EUROfusion

Fundamental aspects of edge physics – a brief overview of our ER achievements

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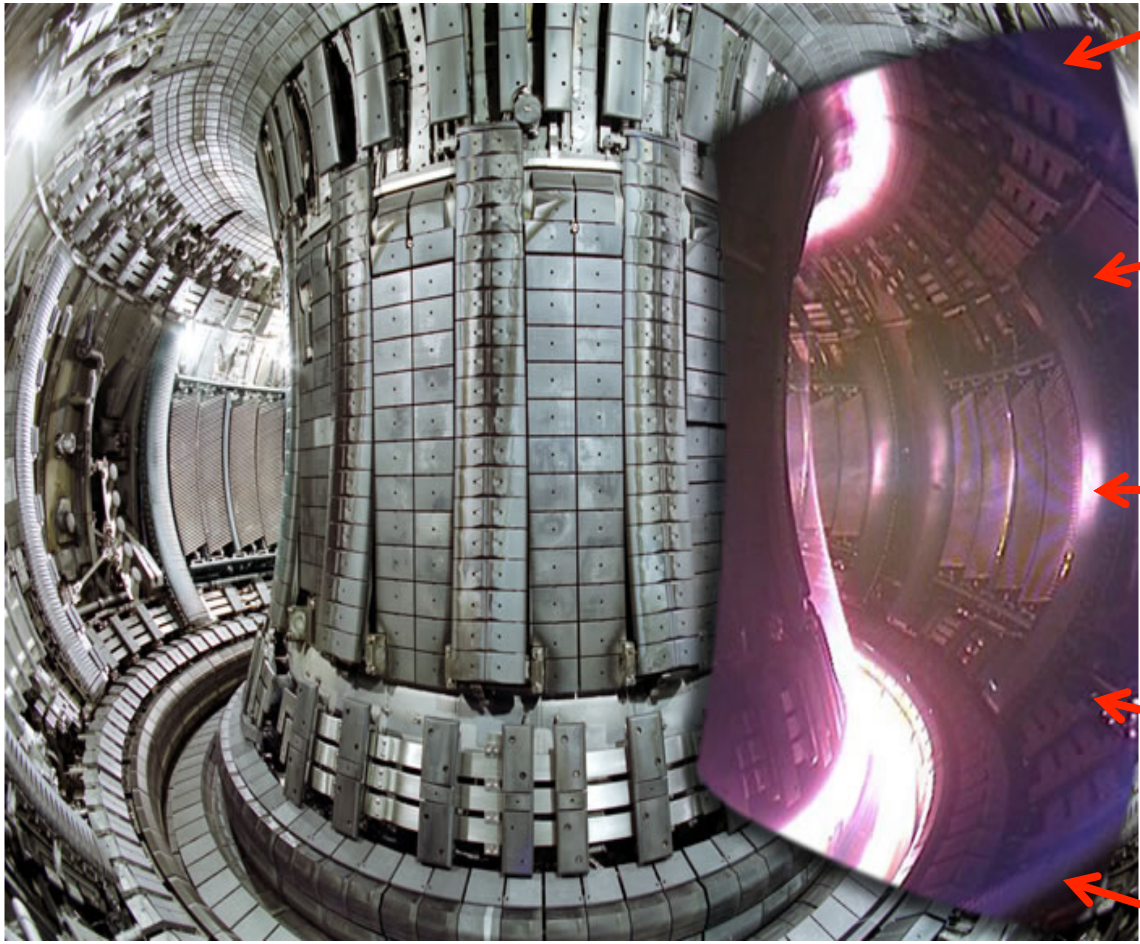
Disentangling fundamental edge phenomena



TURBULENT RADIAL TRANSPORT

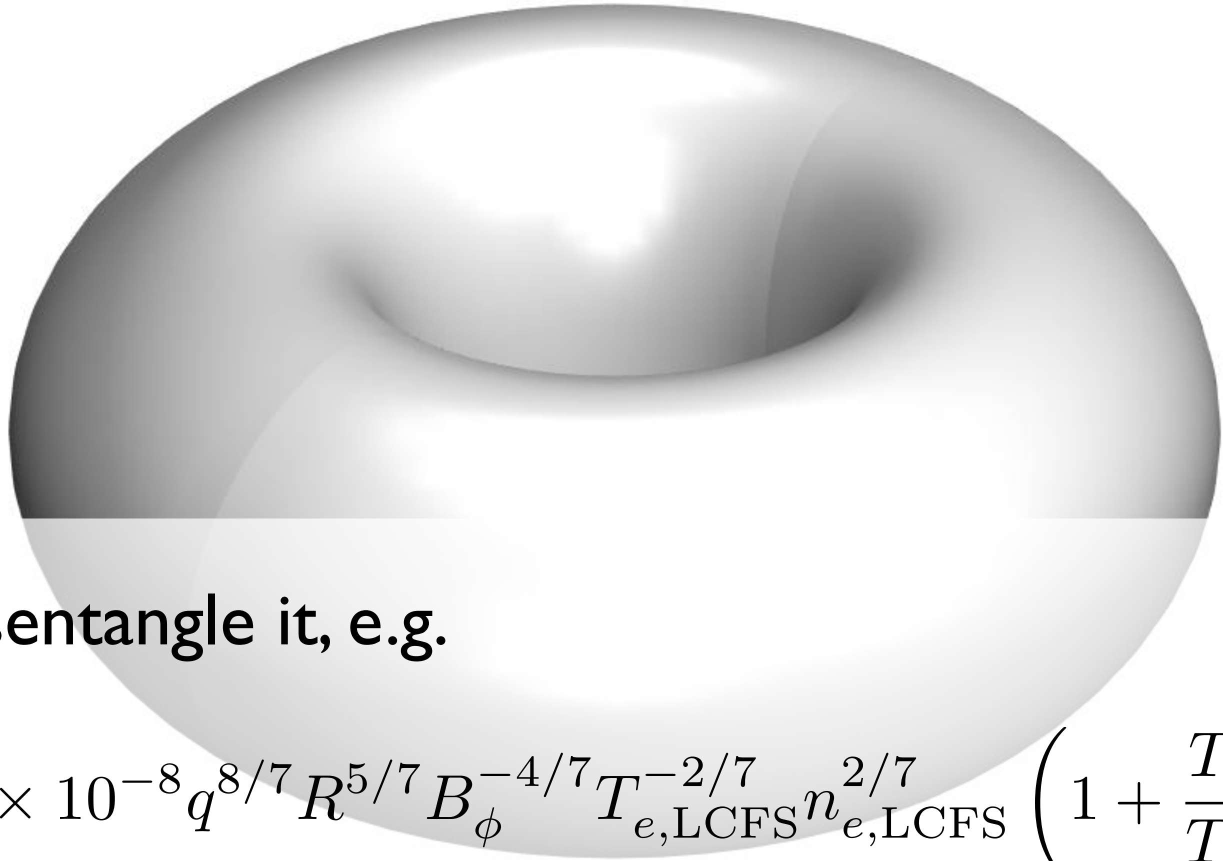
NEUTRAL ATOMS, ATOMIC PHYSICS

IMPURITIES

PARALLEL TRANSPORT

SHEATH PHYSICS

In simple configurations, we can simulate this complexity using first-principles codes

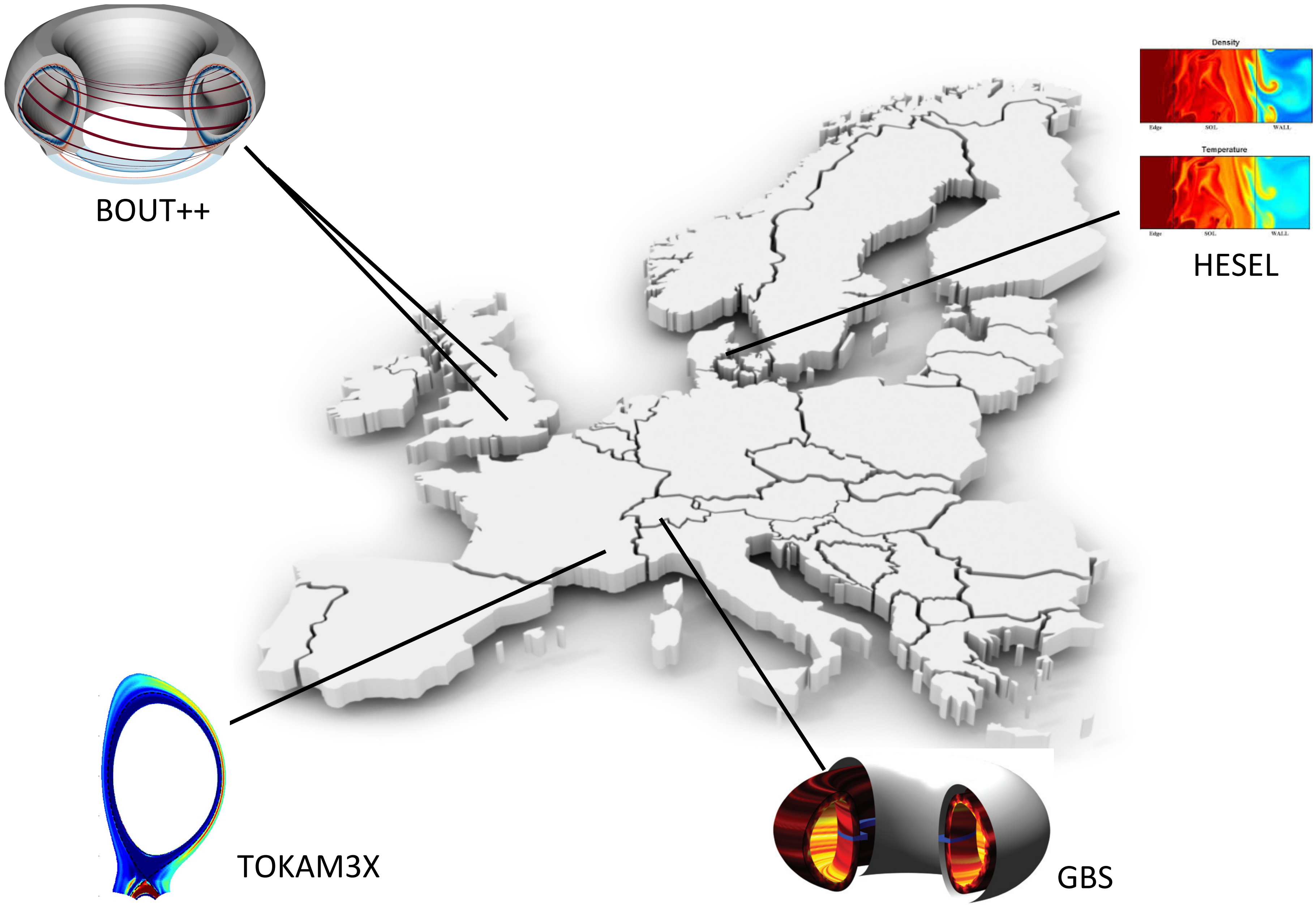


… and disentangle it, e.g.

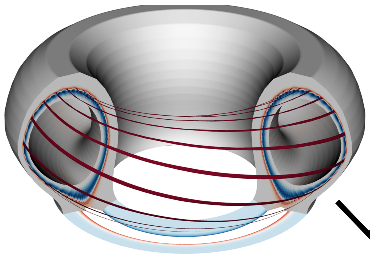
$$L_p \simeq 7.22 \times 10^{-8} q^{8/7} R^{5/7} B_\phi^{-4/7} T_{e,\mathrm{LCFS}}^{-2/7} n_{e,\mathrm{LCFS}}^{2/7} \left(1 + \frac{T_{i,\mathrm{LCFS}}}{T_{e,\mathrm{LCFS}}}\right)^{1/7}$$

in good agreement with experimental results

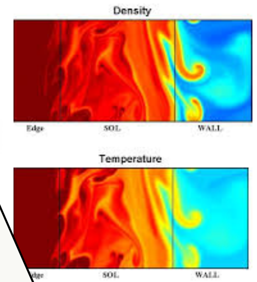
A collective theoretical effort…



A collective theoretical effort...

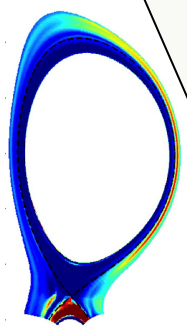


BOUT++

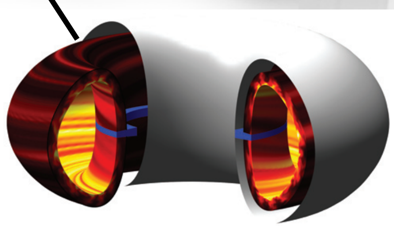


HESEL

- Different assets:
  - BOUT++ (flexibility, ...)
  - HESEL (manageability, ...)
  - GBS (accurate model, ...)
  - TOKAM3X (advanced geometry, ...)
- Ideal for validation exercises, by implementing different models

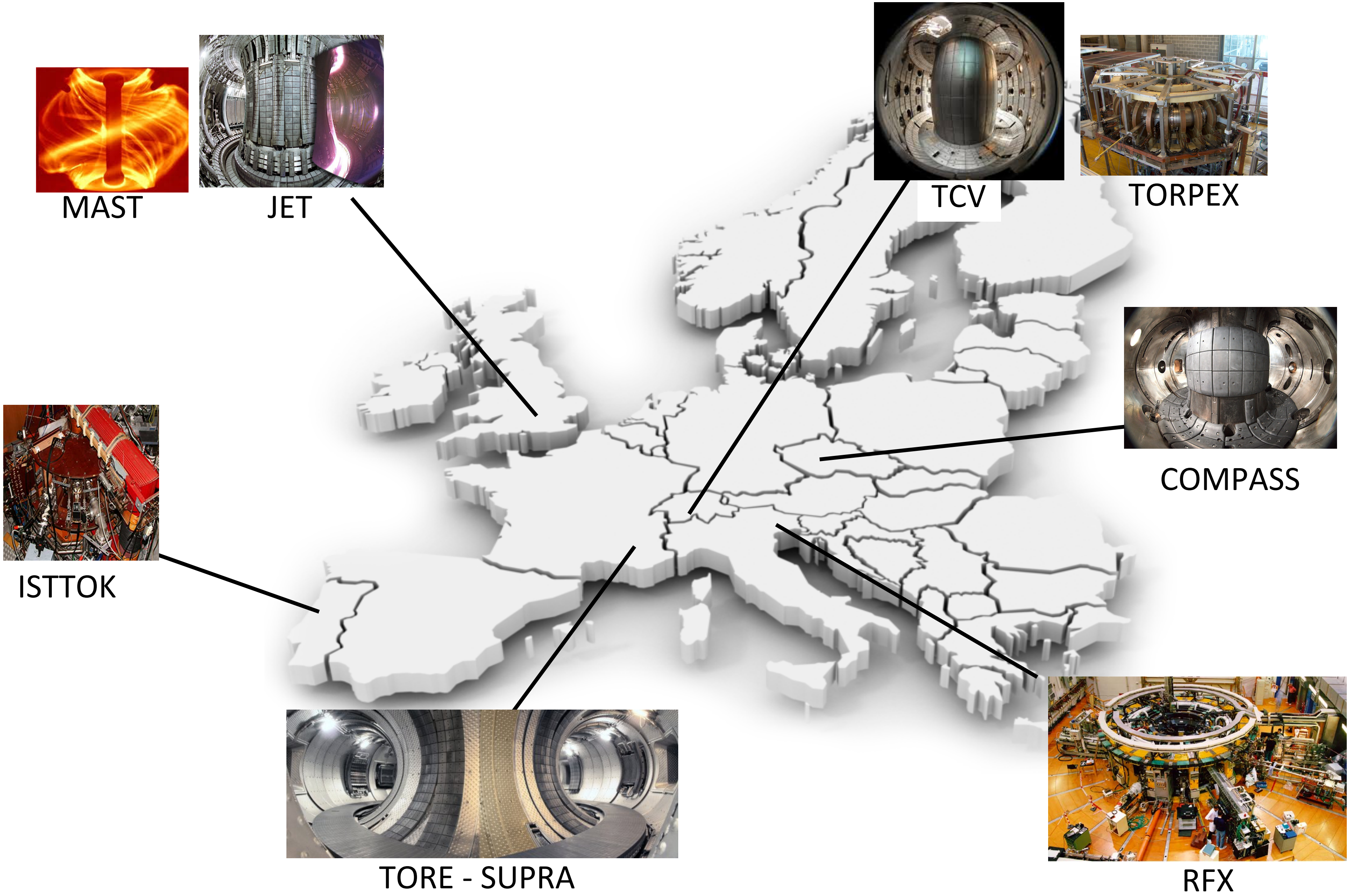


TOKAM3X



GBS

...together with a collective experimental effort



Summarizing our activities...

- Our simulation approach
- Verification and Validation
- Our main achievements
- What's next?

Our plasma models to evolve edge turbulence

Collisional Plasma → Fluid model → $\rho_i \ll L$, $\omega \ll \Omega_{ci}$ → Drift-reduced fluid model

MAGNETIC CURVATURE

IONIZATION

OUTFLOW FROM CORE

$$\frac{\partial n}{\partial t} + [\phi, n] = \hat{C}(nT_e) - n\hat{C}(\phi) - \nabla_{\parallel}(nV_{\parallel e}) + n_n \nu_{\text{ion}} - n\nu_{\text{rec}} + S_n$$

E×B CONVECTION

PARALLEL DYNAMICS

RECOMBINATION

T_e, T_i, Ω (vorticity) → similar equations

$V_{||e}$, $V_{||i}$ → parallel momentum balance

$\nabla_{\perp}^2 \phi = \Omega$

We implemented energy conserving collisions, finite T_i, and advanced boundary conditions [Madsen, PoP 2016; Olsen, PPCF 2016; Dudson, PPCF submitted]

Our models to evolve neutrals self-consistently

+ kinetic neutrals

$$\frac{\partial f_n}{\partial t} + \mathbf{v} \cdot \frac{\partial f_n}{\partial \mathbf{x}} = -\nu_{\text{ion}} f_n - \nu_{\text{CX}}(f_n - n_n f_i / n_i) + \nu_{\text{rec}} f_i$$

STREAMING

IONIZATION $\nu_{\text{ion}} = n \langle v_e \sigma_{\text{ion}} \rangle$

CHARGE EXCHANGE $\nu_{\text{CX}} = n \langle v_{\text{rel}} \sigma_{\text{CX}}(v_{\text{rel}}) \rangle$

RECOMBINATION $\nu_{\text{rec}} = n \langle v_e \sigma_{\text{rec}} \rangle$

Wersal & Ricci, NF 2015

or fluid, or diffusive neutral, or coupling with EIRENE

Thrysøe, PPCF 2016; J. Leddy, JNM (in press)

Solved in 2D or 3D geometry, taking into account plasma outflow from the core, turbulent transport, ionization and charge exchange processes, and losses at the vessel

Code verification, the techniques

1) Simple tests
2) Code-to-code comparisons (benchmarking)

NOT RIGOROUS

3) Convergence tests
4) Order-of-accuracy tests

RIGOROUS, requires analytical solution

Only verification ensuring convergence and correct numerical implementation

Riva et al., PoP 2014; Ricci et al., PoP 2015

Order-of-accuracy tests

Our model: $A(f) = 0, \ \ f$ unknown

We solve $A_n(f_n) = 0$, but $\epsilon_n = f_n - f = ?$

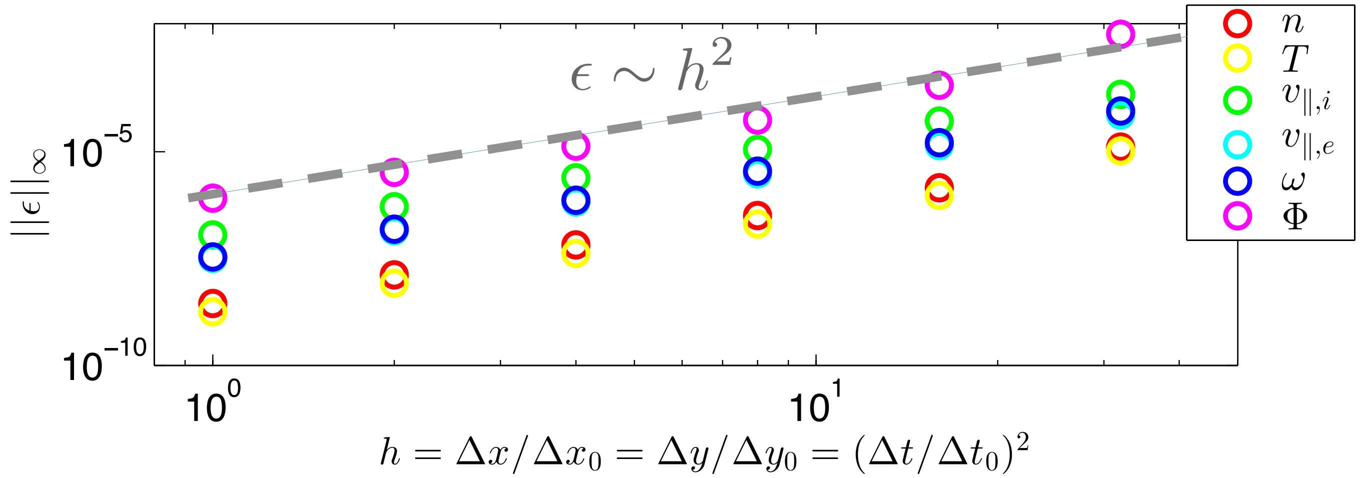
Method of manufactured solution:

1) we choose g, then $S = A(g)$

2) we solve: $A_n(g_n) - S = 0$

$$\epsilon_n = g_n - g$$

For GBS:



Order-of-accuracy tests, MMS

Our model: $A(f) = 0$, f unknown

We solve $A_n(f_n) = 0$, but $\epsilon_n = f_n$ ...

Method of manufactured sol...

1) we choose g th...

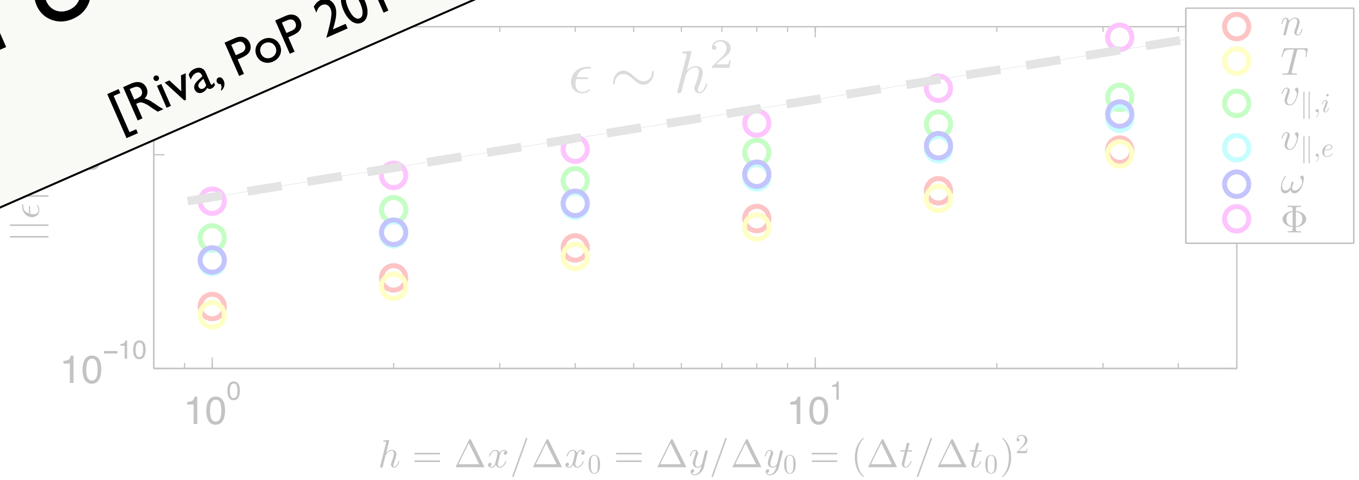
2) we sol...

$\epsilon_n = g_n - g$

For GB...

All our codes verified with MMS

[Riva, PoP 2014; Dudson, PoP 2016; Tamain, JCP 2016]



Order-of-accuracy tests, MMS

Our model: $A(f) = 0$, f unknown

W... $) = 0$, but $\epsilon_n = f_n$ ...

Met...

1) we ...

2) we sol...

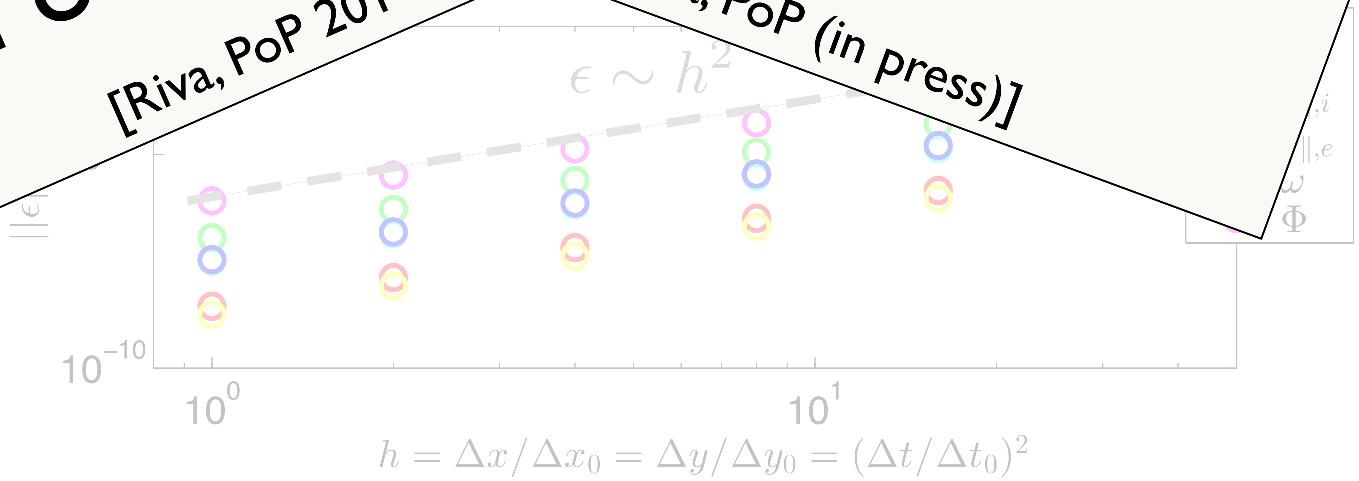
For GB...

We also developed new verification techniques

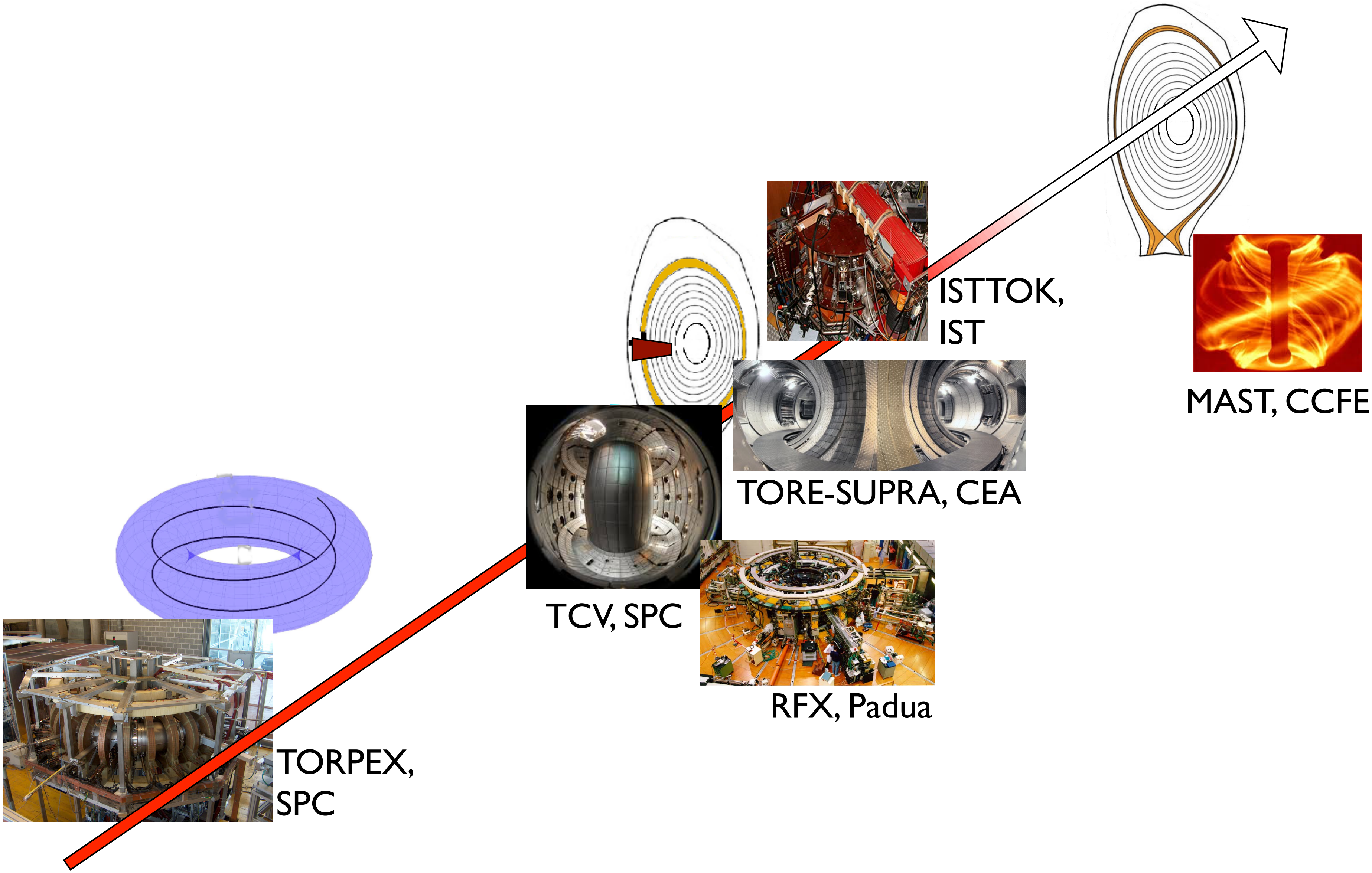
[Cartier-Michaud, PoP 2016; F. Riva, PoP (in press)]

All our co... with MMS

[Riva, PoP 2014; D... P 2016]



A stepladder approach



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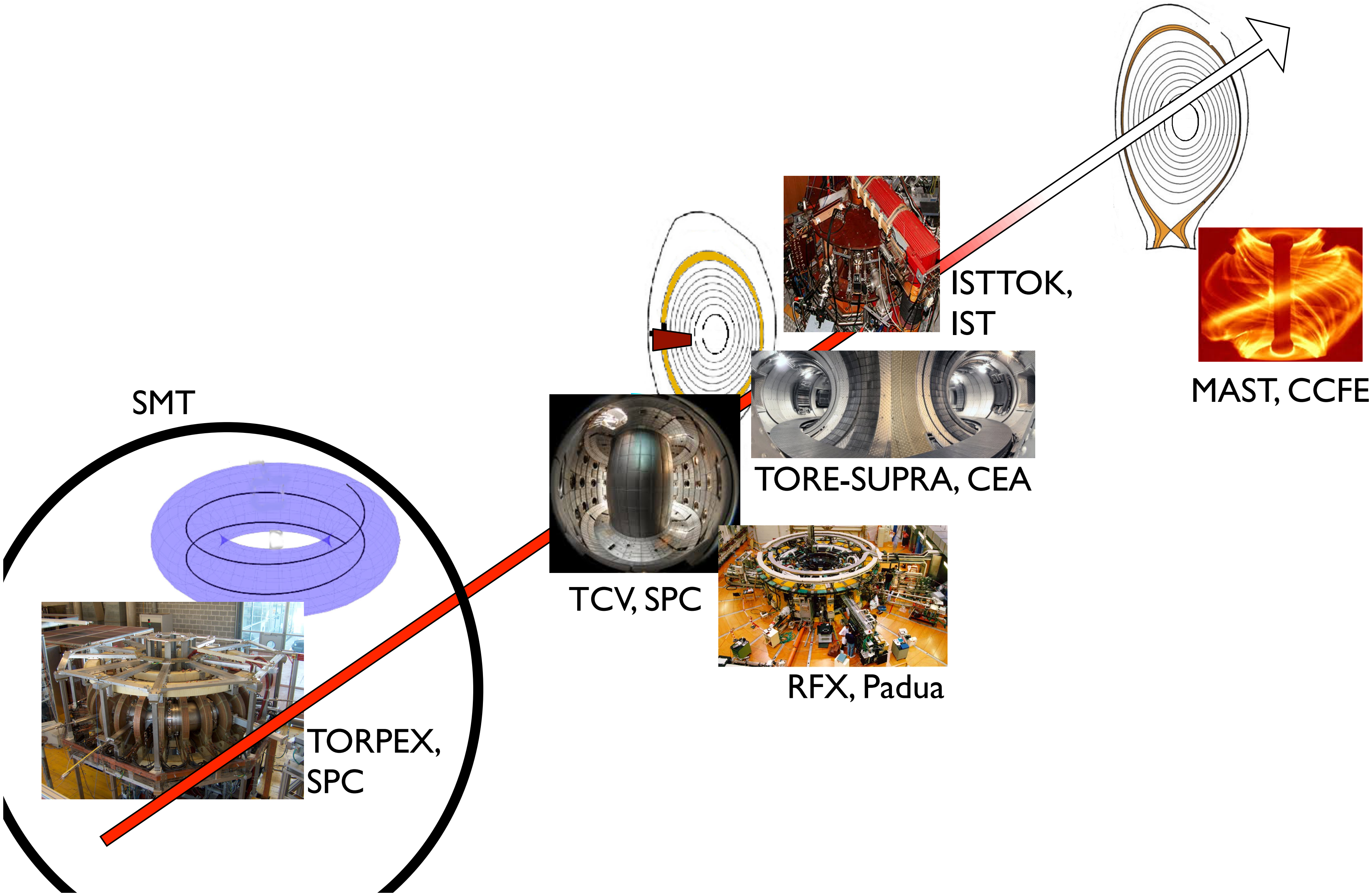
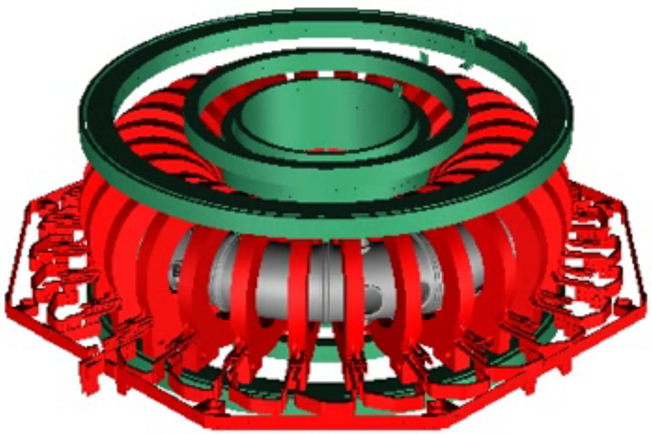


The Simple Magnetized Plasma (SMT) TORPEX



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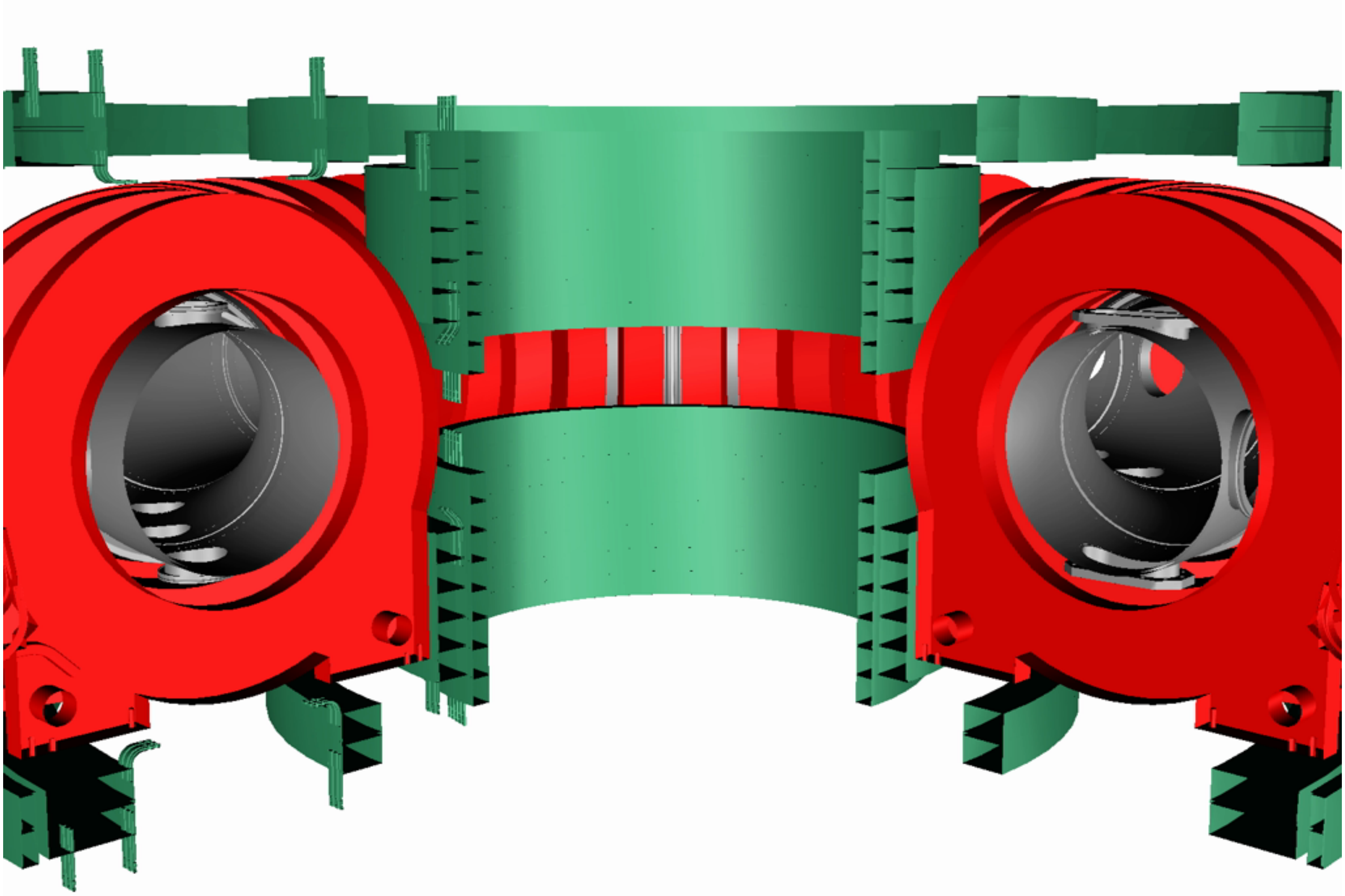

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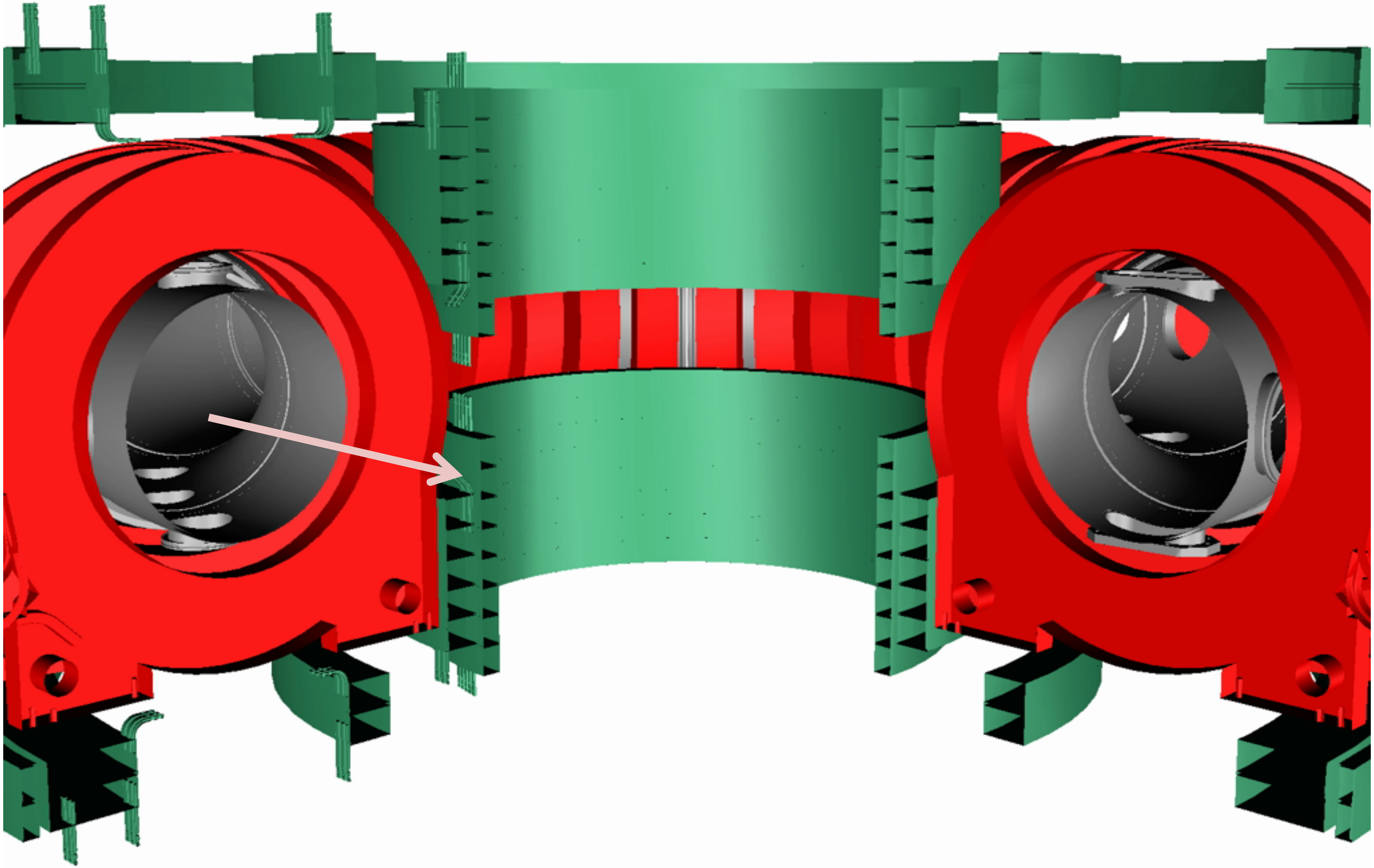

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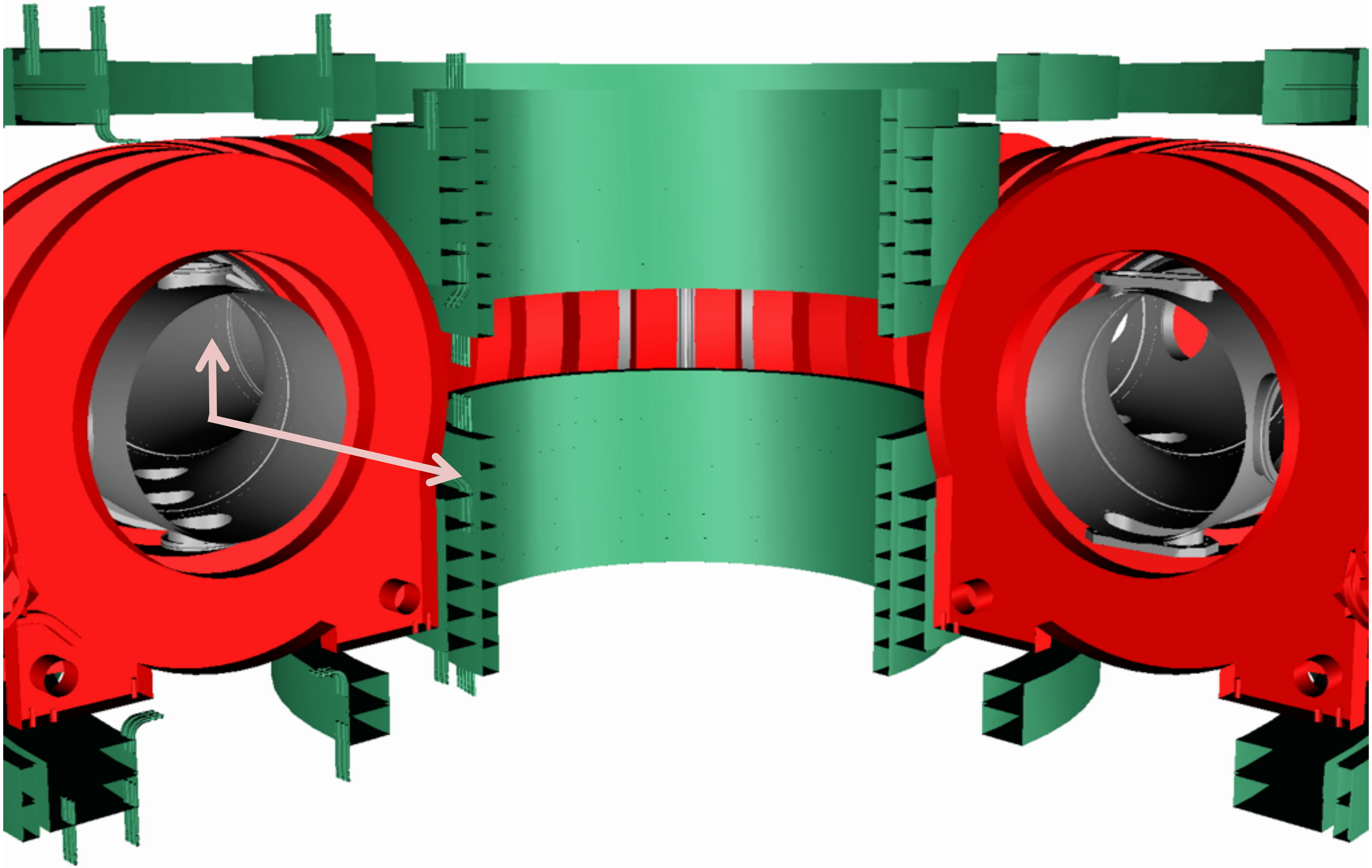

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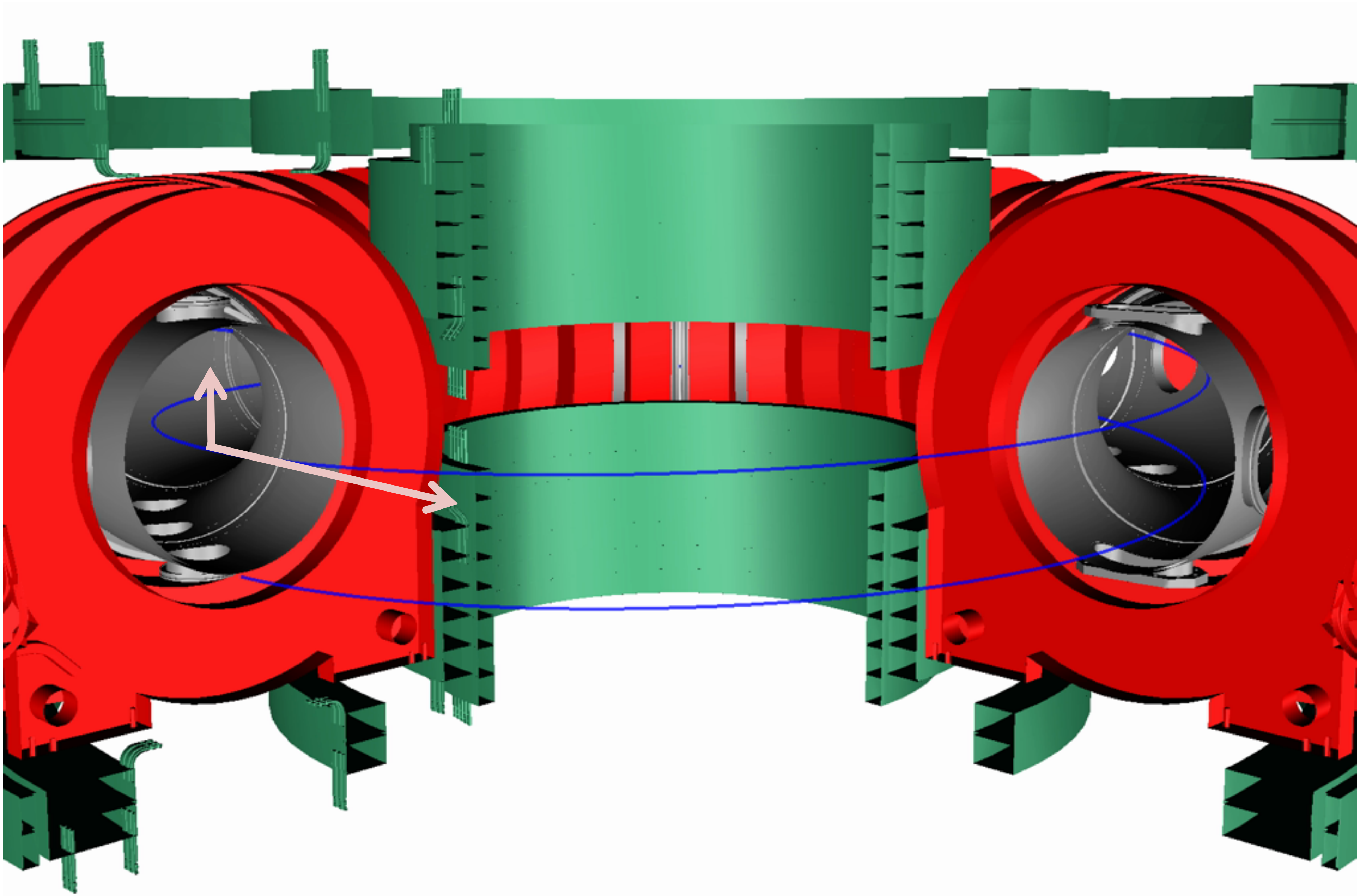
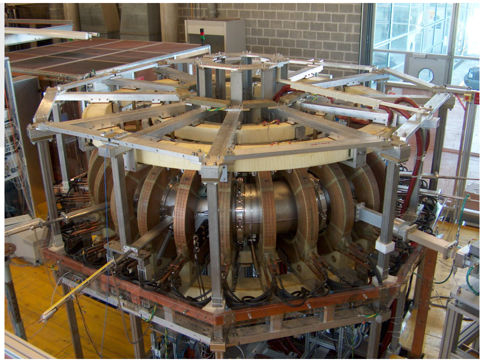
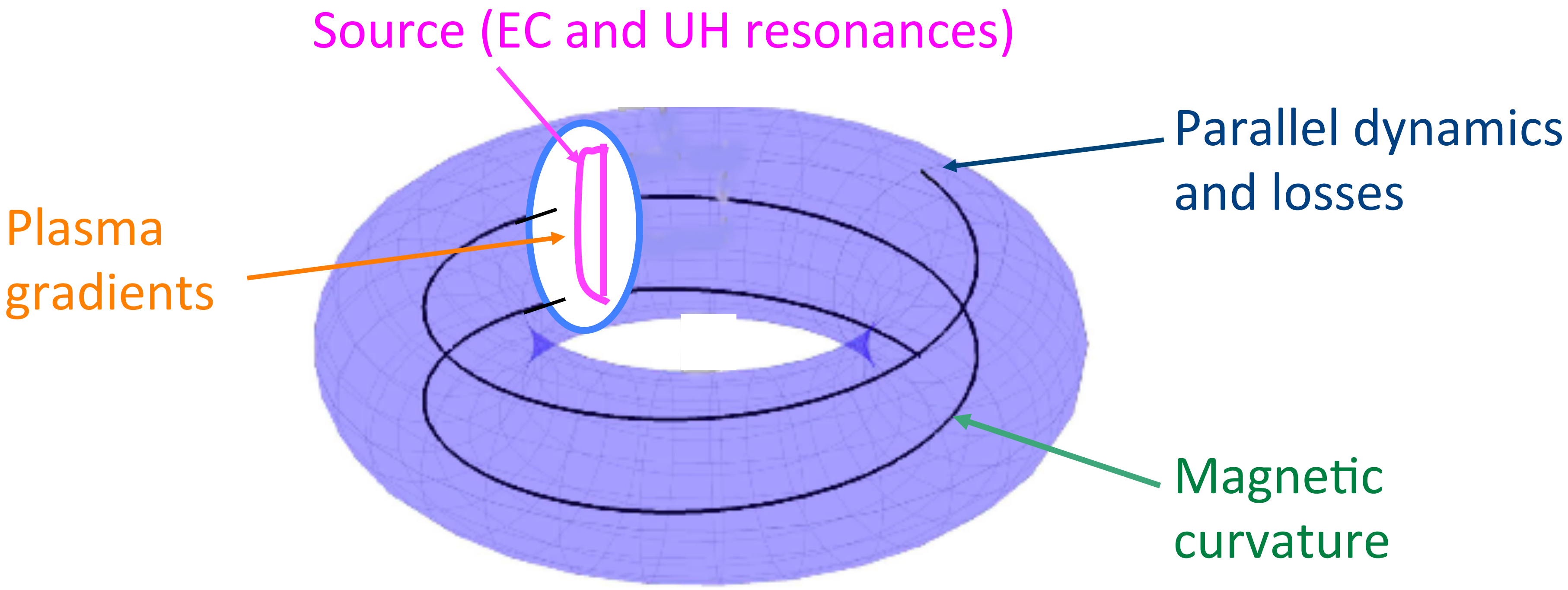


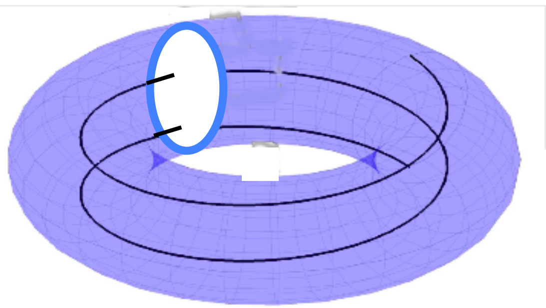
TORPEX key elements

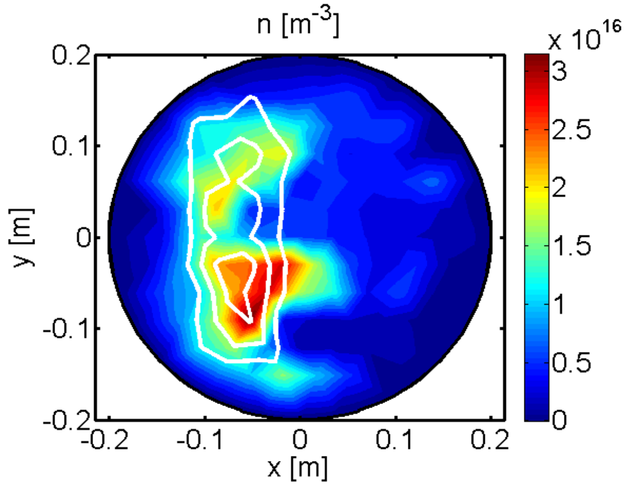




Unique diagnostic capabilities

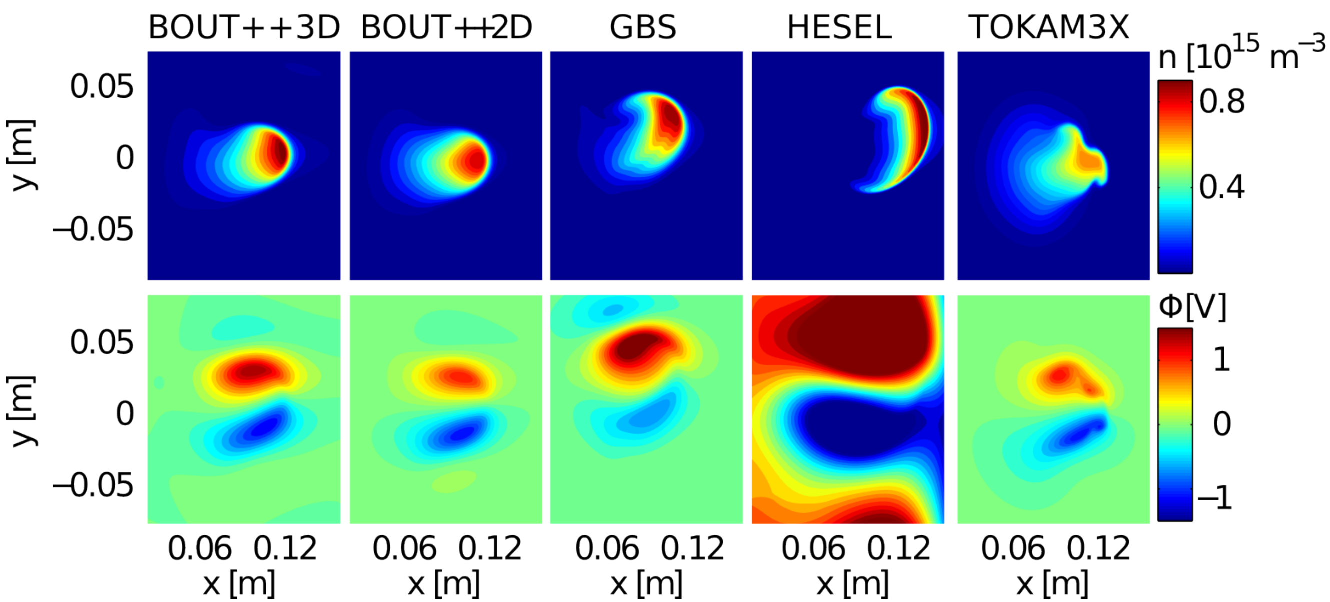
Blob dynamics in TORPEX





Used 5 models to simulate TORPEX blobs

Showed importance of sheath currents and equilibrium flows



[Riva *et al.*, PPCF (2016)]

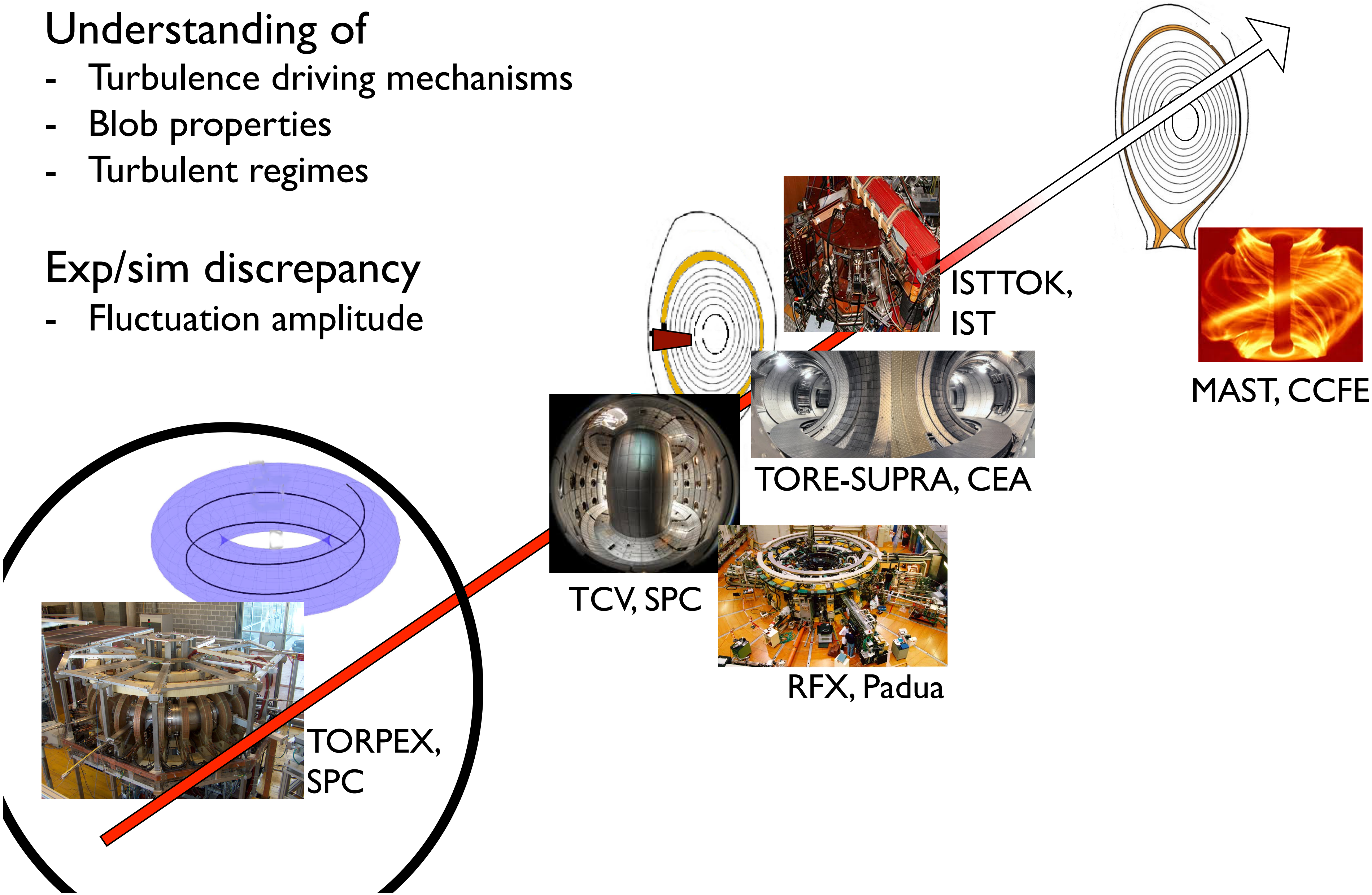
A stepladder approach

Understanding of

- Turbulence driving mechanisms
- Blob properties
- Turbulent regimes

Exp/sim discrepancy

- Fluctuation amplitude



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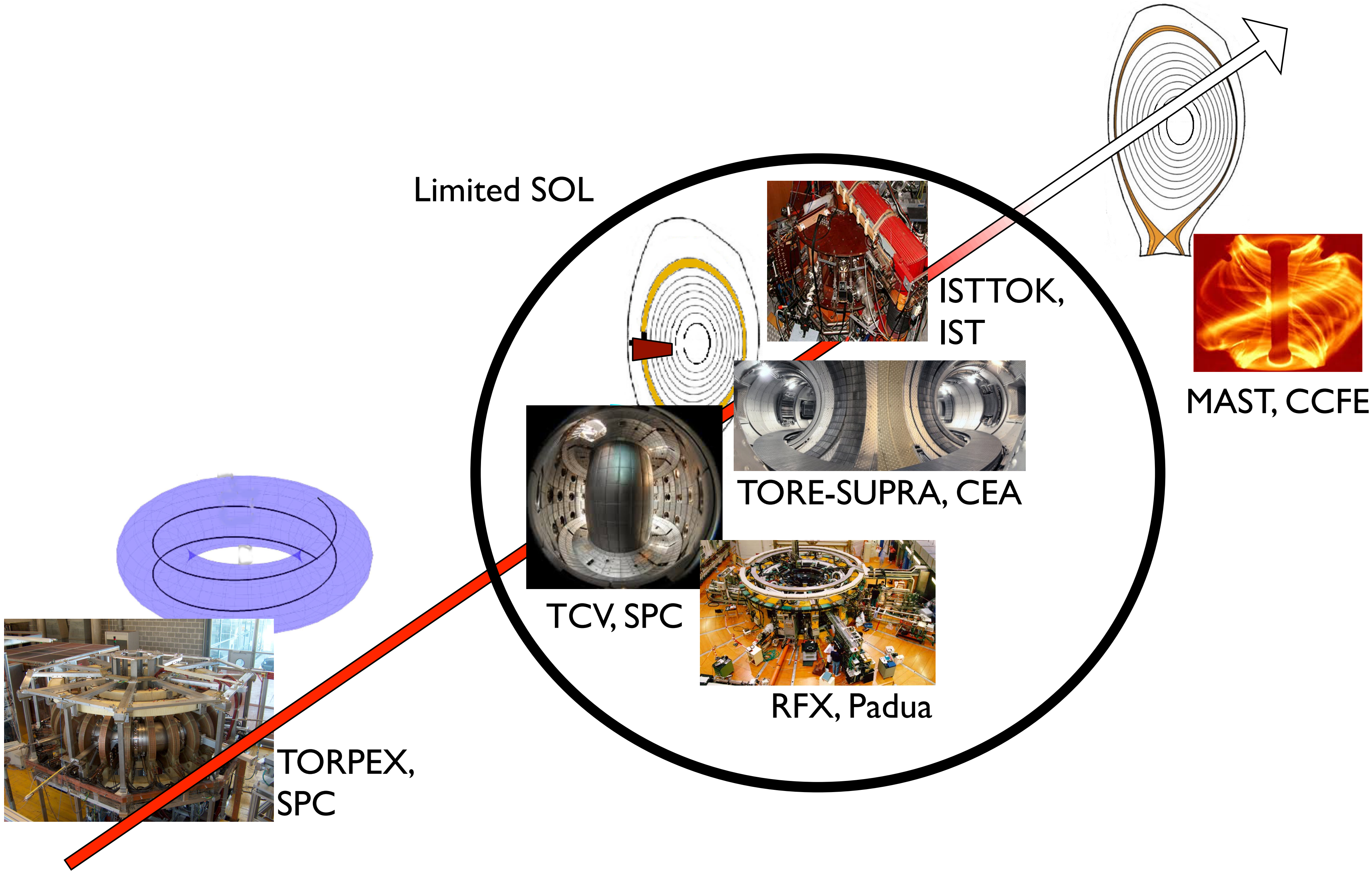
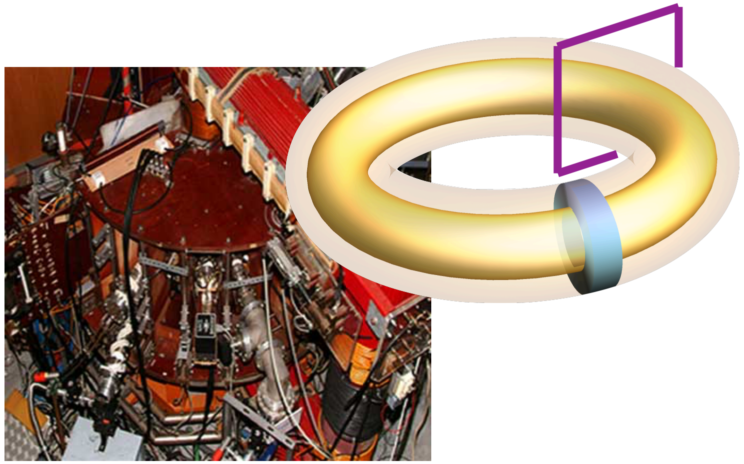
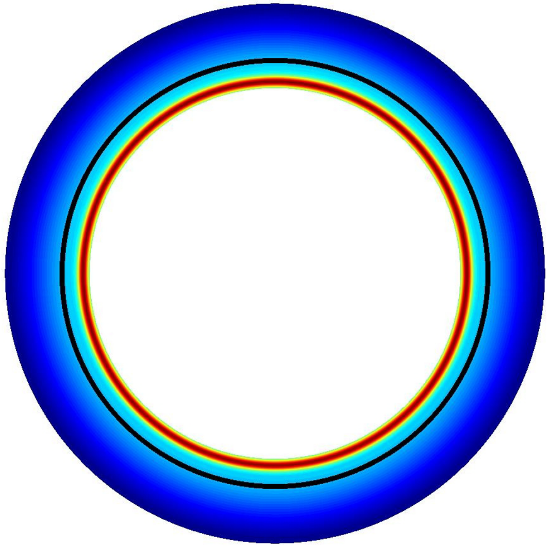


Full-turbulence simulation, a large validation effort

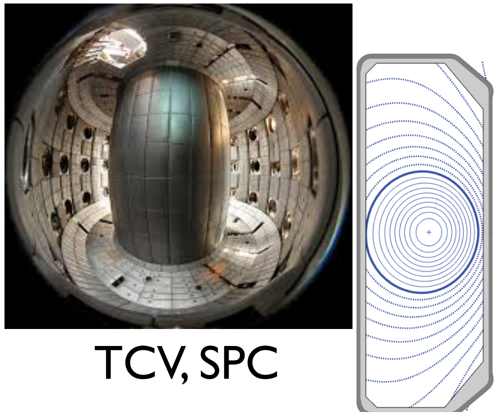


ISTTOK, IST

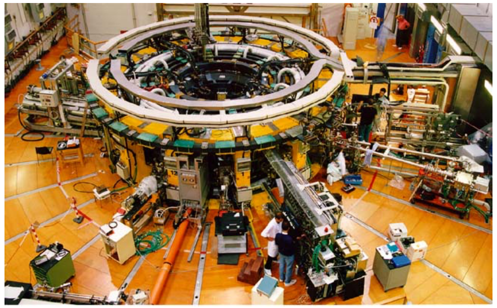


Simulations carried out with 4 codes

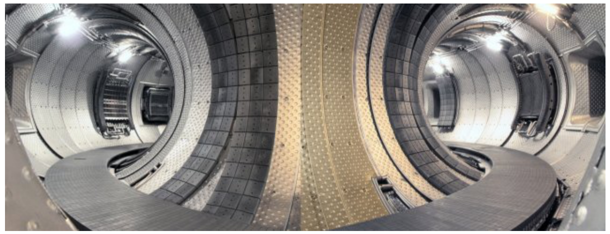
[Jorge, PoP 2016]



TCV, SPC



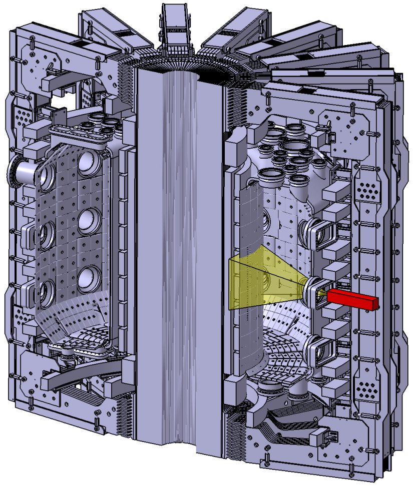
RFX, Padua



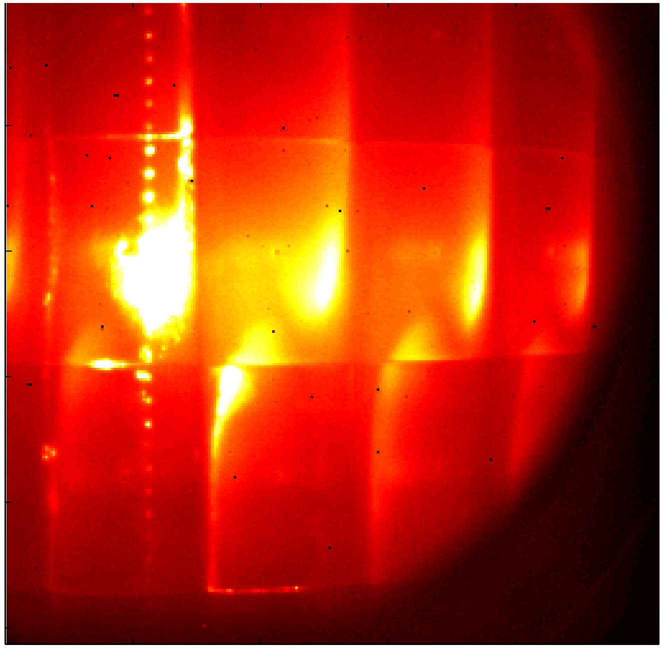
TORE-SUPRA, CEA

What is the heat flux to the wall?
i.e., the SOL width and temperature drop?

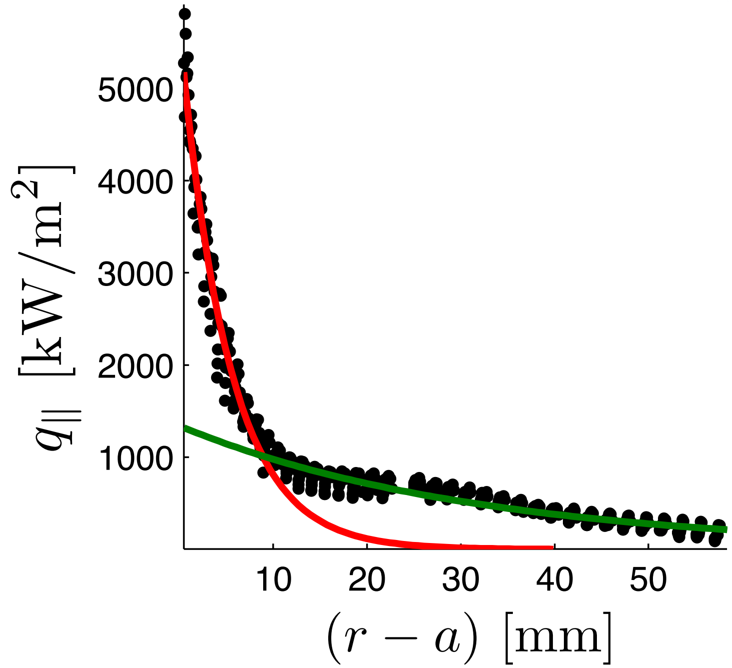
Recent measurements: 2 scale lengths



Infrared Measurement in TCV and COMPASS

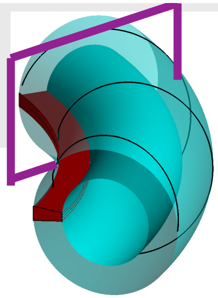


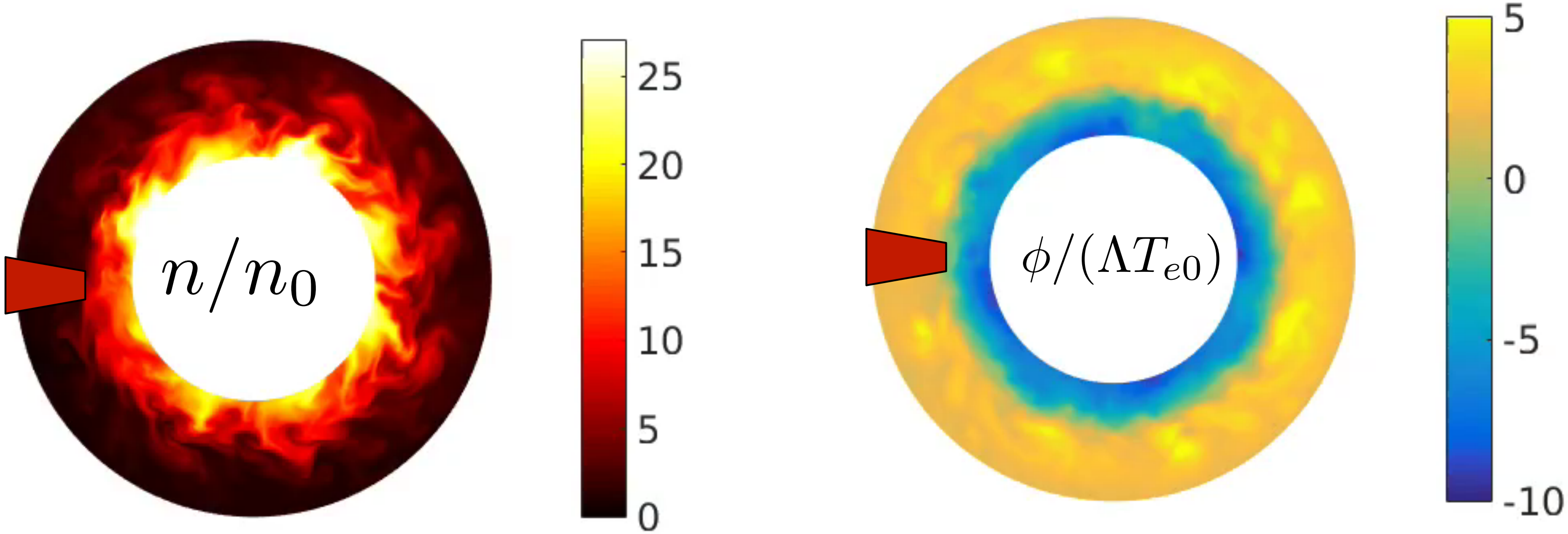
[Nespoli et al., JNM 2015
Nespoli et al., NME (in press)]



ITER inner wall was redesigned

Shear flow sets physics at the near SOL

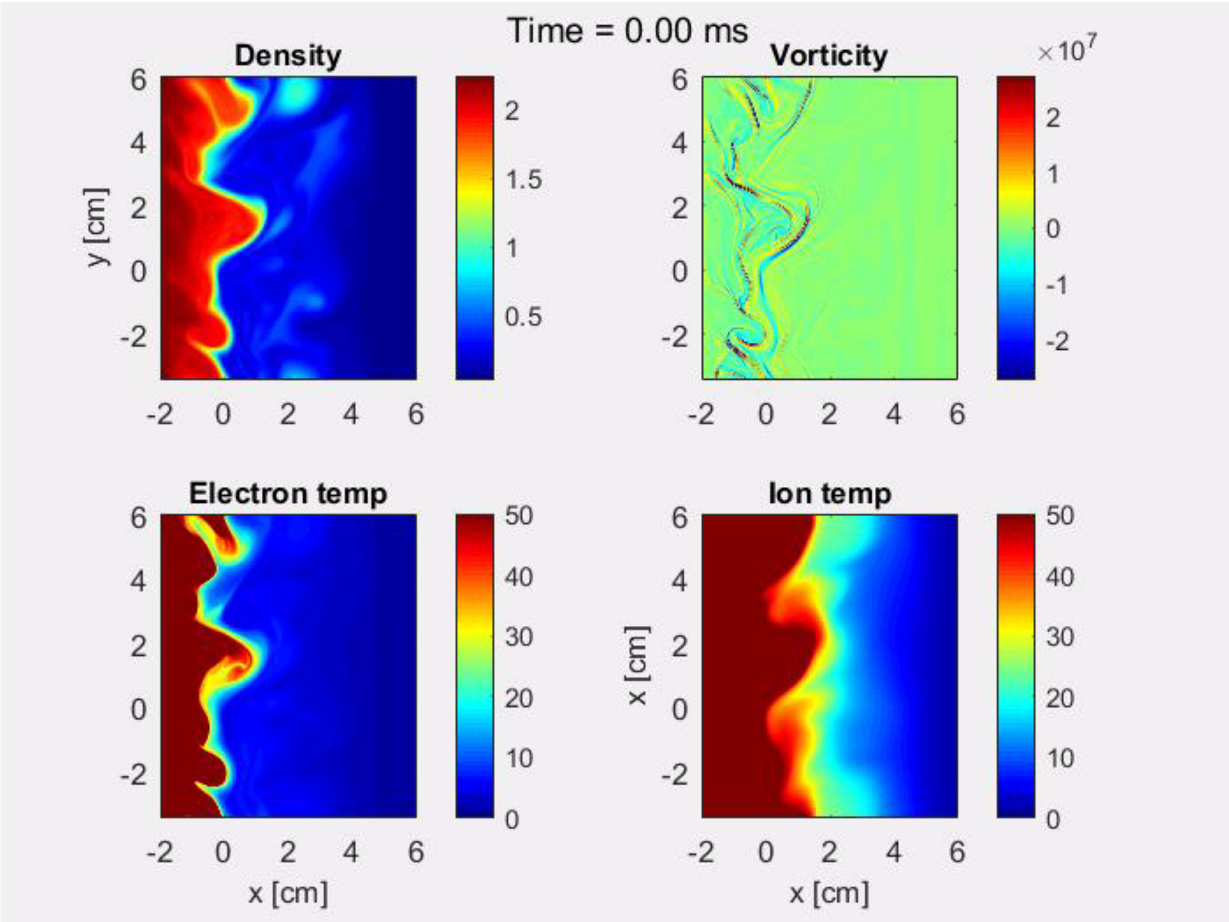




Halpern, NF 2016

The role for the shear flow was also pointed out for the formation of an H-mode like transport barrier
[Madsen PPCF 2015; Nielsen PLA 2015; Rasmussen PPCF 2016]

Far SOL transport dominated by blobs

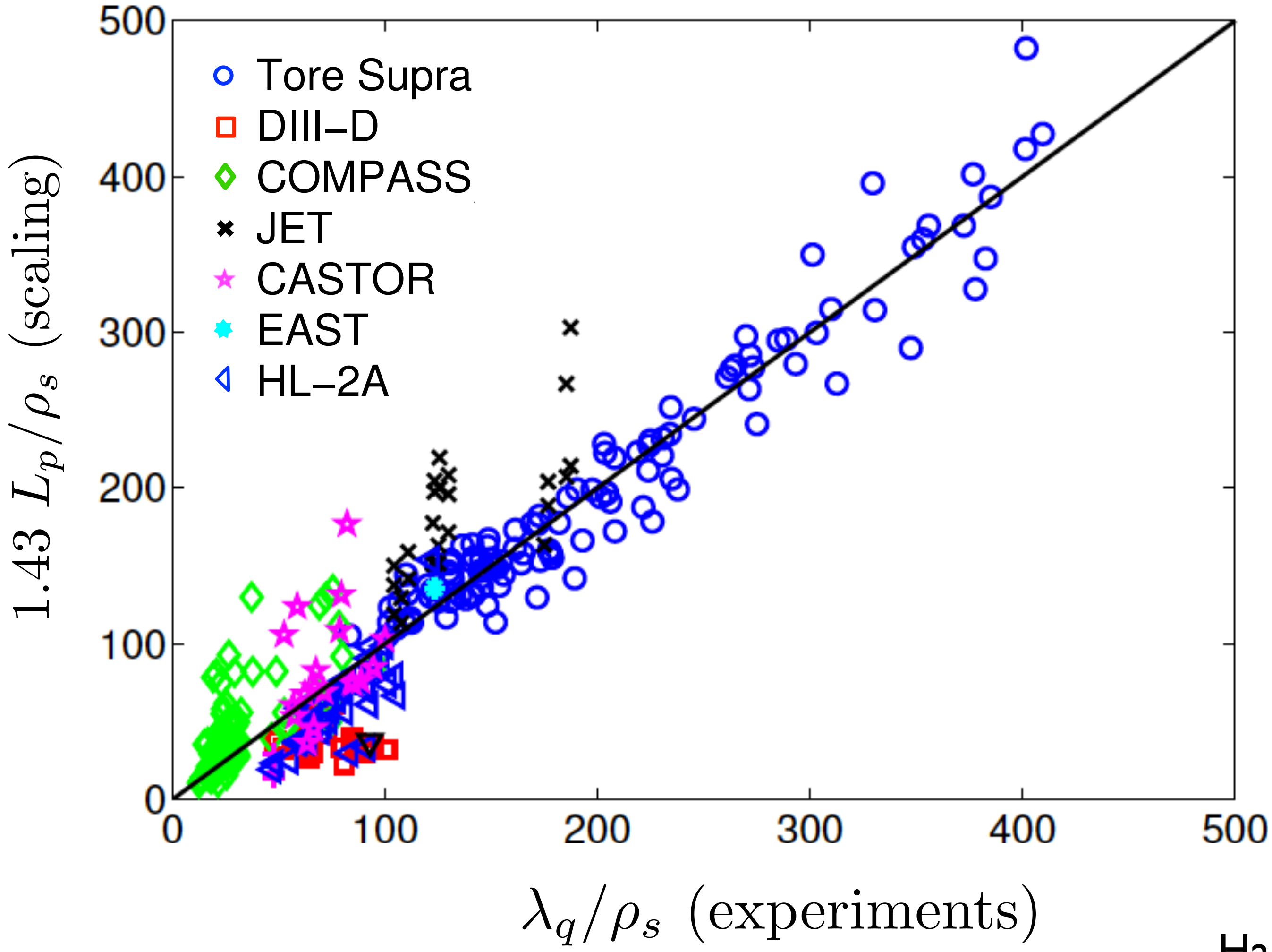


Identified effective collisionality setting attached and detached conditions

A shoulder forms with increasing collisionality and connection length [Nielsen PPCF 2017]

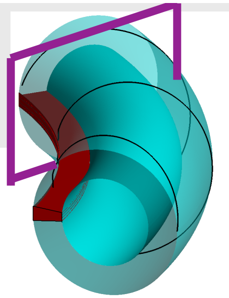
Scaling for the SOL width

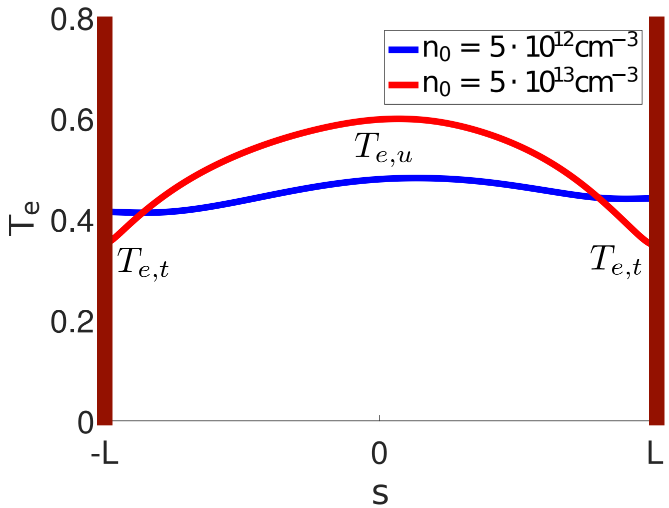
$$L_p \simeq 7.22 \times 10^{-8} q^{8/7} R^{5/7} B_\phi^{-4/7} T_{e,\mathrm{LCFS}}^{-2/7} n_{e,\mathrm{LCFS}}^{2/7} \left(1 + \frac{T_{i,\mathrm{LCFS}}}{T_{e,\mathrm{LCFS}}}\right)^{1/7}$$



Halpern et al, PPCF 2016

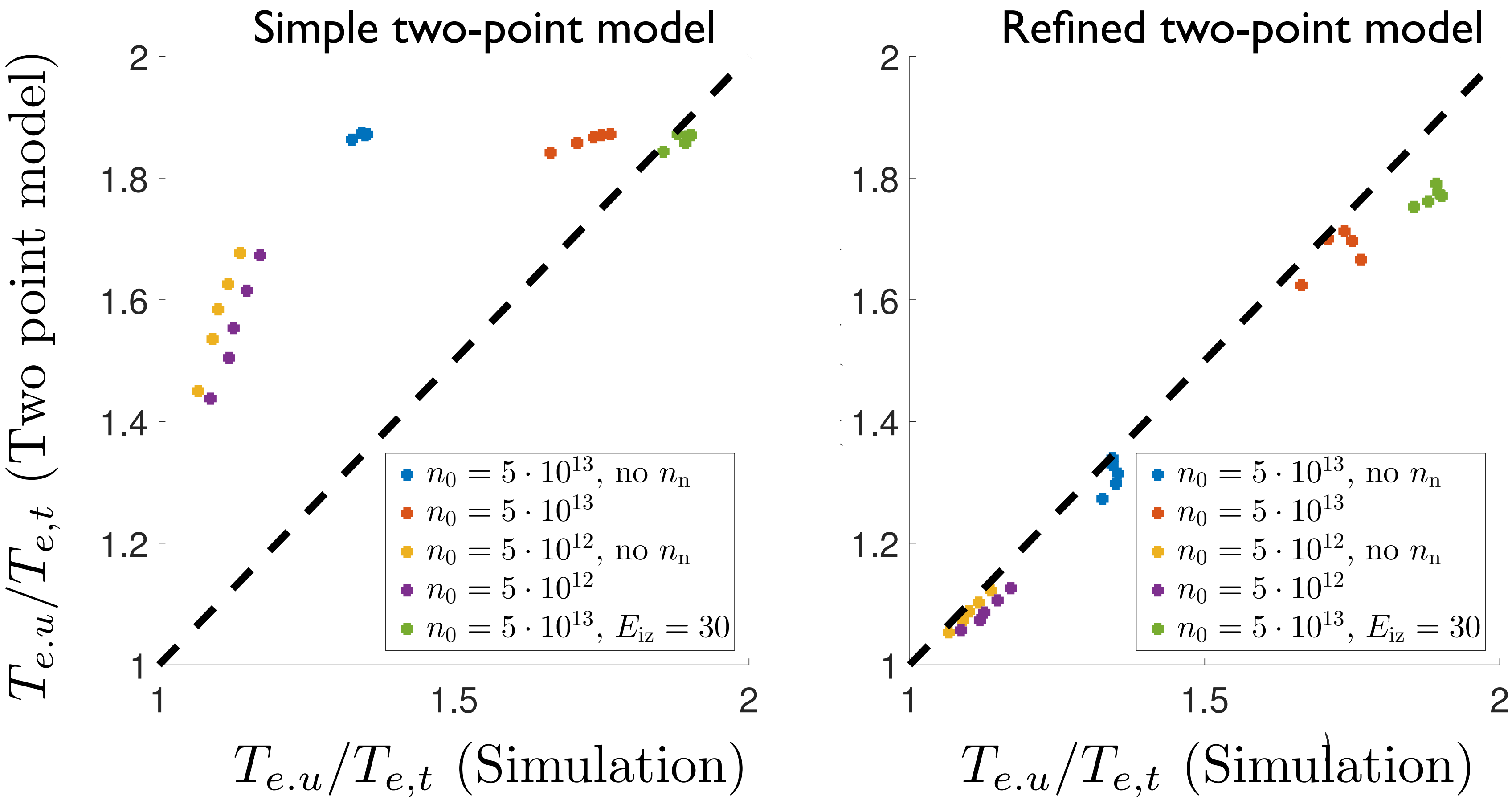
Upstream/limiter temperature drop





Wersal, PPCF 2017

Upstream/limiter temperature drop

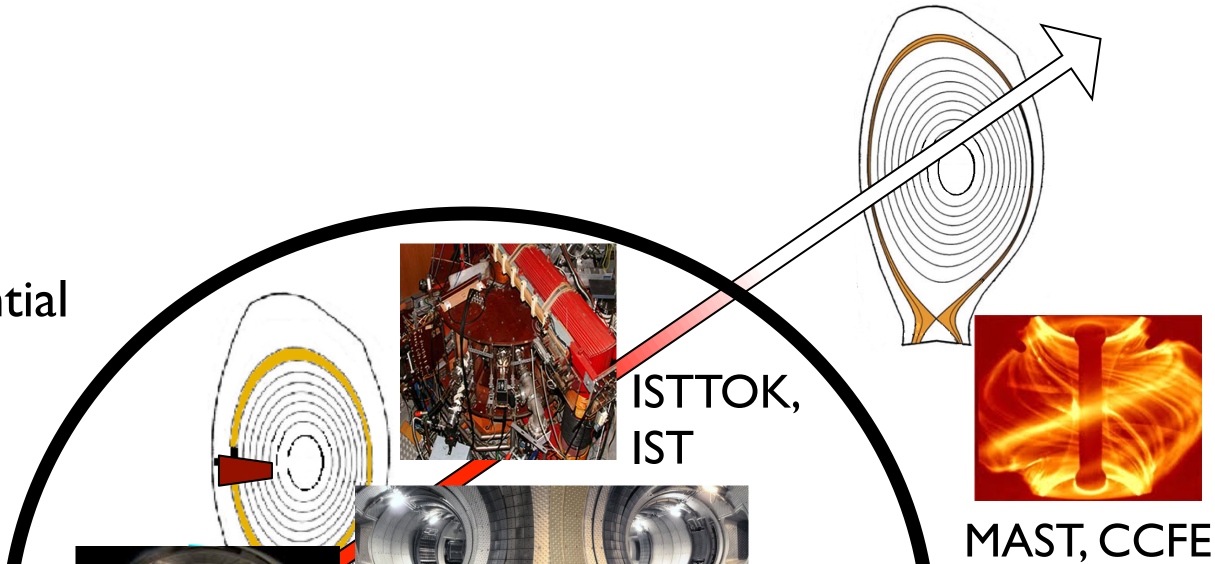


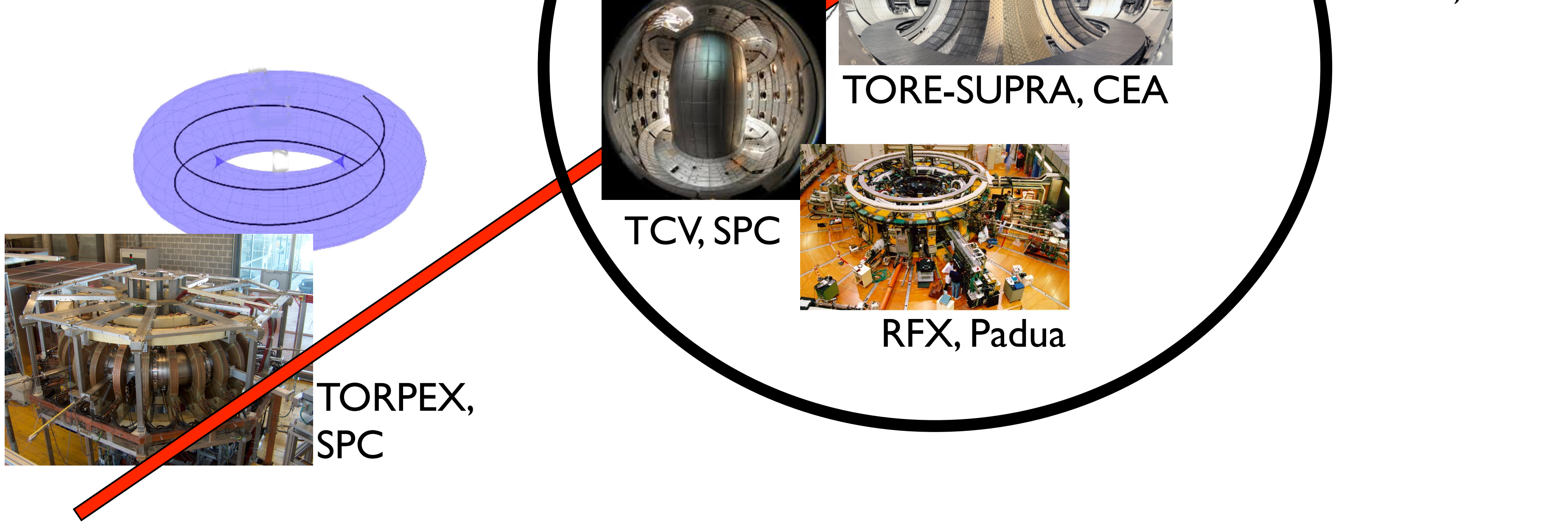
Wersal, PPCF 2017

A stepladder approach

Understanding of
- Basic mechanisms at play
- Fluctuation properties
- SOL width
- Plasma rotation and potential

Exp/sim discrepancy
- Narrow feature strength





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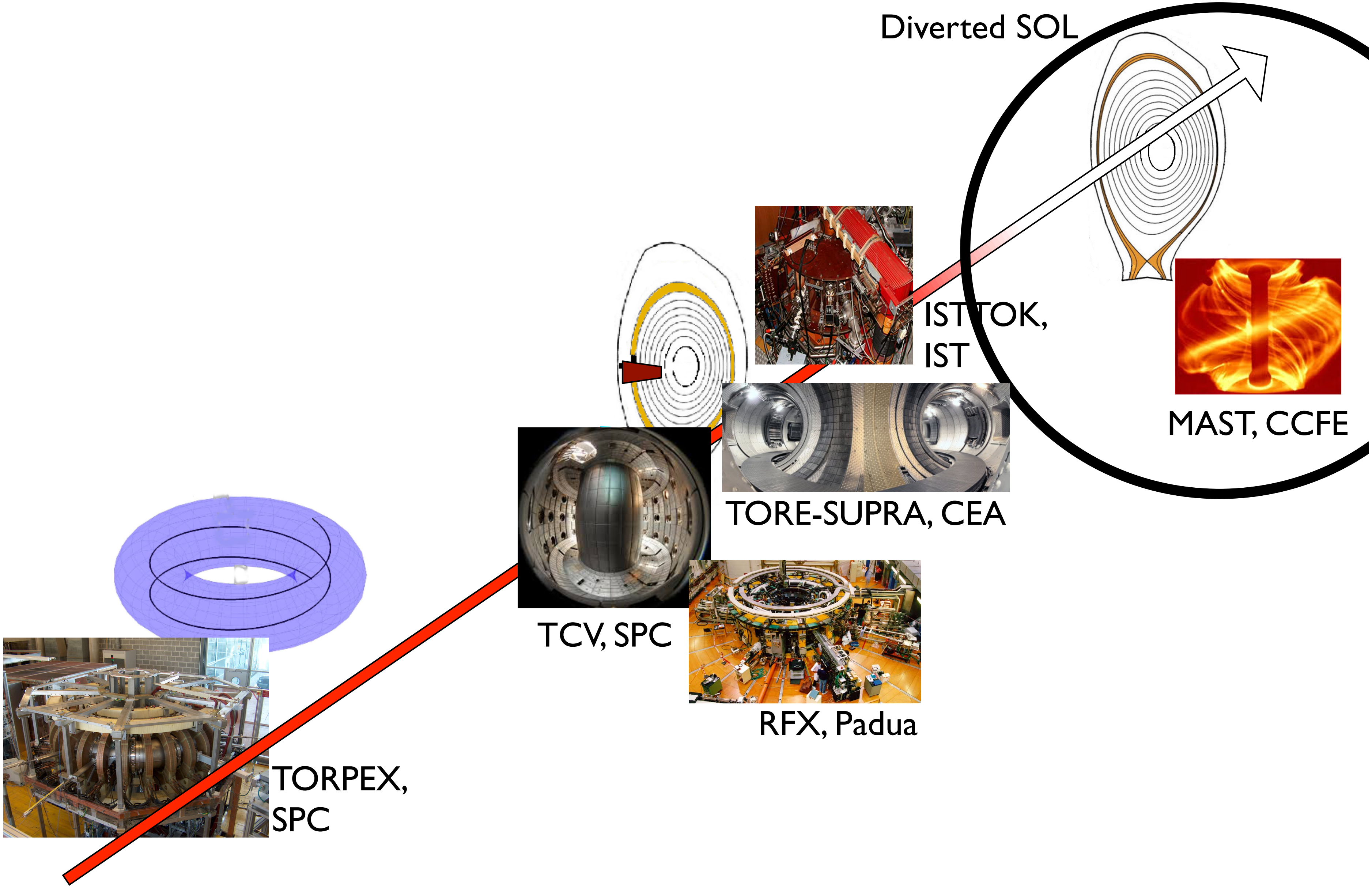
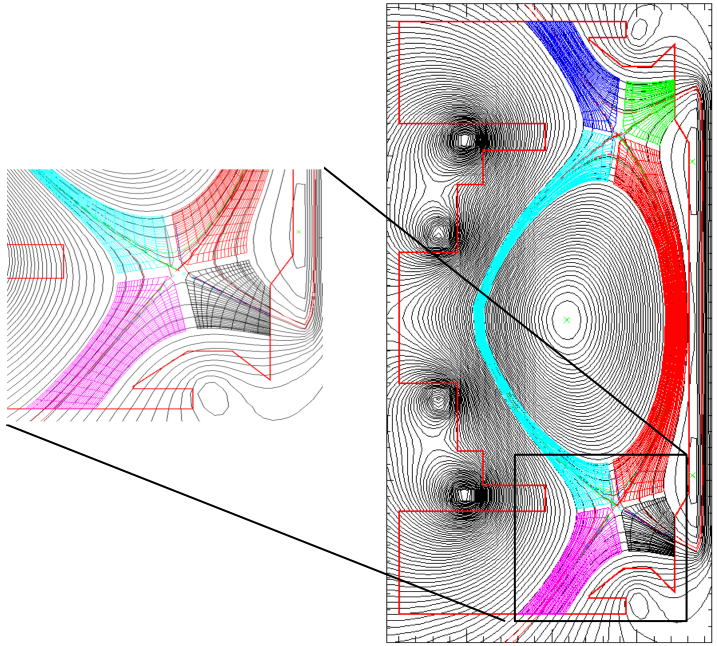
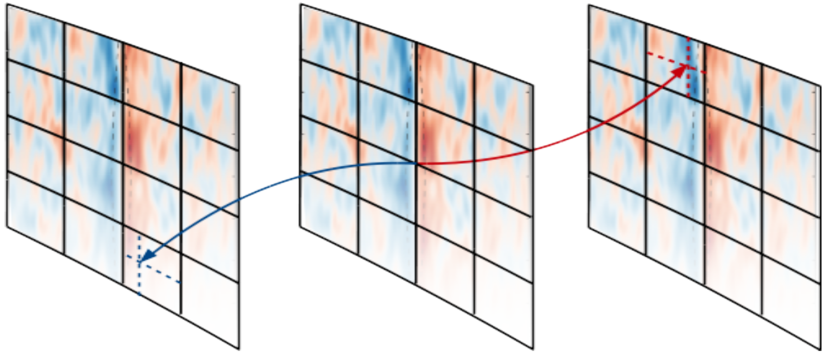


Large development of numerical algorithms

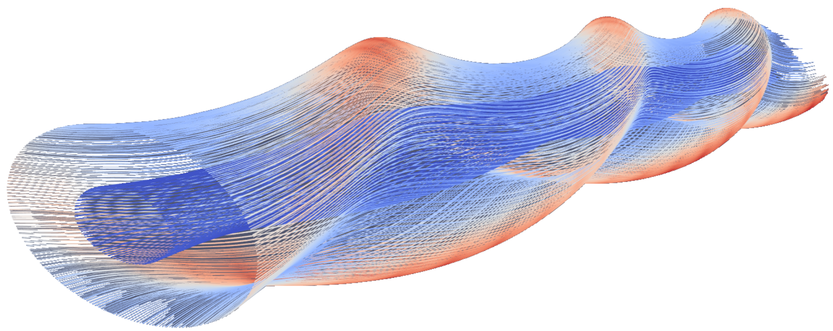
Non-orthogonal field aligned coordinate system to match arbitrary geometry [Leddy, CPC 2016]





Development of a non-field aligned coordinate system [Hill, CPC (in press)]

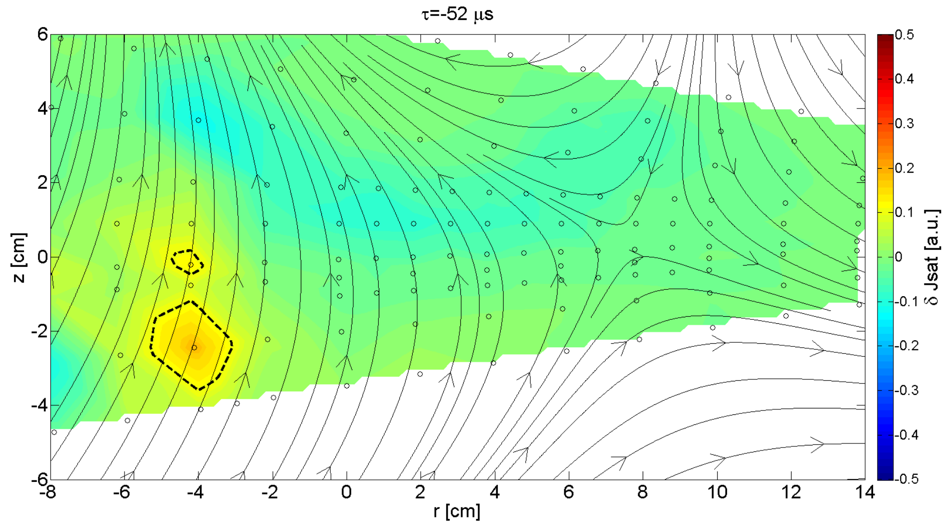
Extension to 3-D geometry [Shanahan, JP-CS 2016]

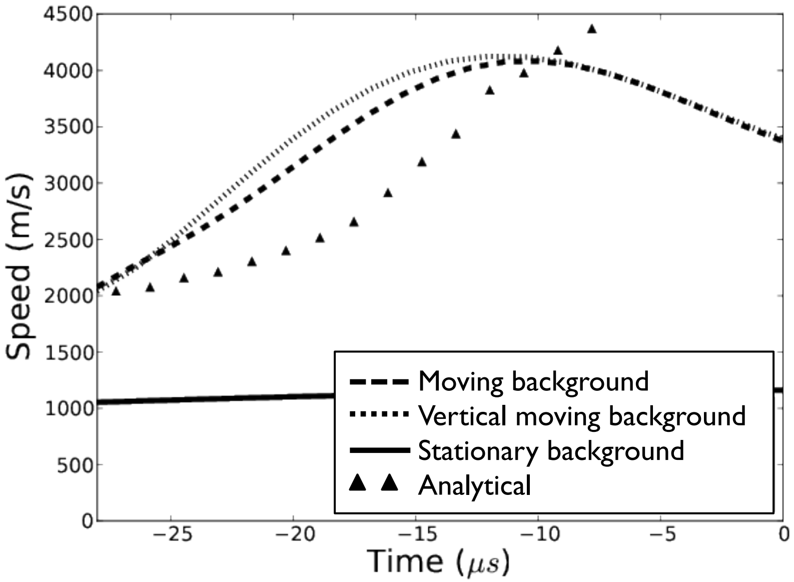


Study of blob dynamics in X point configuration

Blob in X point TORPEX configuration

[Avino, PRL 2016]



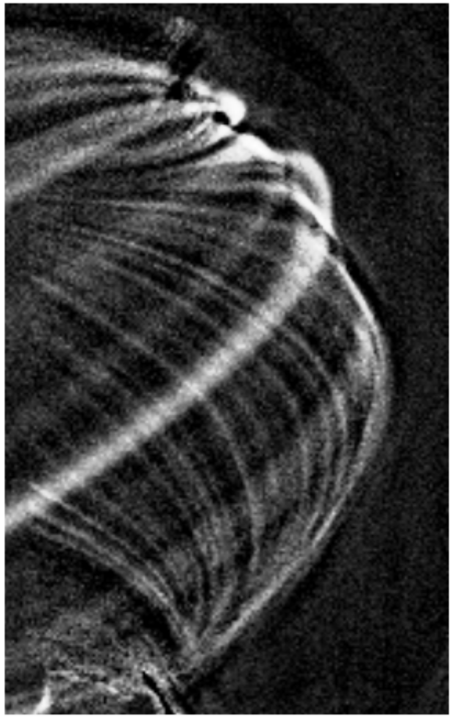


Simulations allowed understanding mechanisms determining blob velocity

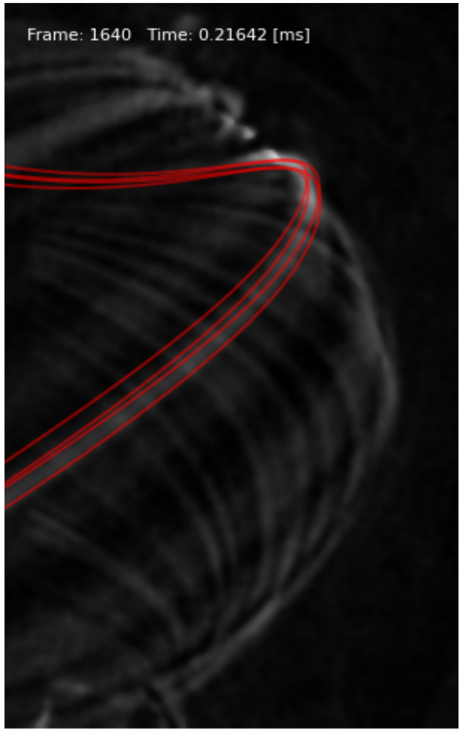
[Shanahan, PPCF 2016]

Blobs in MAST double-null configuration

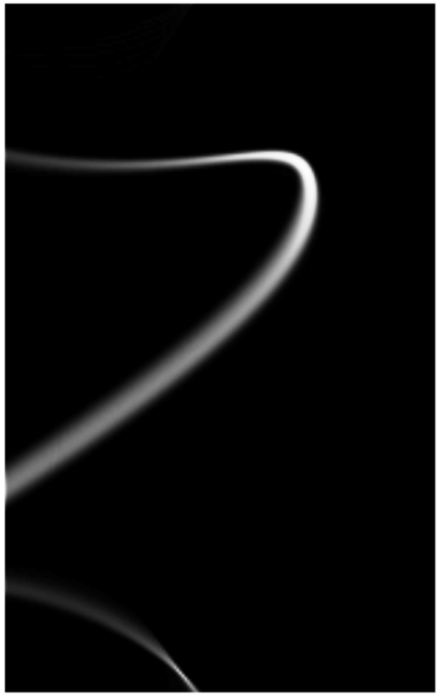
Visible light emission



Single blob identification



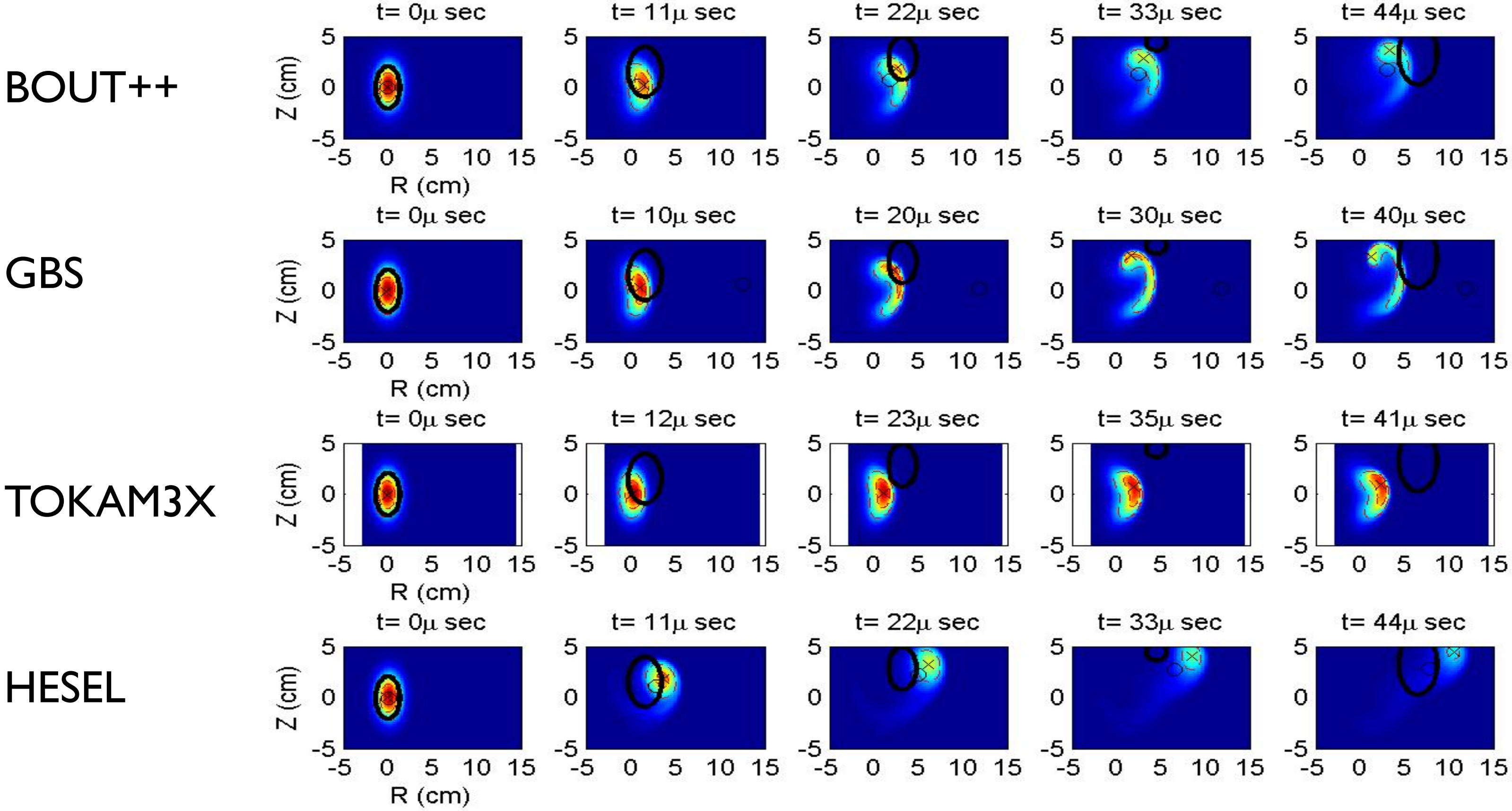
Initial conditions
for simulations



Walkden, NME (submitted)

Blobs in MAST double-null configuration

Simulations carried out with 4 codes

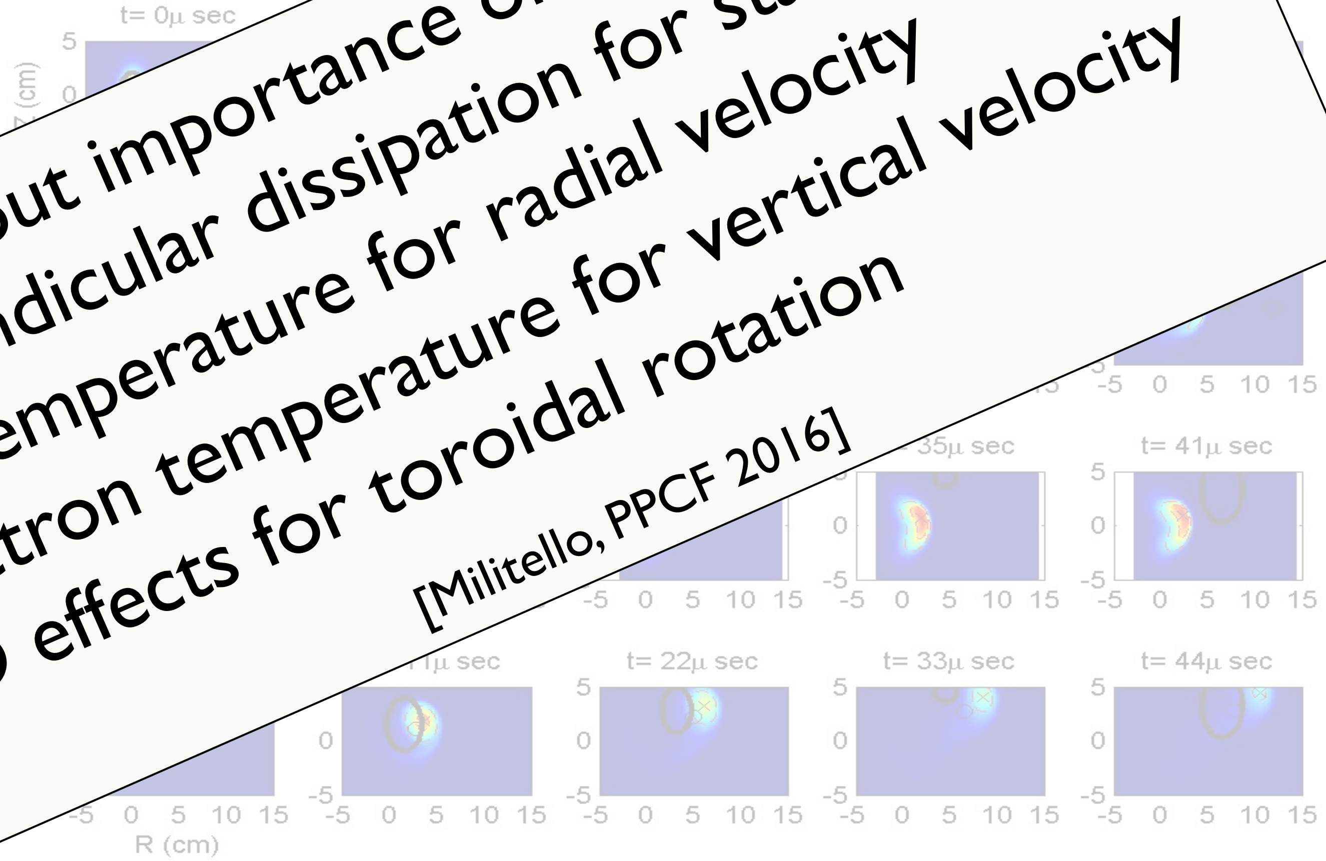


Blobs in MAST double-null configuration

Simulations carried out with 4 codes

BOUT++

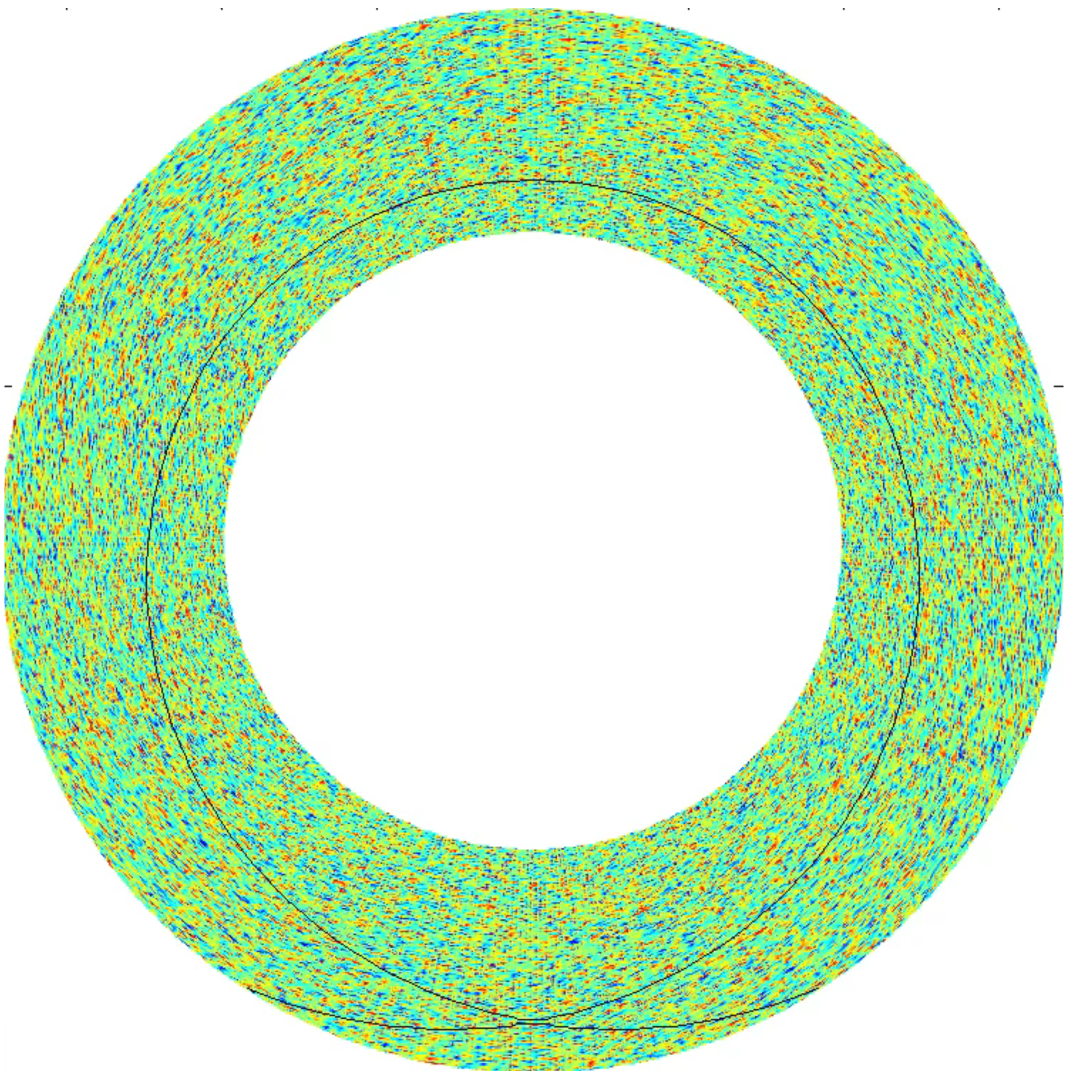
HES



Pointed out importance of
- Perpendicular dissipation for stability
- Ion temperature for radial velocity
- Electron temperature for vertical velocity
- 3D effects for toroidal rotation

[Militello, PPCF 2016]

Full-turbulence simulations in diverted geometry



Turbulence similar to limited case, except at X point; good agreement for parallel velocity

[D. Galassi, NF (in press)]

What's next?

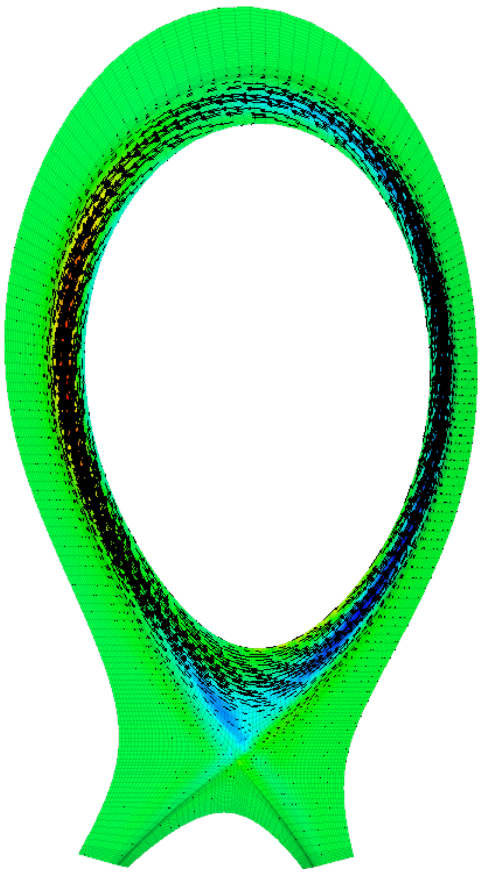
- Detailed analysis of **diverted** and **advanced exhaust** configurations

- Approach **H-mode** scenarios

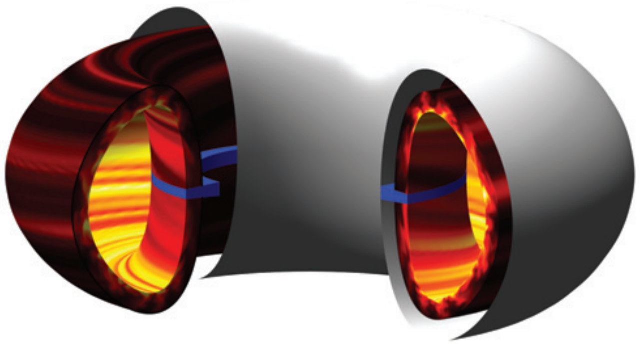
  - Going beyond the **drift approximation**, using high order methods on unstructured meshes

    [Minjaud, JCP 2016]

  - Going beyond the Braginskii model, including **kinetic effects**



Concluding remarks



- By using first-principles approach, we can now disentangle the complex dynamics at the tokamak edge

- Significant advances in physics models and simulation capabilities, rigorously verified

- By using a stepladder approach, progress in physics understanding, starting from relatively simple configurations

- Leveraging this expertise, we are increasing the complexity of simulations, continually approaching target reactor conditions