I: Basic physics of edge plasmas in magnetic confinement fusion

D. Reiter

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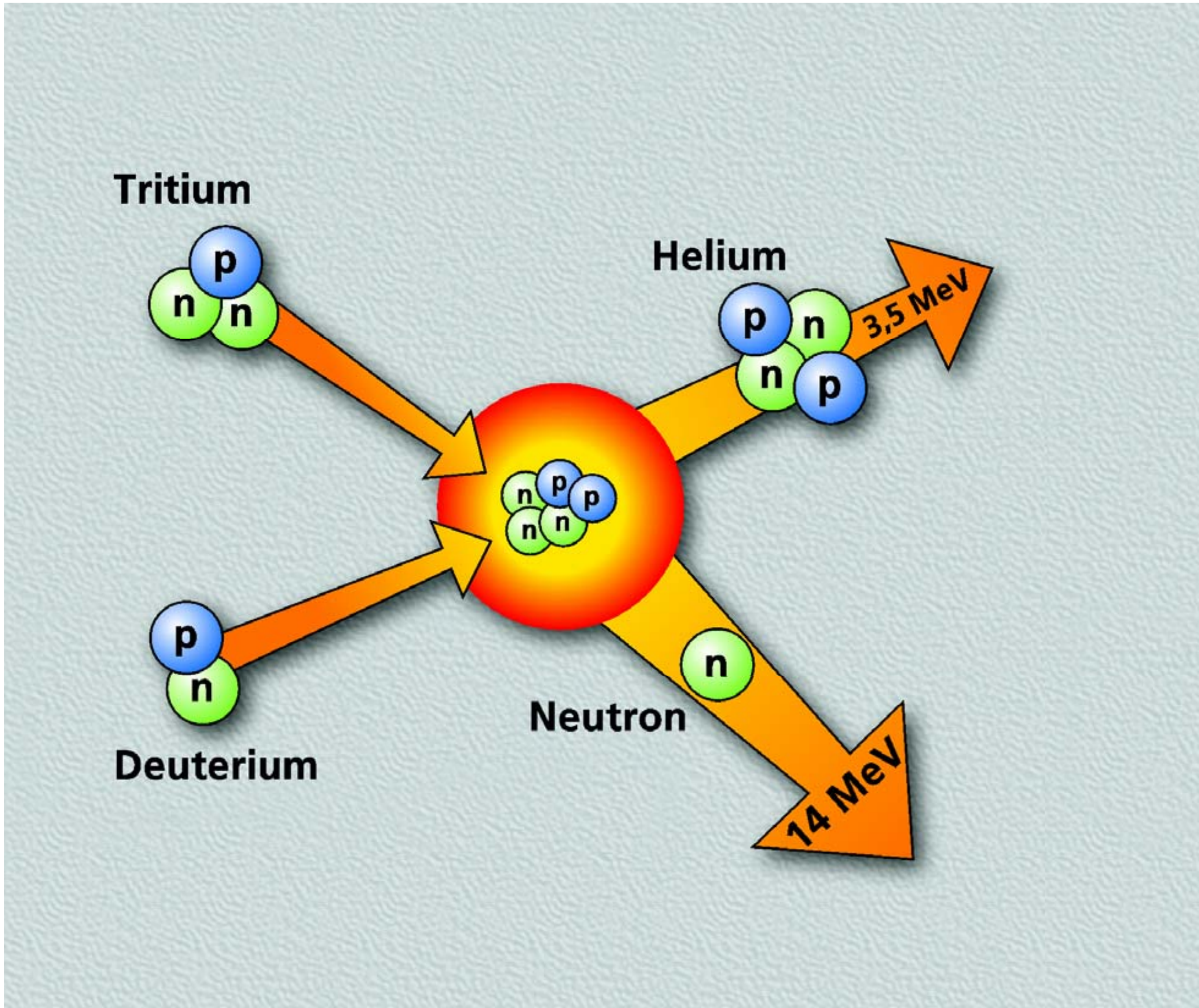
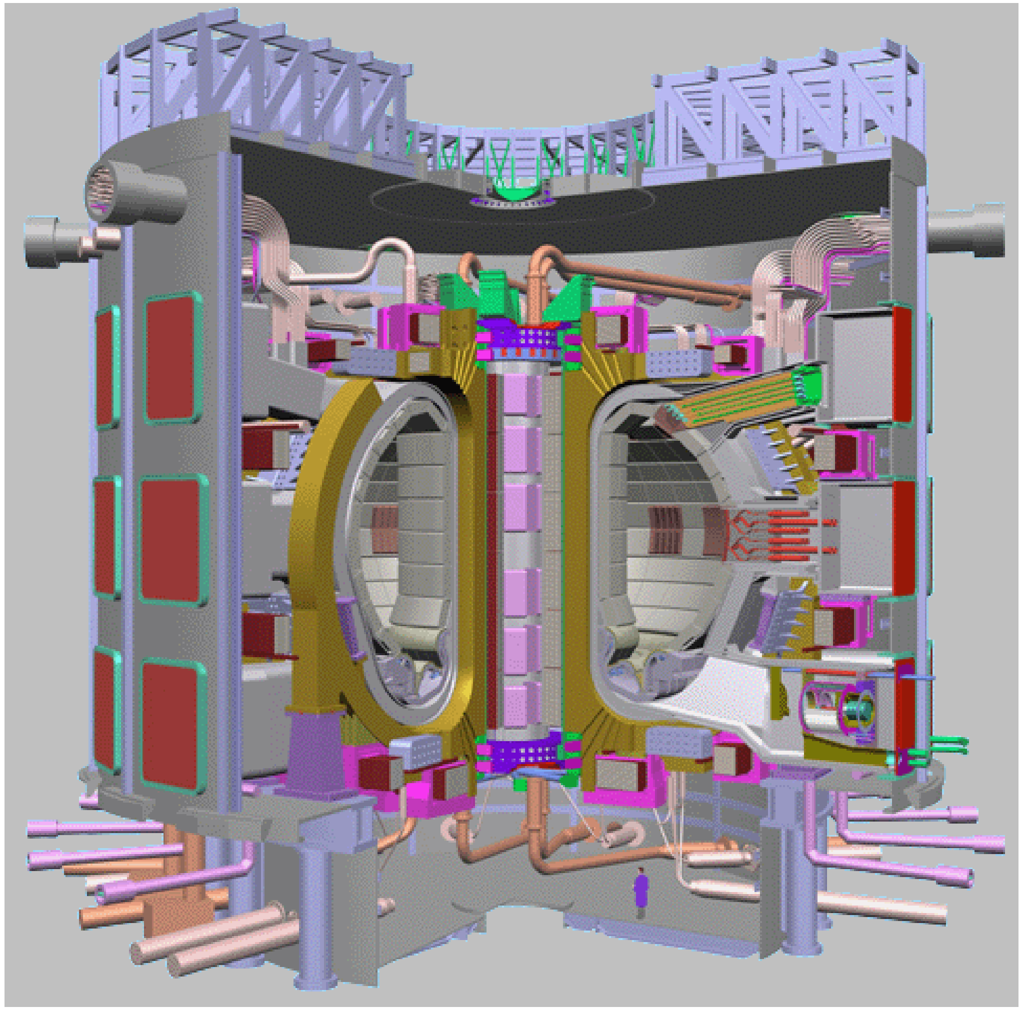
Atomic and Molecular Data for Fusion Energy research, Aug.-Sept. 2006, ICTP, Trieste

The D-T-Reaction

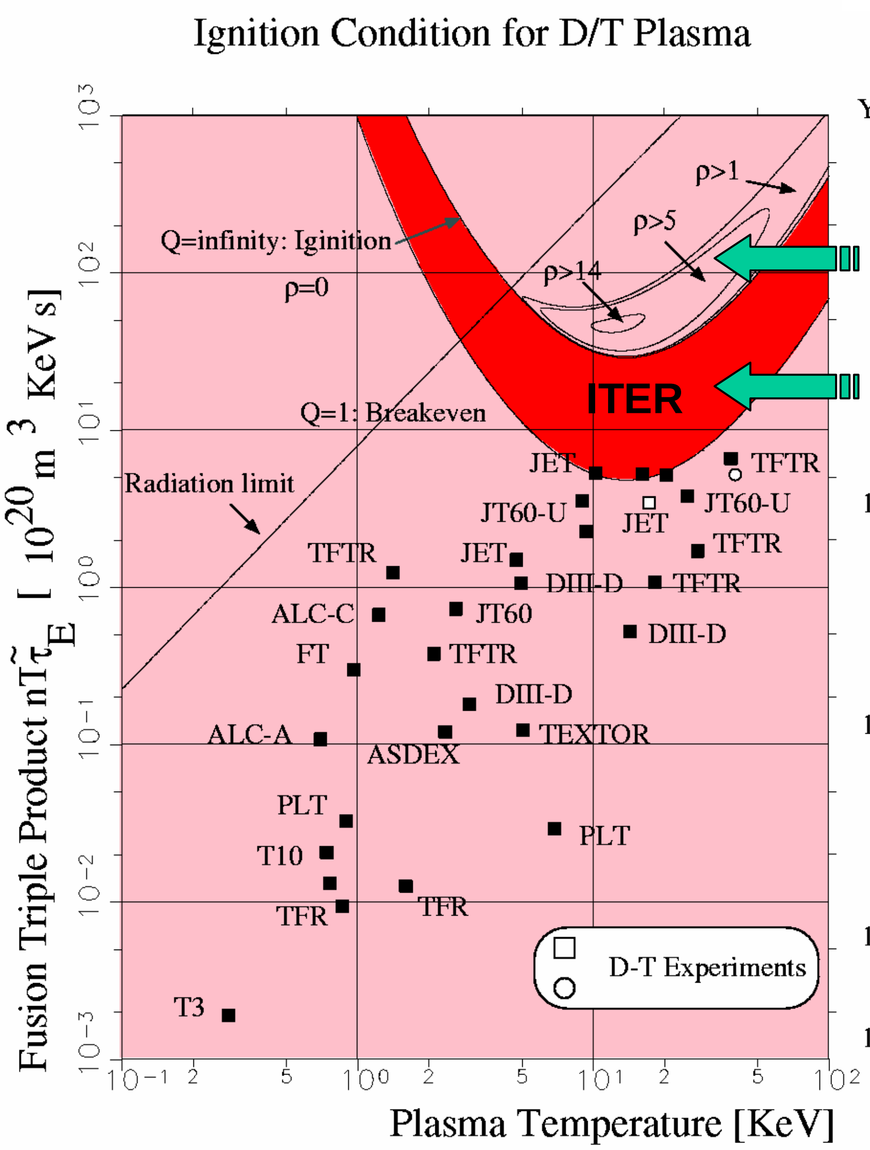


The ITER Challenge



ITER: Furnace chamber:

Ø 15 m   6.8 m high   5.3 T   15 MA   500 MW   8 min



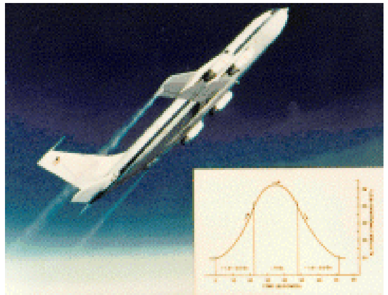
Atomic/Molecular processes, Plasma material interaction

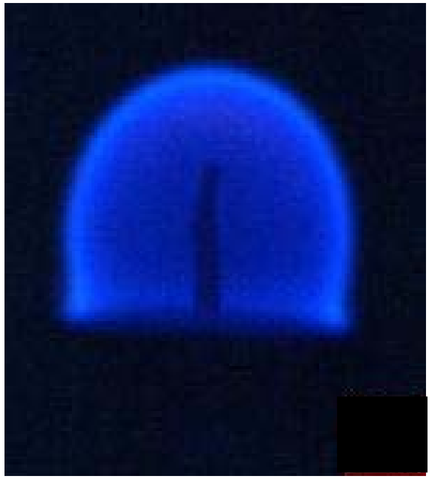
Physics of hot plasma core

Candle, earth

Convection

Candle, microgravity





(only small, dim burn)

Only Diffusion

(no convection)

There is no natural ash removal mechanism from a magnetically confined fusion flame.

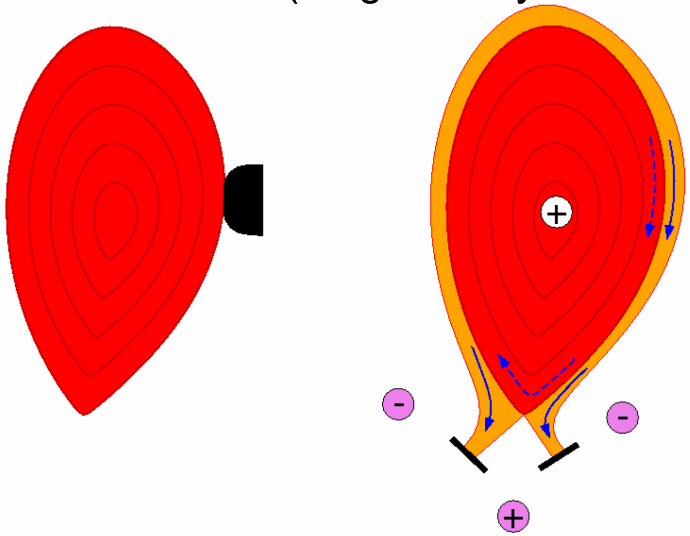
Without active flushing the flame is choked by its own ash within about 100 s, well short of the ITER design values.

Helium ash removal is a critical issue

Two basic concepts for boundary plasma engineering

Limiter
(material boundary)

Divertor
(magnetically defined boundary)

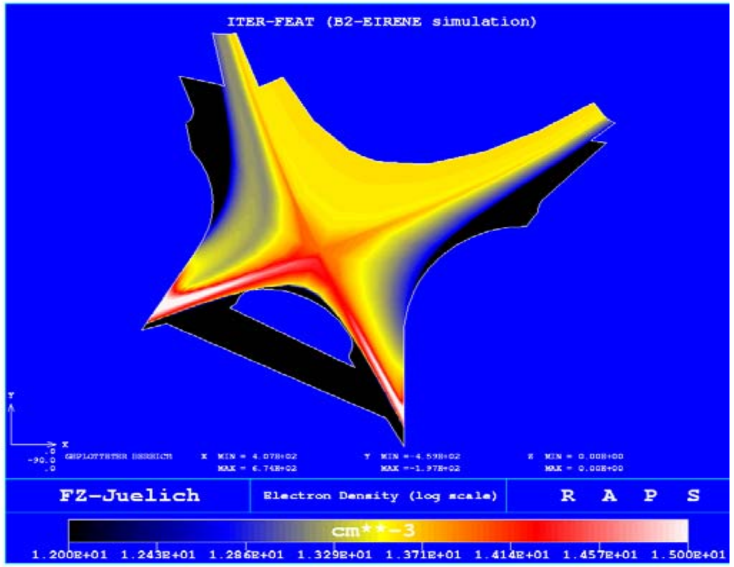


Questions addressed by Divertor Design for ITER

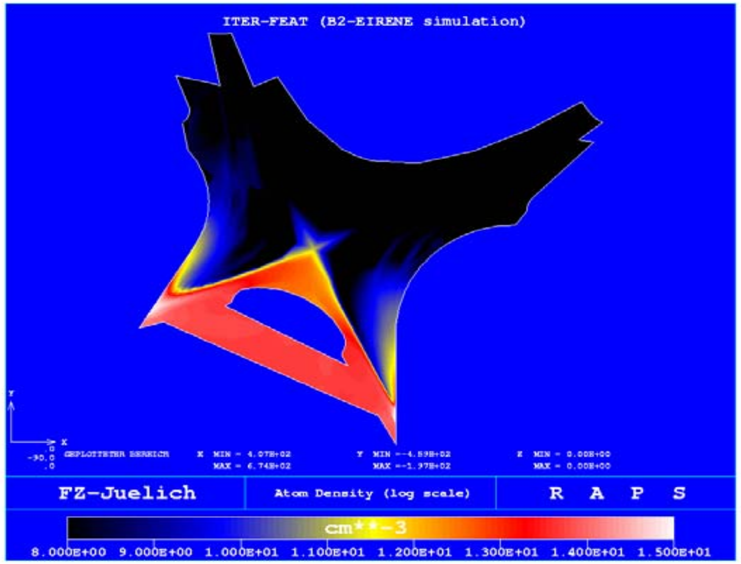
1) Can sufficient particle throughput be maintained?

2) Can, simultaneously, a reactive plasma protect the chamber from a thermonuclear plasma?

Electrons, H^+ Ions



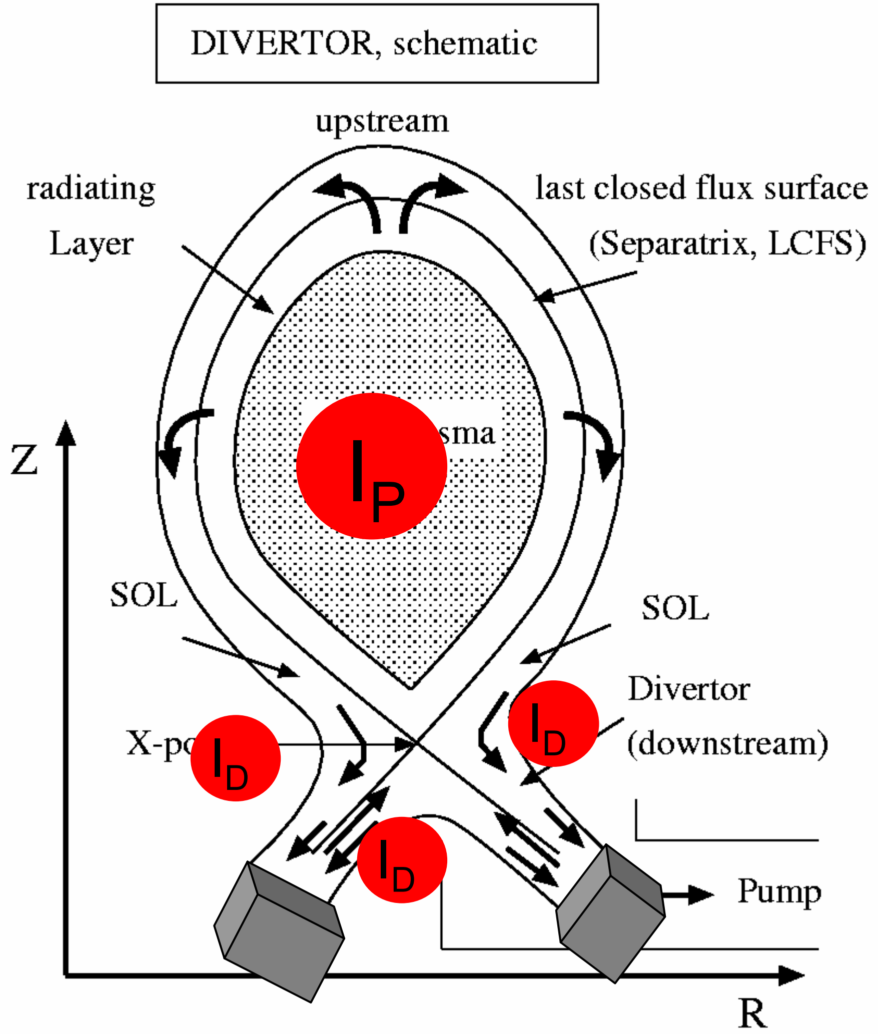
H, H_2, …Neutrals



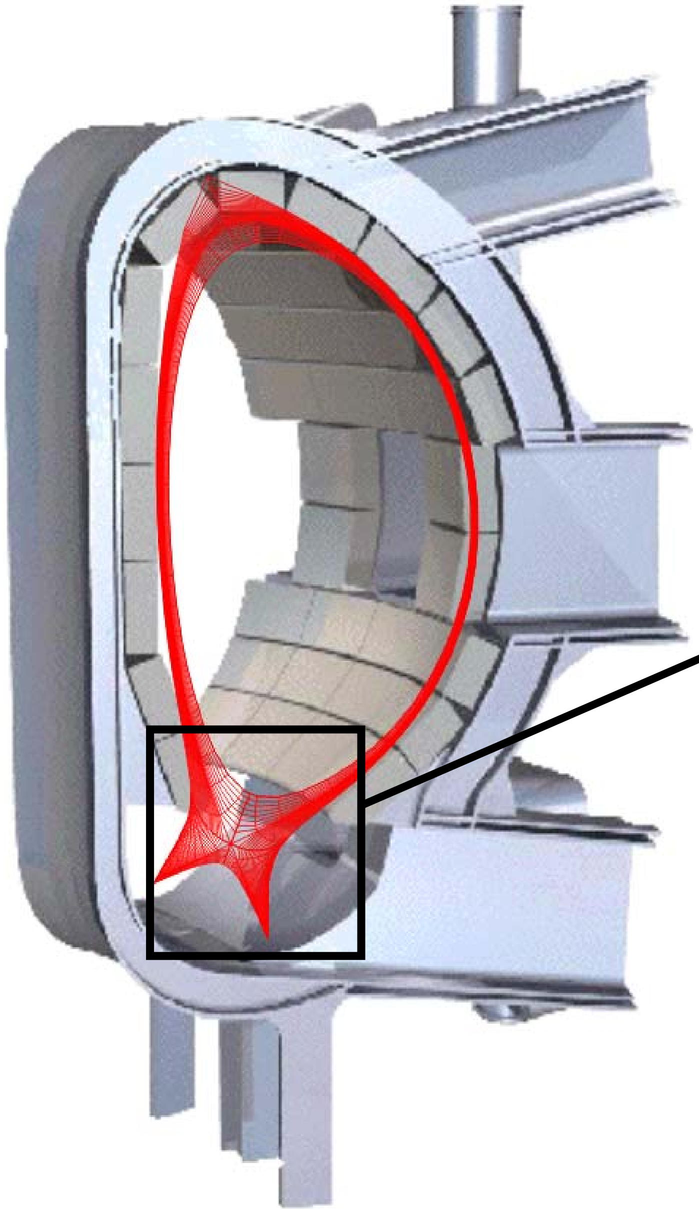
These Talks:

- **Time scales**
- **The ITER Divertor Code**
- **Hydrogen chemisty in low temperature Divertor Plasmas**
- **One critical issue: tritium retention, hydrocarbon chemistry**

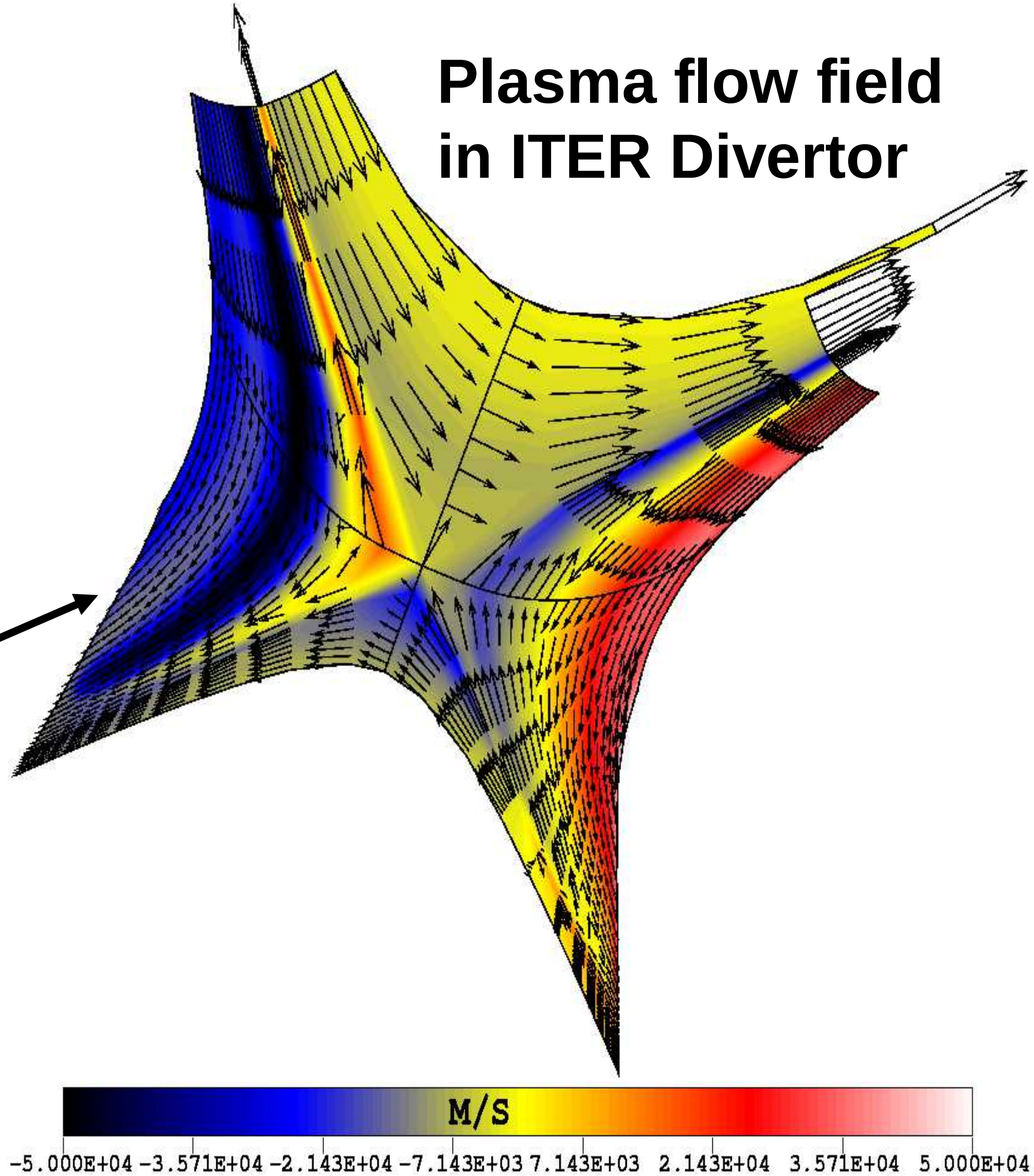
Magnetic Fusion: how to produce convection ? DIVERTOR



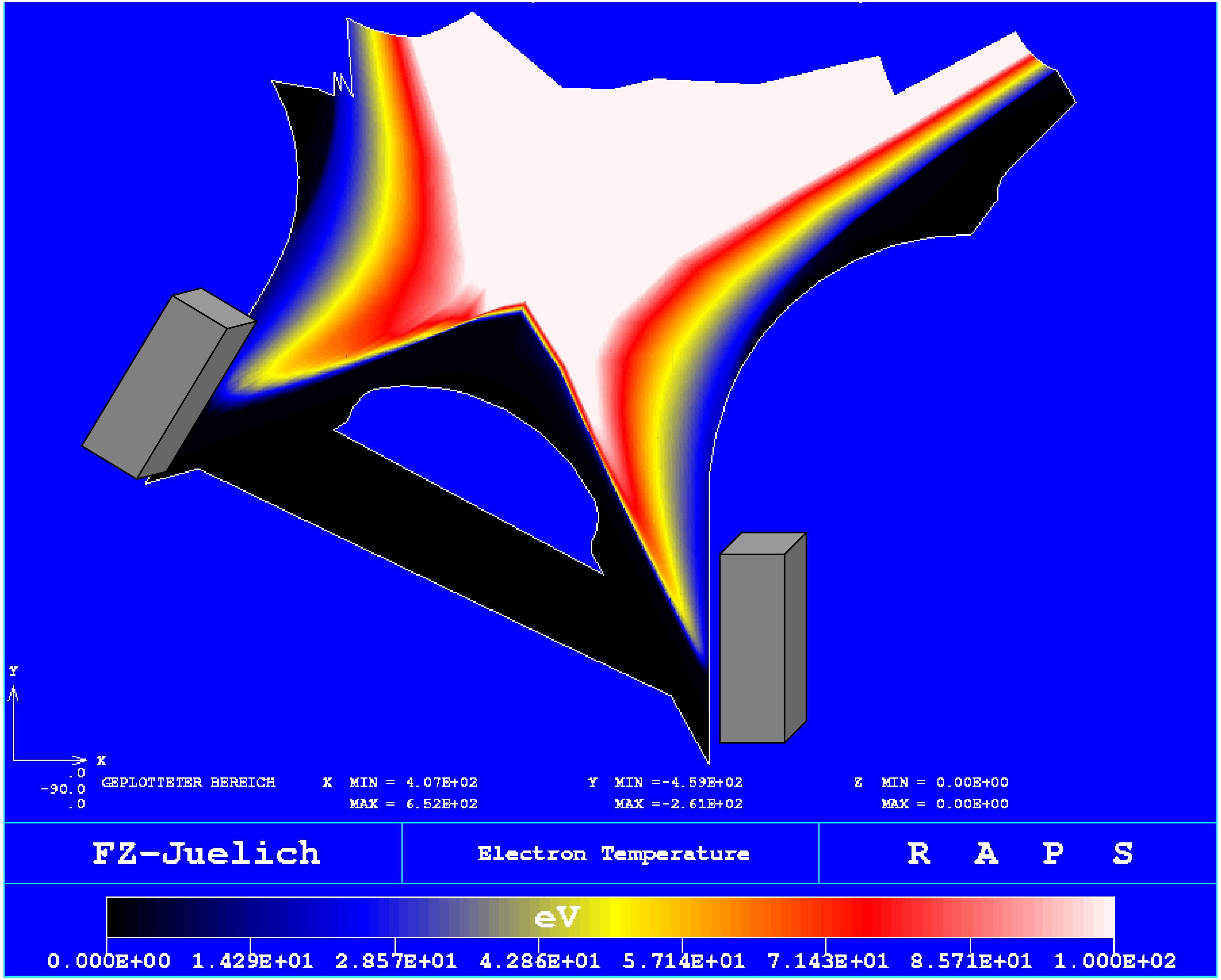
The ITER Divertor



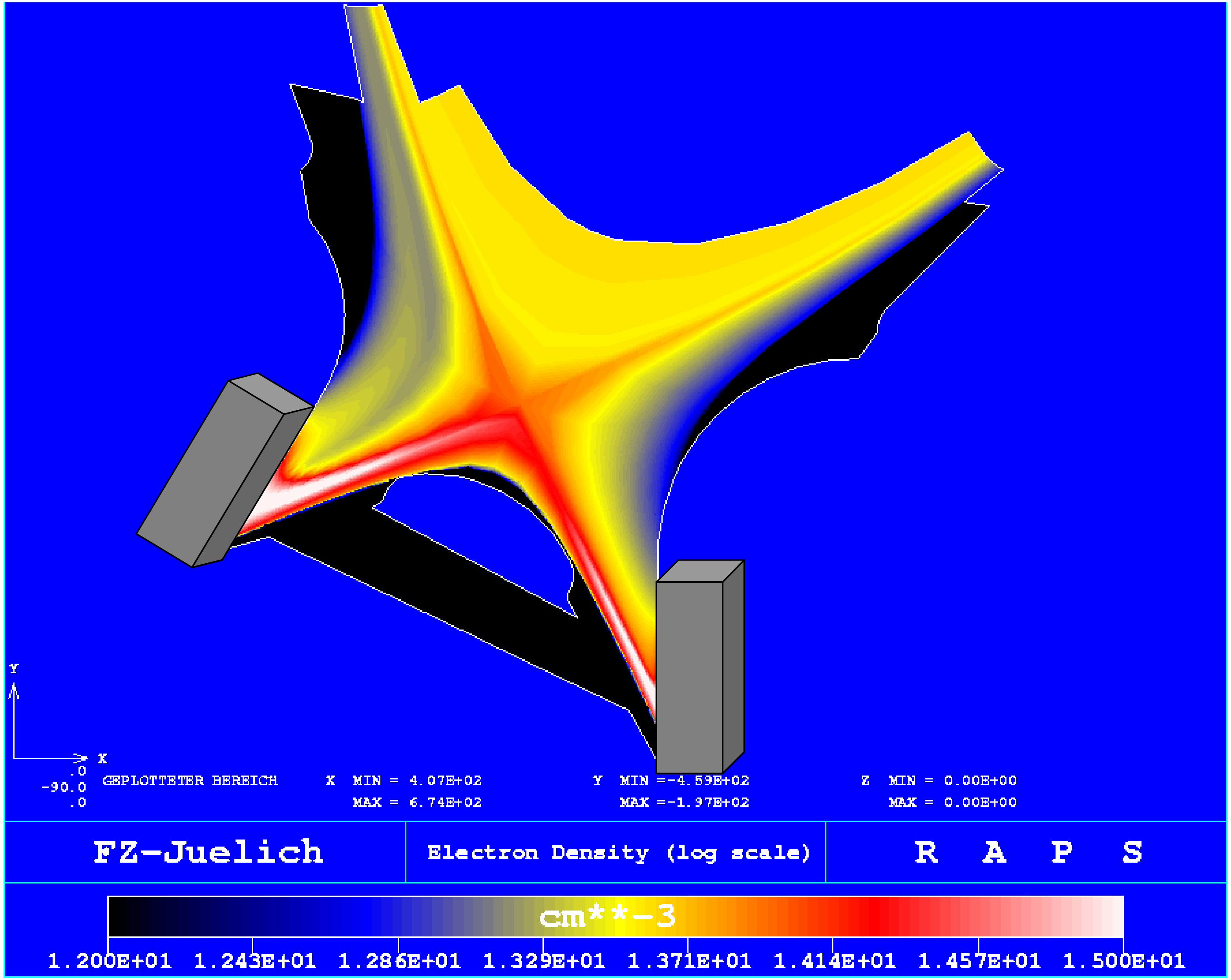
Plasma flow field in ITER Divertor



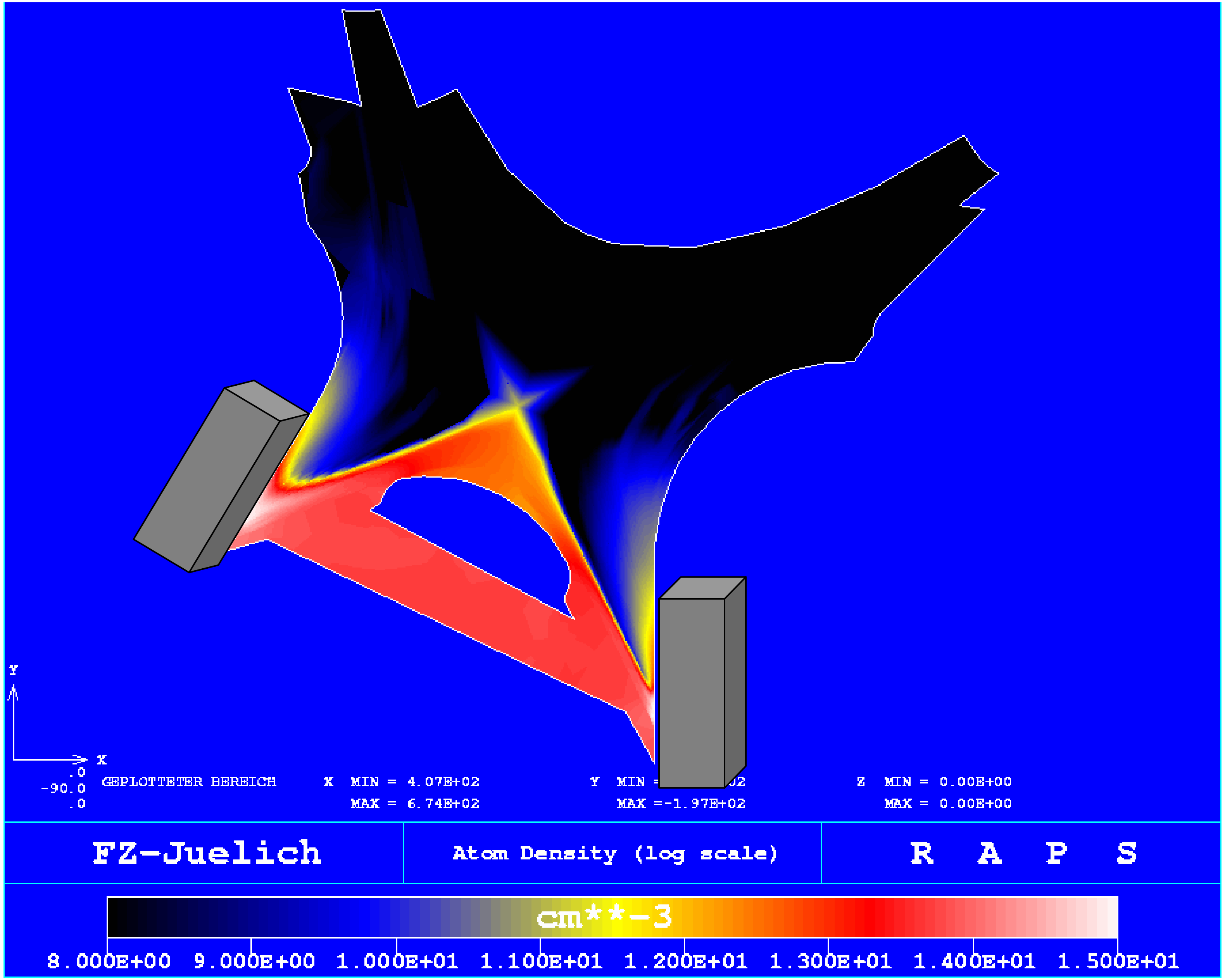
ITER, B2-EIRENE simulation, detached, T_e field



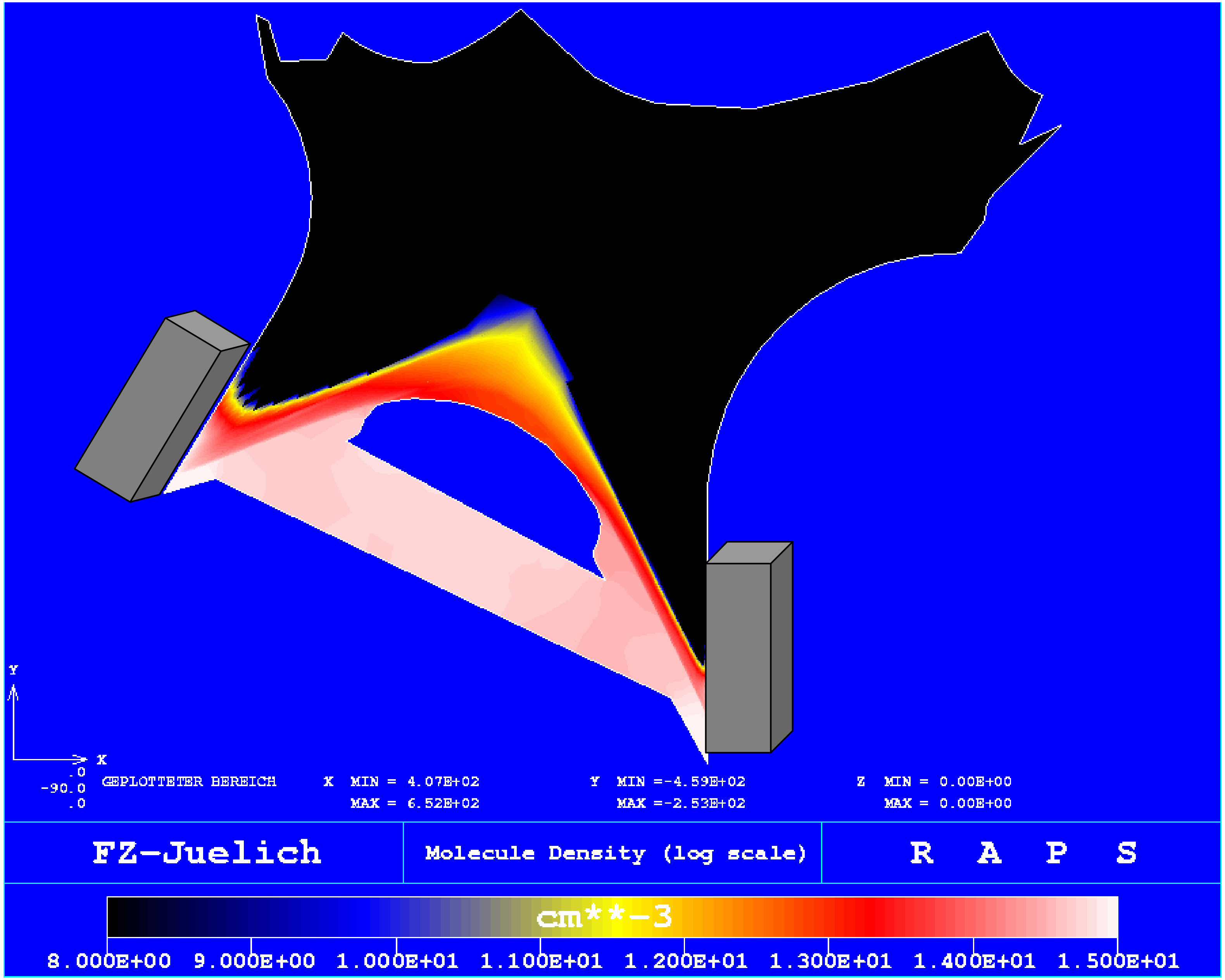
ITER, B2-EIRENE simulation, detached, n_e field



ITER, B2-EIRENE simulation, detached, n_A field

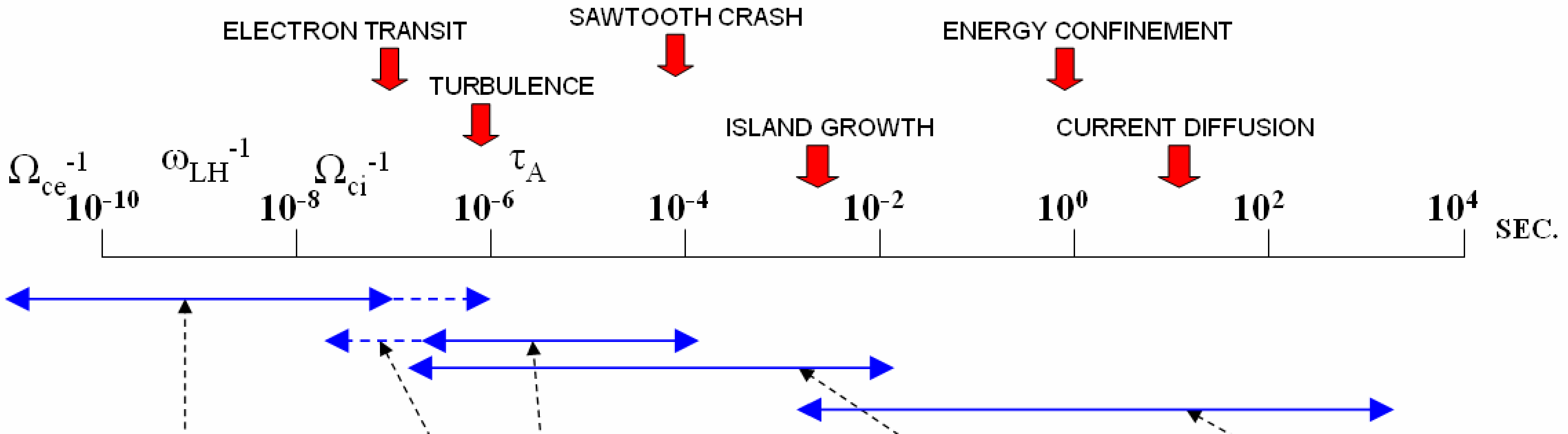


ITER, B2-EIRENE simulation, detached, n_M field



core plasma

Typical Time Scales in a next step experiment with B = 10 T, R = 2 m, $n_e = 10^{14}$ cm^{-3}, T = 10 keV

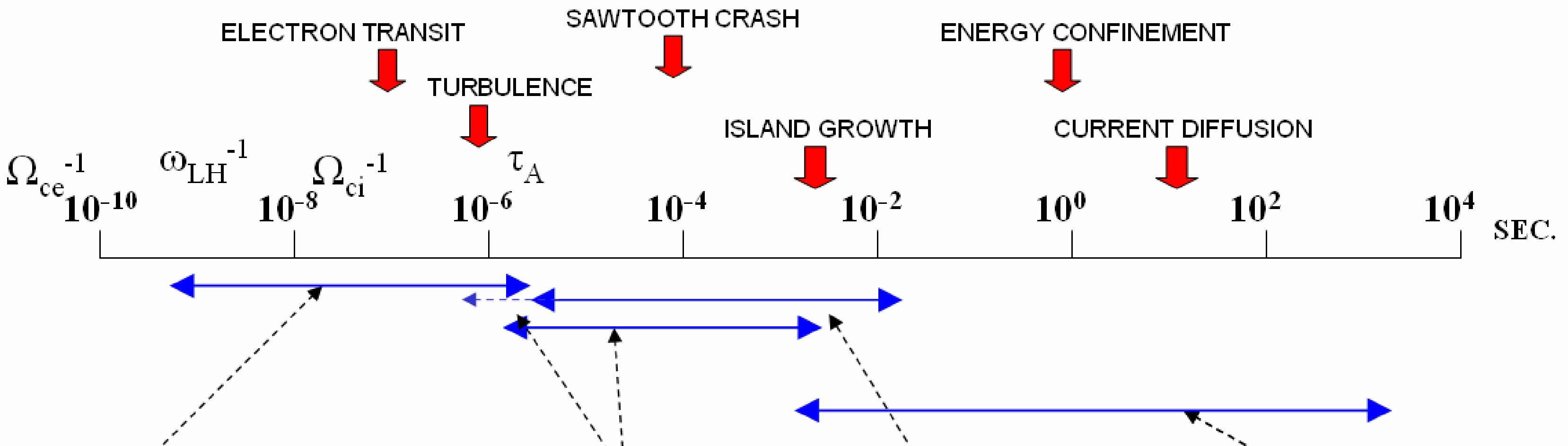


Single frequency and prescribed plasma background	Neglect displacement current, average over gyroangle, (some) with electrons	Neglect displacement current, integrate over velocity space, neglect electron inertia	Neglect displacement current, integrate over velocity space, average over surfaces, neglect ion & electron inertia
RF Codes	Gyrokinetics Codes	Extended MHD Codes	Transport Codes
wave-heating and current-drive	turbulent transport	device scale stability	discharge time-scale

Fusion Simulation Project Vol.2, FESAC ISOFS Subcommittee Final Report, Dec. 2002

edge plasma

Typical Time Scales in a next step experiment with B = 10 T, R = 2 m, $n_e = 10^{14}$ cm^{-3}, T = 10 keV



Atomic & molecular processes

Neutral particle codes, kinetic imp. transport codes
plasma chemistry

Ion drift waves
Transients (ELMs)

ITM

Edge turbulence

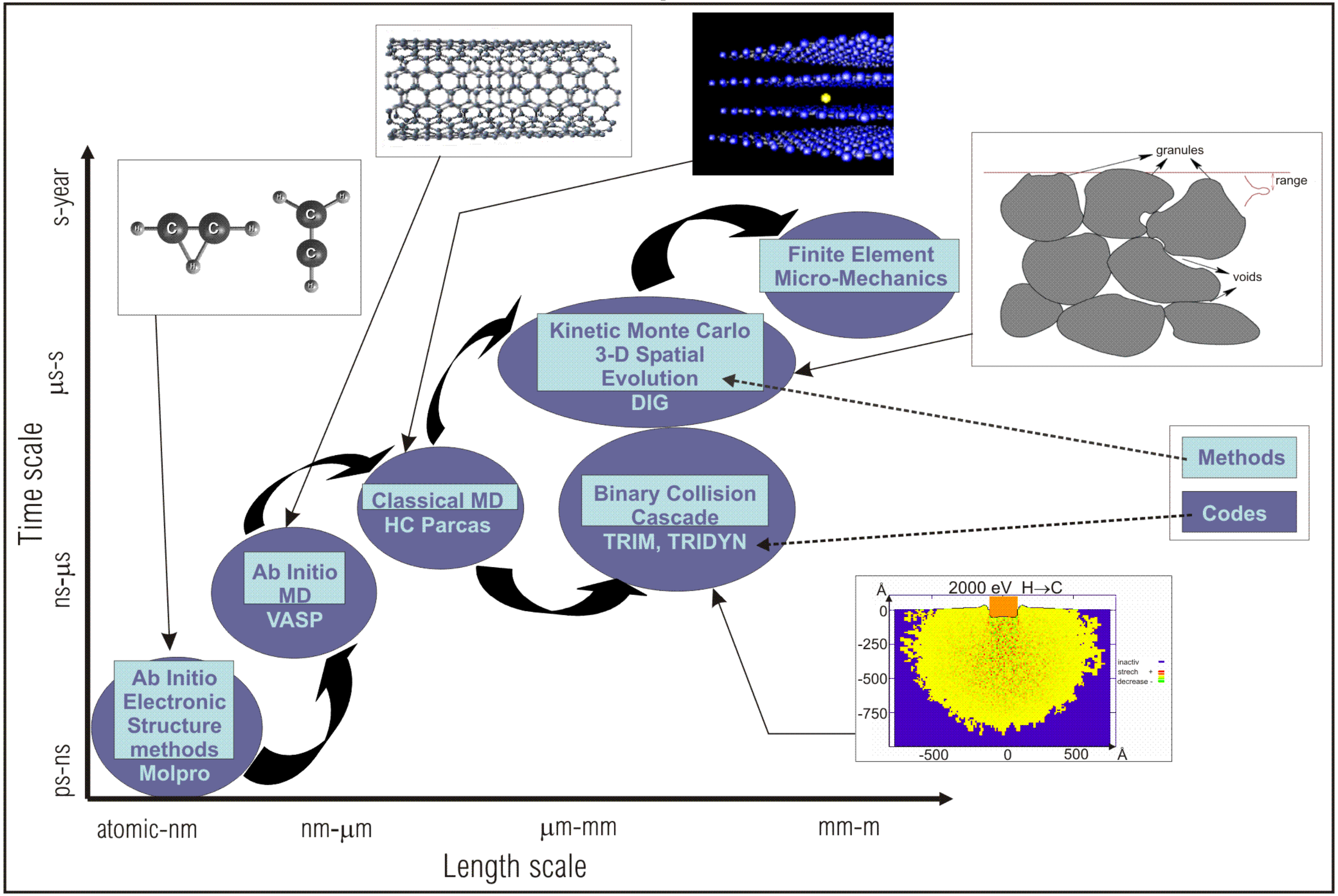
Parallel dynamics:
Ion transit,
Ion collisions
Parallel sound wave
Ditto, electrons

2D transport codes

Neglect displacement current, integrate over velocity space, average over surfaces, neglect ion & electron inertia
Core Transport Codes

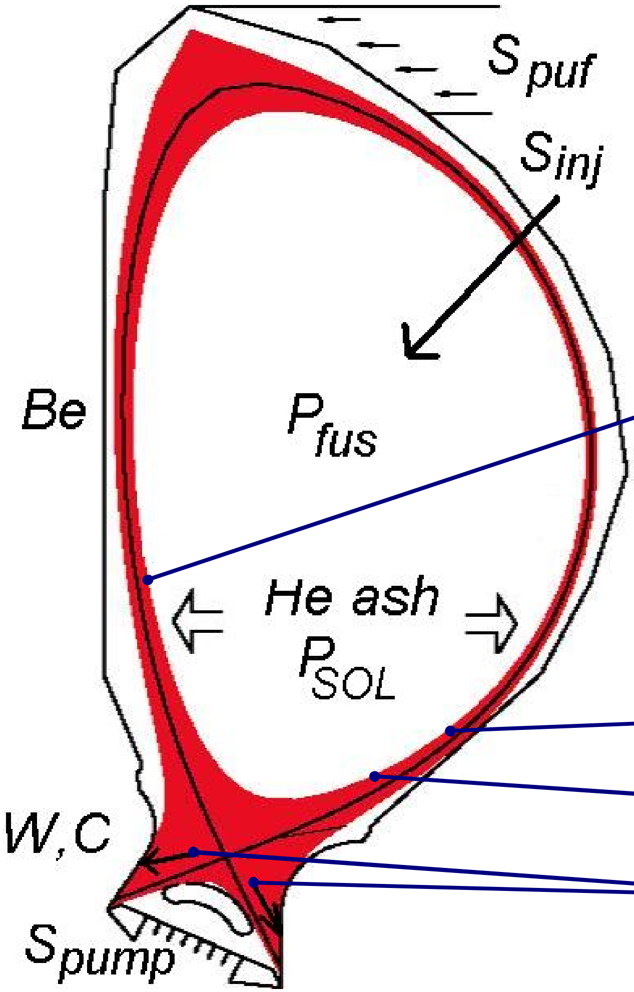
discharge time-scale

PSI time and spatial scales



Thanks to: R.Schneider, IPP Greifswald

Provide sufficient convection without accumulating Tritium and with sufficiently long divertor lifetime (availability).



- $P_{fus} \approx$ 540-600 MW
  $\Rightarrow$ He flux
  $\Rightarrow P_{SOL} \approx$86-120 MW
- $n_s \approx (2\text{-}4) \cdot 10^{19}$ m^{-3}
- $S_{inj} \leq 10 \cdot 10^{22}$ s^{-1}
- $S_{pump} \leq 200$ Pa·m^{-3}/s

!

- $Z_{eff} \leq 1.6$
- $C_{He} \leq 6\%$
- $q_{pk} \leq 10$ MW/m^2

?

Engineering parameter in modelling: $S_{puff} \sim (1\ldots13) \cdot 10^{22}$ s^{-1}

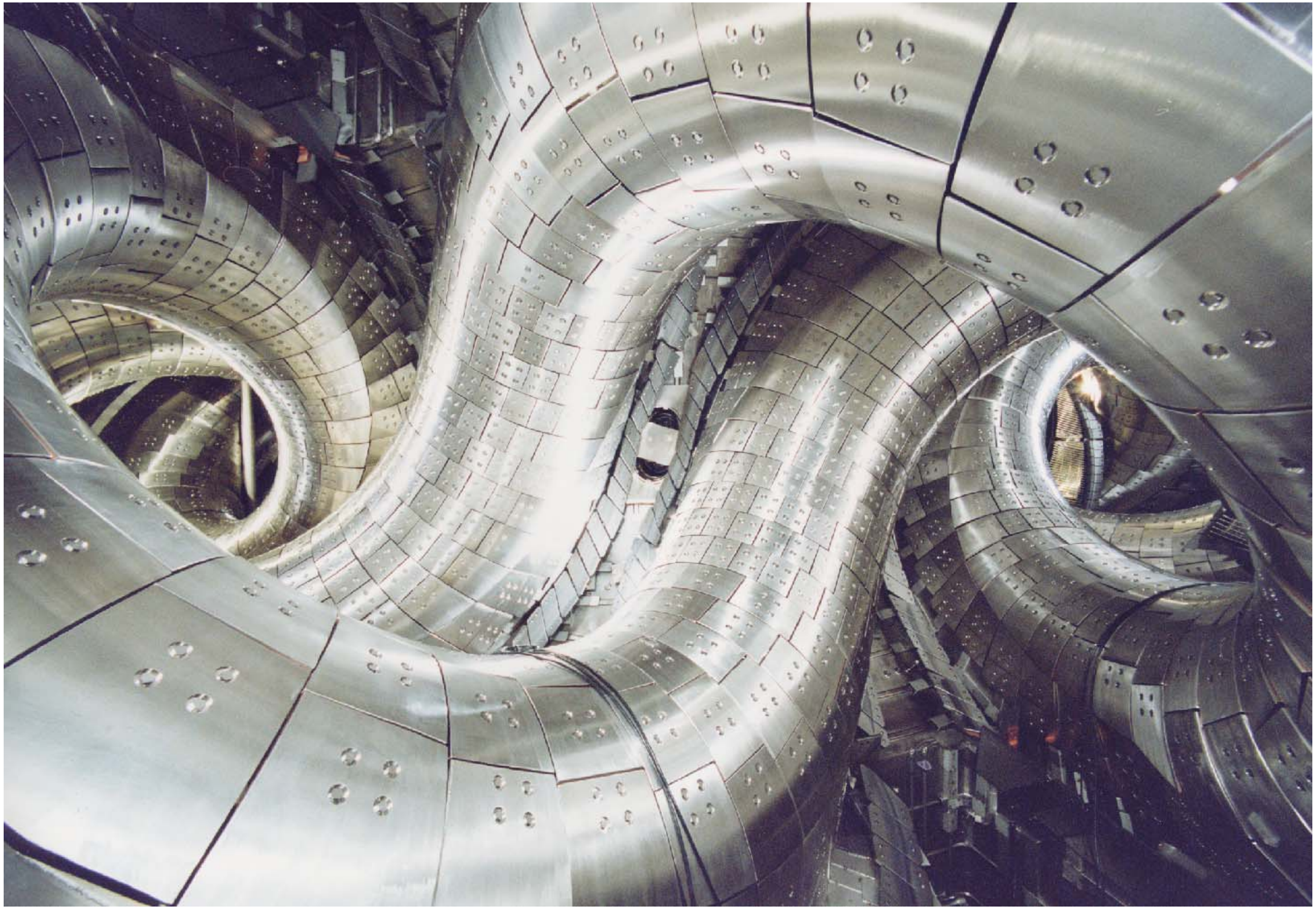
- ITER Divertor design is based upon "detachment"
- Detachment is a chemically complex plasma state:

  "unknown territory" in fusion,

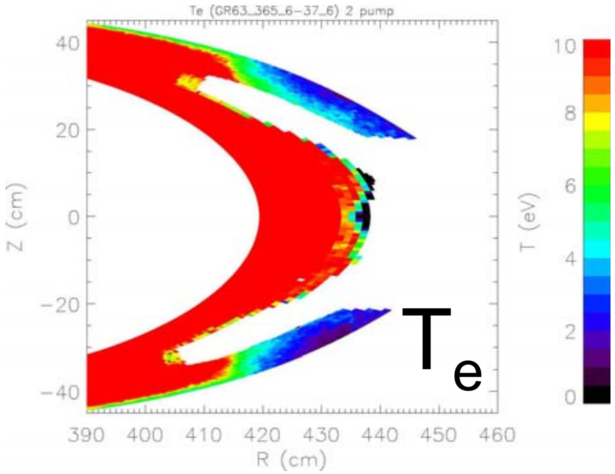
  but well known in low temperature plasma physics

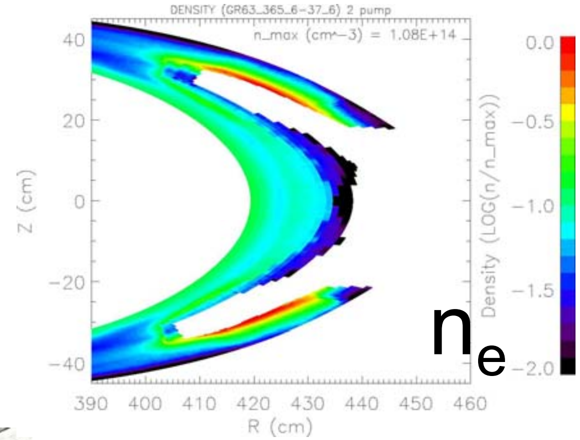
  - gas-plasma friction,
  - recombining plasmas,
  - plasma cooling (radiation)

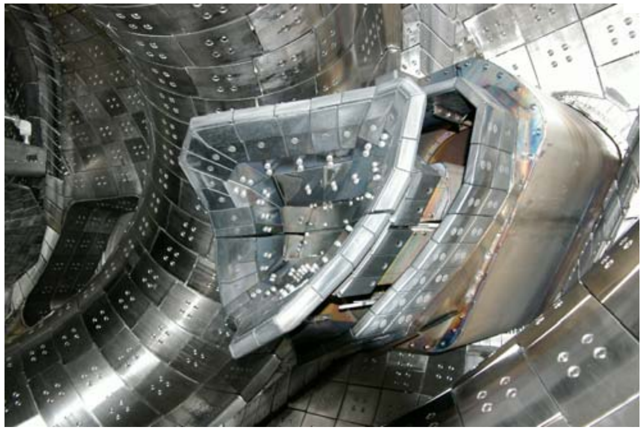
Large Helical Device (LHD), Toki, Japan

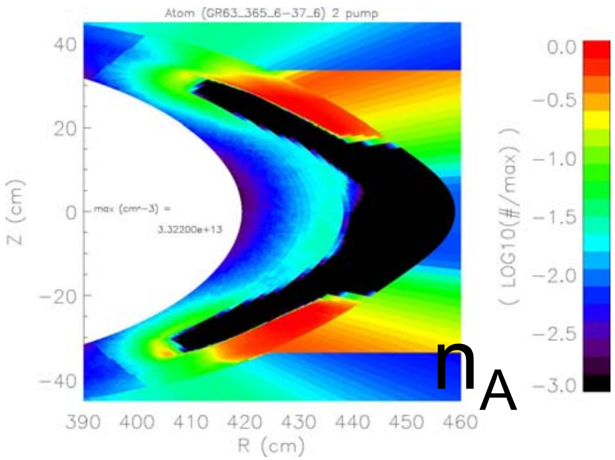


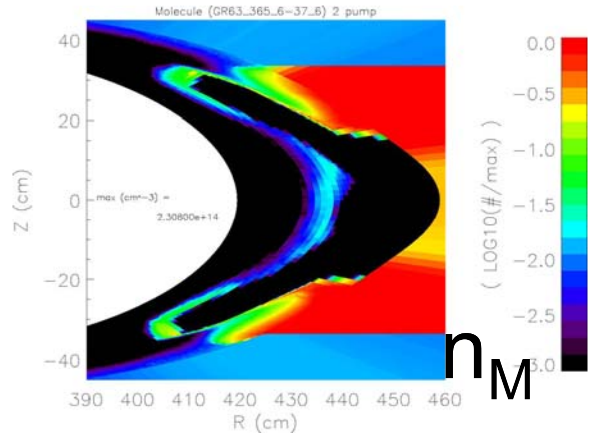
3D LHD Plasma Edge Simulation: EMC3-EIRENE



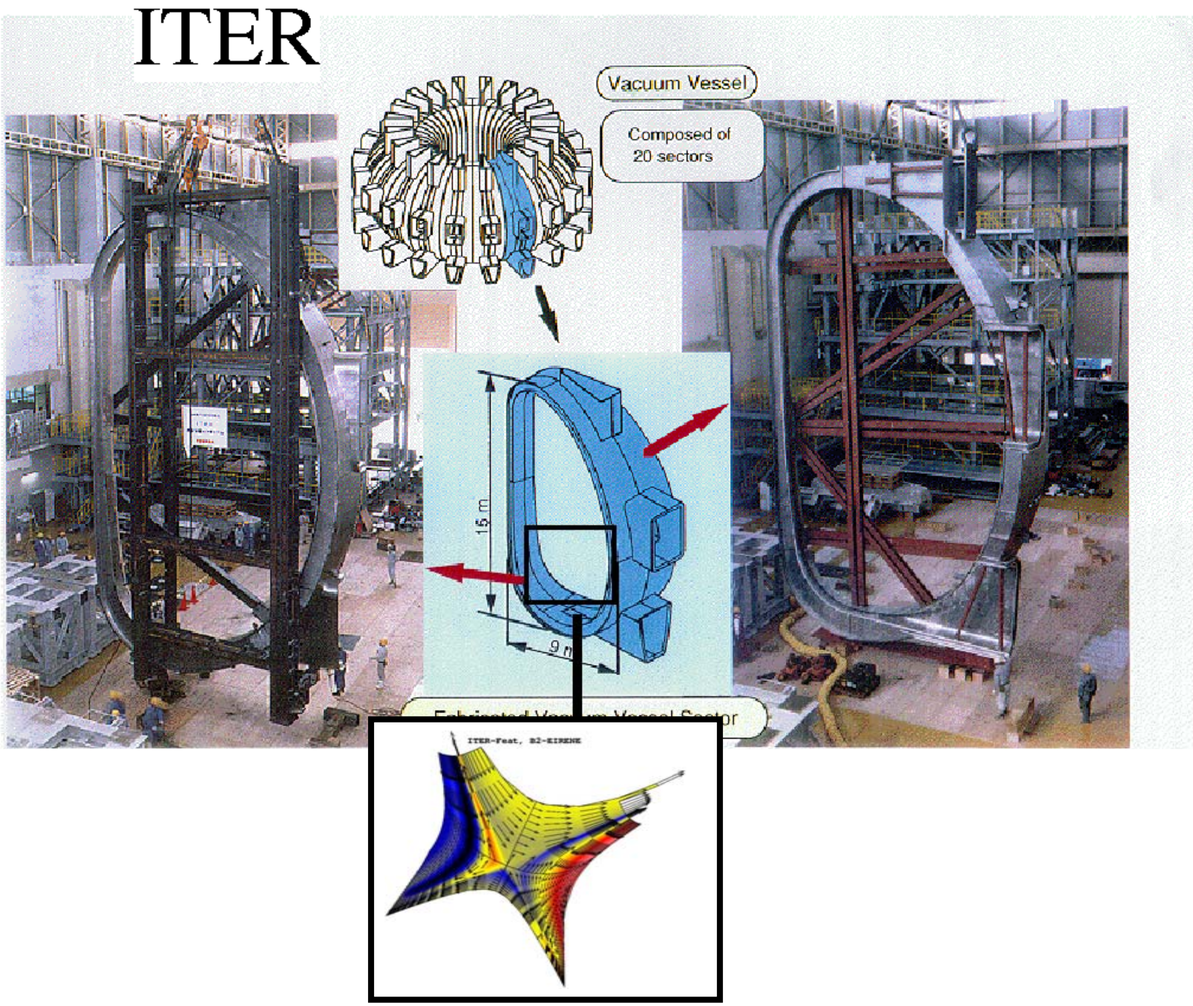




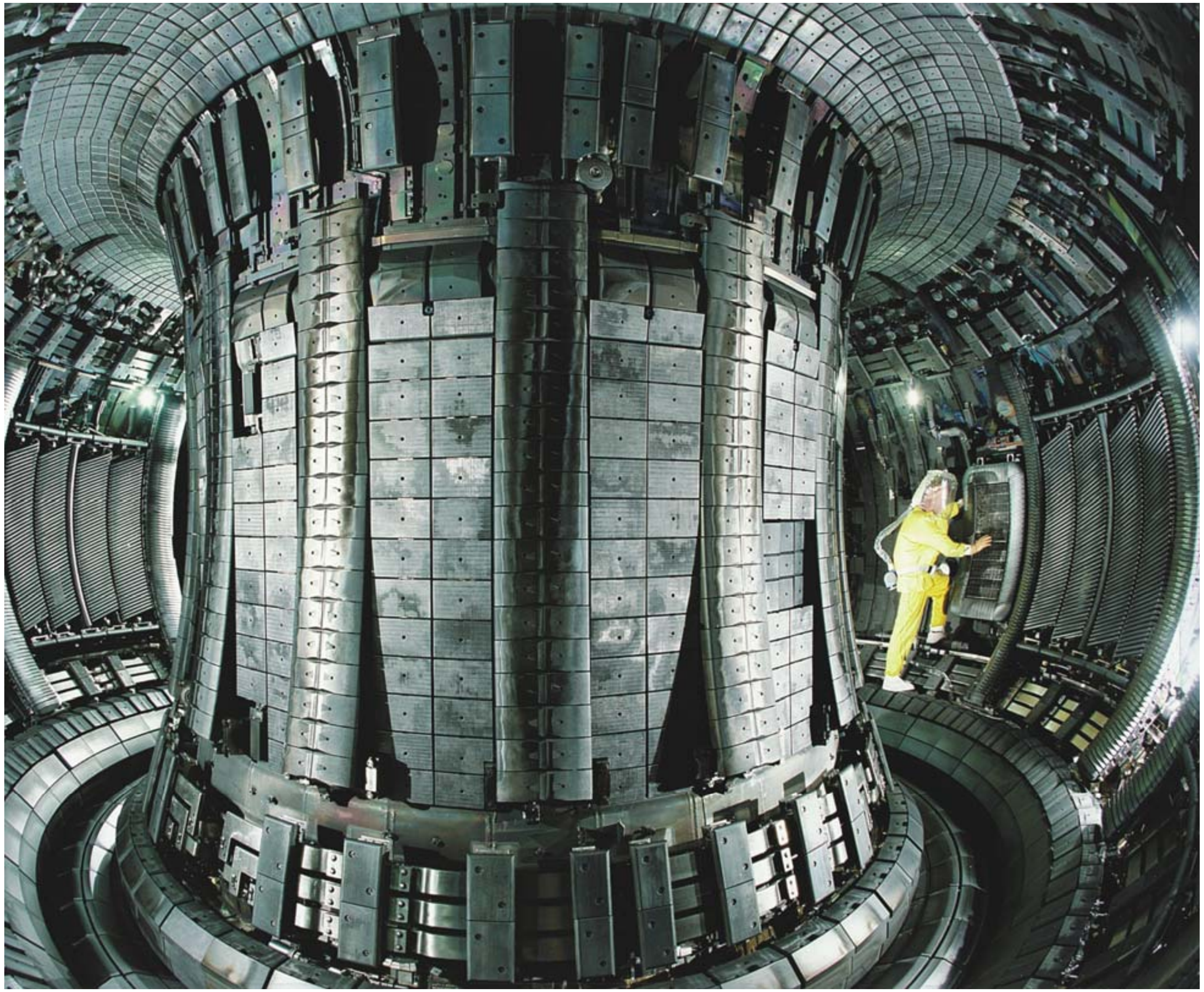




Here: restriction to 2D axi-symmetric plasmas



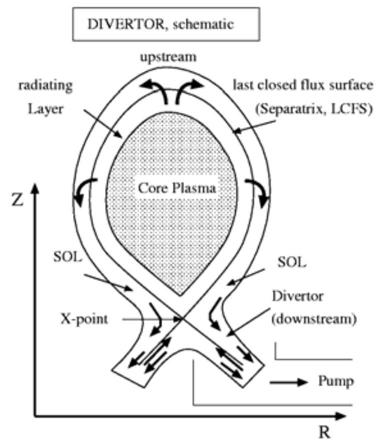
Joint European Torus (tokamak)



Break-Even reached in JET

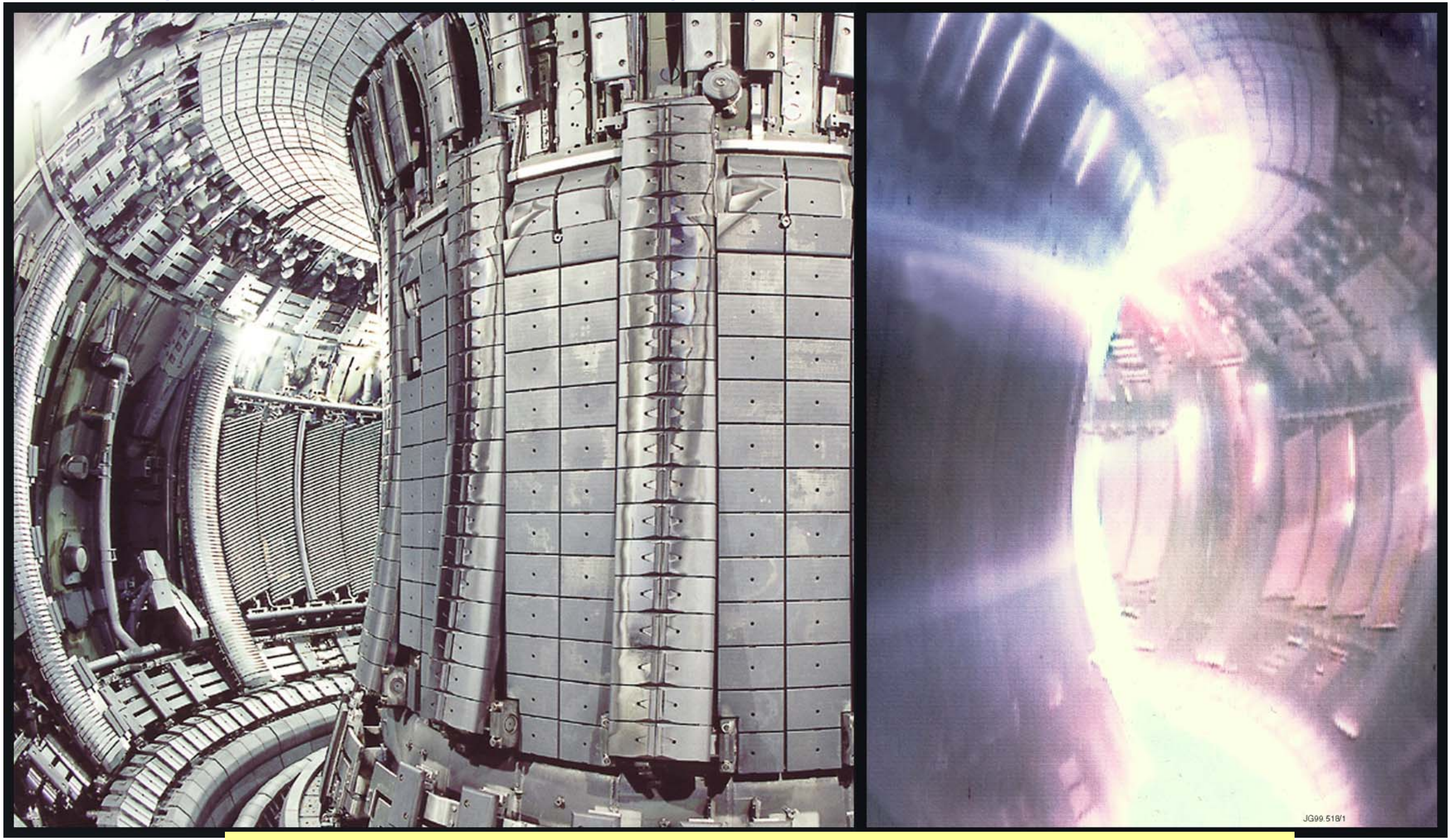
16 MW fusion power
400 Mill deg C

reliable data base for extrapolation to ITER



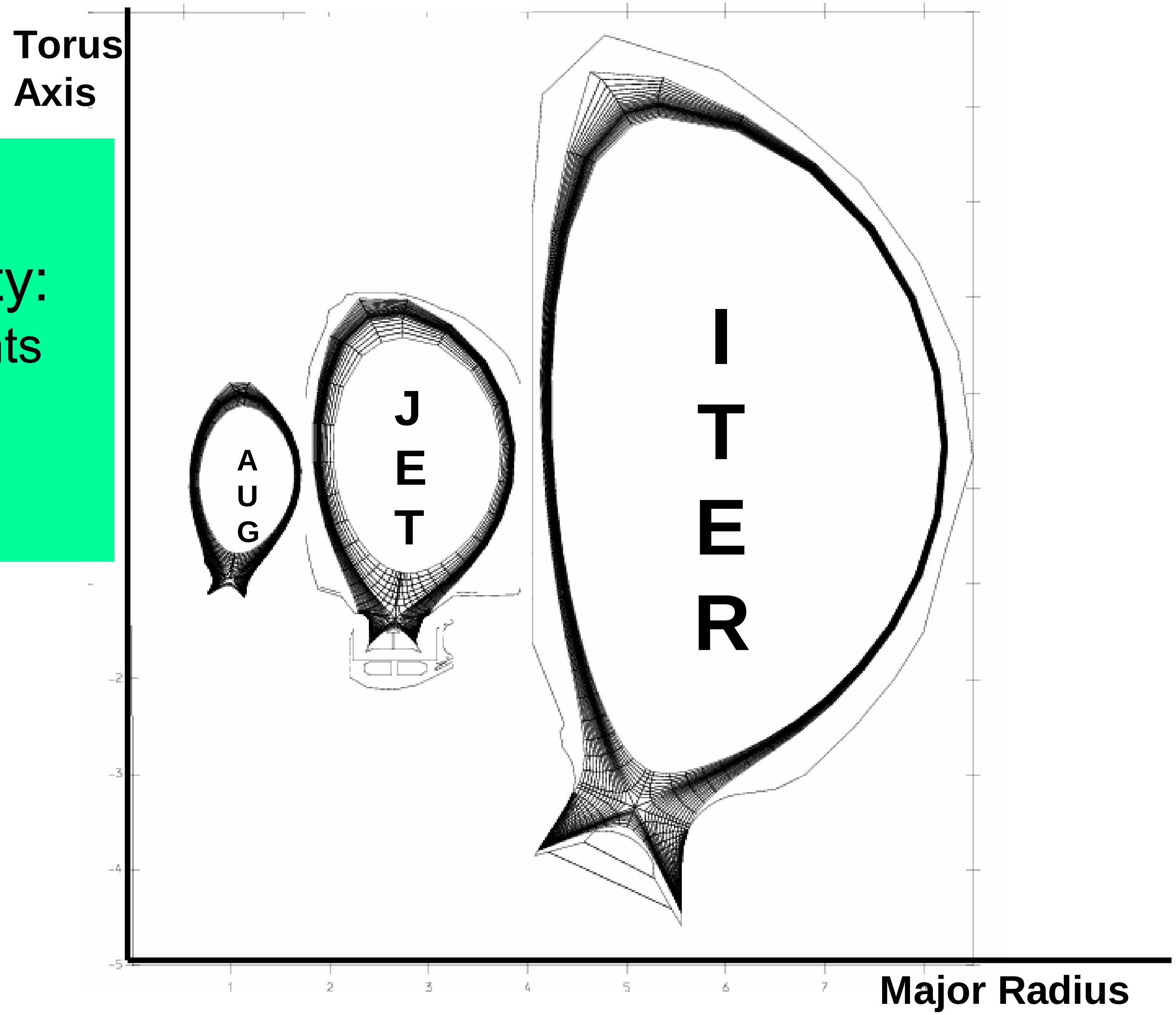
Active role of atomic and molecular processes

cooling the edge plasma, protecting target surfaces from overexposure



Furnace chamber:
Ø 8.5 m   2.5 m high 3.4 T   7 MA 1 min

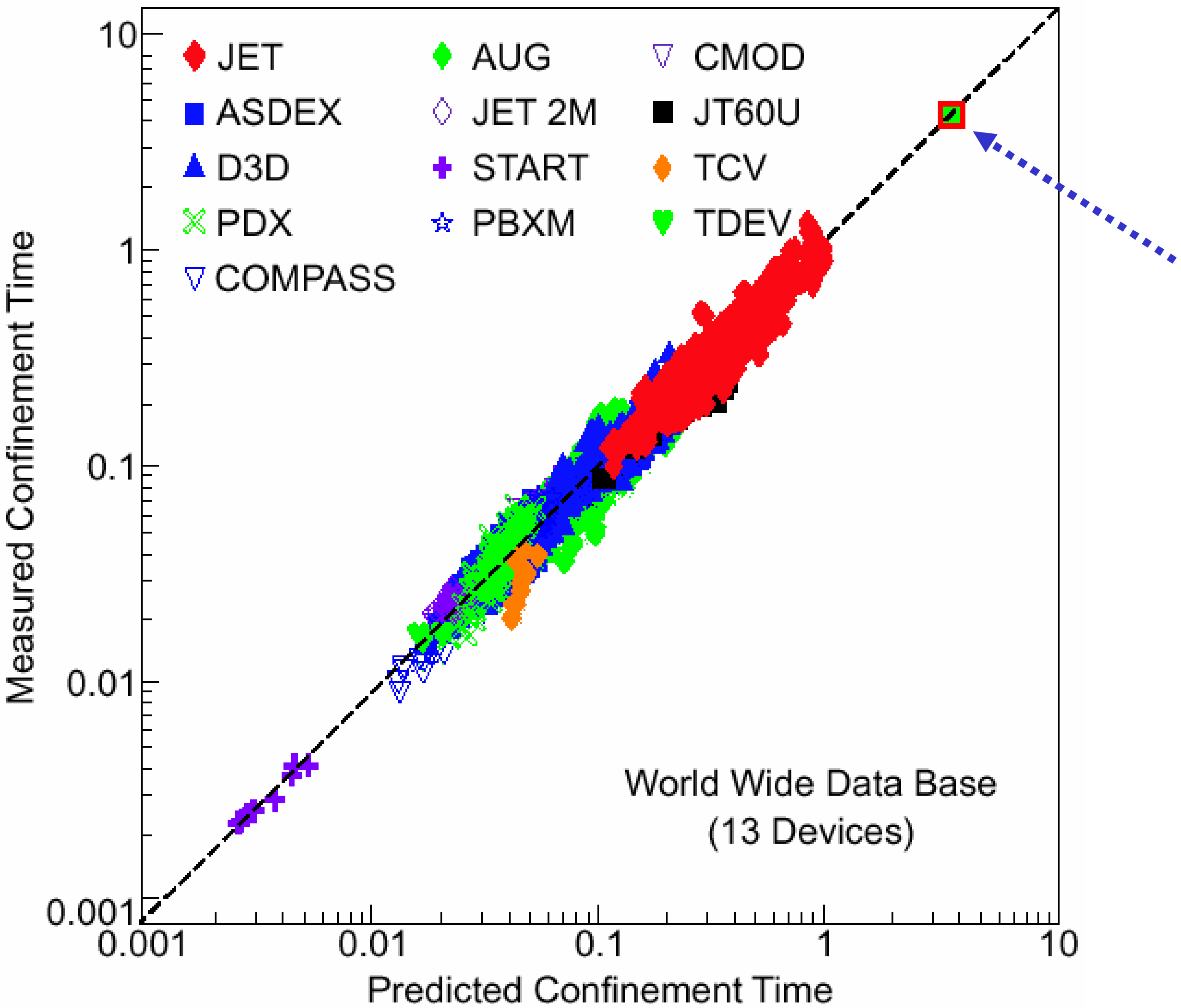
Extrapolation: present experiments ⇒ ITER



Core:
plasma similarity:
present experiments are “wind tunnel experiments” for ITER

Edge: influenced by recycling (of neutral particles), grids
Core: not influenced by recycling

Extrapolation of core plasma confinement to ITER

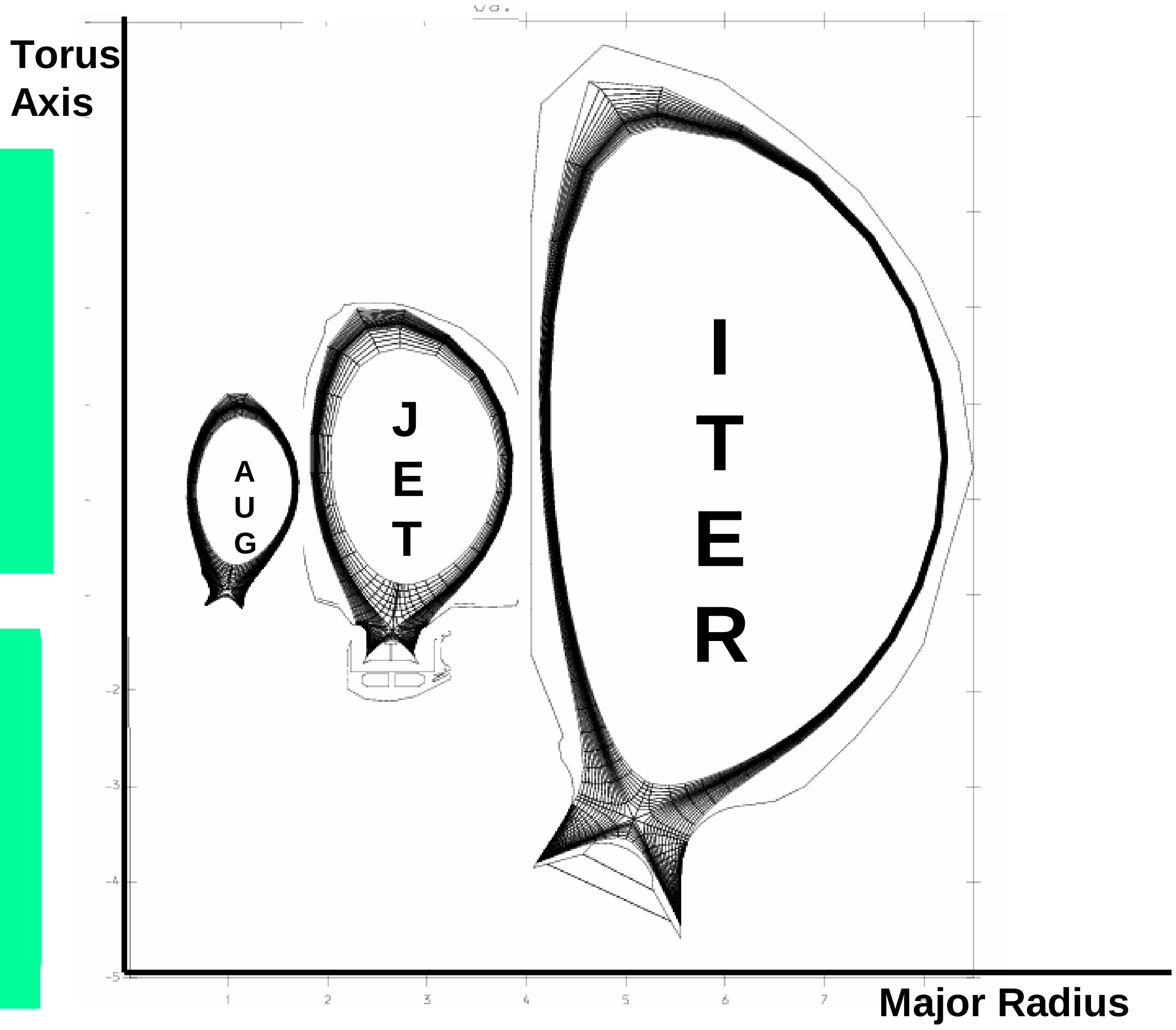


ITER reference scenario

Extrapolation: present experiments ⇒ ITER

Core:
plasma similarity:
present experiments are "wind tunnel experiments" for ITER

Edge:
Computational plasma edge modelling

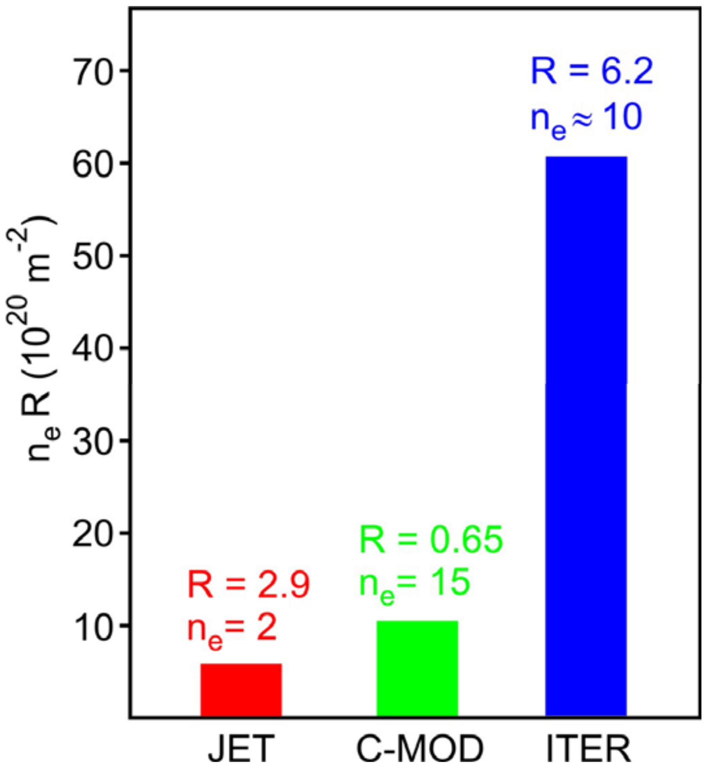


Edge plasma: a) provide conduction
b) protect exposed target areas

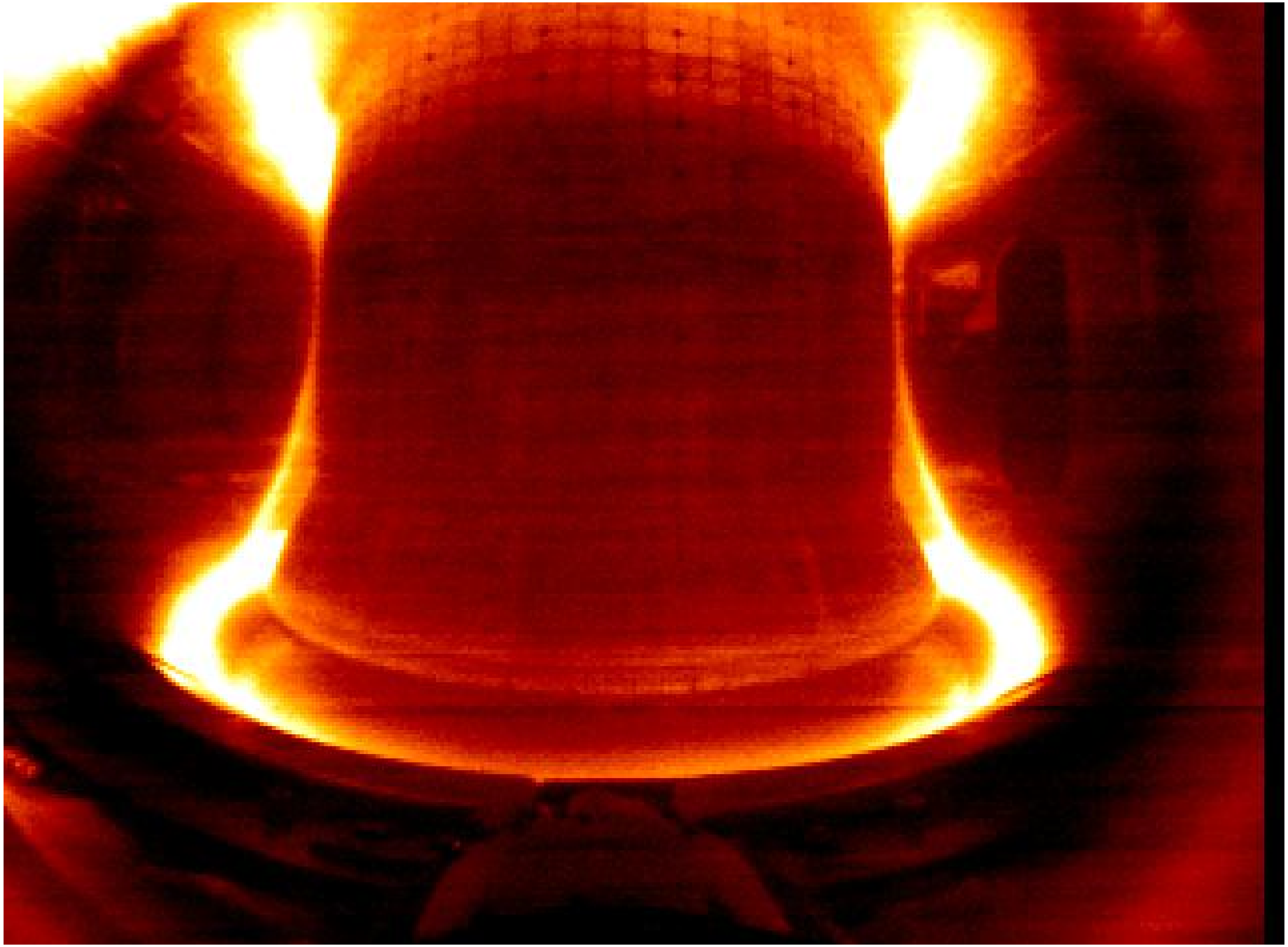
World-wide effort to understand (and predict?) Edge Plasma dynamics on the basis of best known Atomic and Molecular Data

Estimate “Collisionality”: n_eR
-n_e-Divertor Plasma density (10^{20} m^{-3})
-R- Major Radius (m)

Alcator C-Mod (MIT)
10 times smaller than ITER
similar shape
higher density



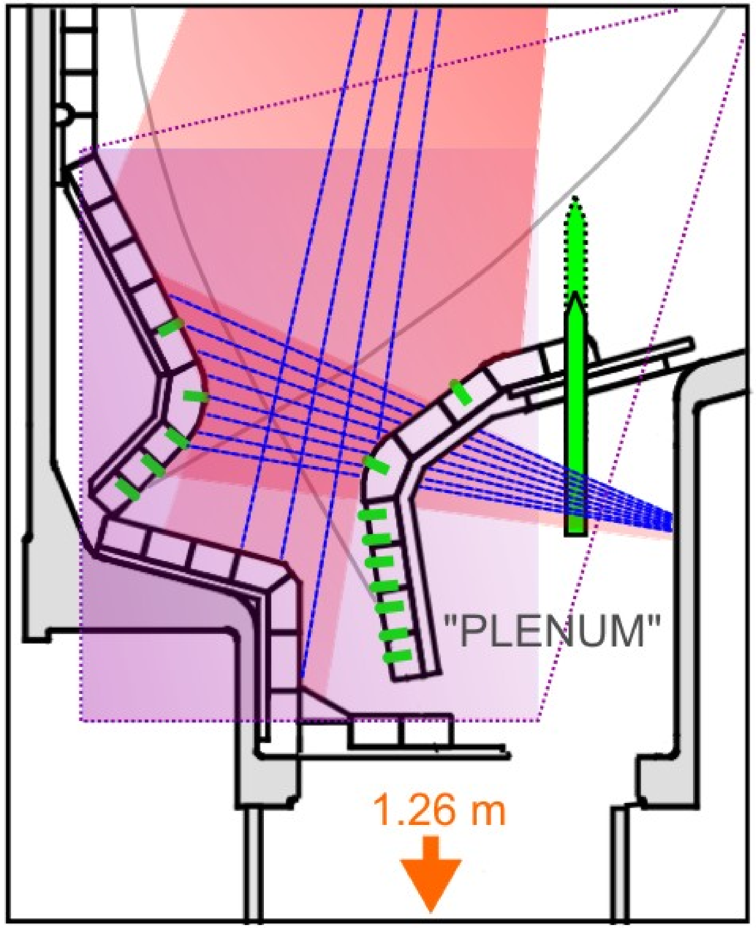
Alcator C-Mod (MIT)



HIGH
RESOLUTION
DIODE ARRAYS
WITH D_α FILTER

TARGET
LANGMUIR
PROBES AND
UPSTREAM
RECIPROCATING
PROBE FOR
n_e AND T_e

DIVERTOR GAS
PRESSURE
(25±3 mTorr)

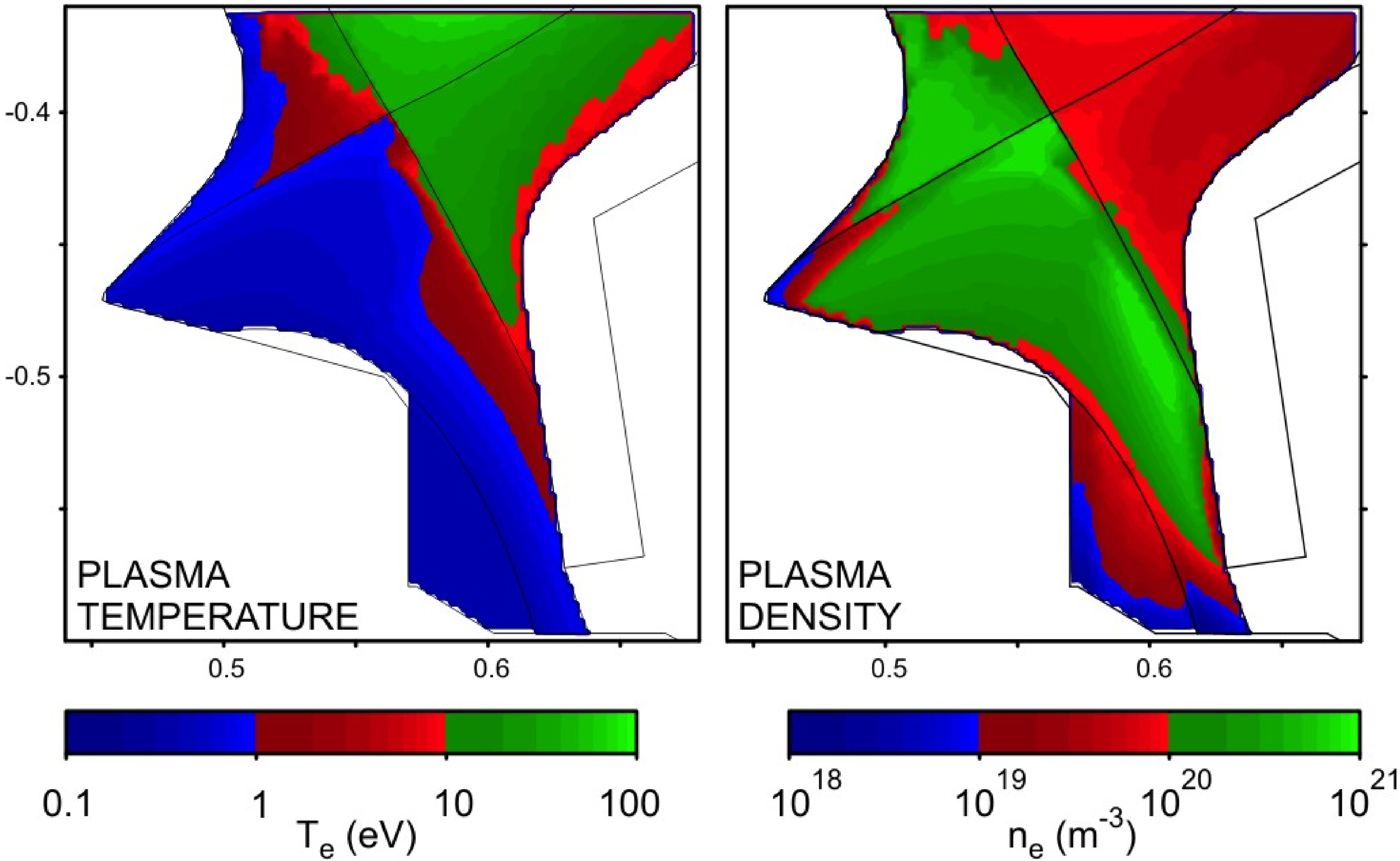


TOROIDALLY
VIEWING CCD
CAMERA WITH
D_γ FILTER

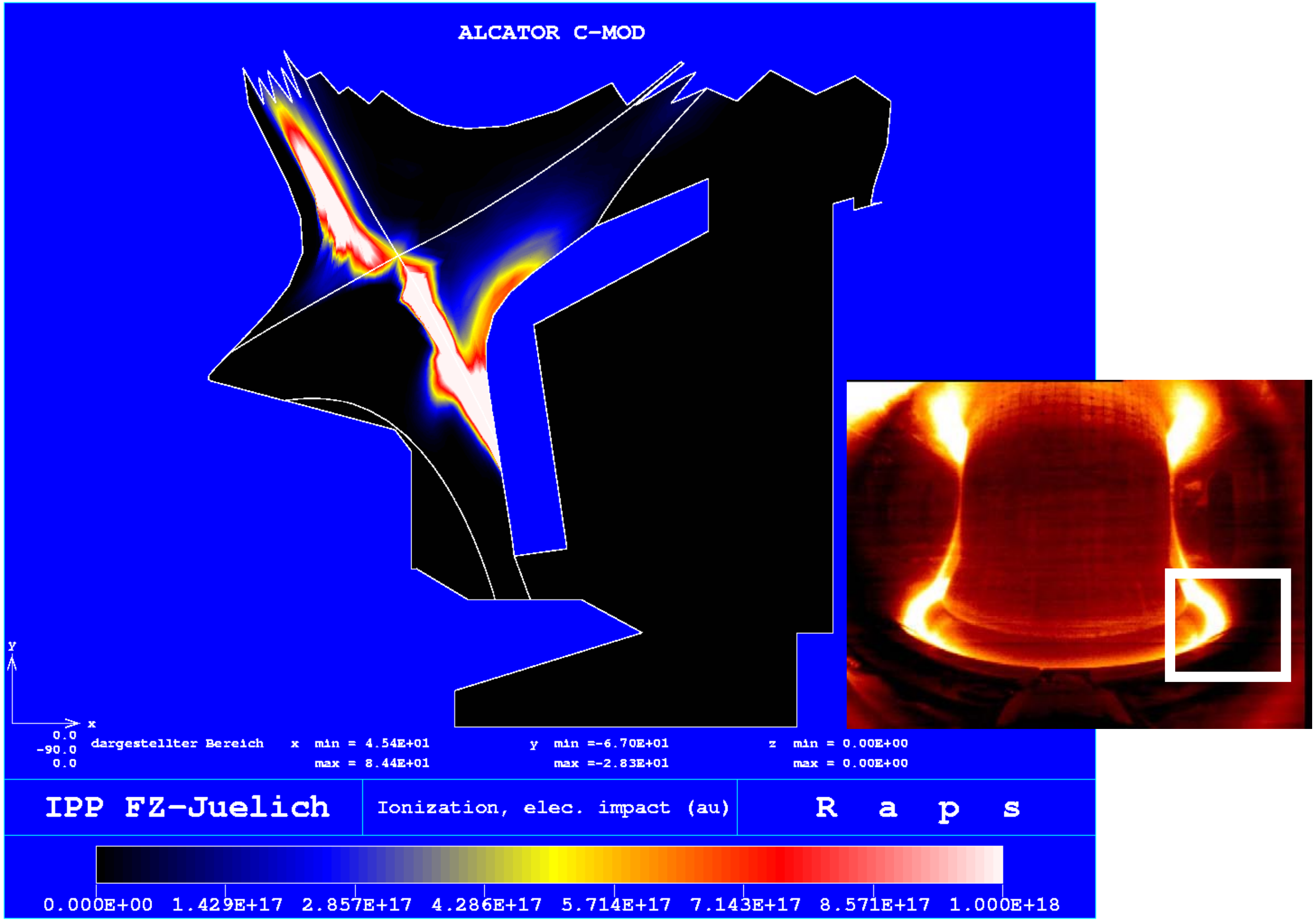
SPECTROMETER
FOR VOLUME
n_e AND T_e

C. BOSWELL
B. LaBOMBARD
B. LIPSCHULTZ
A. NIEMCZEWSKI
S. PITCHER
J. TERRY

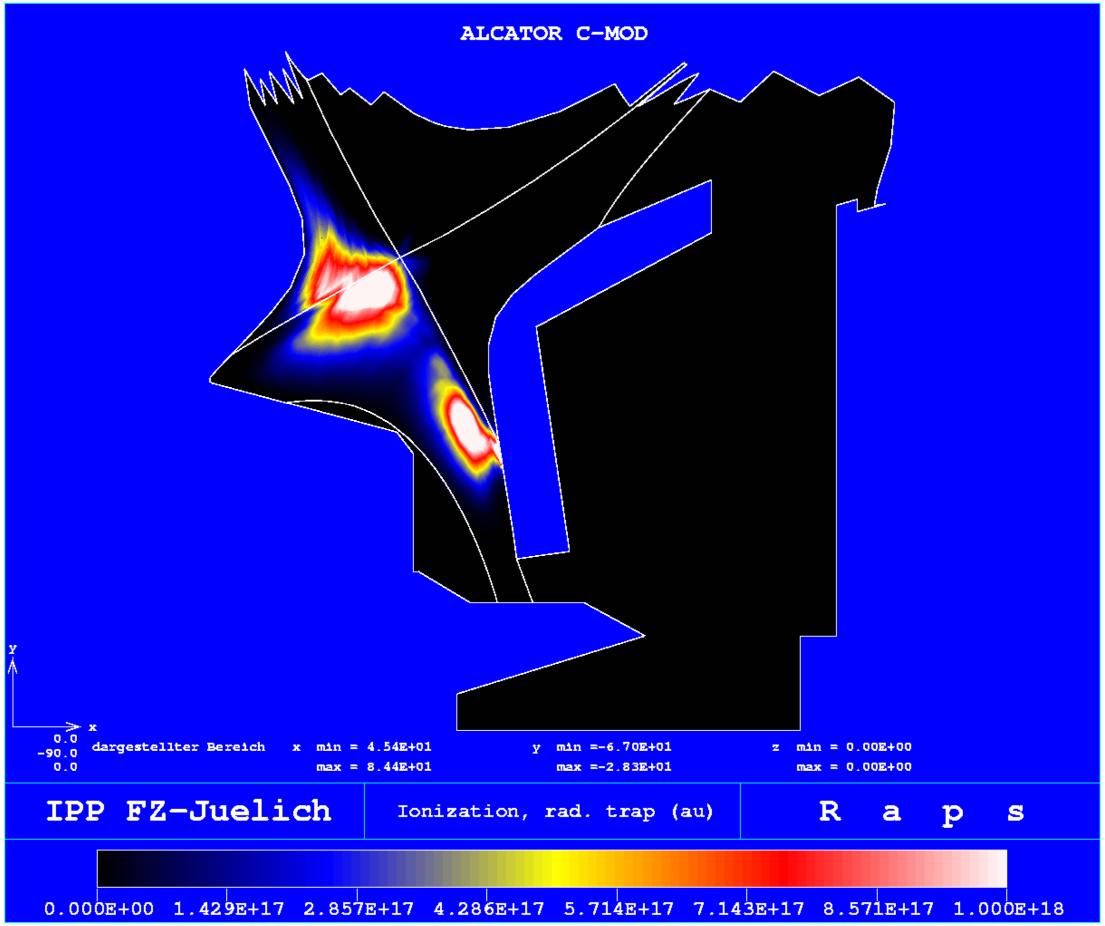
Shot: 990429019, at 950ms,
$\langle n_e \rangle = 1.5\ 10^{20}$, $I_P = 0.8$ MA, $B_{tor} = 5.4$ T
OSM reconstruction (Lisgo et al., 2004)



Ionization by electron impact on neutral gas



However:
Additional Ionization due to Lyman photon trapping



CONCLUSIONS - I

- **Magnetic confinement is now effective enough to contain the main fusion flame, but it is too good for the plasma edge (SOL): very narrow heat-footprints on targets.**

- **Magnetic Confinement Fusion Reactors must operate at reduced target fluxes and temperatures ("detached regime").**

- **n, T upstream (core) fixed by burn criteria, density limit, etc.**

- **For ITER: Detached regime: decrease particle flux to target for given upstream conditions: self sustained neutral cushion (reactive plasma) controlled by PMI and A&M**

- **Divertor detachment physics involves a rich complexity of plasma chemistry not otherwise encountered in fusion devices .**

→ **RECYCLING**

- ## Experimental finding:

  Sheath limited flow $\Rightarrow$ high recycling $\Rightarrow$ detachment

- ## Theoretical hypothesis:

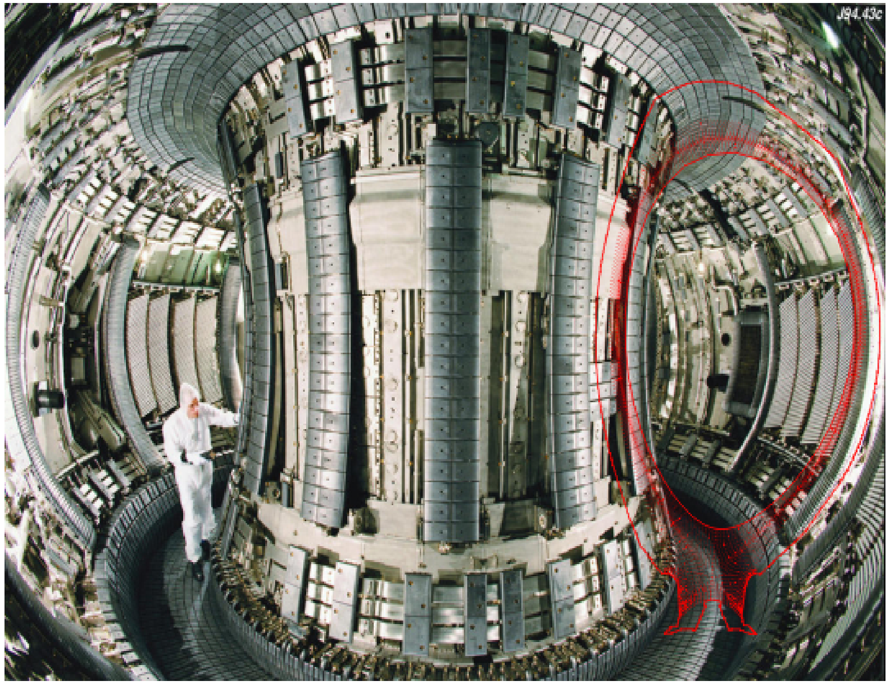
  This is brought about by power- and flux dissipation
  due to a chemically rich self sustained
  plasma formed near exposed target surfaces,
  by the recycling process.

- ## Experimental tests:

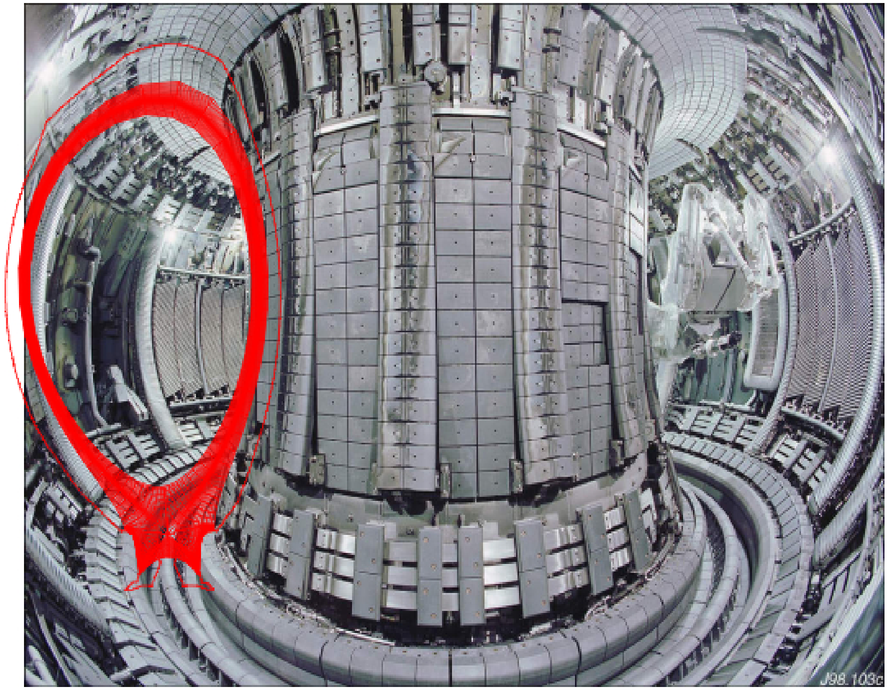
  numerical experiments with
  integrated computational plasma edge models

Experimental findings

JET, 1994, MARK-I Divertor



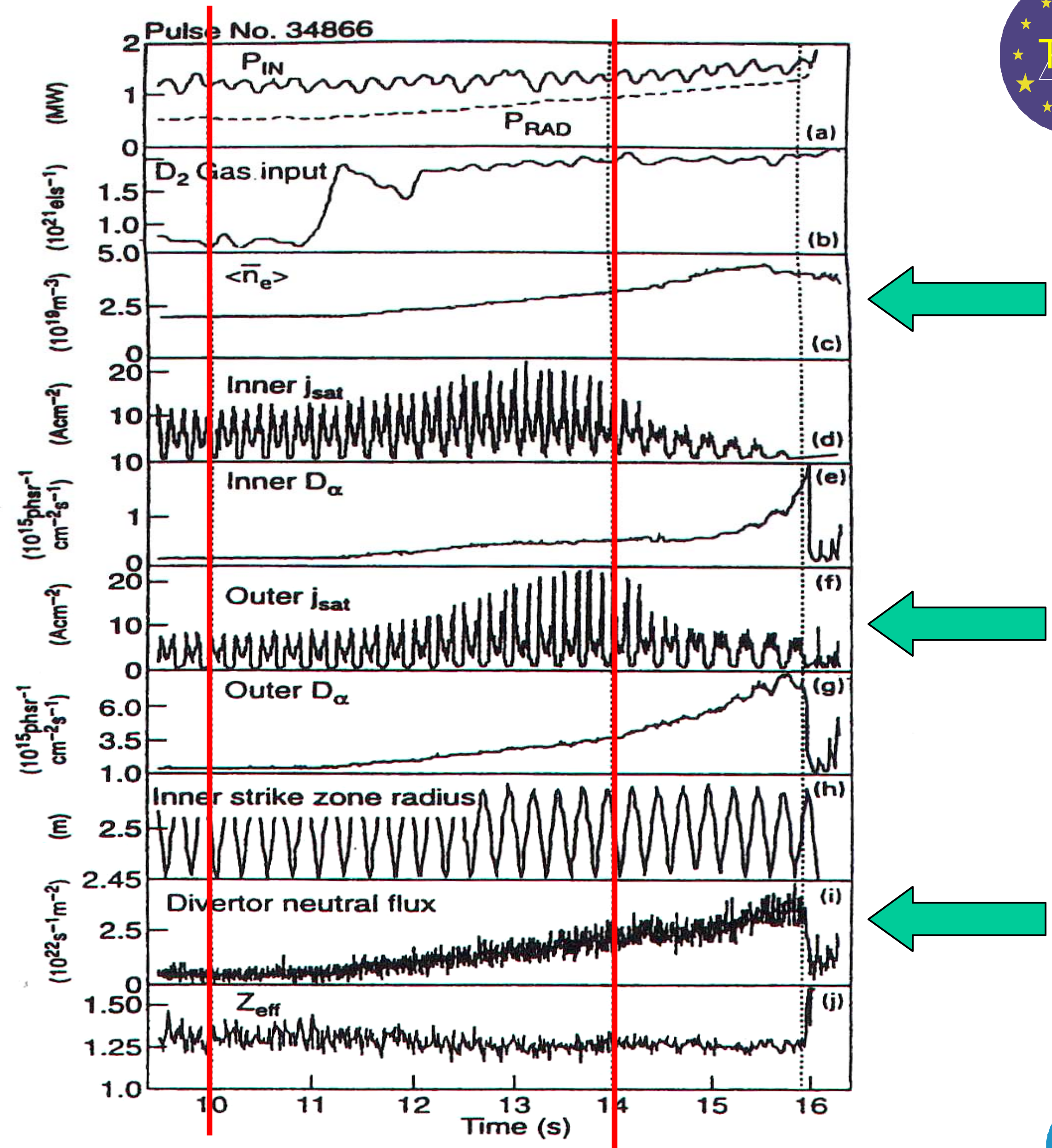
JET, 1998, MARK-II Divertor



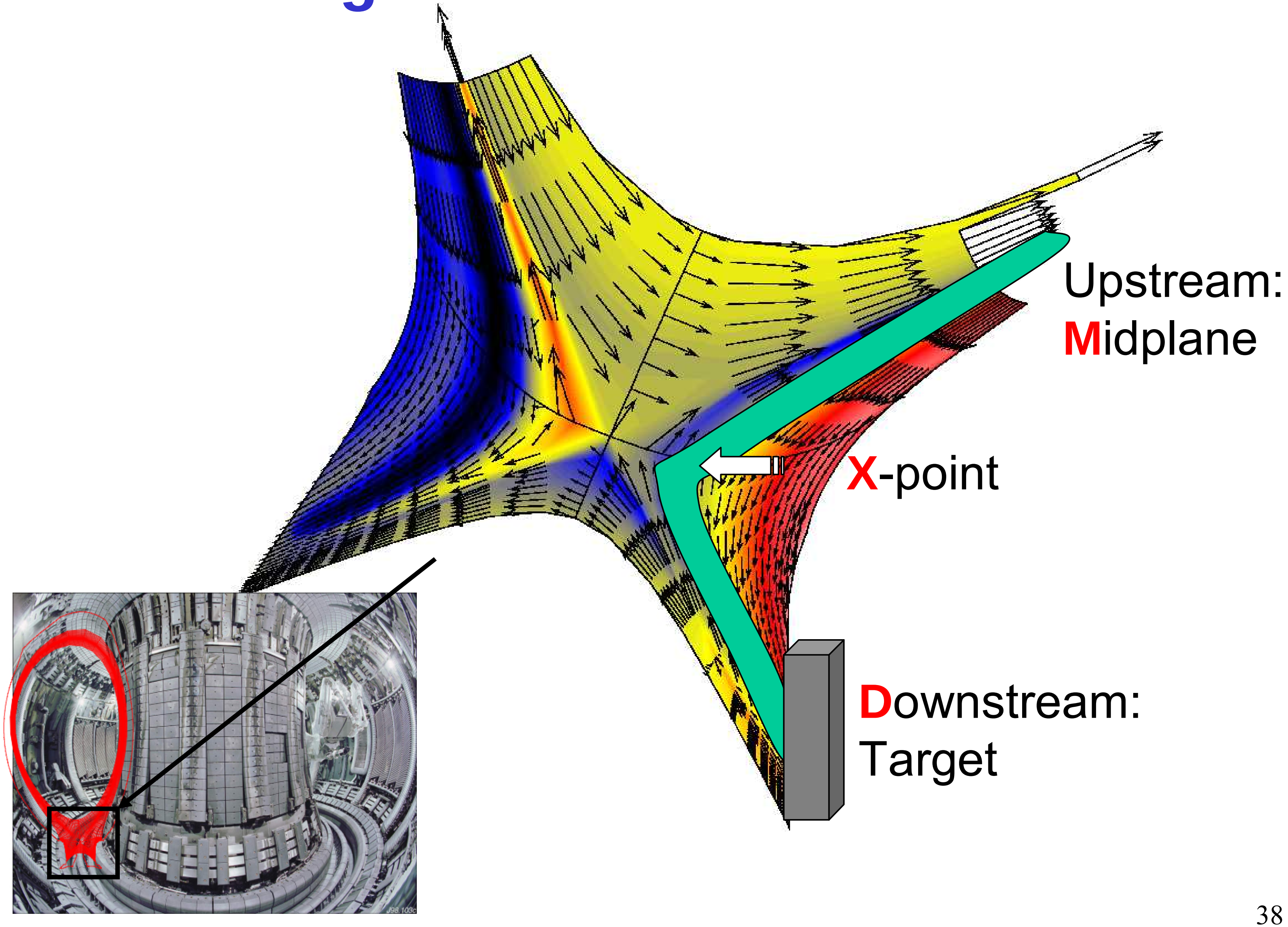
B2-EIRENE-computational grids for JET simulations

JET, MARK-I, density ramp-up

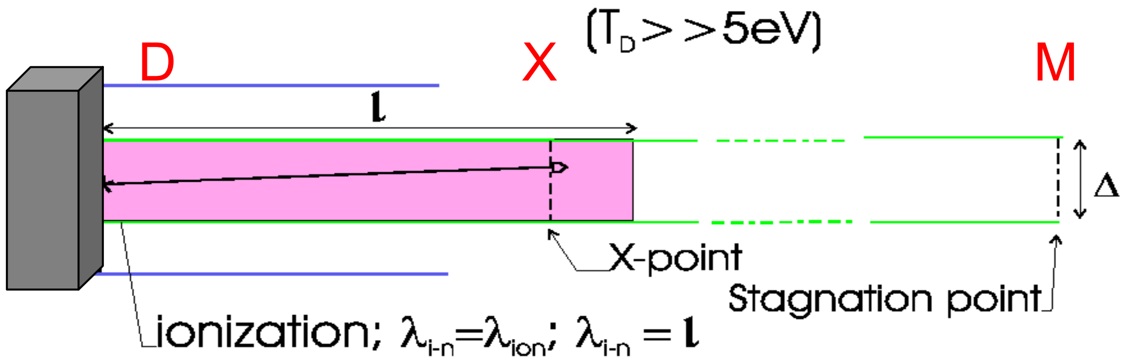
-ohmic
-no imp. injection
-simply: D2-puff



Stretching out a flux-tube: M ⇒ X ⇒ D



Linear, sheath limited regime (convection)
(…. 1985)



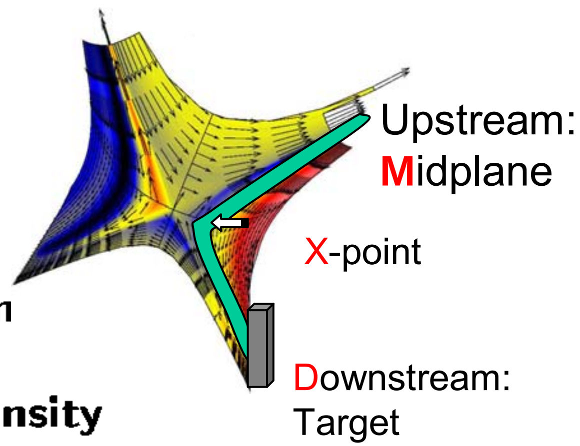
- low density: high temperature, plasma profiles along fieldlines nearly constant, low radiation losses

- energy balance: sheath dominates

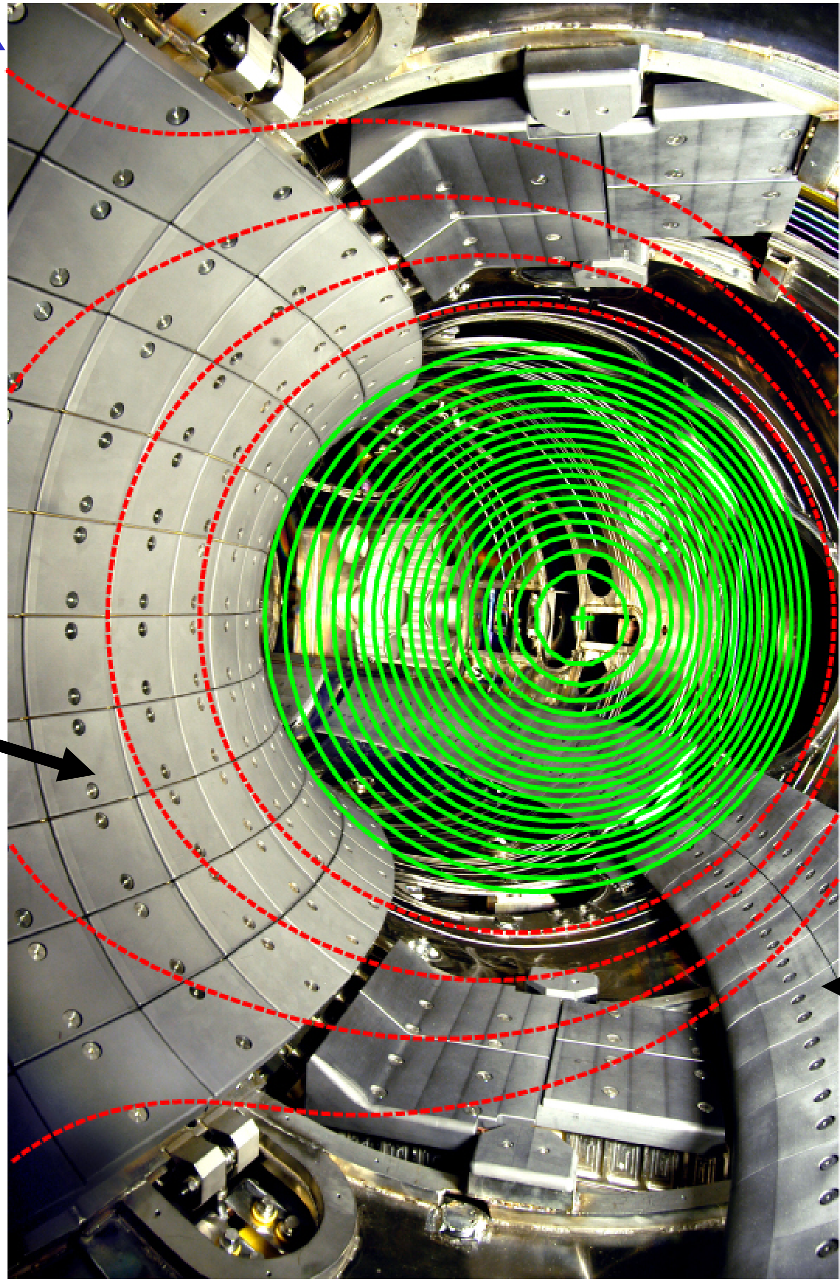
$$q_{\|,M} \approx q_{\|,D} \approx \delta_e^* T_D \Gamma_D$$

- small particle flux to the plate: neutral mean free path >> divertor dimension

- divertor density linearly follows midplane density



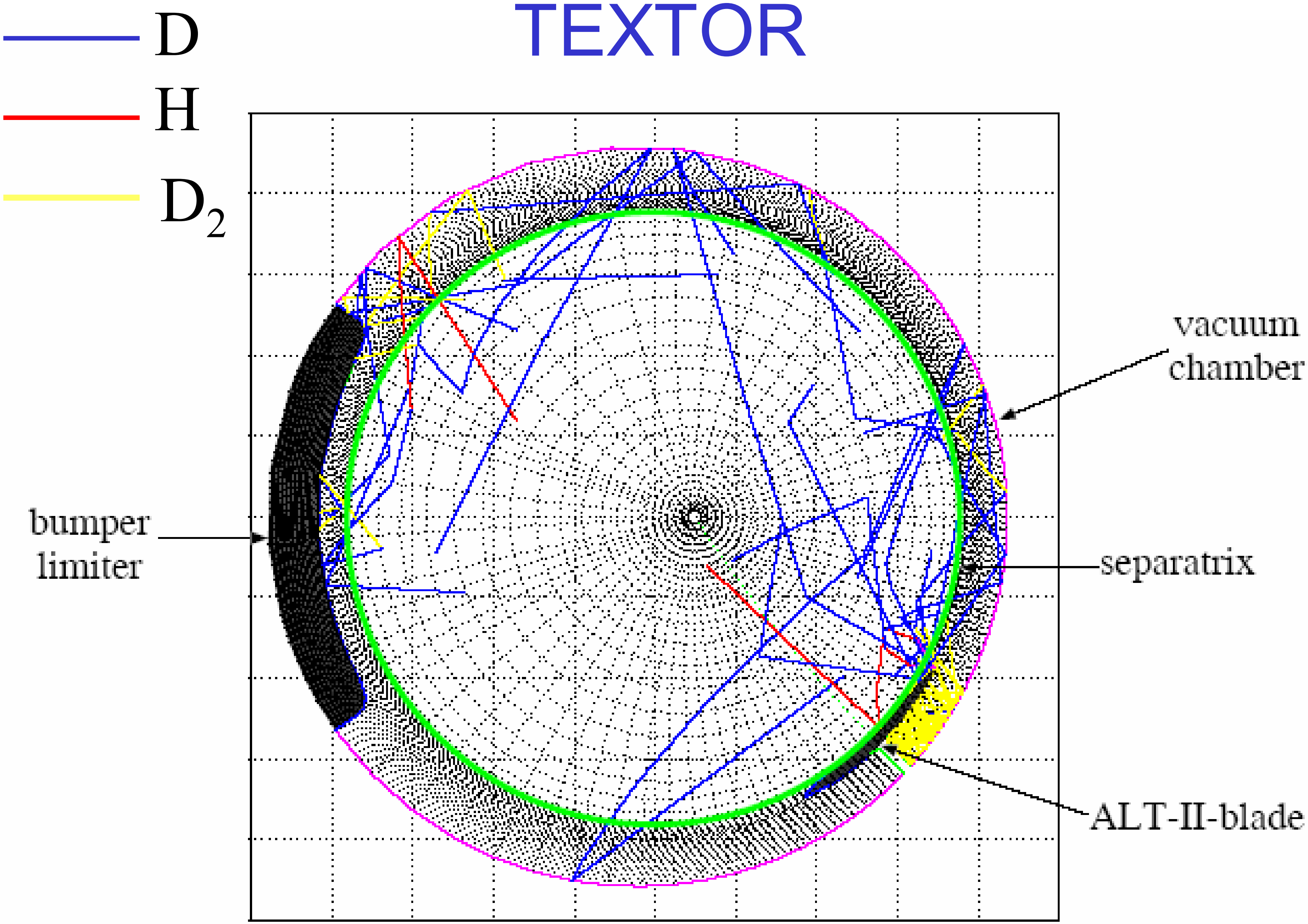
TEXTOR



inner bumper limiter/divertor

ALT-II

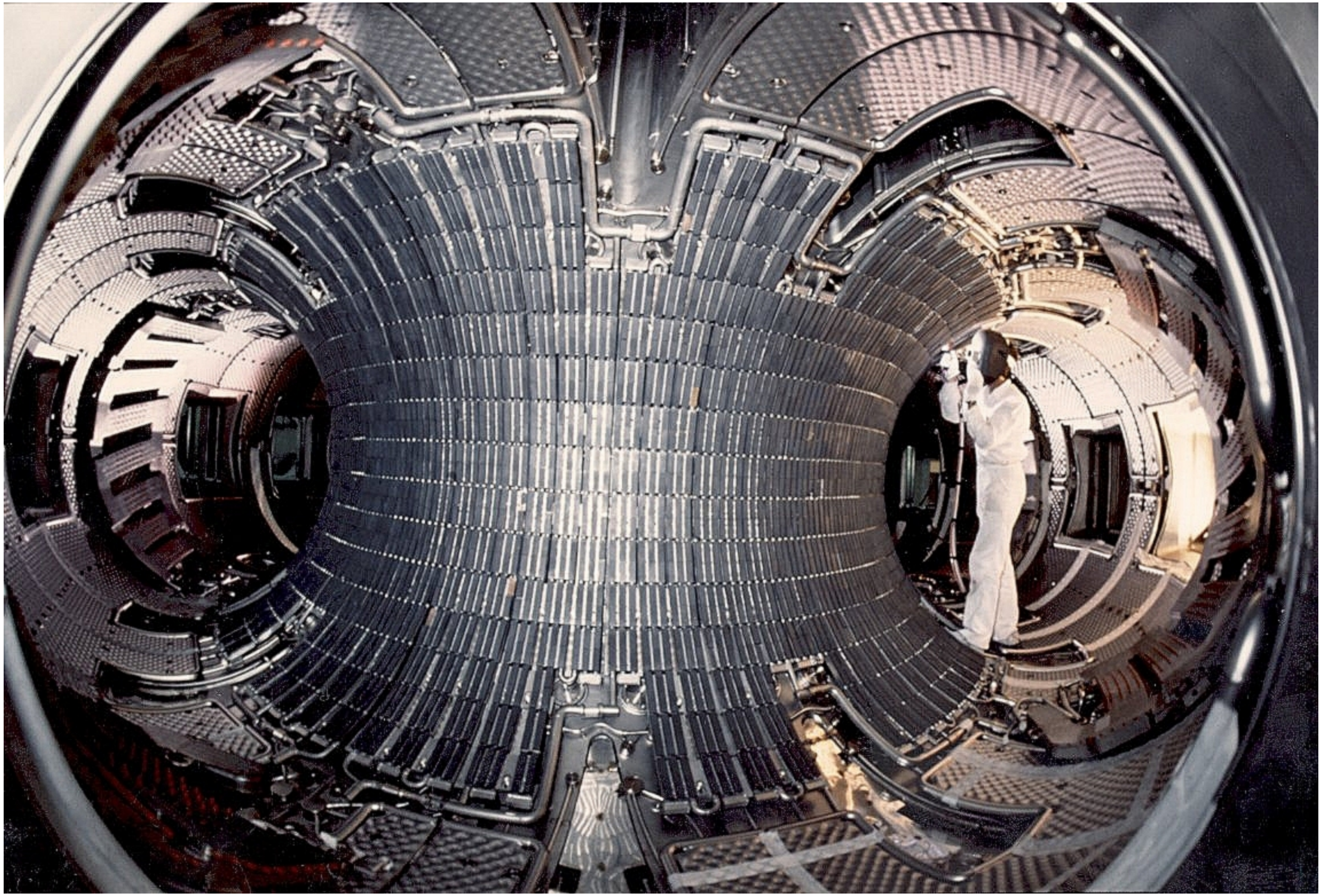
TEXTOR



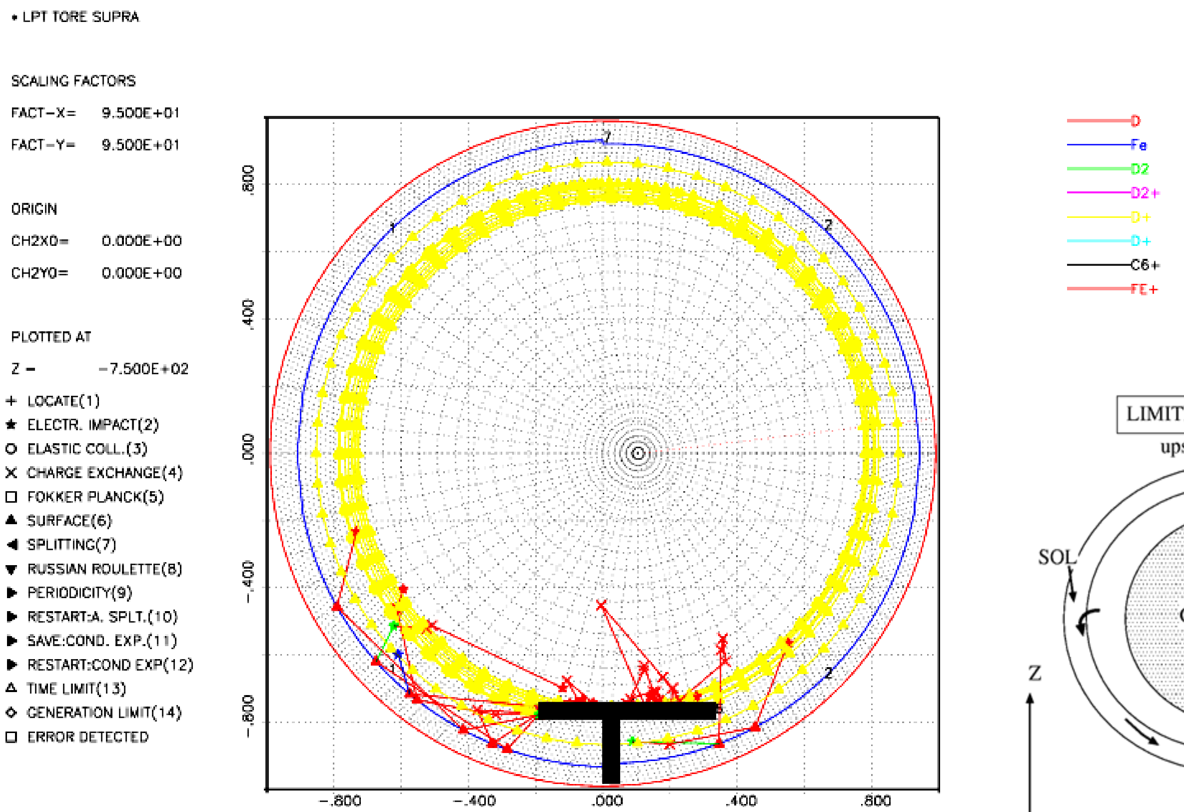
Plasma Data: n_e (r), T_e(r), T_i (r) : directly from experiment

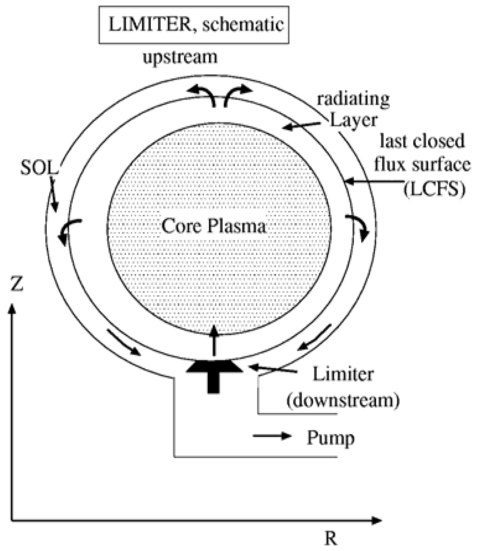
see lecture: Ongena

Tore Supra



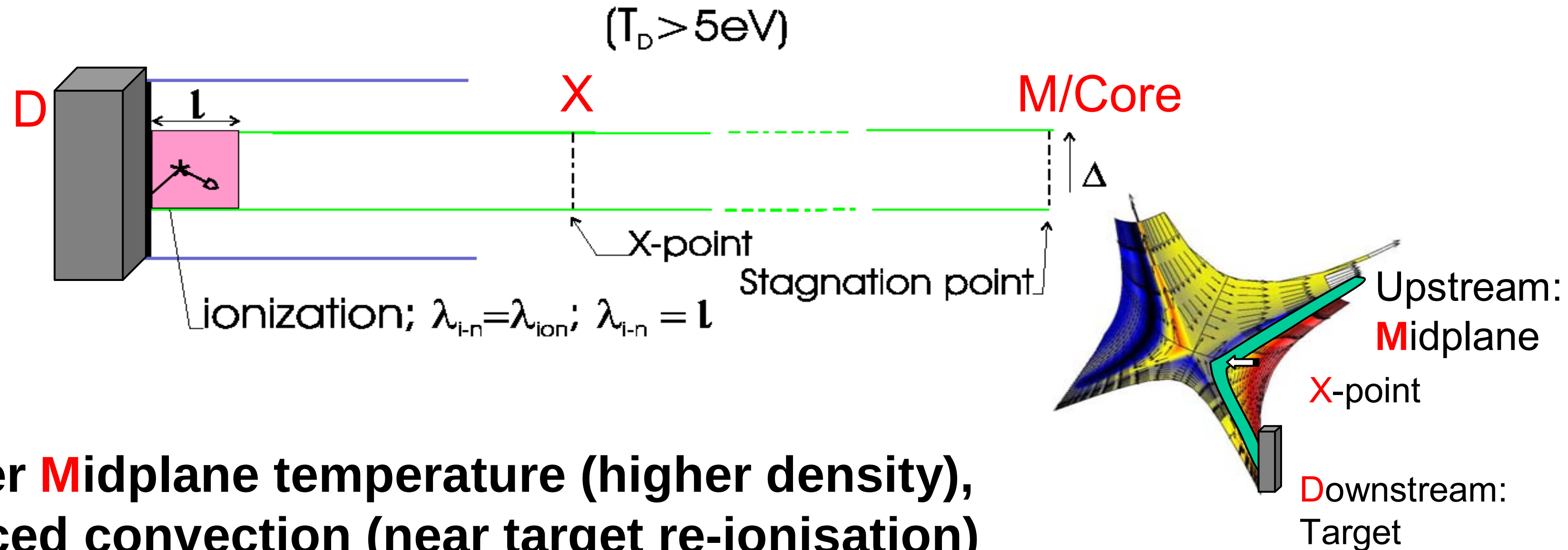
Linear, sheath limited regime: Tore-Supra, TEXTOR





Conduction limited (high recycling): dilution by multiple recycling

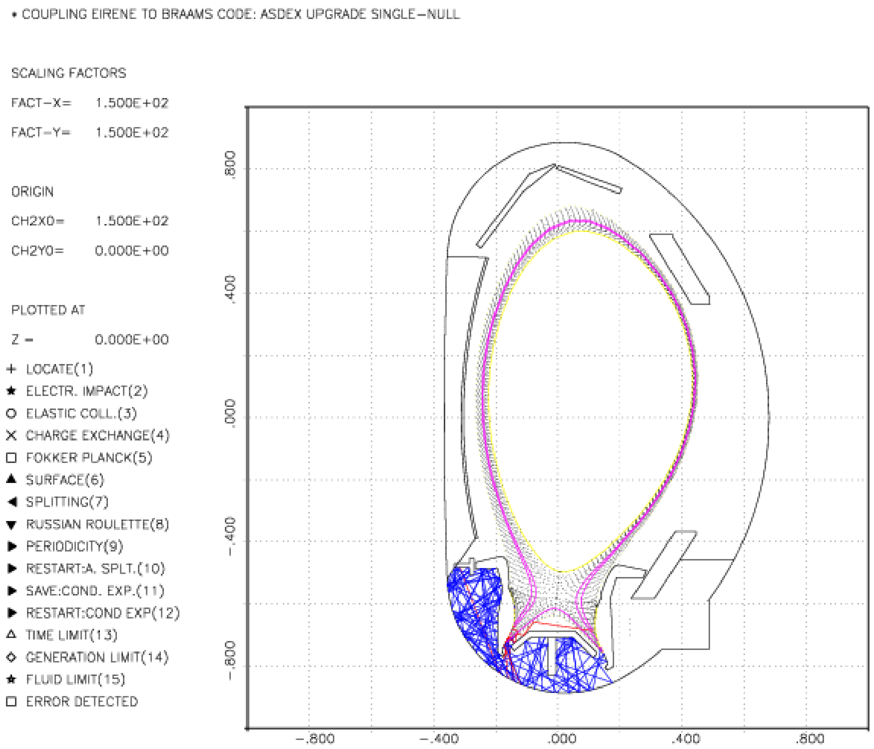
(1985-1995, ITER CDA)

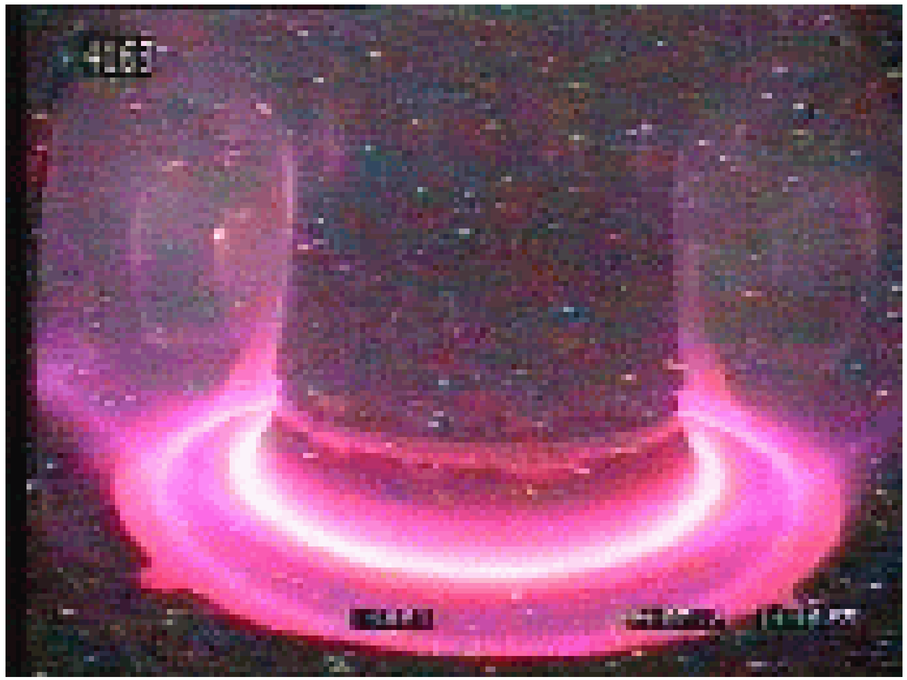


- **Lower Midplane temperature (higher density), reduced convection (near target re-ionisation) $\Rightarrow$ parallel temperature gradients: low T_e, high n_e near the target D**

- **Non-linear regime:** $T_D \sim n_M^{-2}$, $n_D \sim n_M^3$ **and** $\boxed{\text{flux } \Gamma_D \sim n_M^2}$

Trapping of neutral particles in the Divertor: high recycling and detachment regime

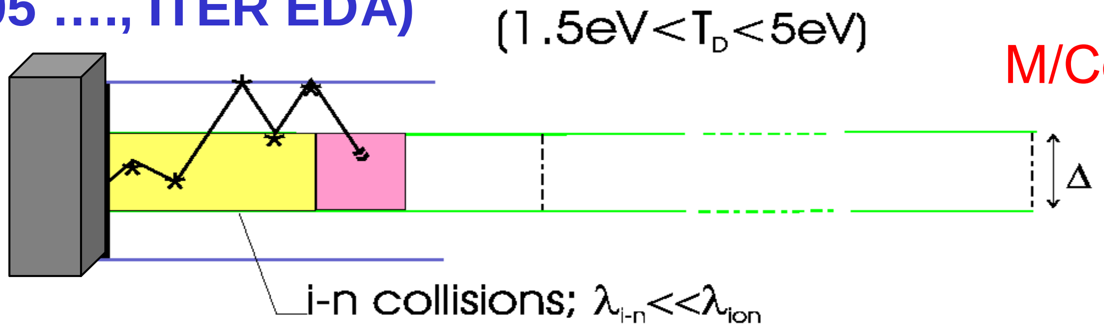




Particle Simulation: PMI, A&M **Visible light from ASDEX-U Divertor**

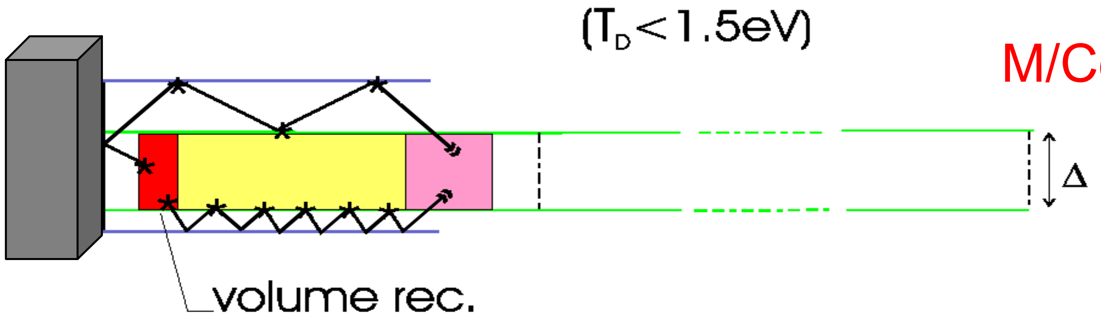
Weak (partial) detachment

(1995 …., ITER EDA)



- **below 5 eV strong momentum dissipation through self sustained A&M processes (CX)**

Strong (complete) detachment

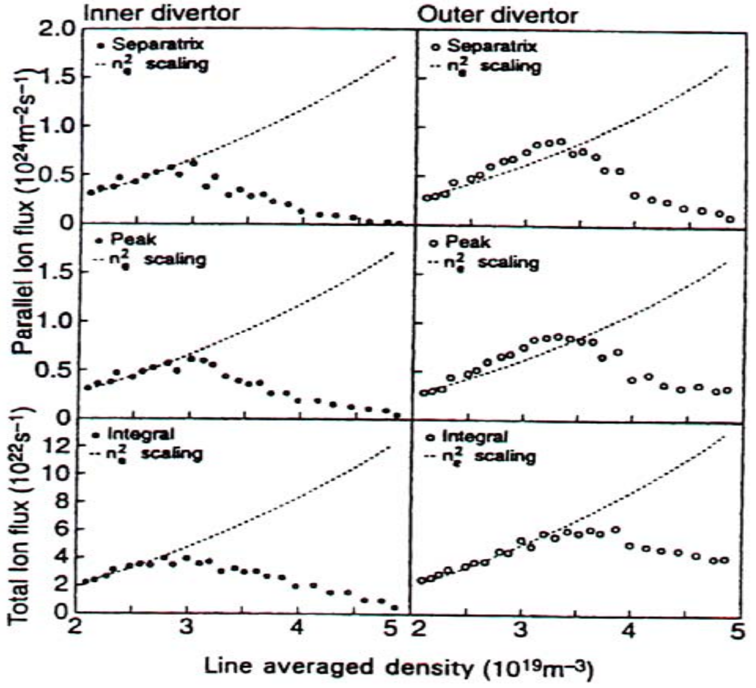


- **Below 1.5 eV additional reduction of plasma flux by volume recombination (virtual target, neutral cushion). Escape of neutrals to the sides followed by ionisation in hotter plasma (6-7 eV) further upstream**

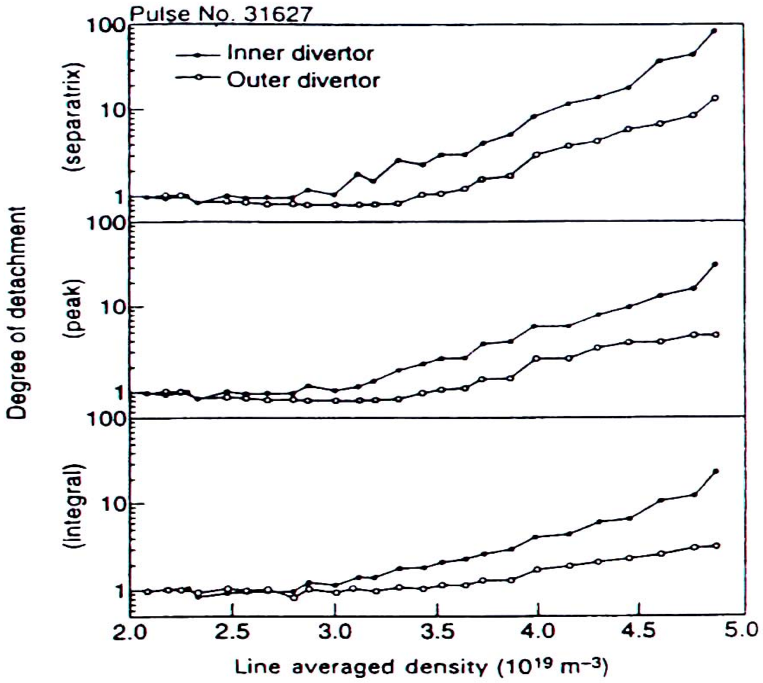
$\Gamma_D \sim n_M^2$ dependence is broken

JET, (ohmic), DETACHMENT

Measured and extrapolated ion fluxes to inner and outer divertors, density ramp

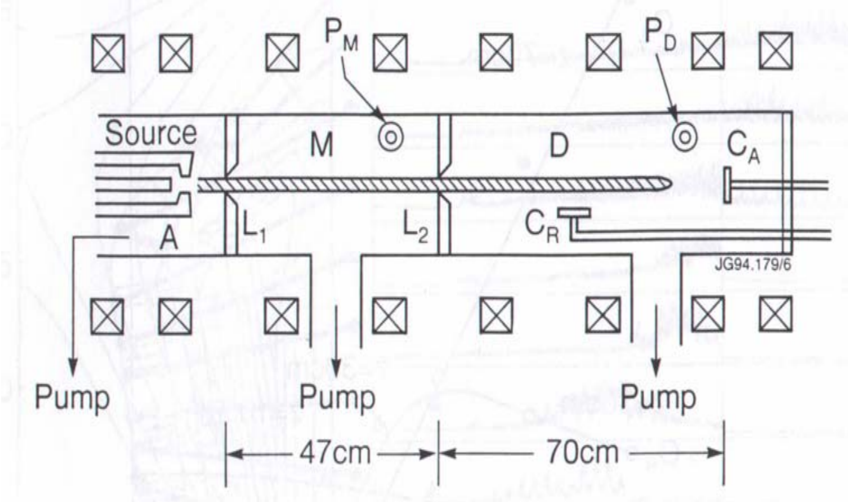


Degree of detachment (DOD)

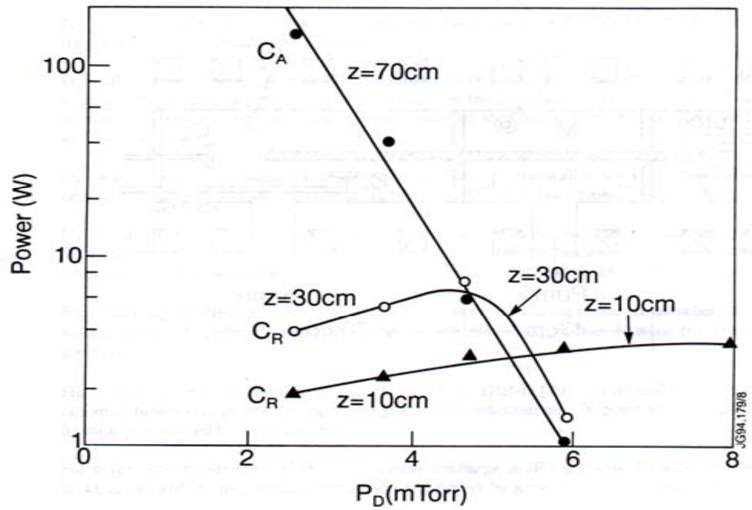


Princeton QED device
(gaseous Divertor concept simulator)

Schematic



Scaling of calorimeter signals
with gas pressure



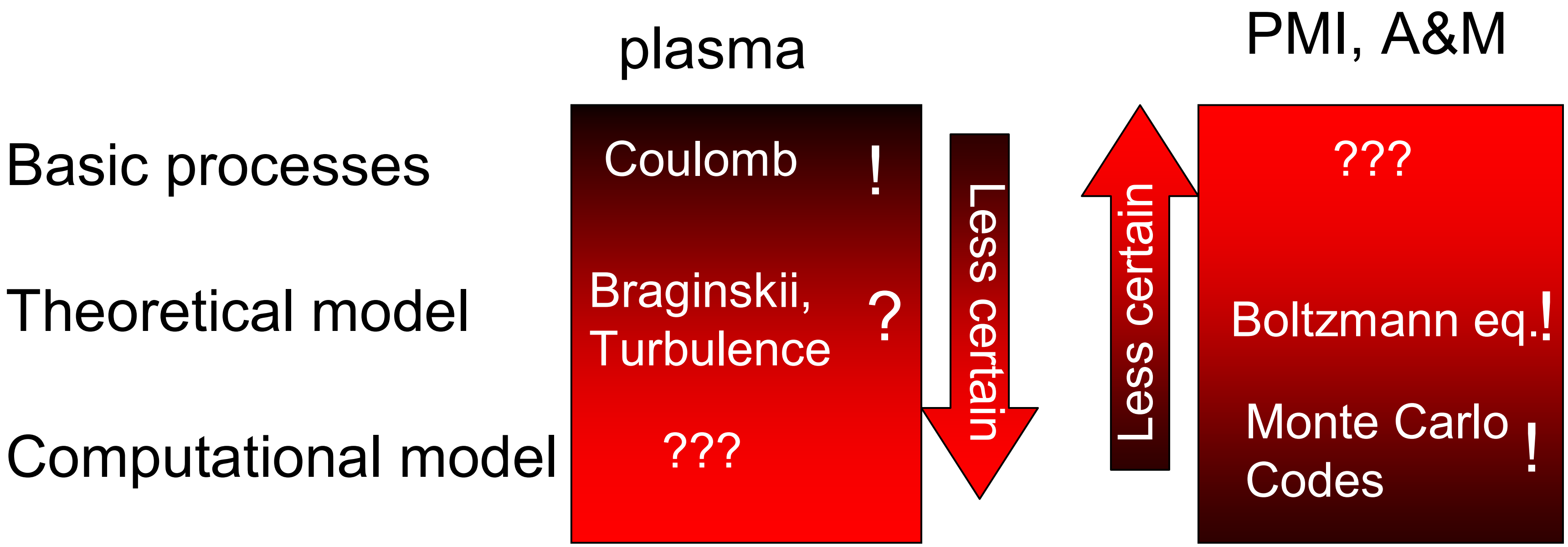
Hsu et al., PRL 49, 1001 (1982): QED
Schmitz et al., J.Nucl.Mat. 196-198, (1992): PISCES
Ohno et al., PRL 81, 818 (1998): NAGDIS

Key difference: here: P_{gas} given. In a fusion device the neutral cushion must be self sustained by recycling process. This issue will be addressed in linear MAGNUM device (FOM)

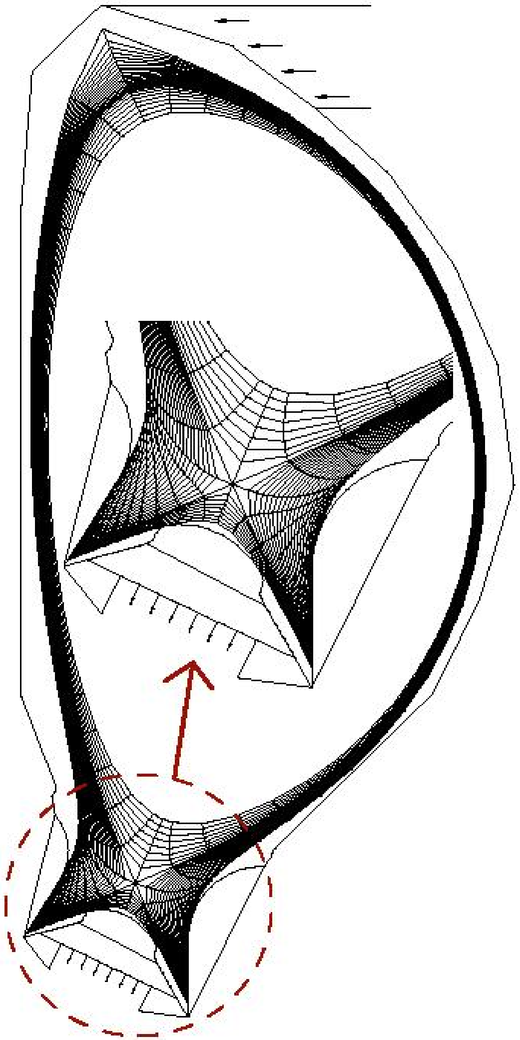
Integrated numerical experiments

plasma edge codes must integrate:

- **plasma physics,**
- **plasma material interaction (PMI)**
- **atomic and molecular processes (A&M)**



Design of the ITER divertor is guided by large scale code simulations (numerical book-keeping for all terms already known)



- Steady state divertor performance for D-He-C plasma.

B2. 2D, time-dependent set of Braginskii equations. Finite-volume scheme on quasi-orthogonal grid, multi-fluid,

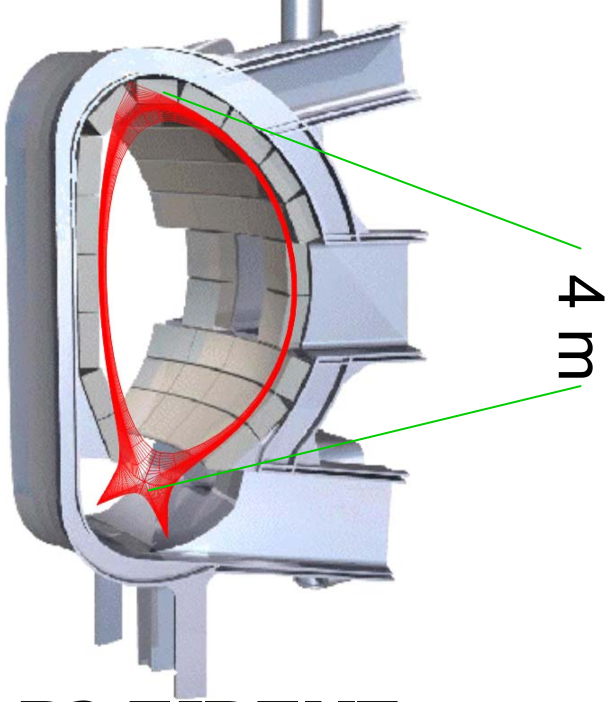
Grad 21-Moments closure.

EIRENE. Monte-Carlo neutral transport (see www.eirene.de). Calculates sources for B2 (S_N, $S_{mu||}$, $S^{i,e}{}_E$), based on 3D kinetic gas transport, plasma surface interaction and atomic and molecular plasma chemistry

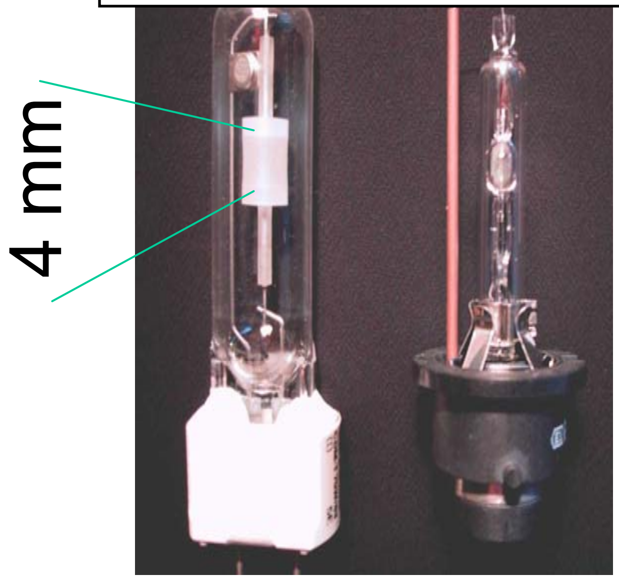
"B2-EIRENE", special issue in: Contrib. Plasma Physics, 46, No 1-2, 2006

Radiation transfer module: verification and validation using HID lamps

ITER



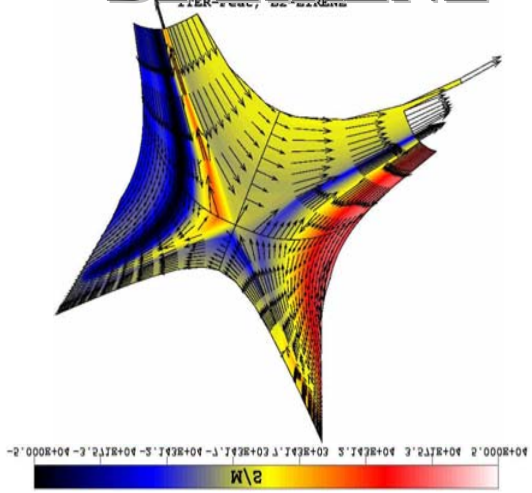
High Intensity Discharge Lamps



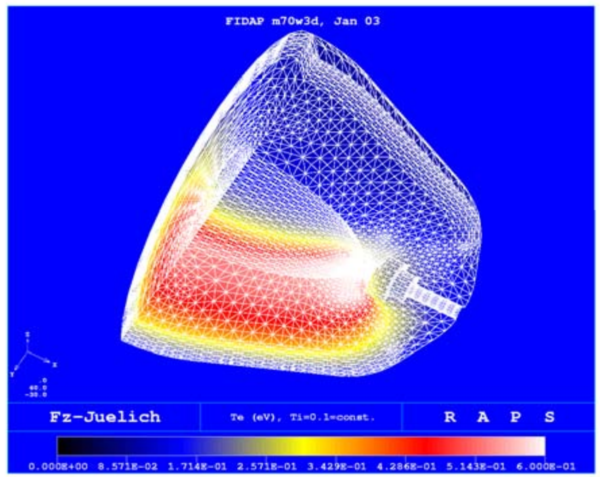
D2-36 W
Automotive
Material:Quartz

CDM-75 W
Shop-Lighting
Material:PCA

B2-EIRENE

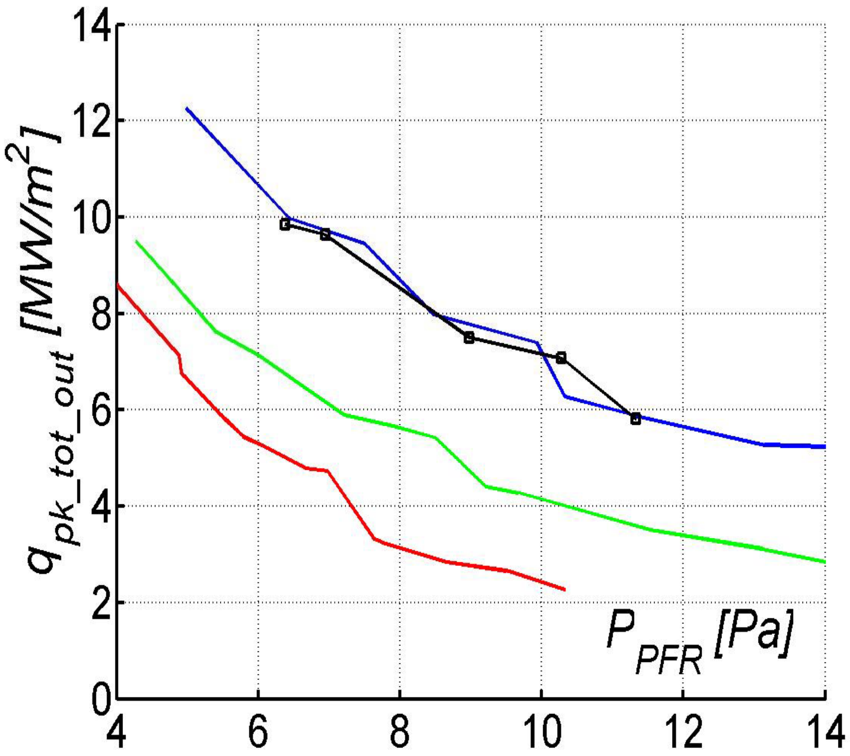


FIDAP-EIRENE



Consequences for ITER design (B2-EIRENE):
shift towards higher divertor gas pressure to maintain a given peak heat flux (Kotov et al., CPP, July 2006)

- ITER divertor engineering parameter:
- target heat flux vs. divertor gas pressure

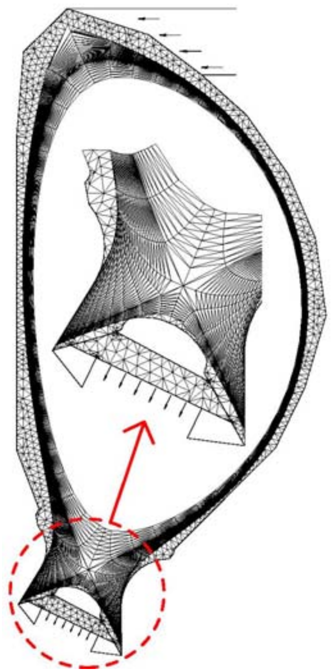


— 1996 (ITER physics basis1999)

— 2003, neutral - neutral collisions

— ….+ molecular kinetics ($D_2(v)+D^+$, MAR)

— 2005, + photon opacity



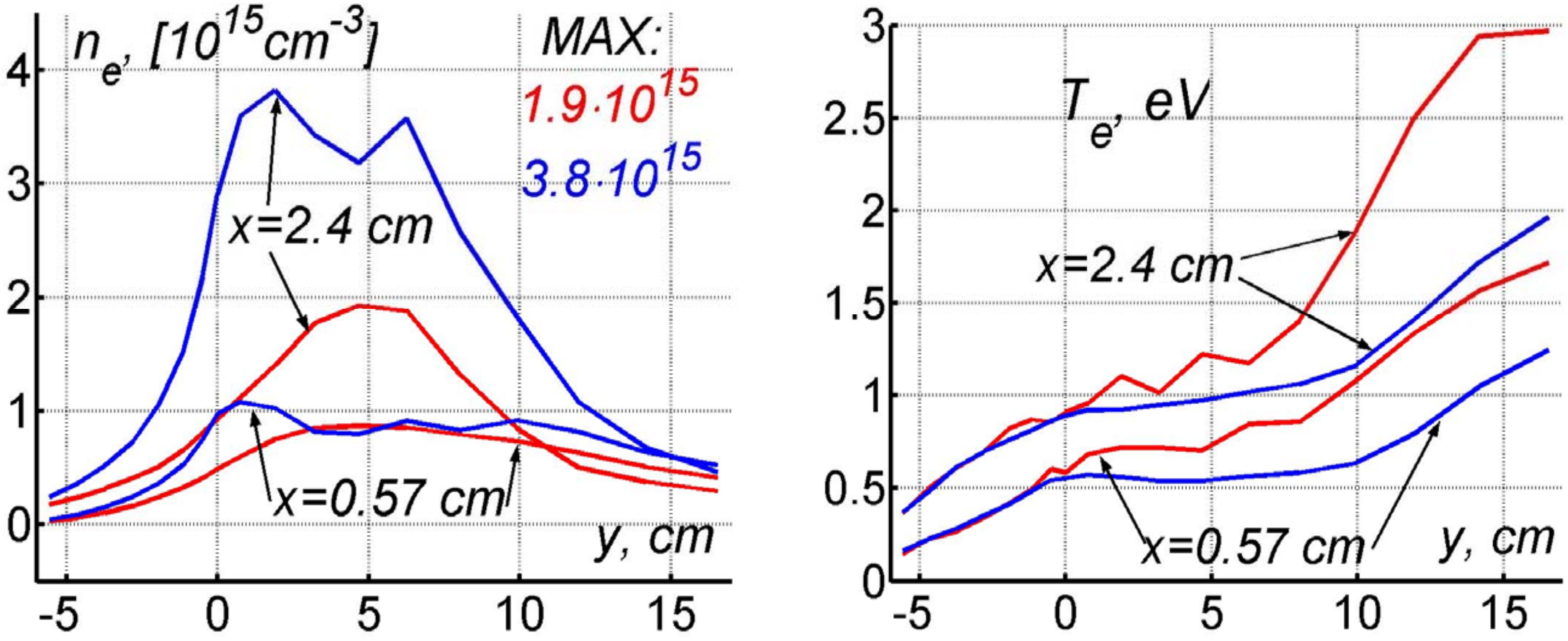
„Dome“ removal now seriously considered

P_{PFR}: average neutral pressure in Private Flux Region

The effect of photon opacity (Ly$_\alpha$: 95%, Ly$_\beta$: 70%)

- Principal effect: higher density (and somewhat lower temperature) in front of the targets

Temperature and density along Inner Target



—ITER, 100 MW SOL Power, Full Carbon Wall
In red: NO photon opacity, In blue: WITH photon opacity

V. Kotov, D. Reiter

Code verification:

- the code is around 15 years,
- used by a large number of people,
- applied to a large number of different experiments
- and it is completely open source and transparent (publicly exposed) from the very beginning

Code validation:

- matching experiments is a (trivial) minium requirement given the sufficiently many free model parameters
- separate unknowns from knowns, by confronting sub-models with dedicated experimental data (Next lecture)