Progress in the understanding of tokamak scrape-off layer plasma turbulence

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Why is it so crucial to understand SOL dynamics?

How can we simulate the SOL? How did we get there?

What are the mechanisms setting the SOL width? ES potential? Toroidal rotation? How can the heat load to the vessel be reduced?

Our current activities?

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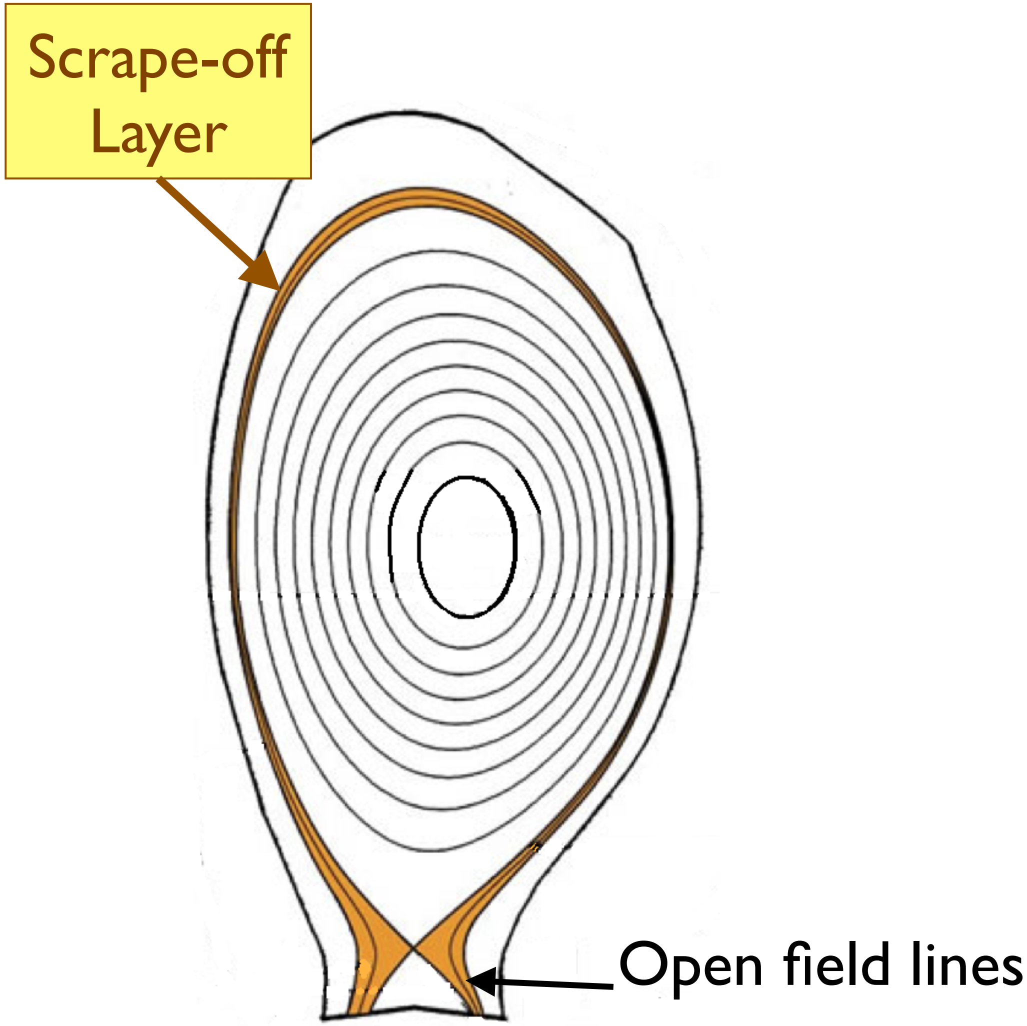
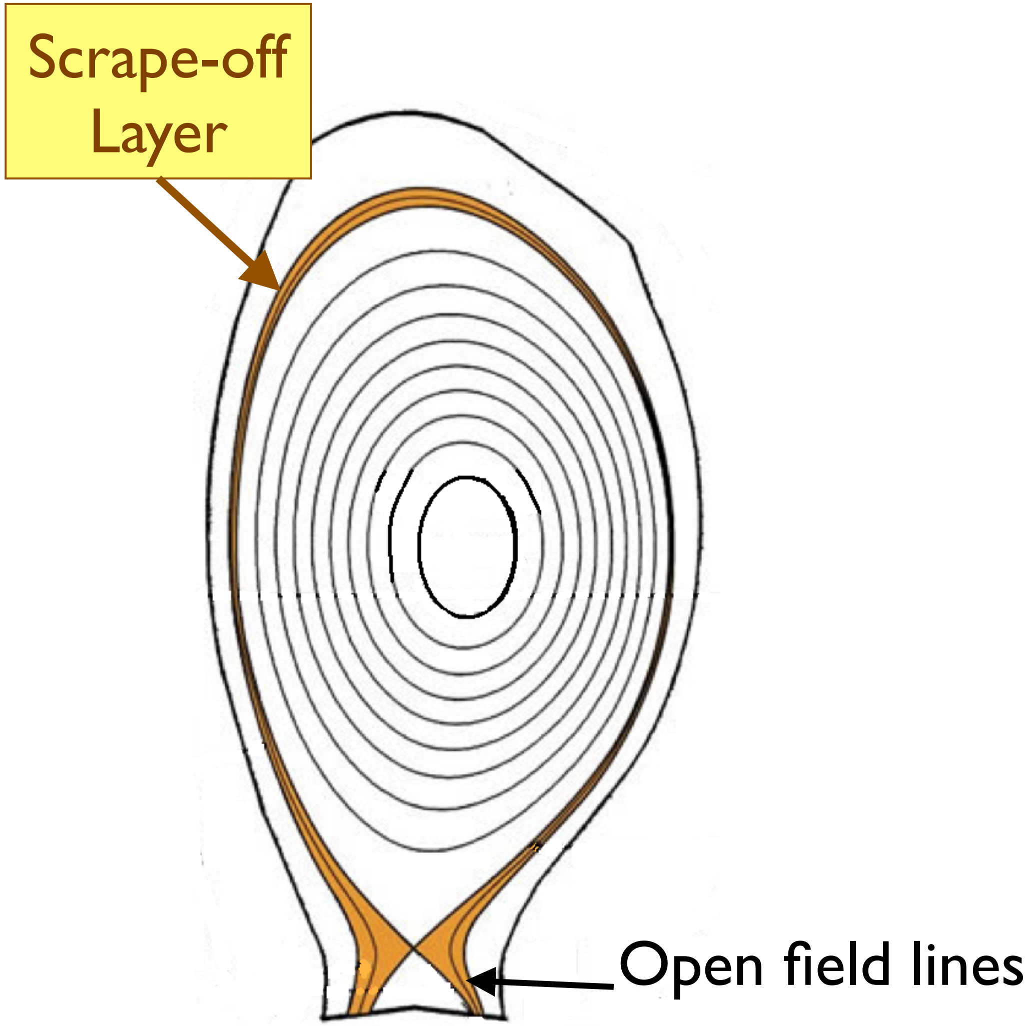
The scrape-off layer (SOL): the most external plasma region in a tokamak



Roles of the SOL:

- Heat exhaust
- Plasma confinement
- Plasma fueling and ashes removal
- Impurity control

The scrape-off layer (SOL): the most external plasma region in a tokamak



Roles of the SOL:

- Heat exhaust
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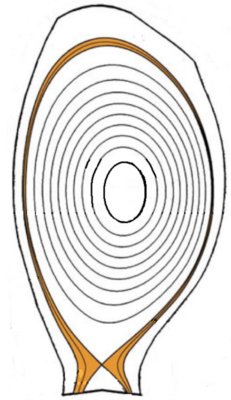
Heat exhaust – a crucial issue for the entire fusion program

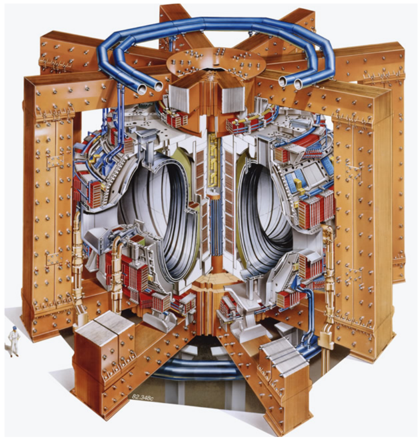


$$P_{\mathrm{wall}} \sim \frac{Q_{\mathrm{sep}}}{A_{\mathrm{wet}}}(1 - f_{\mathrm{rad}})$$

Non-radiated part

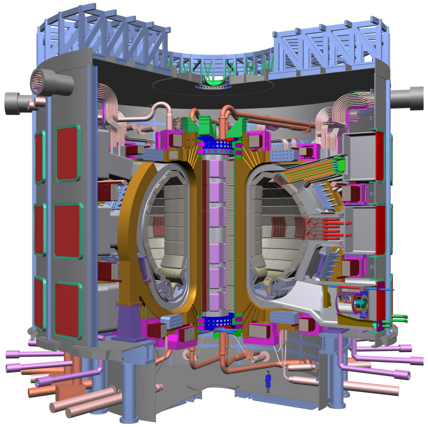
Geometry

JET



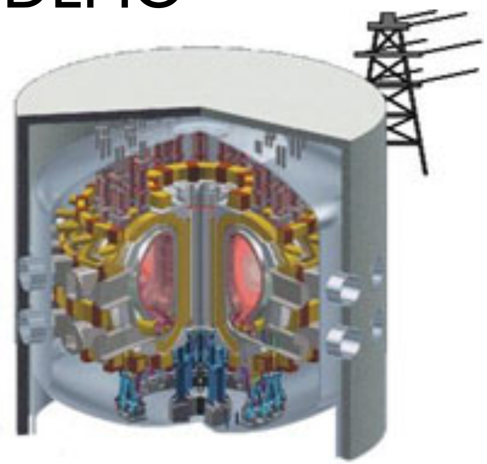
$$\frac{Q_{\mathrm{sep}}}{R} = 7\ \mathrm{MW\ m^{-1}}$$

ITER



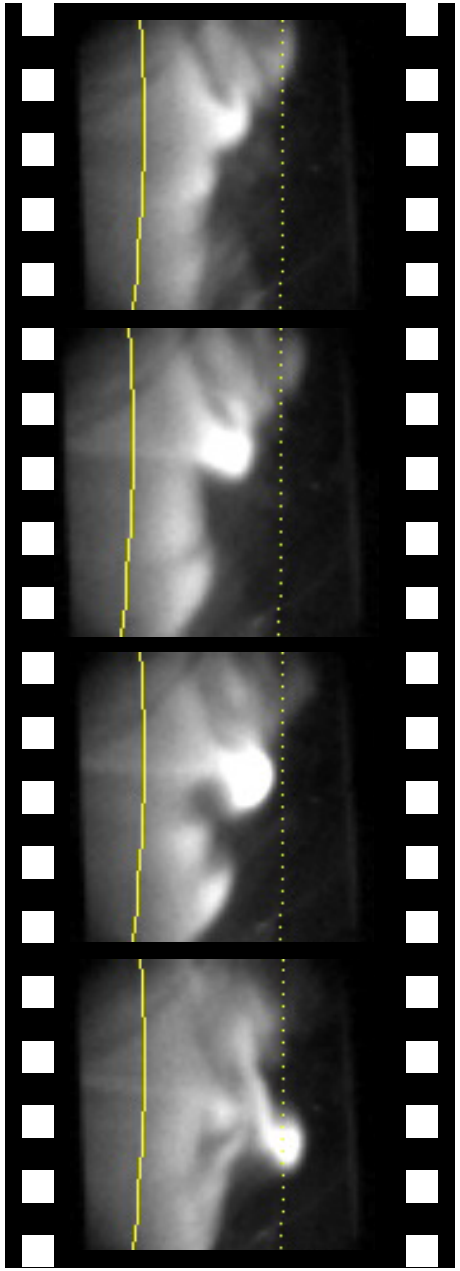
$$\frac{Q_{\mathrm{sep}}}{R} = 20\ \mathrm{MW\ m^{-1}}$$

DEMO

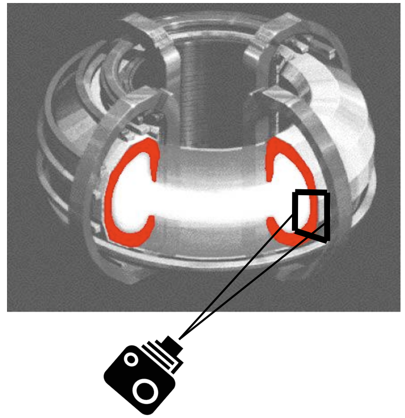


$$\frac{Q_{\mathrm{sep}}}{R} = 80 - 100\ \mathrm{MW\ m^{-1}}$$

Properties of SOL turbulence



Courtesy of R. Maqueda, typical L-mode SOL



- $n_{fluc} \sim n_{eq}$
- $L_{fluc} \sim L_{eq}$
- Fairly cold ($<$ 100 eV, $n_e \sim 10^{19}$ m^{-3}) magnetized plasma
- Role of neutrals
- Sheath physics

A model to evolve plasma turbulence in the SOL

Collisional Plasma $\longrightarrow$ **Braginskii model** $\xrightarrow{\rho_i \ll L,\ \omega \ll \Omega_{ci}}$ **Drift-reduced Braginskii equations**

$$\frac{\partial n}{\partial t} + \underbrace{[\phi, n]}_{\text{E×B CONVECTION}} = \overbrace{\hat{C}(nT_e) - n\hat{C}(\phi)}^{\text{MAGNETIC CURVATURE}} - \underbrace{\nabla_{\parallel}(nV_{\parallel e})}_{\text{PARALLEL DYNAMICS}} + \overbrace{n_n \nu_{\text{ion}}}^{\text{IONIZATION}} - \underbrace{n\nu_{\text{rec}}}_{\text{RECOMBINATION}} + \overbrace{S_n}^{\text{OUTFLOW FROM CORE}}$$

T_e, T_i, Ω (vorticity) $\Rightarrow$ similar equations

$V_{\parallel e}, V_{\parallel i}$ $\Rightarrow$ parallel momentum balance

$$\nabla \cdot (n\nabla_{\perp}\phi) = \Omega - \tau\nabla_{\perp}^2 p_i$$

$$\nabla_{\perp}^2 \psi = j_{\parallel}$$

A model to evolve plasma turbulence in the SOL

+ coupling with neutrals

$$\frac{\partial f_n}{\partial t} + \underbrace{\mathbf{v} \cdot \frac{\partial f_n}{\partial \mathbf{x}}}_{\text{STREAMING}} = \underbrace{-\nu_{\text{ion}} f_n}_{\text{IONIZATION}} \underbrace{- \nu_{\text{CX}}(f_n - n_n f_i/n_i)}_{\text{CHARGE EXCHANGE}} + \underbrace{\nu_{\text{rec}} f_i}_{\text{RECOMBINATION}}$$

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

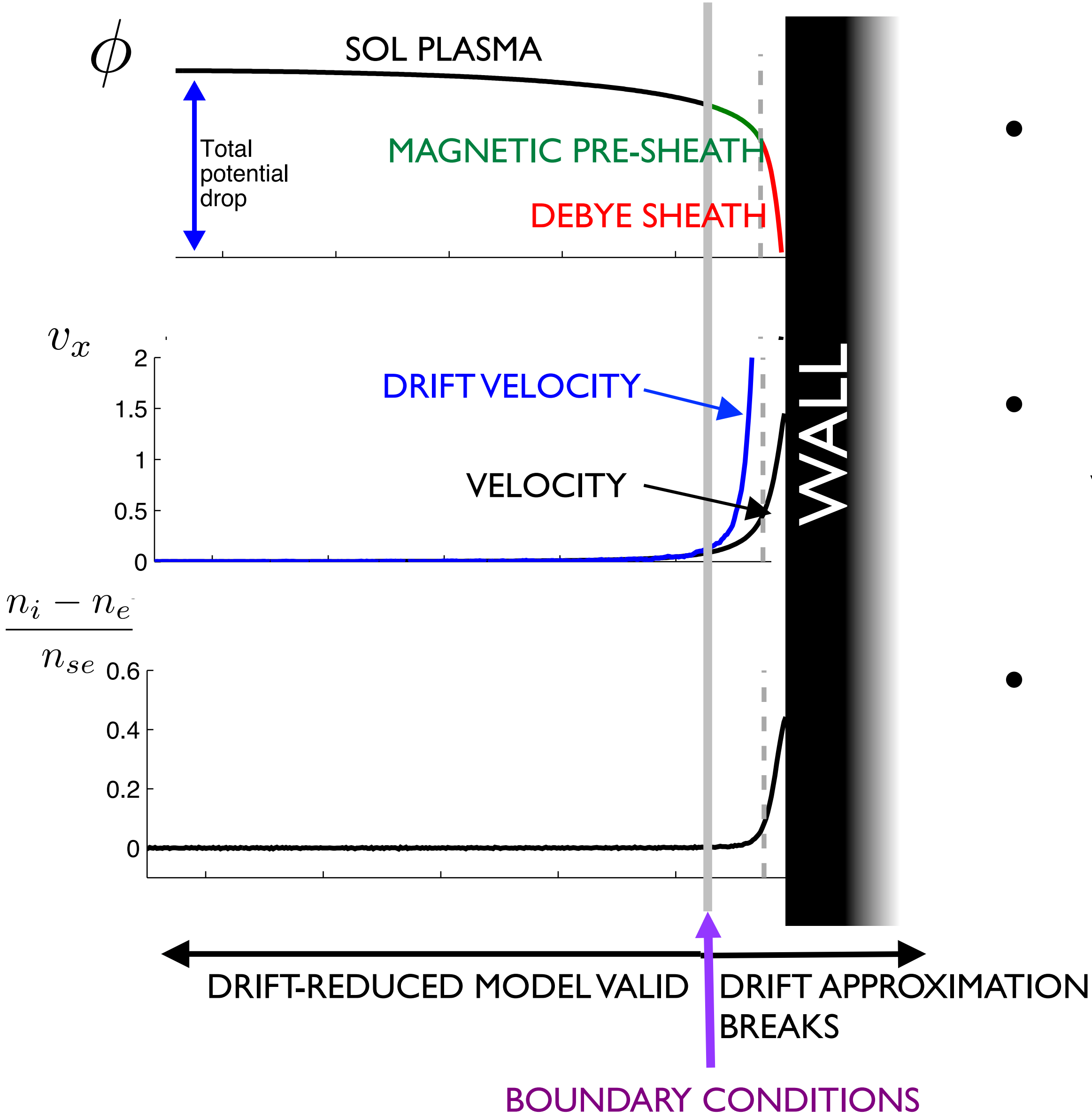
$$\nu_{\text{CX}} = n \langle v_{\text{rel}} \sigma_{\text{CX}}(v_{\text{rel}}) \rangle$$

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

Wersal & Ricci, NF 2015

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

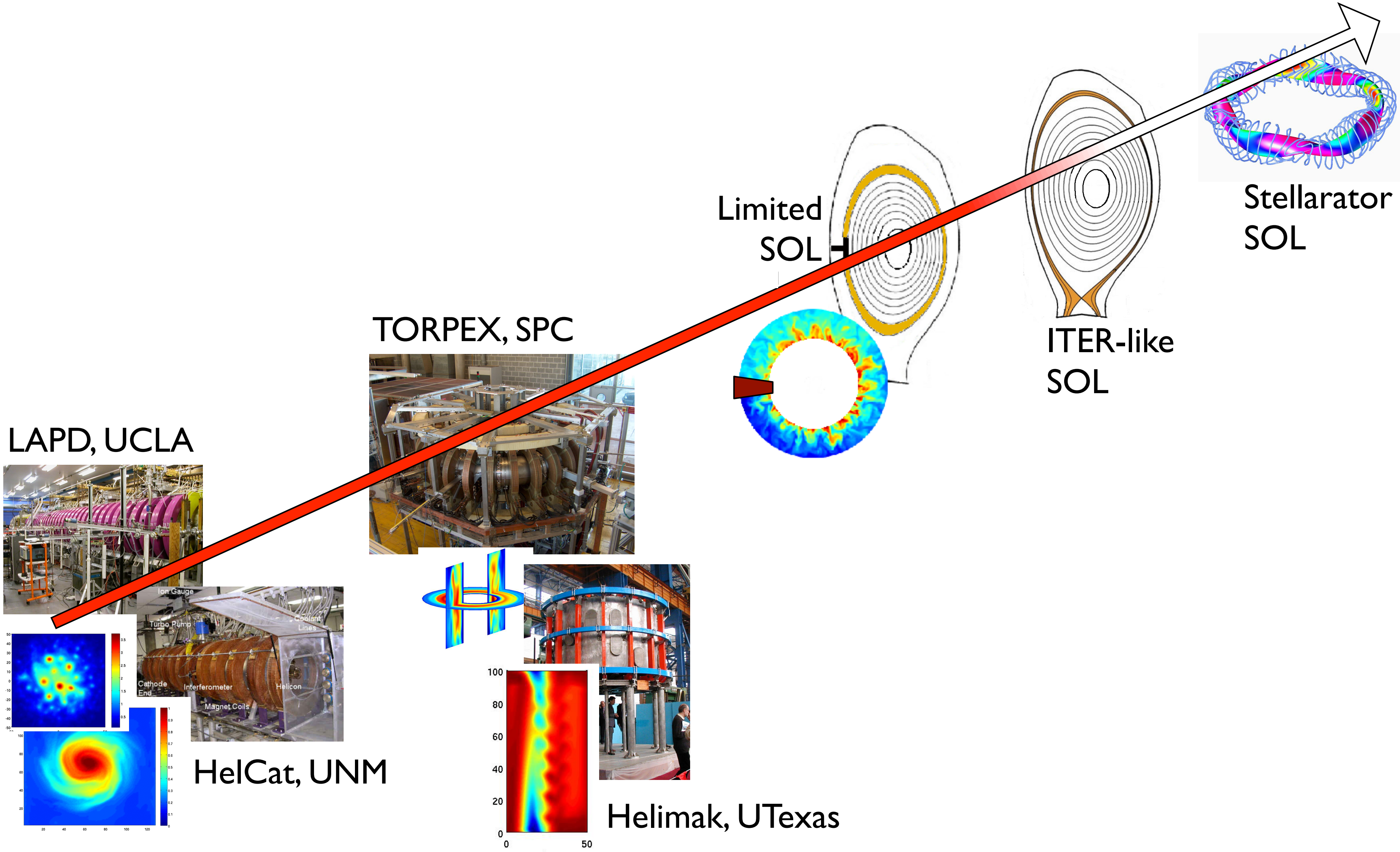
Boundary conditions at the plasma-wall interface



- Set of b.c. for all quantities, generalizing Bohm-Chodura
- Checked agreement with PIC kinetic simulations
- Neutrals: reflection and re-emission with cosine distribution

Loizu et al., PoP 2012

GBS: our simulation tool



Ricci et al., PPCF 2012; Halpern et al., JCP 2016

Code verification, the techniques

1) Simple tests
2) Code-to-code comparisons (benchmarking)
3) Discretization error quantification
4) Convergence tests
5) Order-of-accuracy tests

NOT RIGOROUS

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, method of manufactured solution

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

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

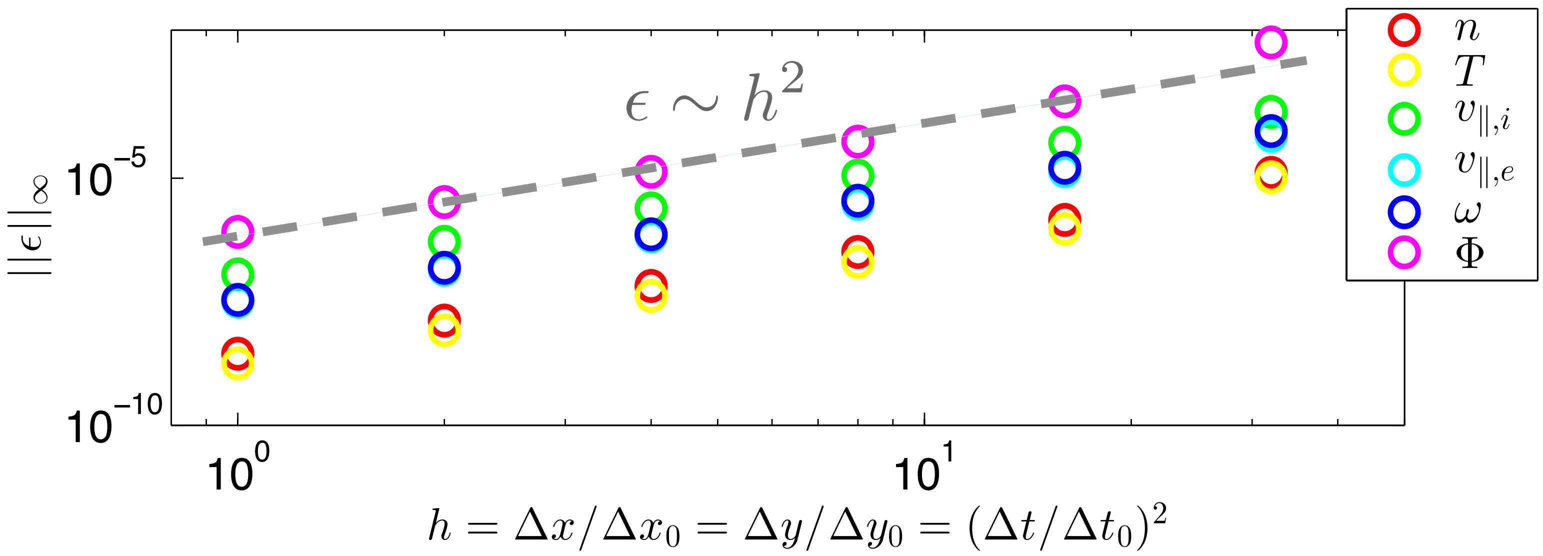
Method of manufactured solution:

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

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

$\boxed{\epsilon_n = g_n - g}$

For GBS:



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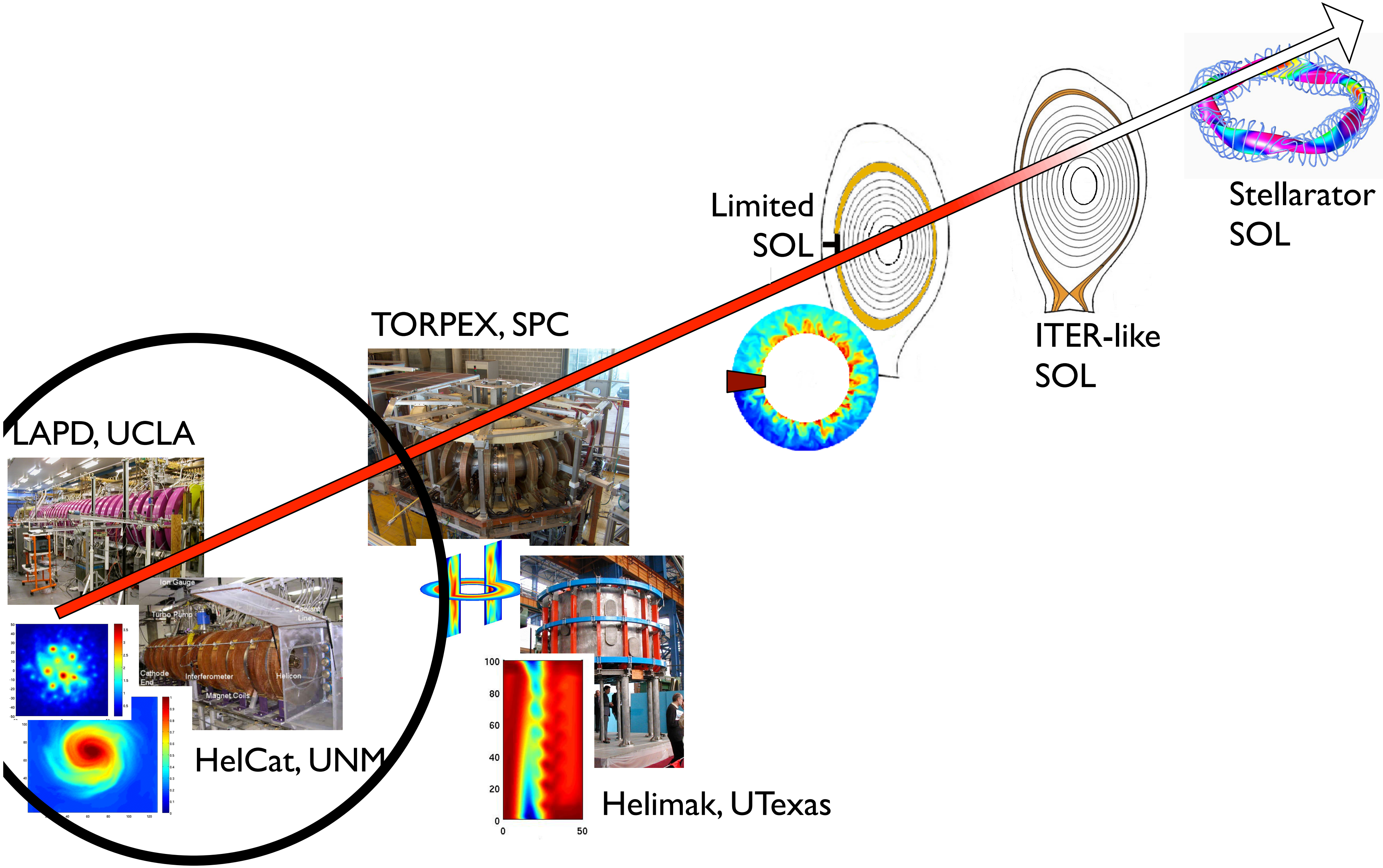
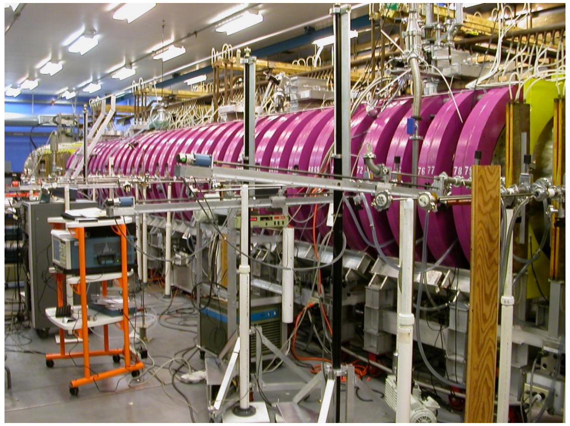
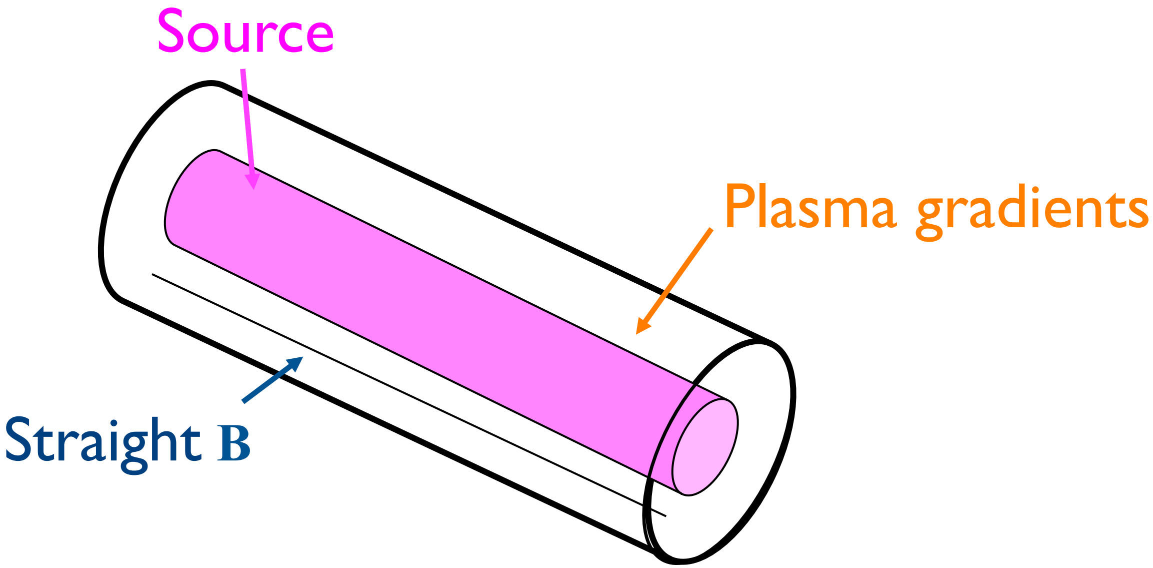
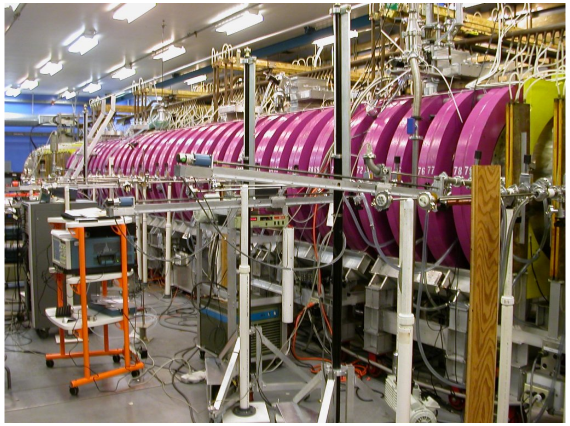




GBS simulation of a linear device: LAPD and HelCat



$$\frac{\partial n}{\partial t} + \overset{\text{ExB}}{\boxed{[\phi, n]}} = \overset{\text{Magnetic curvature}}{\cancel{\boxed{\hat{C}(nT_e) + n\hat{C}(\phi)}}} - \overset{\text{Parallel dynamics}}{\boxed{\nabla_{\parallel}(nV_{\parallel e})}} + \overset{\text{Source}}{\boxed{S}}$$



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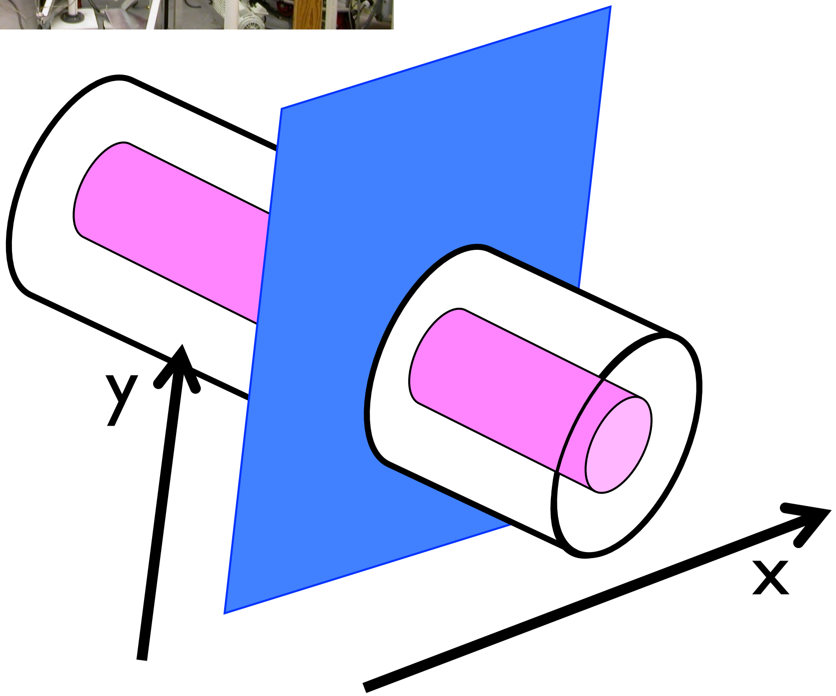
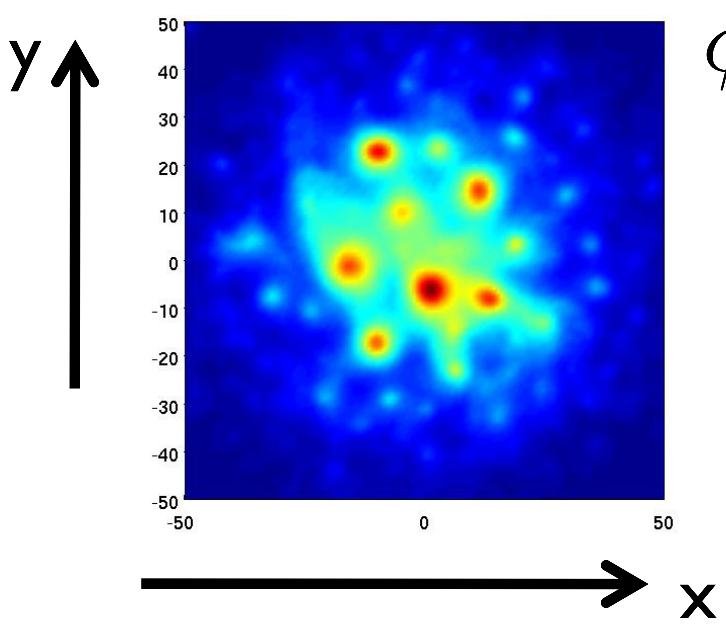
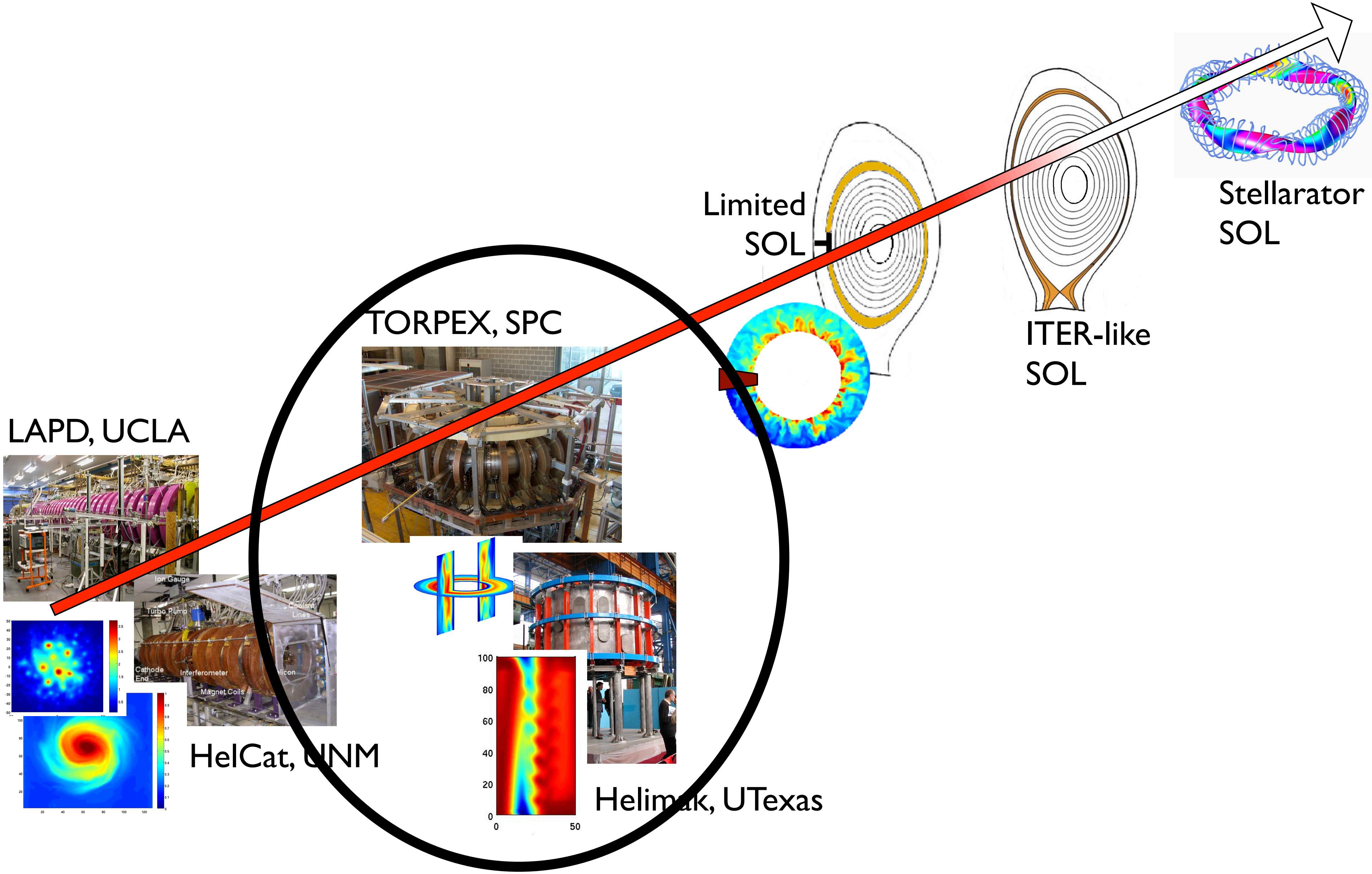




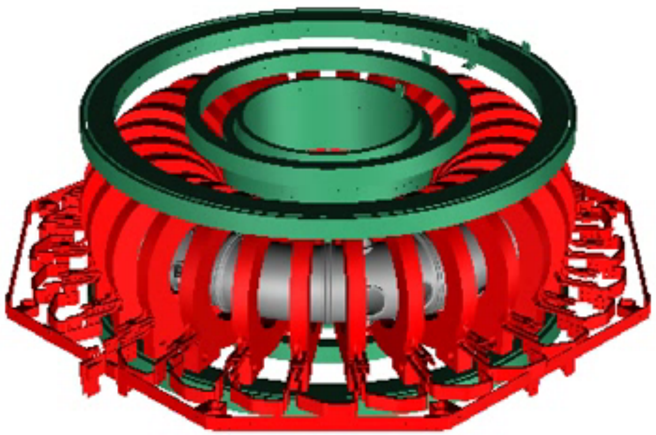
Plasma gradients → Drift waves / Kelvin-Helmholtz / Sheath mode

Rogers & Ricci, PRL 2010

GBS: our simulation tool



The Simple Magnetized Plasma (SMT) TORPEX



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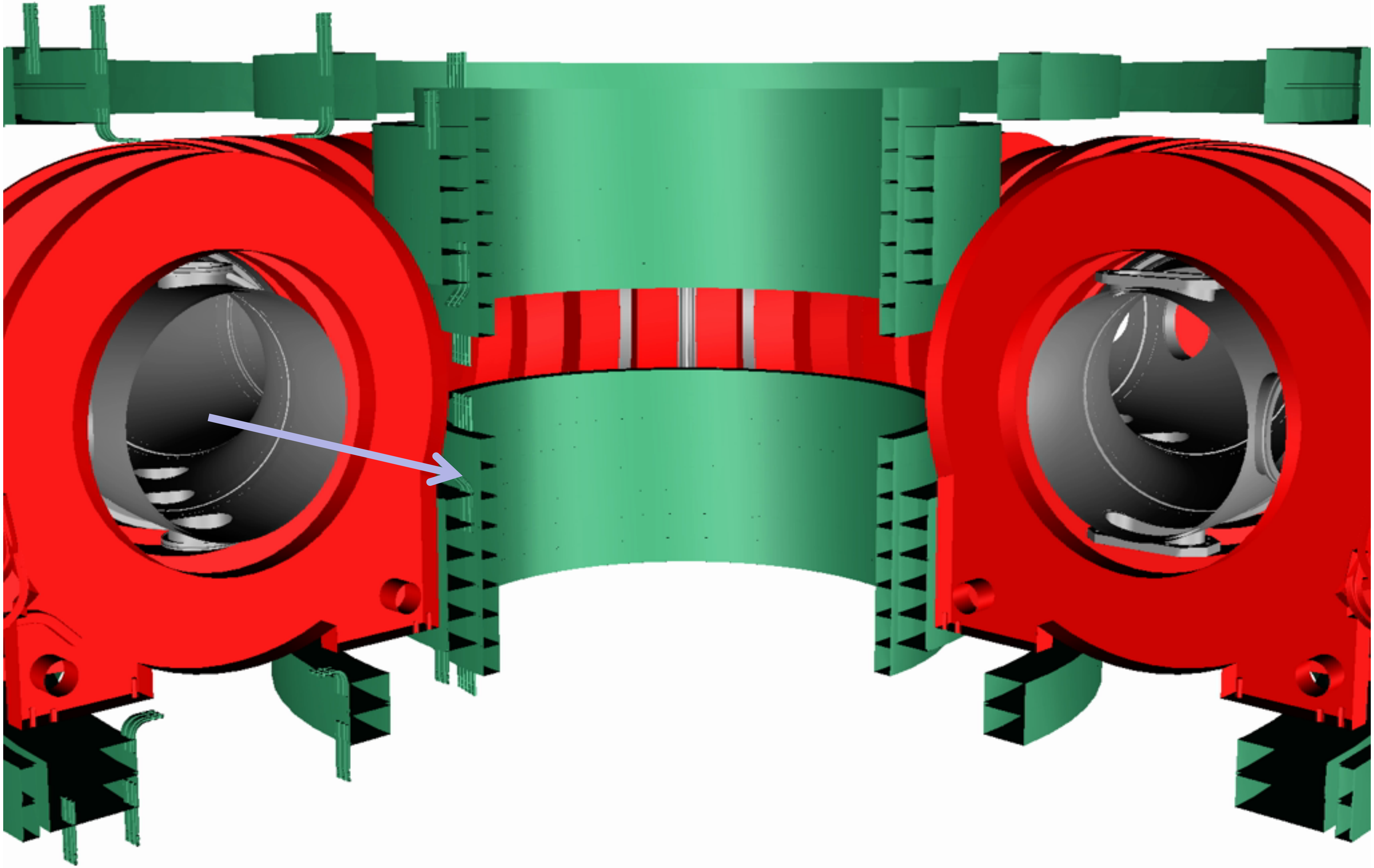

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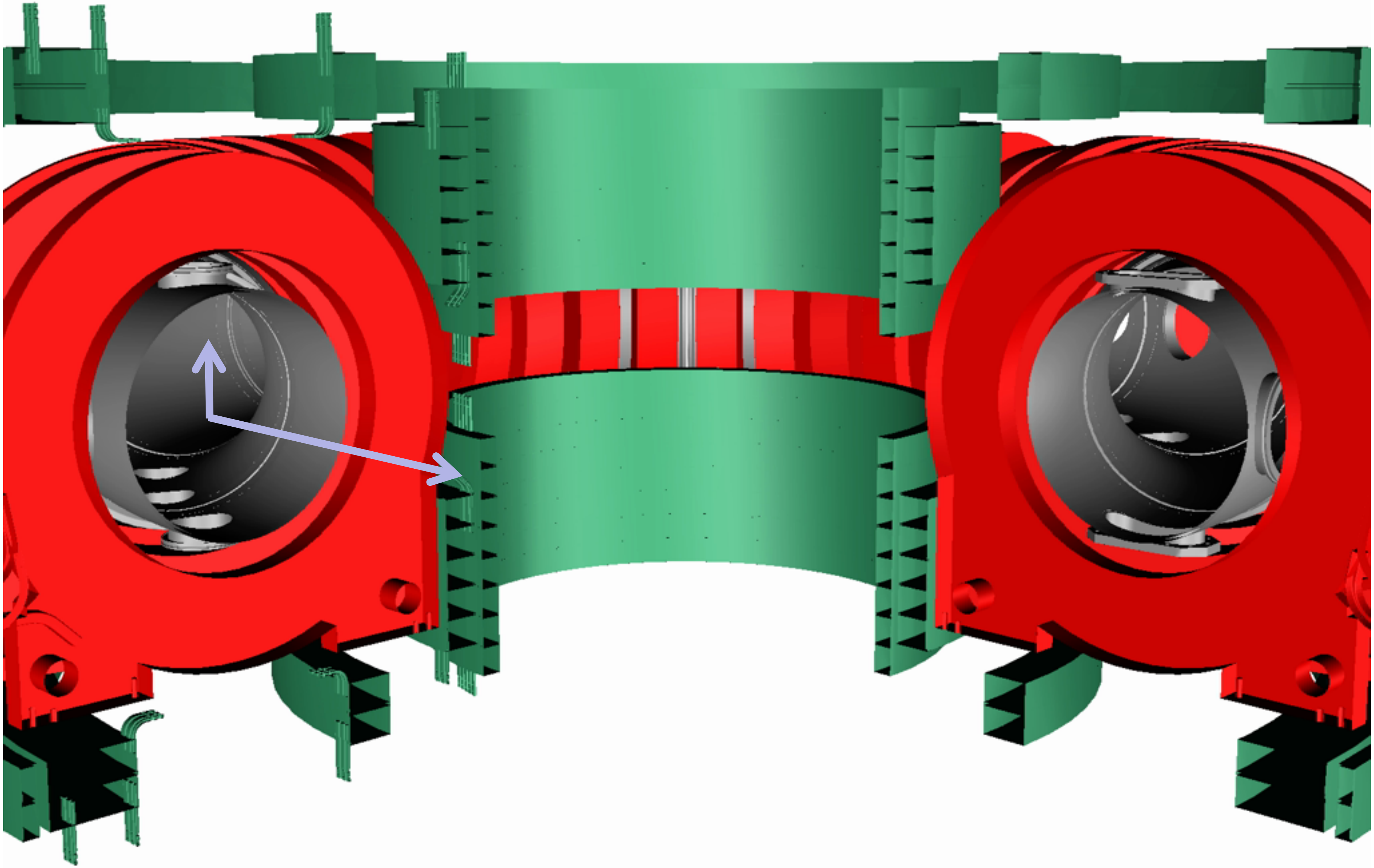

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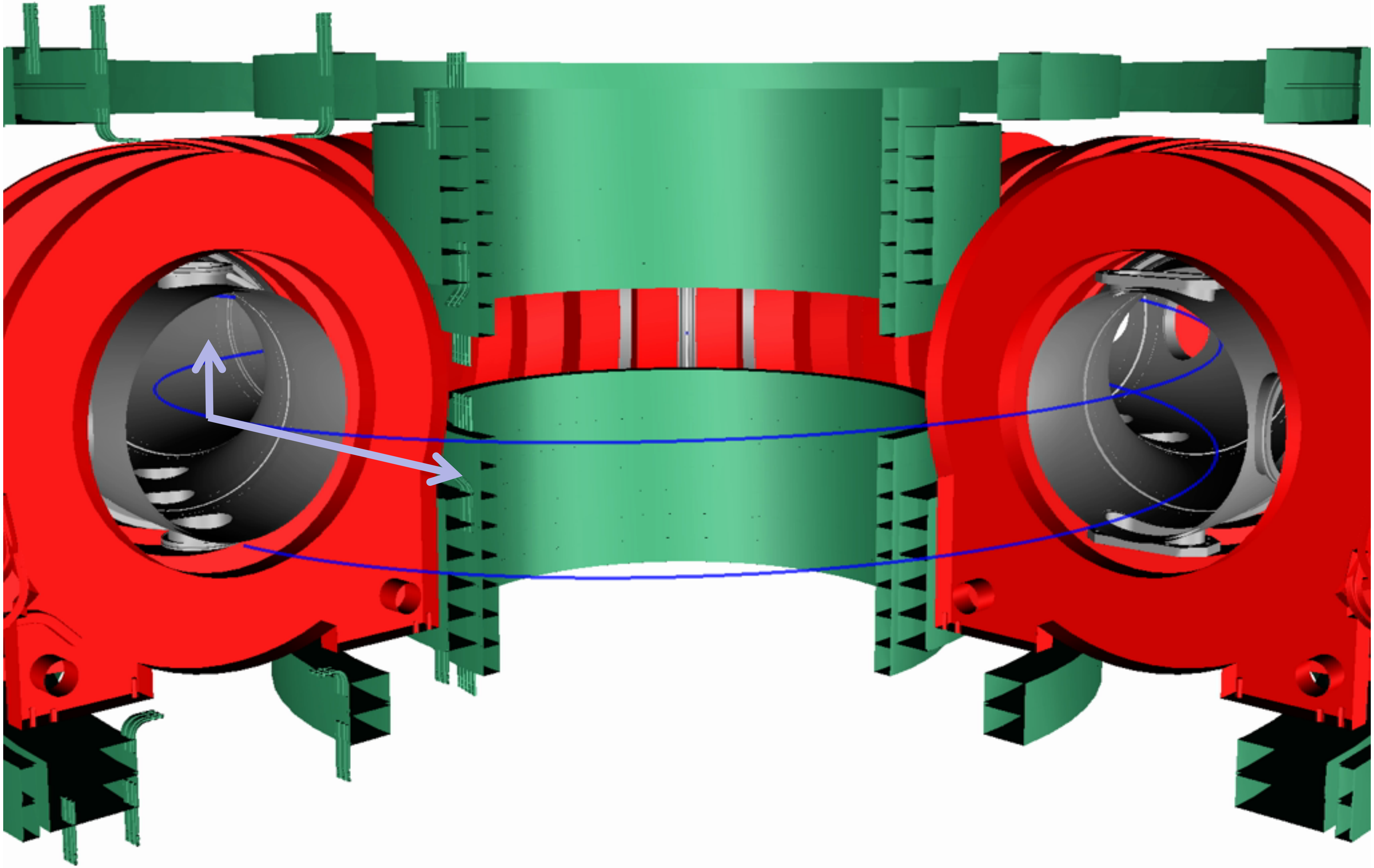
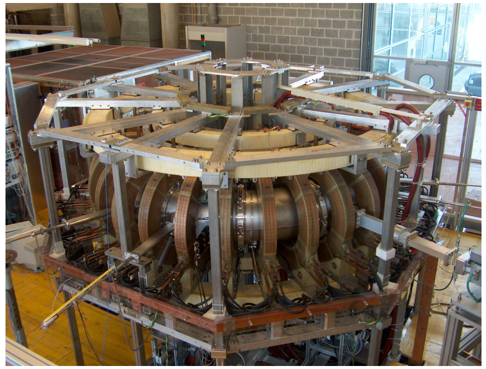
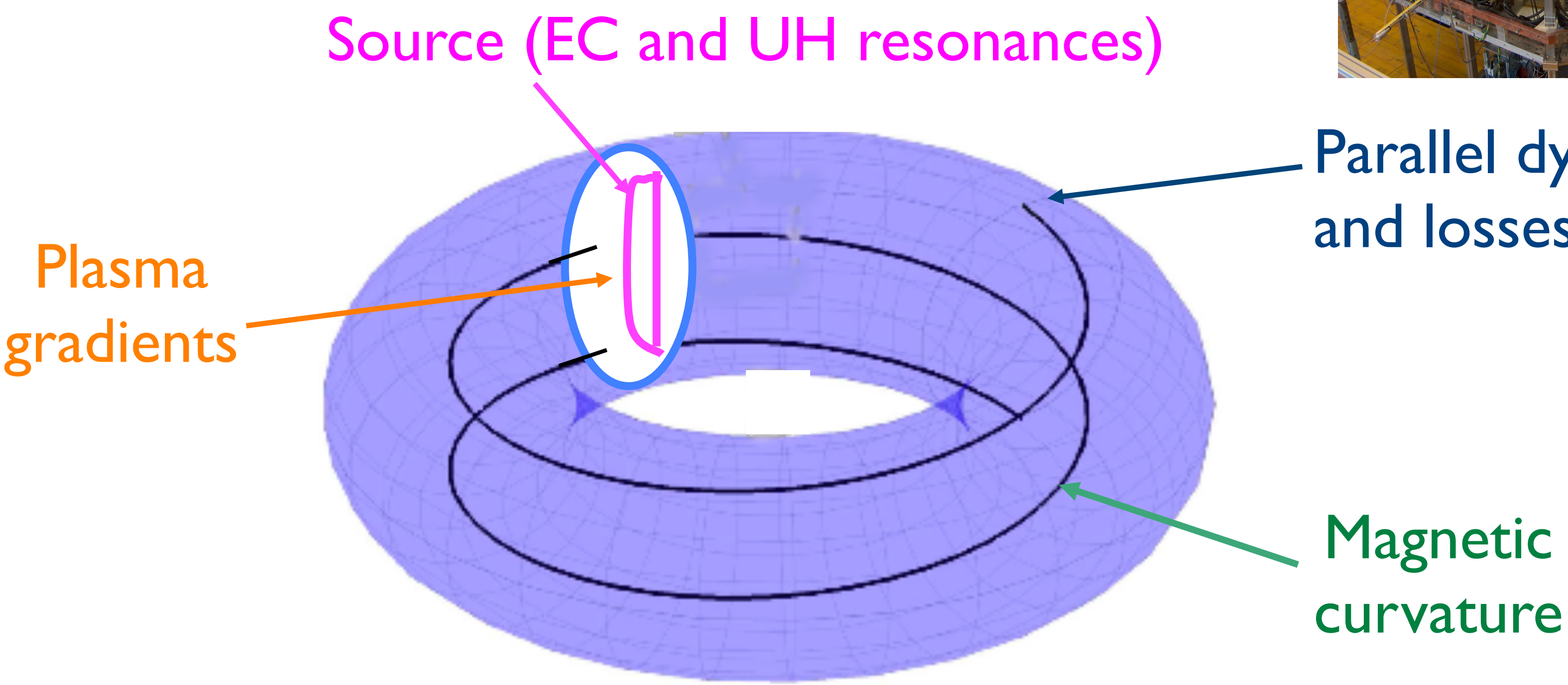


TORPEX key elements



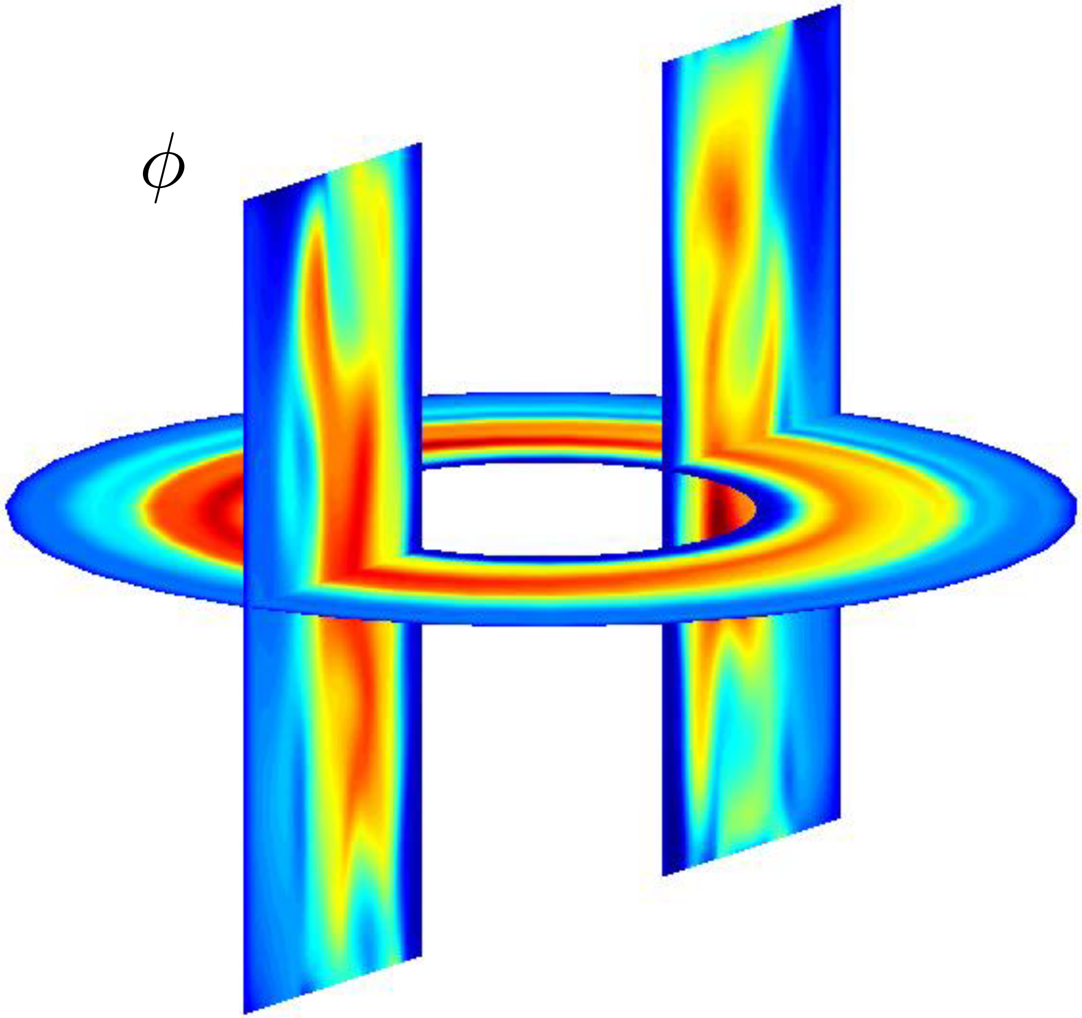


N: number of field line turns

Simple magnetic curvature

$$\frac{\partial n}{\partial t} + [\phi, n] = \frac{2}{R}\frac{\partial (nT_e)}{\partial y} - \frac{2n}{R}\frac{\partial \phi}{\partial y} - \nabla_{\parallel}(nV_{\parallel e}) + S$$

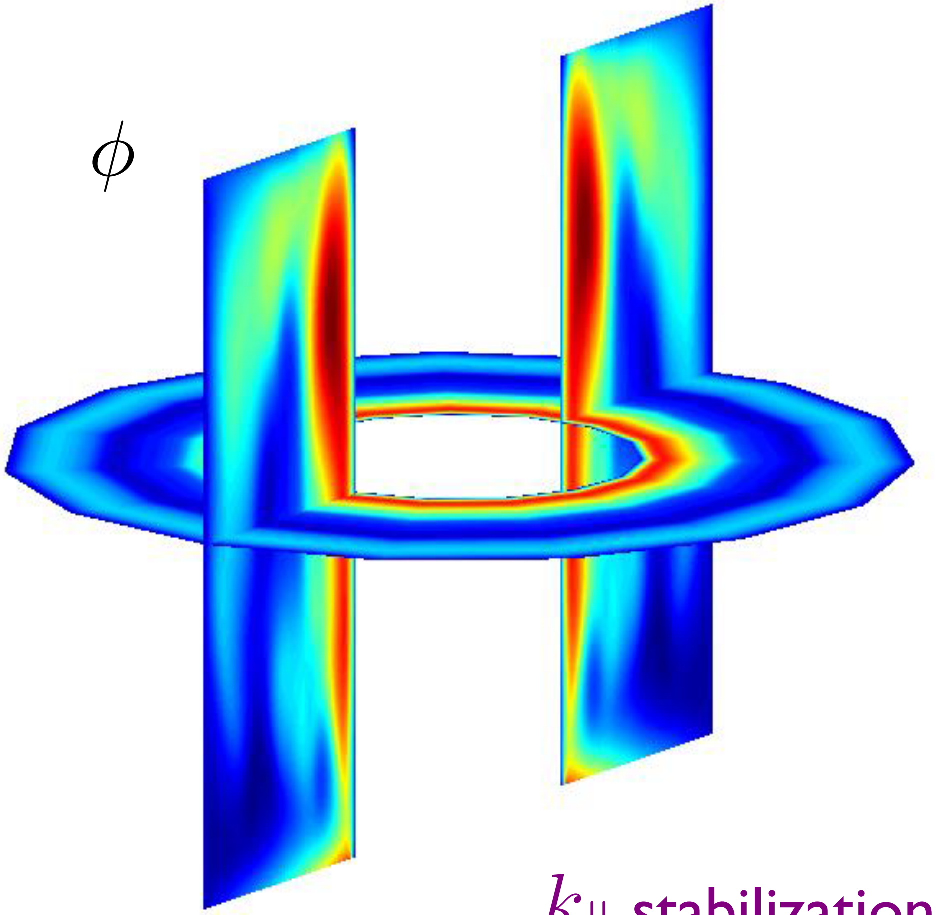
For N~1-6, $k_{\|} = 0$ turbulence



N=2

$$\lambda_v = \frac{L_v}{N}$$

At high N>7, $k_\parallel \neq 0$ turbulence



N=16

Toroidally symmetric

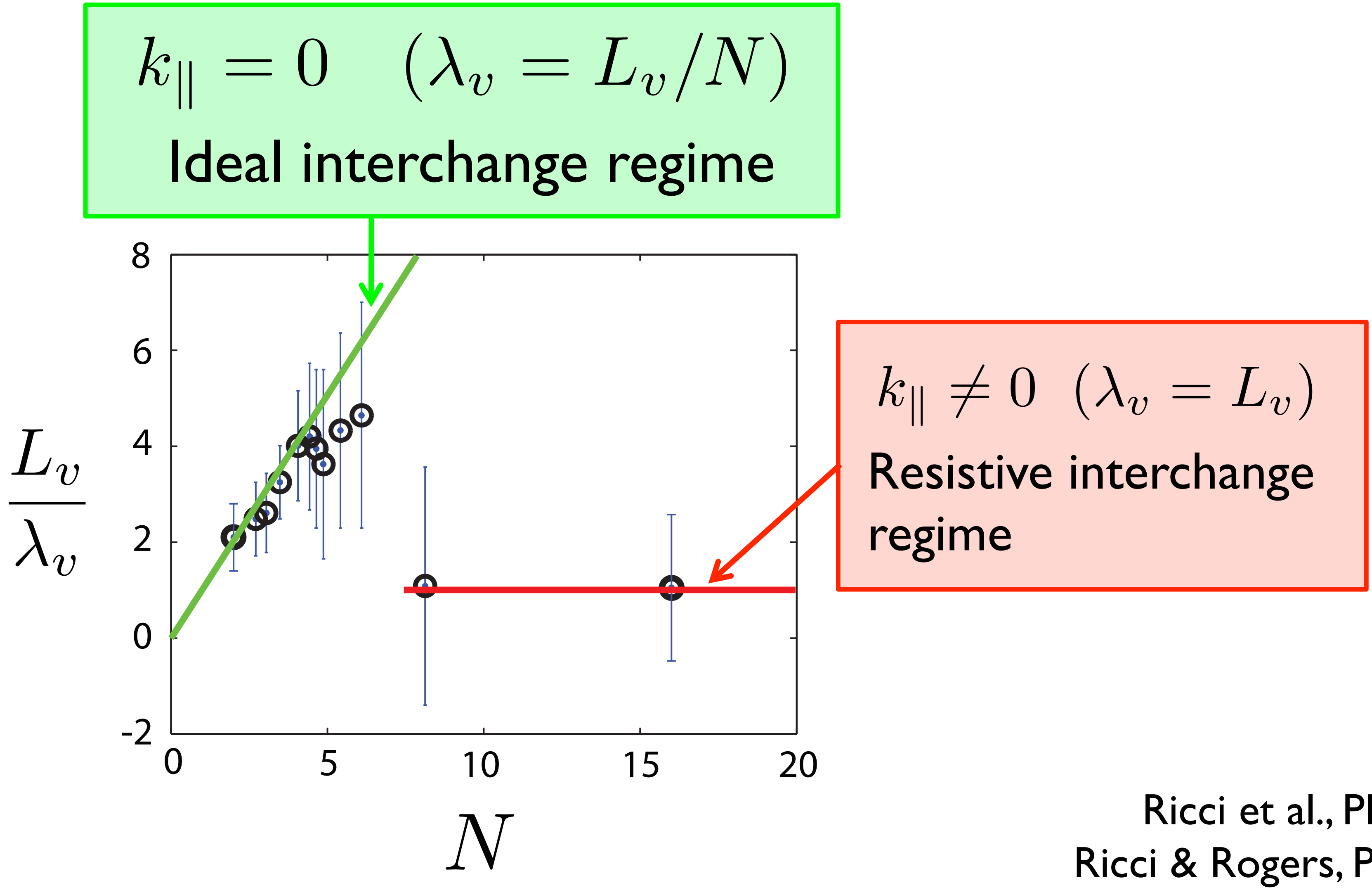
$\lambda_v \sim L_v$

$k_\parallel$ stabilization, requires high N and $\eta_\parallel \neq 0$

$$\gamma^2 = \gamma_I^2 - \gamma \frac{4\pi V_A^2 k_\parallel^2}{\eta_\parallel c^2 k_y^2}, \quad \gamma_I = c_s \sqrt{\frac{2}{RL_p}}$$

TORPEX turbulent regimes

Linear theory, nonlinear simulations, experiments in agreement



Ricci et al., PRL 2008;
Ricci & Rogers, PRL 2010

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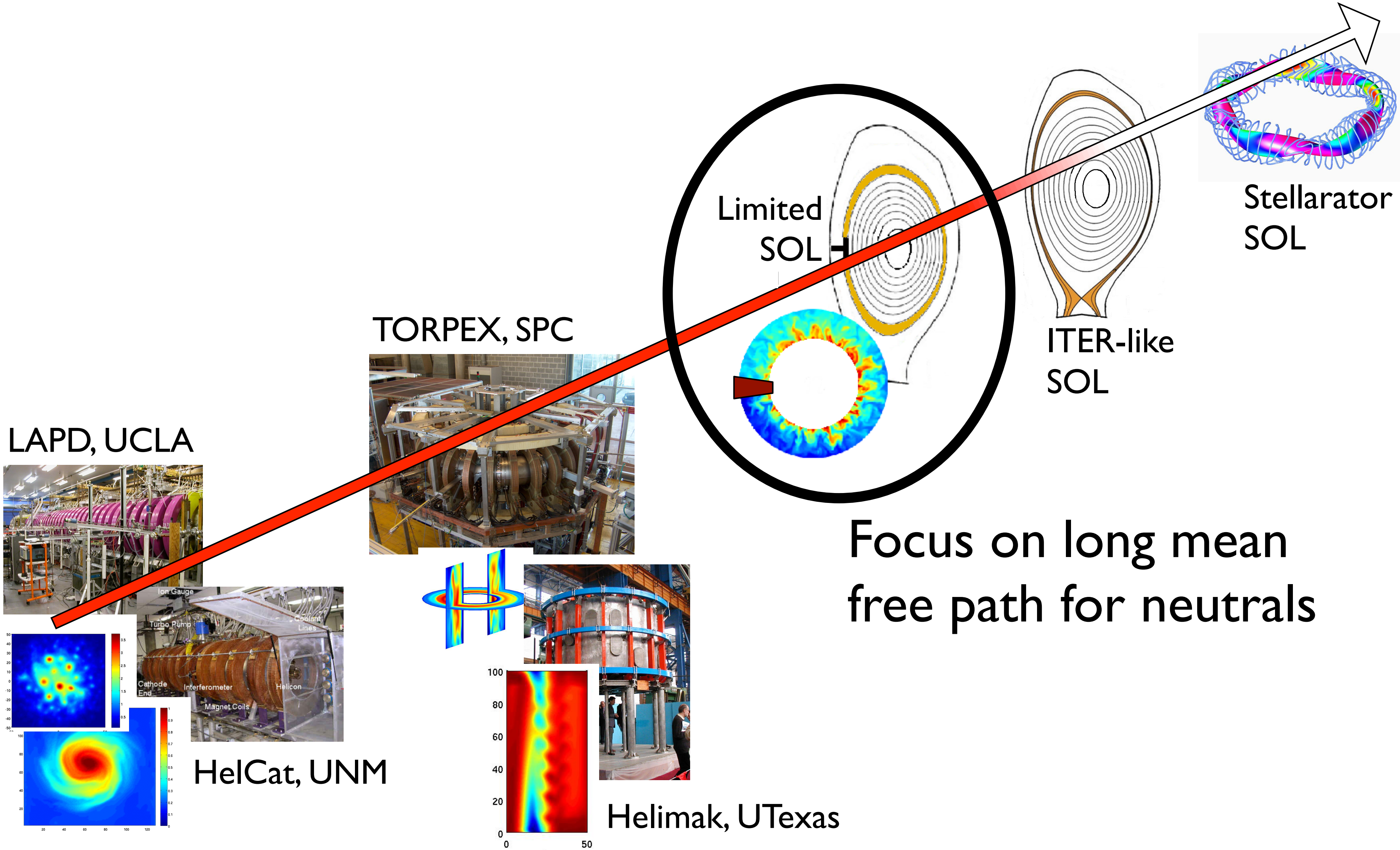
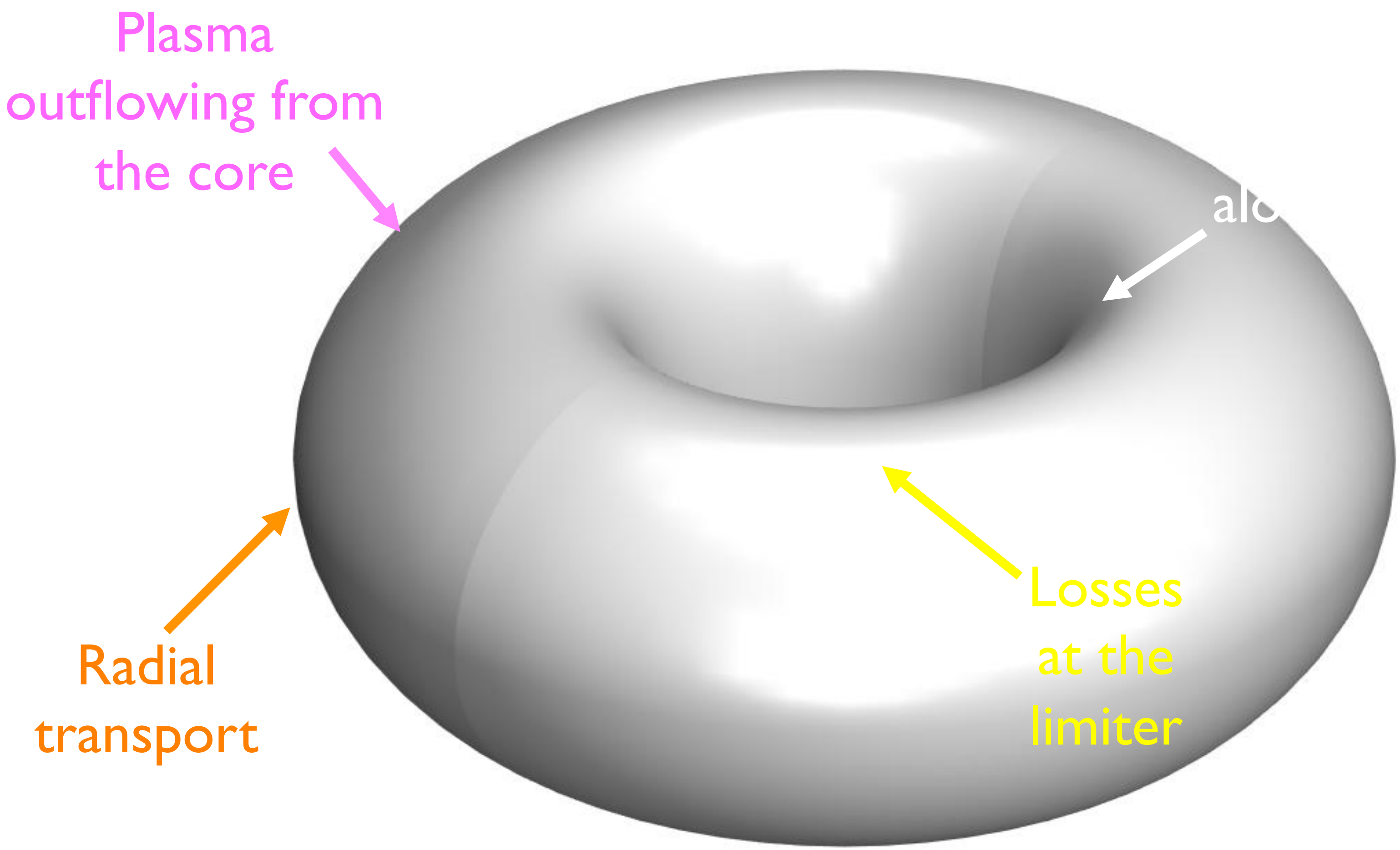
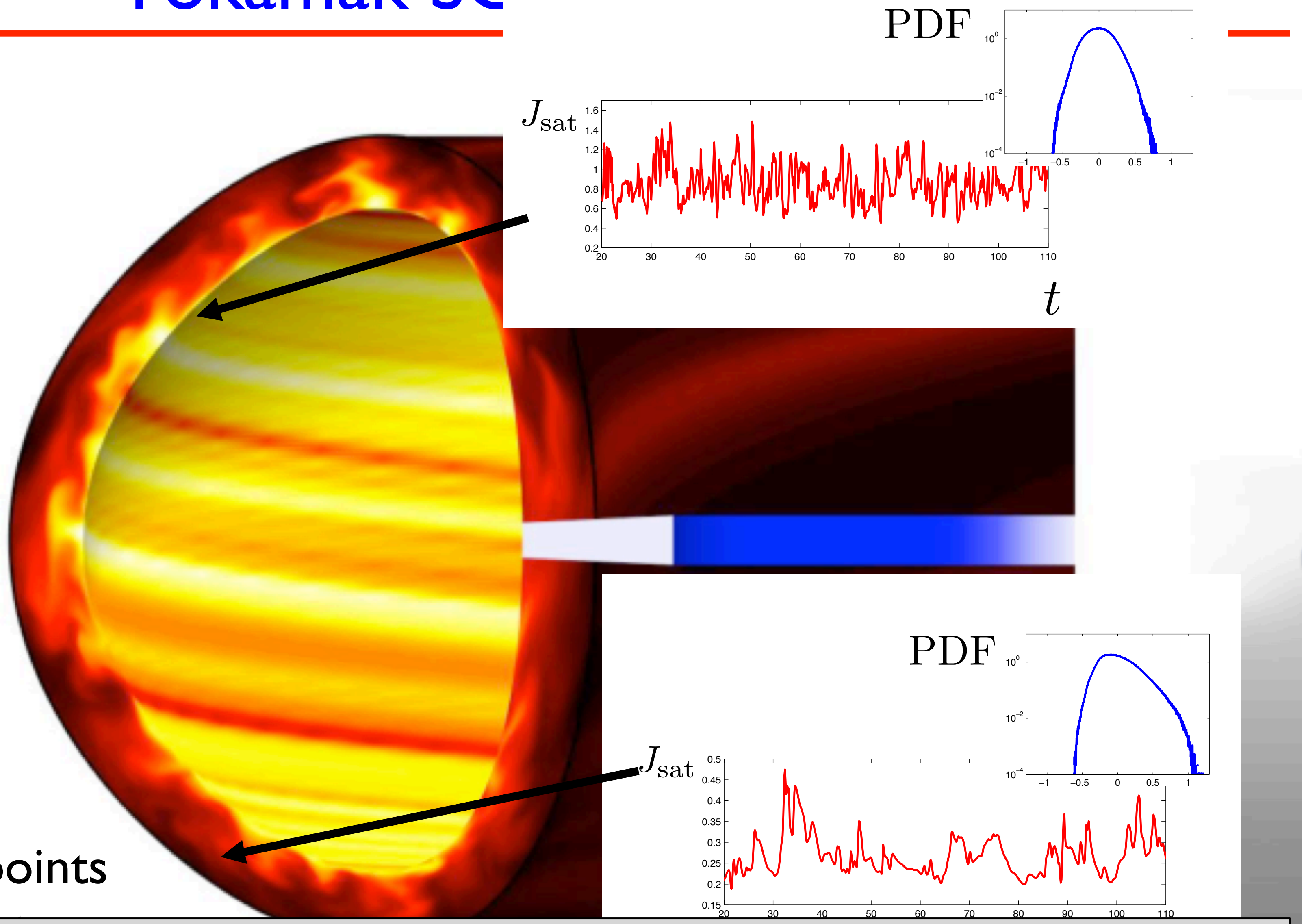


Focus on long mean free path for neutrals

Tokamak SOL simulations



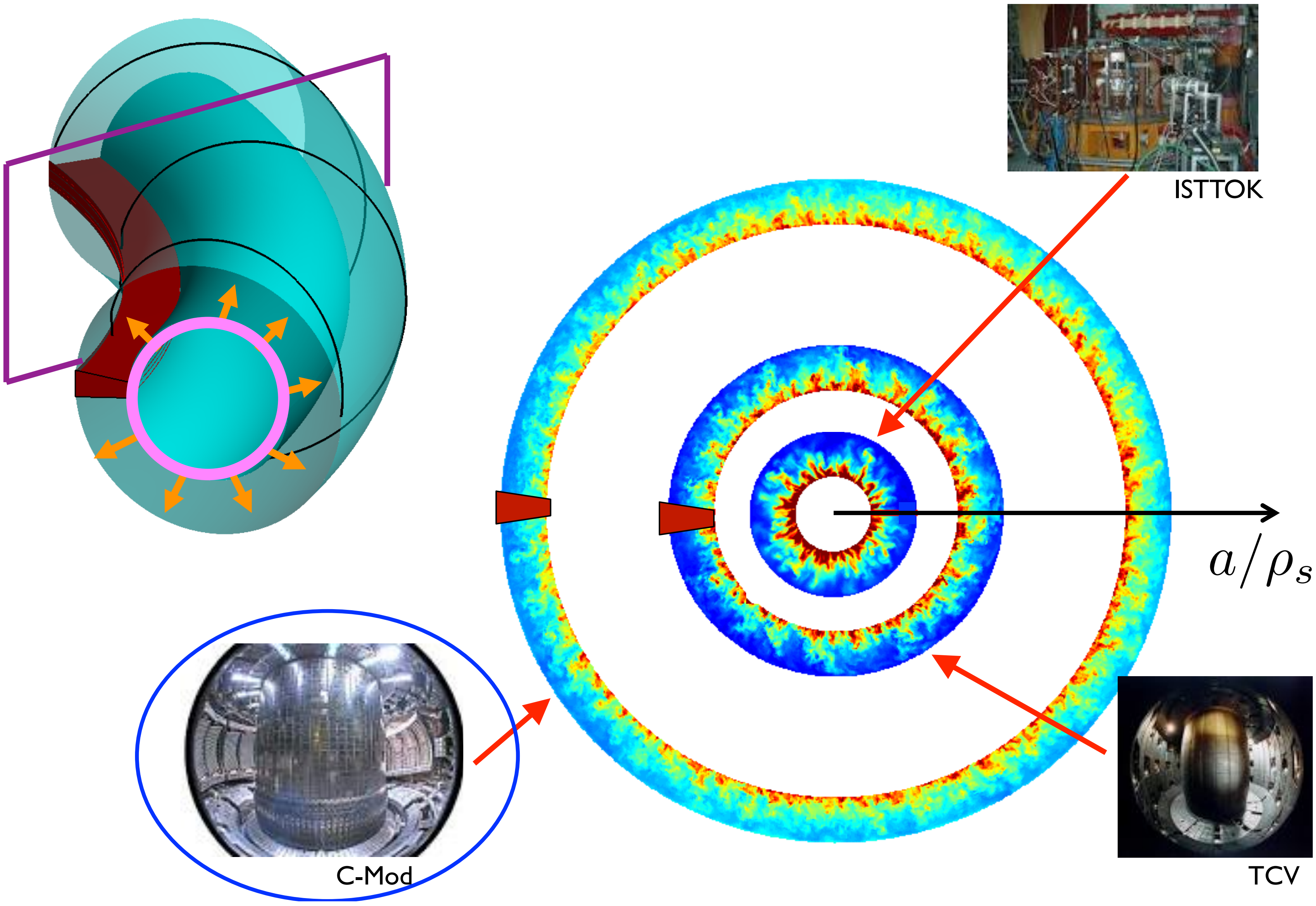
Tokamak SOL simulations



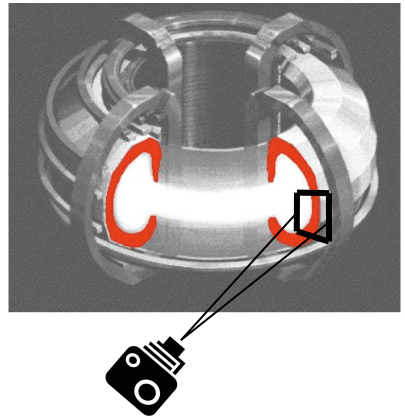
- 10^7 grid points

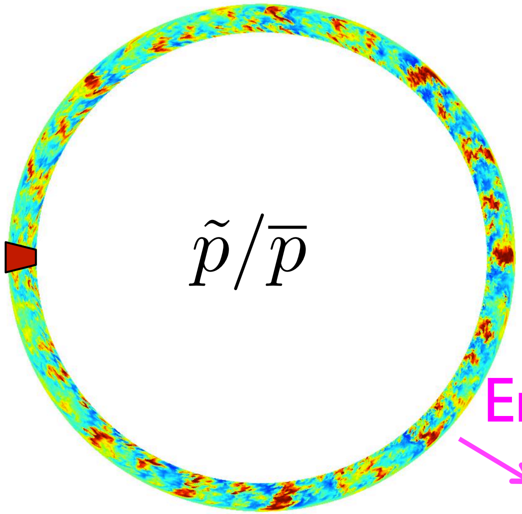
Simulations contain physics of ballooning modes, drift waves, Kelvin-Helmholtz, blobs, parallel flows, sheath losses…

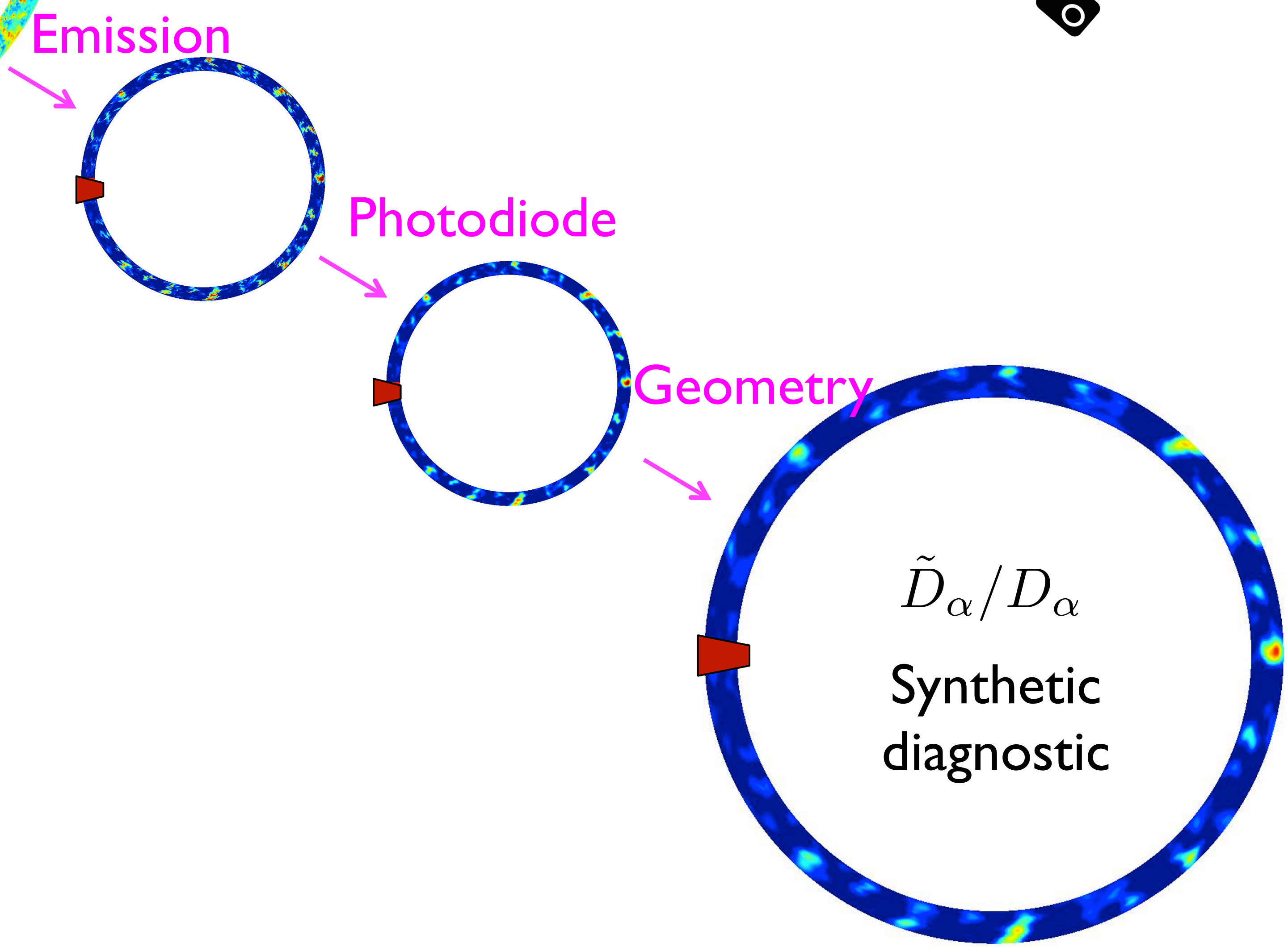
A large validation effort



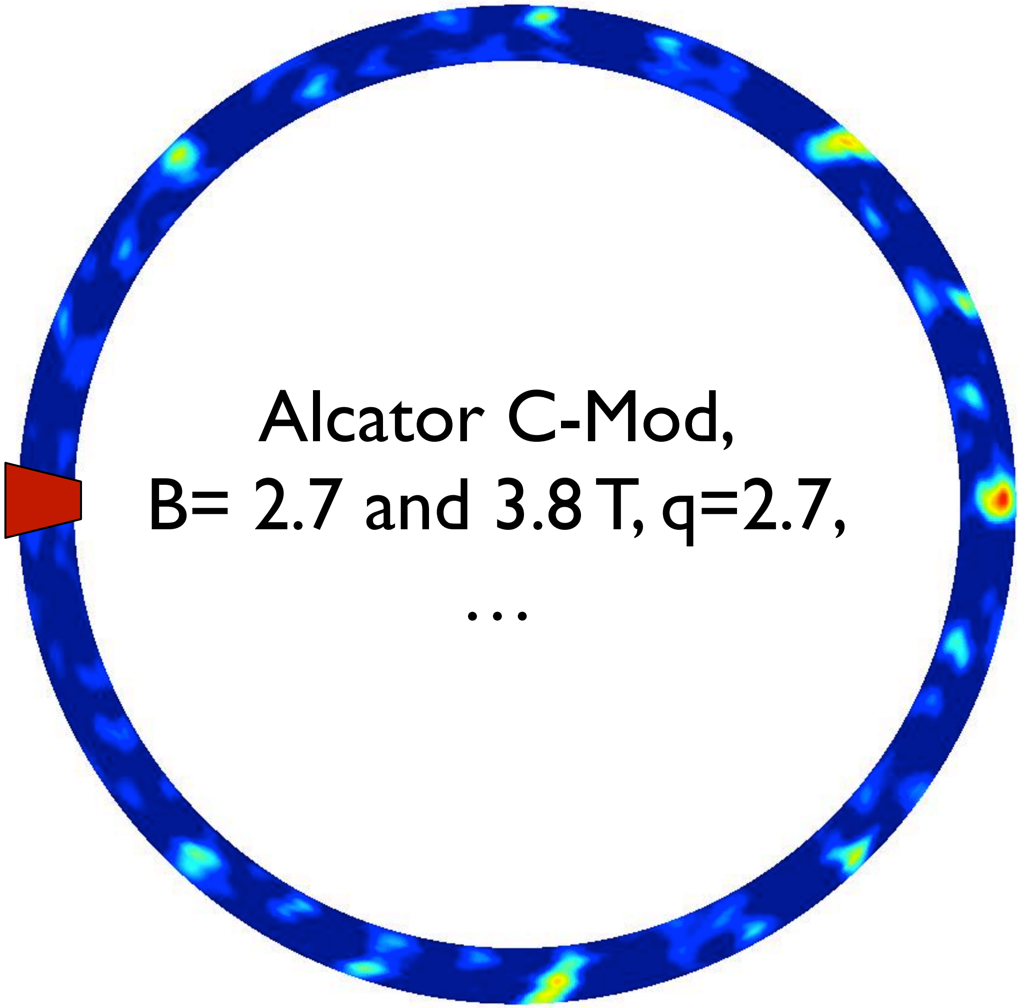
Gas puff imaging diagnostics

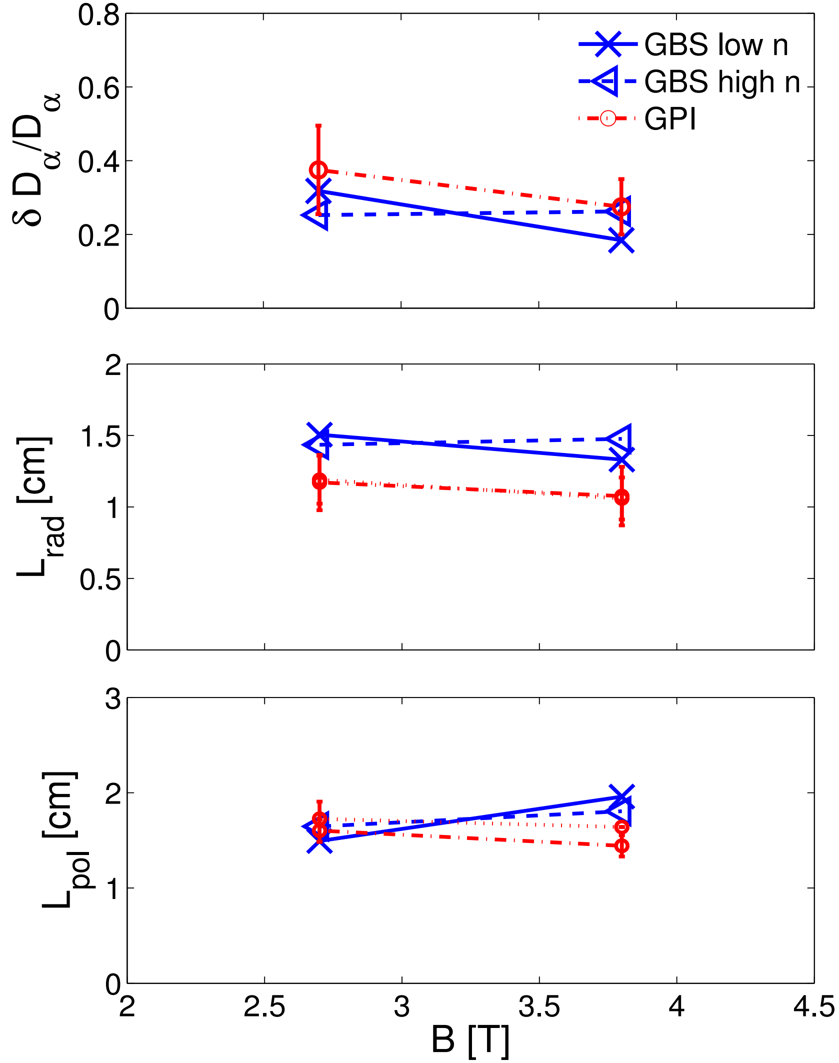






C-Mod fluctuation properties well captured





Halpern et al., PPCF 2015

The key questions we addressed in the past

- How is the SOL width established?
- How to minimize heat load on the vessel walls?
- What determines the SOL electrostatic potential?
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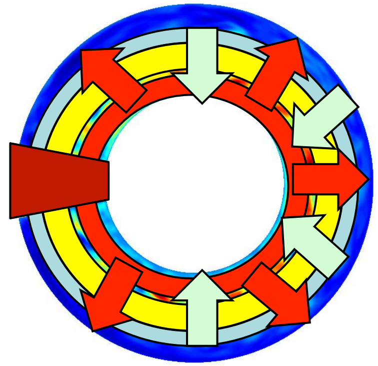
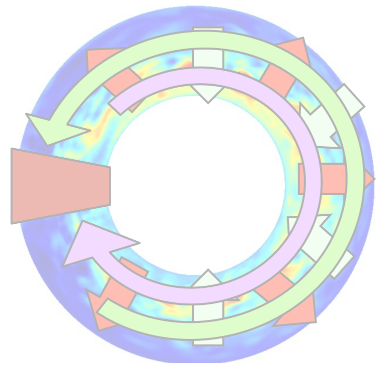
Three possible turbulence saturation mechanisms

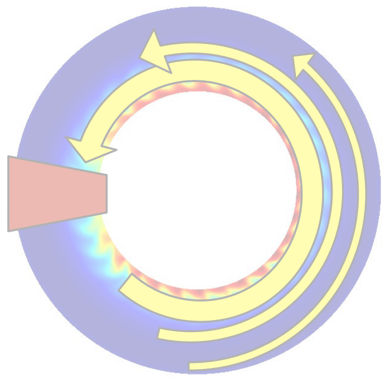
Removal of the turbulence drive (gradient removal):



Kelvin – Helmholtz secondary instability:

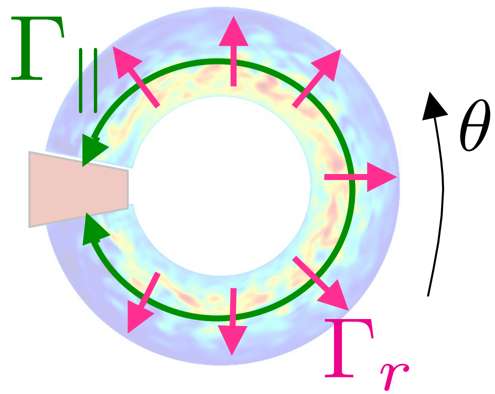


Suppression due to strong shear flow:



Ricci & Rogers, PoP 2013

SOL width – analytical estimate



$$\sim \frac{1}{qR} \qquad \sim c_s p$$

Bohm's

$$\nabla_r \Gamma_r \sim \nabla_\parallel \Gamma_\parallel$$

$$\sim \frac{1}{L_p}$$

$$\frac{\partial p}{\partial t} + \nabla \cdot (p \mathbf{v}_{E\times B}) \simeq 0$$

$$= \langle \tilde{p} \tilde{v}_{E\times B,r} \rangle_t = \frac{1}{B} \left\langle \tilde{p} \frac{\partial \tilde{\phi}}{\partial \theta} \right\rangle_t \sim \frac{\gamma \bar{p}}{L_p k_r^2} \sim \frac{\gamma \bar{p}}{k_\theta}$$

Removal of driving gradient

$$\frac{\partial \tilde{p}}{\partial r} \sim \frac{\partial \bar{p}}{\partial r}$$

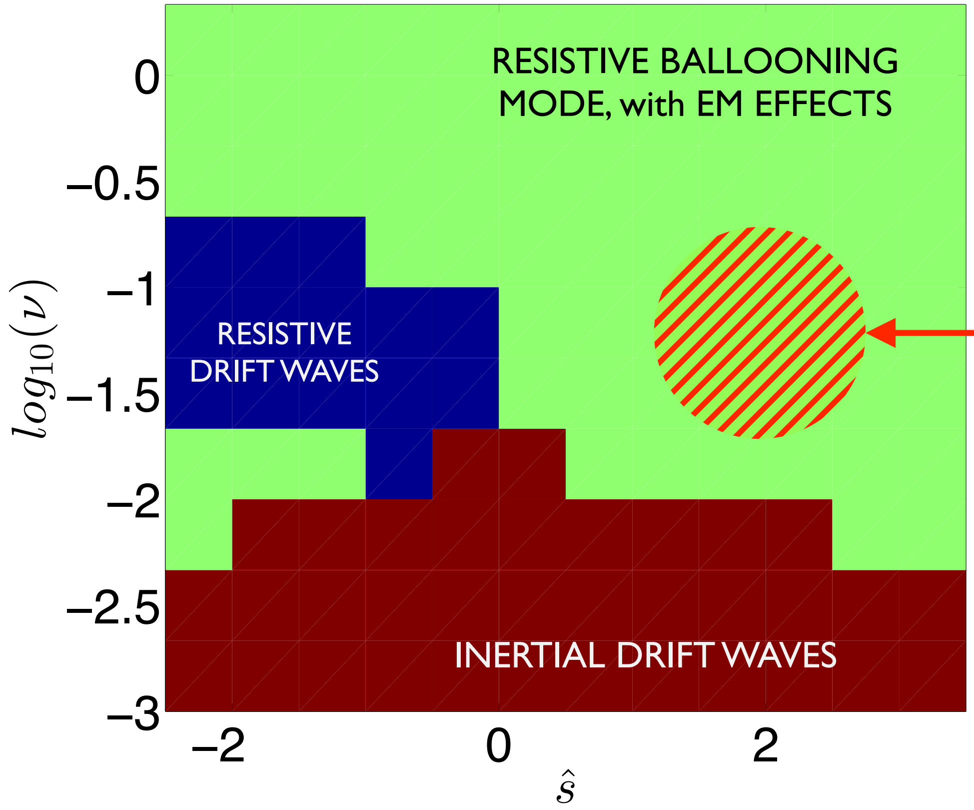
Nonlocal linear theory

$$\boxed{L_p \simeq \frac{qR}{c_s} \left(\frac{\gamma}{k_\theta} \right)_{\max}}$$

Ricci et al., PRL 2008; PoP 2013

SOL turbulent regimes

Instability driving turbulence depends mainly on q, ν, $\hat{s}$.



TYPICAL LIMITED
SOL OPERATIONAL
PARAMETERS

$$L_p = \frac{qR}{c_s}\left(\frac{\gamma}{k_\theta}\right)_{\max}$$

BM

$$\gamma \sim \gamma_b = c_s\sqrt{\frac{2}{RL_p}}$$

BM

$$k_\theta \sim \sqrt{\frac{\mu_0 \sigma_\parallel c_A^2}{q^2 R^2 \gamma_b}}$$

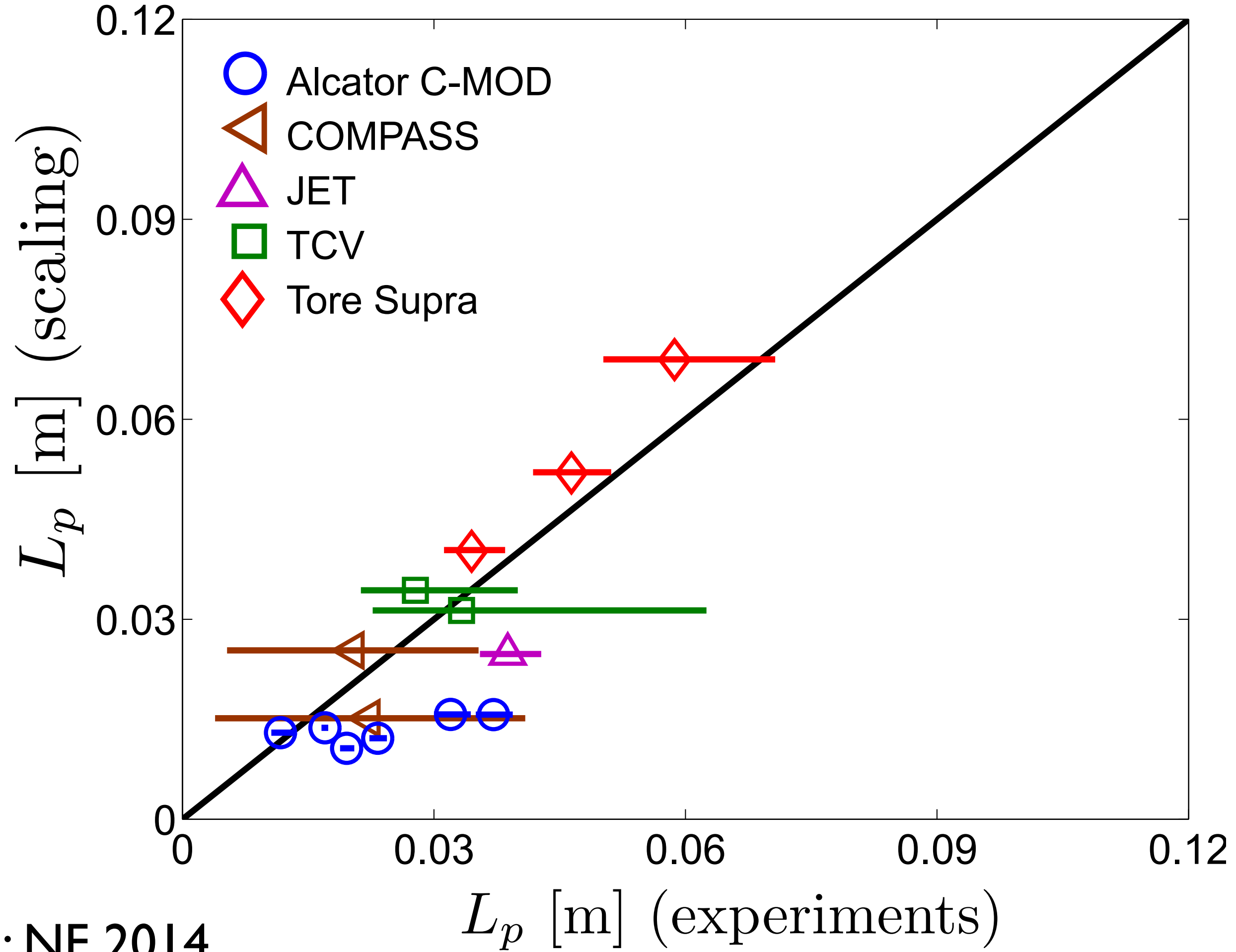
Mosetto et al., PoP 2013; PoP 2015

Ballooning scaling, good agreement with experiments

In SI units:

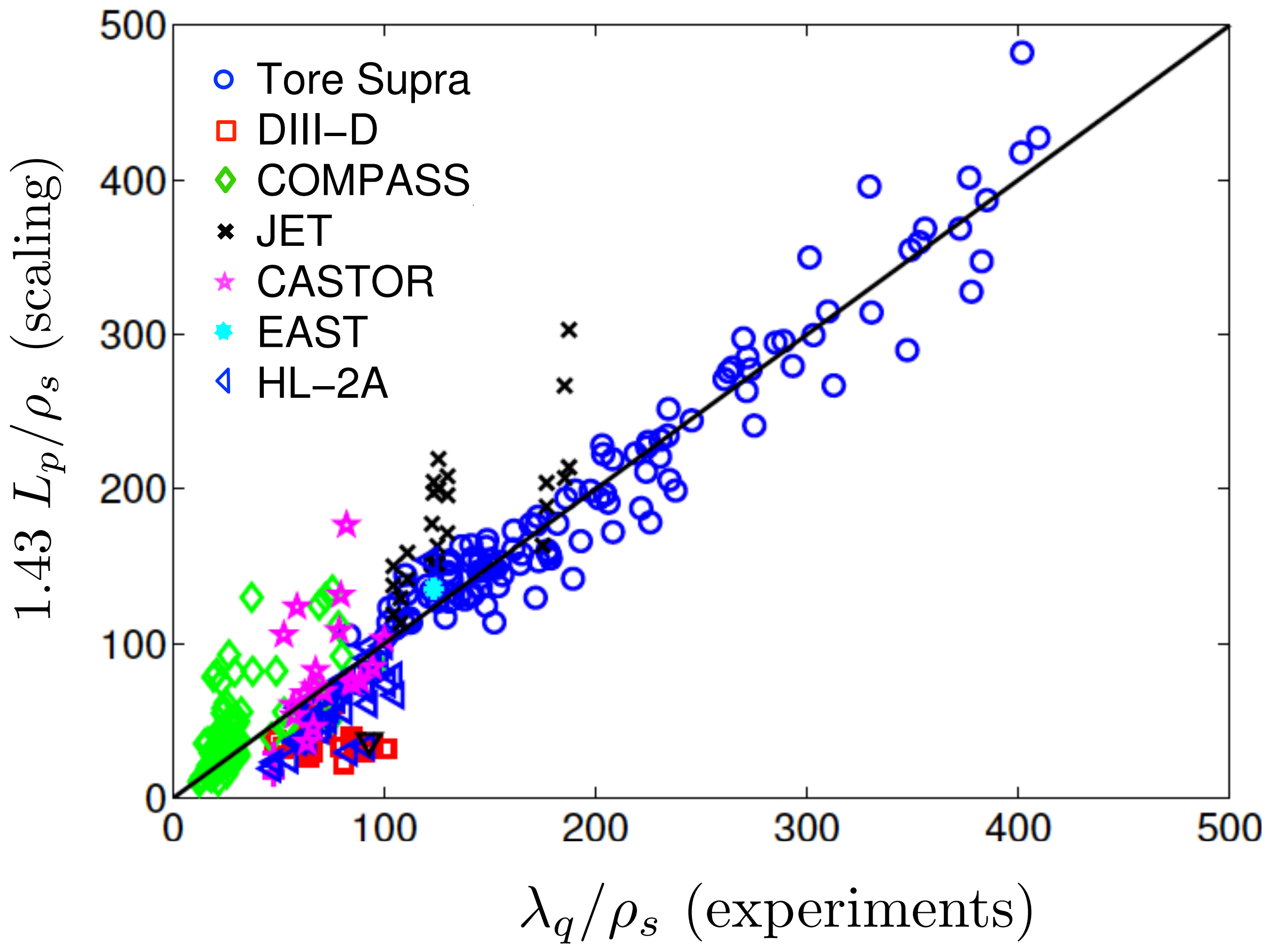
$$L_p \simeq 7.22 \times 10^{-8} q^{8/7} R^{5/7} B_\phi^{-4/7} T_{e,\mathrm{LCFS}}^{-2/7} n_{e,\mathrm{LCFS}}^{2/7} \left(1 + \frac{T_{i,\mathrm{LCFS}}}{T_{e,\mathrm{LCFS}}}\right)^{1/7}$$

Validation with reciprocating probe measurements of n and T_e



Halpern et al., NF 2013; NF 2014

SOL width – comparison with ITPA database



Halpern et al, PPCF 2016

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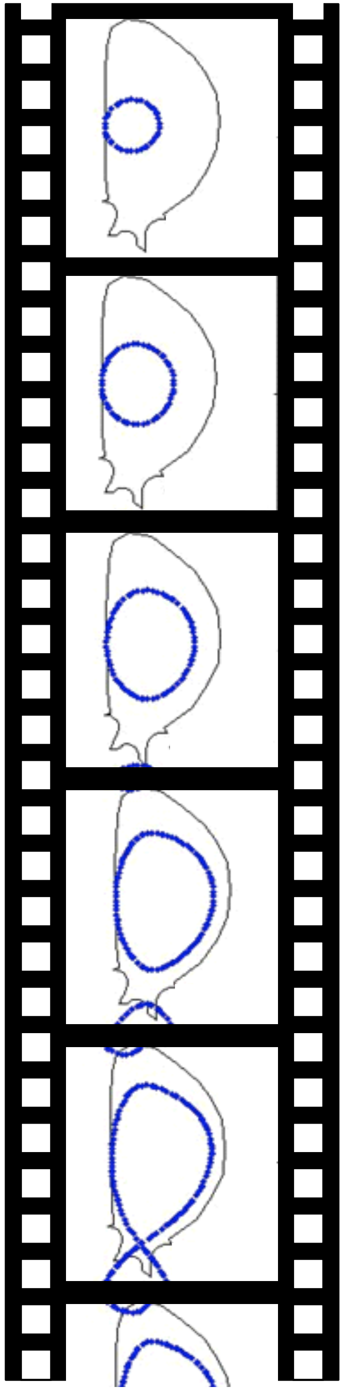
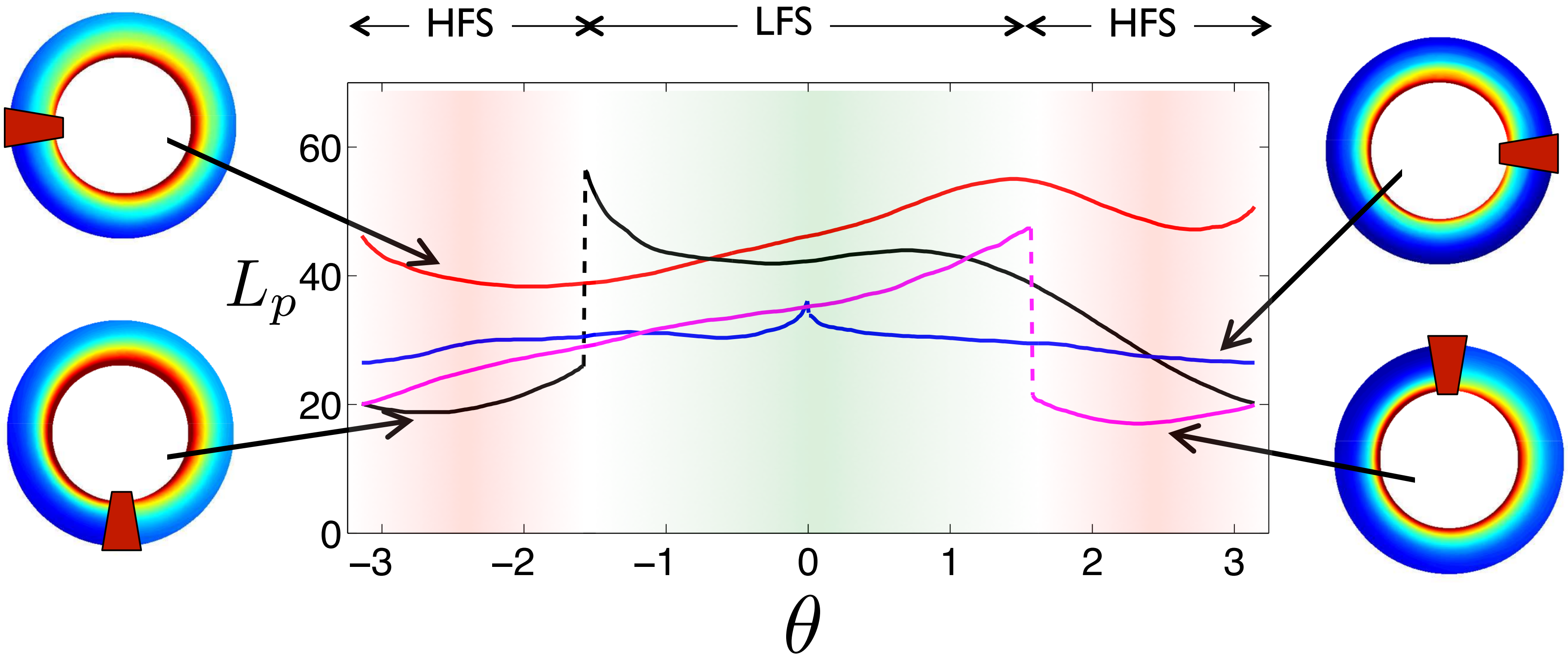
ITER start up and ramp down will be limited



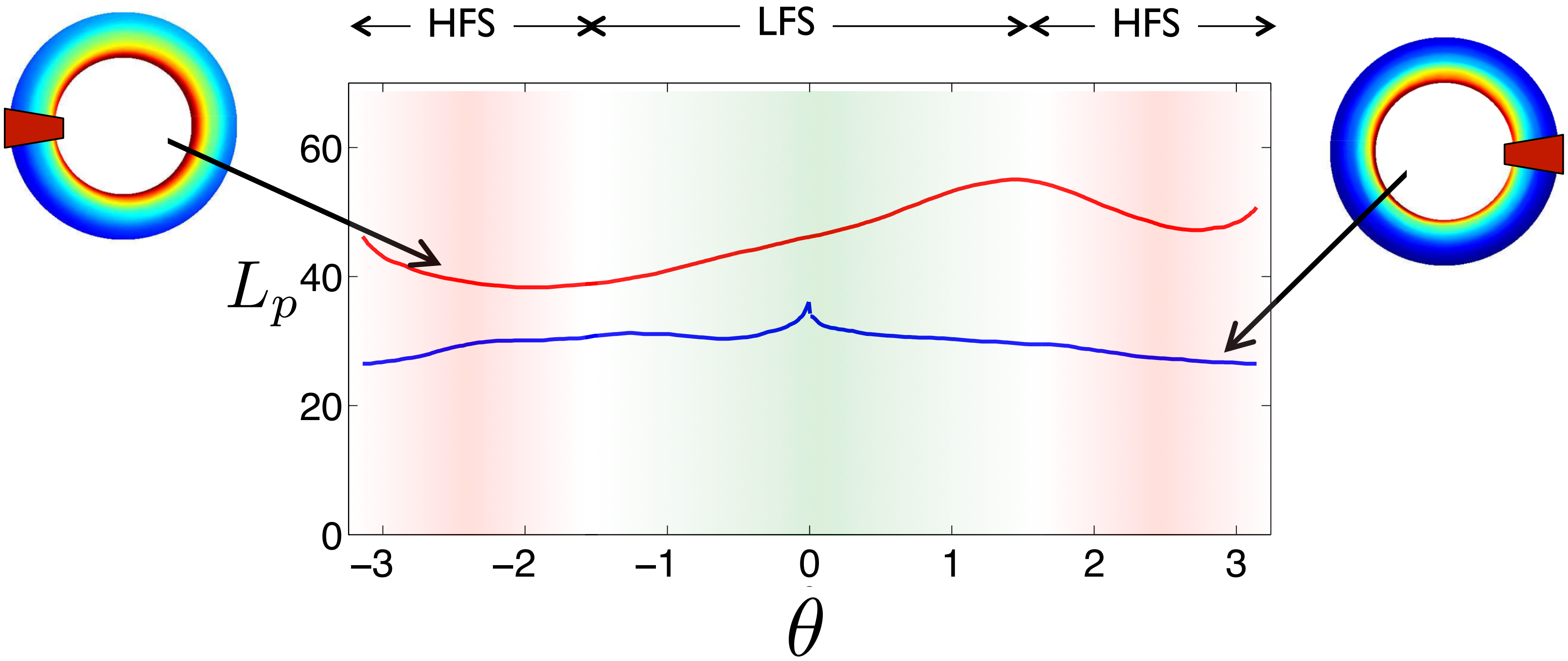
- $P_{\mathrm{wall}} \propto 1/A_{\mathrm{wet}} \propto 1/L_p$
- Is a LFS or HFS limited plasma preferable (L_p larger)?

SOL width larger in HFS limited plasmas



Loizu et al., NF 2014

SOL width larger in HFS limited plasmas



Trends explained by ballooning transport and ExB flow
Confirms experiments, but effects smaller

Loizu et al., NF 2014

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Potential in the SOL set by sheath and electron adiabaticity

Typical estimate: at the sheath

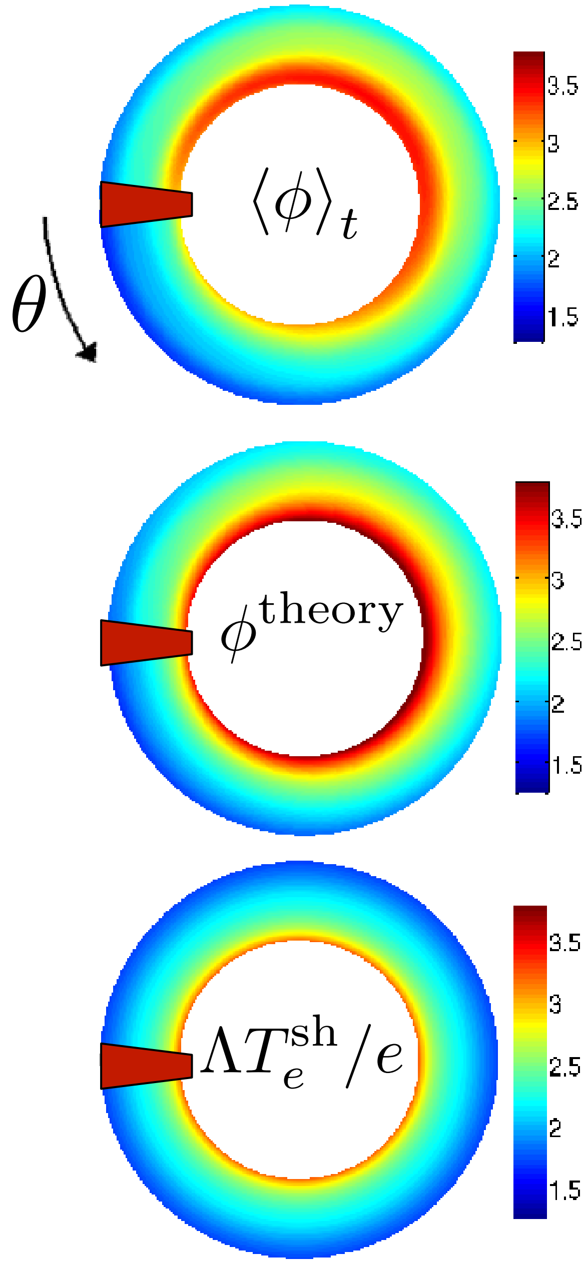
$$v_{\parallel i} = c_s \qquad v_{\parallel e} = c_s \exp(\Lambda - e\phi/T_e^{\mathrm{sh}})$$

to have ambipolar flows, $v_{\parallel i} = v_{\parallel e}$

$$\phi = \Lambda T_e^{\mathrm{sh}}/e \simeq 3T_e^{\mathrm{sh}}/e$$

Our more rigorous treatment, from $v_{\parallel e}$ equation

$$\phi = \underbrace{\Lambda T_e^{\mathrm{sh}}/e}_{\text{Sheath}} + \underbrace{2.71(T_e - T_e^{\mathrm{sh}})/e}_{\text{Adiabaticity}}$$



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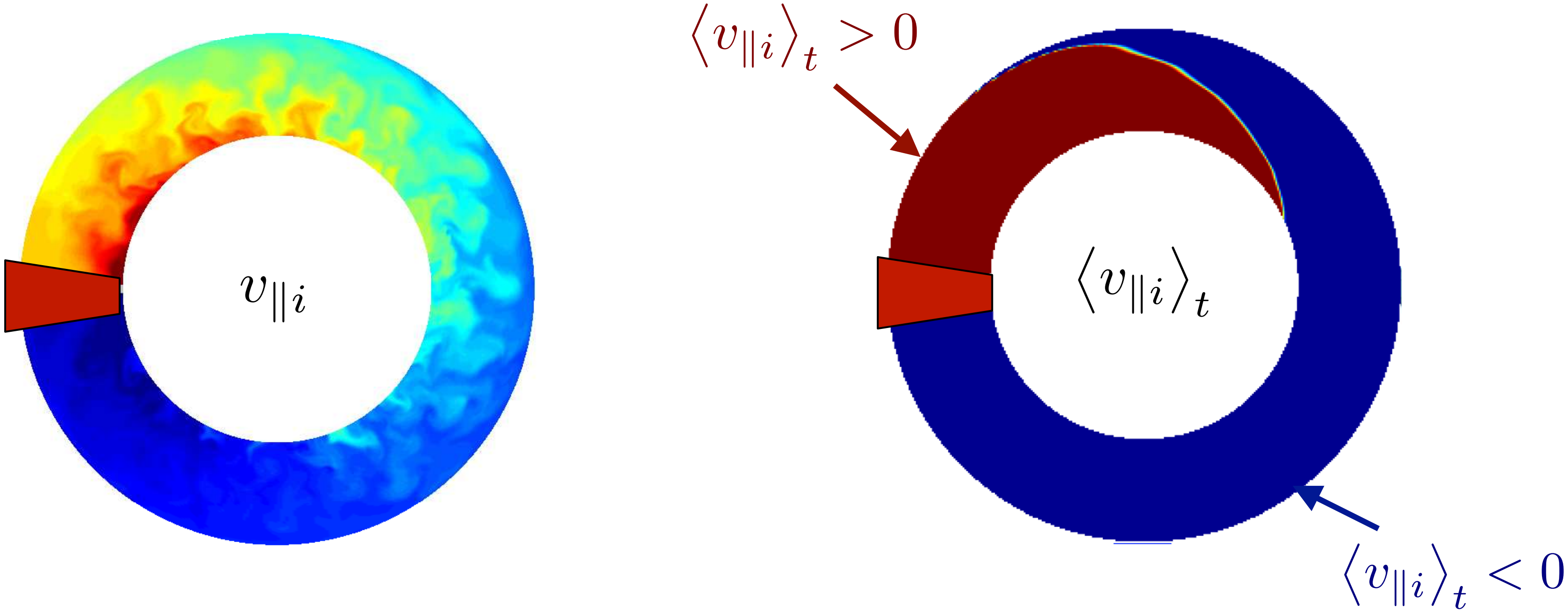
- How to minimize heat load on the vessel walls?

- What determines the SOL electrostatic potential?

- Are there mechanisms to generate toroidal rotation in the SOL?

GBS simulations show intrinsic toroidal rotation



2D equation for the equilibrium flow

$$-\frac{\partial}{\partial r}\left(D_T\frac{\partial \overline{v}_{\parallel i}}{\partial r}\right)+\frac{\sigma_\varphi}{|B_\varphi|}\frac{\partial \overline{\phi}}{\partial r}\frac{\partial \overline{v}_{\parallel i}}{\partial \theta}+\alpha\sigma_\theta \overline{v}_{\parallel i}\frac{\partial \overline{v}_{\parallel i}}{\partial \theta}+\frac{\alpha\sigma_\theta}{m_i\overline{n}}\frac{\partial \overline{p}}{\partial \theta}=0$$

Turbulent driven radial transport, gradient-removal estimate

Poloidal convection

Parallel convection

Pressure poloidal asymmetry

Coupling with core physics

with boundary conditions:

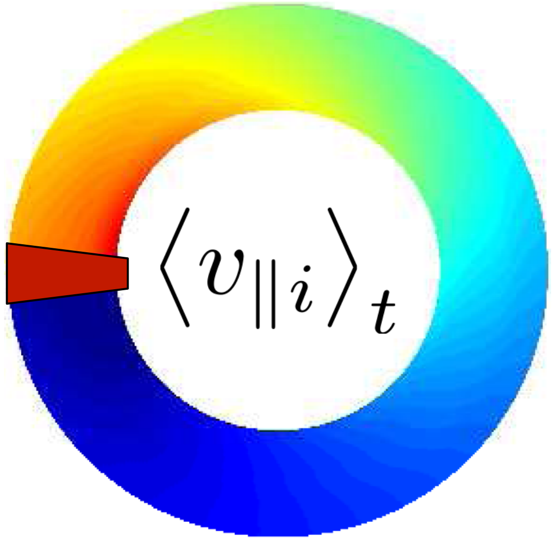
$$\overline{v}_{\parallel i}\Big|_{se}=\pm c_s-\frac{q}{\epsilon}\frac{\partial \overline{\phi}}{\partial r}$$

Bohm's criterion

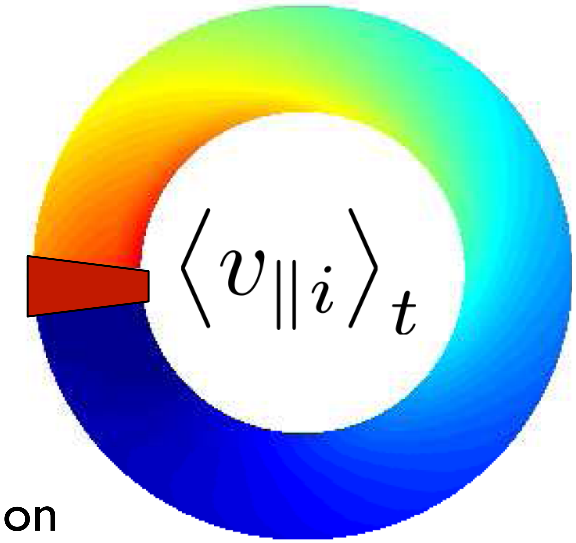
ExB correction

Sources of toroidal rotation

Our model well describes simulation results…



Model



Simulation

… and experimental trends

Analytical solution, far from limiter:

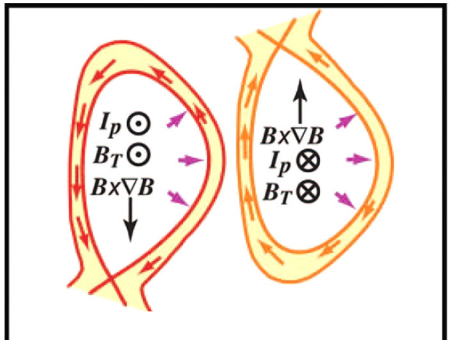
$$M = \boxed{M_s e^{-r/l}} + \left[\boxed{\frac{\Lambda}{2\alpha} \frac{\rho_s}{L_T} e^{-r/L_T}} - \boxed{\frac{\sigma_\varphi}{2} \left(\frac{\delta n}{n} + \frac{\delta T}{T} \right)} \right] \left(1 - e^{-r/l}\right)$$

Core coupling

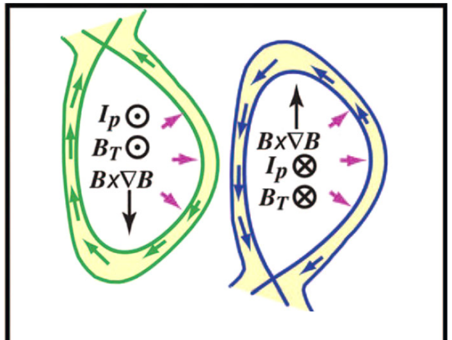
Sheath contribution, co-current

Pressure poloidal asymmetry at divertor plates, due to ballooning transport, direction: depends

- $M_{\|} \lesssim 1$
- Typically co-current
- Can become counter-current by reversing $\mathbf{B}$ or divertor position
- Agreement with C-Mod observations



C-mod CO-CURRENT FLOW



C-mod COUNTER-CURRENT

Loizu et al., PoP 2014

Some of our current research activities

- How does shaping affect SOL turbulence?
- Is it reasonable to use the Boussinesq approximation?
- What happens across the LCFS?
- What is the role of neutrals?
- Can we develop a more accurate plasma model?
- What happens in diverted configurations?

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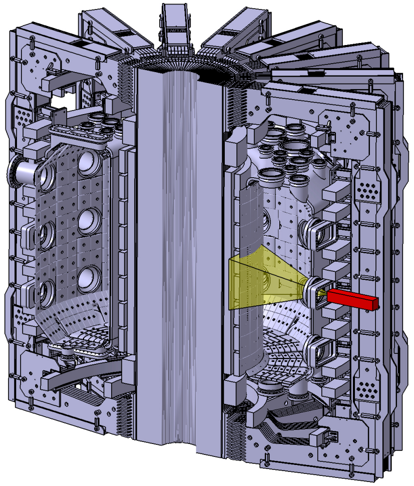
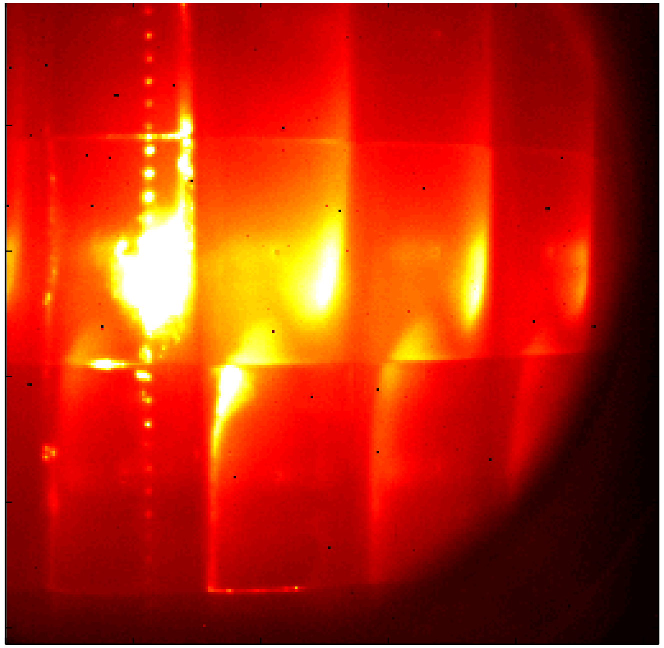
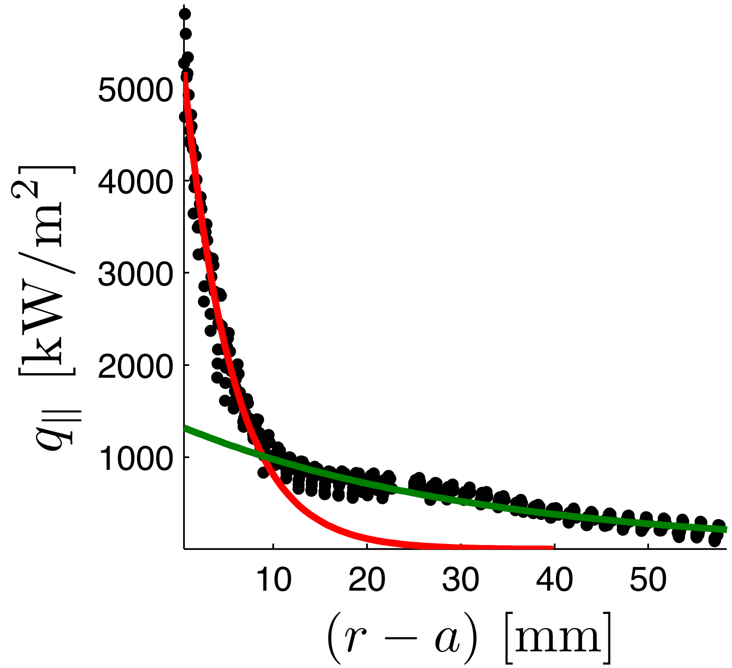
Recent measurements: 2 scale lengths



Infrared Measurement in TCV

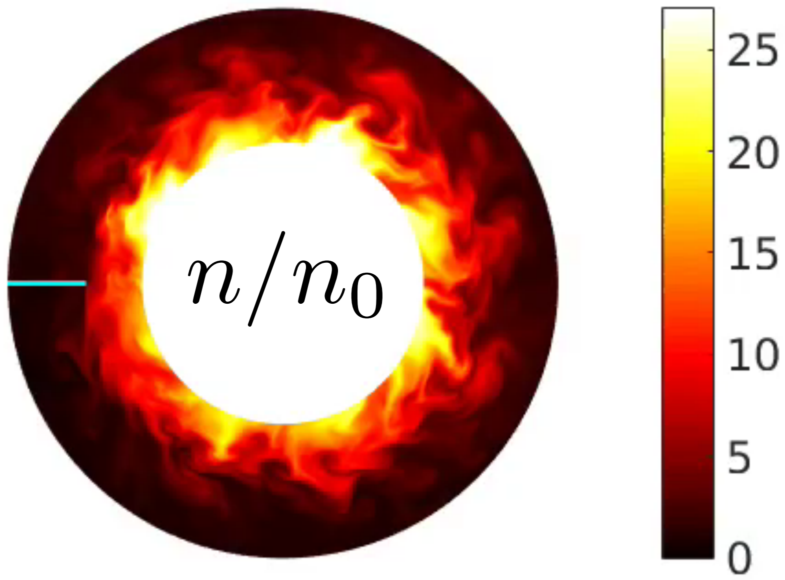




Nespoli et al., JNM 2015
Kocan et al., NF 2015

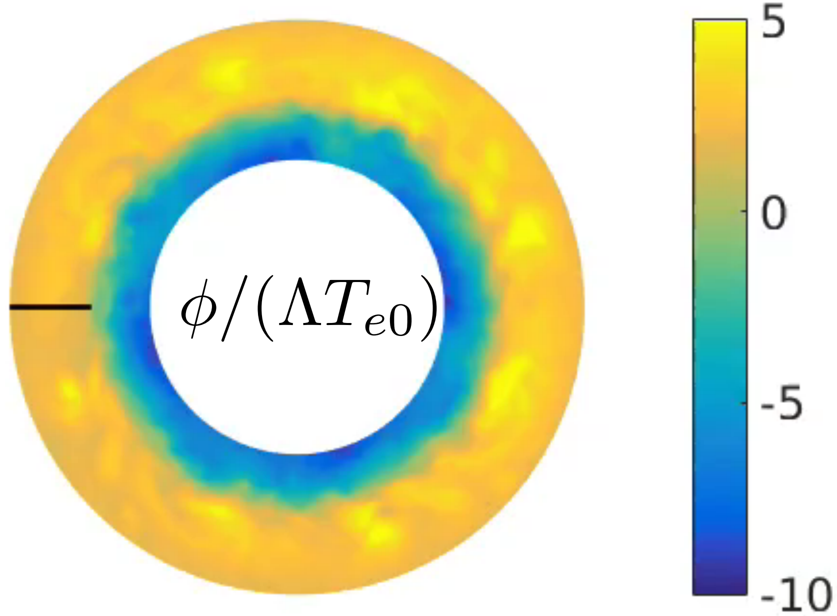
ITER inner wall was redesigned

Simulations of SOL and closed flux surface



Strong pressure gradient at the LCFS…

… associated with strong shear flow



Halpern & Ricci, PRL (sub.)

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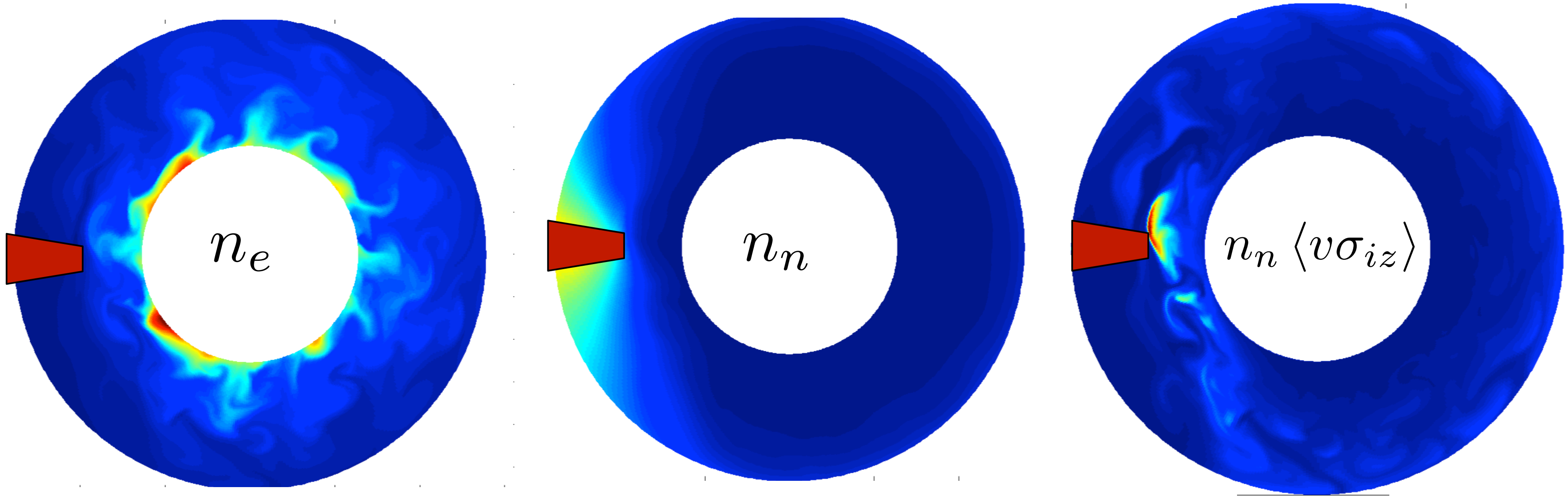
GBS simulations with neutrals

Kinetic neutral equation, solved with method of characteristics



First steps towards simulation of detachment

Some of our current research activities

- How does shaping affect SOL turbulence?
- Is it reasonable to use the Boussinesq approximation?
- What happens across the LCFS?
- What is the role of neutrals?
- Can we develop a more accurate plasma model?
- What happens in diverted configurations?

Going beyond Braginskii

Guiding center eq. of motion, large fluctuations, full Coulomb collisions:

$$\frac{\partial(B_{\|}^{*}\langle f\rangle)}{\partial t}+\nabla\cdot(\dot{\mathbf{R}}B_{\|}^{*}\langle f\rangle)+\frac{\partial(\dot{v}_{\|}B_{\|}^{*}\langle f\rangle)}{\partial v_{\|}}=B_{\|}^{*}\langle C(f)\rangle$$

Moment expansion:

$$\langle f\rangle=\sum_{pj}\frac{F_M}{\psi^p}N^{pj}H_p\left(\frac{v_{\|}-u_{\|}}{v_{th,\|}}\right)L_j\left(\frac{\mu B}{T_{\perp}}\right)$$

In analogy with Ji & Held [PoP 2006], we derived

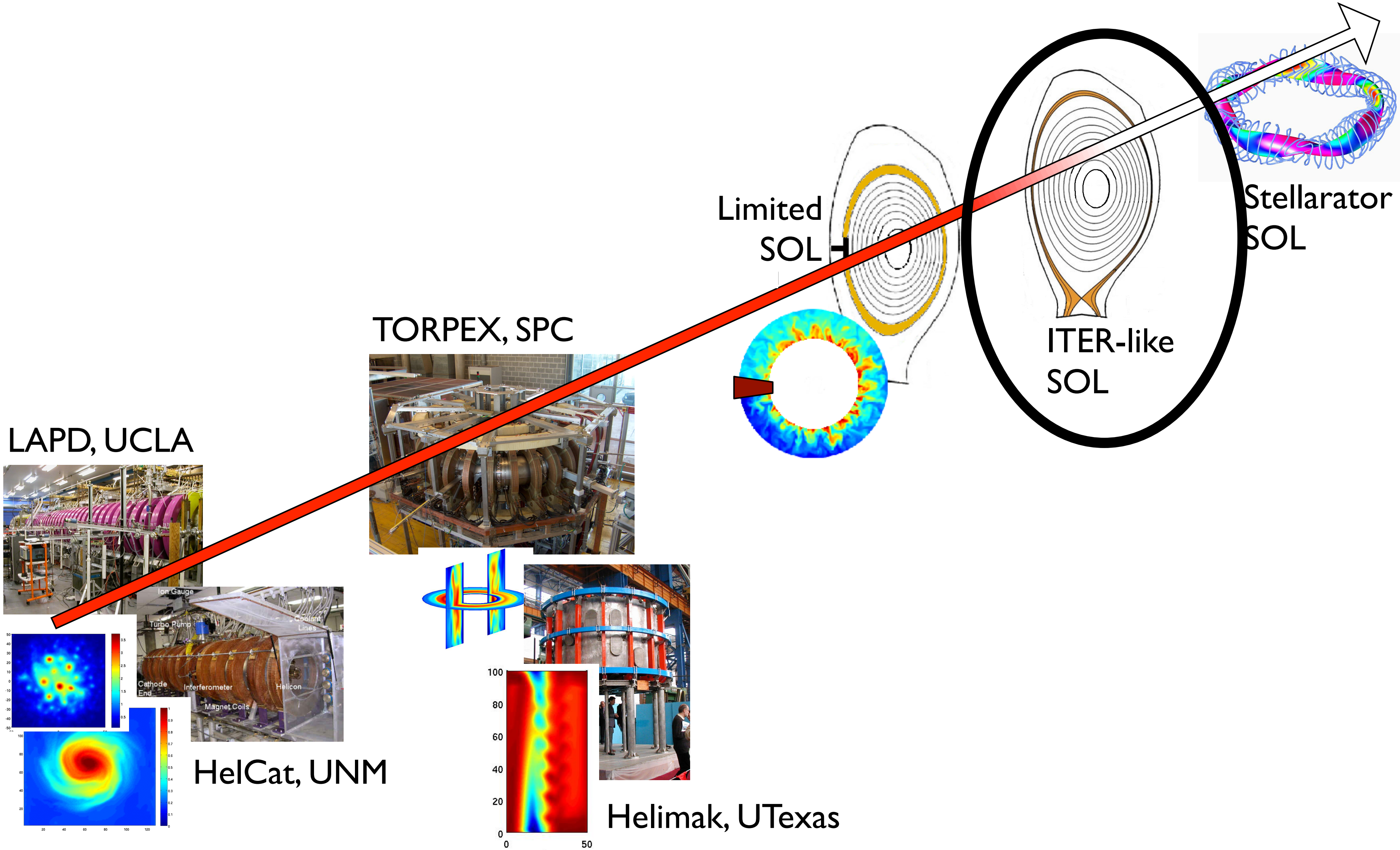
$$\int C(f_a,f_b)H_l\left(\frac{v_{\|}-u_{\|}}{v_{th,\|}}\right)L_k\left(\frac{\mu B}{T_{\perp}}\right)Bdv_{\|}d\mu=\sum_{p,j,n,q}\mathcal{C}_{ab,lk}^{pj,nq}\mathcal{N}_a^{pj}\mathcal{N}_b^{nq}$$

We obtain hierarchy of moment equations, recovering the drift-reduced Braginskii limit

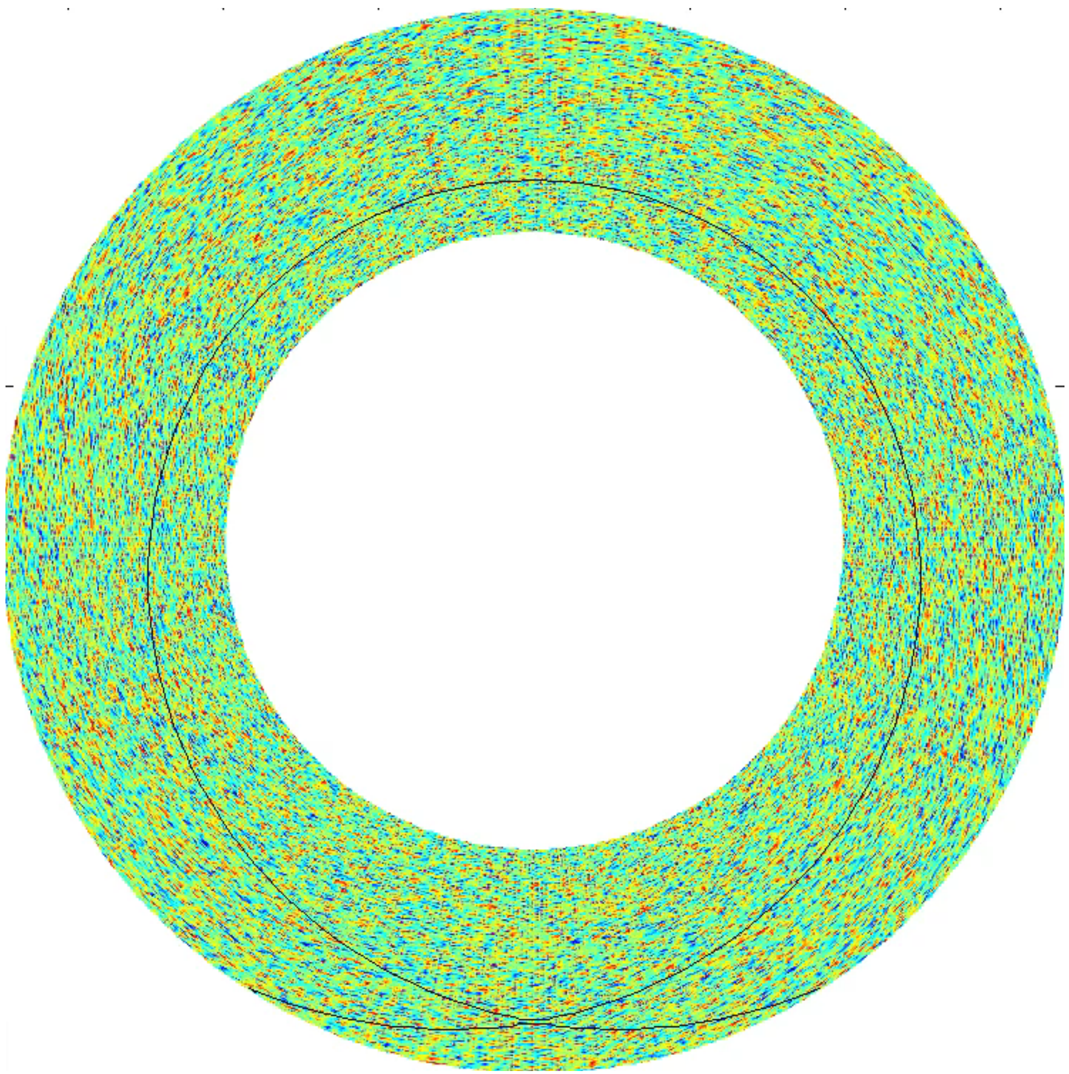
Some of our current research activities

- How does shaping affect SOL turbulence?
- Is it reasonable to use the Boussinesq approximation?
- What happens across the LCFS?
- What is the role of neutrals?
- Can we develop a more accurate plasma model?
- What happens in diverted configurations?

GBS: our simulation tool



GBS simulations of diverted geometry



Use of
a new high-order
non field-aligned
algorithm

What are we learning on SOL dynamics?

- The use first-principles simulations and analysis to investigate SOL plasma dynamics
- Progressive approach to complexity
- Past results in limited configuration:
  - SOL width set by resistive ballooning-driven turbulence saturated by the gradient removal mechanism
  - Good agreement of pressure scale length with multi-machine measurements
  - Mechanisms setting electrostatic potential and toroidal rotation
- Current activities: turbulence across LCFS, neutral physics, more accurate plasma model, and divertor

http://people.epfl.ch/paolo.ricci

Extra slides

The complete set of equations

$$\frac{\partial n}{\partial t} = -\rho_\star^{-1}[\phi, n] + \frac{2}{B}[C(p_e) - nC(\phi)] - \nabla_\parallel(nv_{\parallel e}) + \mathcal{D}_n(n) + S_n + n_n n r_{iz} - n^2 r_{rec} \tag{1}$$

$$\frac{\partial \tilde{\omega}}{\partial t} = -\rho_\star^{-1}[\phi, \tilde{\omega}] - v_{\parallel i}\nabla_\parallel \tilde{\omega} + \frac{B^2}{n}\nabla_\parallel j_\parallel + \frac{2B}{n}C(p) + \mathcal{D}_{\tilde{\omega}}(\tilde{\omega}) \tag{2}$$

$$\frac{\partial v_{\parallel e}}{\partial t} + \frac{m_i}{m_e}\frac{\beta_e}{2}\frac{\partial \Psi}{\partial t} = -\rho_\star^{-1}[\phi, v_{\parallel e}] - v_{\parallel e}\nabla_\parallel v_{\parallel e} + \frac{m_i}{m_e}\left(\nu\frac{j_\parallel}{n} + \nabla_\parallel \phi - \frac{1}{n}\nabla_\parallel p_e - 0.71\nabla_\parallel T_e\right) + \mathcal{D}_{v_{\parallel e}}(v_{\parallel e}) \tag{3}$$

$$\frac{\partial v_{\parallel i}}{\partial t} = -\rho_\star^{-1}[\phi, v_{\parallel i}] - v_{\parallel i}\nabla_\parallel v_{\parallel i} - \frac{1}{n}\nabla_\parallel p + \mathcal{D}_{v_{\parallel i}}(v_{\parallel i}) + n_n(r_{iz} + r_{cx})(v_{\parallel n} - v_{\parallel i}) \tag{4}$$

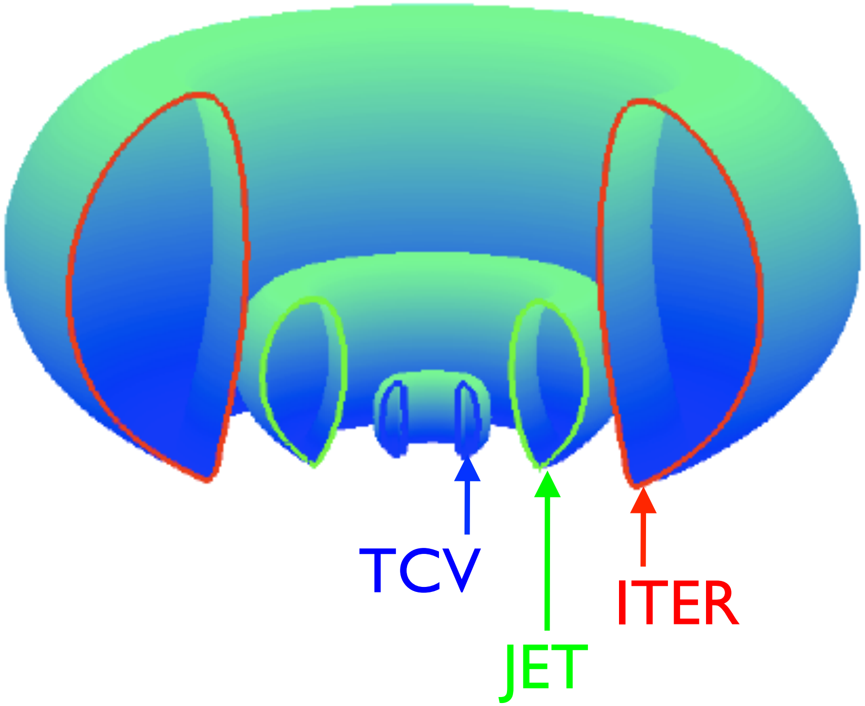
$$\begin{aligned}\frac{\partial T_e}{\partial t} = {} & -\rho_\star^{-1}[\phi, T_e] - v_{\parallel e}\nabla_\parallel T_e + \frac{4T_e}{3B}\left[\frac{1}{n}C(p_e) + \frac{5}{2}C(T_e) - C(\phi)\right] + \frac{2T_e}{3}\left[\frac{0.71}{n}\nabla_\parallel j_\parallel - \nabla_\parallel v_{\parallel e}\right] \\ & + \mathcal{D}_{T_e}(T_e) + \mathcal{D}^\parallel_{T_e}(T_e) + S_{T_e} - n_n r_{iz} E_{iz}\end{aligned} \tag{5}$$

$$\begin{aligned}\frac{\partial T_i}{\partial t} = {} & -\rho_\star^{-1}[\phi, T_i] - v_{\parallel i}\nabla_\parallel T_i + \frac{4T_i}{3B}\left[\frac{1}{n}C(p_e) - \tau\frac{5}{2}C(T_i) - C(\phi)\right] + \frac{2T_i}{3}\left[(v_{\parallel i} - v_{\parallel e})\frac{\nabla_\parallel n}{n} - \nabla_\parallel v_{\parallel e}\right] \\ & + \mathcal{D}_{T_i}(T_i) + \mathcal{D}^\parallel_{T_i}(T_i) + S_{T_i} + n_n(r_{iz} + r_{cx})(T_n - T_i + (v_{\parallel n} - v_{\parallel i})^2)\end{aligned} \tag{6}$$

$$\nabla_\perp^2 \phi = \omega,\ \nabla_\perp^2 \Psi = j_\parallel,\ \rho_\star = \rho_s/R,\ \nabla_\parallel f = \mathbf{b}_0 \cdot \nabla f + \frac{\beta_e}{2}\rho_\star^{-1}[\Psi, f],\ \tilde{\omega} = \omega + \tau\nabla_\perp^2 T_i,\ p = n(T_e + \tau T_i)$$

ITER design based on scaling law

SOL basic physics understanding is still missing



Simulations of SOL turbulence are crucial

The full set of GBS equations

$$\partial_t n = -\frac{R}{B}[\phi, n] + \frac{2}{B}\left[\hat{C}(p_e) - n\hat{C}(\phi)\right] - \nabla_\parallel \left(n v_{\parallel e}\right) + S_n$$

$$\partial_t \nabla_\perp^2 \phi = -\frac{R}{B}\left[\phi, \nabla_\perp^2 \phi\right] + \frac{2B}{n}\hat{C}(p_e) - v_{\parallel i}\nabla_\parallel \nabla_\perp^2 \phi + \frac{B^2}{n}\nabla_\parallel j_\parallel$$

$$\partial_t \left(v_{\parallel e} + \frac{m_i \beta_e}{m_e 2}\psi\right) = -\frac{R}{B}\left[\phi, v_{\parallel e}\right] - v_{\parallel e}\nabla_\parallel v_{\parallel e}$$

$$+ \frac{m_i}{m_e}\left\{-\nu\frac{j_\parallel}{n} + \nabla_\parallel \phi - \frac{1}{n}\nabla_\parallel p_e - 0.71\nabla_\parallel T_e - \frac{2}{3n}\nabla_\parallel G_e\right\}$$

$$\partial_t v_{\parallel i} = -\frac{R}{B}\left[\phi, v_{\parallel i}\right] - v_{\parallel i}\nabla_\parallel v_{\parallel i} - \frac{1}{n}\nabla_\parallel p_e$$

$$\partial_t T_e = -\frac{R}{B}[\phi, T_e] - v_{\parallel e}\nabla_\parallel T_e + \frac{4}{3}\frac{T_e}{B}\left[\frac{7}{2}\hat{C}(T_e) + \frac{T_e}{n}\hat{C}(n) - \hat{C}(\phi)\right] + S_{T_e}$$

$$+ \frac{2}{3}T_e\left[0.71\nabla_\parallel v_{\parallel i} - 1.71\nabla_\parallel v_{\parallel e} + 0.71\left(\frac{v_{\parallel i} - v_{\parallel e}}{n}\right)\nabla_\parallel n\right]$$

Need boundary conditions for:

$n, v_{\parallel e}, v_{\parallel i}, T_e, \nabla_\perp^2 \phi, \psi, \phi$

Gradient-removal estimate of ExB velocity transport

$$\Gamma_{v,r} \sim \left\langle \tilde{v}_{\parallel i} \frac{\partial \tilde{\phi}}{\partial \theta} \right\rangle_t \sim \left\langle \left(\frac{\partial \tilde{\phi}}{\partial \theta} \right)^2 \right\rangle_t \frac{\partial \overline{v}_{\parallel i}}{\partial r}$$

Parallel momentum
$\gamma \tilde{v}_{\parallel i} \sim \partial_r \overline{v}_{\parallel i} \partial_\theta \tilde{\phi}$

$$\sim \langle \tilde{p}^2 \rangle_t \frac{\partial \overline{v}_{\parallel i}}{\partial r} \sim -\frac{\gamma}{k_\theta} L_p \frac{\partial \overline{v}_{\parallel i}}{\partial r}$$

Continuity
$\gamma \tilde{p} \sim \partial_r \overline{p} \partial_\theta \tilde{\phi}$

Grad removal
$\partial_r \tilde{p} \sim \partial_r \overline{p}$

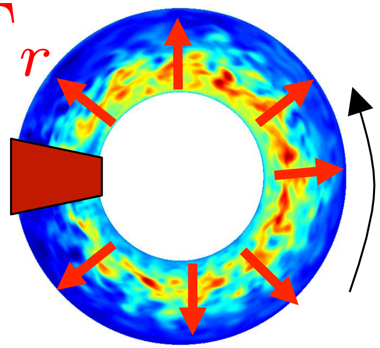
$$\sim -\frac{L_p^2 c_s}{qR} \frac{\partial \overline{v}_{\parallel i}}{\partial r}$$

Lp estimate
$L_p \sim qR\gamma/(c_s k_\theta)$

$$\boxed{\Gamma_{v,r} = -D_{\mathrm{T}} \frac{\partial \overline{v}_{\parallel i}}{\partial r}, \quad D_{\mathrm{T}} = \frac{L_p^2 c_s}{qR}}$$

Turbulent transport with gradient removal (GR) saturation

Turbulence saturates when it removes its drive $\rightarrow \dfrac{\partial \tilde{p}}{\partial r} \sim \dfrac{\partial \overline{p}}{\partial r} \rightarrow k_r \tilde{p} \sim \overline{p}/L_p$



$$\frac{\partial p}{\partial t} \simeq [p, \phi]$$

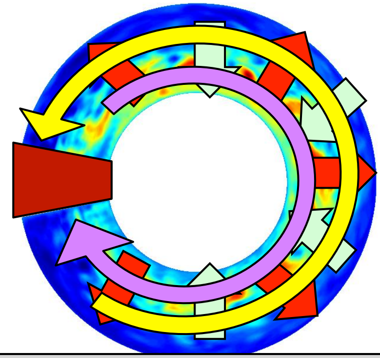
$$\Gamma_r = \left\langle \tilde{p} \frac{\partial \tilde{\phi}}{\partial \theta} \right\rangle_t$$

GR hypothesis

Nonlocal linear theory, $k_r \sim \sqrt{k_\theta / L_p}$

$$\boxed{D_{GR} = \frac{\Gamma_r}{\overline{p}/L_p} \sim \frac{\gamma L_p}{k_\theta}}$$

Turbulence saturation due to Kelvin-Helmholtz instability (KH)



Primary instability grows until it causes KH unstable shear flow $\rightarrow$ $\dfrac{\partial \Omega}{\partial t} \sim [\phi, \Omega] \rightarrow \tilde{\phi} \sim \dfrac{\gamma}{k_\theta^2}$

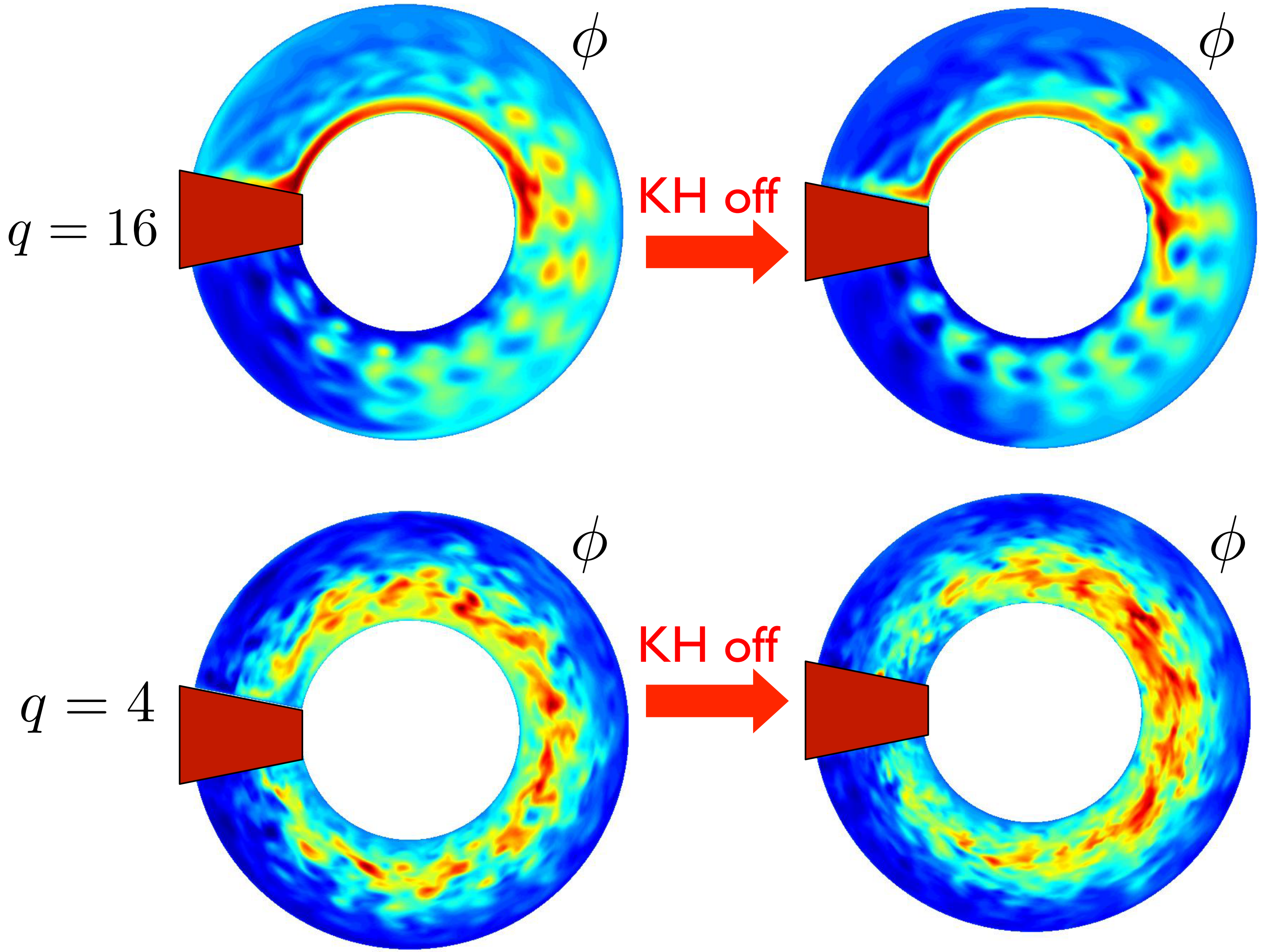
$$\Gamma_r = \left\langle \tilde{p} \frac{\partial \tilde{\phi}}{\partial \theta} \right\rangle_t \sim \frac{\gamma \overline{p}}{L_p k_\theta^2} \Rightarrow \boxed{D_{KH} \sim \frac{\gamma}{k_\theta^2}}$$

KH vs GR mechanism:

$$\frac{D_{KH}}{D_{GR}} \sim \frac{1}{k_\theta L_p} < 1$$

We expect KH to limit the transport, provided that KH is unstable!

Is KH really setting transport?

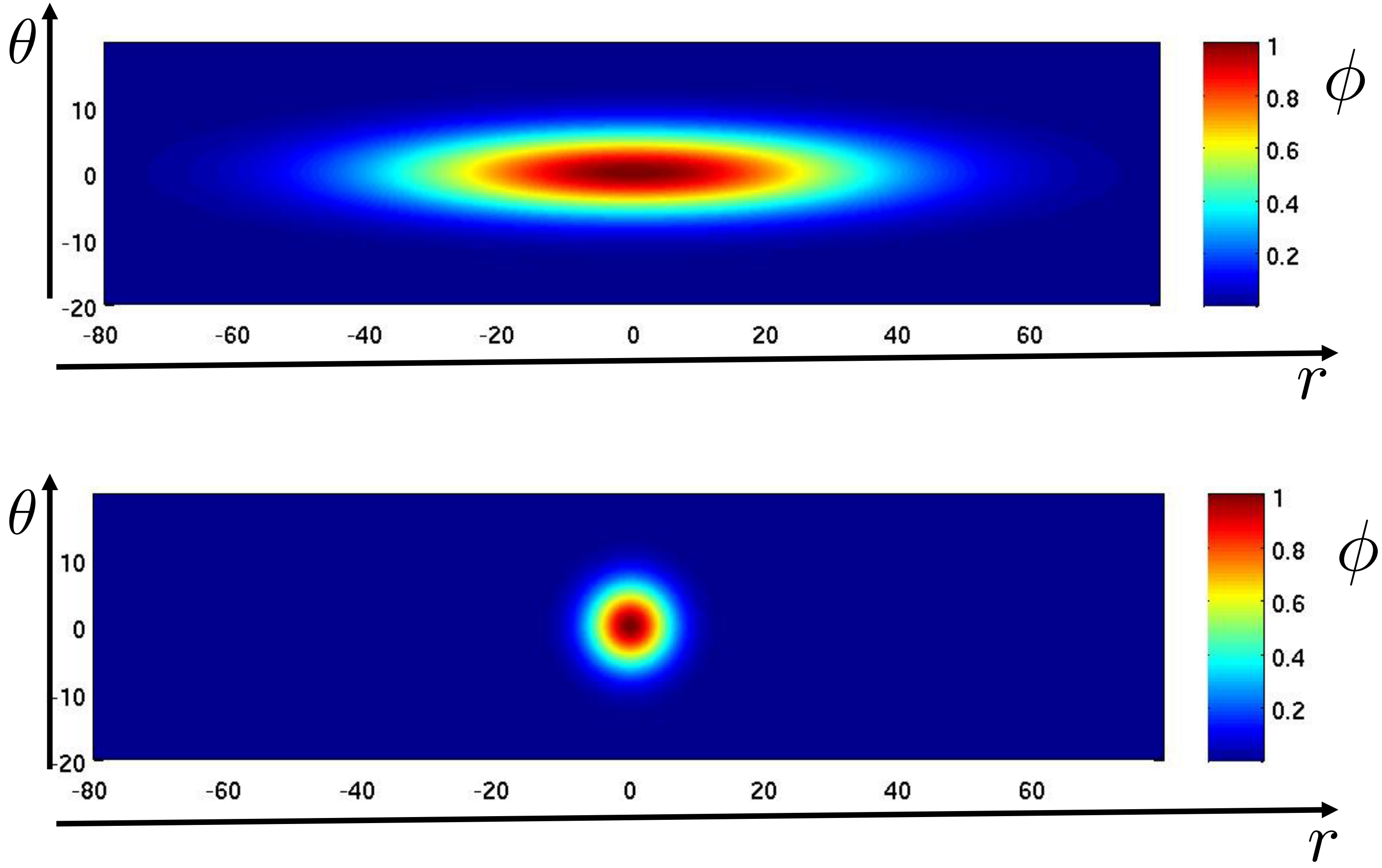


KH saturates turbulence

KH plays a minor role: GR!

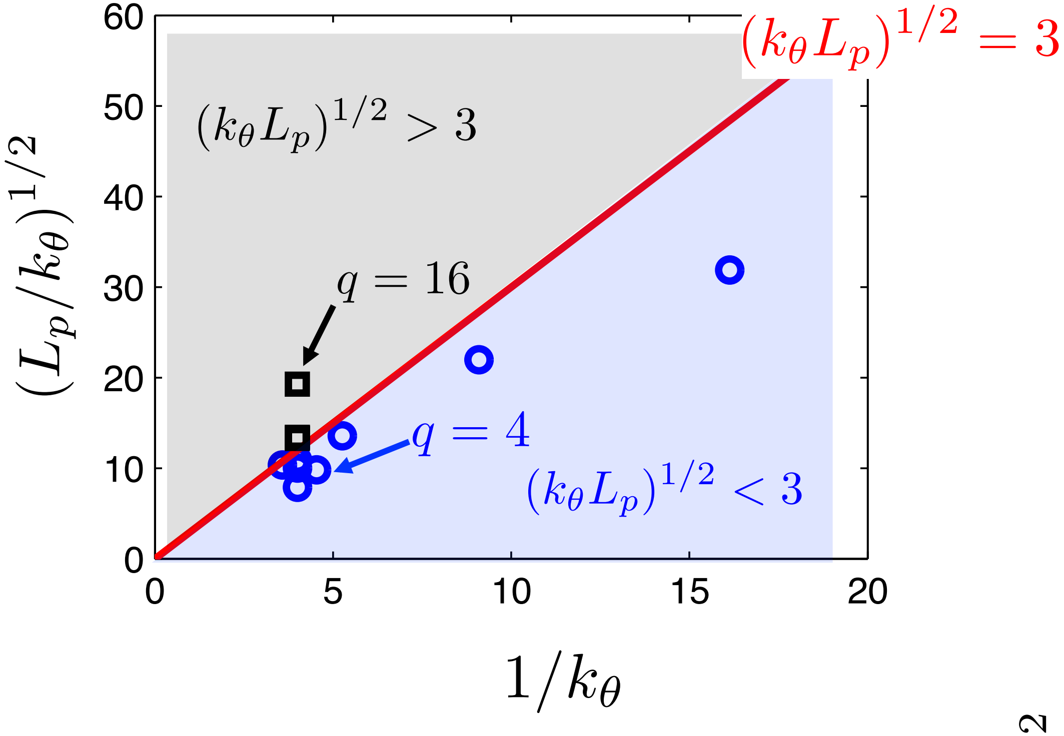
Why is KH stable at low q but not higher q?

Only elongated eddies are KH unstable



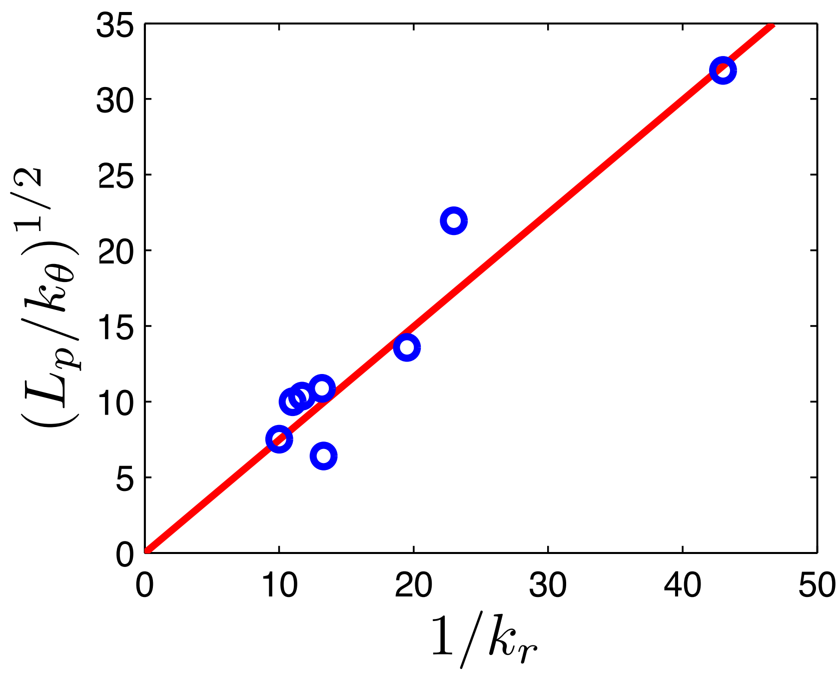
By comparing eddy turn over time and KH growth rate, KH unstable if: $\sqrt{k_\theta L_p} > 3$

Why is KH stable at low q but not higher q?



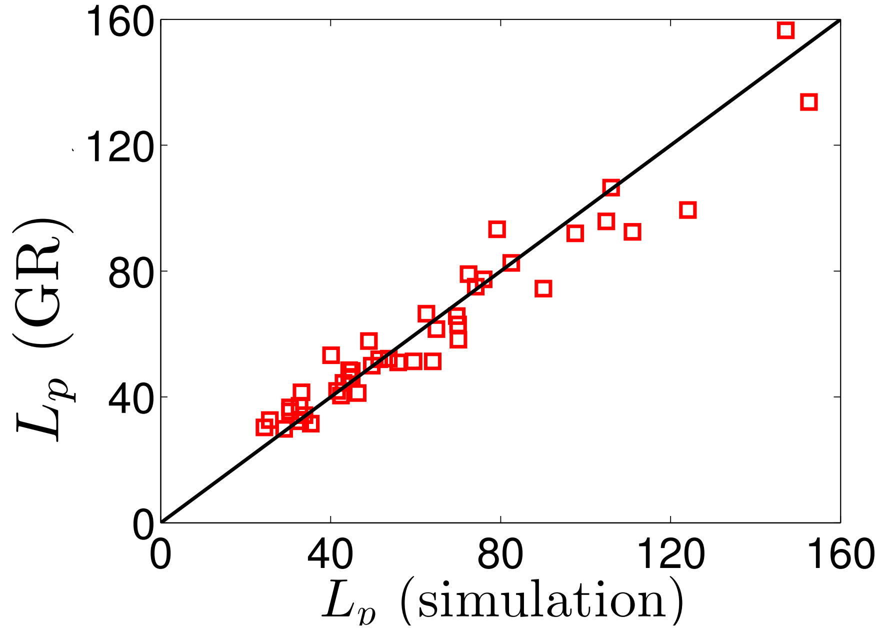
q=4 simulations are in the KH stable region

The eddies show the GR scaling properties

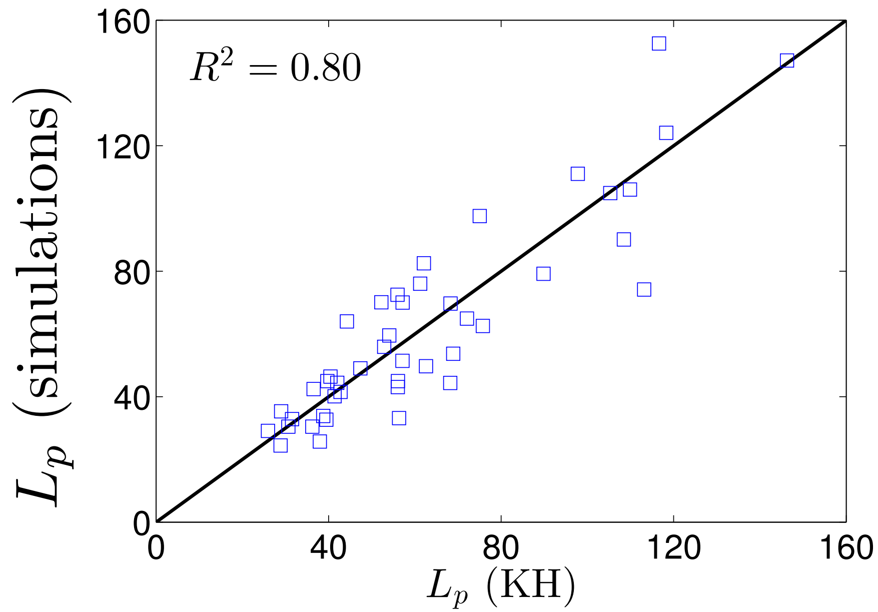


KH vs GR scaling?

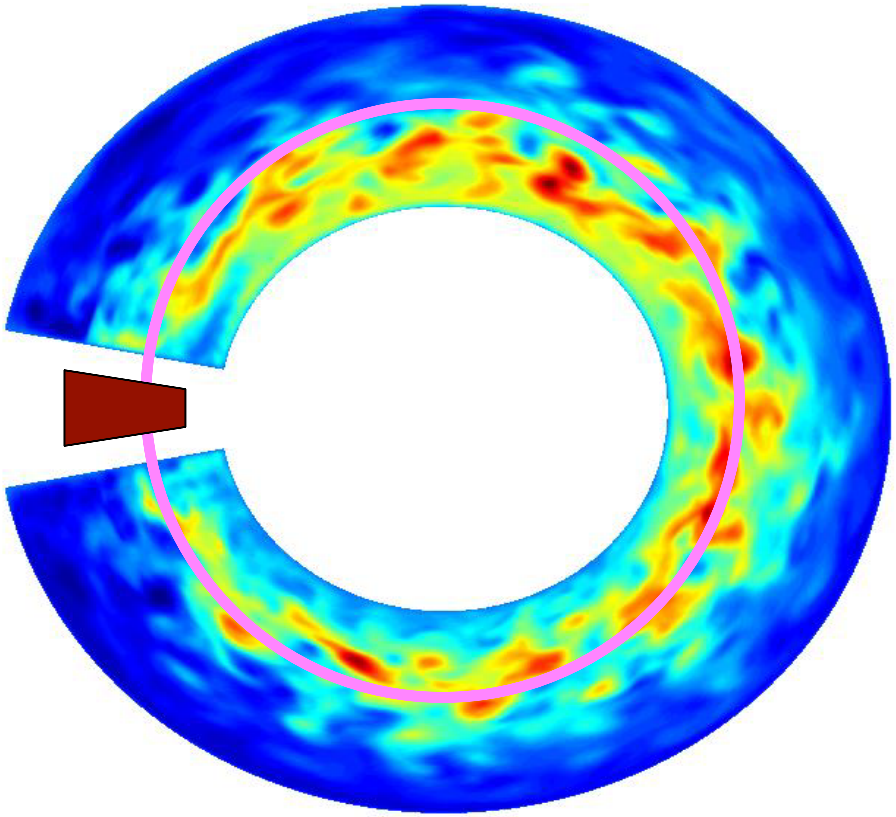
$$R^2 = 93\%$$



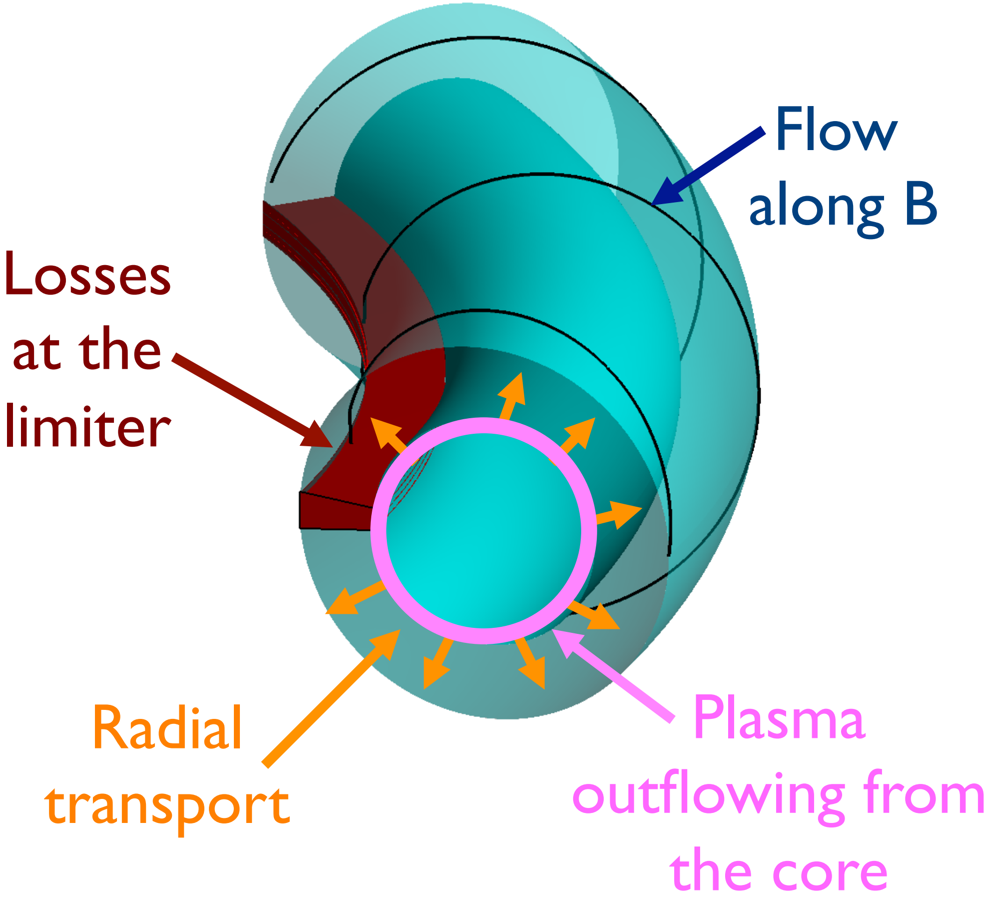
$$R^2 = 80\%$$



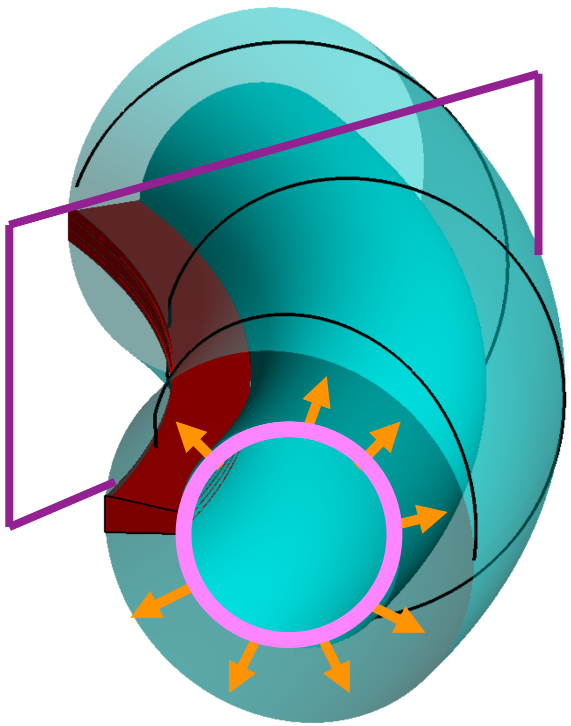
Details of the source



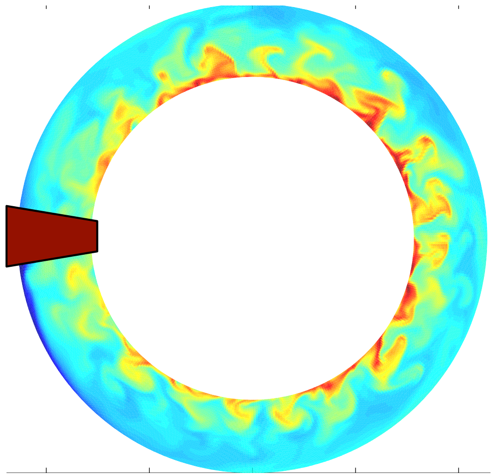
Tokamak SOL simulations

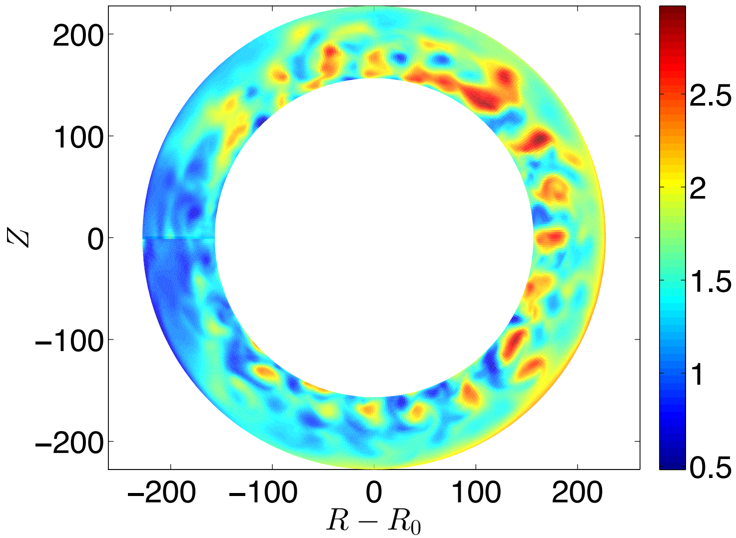


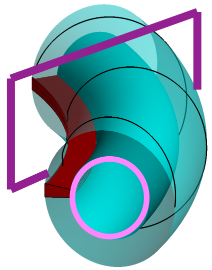
Tokamak SOL simulations



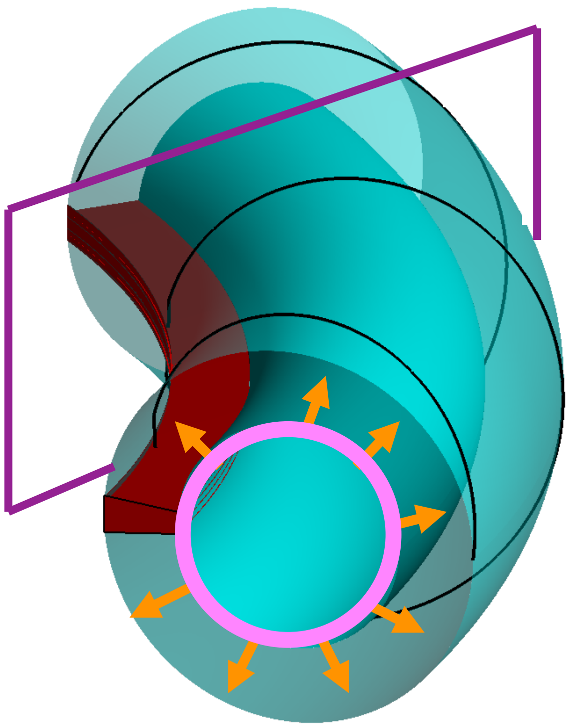
Tokamak SOL simulations

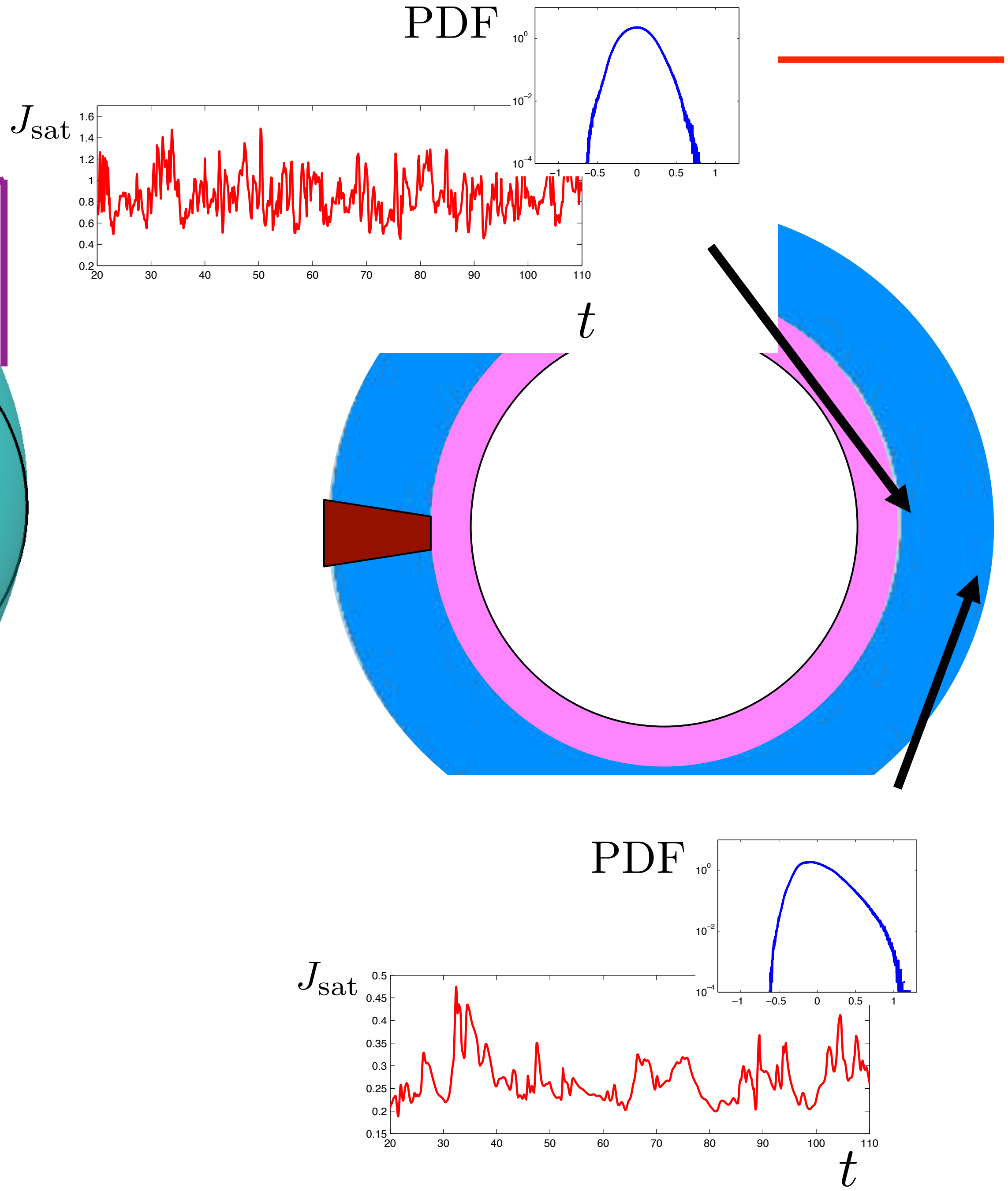




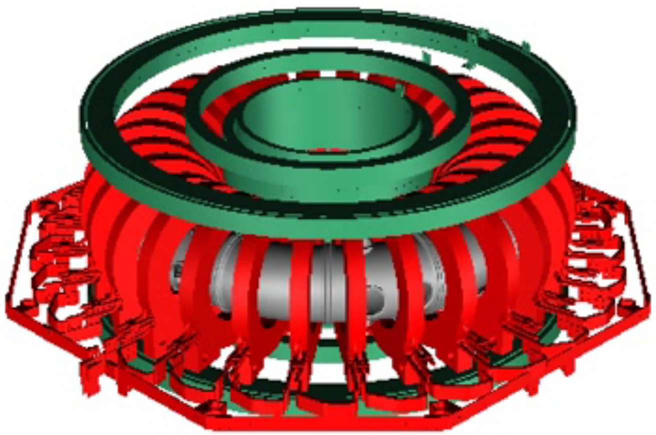


Tokamak

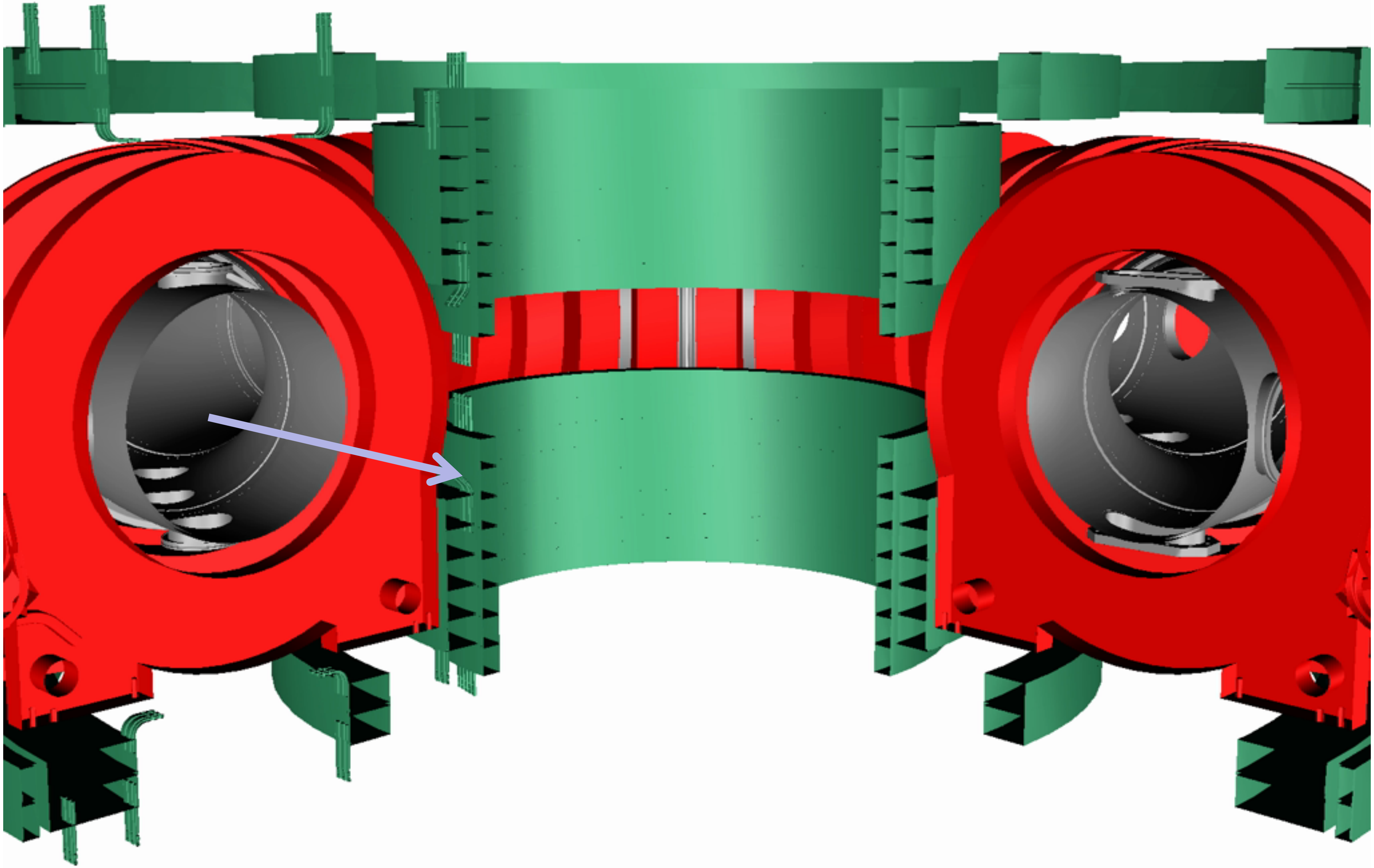




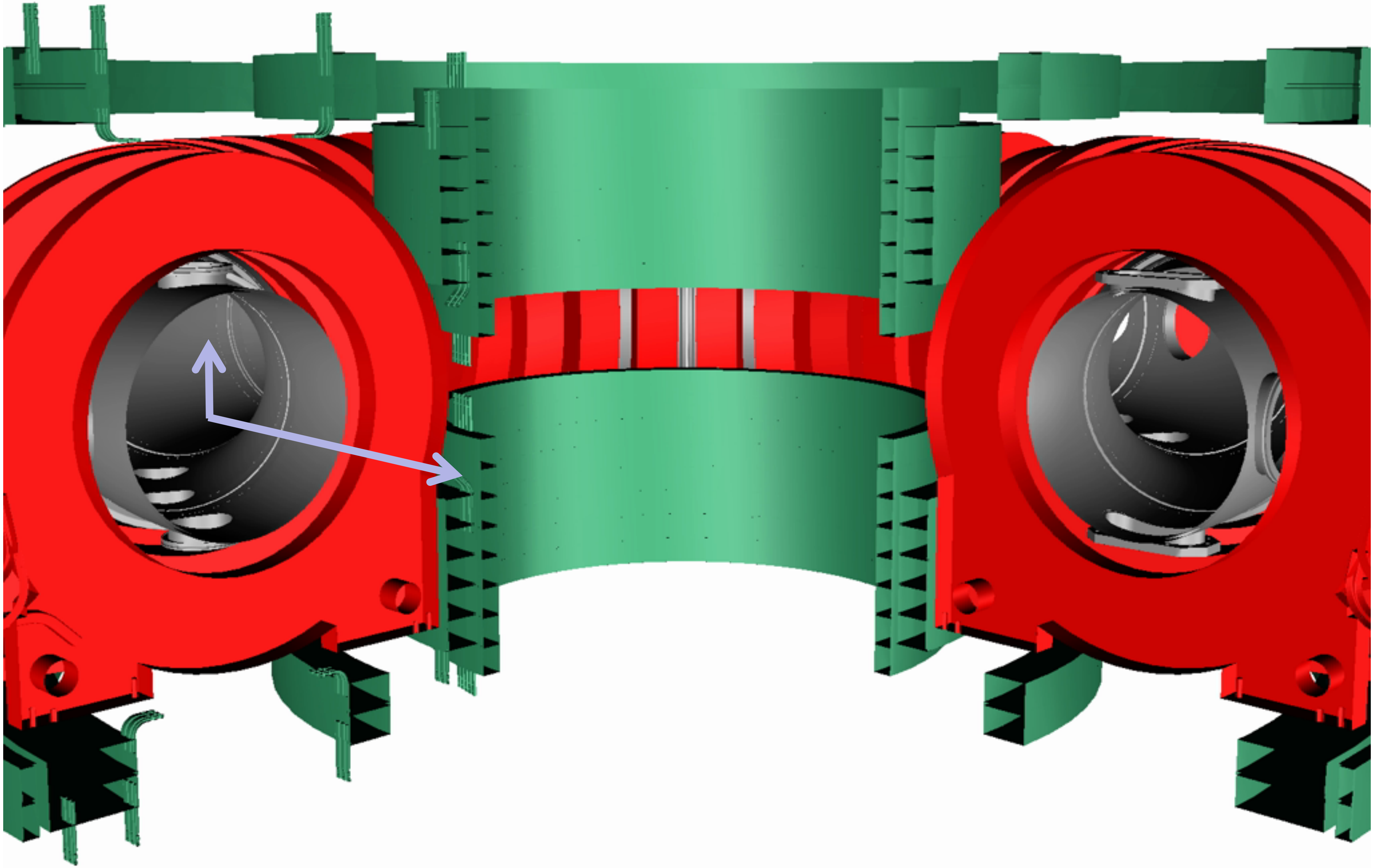
The TORPEX device



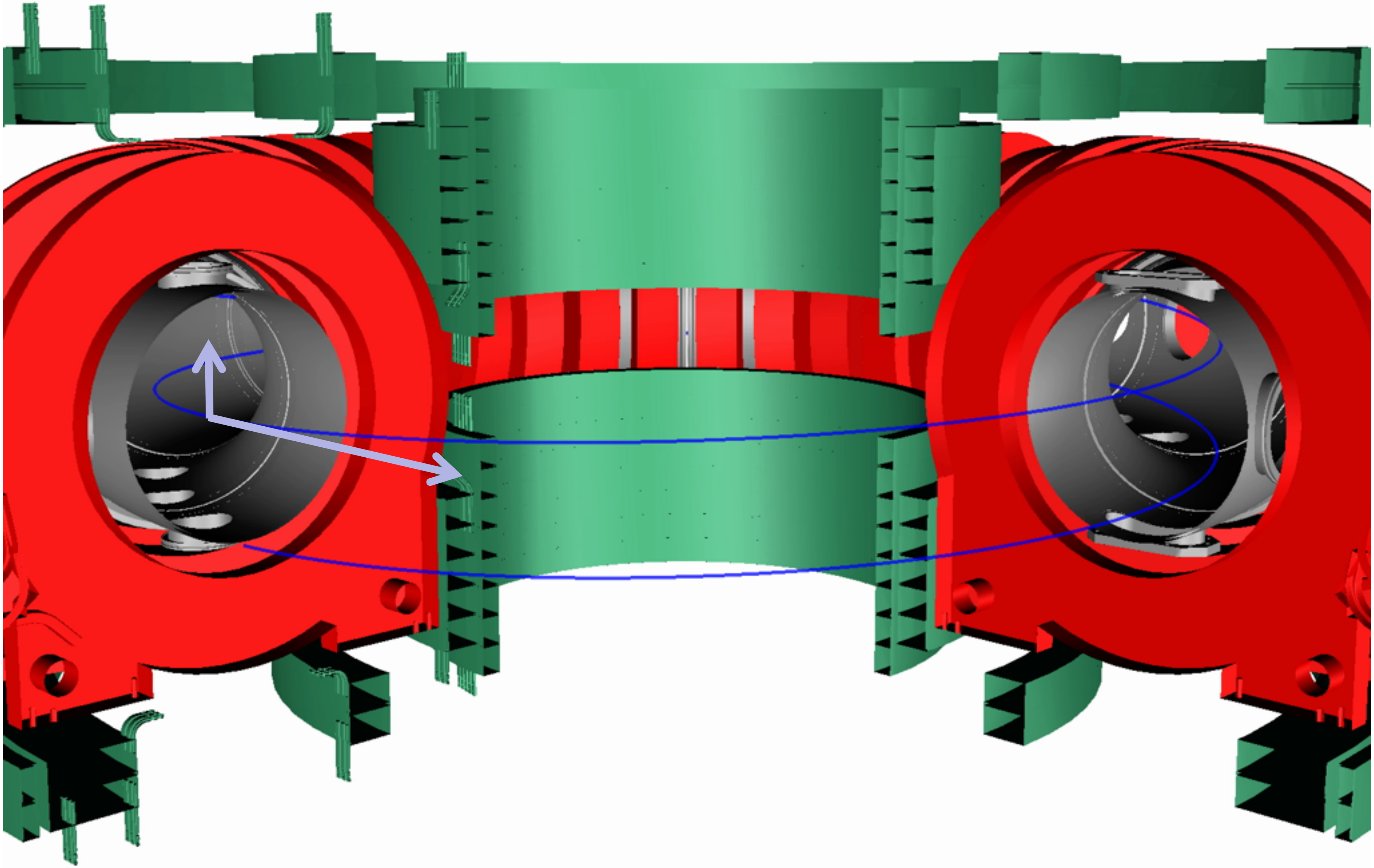
The TORPEX device



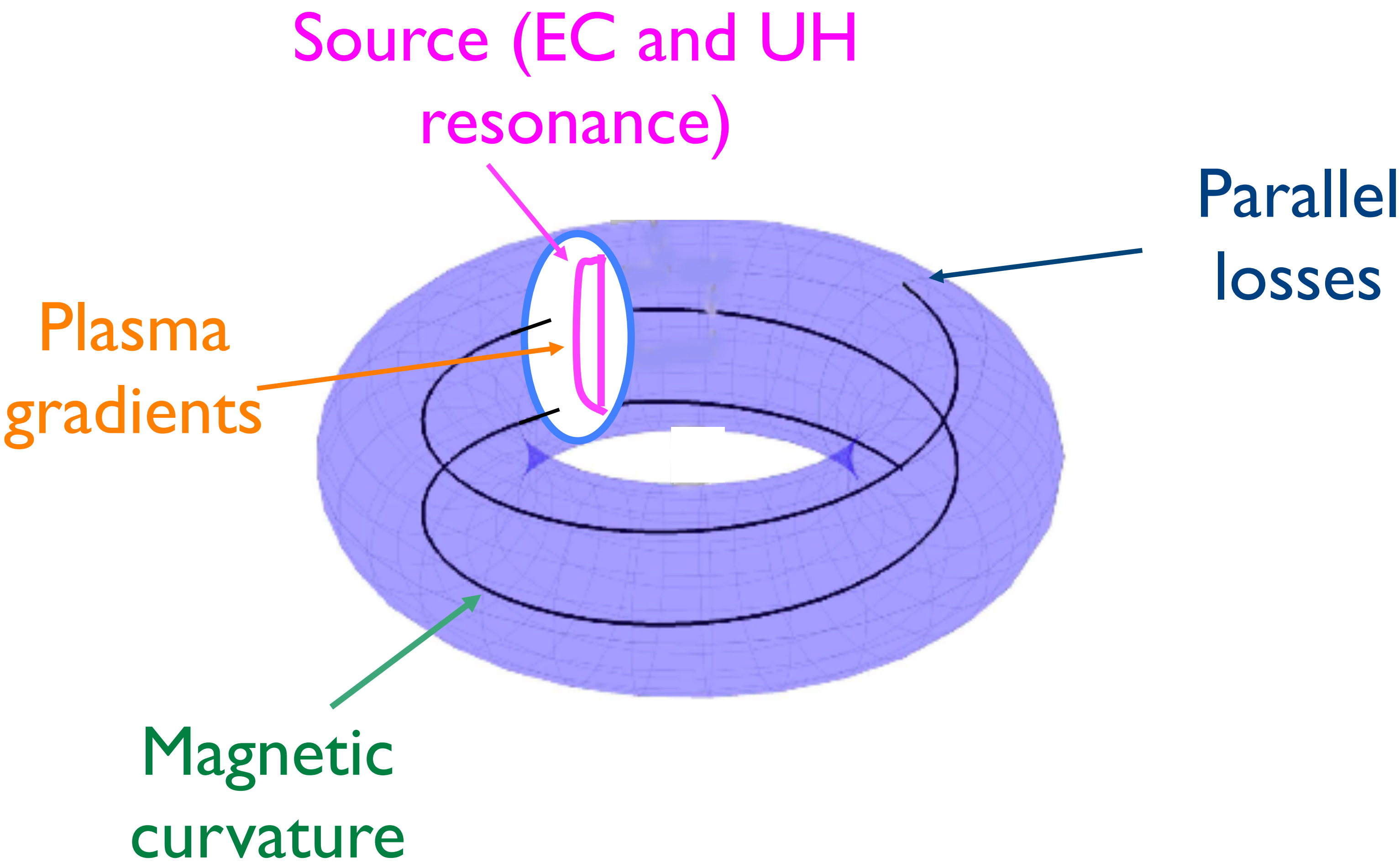
The TORPEX device



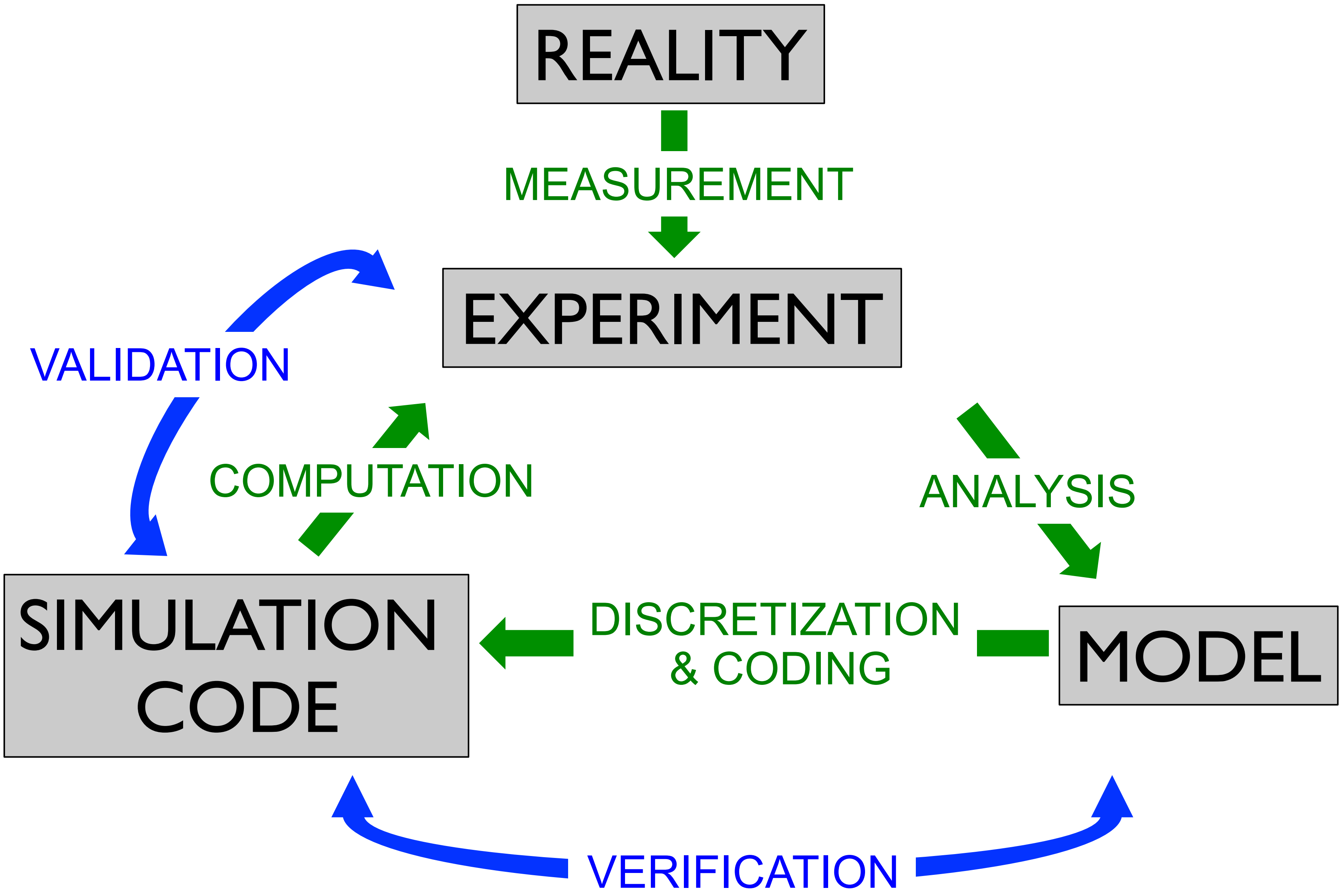
The TORPEX device



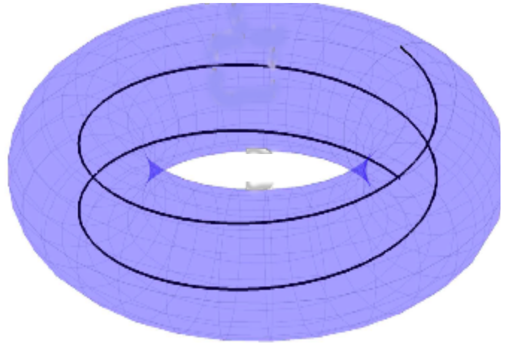
Key elements of the TORPEX device

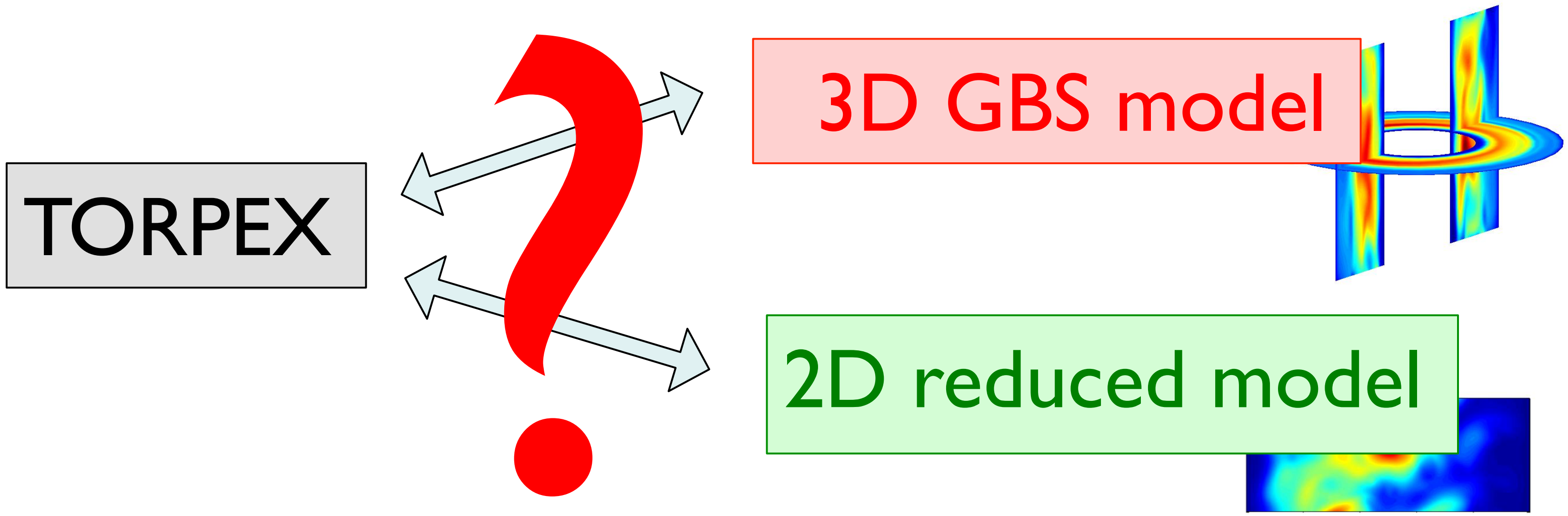


Verification & Validation



Our project, paradigm of turbulence code validation





What is the agreement of experiment and simulations as a function of *N* (number of field line turns)? Is 3D necessary?

What can we learn on TORPEX physics from the validation?

The validation methodology

[Based on ideas of Terry *et al.*, PoP 2008; Greenwald, PoP 2010]

What quantities can we use for validation? The more, the better…

- Definition & evaluation of the validation observables

What are the uncertainties affecting measured and simulation data?

- Uncertainty analysis

For one observable, within its uncertainties, what is the level of agreement?

- Level of agreement for an individual observable

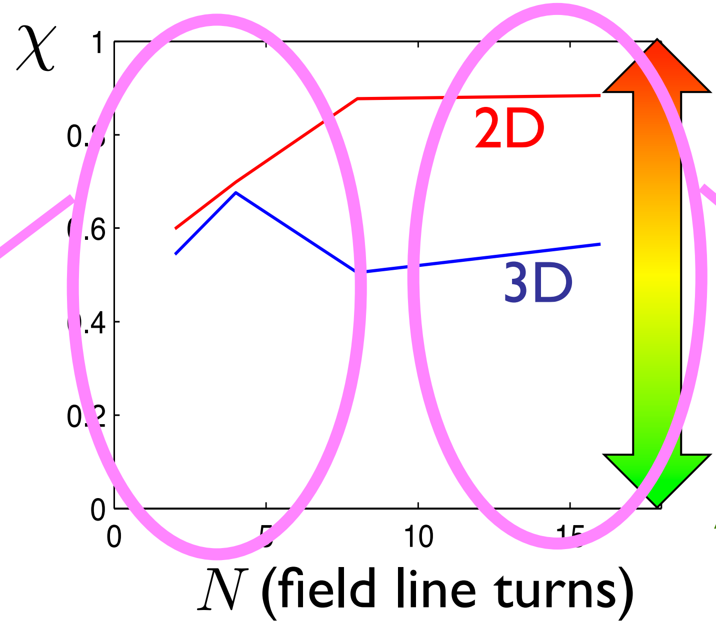
How directly can an observable be extracted from simulation and experimental data? How worthy is it, i.e. what should be its weight in a composite metric?

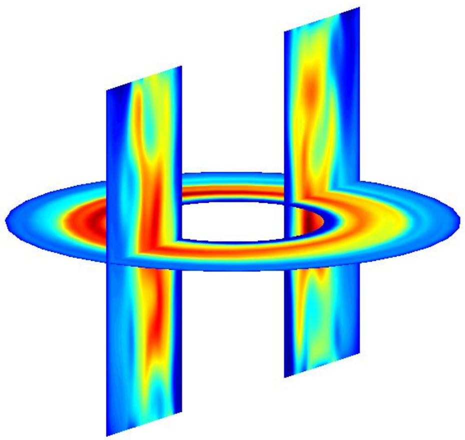
- The observable hierarchy

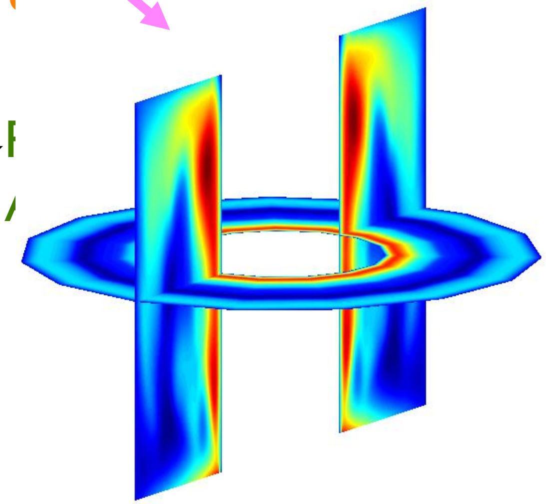
How to evaluate the global agreement and how to interpret it

- Composite metric, χ

Interpretation of the validation results







$k_{\parallel} = 0$

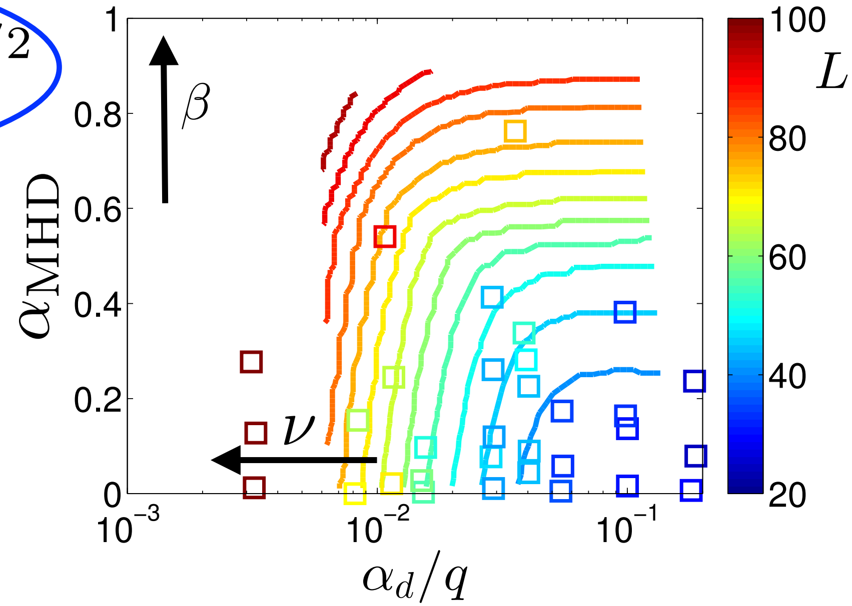
- Ideal interchange turbulence
- 2D model appropriate

$k_{\parallel} \neq 0$

- Resistive interchange turbulence
- 2D model not appropriate

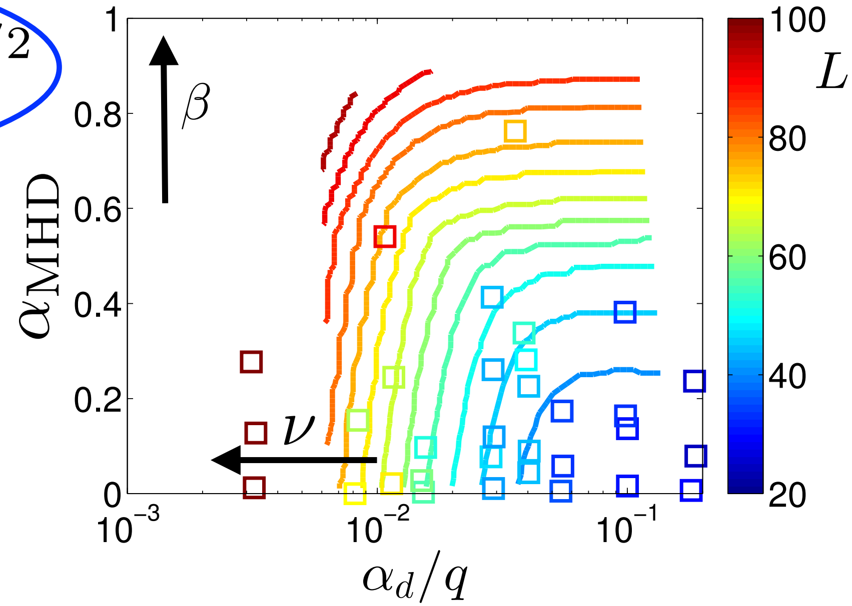
Limited SOL transport increases with β and ν

$$L_p = R^{1/2}[2\pi(1-\alpha_{\mathrm{MHD}})\alpha_d/q]^{-1/2}$$



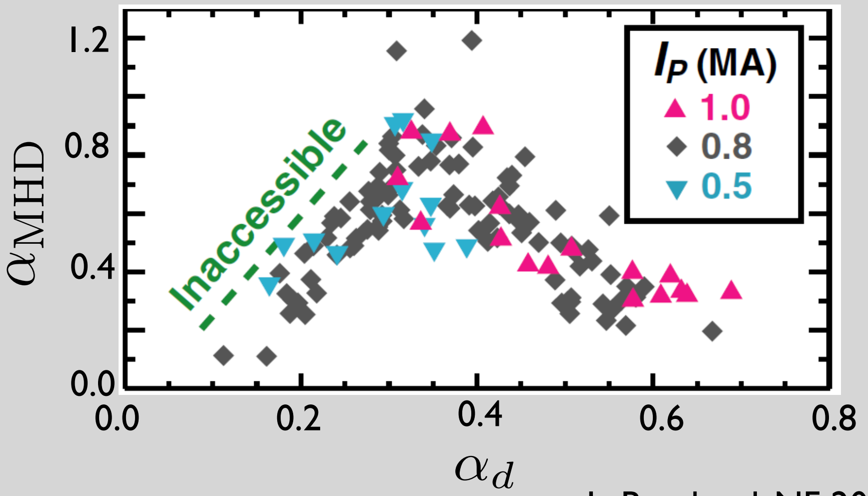
Limited SOL transport increases with β and ν

$$L_p = R^{1/2}[2\pi(1-\alpha_{\mathrm{MHD}})\alpha_d/q]^{-1/2}$$



Maybe related to the density limit?

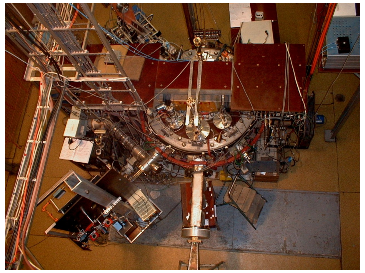
Coupling with core physics needs be addressed…



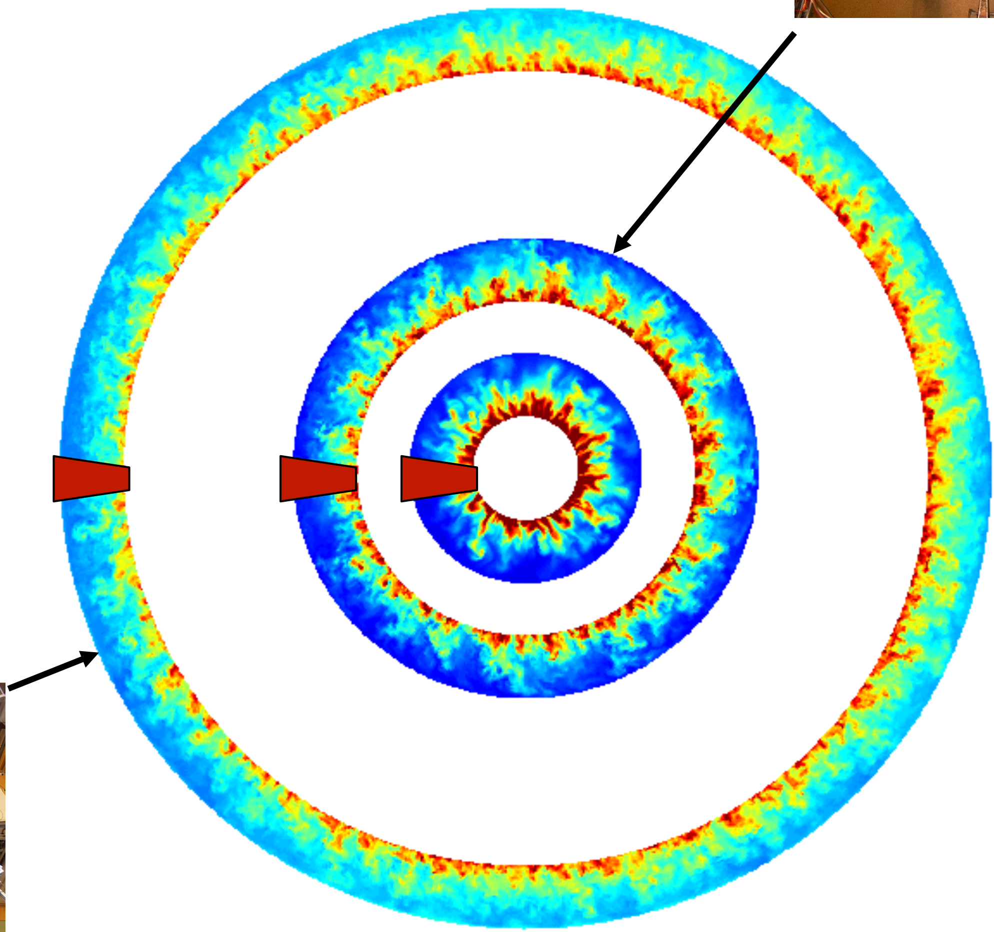
LaBombard, NF 2005

Limited SOL width widens with R

$$L_p = R^{1/2}[2\pi(1-\alpha_{\mathrm{MHD}})\alpha_d/q]^{-1/2}$$



CASTOR



TCV