Integrated Tokamak Modeling: when physics informs engineering and research planning

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For sending material for this tutorial, many thanks go to:

- USA: N. Bertelli, M. Boyer, N. Ferraro, W. Guttenfelder, D. Pfefferle, M. Podesta (PPPL), I. Krebs (PPPL/IPP), V. Soukhanovskii (LLNL), D. Green, J-M Park (ORNL), S. Kruger, T. Jenkins (TechX), P. Bonoli, N. Howard, S. Shiraiwa, J. Wright (PSFC), T. Rafiq (Univ. Lehigh)
- EU: J. Citrin (DiFFer), E. Militello Asp, F. Koechl (CCFE)
- JAPAN: N. Hayashi (QST), A. Fukuyama (Univ. Kyoto)
- ITER Organization: X. Bonnin, Y. Gribov, S-H Kim, R. Pitts

Fusion plasma physics encompasses a wide range of spatial and temporal scales

ω_{EC}^{-1} ω_{LH}^{-1} ω_{IC}^{-1} τ_A τ_E τ_R τ_D

time (s) 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4}

space (m) 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2}

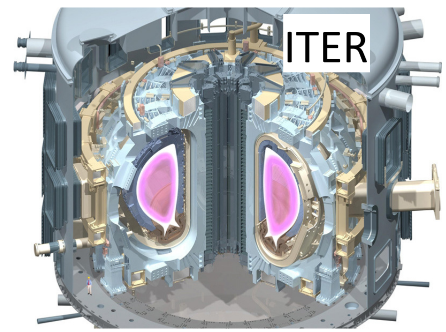
Wave propagation

Macroscopic stability

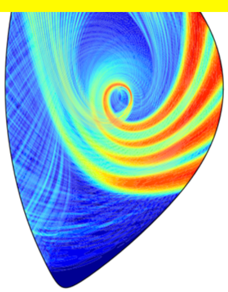
Transport

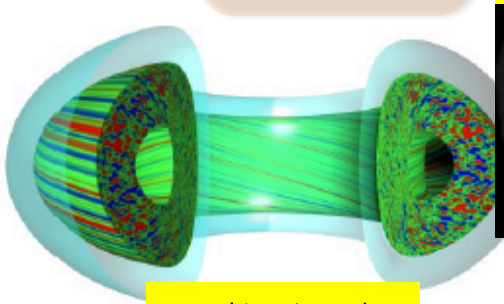
current diffusion

Plasma turbulence



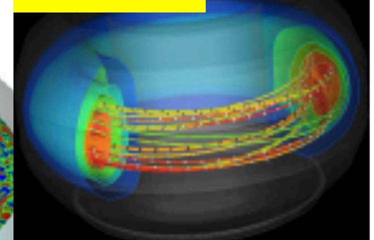
Full wave solvers
<1M CPU Hours



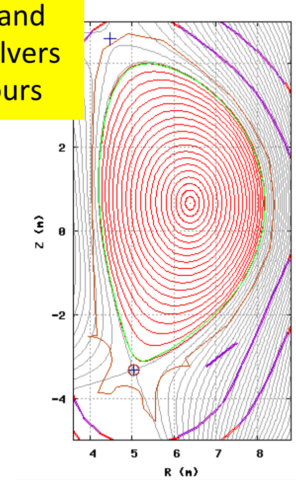


Gyrokinetic codes
<10M CPU hours

MHD codes



Equilibrium and
transport solvers
$<10^2$ CPU hours



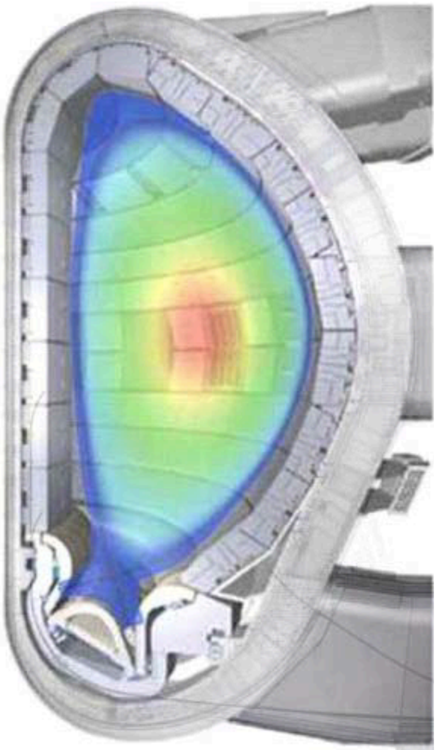
In a tokamak all temporal and spatial scales are coupled

Confined plasma
(closed magnetic field lines)

MHD equilibrium/instabilities,
microturbulence,
energetic particles

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

Microturbulence,
ionization, recombination
radiation



The plasma is surrounded
by solid structures:
Plasma-material interactions

External heating

Radiofrequency waves
Neutral beams

Fueling

Gas injection
Pellets

In a tokamak particles and energy are 'confined' by magnetic fields

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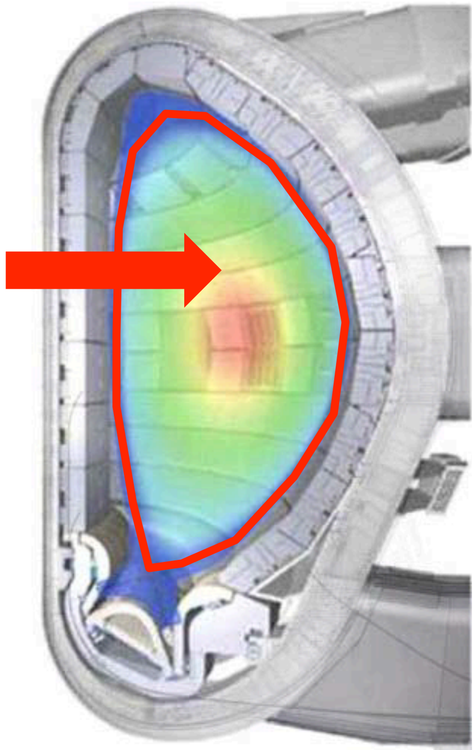
Scrape-Off Layer plasma (SOL)
(open field lines)

Microturbulence,
ionization, recombination
radiation



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and they can also ‘flow’ along open magnetic field lines

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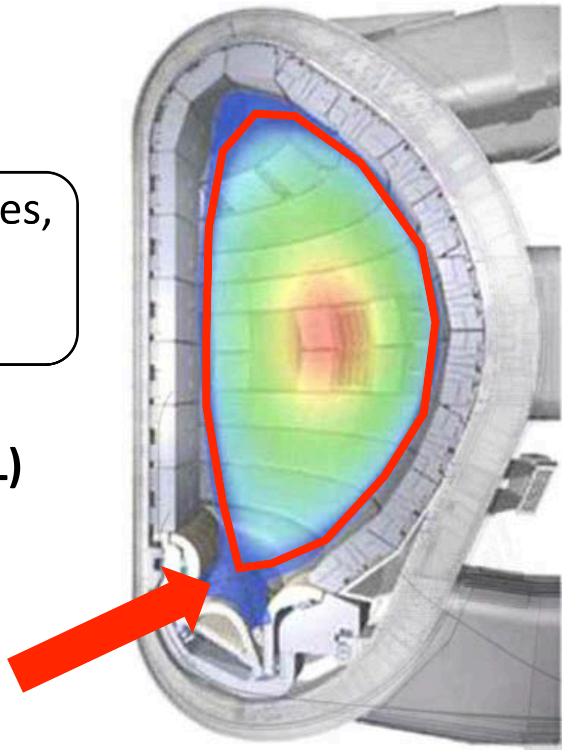
Scrape-Off Layer plasma (SOL)
(open field lines)

Microturbulence,
ionization, recombination
radiation



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Plasmas in a tokamak are in contact with the 'wall'

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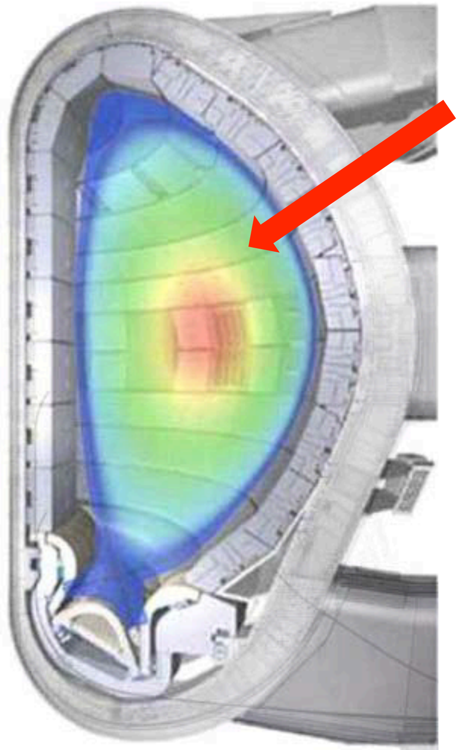
Scrape-Off Layer plasma (SOL)
(open field lines)

Microturbulence,
ionization, recombination
radiation



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Plasmas in a tokamak need to be 'heated'

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Microturbulence,
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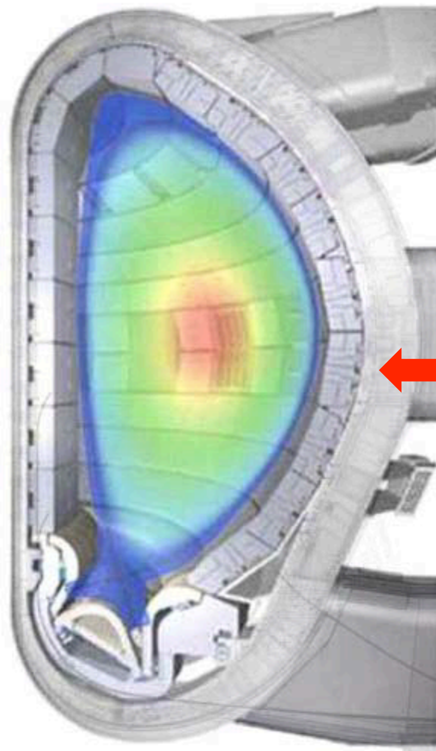
radiation



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Plasmas need frequent pit stops for 're-fueling'

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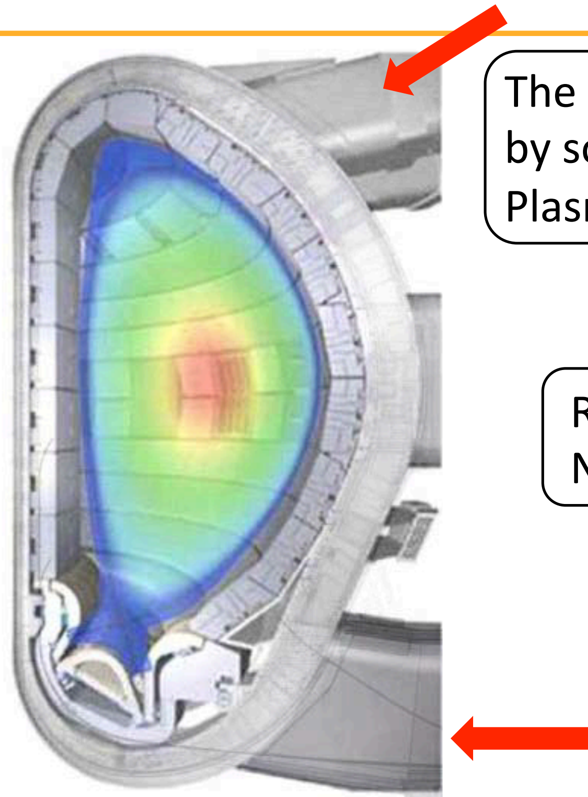

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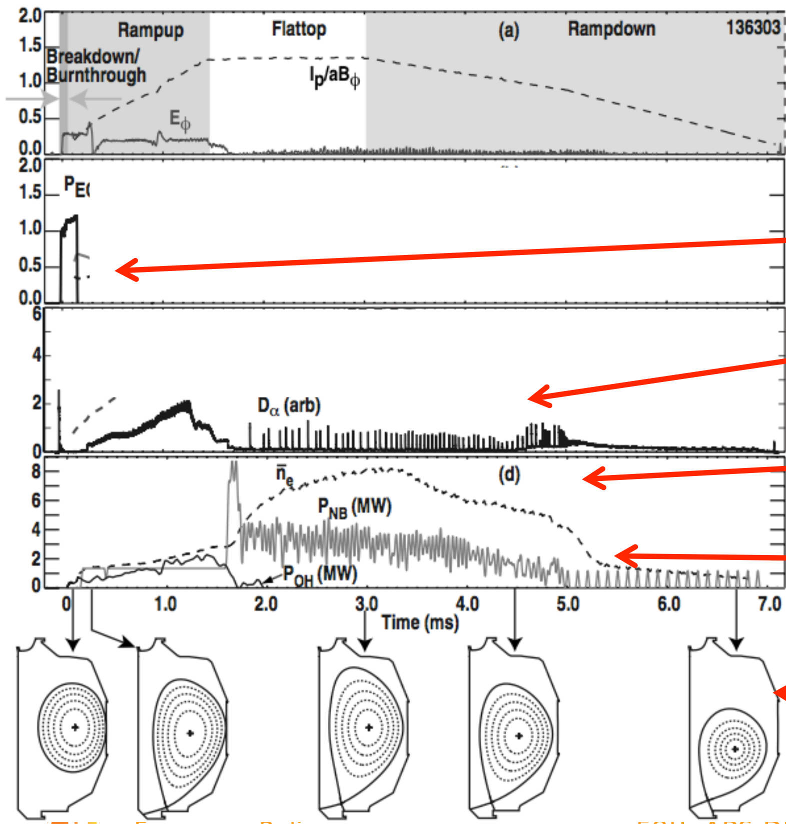
A different perspective on integrated modeling: looking at a tokamak with the eye of an engineer

Goal: simulate an entire plasma discharge from startup to termination optimizing **ACCURATE PHYSICS and FAST TURNAROUND**

- High fidelity physics at the core of time-slice integrated modeling
- Verified and validated reduced models at the core of (time-dependent) integrated modeling

We model tokamaks to understand experiments and to design stable and reliable reactors



Experiment on DIII-D that simulates an ITER-like plasma

*[Fig. 1 - G. Jackson et al, Phys. Plasmas **17** 056116 (2010)]*

Heating and current drive (10^{-11}-10^{-6}s)

MHD instabilities/turbulence (10^{-6}-10^{-2}s)

Density evolution (10^{-6}-10^{-2}s)

Neutral Beams (10^{-6}-10^{-1}s)

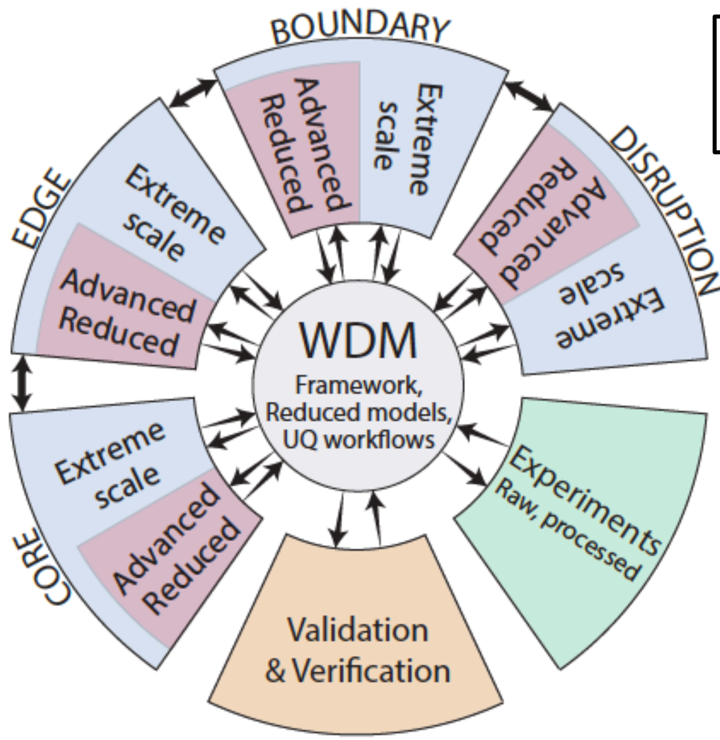
MHD equilibrium (10^{-6}-10^{-2}s)

A Whole Device Model (WDM) is a comprehensive picture of the complexity involved in modeling a tokamak

Extreme scale
First principle (Vlasov eq.)
Gyrokinetic codes
Full wave solvers

verification

Advanced reduced
Fluid codes
Reduced full wave solvers



uncertainty quantification
models and experiments

Validation
Experiments

Reduced
Ray tracing codes
Neural networks

[FES *Integrated Modeling Workshop Report, 2015*]

A Whole Device Model (WDM) is a comprehensive picture of the complexity involved in modeling a tokamak

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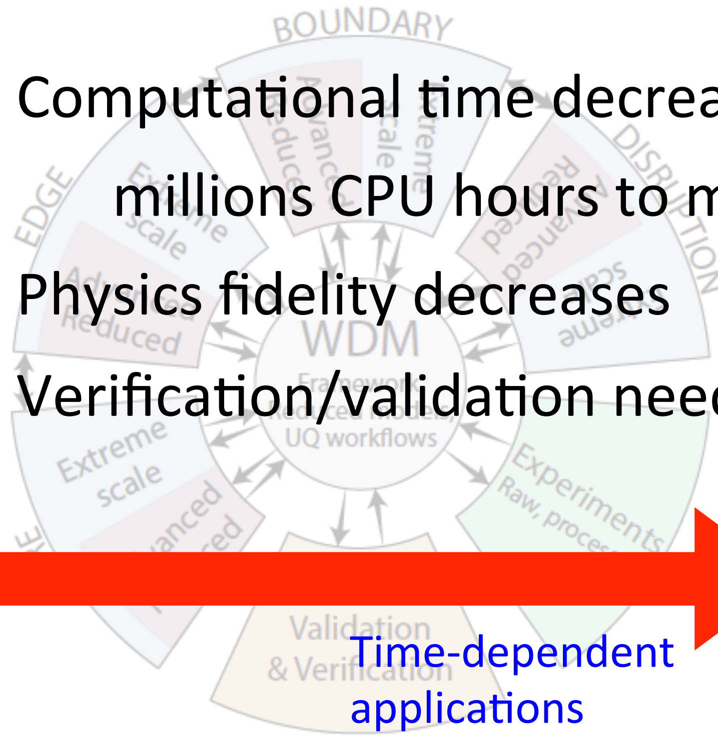
Time-slice applications

Advanced reduced
Fluid codes
Reduced full wave solvers



Computational time decreases:

millions CPU hours to minutes/seconds

Physics fidelity decreases

Verification/validation needed at each step

Time-dependent applications

Reduced
Ray tracing codes
Neural networks

- From high fidelity physics to reduced models
- Combining two or more models for an integrated, converged solution on a time slice

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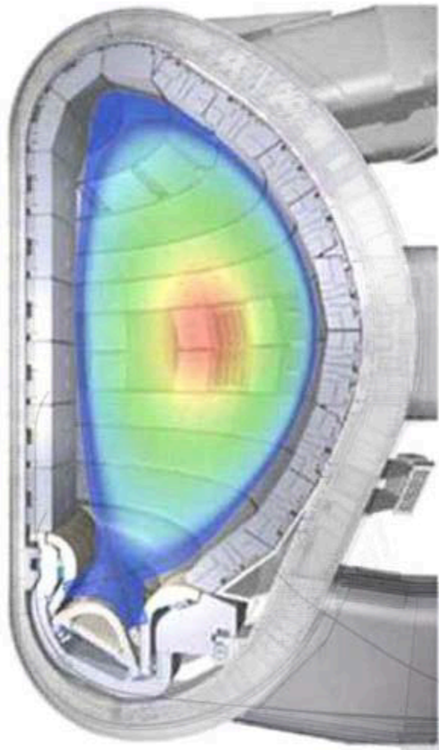
(closed magnetic field lines)

MHD equilibrium/instabilities,
microturbulence,
energetic particles

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

microturbulence,
ionization, recombination
radiation



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A plasma in equilibrium can be described by ideal MHD

Equilibrium condition: $\mathbf{j} \times \mathbf{B} = \nabla p$

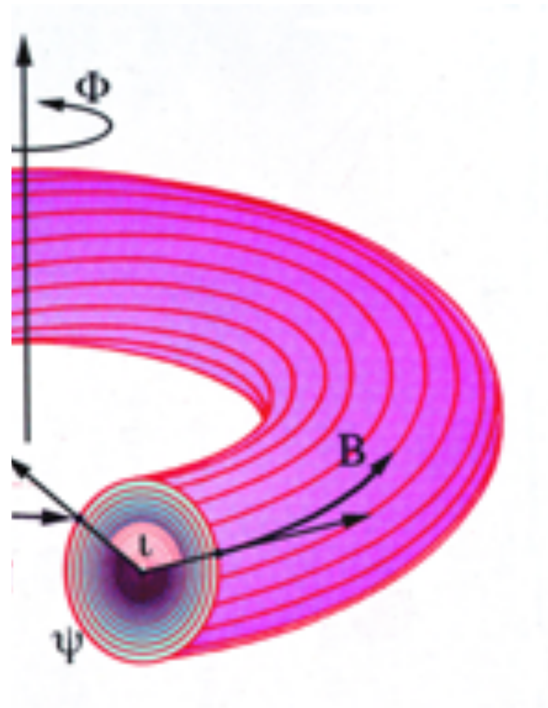
$$\mathbf{B} \cdot \nabla p = 0 \qquad \mathbf{j} \cdot \nabla p = 0$$

$\Longrightarrow$ **j**, **B** lie on nested surfaces

$\Longrightarrow$ **j**, **B**, p are described by a flux function ψ

$\Longrightarrow$ equilibrium entirely defined by:

$$R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial \psi}{\partial R}\right) + \frac{\partial^2 \psi}{\partial z^2} = -\mu_0 R J_\phi$$



[*Credit, DIFFER website, The Netherlands*]

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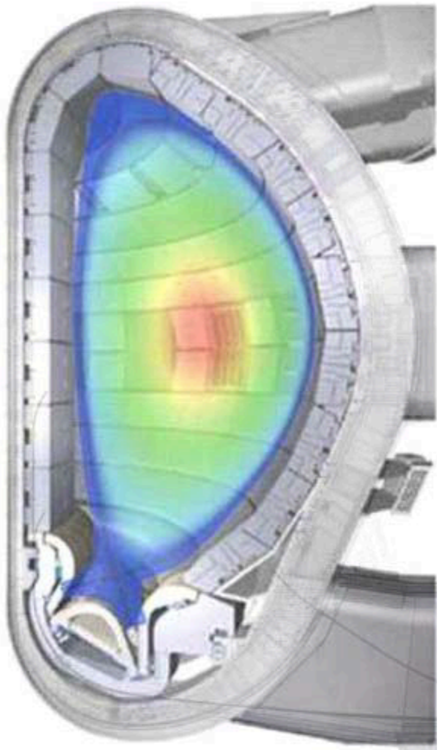

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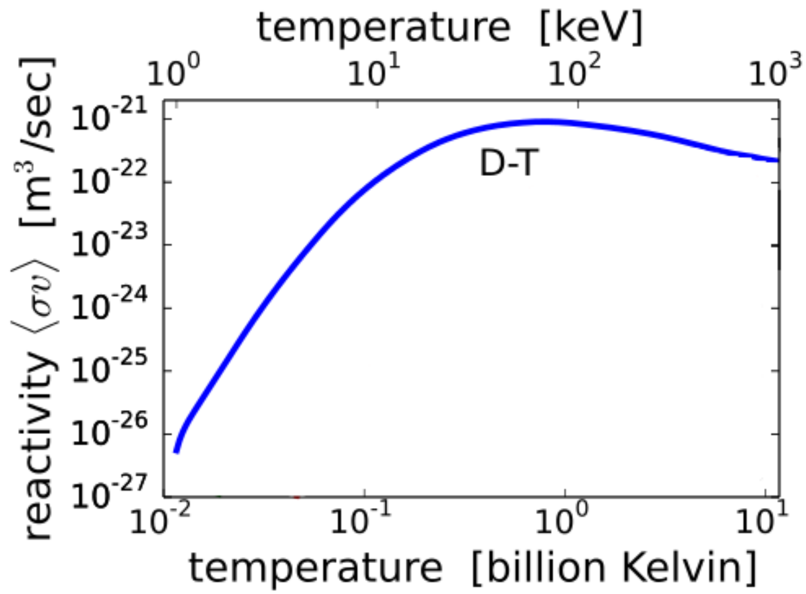
Ignited (burning) plasmas are dominated by alpha heating … but they need a boost from external sources before they can burn

$$S_\alpha = \frac{1}{4} E_\alpha n^2 \langle \sigma v \rangle$$

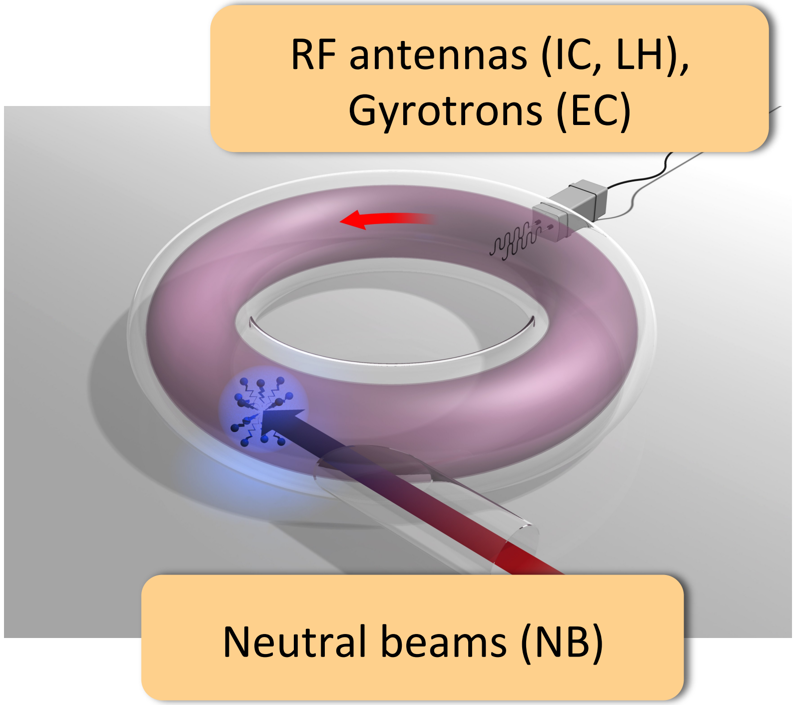
3.5MeV

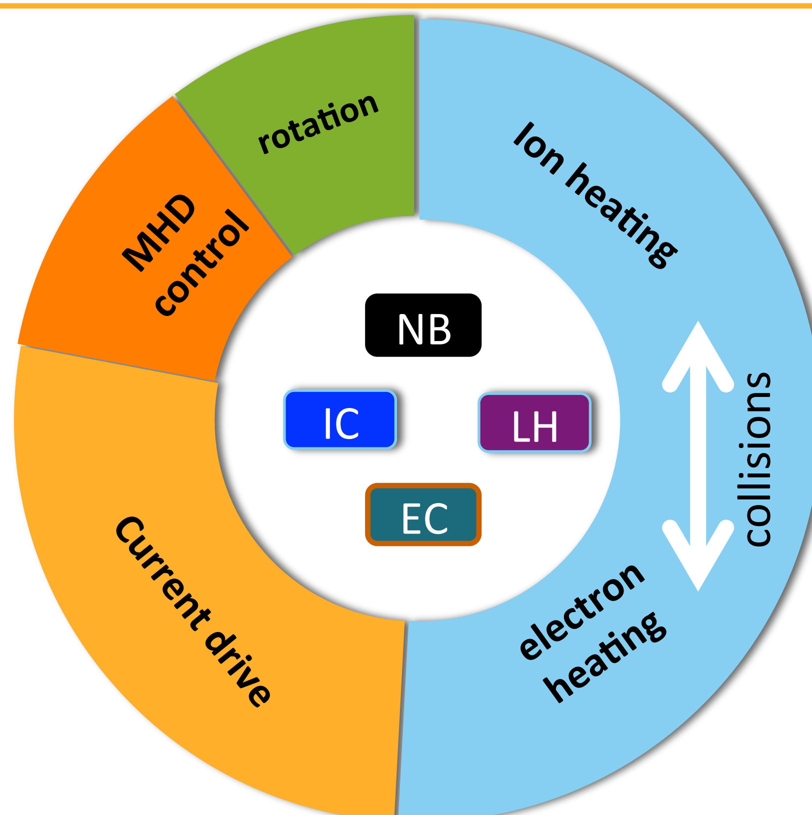
$n_D + n_T$
50-50



$\Rightarrow$ minimum temperature for ignition => 15 keV
$\Rightarrow$ alpha heating dominates at temperature >5-7 keV
$\Rightarrow$ ohmic heating can heat plasmas only up to 3-5 keV

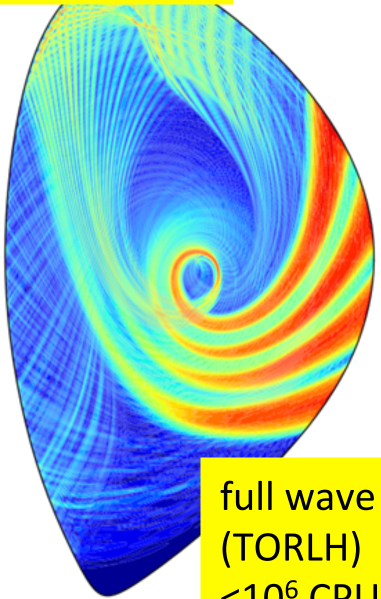
External sources do more than providing heating and current: they can provide momentum and control of MHD instabilities





Perturbation of equilibrium enables description of waves propagation by representing the plasma with a dielectric tensor

CMod plasma



full wave solver (TORLH)
$<10^6$ CPU Hours

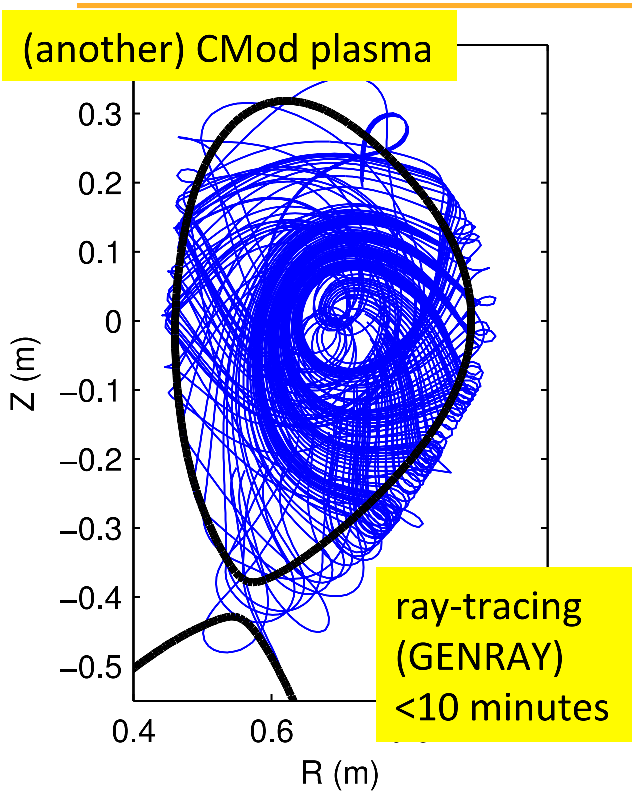
density, temperature → **Dielectric tensor** ← Magnetic equilibrium

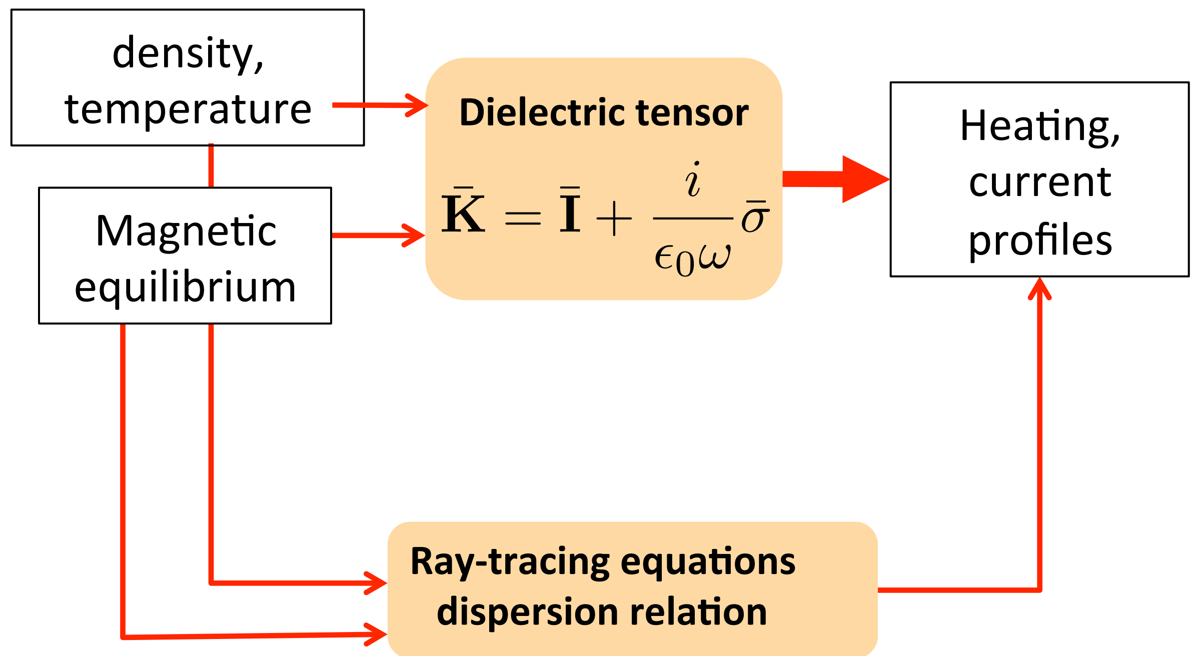
$$\bar{\mathbf{K}} = \bar{\mathbf{I}} + \frac{i}{\epsilon_0 \omega}\bar{\sigma}$$

→ Heating, current profiles

[courtesy of S. Shiraiwa (PSFC), ***VI2.00003****]*

Ray-tracing equations are accurate (and fast) approximations of high frequency wave propagation



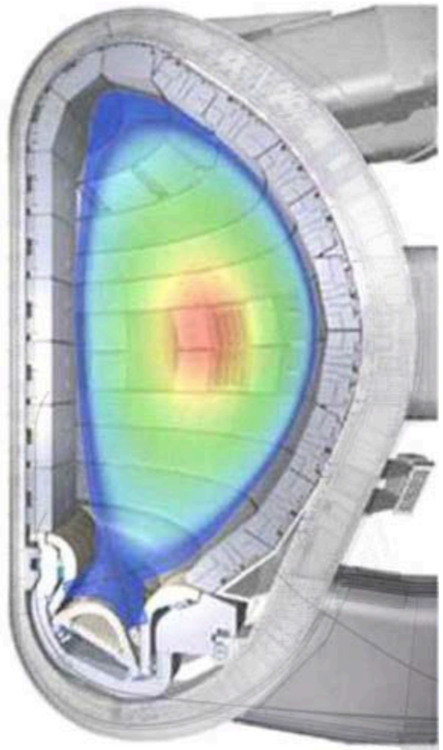


Confined plasma
(closed magnetic field lines)

MHD equilibrium/instabilities,
microturbulence,
energetic particles

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

microturbulence,
ionization, recombination
radiation



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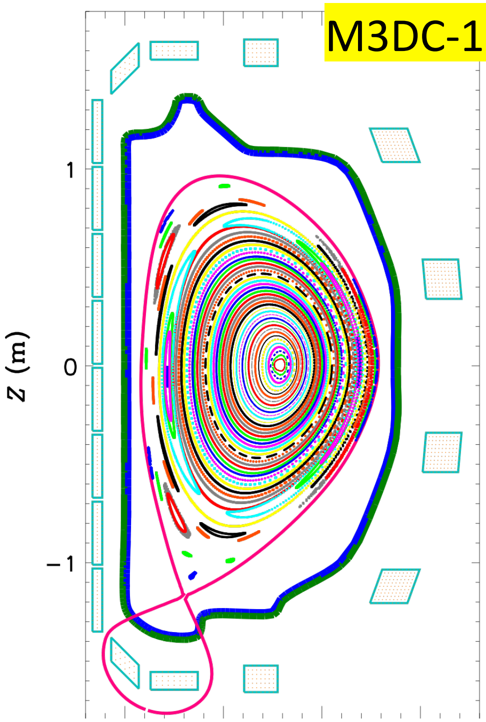
Plasmas develop instabilities that can degrade performance

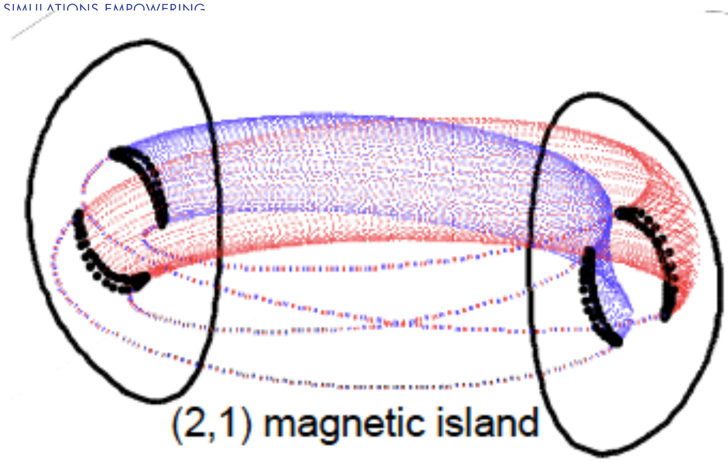


Courtesy of N. Ferraro (PPPL)

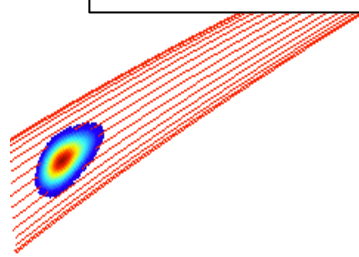
- at specific locations (resonant surfaces)
- they look like magnetic islands
- they can be stabilized by
  highly focalized beams of
  high frequency (~100 GHz) waves

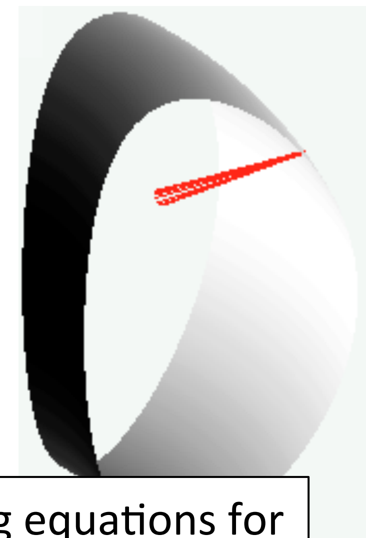
Self-consistent simulations of stabilization of magnetic islands can be done only in the framework of 3D nonlinear MHD

NIMROD/GENRAY



quasilinear corrections
to MHD equilibrium
to account for effect of waves





Ray tracing equations for
wave propagation

T. Jenkins (Tech-X)

Reduced models are based on a Modified Rutherford Equation

$$\frac{dw}{dt} \propto \sum f_{plasma}(w) + \sum f_{EC}(w)$$

Magnetic island evolution described by:

- analytic expressions for instability threshold and driving
- In a cylindrical approximation
- Analytic expressions and fitting parameters for the stabilizing effect of RF waves

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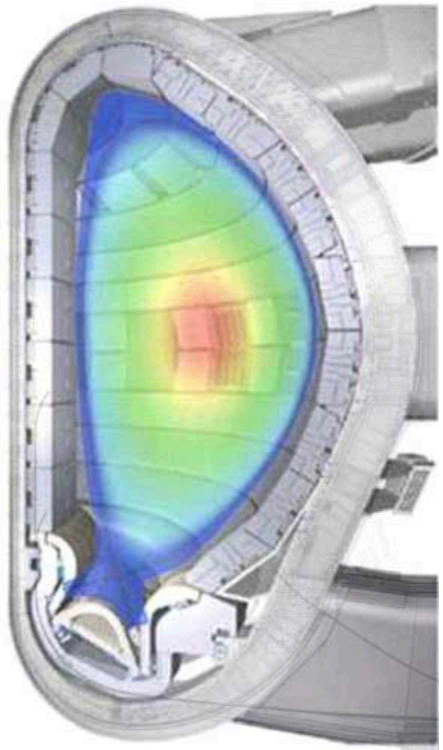
microturbulence,
energetic particles

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

microturbulence,
ionization, recombination
radiation



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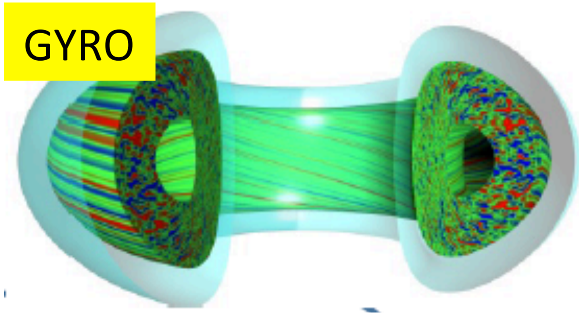
Separation of scales enables representing (almost) any transport problem as a diffusion/convection-like problem

The goal is to obtain a set of diffusion-like equations of the form:

$$\frac{\partial Q}{\partial t} + \nabla \cdot \Gamma = S(Q, \mathbf{r}, t)$$

$\Rightarrow$ for a physical variable **Q**
$\Rightarrow$ identify the flux $\mathbf{\Gamma}$
$\Rightarrow$ and the source and sink terms contained in **S**

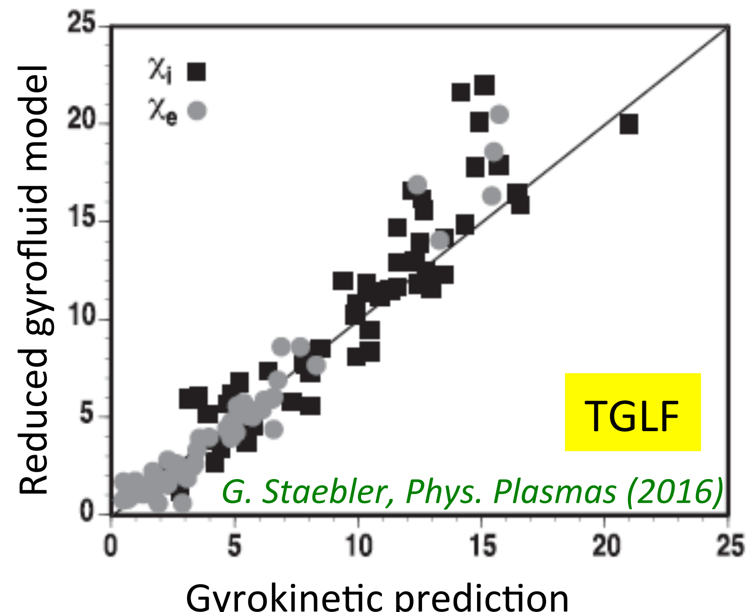
Understanding and modeling tokamak turbulent transport requires theory-based prediction of flux-gradient relationships



6D Vlasov equations =>
5D nonlinear"gyrokinetic"

State-of-the-art multi-scale ($\rho_i \rightarrow \rho_e$)
~50M CPU-hrs for 3-point scan
[*N. Howard, Nucl. Fusion (2016)*]

fluid eq. with right closure =>
Fit over limited set of GK
(< 1 sec with NN)
*[Citrin NF **55** (2015), Meneghini, NF **57** (2017)]*



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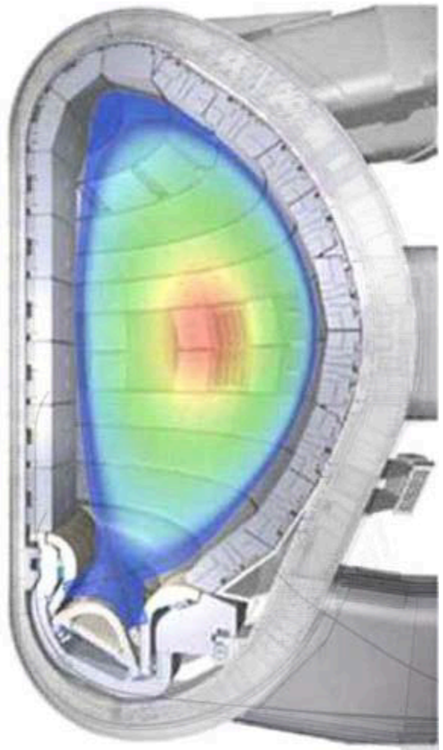
MHD equilibrium/instabilities, microturbulence, energetic particles

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

microturbulence, ionization, recombination radiation



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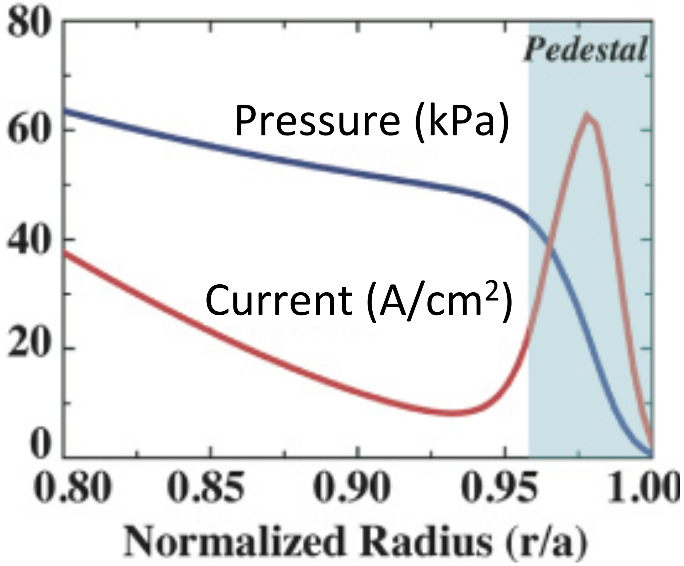
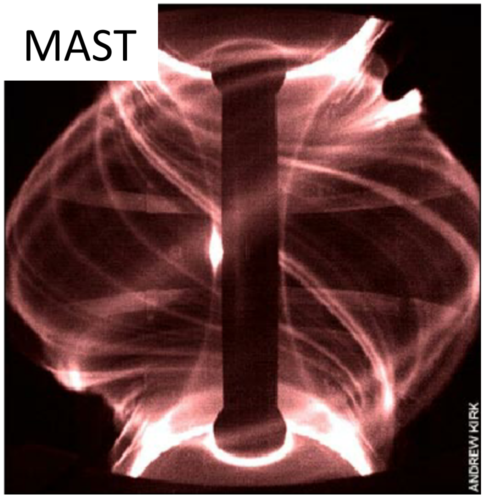
Steep gradient at the plasma edge drives MHD instabilities

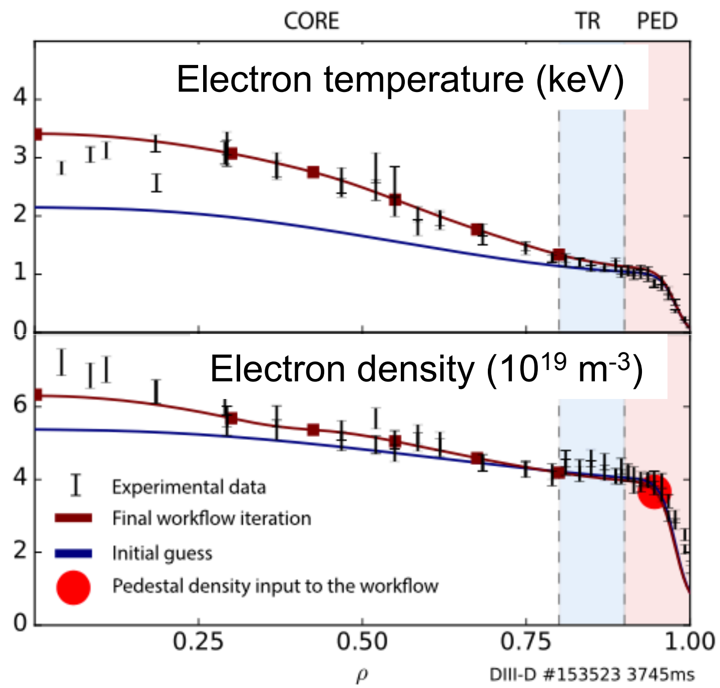


Plasmas spontaneously develop a region (pedestal) that encloses good confinement [*P. Snyder FR1.00001*]

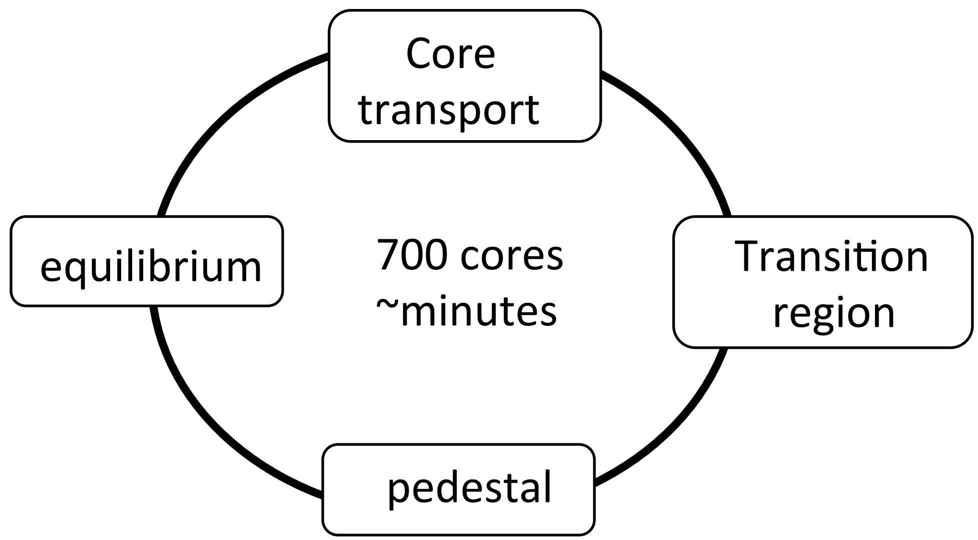


The width and height of the pedestal can be determined univocally by MHD calculations for a given value of density

Efficient workflows allow combined solution of core transport and pedestal MHD stability



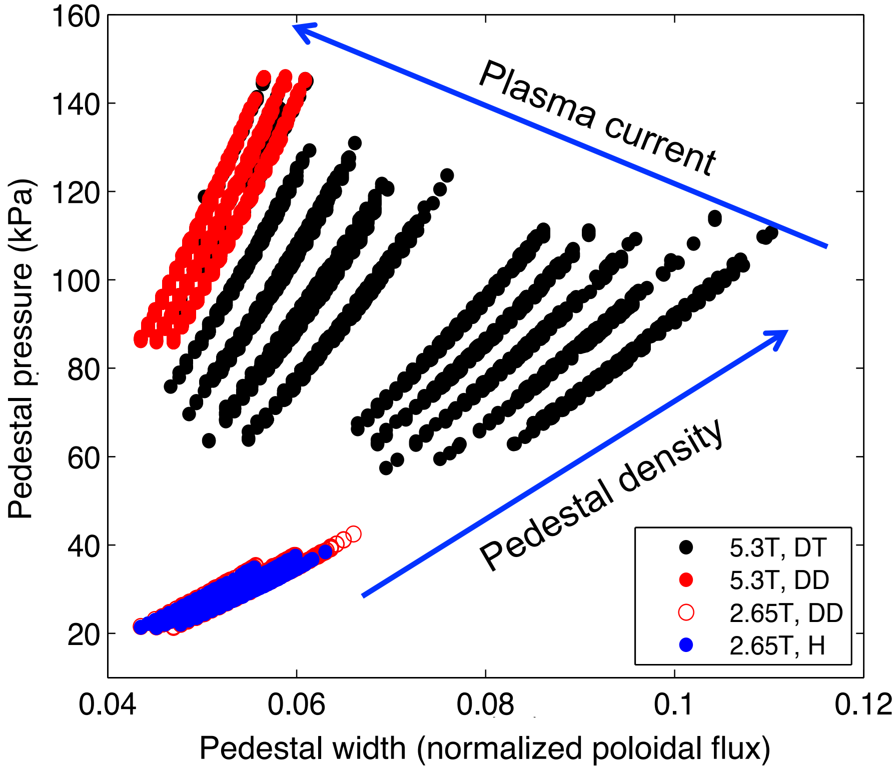
O. Meneghini, Phys. Plasmas ***23*** *(2016)*



Not yet a self-consistent solution:

- model for pedestal density still missing
- model for transition region that includes microturbulence still missing

Replacing MHD stability pedestal calculations with a lookup table advantageous in time-dependent simulations



~6500 points cover the expected ITER operational space

[task under international collaboration]

A neural network has also been developed [*O. Meneghini, NF 57 (2017)*]

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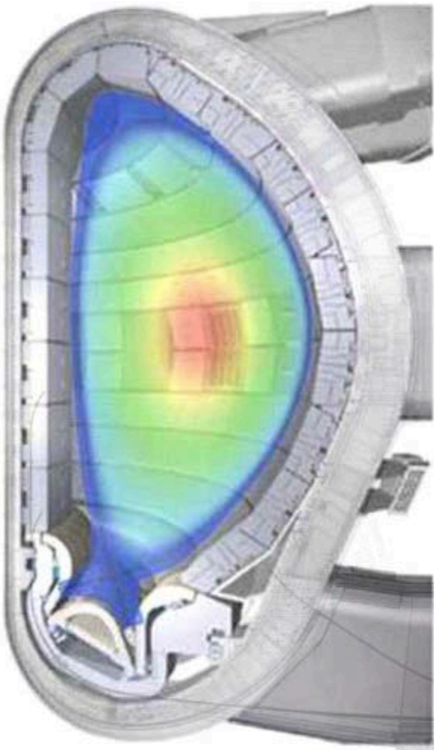

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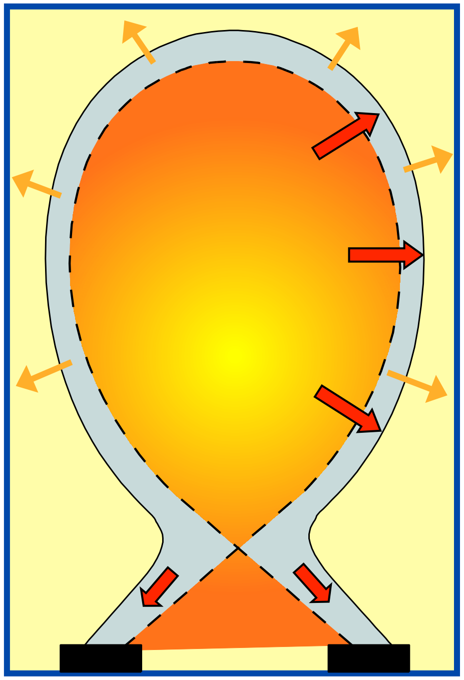
Where the plasma meets the wall: the Scrape-Off-Layer (SOL)



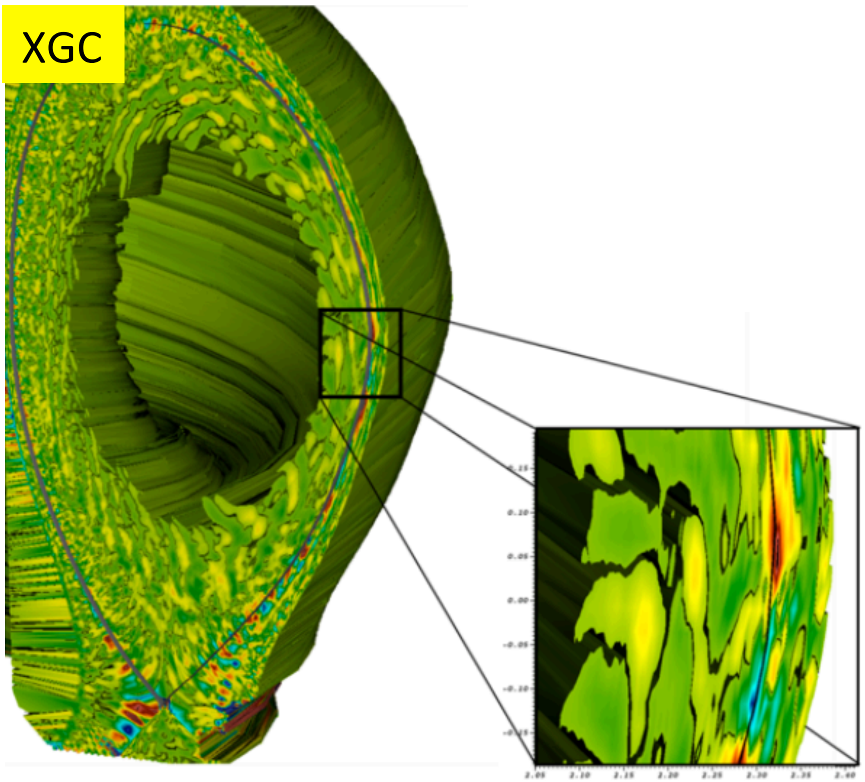
Courtesy of V. Soukhanovskii (LLNL)

Heat losses from the plasma can damage plasma facing components

SOL width determined by competition between parallel and perpendicular transport

*R. Goldston, NF **52** (2012), **PI3.00004***

Gyrokinetics simulations that extend the computation domain to the wall needed to develop reduced models for the edge plasma



S-H Ku, DI2.00004

We need a better model for the plasma edge,
Including the region inside the pedestal,
- Microturbulence
- coherent structures (blobs)
- Separation of ion and electron scales
- Wall sources

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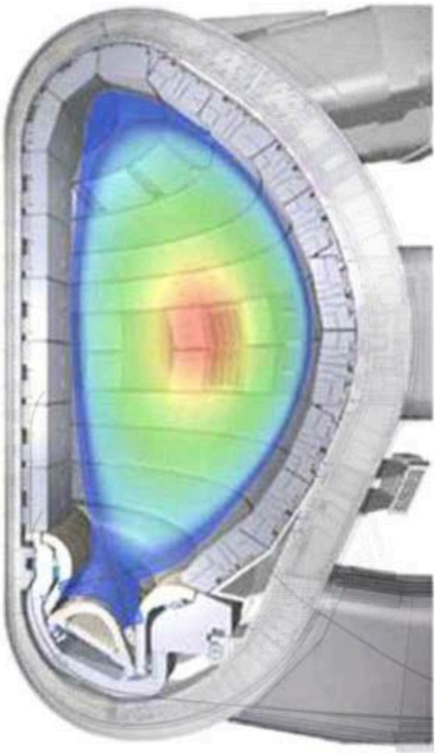

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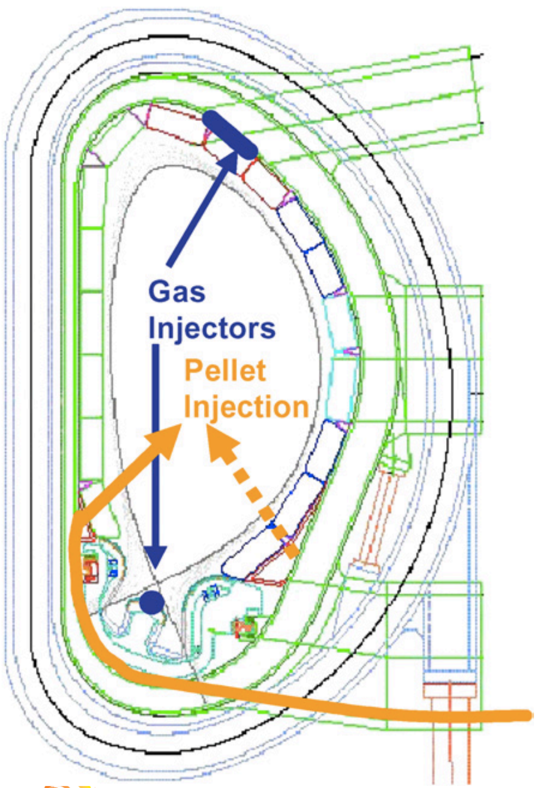
Pellets

Edge transport and fuelling are critical ingredients to model the plasma evolution in burning plasma conditions



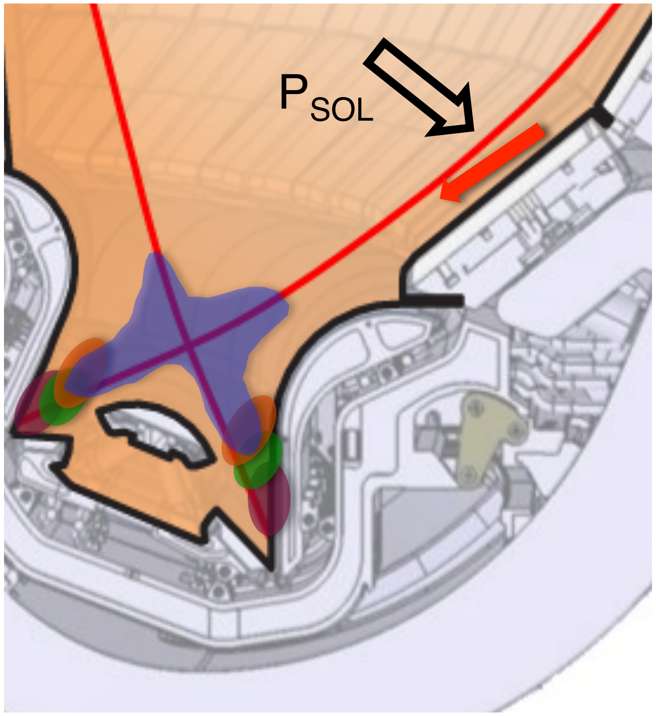
Heat conduction zone

Impurity radiation zone

$H^0/D^0/T^0$ ionization zone
(T_e>5eV)

Neutral friction zone

Recombination zone
(T_e<1eV)



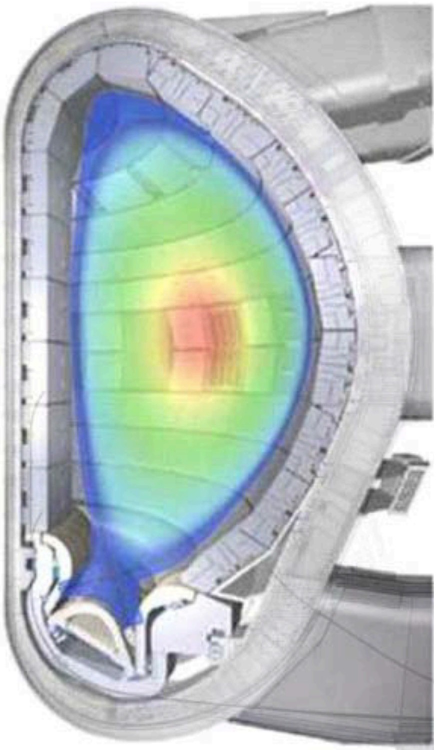
Courtesy of R. Pitts (ITER Organization)

Confined plasma
(closed magnetic field lines)

MHD equilibrium/instabilities,
microturbulence,
energetic particles

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

turbulence,
ionization, recombination
radiation



The plasma is surrounded
by solid structures:
Plasma-material interactions

External heating

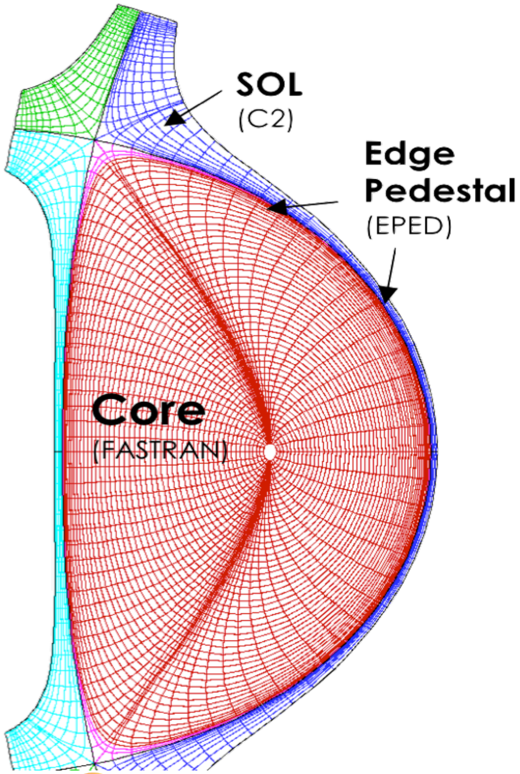
Radiofrequency waves
Neutral beams

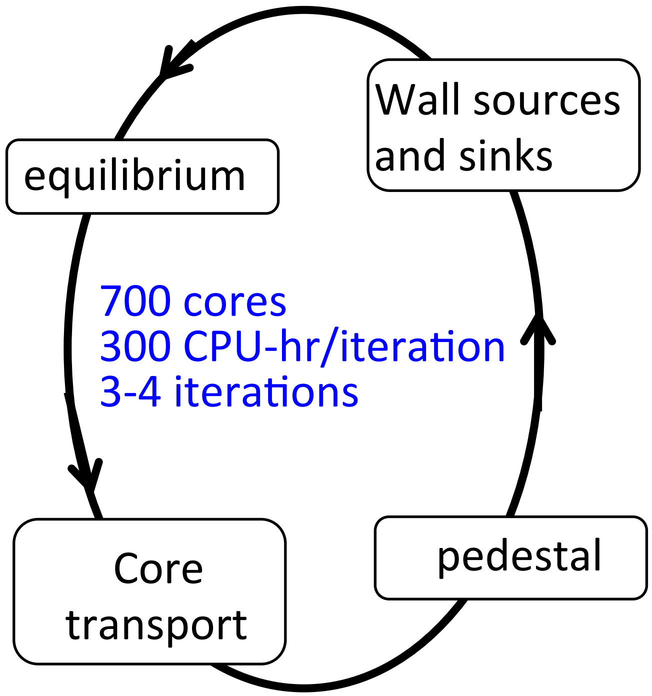
fueling

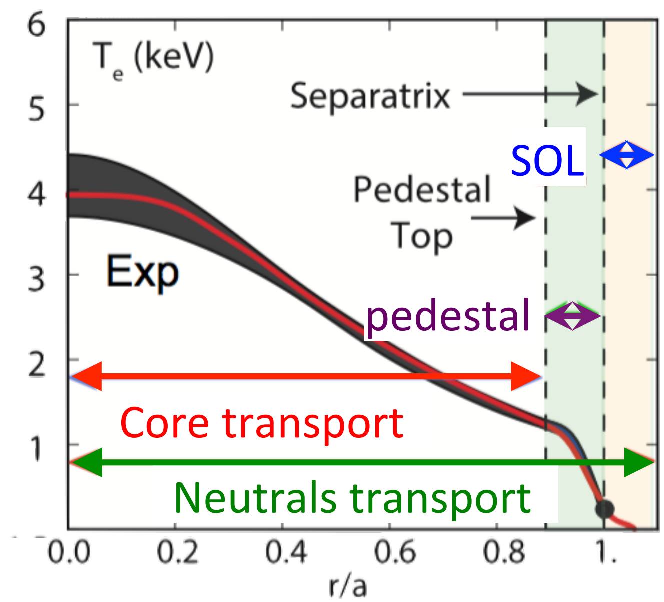
Gas injection
Pellets

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

AToM SciDAC







J-M. Park, D. Green (ORNL)

Integrated modeling on single time-slice has led to great insight

- On small scales dynamics and multi-scale couplings
- On how to plug-in models to describe the plasma from axis to wall

... but plasmas in tokamaks are dynamical, nonlinear systems …

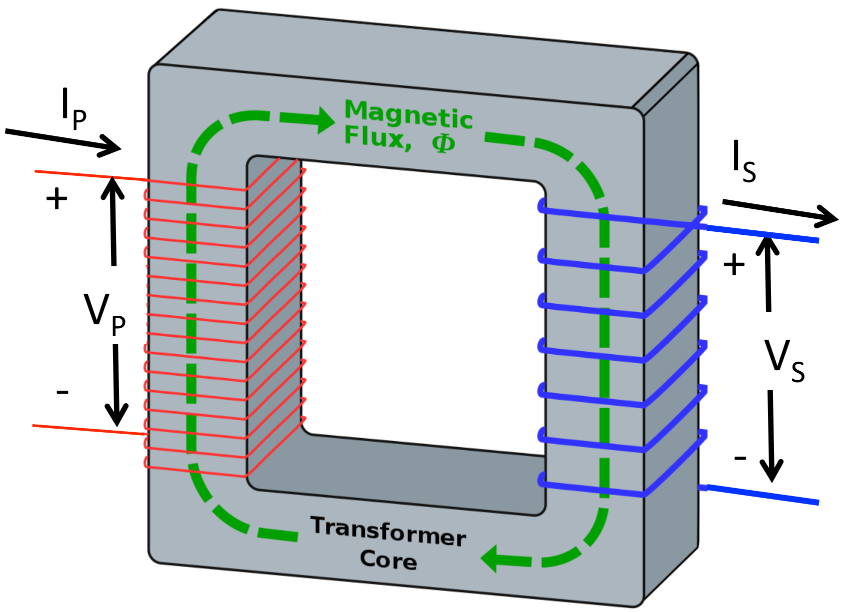
The other side of integrated tokamak modeling:

an entire plasma discharge from startup to termination

The basics …

A tokamak is like a transformer, where the plasma is the secondary winding

In a transformer the circuits are magnetically connected



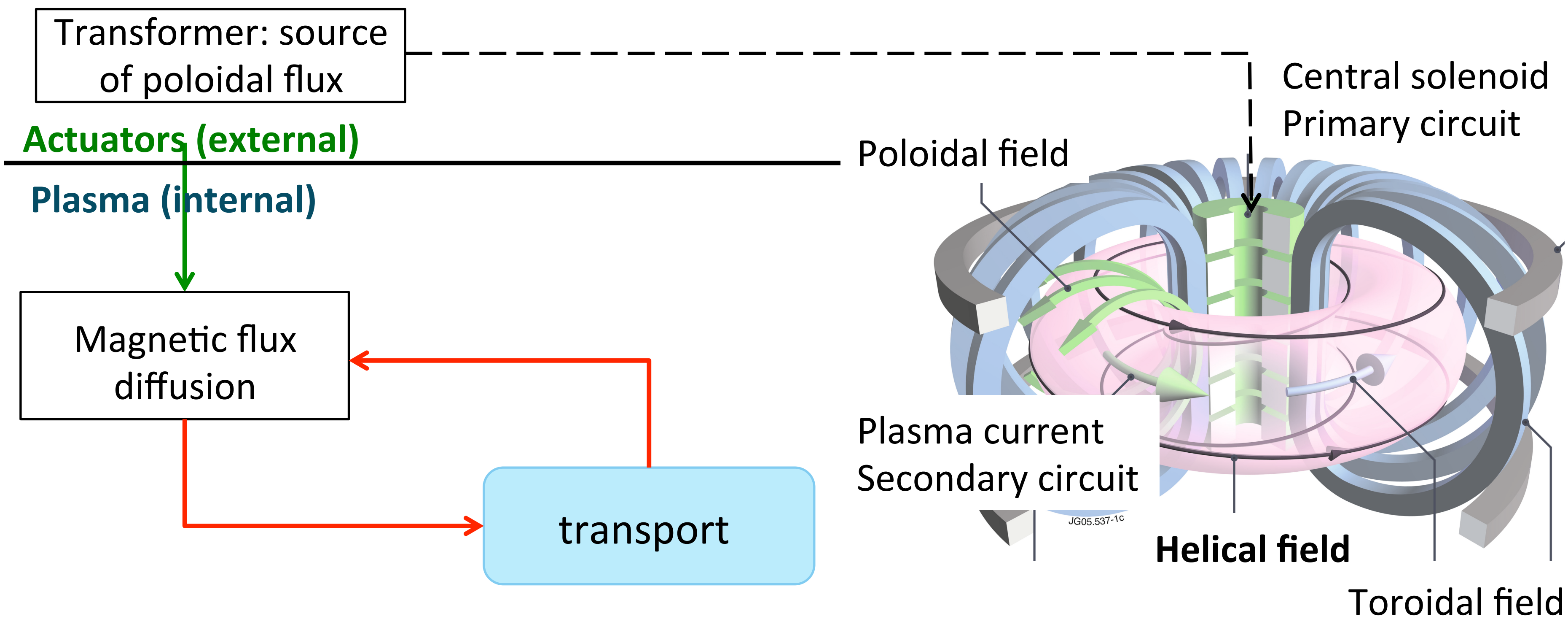
In the primary: $I_P(t) \Rightarrow B_P(t)$

In the secondary: $I_S(t) \Rightarrow B_S(t)$

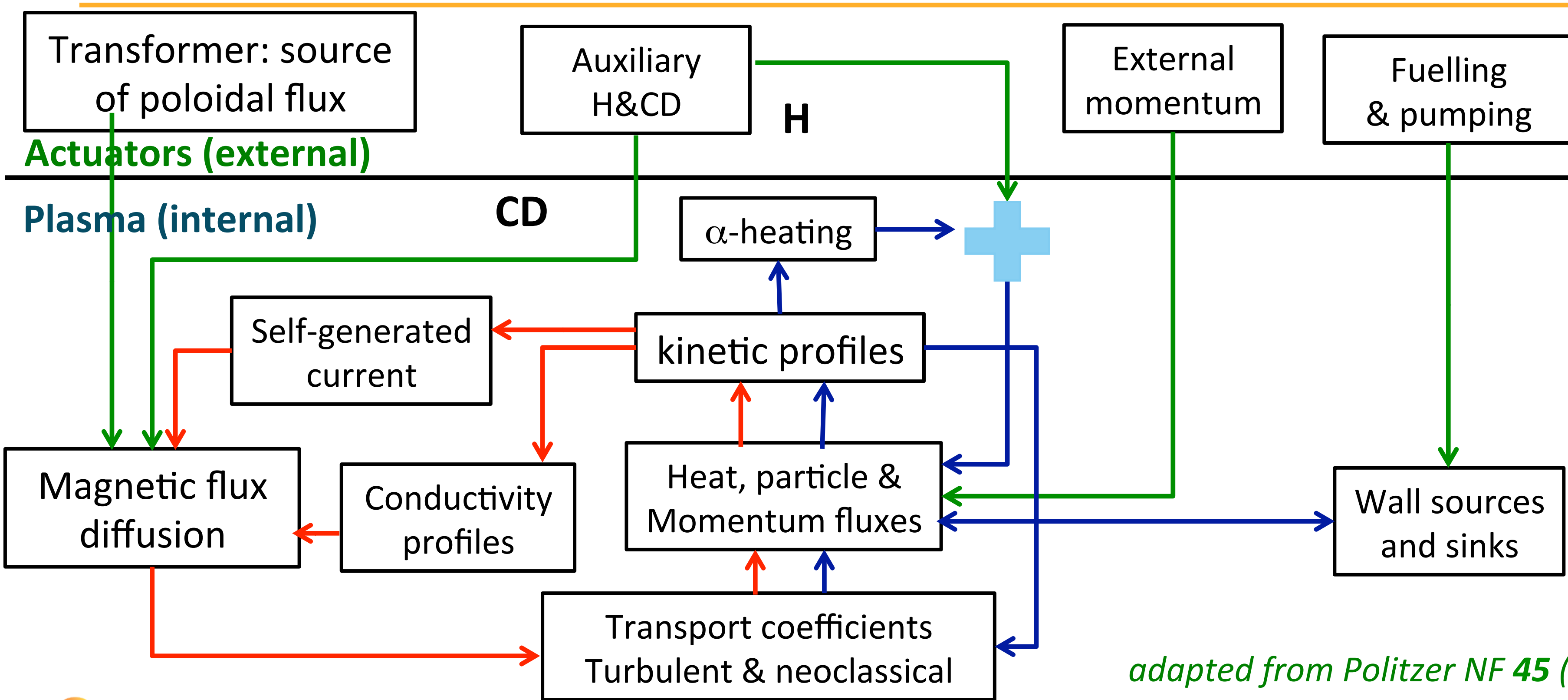
Total magnetic flux density: $B(t)=B_P(t)+B_S(t)$

Limitation: it is pulsed, cannot operate continuously in steady-state

In a tokamak the secondary circuit is a conducting fluid …
… things get complicated



A tokamak simulator needs to connect fast (transport) and slow (current diffusion) time scales



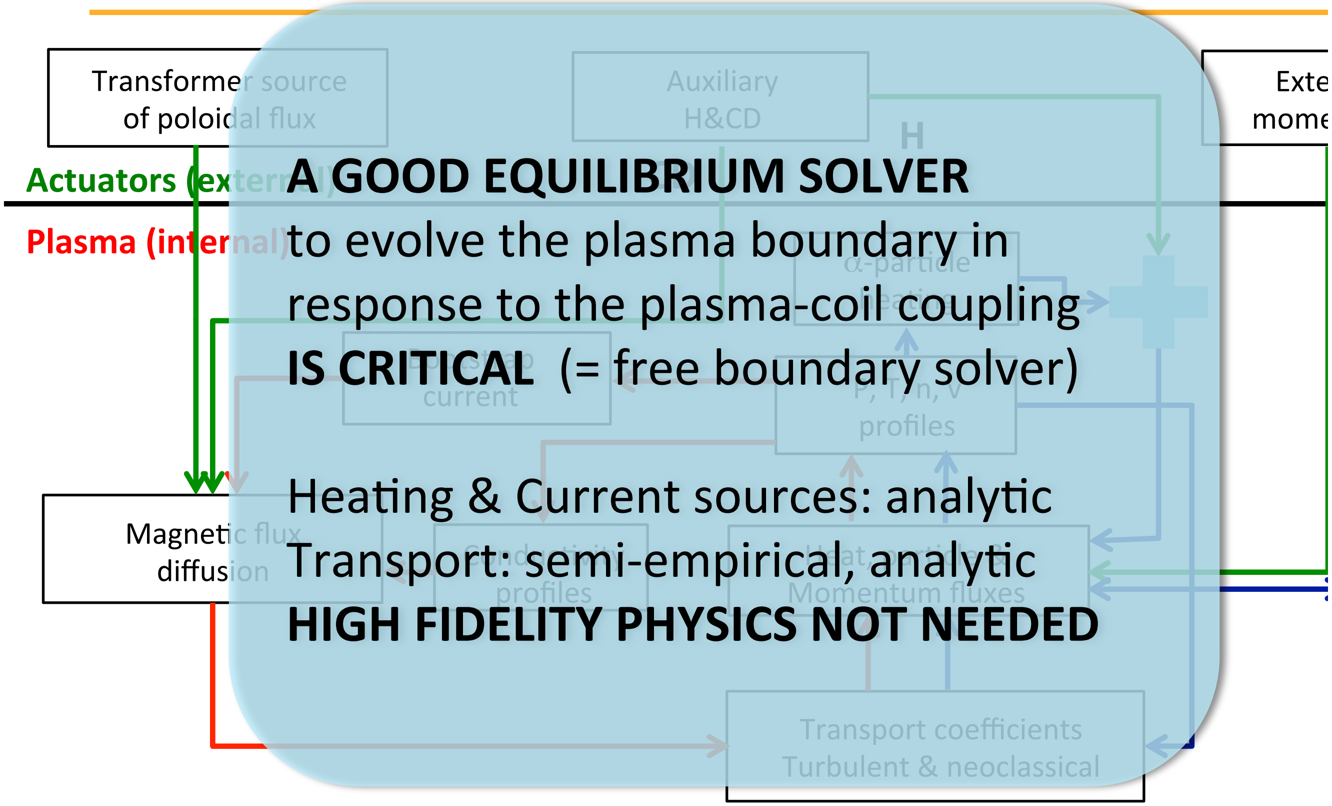
*adapted from Politzer NF **45** (2005)*

All the steps we take when we model an ITER plasma discharge

The goals of ITER: **I**nternational **T**hermonuclear **E**xperimental **R**eactor

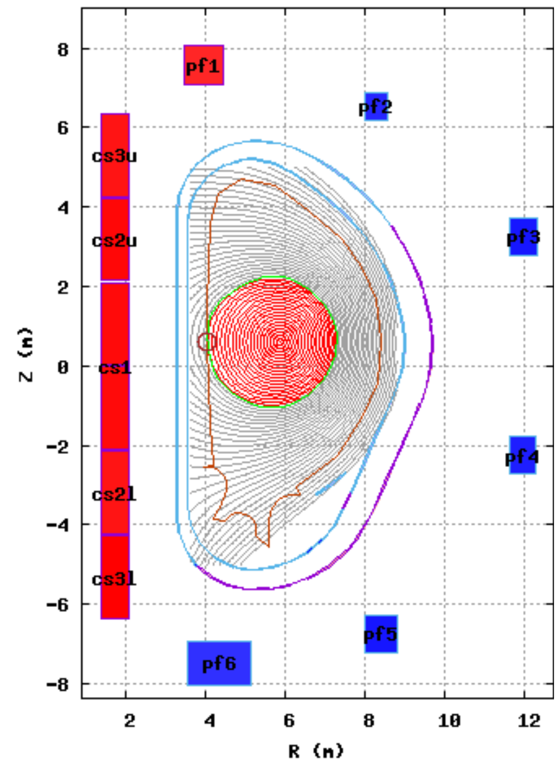
- Produce 500 MW of fusion power
- Demonstrate integrated operation of technologies for a fusion power plant
- Achieve a self-heated deuterium-tritium plasma
- Test tritium breeding
- Demonstrate safety of fusion devices

The first step is to get all coil currents and plasma shape right

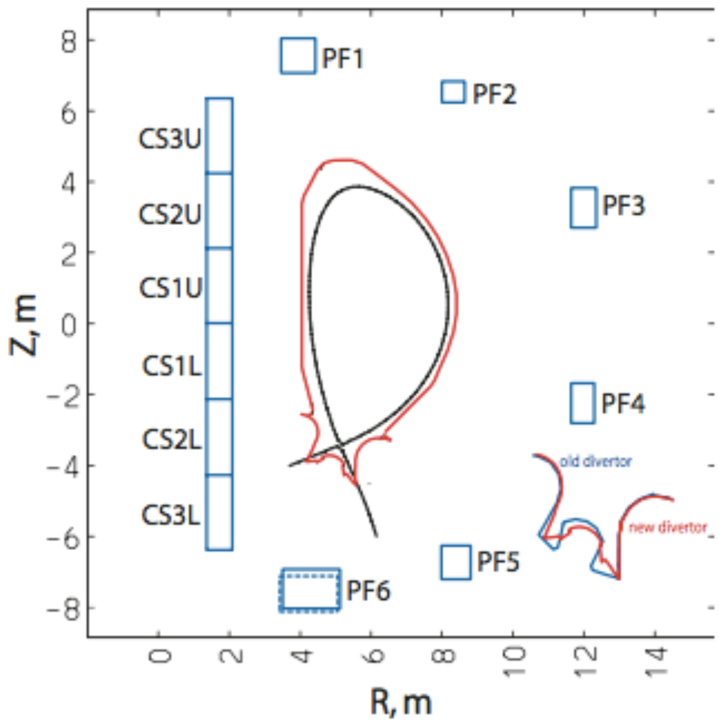


A GOOD EQUILIBRIUM SOLVER
to evolve the plasma boundary in response to the plasma-coil coupling
IS CRITICAL (= free boundary solver)

Heating & Current sources: analytic
Transport: semi-empirical, analytic
HIGH FIDELITY PHYSICS NOT NEEDED



These simulations have been valuable to define and revise the ITER coil operational space and the plasma control capabilities

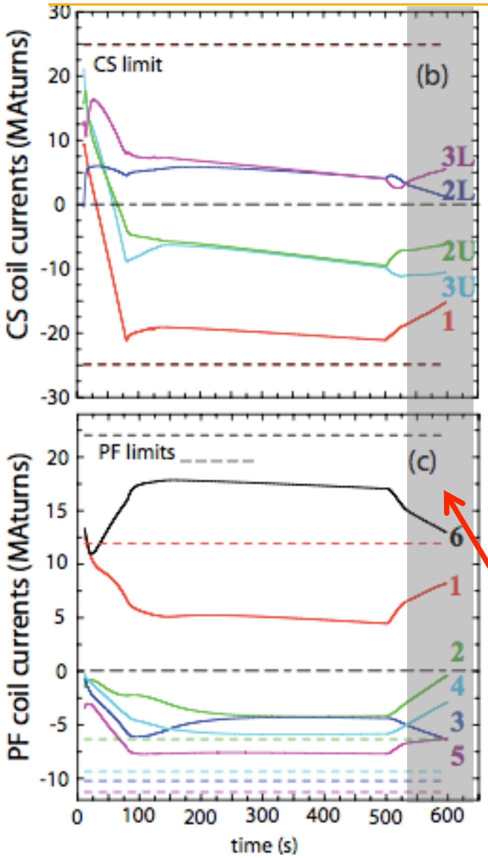


*[C. Kessel et al, NF **49** (2009)]*

New poloidal field coils layout expands operational space:

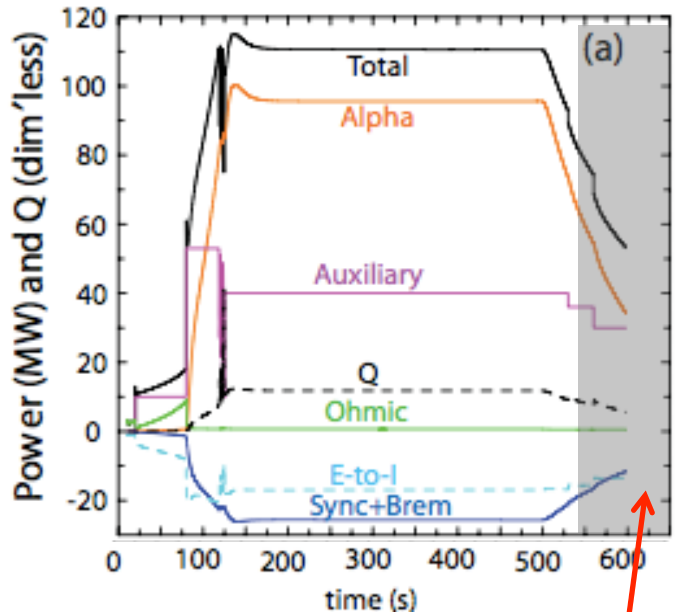
- Flattop burn duration
- Operation with broader current profile

Simulations with simplified transport are designed to test engineering parameters, not to discuss physics



*[T. Casper et al, NF **54** (2014)]*

CORSICA



With assumptions on transport, confinement to satisfy target fusion power

$\Rightarrow$ **Assessment of coil limits**

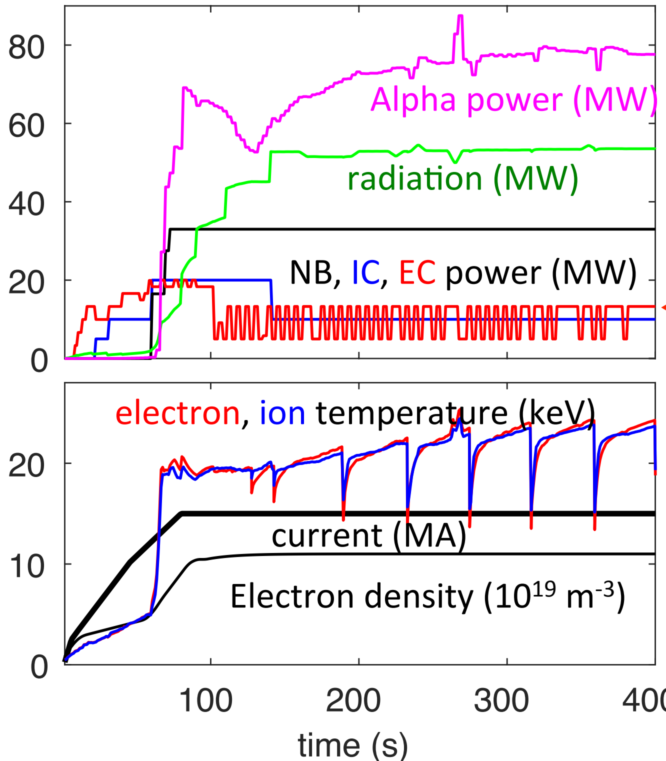
Plasma termination is a critical area of ongoing research

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

- Can this plasma really achieve the target?
- How additional physics constraints affect the results?

Physics-based models for thermal transport and current evolution can move the operational point away from target

TRANSP



alpha power P_α responds nonlinearly to core transport and pedestal width and height

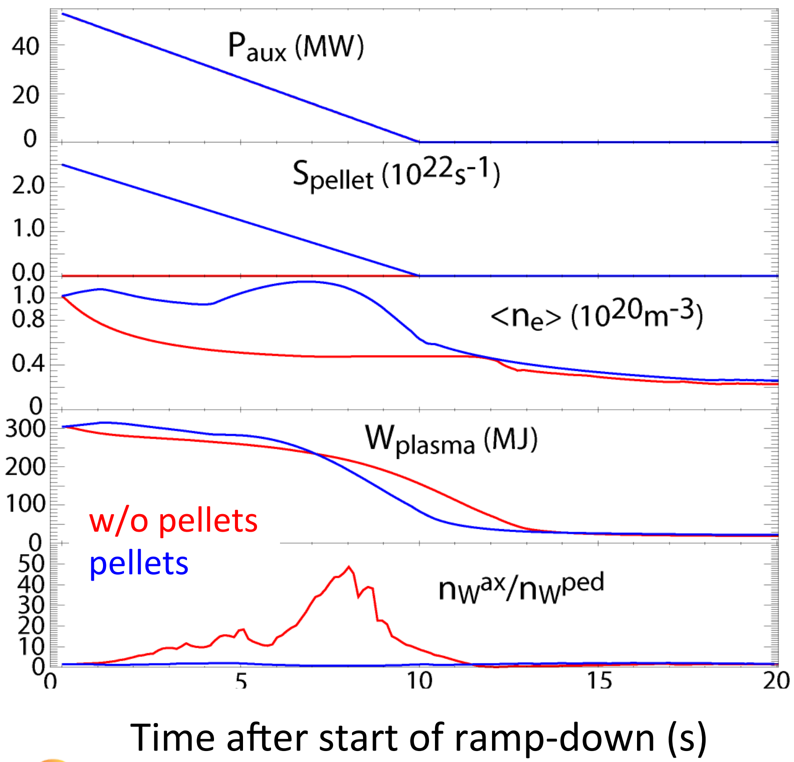
external power under feedback control

global MHD stability included in evolution of temperature and current

Plasma does not achieve the target of P_α=100MW

Simulations with fully integrated 2D edge transport plasma have indicated the importance of fueling during ITER plasma termination

JINTRAC



- Pellet fueling at exit from H-mode needed to avoid accumulation of tungsten in the core
- Model has been validated on JET, in dedicated ITER-like experiments.

A. Loarte IAEA-FEC (2016)
*F. Koechl, **NF** 57 (2017)*

The path forward to an all-inclusive tokamak simulator

- Reduced models:
  - from nonlinear 3D MHD stability
  - for edge plasma turbulence induced transport
  - for wave propagation in the Scrape-off-Layer
  - for energetic particle induced transport
  - Plasma startup (SNU, Univ. Kyoto)

The path forward to an all-inclusive tokamak simulator

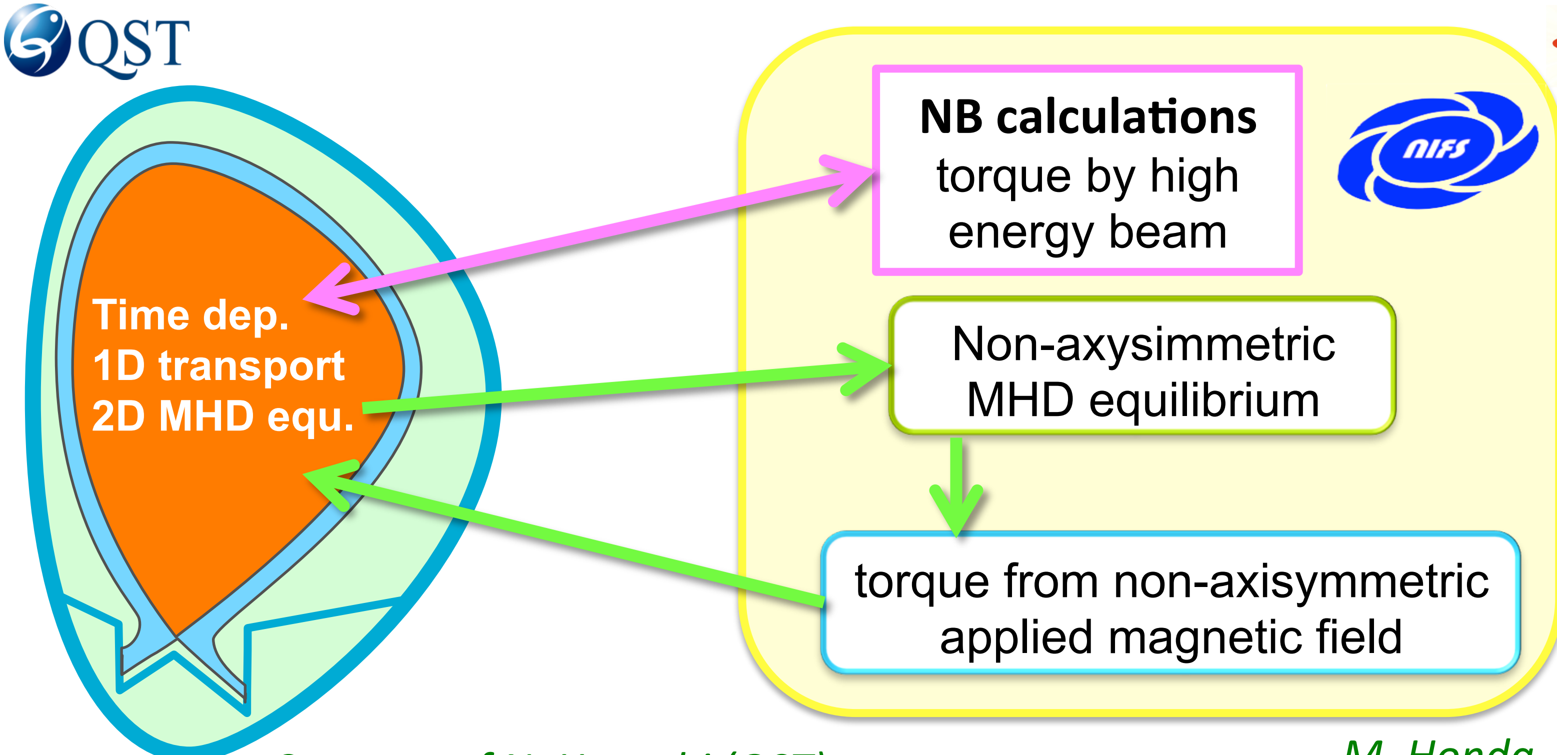
- Reduced models from nonlinear 3D MHD stability
  - **Plasma response to external perturbations**
  - Disruptions (trigger)
  - MHD instabilities (onset, control)
  - global instabilities, like sawtooth cycle [**CP11.00113**]

Reduced models for edge plasma turbulence induced transport

Reduced models for wave propagation in the Scrape-off-layer

Reduced models for energetic particle induced transport

Better models for prediction of plasma rotation needed for modeling plasma response to applied magnetic perturbations



Courtesy of N. Hayashi (QST)

*M. Honda, NF **57** (2017)*

The path forward to an all-inclusive tokamak simulator

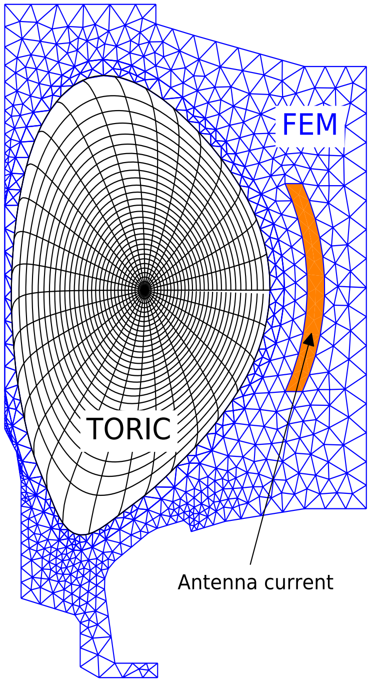
Reduced models from nonlinear 3D MHD stability

Reduced models for edge plasma turbulence induced transport

- Reduced models for wave propagation in the Scrape-Off-Layer

Reduced models for energetic particle induced transport

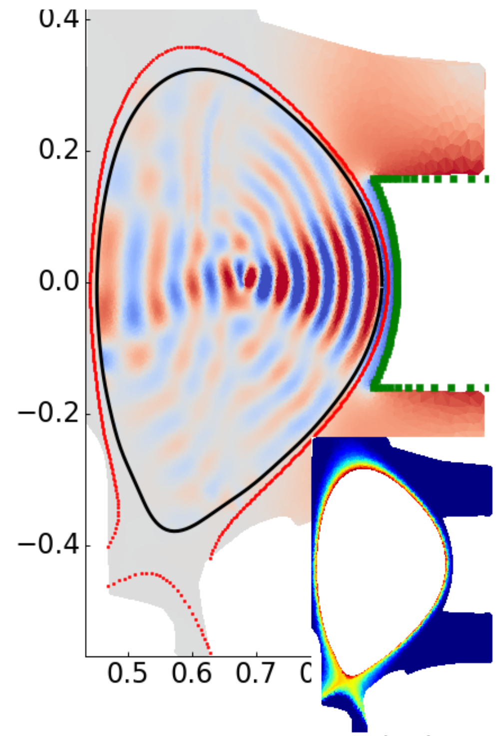
Hybrid approach to modeling of RF wave propagation is a promising avenue towards implementation in tokamak simulator



Core: **Axisymmetric** flux surface 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

Would benefit from realistic model of SOL



Density in SOL

S. Shiraiwa (PSFC) **VI2.00003**

The path forward to an all-inclusive tokamak simulator

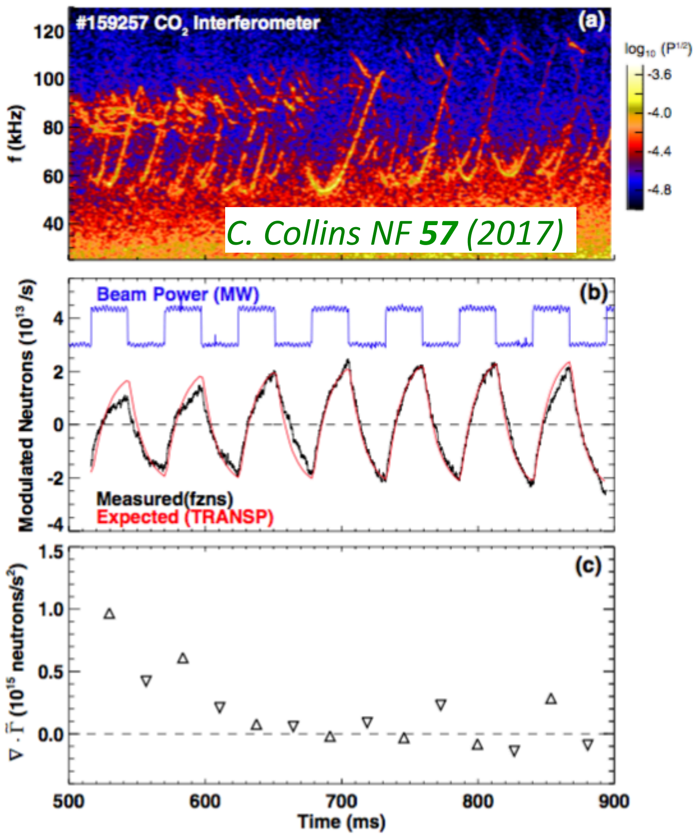
Reduced models from nonlinear 3D MHD stability

Reduced models for edge plasma turbulence induced transport

Reduced models for wave propagation in the Scrape-off-layer

- Reduced models for energetic particle induced transport

Fast particles can drive instabilities, like Alfvenic modes



*C. Collins NF **57** (2017)*

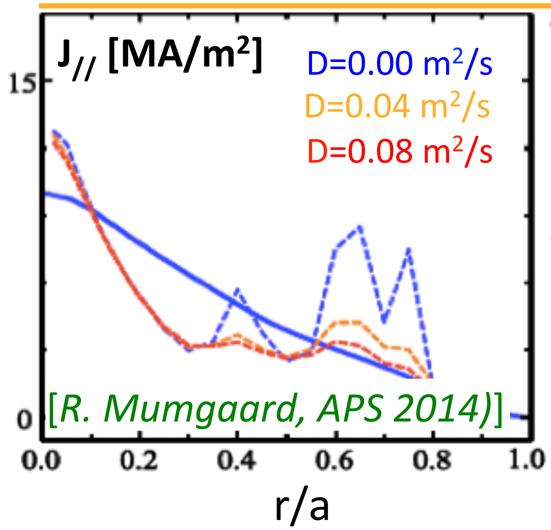
[SciDAC project ISEP]

⇒ Instabilities eject fast particles (e.g. alphas)
- ⇒ Decrease performance
- ⇒ Cause localized losses and damage to wall

⇒ Challenges:
- ⇒ Understand physics to develop scenarios not prone to instabilities
- ⇒ Develop control tools to mitigate/ suppress instabilities

Experimental validation is critical

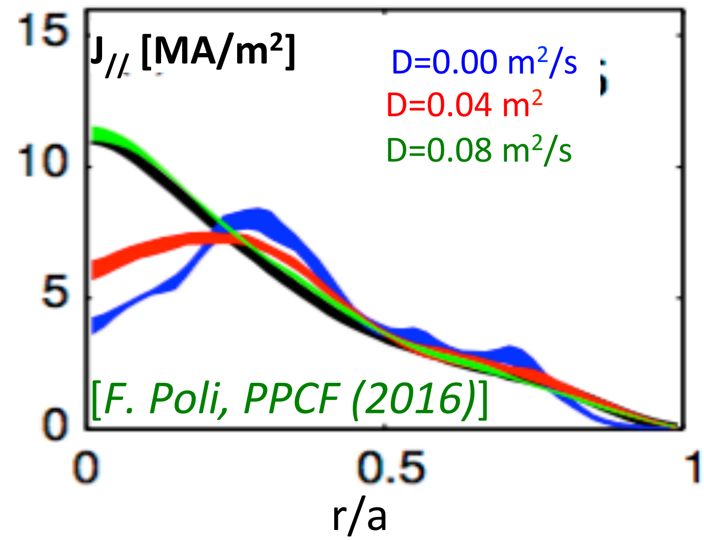
Time-dependent validation is critical for modeling of wave propagation in plasmas



GENRAY/CQL3D

Standalone ray-tracing +Fokker-Planck solver

⇒ large off-axis current, not seen in experiments



Time-dependent simulation

=> self-consistent evolution of wave field and magnetic equilibrium

Concluding remarks

- Increasing computing capabilities allow to solve bigger problems
- Efficient workflows allow to solve complex problems
- The path forward for an all-inclusive tokamak simulator should focus on reduced models
- Validation against experiments and verification against extreme scale calculations are critical to retain fidelity while reducing computational time