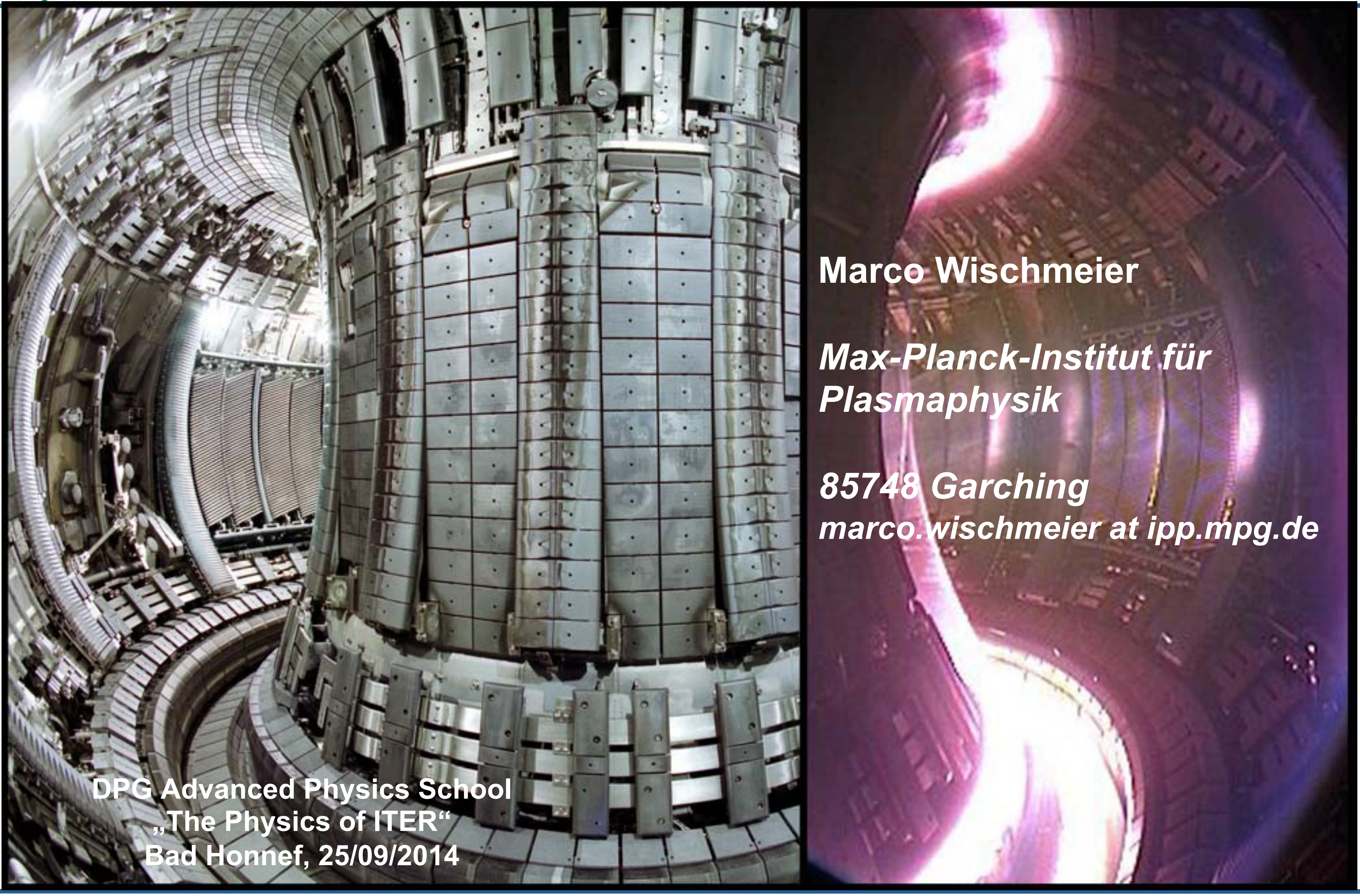
Modelling power exhaust



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DPG Advanced Physics School
„The Physics of ITER“
Bad Honnef, 25/09/2014

Overview

- Motivation
- Introduction to Scrape-Off Layer physics
- Numerical tools
- Validating our understanding in present devices

Fusion exhaust must…

- Maximize pumping of He ash (minimize fuel dilution)
- Provide sufficient pumping of hydrogen fuel
- Minimize damages to the wall (erosion, melting)

Limiter

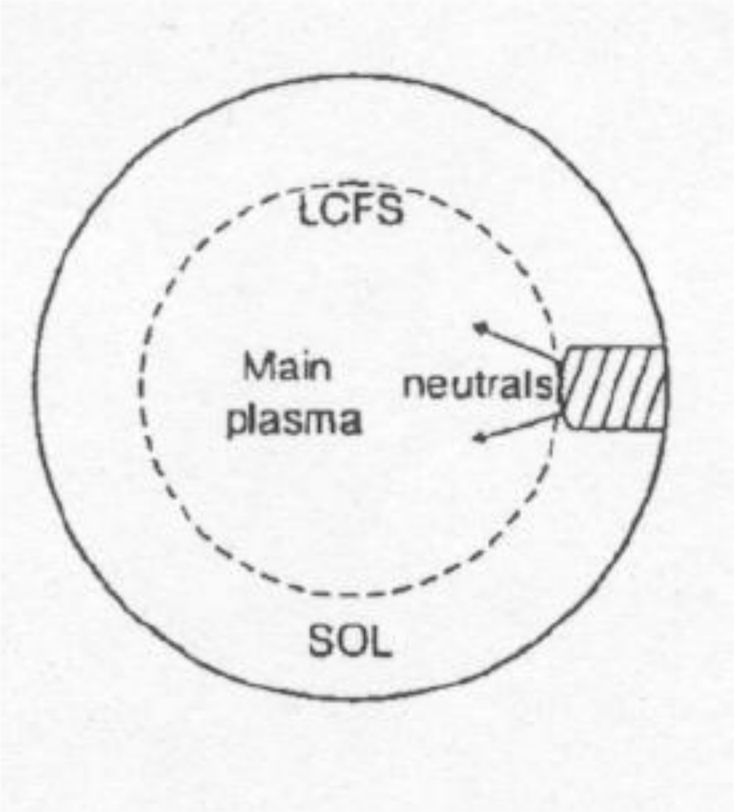


Figure 1.2: *The schematic of a limiter configuration [8].*

P. Stangeby “The plasma boundary of magnetic fusion devices” IOP 2002

Divertor

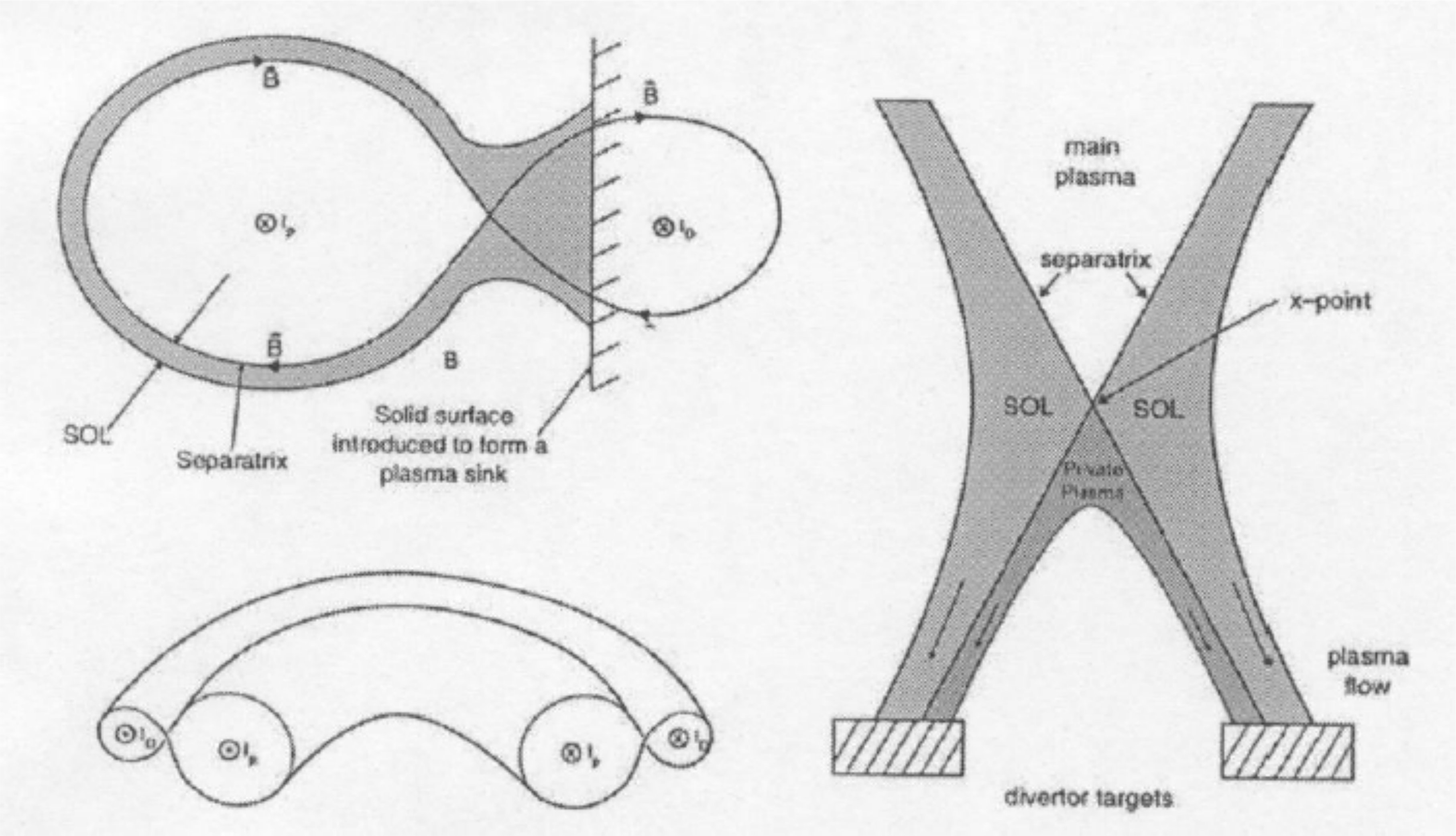
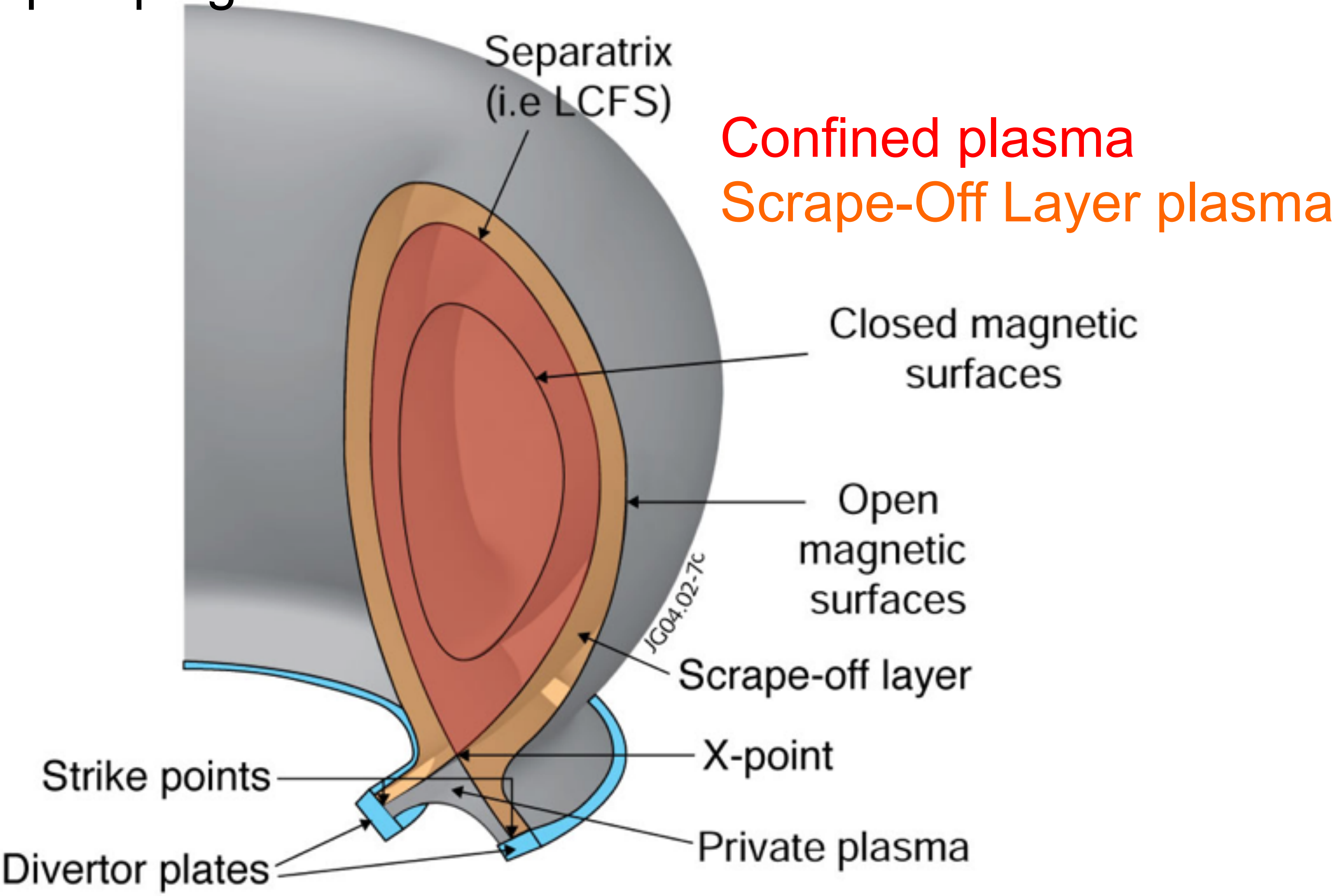


Figure 1.3: *The schematic of a divertor configuration [8].*

Divertor concept

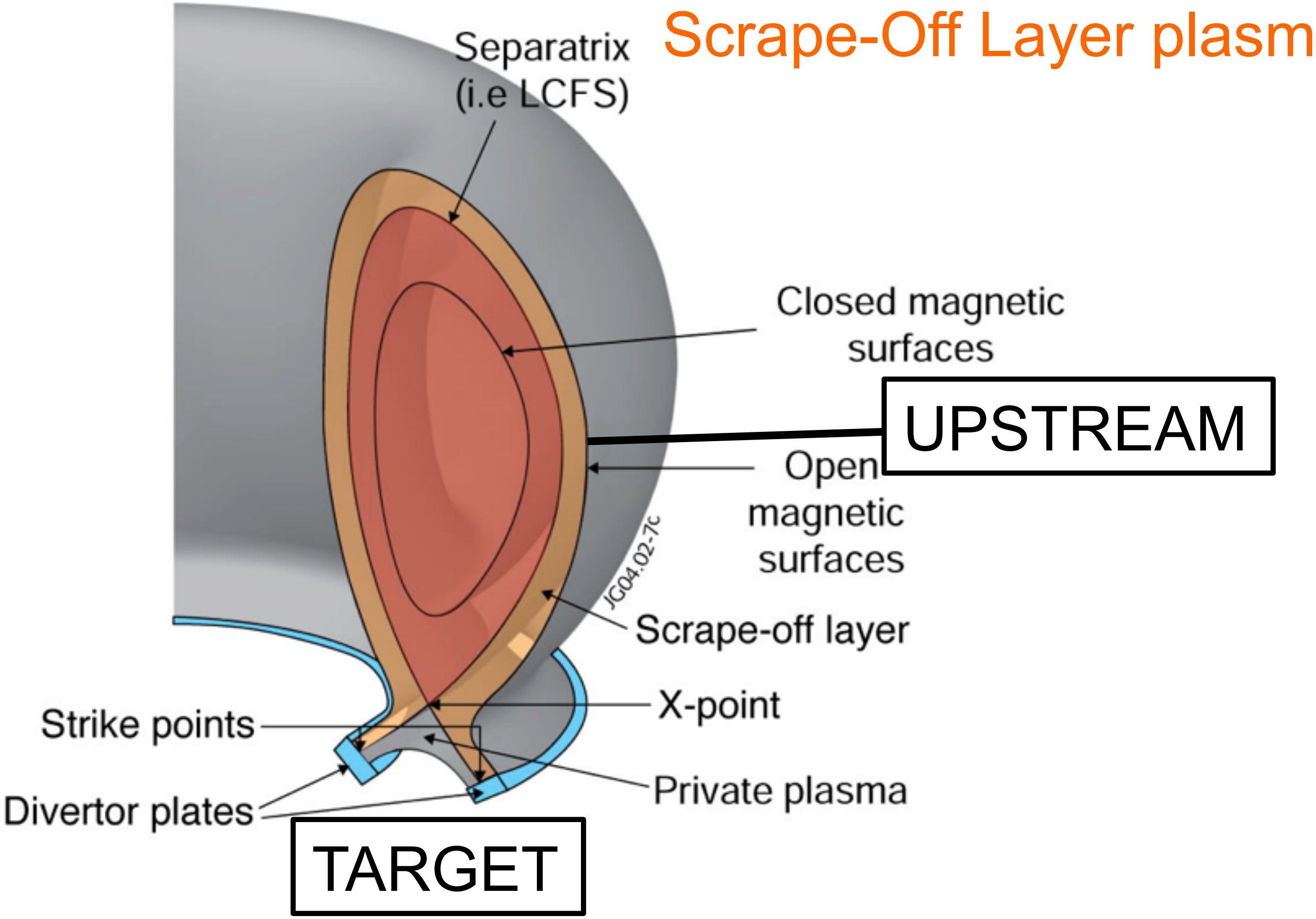
Maximize pumping of He ash and minimize erosion



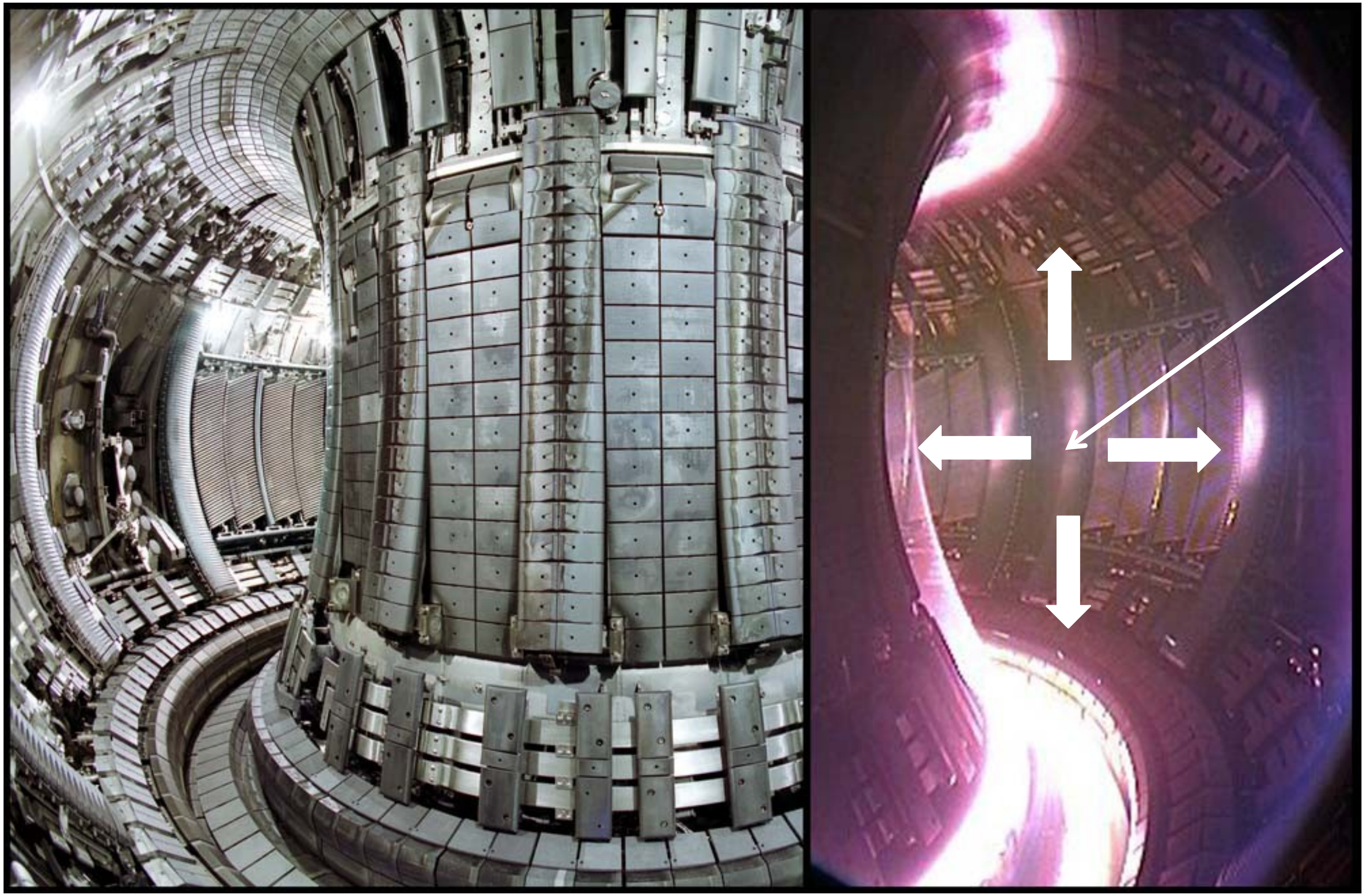
Divertor concept

Confined plasma

Scrape-Off Layer plasma

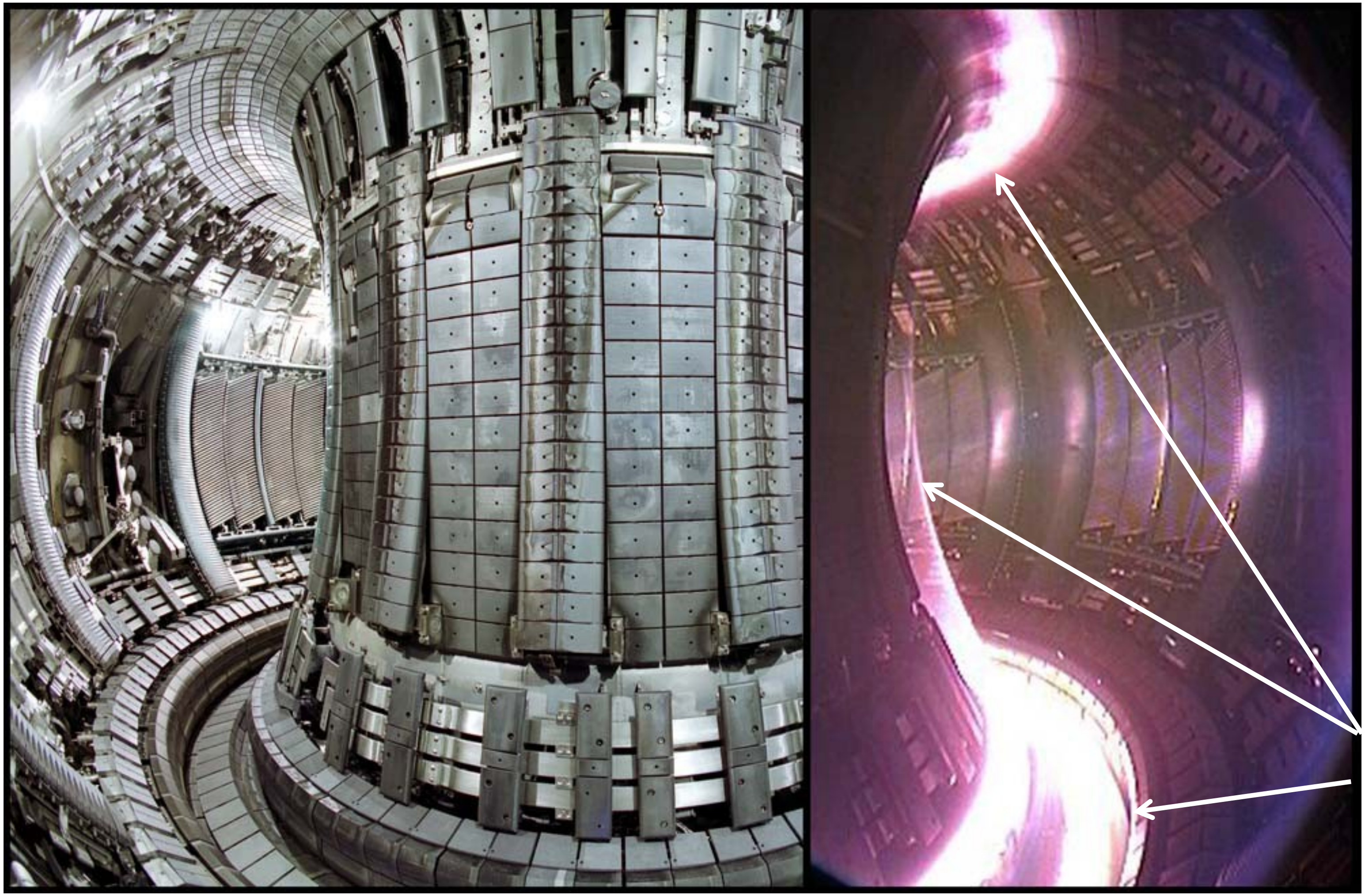


Divertor & Plasma


P_{heat} in centre

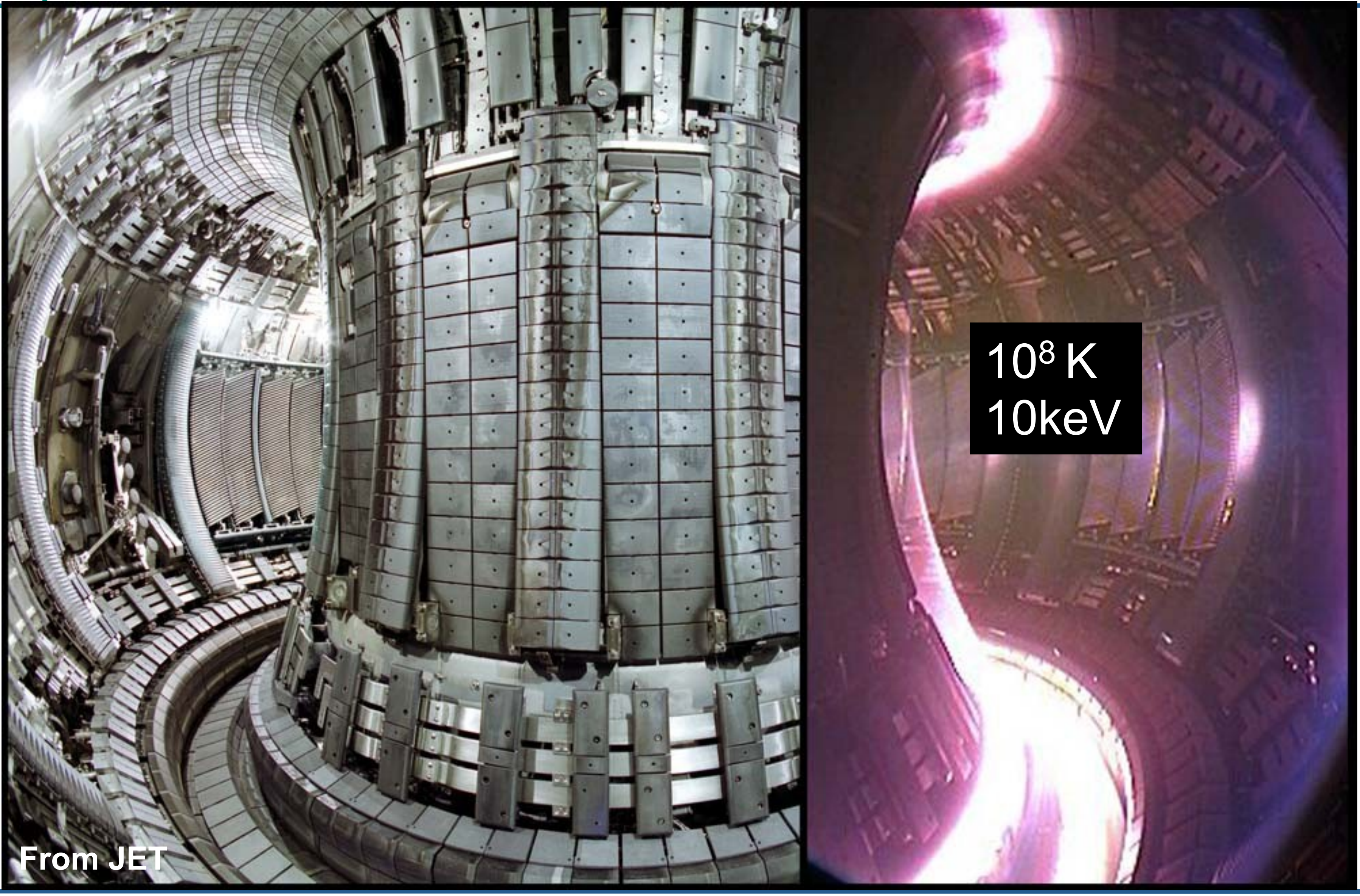
From JET

Divertor & Plasma

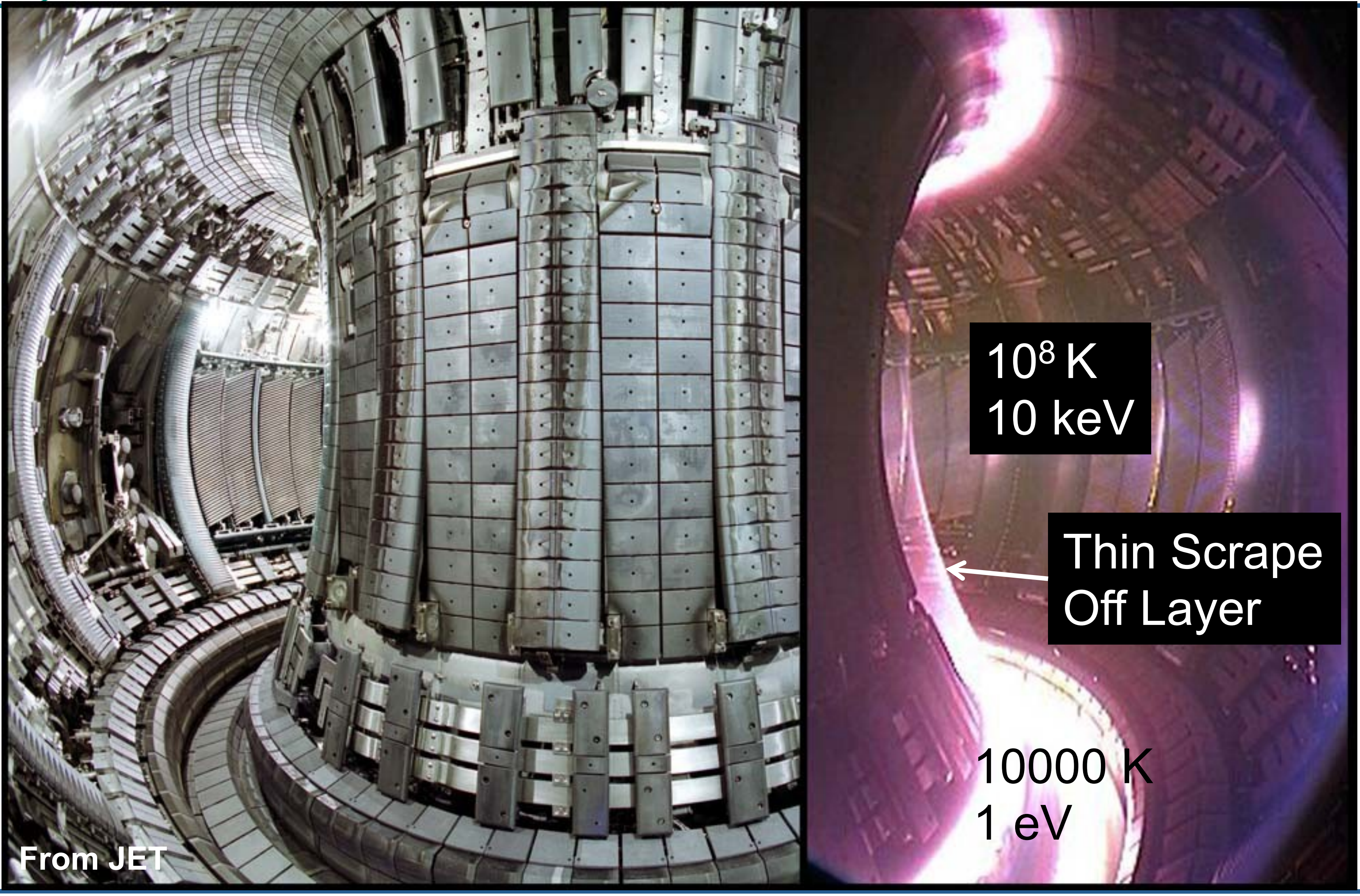

Distributed
Recycling
particles

From JET

Divertor & Plasma

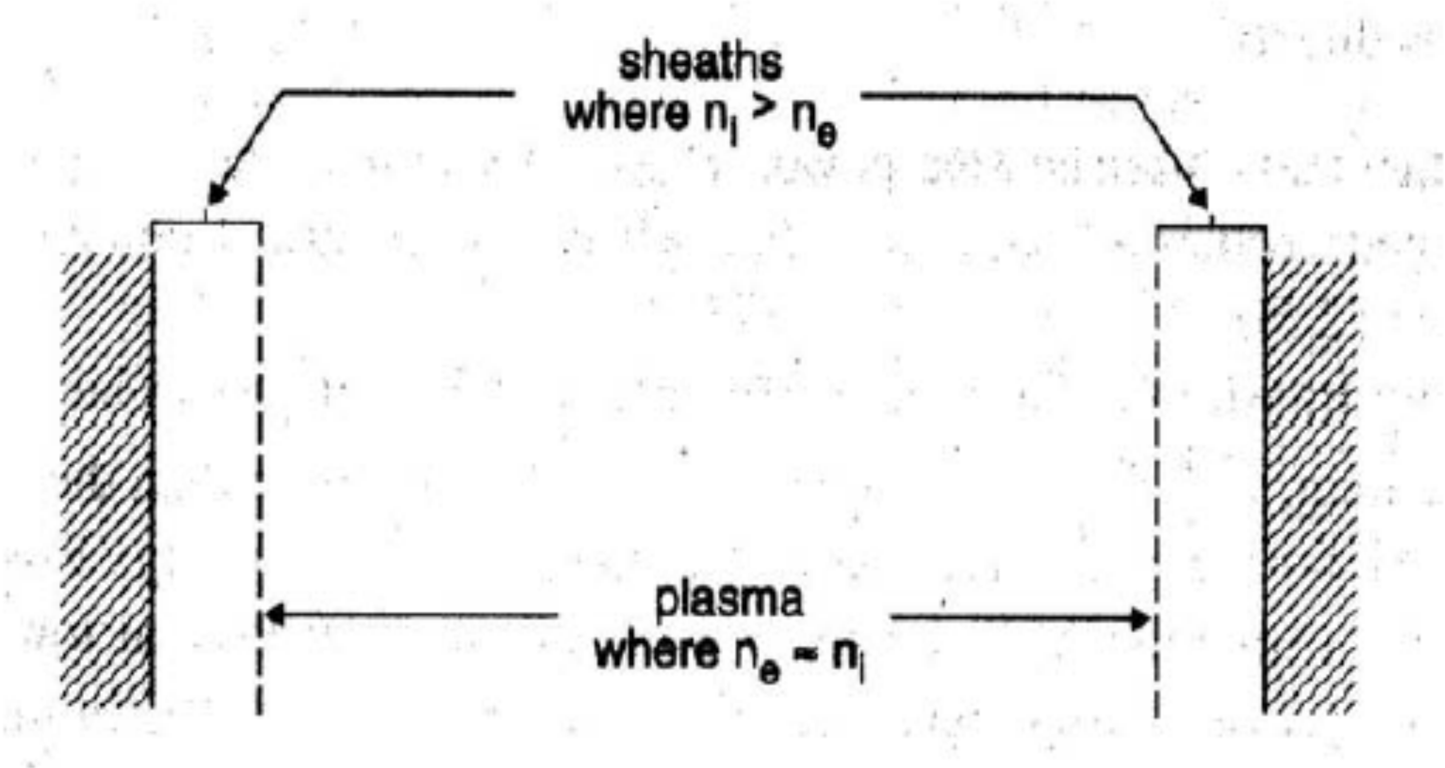


Divertor & Plasma



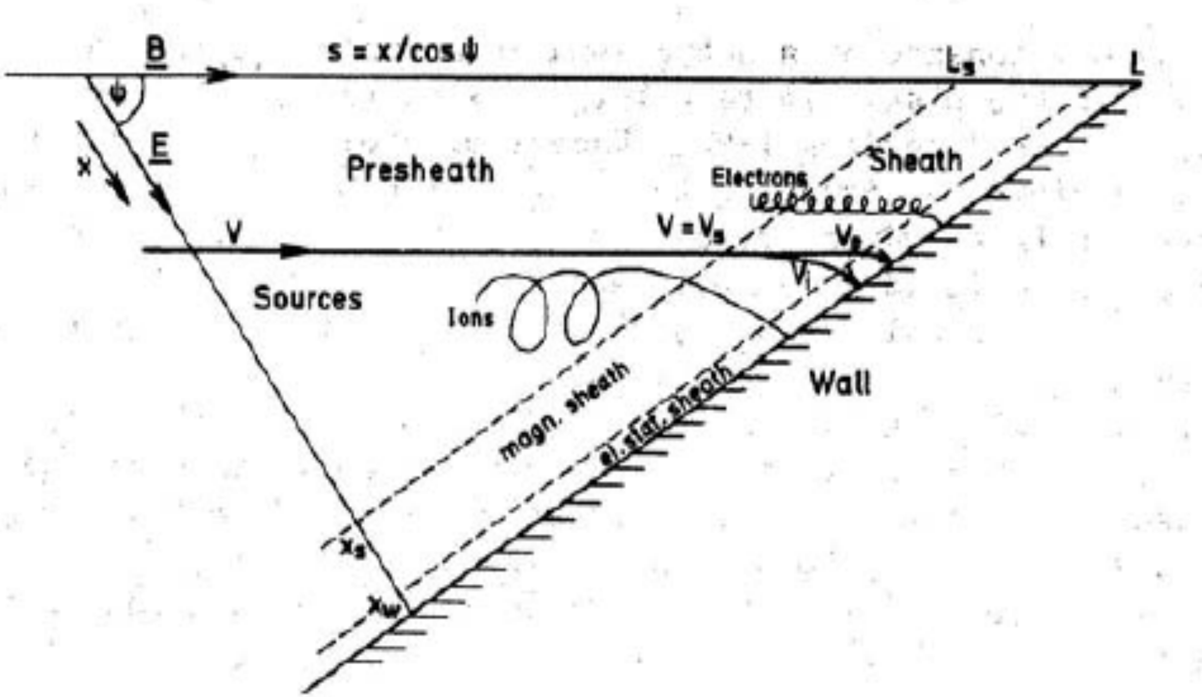
A simple and useful description of the SOL

The Sheath



.1: *Schematic view of the SOL with presheath (plasma) and sheath (from*

The sheath in a magnetic field



ure 2.2: *Schematic view of the presheath and sheath in a scrape off layer with ma*

d $\vec{B}$ *surface (from ref. [38]).*

$$\lambda_{Debye} \equiv (5.53 \times 10^7 T_e/n_e)^{1/2} \; [m],$$

Sheath potentials

$$V_{se} \simeq -0.7\frac{kT_e}{e}.$$

Sheath entrance

$$v_{se} \geq c_s = (e(Z_iT_e + \gamma T_i)/m_i)^{1/2},$$

Bohm Chodura

with Z_i the ion charge, $\gamma = 1$ for isothermal flow, $\gamma = 5/3$ for adiabatic flow with isotropic pressure and $\gamma = 3$ for $1D$ adiabatic flow with no perpendicular heat conduction (see

$$n_{se} = n_0 \exp(V_{se}/(T_e)), \tag{2.49}$$

with n_0 the electron density at $V = 0$. Using the above equation with $V_{se} = -0.7T_e$ gives

$$n_{se} = 0.5n_0 \tag{2.50}$$

Particle and energy fluxes across the sheath

$$\Gamma_{se} = n_{se} v_{se}.$$

Particle flux across sheath

Energy flux across sheath

$$q^{\epsilon}_{se,e} = \gamma_e e T_e \Gamma_{se},$$

where

$$\begin{aligned}\gamma_e &= 2 + |V_{sf}|/(eT_e) + |V_{pre-sheath}|/(eT_e) \\ &\approx 2 + 3 + 0.7 = 5.7\end{aligned}$$

Total heat transfer across the sheath

Ion heat flux across sheath entrance assuming drifting maxwellian ions with Bohm Chodura at sheath entrance as boundary

$$q^{\epsilon}_{se,i} = \left(\frac{5}{2}kT + \frac{1}{2}m_i c_s^2\right)\Gamma_{se},$$

so that $\gamma_i = 3.5$ if $T_e = T_i$. Values of $\gamma_i \approx 2 - 3$ have been found

The total *sheath heat transmission factor* for electrons plus ions is thus

$$\gamma \simeq 7 - 9,$$

Total energy flux across the sheath

However, sheath needs kinetic treatment of ions

Parallel collisional heat transport - conduction

$$q_{\parallel i} \equiv \chi_{\parallel i} \nabla_x T_i = -\kappa_{0i} T_i^{5/2} \nabla_x T_i \tag{2.35}$$

$$q_{\parallel e} \equiv \chi_{\parallel e} \nabla_x T_e = -\kappa_{0e} T_e^{5/2} \nabla_x T_e \tag{2.36}$$

with the ion and electron heat conductivity coefficients:

$$\kappa_{0i} = \frac{1249}{Z_i^4 m_i^{1/2} \ln \Lambda} \approx 60 \tag{2.37}$$

$$\kappa_{0e} = \frac{30692}{Z_i \ln \Lambda} \approx 2000 \tag{2.38}$$

where the temperatures are given in $[eV]$, lengths in $[m]$, the Coulomb logarithm $\Lambda \approx 15$ [28], the mass in units of atomic mass $[amu]$, q in $[W/m^2]$ and the approximate numerical values have been calculated assuming a D plasma. If He^{2+} is the dominant ion species, κ_{0i} is 30 times smaller in a helium plasma.

Simplest assumption for SOL analysis

$$p_t^{tot} = n_t(2kT_t + mc_s^2) = 2n_u kT_u = p_u^{tot}\,;\, T_e = T_i,$$

1. Ion-neutral friction is negligible along the SOL.
2. Radiation losses along the SOL are negligible compared to P_{SOL}.
3. All neutrals recycling from the targets are immediately ionized in front of the targets on the same flux tube as the original impinging ions.
4. The only parallel plasma flow is that between the ionization zone and the target (eqn. 2.48), $v = 0$ upstream and $v = c_s$ at the target sheath entrance.
5. No cross-field particle and momentum transport.
6. Surfaces are the only particle sinks, no volumetric recombination.

The two point model

applying $q_{se}^{\epsilon} = \gamma k T_e \Gamma_{se}$

Two-point model:

$$\begin{aligned} 2n_t T_t &= n_u T_u \\ T_u^{7/2} &= T_t^{7/2} + \frac{7}{2}\frac{q_{||} L_c}{\kappa_{0e}} \\ q_{||} &= \gamma n_t k T_t c_s. \end{aligned}$$

➔

$$\begin{aligned} T_u &\simeq \left(\frac{7}{2}\frac{q_{||} L_c}{\kappa_{0\,e}}\right)^{2/7} \text{with } T[eV]\,, T_u^{7/2} \gg T_t^{7/2} \\ T_t &\propto q_{||}^{10/7} L_c{}^{-4/7} n_u^{-2} \\ n_t &\propto n_u^3 q_{||}^{-8/7} L_c^{6/7} \\ \Gamma_t &\propto n_u^2 q_{||}^{-3/7} L_c^{4/7} \end{aligned}$$

Corrections to the two point model

$$\begin{aligned}
T_t &\propto \frac{(1-f_{power})^2}{f_{mom}^2 f_{cond}^{4/7}} \\
T_u/T_t &\propto \frac{f_{cond}^{6/7} f_{mom}^2}{(1-f_{power})^2} \\
n_t &\propto \frac{f_{mom}^3 f_{cond}^{6/7}}{(1-f_{power})^2} \\
\Gamma_t &\propto \frac{f_{mom}^2 f_{cond}^{4/7}}{1-f_{power}}
\end{aligned}$$

➔ High complexity of interdependent quantities

Numerical Tools

Braginskii Equations

- derived from 0.-2. moments of Landau's equation:

$$\frac{\partial f(\vec{r},\vec{v},t)}{\partial t}+\vec{v}\cdot\nabla_{\vec{r}}f(\vec{r},\vec{v},t)+\dot{\vec{v}}\cdot\nabla_{\vec{v}}f(\vec{r},\vec{v},t)=C\left[f(\vec{r},\vec{v},t)\right]$$

- 0th moment: particle conservation

$$\frac{\partial n_i}{\partial t}+\vec{\nabla}(n_i\vec{v}_i)=S_i \qquad \frac{\partial n_e}{\partial t}+\vec{\nabla}(n_e\vec{v}_e)=S_e$$

- quasi-neutrality: $n_e=n_i\left(=\sum Z_a n_a\right)$

1st moment: momentum conservation

$$\frac{\partial}{\partial t}\left(m_i n_i \vec{v}_i\right) + \vec{\nabla}\left(m_i n_i \vec{v}_i \vec{v}_i\right) = -\vec{\nabla} p_i - \vec{\nabla}\cdot\overleftrightarrow{\Pi}_i + Z_i e n_i\left(\vec{E} + \vec{v}_i \times \vec{B}\right) + \vec{R}_i + \vec{S}_{m_i \vec{v}_i}$$ ions

$$-\vec{\nabla} p_e - e n_e\left(\vec{E} + \vec{v}_e \times \vec{B}\right) + \vec{R}_e = 0$$ electrons

friction: $$\vec{R}_e = -\vec{R}_i = e n_e\left(\frac{\vec{j}_\parallel}{\sigma_\parallel} + \frac{\vec{j}_\perp}{\sigma_\perp}\right) - 0.71 n_e \vec{\nabla}_\parallel T_e - \frac{3}{2}\frac{e n_e^2}{\sigma_\perp B^2}\vec{B} \times \vec{\nabla} T_e$$

total current: $$\vec{j} = e\left(Z_i n_i \vec{v}_i - n_e \vec{v}_e\right)$$

total momentum eqn: $$\frac{\partial}{\partial t}\left(m_i n_i \vec{v}_i\right) + \vec{\nabla}\left(m_i n_i \vec{v}_i \vec{v}_i\right) = -\vec{\nabla} p - \vec{\nabla}\cdot\overleftrightarrow{\Pi}_i + \vec{j} \times \vec{B} + \vec{S}_{m_i \vec{v}_i}$$

[assumption: velocity is linear sum of average + fluctuations, ie: $\langle v\rangle + \tilde{v}$ (no non-linear coupling), re-introduce eg. $\langle \tilde{v}_\alpha \tilde{v}_\beta \rangle$ and off-diagonal terms within turbulent models]

2nd moment: energy conservation

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_iT_i+\frac{1}{2}m_in_i\vec{v}_i^2\right)+\vec{\nabla}\cdot\left[\left(\frac{5}{2}n_iT_i+\frac{1}{2}m_in_i\vec{v}_i^2\right)\vec{v}_i+\overleftrightarrow{\Pi}_i\cdot\vec{v}_i+\vec{q}_i\right]=\left(Z_ien_i\vec{E}-\vec{R}\right)\cdot\vec{v}_i-Q_{ei}+S_{E_i}$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_eT_e\right)+\vec{\nabla}\cdot\left[\frac{5}{2}n_eT_e\vec{v}_i+\vec{q}_e\right]=-en_e\vec{E}\vec{v}_e+\vec{R}\cdot\vec{v}_i+Q_{ei}+S_{E_e}$$

$$Q_{ei}=\frac{3m_e}{m_i}\frac{n_e}{\tau_e}\left(T_i-T_e\right)$$

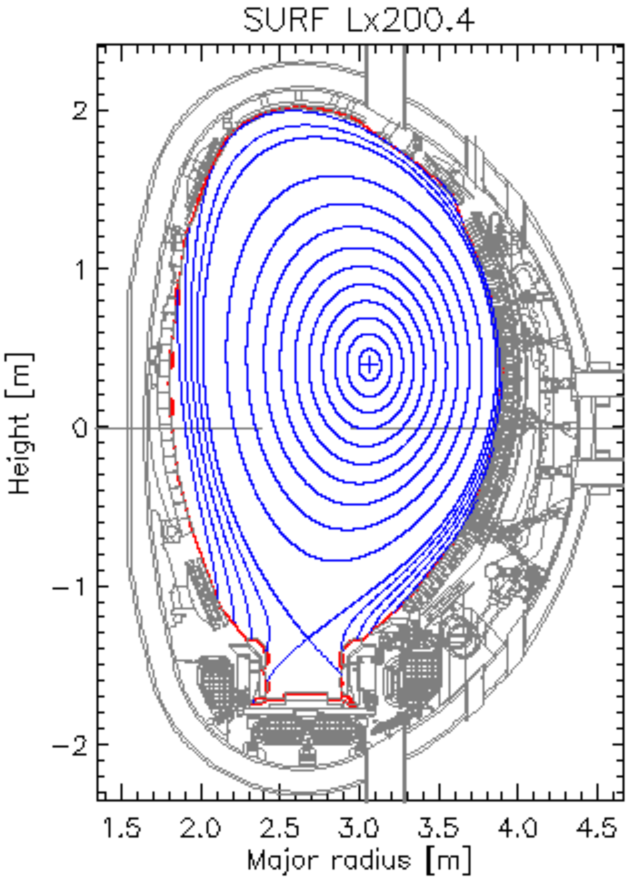
- higher moments > 2nd order disregarded
- close equations via specifying heat fluxes:

$$\vec{q}_i=-\kappa_\parallel^i\nabla_\parallel T_i-\kappa_\perp^i\nabla_\perp T_i+\kappa_\times^i\frac{\vec{B}}{B}\times\vec{\nabla}_\perp T_i$$

$$\vec{q}_e=-\kappa_\parallel^e\nabla_\parallel T_e-\kappa_\perp^e\nabla_\perp T_e+\kappa_\times^e\frac{\vec{B}}{B}\times\vec{\nabla}_\perp T_e-0.71\frac{T_e}{e}\vec{j}_\parallel-\frac{3}{2}\frac{T_e}{2e\omega_e\tau_eB}\vec{B}\times\vec{j}_\perp$$

- plus an expression for the ion viscosity tensor $\overleftrightarrow{\Pi}_i$

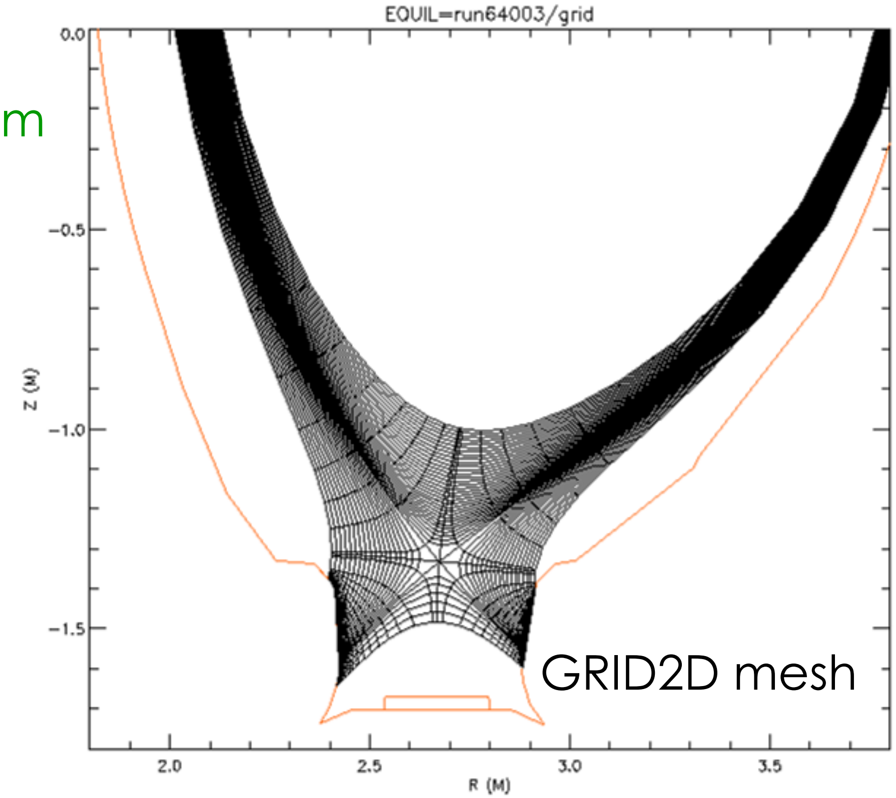
simulation domain, 2D



EFIT-equlibrium

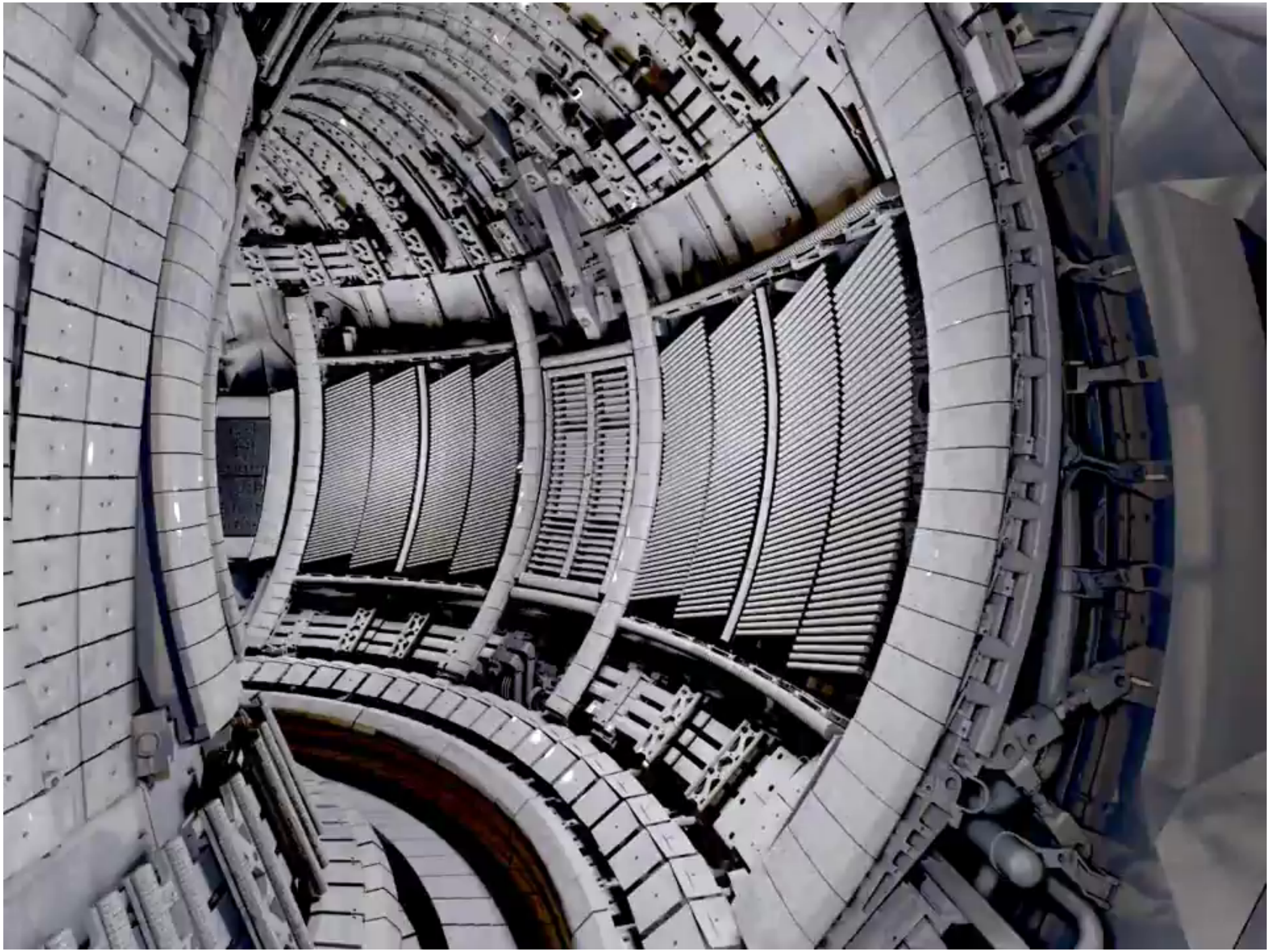
$$\vec{\nabla} p = \vec{j} \times \vec{B}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{j}$$

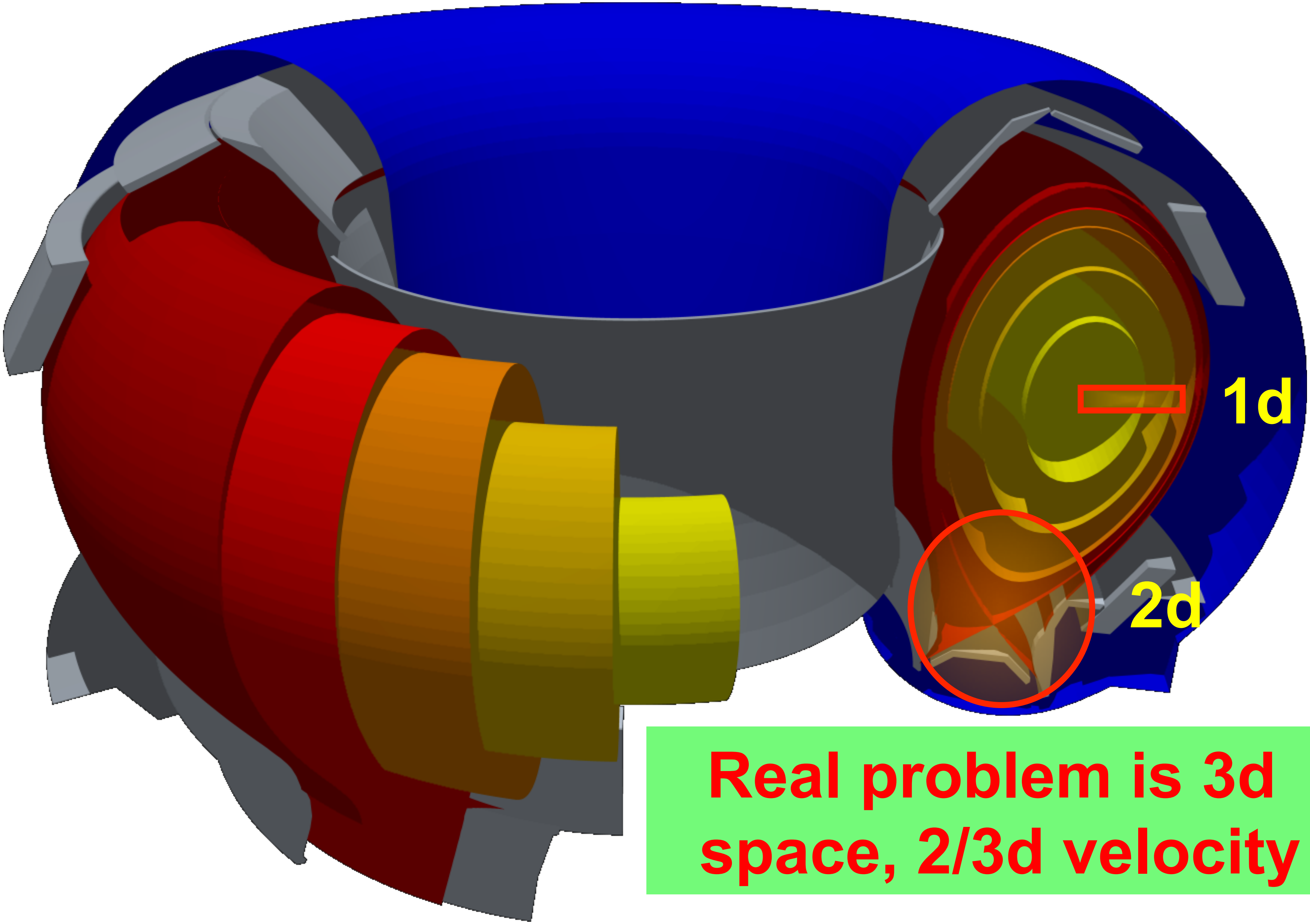


GRID2D mesh

- usual assumption: toroidal symmetry
  → convolutes parallel and diamagnetic transport into combined poloidal transport
- non-homogeneous 2D (ρ,θ)-grid: orthogonal cells aligned to flux-surfaces
- difficulty: strong bending of flux-surfaces, target cell-boundaries tilted
  → possible solution: increase grid resolution



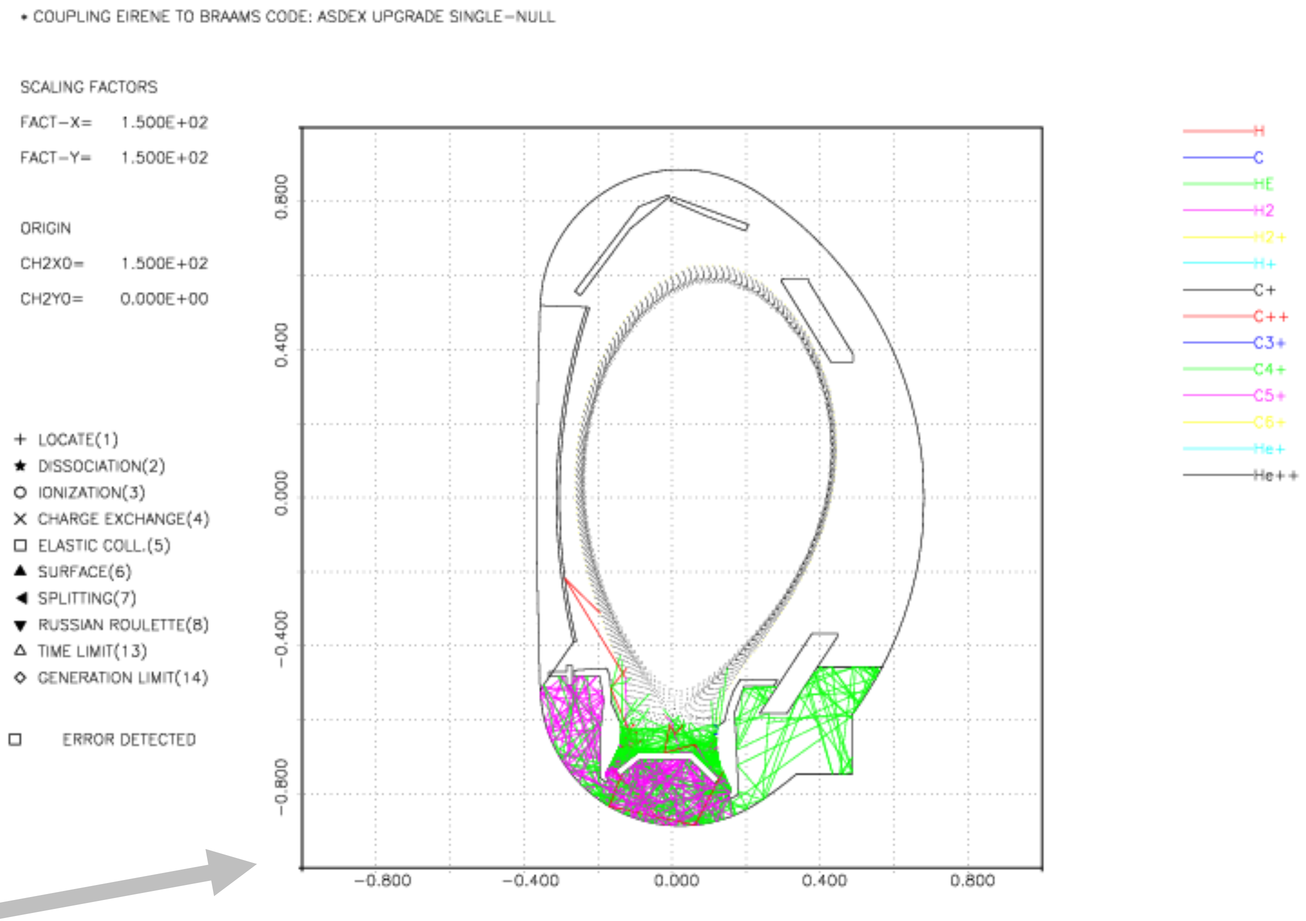
Simulations



Real problem is 3d space, 2/3d velocity

Neutral model

- Plasma recombines to form neutrals
  - at surfaces [interaction with solids/or liquids]
  - in the volume
- Neutrals act as sources of particles, momentum and energy for the plasma
- Neutrals also interact with material surfaces
- Neutrals can be described by one of (or combination of)
  - fluid model
  - kinetic model



Neutral model, fluid or kinetic?

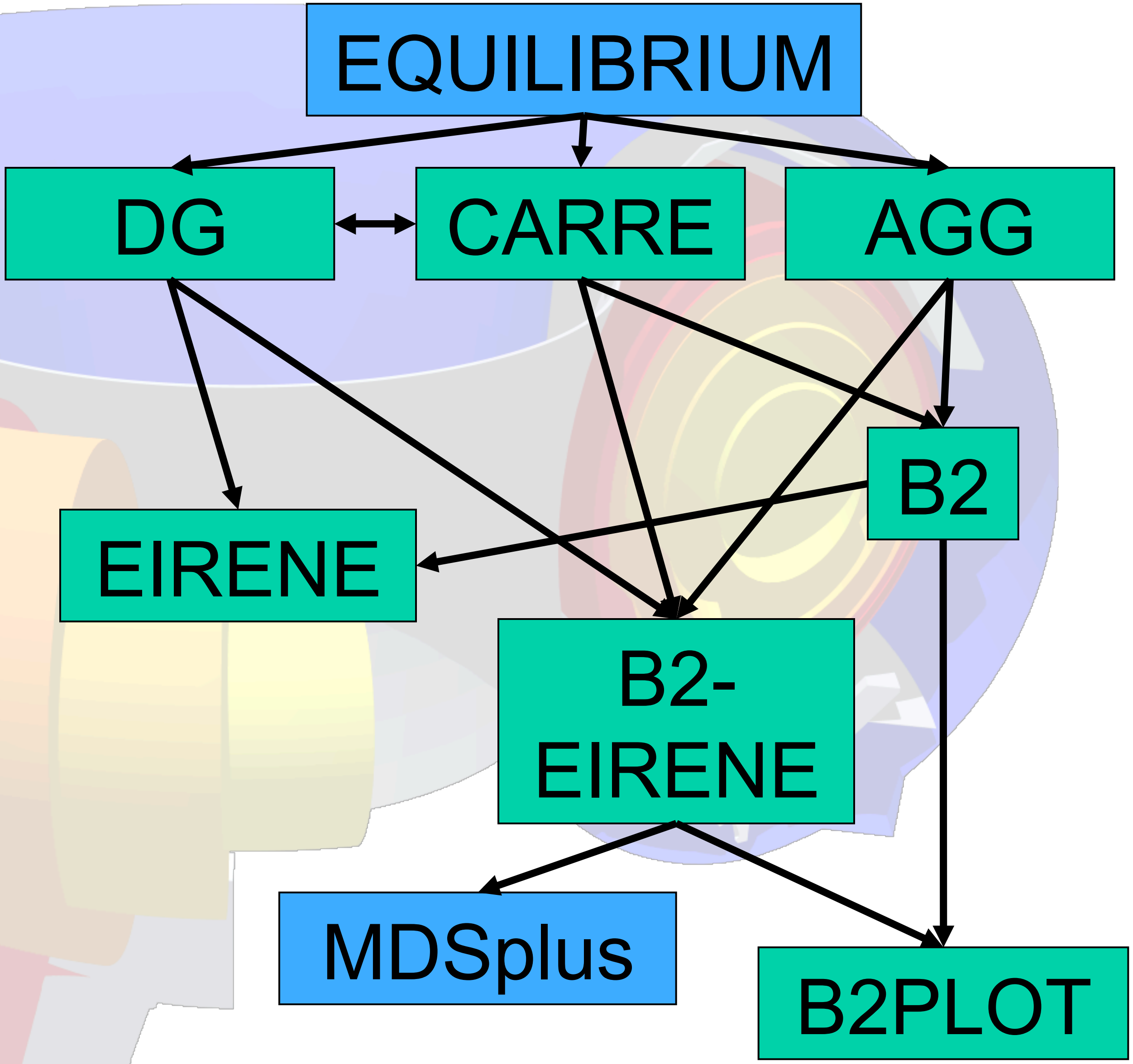
	Fluid	**Kinetic**
Dimensionality	2D	2D or 3D
Speed	Fast	Slower
Accuracy	Satisfactory upstream	Good everywhere
Ease of including details of structures	Difficult	Relatively easy
Ease of including atomic/surface physics effects	Moderate	Relatively easy for most, more difficult for others
Convergence	No new complications	Monte-Carlo noise

Ultimately a choice between speed and accuracy

What is a typical code package for the SOL/divertor?: E.g. SOLPS?

Suite of codes

- Grid preparation
  - CARRE
  - DG
  - AGG
  - (TRIANG)
- Plasma
  - B2, B2.5
- Neutrals
  - EIRENE
- Coupled
  - B2-EIRENE
- Visualization
  - B2PLOT



EQUILIBRIUM

DG

CARRE

AGG

B2

EIRENE

B2-EIRENE

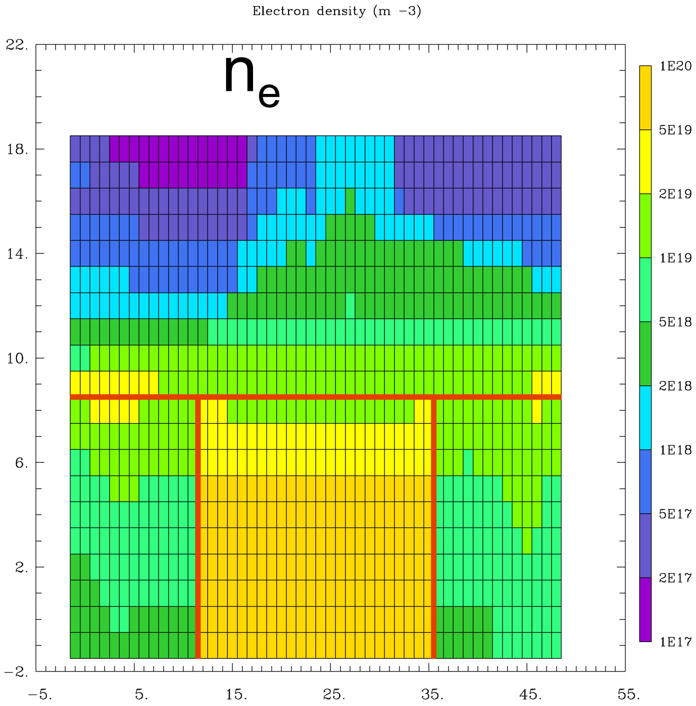
MDSplus

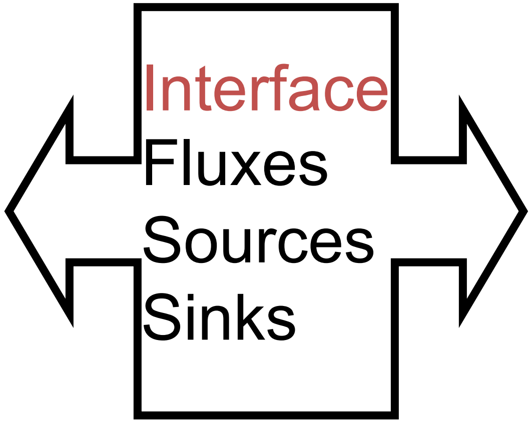
B2PLOT

Numerical tool

- Multi fluid code B2.5 (2D)
  - Solves modified fluid equations in 2D (Braginskii)
  - Includes fluid treatment of neutrals
  - Kinetic limits

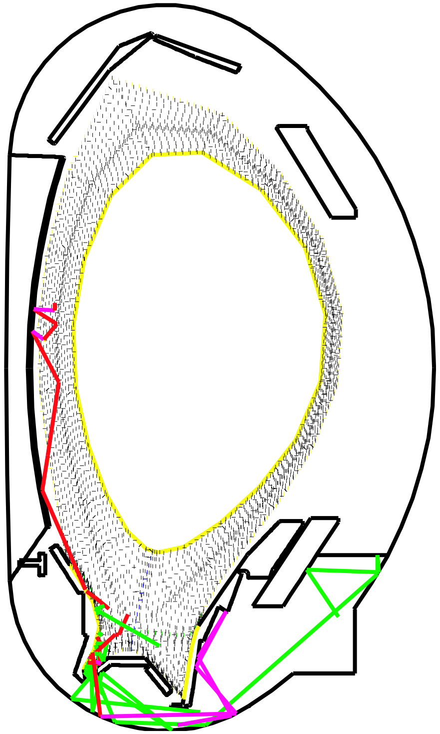
- EIRENE (’96, ’99), 3D
  - Solves time dependant linear transport equations for test particles (photons, neutrals, test ions)





Interface
Fluxes
Sources
Sinks

Can be time dependent



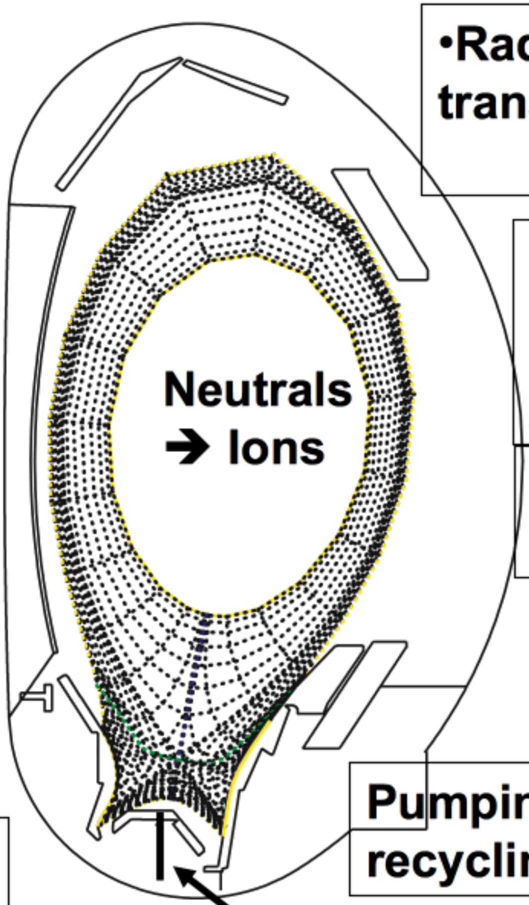
Common setup

- transport, atomic physics, gas puff, %He, density, drifts & no drifts

- Ion surface interaction only at targets, neutrals everywhere

- Chemical sput.: C not C_xD_y

Bohm chodura at targets $M > 1$



•Radially varying transport coefficients

Preset or feedback gas puff // fixed core boundary density //fluxes across core

Power crossing core boundary

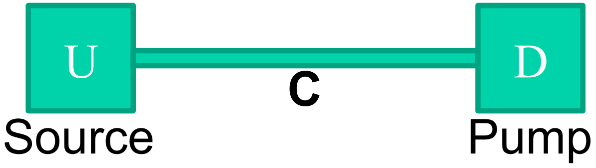
Pumping (walls/pumps) via recycling coefficient

Baffle for gas conductance

Basic considerations

Pumping speed at pump entrance

$$Q = P\frac{dV}{dt} \Rightarrow S \equiv \frac{Q_p}{P_p}$$



Def. of conductance:

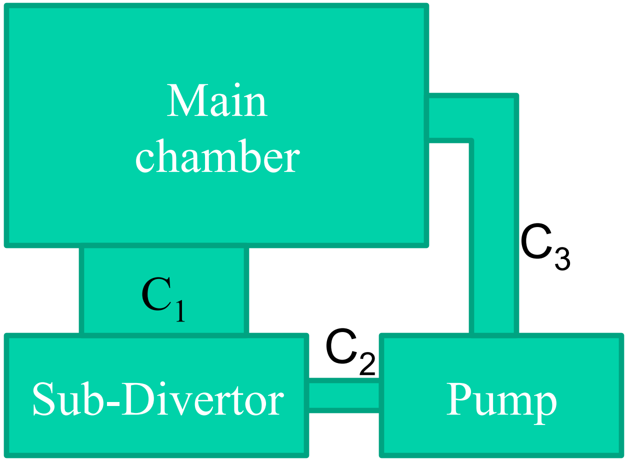
$$Q = C(P_u - P_d)$$

Because of continuity we have:

$$S_{net} = \frac{P_d}{P_u} S_p = \frac{S}{K_p}$$

$$K_p = 1 + \frac{S}{C}$$

AUG as a simple vacuum system



- Gas source are in main chamber and divertor
- Plasma acts both source and sink
- ideally one would like C_3=0 and C_2 >>S. Unfortunately this is not the case!

- Need to know the conductances and intrinsic pumping speed!

In-vessel pressure measurements

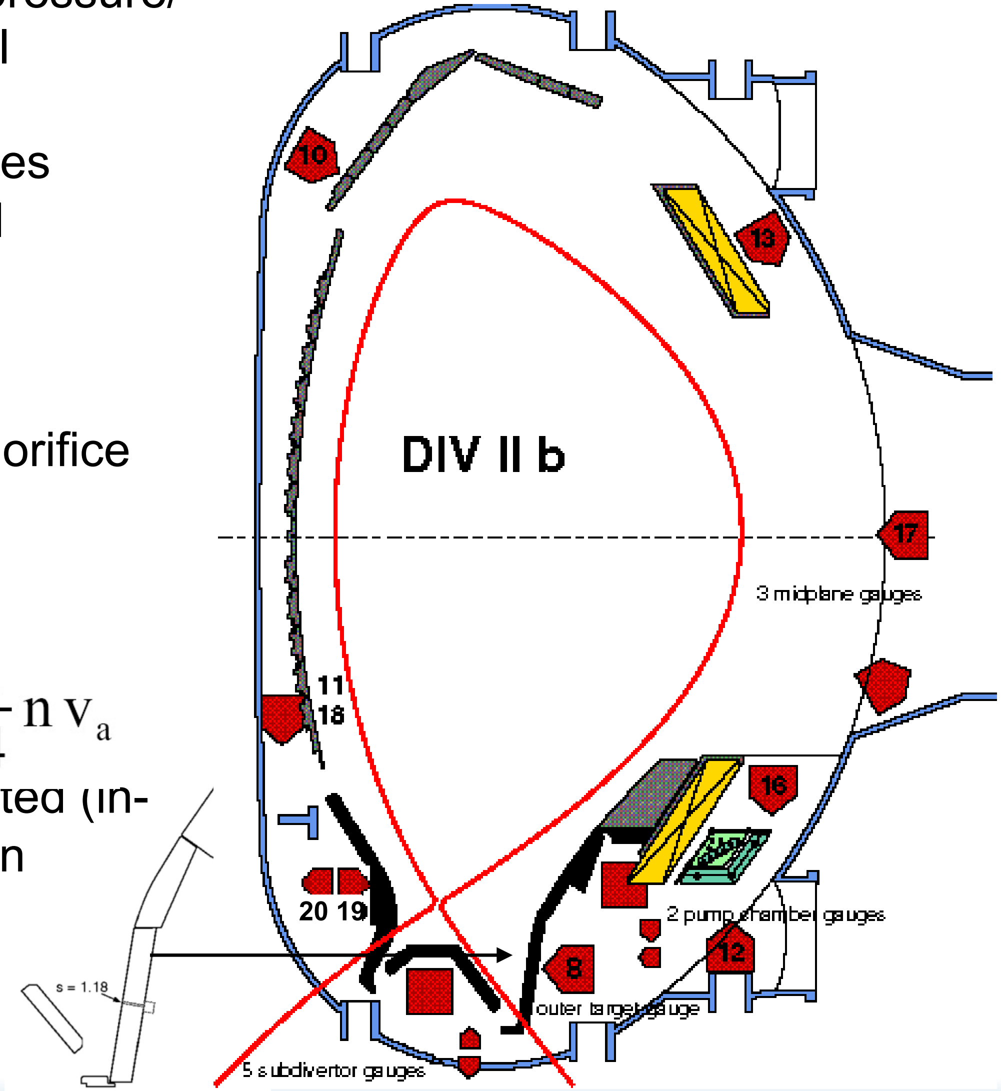
- We can get **S** and **C** by matching the pressure/ flux density distribution inside the vessel

- AUG equipped with 20 ionisation gauges ("ASDEX" type) for polodal and toroidal coverage

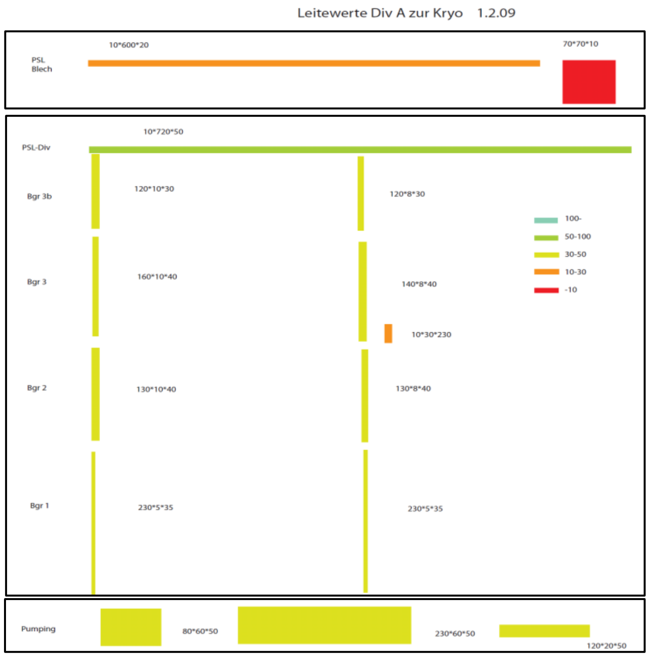
- Gauges installed in a box with a small orifice on top ⇒ measures neutral flux density:

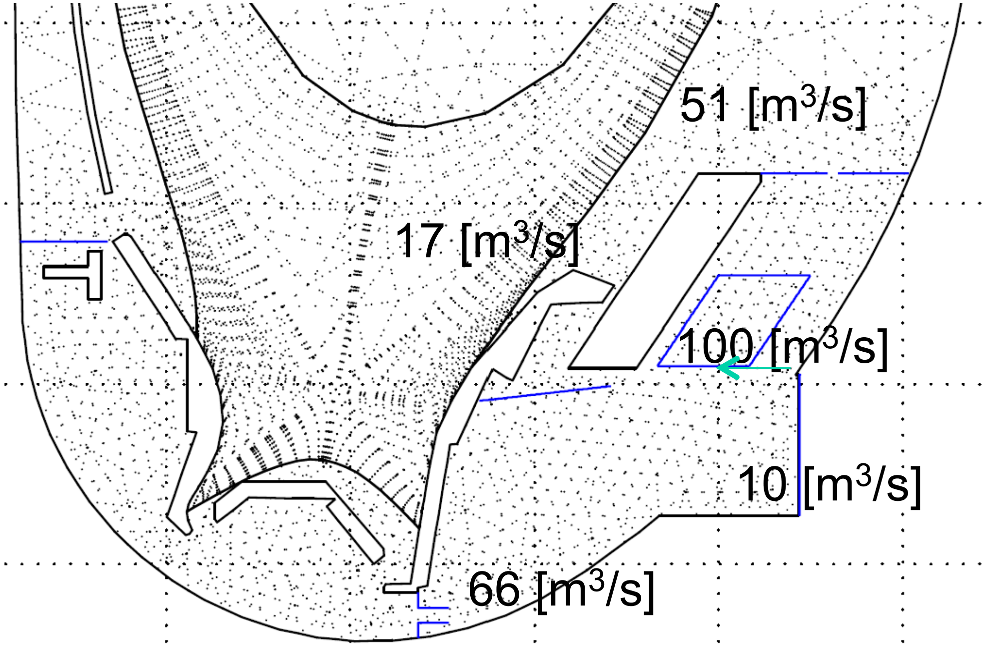
$$\Gamma = \frac{1}{4}\iiint f_n|\vec{v}|\,d\vec{v} = \frac{1}{4}n\sqrt{\frac{8}{\pi}\frac{k_B T}{m}} = \frac{1}{4}n\,v_a$$

- 1ms typical time resolution and calibrated (in-situ) with 10% accuracy against Baratron



AUG conductance modelling in FMR





- The AUG poloidally and toroidally distributed ducts (3D) can be mimed in EIRENE with poloidally distributed (2D) (and toroidally uniform) ducts preserving the total effective conductance in free molecular regime

model	AUG ducts	EIRENE model
Main chamber to pump chamber	51 [m^3/s]	1.5cmx10.37mx0cm
Divertor to pump chamber	17 [m^3/s]	1cmx10.37x3.5cm
Sub-divertor to pump chamber	66 [m^3/s]	3.2cmx10.37mx5cm
Total	134 [m^3/s]	

Model assumption on perpendicular plasma transport

D or v?

$$\boxed{\Gamma_\perp = \overbrace{-D\frac{\partial n}{\partial r}}^{\text{diffusive}} \overbrace{+\, v_\perp n}^{\text{convective}}}$$

- The fluid codes only use Γ in the calculations, information about the underlying nature is lost

- The SOL density depends on the sources and varies in the simulations, leading to rapid changes in Γ_{conv}=> using Γ_{diff} tends to be significantly more stable (practical choice)

- Divertor transport may be sensitive to the model applied upstream

L. Aho-Mantila TTF 2014

Diffusive or convective perpendicular plasma transport model for the code

D or v?

Radial flux: $\Gamma_{diff} = -D\frac{\partial n}{\partial r}$ or $\Gamma_{conv} = v_{\perp}n$

Assuming a density profile: $n(r) = n_0 e^{-r/\lambda_n}$

Then with $v = \sqrt{\frac{D}{\tau_{||}}}$ we get $\Gamma_{diff} = \Gamma_{conv}$

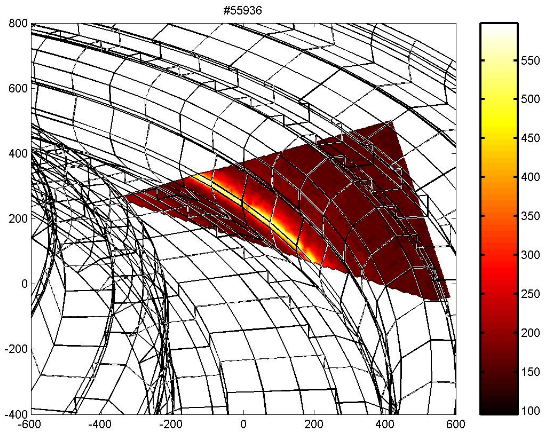
$$\lambda_n = \sqrt{D\tau_{||}} = v\tau_{||}$$

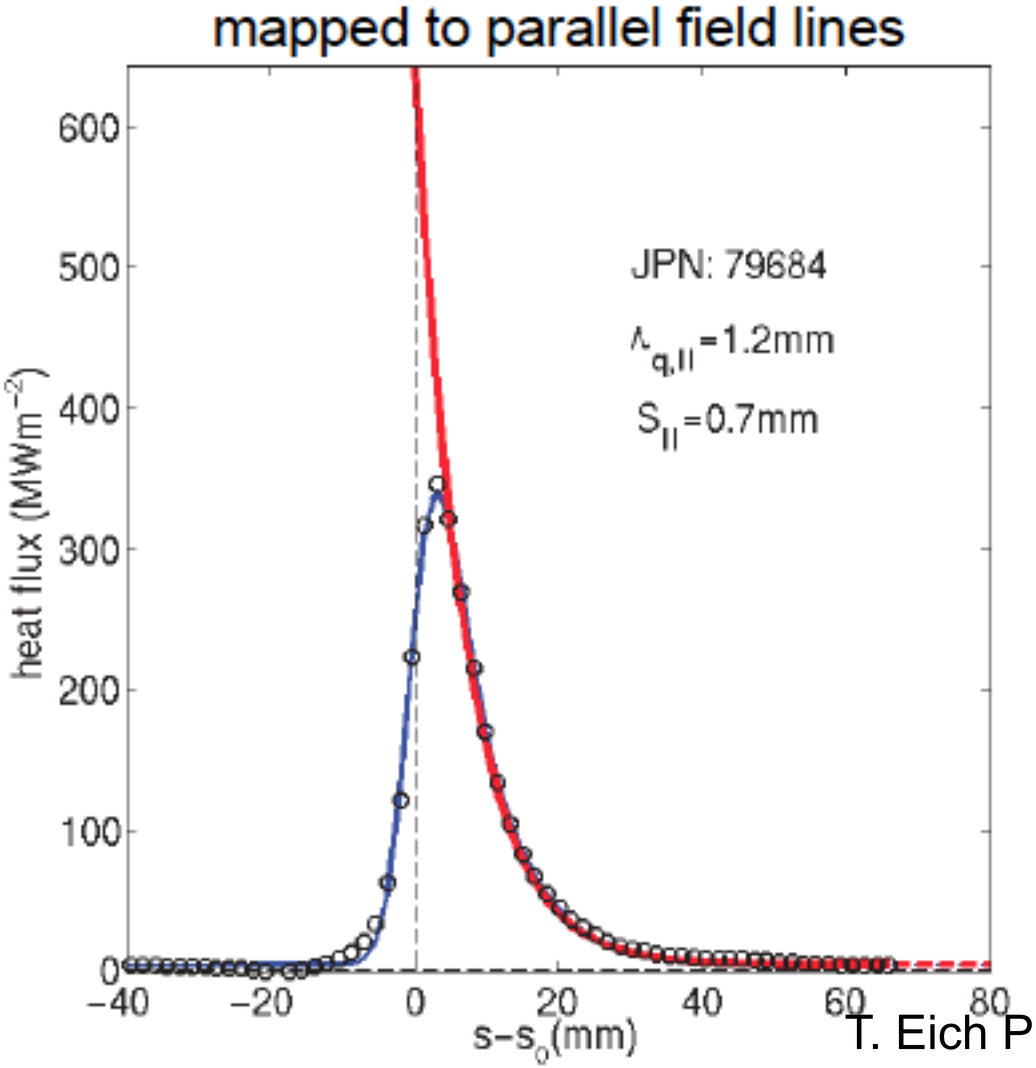
M. Wischmeier,
PhD thesis 2004

Width of Scrape-Off Layer?
What is the power flux?

Measuring power deposition profile

Infrared image of target

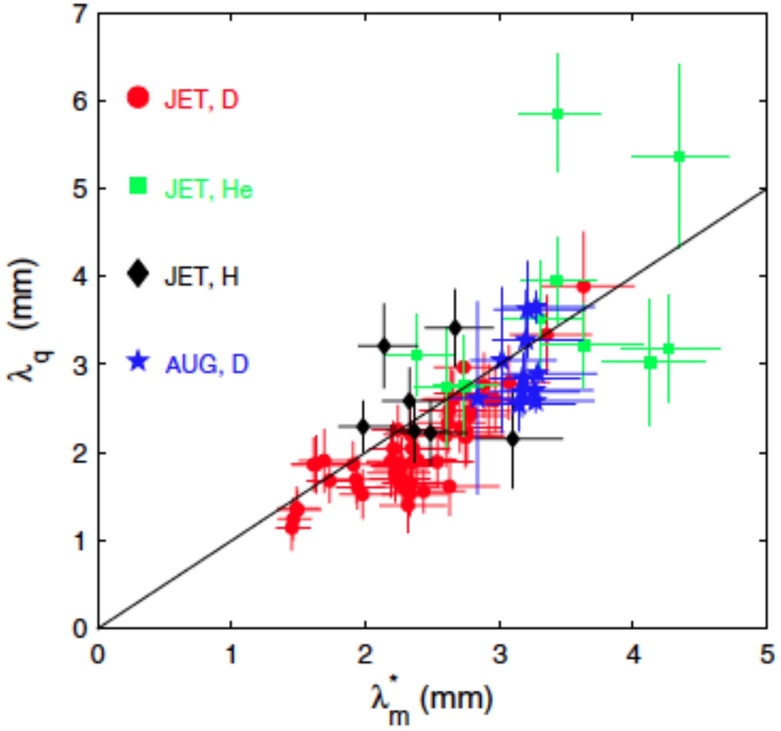




T. Eich PSI 2012

The power decay length λ_q

H-mode (reduced turbulent transport)



T. Eich PRL (2011), T. Eich IAEA FEC 2012, A. Scarabosio PSI 2012

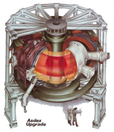
$$\lambda_q = 0.73 \cdot B_{tor}^{-0.78} \cdot q_{cyl}^{1.20} \cdot P_{SOL}^{0.10} \cdot R_{geo}^{0.02}$$

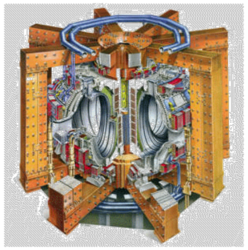
(Carbon divertor, attached conditions, inter ELM)

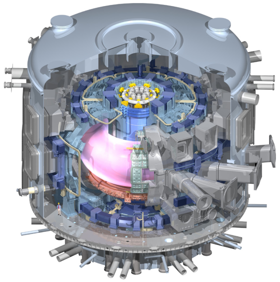
No dependence on machine size R

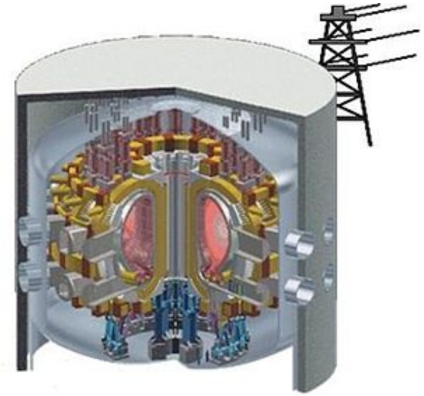
What is the power flux density in the SOL?

Importance of tokamak size R









	ASDEX Upgrade (IPP)	*JET (EU)*	*ITER*	*DEMO*
Major Radius	*1.65 m*	*3 m*	*6.2 m*	*>7 m*
P_{heat}	*23 MW*	*~ 38 MW*	*~ 100 MW*	*~ 600 MW*

Good energy confinement ➔ large R ($P_{fus} \sim R^3$)

P/R as figure of merit

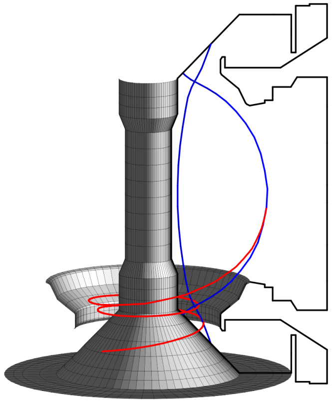
A measure of the severity of the heat flux is

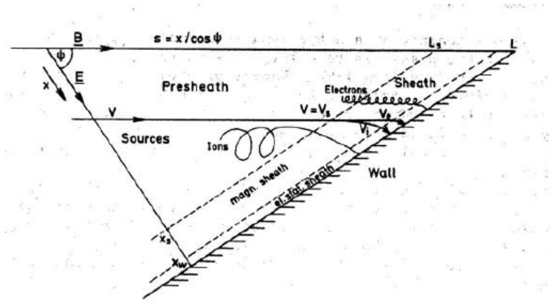
- **P_{heat}/R**

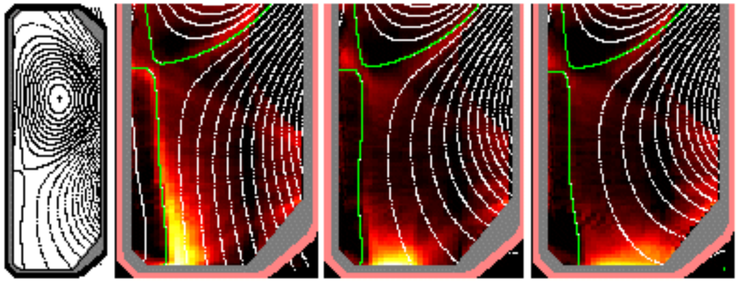
M. Kotschenreuter et al. NF 50 2010
K. Lackner Comm. PPCFusion 15 1994

Device	P_{heat}/R	$q_{\|\|}$ upstream
JET	7	2 GW/m^2
ASDEX Upgrade	14	3.5 GW/m^2
ITER	20	5 GW/m^2
DEMO	80-100	>30 GW/m^2

Power load reduced by geometry







a) #17823 b) #17824, $f_e = 2.8$ c) #17823, $f_e = 6.4$ d) #17822, $f_e = 9.3$

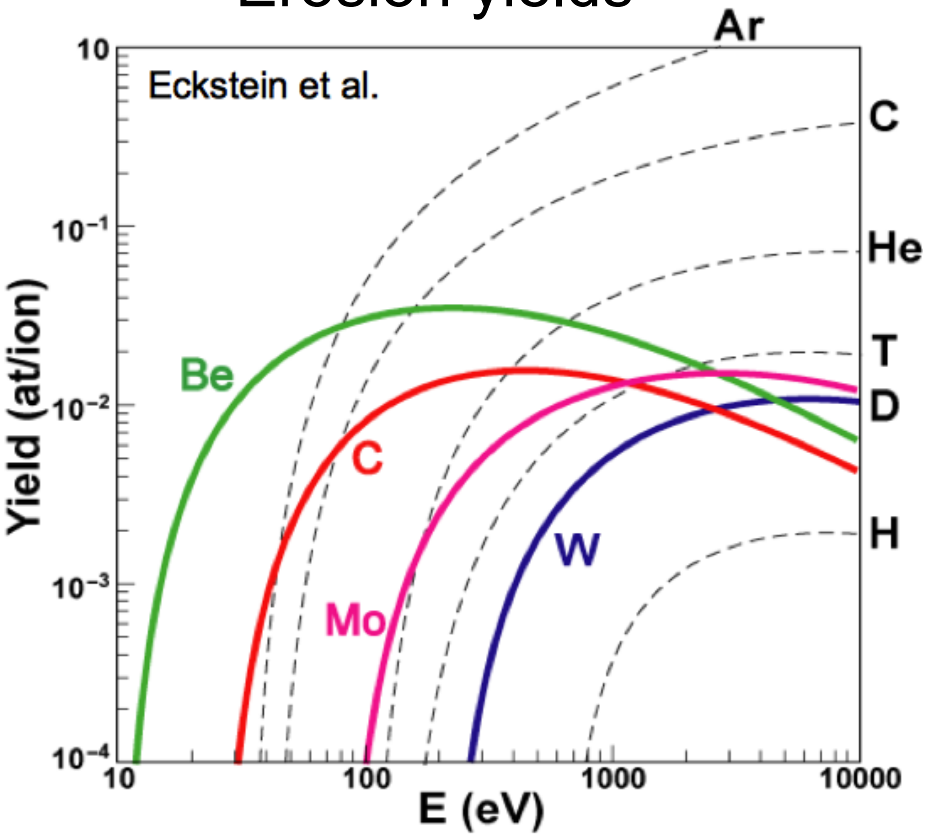
Device	**P_{heat}/R**	**$q_{||}$ upstream**	**q target (geometry)**
JET	7	2 GW/m^2	20 MW/m^2
ASDEX Upgrade	14	3.5 GW/m^2	35 MW/m^2
ITER	20	5 GW/m^2	50 MW/m^2
DEMO	80-100	>30 GW/m^2	300 MW/m^2

What are the limitations imposed by wall materials?

Erosion limits maximum Temperature

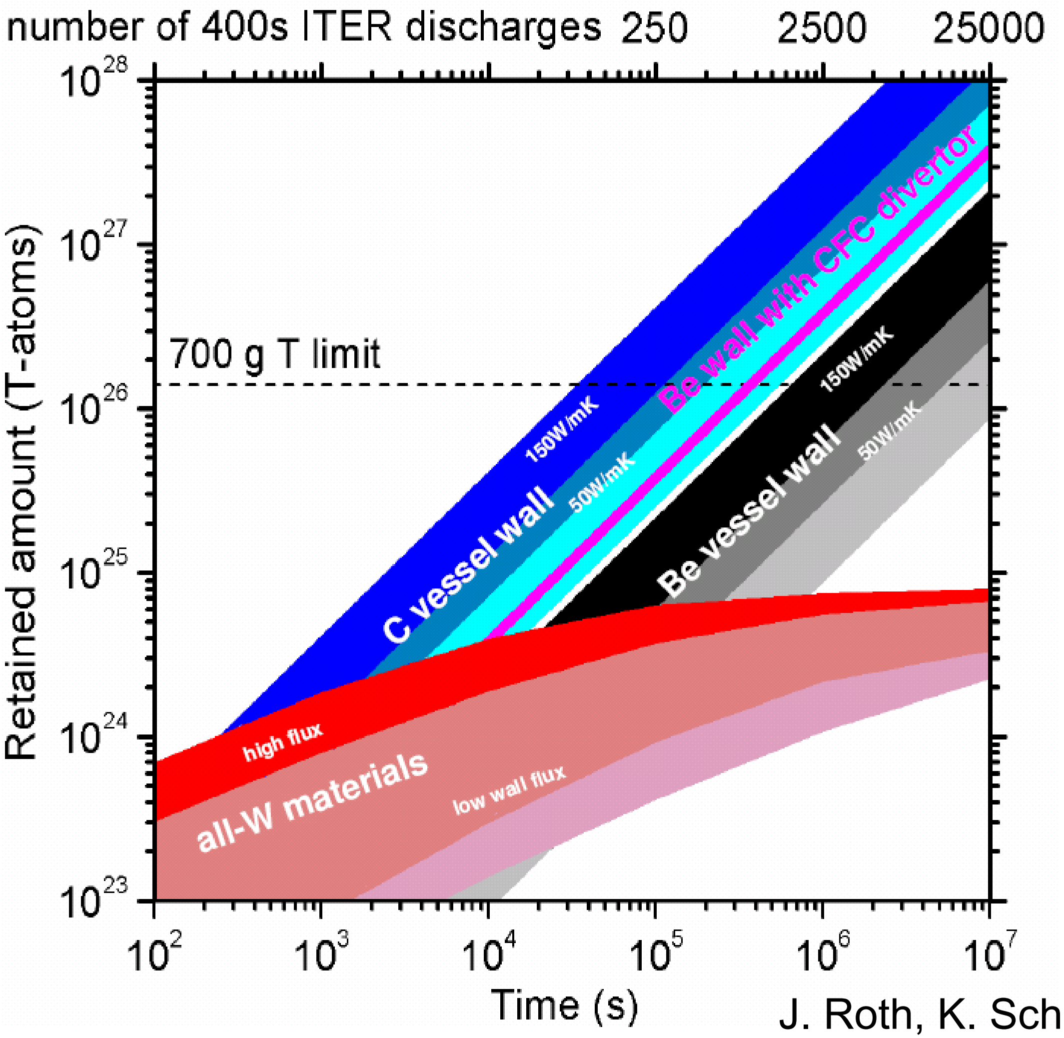
Ions accelerated to energies
~ Z x 3.5 x T_e in electrical field by
sheath potential

Erosion yields



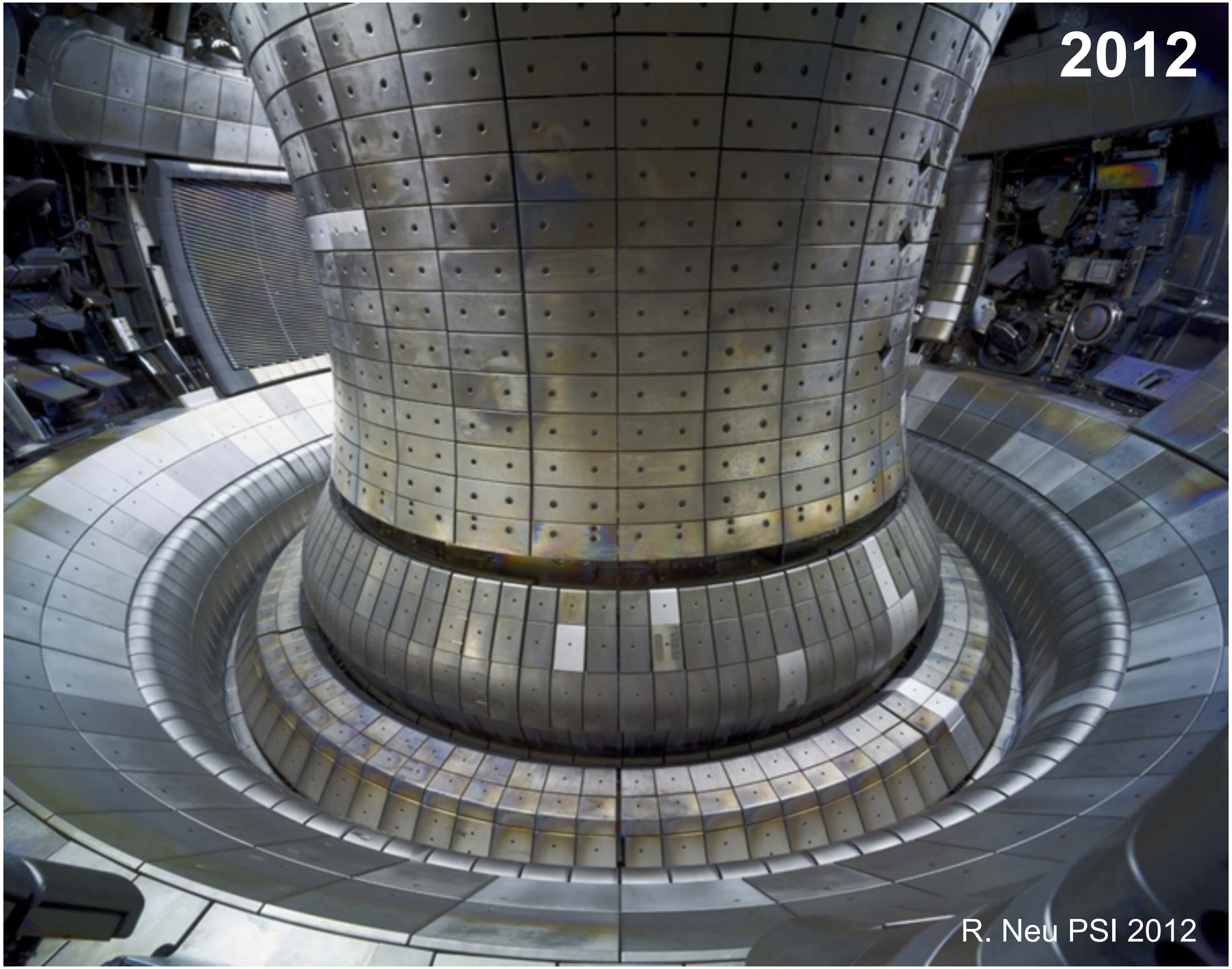
W has low Yield

Tritium retention



J. Roth, K. Schmid, Phys Scripta 2011

All tungsten plasma facing components in ASDEX Upgrade

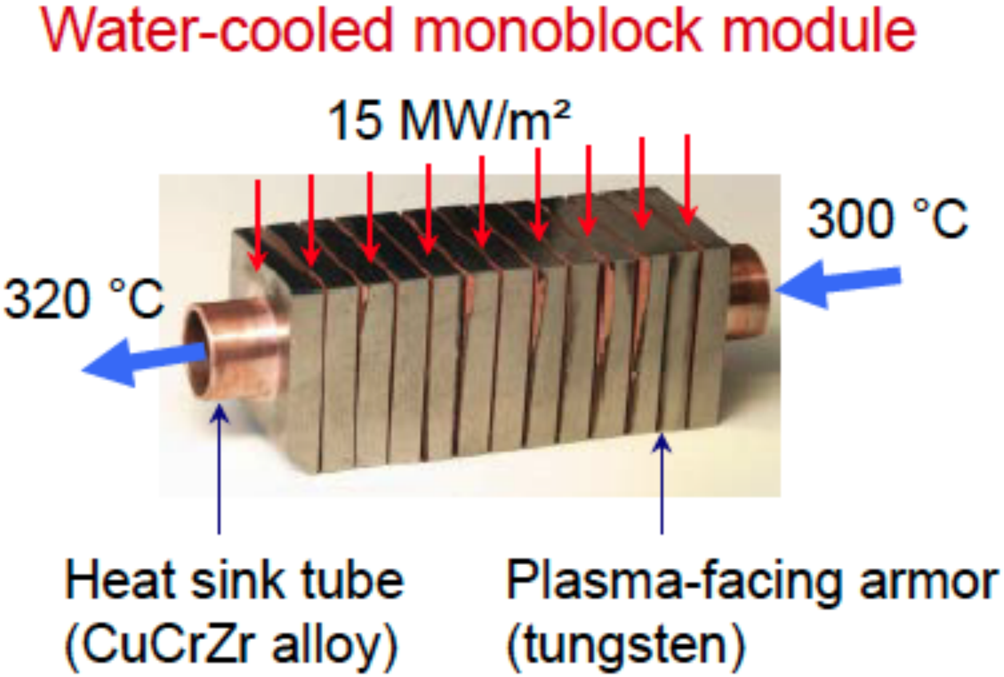


2012

R. Neu PSI 2012

Technological limits under neutron irradiation for a reactor beyond ITER?

Integrated approach:
Combination of coolant, structural material of coolant pipe and armour material?

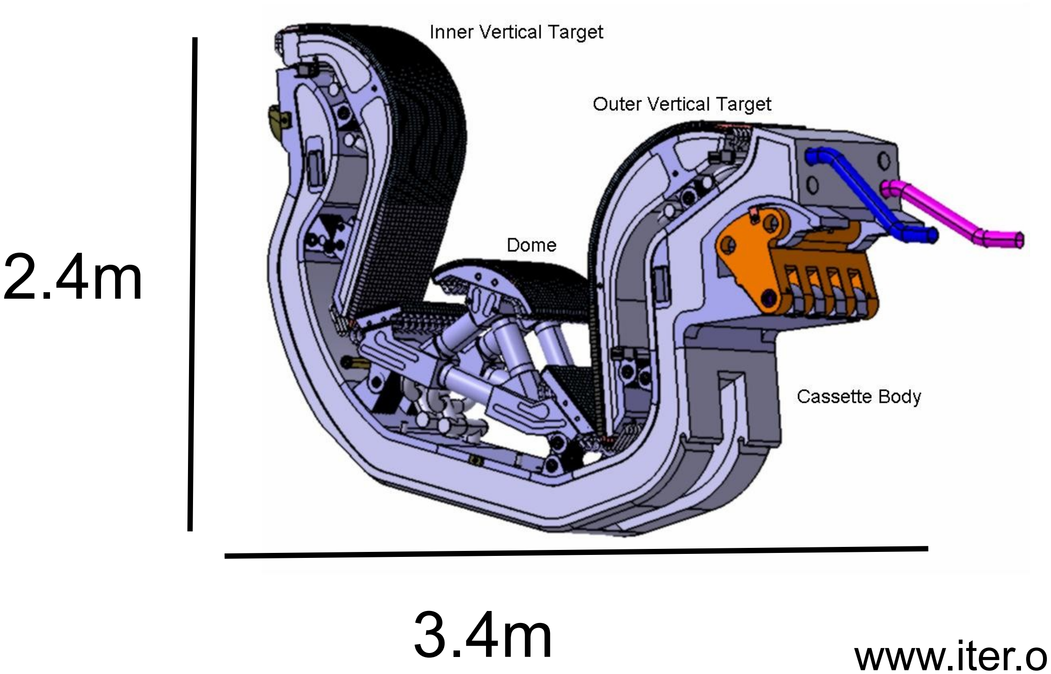


E.U. protoype monoblock

Water cooled divertor segment

10MW/m^2 to 5MW/m^2 is the technological limit

Divertor example



www.iter.org

How can we reduce the power load onto the divertor target plates to match the technological limit?

Divertor Regimes: sheath limited

P_{SOL}

Γ_{SOL}

Convected

Sheath limited regime,
No temperature gradient

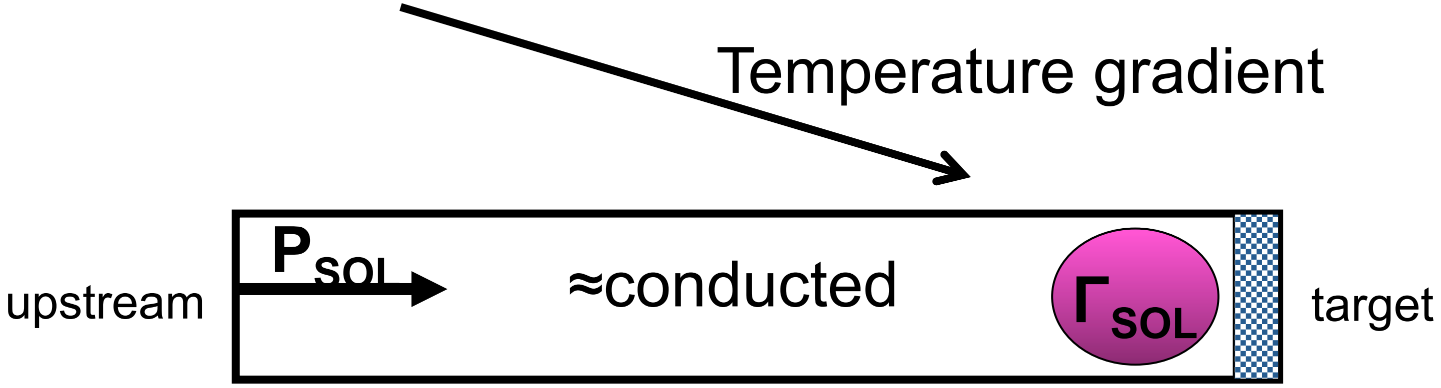
Upstream

Target

T_e at target > 40eV
No reduction of power load

Divertor Regimes: high recycling

Total plasma pressure is constant along magnetic field line
$P_e + P_i$ + dynamic pressure = constant



Temperature gradient

upstream

P_{SOL}

≈conducted

Γ_{SOL}

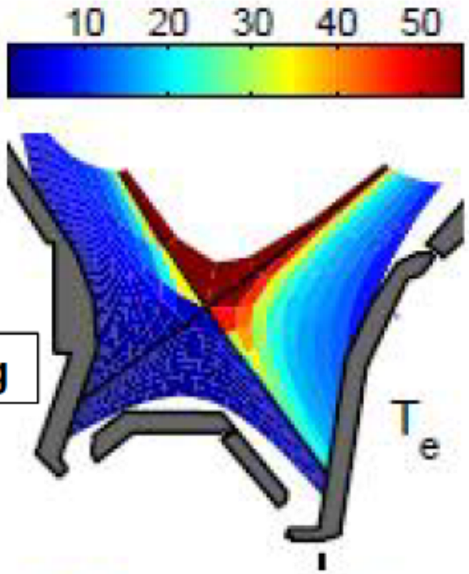
target

➔ High recycling regime: low T_e (< 5eV), high n_e
➔ Satisfactory for existing tokamaks
➔ VERY HIGH PARTICLE FLUXES

Cold divertor by high density and/or impurity seeding

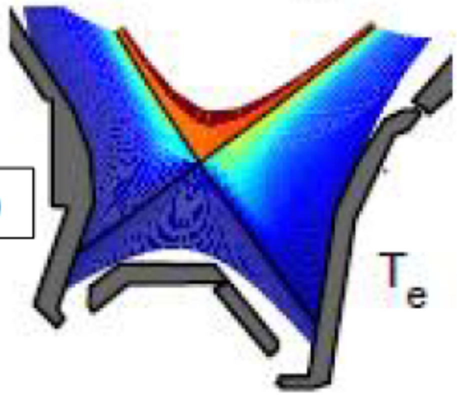
Divertor power dissipation can be controlled also locally by impurity seeding

- Seeding a small amount of low-Z impurities leads to local radiation losses and cooling



Low n_{sep} + N seeding

- High D fuelling required to dissipate power, leading to higher upstream density/collisionality



High n_{sep} (D fuelling)

Neglecting power loads on PFCs from radiation

➔ *Total power* = $(8T + 13.6 + 4.5)\ 1.602\ 10^{-19}\ \Gamma\ [W]\ ;\ T_e = T_i = T\ [eV]$

Power across sheath Surface recombination of D^+ Recombination of D to D_2^{**}

- *For $T_e < 2$ eV → heat flux similar to power deposited by surface recombination processes**
- *Power load via radiation to ~2 MW/m²* (*for ITER* A. Loarte et al. PoP 2011)
- *5 MW/m² with T = 1.5 eV* ➔ $\Gamma < 5e23\ m^{-2}s^{-1}$

*see also: "ITER Physics basis: Chapter 4, power and particle control", Nucl. Fusion 39 (1999) 2391 and A. Loarte Nucl. Fusion 2007

** 2.2eV for recombination if one assumes saturated surface,even less if assume transformation into vibrational excitation via Elay-Rideal process

For ITER (10 MW/m^2 target limit): ~60 - 80% of total plasma heating power needs to be radiated + Ion flux to target reduced to ~$10^{24} m^{-2} s^{-1}$
(60-70% of power entering SOL)

For ITER (10 MW/m^2 target limit): ~60 - 80% of total plasma heating power needs to be radiated + Ion flux to target reduced to ~10^{24}m^{-2}s^{-1}

(60-70% of power entering SOL)

For DEMO (5 – 10 MW/m^2 target limit):

> 95% of power need to be radiated + Ion flux to target reduced to *5 10^{23}m^{-2}s^{-1}*

With divertor of similar size to ITER and radiative power ➔

- *70% of power radiated inside LCFS*
- *Radiation limited mostly to edge/pedestal for core performance*

In addition limit Target T_e to 2eV - 5eV to limit annual erosion of PFCs by impurities

Power flux can be dropped to < 5MW/m^2 (see H. Zohm DEMO talk) in existing devices with high P/R

How is the particle flux limited?

“Modified” two point model as guidance

$$\begin{aligned}
T_t &= \frac{q_{\|}^2}{n_u^2}\left(\frac{7q_{\|}L_c}{2\kappa_{0e}}\right)^{-4/7}\frac{2m_i}{\gamma^2e^2}\frac{(1-f_{pow})^2}{(1-f_{mom})^2(1-f_{conv})^{4/7}}\\
n_t &= \frac{n_u^3}{q_{\|}^2}\left(\frac{7q_{\|}L_c}{2\kappa_{0e}}\right)^{6/7}\frac{\gamma^2e^3}{4m_i}\frac{(1-f_{mom})^3(1-f_{conv})^{6/7}}{(1-f_{pow})^2}\\
\text{Particle flux}\quad \Gamma_t &= \frac{n_u^2}{q_{\|}}\left(\frac{7q_{\|}L_c}{2\kappa_{0e}}\right)^{4/7}\frac{\gamma e^2}{2m_i}\frac{(1-f_{mom})^2(1-f_{conv})^{4/7}}{(1-f_{pow})}
\end{aligned}$$

f_{pow}: power loss factor (0 – 1) → What is the maximum value?
f_{conv} : 0=no convection; 1= only convection → What is the interplay?
f_{mom}: momentum loss factor (0 – 1) → What is the maximum?

- Value of the loss factors and what interdependence?
- System codes will require scaling laws to define operational regime of DEMO type device

Divertor Regimes: detachment

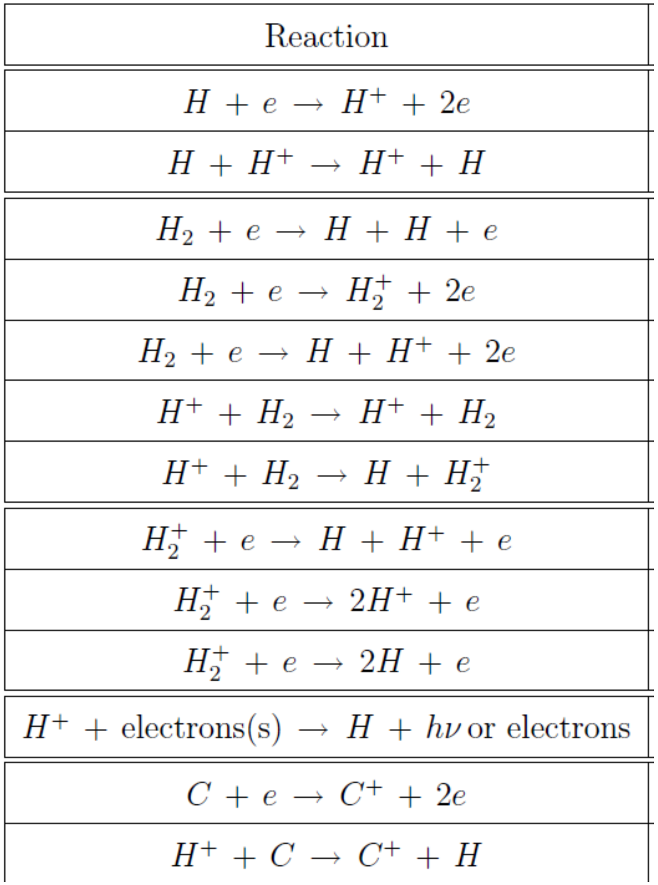
Prerequisite: Loss of plasma pressure

a) Radiation in the edge of the plasma core

➔ Reduction of upstream plasma pressure

➔ Reduced recycling

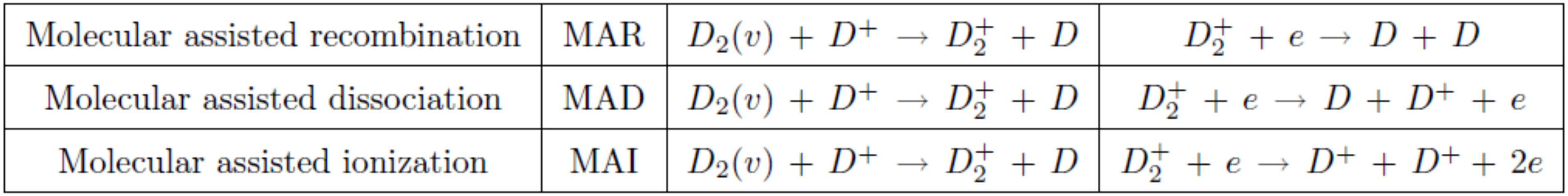
At low Te large Complexity of volumetric and surface processes



Reaction
$H + e \rightarrow H^+ + 2e$
$H + H^+ \rightarrow H^+ + H$
$H_2 + e \rightarrow H + H + e$
$H_2 + e \rightarrow H_2^+ + 2e$
$H_2 + e \rightarrow H + H^+ + 2e$
$H^+ + H_2 \rightarrow H^+ + H_2$
$H^+ + H_2 \rightarrow H + H_2^+$
$H_2^+ + e \rightarrow H + H^+ + e$
$H_2^+ + e \rightarrow 2H^+ + e$
$H_2^+ + e \rightarrow 2H + e$
$H^+ +$ electrons(s) $\rightarrow H + h\nu$ or electrons
$C + e \rightarrow C^+ + 2e$
$H^+ + C \rightarrow C^+ + H$

+ seeded processes for impurities…

+ surface interaction physics (reflection, recycling)



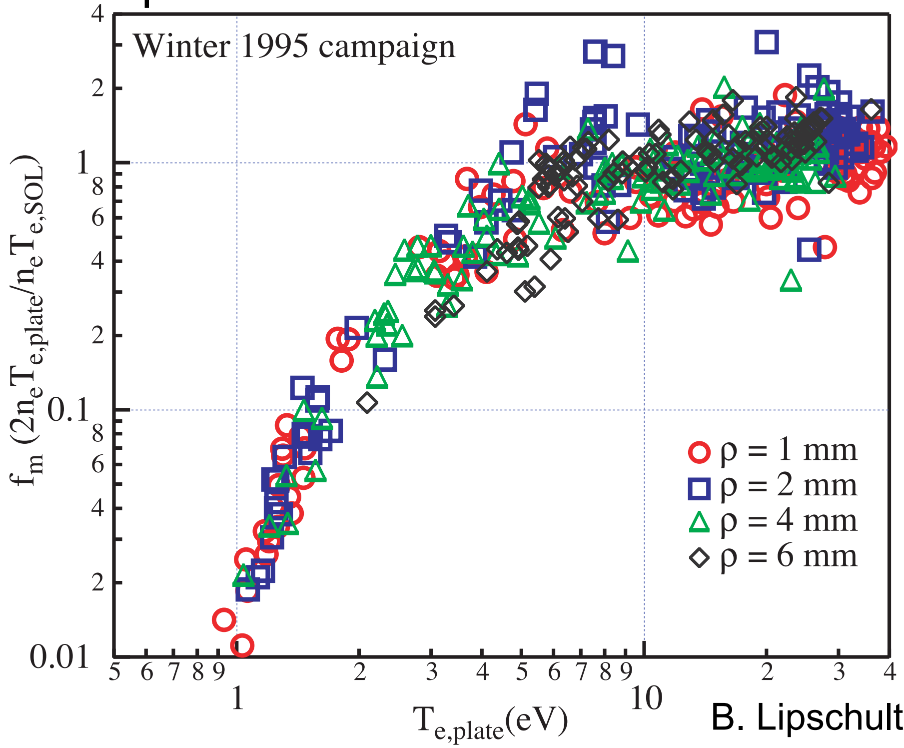
Molecular assisted recombination	MAR	$D_2(v) + D^+ \rightarrow D_2^+ + D$	$D_2^+ + e \rightarrow D + D$
Molecular assisted dissociation	MAD	$D_2(v) + D^+ \rightarrow D_2^+ + D$	$D_2^+ + e \rightarrow D + D^+ + e$
Molecular assisted ionization	MAI	$D_2(v) + D^+ \rightarrow D_2^+ + D$	$D_2^+ + e \rightarrow D^+ + D^+ + 2e$

Divertor Regimes: detachment

b) Pressure loss along field line

- ❖ perpendicular transport (independent of T_e)
- ❖ CX reaction losses (T_e<5eV)

Ratio of target plasma pressure to upstream pressure for C-Mod



B. Lipschultz et al., FST 51 (2007)

$$D + D^+ \rightarrow D^+ + D$$
$$D^+ + D_2 \rightarrow D_2 + D^+$$

Competes with ionization

Divertor Regimes: detachment

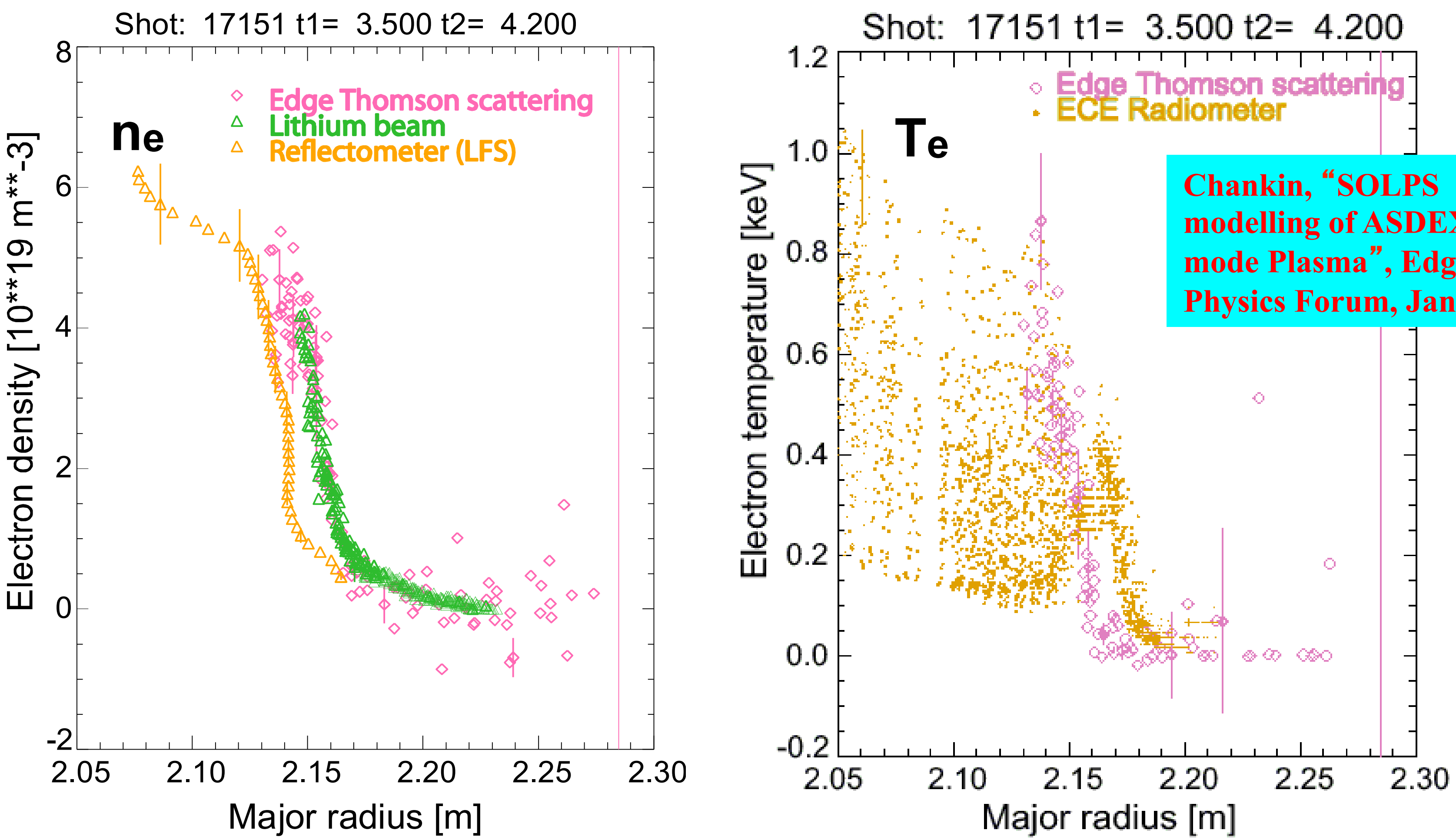
Prerequisite: Loss of plasma pressure on a field line

b) Pressure loss along field line
- perpendicular transport (independent of T_e)
- CX reaction losses (T_e<5eV)

How do we apply these codes…?

Edge/pedestal profiles

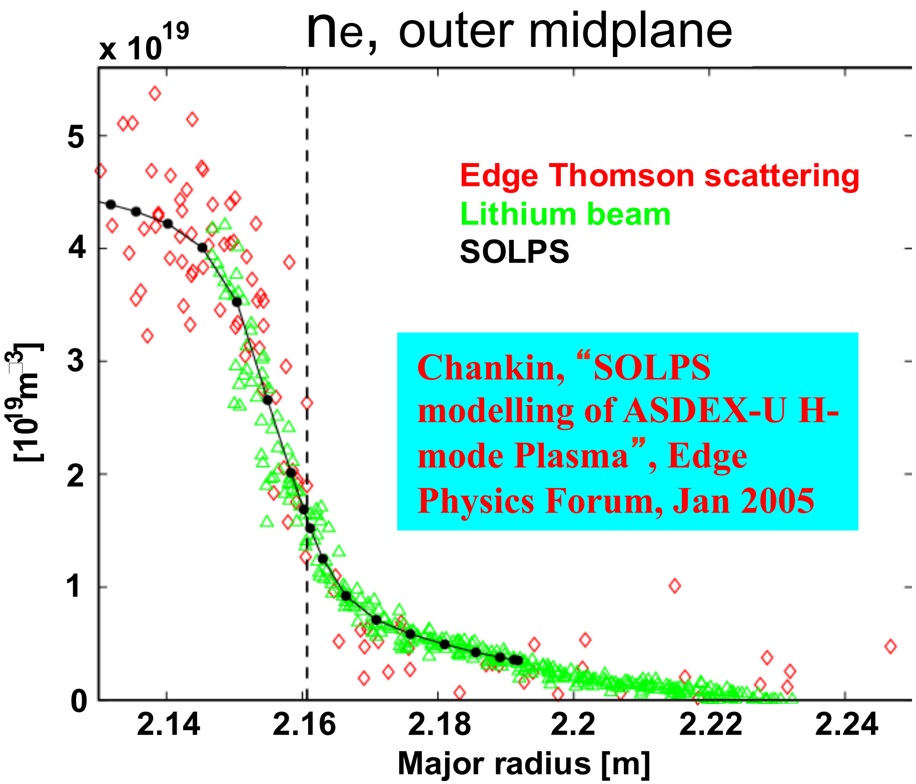
Elm sync: -5,-0.5 ms



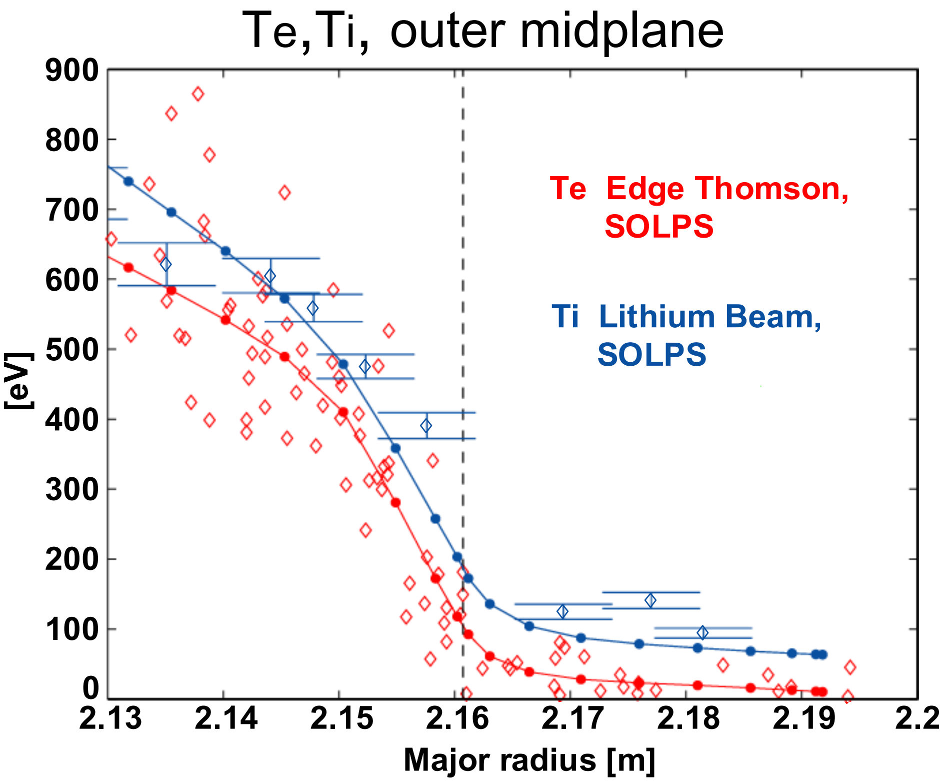
Chankin, "SOLPS modelling of ASDEX-U H-mode Plasma", Edge Physics Forum, Jan 2005

- Edge Thomson scattering (both ne and Te) and Lithium beam (ne) data ⇒ relationship between ne and Te, to be matched by SOLPS
- This relationship + constraint on the input power into SOLPS grid determines choice of separatrix position (if wrong → mismatch between ne and Te at sep.)

SOLPS solution - best fit to experimental profiles

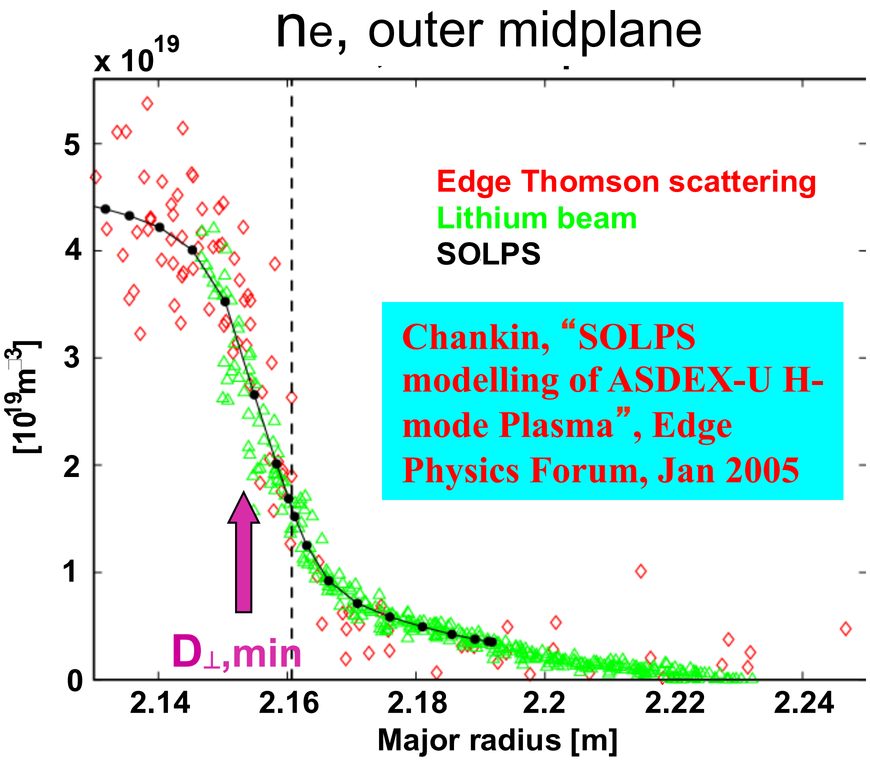

n_e, outer midplane

Chankin, "SOLPS modelling of ASDEX-U H-mode Plasma", Edge Physics Forum, Jan 2005

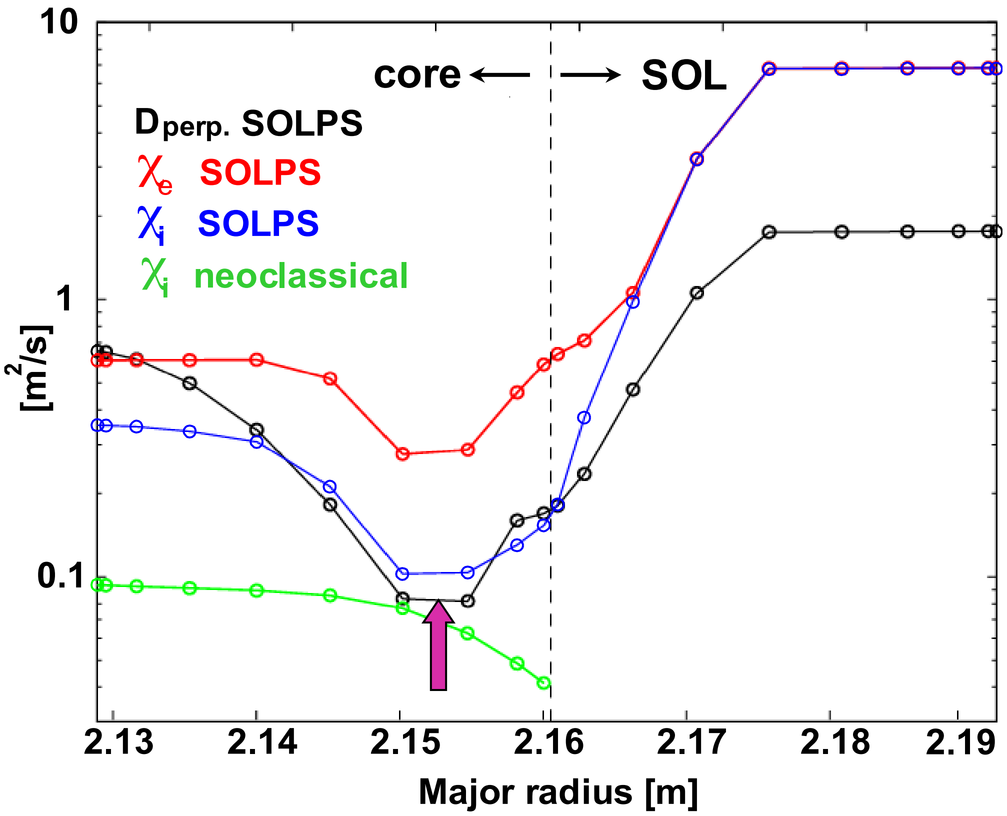

Te,Ti, outer midplane

- **SOLPS: $n_{e,sep} = 1.6 \times 10^{19}$ m^{-3}, $T_{e,sep}$ = 105 eV, $T_{i,sep}$ = 189 eV, assuming:**
  - equal sharing of input power into the grid between ion and electron channels
  - flux limits set for i/e parallel heat fluxes, 0.3 – for electrons, 1.0 – for ions
  - moderate ballooning of transport coefficients (~1/B)
  - only Carbon impurity. Phys. sputt. – fixed, Chem.sput.yield – varied to match Prad
  - no driftts

Transport coefficients – indicate transport barrier inside of sep.



Chankin, "SOLPS modelling of ASDEX-U H-mode Plasma", Edge Physics Forum, Jan 2005

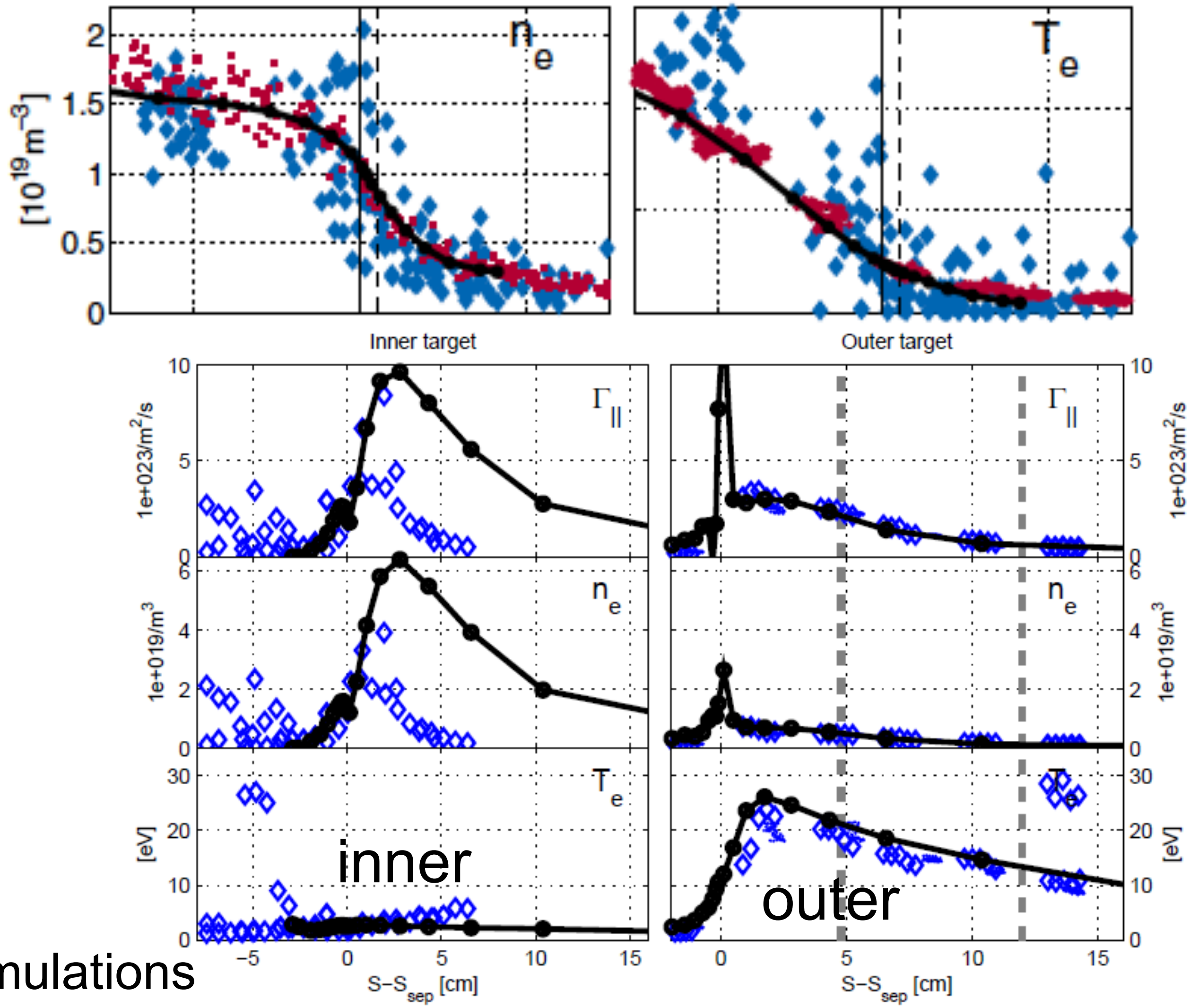


- $D_\perp$ has to be reduced to < 0.1 m^2/s inside of the separatrix, to describe measured n_e – profile (which is strongly affected by ionisation sources)
- Minimum of $D_\perp$ and χ_i inside of the separatrix is also obtained for an H-mode in Hydrogen (#17396, Pin=7.8 MW) (*L.D.Horton, IAEA-2004*)

Low recycling

Upstream

Targets

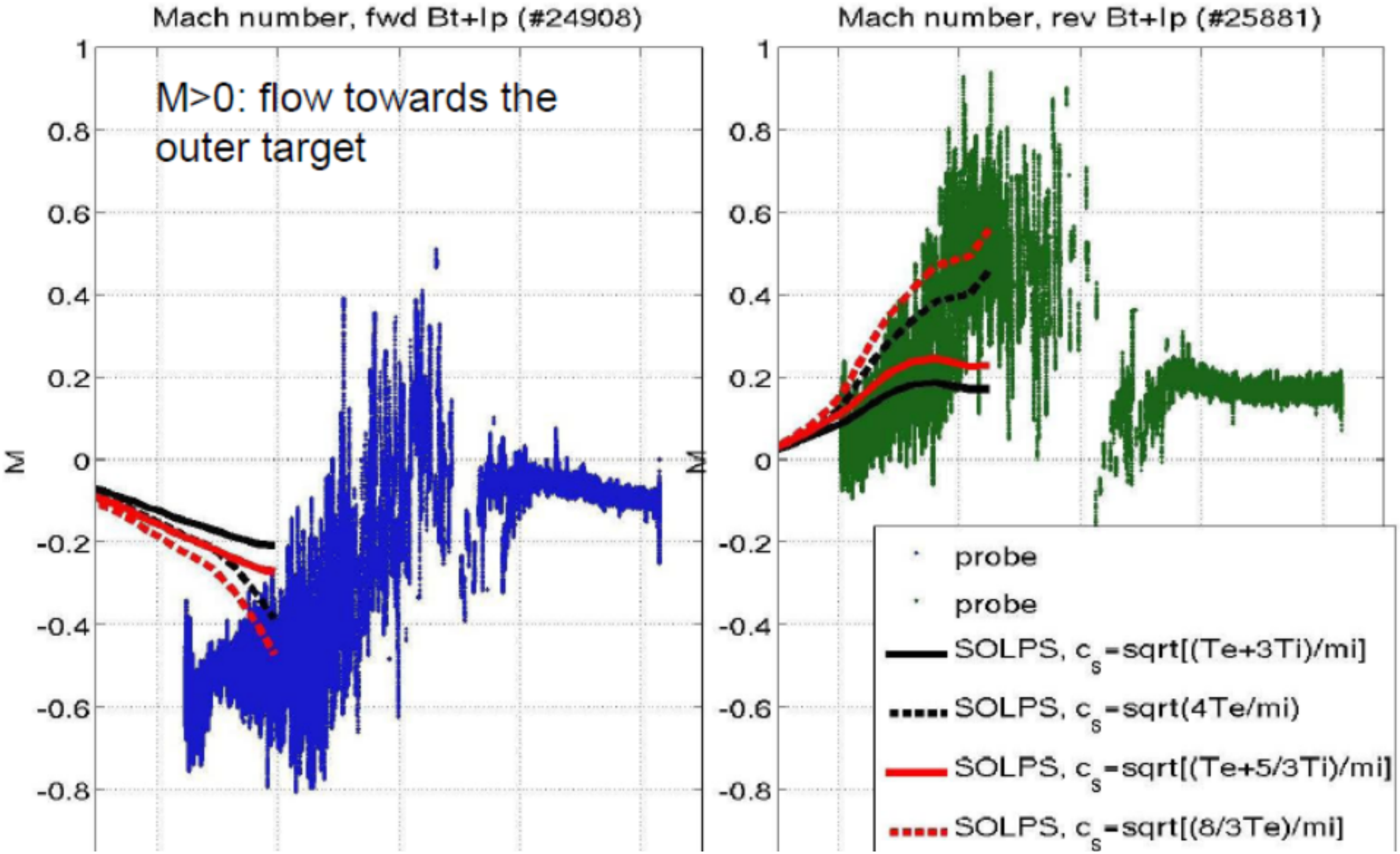


- SOLPS Simulations

Experiment

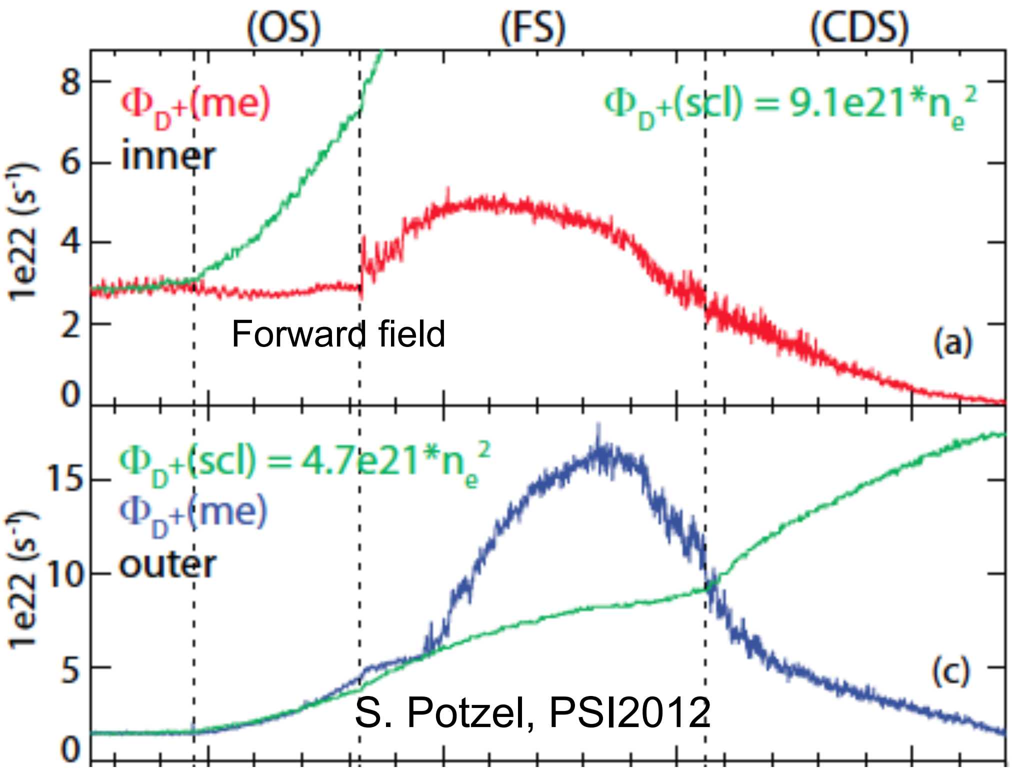
L. Aho-Mantila et al. NF 2012

Simulating flows in the SOL


M>0: flow towards the outer target

Density ramp experiments in ASDEX Upgrade

Total ion flux to inner and outer divertor



S. Potzel, PSI2012

Time /s = increase of density →

Signature of detachment:

- Volumetric recombination processes (visible in Balmer series)
- reduction of ion flux density on target plates

S. Potzel et al. NF 2014

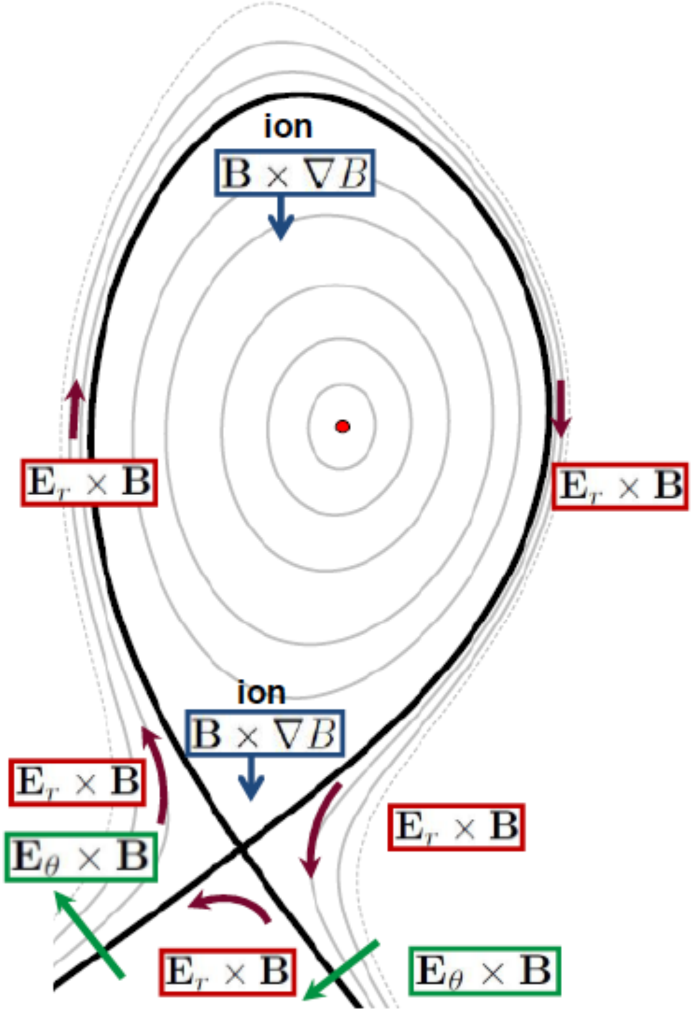
- Asymmetry of particle fluxes
- Integral ‘roll over’ at similar time/density for inner and outer

Direction of Drifts in the SOL

Drifts: electric potential is calculated self-consistently in each computational cell

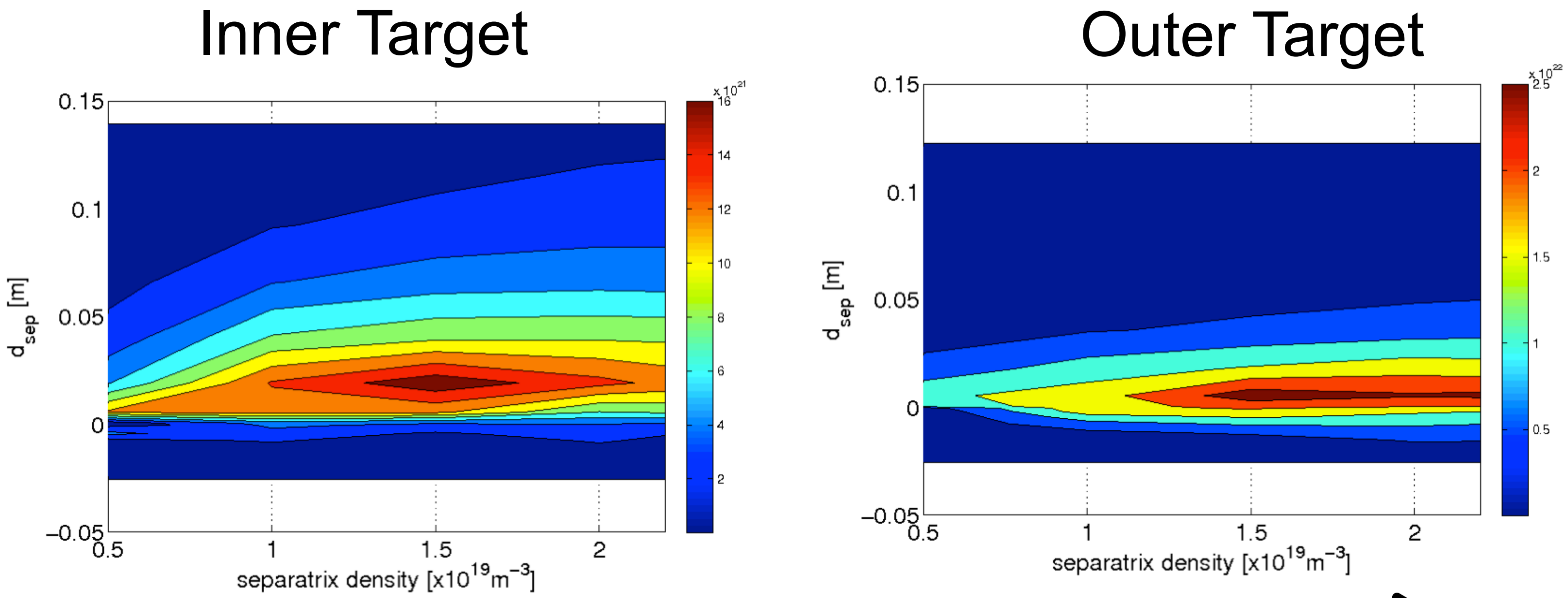
- Diamagnetic drift in the up-down direction, drives current and reverses with B
- **ExB drifts** in poloidal and radial directions, magnitude and direction depend on B and local plasma conditions

$$v_{E\times B} = \frac{\mathbf{E}\times\mathbf{B}}{B^2} \qquad v_{\nabla p} = \frac{\mathbf{B}\times\nabla\mathbf{p}}{enB^2}$$



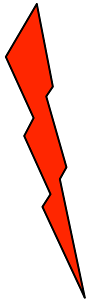
Simulations of ion flux density for ASDEX Upgrade L-mode

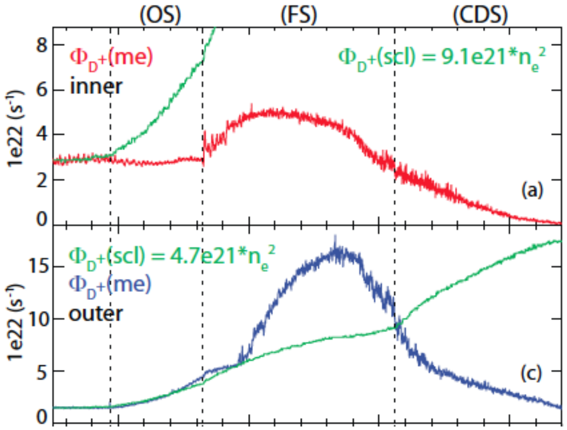
Distance along target



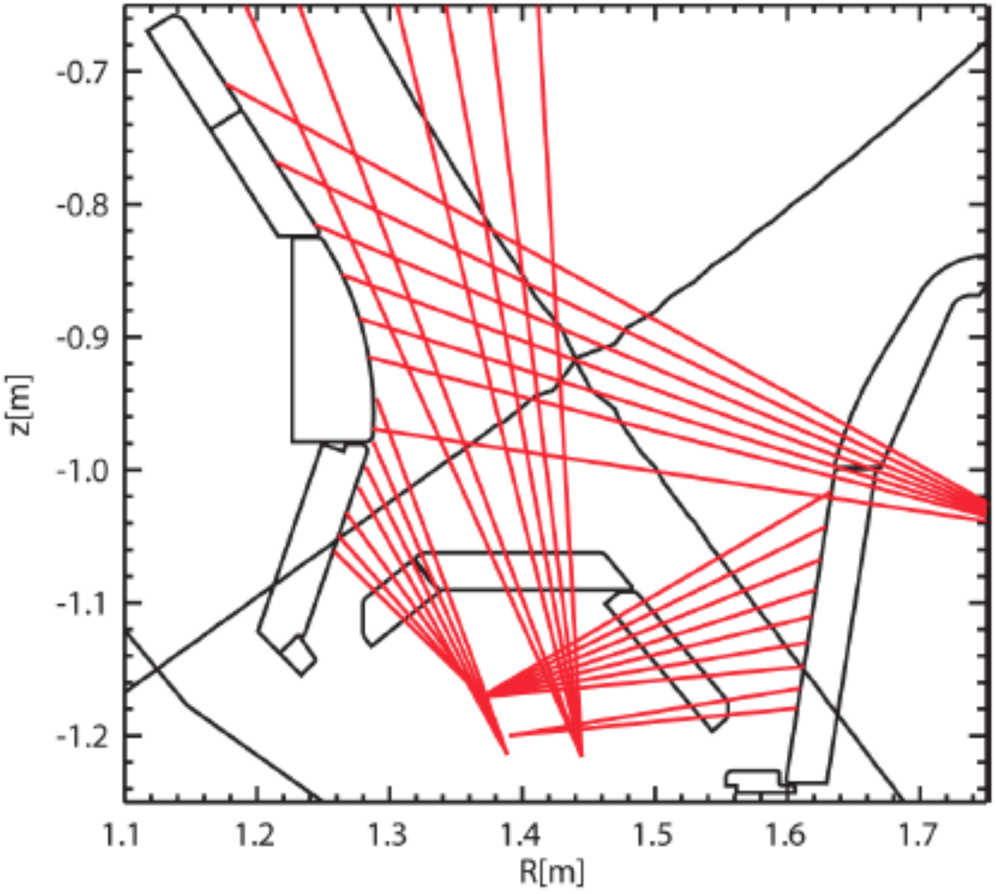
Upstream density

M. Wischmeier et al., JNM 2011

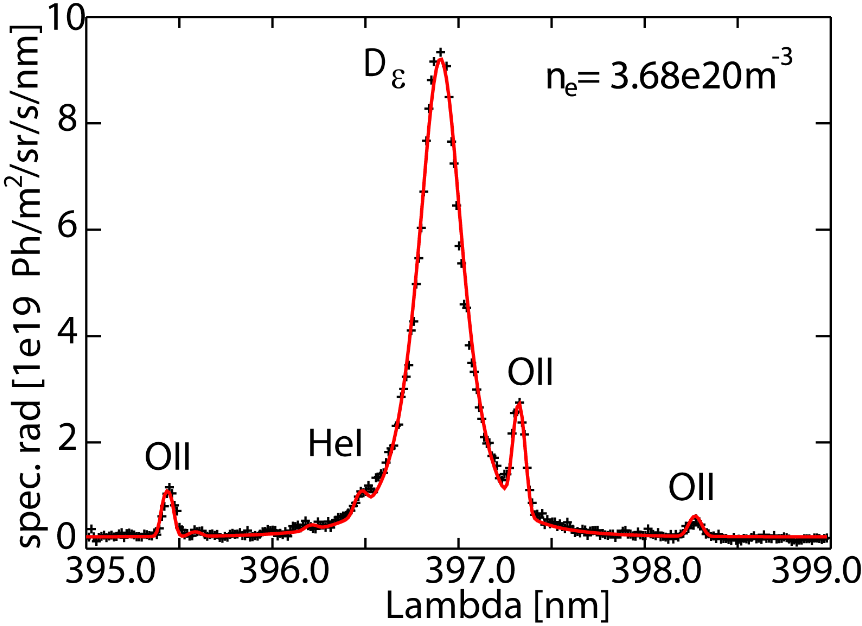




Improved diagnostics to identify missing effects



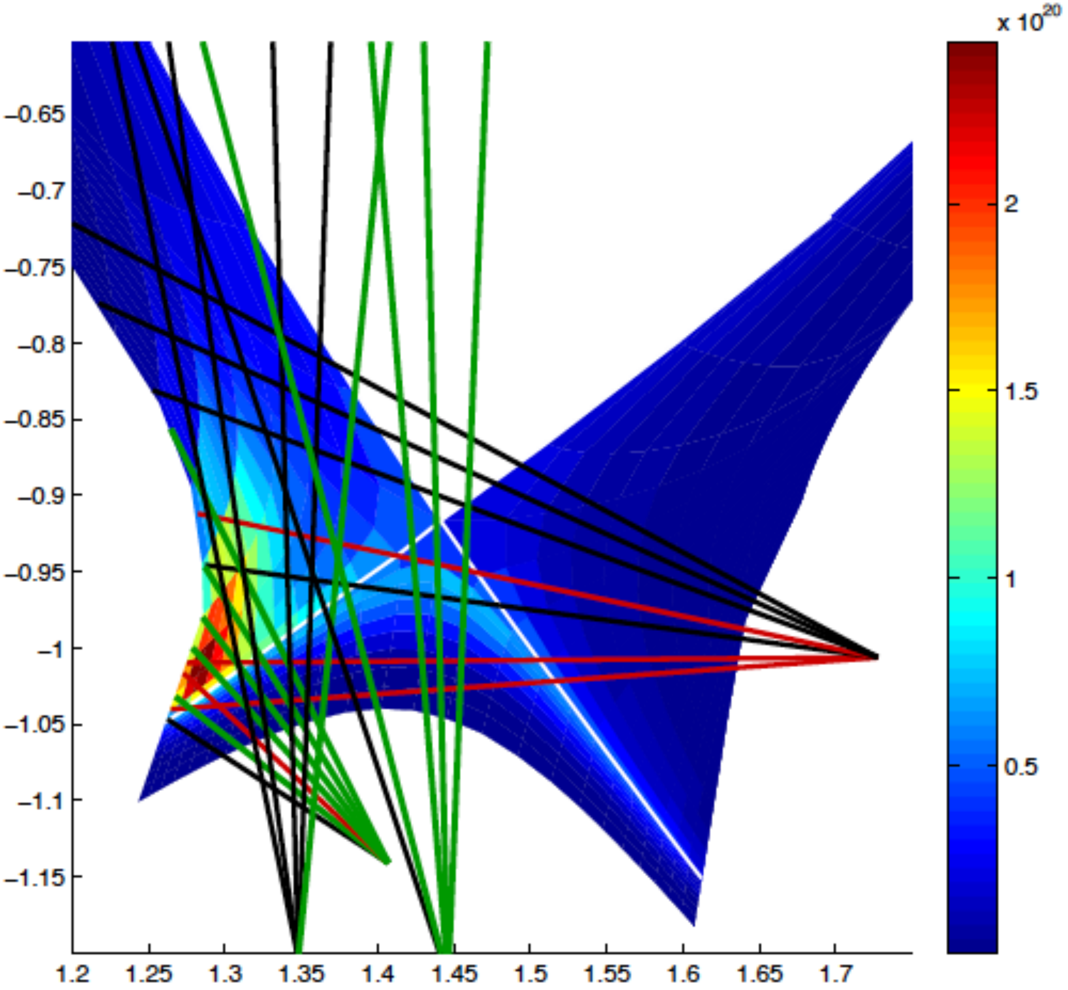
e.g. n_e from Stark broadening



S. Potzel et al. EPS 2011, PSI 2012

Comparing virtual diagnostics: Stark broadening

2D electron density distribution (low density case)



Comparison along spectroscopic LOS

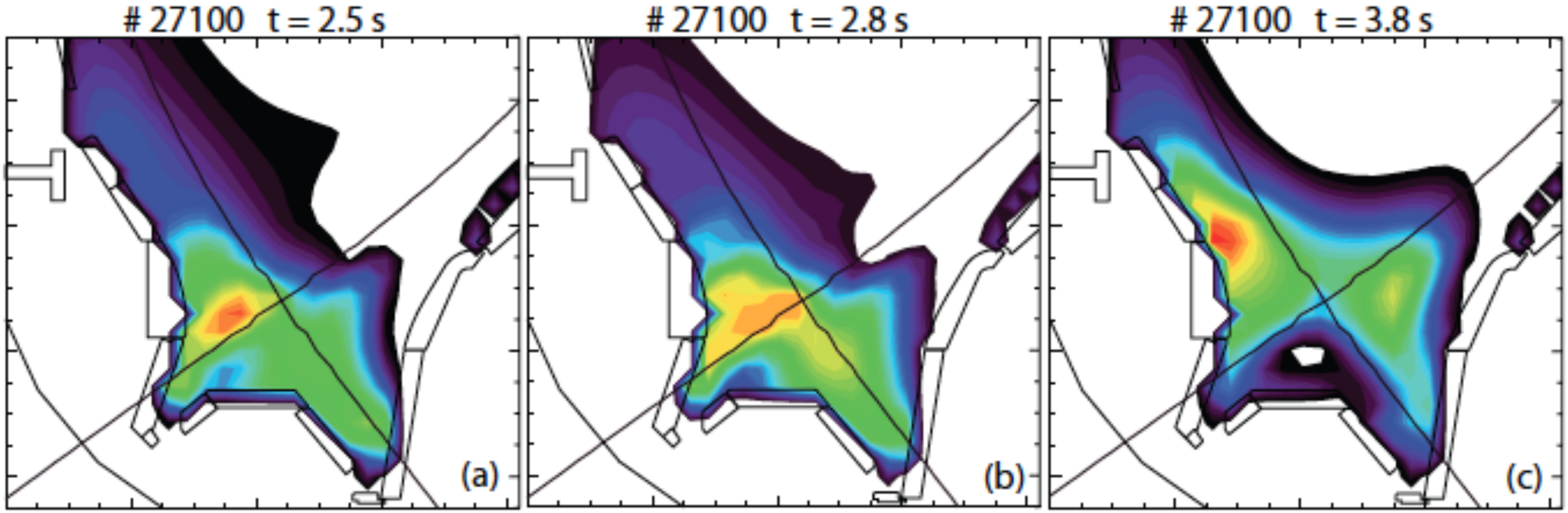
perfect match

SOLPS density lower than Stark Broadening

SOLPS density higher than Stark Broadening

By L. Aho-Mantila & S. Potzel

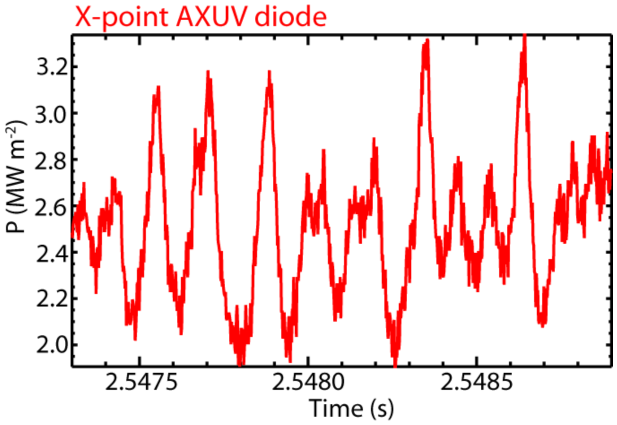
Movement of total radiation and density



Increasing density

S. Potzel et al. NF 2014

- Location of total radiation correlates well with location of high n_e



Not all divertor regimes are satisfactorily described by existing numerical models

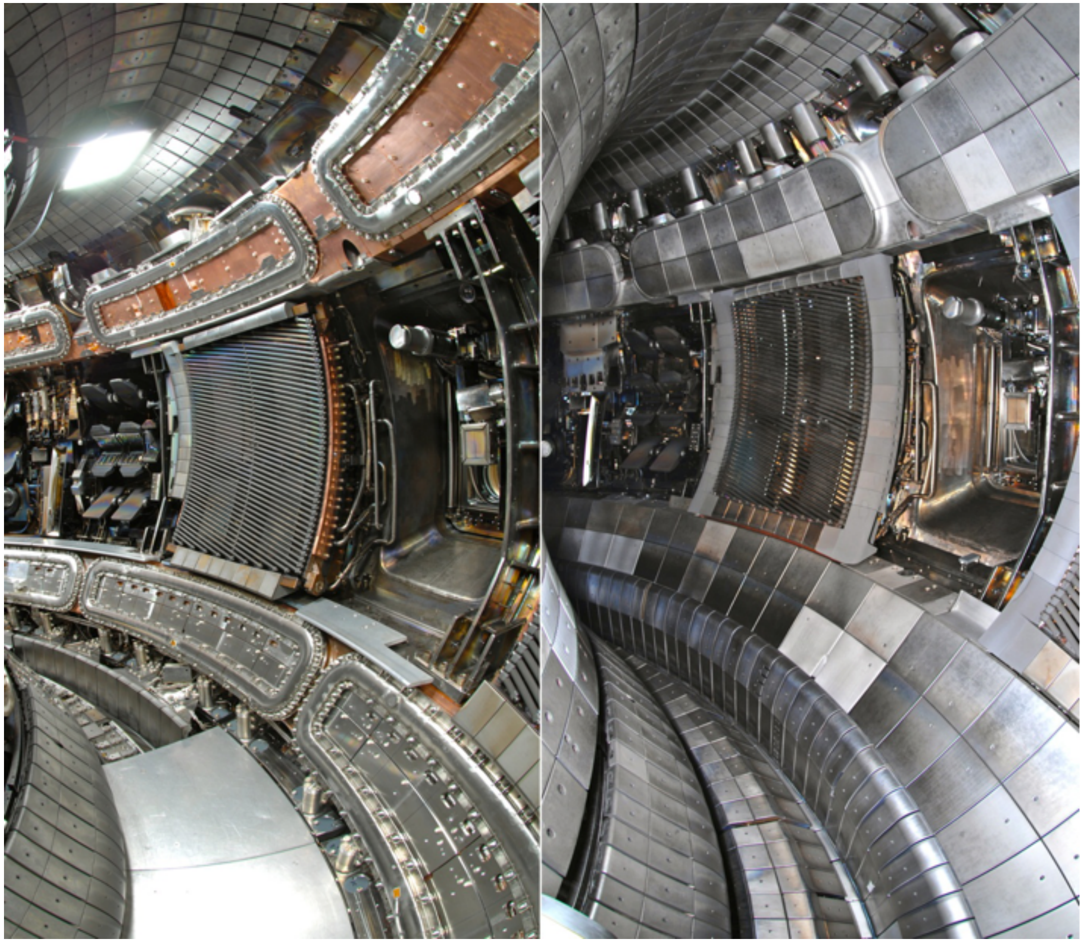
Strategy was/is to identify regimes which can be described and which can’t

→Identify missing physics elements in our models?

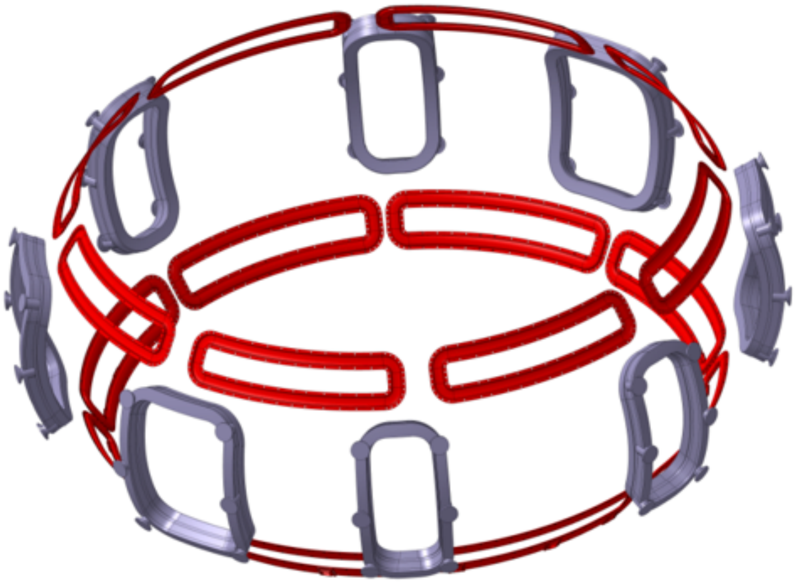
- **But…SOL is may also be 3D**

Mitigation of ELMs

Installation of magnetic perturbation (MP) coils



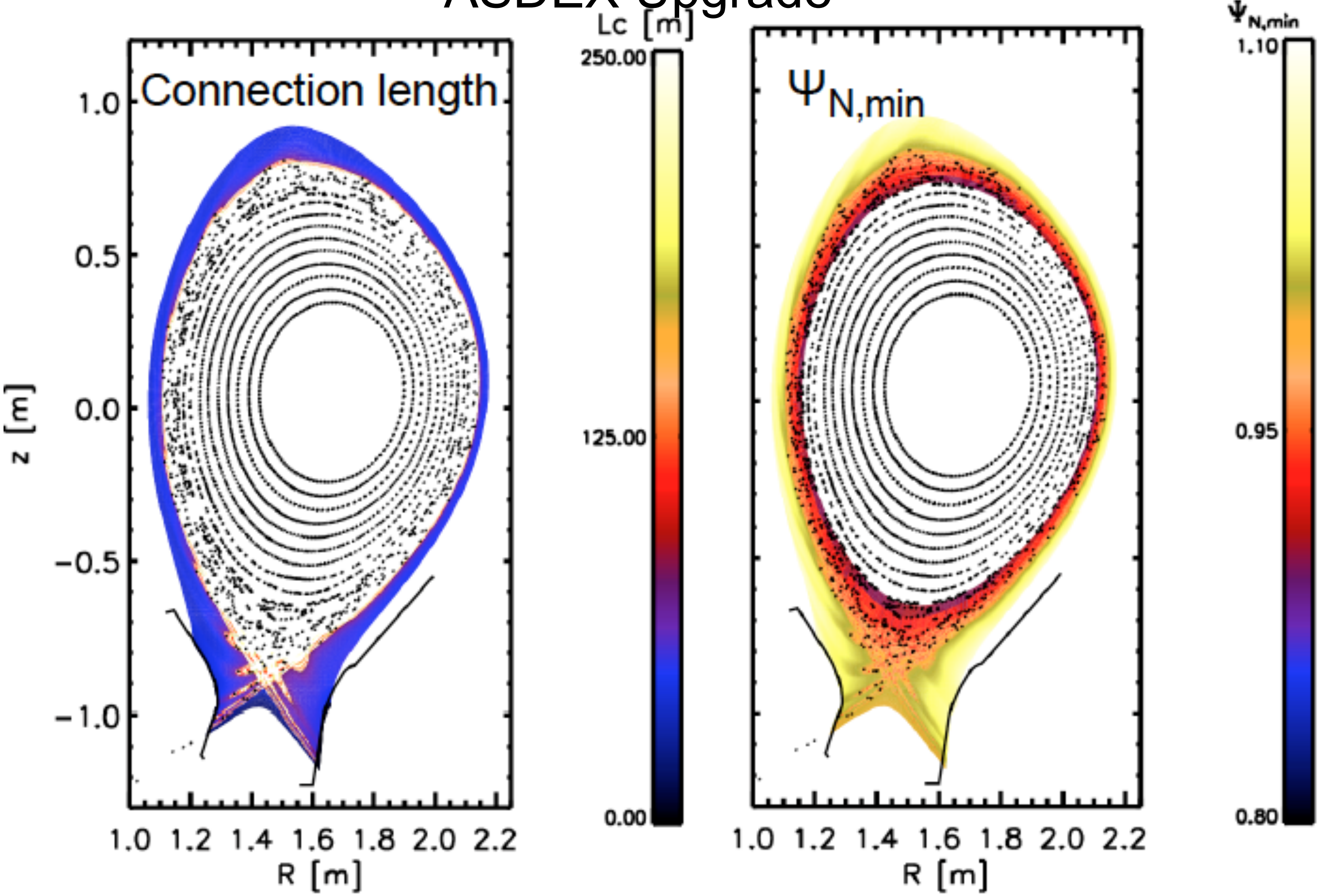
ASDEX Upgrade



W. Suttrop et al. PRL 2011

SOL plasma becomes 3D with MP coils

ASDEX Upgrade

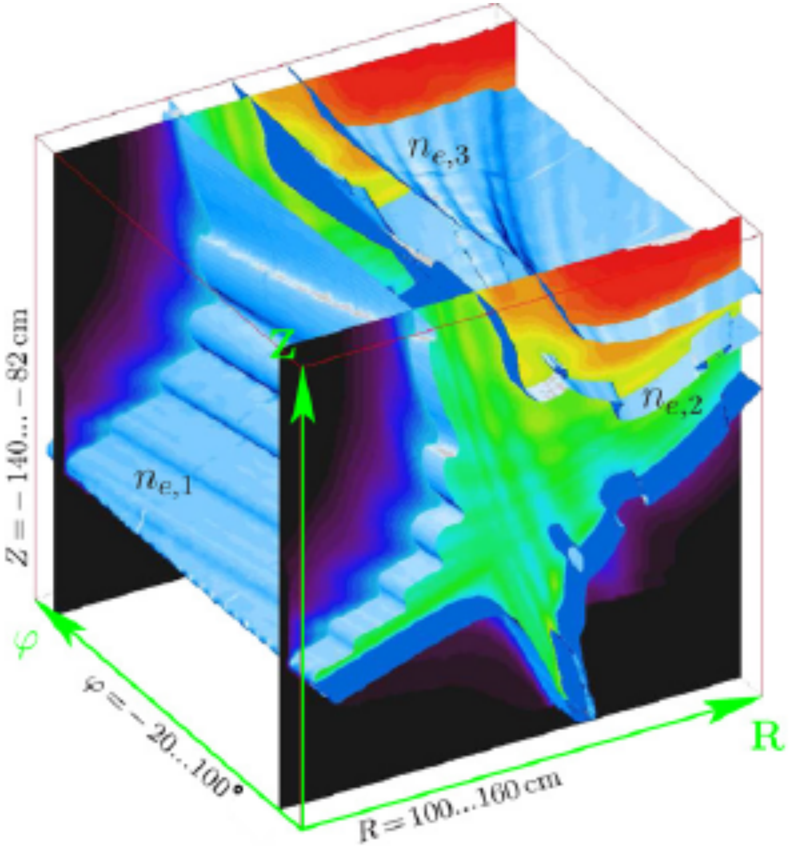


Development of lobe structures

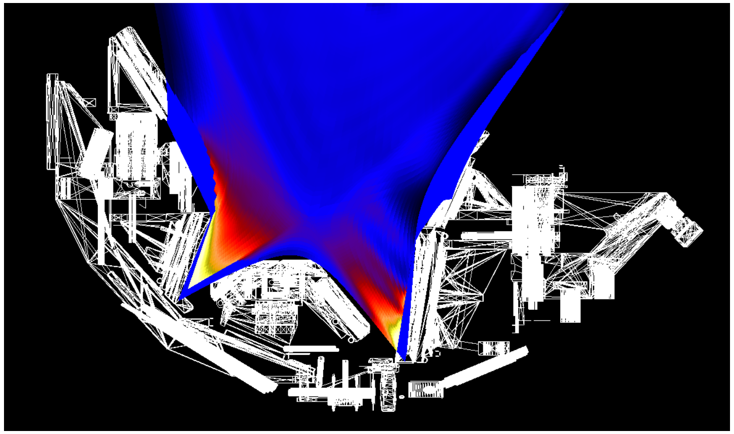
H.W. Müller et al. JNM 2013

3D structures develop

Electron density with MP coils simulated with EMC3- EIRENE



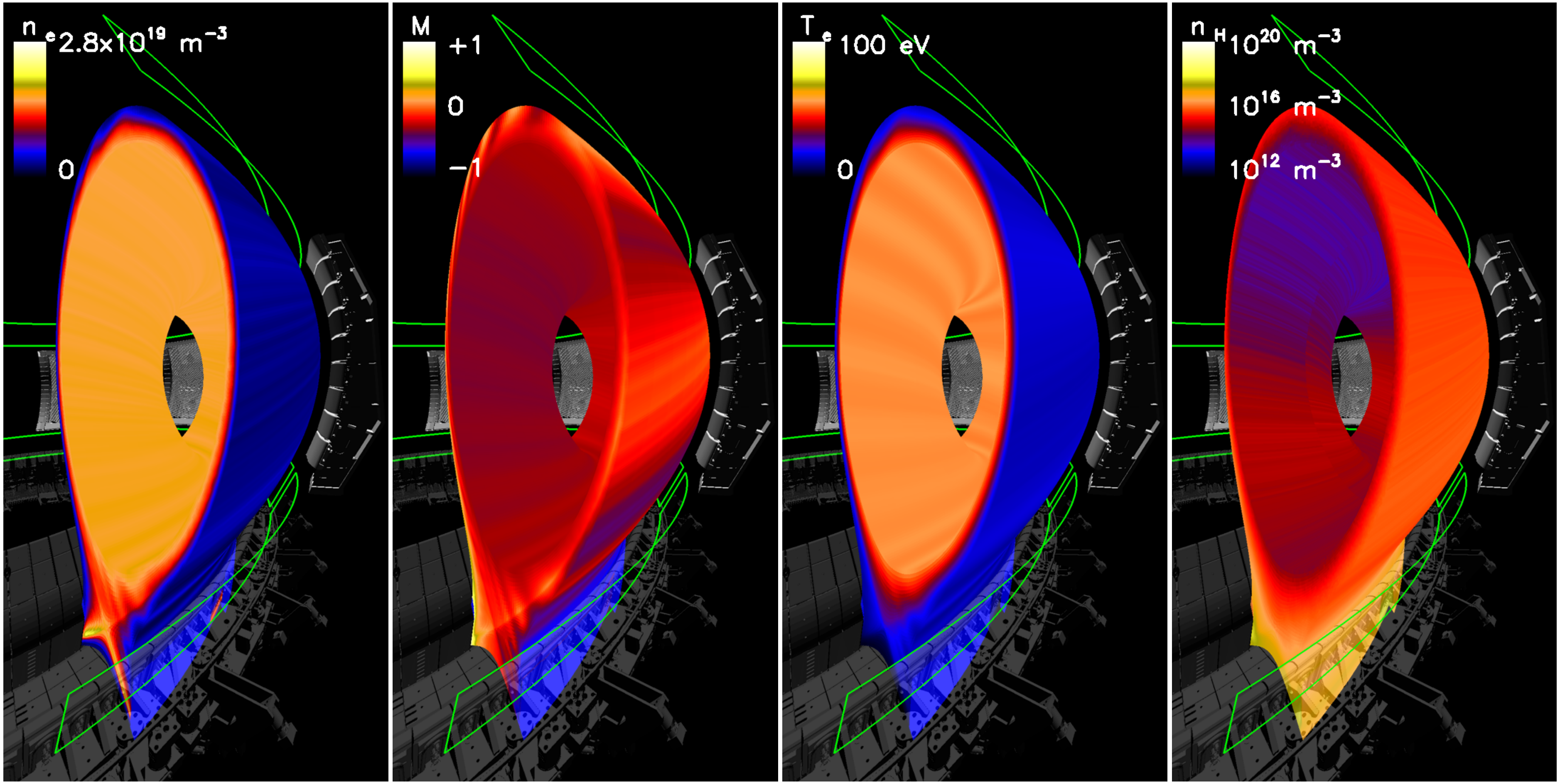
DIII-D, H. Frerichs et al. NF **50** 034004



ASDEX Upgrade, courtesy T. Lunt

Applications for AUG

Simulation of the (resonant) magnetic perturbations



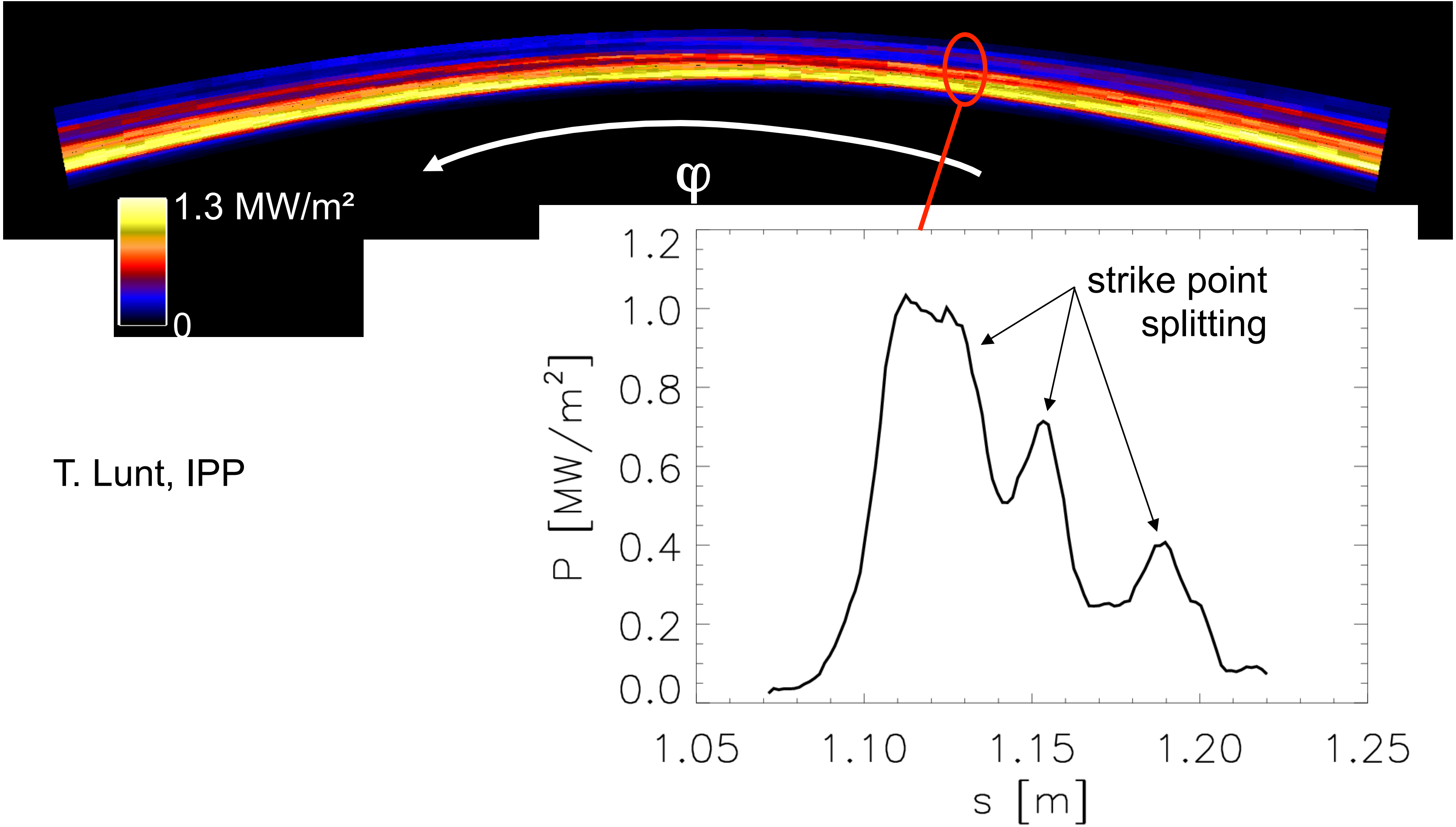
T. Lunt, IPP

L-Mode with 4 kAt (R)MPs (n=4)

Applications for AUG

Simulation of the (resonant) magnetic perturbations

Energy deposition outer target



T. Lunt, IPP