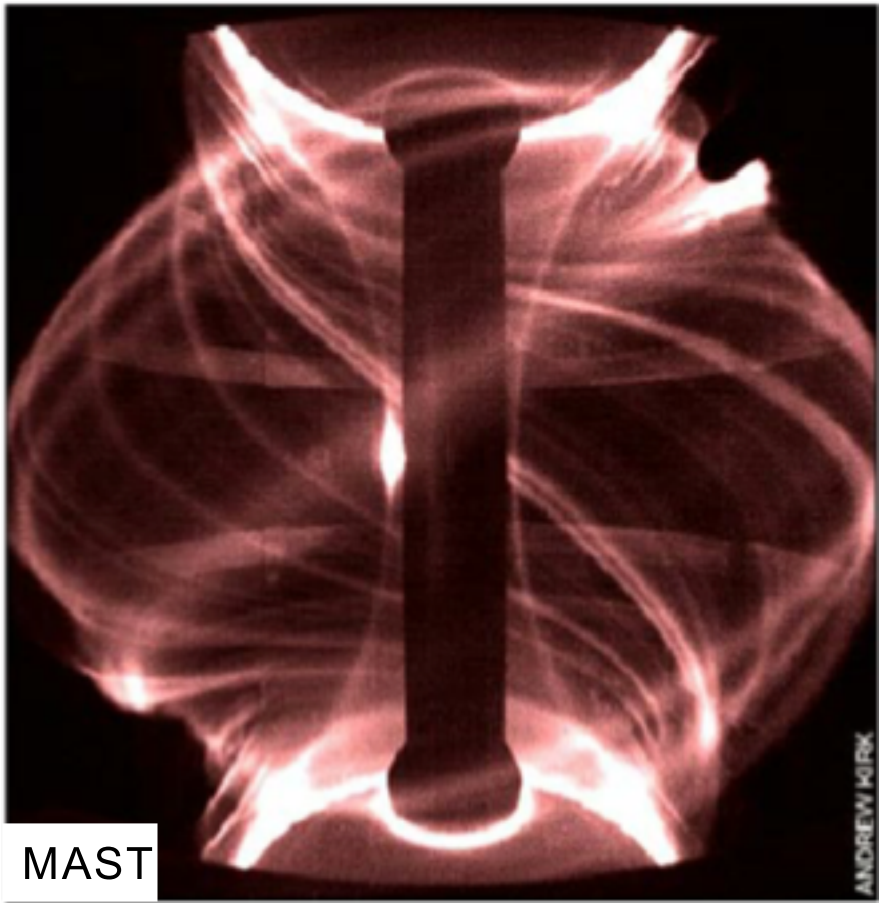
Modeling a tokamak from A to Z

Francesca Poli (fpoli@pppl.gov)
Integrated Modeling and Control group
Princeton Plasma Physics Laboratory

PPPL PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

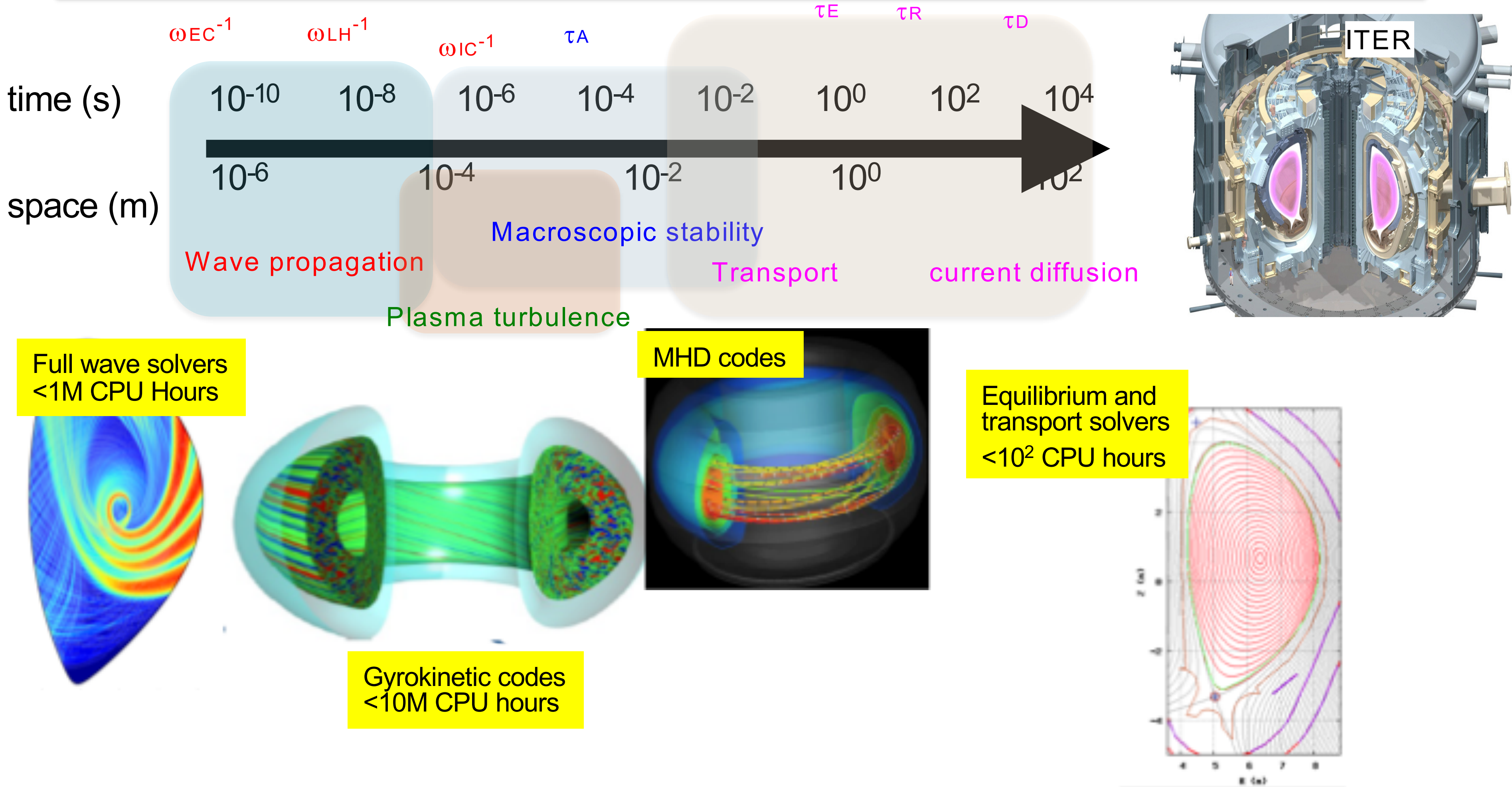
There is a lot going on into a plasma



There is a lot going on into a plasma (including rubbish)

Courtesy of Filippo Scotti [LLNL]

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



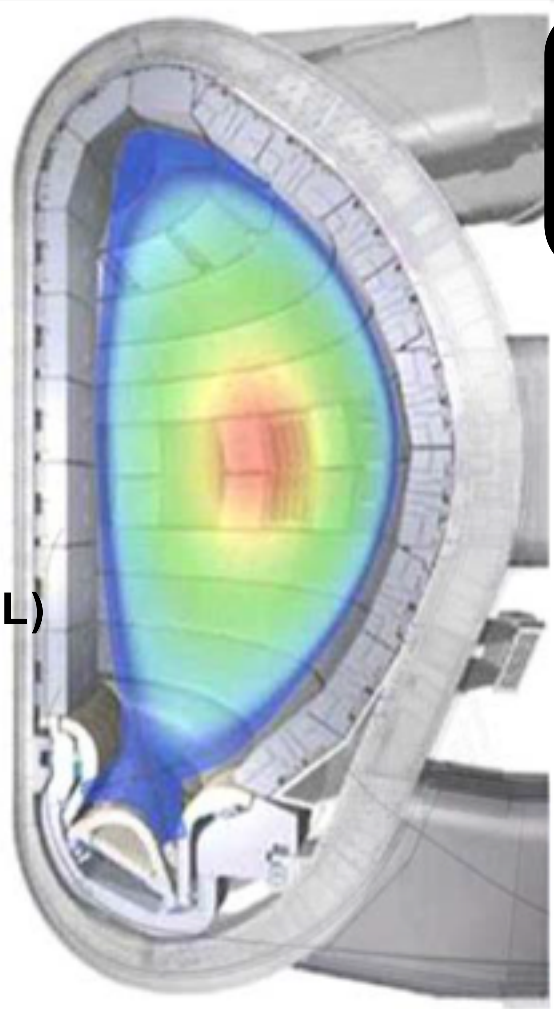
In a tokamak these scales are all coupled

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

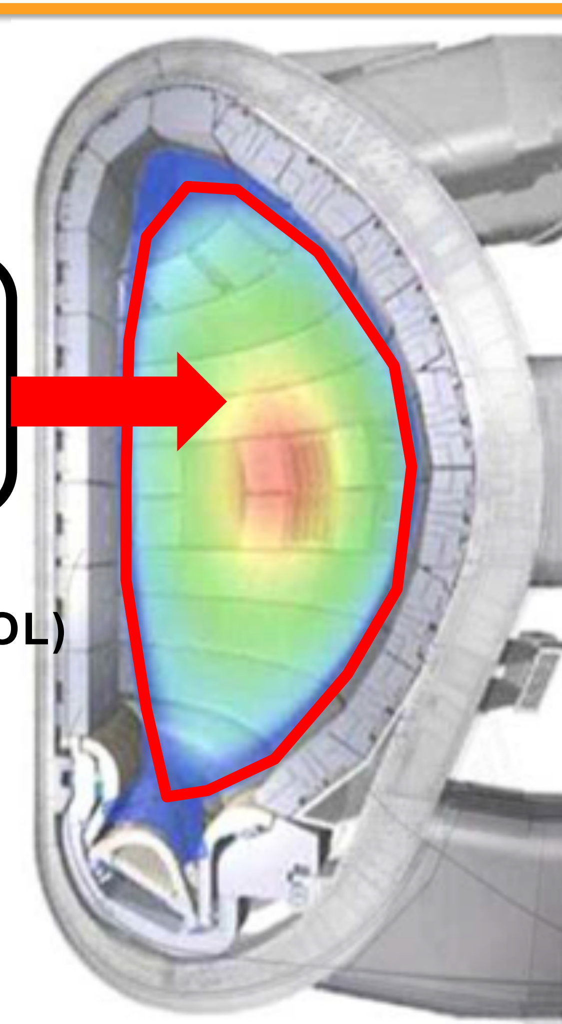
Particles and energy are ‘confined’ by magnetic fields

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

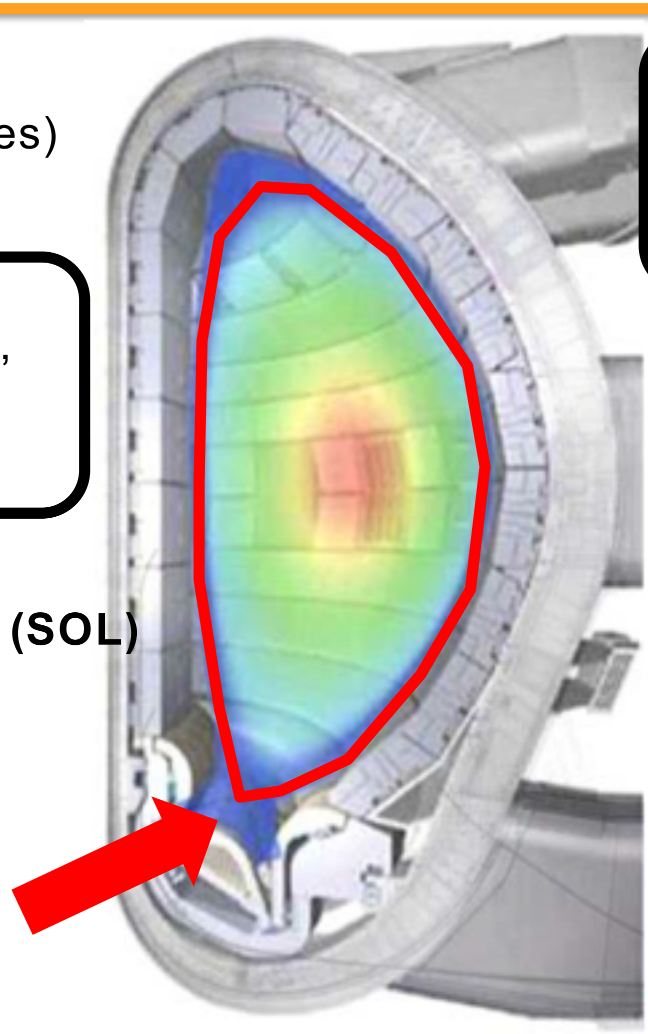
and they can also ‘flow’ along open magnetic field lines

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

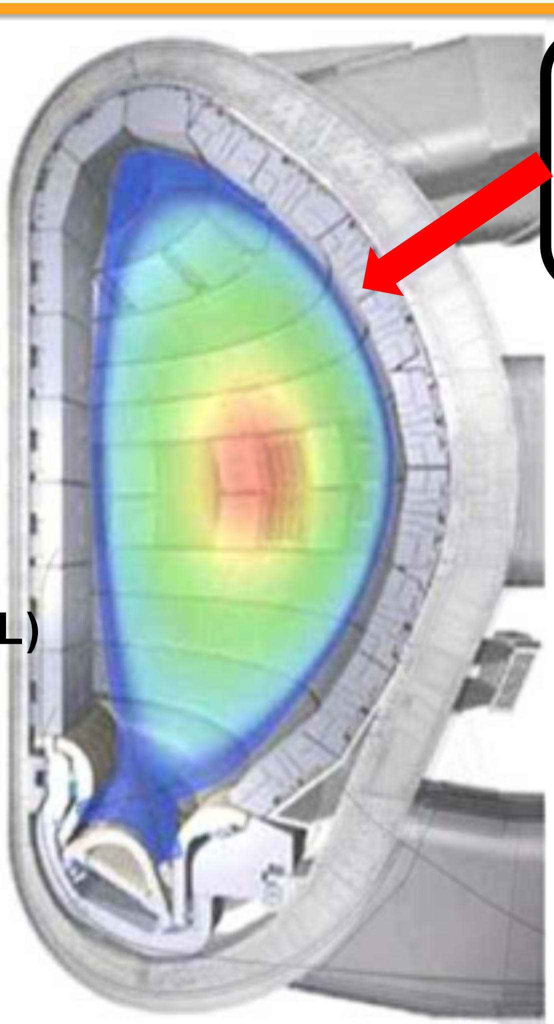
Plasmas in a tokamak are in contact with the 'wall'

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

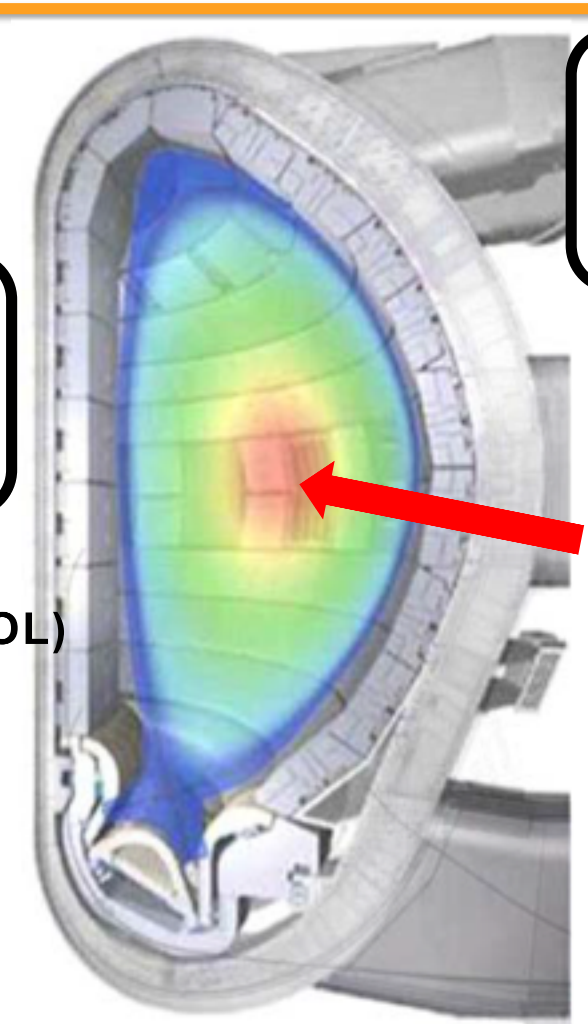
Plasmas in a tokamak need to be 'heated'

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

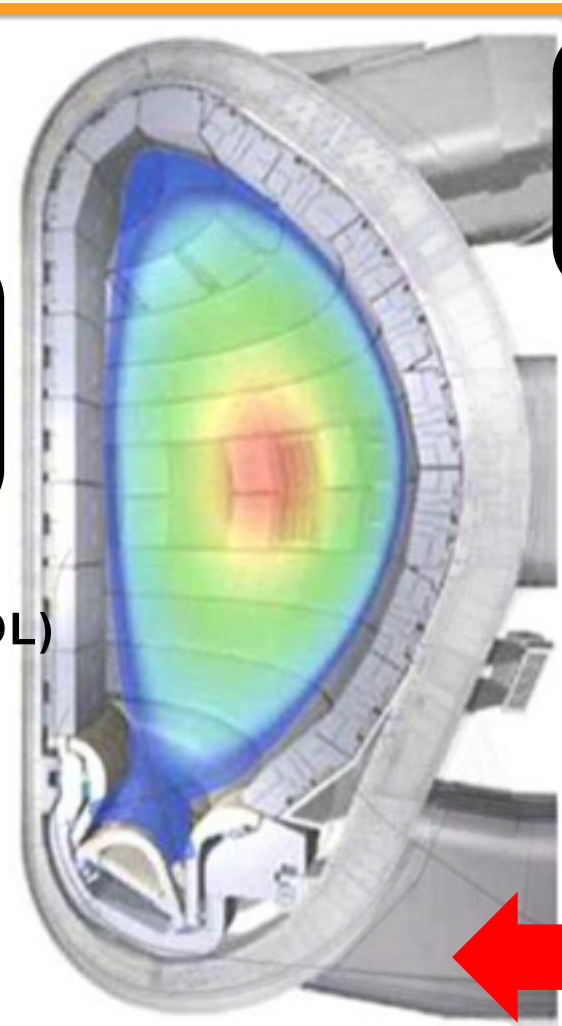
Plasmas need frequent pit stops for 're-fueling'

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

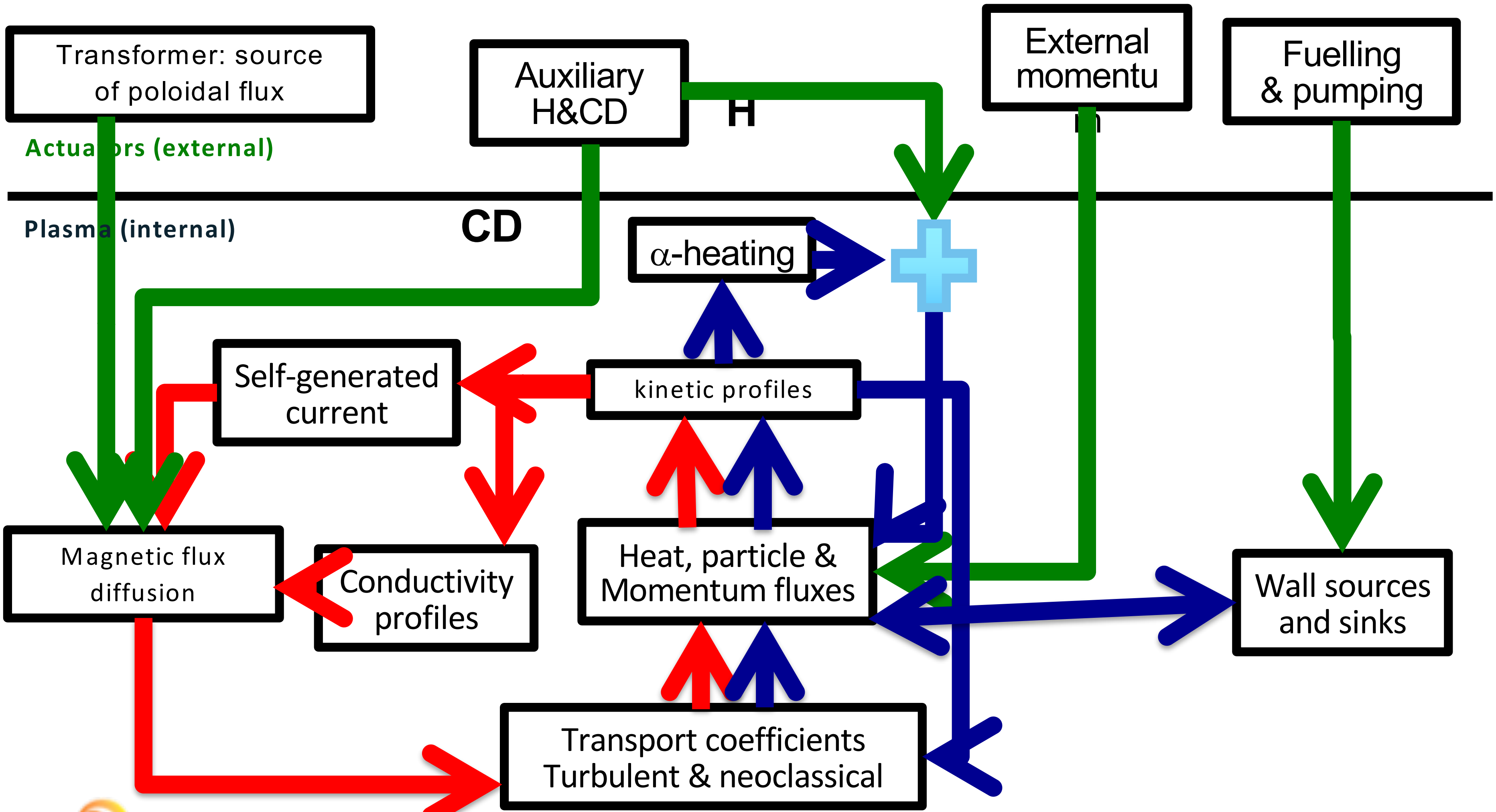
Radiofrequency waves
Neutral beams

Fueling

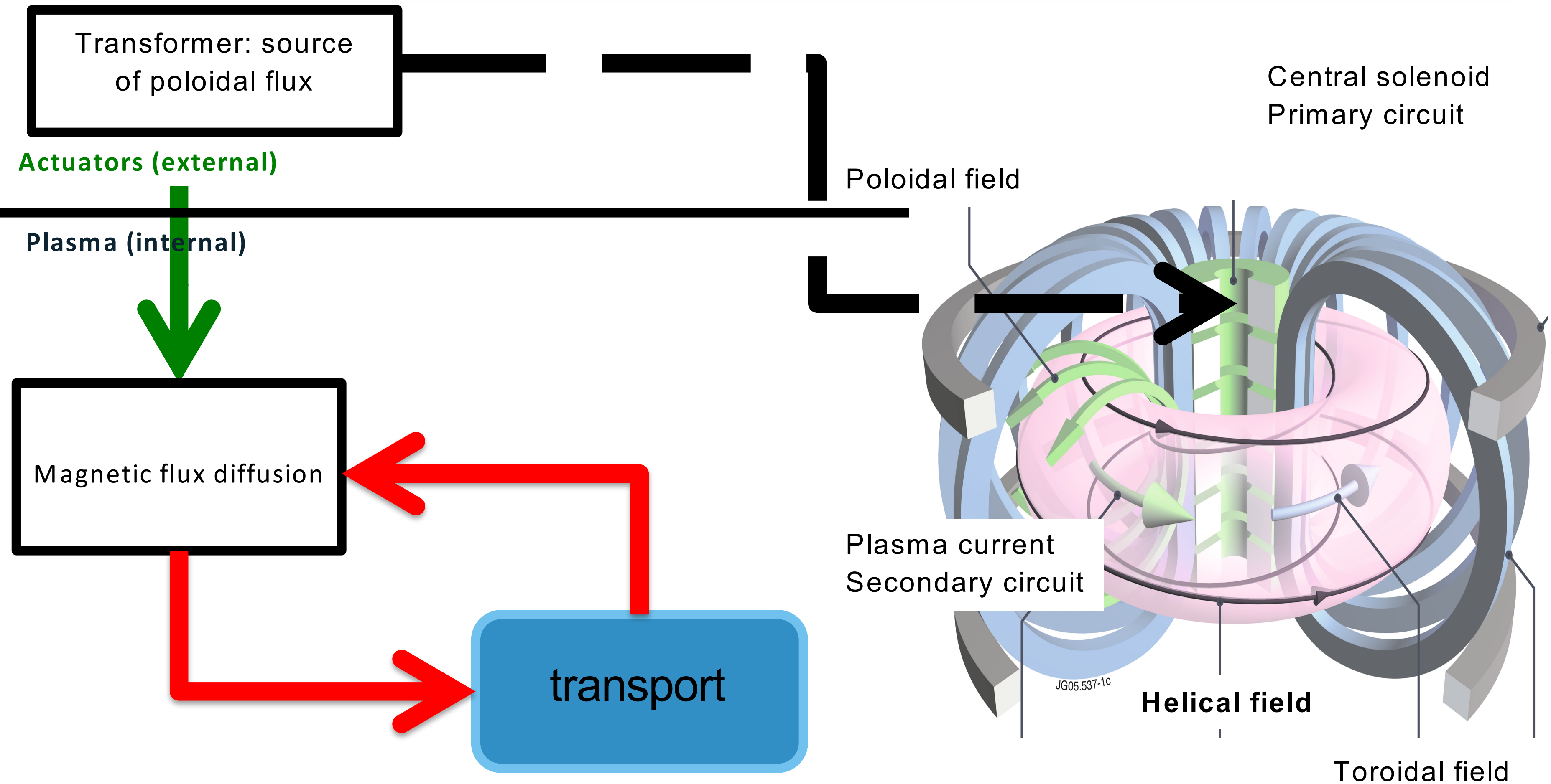
Gas injection
Pellets

Modeling a tokamak is like playing with LEGO®
… all you need is a lot of bricks, the good ones

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



A tokamak is a transformer, but the secondary circuit is a conducting fluid … sooo complicated



A plasma in equilibrium can be described by ideal MHD

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

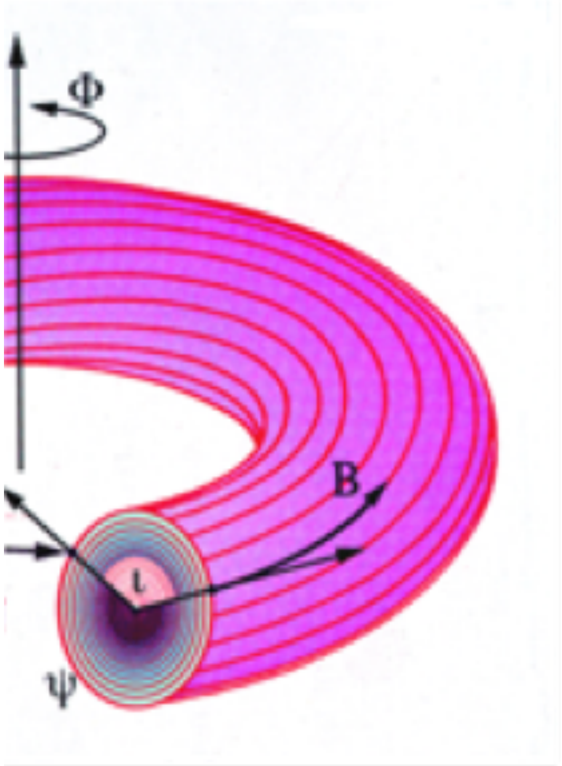
$$\mathbf{B} \cdot \nabla p = 0 \qquad \mathbf{j} \cdot \nabla p = 0$$

⇒ **j**, **B** lie on nested surfaces

⇒ **j**, **B**, p are described by a flux function ψ

⇒ equilibrium entirely defined by:

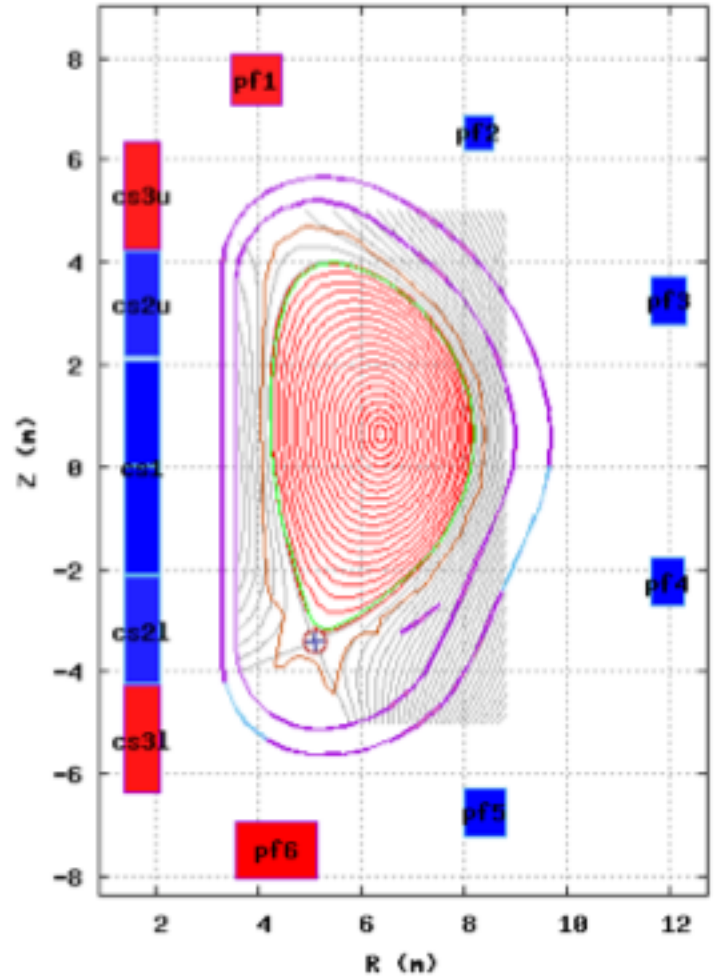
$$R \frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial \psi}{\partial R}\right) + \frac{\partial^2 \psi}{\partial z^2} = -\mu_0 R J_\phi$$



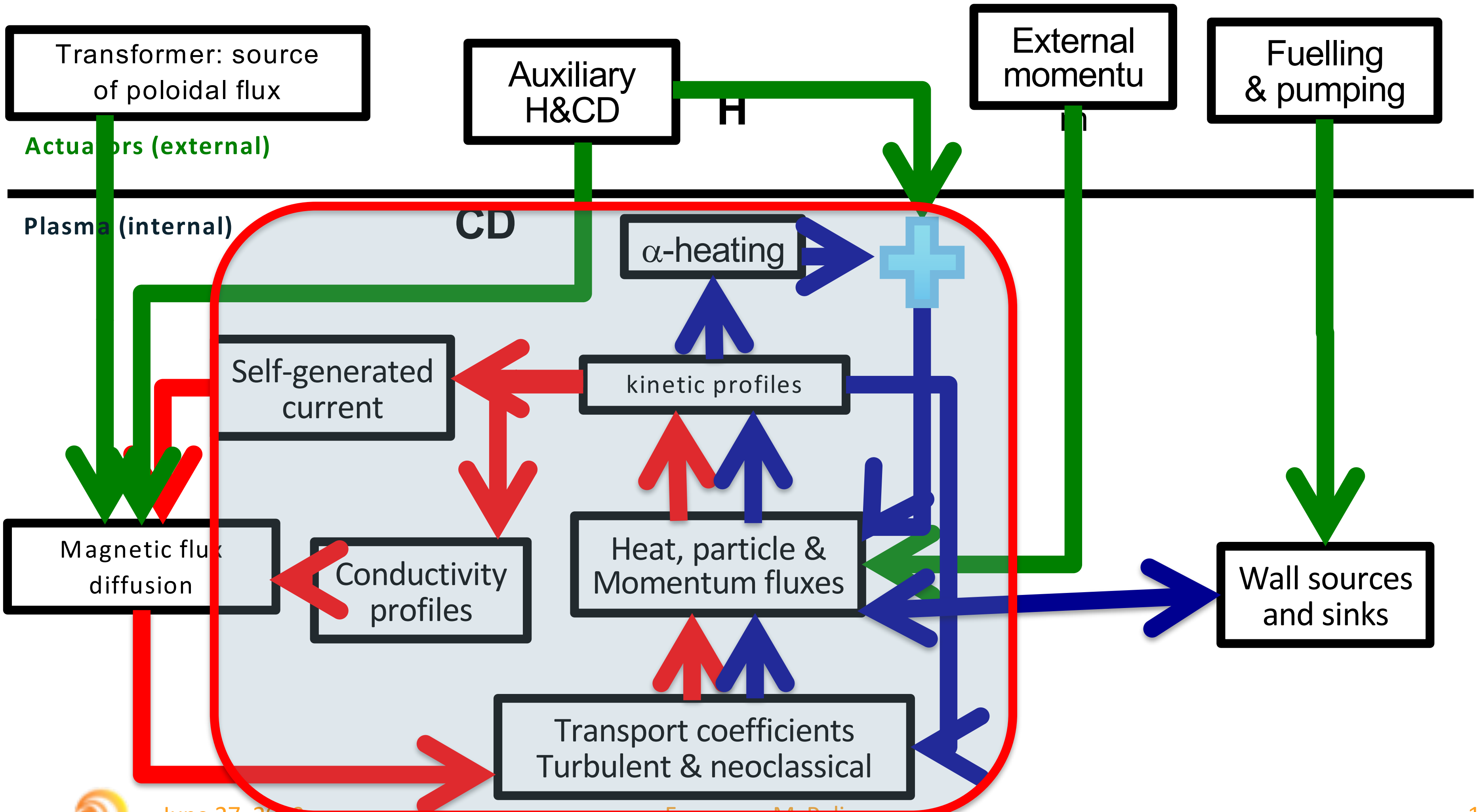
[*Credit, DIFFER website, The Netherlands*]

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

$$R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial\psi}{\partial R}\right)+\frac{\partial^2\psi}{\partial z^2}=-\mu_0 R J_\phi$$
$$=-\mu_0\sum_{i=1}^{N}R_i I_i\delta(R-R_i)\delta(z-z_i)$$



The second step is a good model for core transport



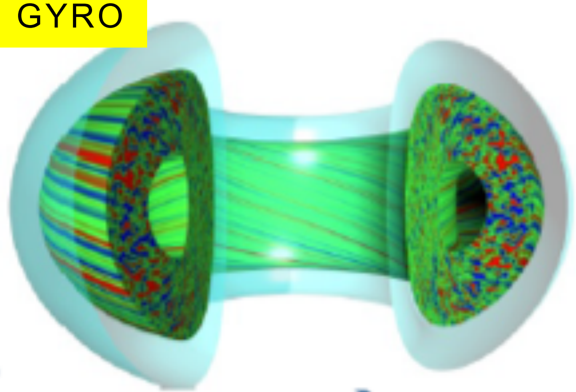
Separation of scales enables representing (almost) any transport problem as a diffusion/convection-like problem

The goal is to obtain a set of diffusion-like equations in 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**

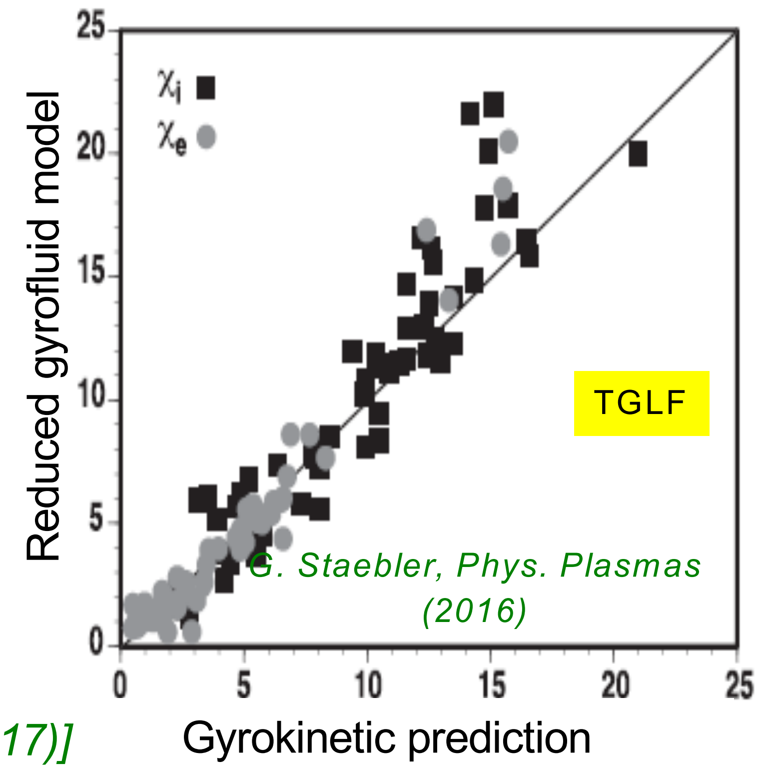
Understanding and modeling tokamak turbulent transport requires theory-based prediction of flux-gradient relationships



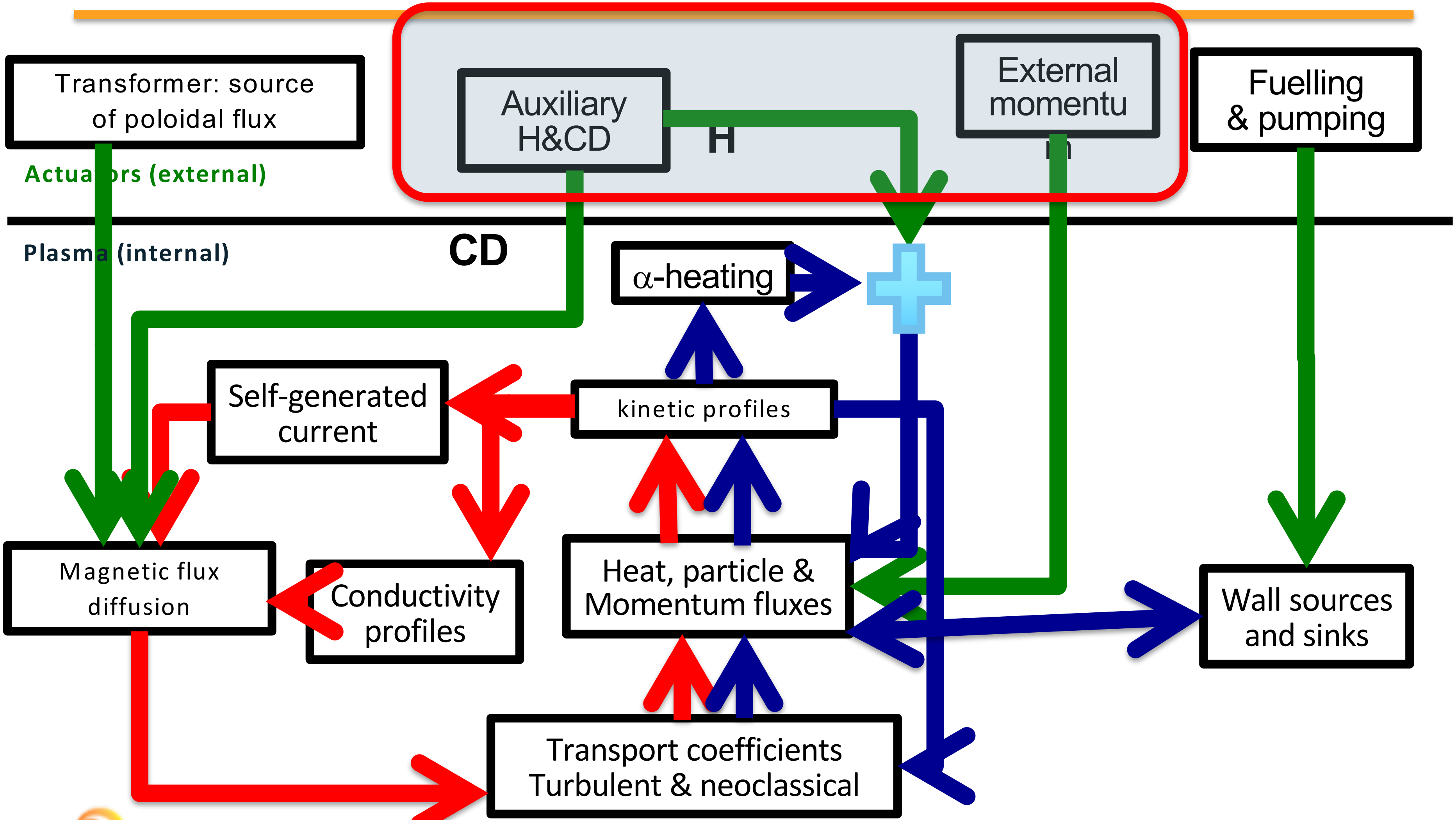
6D Vlasov equations => 5D nonlinear "gyrokinetic"

State-of-the-art multi-scale ($\rho_i \to \rho_e$)
~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)]*

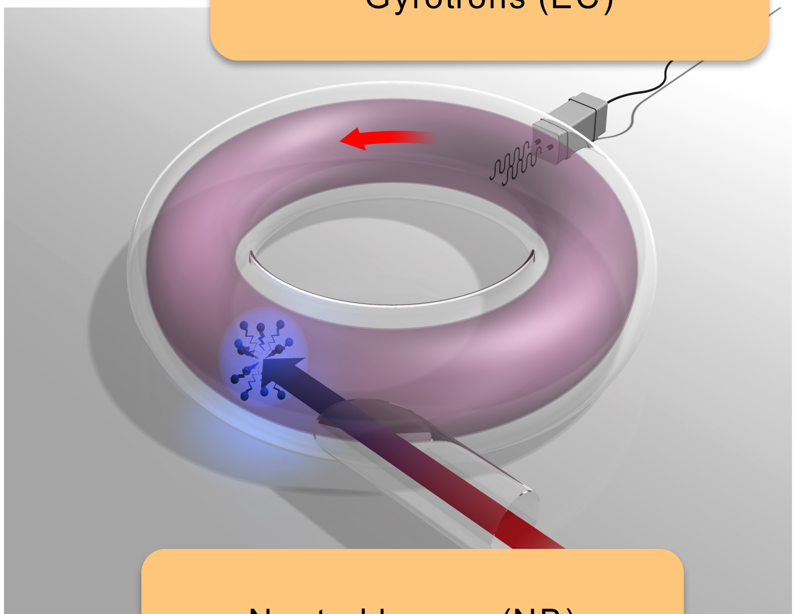


The third step is realistic models for heating, current and momentum

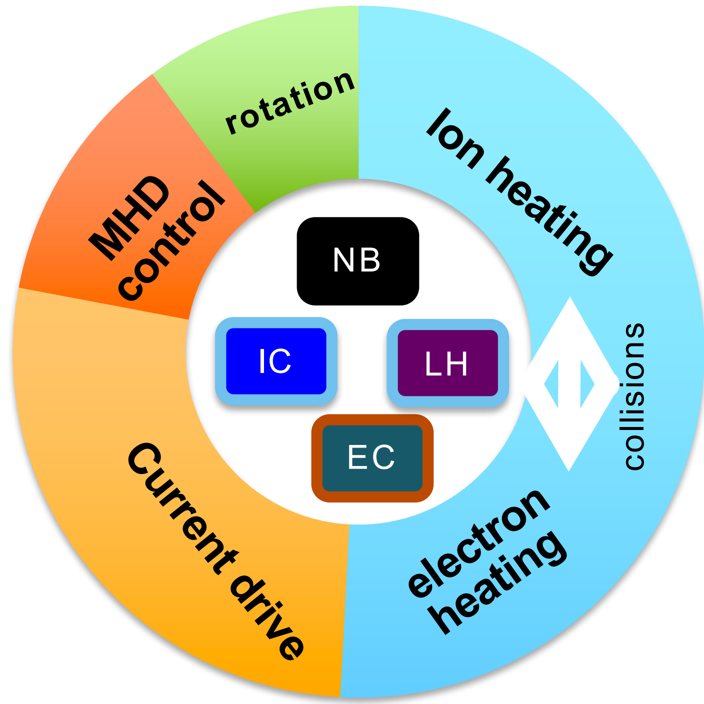


External sources do more than providing heating and current: they can provide momentum and control of MHD instabilities

RF antennas (IC, LH),
Gyrotrons (EC)

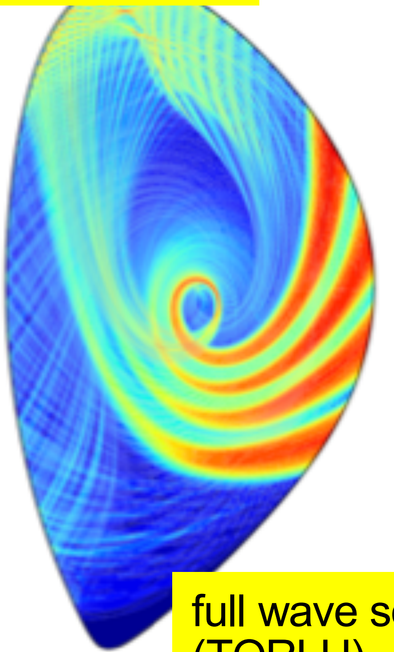


Neutral beams (NB)



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

Magnetic equilibrium

Dielectric tensor

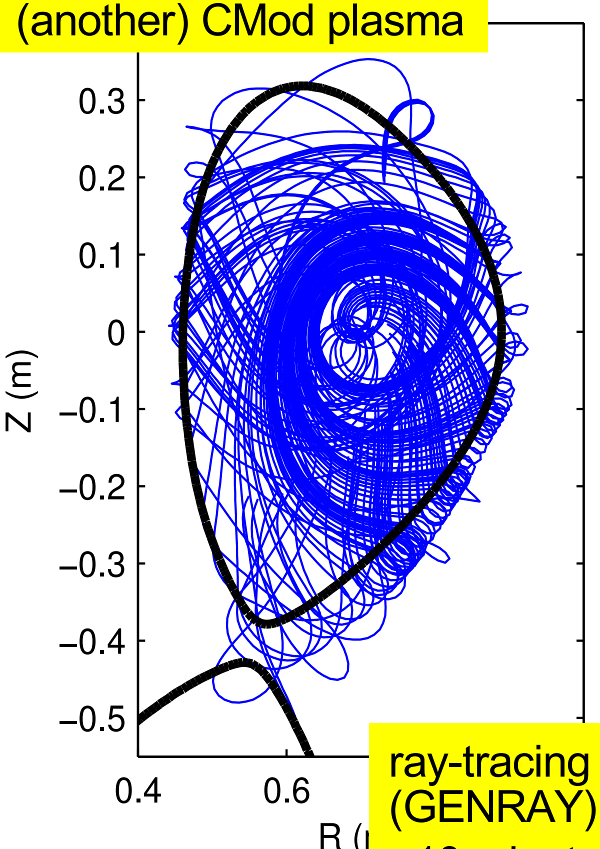
$$\bar{\mathbf{K}} = \bar{\mathbf{I}} + \frac{i}{\epsilon_0 \omega}\bar{\sigma}$$

Heating, current profiles

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

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

(another) CMod plasma



ray-tracing (GENRAY) <10 minutes

density, temperature

Magnetic equilibrium

Dielectric tensor

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

Heating, current profiles

Ray-tracing equations dispersion relation

Let’s put everything together …

TRANSP is a 1.5D equilibrium and transport solver for tokamak plasma simulations developed at PPPL

TRANSP[PPPL]

Particle: $$\frac{\partial}{\partial t}(nV') - \frac{\partial}{\partial \rho}\left(|\nabla\rho|^2 V'D\frac{\partial n}{\partial \rho}\right) = V'\left(S_{gas} + S_{beam} - L_{c-x,recomb,etc}\right)$$

Energy (e^-): $$\frac{\partial}{\partial t}\left[\frac{3}{2}V'n_e kT_e\right] + \frac{\partial}{\partial \rho}\left[V'\left\langle|\nabla\rho|^2\right\rangle n_e k(T_e v_e - \chi_e \nabla T_e)\right] = V'(P_{OH} + P_{beam} - P_{ie} - P_{rad})$$

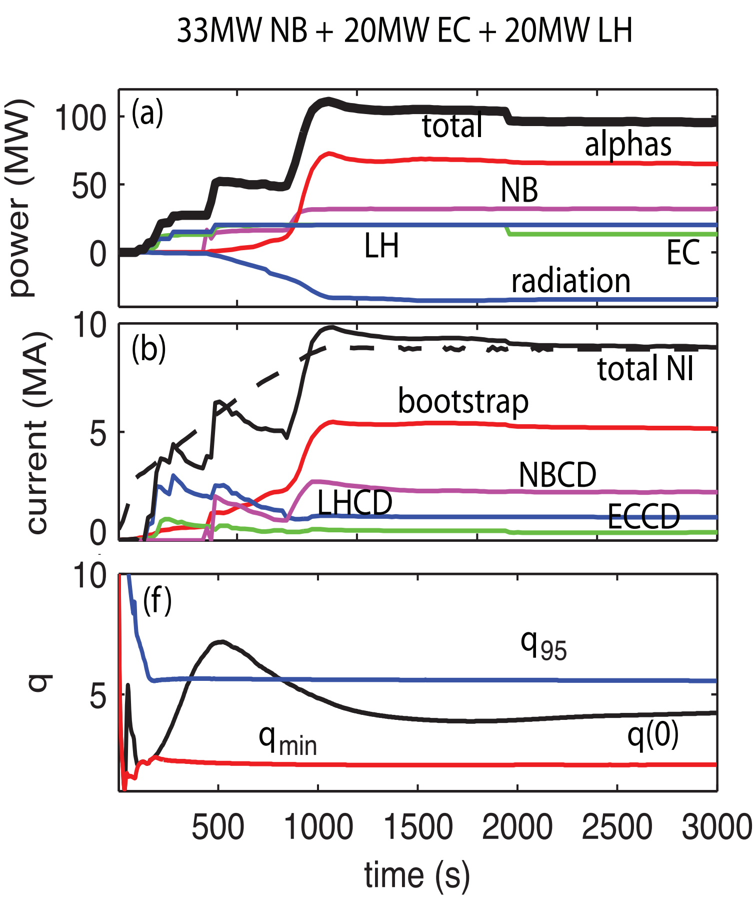
Momentum: $$\frac{\partial}{\partial t}\left(n_i m_i V'\left\langle R^2\right\rangle\omega\right) + \frac{\partial}{\partial \rho}[V'\Gamma_\Omega] = V'\left(\Sigma T_{input} - \nabla\cdot\Pi_\phi - mnR(\omega-\omega^*)\tau_{damp}^{-1}\right)$$

Interpretive: INPUT: T_e, T_i, n_e, v_ϕ,..... OUTPUT: $D_{e,i}$, $\chi_{e,i,\phi}$,.....

Predictive: INPUT (model): $\chi_{e,i}$, $D_{e,i}$, ... OUTPUT: $T_{e,i}$, n_e,.....

We have learnt from modeling of ITER that the ramp-up phase is critical for sustainment of q_{min} as much as a correct choice of H&CD mix

TRANSP



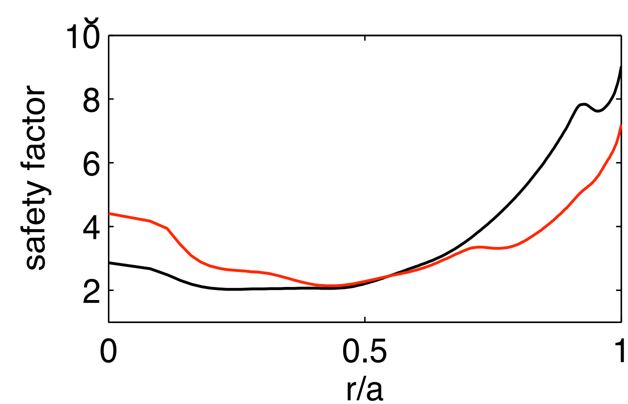
- slower current ramp-up rate
- Early RF core heating

=> Delay current penetration and q relaxation

- Core electron heating and current early
- Off-axis current after H-mode formation

⇒ Sustains bootstrap current at mid-radius

⇒ Prevents q relaxation

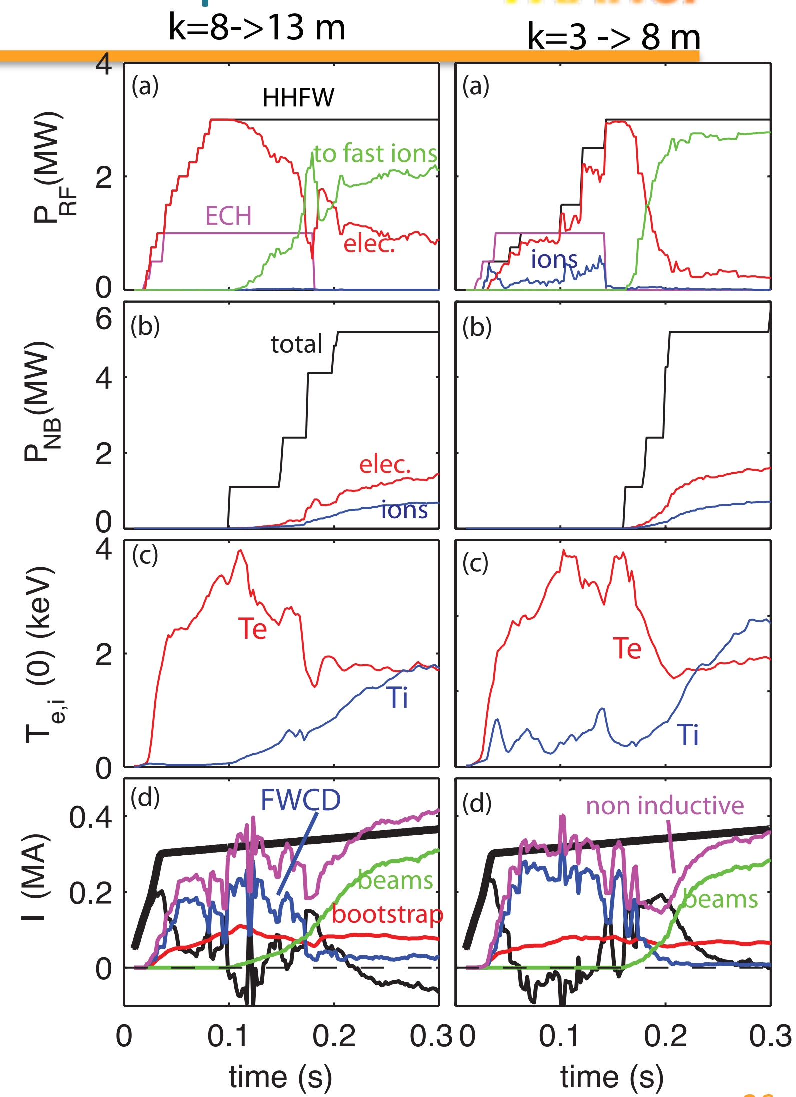


Time-dependent modeling of current ramp-up has highlighted the role of RF to heat the plasma

- Minimize power needs to obtain the same current

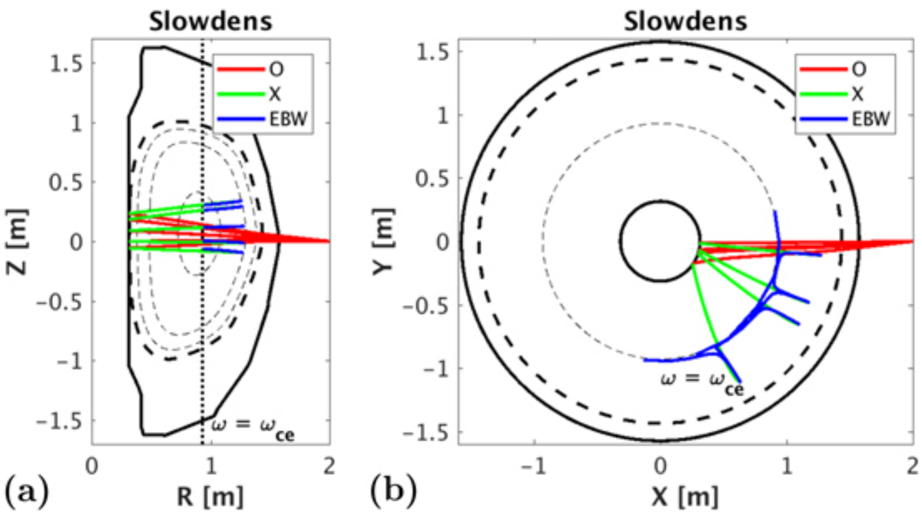
Everything works on paper …

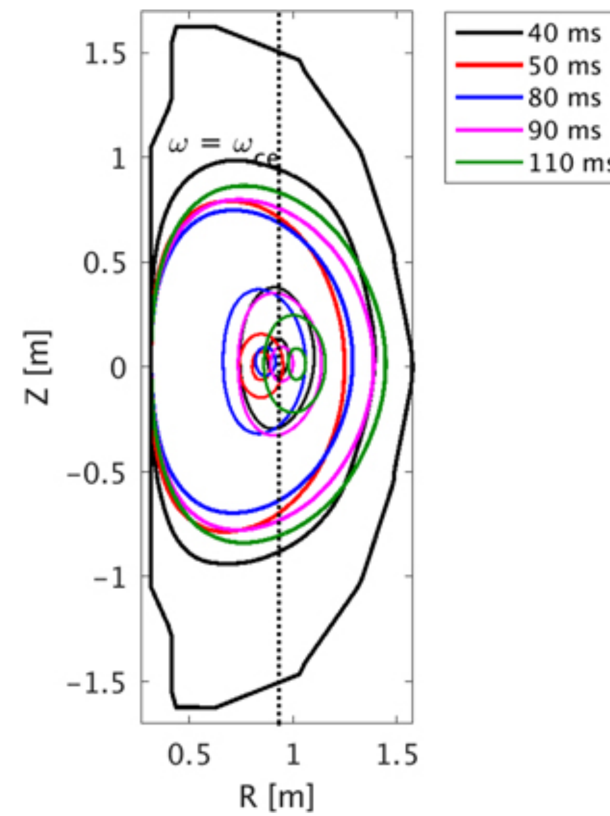
The challenge now is to demonstrate it in experiments.



Time-dependent application: assessment of O-X-B startup in NSTX-U

[N. Lopez (Princeton University) PPCF 2016]



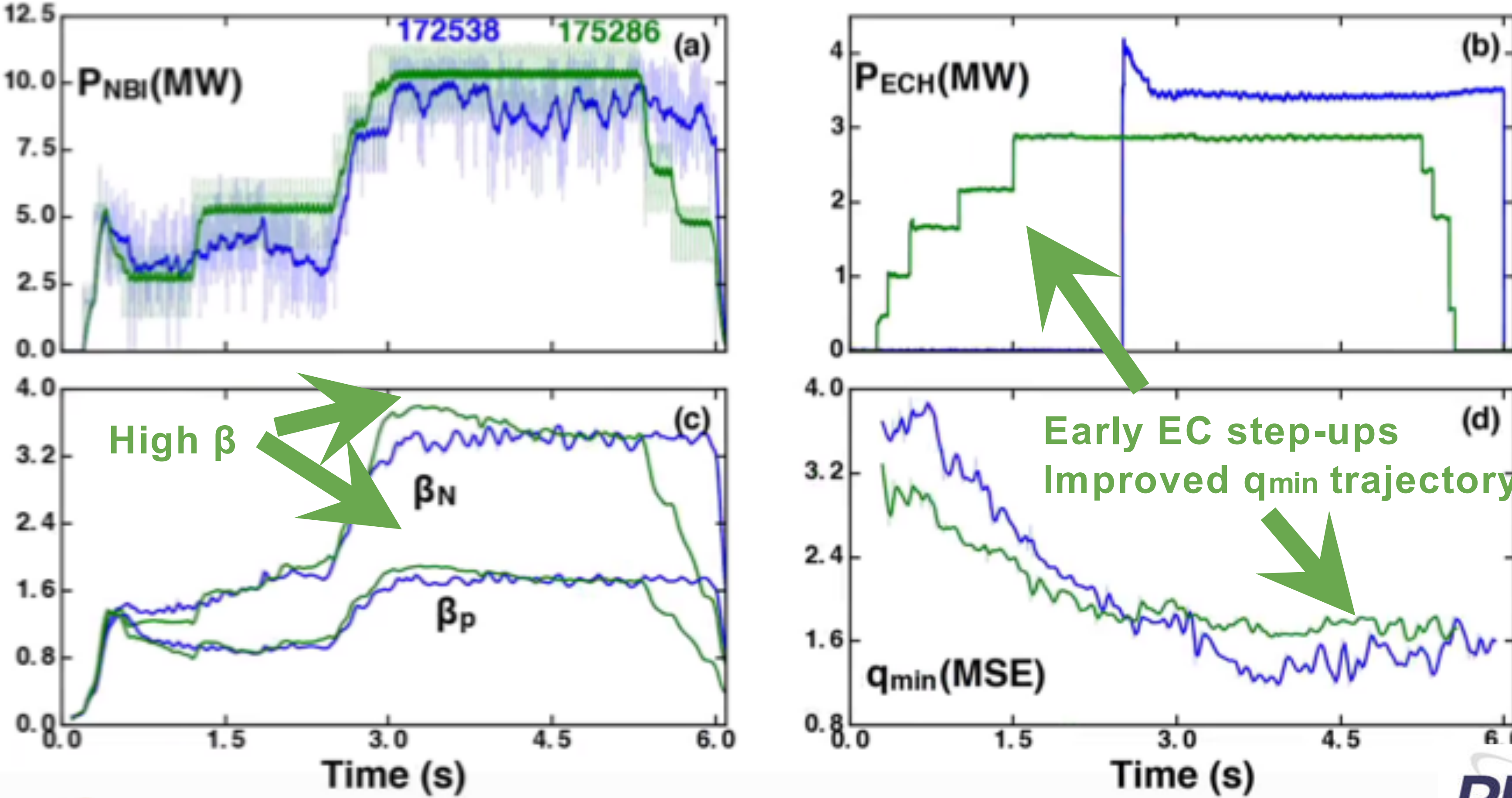


Used TRANSP to assess the propagation and conversion of EC waves in NSTX-U

GOAL: find optimal launching geometry
that maximizes both heating and current
that does not make the plasma unstable

Used integrated modeling to design experiments BEFORE going to the control room

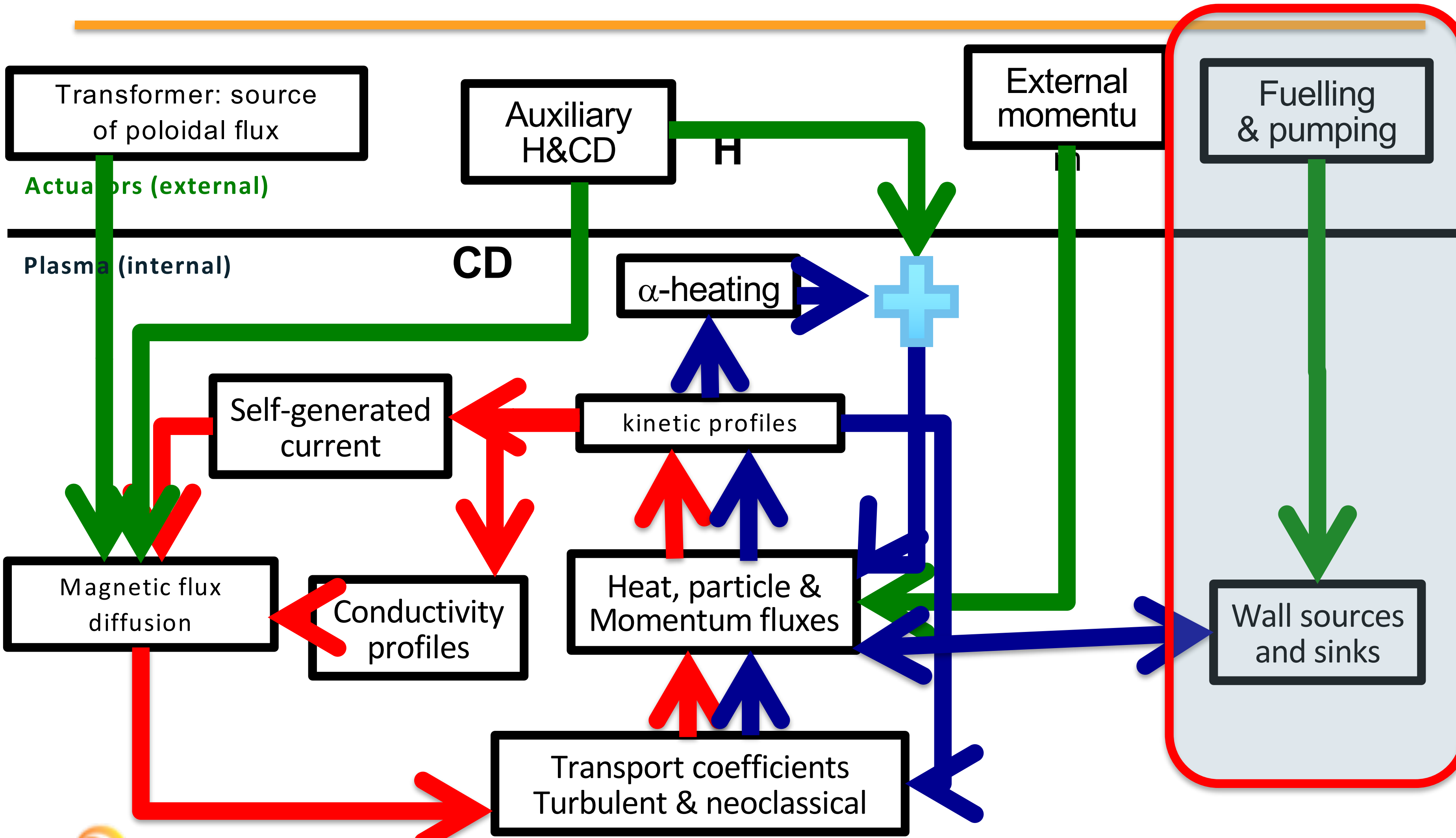
- Feed-forward NBI and EC predicted first with TRANSP (no feedback)
- Improved access to high beta with little MHD



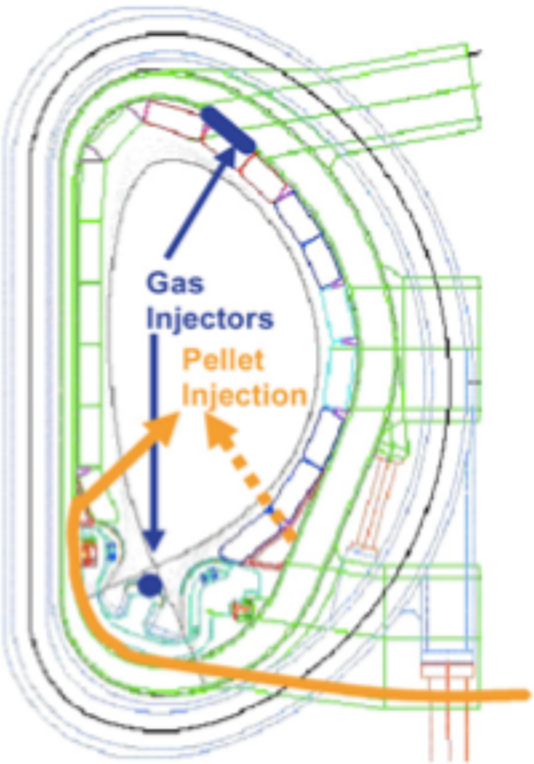
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

What is missing?

What happens close to the plasma wall is very important



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



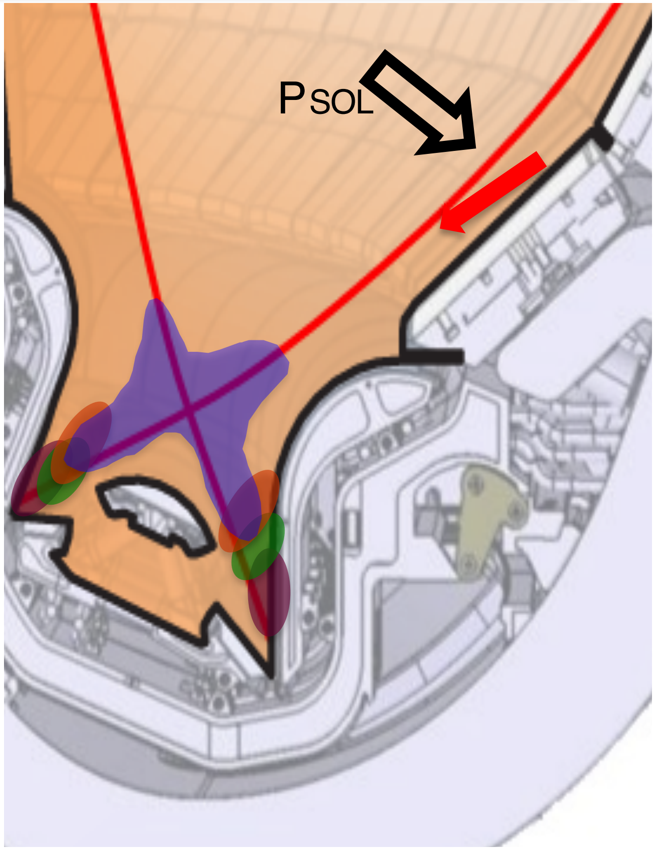
Heat conduction zone

Impurity radiation zone

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

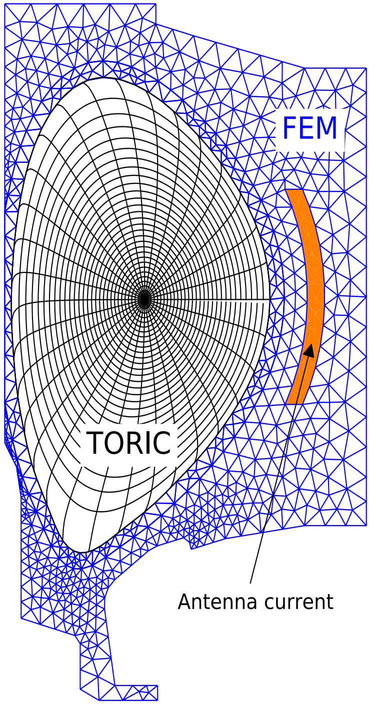
Neutral friction zone

Recombination zone (T_e<1eV)



Courtesy of R. Pitts (ITER Organization)

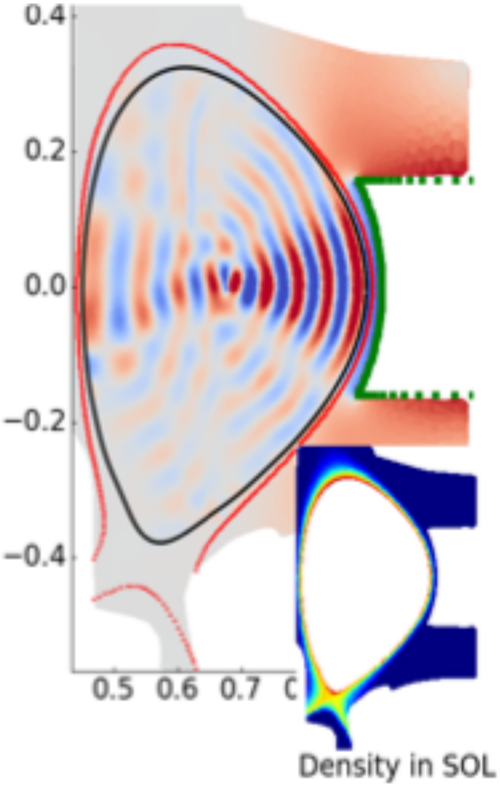
Hybrid approach to modeling of RF wave propagation is a promising avenue towards implementation in tokamak simulator



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



Courtesy of S. Shiraiwa (PSFC)

Would benefit from realistic model of SOL

Integrated Tokamak Modeling offers plenty of opportunities to understand and model experiments (we have collaborations all over the world)

… and it is a lot of FUN !

JOIN OUR TEAM

fpoli@pppl.gov