Plasma simulations in the tokamak scrape-off layer

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Many thanks to CRPP colleagues for discussions and images

What is the SOL? Its main roles? Its regimes?

Why a diverted configuration?

How can we simulate the SOL? First-principle kinetic and fluid simulations. Phenomenological approach.

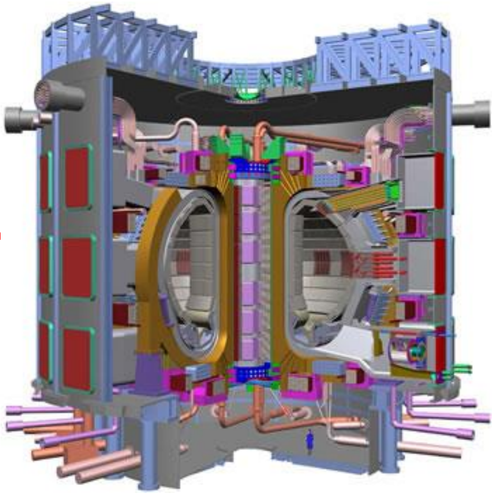
The questions

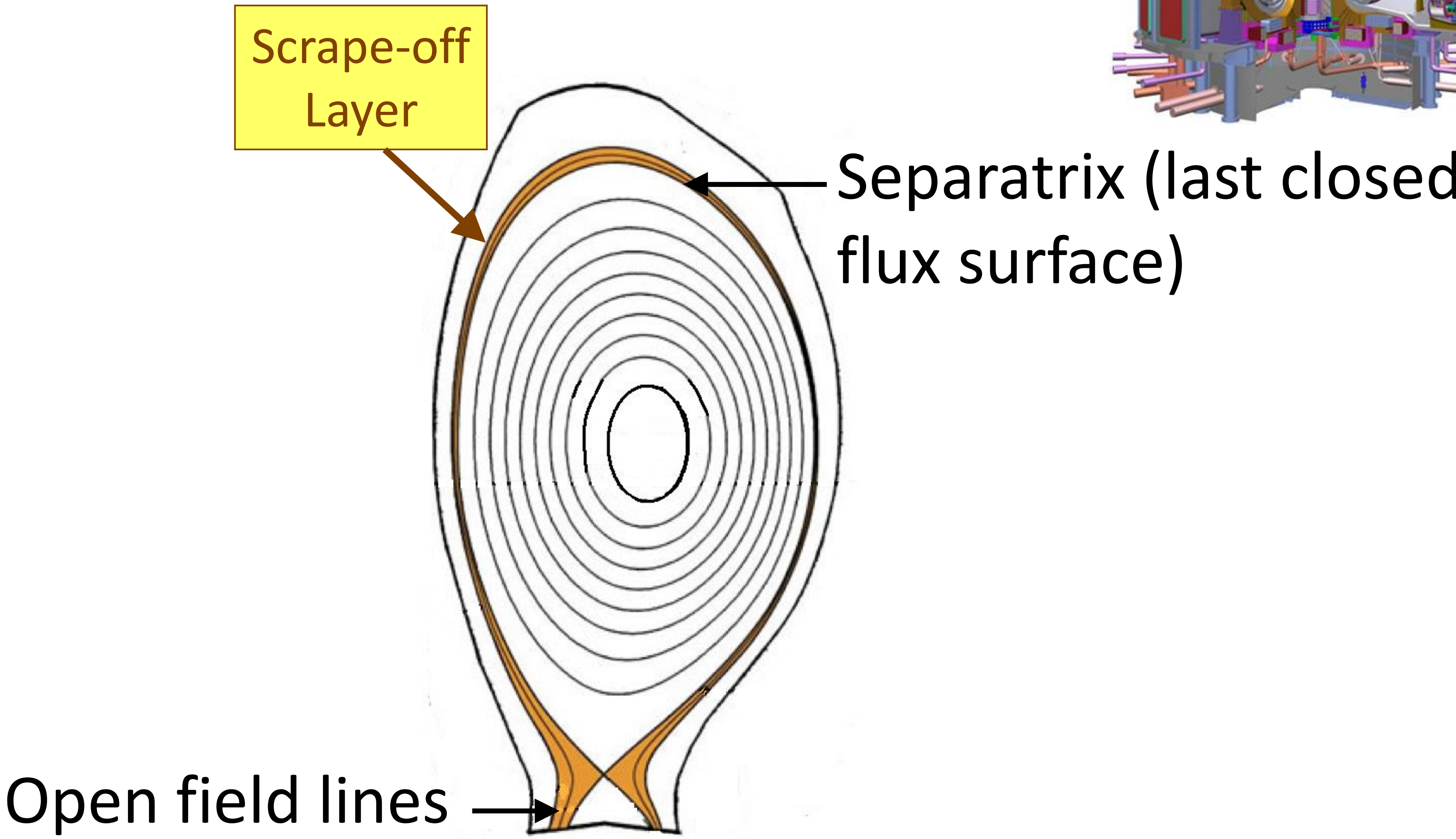
What is the SOL? Its main roles? Its regimes?

Why a diverted configuration?

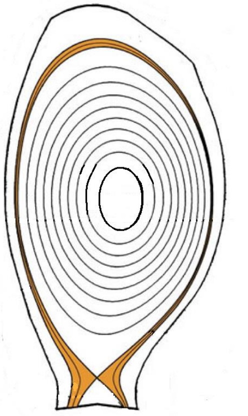
How can we simulate the SOL? First-principle kinetic and fluid simulations. Phenomenological approach.

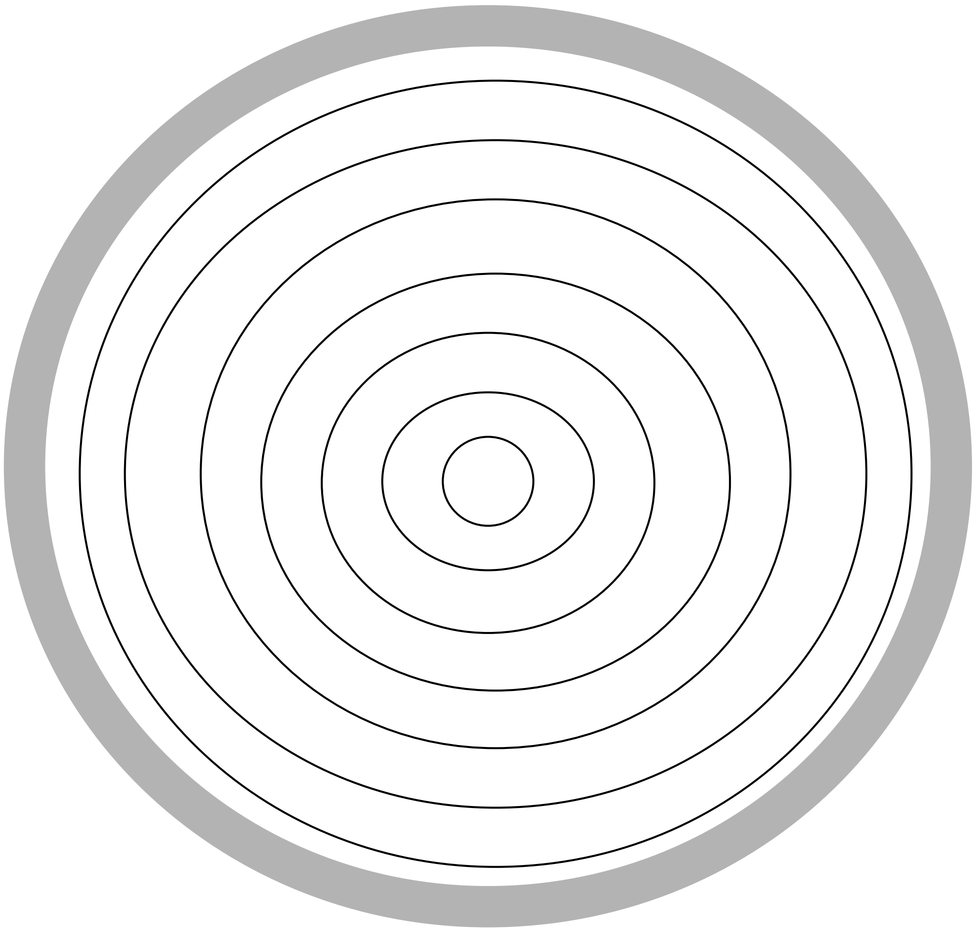
The scrape-off layer (SOL) – the most external region in a tokamak





Why the SOL? If we didn't think about it…





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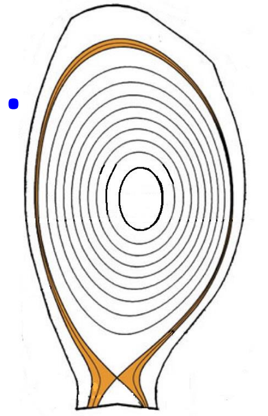
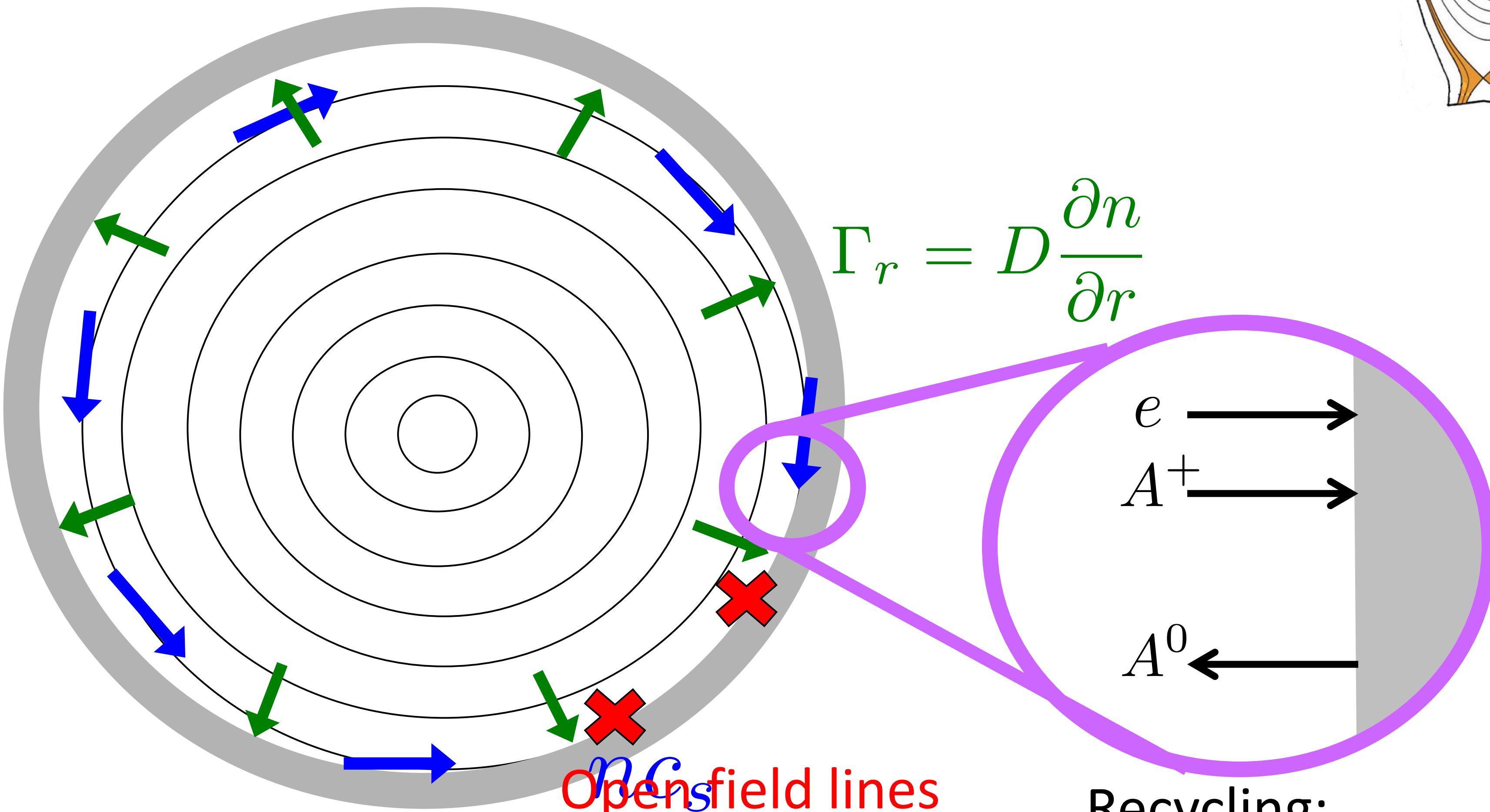
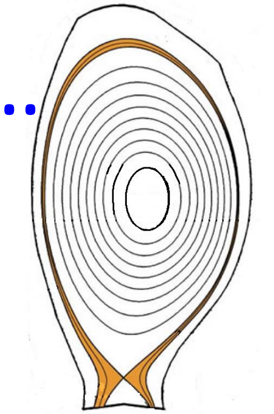
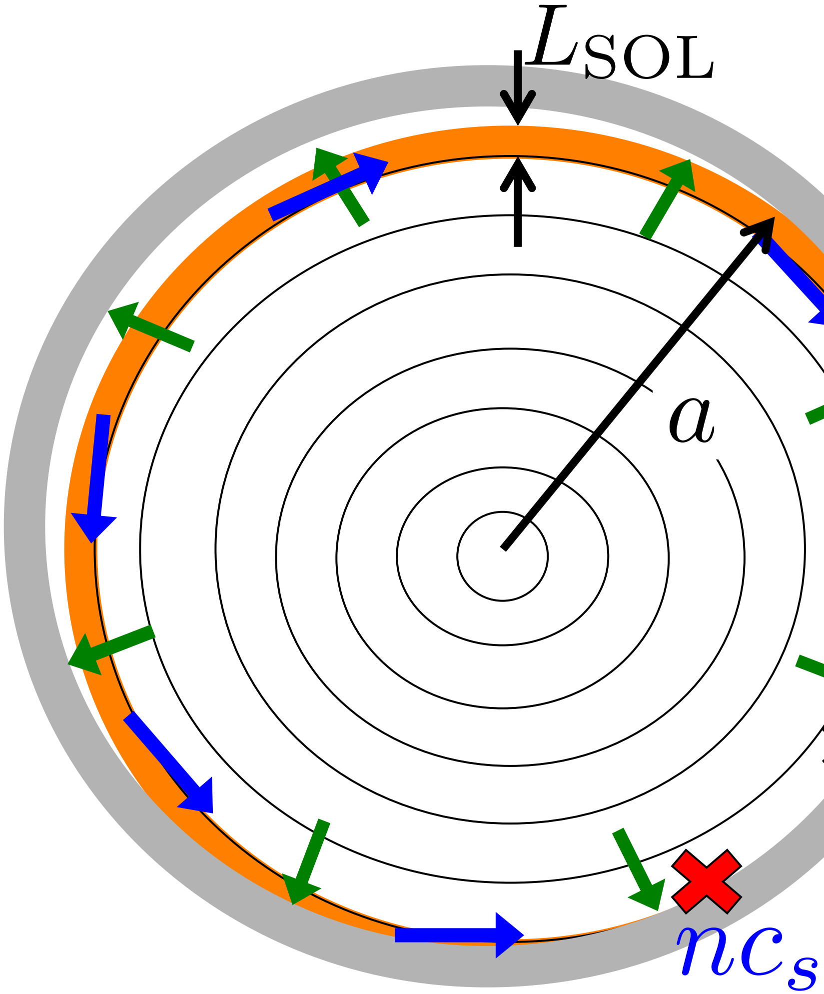




Recycling:
- plasma sink
- source of neutrals

Why the SOL? If we didn't think about it…





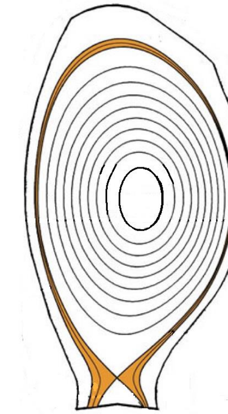
$$\Gamma_r = D\frac{\partial n}{\partial r}$$

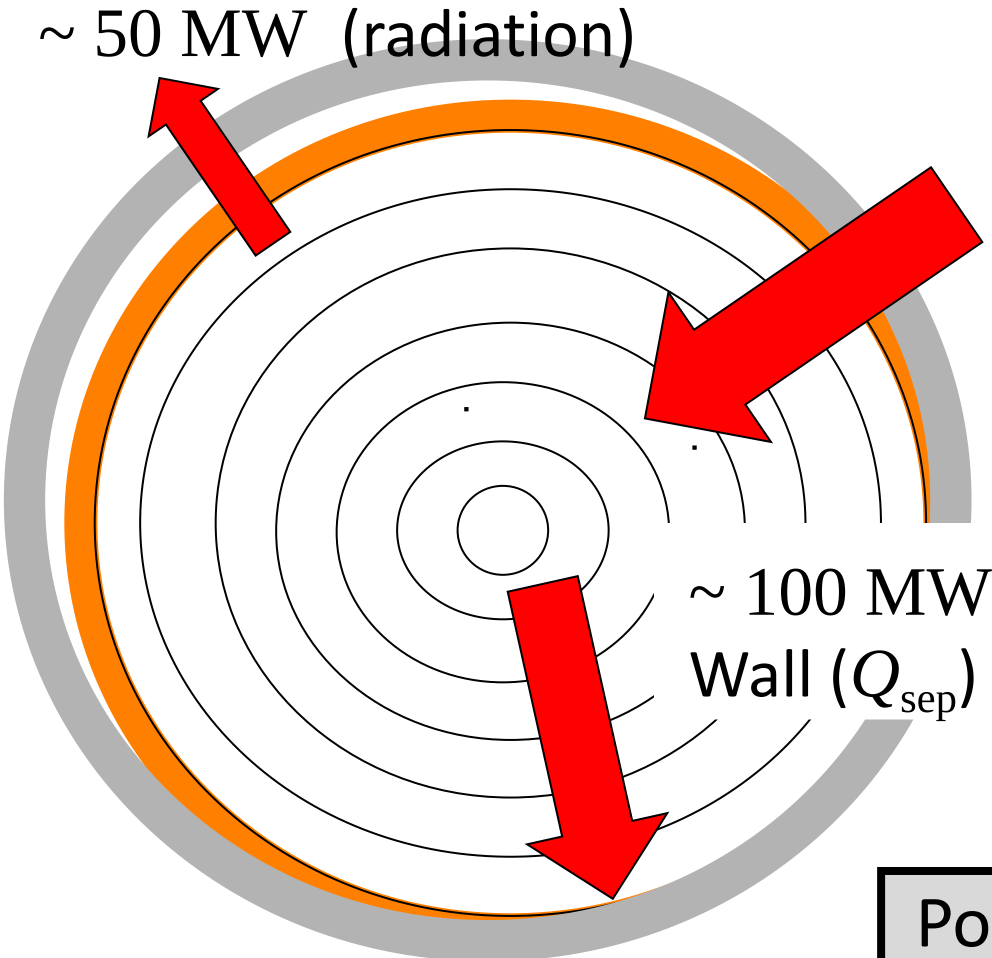
$$2\pi a \Gamma_r \sim 2nc_s L_{\mathrm{SOL}}$$

$$2\pi a D\frac{n}{L_{\mathrm{SOL}}} \sim 2nc_s L_{\mathrm{SOL}}$$

$$L_{\mathrm{SOL}} \sim \sqrt{\frac{\pi a D}{c_s}} \sim 1 \text{ cm}$$

Why the SOL? ITER numbers

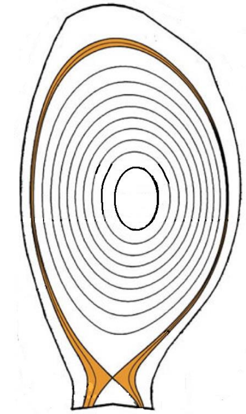




Power flux to the wall:

$$\frac{Q_{\rm sep}}{4\pi R L_{\rm SOL}} > 100\ \mathrm{MW\ m^{-2}}$$

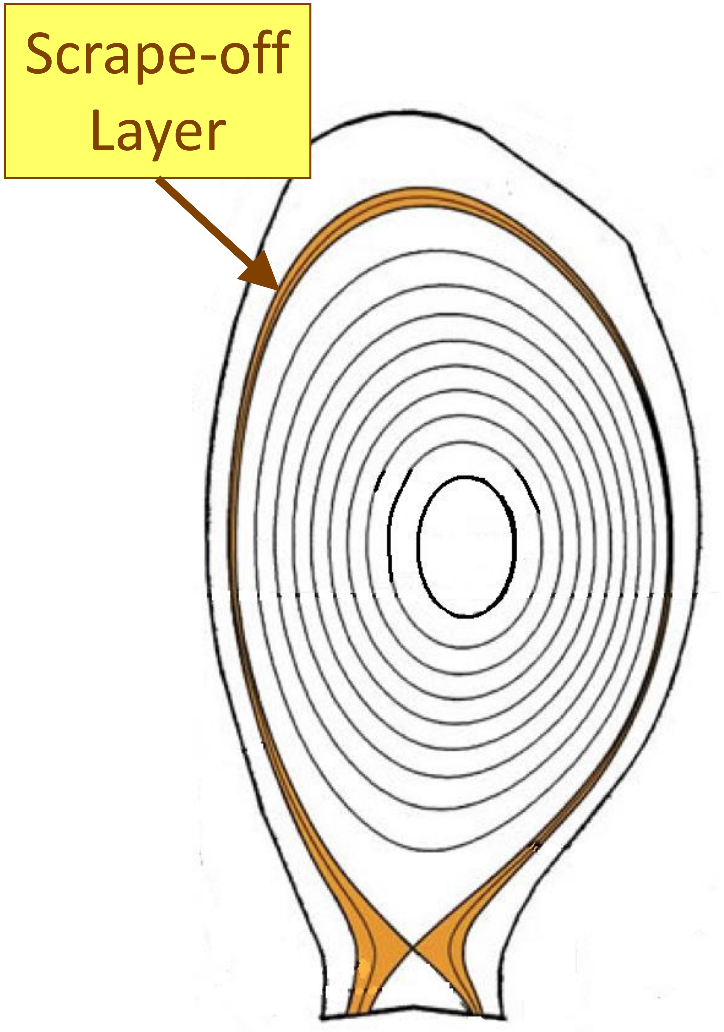
Heat fluxes



$\sim 1 \text{ MW m}^{-2}$

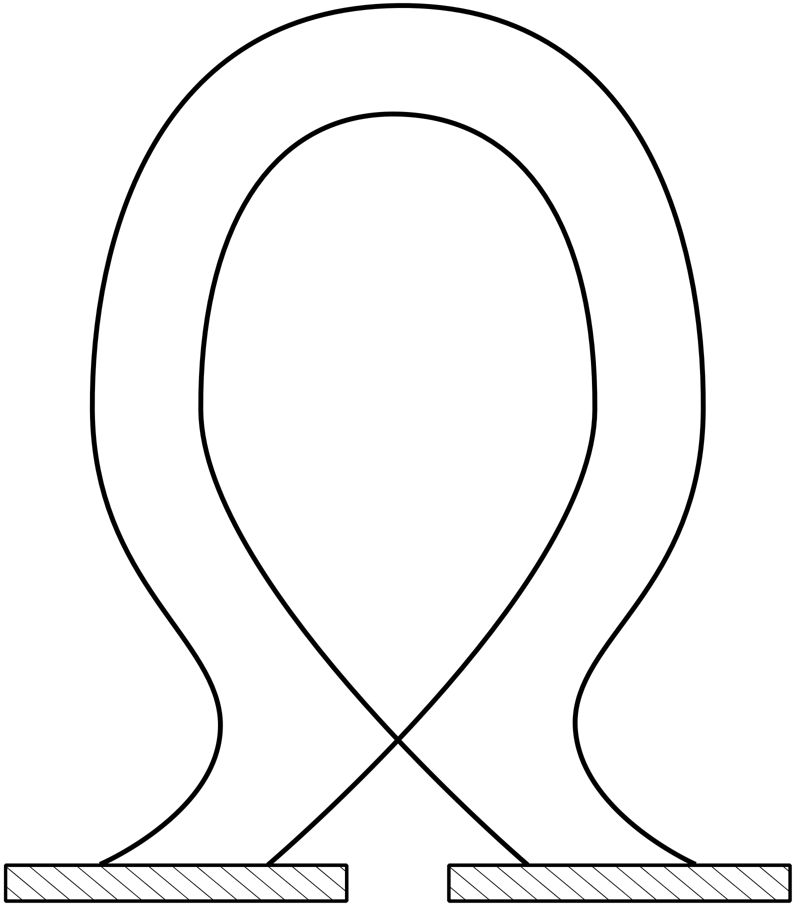
$\sim 80 \text{ MW m}^{-2}$

The roles of the SOL



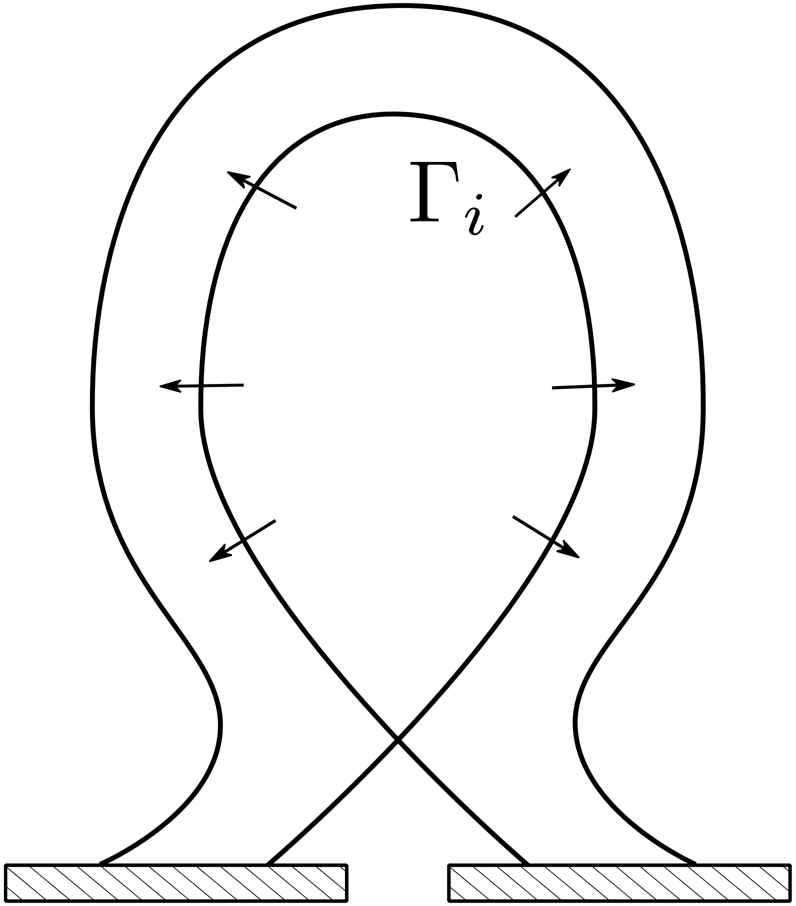
- Heat exhaust
- Plasma confinement
- Plasma fueling
- Regulating neutral density
- Ashes removal (He < 10%)
- Impurity control

Convective, conduction, and detachment regimes



Convective regime

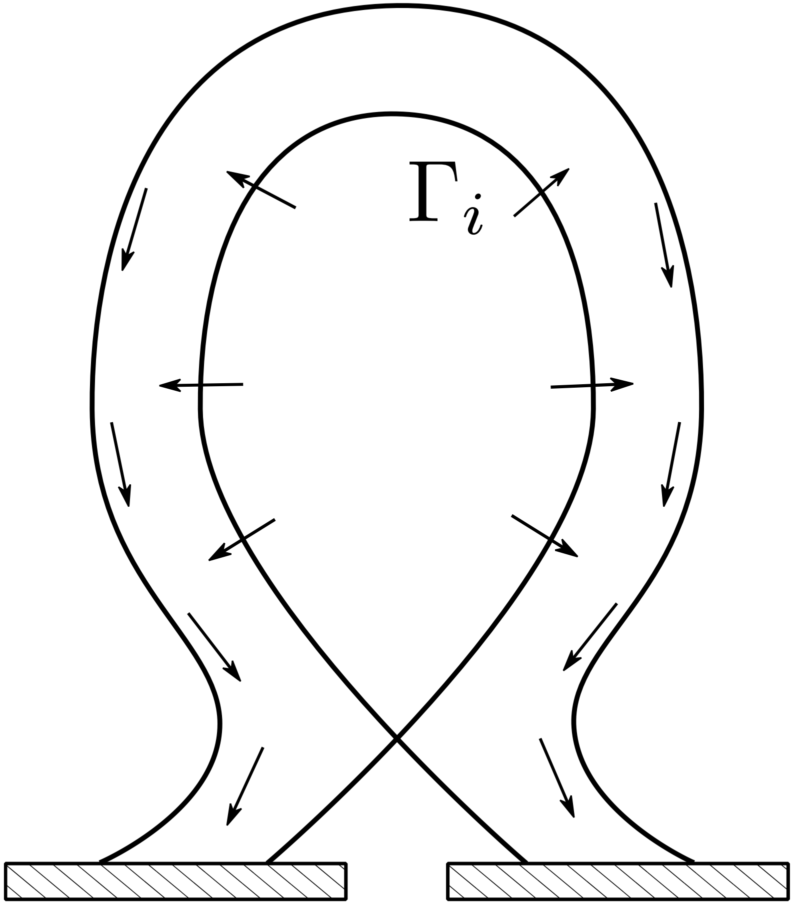
Convective, conduction, and detachment regimes



Convective regime

- Plasma outflowing from core to the SOL

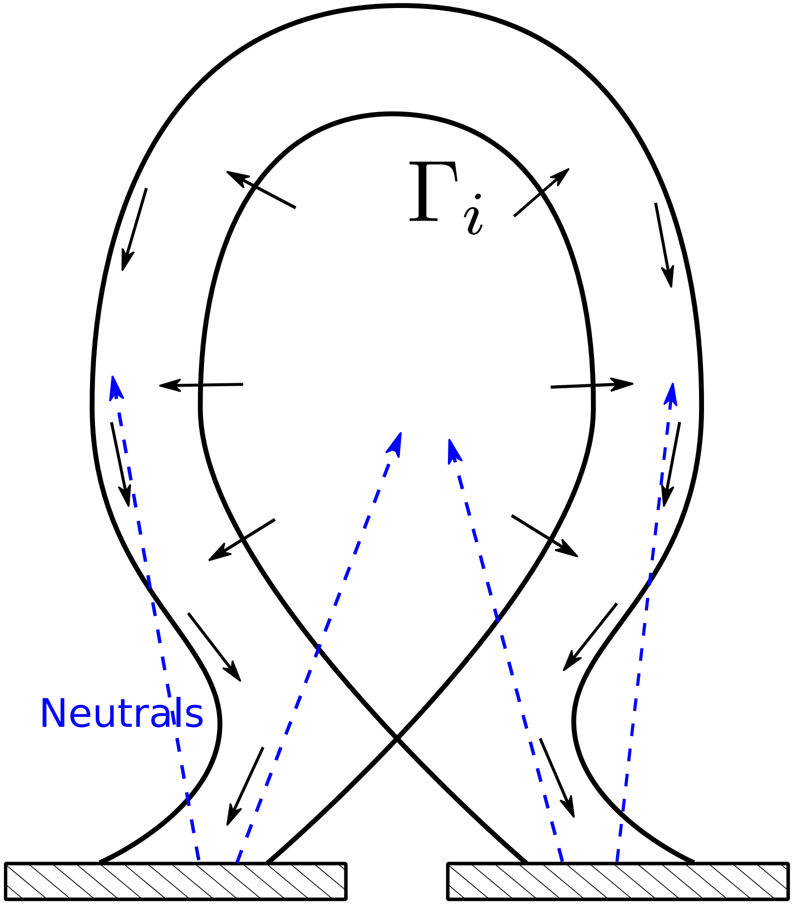
Convective, conduction, and detachment regimes



Convective regime

- Plasma outflowing from core to the SOL
- Flow to the divertor

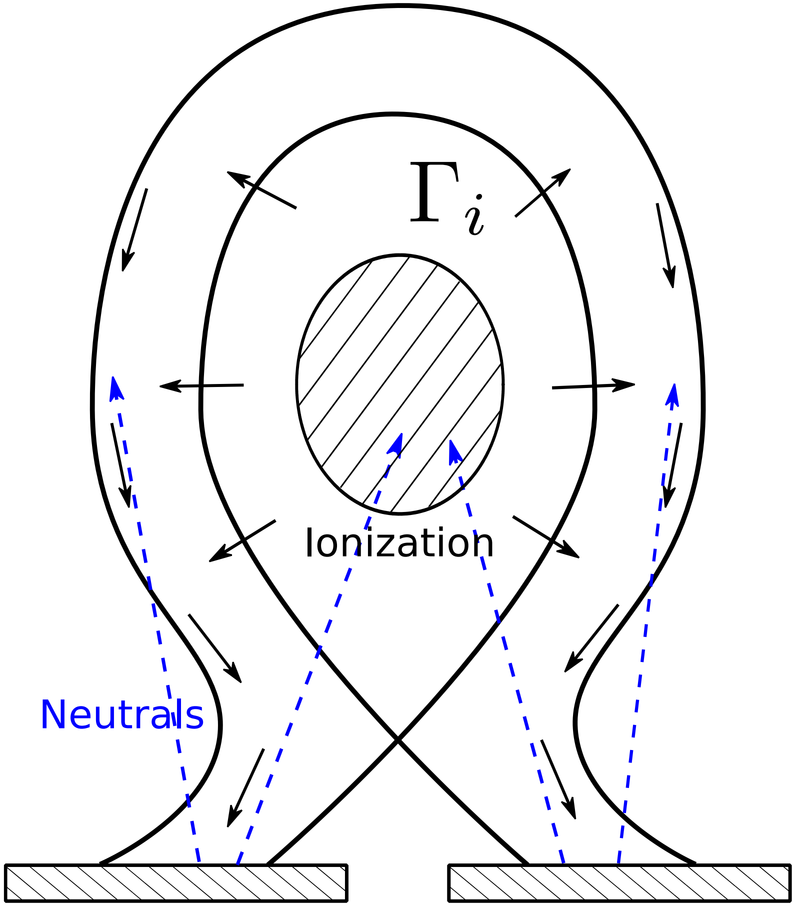
Convective, conduction, and detachment regimes



Convective regime

- Plasma outflowing from core to the SOL
- Flow to the divertor
- Recycling

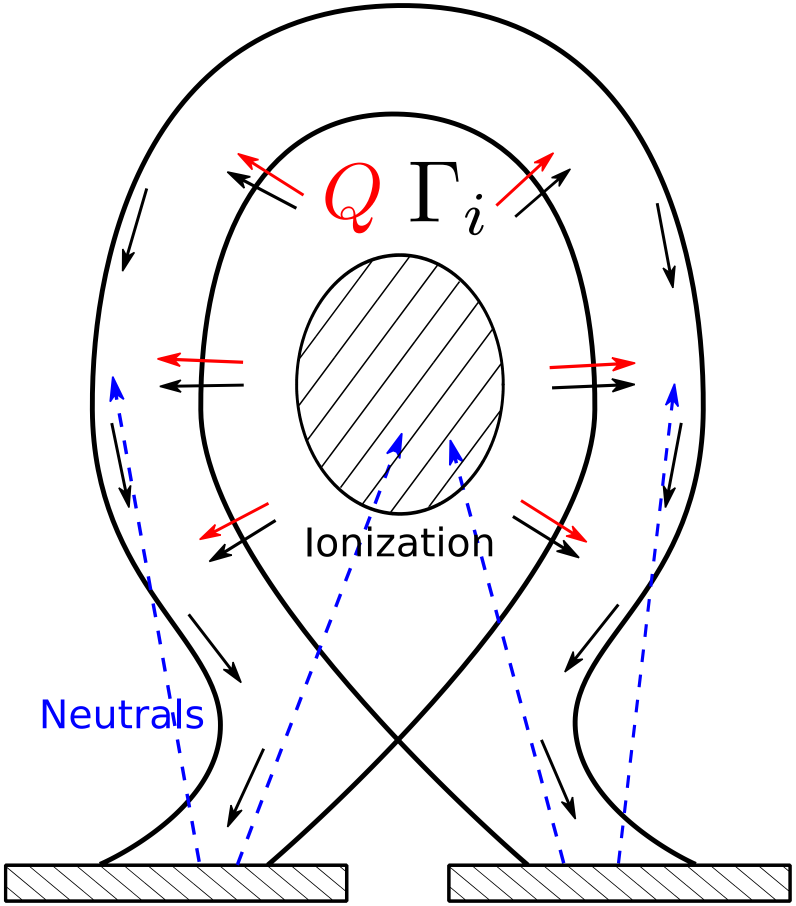
Convective, conduction, and detachment regimes



Convective regime

- Plasma outflowing from core to the SOL
- Flow to the divertor
- Recycling
- **Low density**: Ionization in core

Convective, conduction, and detachment regimes



Convective regime

- Plasma outflowing from core to the SOL
- Flow to the divertor
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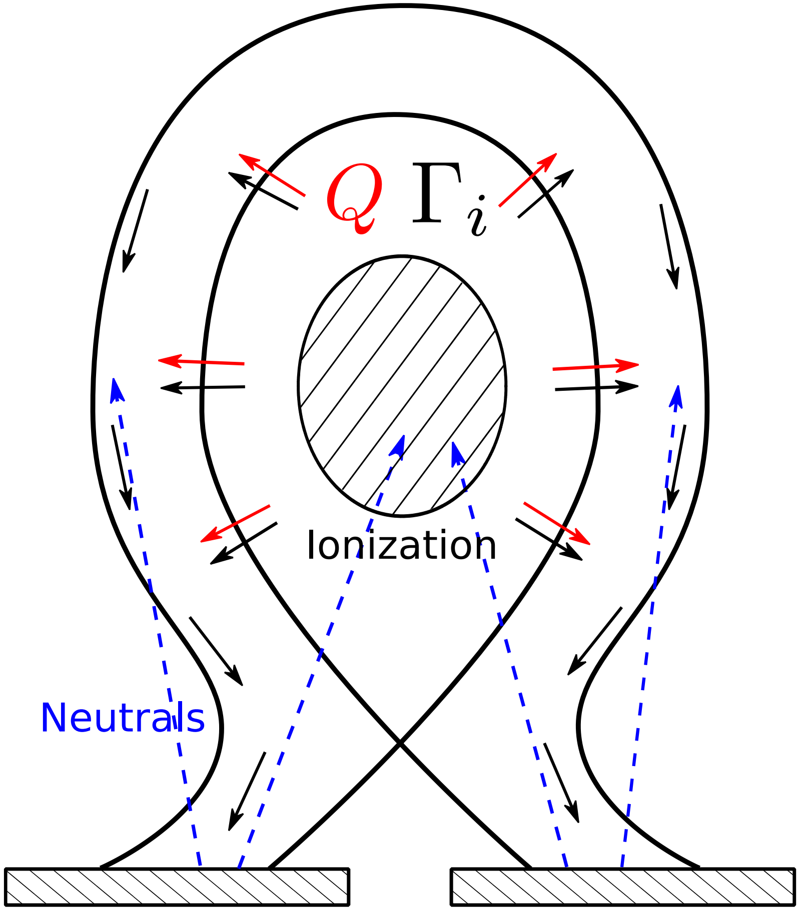
- **Low density**: Ionization in core
- Heat flux from core

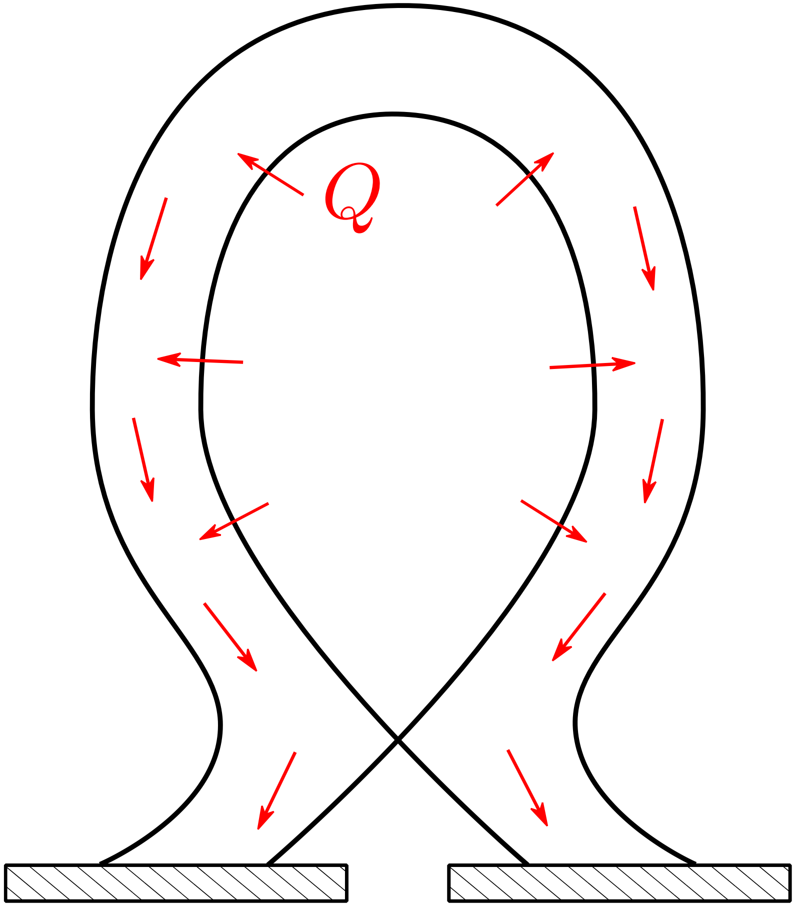
Convective, conduction, and detachment regimes



Convective regime

- Plasma outflowing from core to the SOL
- Flow to the divertor
- Recycling
- **Low density**: Ionization in core
- Heat flux from core
- Mainly convective Q, low temperature gradients

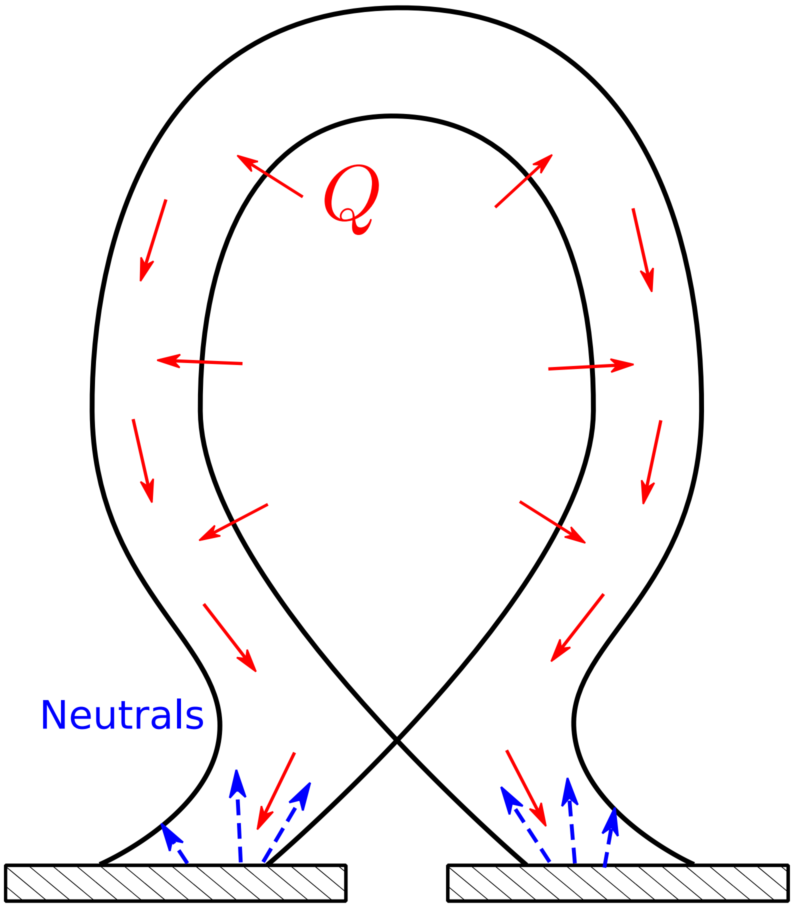
Convective, conduction, and detachment regimes



Conduction regime

- Same heat flux

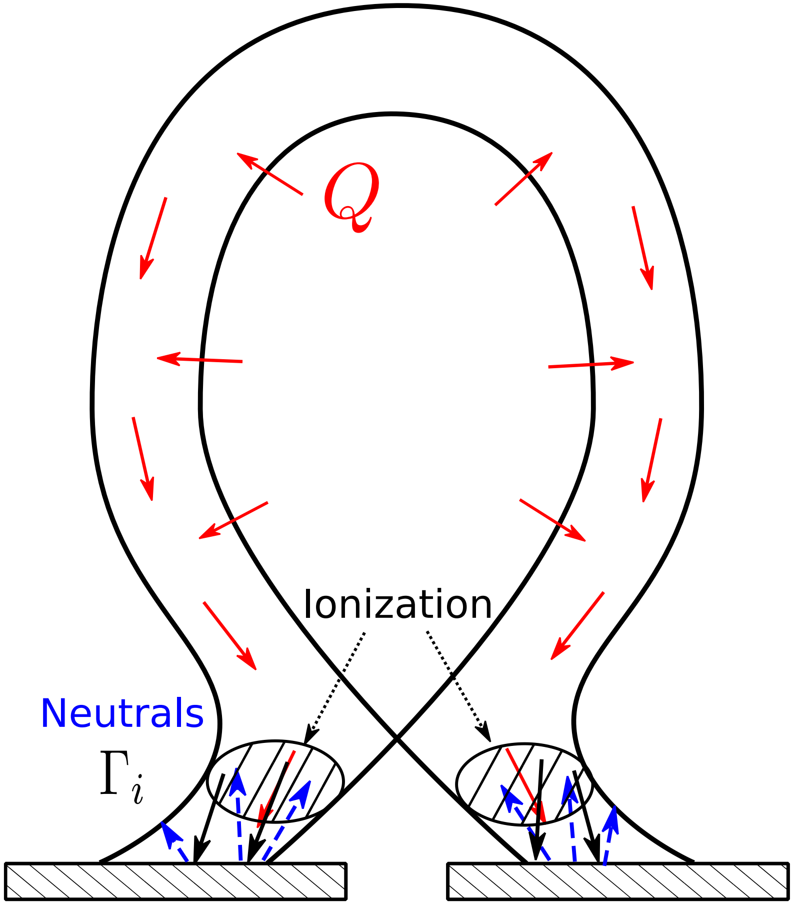
Convective, conduction, and detachment regimes



Conduction regime

- Same heat flux
- **High density**: short ionization mean free path

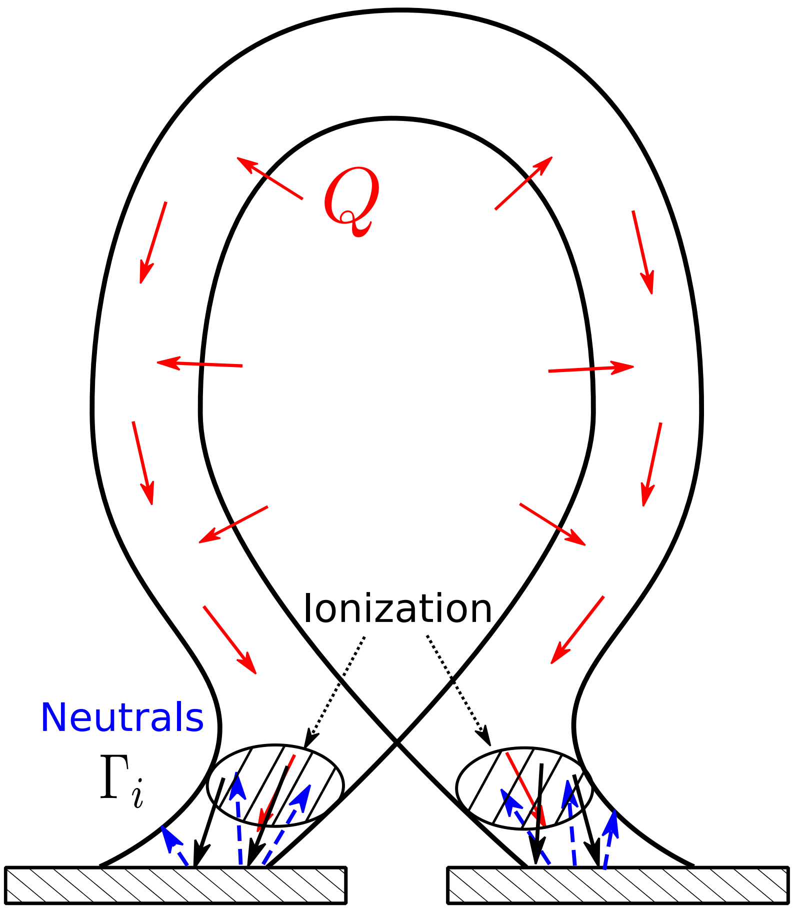
Convective, conduction, and detachment regimes



Conduction regime

- Same heat flux
- **High density**: short ionization mean free path
- Ionization close to target
- Q is mainly conductive
- Temperature gradients may form

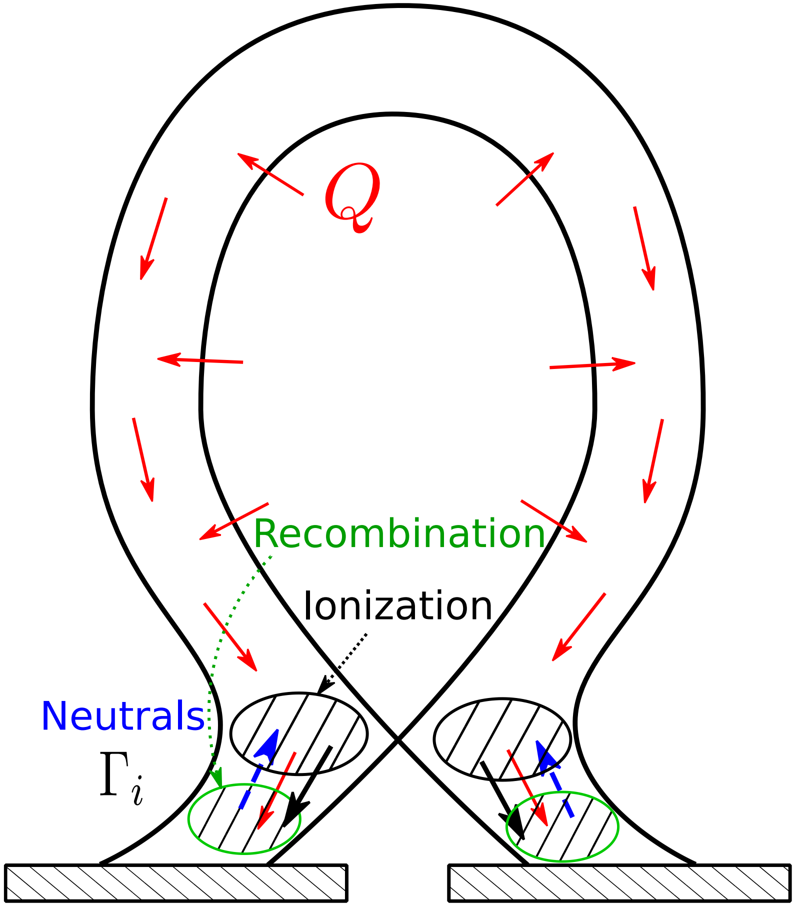
Convective, conduction, and detachment regimes



Conduction regime

- Same heat flux
- **High density**: short ionization mean free path
- Ionization close to target
- Q is mainly conductive
- Temperature gradients may form

Convective, conduction, and detachment regimes



Detachment regime

- **Very High density**
- Low temperature at the divertor
- Volumetric recombination close to the targets
- Ion-neutral friction drag becomes important
- Low energy flux to the target

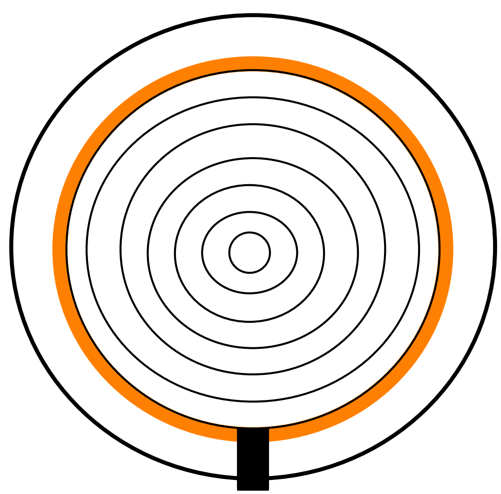
The questions

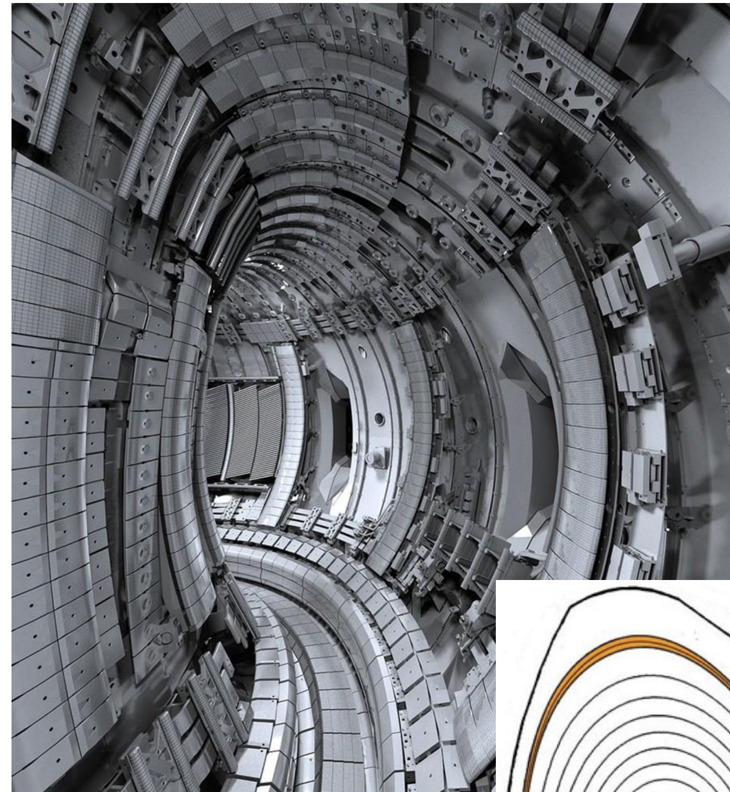
What is the SOL? Its main roles? Its regimes?

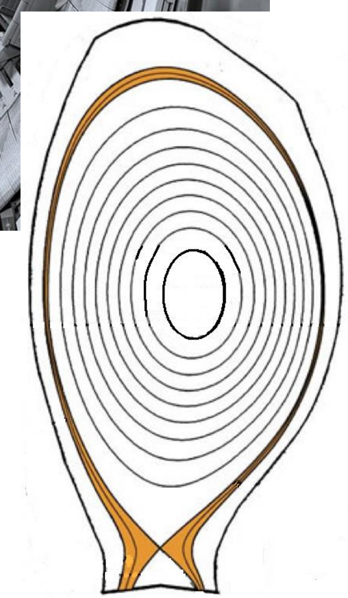
Why a diverted configuration?

How can we simulate the SOL? First-principle kinetic and fluid simulations. Phenomenological approach.

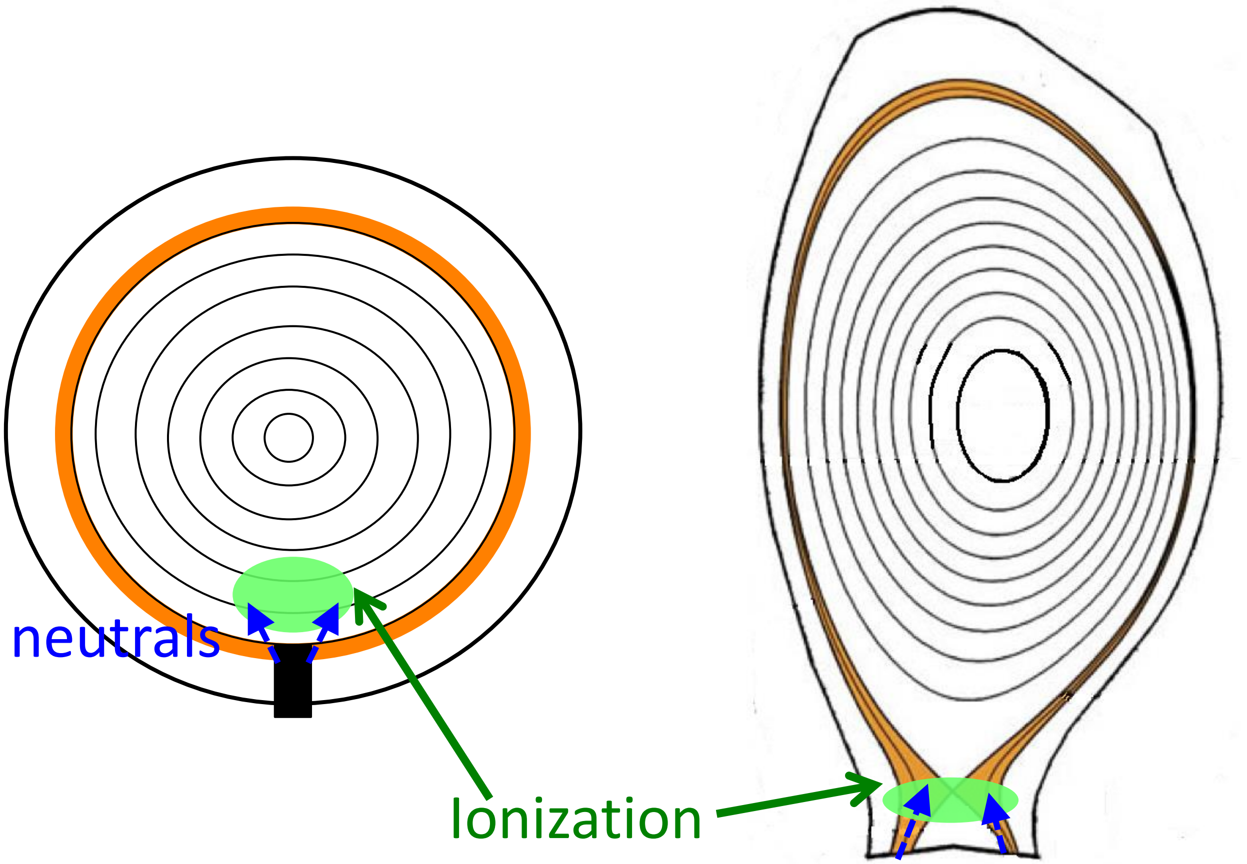
Limited and diverted SOL







Advantages of the diverted configuration



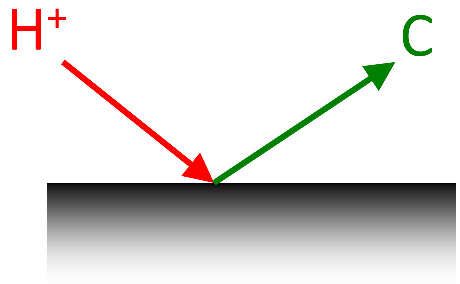
Diverted configuration can lead to reduced plasma convection, heat is conducted, temperature gradients might arise

- Temperature gradient
- Impurity production
- Impurity transport
- Pumping
- Heat exhaust
- Detachment
- Plasma confinement

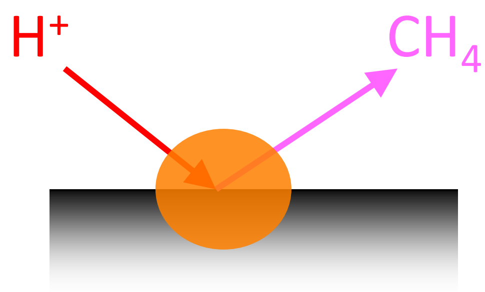
Advantages of the diverted configuration

Impurity production by **ion** impact

- Physical sputtering (energetic ions)



- Chemical sputtering (reduced energy requirement)



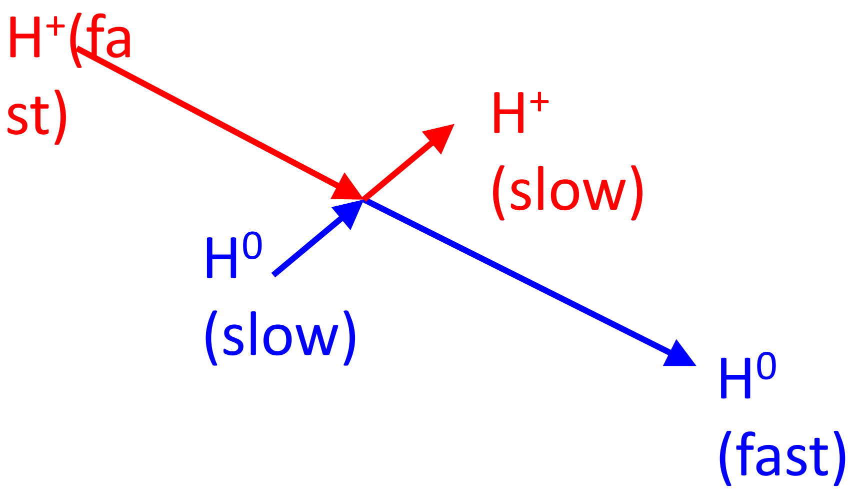
Sputtering yields minimized with plasma temperature: divertor allows low plasma temperature

- Temperature gradient
- **Impurity production**
- Impurity transport
- Pumping
- Heat exhaust
- Detachmen
- Plasma confinement

Advantages of the diverted configuration

Impurity production by **neutral** impact

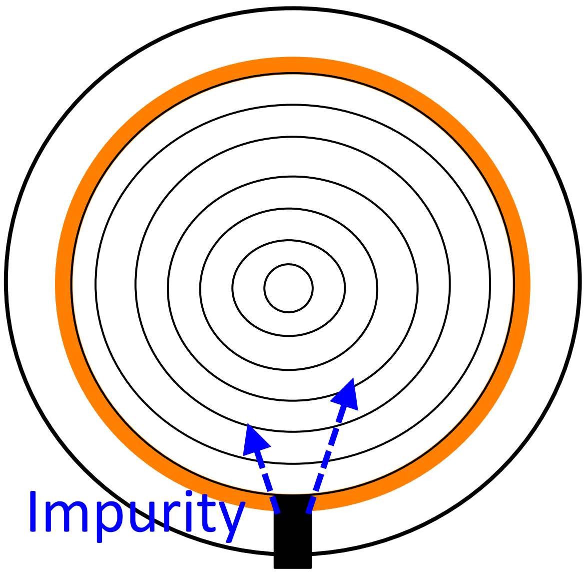
Charge-exchange collisions

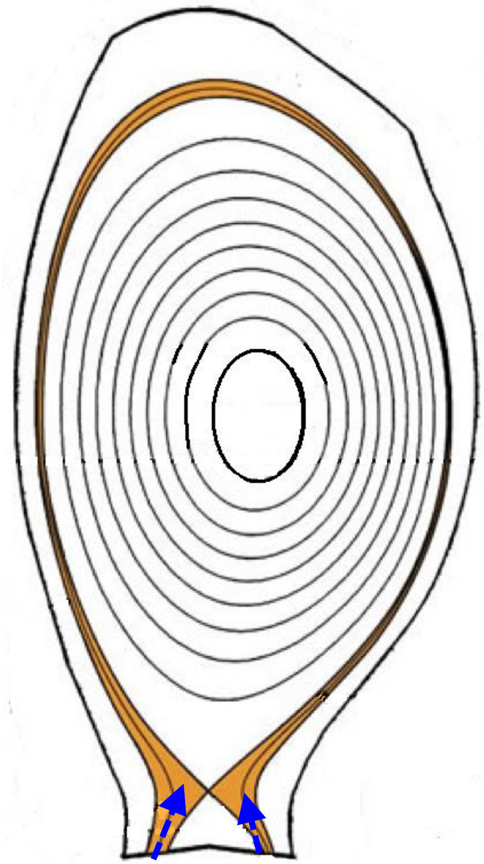


Energetic neutrals might cause sputtering – the yield is reduced with plasma temperature. However, higher recycling rate in diverted configurations

- Temperature gradient
- Impurity production
- Impurity transport
- Pumping
- Heat exhaust
- Detachment
- Plasma confinement

Advantages of the diverted configuration

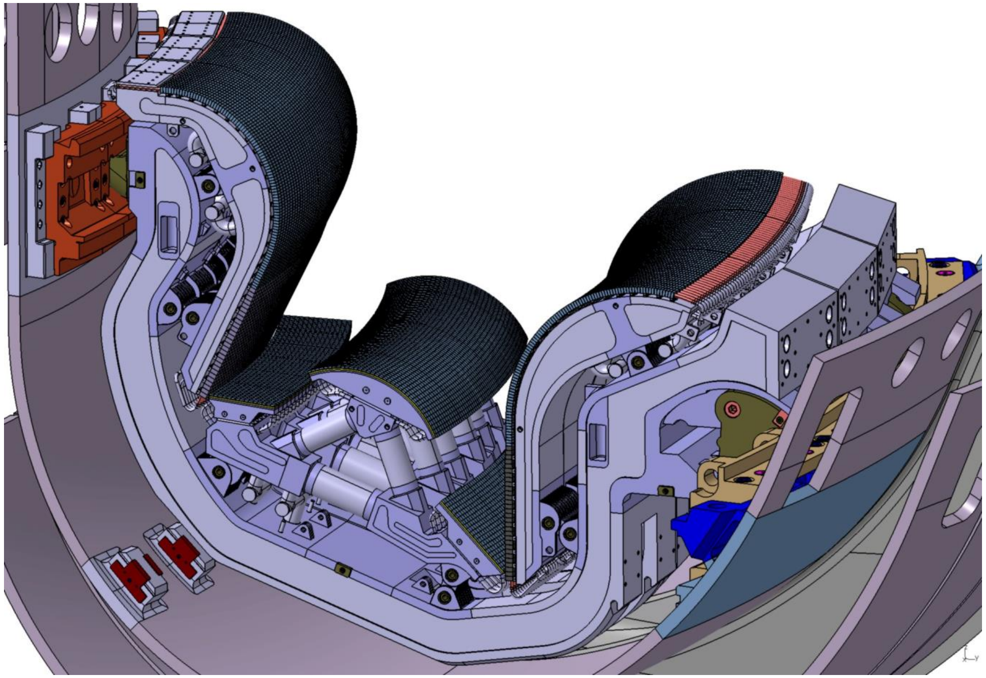




With limiter, impurities are transported more easily to the main plasma, however 100% impurity free plasma is not achieved (sputtering from main vessel)

- Temperature gradient
- Impurity production
- **Impurity transport**
- Pumping
- Heat exhaust
- Detachment
- Plasma confinement

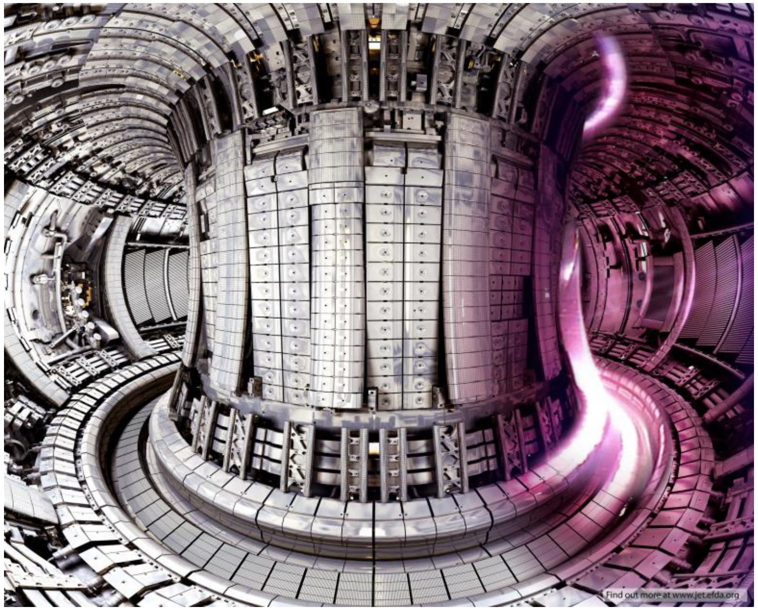
Advantages of the diverted configuration



Divertors allow a higher neutral pressure, improving pumping efficiency. Pumped limiters have to be used in limited configuration

- Temperature gradient
- Impurity production
- Impurity transport
- **Pumping**
- Heat exhaust
- Detachment
- Plasma confinement

Advantages of the diverted configuration

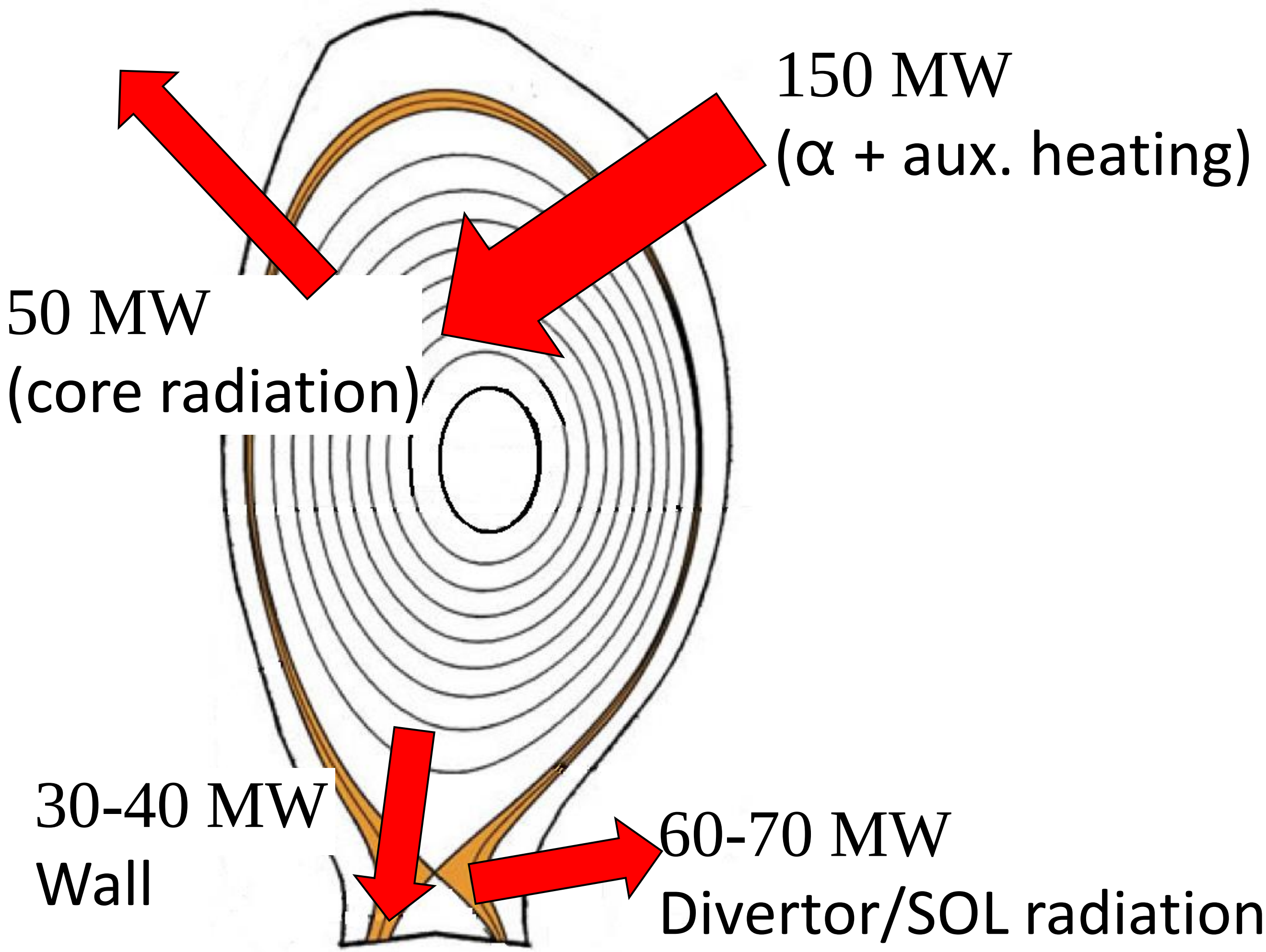


Opportunity of power removal by volumetric loss processes:

- Radiation (from puffed impurities, enhanced radiation at low temperature)
- Charge exchange

- Temperature gradient
- Impurity production
- Impurity transport
- Pumping
- Heat exhaust
- Detachment
- Plasma confinement

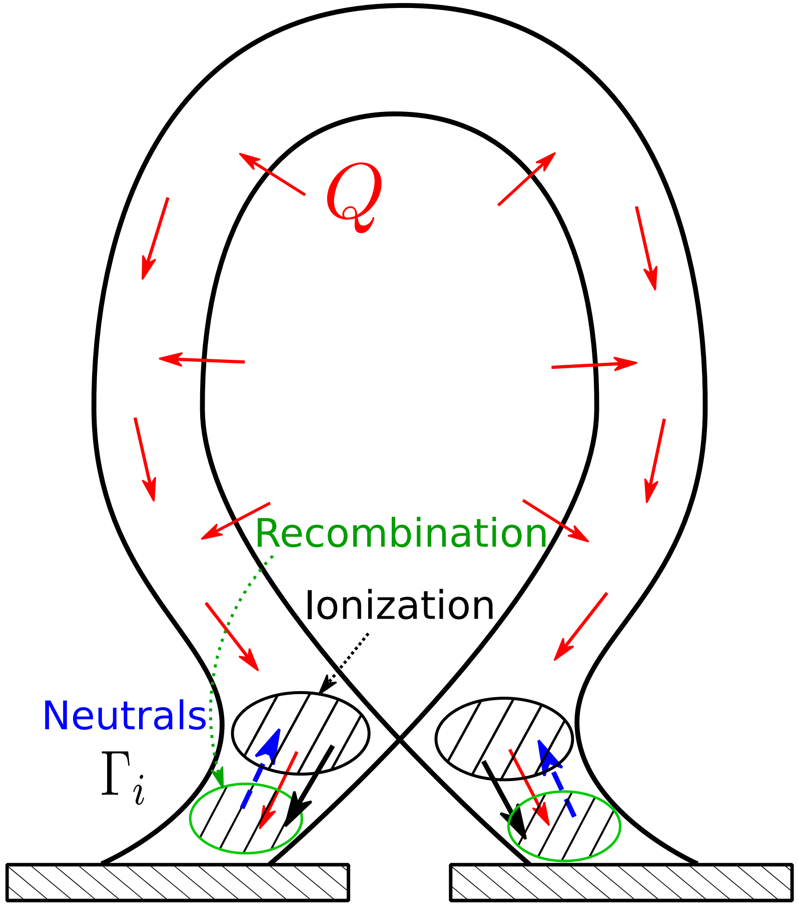
Advantages of the diverted configuration



With 3.5 m^2 wetted area, $P_{wall} < 10$ MW m^{-2}

- Temperature gradient
- Impurity production
- Impurity transport
- Pumping
- **Heat exhaust**
- Detachment
- Plasma confinement

Advantages of the diverted configuration



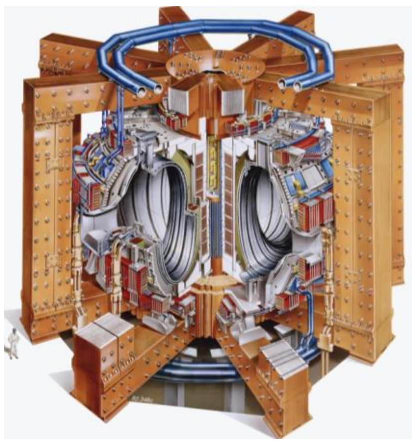
Divertors allow low temperature necessary for detachment; in limited plasmas radiative detachment possible by injecting Ne, but core contamination

- Temperature gradient
- Impurity production
- Impurity transport
- Pumping
- Heat exhaust
- **Detachment**
- Plasma confinement

Advantages of the diverted configuration

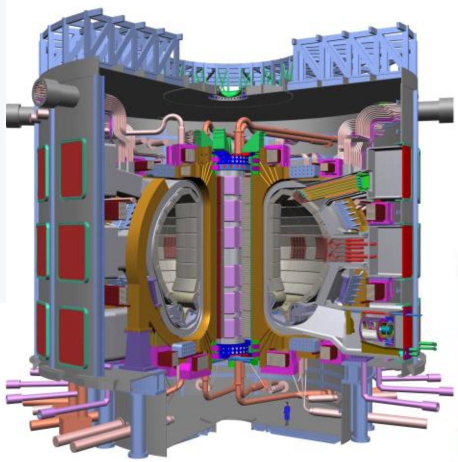
$$P_{\mathrm{wall}} \sim \frac{Q_{\mathrm{sep}}}{A_{\mathrm{wet}}}(1 - f_{\mathrm{rad}}) \sim \frac{Q_{\mathrm{sep}}}{4\pi g R L_p}(1 - f_{\mathrm{rad}}) \leq 10\ \mathrm{MW\ m^{-2}}$$

JET



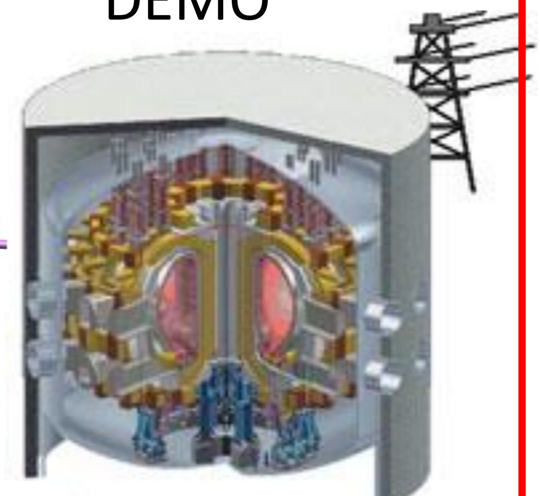
$$\frac{Q_{\mathrm{sep}}}{R} = 7$$

ITER



$$\frac{Q_{\mathrm{sep}}}{R} = 20$$

DEMO



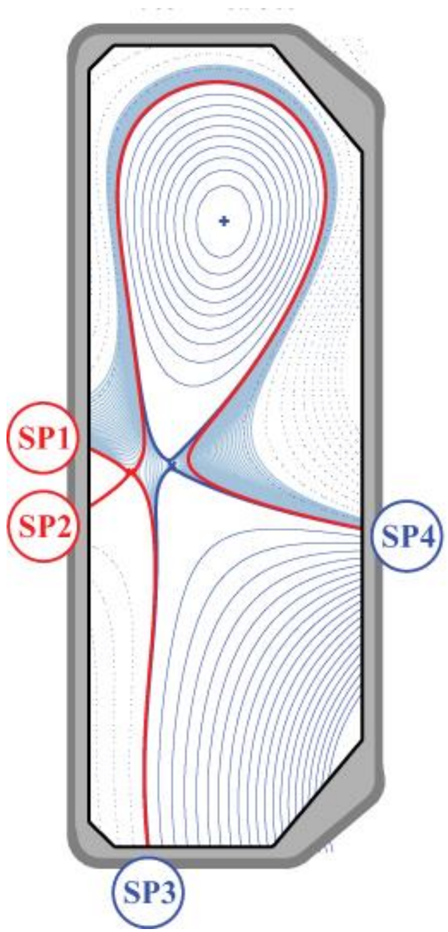
$$\frac{Q_{\mathrm{sep}}}{R} = 80 - 100$$

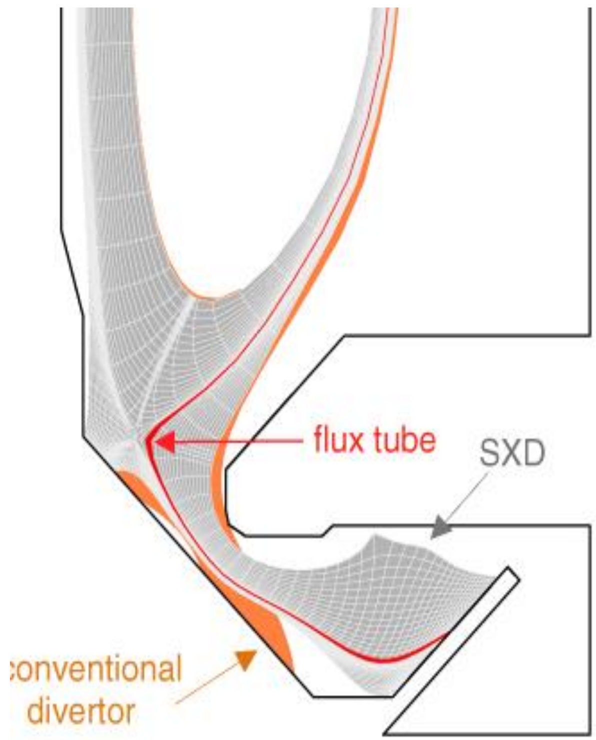
Fusion reactor will probably be operated in detachment conditions

- Temperature gradient
- Impurity production
- Impurity transport
- Pumping
- Heat exhaust
- **Detachment**
- Plasma confinement

Advantages of the diverted configuration

More advanced SOL configurations might be needed for DEMO…

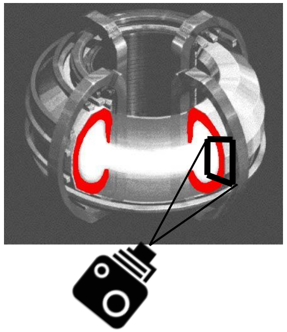




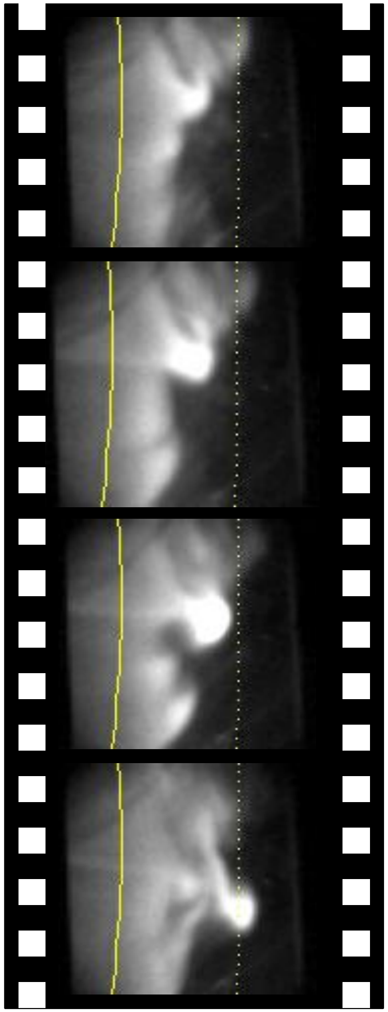
snowflake, super-X divertor…

- Temperature gradient
- Impurity production
- Impurity transport
- Pumping
- Heat exhaust
- **Detachment**
- Plasma confinement

Advantages of the diverted configuration



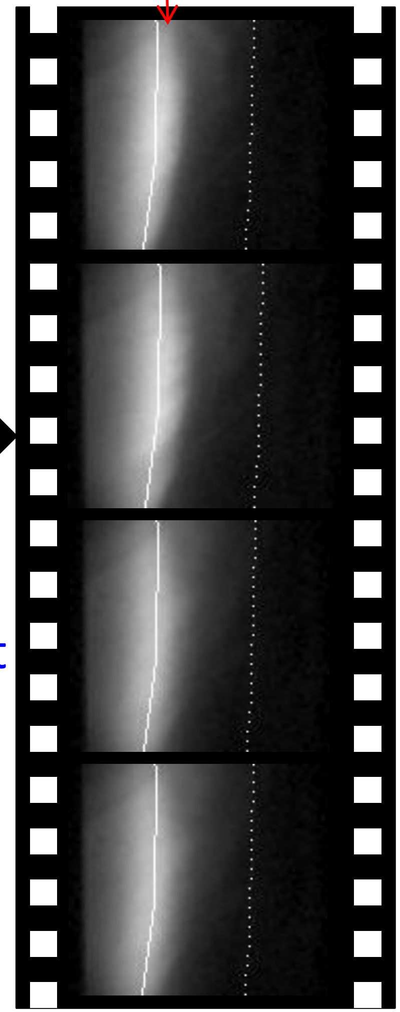
Transport barrier



Heat source increases

Turbulence decreases

Confinement improves



- Temperature gradient
- Impurity production
- Impurity transport
- Pumping
- Heat exhaust
- Detachment
- **Plasma confinement**

H mode is achieved more easily in diverted plasmas

The questions

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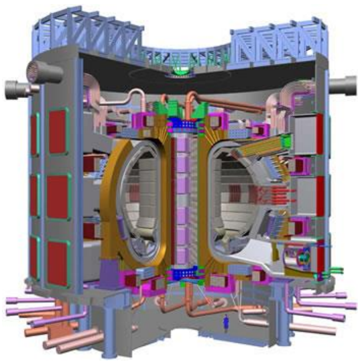
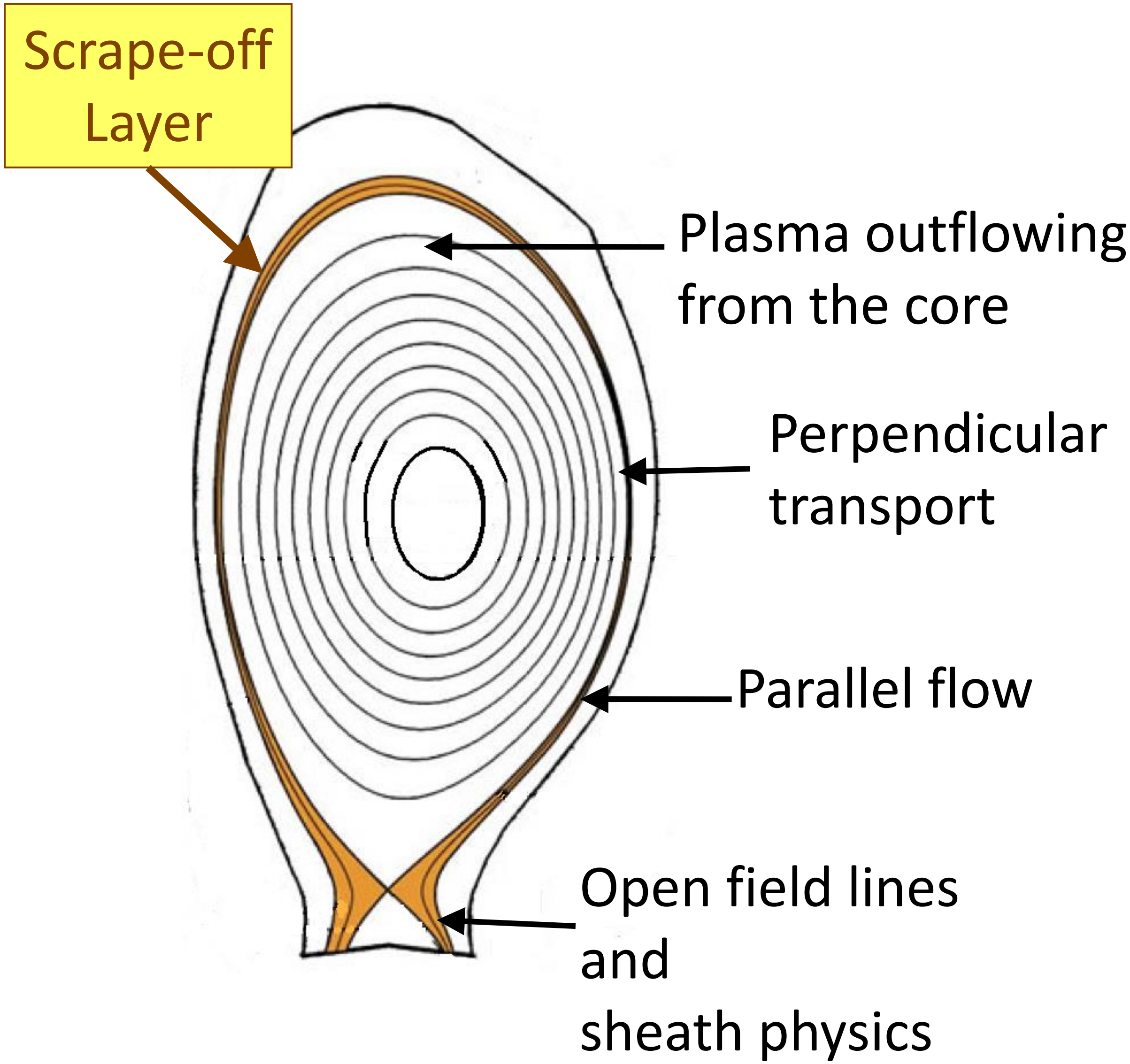
Why a diverted configuration?

How can we simulate the SOL? First-principle kinetic and fluid simulations. Phenomenological approach.

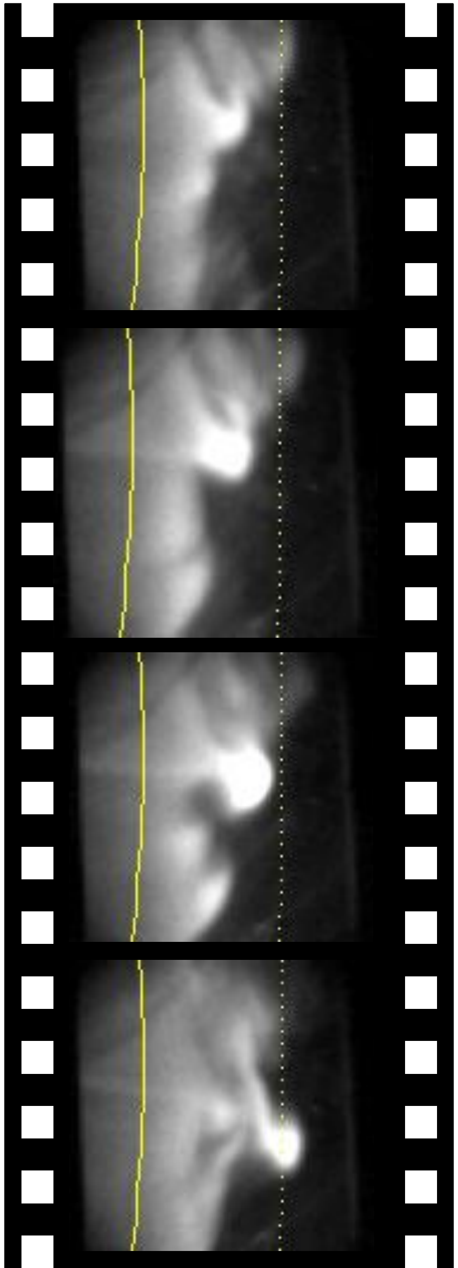
Simulating the SOL

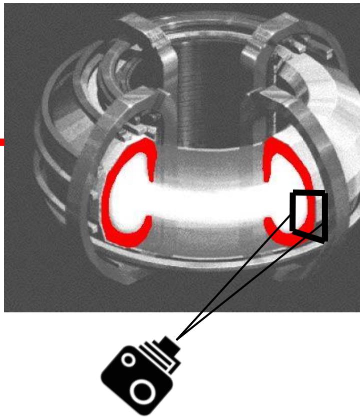




- Turbulent perpendicular transport
- Parallel transport
- Wall interaction
- Neutrals
- Impurities
- Radiation

Properties of SOL turbulence





Courtesy of R. Maqueda

$$L_{fluc} \sim L_{eq}$$

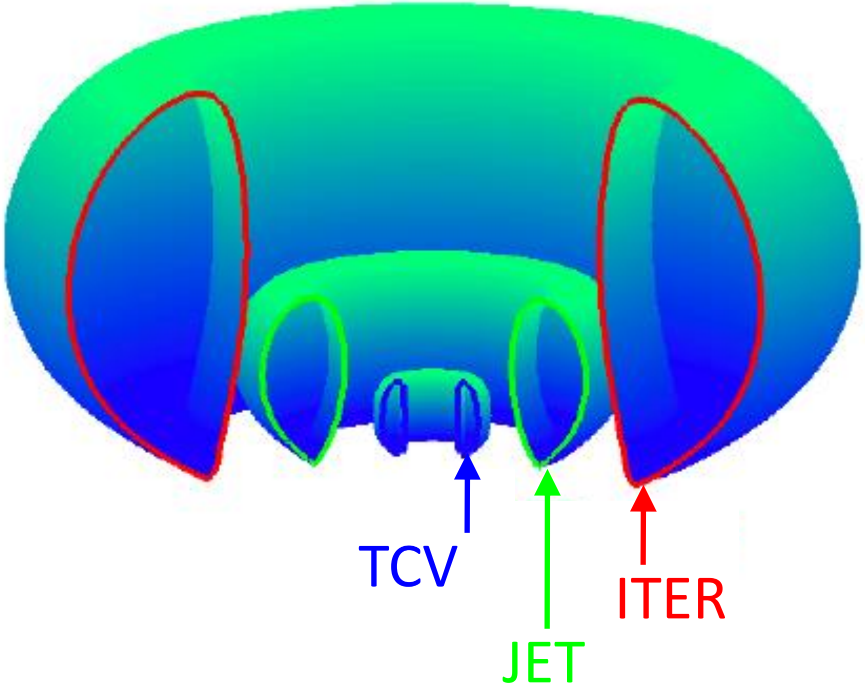
$$n_{fluc} \sim n_{eq}$$

Collisional plasma (but not always)

Nonlinear phenomena

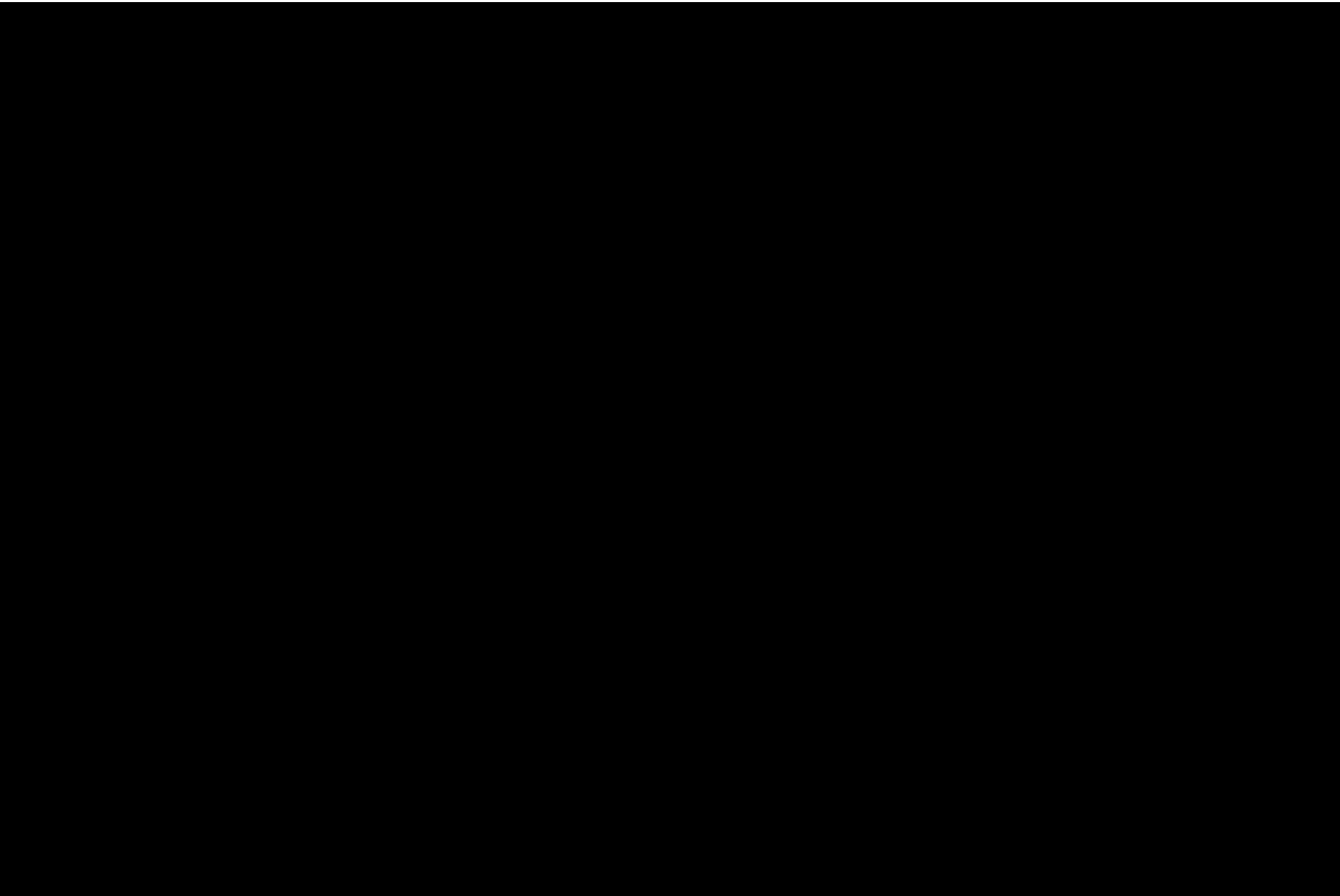
ITER design based on scaling law

Basic physics understanding is still missing



Simulations of SOL dynamics are crucial

A fairly complete SOL model 1/2



A fairly complete SOL model 1/2

$$\frac{\partial f_n(\mathbf{x},\mathbf{v}_n,t)}{\partial t} + \mathbf{v}_n \cdot \frac{\partial f_n(\mathbf{x},\mathbf{v}_n,t)}{\partial \mathbf{x}} = -f_n(\mathbf{x},\mathbf{v}_n,t)\int \sigma_{ion}(v_e) v_e f_e(\mathbf{x},\mathbf{v}_e,t) d\mathbf{v}_e$$

$$-\int \sigma_{CX}(\mathbf{v}_n - \mathbf{v}_i)\left|\mathbf{v}_n - \mathbf{v}_i\right|\left[f_n(\mathbf{x},\mathbf{v}_n,t) f_i(\mathbf{x},\mathbf{v}_i,t) - f_i(\mathbf{x},\mathbf{v}_n,t) f_n(\mathbf{x},\mathbf{v}_i,t)\right] d\mathbf{v}_i$$

1 neutral species

$$+f_i(\mathbf{x},\mathbf{v}_n,t)\int \sigma_{rec}(v_e) v_e f_e(\mathbf{x},\mathbf{v}_e,t) d\mathbf{v}_e$$

$$\frac{\partial f_i(\mathbf{x},\mathbf{v}_i,t)}{\partial t} + \mathbf{v}_i \cdot \frac{\partial f_i(\mathbf{x},\mathbf{v}_i,t)}{\partial \mathbf{x}} + \frac{q_i}{m_i}\left(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}\right) \cdot \frac{\partial f_i(\mathbf{x},\mathbf{v}_i,t)}{\partial \mathbf{v}_i} =$$

$$C(f_i,f_i) + C(f_e,f_i) + f_n(\mathbf{x},\mathbf{v}_i,t)\int \sigma_{ion}(v_e) v_e f_e(\mathbf{x},\mathbf{v}_e,t) d\mathbf{v}_e$$

$$-\int \sigma_{CX}(\mathbf{v}_n - \mathbf{v}_i)\left|\mathbf{v}_n - \mathbf{v}_i\right|\left[f_i(\mathbf{x},\mathbf{v}_i,t) f_n(\mathbf{x},\mathbf{v}_n,t) - f_n(\mathbf{x},\mathbf{v}_i,t) f_i(\mathbf{x},\mathbf{v}_n,t)\right] d\mathbf{v}_n$$

$$-f_i(\mathbf{x},\mathbf{v}_i,t)\int \sigma_{rec}(v_e) v_e f_e(\mathbf{x},\mathbf{v}_e,t) d\mathbf{v}_e$$

Ion

$$\frac{\partial f_e(\mathbf{x},\mathbf{v}_e,t)}{\partial t} + \mathbf{v}_e \cdot \frac{\partial f_e(\mathbf{x},\mathbf{v}_e,t)}{\partial \mathbf{x}} + \frac{q_e}{m_e}\left(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}\right) \cdot \frac{\partial f_e(\mathbf{x},\mathbf{v}_e,t)}{\partial \mathbf{v}_e} =$$

$$C(f_e,f_e) + C(f_e,f_i) - n_n \sigma_{ion}(v_e) v_e f_e(\mathbf{x},\mathbf{v}_e,t)$$

$$+2n_n \int \sigma_{ion}(v_e') \Phi_{ion}(\mathbf{v}_e', \mathbf{v}_e) v_e' f_e(\mathbf{x},\mathbf{v}_e',t) d\mathbf{v}_e' - n_i \sigma_{rec}(v_e) v_e f_e(\mathbf{x},\mathbf{v}_e,t)$$

$$-n_n \sigma_{el}(v_e) v_e f_e(\mathbf{x},\mathbf{v}_e,t) + \frac{1}{4\pi} n_n \int \sigma_{el}(v_e) v_e f_e(\mathbf{x},\mathbf{v}_e,t) d\mathbf{\Omega}$$

Electrons

A fairly complete SOL model 2/2

+ Maxwell equations
+ Boundary conditions

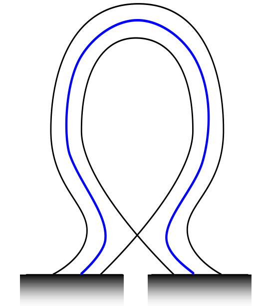
$$f_i(\mathbf{x}_w, \mathbf{v}_\perp < 0, t) = 0$$

$$f_e(\mathbf{x}_w, \mathbf{v}_\perp < 0, t) = 0$$

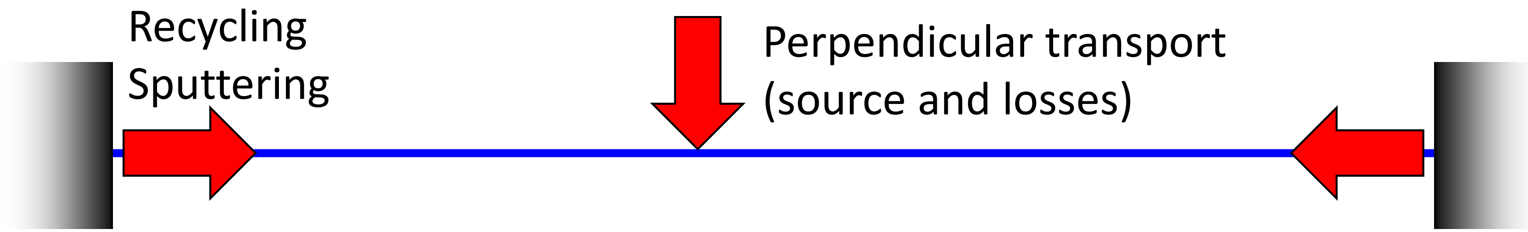
$$f_n(\mathbf{x}_w, \mathbf{v}_\perp < 0, t) \propto \cos(\theta) \exp[-mv^2/2T_w]$$

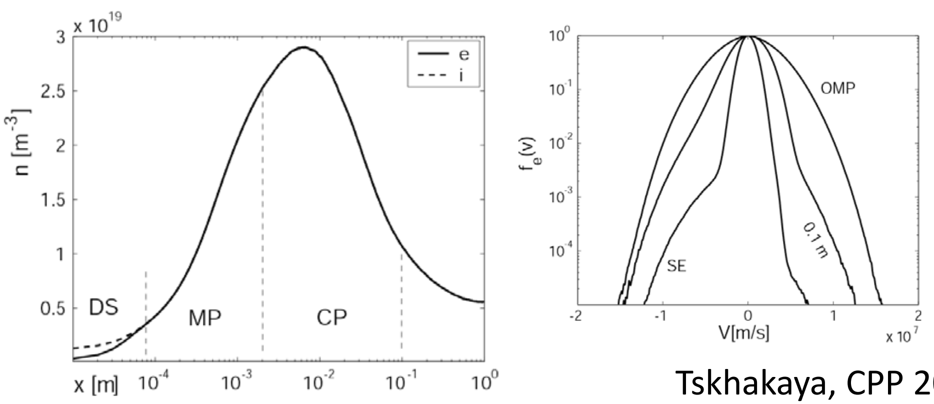
- Equation for neutrals: linear, easy to solve, once plasma profile is known (EIRENE [De], DEGAS [US], …)
- Plasma equations: nonlinear, complex to solve

1D Kinetic SOL simulations



Carried out with massive PIC codes, with multiple plasma and neutral species





Tskhakaya, CPP 2012

Results: electron, ion and neutral distribution functions

Useful to evaluate parallel transport coefficients, to understand the key processes in the SOL

Fluid modeling

Typically (but not always) in the SOL: $\lambda_{\mathrm{mfp}} \ll L,\ \tau_{\mathrm{coll}}\omega_{ci} \gg 1$

→ Kinetic equations can be integrated, fluid equations can be found, with closure provided by Braginskii (1965)

Fluid modeling

Typically (but not always) in the SOL: $\lambda_{\mathrm{mfp}} \ll L, \;\; \tau_{\mathrm{coll}}\omega_{ci} \gg 1$

➡ Kinetic equations can be integrated, fluid equations can be found, with closure provided by Braginskii (1965)

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \mathbf{v}_\alpha) = S_n$$

$$m_\alpha n \left(\frac{\partial}{\partial t} + \mathbf{v}_\alpha \cdot \nabla \right) \mathbf{v}_\alpha = -\nabla p_\alpha + q_\alpha n \left(\mathbf{E} + \frac{1}{c} \mathbf{v}_{\perp\alpha} \times \mathbf{B} \right) - \nabla \cdot \underline{\underline{\pi_\alpha}} + \mathbf{R}_\alpha$$

...

Typically considered in low density (no neutral interaction)

Too expensive to perform 3D SOL simulations!

Drift-reduced Braginskii equations 1/3

SOL turbulence is low frequency and long scale length: $\frac{\partial}{\partial t} \ll \omega_{ci},\ k_\perp \rho < 1$

$$\left\{ m_\alpha n \left(\frac{\partial}{\partial t} + \mathbf{v}_\alpha \cdot \nabla \right) \mathbf{v}_\alpha = -\nabla p_\alpha + q_\alpha n \left(\mathbf{E} + \frac{1}{c} \mathbf{v}_{\perp\alpha} \times \mathbf{B} \right) - \nabla \cdot \underline{\underline{\pi_\alpha}} + \mathbf{R}_\alpha \right\} \times \mathbf{B}$$

$$\mathbf{v}_{\perp\alpha} \times \mathbf{B} \times \mathbf{B} = -B^2 \mathbf{v}_{\perp\alpha}$$

$$\mathbf{v}_{E\times B} = \frac{c\mathbf{E} \times \mathbf{B}}{B^2}$$

$$\mathbf{v}_{d\alpha} = \frac{c\mathbf{B} \times \nabla p_\alpha}{q_\alpha n B^2}$$

$$\mathbf{v}_{\mathrm{pol},\alpha} = \frac{\mathbf{b}}{\omega_{c\alpha}} \times \frac{\partial \mathbf{v}_{\perp\alpha}}{\partial t} + \ldots \ll \mathbf{v}_{E\times B}, \mathbf{v}_{d\alpha}$$

$$\longrightarrow \quad \mathbf{v}_{\mathrm{pol},\alpha} \simeq \frac{\mathbf{b}}{\omega_{c\alpha}} \times \frac{\partial(\mathbf{v}_{E\times B} + \mathbf{v}_{d\alpha})}{\partial t} + \ldots$$

Drift-reduced Braginskii equations 2/3

SOL turbulence is low frequency and long scale length: $\frac{\partial}{\partial t} \ll \omega_{ci},\ k_\perp \rho < 1$

$$\left\{ m_\alpha n \left(\frac{\partial}{\partial t} + \mathbf{v}_\alpha \cdot \nabla \right) \mathbf{v}_\alpha = -\nabla p_\alpha + q_\alpha n \left(\mathbf{E} + \frac{1}{c} \mathbf{v}_{\perp\alpha} \times \mathbf{B} \right) - \nabla \cdot \underline{\underline{\pi_\alpha}} + \mathbf{R}_\alpha \right\} \times \mathbf{B}$$

$$\mathbf{v}_{\perp\alpha} \times \mathbf{B} \times \mathbf{B} = -B^2 \mathbf{v}_{\perp\alpha}$$

$$\mathbf{v}_{E\times B} = c\mathbf{E} \ldots$$

$$\mathbf{v}_\alpha = v_{\parallel\alpha} \mathbf{b} + \mathbf{v}_{E\times B} + \mathbf{v}_{d\alpha} + \mathbf{v}_{\mathrm{pol},\alpha}$$

$$\mathbf{v}_{d\alpha} = \frac{c\mathbf{B} \times \nabla p_\alpha}{q_\alpha n B^2}$$

$$\mathbf{v}_{\mathrm{pol},\alpha} = \frac{\mathbf{b}}{\omega_{c\alpha}} \times \frac{\partial \mathbf{v}_{\perp\alpha}}{\partial t} + \ldots \ll \mathbf{v}_{E\times B}, \mathbf{v}_{d\alpha}$$

$$\longrightarrow \quad \mathbf{v}_{\mathrm{pol},\alpha} \simeq \frac{\mathbf{b}}{\omega_{c\alpha}} \times \frac{\partial (\mathbf{v}_{E\times B} + \mathbf{v}_{d\alpha})}{\partial t} + \ldots$$

Drift-reduced Braginskii equations 3/3

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot [n_\alpha (v_{\|\alpha} \mathbf{b} + \mathbf{v}_{E\times B} + \mathbf{v}_{d\alpha} + \mathbf{v}_{\text{pol},\alpha})] = S$$

For electrons

E × B Convection | Magnetic curvature | Parallel dynamics | Outflow from core

$$\frac{\partial n}{\partial t} + [\phi, n] = \hat{C}(nT_e) - n\hat{C}(\phi) - \nabla_\| (nV_{\|e}) + S$$

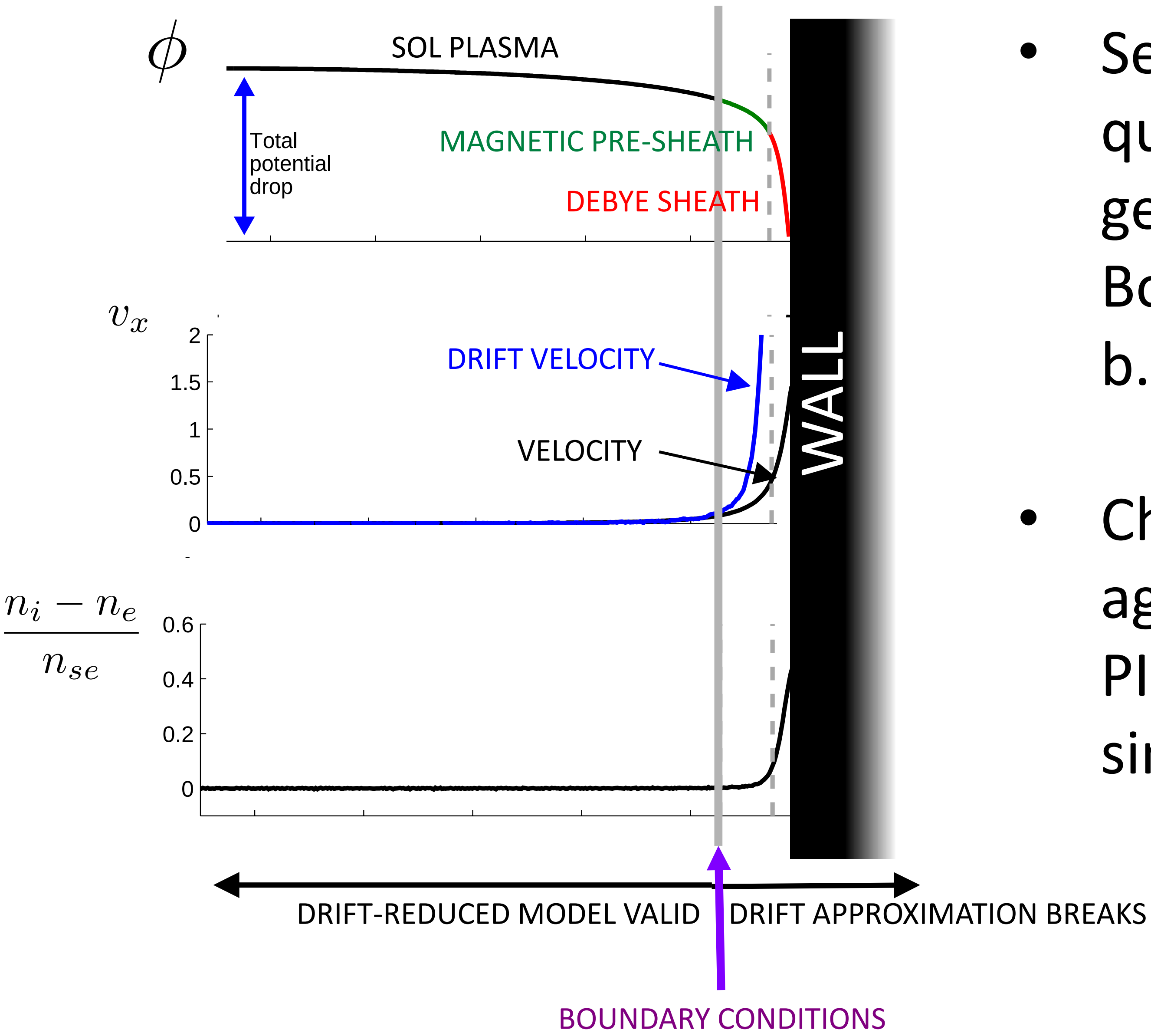
Quasi neutrality → Equation for the vorticity,

T_e, T_i → similar equations as n

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

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

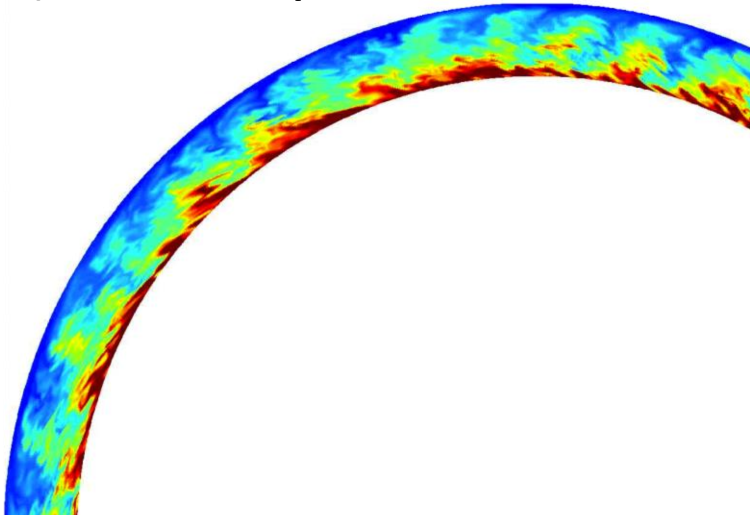
Boundary conditions at the plasma-wall interface



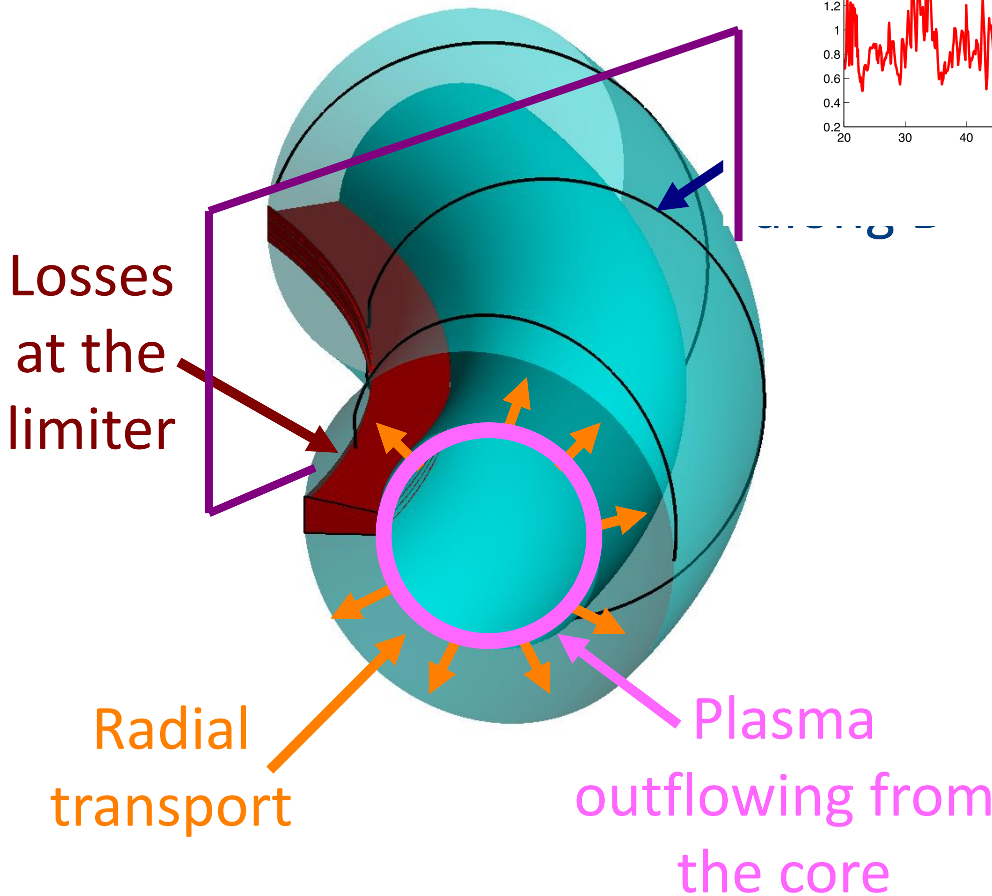
- Set of b.c. for all quantities, generalizing Bohm-Chodura b.c. ($v_w = c_s$)
- Checked agreement with PIC kinetic simulations

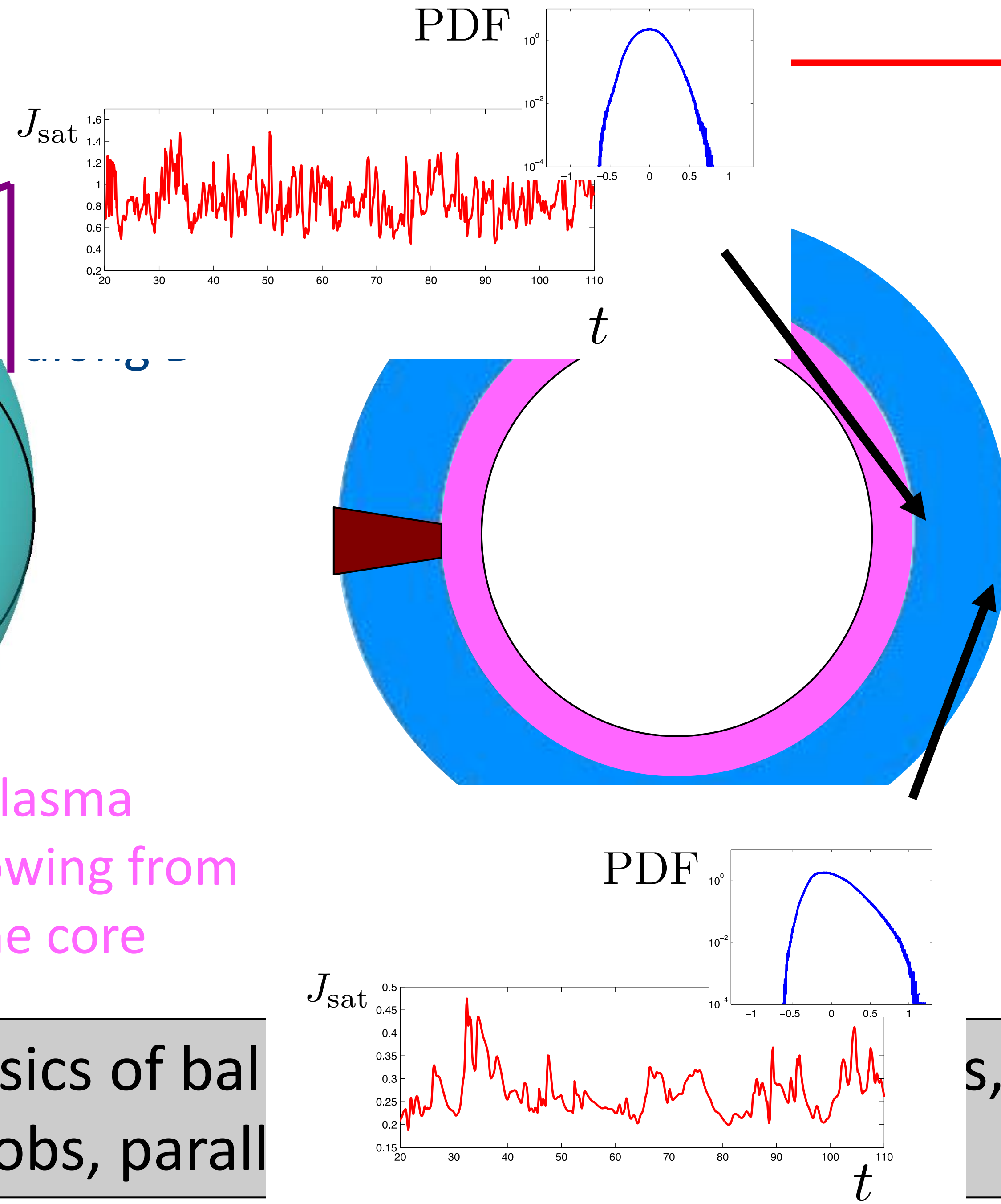
SOL with drift-reduced Braginskii equations

- A number of codes developed: BOUT++ (flexible framework, UK-US), TOKAM3X (Fr), GBS (CH)
- Solved in 3D, dynamics resulting from: plasma outflow, turbulent transport, and parallel losses
- Simulations contain drift physics, turbulence (ballooning modes, drift waves, …), blobs, parallel flows, sheath losses…



Tokamak





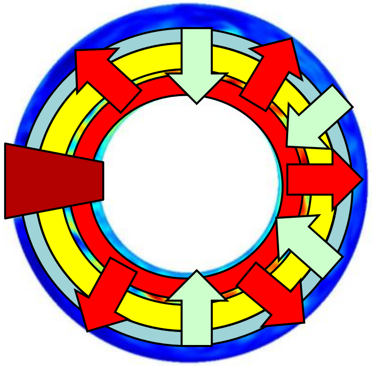
Simulations contain physics of bal s,
Kelvin-Helmholtz, blobs, parall

The key questions

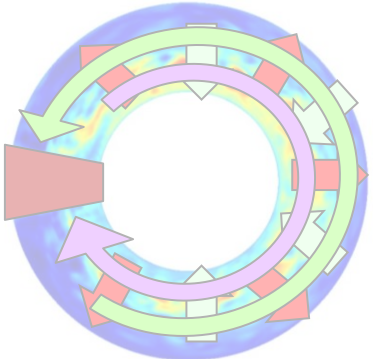
- How is the SOL width established?
- The differences between LFS and HFS limited configurations?
- What determines the SOL electrostatic potential?
- Are there mechanisms to generate toroidal rotation in the SOL?

Three possible saturation mechanisms

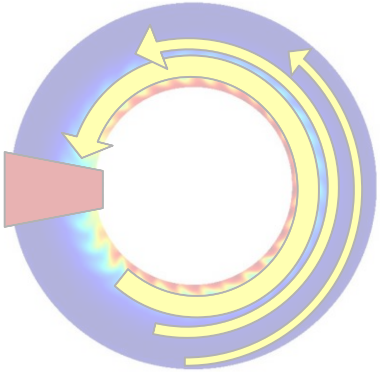
Removal of the turbulence drive (gradient removal):



Kelvin – Helmholtz secondary instability:

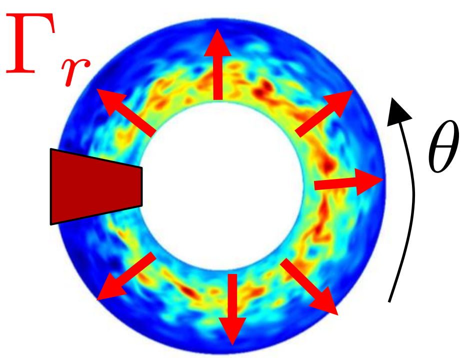


Suppression due to strong shear flow:



Turbulent transport with gradient removal 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

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

SOL width – operational parameter estimate

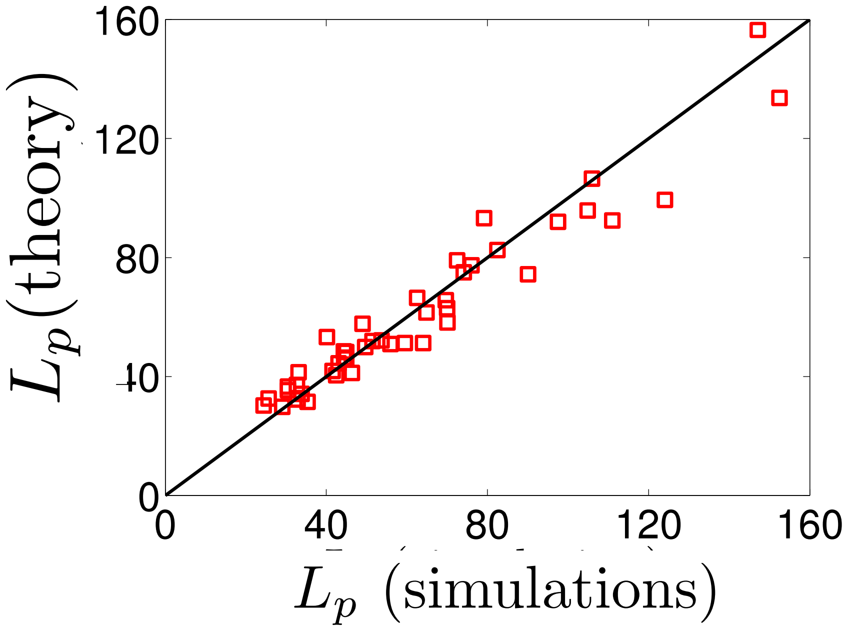
Balance of perpendicular transport and parallel losses $\rightarrow \dfrac{d\Gamma_r}{dr} \sim L_\parallel \sim \dfrac{nc_s}{qR}$

Bohm's

Simulations show expected scaling

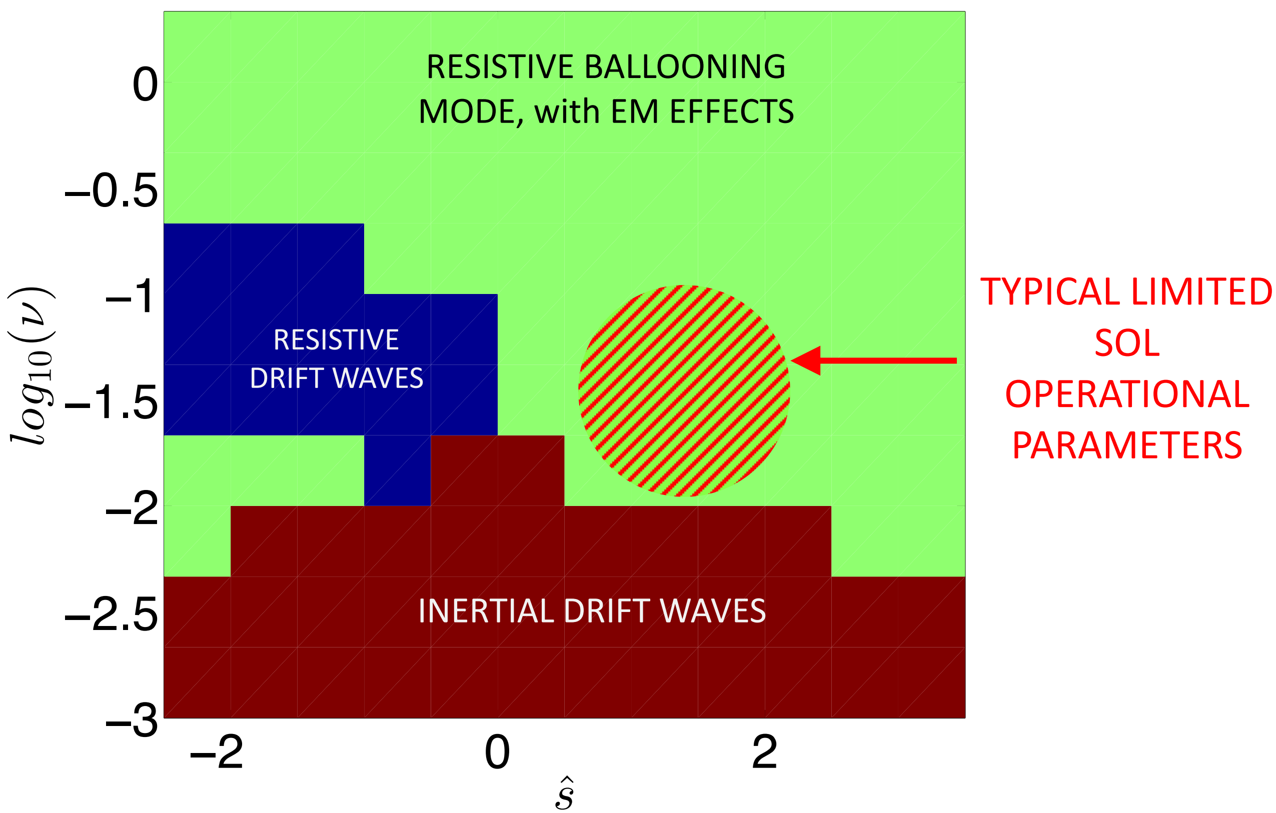
$$L_p \simeq q\left(\frac{\gamma}{k_\theta}\right)_{\max}$$

$$L_p = L_p(\rho_*, q, \hat{s}, \beta, \nu)$$



SOL turbulent regimes

Instabilities driving turbulence depends mainly on $q, \nu, \hat{s}$.



SOL width in ballooning regime

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

BM: $\gamma \sim \gamma_b = \sqrt{2R/L_p}$

BM: $k_\theta \sim k_b = \sqrt{\frac{1-\alpha_{\mathrm{MHD}}}{\nu q^2 \gamma_b}}$

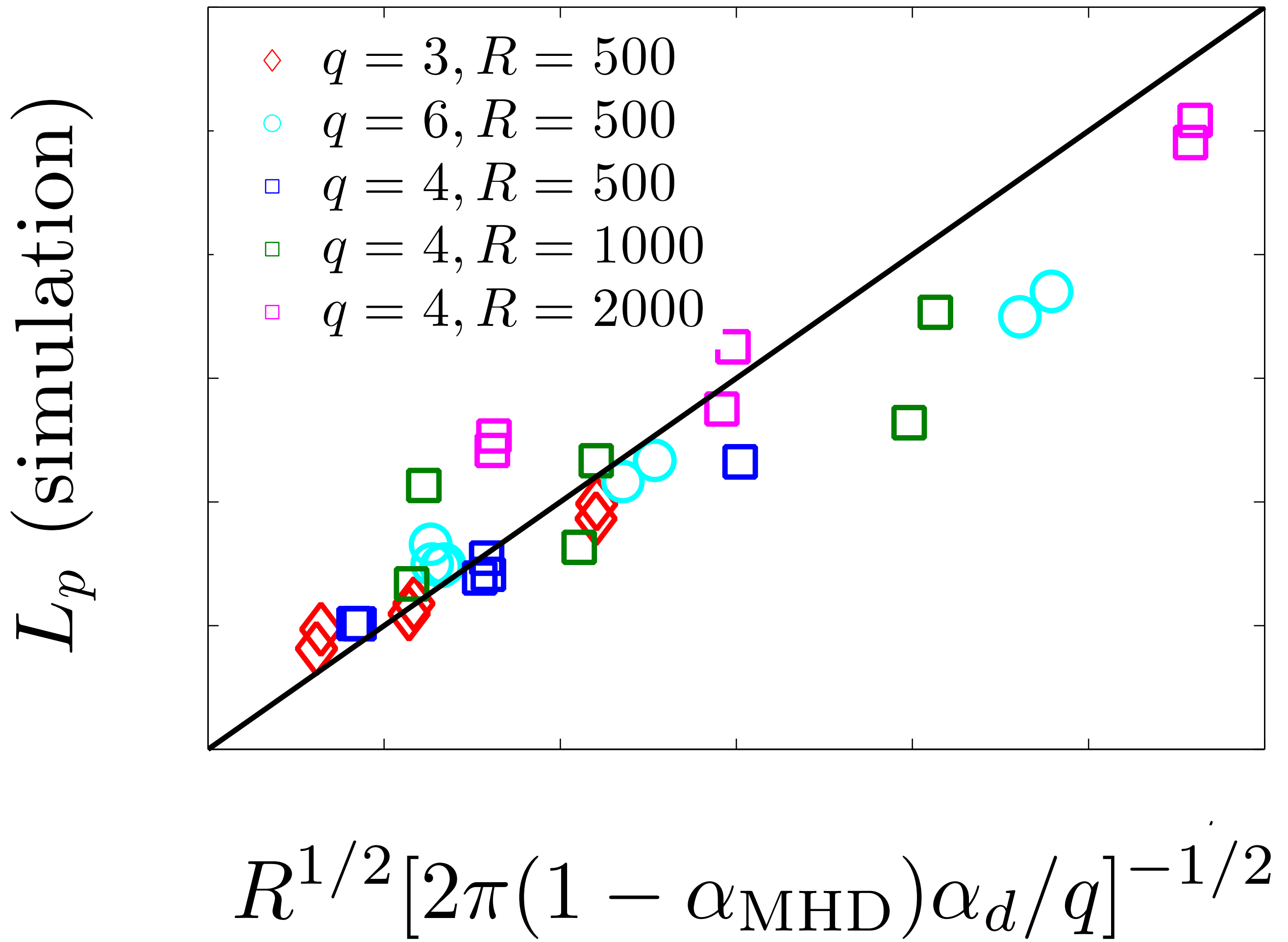
$$L_p = [2\pi \rho_* (1 - \alpha_{\mathrm{MHD}}) \alpha_d / q]^{-1/2}$$

TOKAMAK SIZE (ρ_*)

$\alpha_{MHD} \sim q^2 \beta R / L_p$

$\alpha_d \sim (R/L_p)^{1/4} \nu^{-1/2} / q$

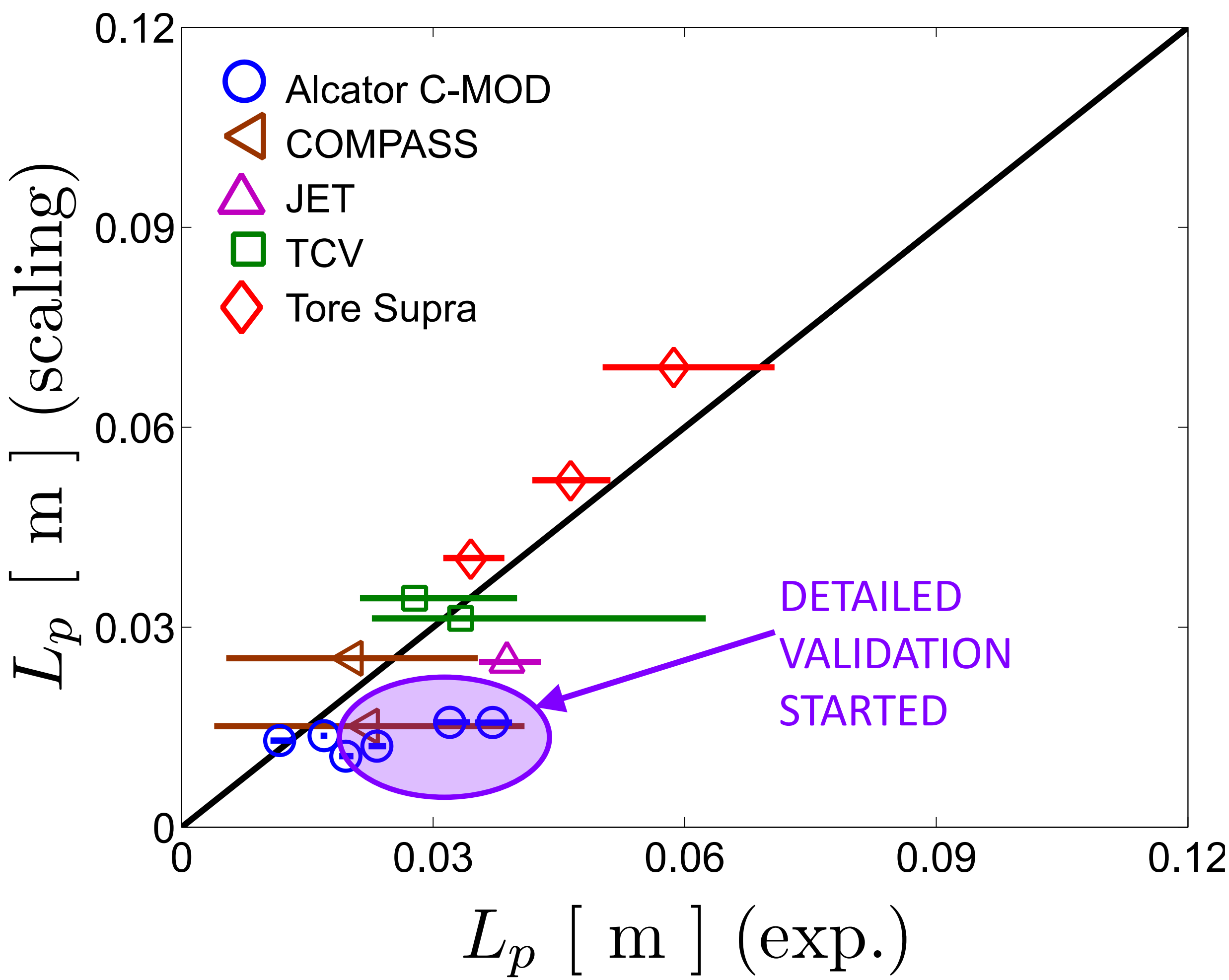
Simulations agree with ballooning estimates



Good agreement with multi-machine measurements

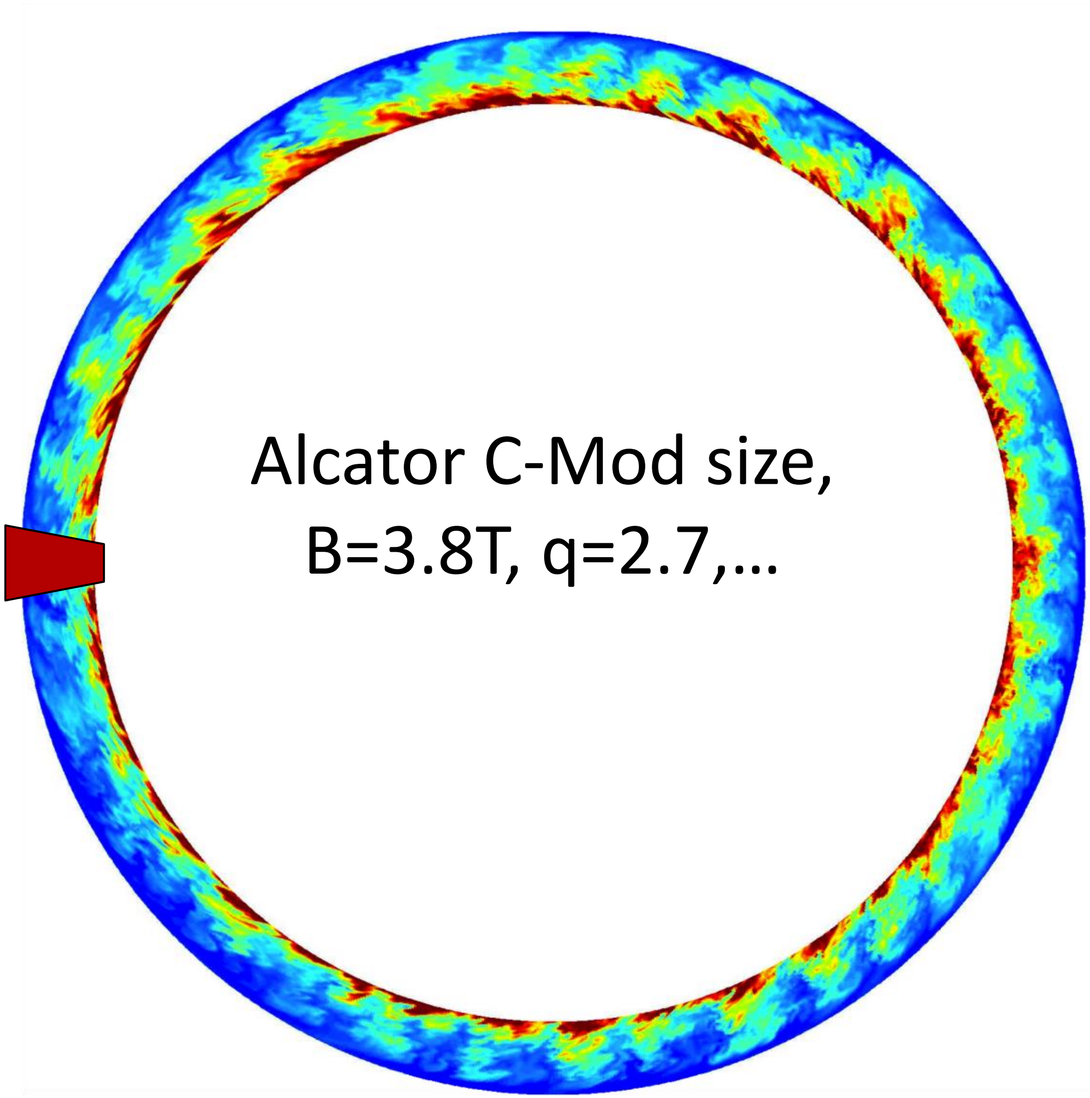
The ballooning scaling, in SI units:

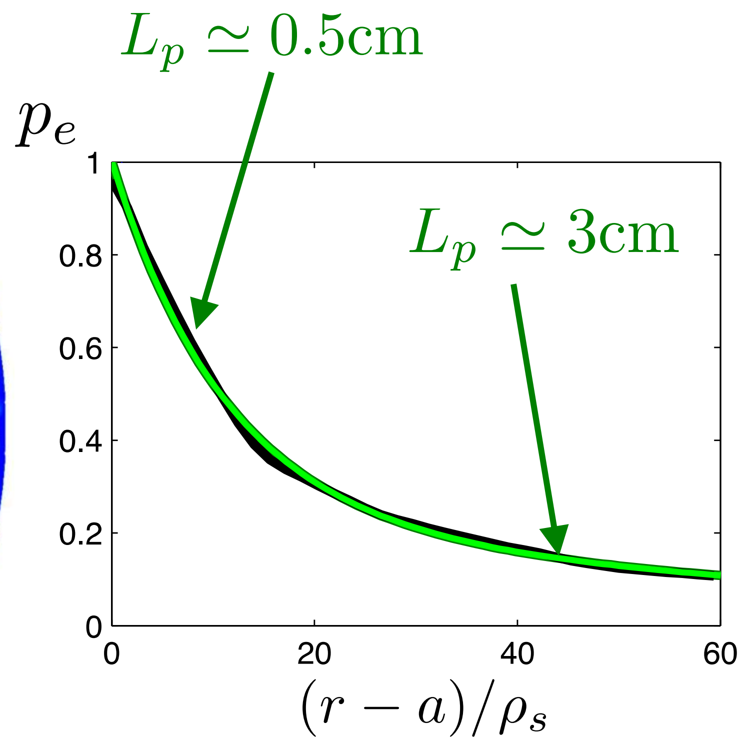
$$L_p \simeq 7.22 \times 10^{-8} q^{8/7} R^{5/7} B_\phi^{-4/7} T_{e,\mathrm{LCFS}}^{-2/7} n_{e,\mathrm{LCFS}}^{2/7} \left(1 + \frac{T_{i,\mathrm{LCFS}}}{T_{e,\mathrm{LCFS}}}\right)^{1/7}$$



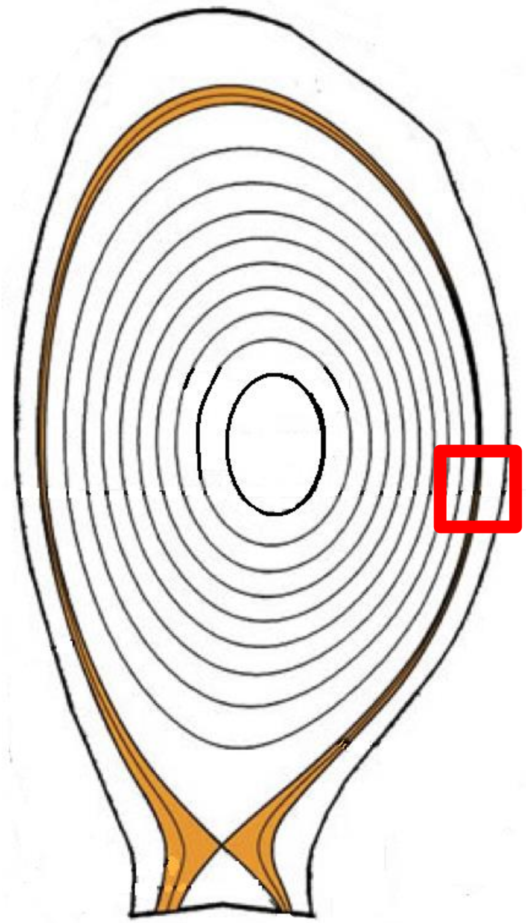
Experimental results provided by G. Arnoux, I. Furno, J.P. Gunn, J. Horacek, M. Kocan, B. LaBombard, B. Labit, and C. Silva.

C-Mod simulations: 2 pressure scale length





2D SOL fluid simulations



- Consider small 2D poloidal region
- Assume weak dependence along B
- Integrate density equation

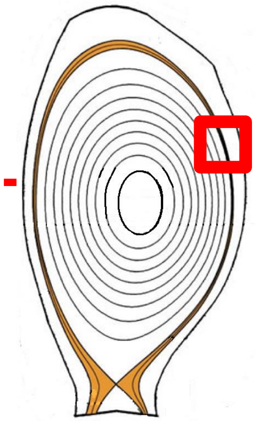
$$\frac{\partial n}{\partial t} + [\phi, n] = \hat{C}(nT_e) - n\hat{C}(\phi) - \nabla_\parallel(nV_{\parallel e}) + S$$

along B

- Introduce $\overline{n} = \frac{1}{L_\parallel}\int n dl_\parallel$
- Obtain

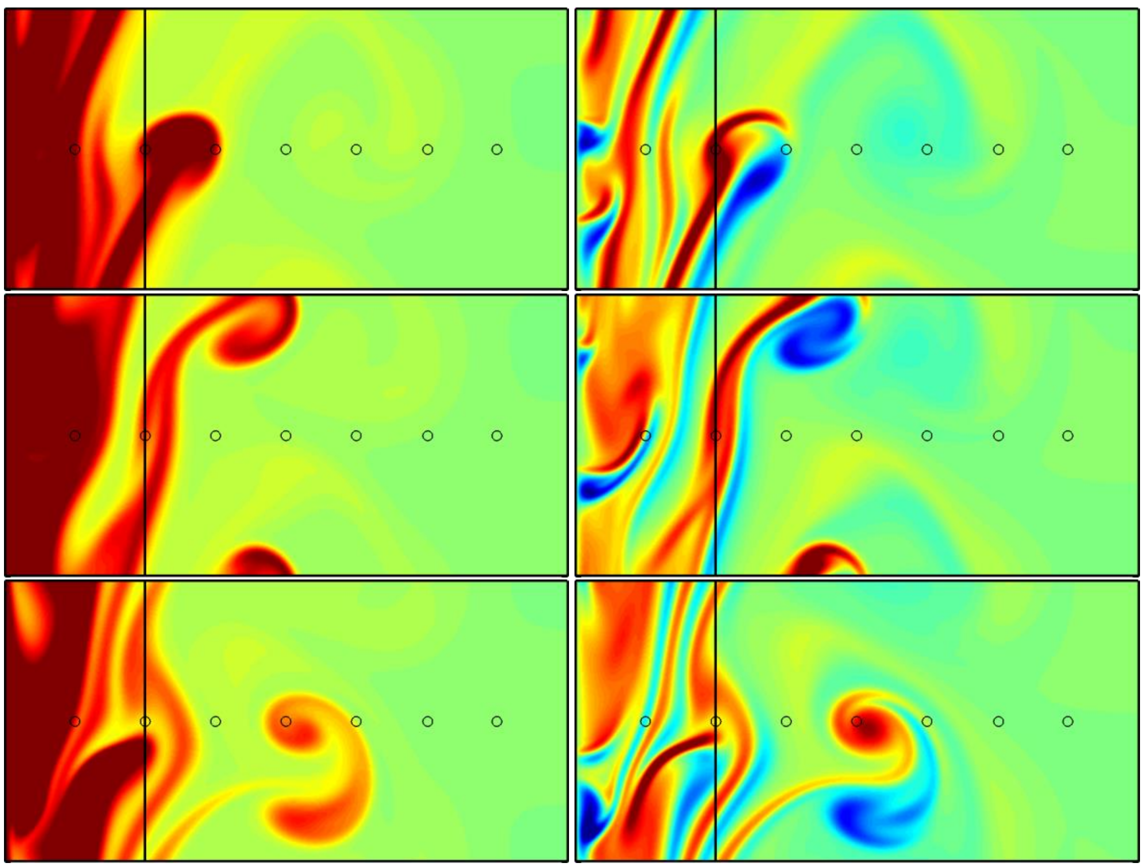
$$\frac{\partial \overline{n}}{\partial t} + [\overline{\phi}, \overline{n}] = \hat{C}(\overline{n}\overline{T}_e) + \overline{n}\hat{C}(\overline{\phi}) - \overline{n}V_\parallel\big|_{\text{divertor}} + S$$

- 2D system of equations solved by TOKAM2D (Fr), SOLT (US), ESEL (DK), …

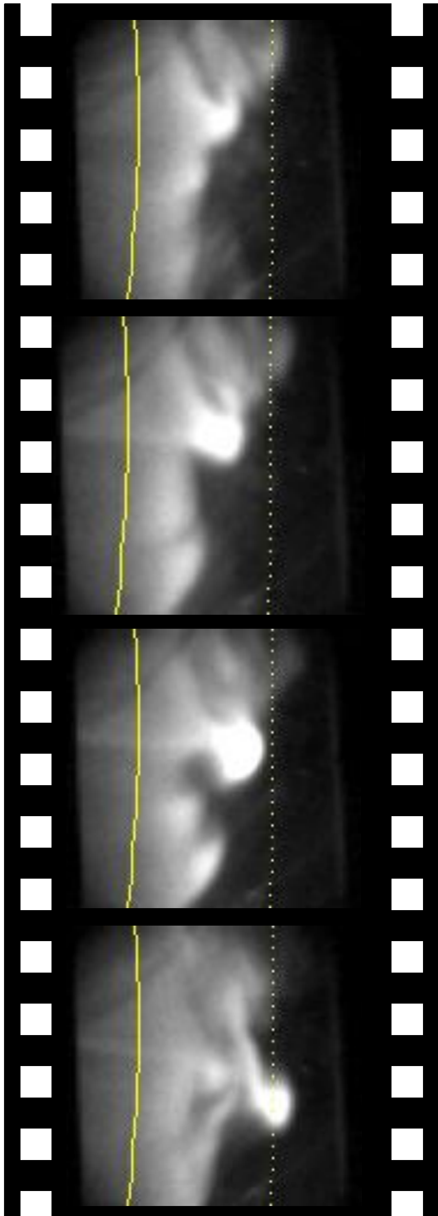


2D investigations of blob dynamics

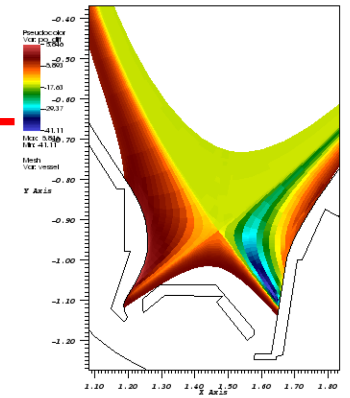
Blob: coherent elongated structures, giving important heat loads



Courtesy of V. Naulin



The phenomenological approach



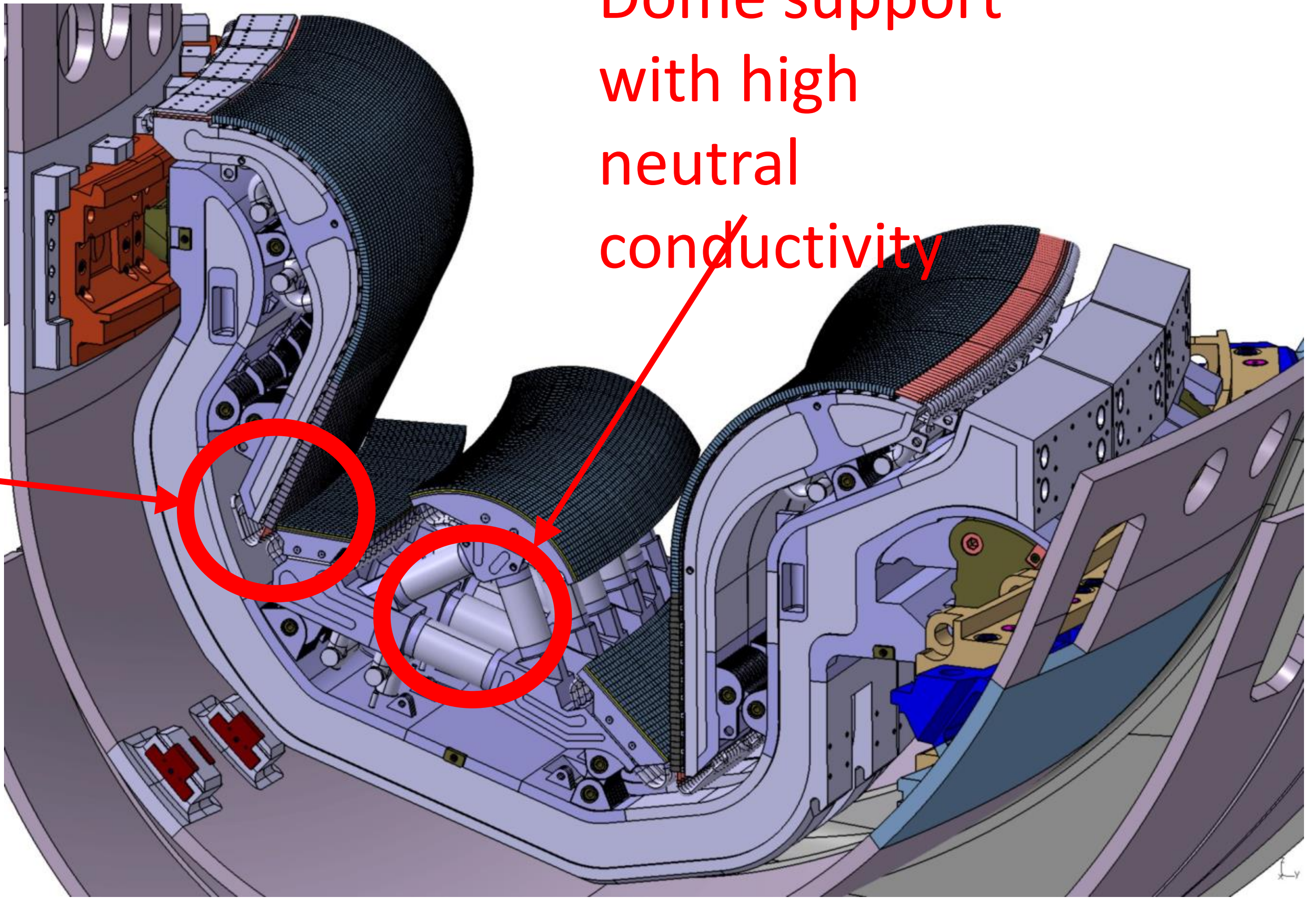
- Starting point: Braginskii equations
- Perpendicular turbulent transport modeled as diffusive process:

$$\nabla_\perp \cdot (D_\perp \nabla_\perp n) + \nabla_\parallel (n V_\parallel) = S - L$$

- Similar equations for T_i, T_e, $V_\parallel$
- Diffusion coefficients to fit experimental data (interpretative mode), extrapolated (predictive mode)
- Particle drifts have been introduced
- Coupled to neutral codes (EIRENE, DEGAS…), fast ion codes (ASCOT), impurity dynamics (REDEP and DIVIMP), strong heat impulse (HEIGHTS and FOREV-2)
- Huge effort from the community: SOLPS (B2-EIRENE): 2×10^5 lines, 100 ppy. Other codes: EDGE2D, UEDGE, …

The phenomenological approach

- It constitutes the design tool for ITER



What have we learned?

- The importance of the SOL region, and its key role in the success of the fusion program
- Diverted SOL have clear advantages; for DEMO more advanced configurations might be necessary
- Simulations of the SOL: extremely complex region, where turbulent nonlinear phenomena, neutrals, sheath physics, impurities, … , are present
- The approaches
  - Fully kinetic
  - Drift-reduced Bragiskii fluid approach (3D and 2D)
  - Phenomenological approach

Some references

- P.C. Stangeby, The Plasma boundary of magnetic fusion devices, 2000
- ITER Physics basis, NF 1999 and 2007 (Ch. 4)
- Pitts, et al, Phys. Scripta 2009
- Tskhakaya, Contrib. Plasma Phys. 2012
- Ricci, et al, PPCF 2012
- Chang, et al., Journal of Physics: Conference Series 2009
- Kukushkin, et al., Fusion Engineering and Design 2011

- paolo.ricci@epfl.ch -

The full set of GBS equations

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

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

$$\partial_t\left(v_{\parallel e} + \frac{m_i \beta_e}{m_e 2}\psi\right) = -\frac{R}{B}\left[\phi, v_{\parallel e}\right] - v_{\parallel e}\nabla_{\parallel} v_{\parallel e} + \frac{m_i}{m_e}\left\{-\nu\frac{j_{\parallel}}{n} + \nabla_{\parallel}\phi - \frac{1}{n}\nabla_{\parallel} p_e - 0.71\nabla_{\parallel} T_e - \frac{2}{3n}\nabla_{\parallel} G_e\right\}$$

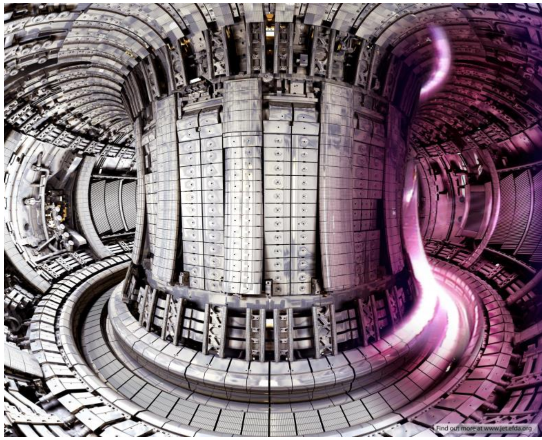
$$\partial_t v_{\parallel i} = -\frac{R}{B}\left[\phi, v_{\parallel i}\right] - v_{\parallel i}\nabla_{\parallel} v_{\parallel i} - \frac{1}{n}\nabla_{\parallel} p_e$$

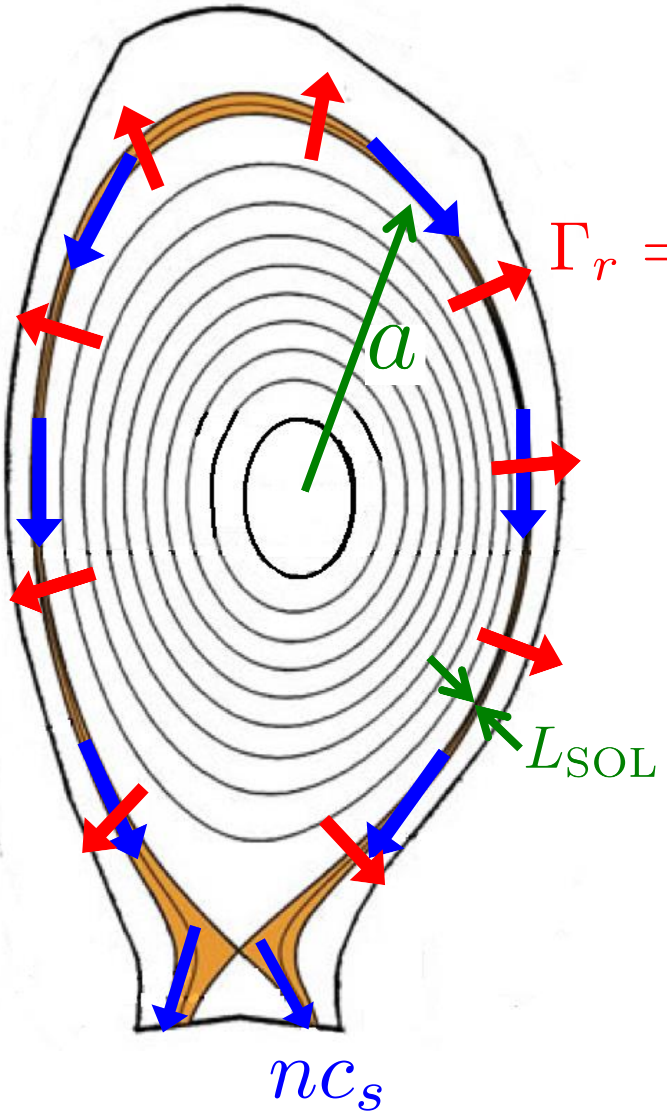
$$\partial_t T_e = -\frac{R}{B}[\phi, T_e] - v_{\parallel e}\nabla_{\parallel} T_e + \frac{4}{3}\frac{T_e}{B}\left[\frac{7}{2}\hat{C}(T_e) + \frac{T_e}{n}\hat{C}(n) - \hat{C}(\phi)\right] + S_{T_e} + \frac{2}{3}T_e\left[0.71\nabla_{\parallel} v_{\parallel i} - 1.71\nabla_{\parallel} v_{\parallel e} + 0.71\left(\frac{v_{\parallel i} - v_{\parallel e}}{n}\right)\nabla_{\parallel} n\right]$$

Need boundary conditions for:

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

The SOL: a very thin region





$$2\pi a \Gamma_r \sim 2nc_s L_{\rm SOL}$$

$$2\pi a D \frac{n}{L_{\rm SOL}} \sim 2nc_s L_{\rm SOL}$$

$$L_{\rm SOL} \sim \sqrt{\frac{\pi a D}{c_s}} \sim 1 \text{ cm}$$