Modelling ITER Heating and Current Drive Systems

12th International ITER School 2023
27 June 2023
The Impact and Consequences of Energetic Particles on Fusion Plasmas

Mireille Schneider
mireille.schneider@iter.org

ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul-lez-Durance, France

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

Outline

- The ITER mission goals and Research Plan
- Why do we need Heating and Current Drive on ITER?
- The IMAS Integrated Analysis and Modelling Suite
- The ITER H&CD Systems
- Modelling H&CD for ITER using IMAS
- Some results
- Conclusion

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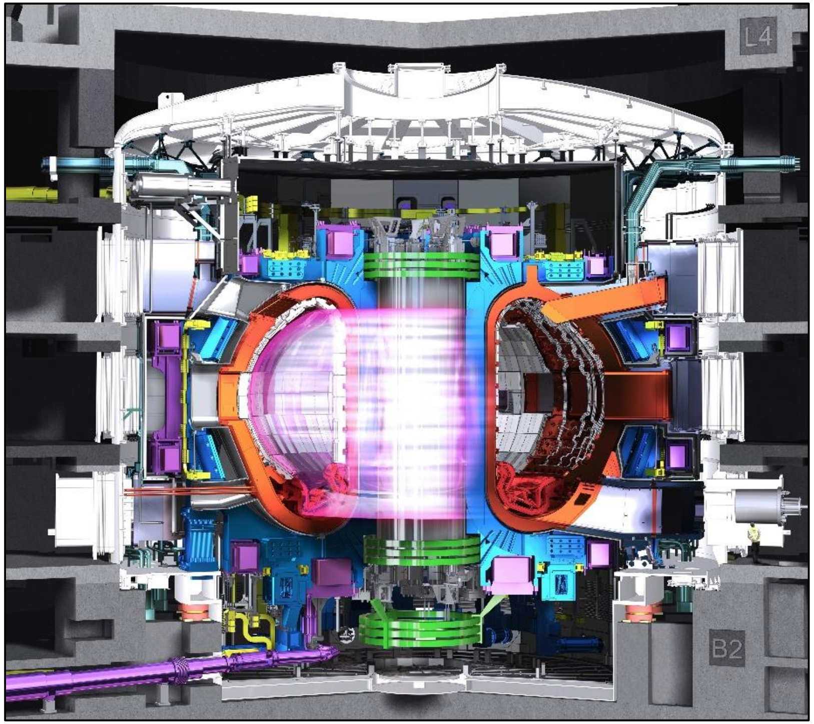
ITER mission goals

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.

The ITER Research Plan

- 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 is currently being revised:

First Plasma
18 months — **FP**
H plasmas
ECH - 6.7 MW
Integrated commissioning of tokamak core components

Pre-Fusion Power Operation 1
18 months — **PFPO-1**
H, ^{4}He plasmas
ECH - 20 (+10) MW
- Main plant systems commissioning
- $P_{L\text{-}H}$ determination

Pre-Fusion Power Operation 2
21 months — **PFPO-2**
H, ^{4}He plasmas
ECH, ICRH, NBI
73 (+10) MW
- Raise current and power
- Increase pulse duration

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

Augmented First Plasma
~ 2 years — **AFP**
H, D plasmas
ECH - 40 MW
ICWC / ICH - 5 MW
- Main plant systems commissioning
- $P_{L\text{-}H}$ determination
- ICWC, test ICH

Fusion Power Operation
~ 10 years — **FPO DT-1**
D, DT plasmas
ECH, ICRH, NBI (+ fusion)
~ 105-120 MW (+100 MW)
- Q=10
- Burning plasmas

Fusion Power Operation
tbd — **FPO DT-2**
D, DT plasmas
ECH, ICRH, NBI (+ fusion)
Upgrades tbd
- Long pulse operation

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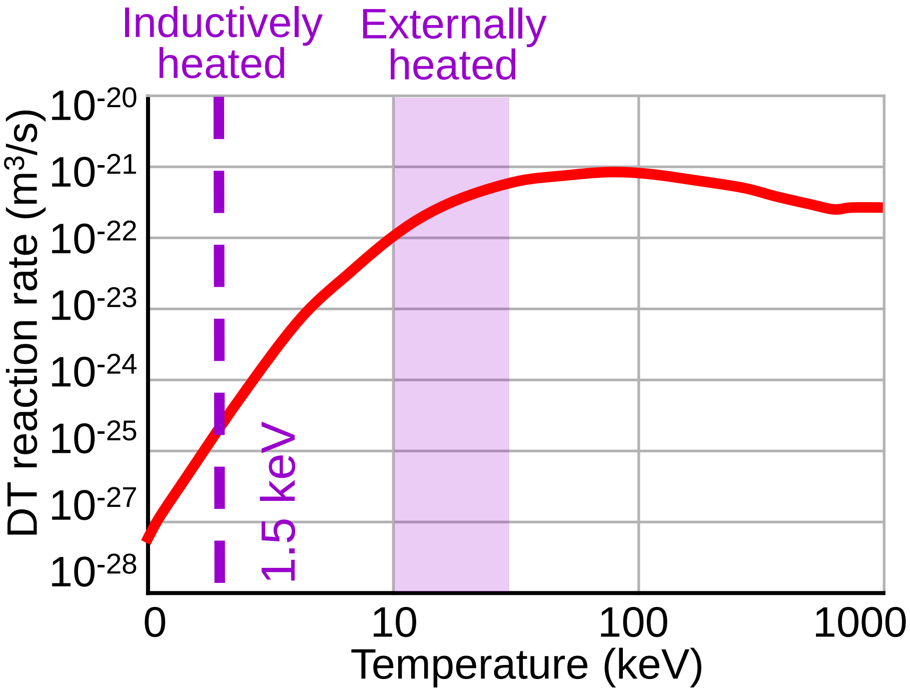
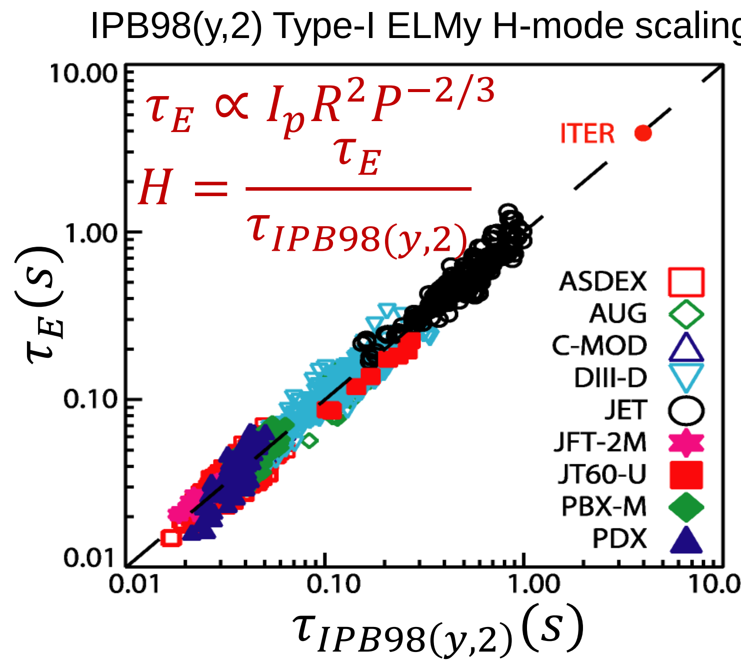
H&CD systems to reach fusion burn conditions





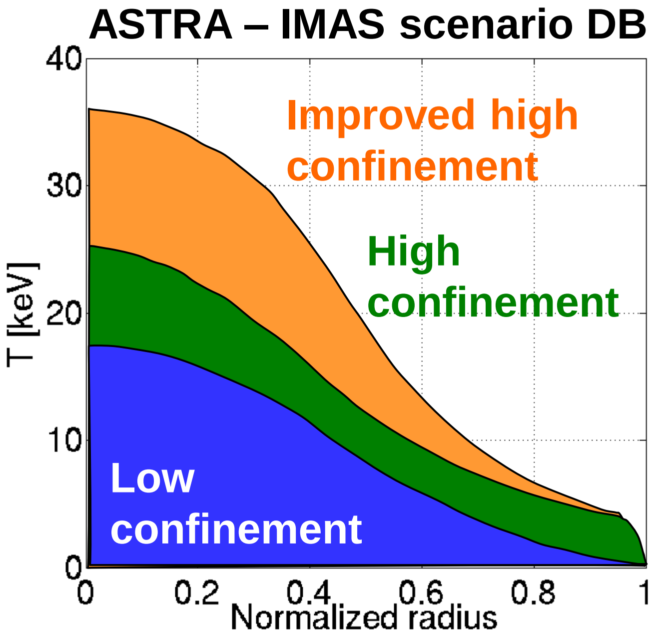
- <T> ~ several 10 keV required for high DT reactivity.
- Inductive current in ITER can ohmically heat up to <T> ~ 1.5 keV ($\eta \sim T^{-3/2}$)

→ External heating required to reach:
High confinement → high temperature → high Q → α self-heating

Confinement regimes

Three confinement regimes:

- Low confinement (L-mode): pulsed operation ($H \sim 0.5$)
- High confinement (H-mode): pulsed operation ($H \sim 1$)
- Improved high confinement: long pulse ($H \sim 1.2$) / steady-state ($H \sim 1.6$)



Power threshold for transition from L to H-mode:

$$P_{LH} \propto n_e^{0.7} \times B^{0.8}$$

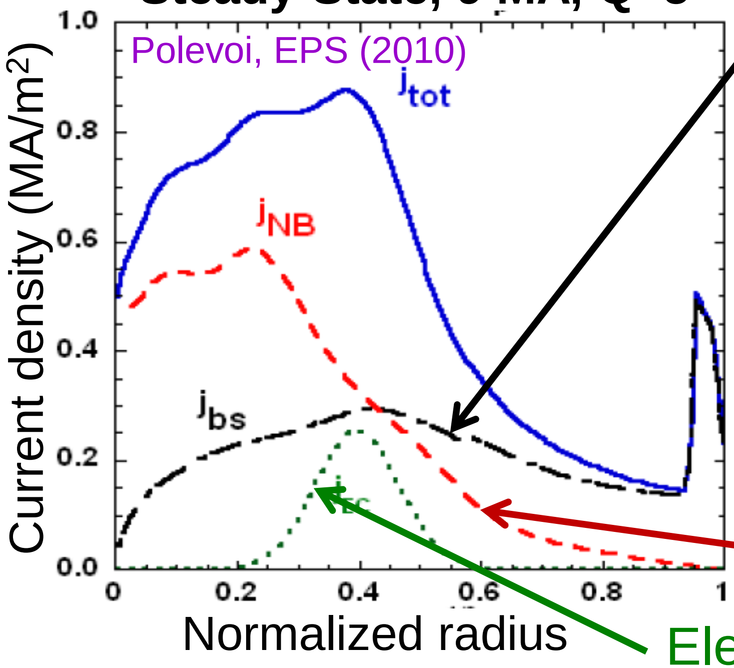
→ Low density and B-field operation when H&CD is limited.

$$P_{LH}(T) < P_{LH}(D) < P_{LH}(H)$$

H&CD to drive current for long pulse operation

- The inductive flux of a tokamak is finite → pulsed, limited in time.
- Long pulse operation requires that I_p be driven by other means:

Steady-State, 9 MA, Q=5



Bootstrap current j_{bs}: self-driven from gradients; increases with β:

- Plasma performance:

$$\beta = \frac{p_{plasma}}{p_{magnetic}} = \frac{\langle p \rangle}{B^2/2\mu_0}$$

- Plasma stability limit (~3-4):

$$\beta_N = \beta \frac{aB_T}{I_p}$$

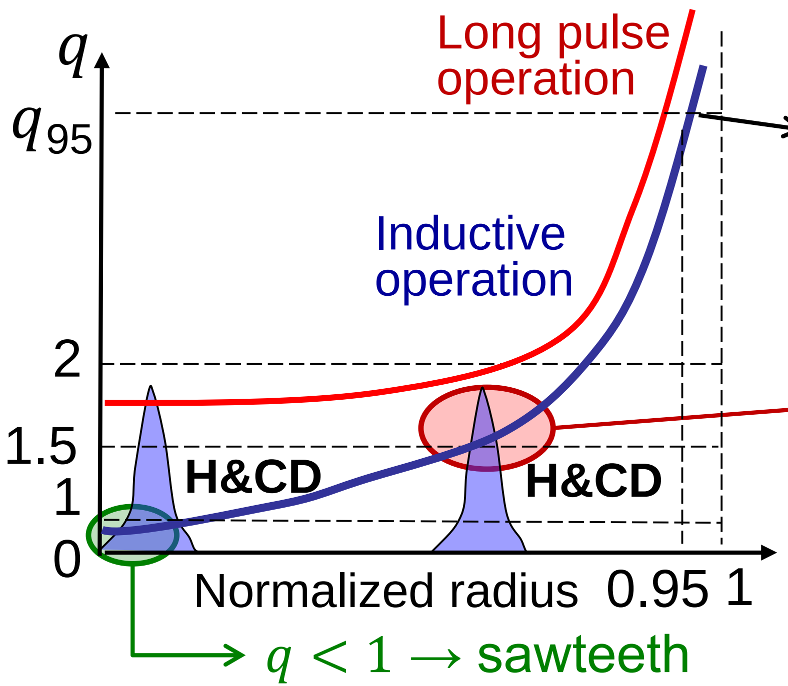
External sources:

- Neutral Beam Current Drive $\mathbf{j_{NB}}$ (NBCD)
- Electron Cyclotron Current Drive $\mathbf{j_{EC}}$(ECCD)

H&CD system to control MHD instabilities

Instabilities can deteriorate plasma confinement:

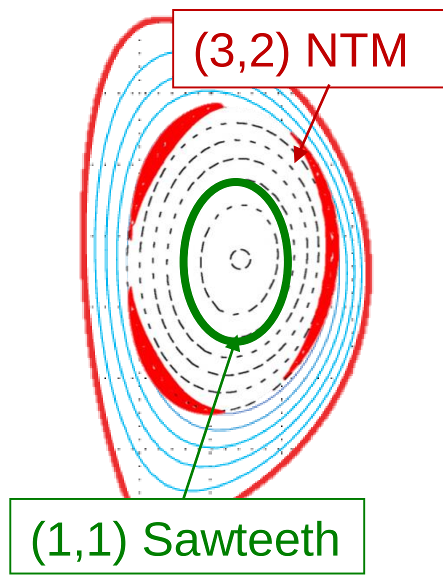
- Characterized by safety factor, $q = toroidal/poloidal$ turns
- Instabilities on rational q surfaces, driven by pressure and current gradients
- ITER H&CD systems can influence both.



- Plasma can disrupt if $q_{95} < 2$
- ITER routine operation: $q_{95} \geq 3$

$q = 3/2 \rightarrow$ NTM
(Neoclassical Tearing Modes)

ITER baseline Q=10 magnetic equilibrium



Plasma initiation

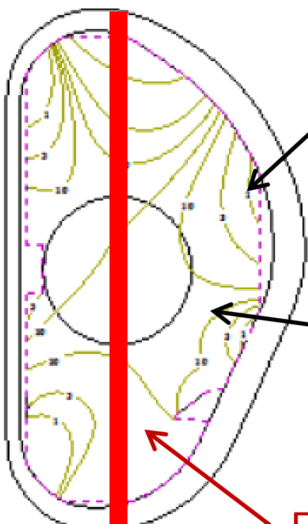
Initiation = **breakdown** (ionization) + **burnthrough** (heating)

- **Breakdown:**

j_{coil} variation → E-field formation → Acceleration of electrons → Ionization (avalanche) → Plasma

- **Burnthrough:**

→ Temperature increase → Enhanced by ECRH

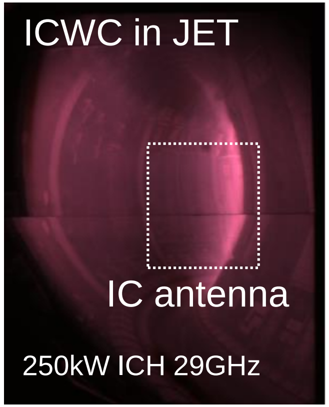


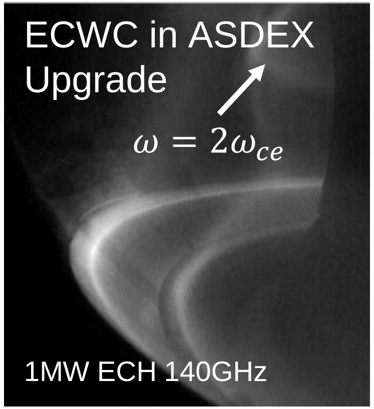
EC will assist plasma initiation to ensure robust start-up for a wider range of plasma conditions.

Wall Conditioning

Wall conditioning tasks in ITER

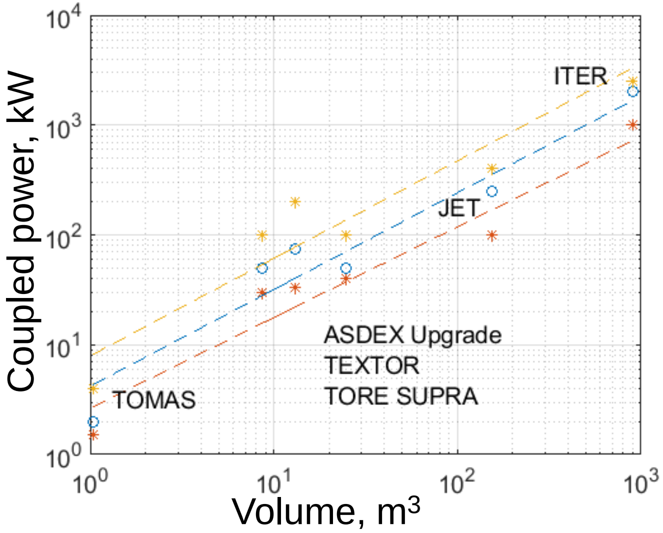
- Reduce impurity content
- Allow start-up of tokamak: density control
- Recover from events : mitigated plasma disruption, leak
- Transition from operation in one isotope or gas to another
- Ease access to advanced scenarios
- **Tritium recovery (700g inventory limit)**





ICWC

- Uniform discharge produced by **collisional** absorption of ICH waves
  - $E_{//}$ needed to breakdown the neutral gas
  - Fast Wave excitation ($E_{\perp}$) needed for uniform power coupling in wave phase (monopole)
  - Frequency: 40 MHz at 2.65 T and 5.3 T
    → demonstrated at scale in JET
- Requires 2-2.5 MW coupled to plasma at 40-50% efficiency



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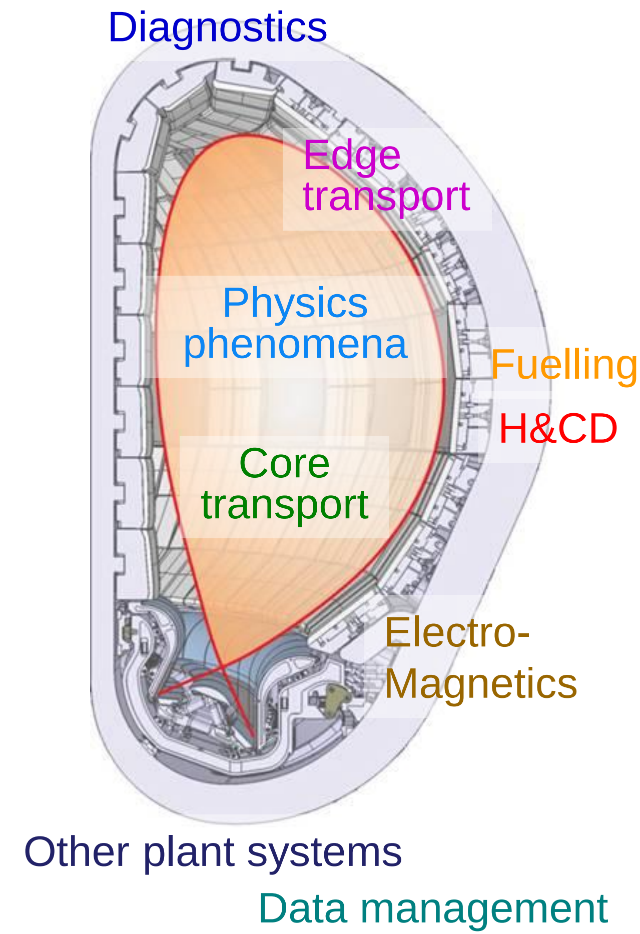
The ITER Integrated Modelling & Analysis Suite (IMAS)

- IMAS is the suite of physics tools being developed to support ITER through delivering:
  - Predictive simulations that support the preparation for ITER operation and ITER Research Plan
  - Tools to interpret and analysis ITER data thus supporting the ITER research programme
- It relies on standard Interface Data Structures (IDS) to represent experimental and simulated data

Data Model	• Machine independent data structures • Able to serve as code coupling interface • Meta-data and provenance
Generic Tools	• Data access, storage, discovery, manipulation, visualization • Support for simulation management and exploitation of datasets / databases
Applications	• Independent physics codes • Complex workflows • Experimental data processing pipelines • Multi-machine databases

The IMAS Data Dictionary

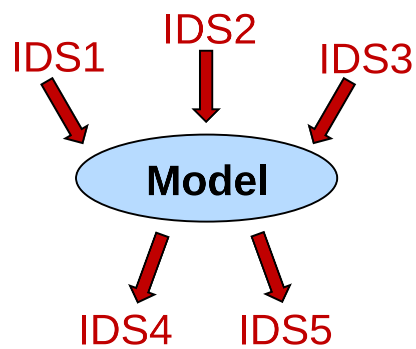
amns_data
barometry
bolometer
bremsstrahlung_visible
calorimetry
camera_ir
camera_visible
camera_x_rays
charge_exchange
coils_non_axisymmetric
controllers
core_instant_changes
core_profiles
core_sources
core_transport
cyrostat
dataset_description
dataset_fair
disruption
distribution_sources
distributions
divertors
ec_launchers
ece
edge_profiles
edge_sources
edge_transport
em_coupling
equilibrium
gas_injection
gas_pumping
gyrokinetics
hard_x_rays
ic_antennas
interferometer
iron_core
langmuir_probes
lh_antennas
magnetics
mhd
mhd_linear
mse
nbi
neutron_diagnostic
ntms
pellets
pf_active
pf_passive
plasma_initiation
polarimeter
pulse_schedule
radiation
real_time_data
reflectometer_profile
refractometer
sawteeth
soft_x_rays
spectrometer_mass
spectrometer_uv
spectrometer_visible
spectrometer_x_ray_crystal
summary
temporary
thomson_scattering
tf
transport_solver_numerics
turbulence
wall
waves
workflow



Extension of Data Dictionary mainly through application to new Use Cases and user feedback.

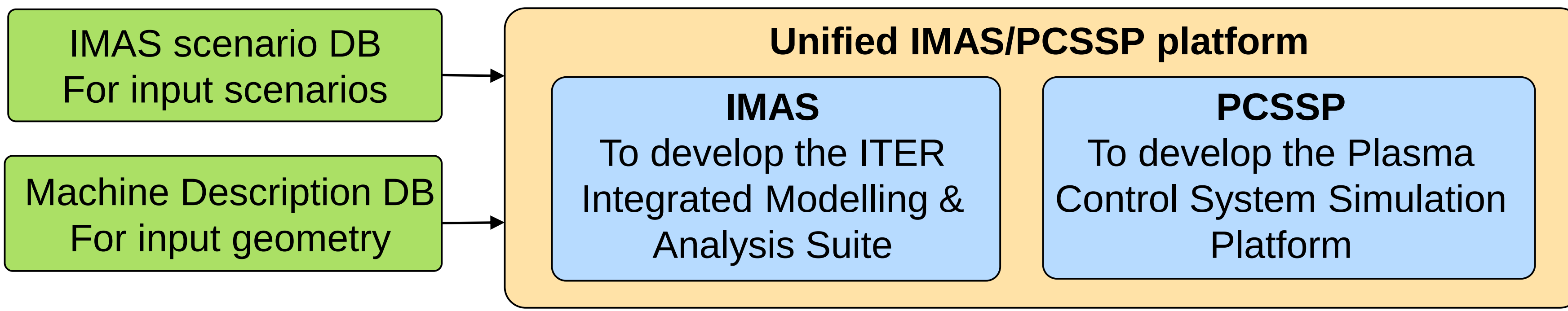
Models in IMAS

- An IMAS model exchanges IDSs exclusively:



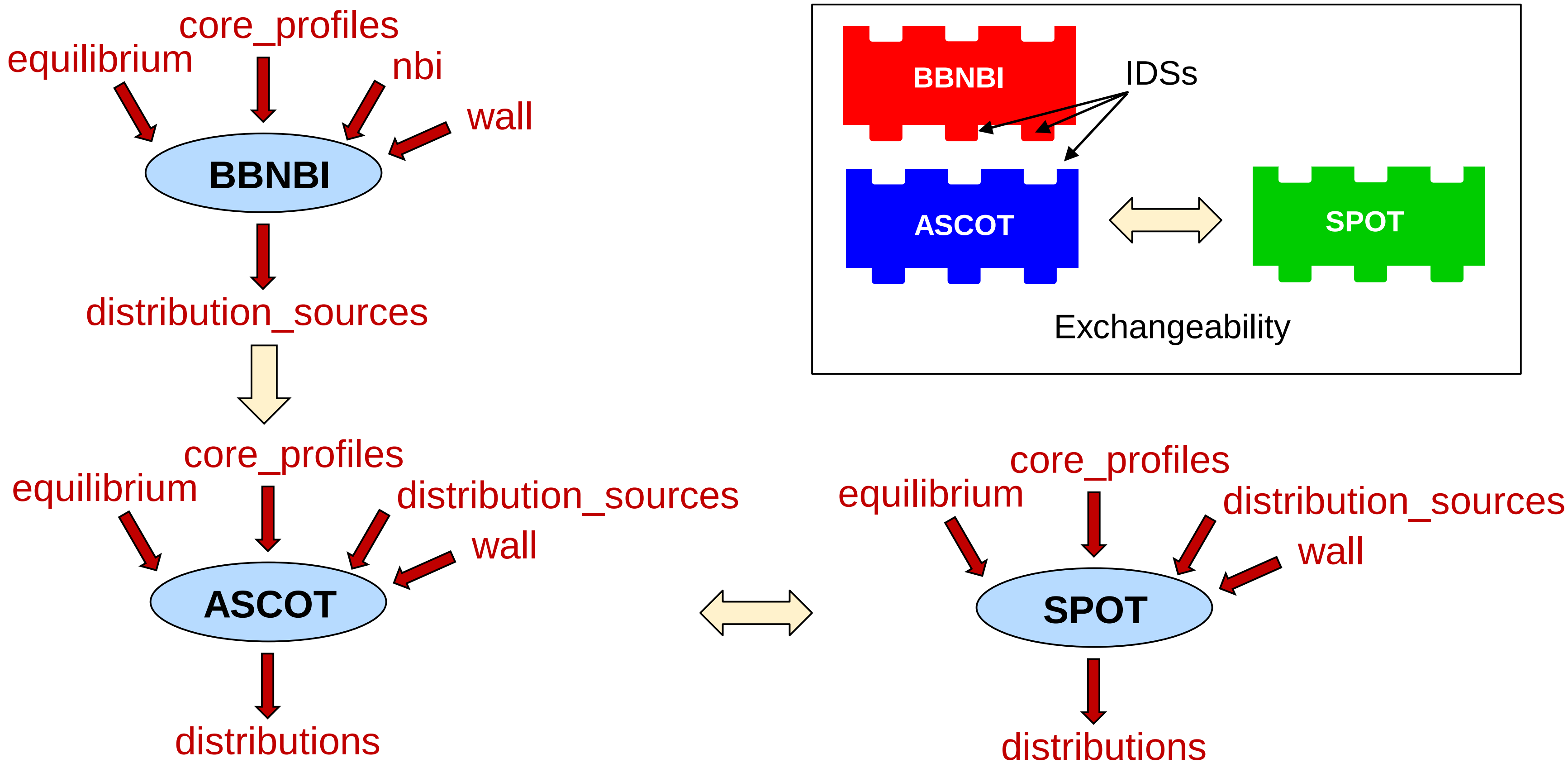
It is a single component that can be integrated into any IMAS workflow.

- An IMAS model usually takes its input from the Scenario and Machine Description database:



IMAS modelling is like playing legos

- Example of NBI modelling: we first calculate beam deposition followed by a Fokker-Planck to compute the evolution of the fast ion distribution.



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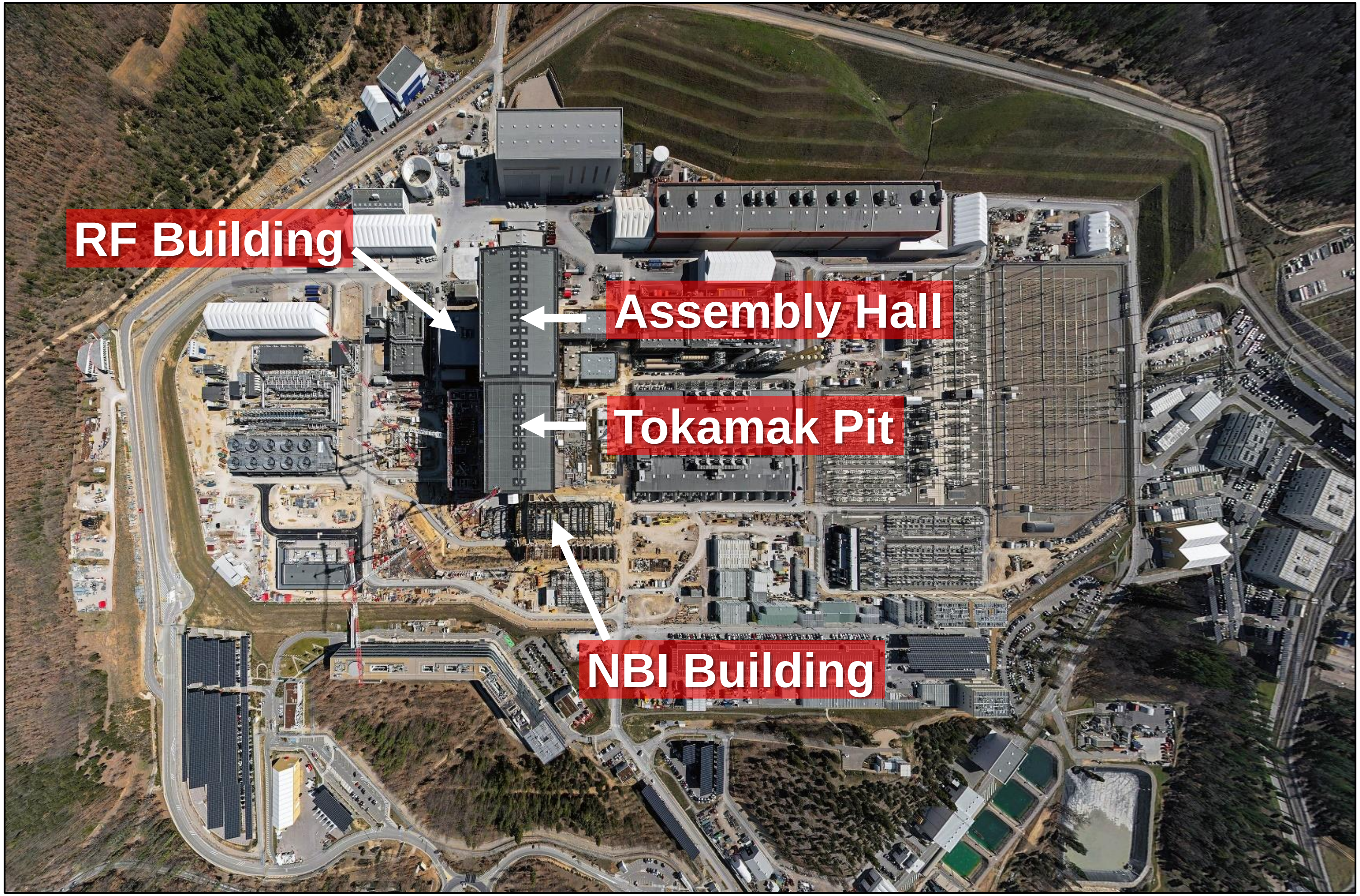
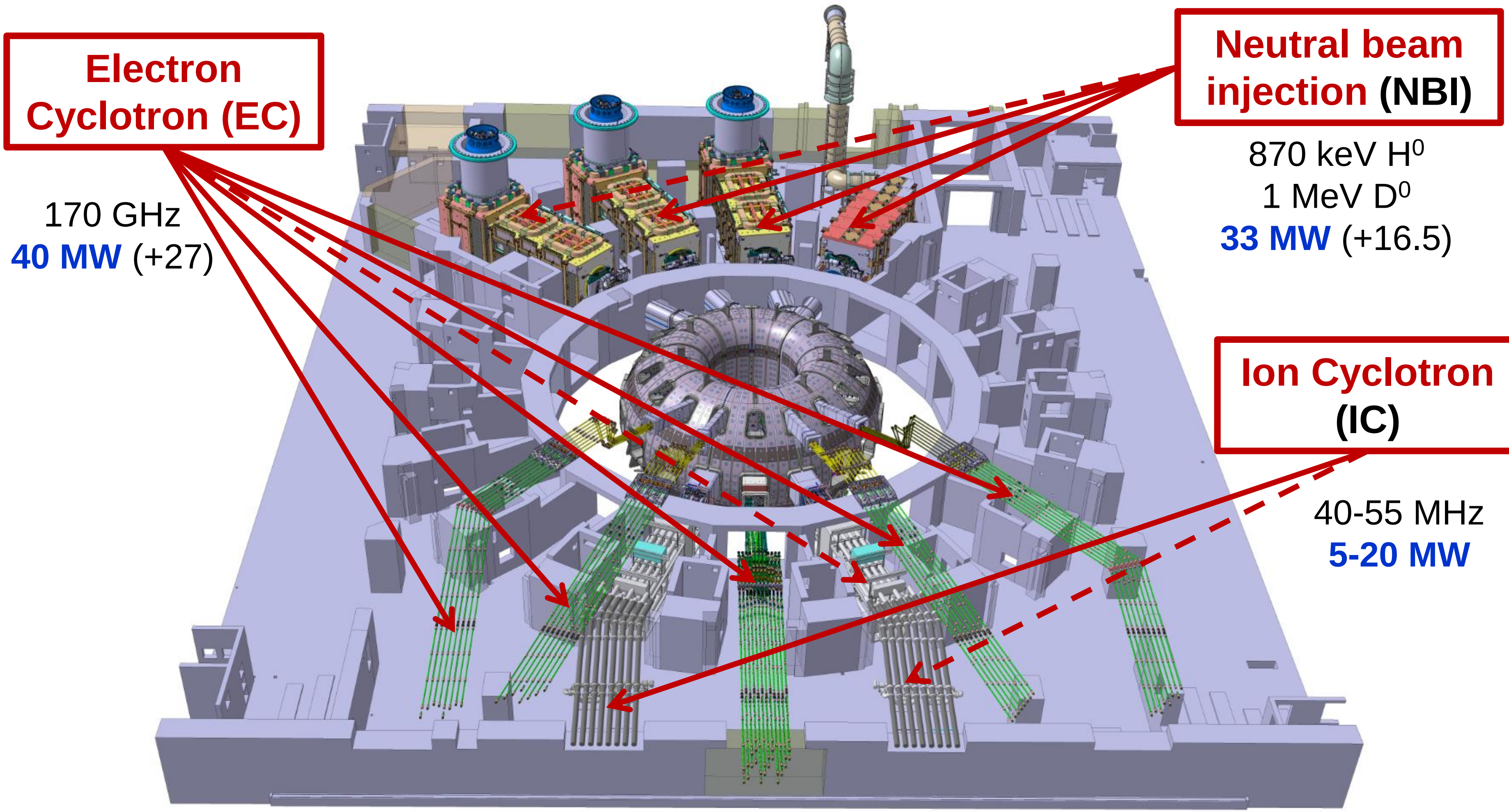
H&CD buildings on the ITER site



ITER H&CD systems

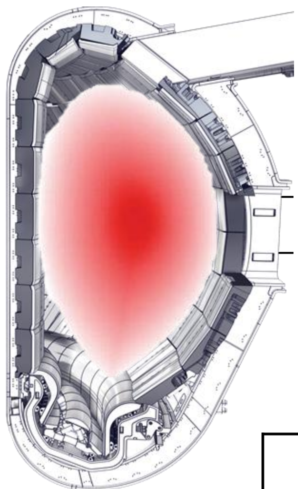


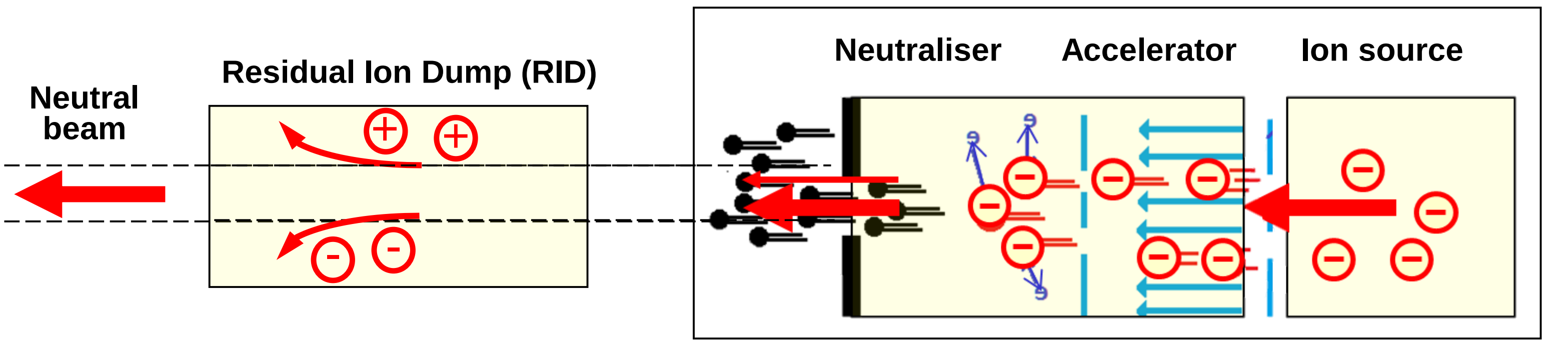
Neutral Beam Injection (NBI)

ITER has a large, high density, hot plasma.

→ Needs high energy neutral beams to penetrate up to the core

→ Achievable by accelerating negative ions up to 1 MeV.

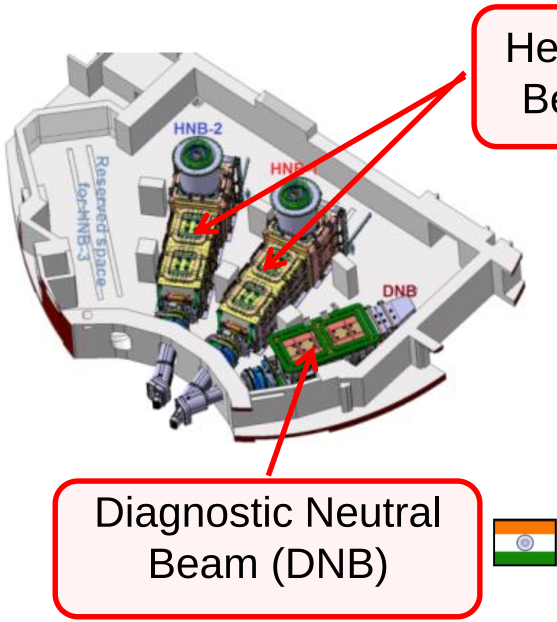


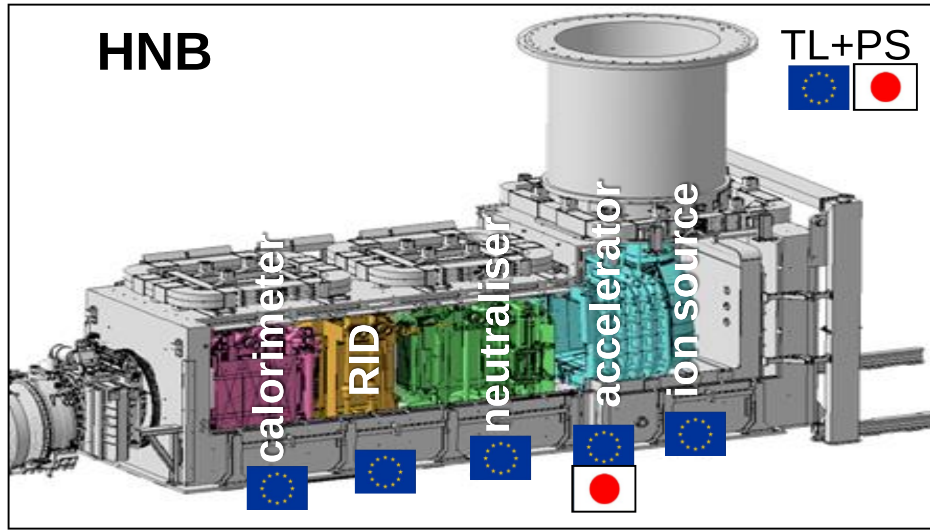


NBI functionalities
• Heating (mostly electrons) • Main source of current drive • Torque source (rotation) • Current profile measurements

Operational constraints
Minimum density (shinethrough)

ITER Neutral Beam Injection system





- Neutral Beam Test Facilities (NBTF) to develop beam source:
  - ELISE: half ITER ion source, IPP Garching
  - SPIDER: full ITER ion source, RFX Padua
  - MITICA: full ITER ion source + accelerator, RFX, Padua

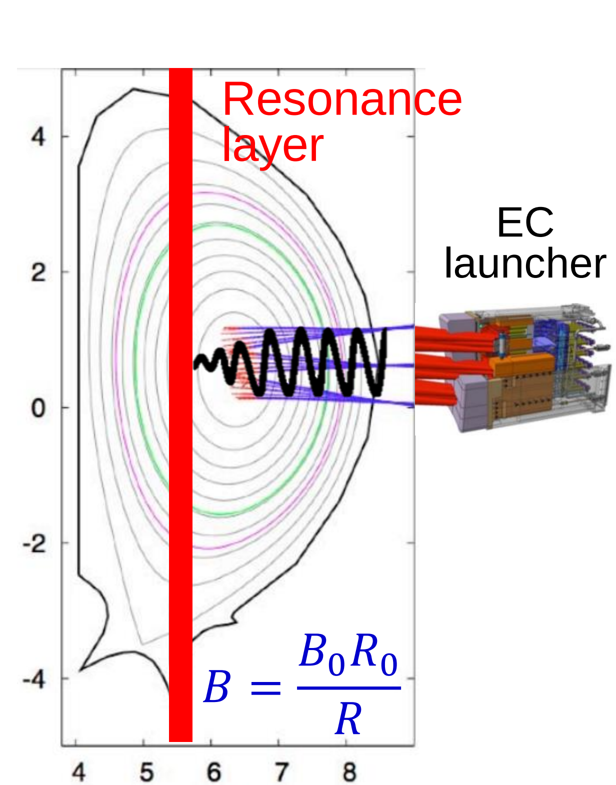
Electron cyclotron resonance with EC waves

Wave frequency ω to match electron cyclotron frequency Ω_{ce} for energy transfer:

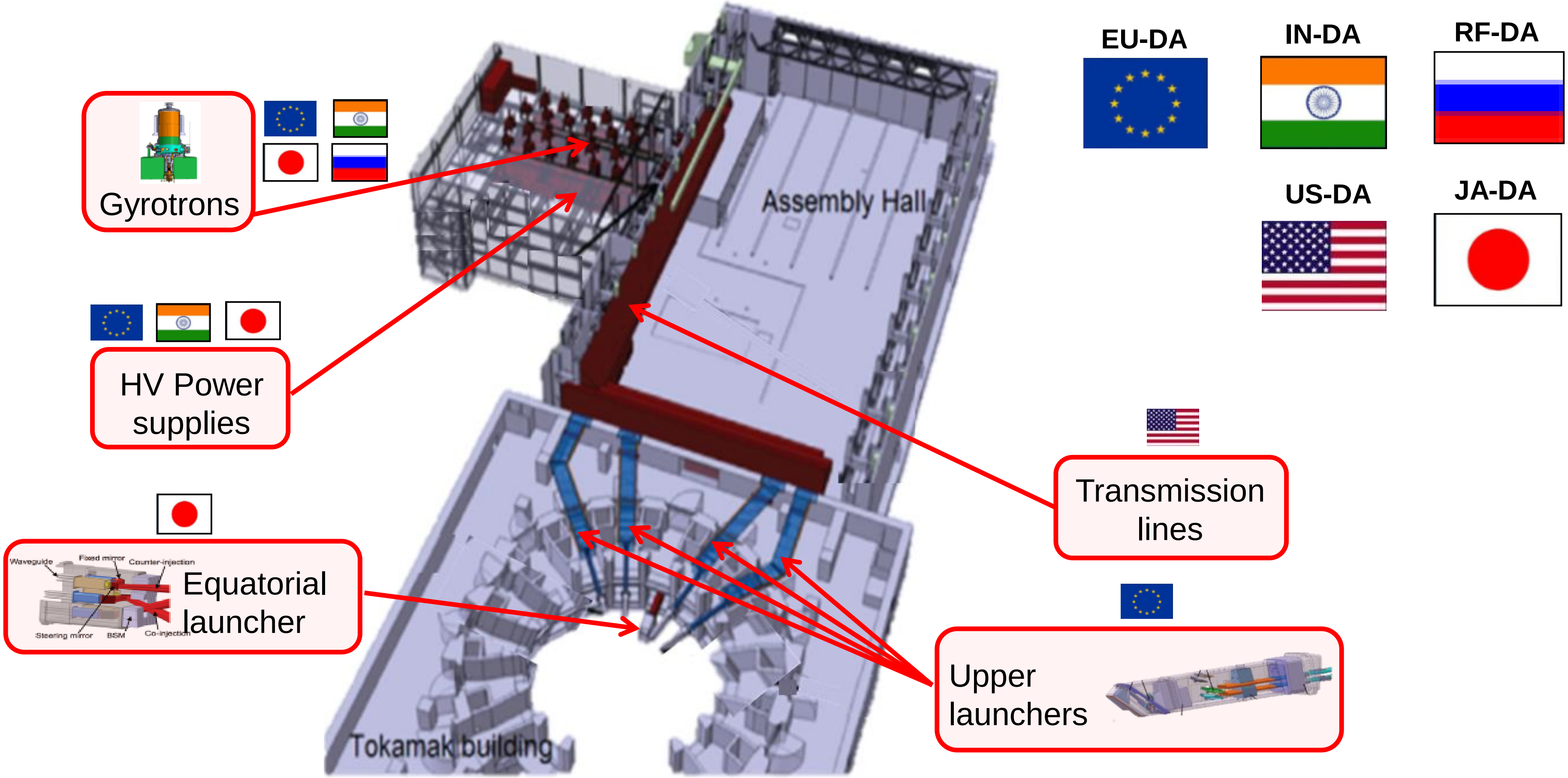
$$\omega - n\Omega_{ce} - \vec{k} \cdot \vec{v} = 0$$

- $\Omega_{ce} = eB/m$ → Vertical resonance layer
- $\omega \sim 170\ GHz$ → No evanescence region.

EC functionalities
• Heating (electrons) • Current drive • Current profile control (MHD) • Assisted plasma startup
Operational constraints
Magnetic field



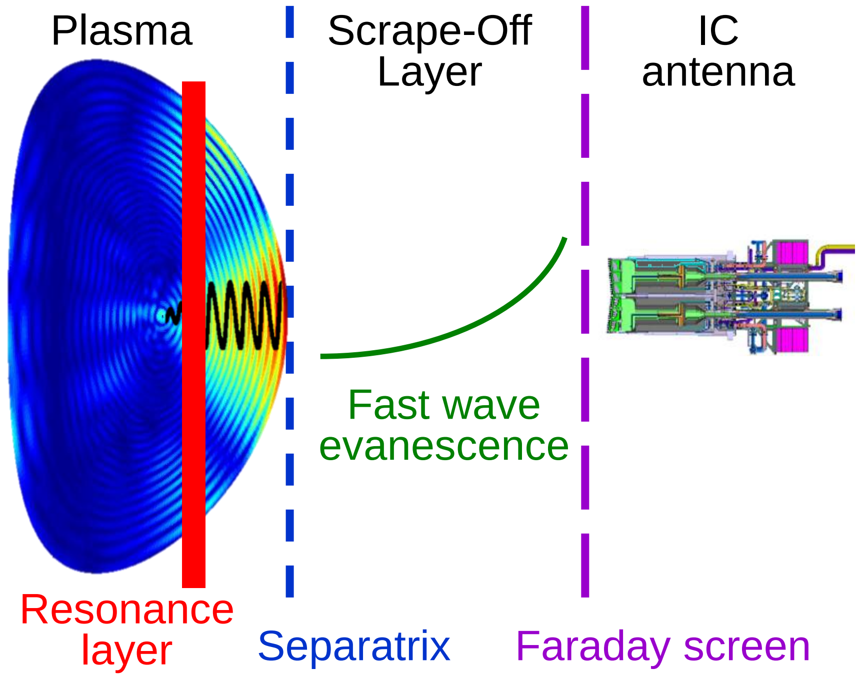
ITER Electron Cyclotron Resonance Heating system (ECRH)



- $\Omega_{ce} = eB/m \rightarrow$ Vertical resonance layer

Ion Cyclotron resonance with IC waves

- Also based on resonance wave absorption mechanisms.
- Heats specific ions according to schemes (minority/majority)
- $\omega \sim [40 - 55]\ MHz$ → Fast wave evanescent at low density:

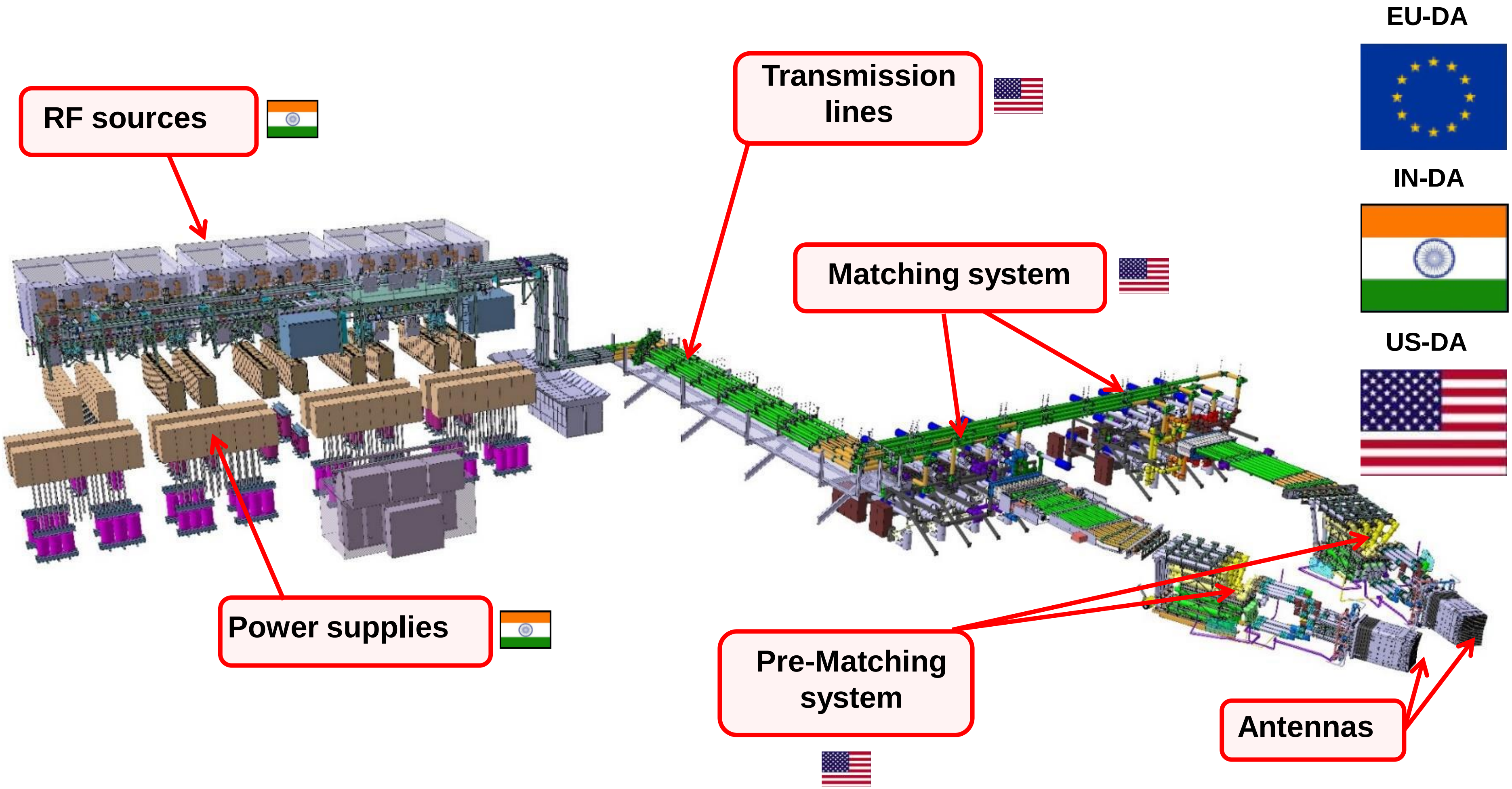


2 criteria for IC coupling:

- Sufficient density near antenna
- Moderate edge density gradients

IC functionalities
• Heating (ions/electrons) • Current Drive • Sawtooth control • Wall conditioning
Operational constraints
B-field, minimum density, ion mix

ITER Ion Cyclotron Resonance Heating system (ICRH)



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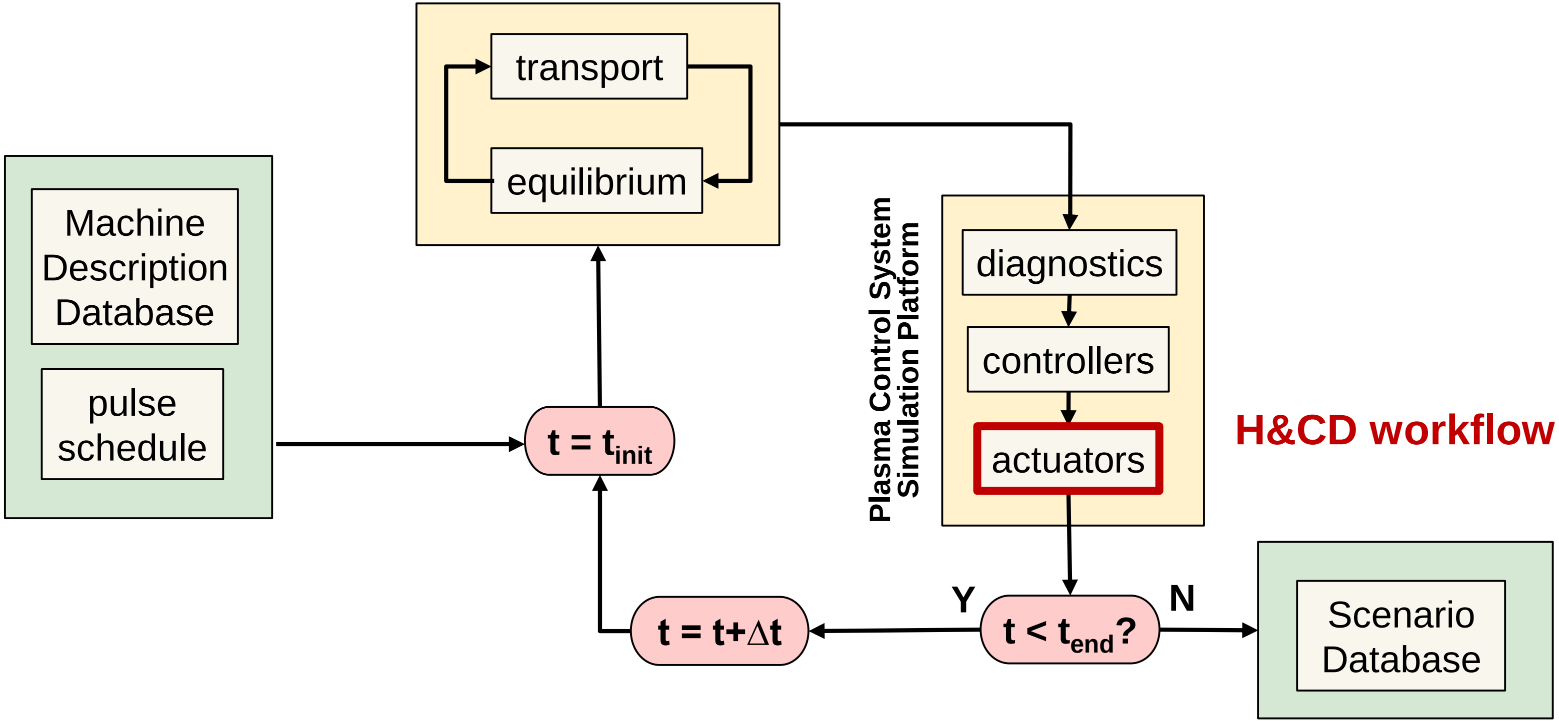
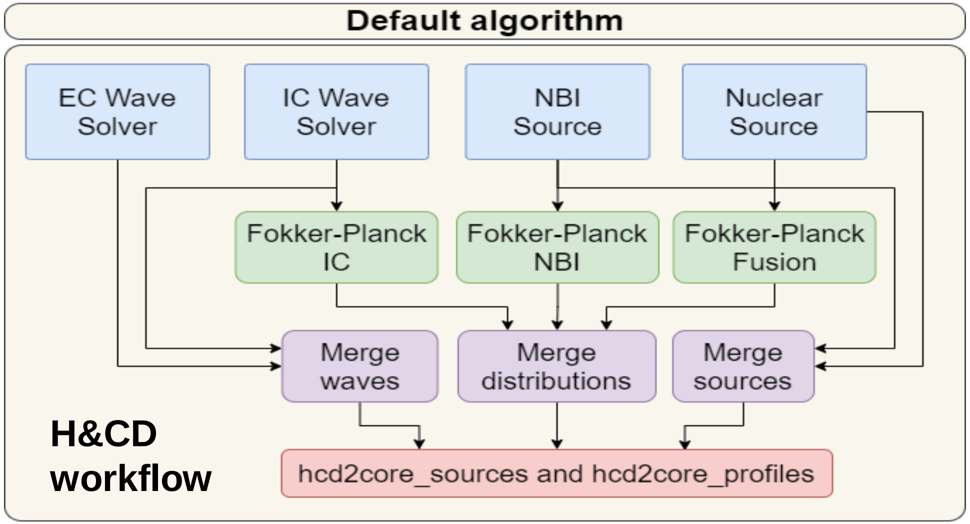
Towards a high-fidelity / pulse design plasma simulators

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



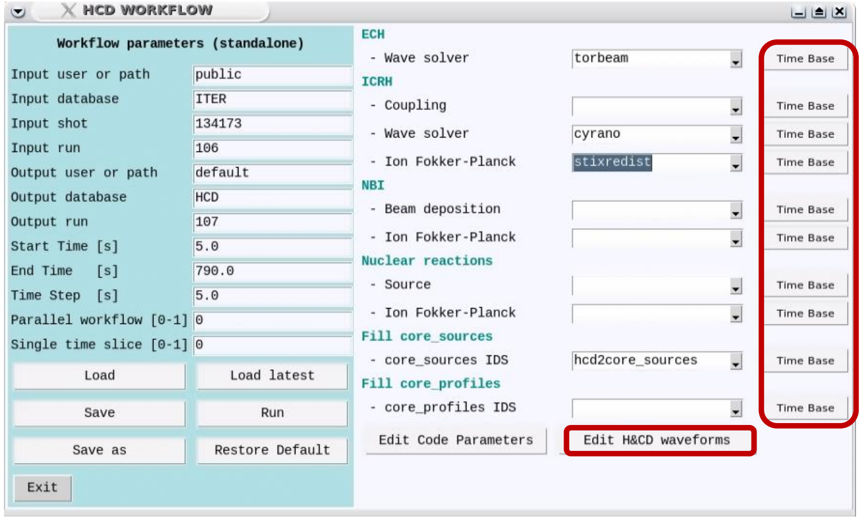
The IMAS H&CD workflow

- The H&CD workflow can be used in different contexts:
  - As an internal component of a transport solver, as part of a high fidelity plasma simulator
  - As a standalone tool to run H&CD codes from existing plasma scenarios, through a graphical interface

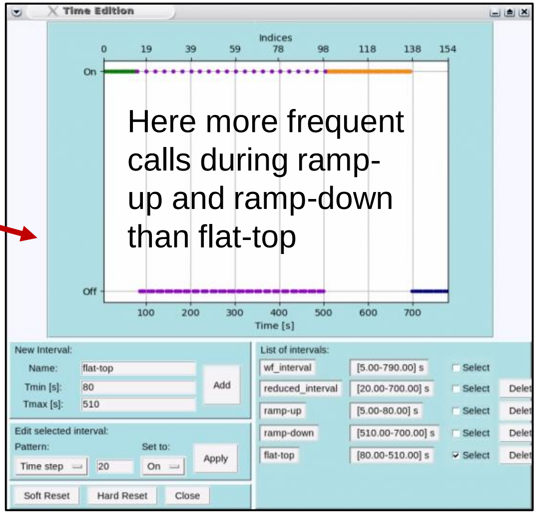


	ECRH	ICRH	NBI	Nuclear reactions
Wave or particle source	GENRAY GRAY GRAYSCALE TORBEAM TORAY-FOM	CYRANO LION PION TOMCAT TORIC	BBNBI NEMO	AFSI SPOT (α)
Fokker-Planck	RELAX	FOPLA PION ASCOT SPOT	ASCOT SPOT RISK	ASCOT SPOT

H&CD Python GUI

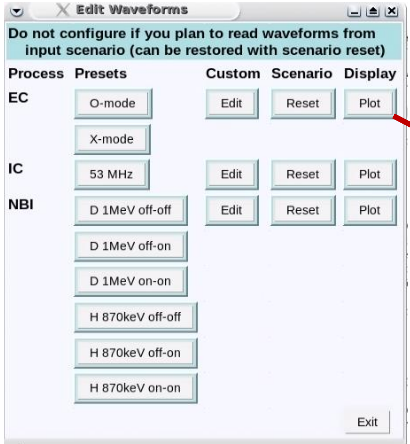


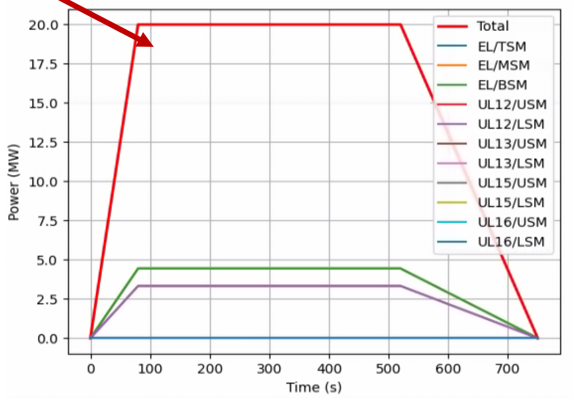
Functionalities to configure independent time bases for each process



Pre-configured waveforms via Waveform-Cooker

Possibility to configure H&CD waveforms on the fly





Configuration files stored locally:

- workflow configuration
- code parameters of H&CD actors
- time base configuration
- waveform configuration

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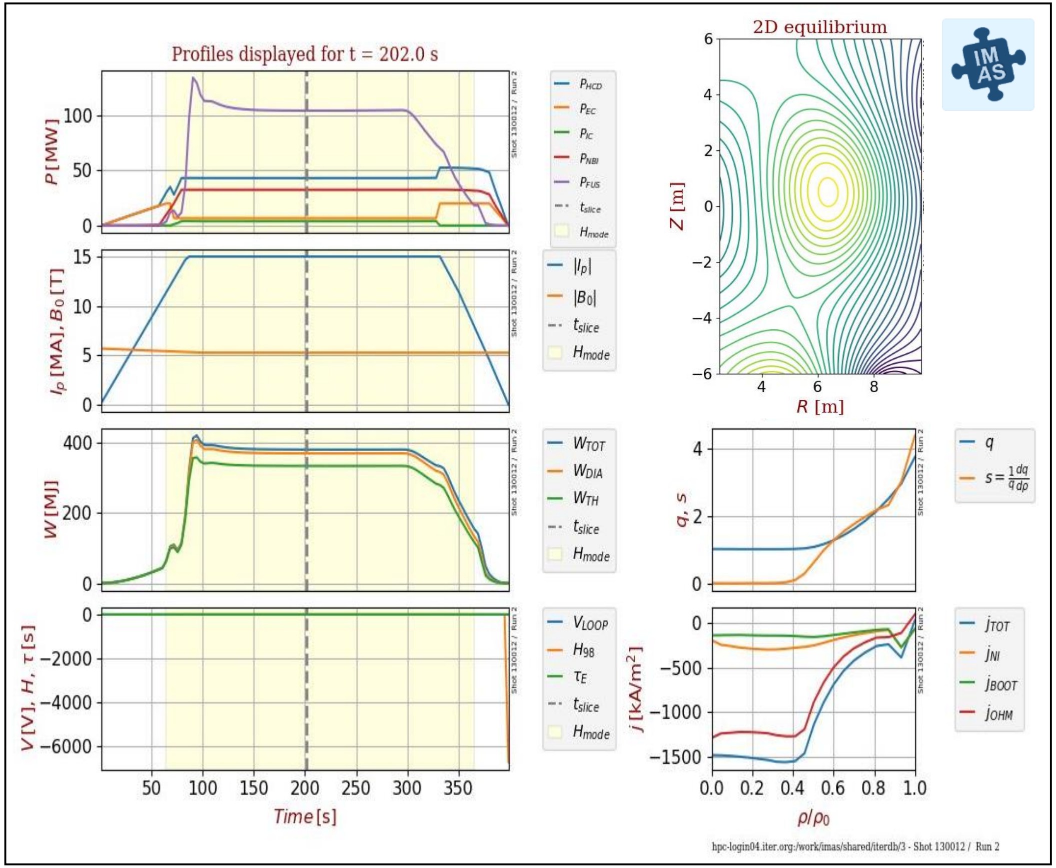
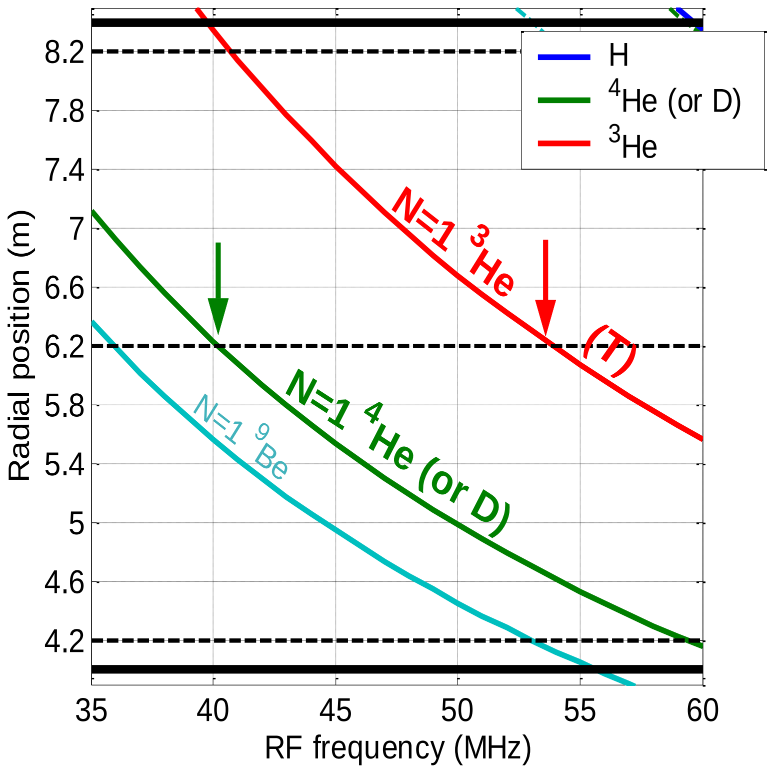
H&CD modelling for an ITER 15MA / 5.3T DT scenario

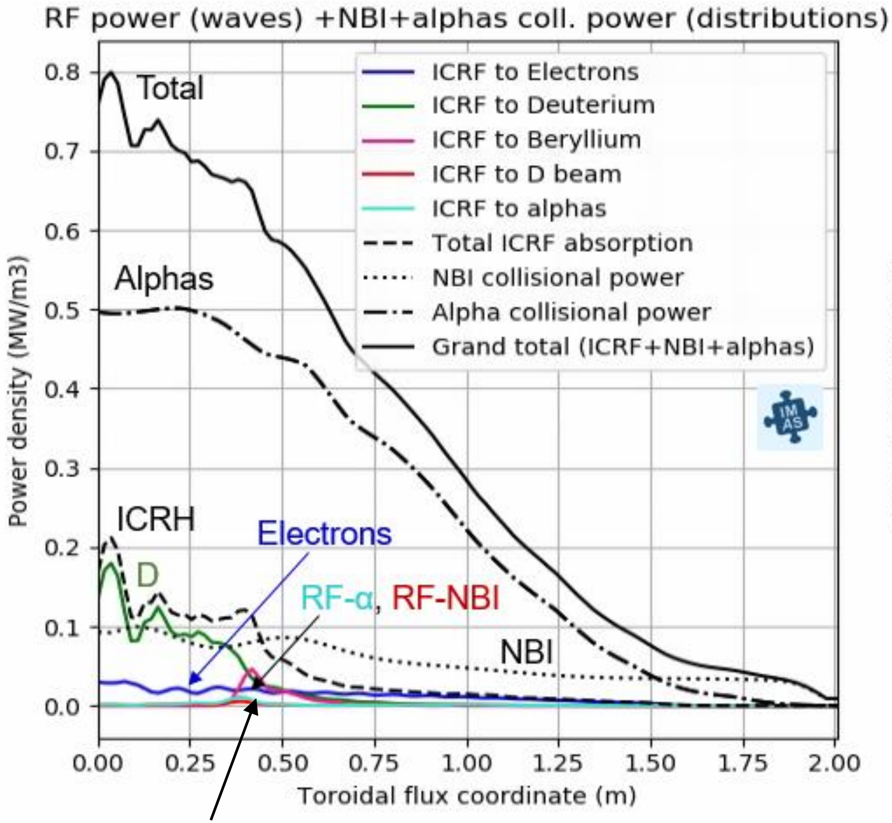
- Input scenario from IMAS scenario database: ITER DT 15 MA / 5.3 T (from METIS)

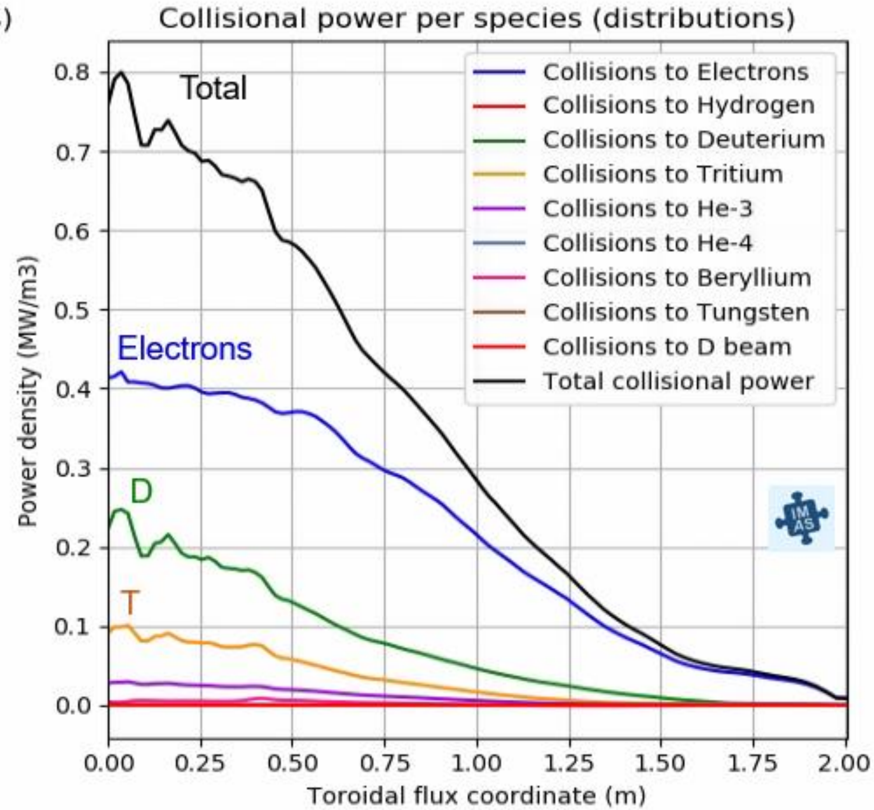


- ICRH modelling: 20 MW:
  - 40 MHz, for N=1 D(+Be)
  - 53 MHz for N=2 T heating



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

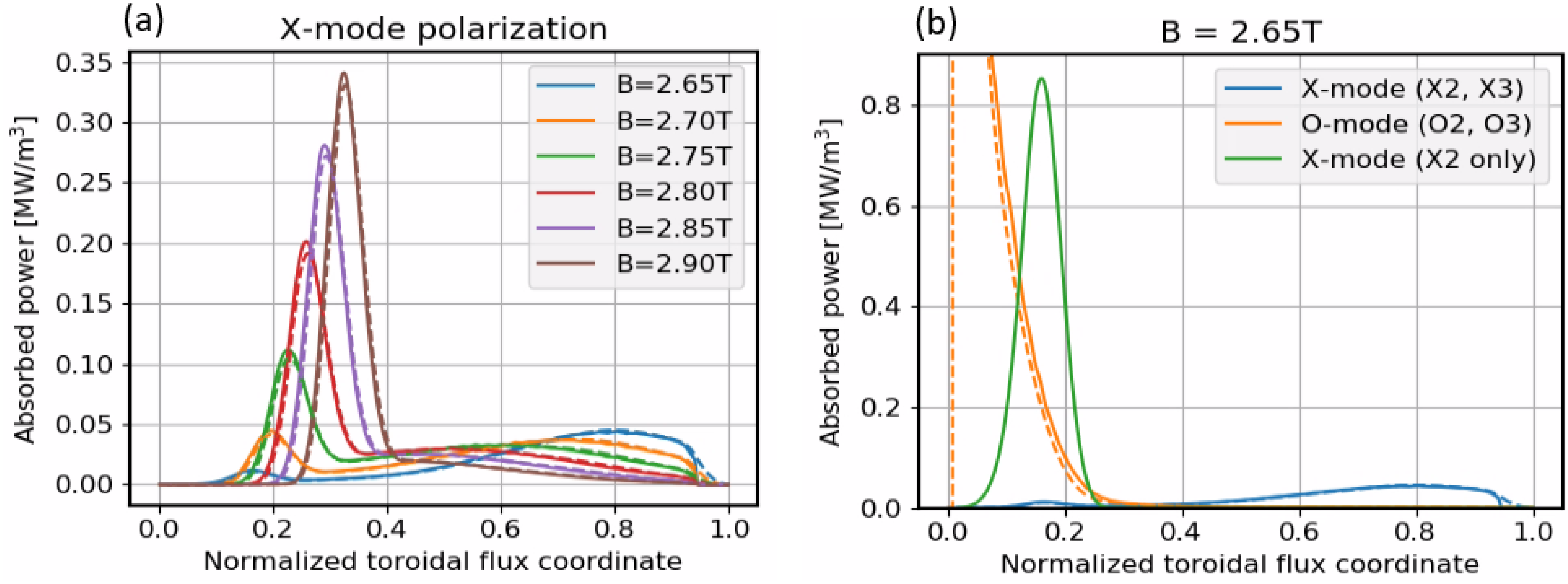




Weak RF-α and RF-NBI synergy (<5% ICRH)

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

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



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

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Conclusion

- ITER H&CD systems are being designed, tested and procured to meet the objectives of the ITER Research Plan.

- The EC, IC, NBI systems have been desined to provide:
  - Assistance to plasma initiation
  - Heating to access to high confinement regimes and high Q
  - Current drive to develop long pulse scenarios
  - MHD control and prevention of impurity accumulation
  - Robust plasma operation

- IMAS supports the ITER Research Plan by providing a standard for integrated modelling delivering a high level of modularity and flexibility

- IMAS contains 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 plasma simulator, enabling the modelling of the synergy between different H&CD sources