Simulation of Heating and Current Drive sources and Synthetic Diagnostics in IMAS

IMAS framework - Tutorial session
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Heating and Current Drive sources

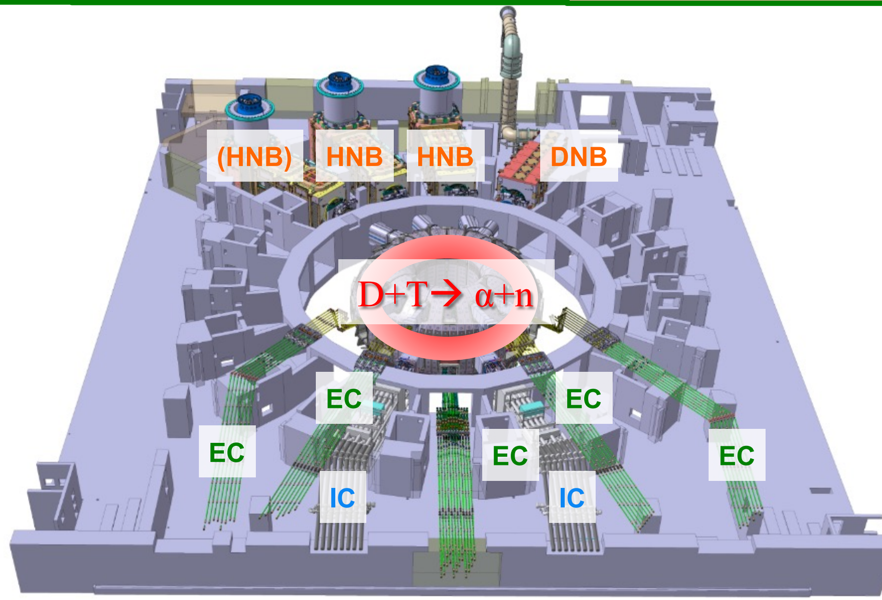
Outline

- The Heating & Current Drive (H&CD) systems in the ITER Research Plan
- H&CD modelling using the ITER Integrated Modelling & Analysis Suite (IMAS)
- Synergetic effects between NBI and ICRH systems in presence of fusion-born alphas for an ITER DT 15MA / 5.3T scenario
- Conclusion

The H&CD systems in the ITER Research Plan

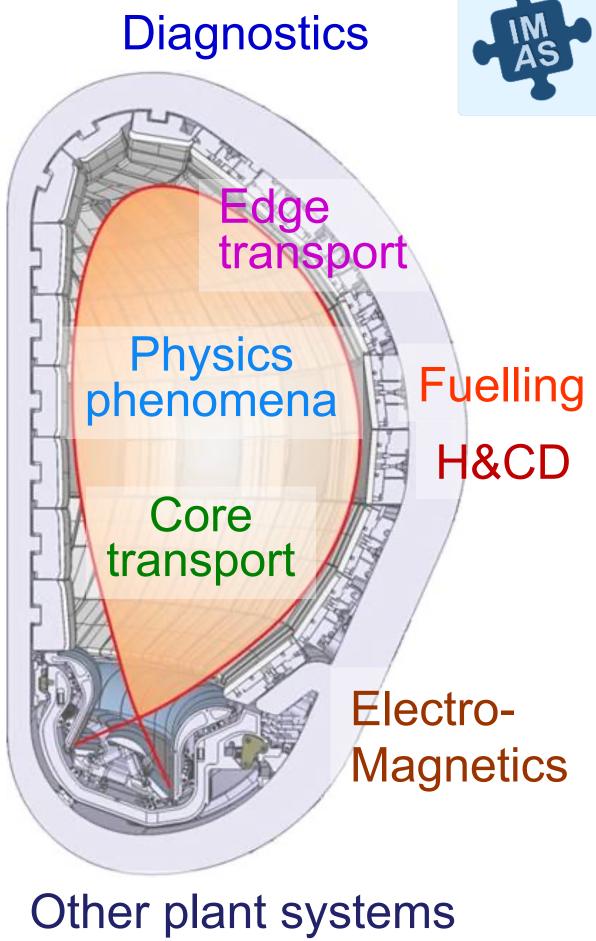
2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036, …
	H plasma: 6 m 1st plasma	Assembly / commissioning		H, ^{4}He plasmas: 18 m Pre-Fusion Power Operat. 1		Assembly / commis.	H, ^{4}He plasmas: 21 m Pre-Fusion Power Operat. 2		Assembly / commis.		D, DT: Fusion Power Operation (EC, IC, NBI)

- Three external H&CD systems:
  - Electron Cyclotron wave: 170 GHz, 20MW (+20)
  - Ion Cyclotron wave: 40-55 MHz, 20 MW (+20)
  - Neutral Beam Injection: 870 keV H^0, 1 MeV D^0, 33 MW (+16.5)
- One intrinsic H&CD process:
  - Fusion reactions! 3.5 MeV ~80-100 MW for DT 15 MA/5.3T baseline scenario



The ITER Integrated Modelling & Analysis Suite (IMAS)

- IMAS provides a standard and managed access to experimental and simulated data via Interface Data Structures (IDS)
- Aims at integrating free-boundary evolution, core-edge-SOL transport, divertor physics and PFC models to allow high fidelity physics simulations
- Is suitable for any fusion tokamak device
- Will be used for ITER data processing and analysis
- To know more: https://imas.iter.org



The IMAS Data Dictionary

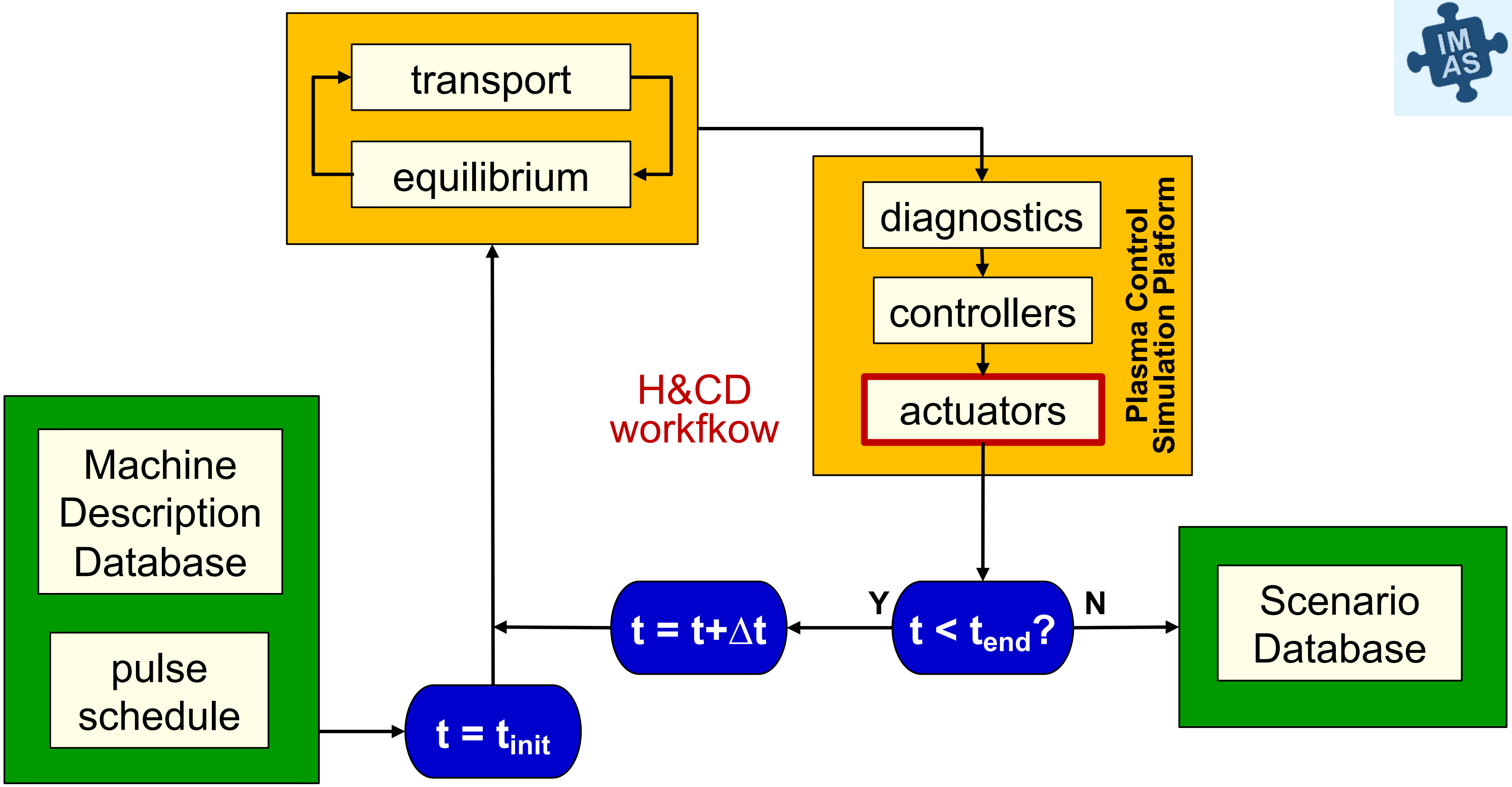
- Core
- Edge
- Electro-Magnetics
- Physics phenomena
- Fuelling
- H&CD
- Other plant systems
- Diagnostics
- Data management

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
tf
cryostat
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

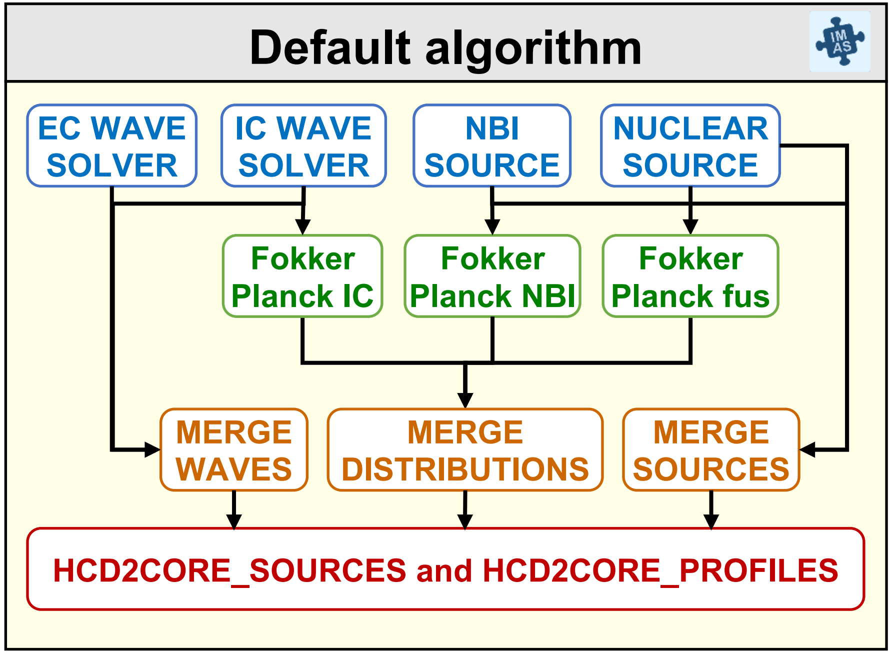
dataset_description
summary
transport_solver_numerics
numerics
temporary
dataset_fair
controllers
pulse_schedule
amns_data
sdn

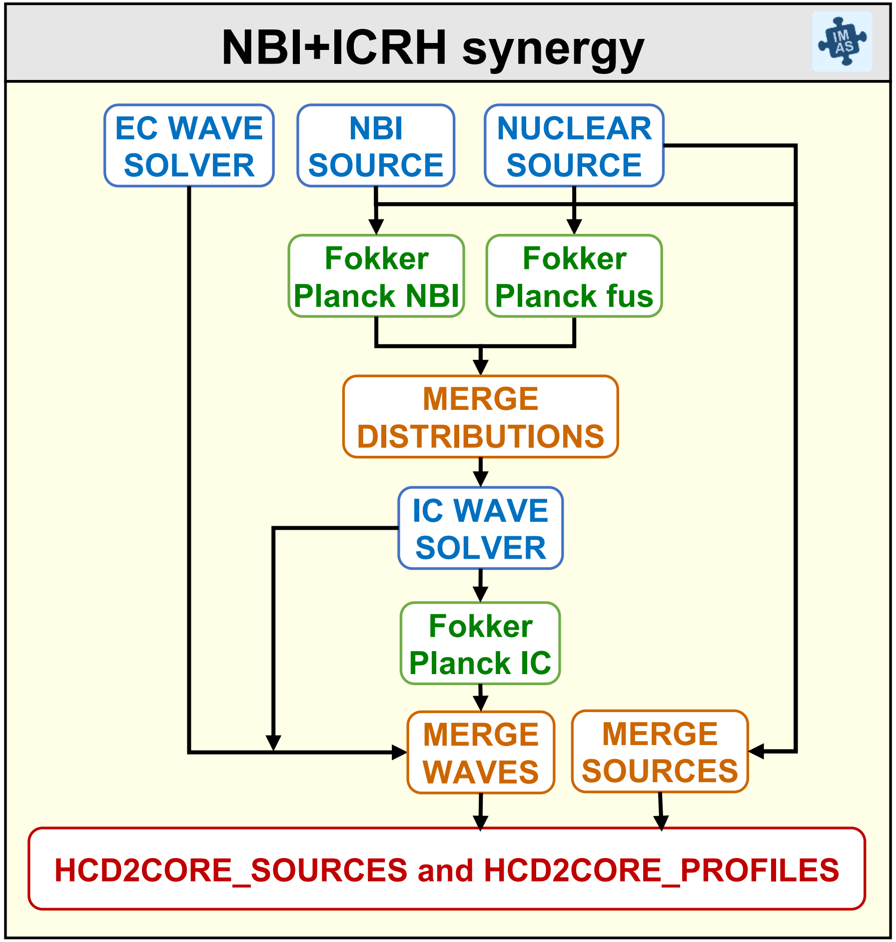
The dictionary evolves with the development of the IM platform.

Towards a high-fidelity plasma simulator



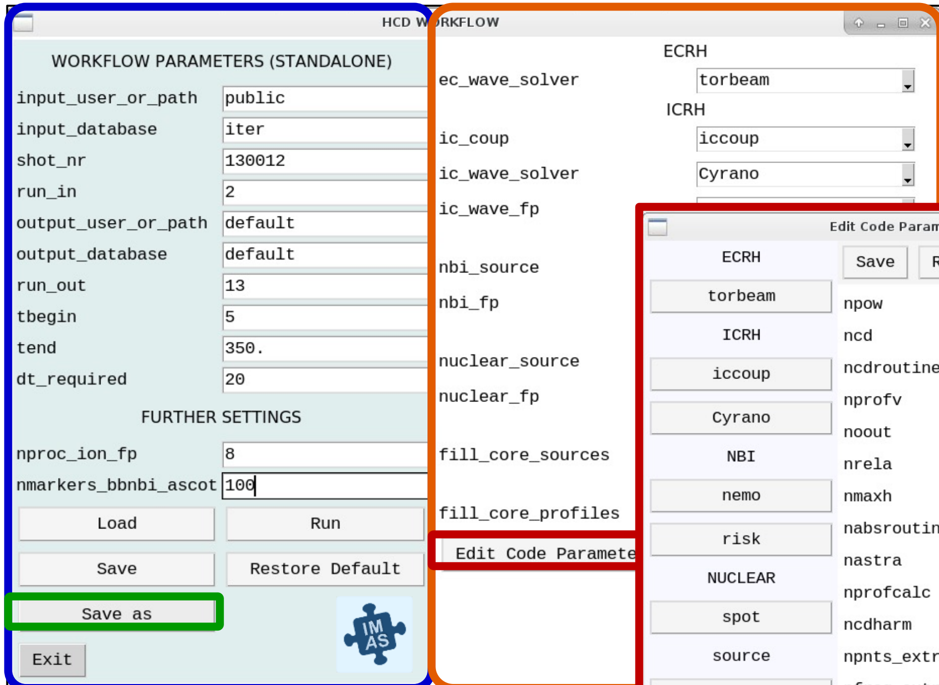
The H&CD workflow

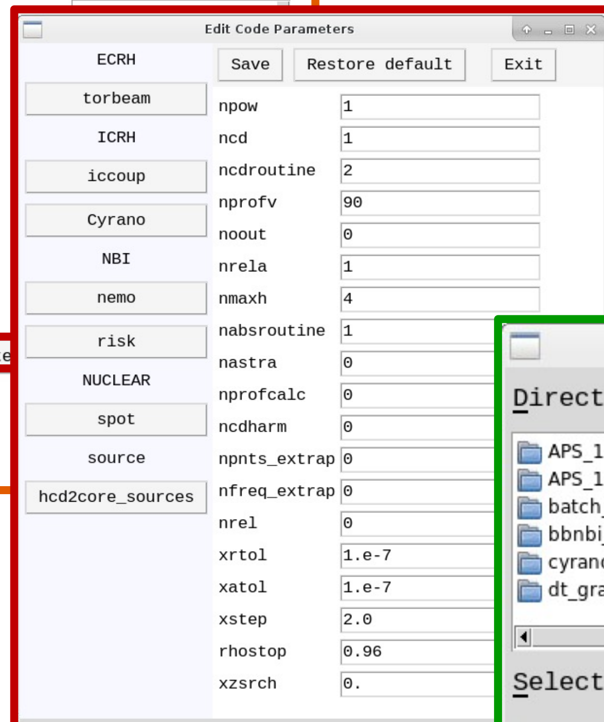


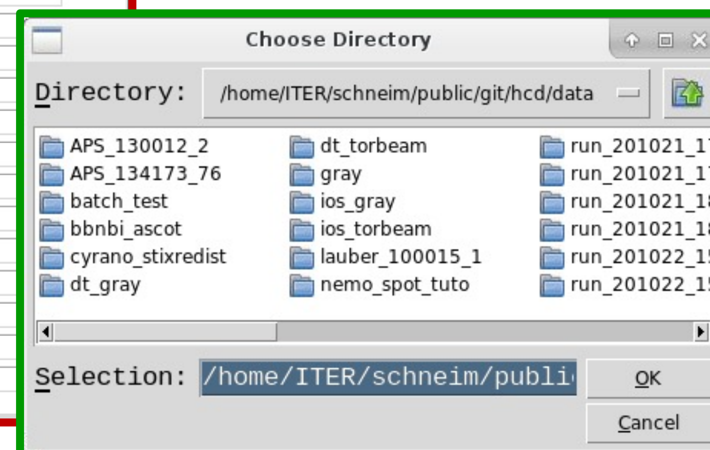


The flexible/composable workflow approach allows for various algorithms implementations.

GUI to configure the H&CD workflow





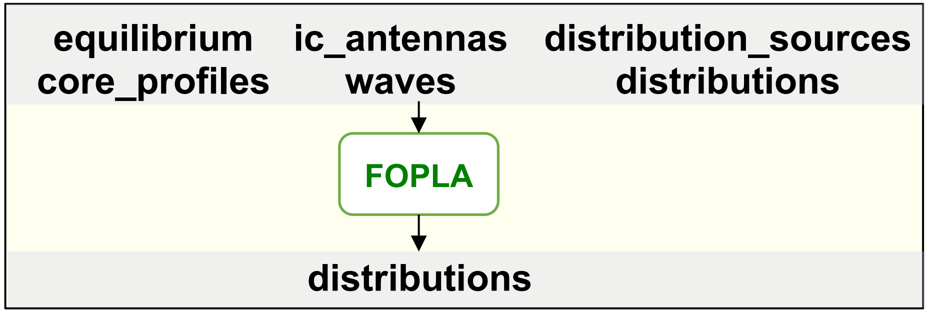


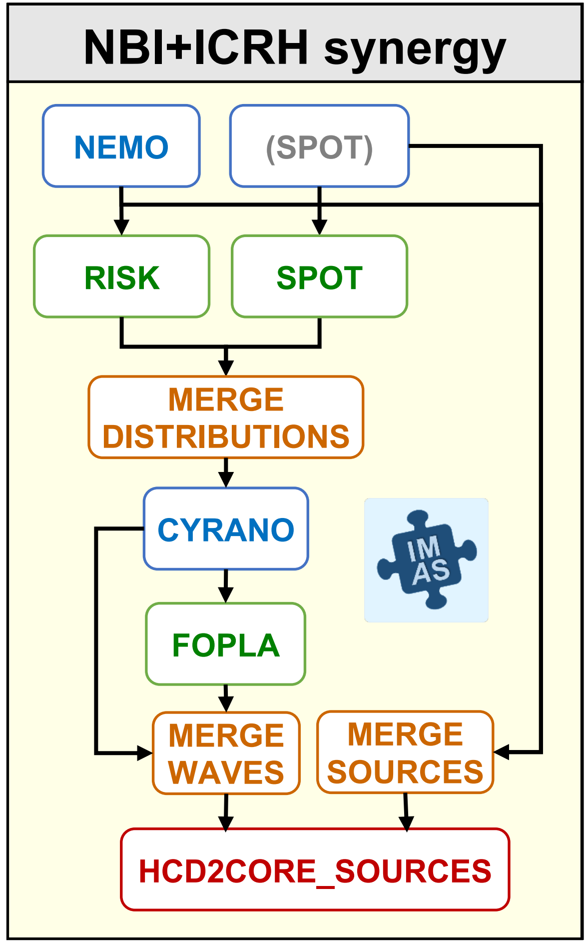
- Choice of H&CD codes for each source
- Configuration of code parameters for each code
- Workflow and code-specific configuration stored in a specific configuration folder
- Possibility to configure a time loop for standalone H&CD execution on an existing scenario

NBI+ICRH synergetic effects in presence of fusion alphas

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

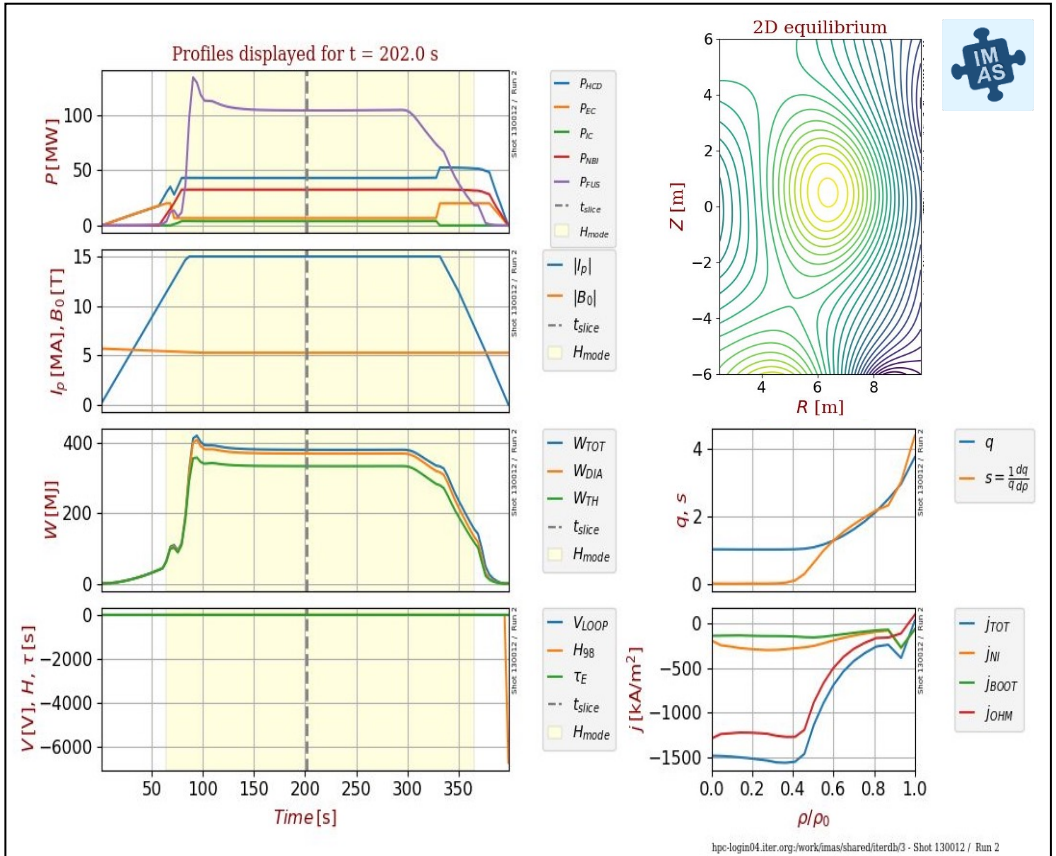
- **FOPLA**: 1D Fokker-Planck solver for IC-accelerated ions, handling NBI sources → NBI+ICRH synergy



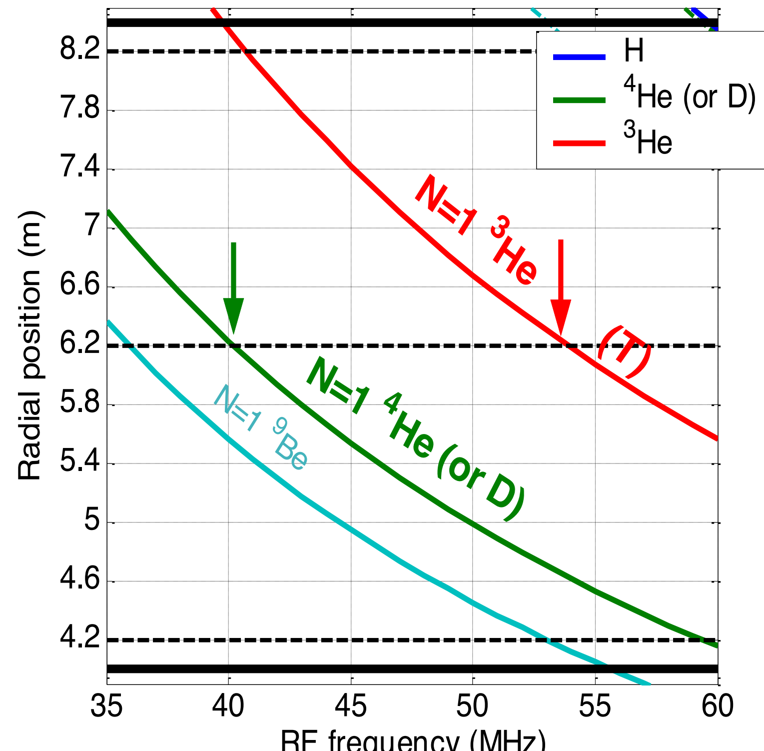


Application to an ITER 15MA / 5.3T DT scenario

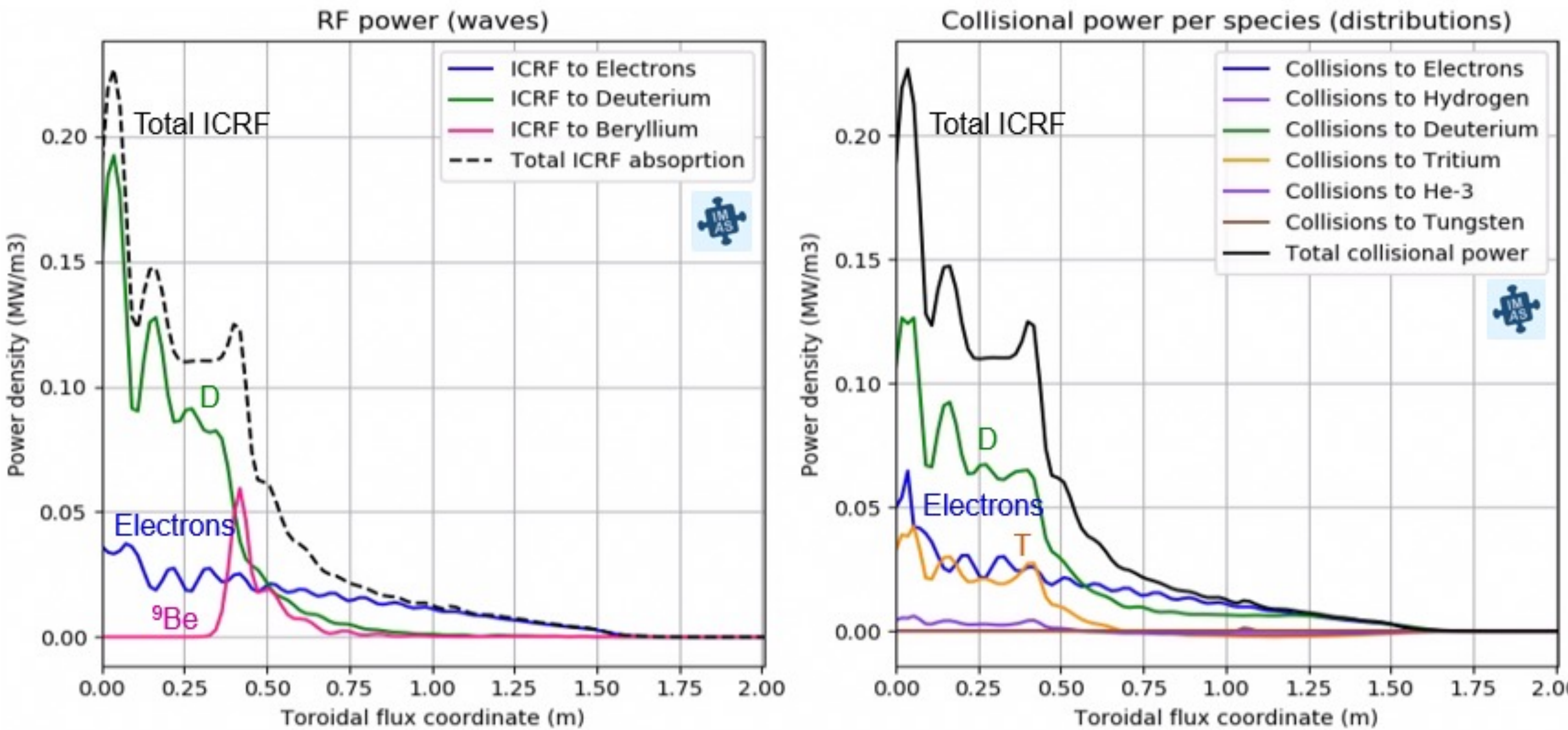
- Input scenario from IMAS scenario database: ITER DT 15 MA / 5.3 T (from METIS)



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



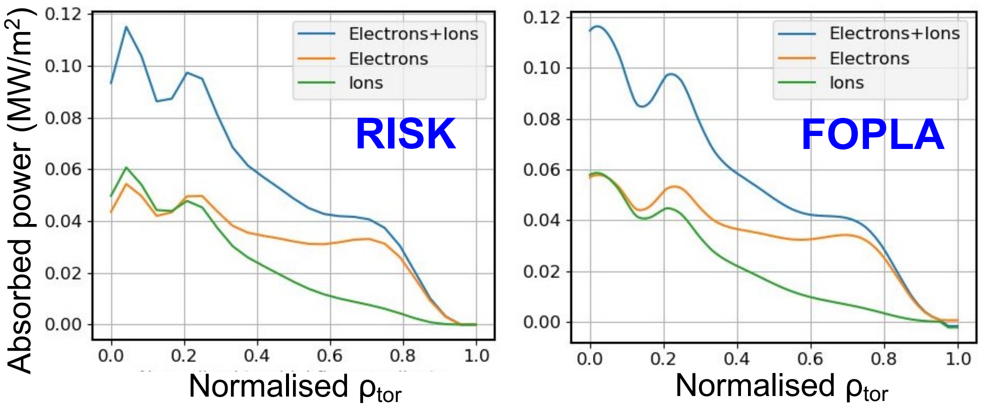
Results for ICRH only (20 MW)



- Ion heating is dominant in the core
- ICRH: Collisional power (D) > Collisional power (T)

Preliminary check: NBI modelling

- NBI only to check the consistency of the NBI treatment:



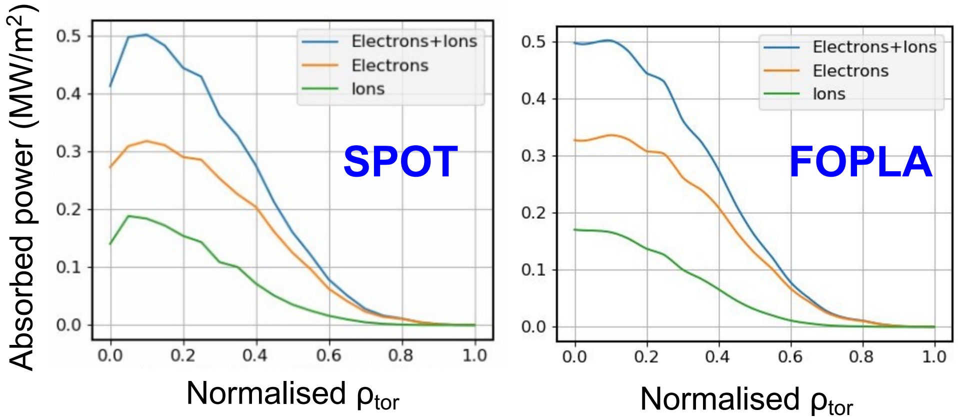
Total NBI (MW)	33		
On electrons	24.5		
On ions	8.5	D	4.1
		T	2.8
		Others	1.6

→ The NBI modelling is consistent between the RISK and FOPLA Fokker-Planck codes, despite FOPLA being 1D, $F_0(v)$.

- Ion and electron heating are similar in the core
- Electron heating dominant in the outer half of the plasma
- NBI: Collisional power (D) > Collision power (T)

Preliminary check: fusion-born alpha modelling

- Fusion only to check the consistency of the fusion-born alpha particles:

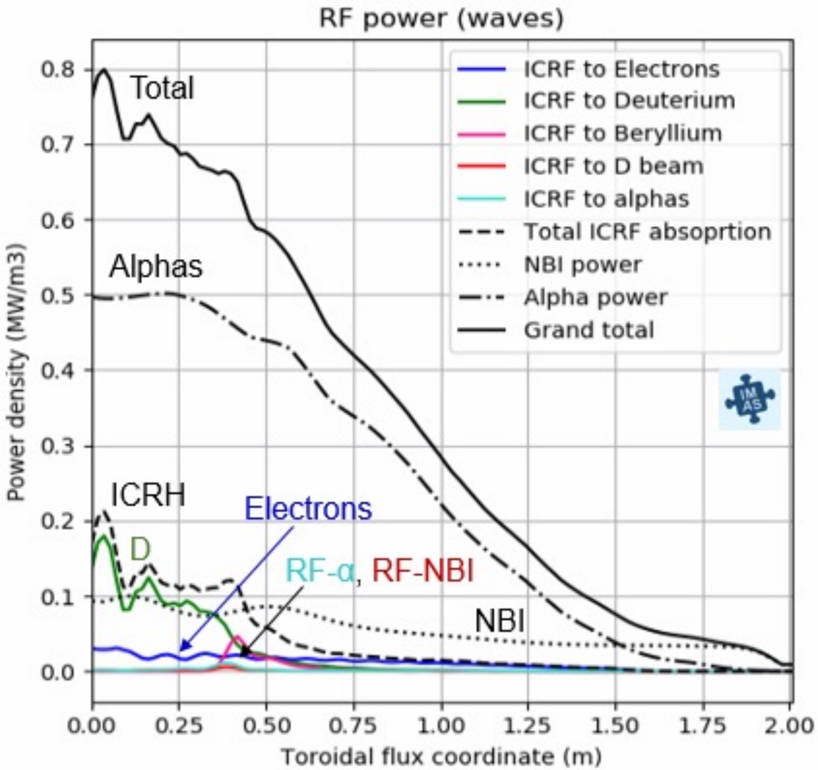


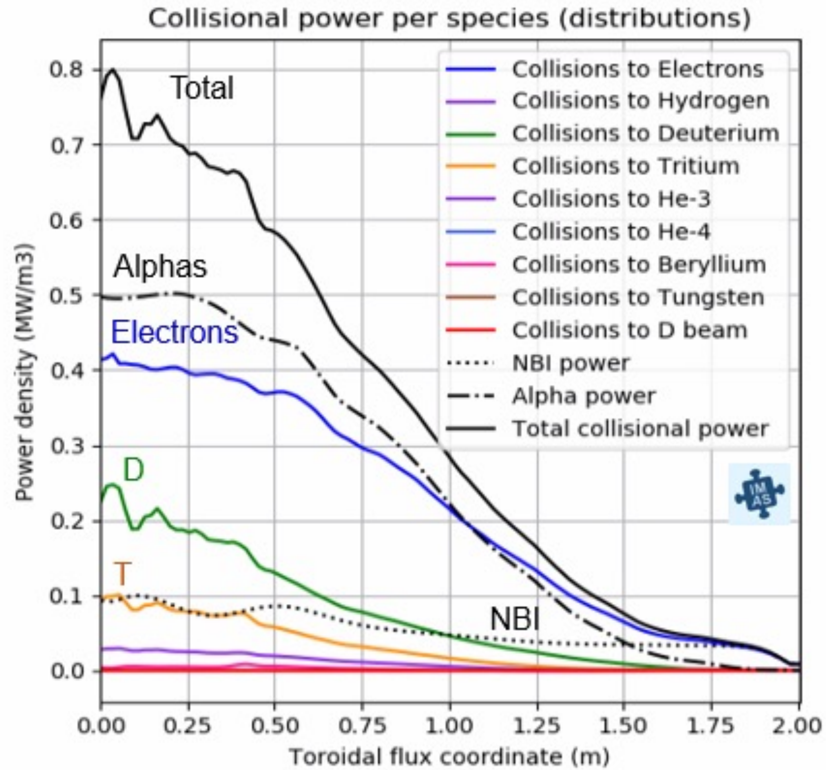
Total fus (MW)	96.6		
On electrons	69.1		
On ions	27.5	D	11.4
		T	7.7
		Others	8.4

→ The fusion-born alpha modelling is consistent between the SPOT and FOPLA Fokker-Planck codes, despite FOPLA being 1D, $F_0(v)$.

- Electron heating dominant throughout, ~75%
- Some ion heating from slowed-down alphas, ~25%
- Alphas: Collisional power (D) > Collisonal power (T)

Results for NBI (33MW) + alphas (96MW) + ICRH (10MW)





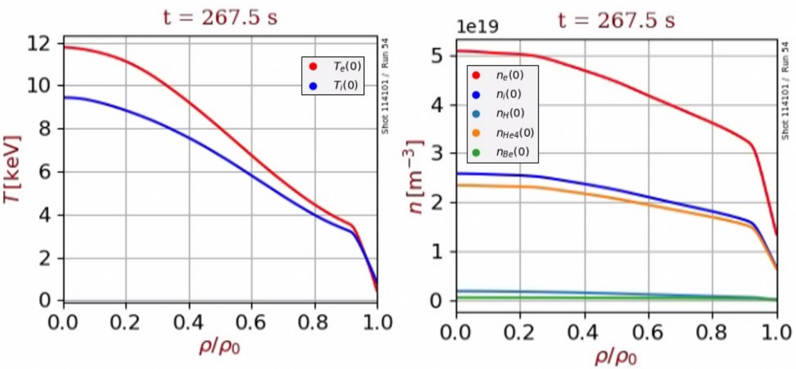
Weak RF-α and RF-NBI synergy (<5% ICRH)

Note: higher NBI+ICRH synergy in PFPO-2:
[A. Polevoi et al, NF 2020]

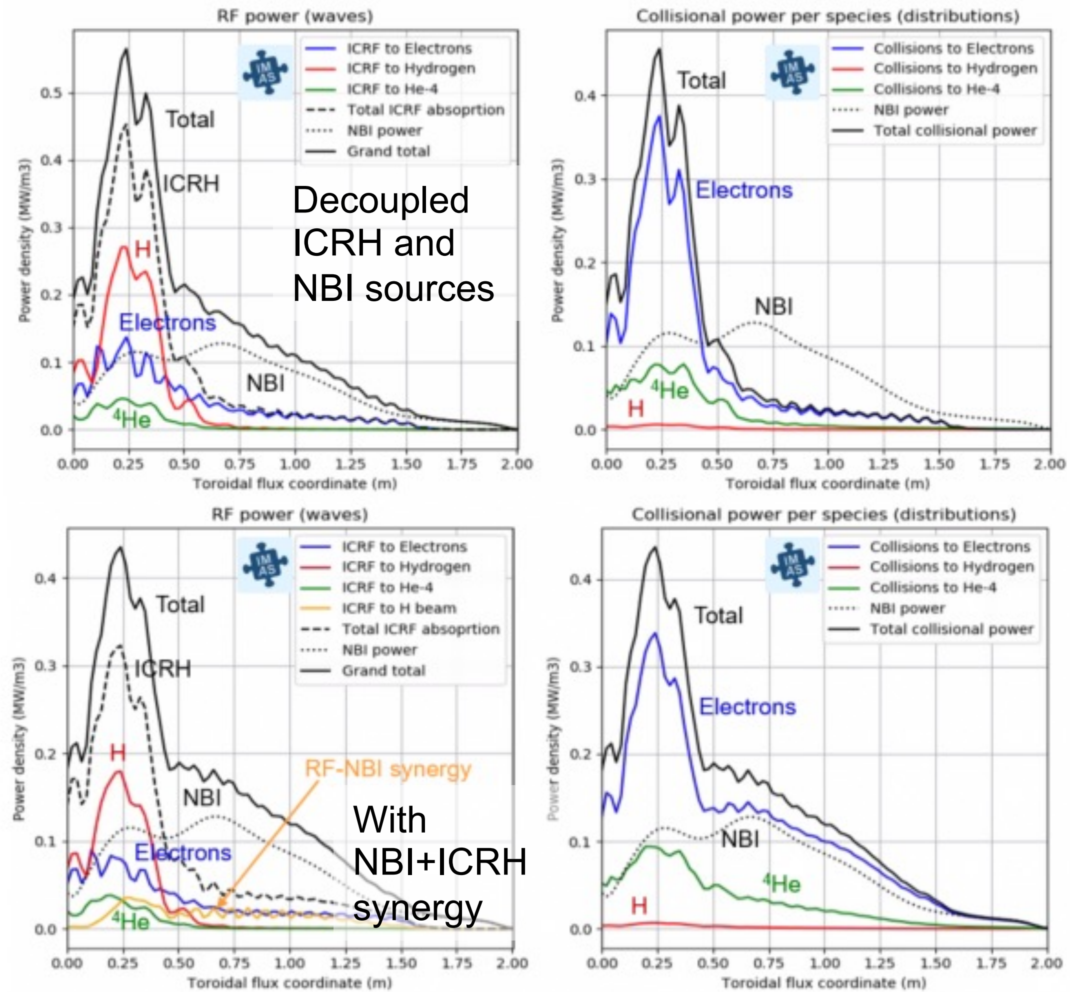
- Dominant electron heating (alphas)
- Significant core ion heating (~40%) due to combined ICRH, NBI and α heating

Synergy between NBI and ICRH for ITER Helium scenario

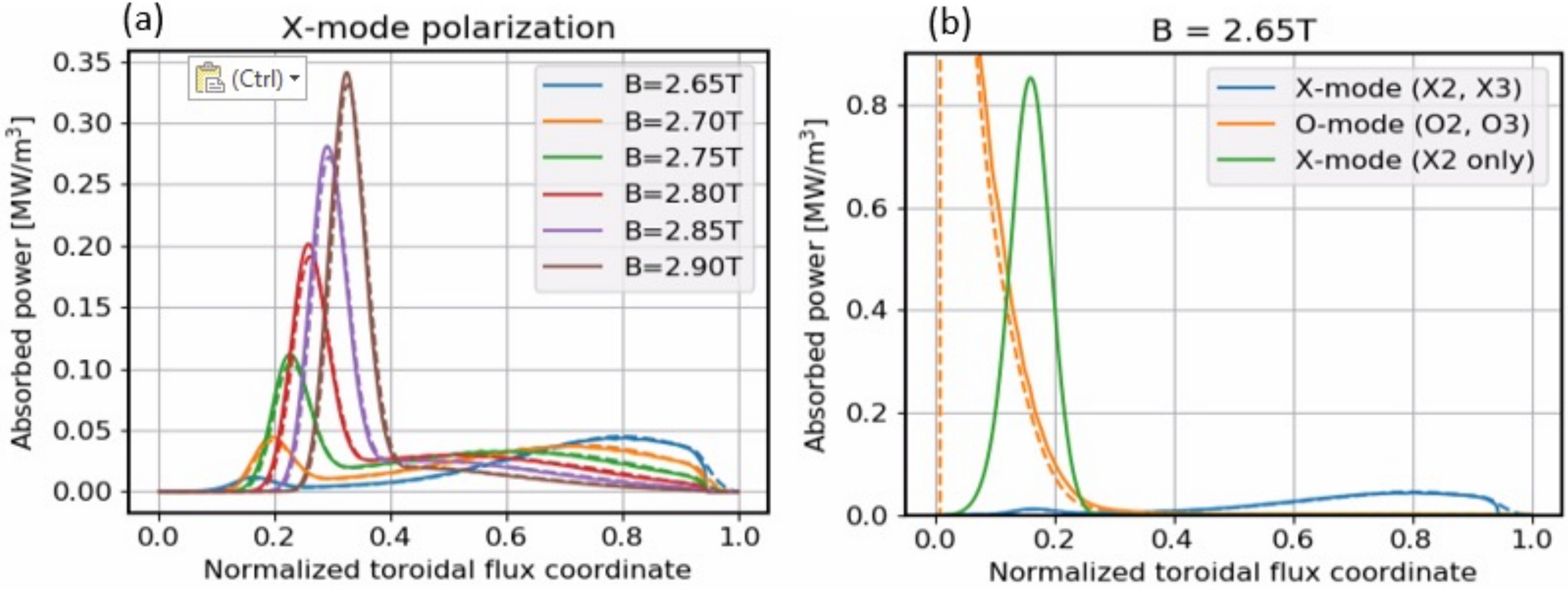
- 2.65 T / 7.5 MA scenario
- 20 MW ICRH 43 MHz
- 33 MW NBI 870 keV



Significant synergetic effect between NBI and ICRH for this scenario.



Study of ECH absorption profiles in 2.65 T / 2.7 MA scenarios



Excellent agreement between TORBEAM (solid) and GRAY (dashed).

On developing Synthetic Diagnostic models in IMAS

https://confluence.iter.org/display/IMP/Synthetic+Diagnostics

Outline

- Synthetic Diagnostics (SD) in the ITER Research Plan (IRP)
- Synthetic Diagnostics models in IMAS
- Examples: interferometry, refractometry, bolometry, neutron fluxes, visible spectroscopy
- IMAS workflow for Synthetic Diagnostics
- Summary and Conclusion

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- **Synthetic Diagnostics (SD) in the ITER Research Plan (IRP)**
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SD models to be ready prior each phase of the IRP

2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036, …

H plasma	H, ^{4}He plasmas	H, ^{4}He plasmas	D, DT
6 m: 1st plasma; Assembly / commissioning	18 m: Pre-Fusion Power Operat. 1; Assembly / commis.	21 m: Pre-Fusion Power Operat. 2; Assembly / commis.	Fusion Power Operation
Demonstrate integration of tokamak core components.	• Main plant system Commissioning • 7.5MA/2.65T L-mode • 5MA/1.8T H-mode	• Raise current & power to 15 MA and 73 MW • Increase pulse duration • 7.5MA/2.65T H-mode	• Q=10, long-pulse scenarios • **Burning plasma physics**

First Plasma
Basic set (magnetics, breakdown, investment protection, density)
→ End 2021

PFPO-1
Subset for measurements of plasma parameters & control
→ End 2023

PFPO-2
Nearly complete set
→ Mid 2027

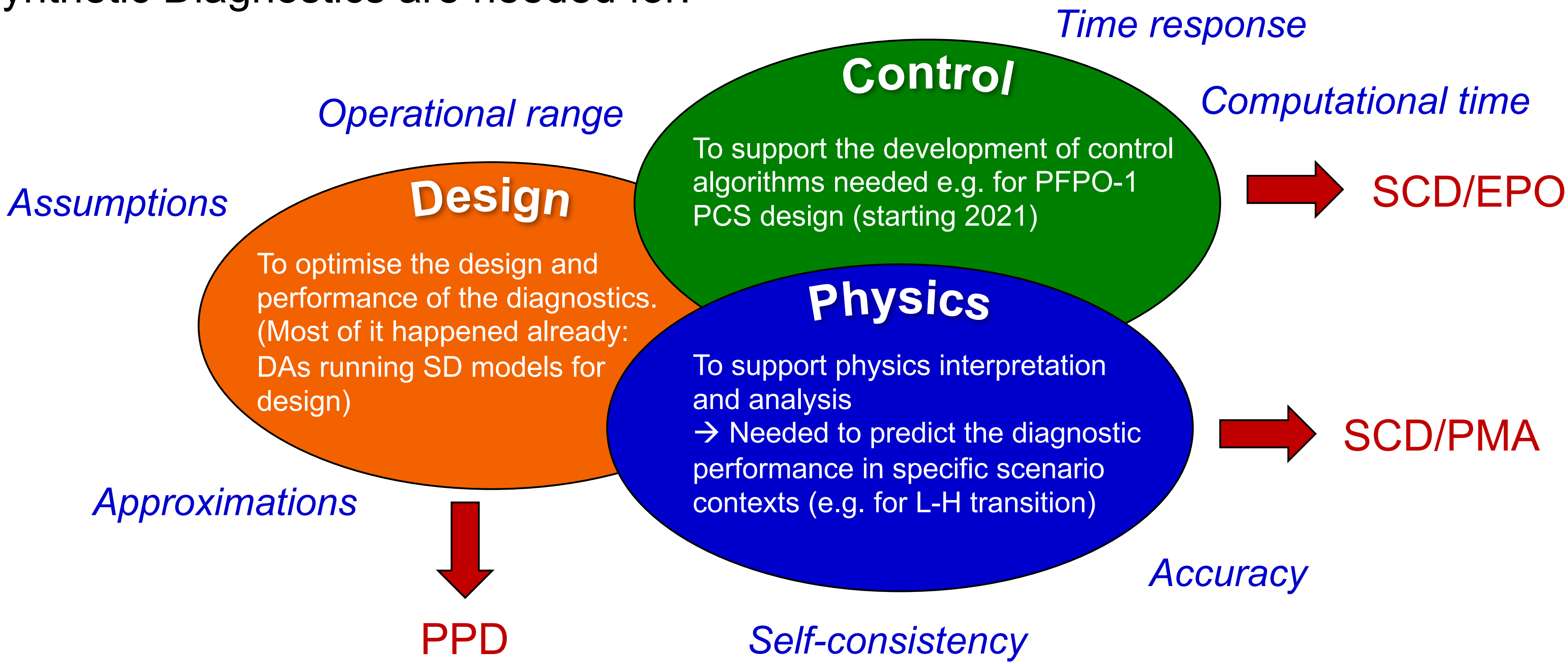
FPO
Complete set including DT fusion products
→ Spring 2030

→ Working group to coordinate the SD development in ITER:

- Science Division: Mireille Schneider
- Port Plugs & Diagnostics Division: Maarten De Bock

SD models categories & requirements

- Synthetic Diagnostics are needed for:



- Requirements for each category still to be defined.
- A model can belong to one or more of the D/P/C categories.

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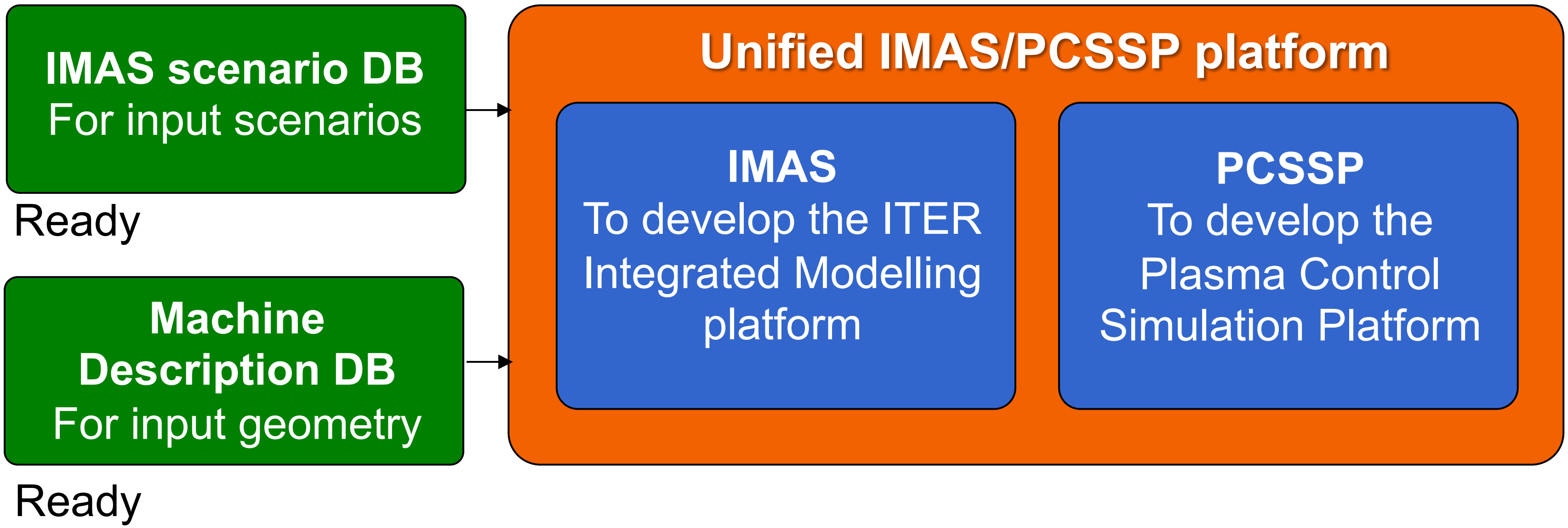
SD models in IMAS

- Why do we need SD models to be adapted to iMAS?

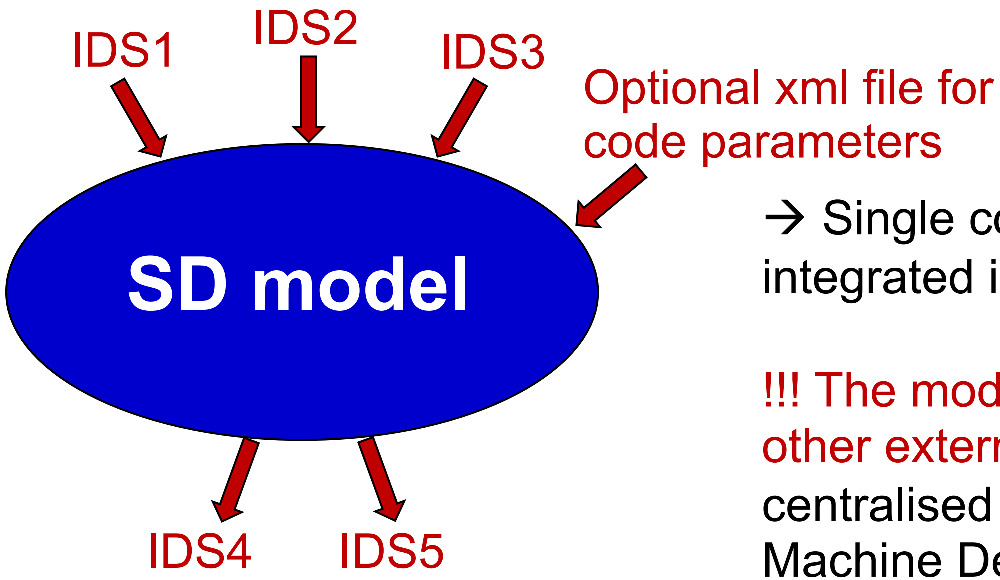


→ SD models to be adapted to IMAS for a better portability and traceability of data

→ Synthetic signals to be stored in the scenario database.

Criteria for SD models in IMAS

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



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

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

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

- Associated development needed:
  - 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

List of available SD models

- We maintain a list of SD codes that contribute to the development of the ITER IM platform: https://confluence.iter.org/display/IMP/Synthetic+Diagnostics

Synthetic Diagnostics

Created by Schneider Mireille, last modified just a moment ago

Diagnostic (+ITER PBS identifier)	Contacts	Source Code Repository	Dependencies	In IMAS	Regression Tests	Documentation	Demonstration input data	Applications: Design, Physics, Control
Charge Exchange Recombination Spectroscopy, for Core / Edge / Pedestal 55.E1 / 55.EC / 55.EF	Author: Alexey Shabashov IO contact: @De Bock Maarten	CXRS	CHERAB	yes	no	Presentation: 3U2DBZ Report by Maxim Bykov based on old material (Matlab): X3NAVL		D/P
H-alpha and Visible Spectroscopy 55.E2	Author: @Khusnutdinov Radmir IO contact: @De Bock Maarten	H-alpha	CHERAB	yes	no	Report: 2N57XR		D/P
Divertor Impurity Monitor (DIM) 55.E4	Author: @Natsume Hiroki IO contact: @De Bock Maarten	DIM	CHERAB	yes	no	Presentation: 2C7R9M To be published in Plasma and Fusion Research: 3Z47PC		D/P
Visible Spectroscopy Reference System (VSRS) 55.E6	Author: Bart van den Boorn IO contact: @De Bock Maarten	VSRS	CHERAB	yes	no	Report: 3AKPSV Presentation: 3TY5AU	134000/60/public/ITER 122264/2/public/ITER	D/P
Toroidal Interferometer Polarimeter (TIP) 55.C5 (+ soon: DIP 55.FA, PoPola 55.C6)	Author, IO contact: @Medvedeva Anna	TIP	-	yes	no	Described in the following presentation: IMEG 2020-21 - Development of Synthetic Diagnostics for ITER	100002/1/public/ITER	D/P/C
Refractometer 55.F9	Author: Kirill Afonin IO contact: @Polevoi Alexei	Refractometer	-	yes	no	Described in the following presentation: 55.F9 Refractometry channel Synthetic Diagnostic Project	130501/1/public/ITER	D/P/C

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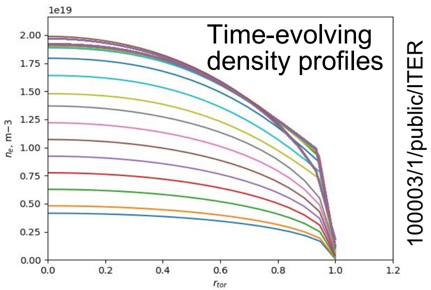
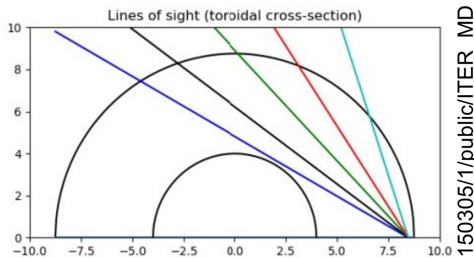
Example of IMAS SD model: the DIP_TIP_POP model

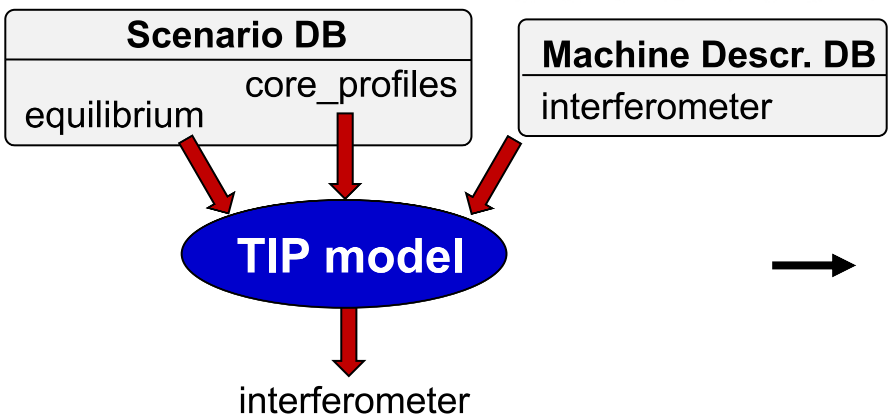
- 55.FA Density Interfer. Polarim (DIP), First Plasma
- 55.C5 Toroid. Interfer. Polarim. (TIP), PFPO-1
- 55.C6 Poloid. Polarim. (POP), PFPO-2

→ Python SD model developed by A. Medvedeva

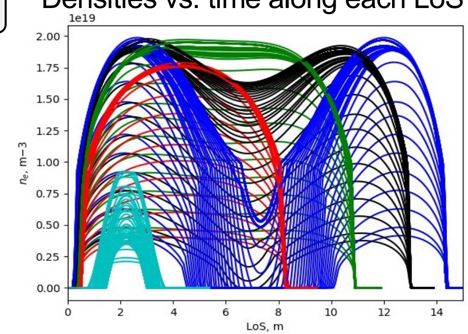




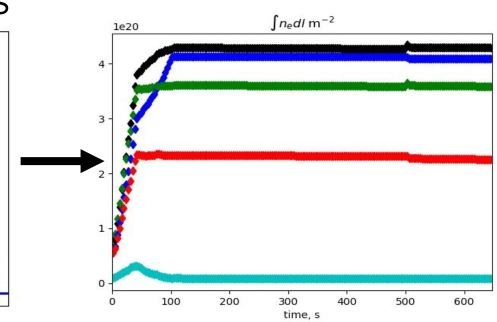
- Model: categories D/P/C
- Measurements:
  - Primary: $\int n_e dl$, $\delta n_e / n_e$, $\delta T_e / T_e$
  - Suppl.: Core and edge n_e profiles



Densities vs. time along each LoS



Line-averaged densities:

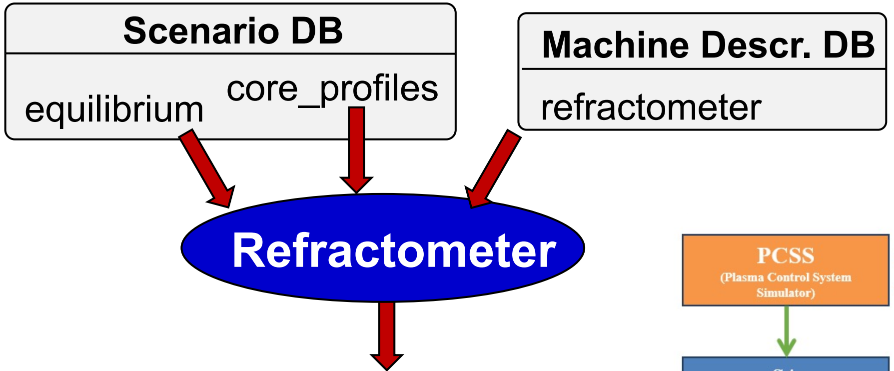



```
out_interferometer = dip_tip_model(equilibrium,core_profiles,interferometer_md)
out_polarimeter    = pop_model(equilibrium,core_profiles,polarimeter_md)
```

Example of IMAS Synthetic Diagnostic: Refractometer

- 55.F9.40: refractometry channel of HFS reflectometer, PFPO-2
  → Python SD model (K. Afonin):

- Measures $\int n_e dl$ (supplementary)



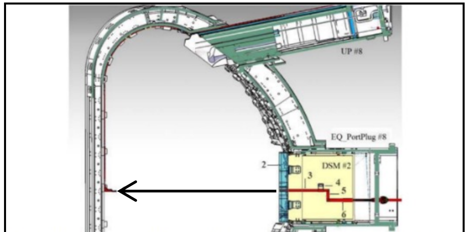
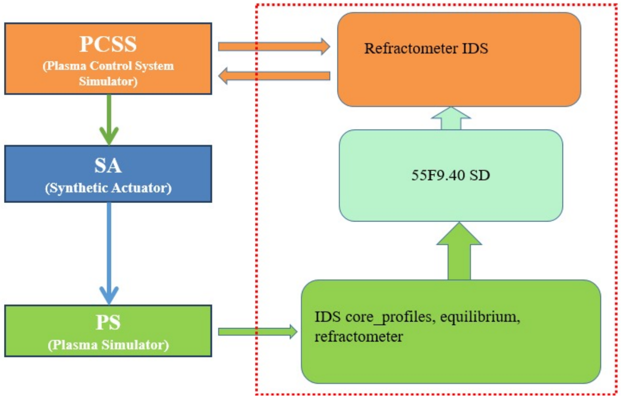
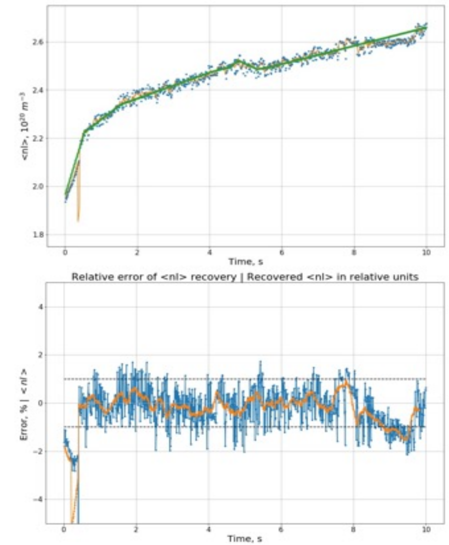


Fig. 6.6. Refractometer in-vessel layout (1 – HFS reflectometer antenna system (receiving antenna for refractometer); 2 – DFW (Diagnostic First Wall); 3 – Transmitting antenna; 4 – Support; 5 – Dog leg; 6 – Horns).



Line-averaged density vs. time



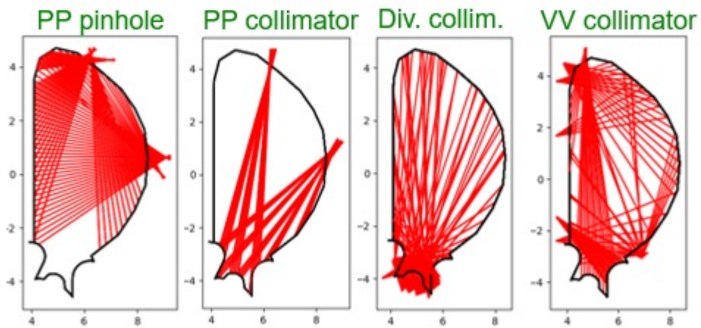
- Model belongs to categories D/P/C (used for basic machine control)

- Integrated into DINA PCS workflow

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

ITER bolometers with ToFu

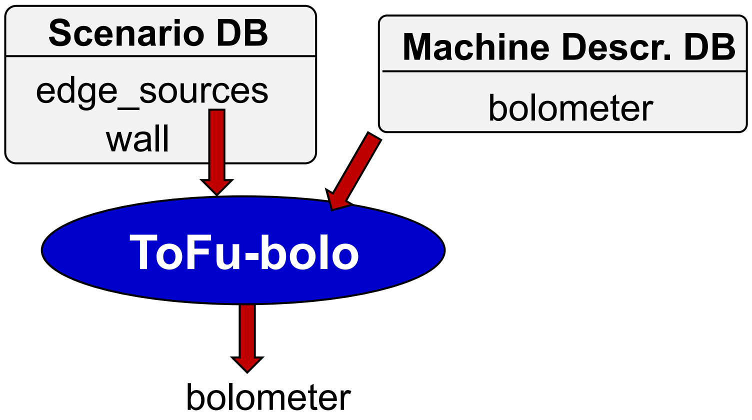
- 55.D1: Bolometers, using ToFu: Open Source Python library natively compatible with IMAS, made for Synthetic Diagnostics and tomography for Fusion devices (D. Vezinet)



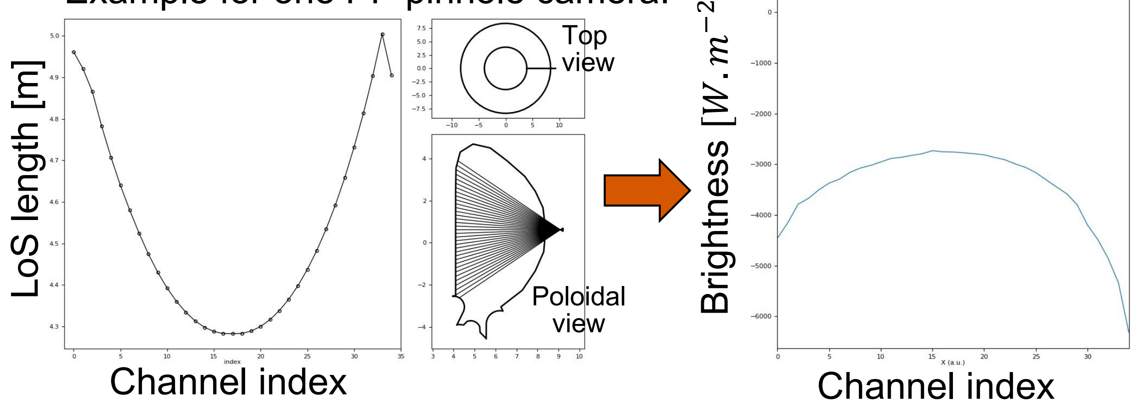
Code parameters:

- Brightness ($W.m^{-2}$) or received power (W)
- Integration step along LoS (resolution)

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

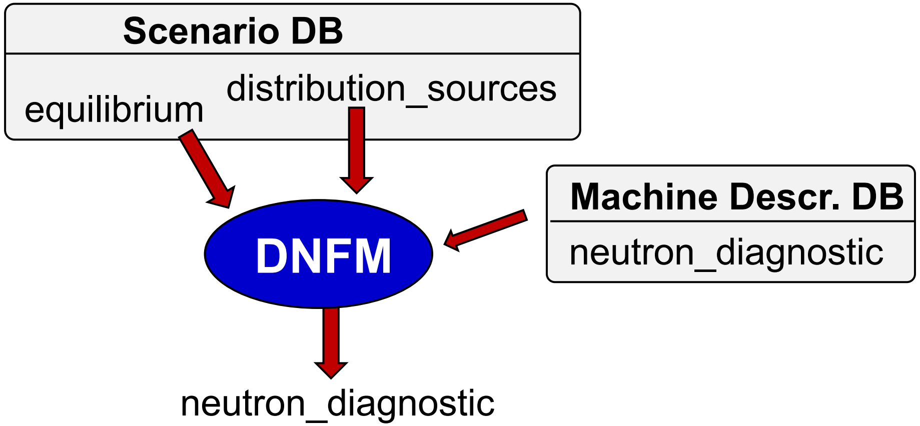


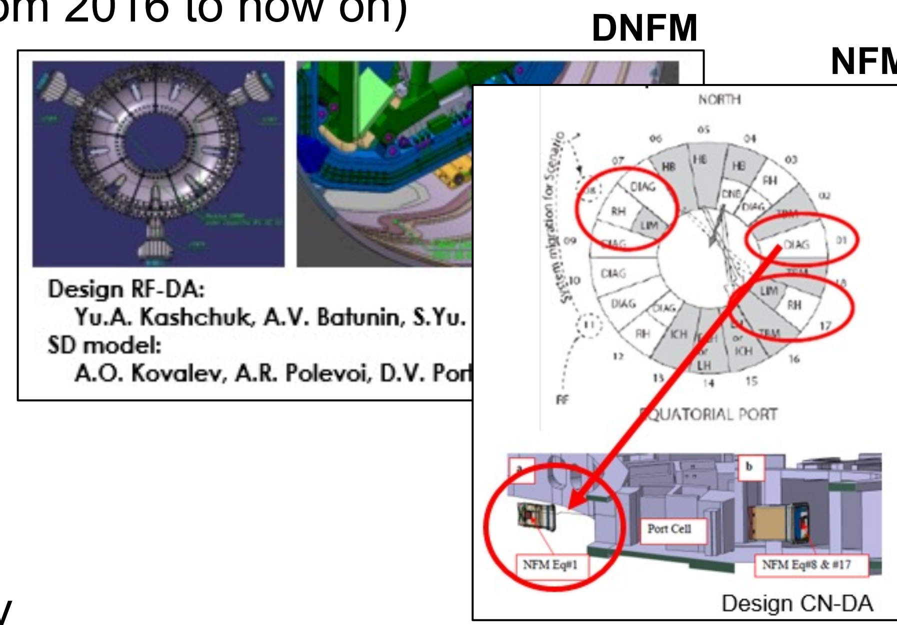
Example for one PP pinhole camera:



(Divertor) Neutron Flux Monitors in IMAS

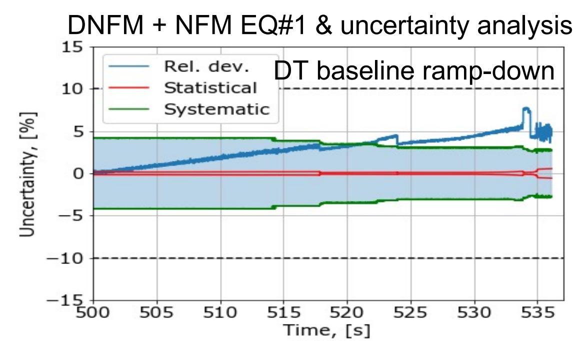
- 55.BC: DNFM developed by A. Kovalev (from 2016 to now on)
- Fortran and Python versions, all in IMAS:





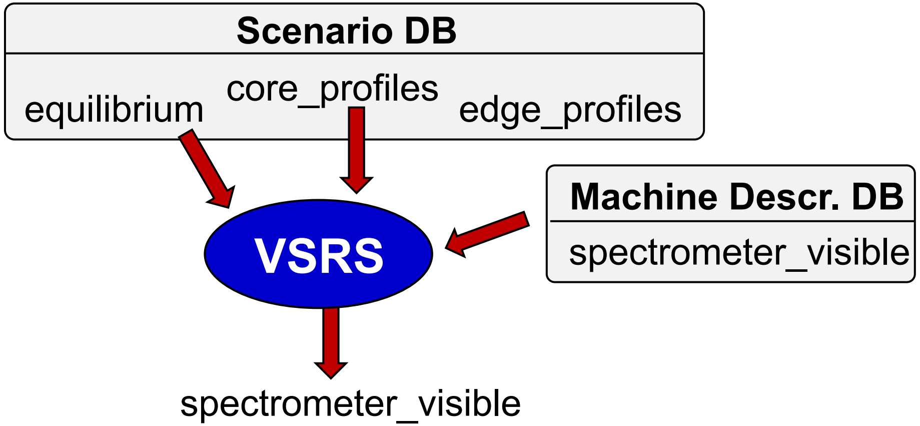
- 55.B4: NFM being developed by A. Kovalev
- DNFM and NFM measure the total neutron flux and fusion power:
  - DNFM more sensitive to vertical plasma shift
  - NFM more sensitive to horizontal plasma shift

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



Example: VSRS Synthetic Diagnostic

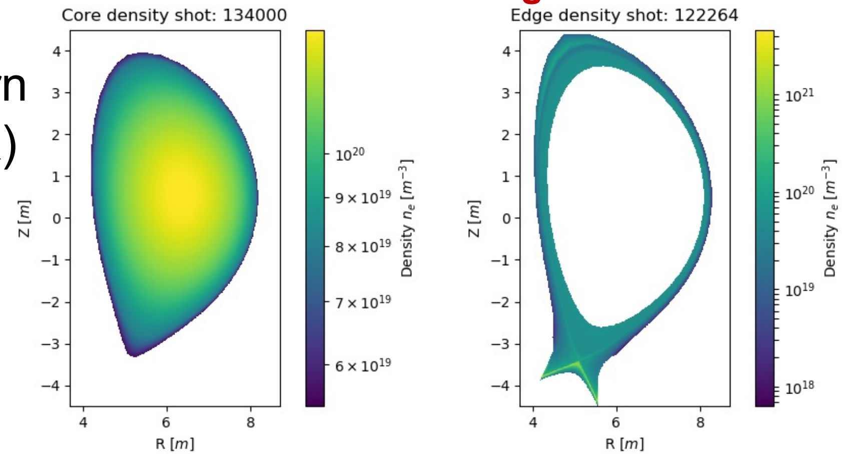
- 55.E6 VSRS = Visible Spectroscopy Reference System, First Plasma
- Developed 2 years ago by Bart van den Boorn (intern supervised by M. de Baar, M. de Bock)
- Main measurements : line-averaged Z_{eff}, n_e



- Written in Python
- Developed in IMAS
- Uses Raysect and CHERAB
- Can use either OpenADAS or ADAS

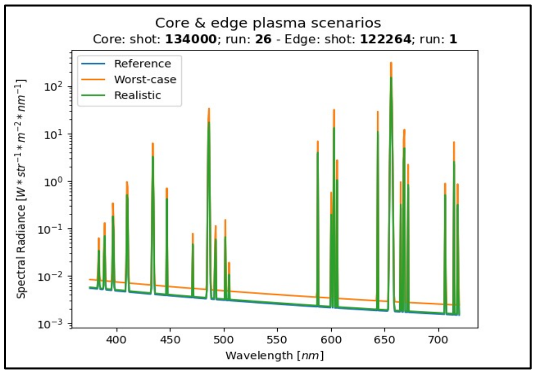
Input from IMAS scenario database

Core: JINTRAC **Edge: SOLPS-ITER**



VSRS result

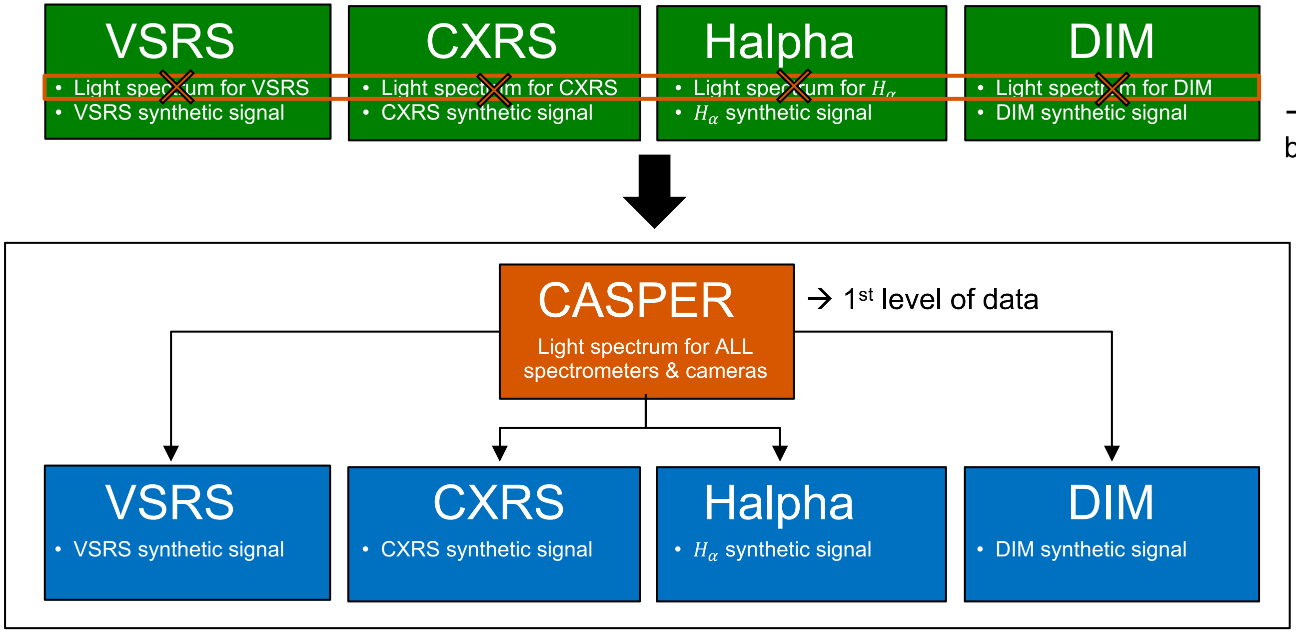
equilibrium
core_profiles
edge_profiles



→ spectrometer_visible

Development of the CASPER code

- CAmera & SPectroscopy Emission Ray-tracer: born from extracting all the features of the VSRS, CXRS, H-alpha and DIM codes for light spectrum calculation:



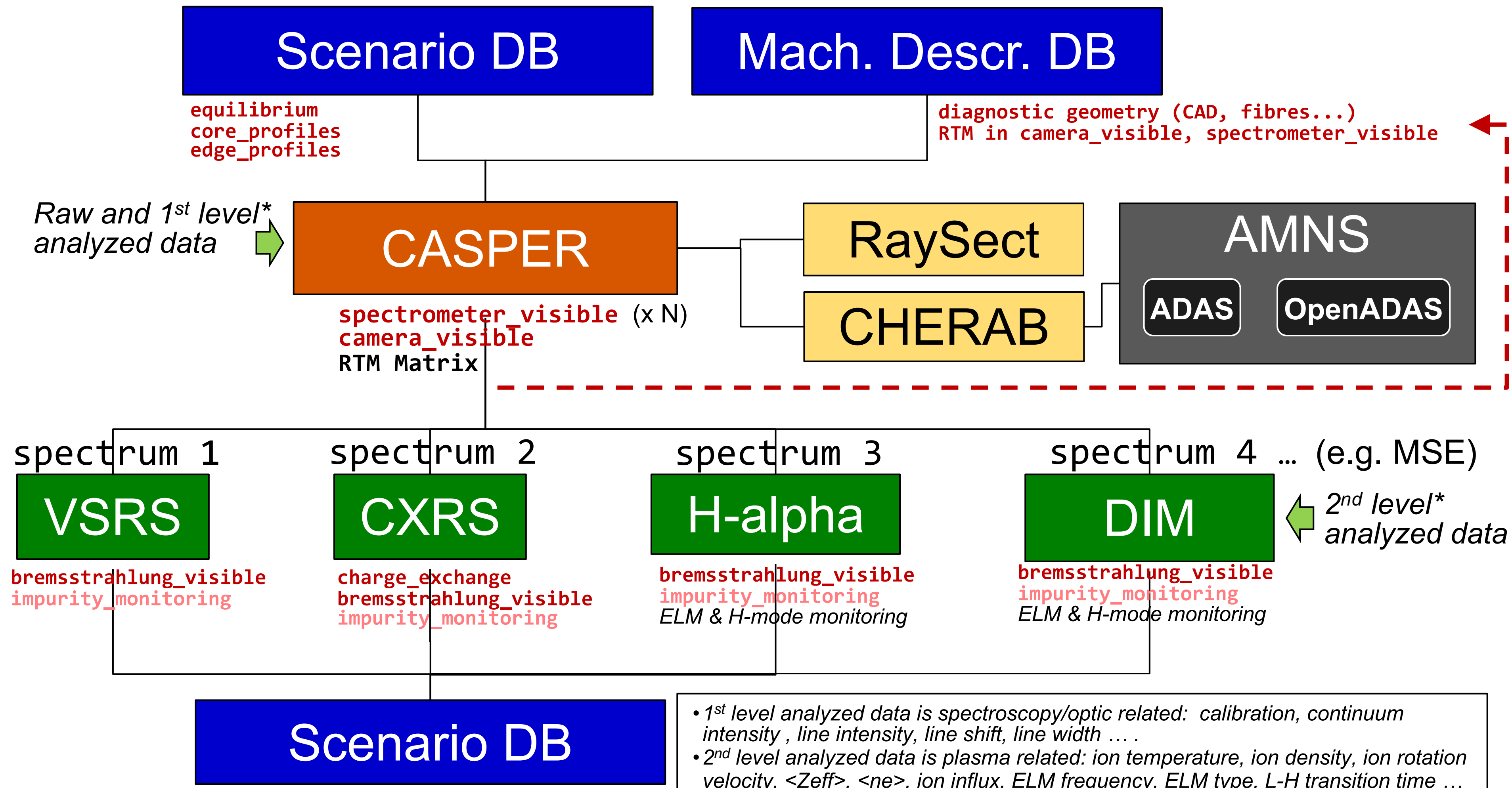
→ Only 2nd level of data to be kept in each SD model

→ RTM to be computed by CASPER for each SD and stored in the Machine Description database (`camera_visible`, `spectrometer_visible`)

→ Detector geometry to be extracted from CAD files and stored in the MD database, with a clean **tracking of data provenance**

- Improvements of the VSRS code by M. Majeed, support from A. Shabashov
- Collaboration with JA-DA: H. Natsume, S. Kajita
  - Extension of RaySect to include BRDF for reflection computation
  - Benchmark of RaySect (open-source) with LightTools (commercial)

Goal: workflow for SD Spectrometry (to be extended)



- *1st level analyzed data is spectroscopy/optic related: calibration, continuum intensity , line intensity, line shift, line width … .*
- *2nd level analyzed data is plasma related: ion temperature, ion density, ion rotation velocity, <Zeff>, <ne>, ion influx, ELM frequency, ELM type, L-H transition time …*

Outline

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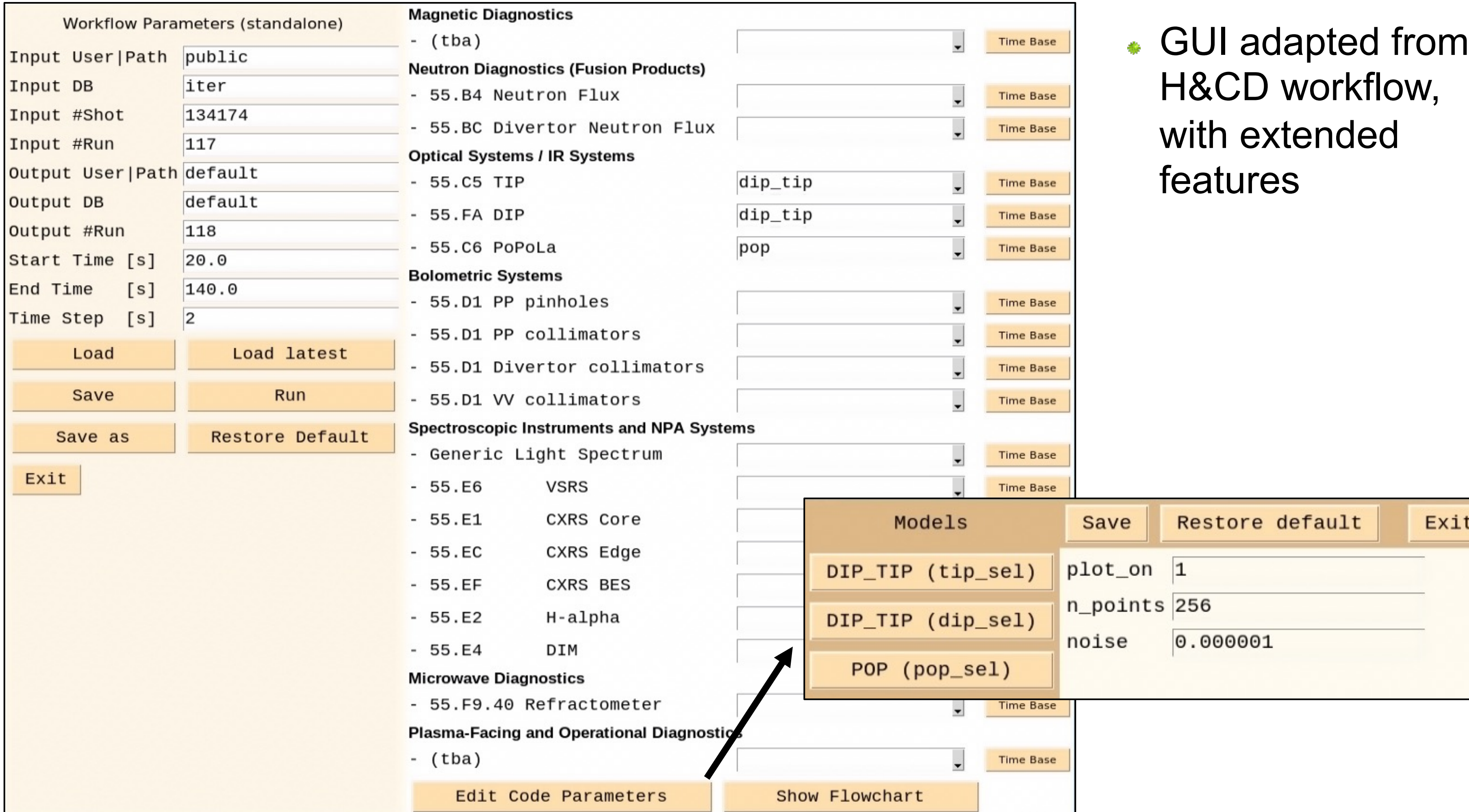
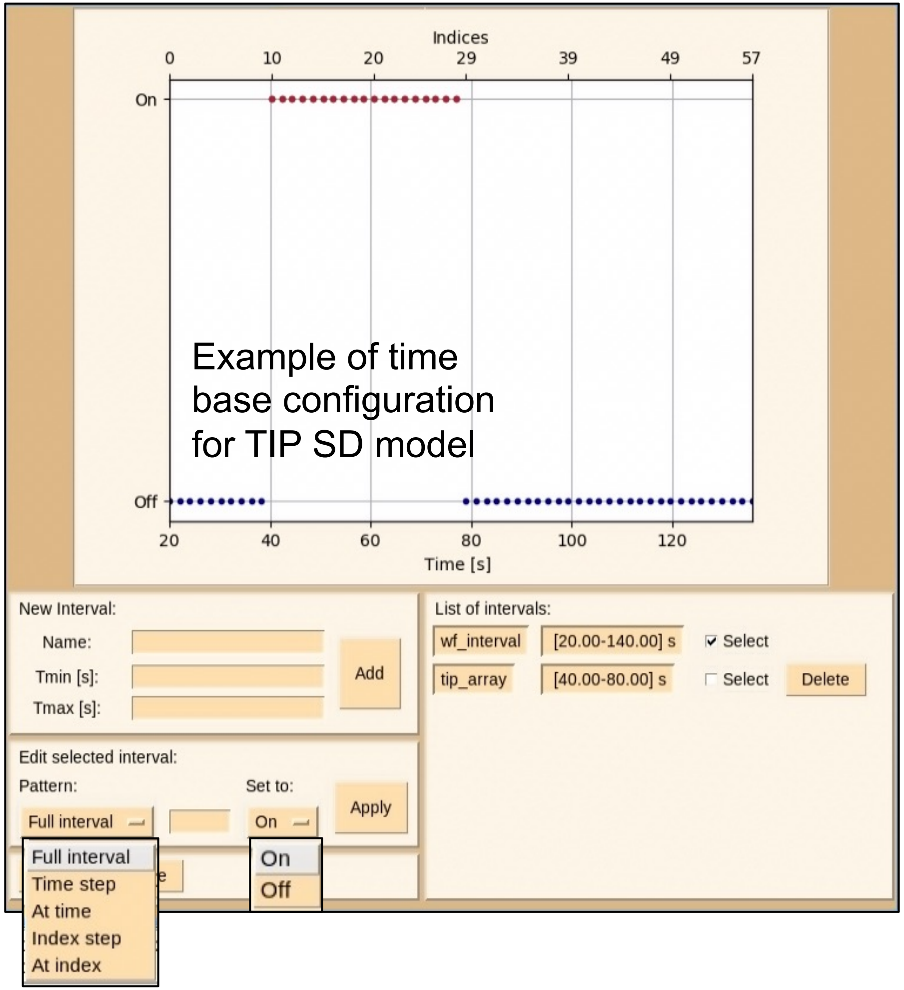
- Synthetic Diagnostics models in IMAS
- Examples: interferometry, refractometry, bolometry, neutron fluxes, visible spectroscopy
- **IMAS workflow for Synthetic Diagnostics**
- Summary and Conclusion

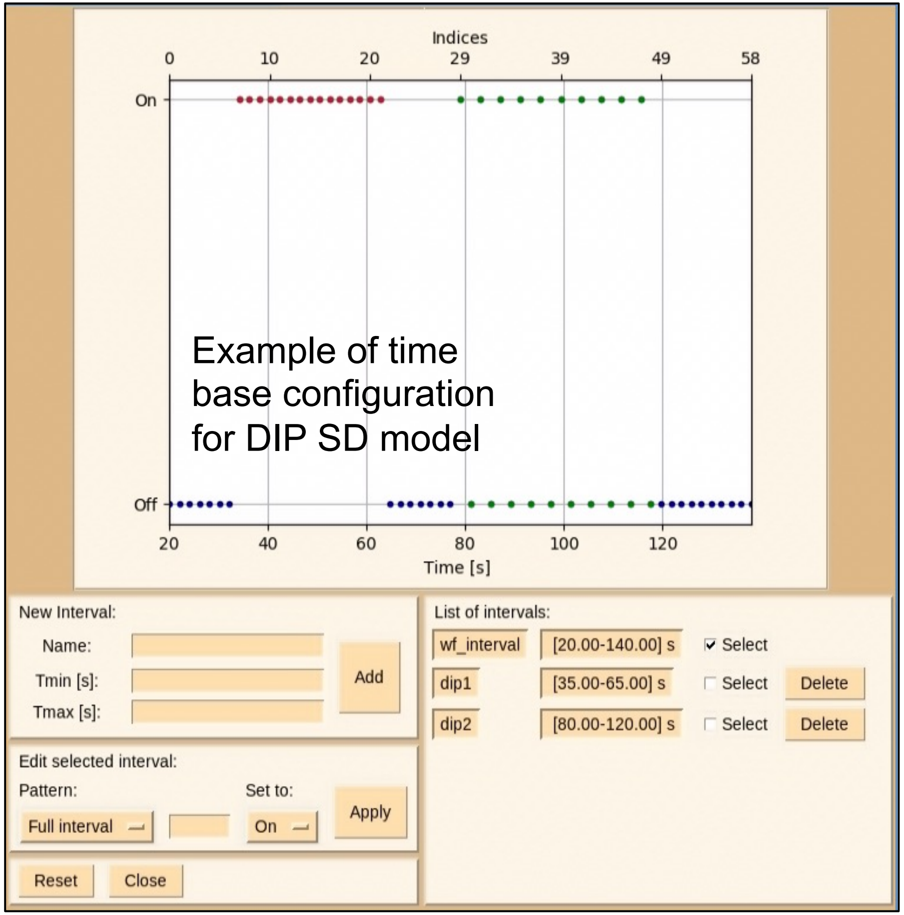
First version of the Synthetic Diagnostic workflow



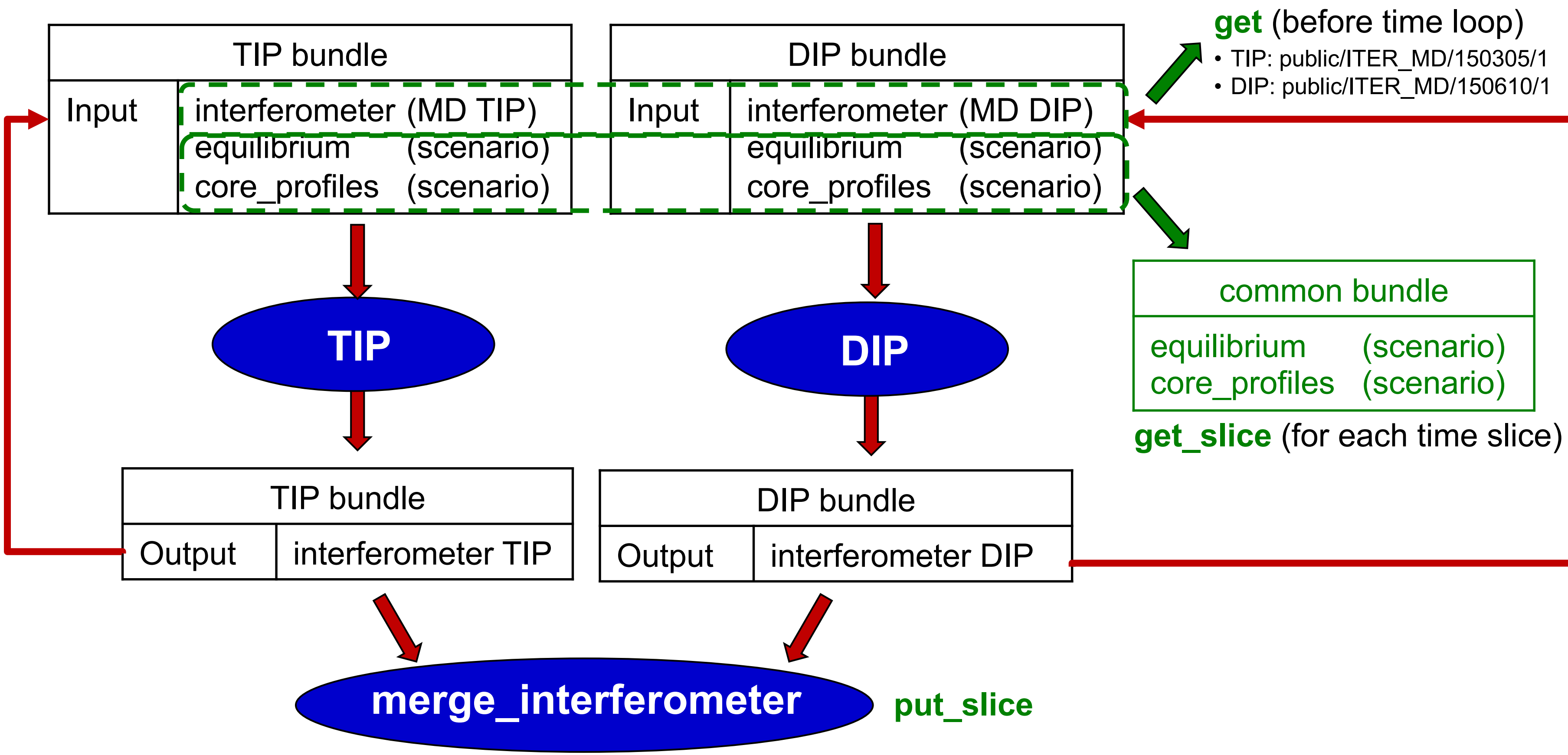
- GUI adapted from H&CD workflow, with extended features

Independent time base management for each SD model





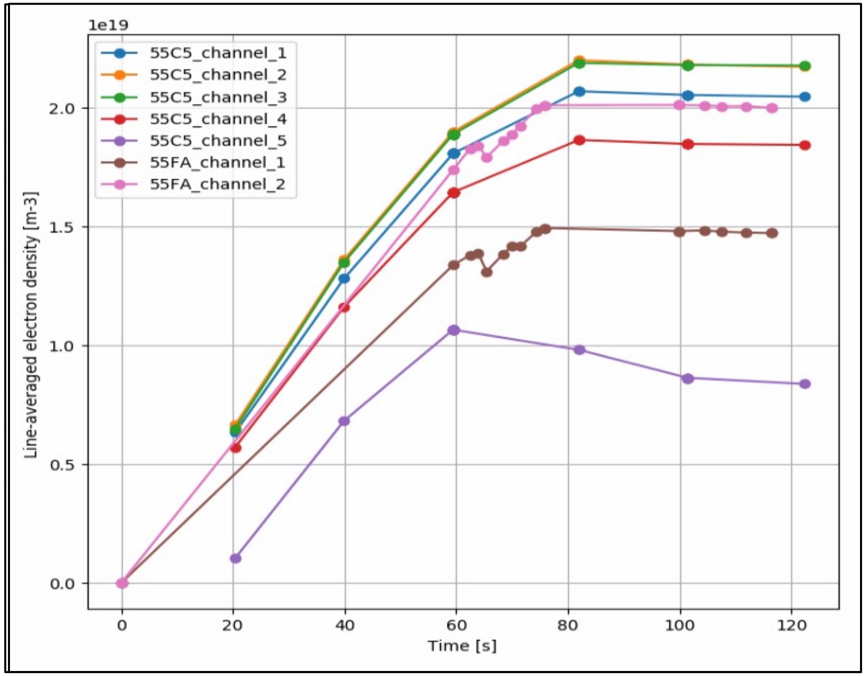
Individual IDS bundles within the SD workflow



- Each SD model receives it own output back as an input for the next time slice
- Mergers needed only to write a single instance of IDS (here `interferometer`) to disk

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
---------------------------------------------
```

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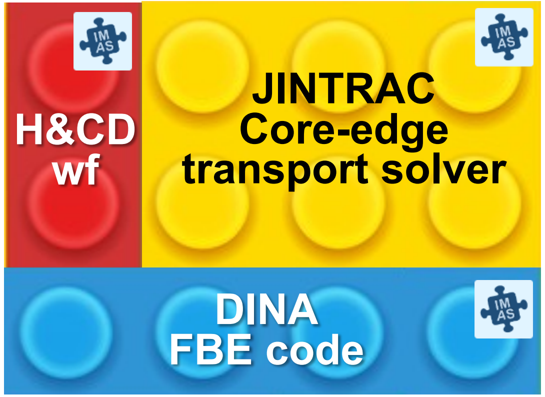
Conclusion H&CD

- IMAS provides a standard for integrated modelling delivering a high level of modularity and flexibility
- A key deliverable is a high-fidelity plasma simulator including self-consistent calculation of free-boundary equilibrium + core-edge transport
- The H&CD workflow has been developed as an essential element of any high-fidelity plasma simulator, enabling the modelling of the synergy between H&CD sources
- The H&CD workflow has been integrated within the core-edge JINTRAC transport solver
- The DINA free boundary equilibrium code is being coupled to the JINTRAC transport solver



- A first version of a high-fidelity plasma simulator is expected soon!

Conclusion Synthetic Diagnostics

- The SD development is already well covered by internal activities and collaborations
- A workflow for Synthetic Diagnostics is being developed, based on the same spirit as the IMAS H&CD workflow:
  - Enable direct access to IMAS scenario and Machine Description databases
  - Time edition tool to allow executing SD models with different time bases
  - Now limited to just a few SD models but expected to grow quickly!
- We have a very active sub-group on visible spectroscopy modelling (meetings every Thursday):
  - Development of CASPER code for generic light spectrum calculation
  - Building modularity with visible spectrometers and cameras downstream
  - Benchmark activity
- Global information on SD development for ITER here: https://confluence.iter.org/display/IMP/Synthetic+Diagnostics