Material transport in the frame of PSI

K. Krieger

with contributions from many colleagues (credits inside)

Association EURATOM Max-Planck Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany

Outline

Overview and rationale

Material transport processes

- Particle collisions
- Plasma turbulence

Experiments

- Phenomenological observations
- Specific experiments

Summary and outlook

Outline

Overview and rationale

Material transport processes

Particle collisions

Plasma turbulence

Experiments

Phenomenological observations

Specific experiments

Summary and outlook

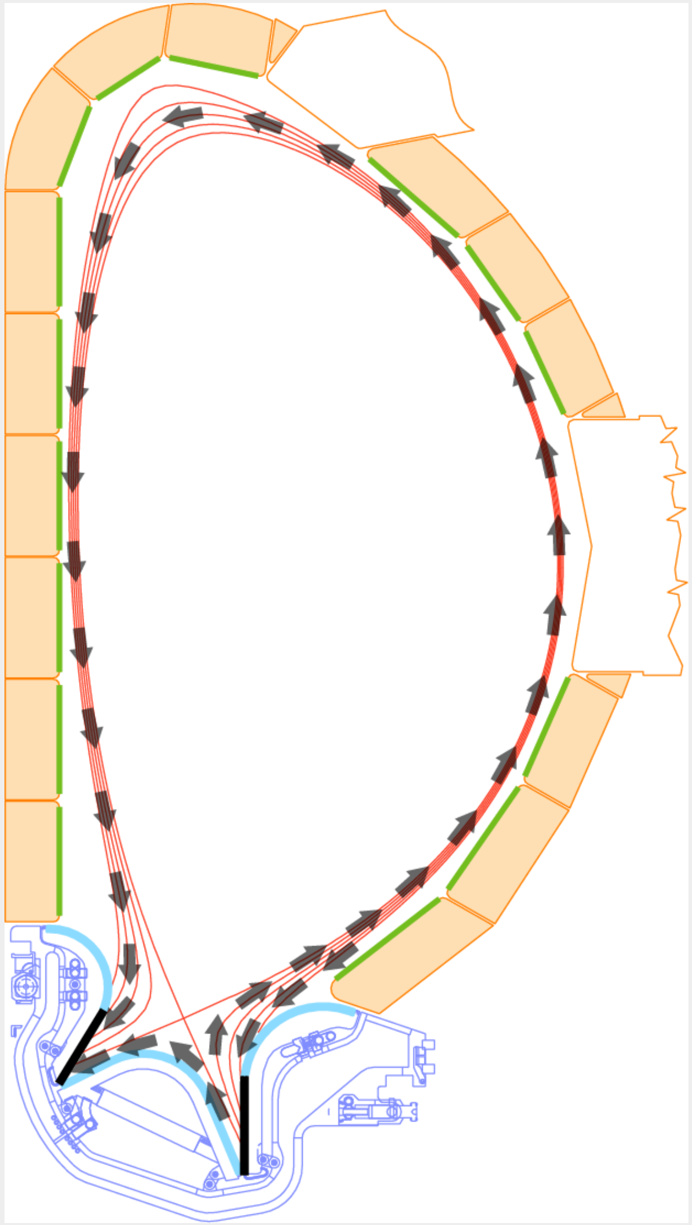
What are the basic ingredients of material migration?

Plasma

Fuel ions + atoms (charge exchange) + impurity ions bombard 1st wall

Wall materials

Erosion → Transport → Deposition → Re-erosion



What's the connection to the other lectures?

Material sources

Transport in plasma

Material redeposition

Erosion by energetic particles ⇨ K. Schmid

Erosion by thermal transients ⇨ A. Loarte

Experiments ⇨ THIS TALK

J. Strachan

Modelling ⇨ J. Strachan

A. Kukushkin

T. Takizuka

M. Kobayashi

K. Ohya

IMPORTANT BUT...

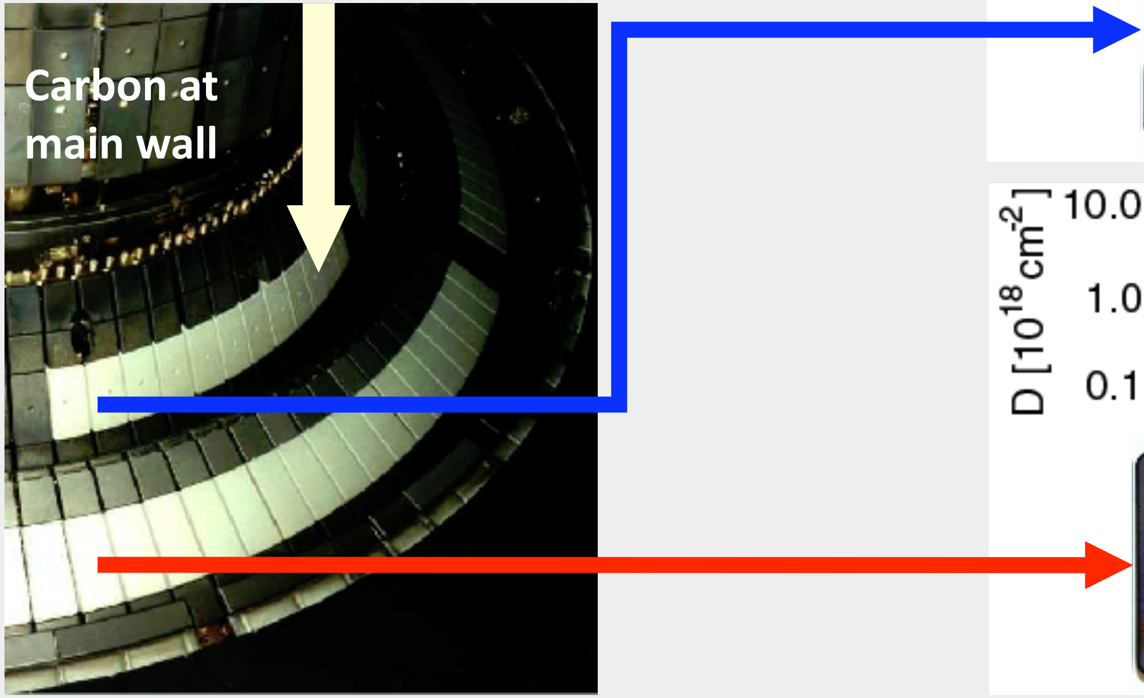
Material mixing ⇨ Y. Ueda

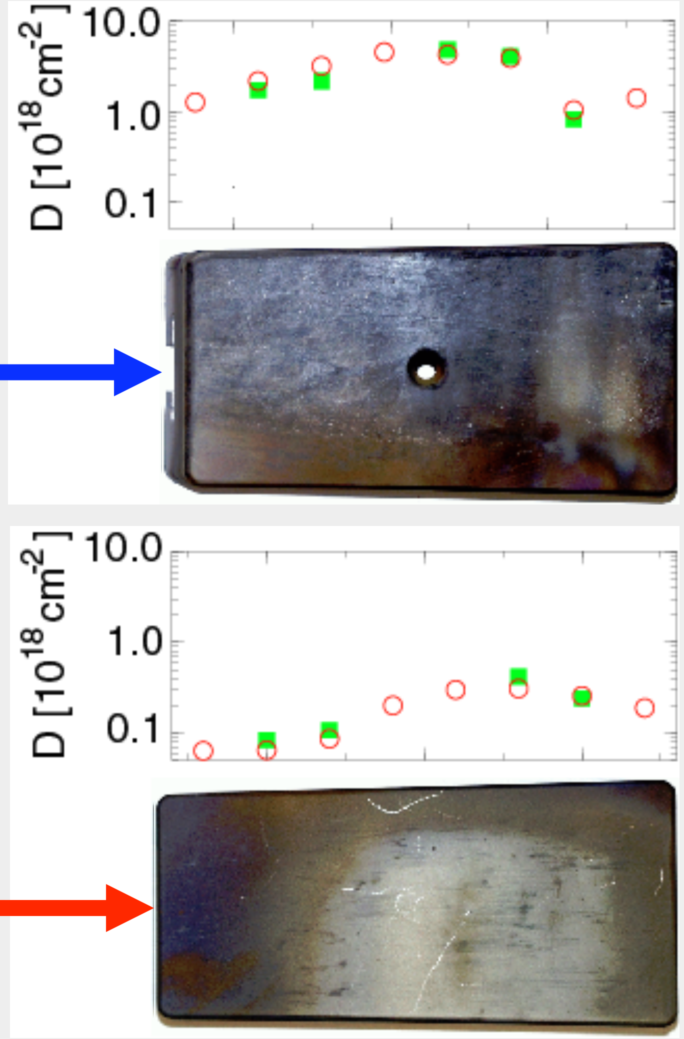
Nanoscopic effects ⇨ N. Yoshida

What are the consequences of material migration?

Layer deposition and material mixing!

Freshly installed tungsten divertor in ASDEX Upgrade



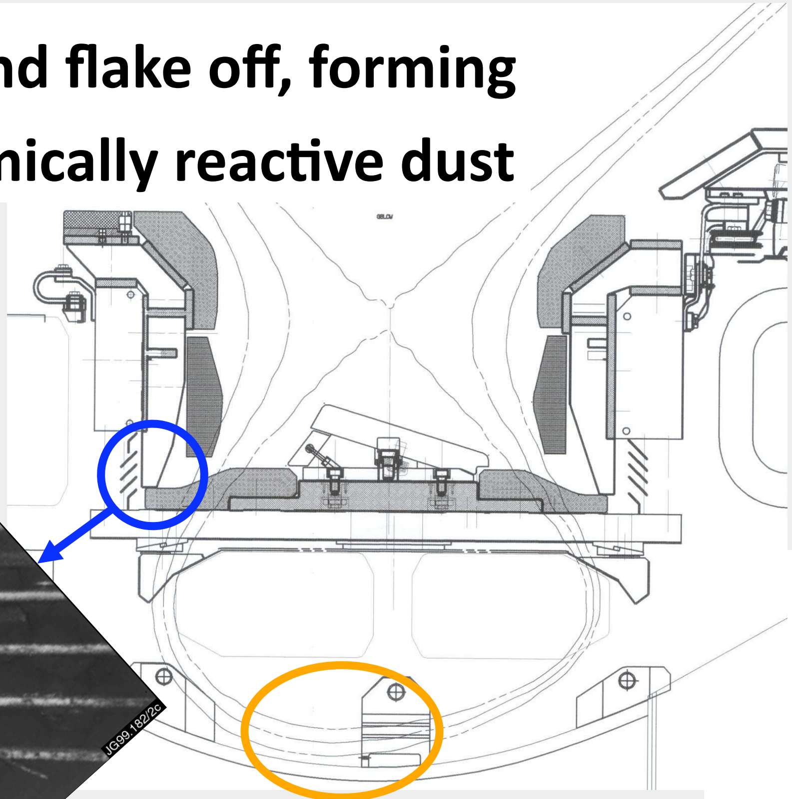


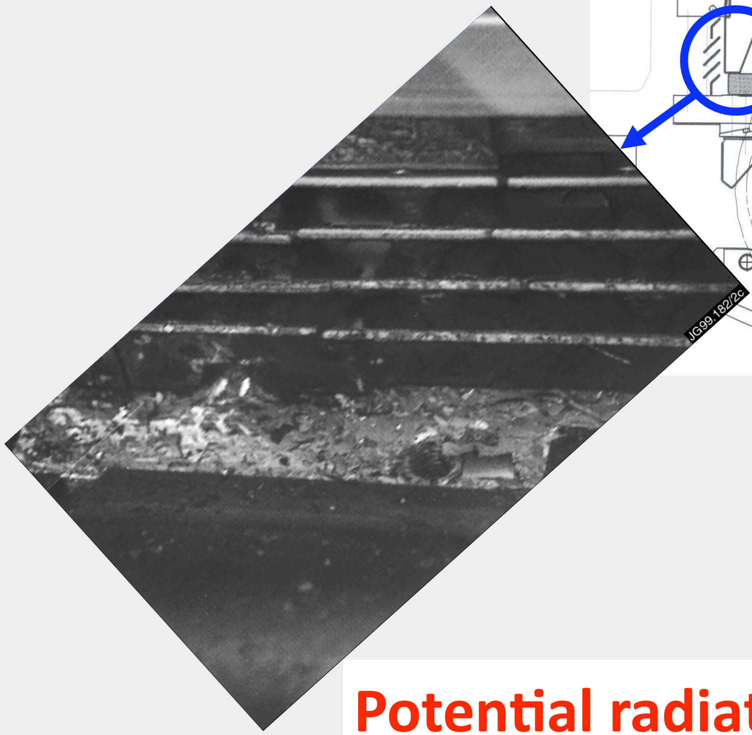
Deposited layers may form ever growing inventory of buried fuel!

What happens if deposited layers become too thick?

S. Brezinsek

Layers delaminate and flake off, forming radioactive and chemically reactive dust



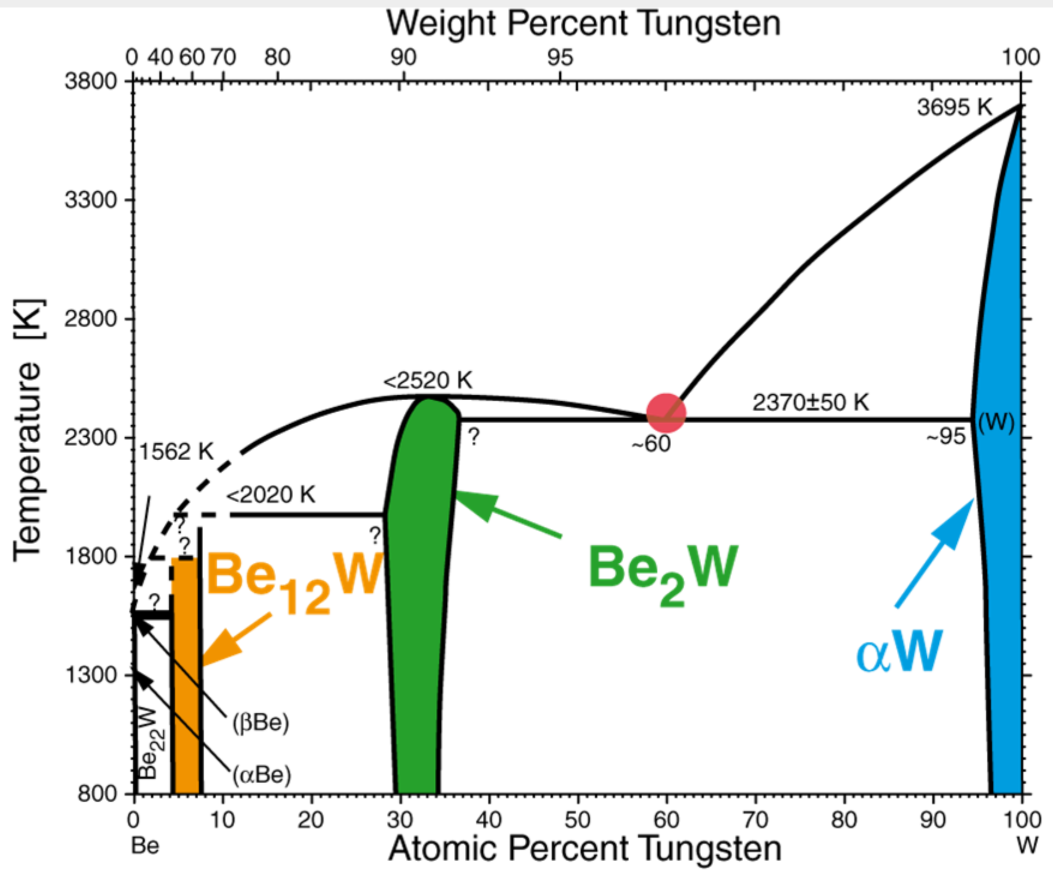


Potential radiation + explosion hazard!

Negative consequences of material mixing?

YES! Example: beryllium and tungsten can form alloys

Ch. Linsmeier



melting point: 3695 K → 2370 K → 2520 K → ~1570 K
with increasing Be content

Outline

Overview and rationale

Material transport processes

Particle collisions

Plasma turbulence

Experiments

Phenomenological observations

Specific experiments

Summary and outlook

Key questions of material (impurity) transport

For given impurity edge density,
what is the impurity density in the plasma centre?
or
What is the impurity residence time compared to the fuel ion residence time in the plasma?

Core transport coefficients

For given material erosion source,
how much gets into the confined plasma?

Screening factor, divertor retention

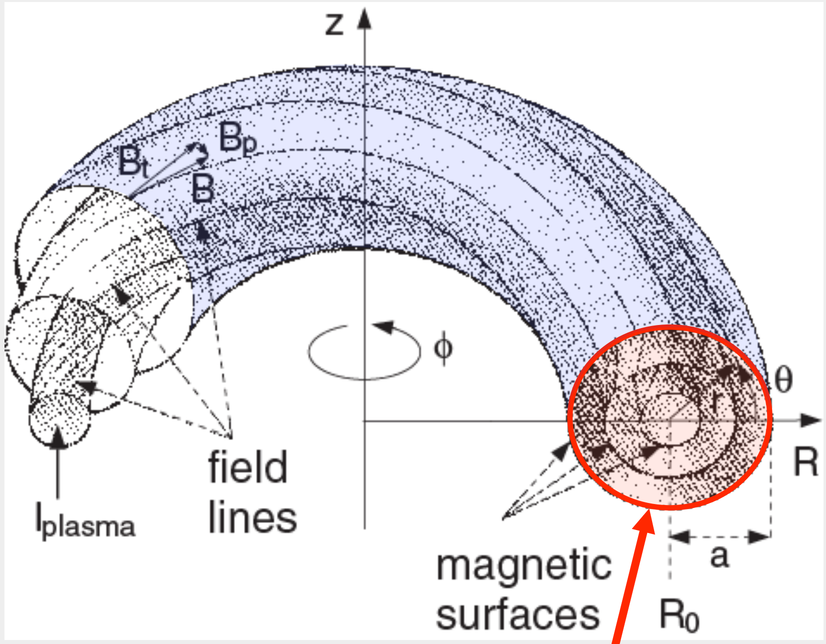
Where are eroded impurities re-deposited?

Migration paths

Impurity transport ⊥ B by particle collisions

Particle conservation

$$\frac{\partial n_{I,Z}}{\partial t} = -\nabla \cdot \Gamma_{I,Z} + Q_{I,Z}$$



Ions bound to flux surface

$$\langle n_I \rangle = n_I$$

i.e. densities constant on flux surface

Impurity density is only a function of flux surface label

$$r = \sqrt{V/(2\pi^2 R_0)}$$

and flux is described by diffusion + convection

$$\frac{\partial n_{I,Z}}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r \left(D^* \frac{\partial n_{I,Z}}{\partial r} - v^* n_{I,Z} \right) + Q_{I,Z}$$

Transport coefficients ⇨ averages over flux surface

Impurity transport ⊥ B by particle collisions

$$D = D^{CL} + D^{PS} + D^{BP}$$

$$D^{CL} \cong \frac{m_I kT \upsilon_{ID}}{B_0^2 e^2 Z^2} \propto \frac{1}{\sqrt{T} B_0^2 Z^2}$$

Classical transport
due to collisional friction forces ⊥ B

$$D^{PS} \cong 2q^2 D^{CL} \propto \frac{1}{\sqrt{T} B_p^2 Z^2}$$

Pfirsch-Schlüter transport
due to collisional friction forces || B

$$D^{BP} \cong \frac{q^2}{\varepsilon^2} \frac{kT \mu_{ID}^*}{B_0^2 e^2 Z n_I} \propto \frac{1}{\sqrt{T} B_p^2 Z n_I}$$

Banana-Plateau transport
due to viscosity forces || B

$$\varepsilon = \frac{r}{R_0}$$

$$q = \varepsilon \frac{B_T}{B_P}$$

Impurity transport ⊥ B by particle collisions

$$V = V^{CL} + V^{PS} + V^{BP}$$

$$V^{XX} = D^{XX} Z \left(\frac{d \ln n_D}{dr} + H^{XX} \frac{d \ln T}{dr} \right)$$

All drifts have the same form but the sign of H^{XX} may change!

Why is this important?

$$\frac{d \ln n_Z}{dr} = Z \frac{d \ln n_I}{dr} \left(1 + H_{eff} \frac{d \ln T}{dr} \Big/ \frac{d \ln n_I}{dr} \right)$$

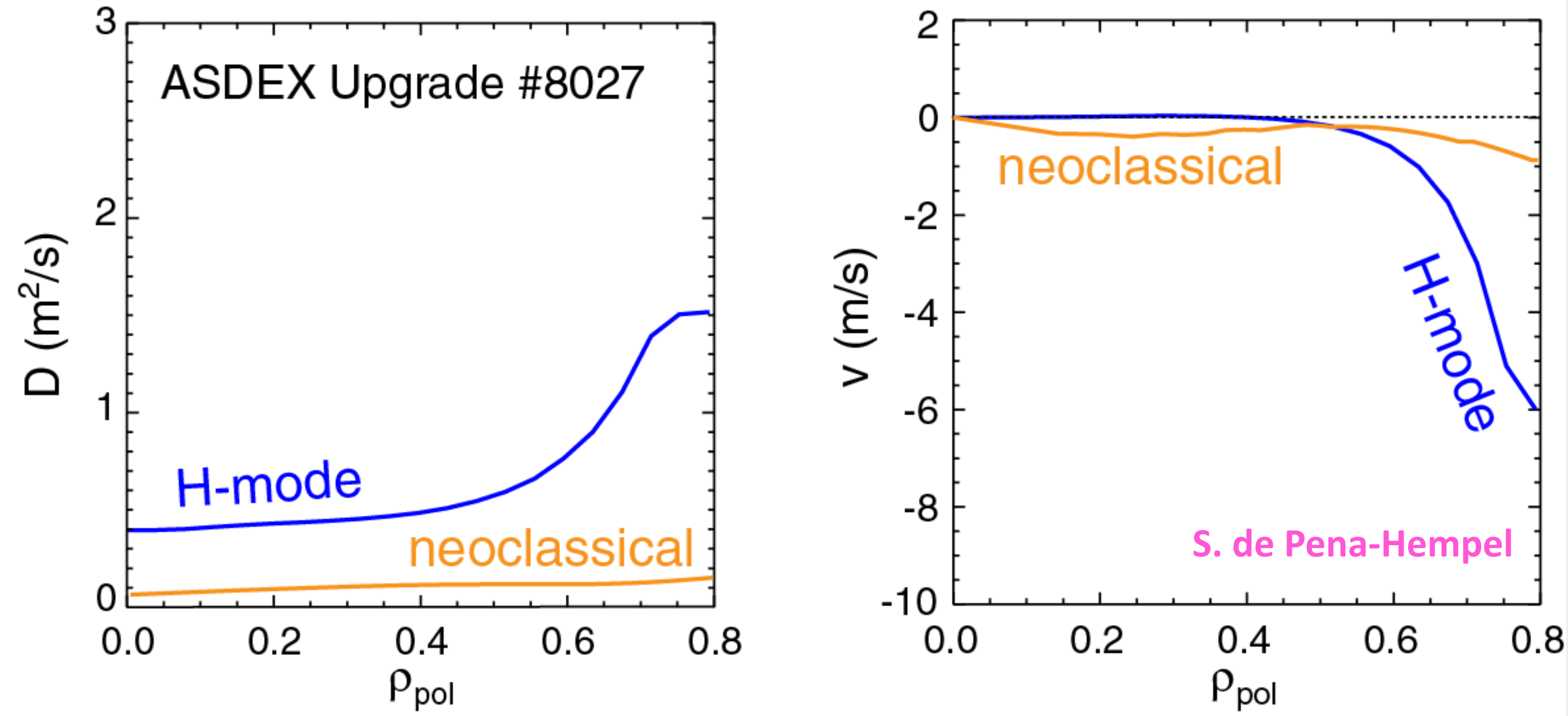
Temperature screening factor ⇨ generally negative!

Pure neoclassical transport leads to central impurity peaking

Peaked temperature profile alleviates problem

Is transport really only due to collisions?

Measure $n_z(r,t)$ after transient applied disturbance
➩ ***D(r)*** **and** ***v(r)***



NO: "Anomalous diffusion" generally much larger!

Is "anomalous" transport good or bad?

Recall expression for impurity profile shape:

$$\frac{d\ln n_Z}{dr} = Z\frac{d\ln n_I}{dr}\left(1 + H_{eff}\frac{d\ln T}{dr}\bigg/\frac{d\ln n_I}{dr}\right)\left(\frac{D}{D + D_{AN}}\right)$$

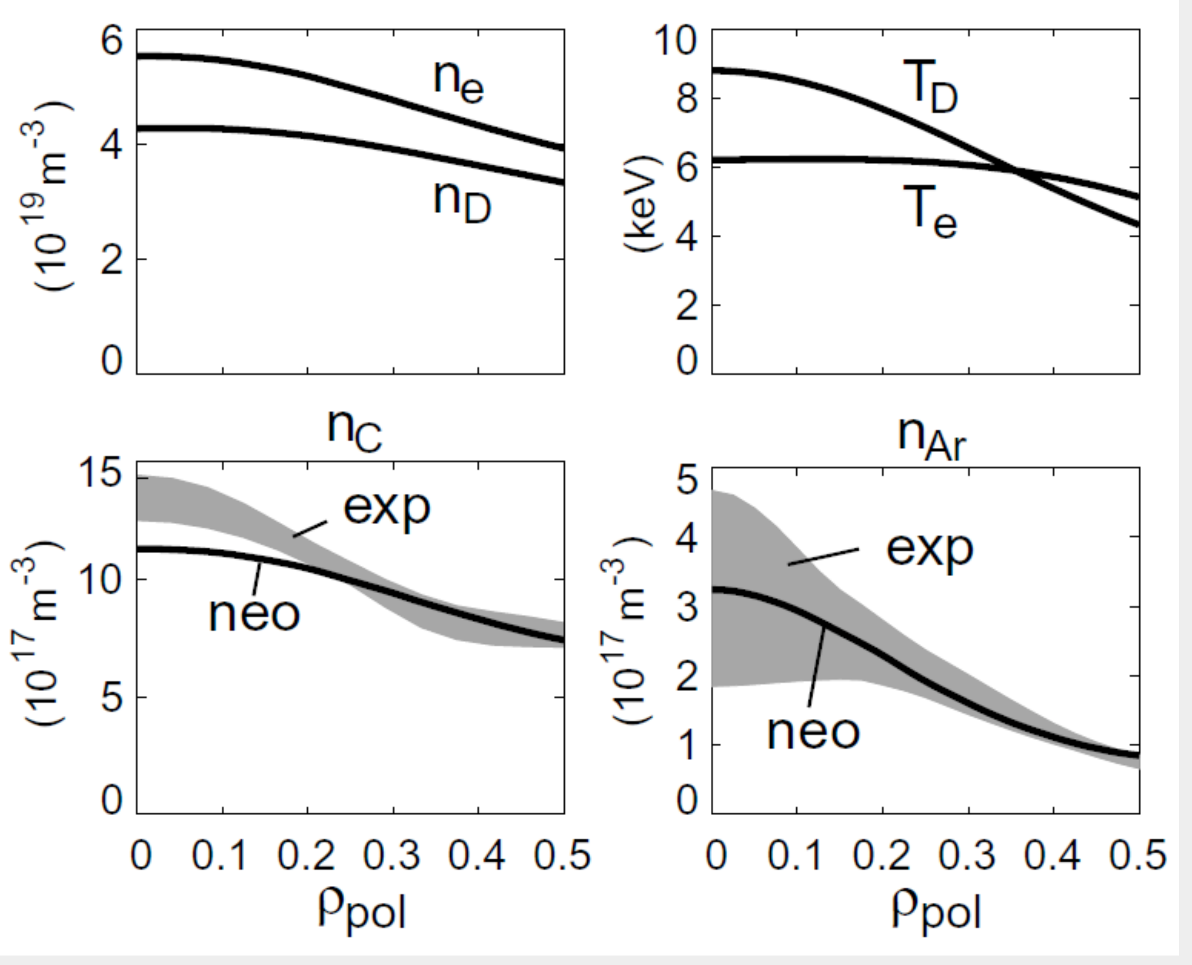
GOOD! D_{AN} decreases impurity profile peaking

Also holds for fuel ions so that $d\ln n_I / dr$ ↘

Purely collisional transport

Discharge with quiescent plasma

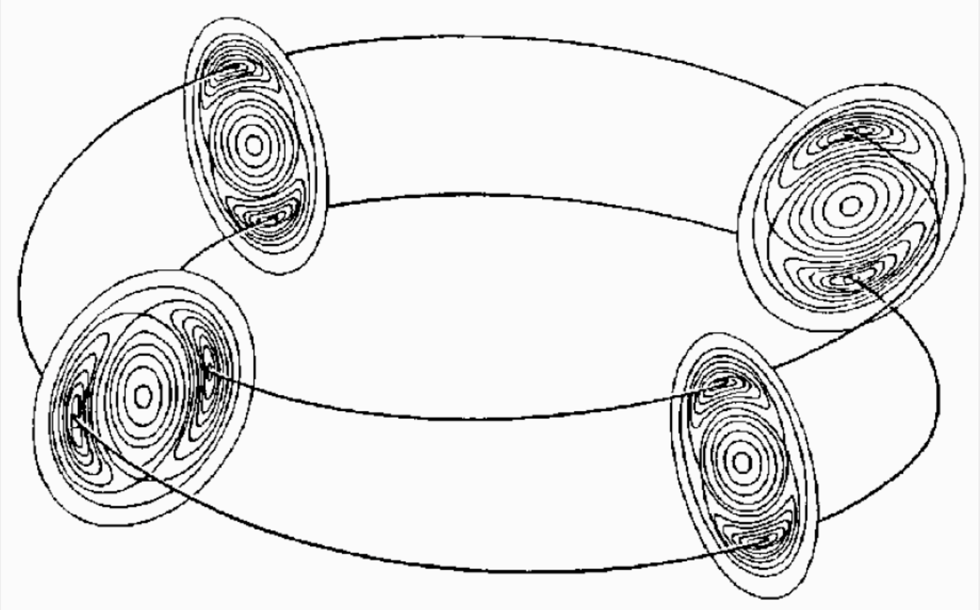
R. Dux



Impurity peaking in centre according to neoclassical *D* and *v*

What are the origins of "anomalous" transport?

Large scale MHD instabilities create radial "shortcut"

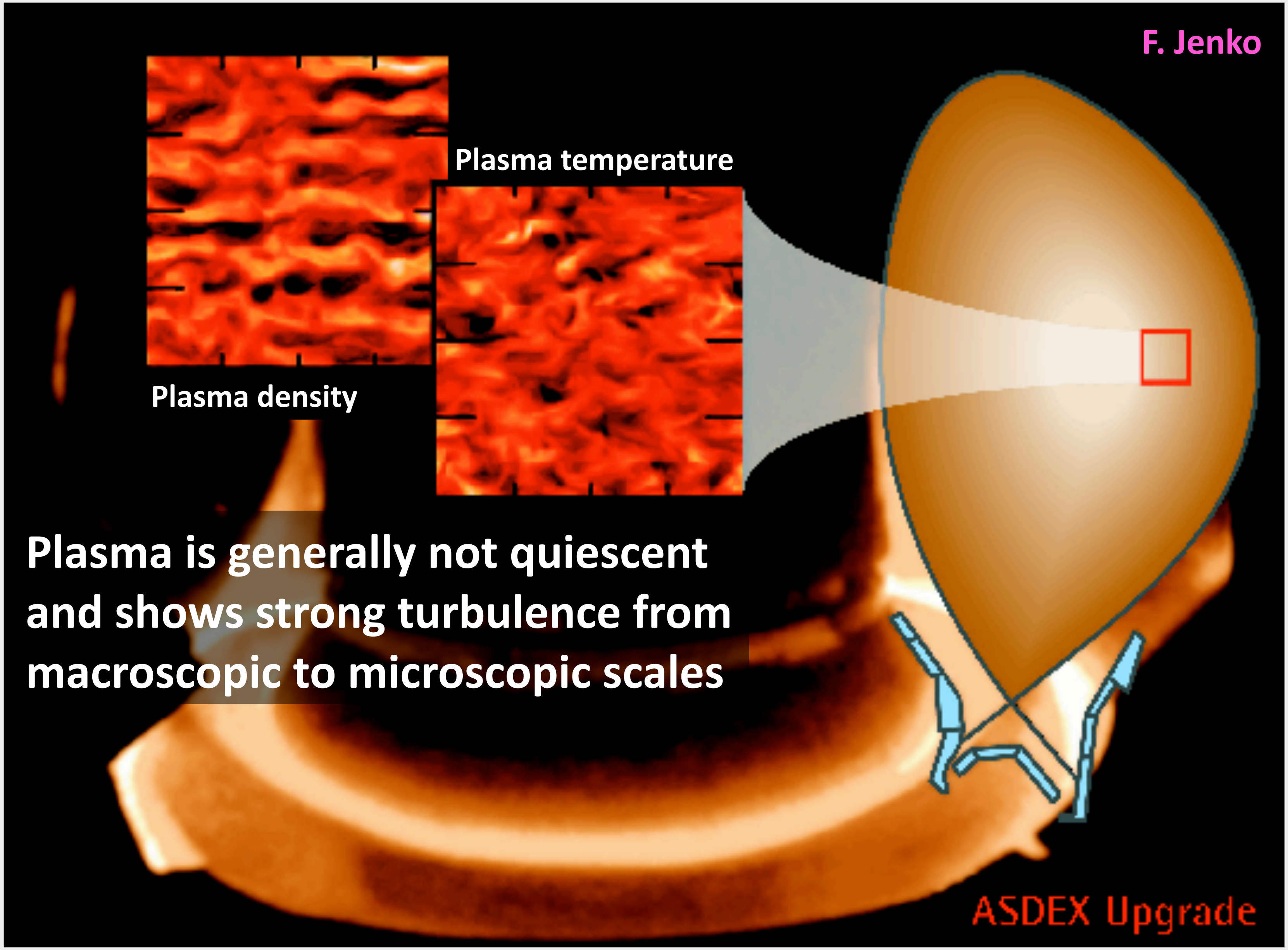


Not the whole story:

Anomalous diffusion shows also in absence of MHD instabilities

⮩ Turbulence, carrying impurities with it!

Turbulent processes in a Tokamak plasma?



How can plasma turbulence be described?

F. Jenko

Ab initio model of plasma microturbulence
⇨ nonlinear gyrokinetic theory

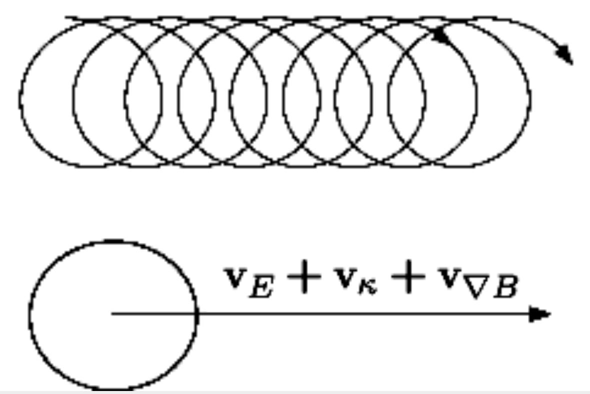
Hot fusion plasmas are almost collisionless (even in the edge!)

Vlasov-Maxwell equations
(self-consistent, nonlinear problem)

$$\left[\frac{\partial}{\partial t} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{x}} + \frac{q}{m}\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)\cdot\frac{\partial}{\partial \mathbf{v}}\right] f(\mathbf{x},\mathbf{v},t) = 0$$

Eliminating the fast gyromotion…
[Frieman, Chen, Lee, Hahm, Brizard *et al*. in the 1980s]

$\omega \ll \Omega$



Charged rings as quasiparticles; important kinetic effects retained non-perturbatively!

⮊ Irrelevant (small) spatio-temporal scales are removed!

The nonlinear gyrokinetic equations

$$f = f(\mathbf{X}, v_{\|}, \mu; t)$$

advection equation/conservation law

$$\frac{\partial f}{\partial t} + \dot{\mathbf{X}} \cdot \frac{\partial f}{\partial \mathbf{X}} + \dot{v}_{\|} \frac{\partial f}{\partial v_{\|}} = 0$$

$$\dot{\mathbf{X}} = v_{\|}\,\mathbf{b} + \frac{B}{B_{\|}^{*}} \left(\frac{v_{\|}}{B} \bar{\mathbf{B}}_{1\perp} + \mathbf{v}_{\perp} \right)$$

$$\mathbf{v}_{\perp} \equiv \frac{c}{B^2} \bar{\mathbf{E}}_1 \times \mathbf{B} + \frac{\mu}{m\Omega} \mathbf{b} \times \nabla (B + \bar{B}_{1\|}) + \frac{v_{\|}^2}{\Omega} (\nabla \times \mathbf{b})_{\perp}$$

$$\dot{v}_{\|} = \frac{\dot{\mathbf{X}}}{m v_{\|}} \cdot \left(e \bar{\mathbf{E}}_1 - \mu \nabla (B + \bar{B}_{1\|}) \right)$$

X = position of the gyrocenter

$V_{||}$ = parallel velocity

μ = magnetic moment

F. Jenko

Corresponding field equations

$$\frac{n_1}{n_0} = \frac{\bar{n}_1}{n_0} - \left(1 - \|I_0^2\|\right) \frac{e\phi_1}{T} + \|x I_0 I_1\| \frac{B_{1\|}}{B}$$

$$\nabla_{\perp}^2 A_{1\|} = -\frac{4\pi}{c} \sum \bar{J}_{1\|}$$

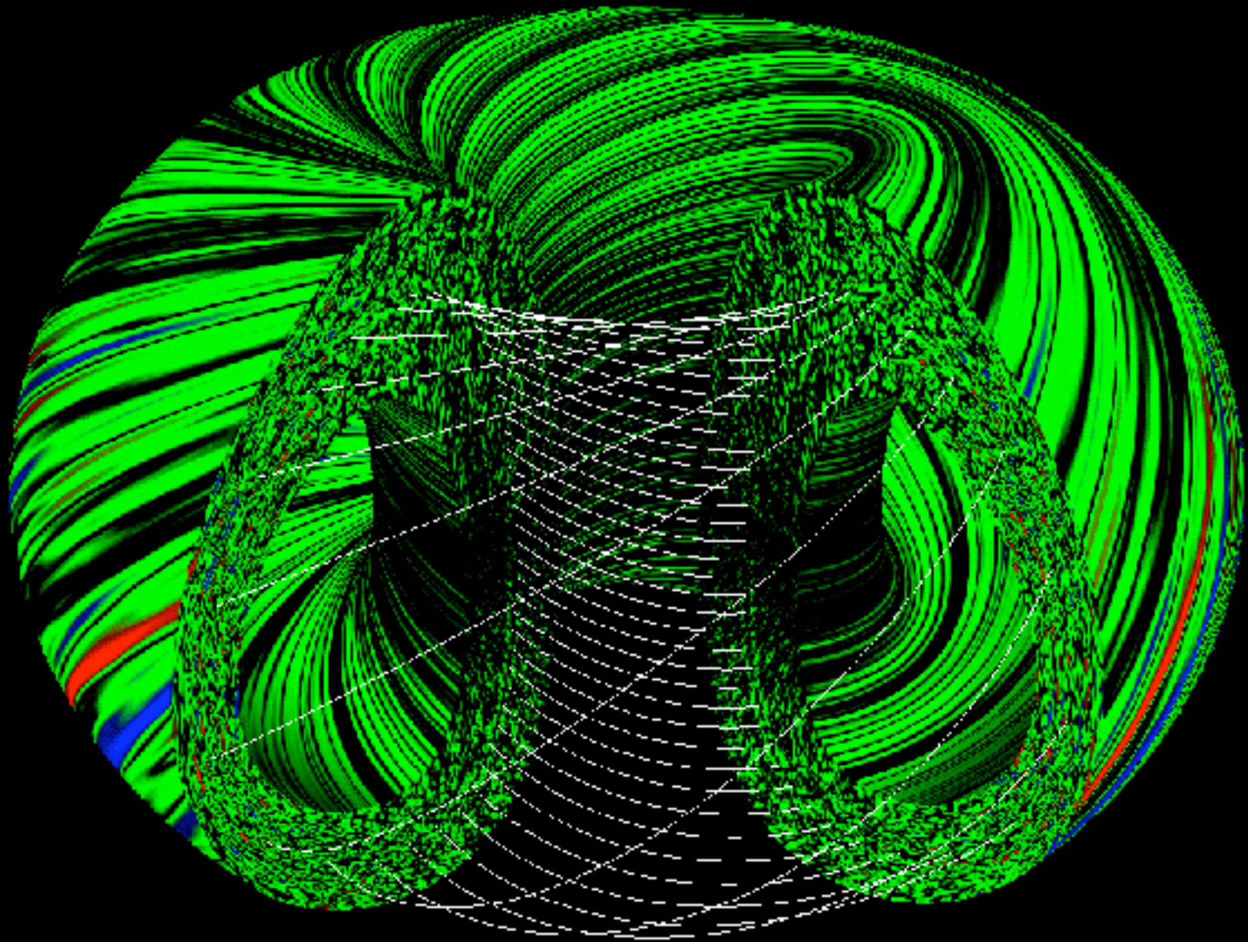
$$\frac{B_{1\|}}{B} = -\sum \epsilon_{\beta} \left(\frac{\bar{p}_{1\perp}}{n_0 T} + \|x I_1 I_0\| \frac{e\phi_1}{T} + \|x^2 I_1^2\| \frac{B_{1\|}}{B} \right)$$

Nonlinear integro-differential equations in 3+2 dimensions

Progress only recently due to complexity of the system

Plasma turbulence is quasi-two-dimensional

➩ Work with flux tubes, using field-aligned coordinates



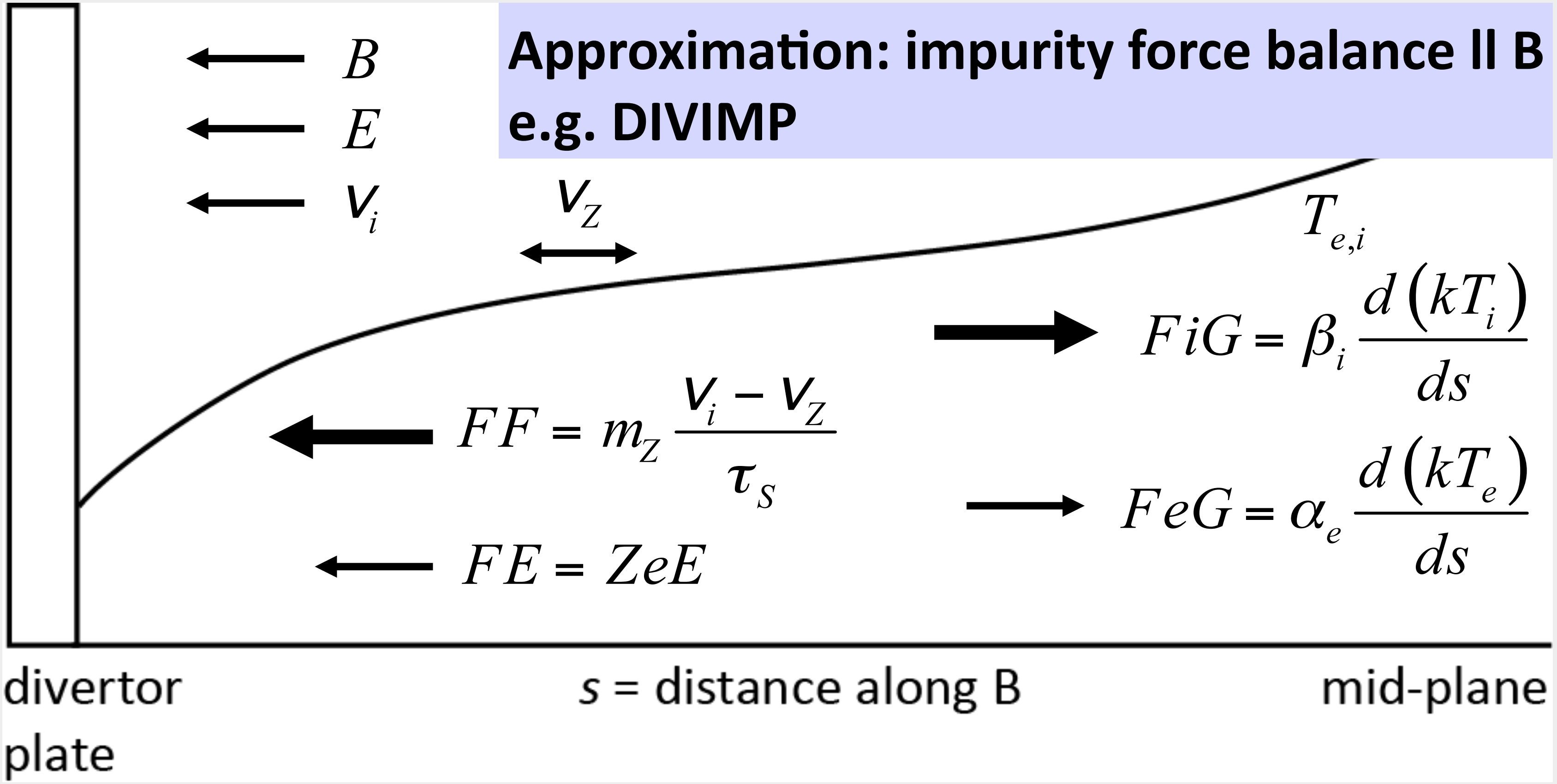
Still requires O(100000) CPU-hours!

F. Jenko

Impurity transport in SOL

B-field intersects material surface ⇒ transport ll B becomes important!

Approximation: impurity force balance ll B
e.g. DIVIMP



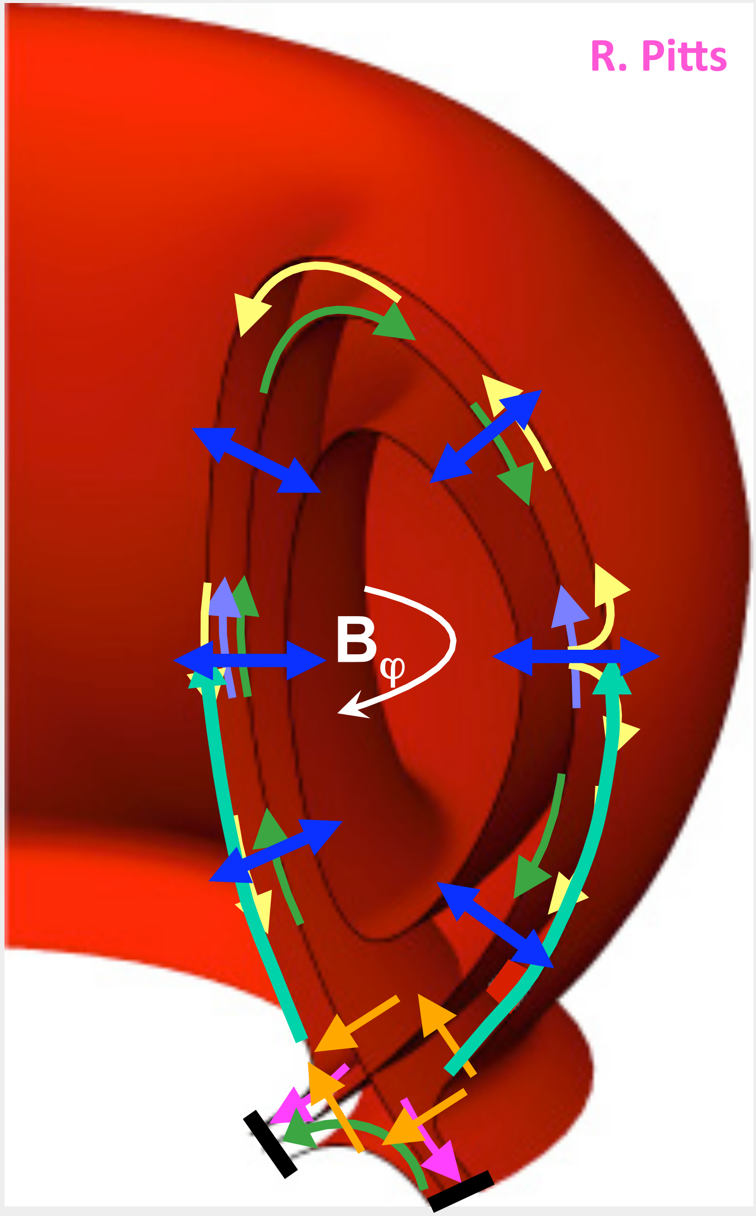
$$F_Z = -\frac{1}{n_Z}\frac{dp_Z}{ds} + FF + FE + FiG + FeG + \ldots$$

$$\tau_s \propto m_Z \frac{T_i^{3/2}}{n_i Z^2}$$

$$\alpha_e \cong 0.71 Z^2$$

$$\beta_i \cong 2.65 Z^2$$

Is that the whole story?



Diffusion and convection $\perp$ B

T gradients ll B

NO: drifts & flows

$E_r \times B$, $\nabla p \times B$	green arrow
$E_\theta \times B$	orange arrow
Pfirsch-Schlüter	blue arrow
Ballooning	yellow arrow
Divertor sink	magenta arrow

How to improve the quasi 1D-model?

Kinetic equations → Moments of ion and electron distribution functions → Fluid equations (Braginskii)

Particle balance

Momentum balance

Diffusion

Electron energy balance

Ion energy balance

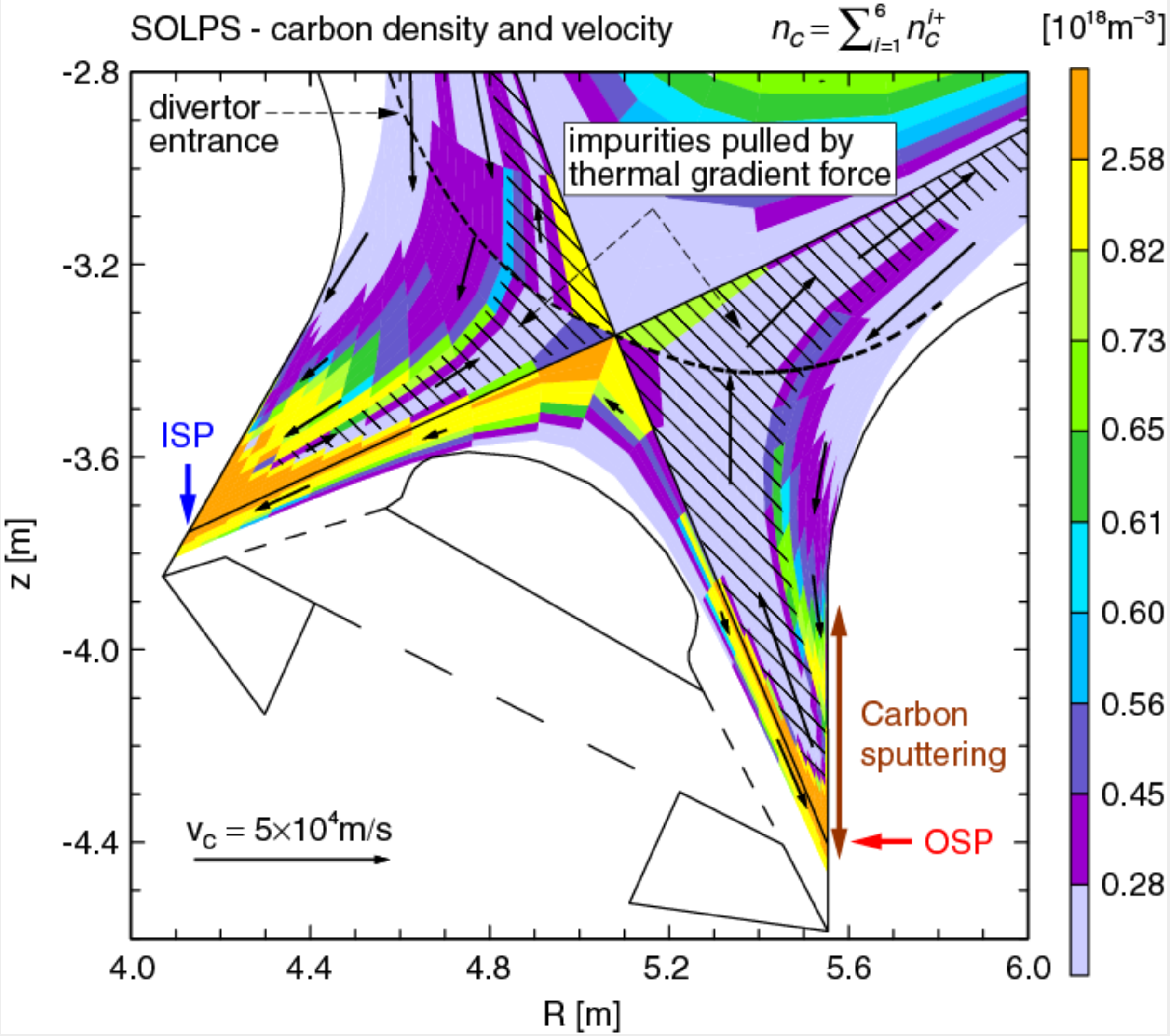
PLUS

Kinetic correction terms
(flux limiters)

Self consistent treatment of recycling
by iterative coupling to neutral transport code

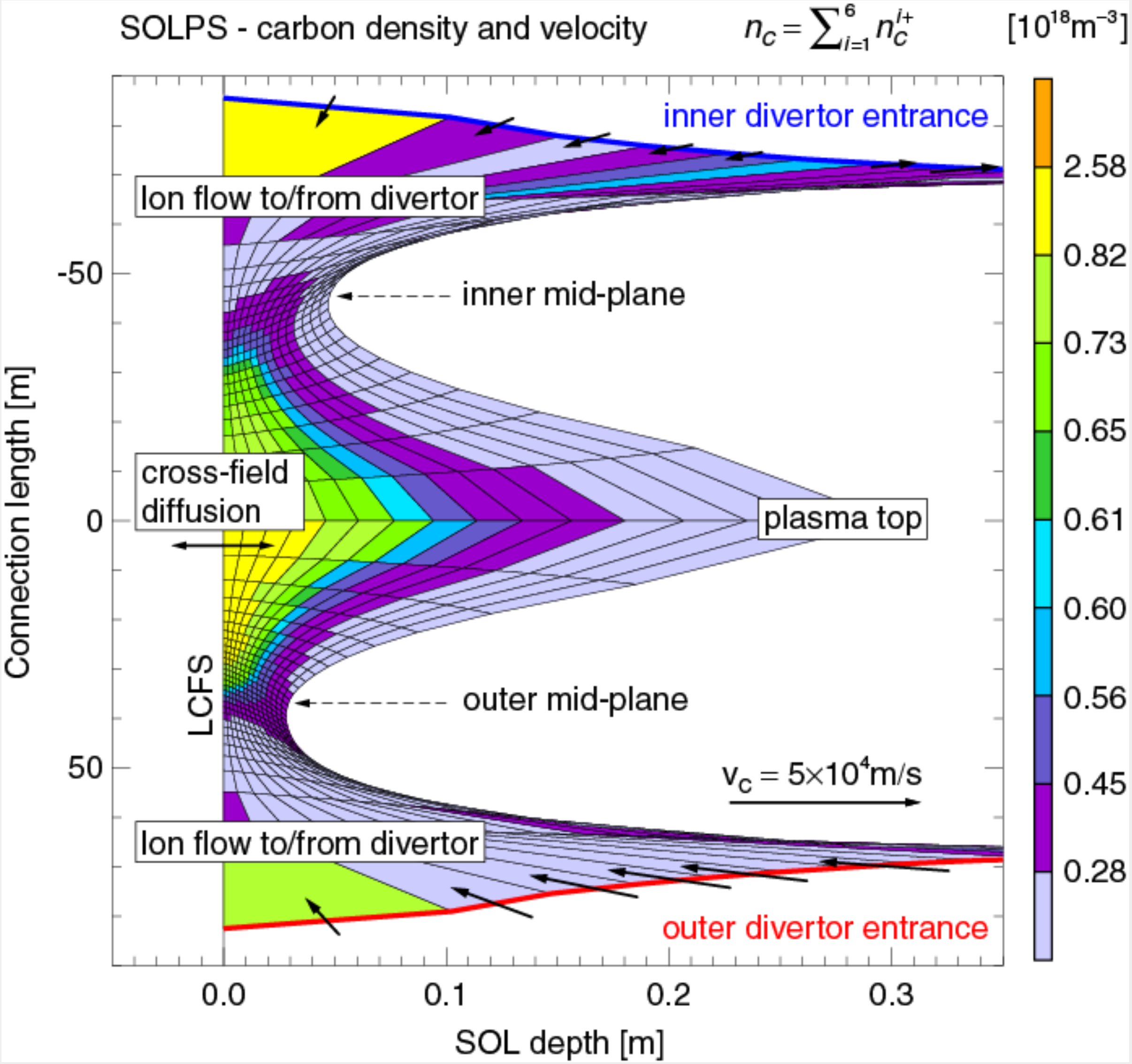
Standard used for ITER: B2-EIRENE

Example solution for ITER plasma



Data from A. Kukushkin

Example solution for ITER plasma



Data from A. Kukushkin

How to benchmark the codes?

Challenge with experimental data

Outline

Overview and rationale

Material transport processes

- Particle collisions
- Plasma turbulence

Experiments

- Phenomenological observations
- Specific experiments

Summary and outlook

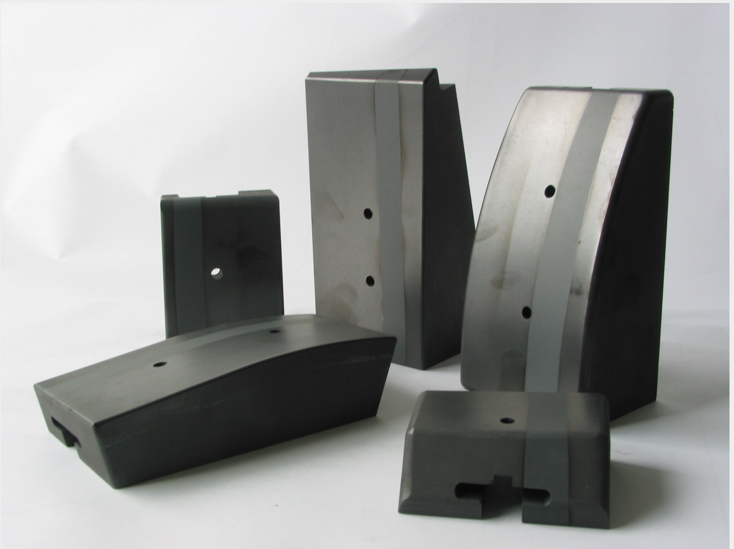
Experimental method

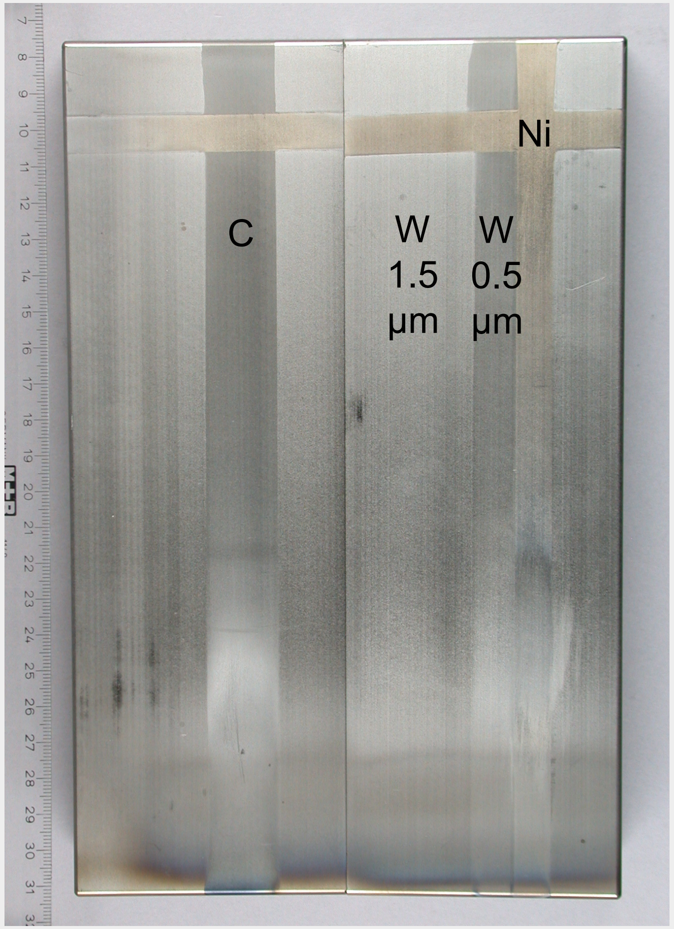
Quantify material erosion and redeposition by ex-situ surface analysis of retrieved wall tiles and/or long term probes

Identification of erosion and deposition dominated areas

Identification of net material migration balance

Example: ASDEX Upgrade - marker tiles



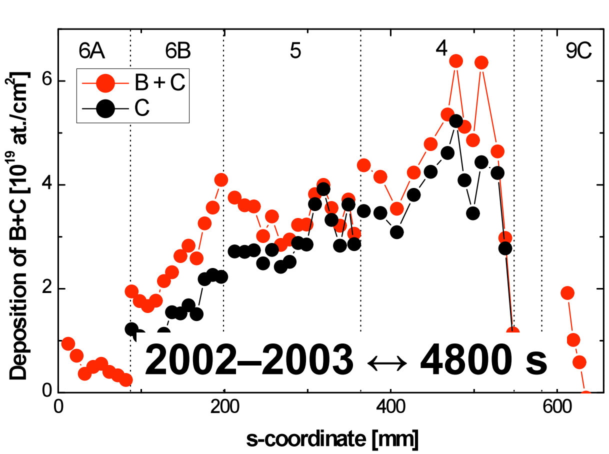


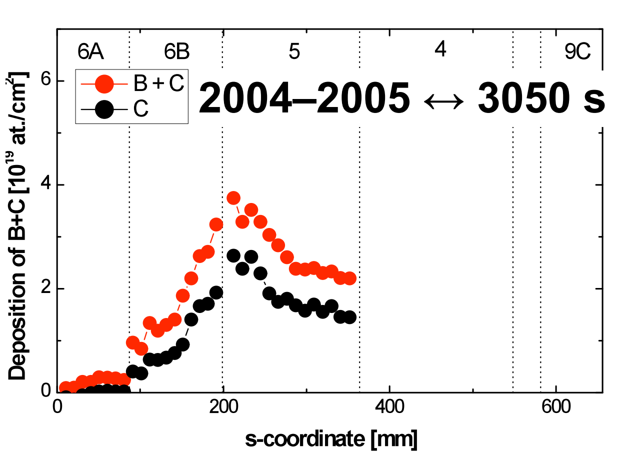
M. Mayer

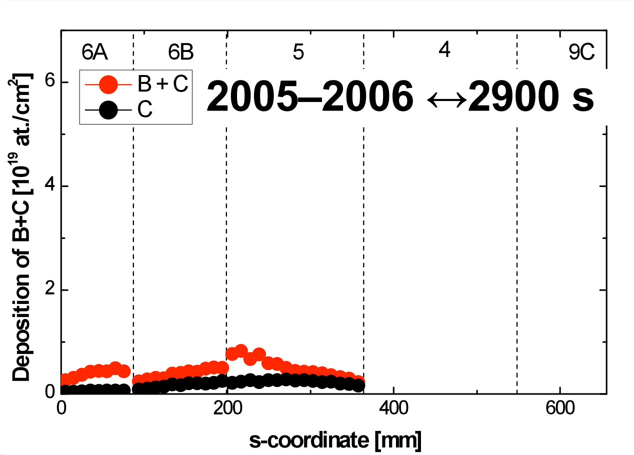
Example: ASDEX Upgrade - marker tiles

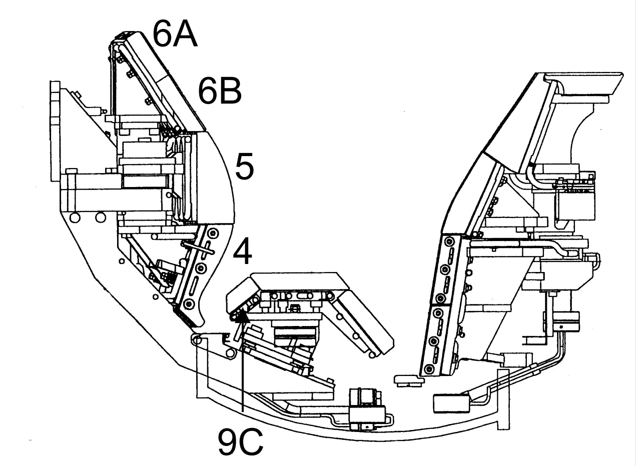
Carbon deposition in the inner divertor of ASDEX Upgrade

M. Mayer



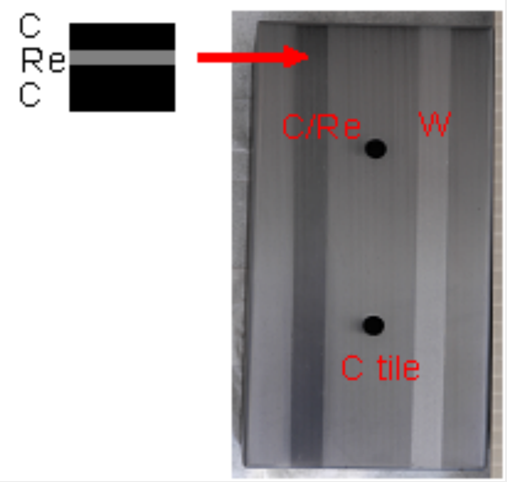






- Decrease of C-deposition on divertor tiles by factor 7 after W coverage of outer limiters
- No change in outer divertor erosion

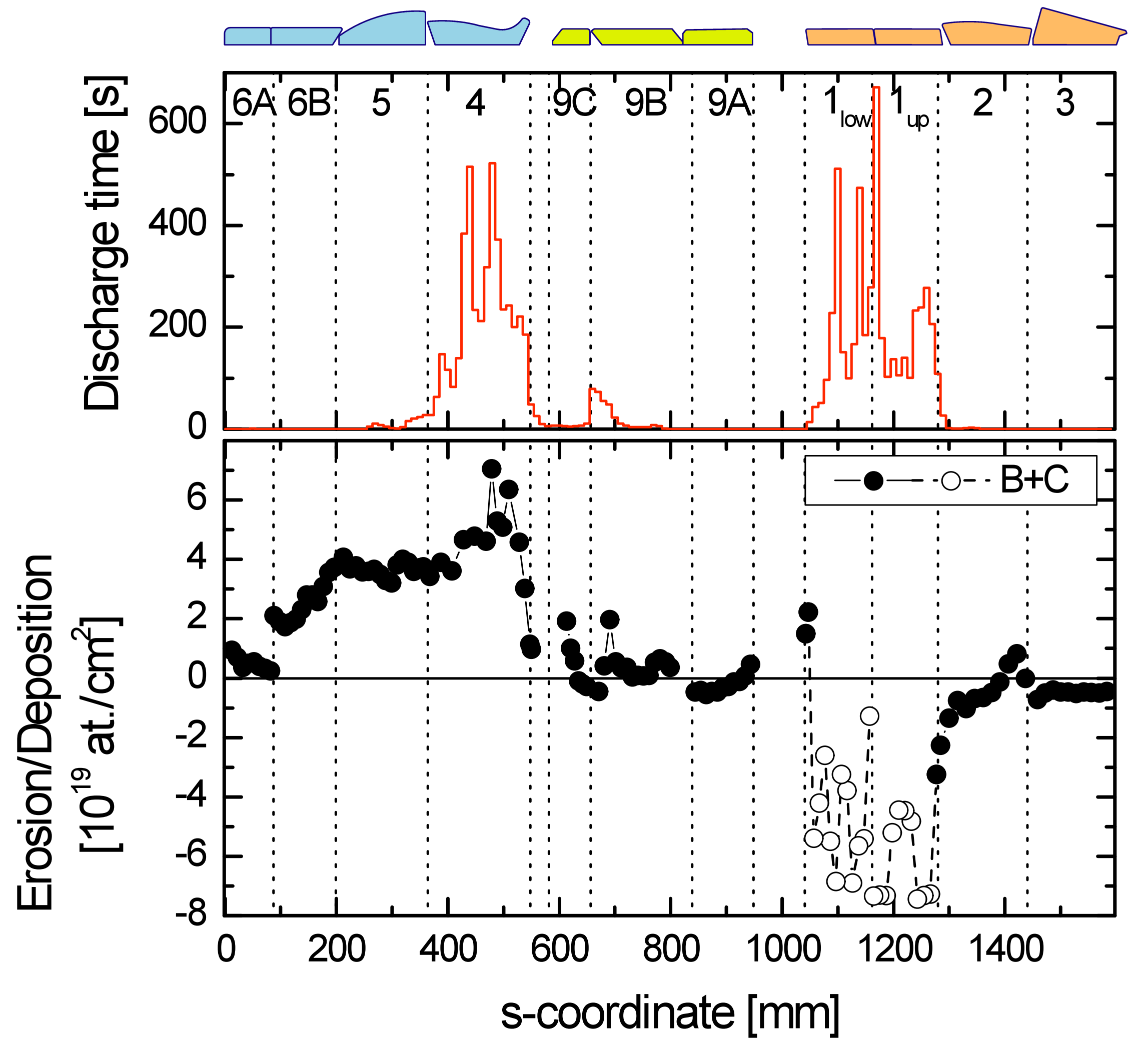
➩ **Outboard limiters identified as main carbon source**

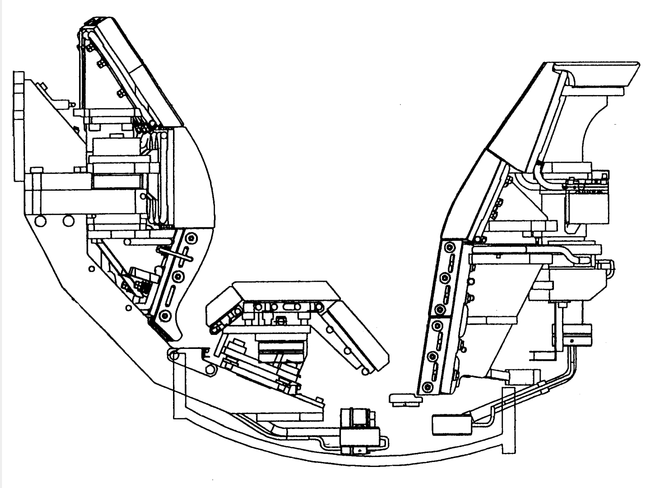


Example: ASDEX Upgrade - marker tiles

Carbon deposition / erosion in lower divertor of ASDEX Upgrade

M. Mayer



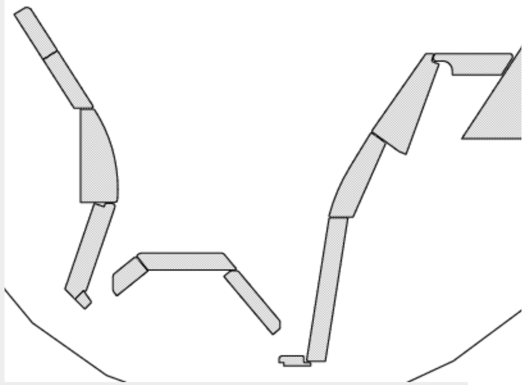


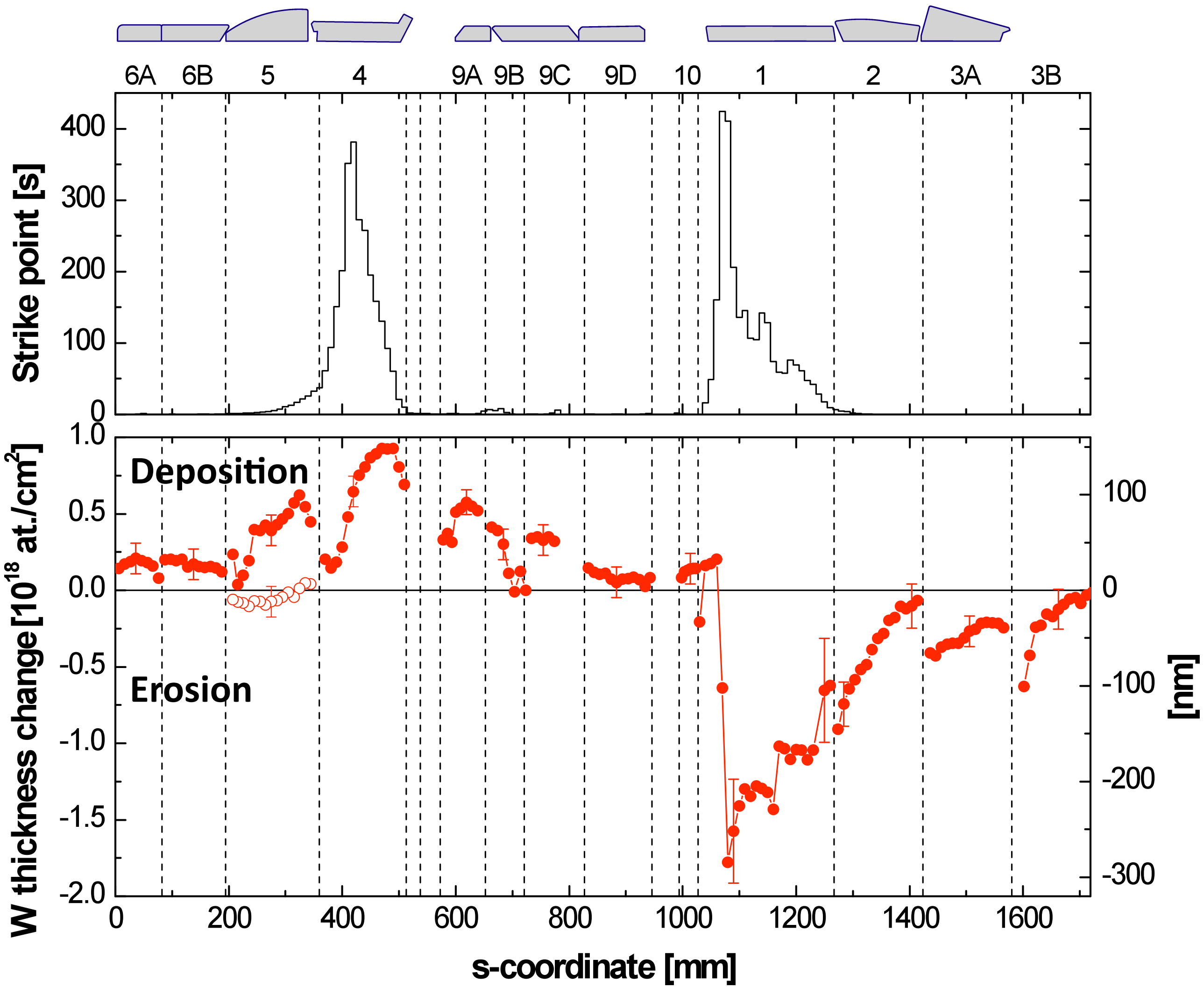
Deposition in inner divertor

Erosion in outer divertor

Example: ASDEX Upgrade - marker tiles

Tungsten deposition / erosion in lower divertor of ASDEX Upgrade





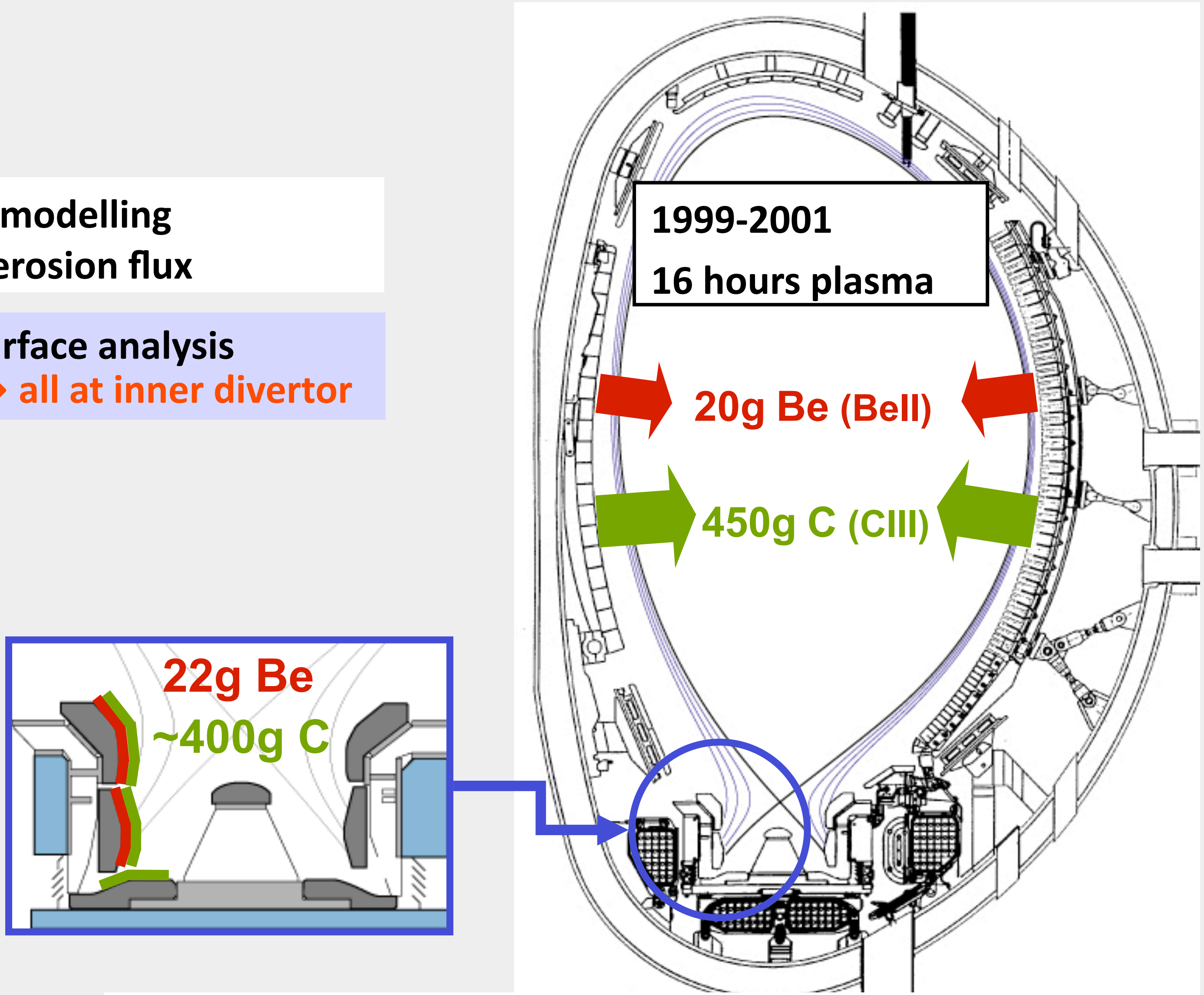
Deposition in inner divertor

Erosion in outer divertor

Example: JET accounting of Be & C erosion / deposition

- Spectroscopy + modelling
  ➩ integral erosion flux

- Post mortem surface analysis
  ➩ re-deposition → all at inner divertor



Likonen et al, JNM 337-339 (2005) 60, Matthews et al., EPS 2003

Summary

Advantages:

Independent of experiment programme

Possible to survey large vessel areas

Disadvantages:

Integral over many plasma scenarios makes interpretation and code benchmarking difficult

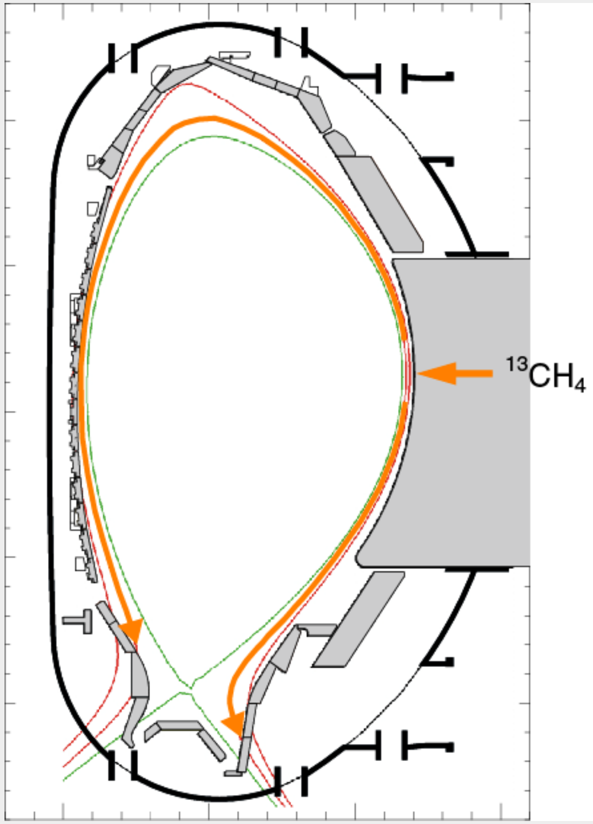
Experimental method

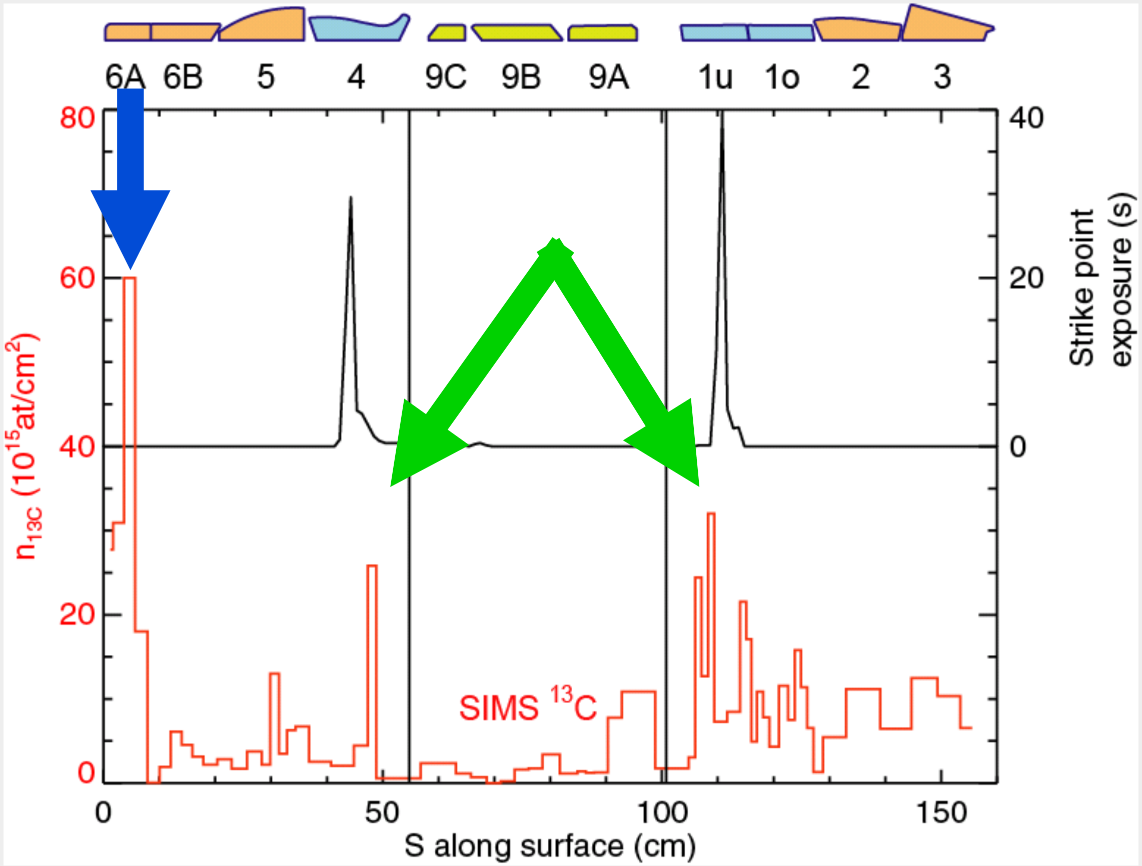
Inject tracer material in discharges at the end of an experimental campaign

Quantify tracer deposition by ex-situ surface analysis of retrieved wall tiles and/or long term probes

Identification of net material migration path (locally or globally) for particular discharge scenario

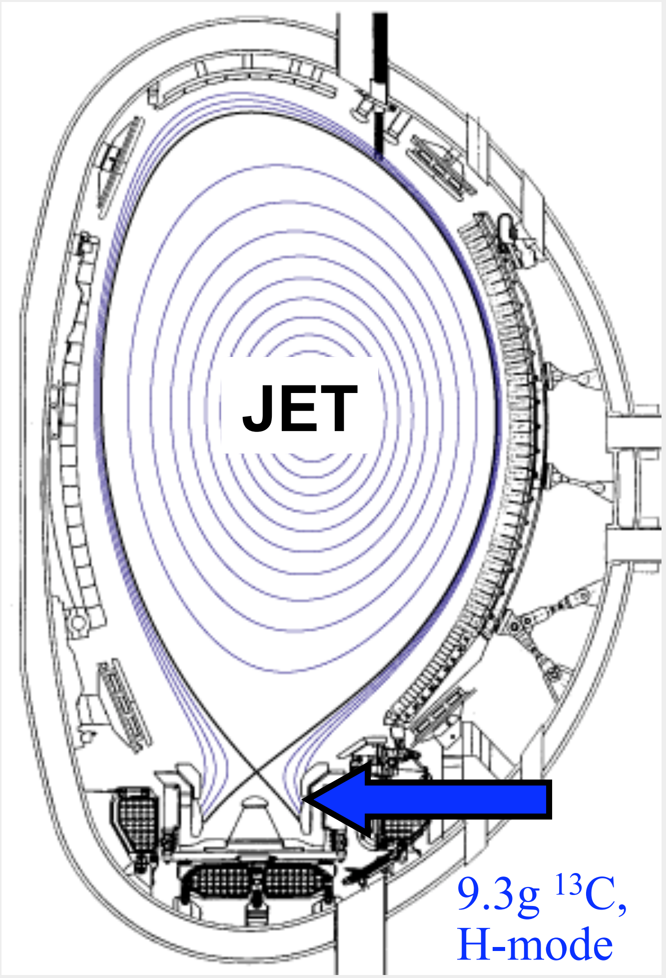
Example: 13CH4 injection in ASDEX Upgrade

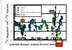




Observed deposition pattern determined by both plasma flow and by geometry

Example: 13CH4 injection in JET

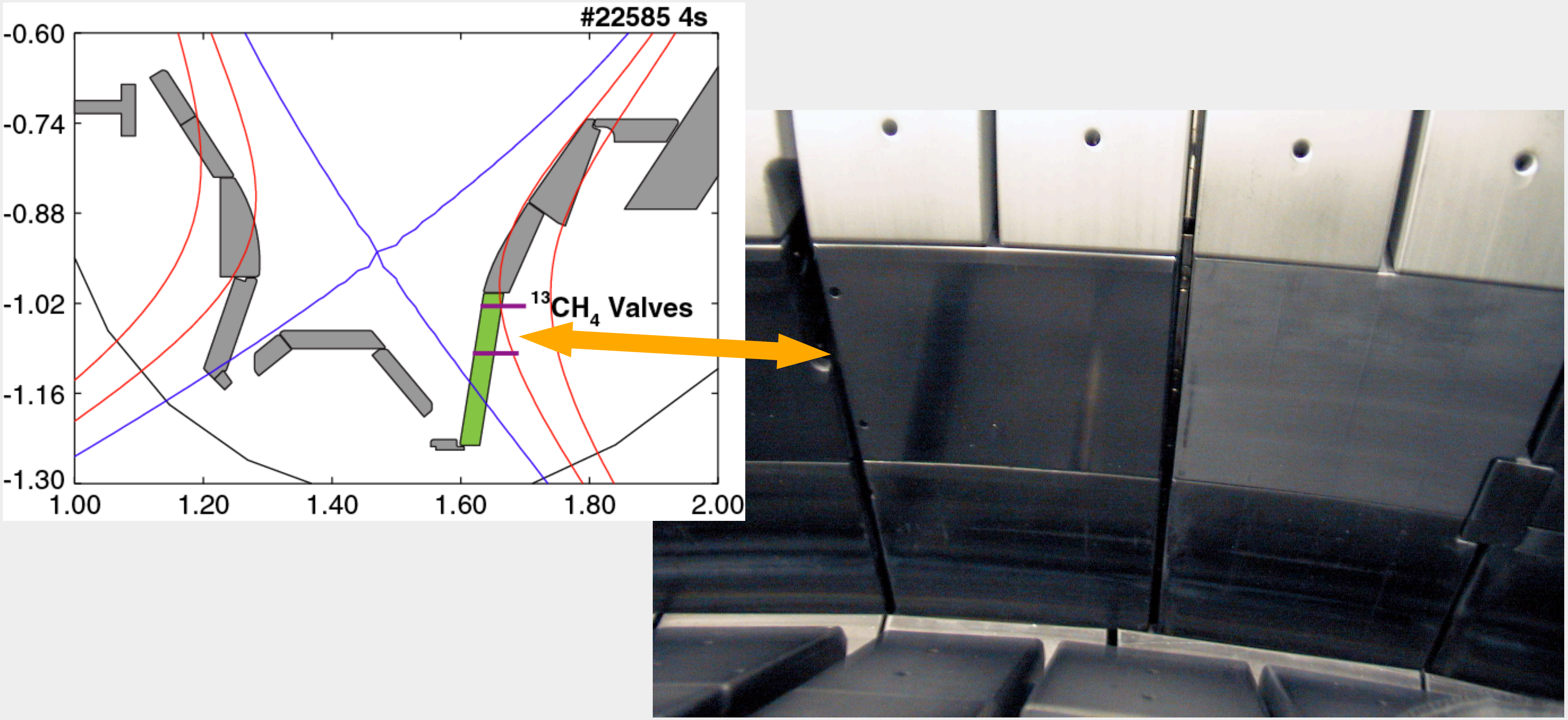




J. Strachan

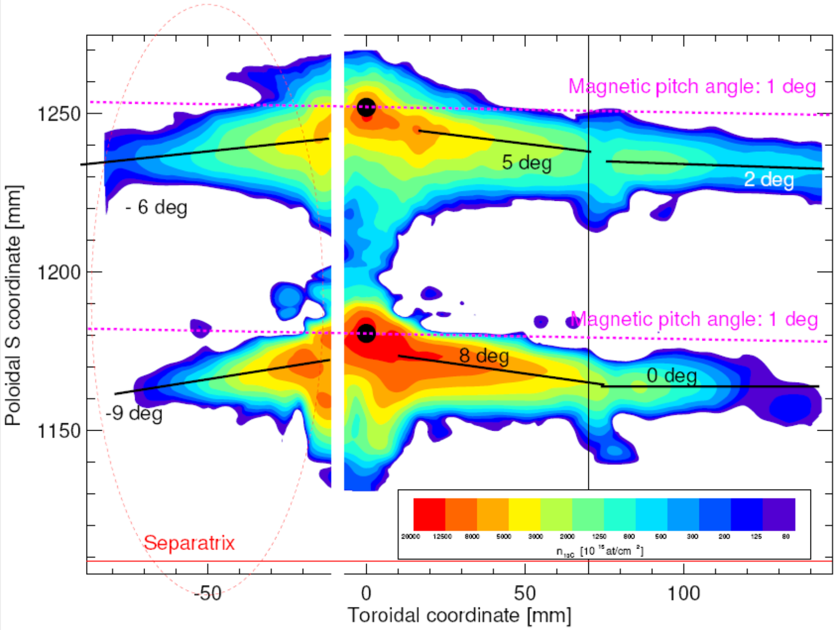
Benchmarking EDGE2D fluid code model

Example: 13CH4 local injection in ASDEX Upgrade



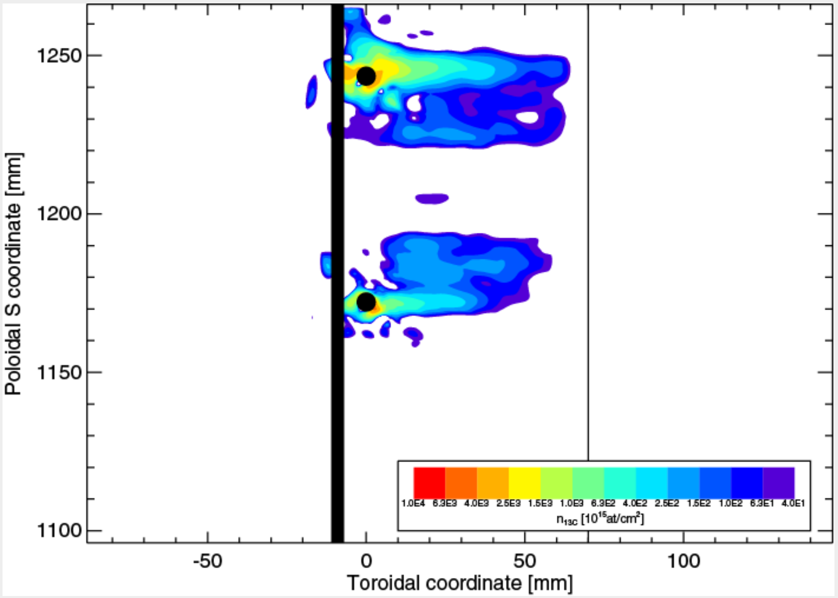
- **Puff trace amounts of $^{13}CD_4$ in series of similar discharges and measure local ^{13}C deposition 2D-distribution at retrieved tiles.**
- ➩ **Benchmark data for ERO and for spectroscopic CD flux measurements**

Example: 13CH4 local injection in ASDEX Upgrade



- 11 L-mode discharges
- $^{13}CH_4$ puff 1.6−4.6 s

Reversal of deposition shift at B-field reversal
➩ Shift due to ExB drift

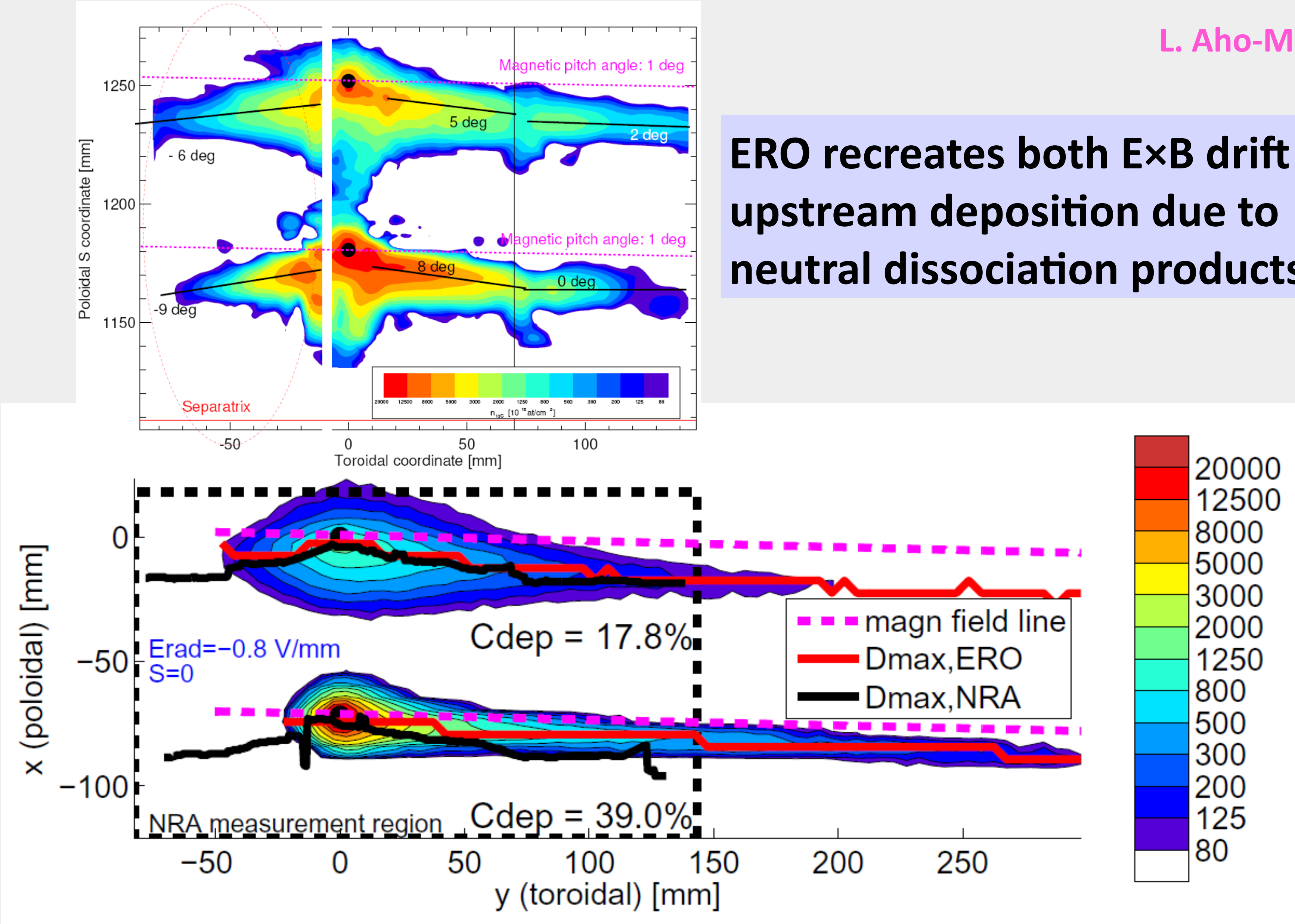


- 3 L-mode discharges
- $^{13}CH_4$ puff 1.6−4.3 s
- Reversed B_t, I_p

Example: 13CH4 local injection in ASDEX Upgrade

L. Aho-Mantila

ERO recreates both E×B drift and upstream deposition due to neutral dissociation products



Summary

Advantages:

Well defined particular discharge scenario for code benchmarking

Very sensitive quantification of tracer materials

Disadvantages:

Provides only net-deposition data. Re-erosion only by indirect evidence

Only one scenario per campaign

Experimental method

Cover main chamber wall with Be by heavy Be evaporation.

Follow relaxation of Be/C wall sources, plasma concentration and QMB deposition towards steady state situation.

Compare to reference discharge immediately before Be evaporation.

Spectroscopic measurements allow to determine gross erosion flux.

Allows to study global screening by comparison with plasma impurity concentration.

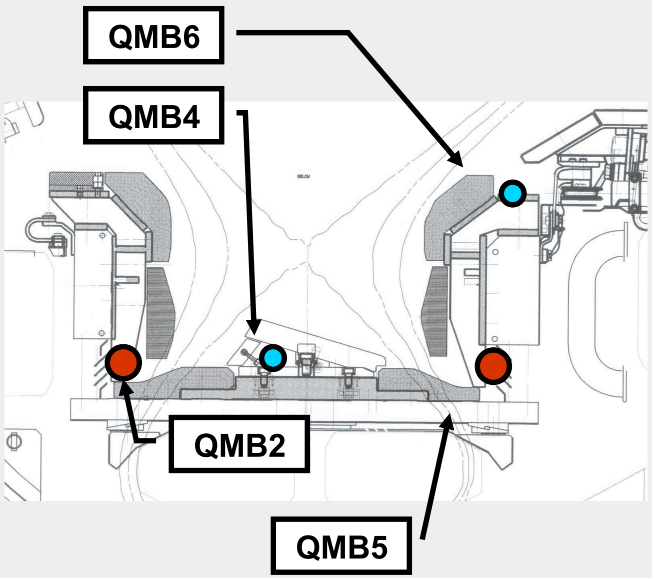
Evolution of wall composition provides information on material migration.

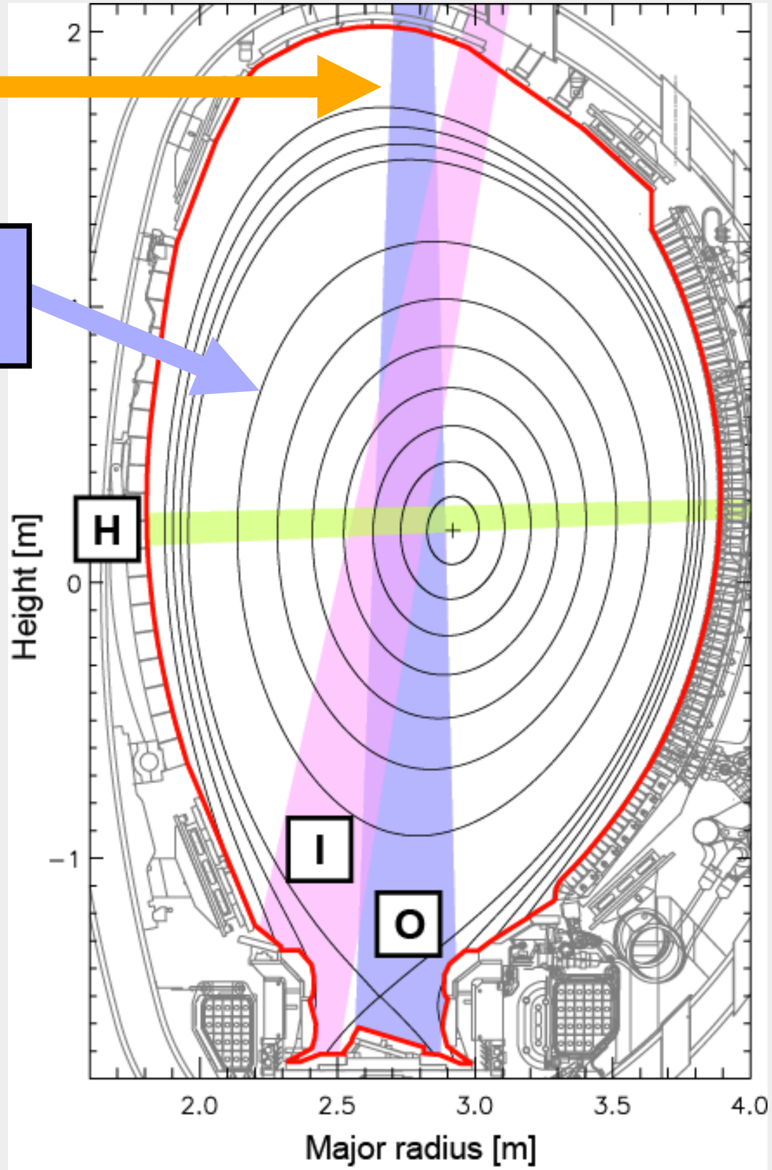
Diagnostic array

Sources by VIS spectroscopy

Deposition by QMB monitors

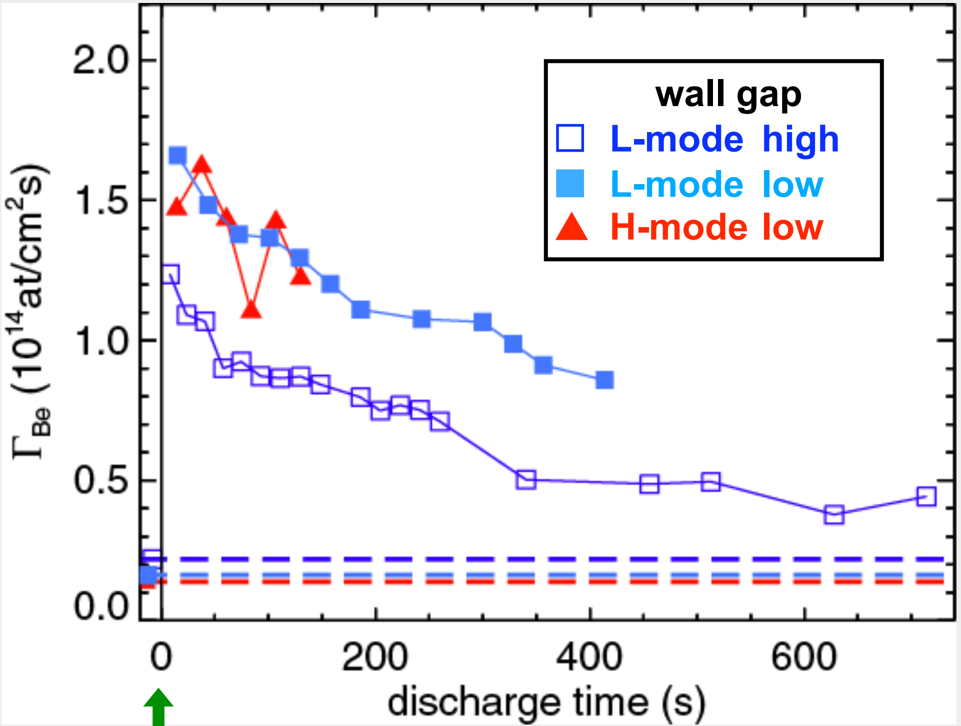
Plasma conc. by CX spectroscopy



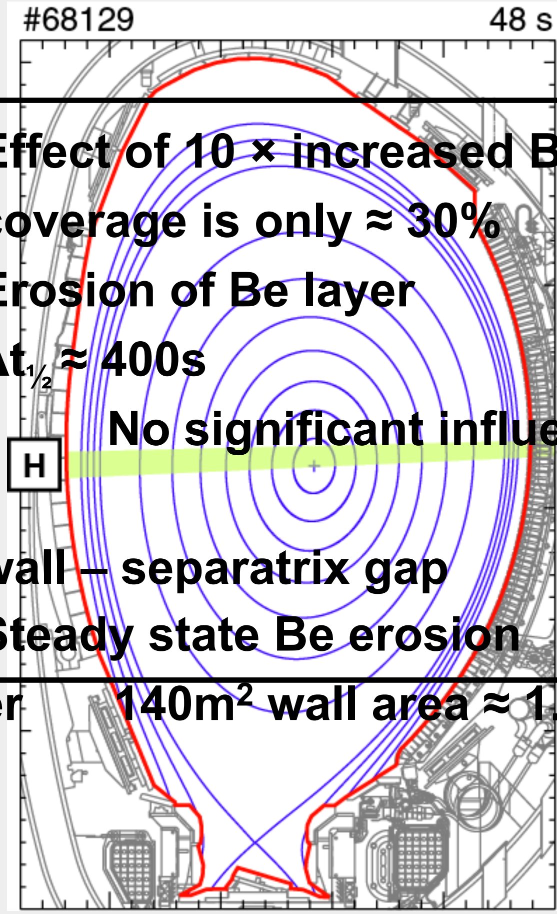


Evolution of Be wall sources

Local Be flux at first wall mid-plane from Be II line (527nm)



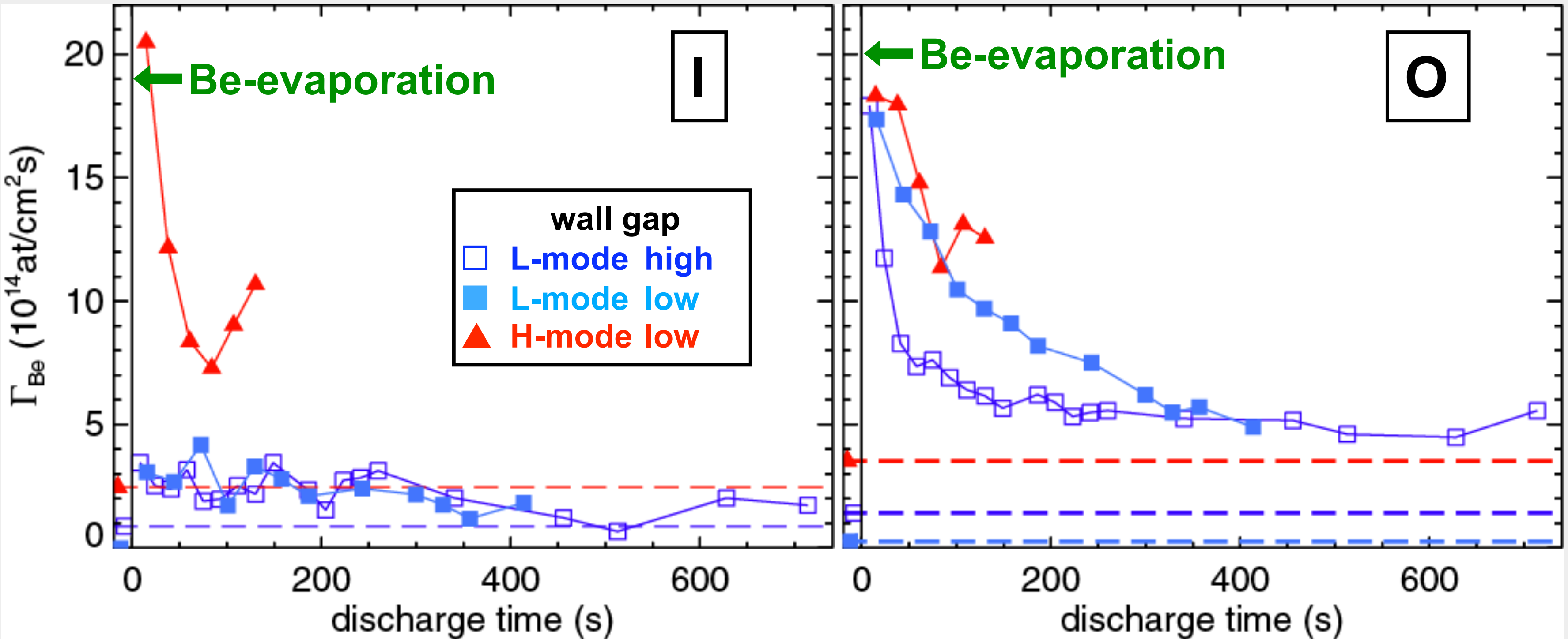
Be-evaporation

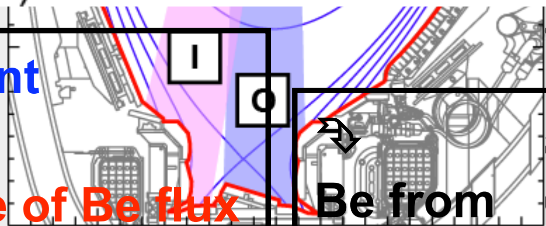


- Effect of 10 × increased Be coverage is only ≈ 30%
- Erosion of Be layer $\Delta t_{1/2}$ ≈ 400s
- No significant influence of wall – separatrix gap
- Steady state Be erosion over 140m^2 wall area ≈ 1.5 g/h

Evolution of Be divertor sources

Integrated Be flux from inner (I) and outer (O) divertor from Be II (527nm)





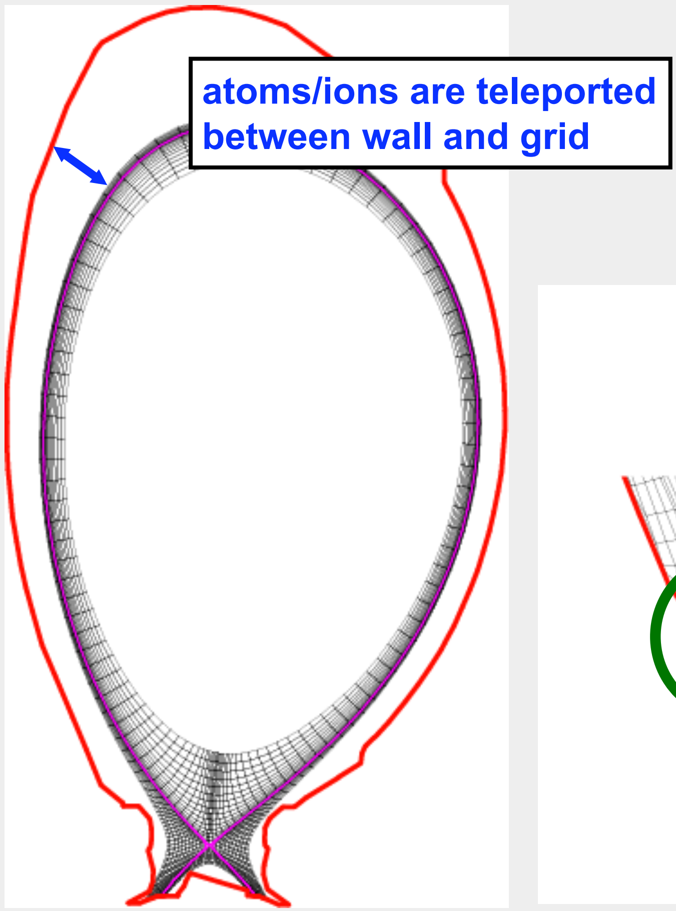
- ❑ L-mode: Be flux ≈ constant
  - ➩ Deposition zone
- ❑ H-mode: Strong decrease of Be flux
  - ➩ Erosion zone

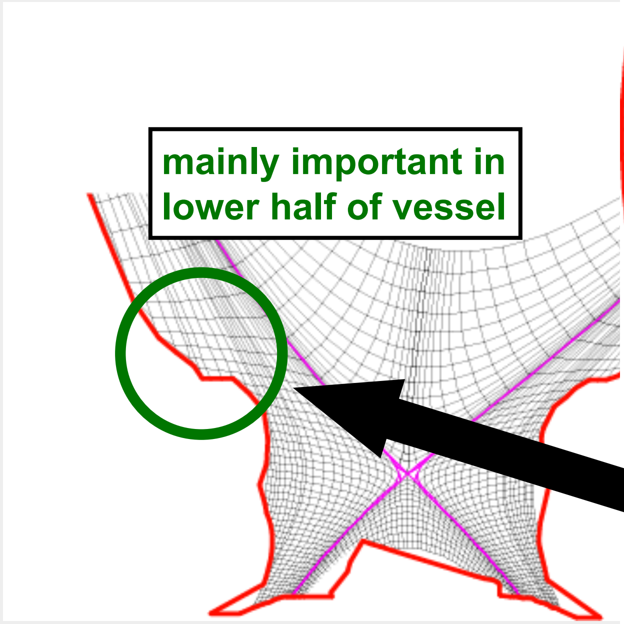
- ❑ ...ll gap: Be flux ... on time scale ≈ main
  - ➩ Mainly re-erosion of Be from main wall
- ❑ Large gap: Be flux ≈ constant after 100s

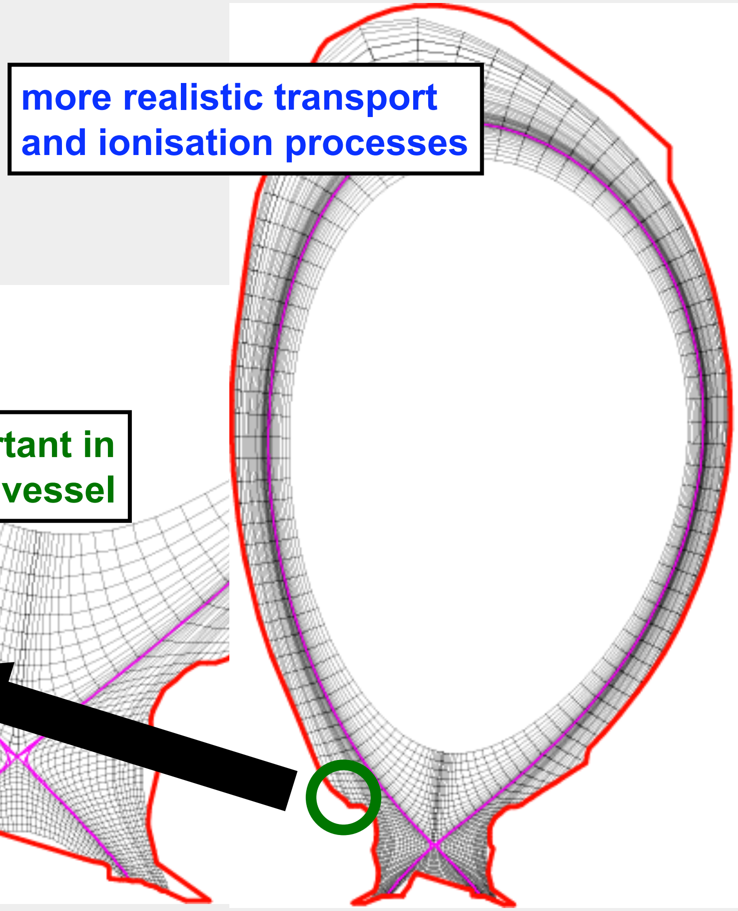
Modelling wall composition change by migration

- ❑ Standard grid topology is restricted to plasma-wall contact at target plates
- ➩ Missing processes at "white spots":
  - || and ⊥ transport to wall
  - ionisation & transport of eroded atoms

- ❑ Extend grid and tailor to 1st wall
- ❑ Fill with plasma using extrapolation from original grid







Summary

Advantages:

Well defined particular discharge scenario for code benchmarking

Trace several materials simultaneously

Disadvantages:

Provides only gross erosion data. Deposition only by indirect evidence

Quantitative impurity flux quantification requires local plasma parameters

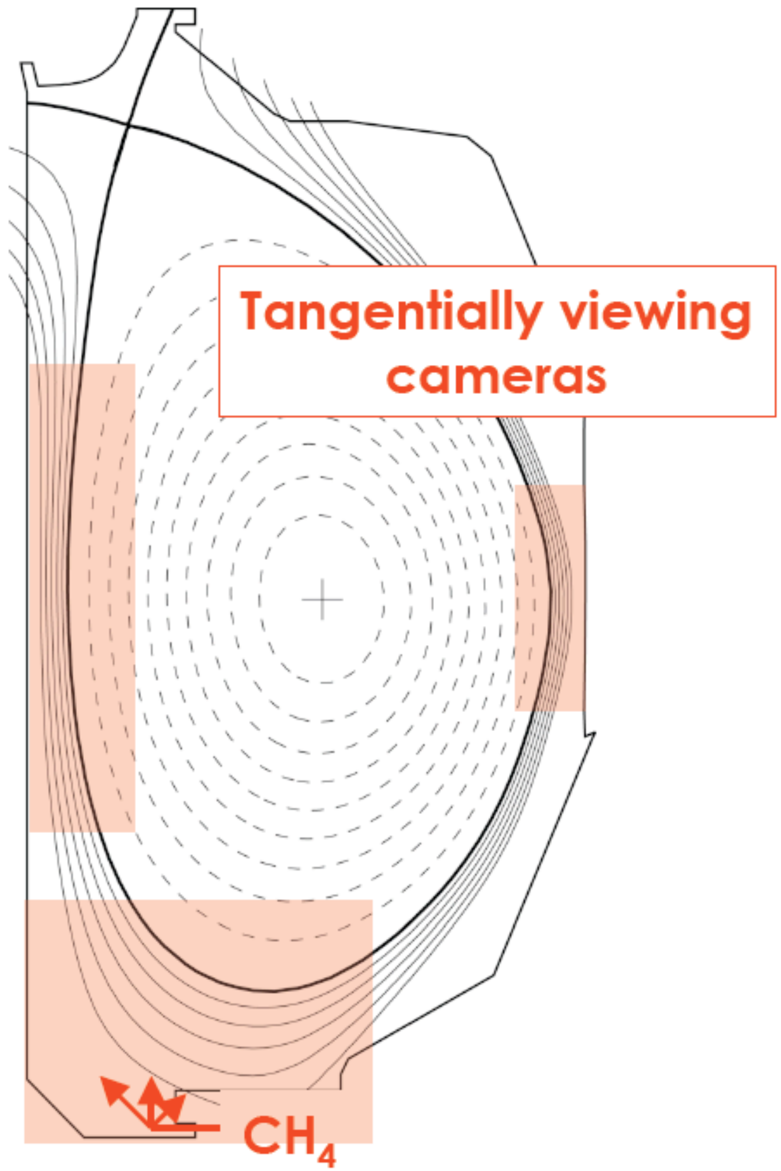
Experimental method

Direct observation of impurity radiation during injection

Spectroscopic measurements allow to determine spatial distribution of emission by successive ionisation states

Allows to directly observe the influence of transport

Example: carbon flow measurements in DIII-D

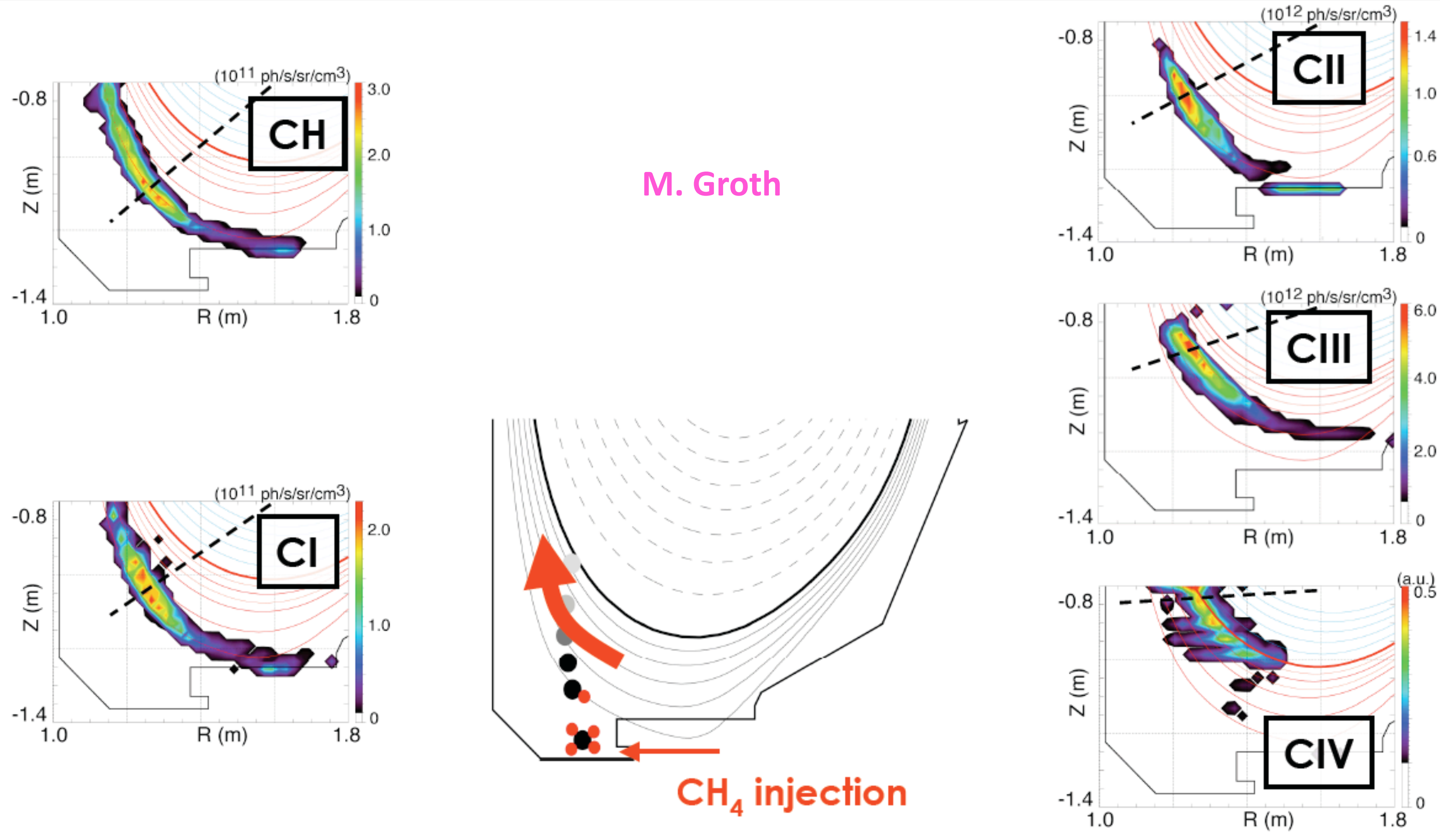


- **Principal flow measurements in the plasma crown**
  - Multi-tipped, reciprocating Langmuir probe: parallel-**B** v_{D+}
  - Passive Doppler spectroscopy: parallel-**B** v_{C+}, v_{C2+}
- **Toroidally symmetric injection of CH_4 from lower outer pumping plenum + tangential cameras**
  - Emission profiles: direction of low charge-state carbon flow
  - Order-of-magnitude estimate of C^+ poloidal velocity

M. Groth

Example: carbon flow measurements in DIII-D

Carbon emission profiles of CH4 break-up are progressively shifted radially inward and poloidally toward inner plate



Outline

Overview and rationale

Material transport processes

Particle collisions

Plasma turbulence

Experiments

Phenomenological observations

Specific experiments

Summary and outlook

Outlook

Experiment side

Implement new PSI and impurity transport diagnostics
to study timedepent processes in single discharges

Improve diagnostics for characterisation of incident plasma flux

Modelling side

Get complete treatment of transport processes

Coupled codes for plasma and material side

Extend computational domain for plasma towards entire 1st wall

Develop 3D codes for near wall domain