Assist the machine protection and operation, especially the r

A SD model can be used for three different types of application:

Status and Plans for Synthetic Diagnostic development

The following table describes the current status or the plans for developing SD models for each phase of the ITER Research Plan. This table is aimed to be ALIVE, i.e. it will regularly be updated as the status of a specific SD model evolves.

Color code:

- **Black**: we have a plan!
- **Green**: the model is already available in IMAS and tested
- **Red**: there is no plan or the suggestion for the development has not been confirmed

Diagnostics have either a Primary, Backup or Supplementary role for a specific measurement. Only primary measurements are indicated in parentheses in the second column, as a raw indication. The complete diagnostics matrix flow down can be found here: Diagnostics Matrix flow down.

Note: even when there is already a plan for SD development, every contribution is welcome as we need flexibility for choosing SD models according to the specific Design, Control or Physics study to be undertaken.

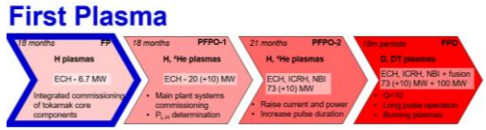
Category	Diagnostic list and IRP staging	SD Status or Plan
Magnetic Diagnostics (magnetic coils, magnetic loops and halo sensors) General purpose: Determination of plasma equilibrium, current and stored energy, control of plasma shape and position Measured parameters: Plasma current, plasma position, plasma shape, loop voltage, plasma energy, locked modes, low (m,n) MHD modes, sawteeth, disruption precursors, halo currents, toroidal B-field, static PF and TF error fields, high frequency macro-instabilities (fishbones, TAEs)	First Plasma: • 55.A0: Magnetics System Electronics & Software • 55.A1: Continuous External Rogowski coils (I_{tor}) • 55.A3/A4/A9: Outer Vessel coils (B_T) • 55.A5/A6: Steady-State sensors (suppl.) • 55.A7/AD/AE/AI: Flux loops (dz/dt, plasma gaps, D_{sep}, divertor channel location, V_{loop}, $B_r/<B_p>$: RWM and error fields) • 55.AA/AB/AC: Inner Vessel Coils (I_p, dz/dt, plasma gaps, D_{sep}) • 55.AF/AG/AH: Diamagnetic Sensors (β_p) PFPO-1: • 55.A8: Fibre Optic Current Sensors (suppl.) • 55.AJ: High Frequency Sensors ($B_\theta/<B_p>$: complex, at wall, fishbone, TAE) • 55.AL/AO: Divertor coils (divertor channel location) • 55.AM: Divertor shunts (suppl.) • 55.AN/AP: Divertor & Blanket Rogowski coils (current distribution in div. cassette, poloidal current in one sector)	First Plasma: • 55.A0: not needed • 55.A1: being covered by work on a prototype data analysis platform (J. Svensson, L. Appel et al.) • 55.A3/A4/A9: idem • 55.A5/A6: idem • 55.A7/AD/AE/AI: idem • 55.AA/AB/AC: idem • 55.AF/AG/AH: idem PFPO-1: • 55.A8: being covered by A. Goussarov in WPPrIO • 55.AJ: being covered by work on a prototype data analysis platform (J. Svensson, L. Appel et al.) • 55.AL/AO: idem • 55.AM: will be covered by intern working with T. Ravensbergen (September 2021) • 55.AN/AP: being covered by work on a prototype data analysis platform (J. Svensson, L. Appel et al.)
Neutron and Fusion Products Diagnostics (neutron flux monitors, neutron cameras, neutron and gamma-ray spectrometers, fast ion loss detectors) General purpose: Measurement of fusion power, fusion products and fast ion losses Measured parameters:	PFPO-1: • 55.B3: Microfission Chambers (suppl.) • 55.B4: Neutron Flux Monitor Systems (fusion power, total neutron flux) • 55.B8: Neutron Activation System (first wall neutron fluence) • 55.BC: Divertor Neutron Flux Monitors (fusion power, total neutron flux) • 55.BV: Neutron Calibration 2.5 MeV • 55.BT: Neutron Facility Area FPO: • 55.B1: Radial Neutron Camera RNC (fusion power density, neutron/α source profile) • 55.B2: Vertical Neutron Camera VNC (fusion power density, neutron/α source profile) • 55.B7: Radial Gamma Ray Spectrometer RGRS ($E_{max,runaway}$, $I_{runaway}$, α density profile)	PFPO-1: • 55.B3: being developed by A. Kovalev • 55.B4: developed by A. Kovalev • 55.B8: may be covered by ITPA-EP? • 55.BC: developed by A. Kovalev • 55.BV: may be covered by ITPA-EP? • 55.BT: not needed FPO: • 55.B1: can possibly be covered by ITPA-EP + Eurofusion WPPrIO? • 55.B2: idem • 55.B7: idem

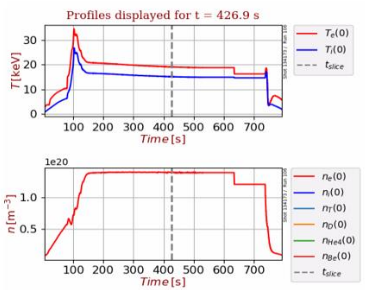
Examples of IMAS-adapted Synthetic Diagnostics for ITER

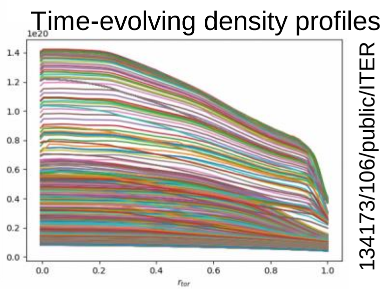
Model	Modelled diagnostic or signal	Input IDSs from scenario	Input IDSs from Machine Description or upstream code	Output IDSs
CASPER	Generic light spectrum for visible spectrometry	equilibrium core_profiles edge_profiles	spectrometer_visible nbi	spectrometer_visible
CXRS	Fit to create synthetic CXRS signal from spectrum	-	spectrometer_visible	charge_exchange
DIP_TIP_POP	Toroidal Interfero-Polarimeter Density Interfero-Polarimeter	equilibrium core_profiles	interferometer	interferometer
DIP_TIP_POP	Poloidal Polarimeter	equilibrium core_profiles	polarimeter	polarimeter
ECRad	Electron Cyclotron Emission	equilibrium core_profiles	ece	ece
REFI	LFS and HFS reflectrometers	equilibrium core_profiles	reflectometer_profile	reflectometer_profile
Refractometer	Refractometry channel of the HFS reflectometer	equilibrium core_profiles	refractometer	refractometer
TOFU_bolo	Bolometers	edge_sources wall	bolometer	bolometer
DNFM	Divertor Neutron Flux Monitor	equilibrium distribution_sources	neutron_diagnostic	neutron_diagnostic
NFM	Neutron Flux Monitor	equilibrium distribution_sources	neutron_diagnostic	neutron_diagnostic
XICSRT	X-ray Core diagnostic	equilibrium core_profiles	spectrometer_x_ray_crystal	spectrometer_x_ray_crystal

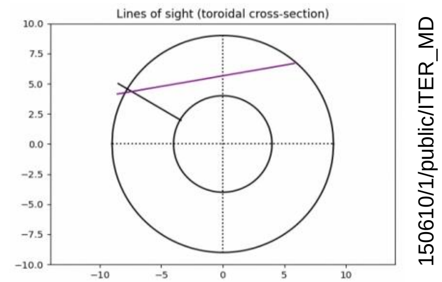
Density Interfero-Polarimeter

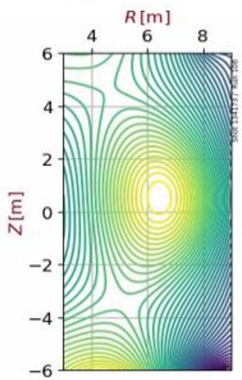
- 55.FA Density Interfero-Polarimeter (DIP), measures $\int n_e dl$
- Python model by A. Medvedeva











Scenario DB

equilibrium

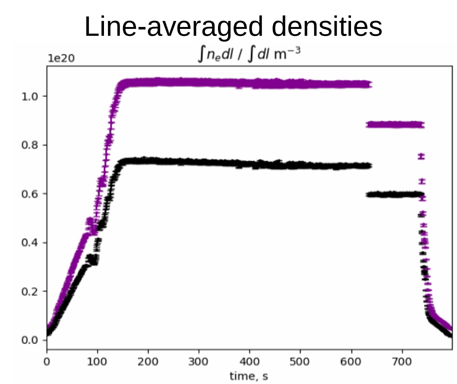
core_profiles

Machine Descr. DB

interferometer

DIP model

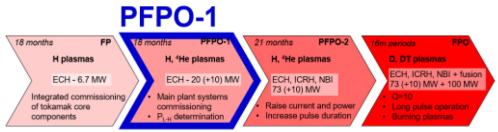
interferometer

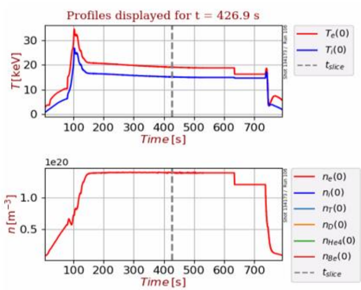


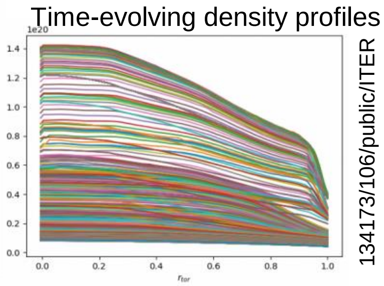

```
out_interferometer = dip_tip_pop(equilibrium,core_profiles,interferometer_md)
```

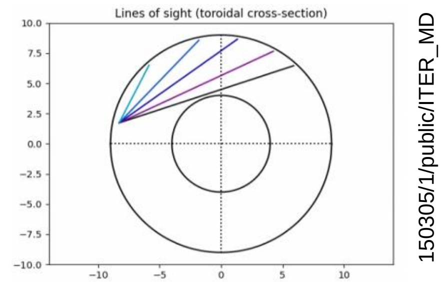
Toroidal Interfero-Polarimeter

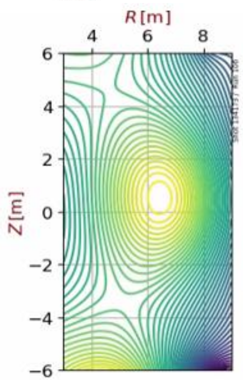
- 55.C5 Toroid. Interfer. Polarim. (TIP), measures $\int n_e dl,\ \delta n_e/n_e,\ \delta T_e/T_e$
- Python model by A. Medvedeva

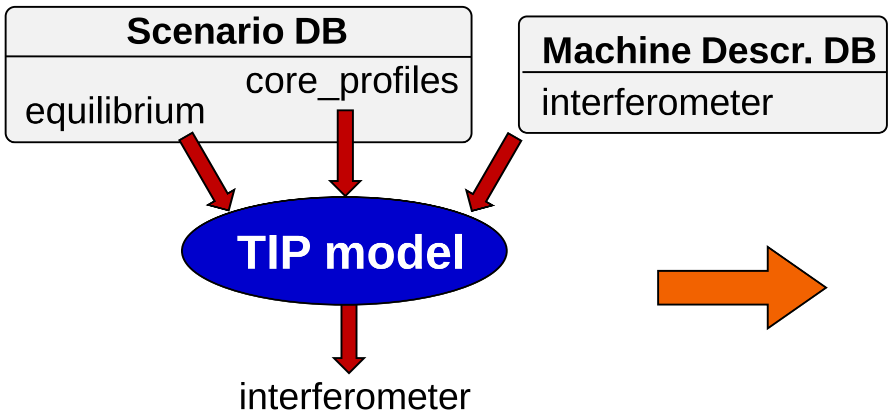


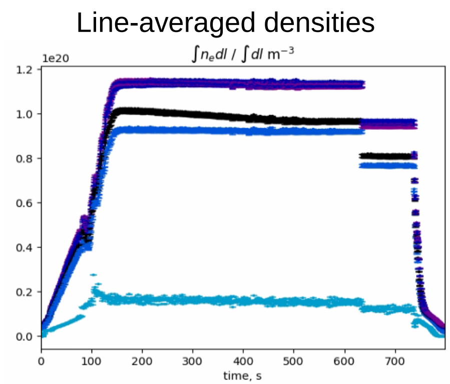








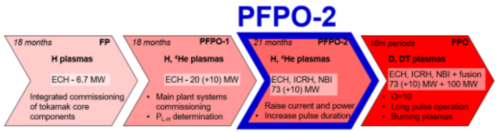


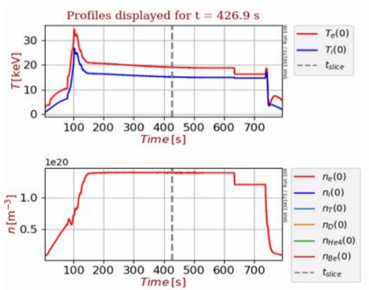


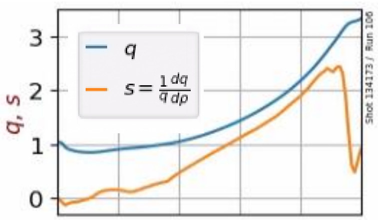

```
out_interferometer = dip_tip_pop(equilibrium,core_profiles,interferometer_md)
```

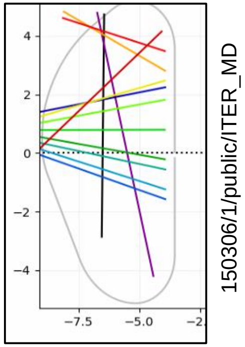
Poloidal Polarimeter

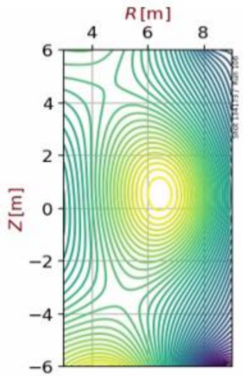
- 55.C6 Poloid. Polarim. (POP), measures q profile
- Python model by A. Medvedeva

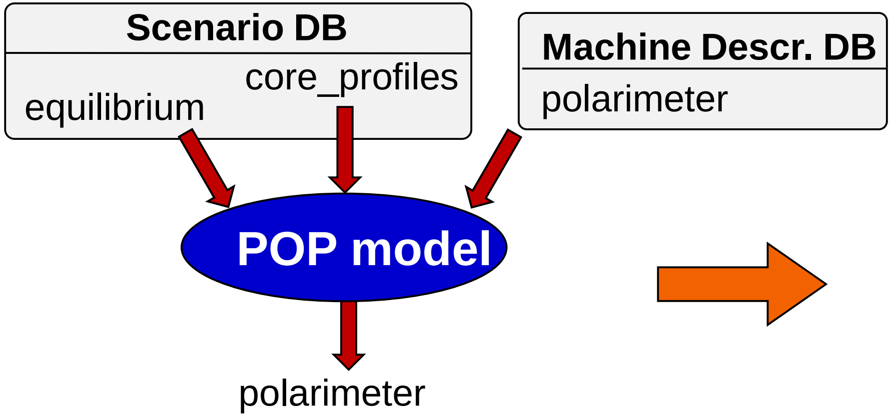


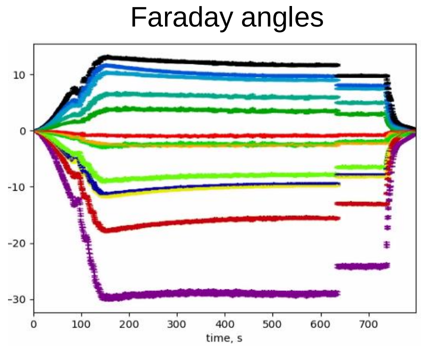








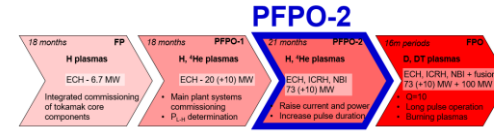


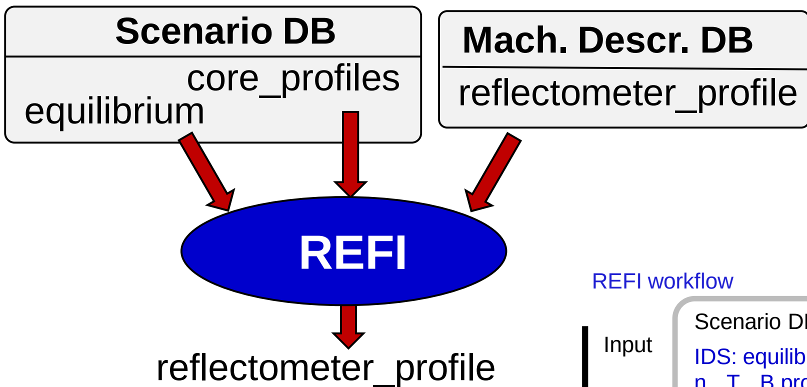


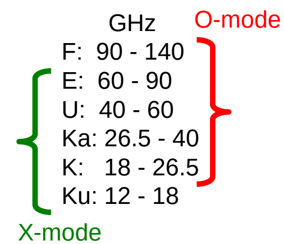

```
out_polarimeter = dip_tip_pop(equilibrium,core_profiles,polarimeter_md)
```

Reflectometry

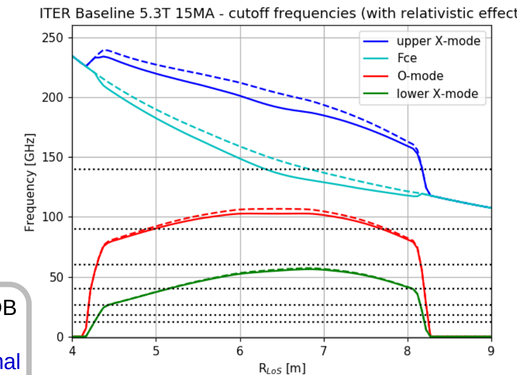
- 55.F9 (HFS) and 55.F2 (LFS)
- Measure core/edge n_e profiles, $\delta n_e/n_e$, $\delta T_e/T_e$
- REFI model developed by V. Nikolaeva

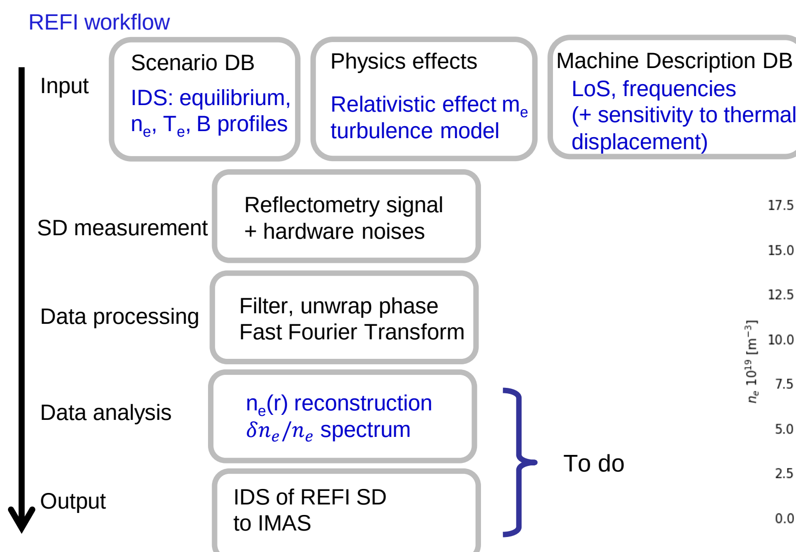


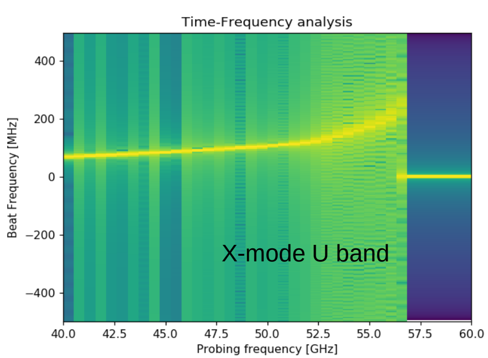


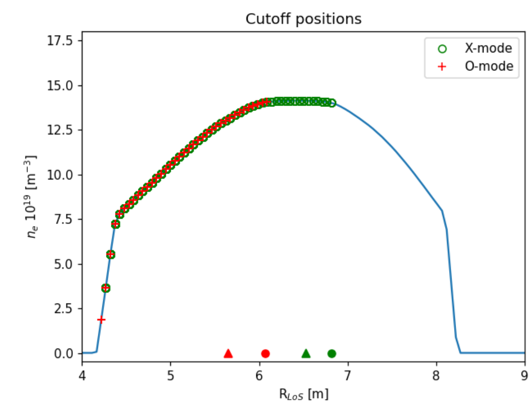


Input: shot 134173, run 106, time slice 296.9 s







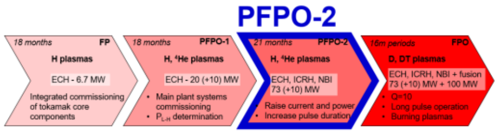


- Beat frequency → tof delay → radial locations
- Probing frequency → density

Refractometer

- 55.F9.40: refractometry channel of HFS reflectometer
- Measures $\int n_e dl$ (supplementary)

→ Python model developed by K. Afonin



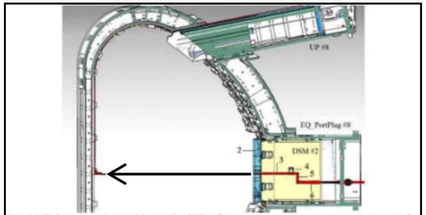
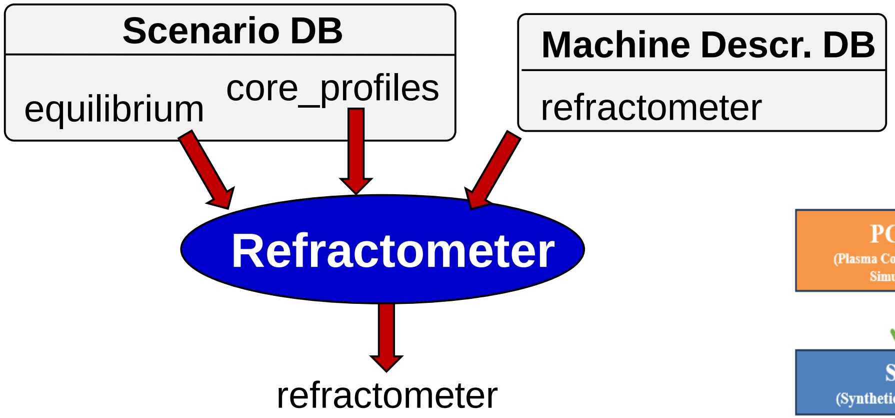
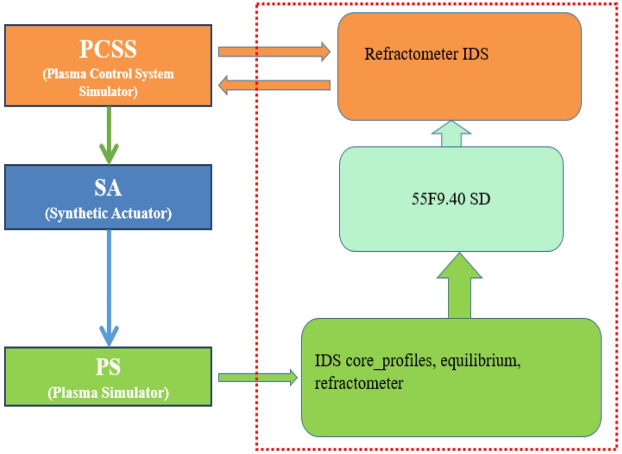
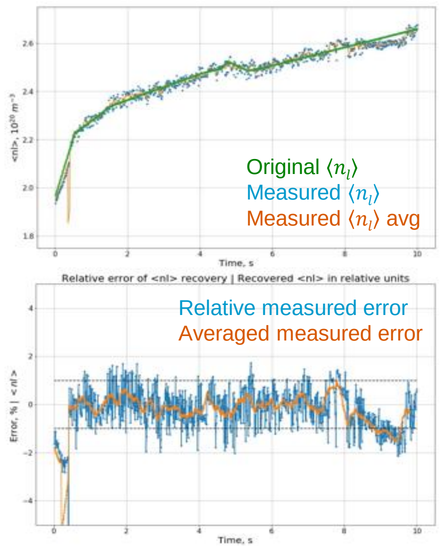


Fig. 6.6. Refractometer in-vessel layout (1 – HFS reflectometer antenna system (receiving antenna for refractometer); 2 – DFW (Diagnostic First Wall); 3 – Transmitting antenna; 4 – Support; 5 – Dog leg; 6 – Horns).





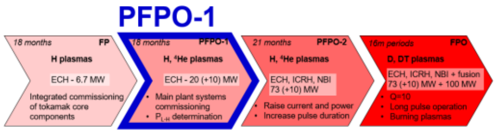
Line-averaged density vs. time



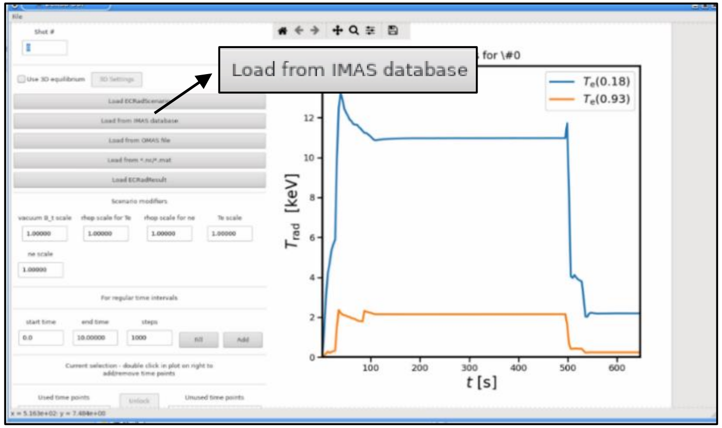
- Model used for basic machine control
- Integrated into DINA PCS workflow

```
refractometer = sd.slice_xml_wrapper(equilibrium,core_profiles,refractometer,xml_filename)
```

ECE synthetic diagnostic for ITER with ECRad

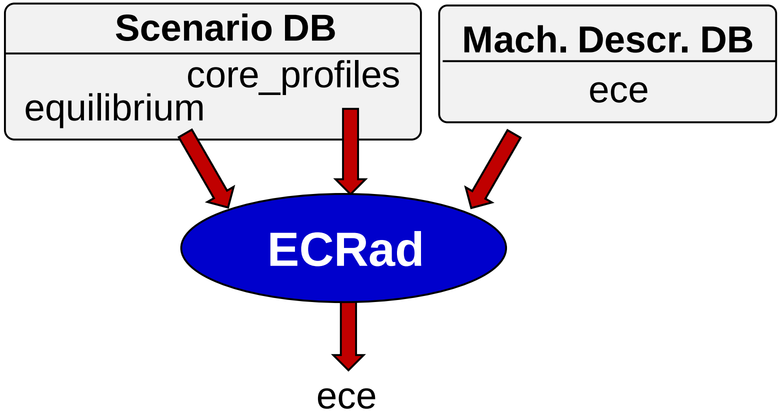


- 55.F1 Electron Cyclotron Emission (ECE)
- Measures T_e profile and $\delta T_e / T_e$
- ECRad model developed by S. Denk, adapted to IMAS with A. Medvedeva
- First tests for 1.8 T and 2.65 T PFPO scenarios done to predict the ECE system operation and radial resolution

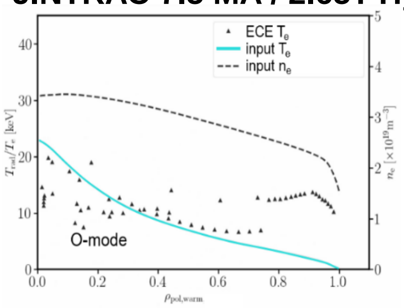


[S.S. Denk, CPC 2020]

(radial and oblique ECE channels 123-353 GHz, O- and X-mode)



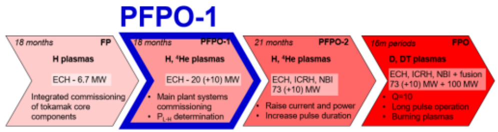
JINTRAC 7.5 MA / 2.65T Hydrogen

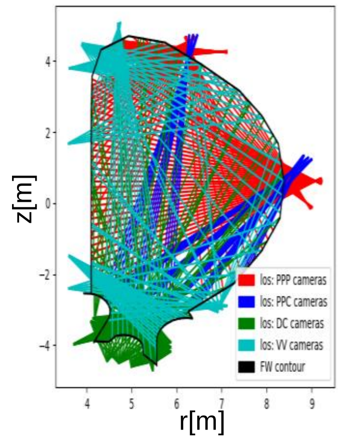


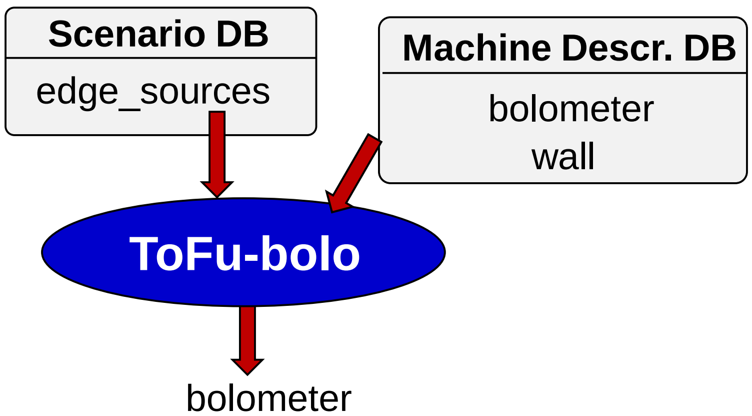
[A. Medvedeva et al., AAPPS-DPP2021]

Bolometers

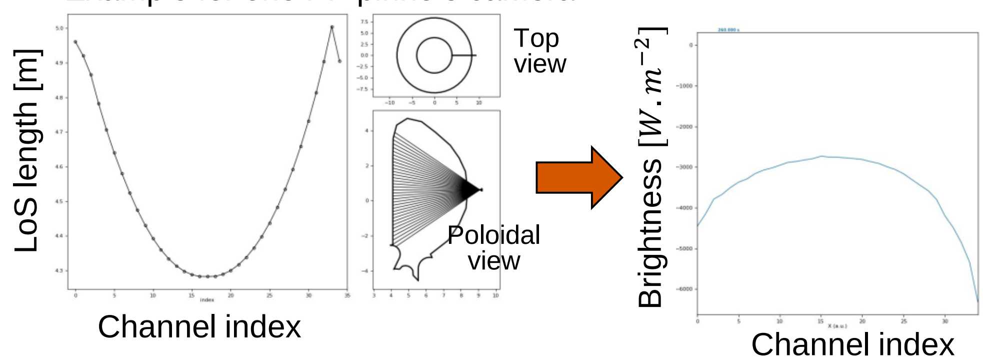
- 55.D1: bolometers, measure radiated power (total + profiles)
- Model using ToFu developed by D. Vezinet: Open Source Python library natively IMAS-compatible, made for SDs and tomography for Fusion
- Forward model and tomographic reconstruction of bolometers using CHERAB, TOFU and TOMOTOK, by M. Brank







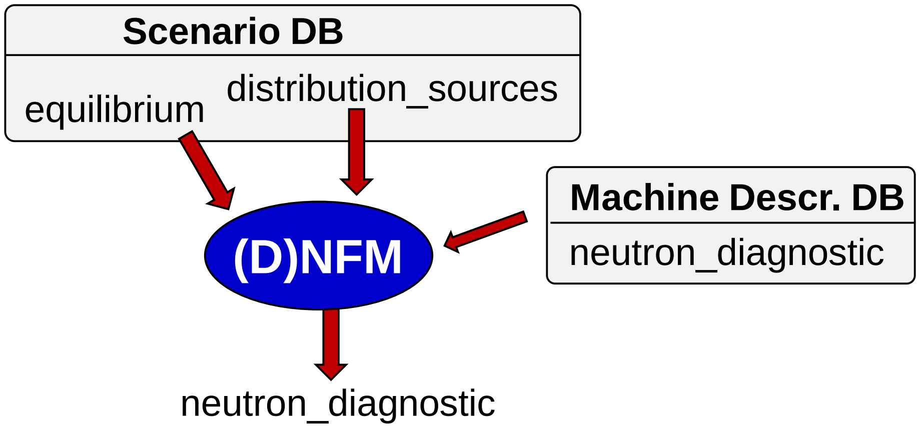
Example for one PP pinhole camera

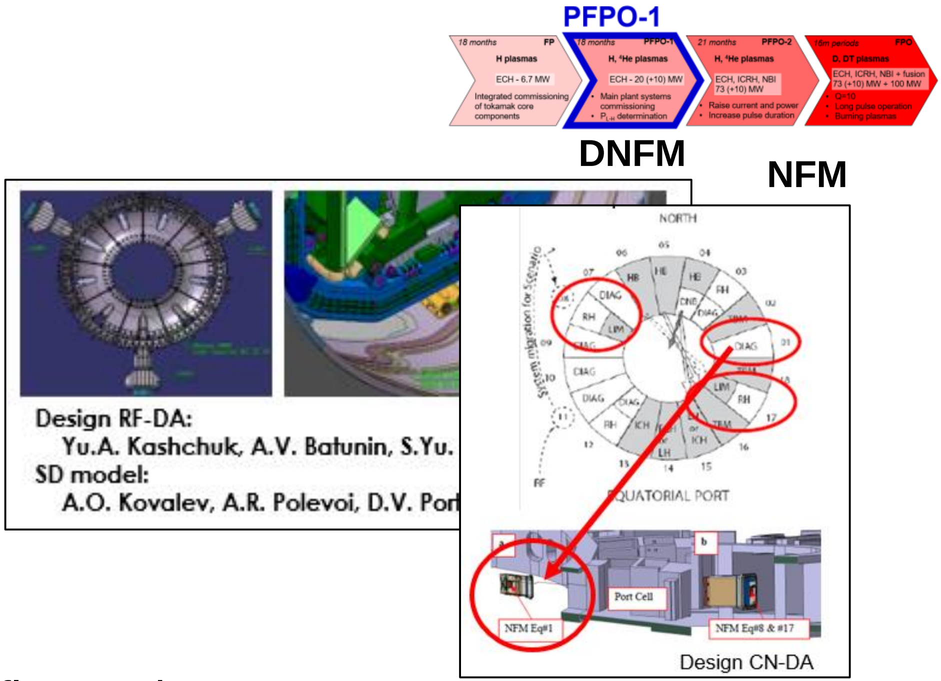



```
bolometer_sd = tofu_bolo(edge_sources, wall, bolometer_md, xml_codeparam)
```

(Divertor) Neutron Flux Monitors

- 55.BC: DNFM developed by A. Kovalev
- Fortran and Python versions, all in IMAS

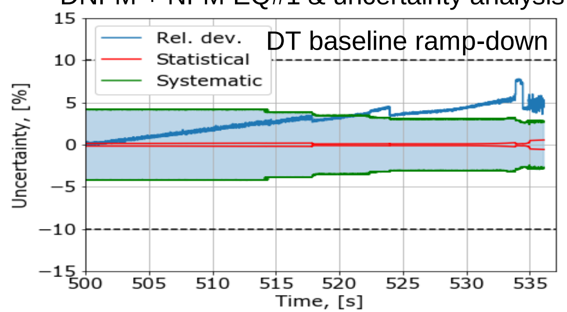




- 55.B4: NFM developed by A. Kovalev
- DNFM and NFM measure the total neutron flux and fusion power:
  - DNFM more sensitive to vertical plasma shift
  - NFM more sensitive to horizontal plasma shift

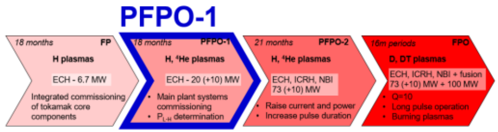
→ To be combined to deliver a measurement with less systematic error.

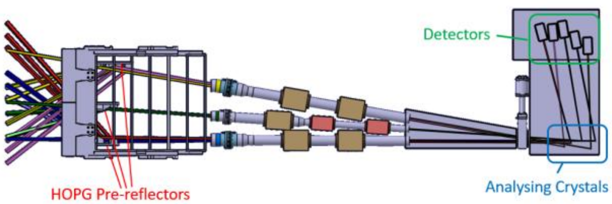
DNFM + NFM EQ#1 & uncertainty analysis

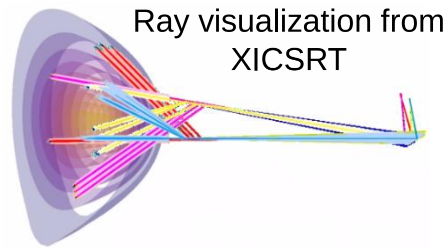


X-Ray Crystal Spectrometer Core

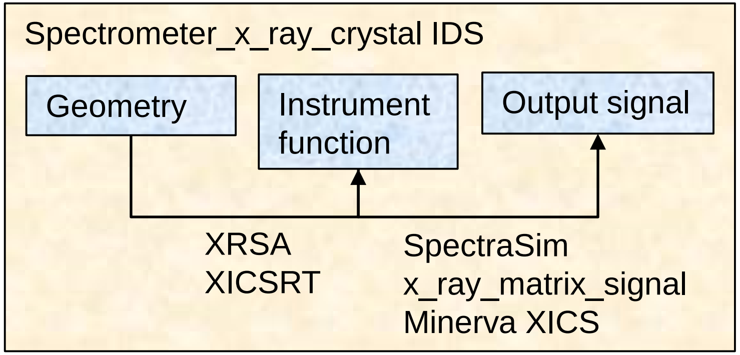
- 55.E5 X-Ray Crystal Spectrometer Core, measures T_i and v_{tor}
- XICSRT python code developed by N. Pablant, IMAS-adapted by E. Bourcart and Z. Cheng

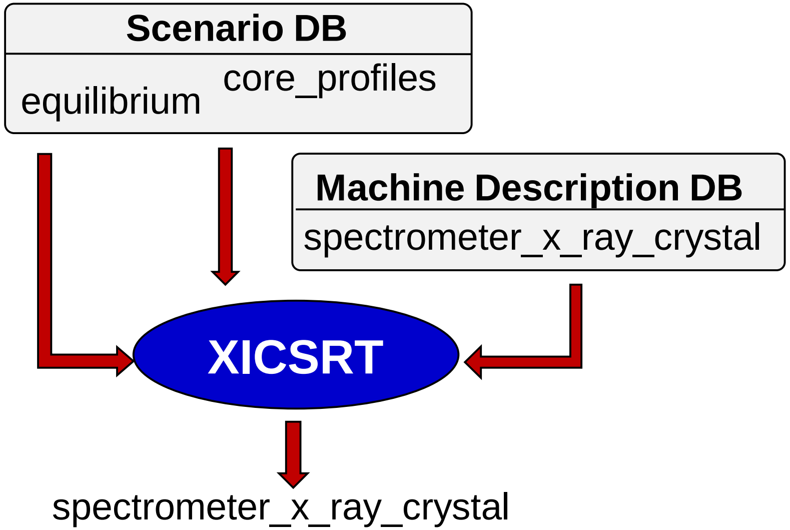






Ray visualization from XICSRT

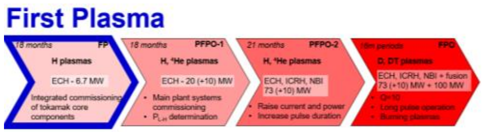


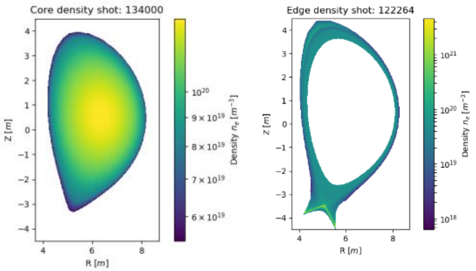


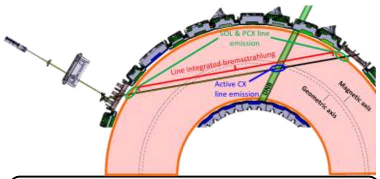
- Ray-tracing codes (on-going comparison):
  - XICSRT (Python, N. Pablant)
  - XRSA (Matlab, Z. Cheng)
- Output signal computed from RTM:
  - SpectraSim (Matlab, Z. Cheng)
  - x_ray_matrix_signal (Python, E. Bourcart)
  - Minerva XICS (Java, A. Langenberg)

Visible Light Spectrum

- CASPER: CAmera & SPectroscopy Emission Ray-tracer: generates the light spectrum for visible spectroscopy and cameras synthetic diagnostics







Scenario DB

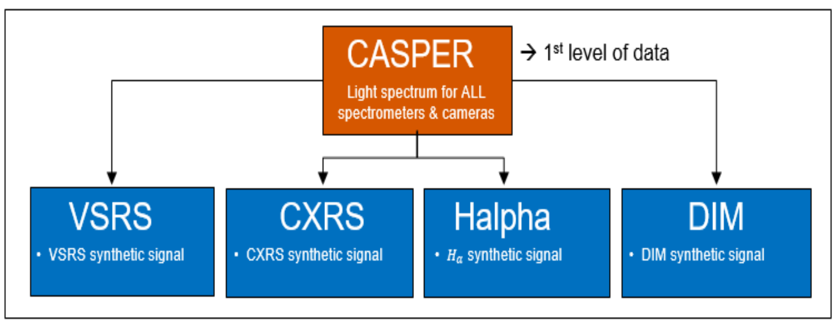
core_profiles
equilibrium
edge_profiles

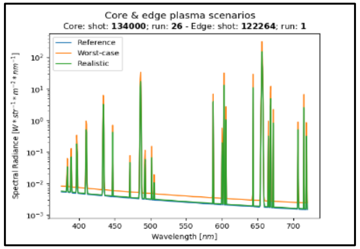
Mach. Descr. DB

spectrometer_visible
nbi

CASPER

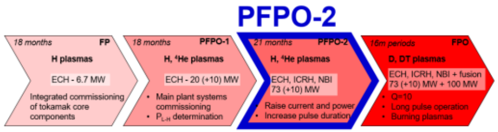
spectrometer_visible



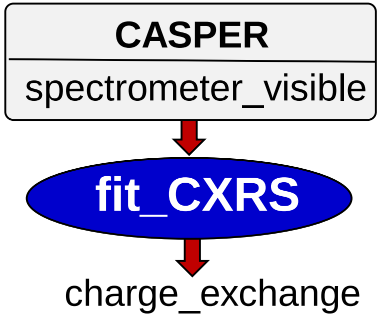


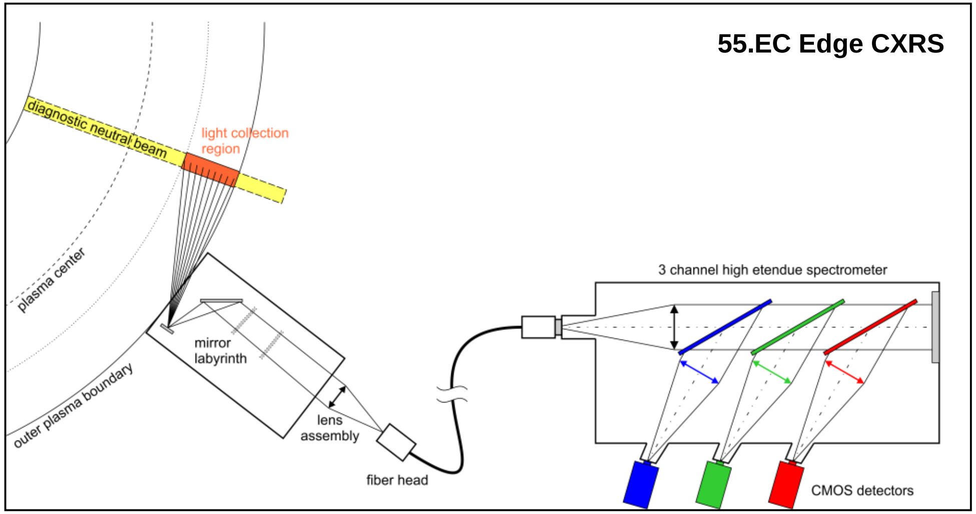
- Current status:
  - CASPER provides light spectrum for VSRS and CXRS
  - H-alpha and Divertor Impurity Monitor to be added (with RTM calculation)

Charge Exchange Recombination Spectroscopy

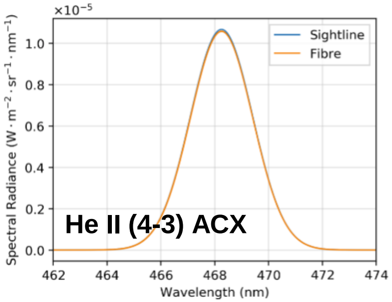


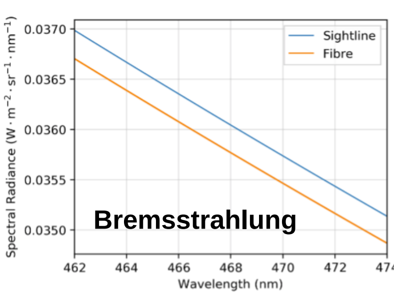
- 55.E1 / 55.EC / 55.EF Core / Edge / Pedestal Charge Exchange Recombination Spectroscopy
- Measure T_i, Z_{eff}, He, impurity profiles, toroidal and poloidal rotation
- Python fit_CXRS model developed by A. Shabashov: → reconstruct plasma parameters from spectrum fit





- On-going comparison between sightline and simplified fibre source models





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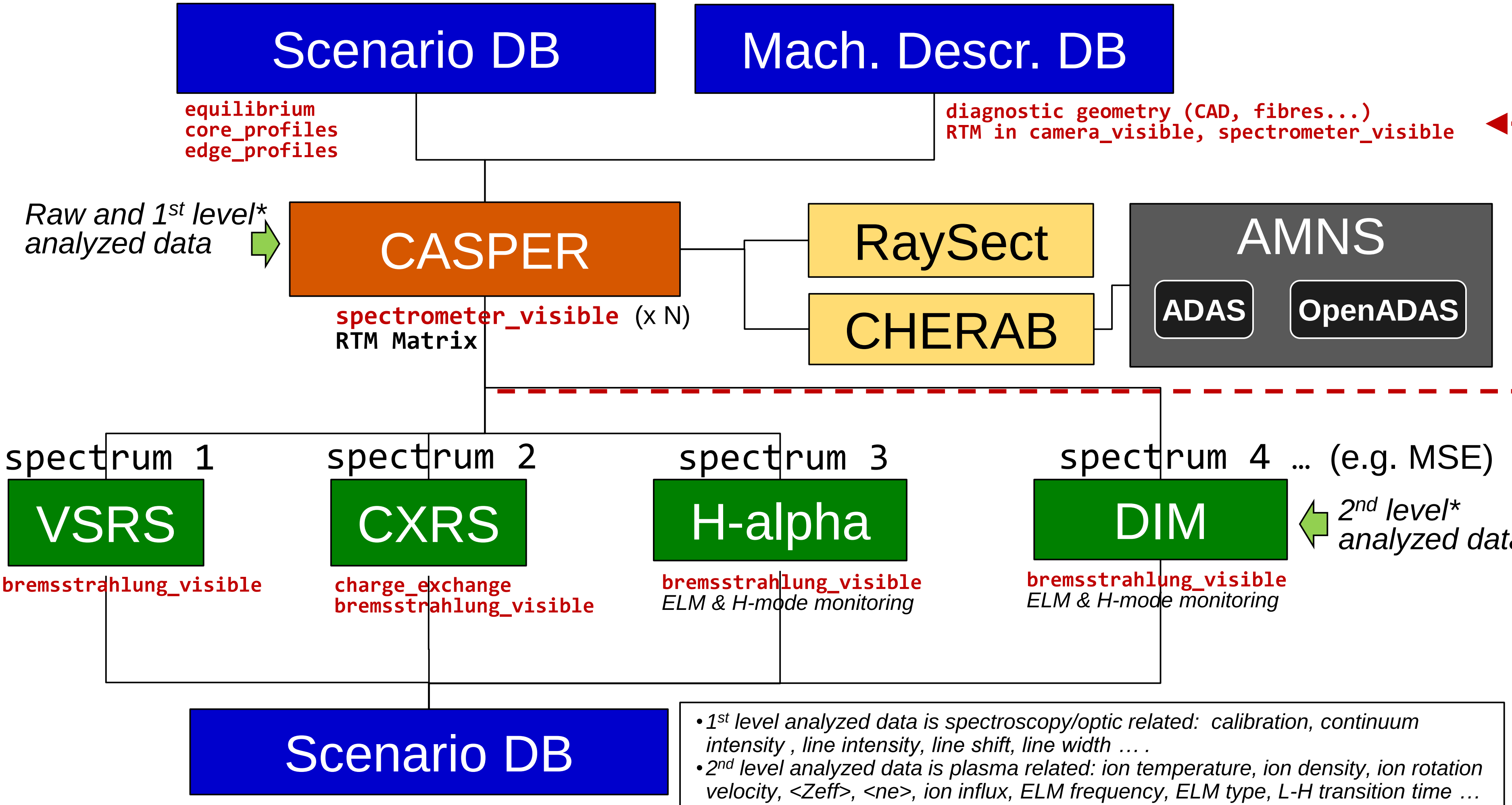
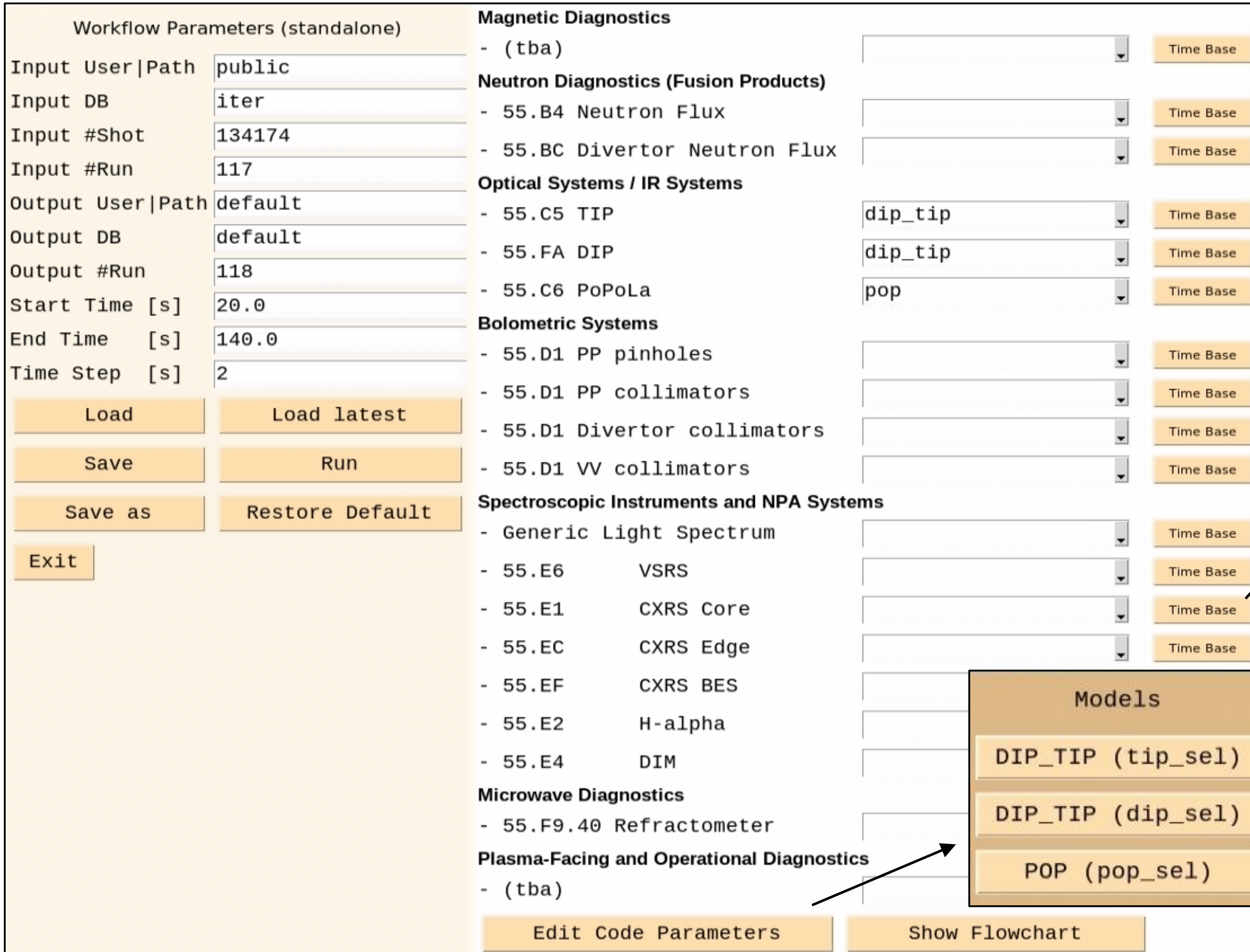
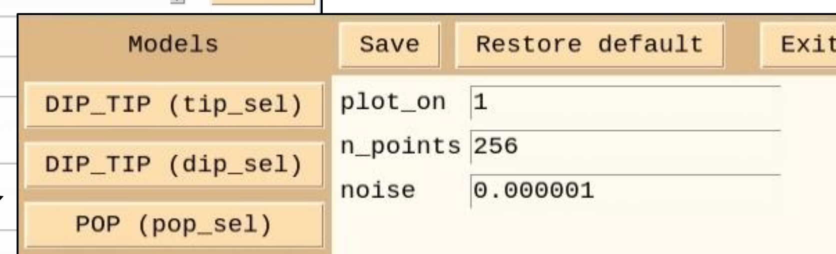
Workflow for Spectrometry Modelling



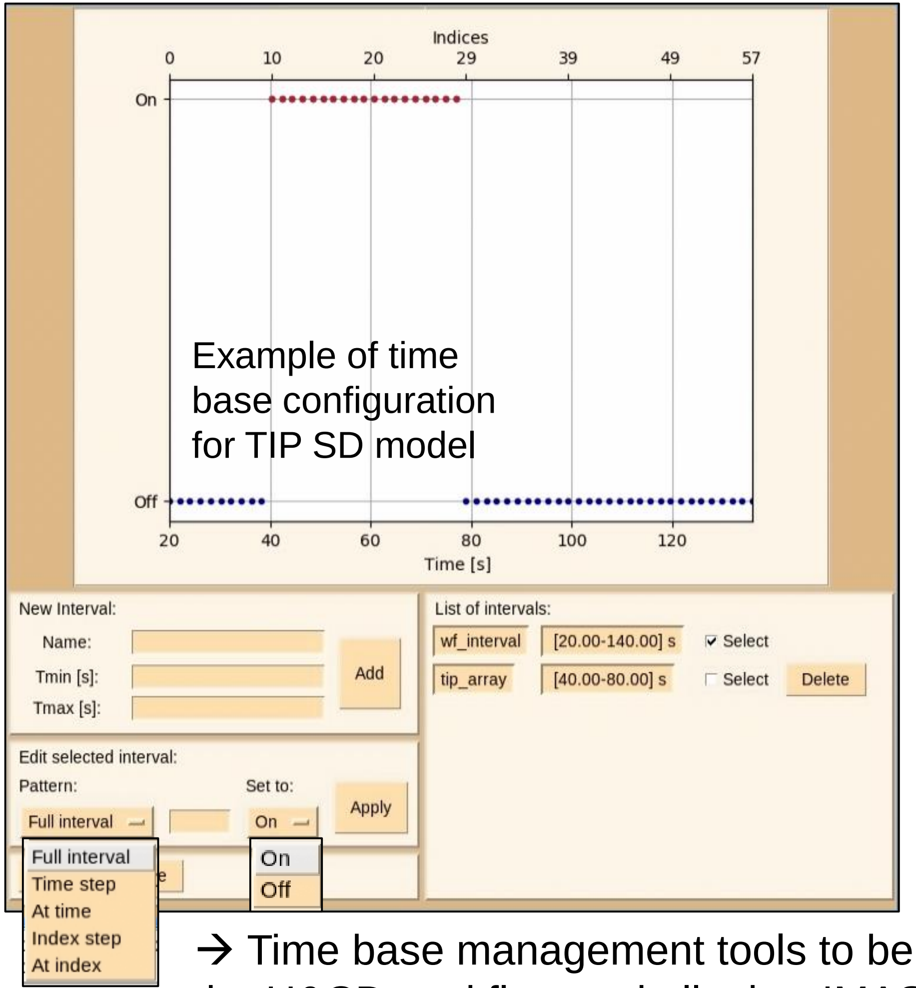
Workflow for Synthetic Diagnostics (still under developement)

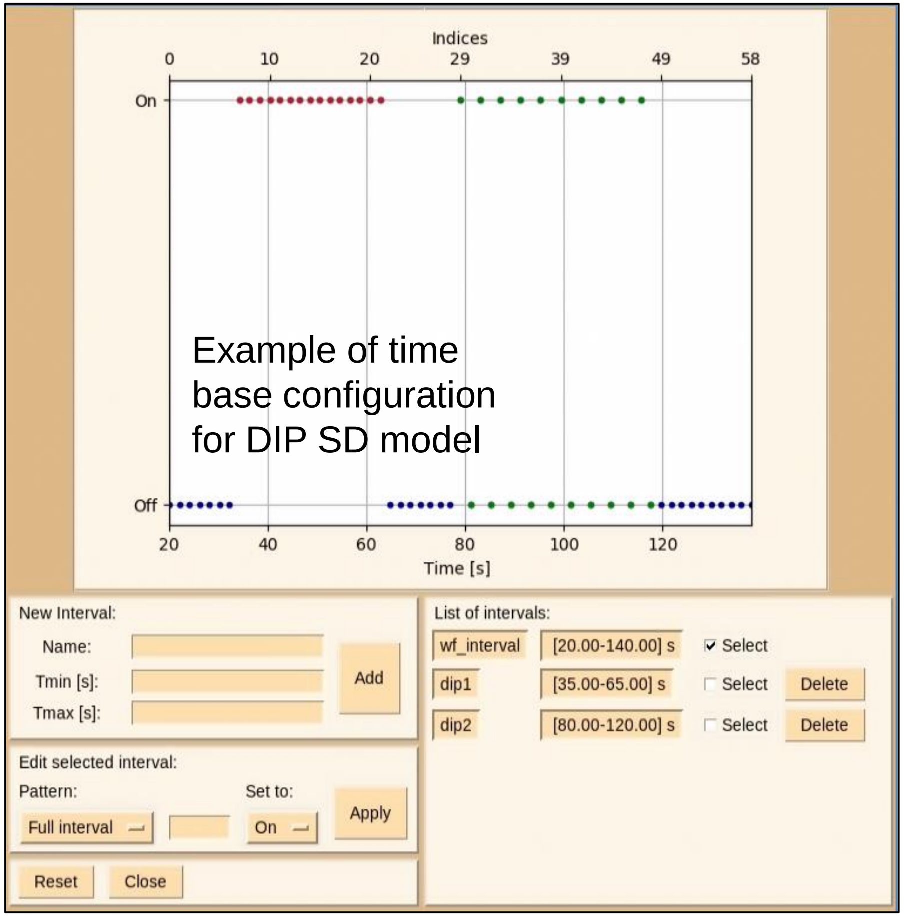




- GUI adapted from H&CD workflow, with extended features
- This illustrates the need to make the workflow tools generic and to extract them as an independent tool package
- New feature! (complex_mode.py)

Independent time base management for each SD model

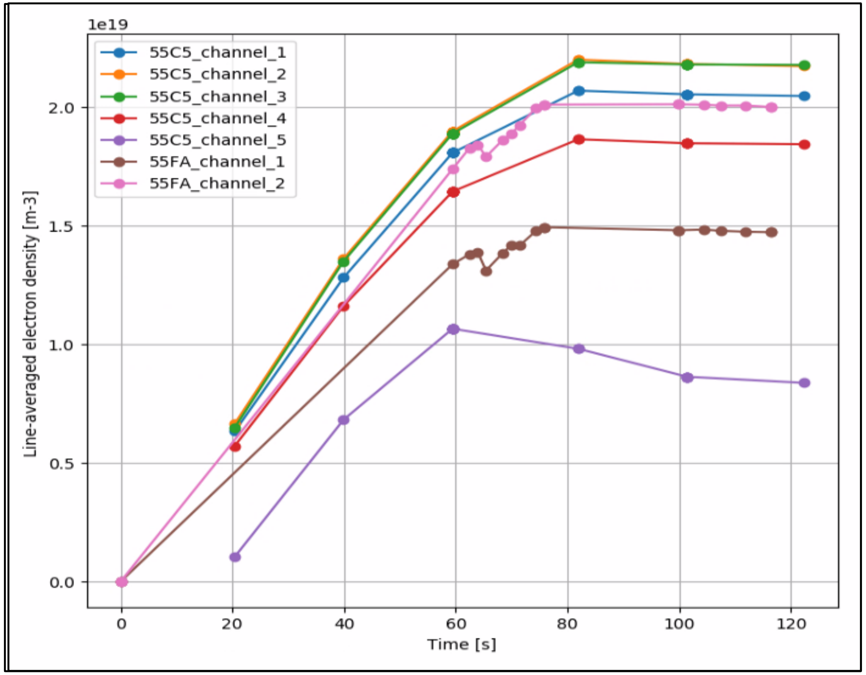




→ Time base management tools to be extracted and made generic to be used also in the H&CD workflow and all other IMAS Python workflows.

Example of using different time bases for SD models

- DINA-JINTRAC scenario with free boundary core-edge-SOL transport
- DT, 15 MA / 5.3 T, L-mode
- Results read from the interferometer IDS output by the diagnostic workflow (where DIP and TIP results are merged).

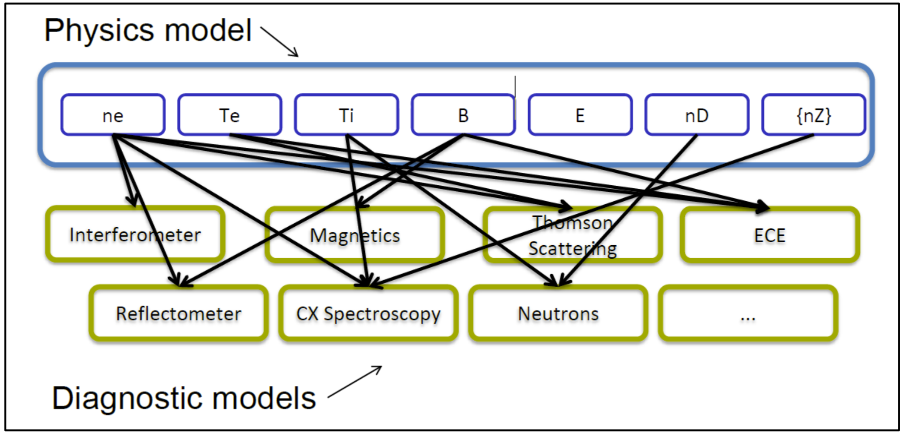


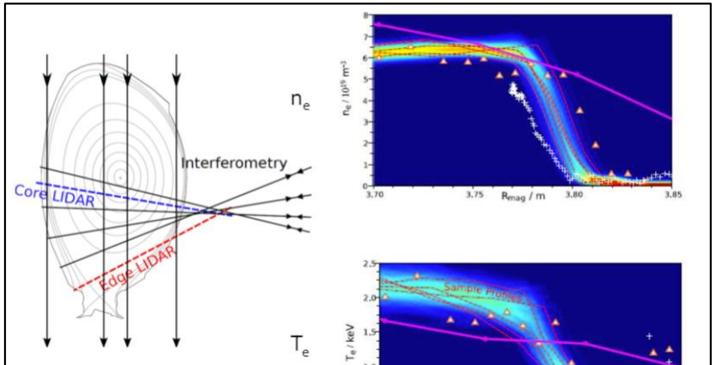
Extract of the logfile:

```
---------------------------------------------
Step = 21/60
Time = 60.00 s
dt   =  2.00 s
  Get equilibrium
  Get core_profiles
Execute Diagnostic workflow for current time slice
--- Default algorithm ---
Algorithm = ['tip_sel', 'dip_sel', 'merge_interferometer', 'pop_sel']
 PROCESS --> tip_sel = DIP_TIP
 PROCESS --> dip_sel = DIP_TIP
 PROCESS --> merge_interferometer
 PROCESS --> pop_sel = POP
End of time slice
Copy interferometer from output to input for tip_sel for next time
slice
Copy interferometer from output to input for dip_sel for next time
slice
Copy polarimeter from output to input for pop_sel for next time slice
---------------------------------------------
```

Bayesian inference with the Minerva framework

- Minerva is a platform for building large scale scientific models and performing corresponding inference using those models
  - Modular, traceable, versioned
  - Single or combination of diagnostics without information loss





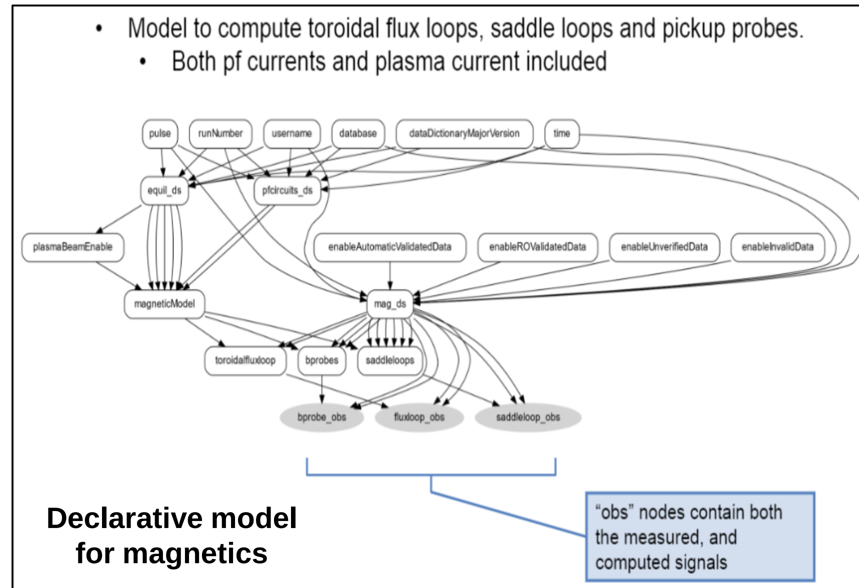
Combination of JET core LIDAR, edge LIDAR and interferometer channels

[O. Ford. "*Tokamak Plasma Analysis through Bayesian Diagnostic Modelling*", PhD thesis, University of London, 2010]

  - Accounts for uncertainties from measurement, systematic errors and model
  - Based on Bayesian probability theory: uncertainties = probability distributions
  - Used for forward analysis and experimental design
- Minerva installed in ITER cluster and reads IDSs

Synthetic Diagnostics in Minerva

- First focus on magnetics, VSRS, H-alpha, interferometer, X-ray spectrometer
- Associated Machine Description data (being populated):
  - Coils, flux loops, Rogowski loops:
    - input = magnetics, pf_active, pf_passive, equilibrium
    - output = magnetics
  - EFIT++ reconstruction:
    - input = pf_active, pf_passive, wall, tf
    - output = pf_passive, equilibrium
  - VSRS, H-alpha:
    - spectrometer_visible
  - interferometry:
    - interferometer
  - X-ray spectrometer (edge/core/survey):
    - x_ray_crystal_spectrometer



- Near-term application:
  - Assessment of diagnostic coverage for L-H transition in PFPO

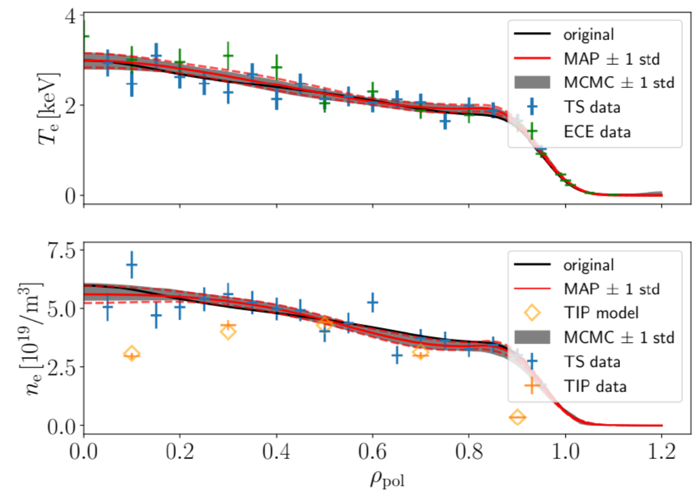
Bayesian techniques with Integrated Data Analysis (IDA)

- Development of a workflow to combine the signals from ECE, TS and interferometry
- First prototype by R. Fischer using the TIP model from A. Medvedeva
- Adaptation of physics models to be compatible with IDA iteration loops:

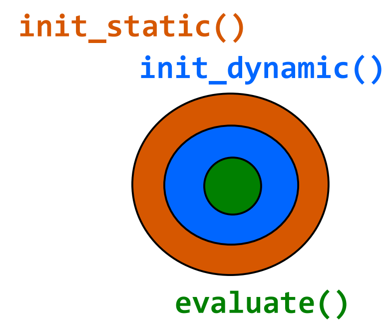
  → Separate methods between initialisation steps and evaluation of SD signals

  → Future IMAS development planned for 2022 on “persistent actors” that would facilitate this

ITER IDA n_e and T_e profile and uncertainty estimation



Initialisation of static variables	Defines input scenario, generates time loop, initialise all static data	`init_static()`
Initialisation of dynamic variables according to scenario time step	Execution within the time loop: get_slice, put_slice, etc. (e.g. read equilibrium for this time slice)	`init_dynamic()`
Evaluation of SD signal to be iterated in the IDA loop	Execution within the IDA convergence loop (adjustment of core_profiles quantities)	`evaluate()`



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Reminder on the H&CD workflow

- Written in Python but orginally based on the Kepler version developed by T. Johnson
- Contains IMAS-adapted models to simulate all ITER H&CD sources:

	ECRH	ICRH	NBI	Nuclear reactions
Wave or particle source	GENRAY GRAY TORBEAM	CYRANO LION PION TOMCAT	BBNBI NEMO	AFSI SPOT (α)
Fokker-Planck	Ø	FOPLA PION ASCOT SPOT	ASCOT SPOT RISK	ASCOT SPOT

Validation of H&CD models in TRANSP

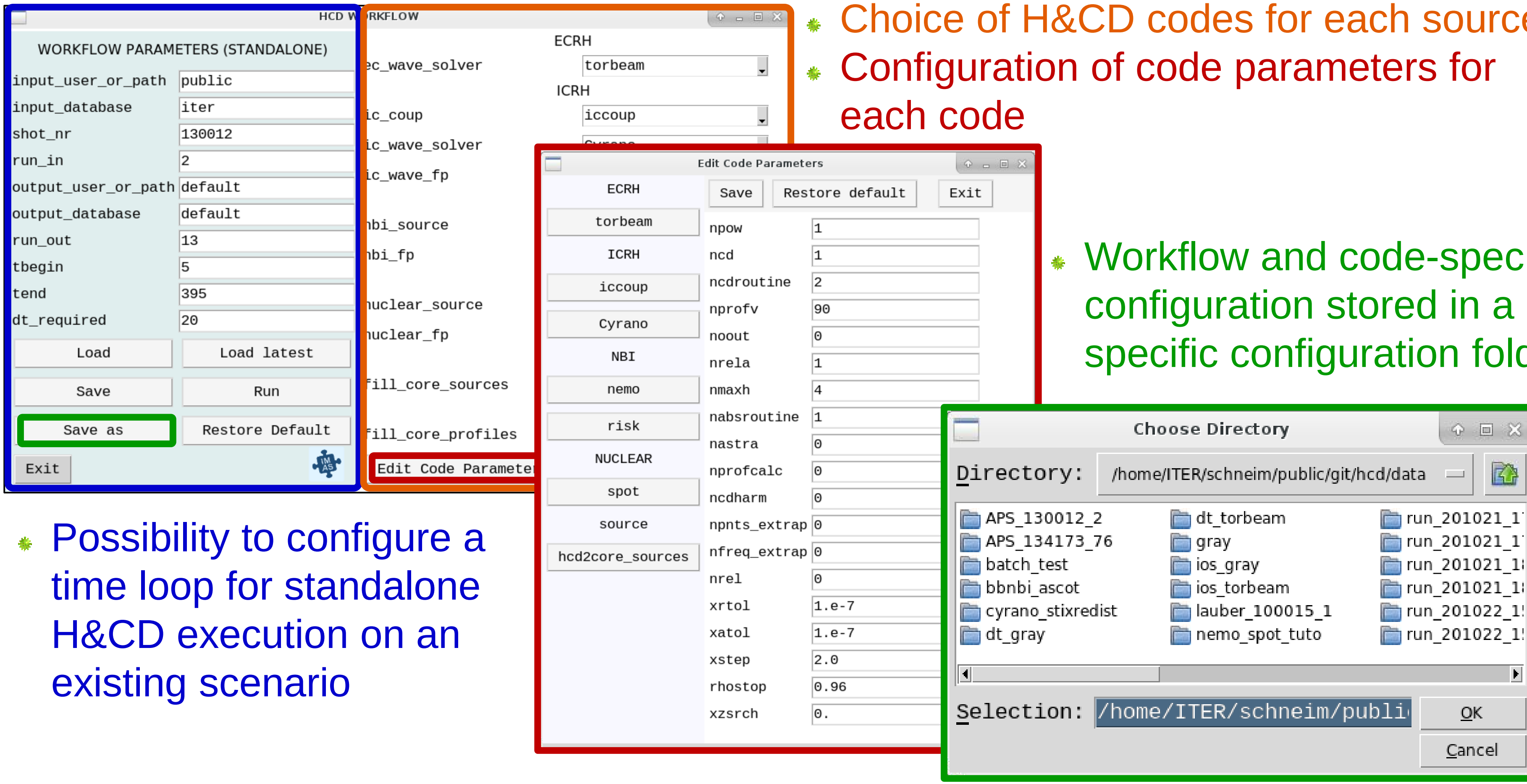
NUBEAM, TORAY-GA, CQL3D could be part of it!

- The core of the workflow has an interface similar to actors (IDSs+codeparams) to make it easy to plug into other workflows
- Includes a Tk GUI for standalone H&CD simulation

GUI to configure the H&CD workflow

GUI dynamically built from code-specific parameters files (xml validated through xsd files)

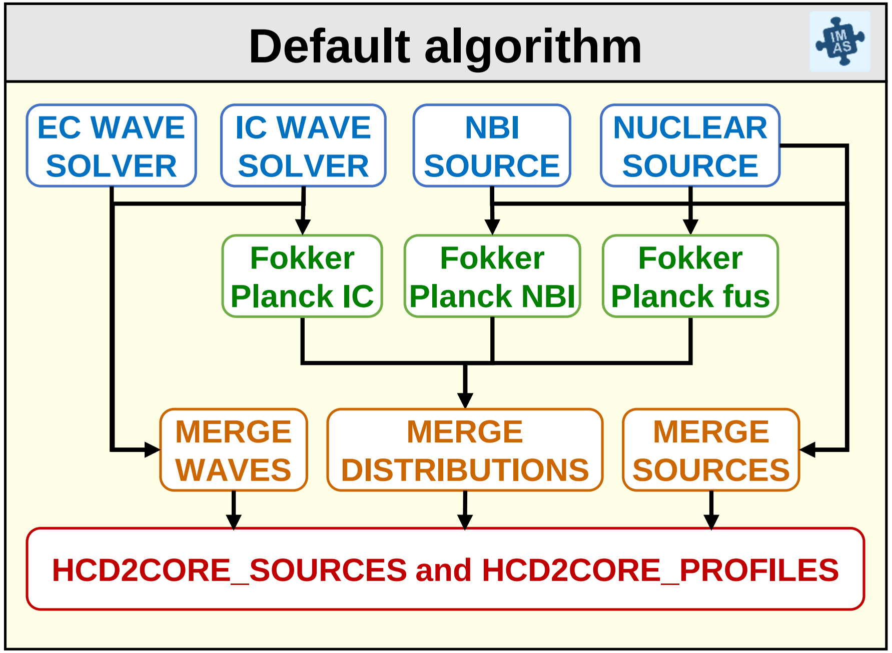
- Choice of H&CD codes for each source
- Configuration of code parameters for each code

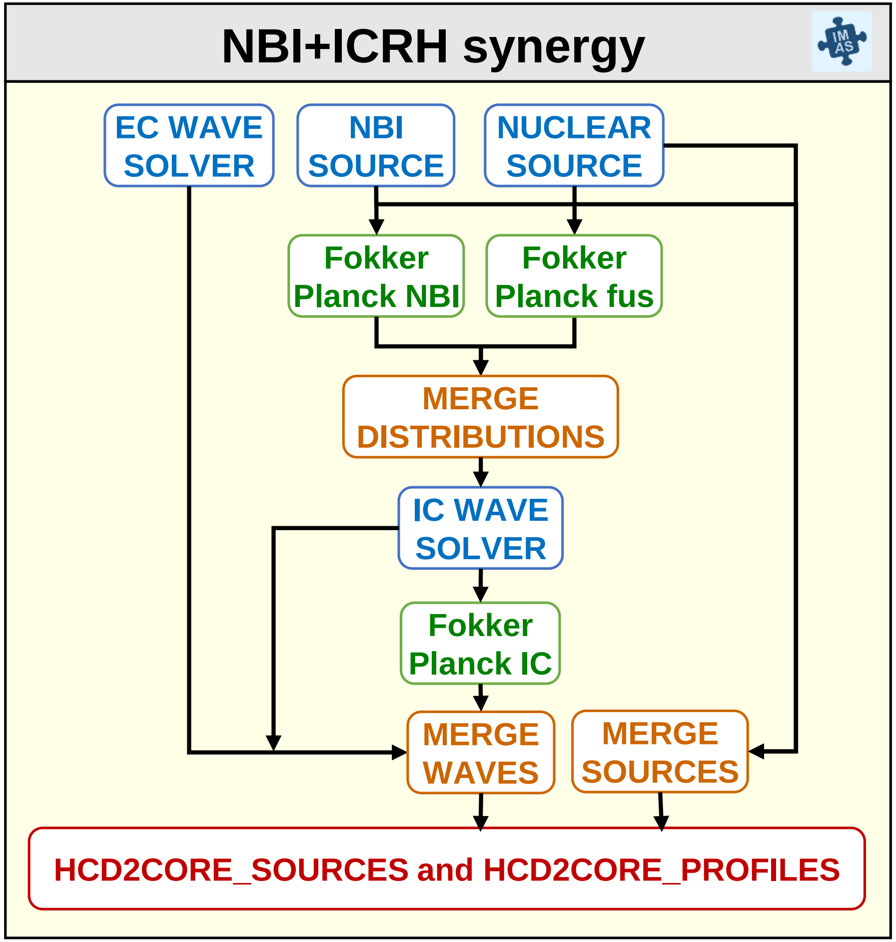


- Workflow and code-specific configuration stored in a specific configuration folder

- Possibility to configure a time loop for standalone H&CD execution on an existing scenario

The universal algorithm of the H&CD workflow



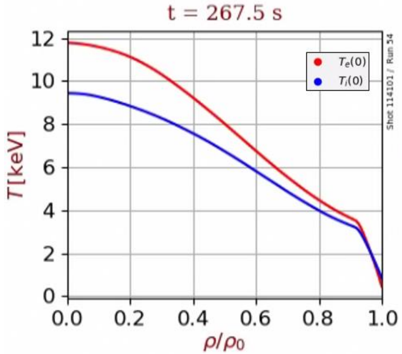


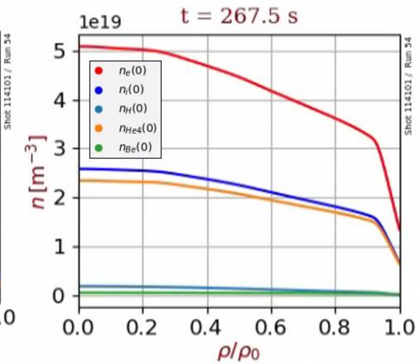
The H&CD workflow has a flexible and composable approach which allows for various algorithms implementations.

Integration of the H&CD workflow within TRANSP

Synergy between NBI and ICRH for ITER Helium scenario

- 2.65 T / 7.5 MA H-mode scenario (JINTRAC)
- 20 MW ICRH, 43 MHz, N=1 H (CYRANO/FOPLA)
- 33 MW NBI, 870 keV (NEMO/RISK)

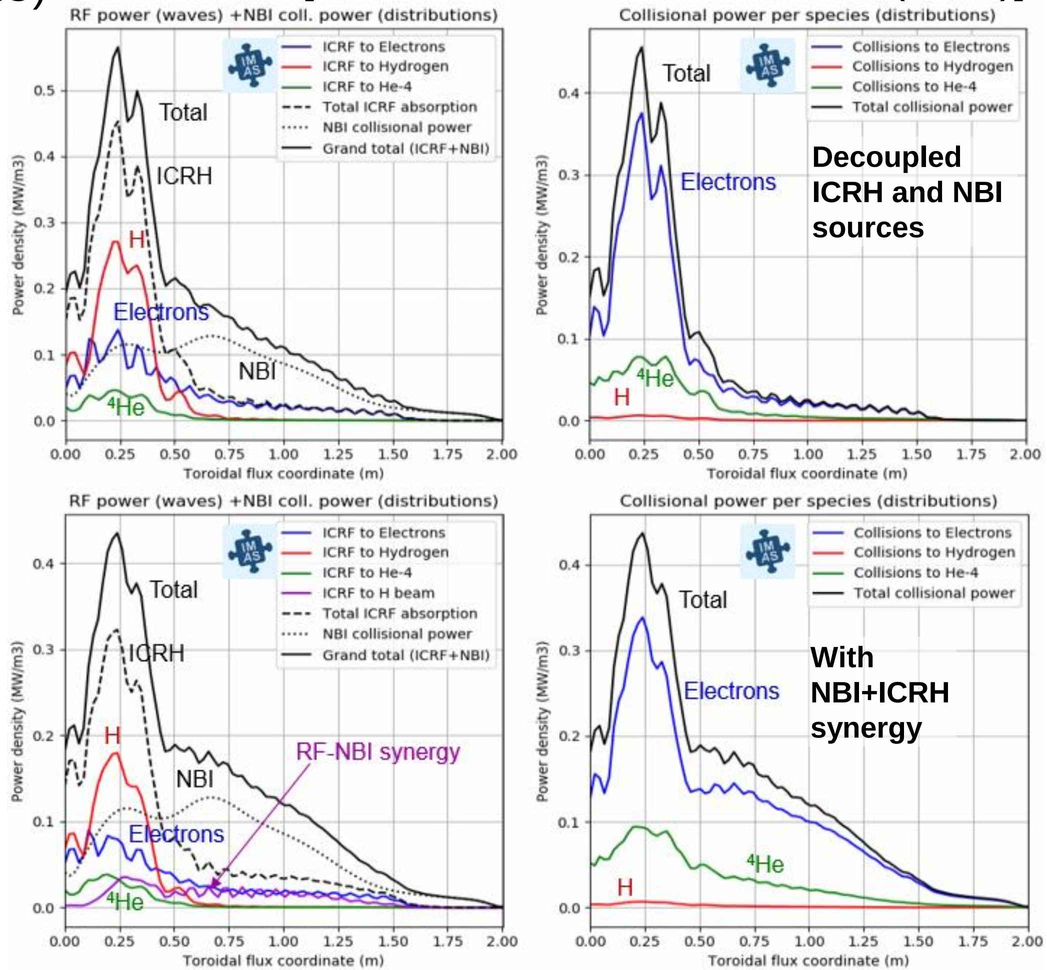




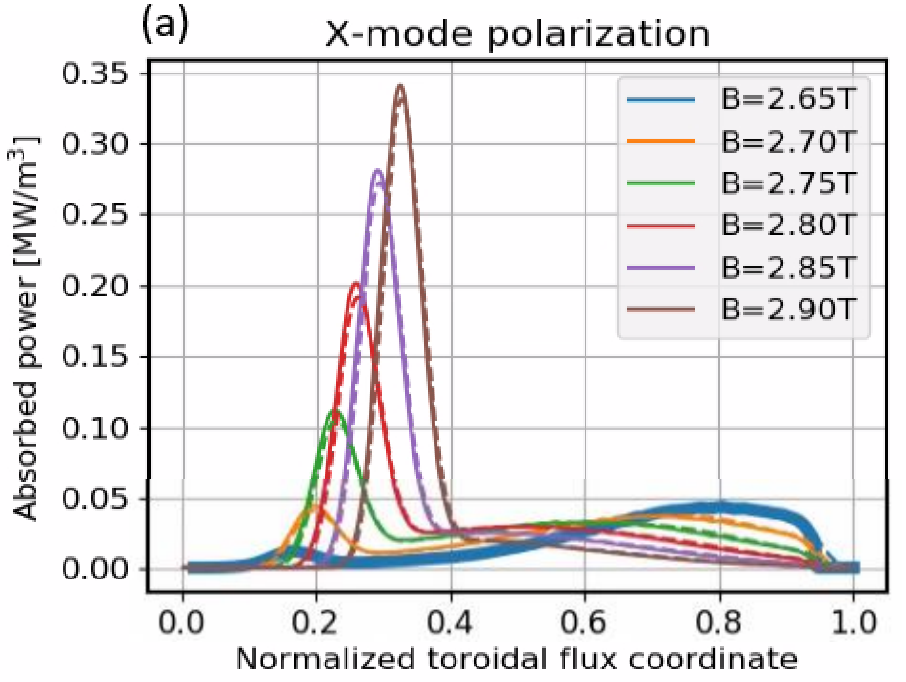
- Significant synergetic effect between NBI and ICRH
- Fraction of RF power absorbed off-axis by H beams (higher collisionality)

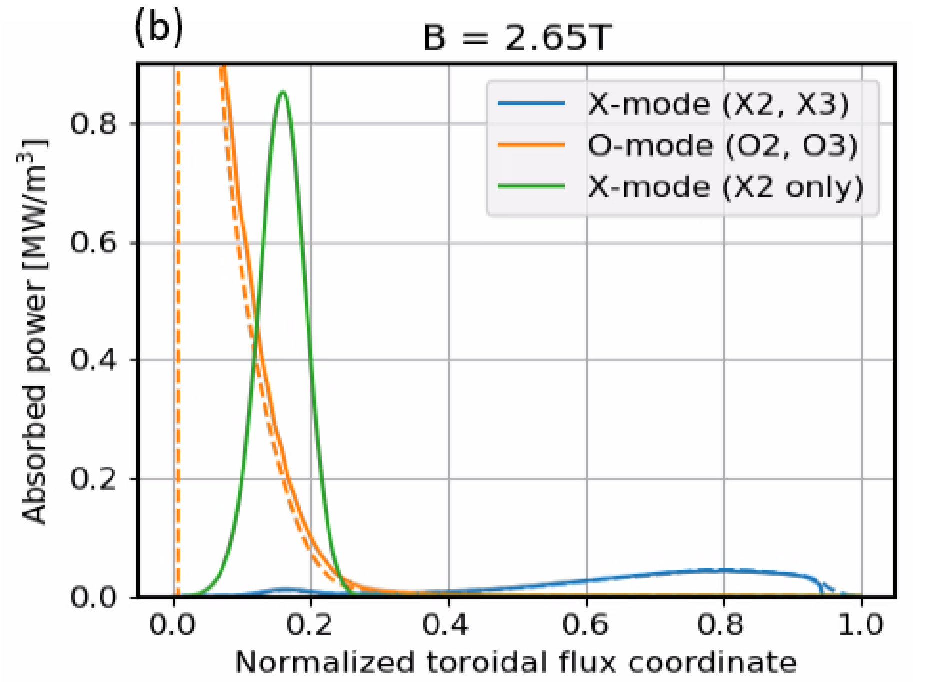
→ Less energetic fast H distribution, leading to reduced neutron production [A. Polevoi et al, NF (2021)]

[M. Schneider et al, sub. to NF (2021)]



Study of ECH absorption profiles in 7.5 MA / 2.65 T scenarios



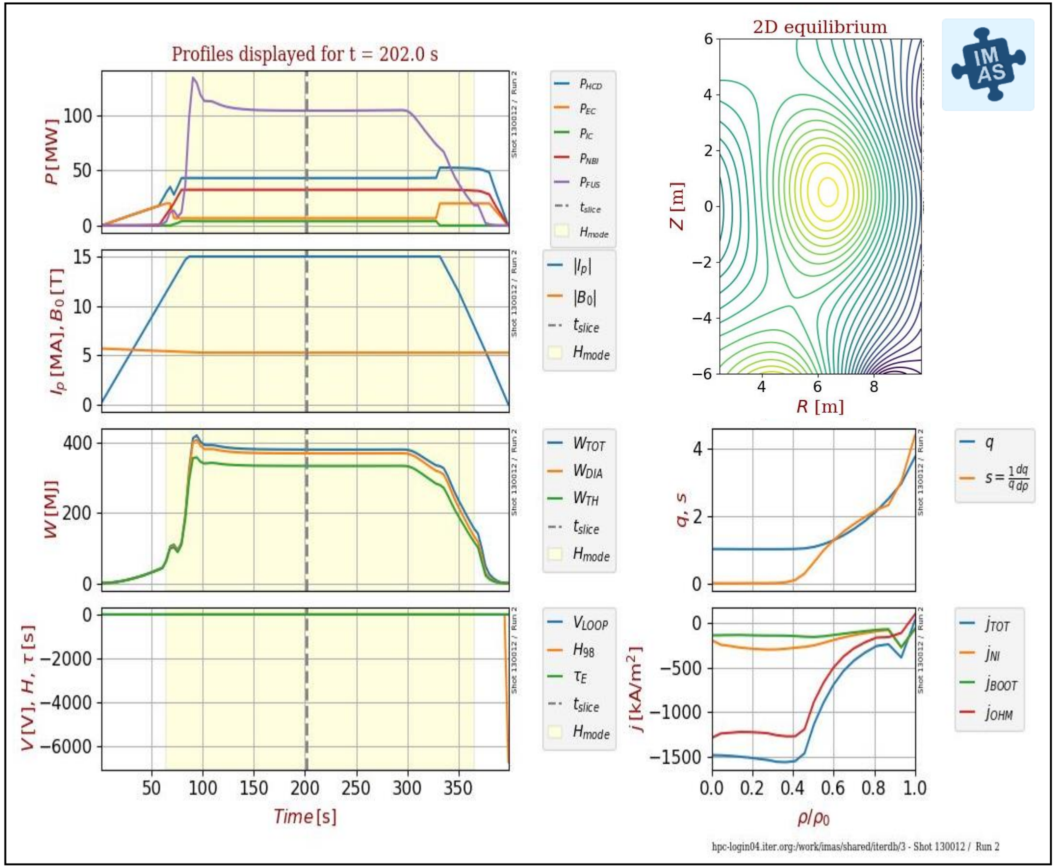


- X3 parasitic absorption at the edge: can be compensdated by either increasing B-field or switching to O-mode polarization
- Excellent agreement between TORBEAM (solid) and GRAY (dashed).

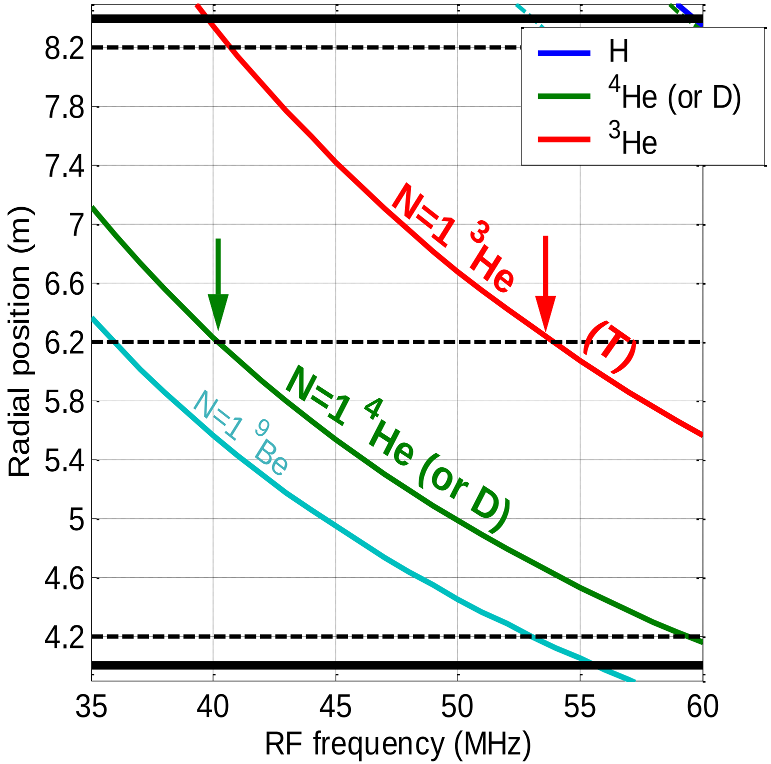
[M. Schneider et al, NF (2021)]

H&CD modelling for an ITER 15MA / 5.3T DT scenario

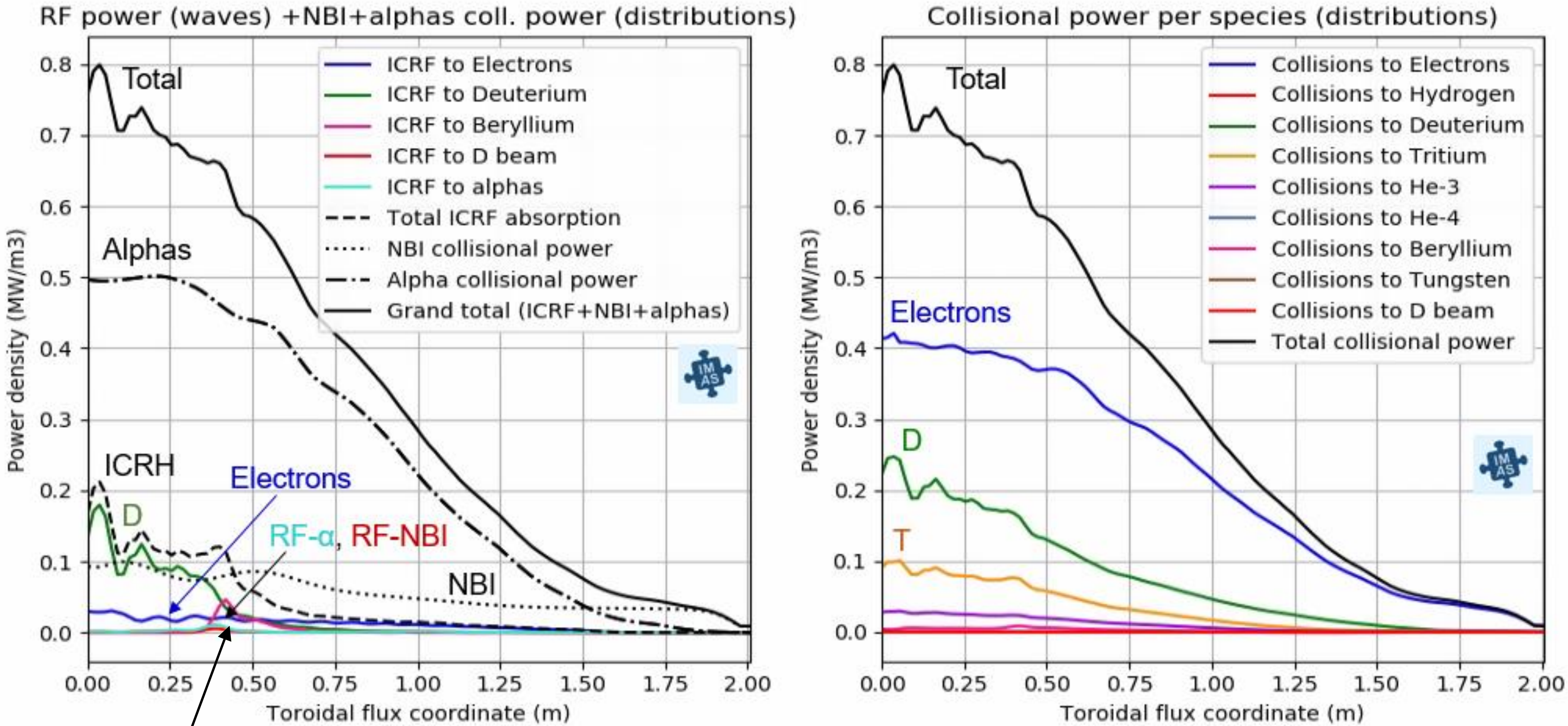
- Input scenario from IMAS scenario database: ITER DT 15 MA / 5.3 T (from METIS)



- ICRH modelling: 20 MW:
  - 40 MHz, for N=1 D(+Be)
  - 53 MHz for N=2 T heating



Results for NBI (33MW) + alphas (96MW) + ICRH (20MW)



Weak RF-α and RF-NBI synergy (<5% ICRH)

- Dominant electron heating (alphas)
- Significant core ion heating (~40%) due to combined ICRH, NBI and α heating

[M. Schneider et al, sub. to NF (2021)]

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Summary

- IMAS supports the ITER Research Plan by providing a standard for integrated modelling delivering a high level of modularity and flexibility
- Scenarios are available for each phase of the ITER Research Plan
- A Machine Description database is available to describe ITER plant systems
- IMAS will provide a high-fidelity plasma simulator including self-consistent calculation of free-boundary equilibrium + core-edge transport → to be used for predictive and interpretive modelling
- Progress in synthetic diagnostics development:
    - for generating synthetic data in IMAS (python workflow under development)
    - in preparation for ITER data analysis and interpretation using Bayesian modelling
    - for supporting controller development in connection with the PCS Simulation Platform
- The H&CD workflow is as an essential element of any high-fidelity plasma simulator, enabling the modelling of the synergy between different H&CD sources
- Other workflows being prepared for ITER operation using IMAS include those for interpretive equilibrium reconstruction and stability (including EPs) assessment.

PPPL could contribute through the use of these H&CD and SD models and workflows, and through the IMAS adaptation of TRANSP and its modules.