Integrated tokamak modeling: when physics informs engineering and research planning

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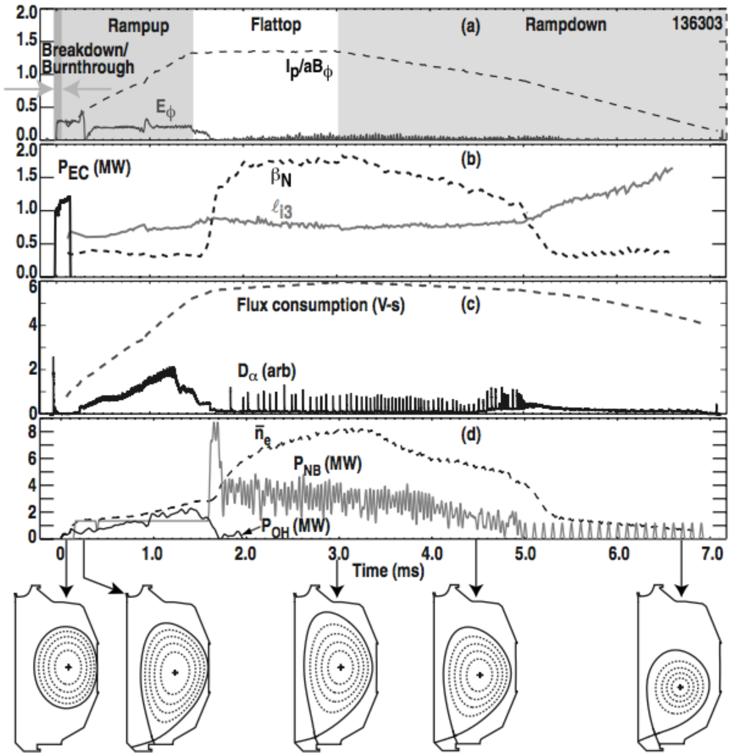
Integrated tokamak modeling: the hows and the whys

- Why we simulate plasma discharges and how we do it:
  - the building blocks
- First principle vs reduced models
  - When less is better and when more is needed
- Self-consistent simulations for research planning
  - Because refinement of operational points require physics
- Modeling gaps and experiment support:
  - Where integration is critical for the success of ITER

Modeling tokamak discharges is important for physics understanding and experimental planning

Simulation of an ITER-like plasma on DIII-D



*G. Jackson et al, Phys. Plasmas **17** 056116 (2010)*

Evolve plasma current from breakdown to termination

Maximize plasma pressure/magnetic pressure

How to deal with edge MHD oscillations (ELMs)

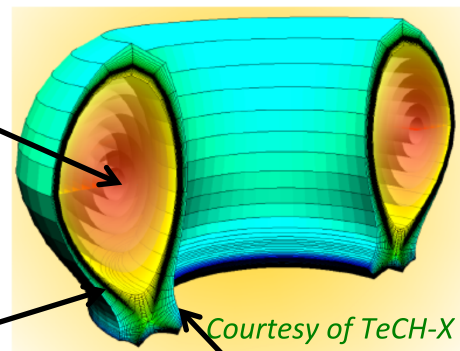
How to use heating to maximize performance

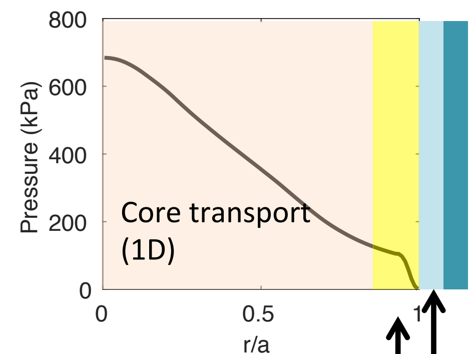
How to control the plasma shape

Modeling a plasma requires knowledge of transport, turbulence, MHD, atomic physics, waves, materials …

Confined plasma
(closed field lines)

MHD stability,
core transport, radiation
Energetic particles





pedestal

Edge transport
(2D)

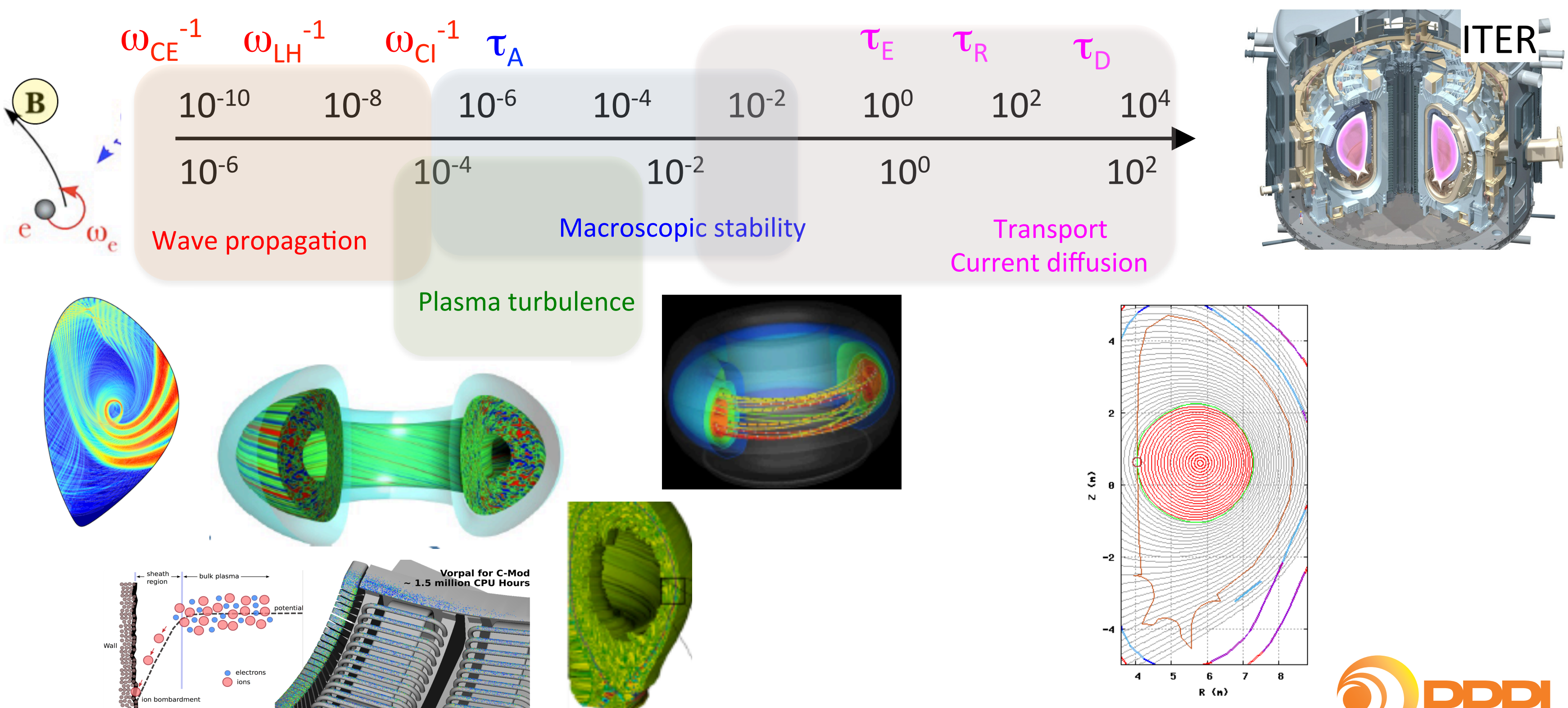
Scrape-Off Layer plasma (SOL)
(open field lines)

Atomic physics
ionization, recombination
radiation

wall

Plasma-material interactions
Atomic physics

The physics in a tokamak involves a wide range of spatial and temporal scales, all coupled together



A major challenge is finding a balance between accuracy, self-consistency and computational time

- Increased computer power allows to solve bigger problems
  - 10^6 CPU @10^4 cores for single ion species
  - 10^9 CPU @10^4 cores for multi-ion/multi-scale
  - 10^{11} CPU for ITER (exa)
- BUT does bigger equal better?

At the top of the wish list of an integrated tokamak modeler is:

get everything in and make it fast

The plasma is magnetically coupled to external conductors

Transformer source of poloidal flux

Actuators (external)

Plasma (internal)

Magnetic flux diffusion

$$\mathbf{E} + \mathbf{v} \cdot \mathbf{B} = \eta_{\|} \mathbf{J}$$

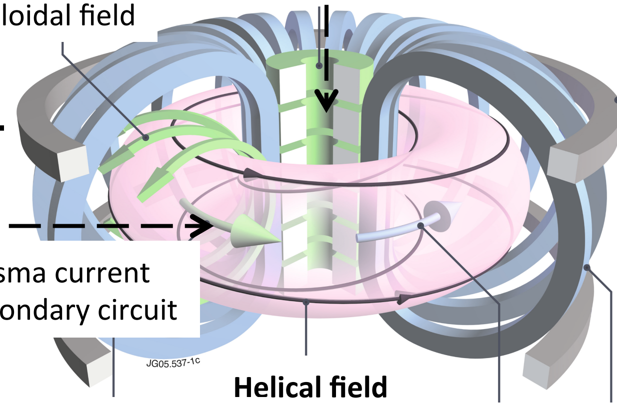
Equilibrium

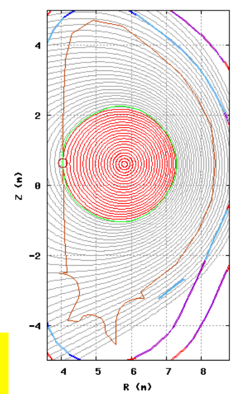
$$\mathbf{j} \times \mathbf{B} = \nabla p$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$$

Transport

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (n_j \mathbf{u_j}) = S_j$$

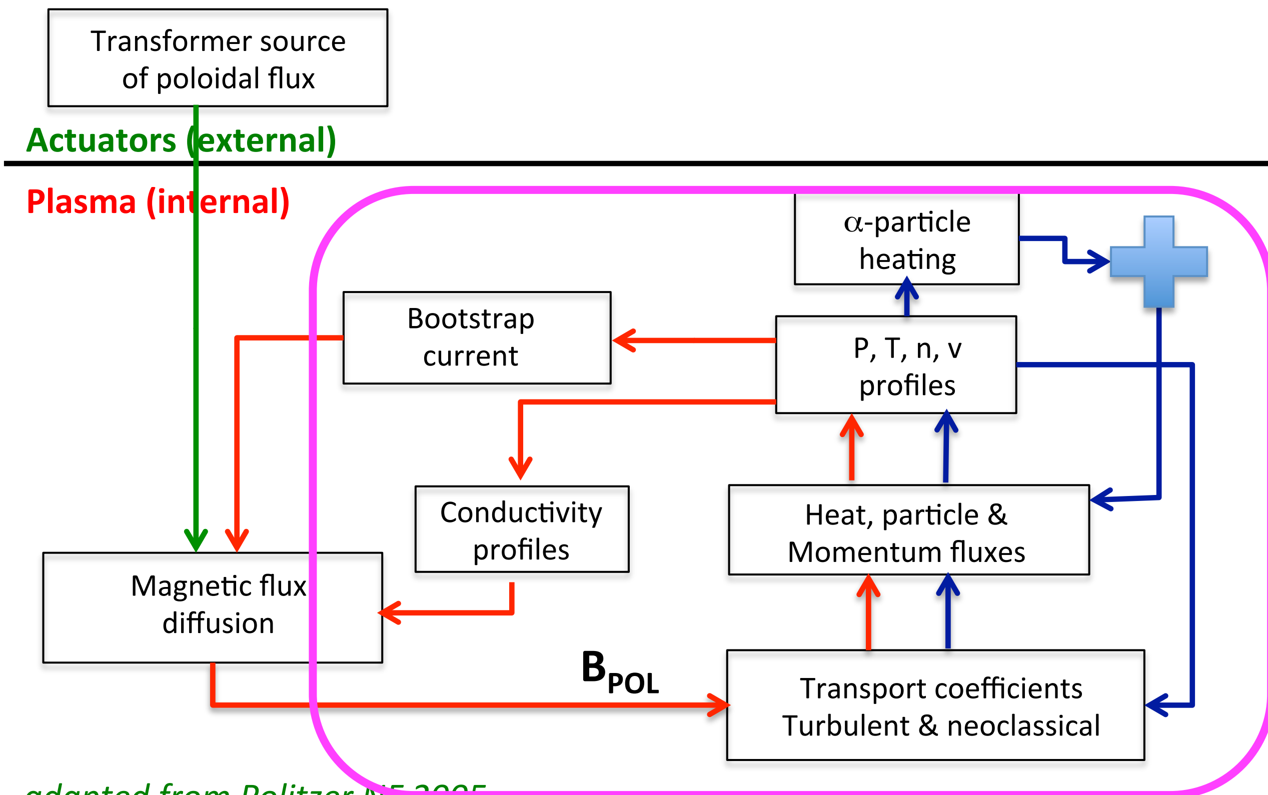
$$\frac{3}{2}\frac{\partial p_e}{\partial t} + \nabla \cdot \left(\mathbf{q_e} + \frac{5}{2} p_e \mathbf{u_e}\right) =$$
$$= \mathbf{j} \cdot \mathbf{E} - Q_{ei} - \mathbf{u_i} \cdot \nabla p_i + Q_e$$

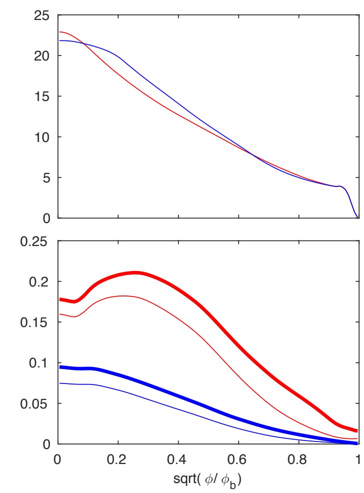




Maybe replace

fast (transport) vs slow (current diffusion) time scales are nonlinearly coupled together

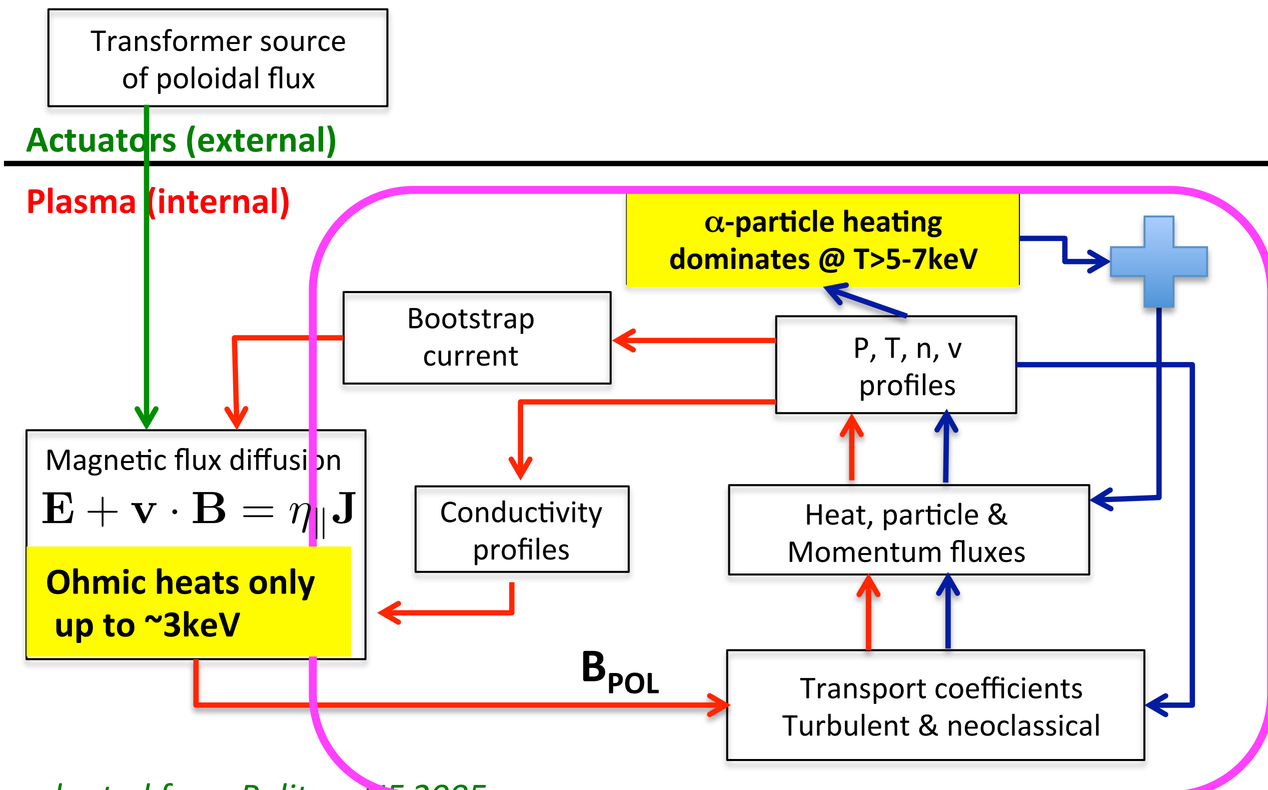


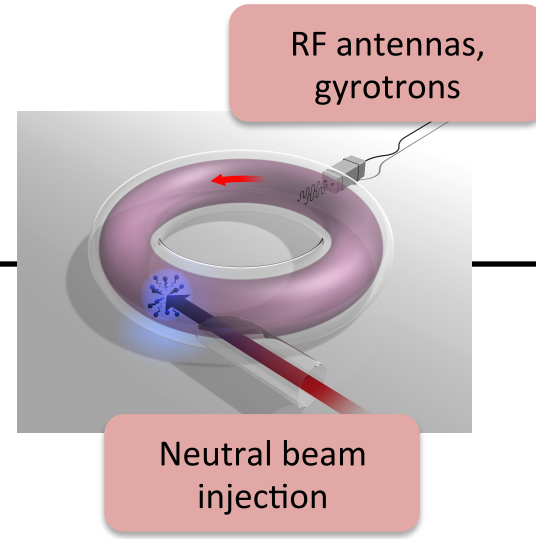


Maybe replace

adapted from Politzer NF 2005

Burning plasmas need external heating to bust alpha heating





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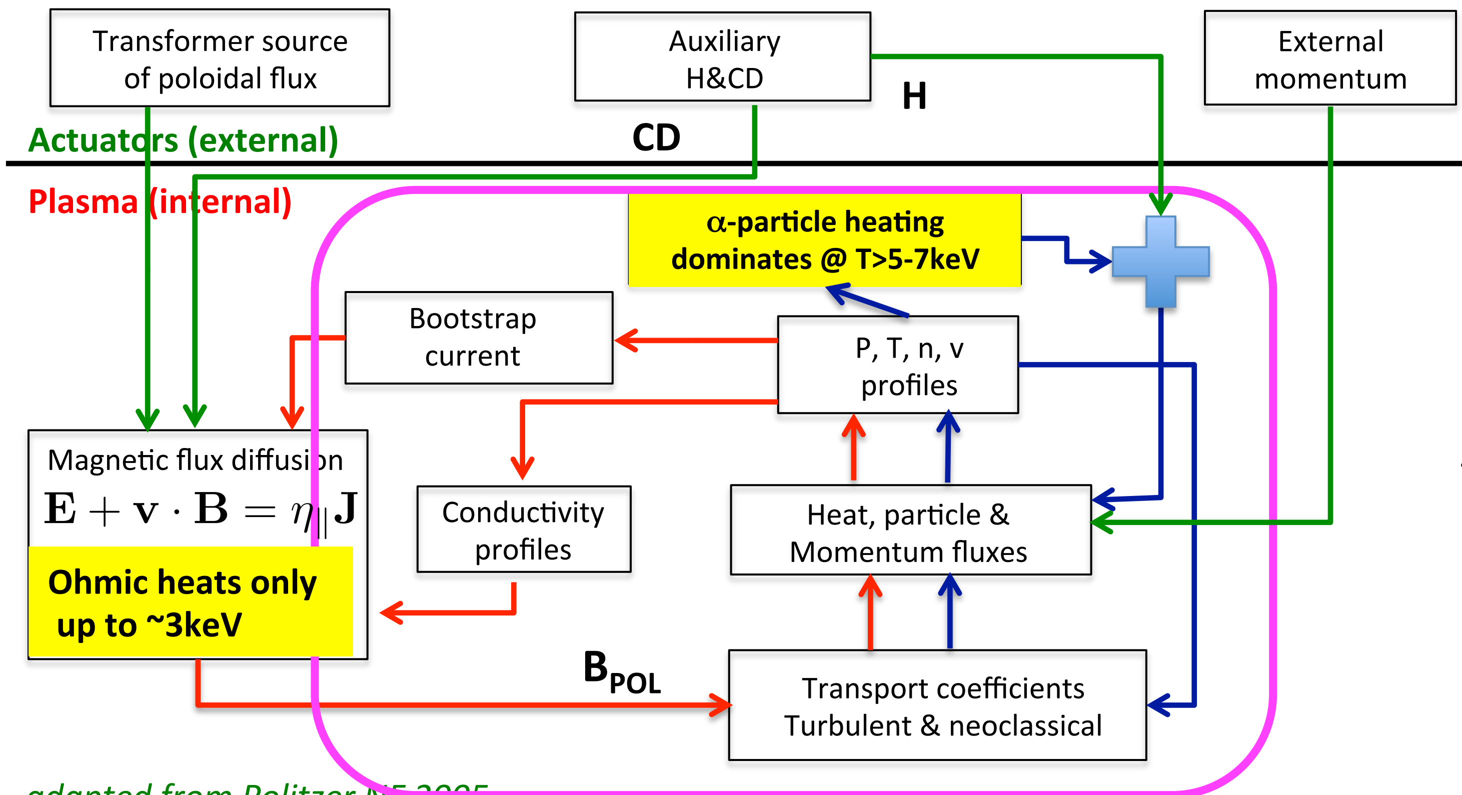
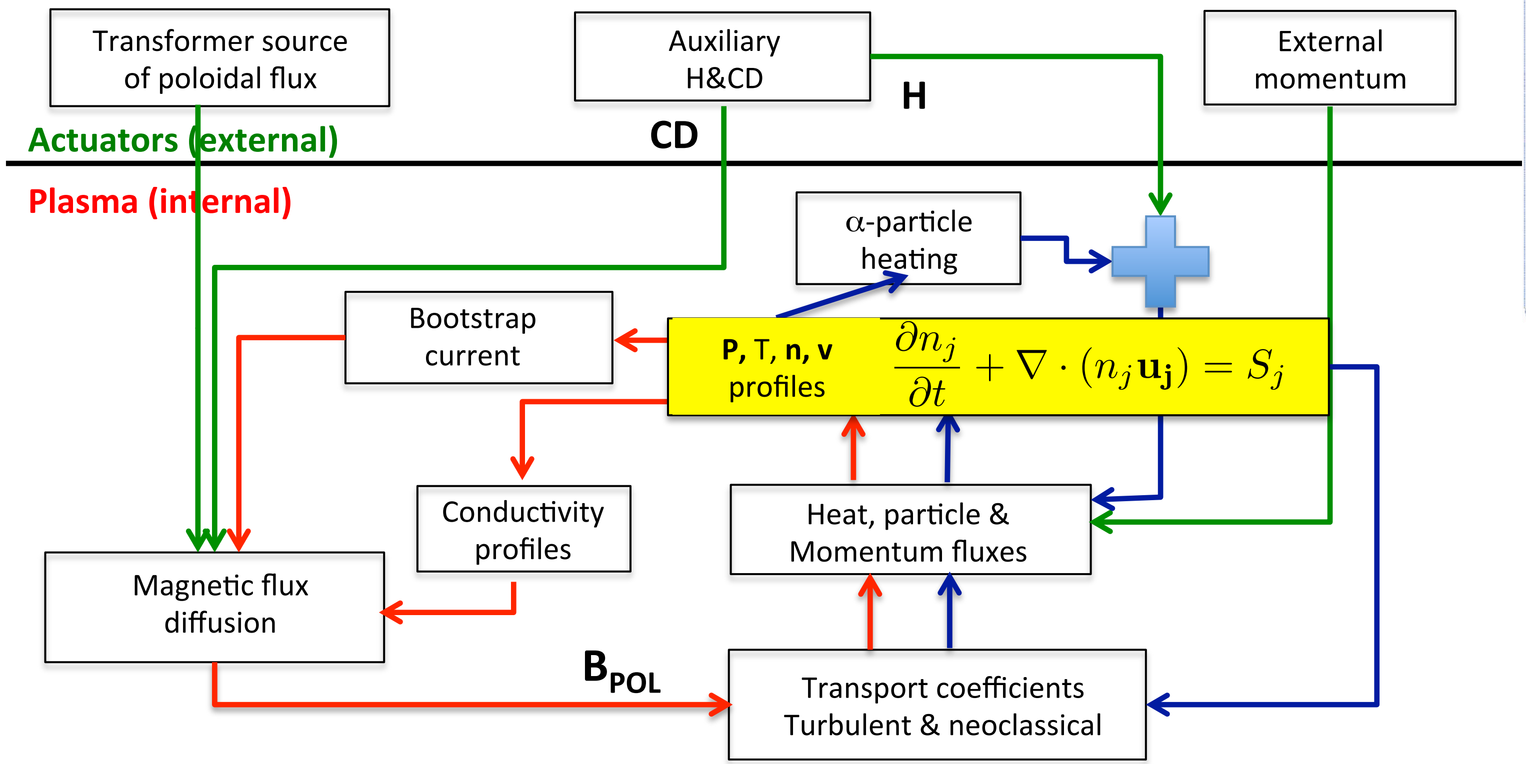
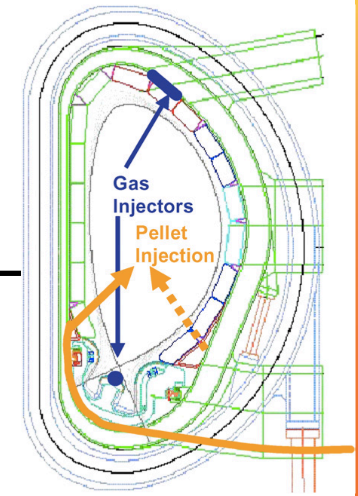


Here figure with HCD profiles Current and temperature

adapted from Politzer NF 2005

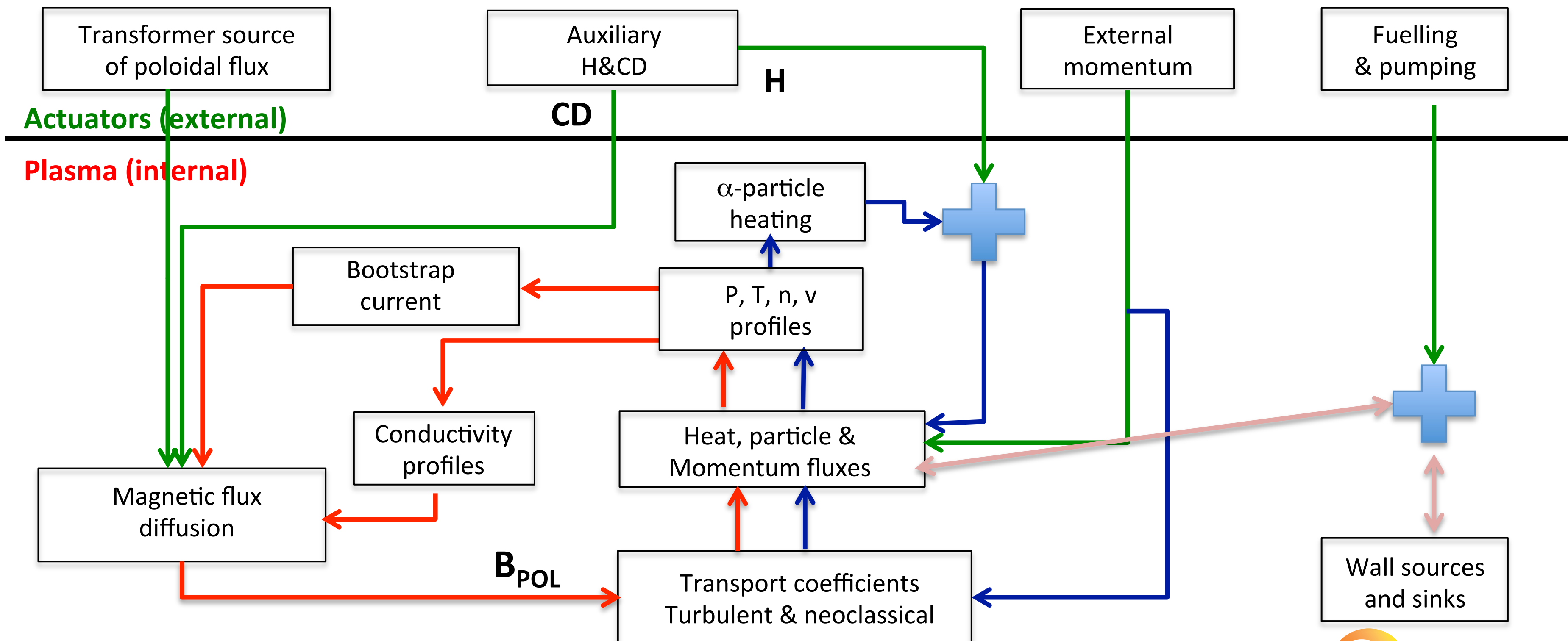
Plasma density build-up relies on sources of particle and momentum





adapted from Politzer NF 2005

Core is connected to wall via particle and energy transport

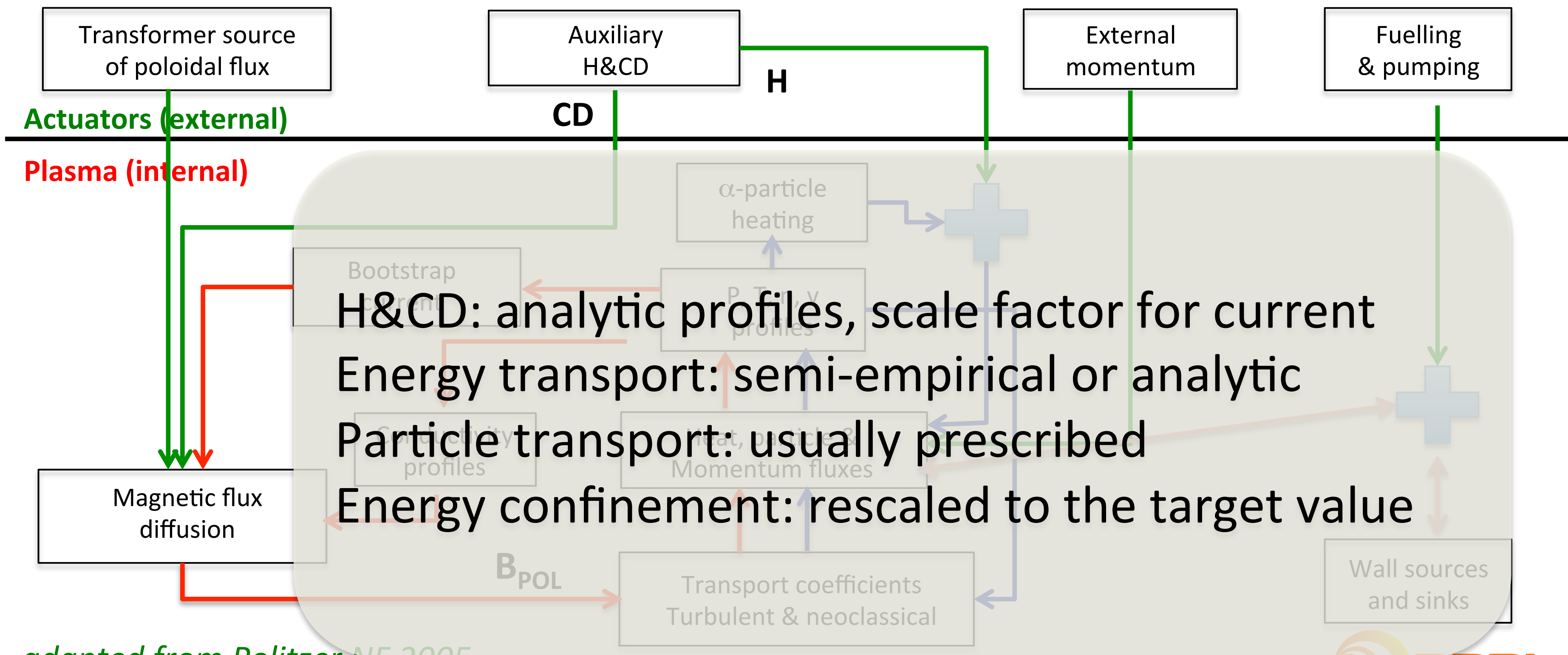


adapted from Politzer NF 2005

‘Integrated’ stands for combining available resources to fill existing gaps

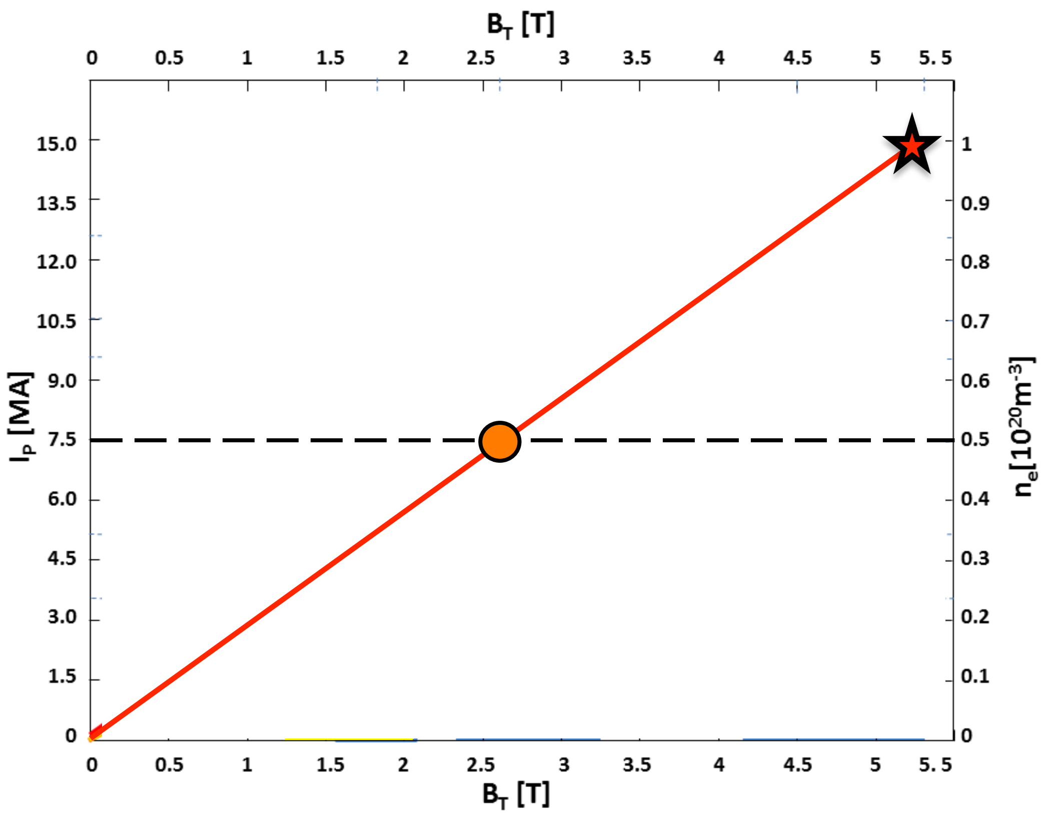
- The complexity of a tokamak cannot be resolved by a single code
- The more physics we need to integrate, the more the models need to be reduced/simplified
- Need to find a balance between reduced models for fast turnaround and high-fidelity offline calculations to provide boundary conditions.

At the lowest approximation is a simplified transport with a good free-boundary equilibrium solver



adapted from Politzer NF 2005

Characterization of an operational point starts from a chart



Target: ★ DT plasma
500 MW fusion power
fusion gain Q=10

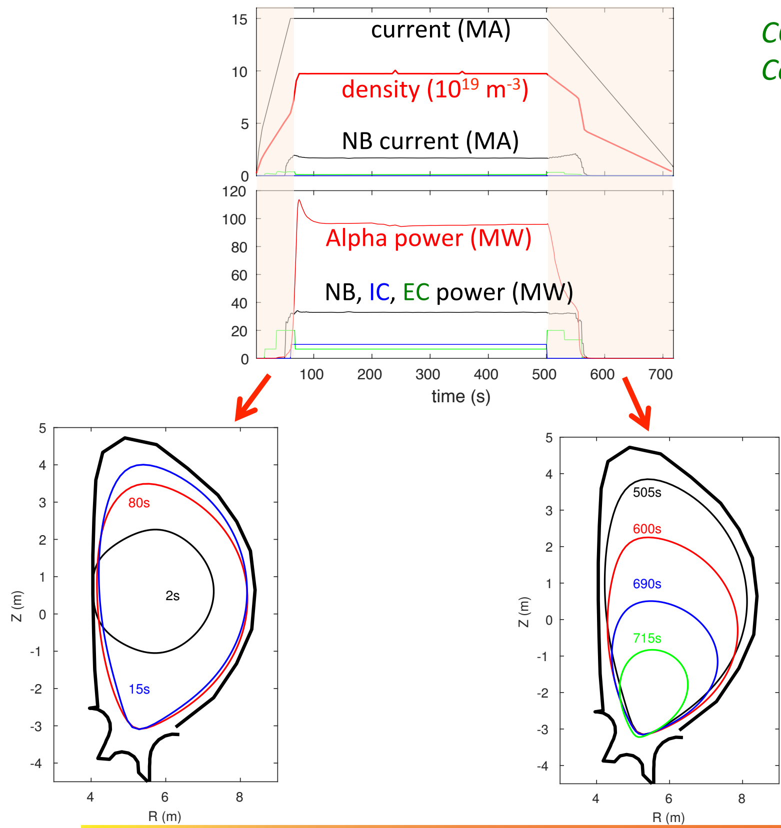
Get there from ● low field/low current

Step 1: rescale from target

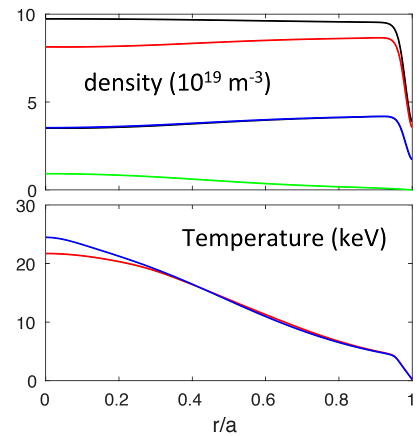
⇒ $\langle n_e \rangle \sim 5.0 \times 10^{19} m^{-3}$

⇒ B_T=2.65 T, I_P=7.5 MA

The operational space is usually defined by simulations with simplified physics assumptions



CORSICA simulation of ITER ELMy-Hmode
Courtesy of S-H Kim (ITER Organization)



Electron density profiles prescribed
Ion density profiles from quasi-neutrality
Impose deuterium and tritium equal fraction
Helium ashes profile from assumed transport

Semi-empirical transport model (Coppi-Tang) for electron and ion temperature

Reference to work on ITER operational space TSC, DINA, CORSICA

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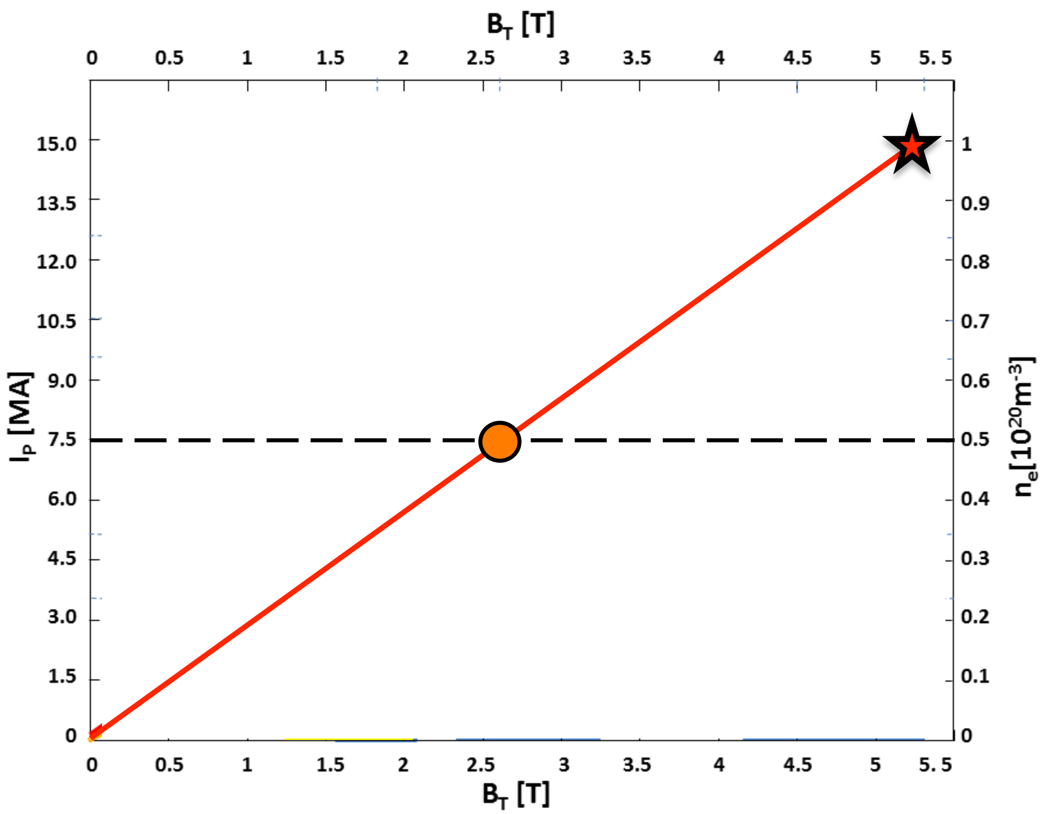

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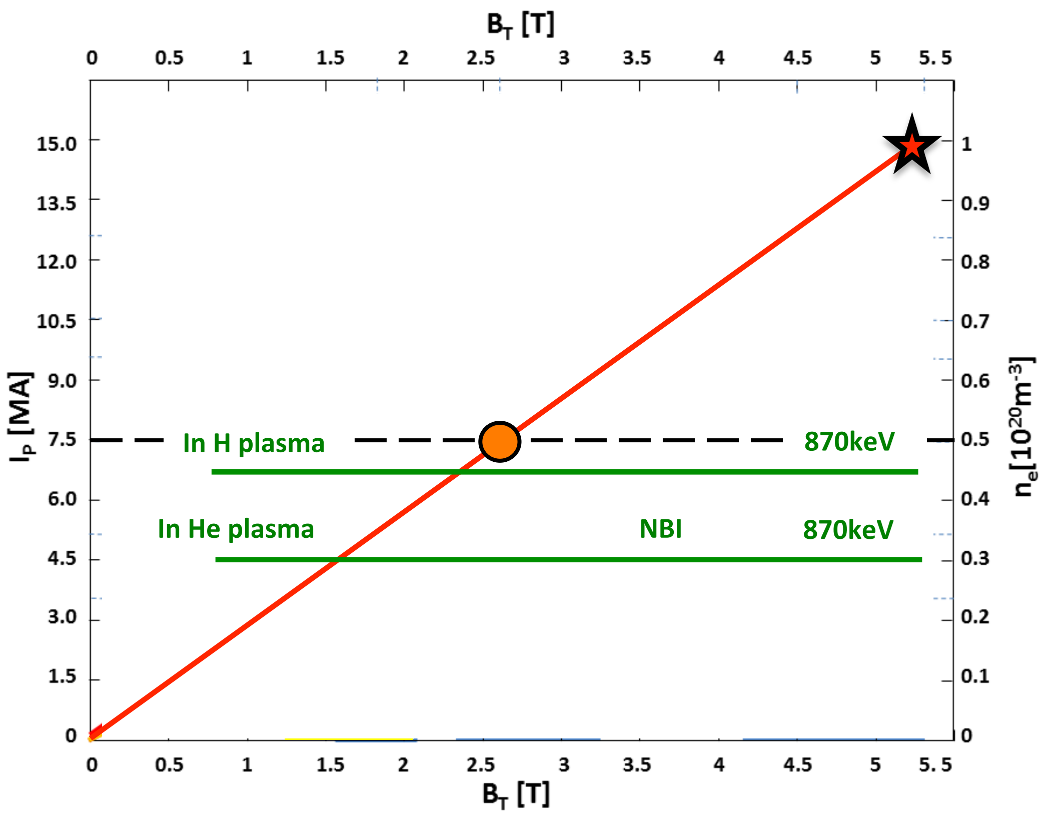

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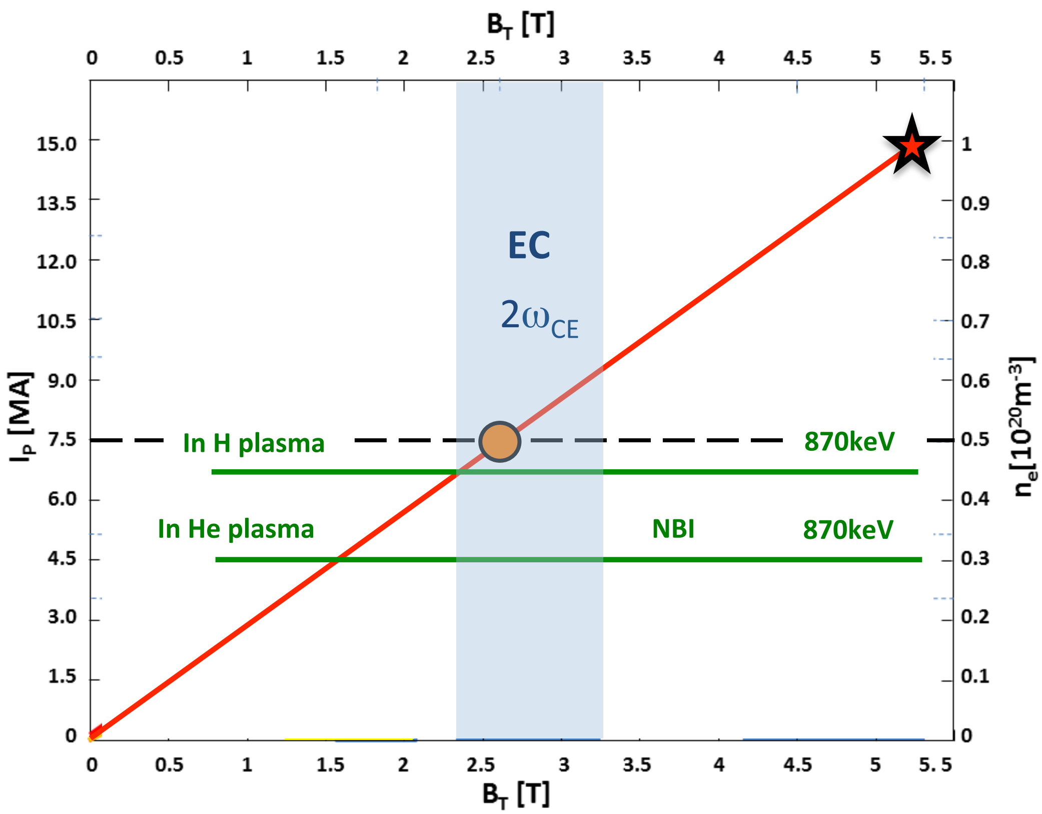
Step 2: identify H&CD operation

⇒ E_{NBI}=870 keV (full energy)

⇒ EC: resonance @ $2\omega_{CE}$

⇒ IC: resonance @ 42MHz

Characterization of an operational point starts from a chart



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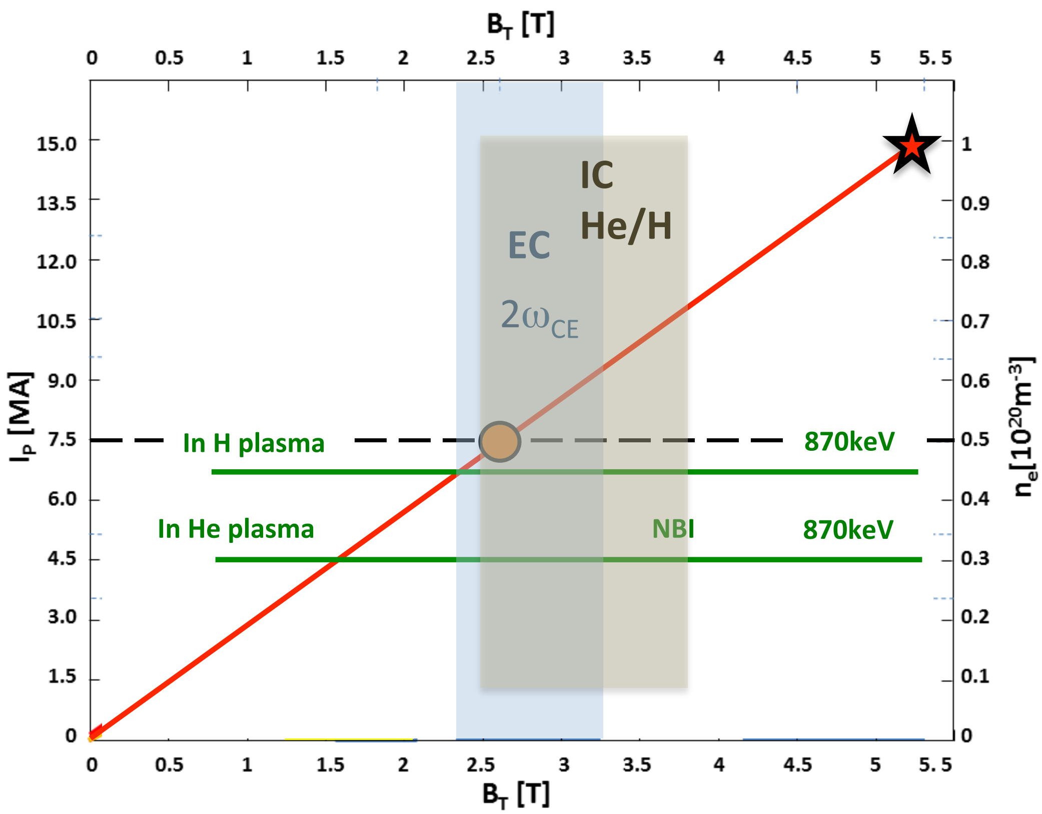

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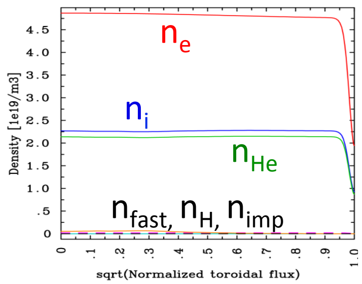
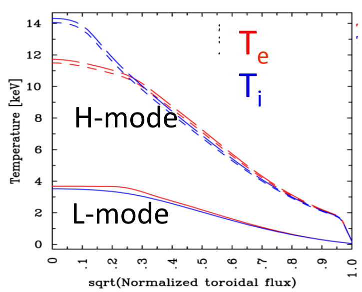
Simplified physics models teach us that the available H&CD power is sufficient to sustain H-mode in He/H plasmas

He plasma, 2.65T/7.5MA

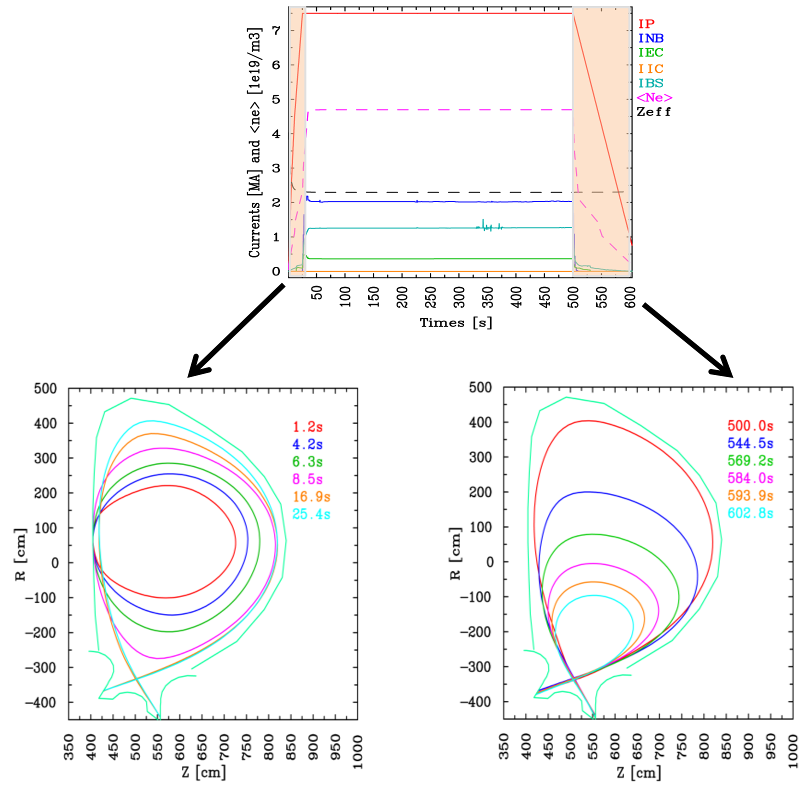


Prescribe electron density profile
Impurities are a fix fraction of n_e
Ion density from quasi-neutrality



Semi-empirical model for thermal transport (Coppi-Tang)

Pedestal from EPED1,
Usually pre-set, with feedback

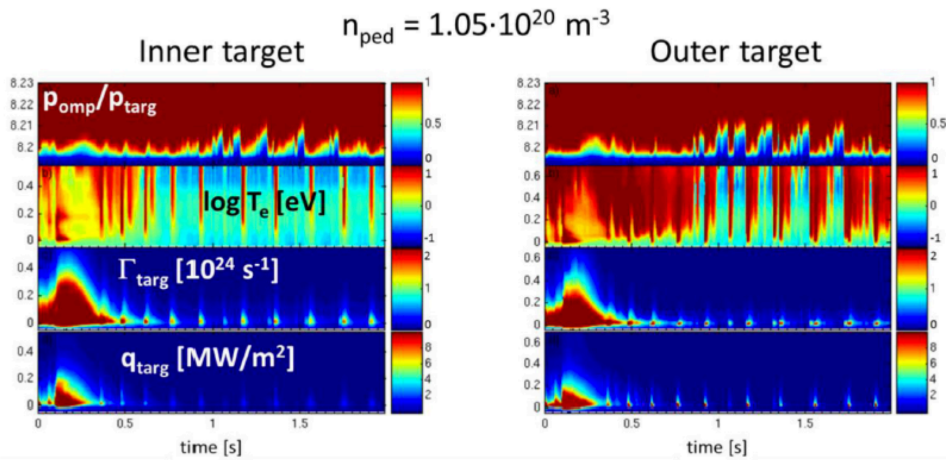


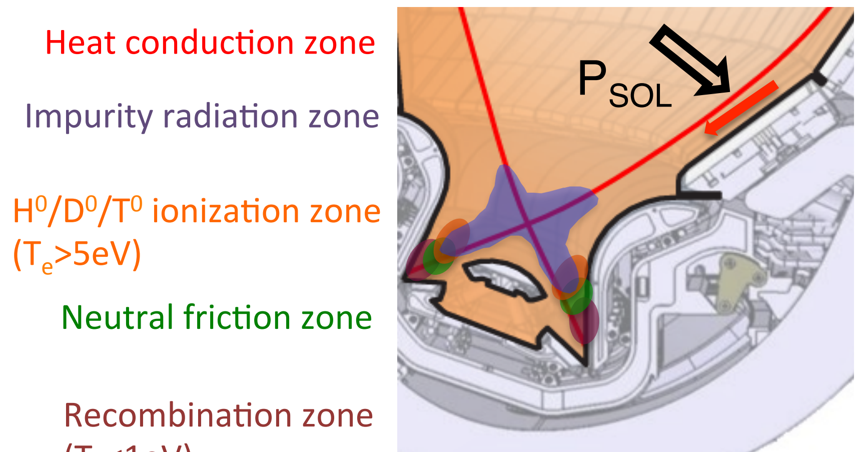
CORSICA simulation
Courtesy of Sun-Hee Kim (ITER Organization)

Simulations with simplified transport cannot inform on plasma dynamic response to external actuators and internal MHD stability

- Transition to high confinement regimes
- Power management in transient phases
- Core fuelling, density buildup
- Impurity transport and core impurity accumulation
- Control of MHD instabilities
- Fast ion transport

Fully integrated JINTRAC core-edge transport simulations highlight dynamical heat loads to the divertor





Courtesy of R. Pitts (ITER Organization)

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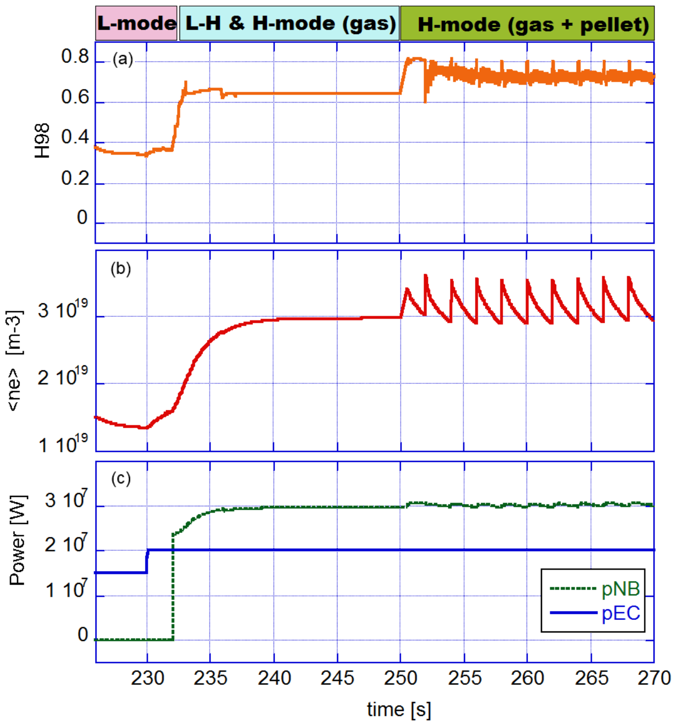
Need a better figure

S. Wiesen, Nucl. Fusion ***57*** *(2017)*

Fully integrated JINTRAC core-edge transport simulations constrain maximum achievable density with He gas injection



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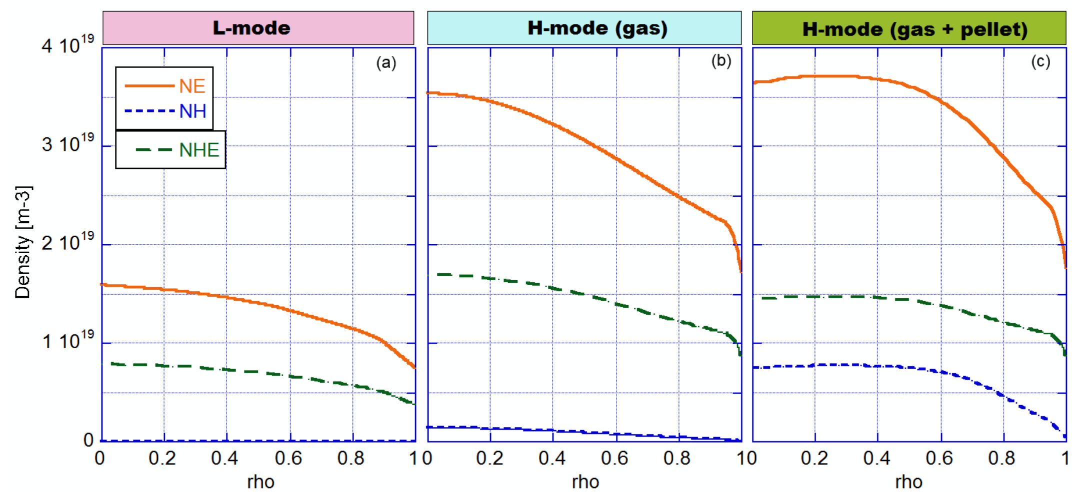
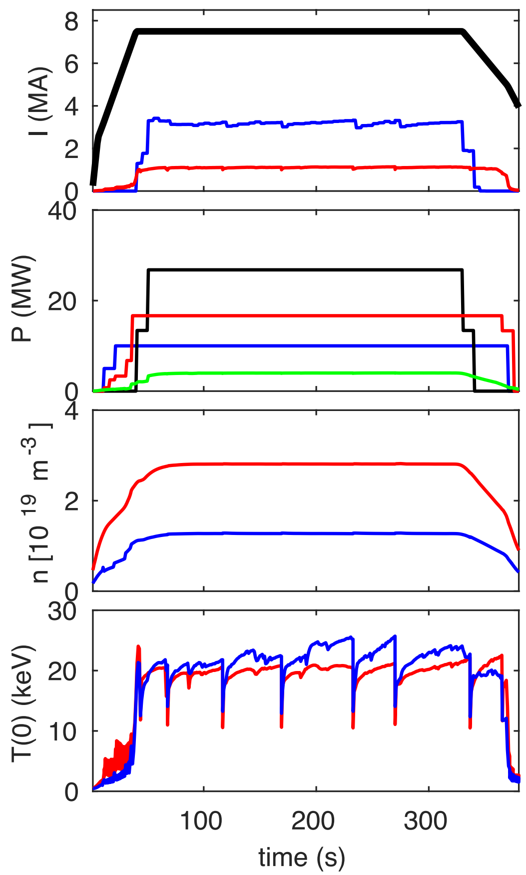


*S-H Kim, Nucl. Fusion **57** (2017)*

Title title



NBI energy needs to be reduced
Cannot use full energy sources

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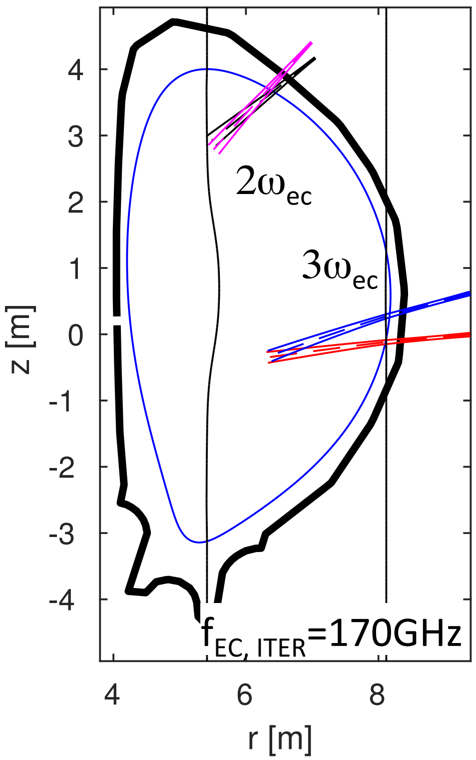
The sawtooth period is longer than predicted at higher density
Risk for triggering of NTMs

Time-dependent simulations with physics-based transport model indicate spurious absorption of EC waves at the edge

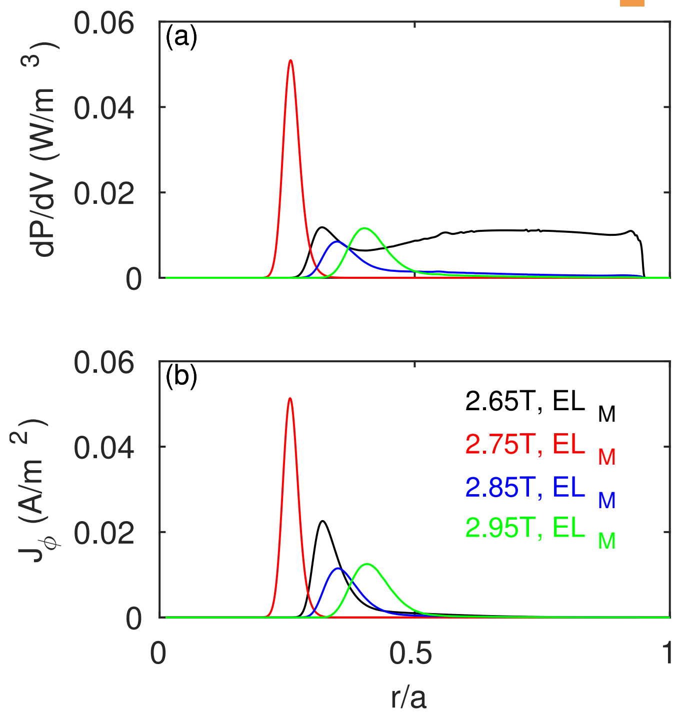


Power absorbed locally where **B** satisfies:

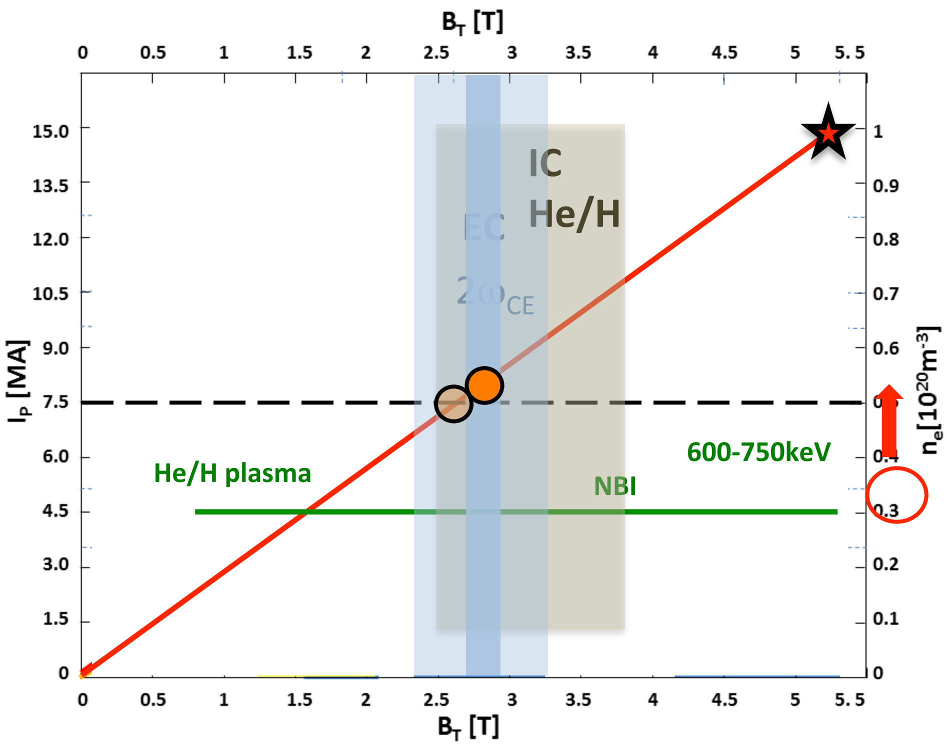
$$\omega_{RF} = \frac{eB}{\gamma m} + \mathbf{k}_{\parallel} \cdot \mathbf{v}_{\parallel}$$

ω_{ec}

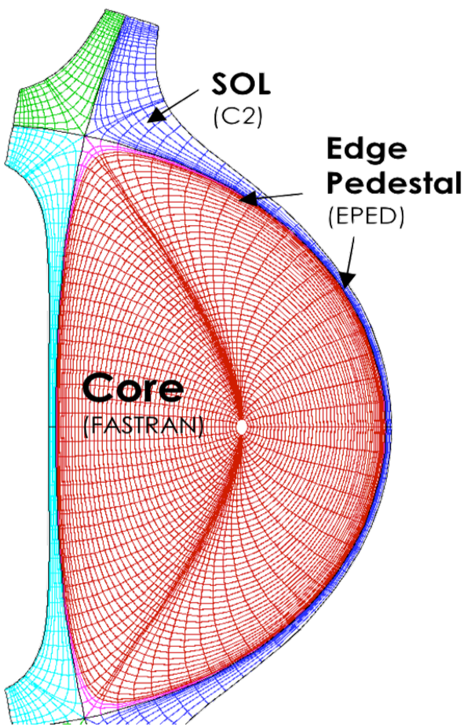
Doppler shift
(toroidal injection for CD)



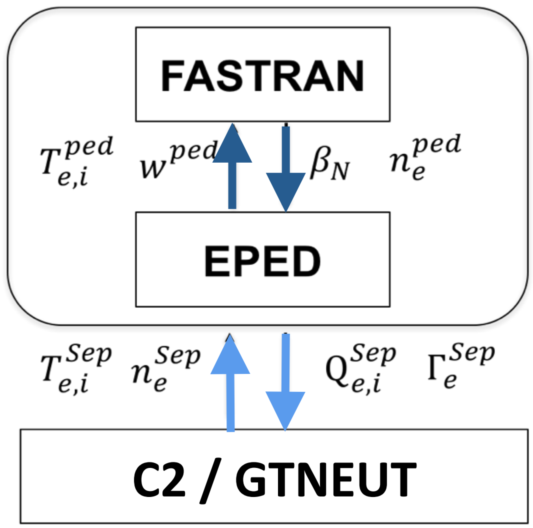
Time-dependent simulations with high-fidelity models have reduced the window around half-field operation

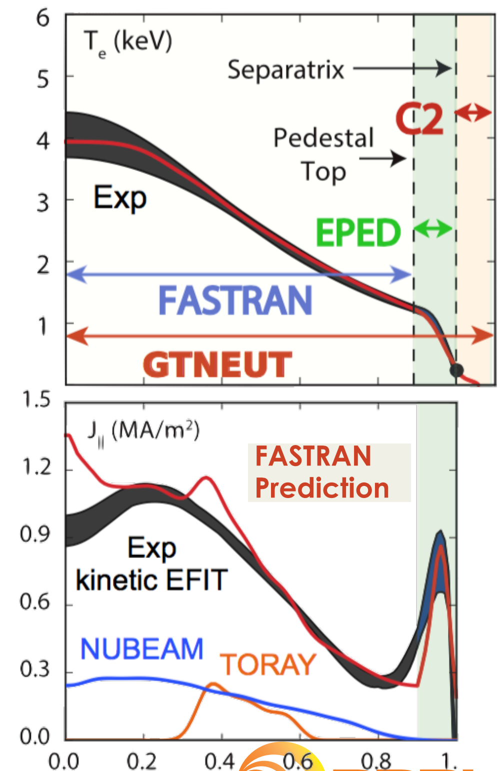


Modular coupling of 1.5D core and 2D edge transport implemented in ATOM and validated on DIII-D steady-state



- Plug&play, modular => exportable
  - 3 to 4 iterations needed.
  - 300 CPU hours per iteration
  - on 700 cores





Courtesy of D. Green (ORNL, USA)

Do we really need a fully integrated core-pedestal-edge transport model?

Can we get along with a reduced model?

How much can a model be reduced?

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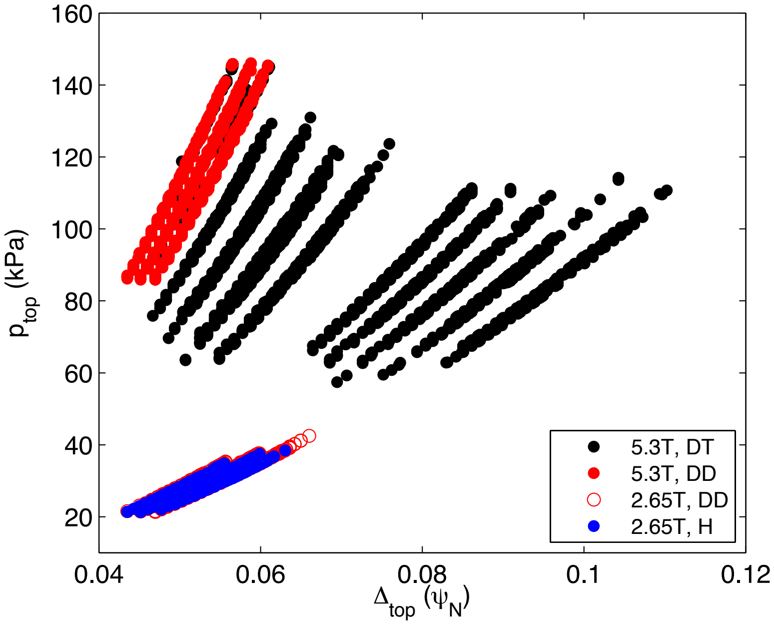
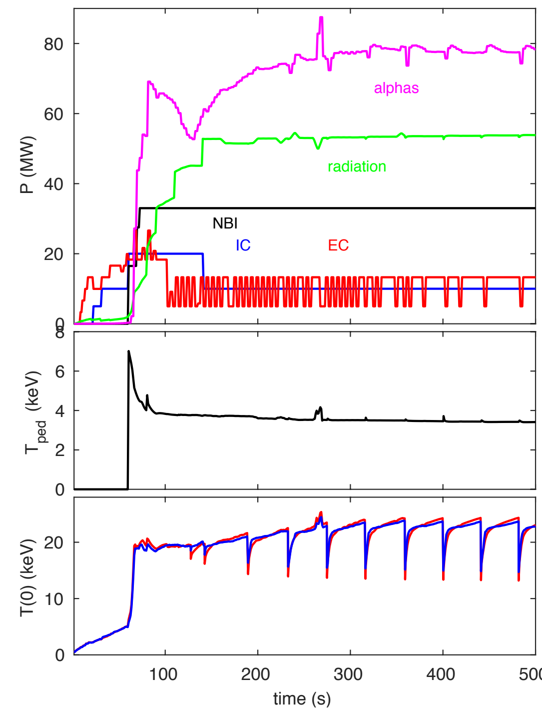
MHD stability pedestal calculations can be replaced by a lookup table for interpolation of pedestal width and height



dynamic features:
P_α and T_e respond to transport



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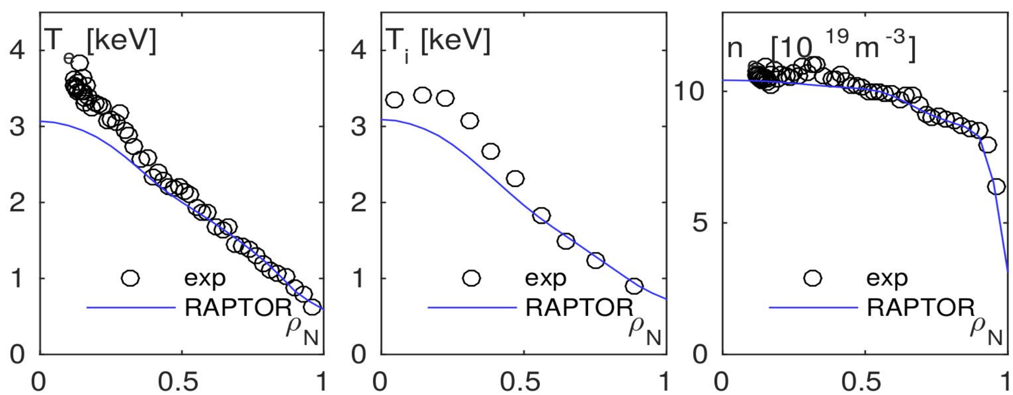
About 6500 points cover the ITER operational space

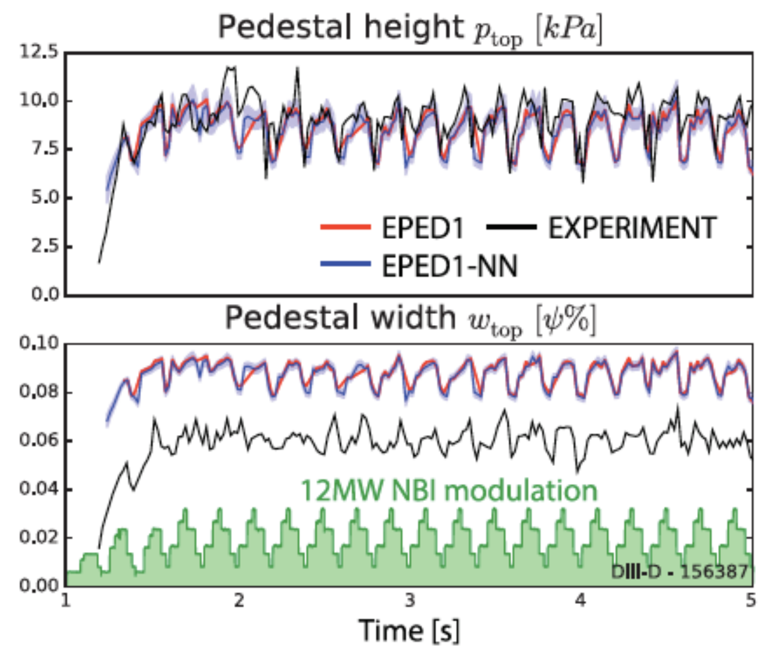
$P, \Delta = f(n_{ped}, \text{shape}, \text{Zeff}, B, I_P, \beta_N)$

The path forward for fast, reliable, integrated simulations of plasma discharges involves neural networks for core and edge transport

JET 73342 C-wall baseline.



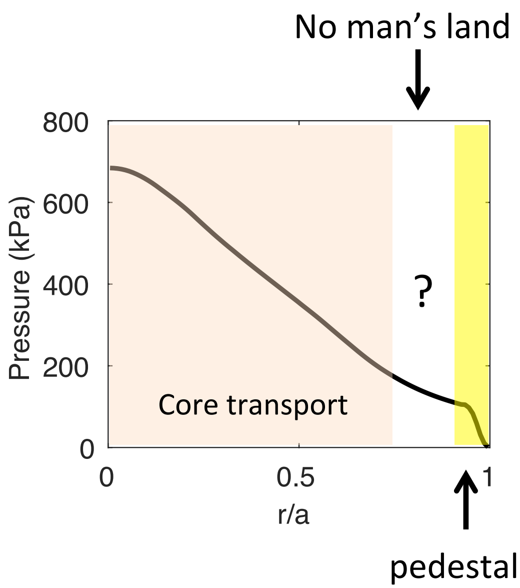
J. Citrin, Nucl. Fusion ***55*** *(2015). F. Felici, Nucl. Fusion (2017)*



QuaLiKiz: regression of turbulence quasi-linear calculations.
Proof of principle: 4D input for ITG turbulence
Extension to higher dimension ongoing

O. Meneghini, Nucl. Fusion ***57*** *(2015)*

Core-pedestal integration is incomplete without a transport model for the region inside the pedestal



- Core transport models cover r/a~0.1-0.75
- Pedestal scaling from MHD covers r/a>0.9
- In-between there is no transport model available (no-man's land)

We have no choice but imposing continuity between the core and the pedestal solution

THIS IS NOT A SELF-CONSISTENT SOLUTION

Plasmas develop instabilities that degrade the energy confinement and may lead to disruptions

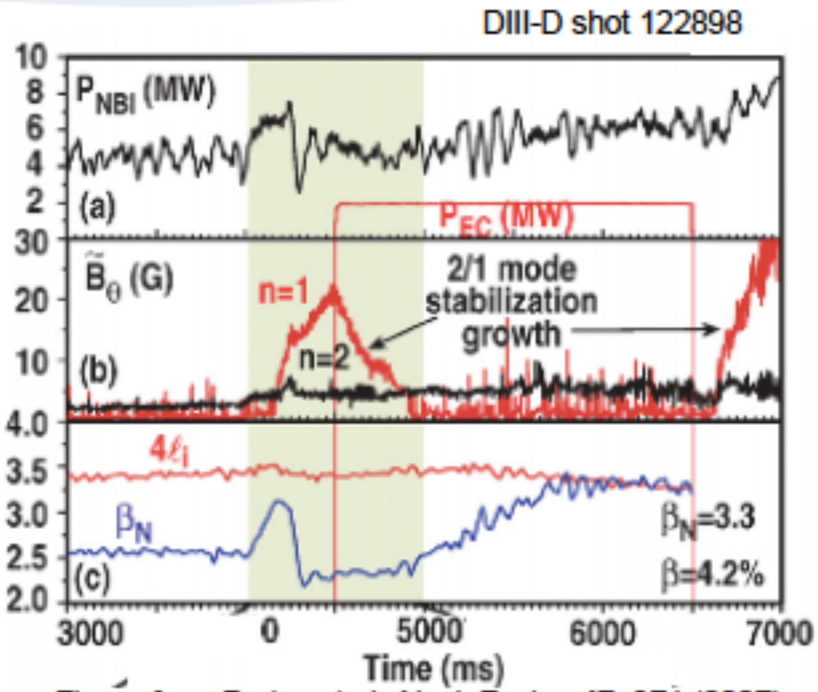
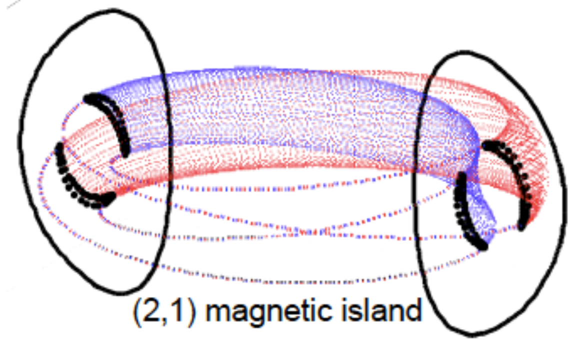


Figure from Prater *et al.*, Nucl. Fusion **47**, 371 (2007).



Courtesy of T. Jenkins (Tech-X)

EC heating and current drive is effective
at stabilizing and suppressing magnetic islands

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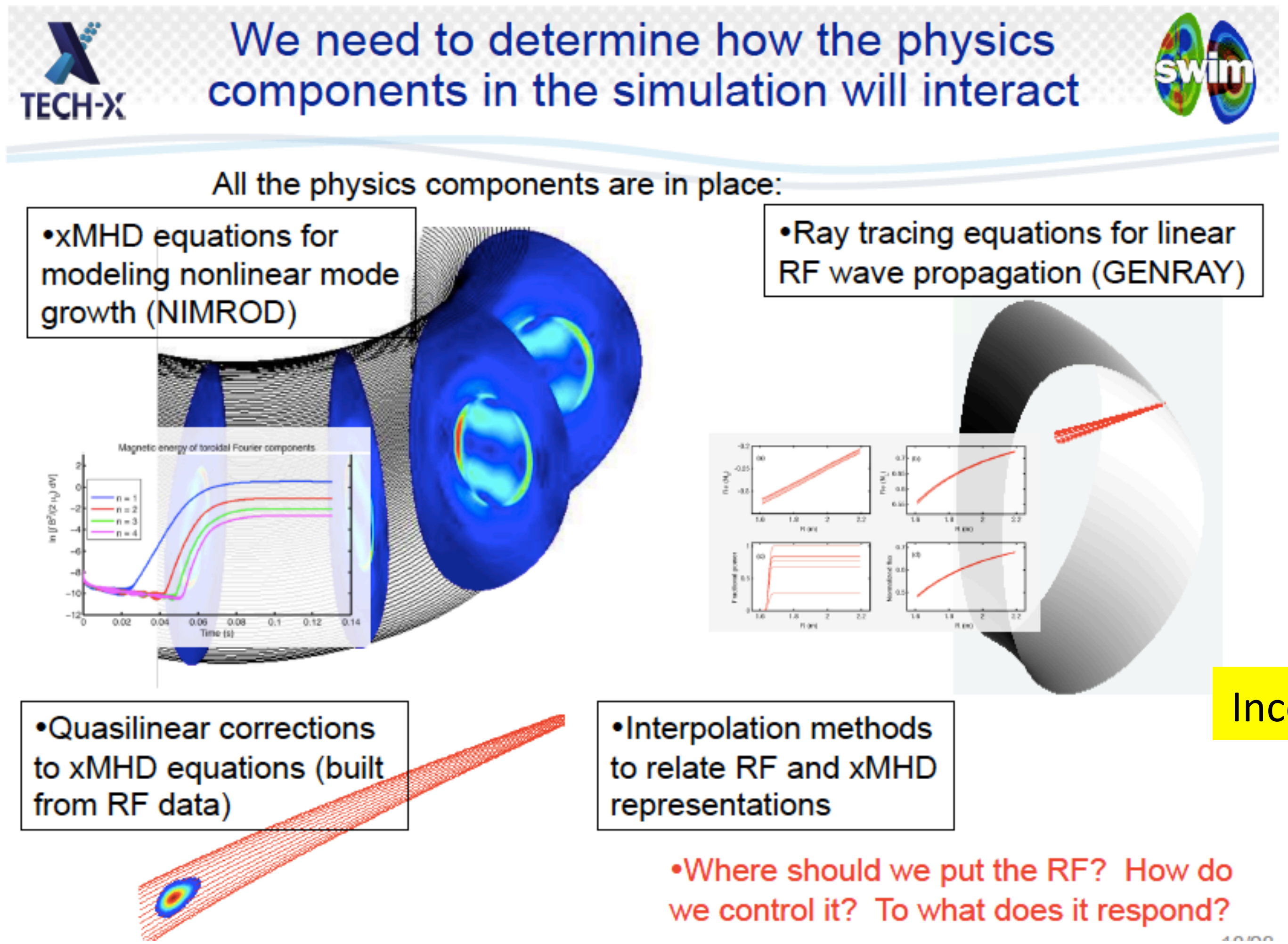

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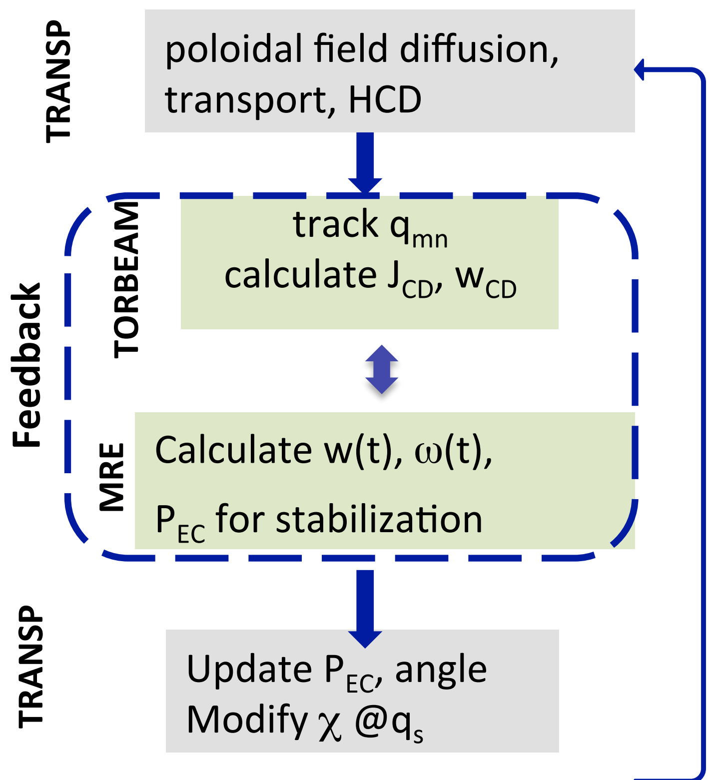
Reduced models from MHD are needed in time-dependent simulations to understand the plasma response to NTM control



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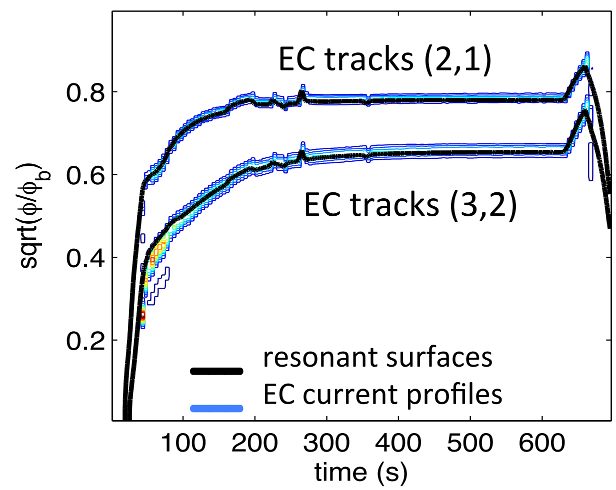

*F. Poli, Nucl. Fusion **57** (2017)*

Heat load on the divertor increases when the effects of fast ions is taken into account

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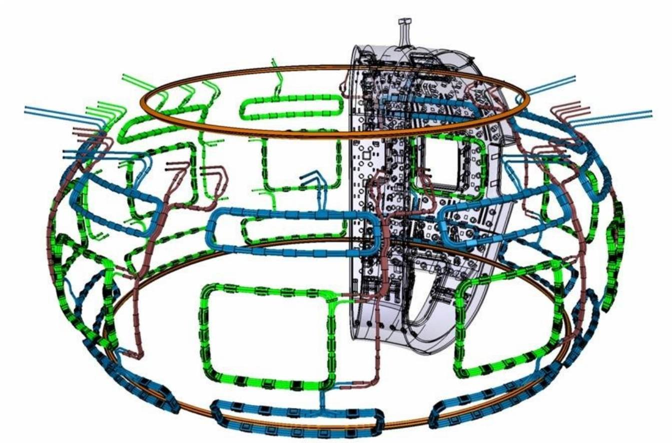
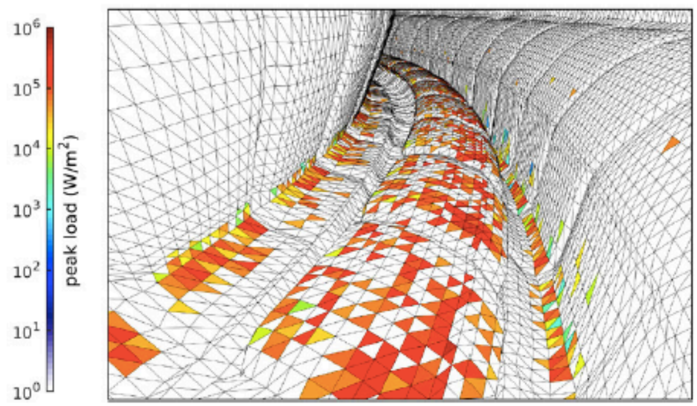
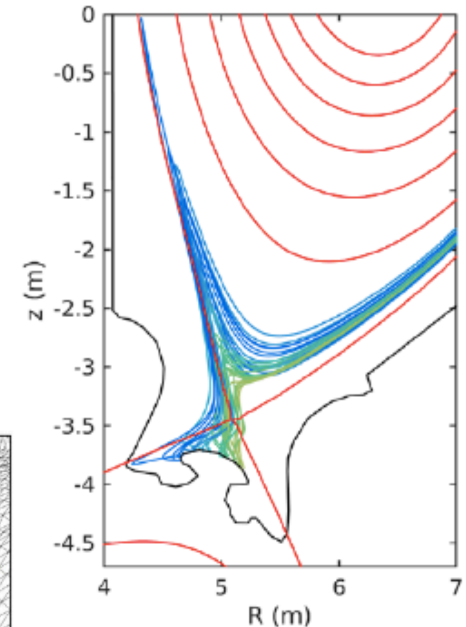
ITER in-vessel coils for control of Edge Localized Modes



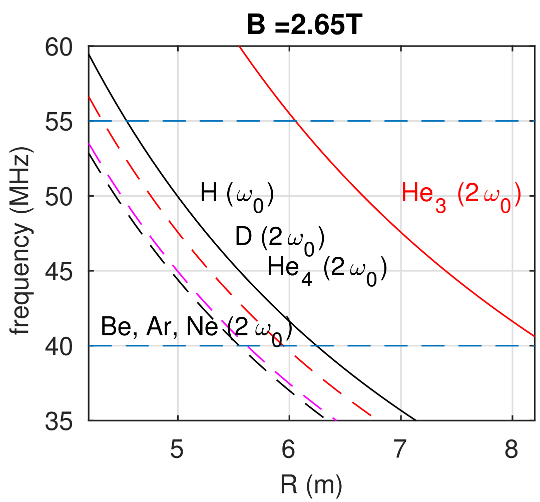
Courtesy of ITER Organization



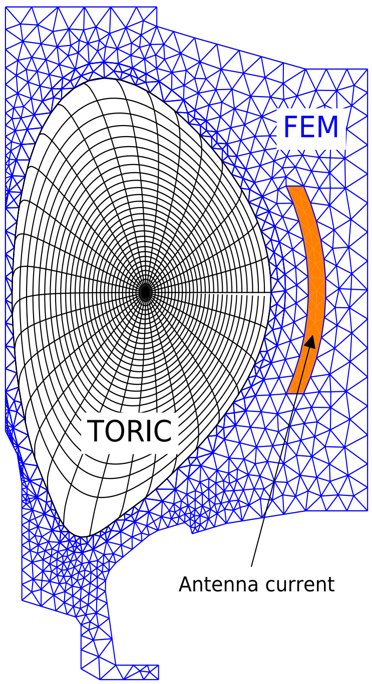


J. Varje, NF ***56*** *(2016)*

- One slide on IC and NBI synergy?



Recent effort in the US to model self-consistently RF wave propagation from the antenna to the core



Hybrid approach that retains computational features

Core: **Axisymmetric** flux surface regular grid

Hot plasma conductivity

Dense Matrix Solver

Edge: **Unstructured mesh** with complicated geometry (either 2D or **3D**)

Cold plasma with collision.

Boundary: **matching technique** to build integrated solution

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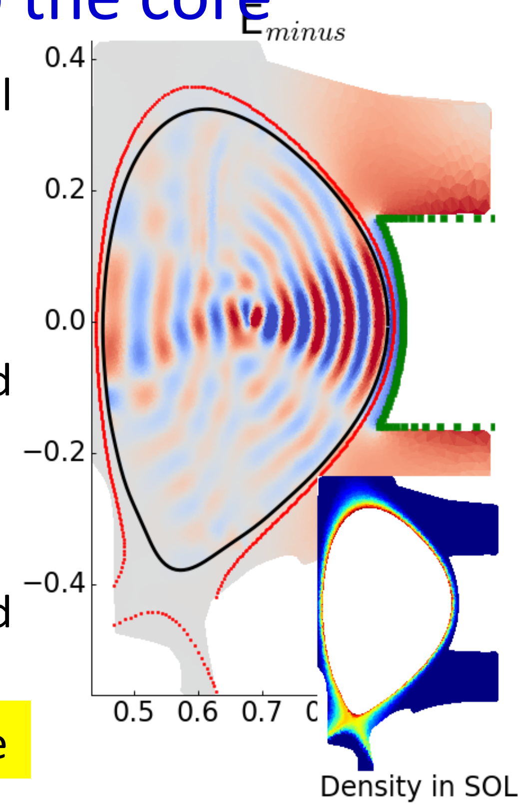

However, realistic model of the density and temperature in the SOL is needed

A large database of experiments exists for validation of integrated models in ITER-like conditions

- Here connection with experimental database of IBL plasmas

Incomplete slide

- Need link with experiments in He/H for validation and projection

Time-dependent integrated tokamak simulations are critical for experimental planning, including future devices

- They rely on reduced models that need
  - to be validated against experiments
  - to be verified against first principle codes
- More reduced models needed to fill the gaps:
  - Integrated simulations that evolve equilibrium, transport, MHD
  - Edge transport in time-dependent solvers for self-consistent propagation of RF waves from antenna to core plasma

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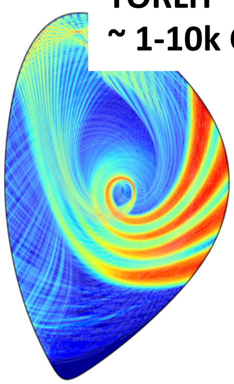
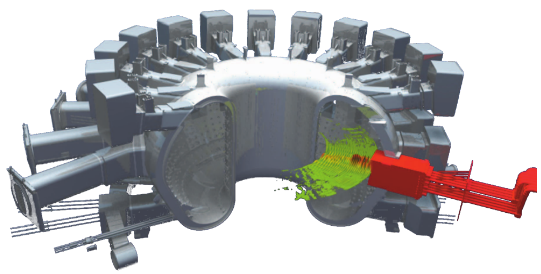
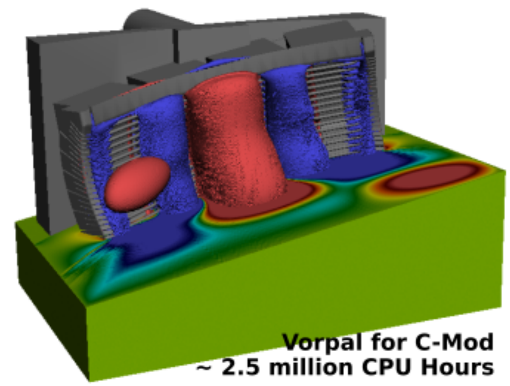
PPPL

PPPL

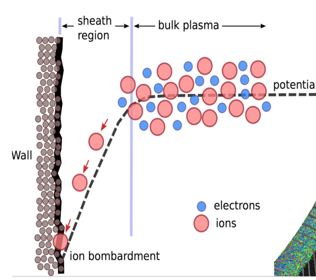
Leading-class computers allows for RF wave physics in core and edge regions with great details

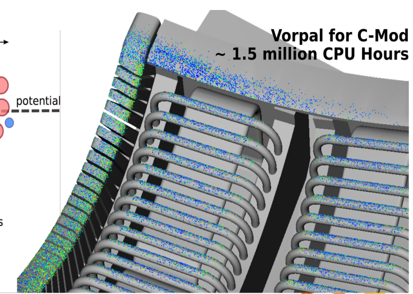




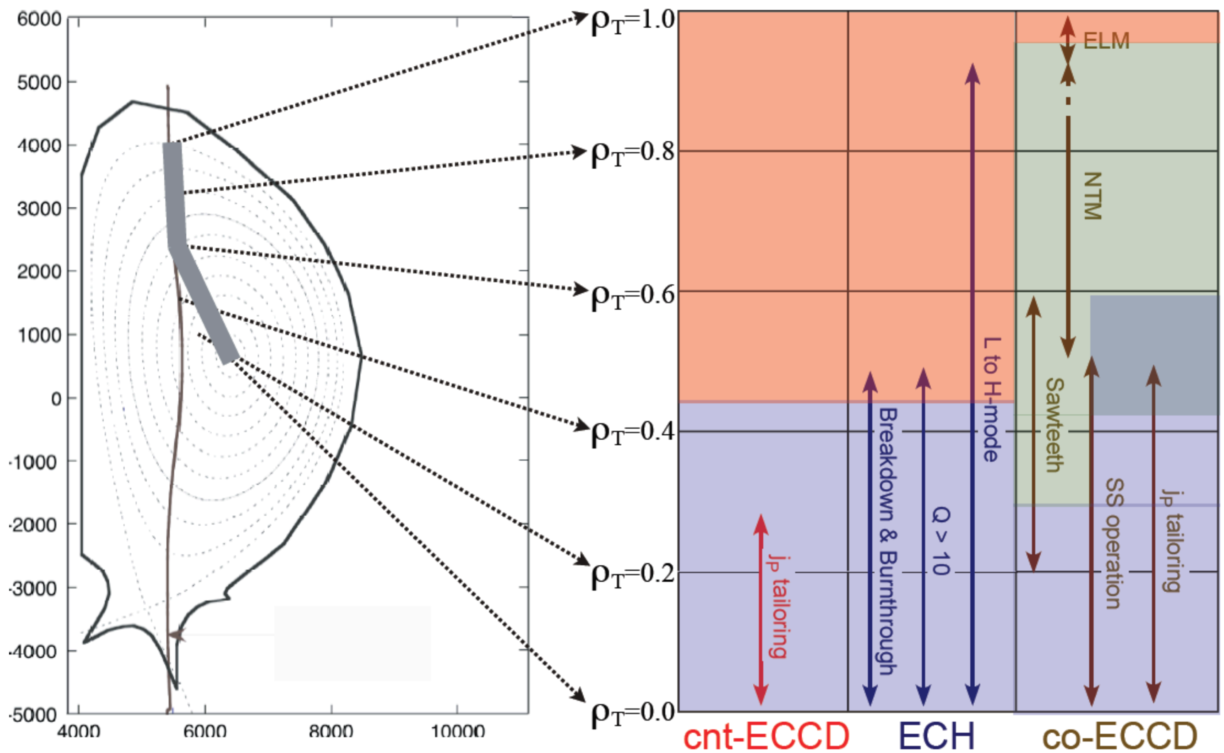


- RF field in
  - Core
  - SOL/antenna
- RF sheath
- However, core and edge regions are modeled separately…





EC system on ITER driven by MHD and radial accessibility



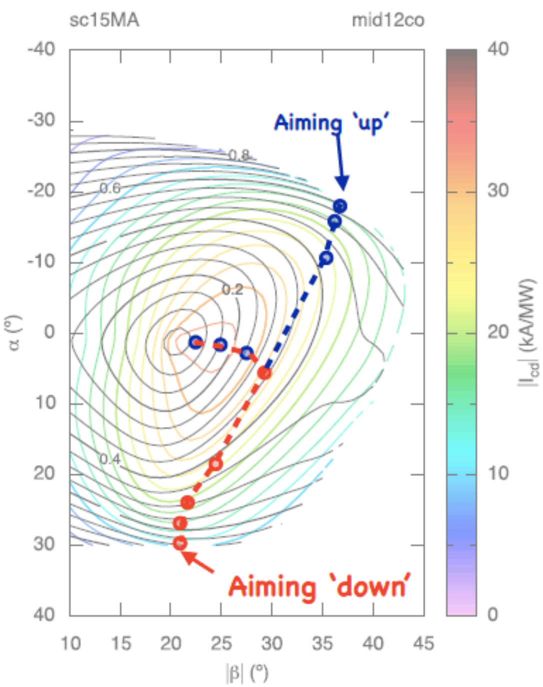
NTM stabilization
- localized deposition
- narrow profile

Core heating
- broad profile
- core accessibility

Current profile tailoring
- cntr-ECCD
- broad profile
- wide radial accessibility

The optimization of the steering geometry of the Equatorial Launcher on ITER is based on ray tracing simulations

Power absorbed locally



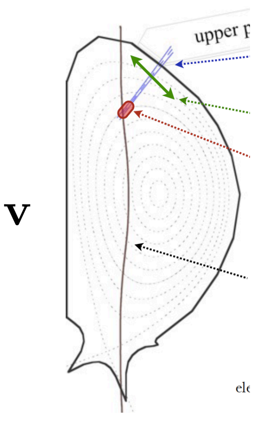
Courtesy of D. Farina, IFP (Italy)

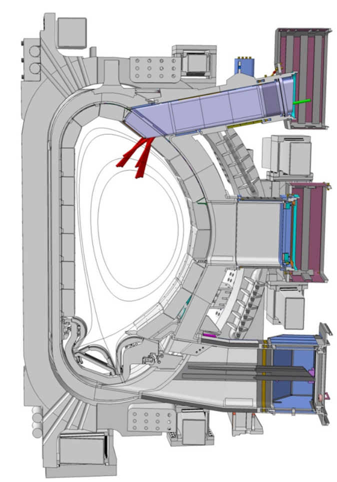
where **B** satisfies:

$$\omega_{RF} = \frac{eB}{\gamma m} + \mathbf{k}_{\|} \cdot \mathbf{v}$$

ω_{ec}

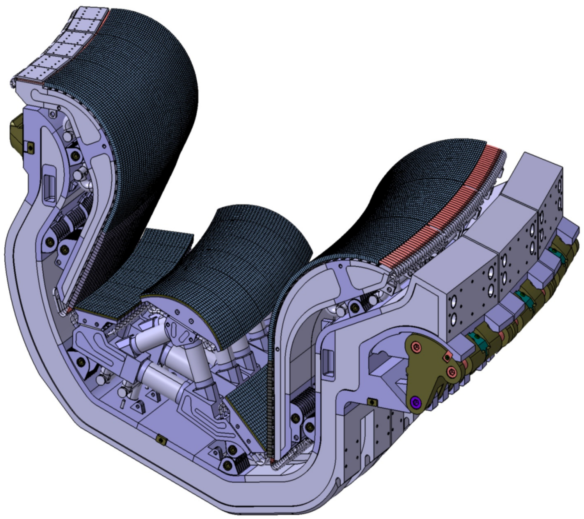
Doppler shift
(toroidal injection for CD)

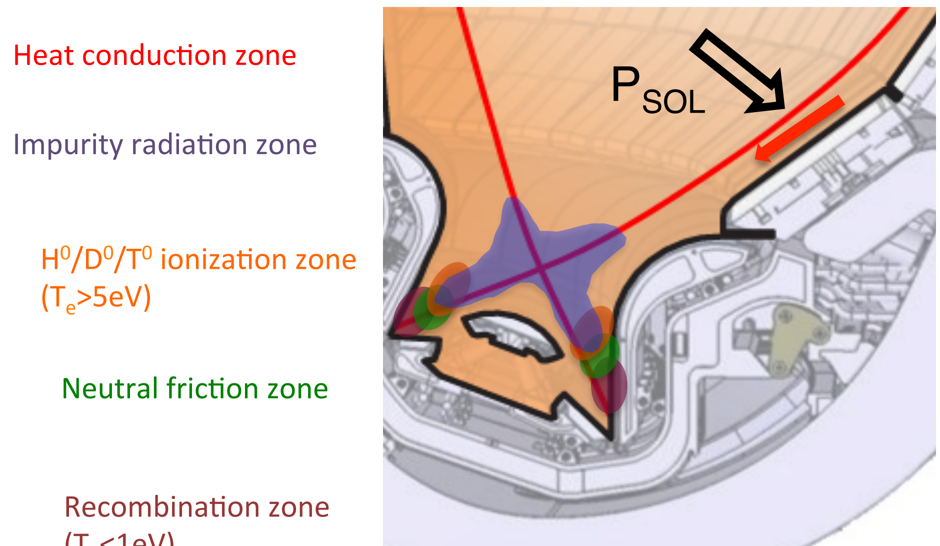




f_{EC}=170GHz

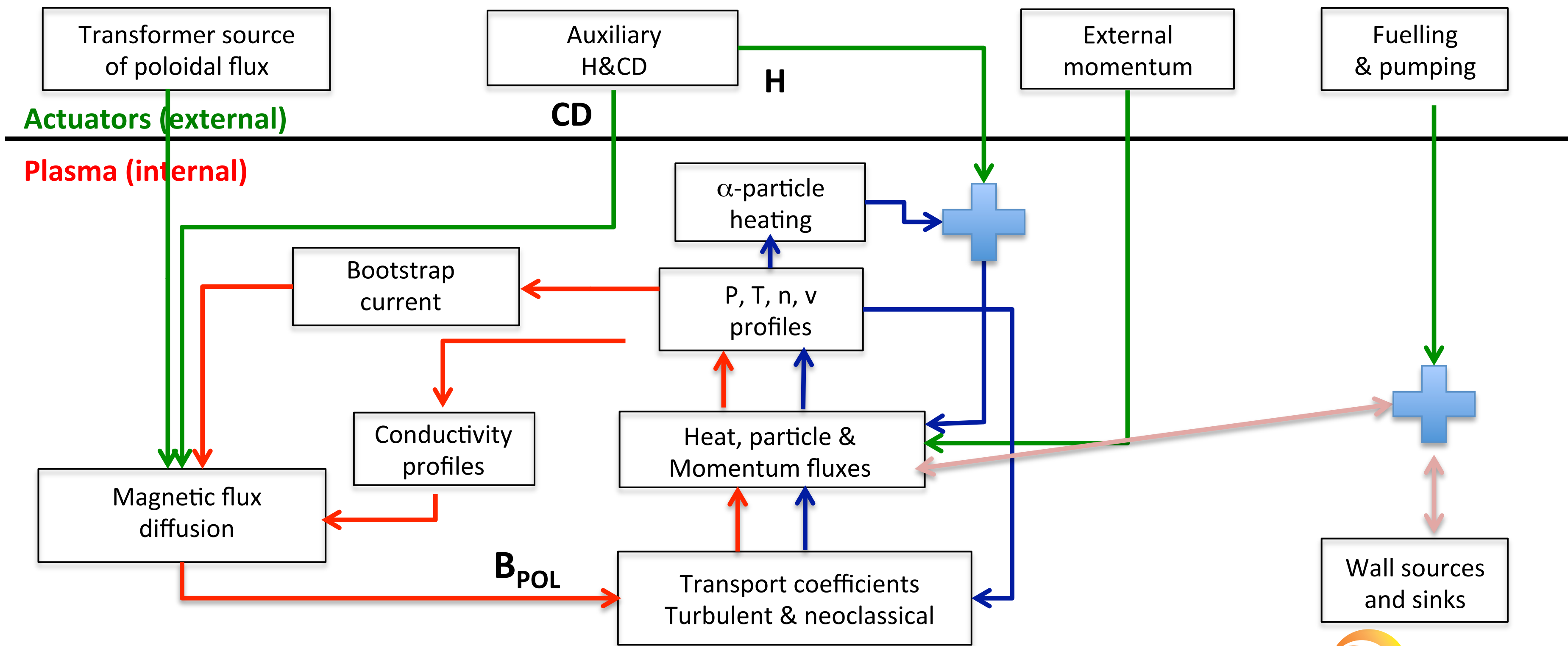
The divertor design on ITER is entirely based on a very extensive set of SOLPS-4.3 simulations conducted over 15 years



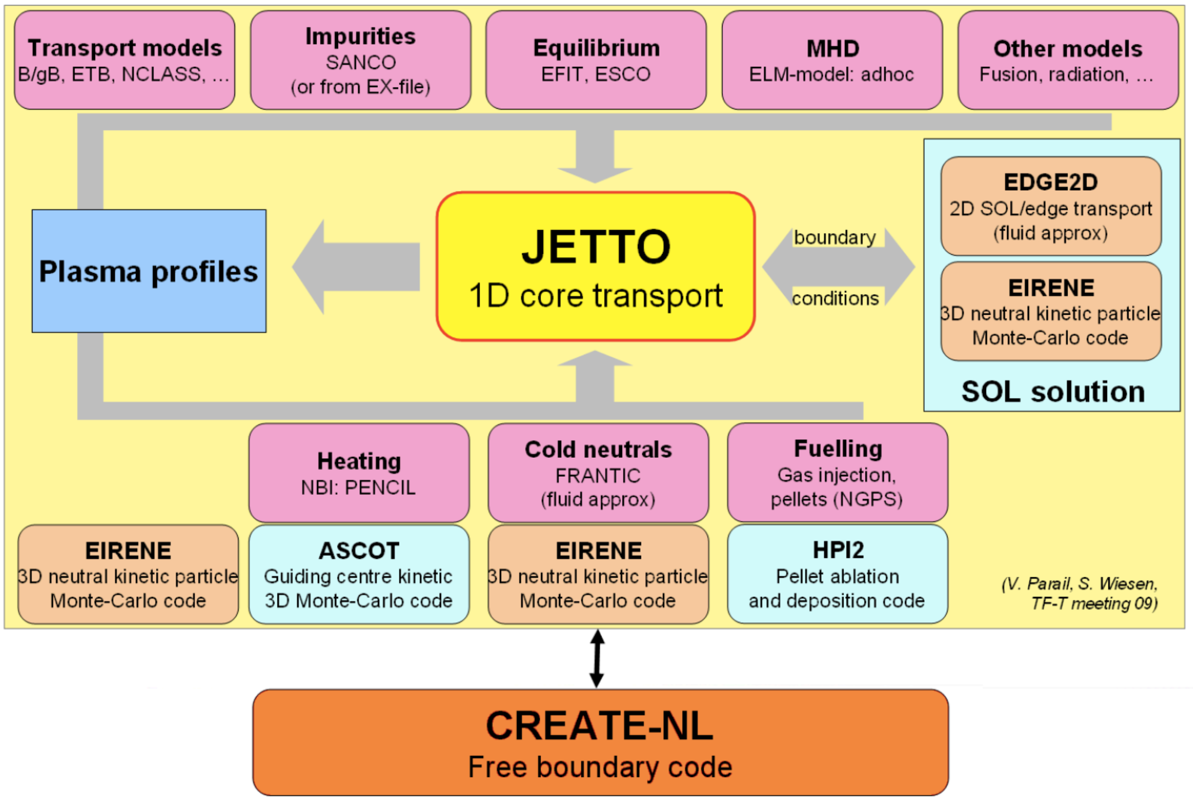


Courtesy of R. Pitts, ITER Organization

fast (transport) vs slow (current diffusion) time scales are nonlinearly coupled together

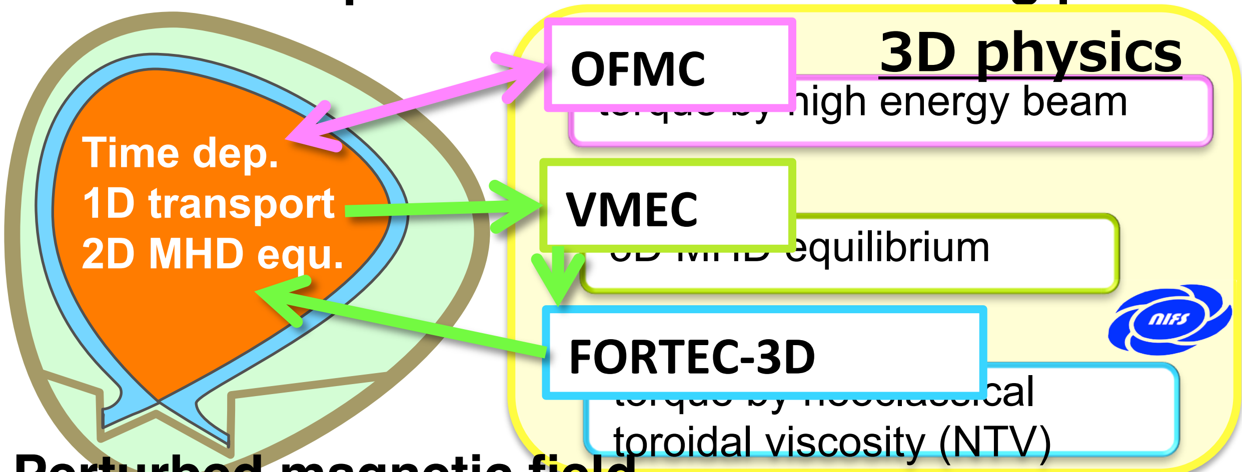


adapted from Politzer NF 2005

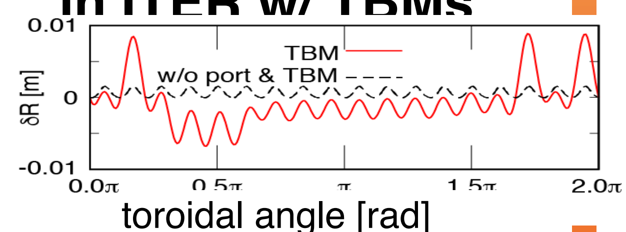

Transport models
B/gB, ETB, NCLASS, ...
Impurities
SANCO
(or from EX-file)
Equilibrium
EFIT, ESCO
MHD
ELM-model: adhoc
Other models
Fusion, radiation, ...
Plasma profiles
JETTO
1D core transport
boundary
conditions
EDGE2D
2D SOL/edge transport
(fluid approx)
EIRENE
3D neutral kinetic particle
Monte-Carlo code
SOL solution
Heating
NBI: PENCIL
Cold neutrals
FRANTIC
(fluid approx)
Fuelling
Gas injection,
pellets (NGPS)
EIRENE
3D neutral kinetic particle
Monte-Carlo code
ASCOT
Guiding centre kinetic
3D Monte-Carlo code
EIRENE
3D neutral kinetic particle
Monte-Carlo code
HPI2
Pellet ablation
and deposition code
(V. Parail, S. Wiesen,
TF-T meeting 09)
CREATE-NL
Free boundary code

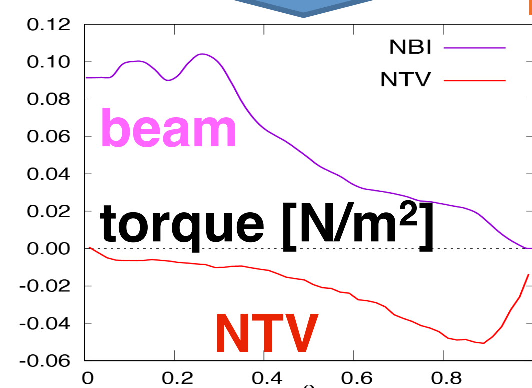
Integrated modeling code TOPICS
- Application to plasma rotation prediction -

Various torques drive rotation affecting plasma transport and stability.

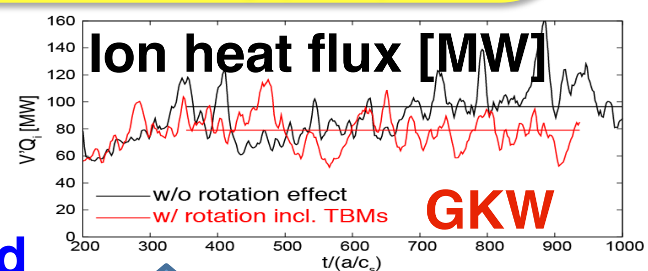


displacement of equ. in ITER w/ TBMs





Perturbed magnetic field produces NTV torque comparable to beam.

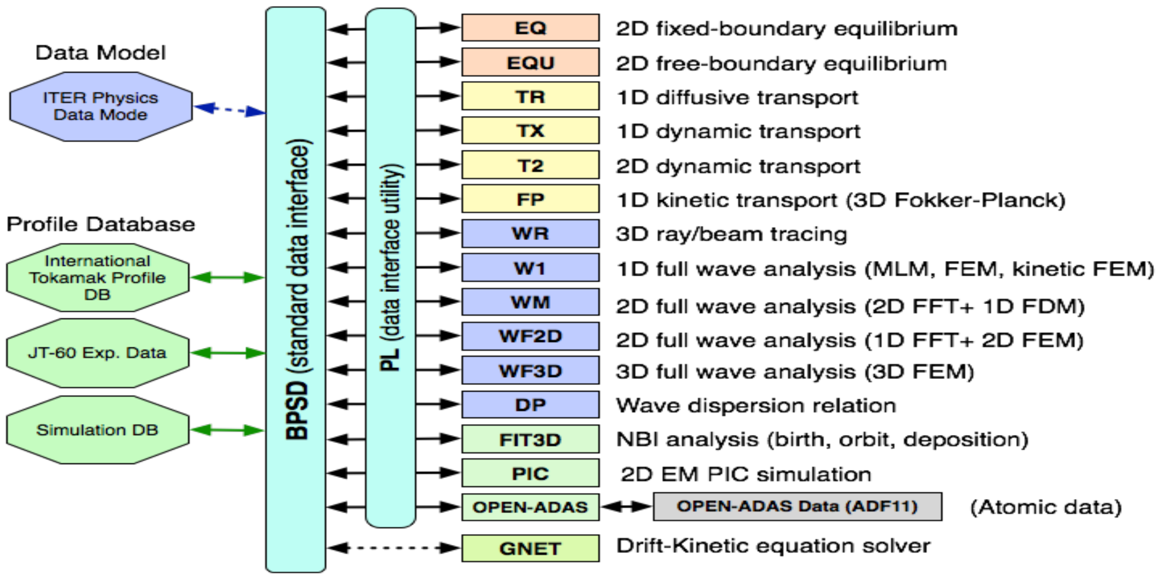


Modeling could evaluate plasma rotation speed and effects on transport in ITER scenario [Honda NF 2017]

change in predicted toroidal rotation

Integrated modeling code: TASK

Structure of TASK



Open source

https://bpsi.nucleng.kyoto-u.ac.jp/task/

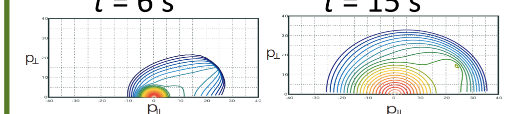
Recent activity

Kinetic transport modeling of burning start-up in ITER plasma

3D Fokker-Planck analysis of distribution function of e, D, T, and He

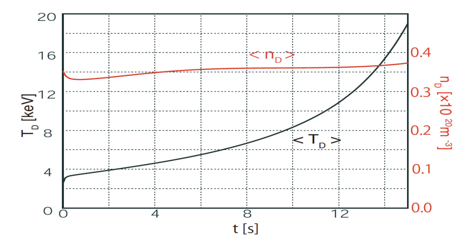
Momentum distribution of D

t = 6 s　　*t* = 15 s



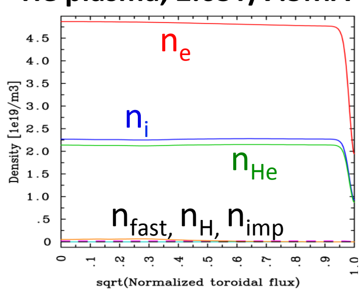
NBI　　NBI + α

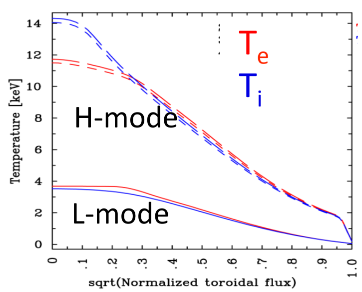
Time evolution of n_D and T_D



Free-boundary solvers with poor physics cam still be valuable to define operational limits and plasma boundary evolution

He plasma, 2.65T/7.5MA



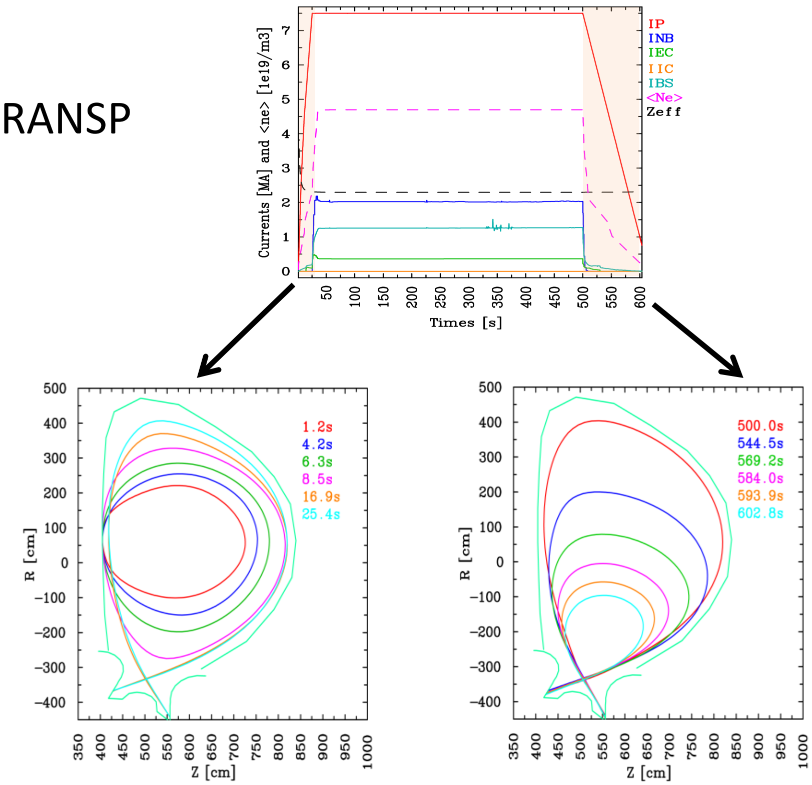


Replace with TRANSP

Prescribe electron density profile
Impurities are a fix fraction of n_e
Ion density from quasi-neutrality

Semi-empirical model for thermal transport (Coppi-Tang)

Pedestal from EPED1,
Usually pre-set, with feedback



CORSICA simulation
Courtesy of Sun-Hee Kim (ITER Organization)