2028-20

Joint ICTP/IAEA Workshop on Atomic and Molecular Data for Fusion

20 - 30 April 2009

HOW/WHY - Can we tend the fire?

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Can we tend the fire?

Three lectures course on plasma surface interaction and edge physics

III.) WHY ? Understanding plasma surface interaction

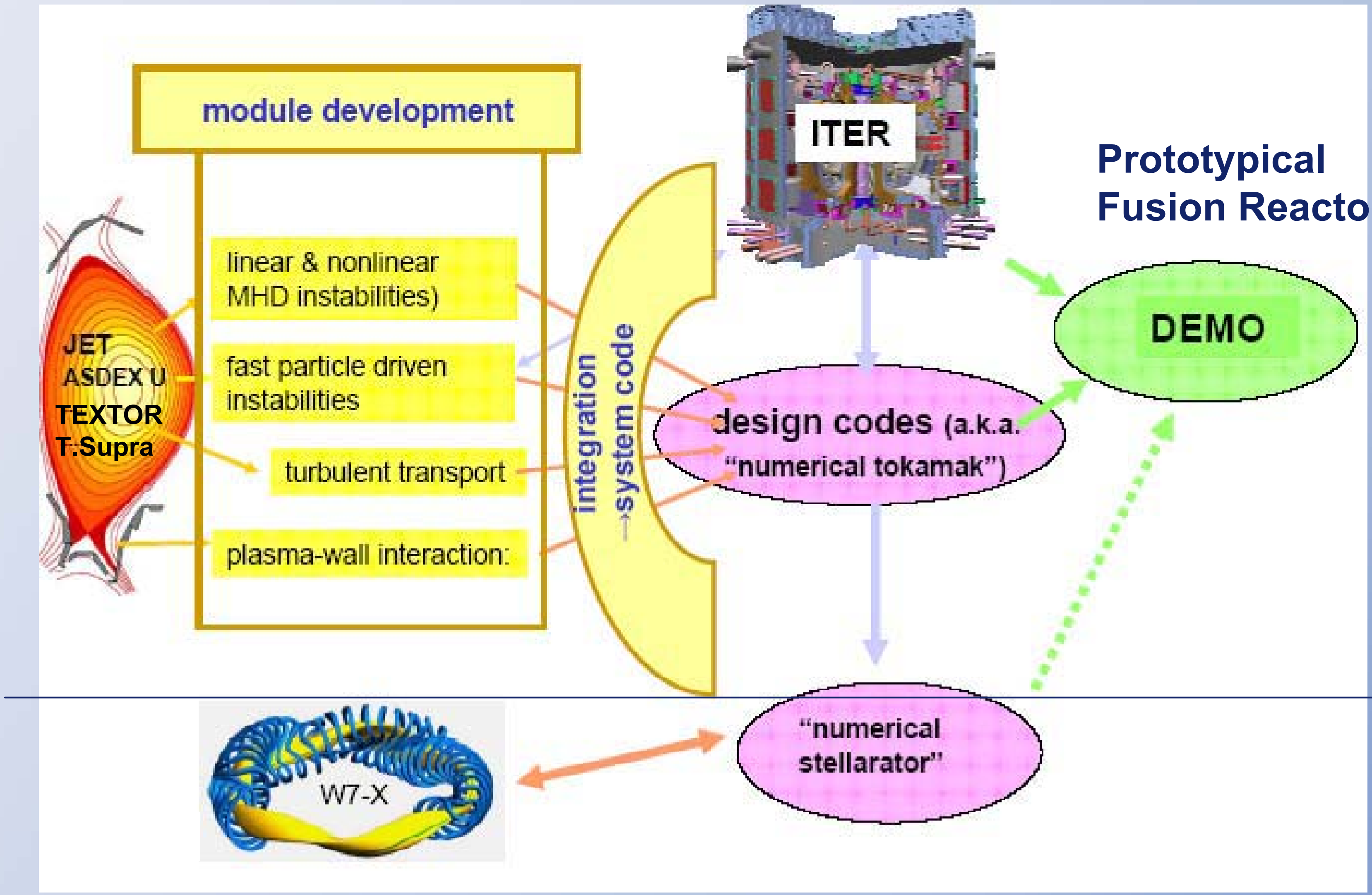
Detlev Reiter

Forschungszentrum Jülich GmbH, Institut für Energieforschung-4
52425 Jülich, Germany

Thanks to: V. Kotov, P. Börner

The vision……

NOW **2015-2025** **2025 ……**



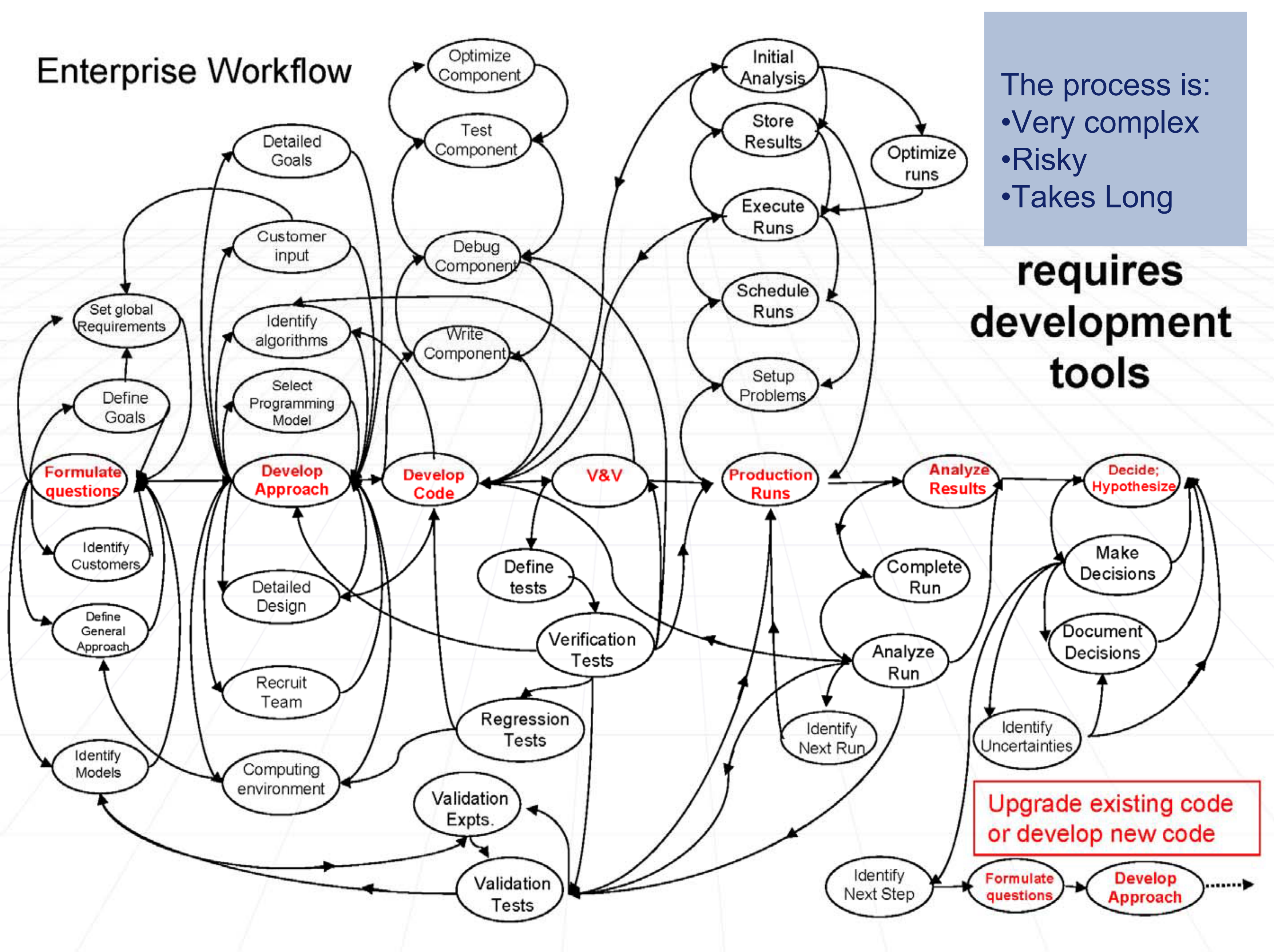
Prototypical Fusion Reactor

Computational Science Workflow
“Waterfall Model” (1960-th...)
(the dream of code development managers)

1) ~~Requirement (e.g.: integrated fusion code for ITER)~~
2) ~~Planning and design~~
3) ~~Code (Programming)~~
4) ~~Test~~
5) ~~Run~~

Computational Science and Engineering is moving from “few effects” codes developed by small teams (1-3 scientists) to “many effect codes” codes developed by larger teams (10-20 or more).

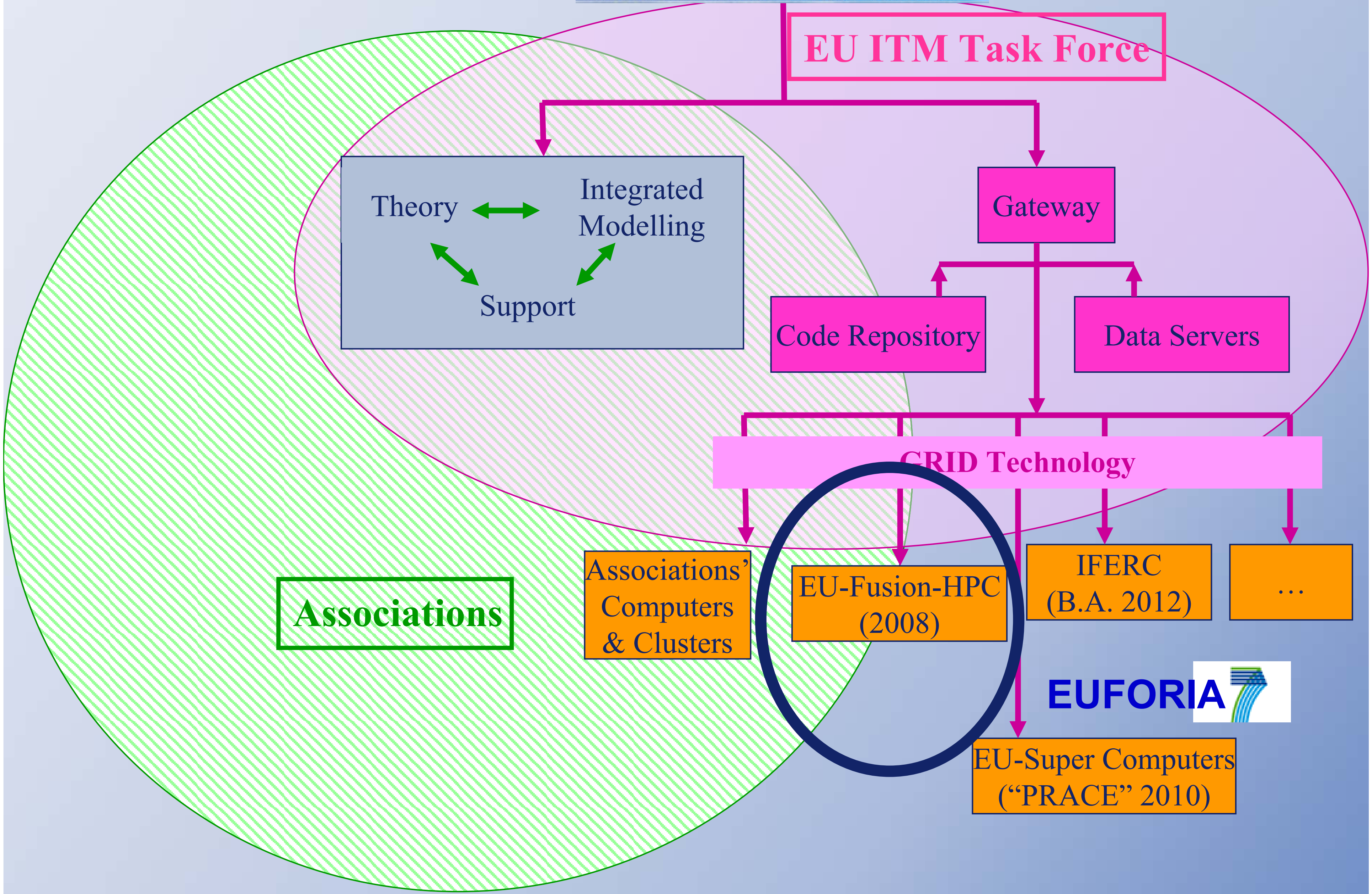
The reality in large scale code development projects



The process is:
- Very complex
- Risky
- Takes Long

requires development tools

EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT



EU ITM Task Force

Theory ↔ Integrated Modelling ↔ Support

Gateway

Code Repository

Data Servers

GRID Technology

Associations

Associations' Computers & Clusters

EU-Fusion-HPC (2008)

IFERC (B.A. 2012)

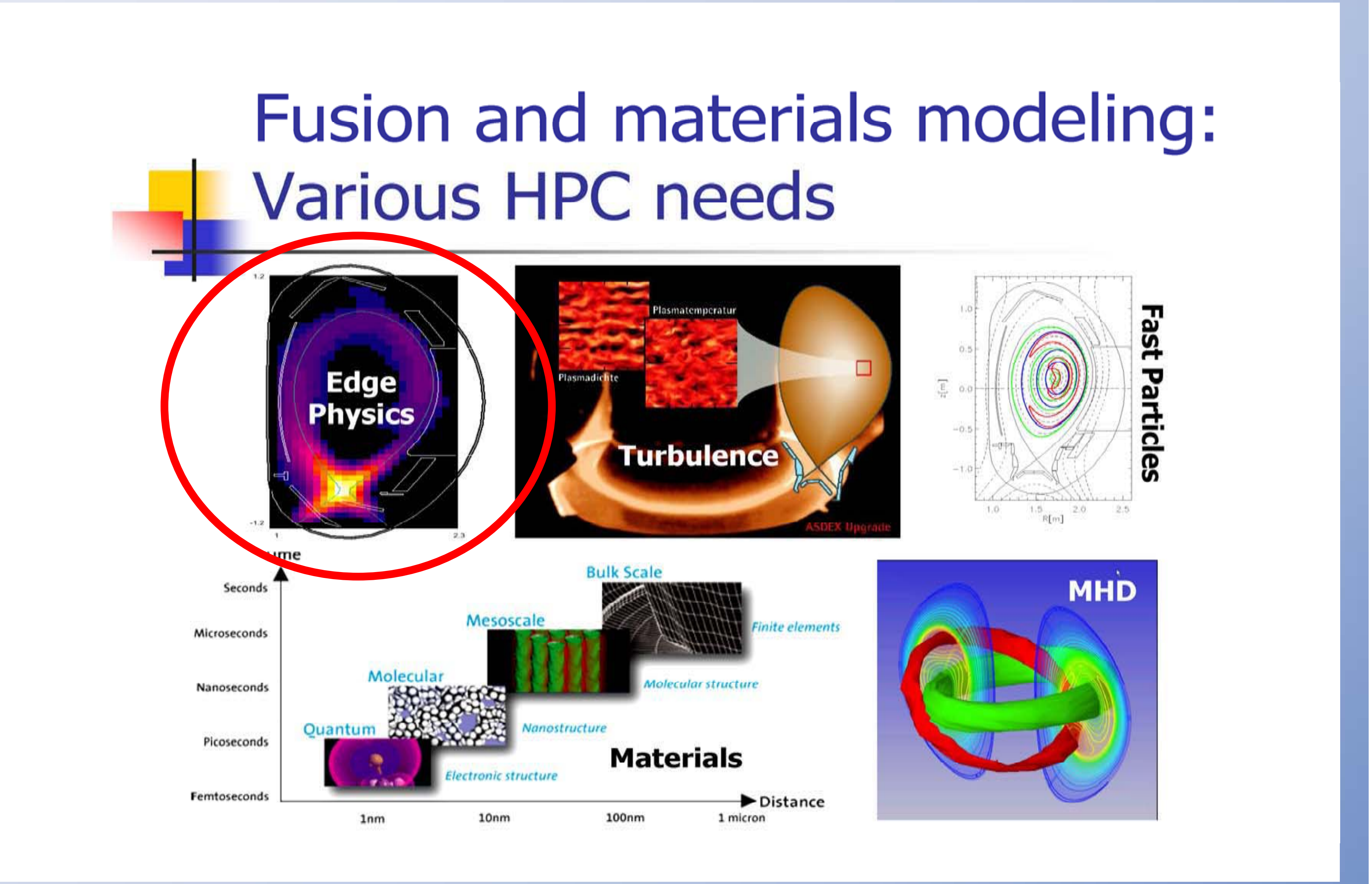
…

EUFORIA

EU-Super Computers ("PRACE" 2010)

Courtesy: A.Becoulet

The EU 100 TF HPC-FF will start operation in spring 2009



Fusion and materials modeling: Various HPC needs

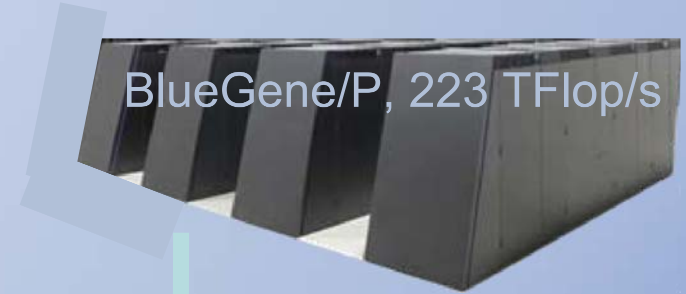
Supercomputer for Fusion Science @ Jülich

Institute for Advanced Simulation
Jülich Supercomputing Centre
(JSC)

Present Supercomputer Environment FZJ

General Purpose Supercomputer

JUMP, 1312 processor Regatta p690+,



High Scalable Supercomputer

BlueGene/P, 223 TFlop/s

No. 2 in Top500-List
Nov. 2007

On-line Storage, 1 PByte

Robot Silo, 4 PByte

Supercomputer Environment by End of 2008

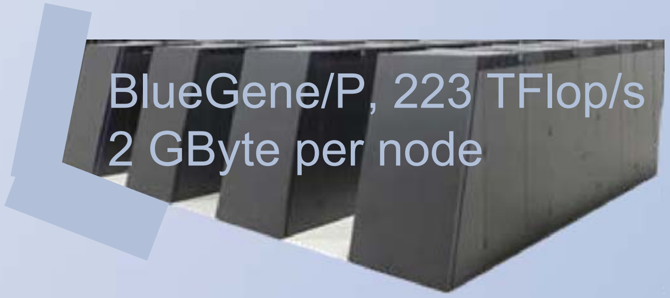
Flexible swapping of resources

Jülich‘s next General Purpose Supercomputer
to be installed in 2008

- 2048 nodes @ 8 cores
- 24 GByte per node
- Intel NEHALEM
- Network: QSnet^{III}
- Peak Performance about 200 TFlop/s

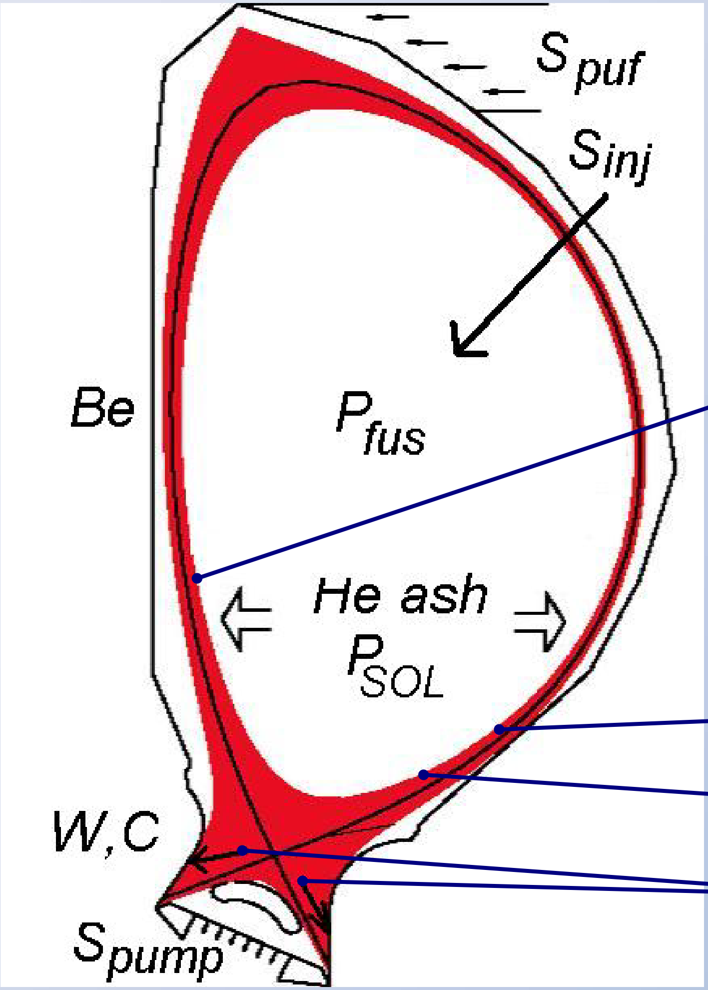
Supercomputer for
Fusion Science

- 1000 nodes @ 8 cores of same architecture
- Estimated Peak Performance about 100 TFlop/s


BlueGene/P, 223 TFlop/s
2 GByte per node


Storage
Environment

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**

$n_s \approx (2\text{-}4)\cdot10^{19}$ m^{-3}

$S_{inj} \lesssim 10\cdot10^{22}$ s^{-1}

$S_{pump} \lesssim 200$ Pa·m^{-3}/s

!

$Z_{eff} \lesssim 1.6$

$C_{He} \lesssim 6\%$

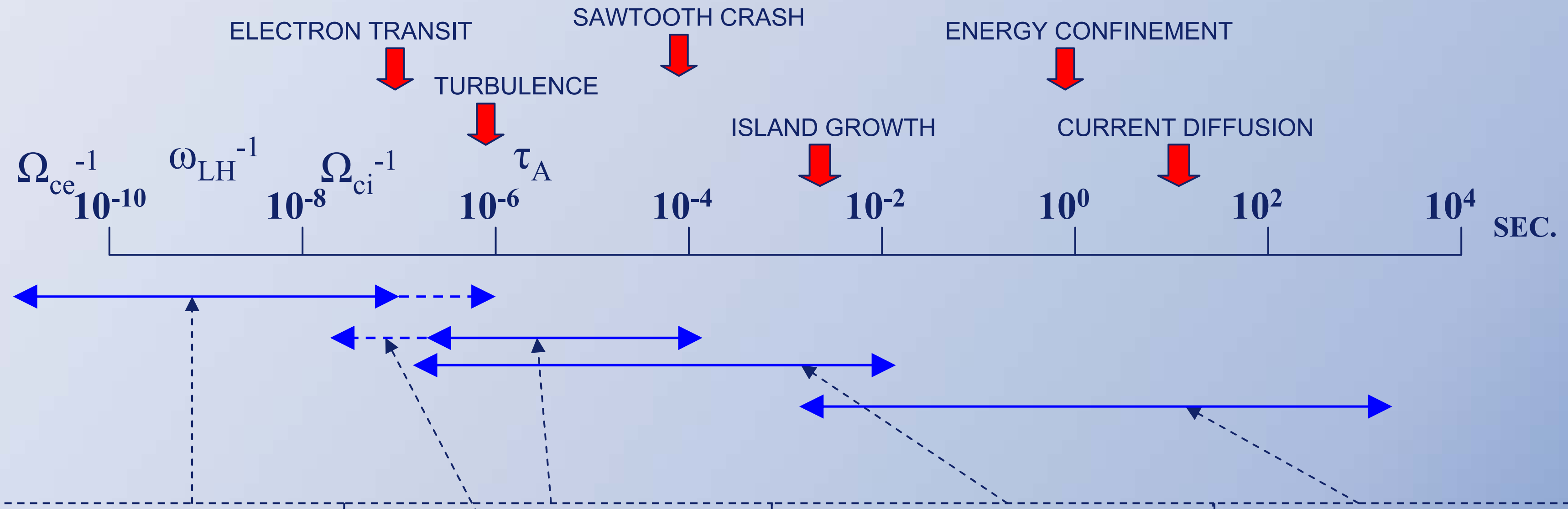
$q_{pk} \lesssim 10$ MW/m^2

?

Engineering parameter : $S_{puff} \sim (1\ldots13)\cdot10^{22}$ s^{-1}

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

RF Codes

wave-heating and current-drive

Neglect displacement current, average over gyroangle, (some) with electrons

Gyrokinetics Codes

turbulent transport

Neglect displacement current, integrate over velocity space, neglect electron inertia

Extended MHD Codes

device scale stability

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

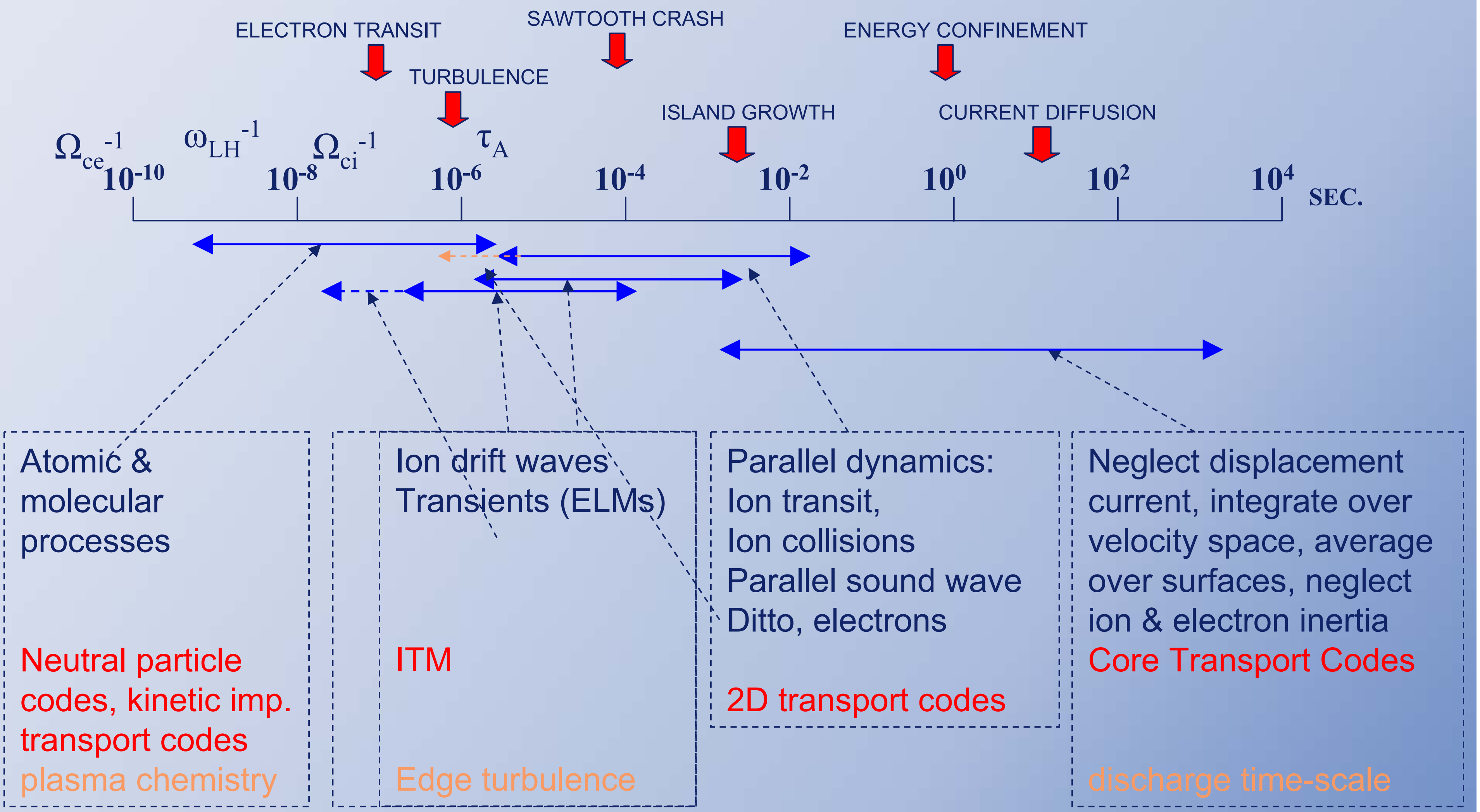
Transport Codes

discharge time-scale

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

Well separated: transport – turbulence: good !

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

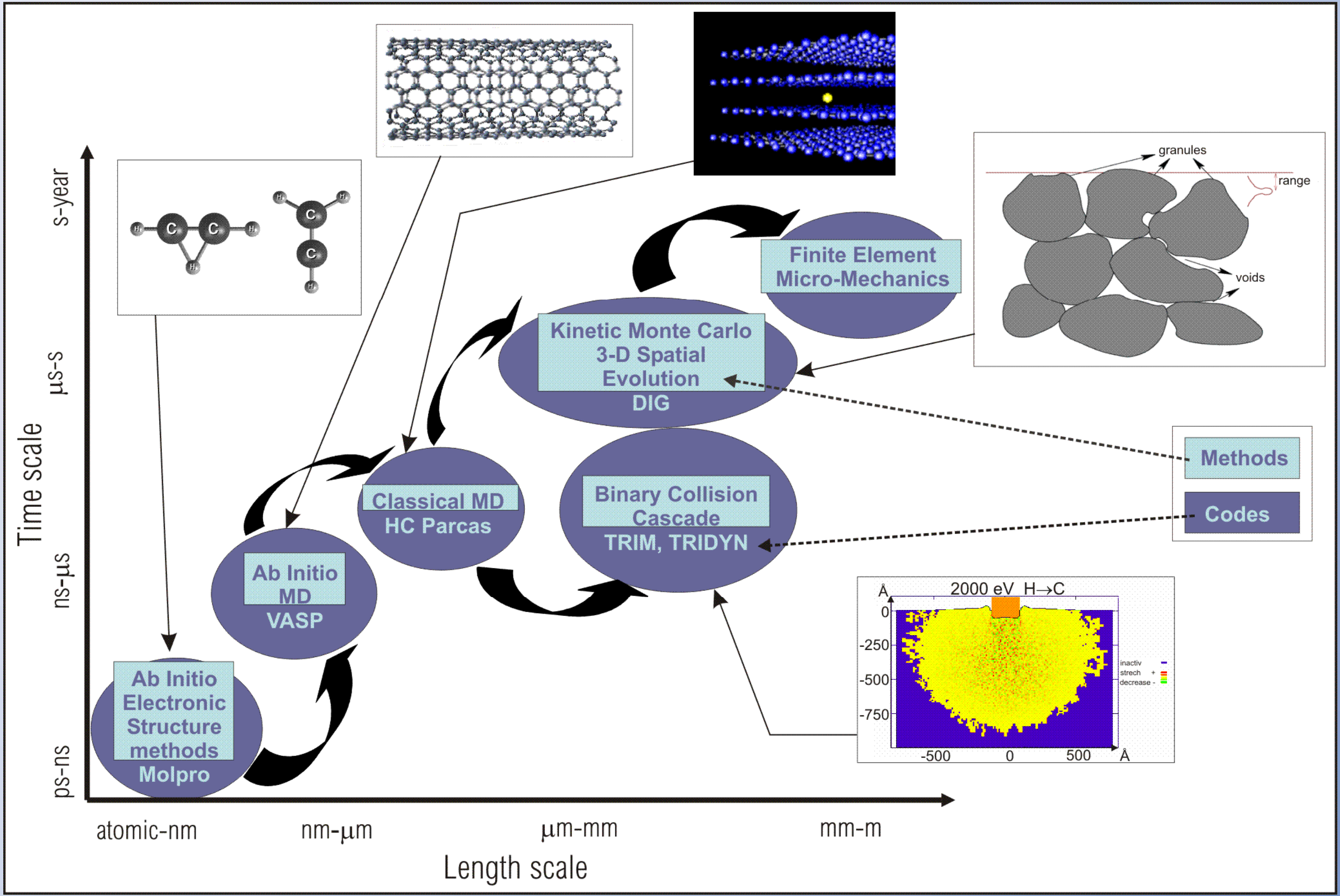
EDGE plasma

- No clearly separated timescales, i.e. no natural separation into reduced sub-models.

- Far more challenging than at inito core plasma transport: There turbulence and transport time scales are clearly separable.

- Similar situation: Computational material and PWI science

Material and PSI time- and spatial scales



Ab Initio Electronic Structure methods
Molpro

Ab Initio MD
VASP

Classical MD
HC Parcas

Kinetic Monte Carlo 3-D Spatial Evolution
DIG

Binary Collision Cascade
TRIM, TRIDYN

Finite Element Micro-Mechanics

Methods

Codes

Time scale: ps-ns, ns-µs, µs-s, s-year

Length scale: atomic-nm, nm-µm, µm-mm, mm-m

Thanks to: R.Schneider, IPP Greifswald

Generic kinetic (transport) equation (L. Boltzmann, ~1870)

- for particles travelling in a background (plasma) between collisions
- with (ions) or without (neutrals) forces (Lorentz) acting on them between collisions

Basic dependent quantity: distribution function $f(\vec{r},\vec{v},t)$

$$\frac{\partial f\left(E,\vec{\Omega}\right)}{\partial t}+v\vec{\Omega}\cdot\nabla f\left(E,\vec{\Omega}\right)+Forces=S\left(E,\vec{\Omega}\right)-v\sigma_a(E)f\left(E,\vec{\Omega}\right)$$

Free flight

External source

Absorption

$$+\int_0^\infty dE'\int_{4\pi}d\vec{\Omega}'\left[v'\sigma_s\left(E'\rightarrow E,\vec{\Omega}'\cdot\vec{\Omega}\right)f\left(E',\vec{\Omega}'\right)-v\sigma_s\left(E\rightarrow E',\vec{\Omega}\cdot\vec{\Omega}'\right)f\left(E,\vec{\Omega}\right)\right]$$

Collisions, boundary conditions

Characteristics (=Trajectories) of kinetic transport equation here: MAST, Culham, UK

* CMOD (OSM–EIRENE INTERFACE) TEMPLATE

SCALING FACTORS

FACT–X= 2.300E+02

FACT–Y= 2.300E+02

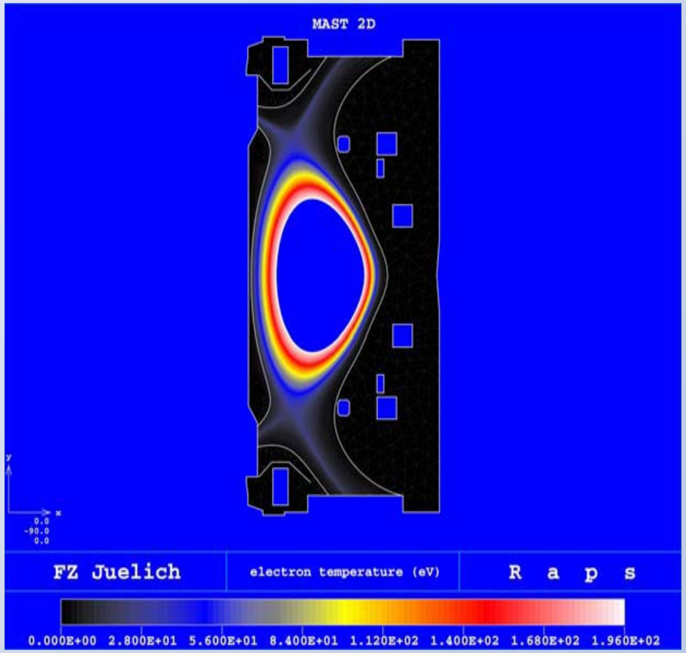
ORIGIN

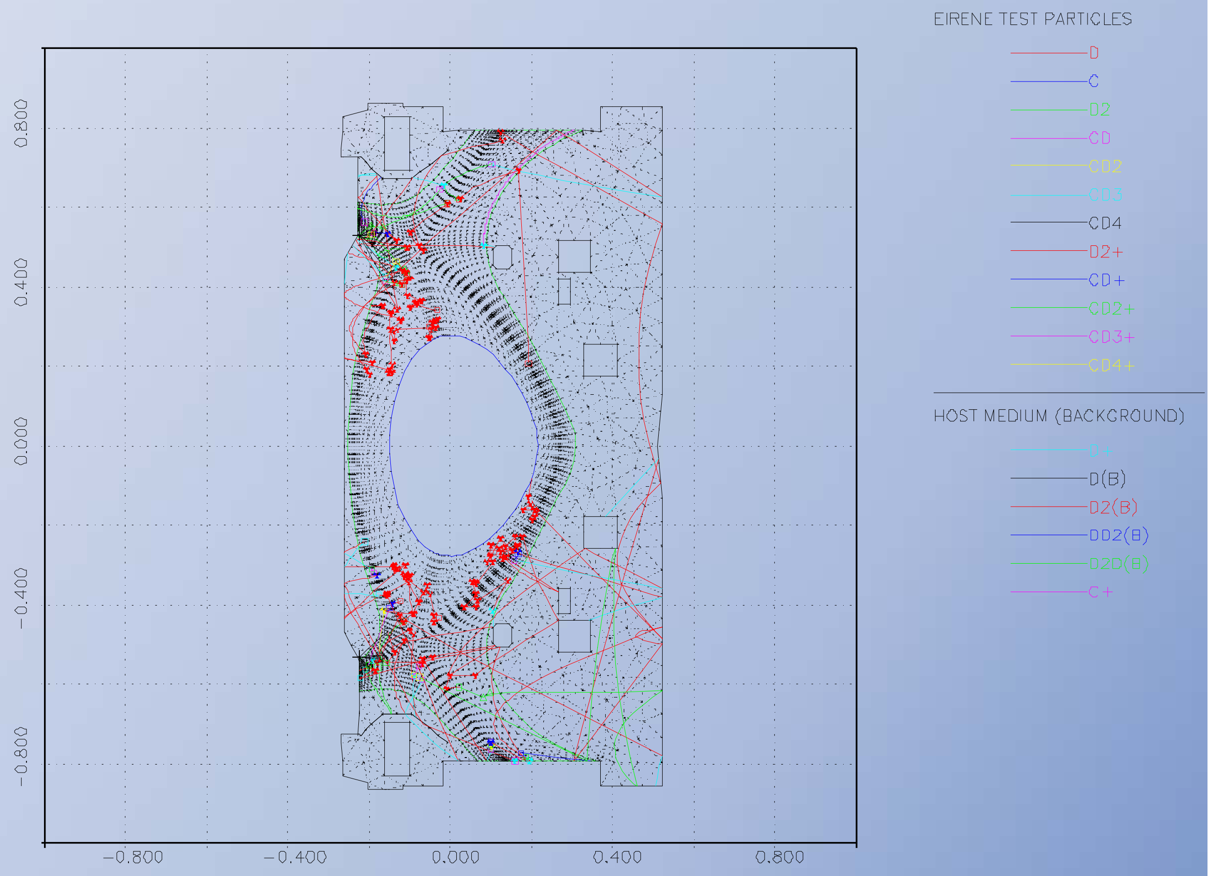
CH2XD= 8.000E+01

CH2Y0= 0.000E+00

PLOTTED AT

Z = –7.500E+02

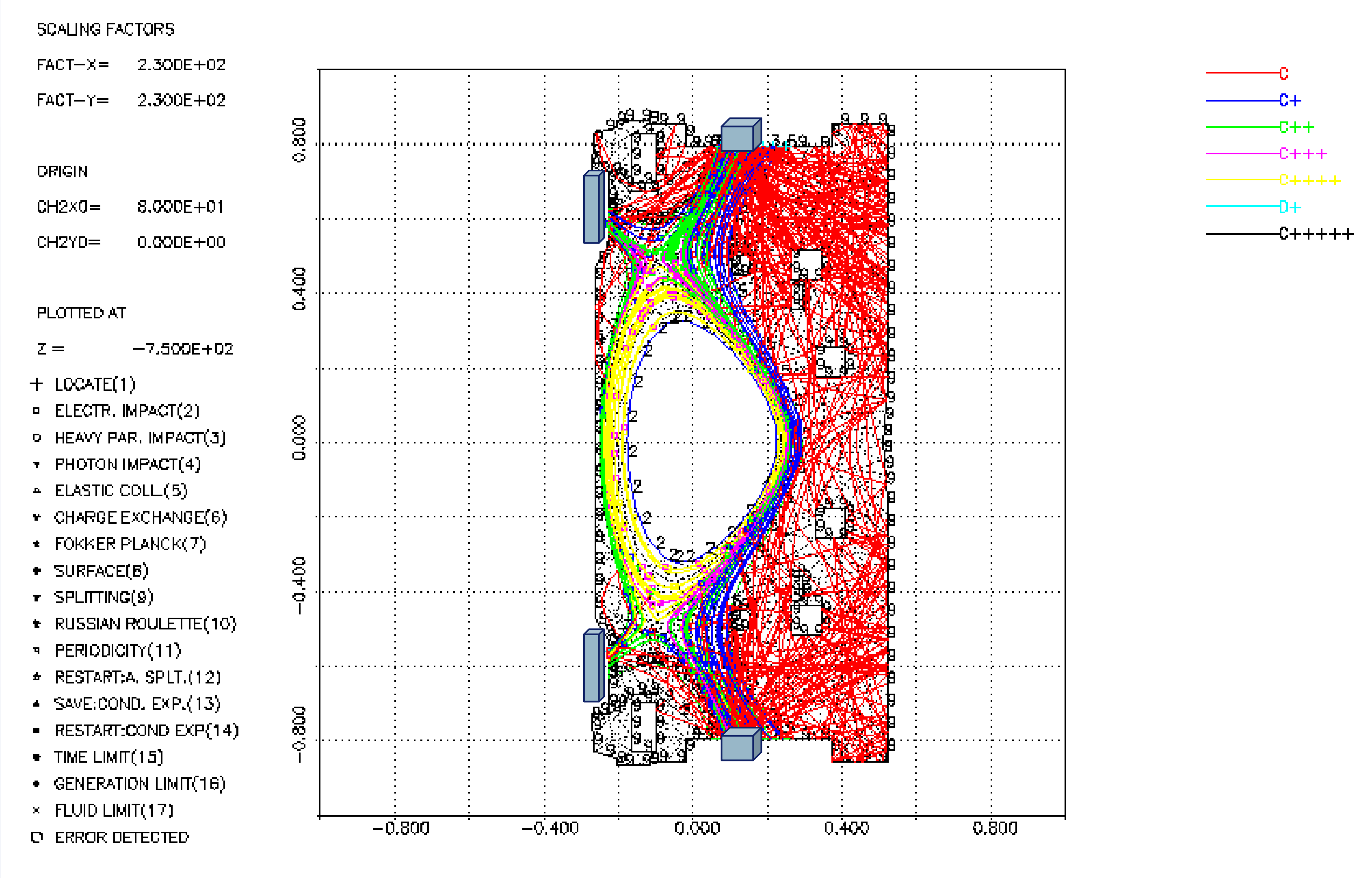




Here: mainly H, H_2, C_xH_y neutrals

MAST: Geometry and exp. plasma data provided by S. Lisgo, UKAEA, 2007

EIRENE kinetic transport code (www.eirene.de): gyro averaged ion kinetic up to edge-core interface



SCALING FACTORS

FACT−X= 2.300E+02

FACT−Y= 2.300E+02

ORIGIN

CH2X0= 8.000E+01

CH2Y0= 0.000E+00

PLOTTED AT

Z = −7.500E+02

Here: C, C^+, C^{2+}, … atomic carbon neutrals and ions

MAST: Geometry and exp. plasma data provided by S. Lisgo, UKAEA

Collisionality → plasma fluid approximation

multi-ion fluid (α ion species, $T_\alpha = T_i$, and electrons)

multi-species Boltzmann eq. for neutrals (n neutral species)

Braginskii, Reviews of Plasma Physics, 1965

Continuity equation for ions and electrons

$$\frac{\partial}{\partial t} n_i + \vec{\nabla}\cdot\left(n_i \vec{V}_i\right) = S_{n_i} \qquad \xcancel{\frac{\partial}{\partial t} n_e + \vec{\nabla}\cdot\left(n_e \vec{V}_e\right) = S_{n_e}}$$

Momentum balance for ions and electrons

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

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

Energy balances for ions and electrons

$$\frac{\partial}{\partial t}\left(\frac{3}{2} n_i T_i + \frac{m_i n_i}{2}\vec{V}_i^2\right) + \vec{\nabla}\cdot\left[\left(\frac{5}{2} n_i T_i + \frac{m_i n_i}{2}\vec{V}_i^2\right)\vec{V}_i + \overleftrightarrow{\Pi}_i \cdot \vec{V}_i + \vec{q}_i\right] = \left(e n_i Z_i \vec{E} - \vec{R}\right)\cdot\vec{V}_i - Q_{ei} + S_E^i$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2} n_e T_e\right) + \vec{\nabla}\cdot\left(\frac{5}{2} n_e T_e \vec{V}_e + \vec{q}_e\right) = -e n_e \vec{E}\cdot\vec{V}_e + \vec{R}\cdot\vec{V}_i + Q_{ei} + S_E^e$$

ASIDE

Momentum balance for ions and electrons
(Navier Stokes „Braginskii“ equations)

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

In edge codes often used only for $v_{\alpha_{\parallel}}$ the flow parallel to B-field

The cross field momentum balance is replaced by diffusion-convection ansatz:

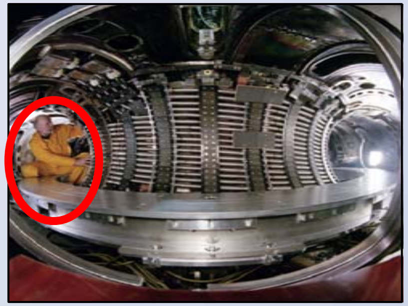
$$v_{\alpha\perp}=-\frac{D_n^{\alpha}}{h_{\perp}}\partial_{\perp}\left(\ln n_{\alpha}\right)-\frac{D_p^{\alpha}}{h_{\perp}}\partial_{\perp}\left(\ln p_{\alpha}\right)+V_{\perp}$$

with ad hoc (anomalous?) $D_{\perp}$,$V_{\perp}$ $\kappa_{\perp}$, $\eta_{\perp}$,

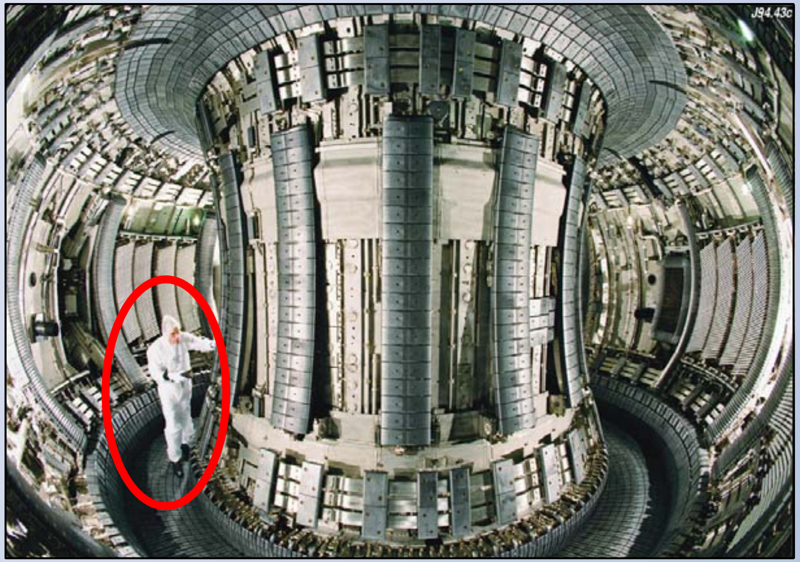
e.g. Strahl code,…..

Fusion devices

TEXTOR (R=1.75 m), Jülich, GER

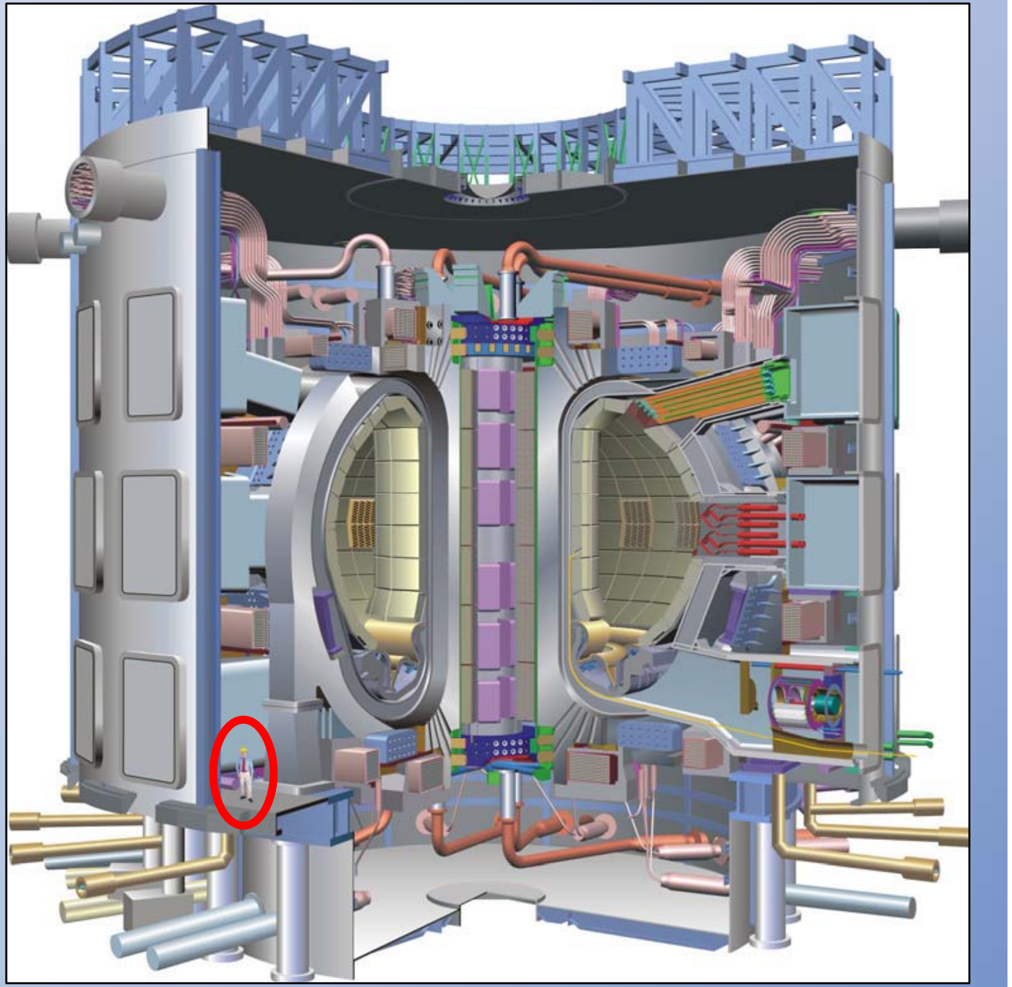


JET (R=2.96 m), Oxford, UK



joint: EU

ITER (R=6.2 m), Cadarache, FRA



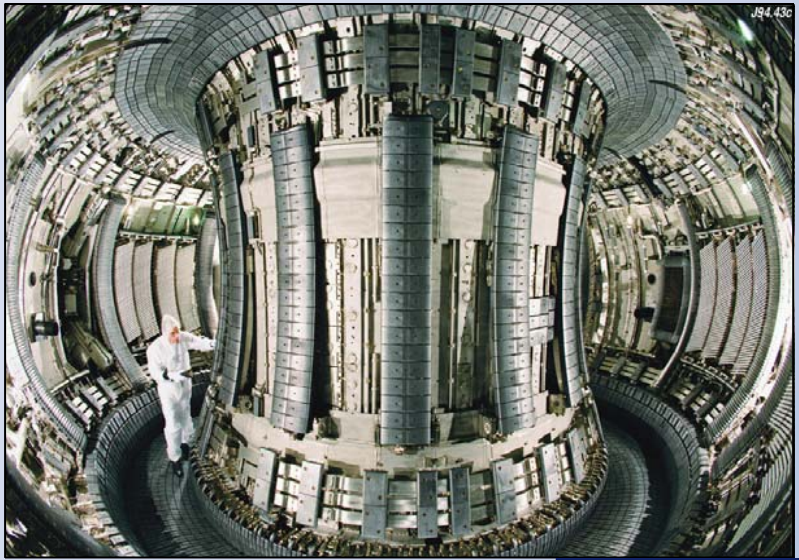
joint: world-wide

Fusion devices: typical transport code runtime

TEXTOR (R=1.75 m), Jülich, GER

1 day

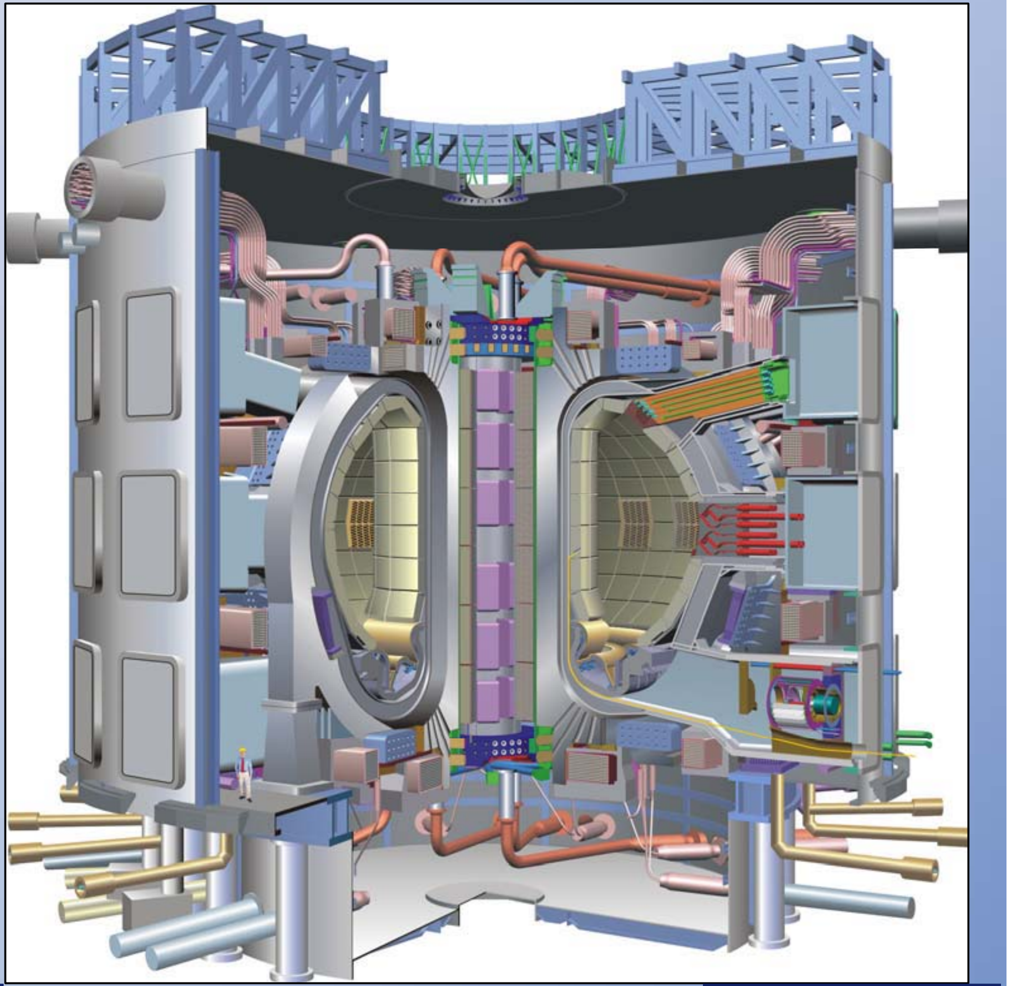
JET (R=2.96 m), Oxford, UK



joint: EU

1-2 weeks

ITER (R=6.2 m), Cadarache, FRA



joint: world-wide

3 months

Why become transport codes so slow for ITER sized machines?
(for same model, same equations, same grid size)

Because of more important
plasma chemistry
(increased non-linearity,
non-locality, in sources).

Fluid equations for charged particles

Continuity equation for ions and electrons

$$\frac{\partial}{\partial t}n_i + \vec{\nabla}\cdot\left(n_i\vec{V}_i\right) = \boxed{S_{n_i}}$$

Momentum balance for ions and electrons

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

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

Energy balances for ions and electrons

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_i T_i + \frac{m_i n_i}{2}\vec{V}_i^2\right) + \vec{\nabla}\cdot\left[\left(\frac{5}{2}n_i T_i + \frac{m_i n_i}{2}\vec{V}_i^2\right)\vec{V}_i + \overleftrightarrow{\Pi}_i\cdot\vec{V}_i + \vec{q}_i\right] = \left(e n_i Z_i \vec{E} - \vec{R}\right)\cdot\vec{V}_i - Q_{ei} + \boxed{S_E^i}$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_e T_e\right) + \vec{\nabla}\cdot\left(\frac{5}{2}n_e T_e \vec{V}_e + \vec{q}_e\right) = -e n_e \vec{E}\cdot\vec{V}_e + \vec{R}\cdot\vec{V}_i + Q_{ei} + \boxed{S_E^e}$$

System of PDGL’s with locally increasing dominating sources:
“diffusion-reaction-equations” rather than pure CFD

Separating time scales in plasma chemistry:

Kinetic (transport) equation, one for each species

$$\frac{\partial f\left(E,\vec{\Omega}\right)}{\partial t} + \frac{\partial f\left(E,\vec{\Omega}\right)}{\partial t} + \frac{f}{\tau} = S\left(E,\vec{\Omega}\right) - v\sigma_a(E) f\left(E,\vec{\Omega}\right)$$

System then becomes analogous to:

$$\frac{\partial \vec{f}}{\partial \mathrm{t}} = \overleftrightarrow{M}\vec{f} + \vec{S}$$

for those f_i, for which the transport has been removed from kinetic equation

Separating time scales in plasma chemistry:

Kinetic (transport) equation, one for each species

$$\frac{\partial f\left(E,\vec{\Omega}\right)}{\partial t} + v\vec{\Omega}\cdot\nabla f\left(E,\vec{\Omega}\right) + Forces \quad = S\left(E,\vec{\Omega}\right) - v\sigma_a(E)\, f\left(E,\vec{\Omega}\right)$$

Transport

External source Absorption

$$+\int_0^\infty dE' \int_{4\pi} d\vec{\Omega}' \left[v'\sigma_s\left(E'\to E,\vec{\Omega}'\cdot\vec{\Omega}\right) f\left(E',\vec{\Omega}'\right) - v\sigma_s\left(E\to E',\vec{\Omega}\cdot\vec{\Omega}'\right) f\left(E,\vec{\Omega}\right)\right]$$

Collisions

$$\frac{\partial \vec{f}}{\partial t} = \overset{\leftrightarrow}{M}\vec{f} + \vec{S}$$

for those f_i, for which the transport has been removed from kinetic equation

CR Models in Transport Codes (“bundled states”)

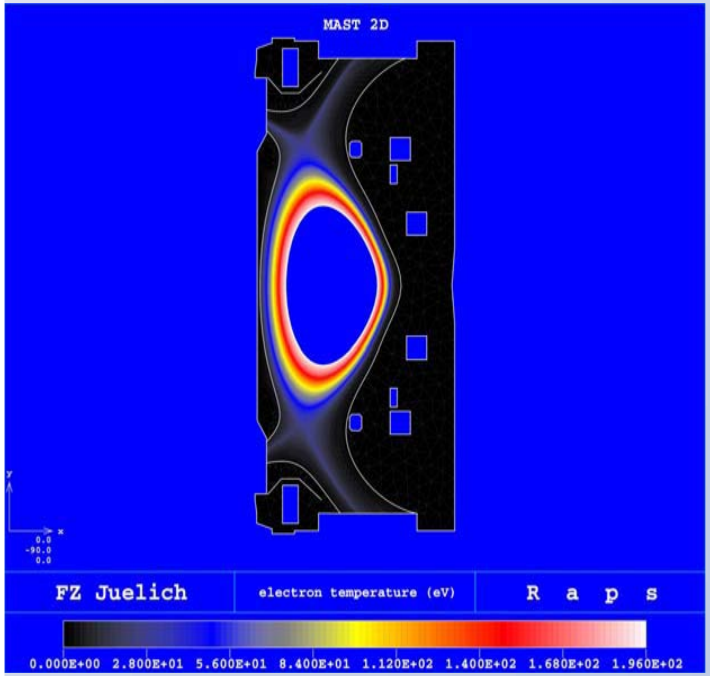
1) System of N kinetic (or fluid) equations
   (PDGL, IGL)

2) select M species, remove transport term
   and explicit time derivative
   (Interpretation: their lifetime is short compared to
   transport time)

3) System reduced to N – M transport equations
   plus one linear algebraic system (CR Model), of
   order M

The M states are in quasi steady state with the N – M transported species.
CR models are QSS models
(this is also known as “bundled state model”)

Characteristics (=Trajectories) of kinetic transport equation here: MAST, UKAEA Culham, UK



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* CMOD (OSM-EIRENE INTERFACE) TEMPLATE

SCALING FACTORS
FACT-X=     2.300E+02
FACT-Y=     2.300E+02

ORIGIN
CH2XD=      8.000E+01
CH2Y0=      0.000E+00
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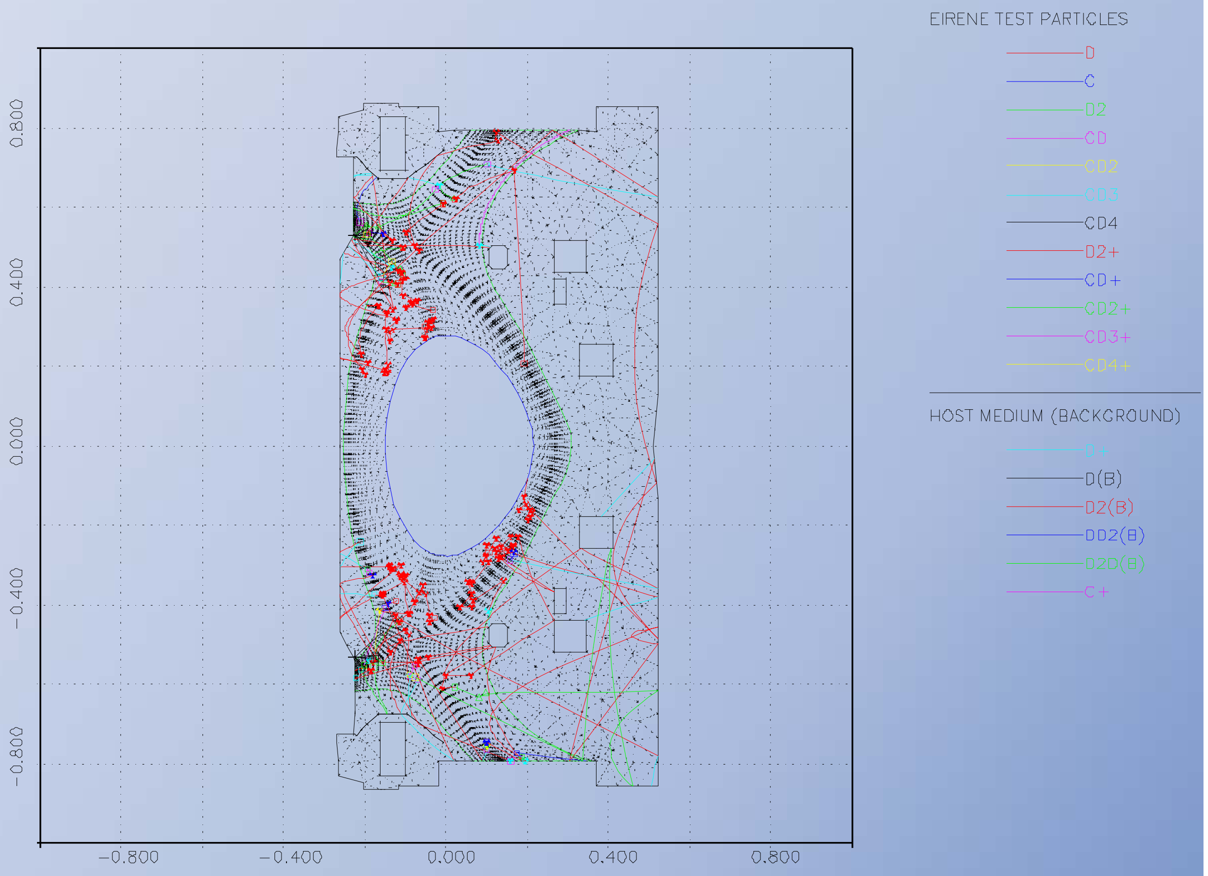


Here: mainly H, H_2, C_xH_y neutrals

QSS (condensed): H_2^+, and all excited states

MAST: Geometry and exp. plasma data provided by S. Lisgo, UKAEA, 2007

EXAMPLE

Collision-radiative model (CR) [K. Sawada, T. Fujimoto, 1995] for H,p,H_2,H_2^+ (and H*, H_2^*, H_2^{+*} as fast QSS-species)

$$\frac{dn_{p>1}}{dt} = 0 = \sum_{q<p} C_{qp} n_e n_q - \sum_{q>p} C_{pq} n_e n_p - \sum_{q<p} F_{pq} n_e n_p - \sum_{q<p} A_{pq} n_p$$

$$- S_p n_e n_p$$

$$\underline{+ C_{1p} n_e \enclose{circle}{n_1}} \underline{+ R_p n_e \enclose{circle}{n_+}} \underline{+ D_{H_2 p} n_e \enclose{circle}{n_{H_2}}} \underline{+ D_{H_2^+ p} n_e \enclose{circle}{n_{H_2^+}}}$$

Similar for nH_2^*, nH_2^{+*}, total: ~ 100 species, N – M = 4

C: **electronic excitation;** ***F***: **electronic de-excitation;**

A: **radiative decay;**

R: **recombination;** ***S***: **ionization;** ***D***: **dissociation.**

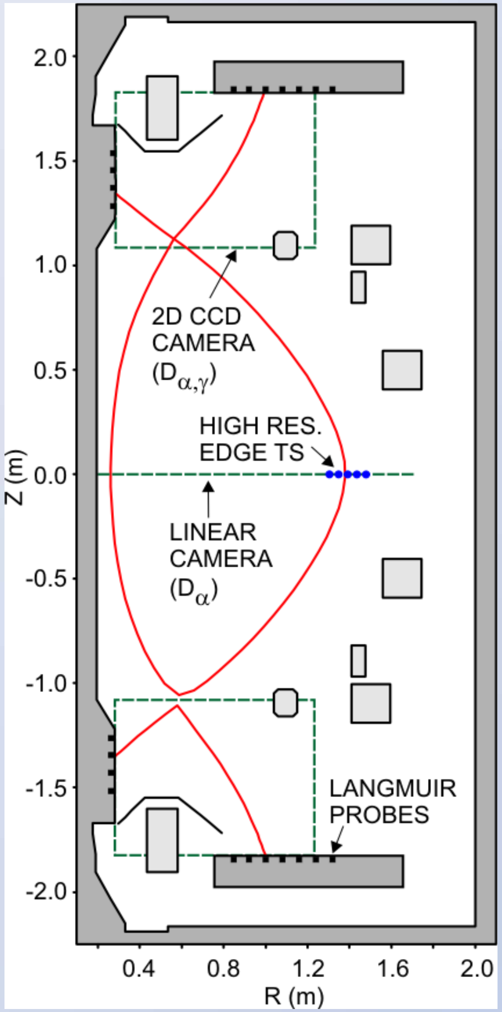
How to select M "fast" states

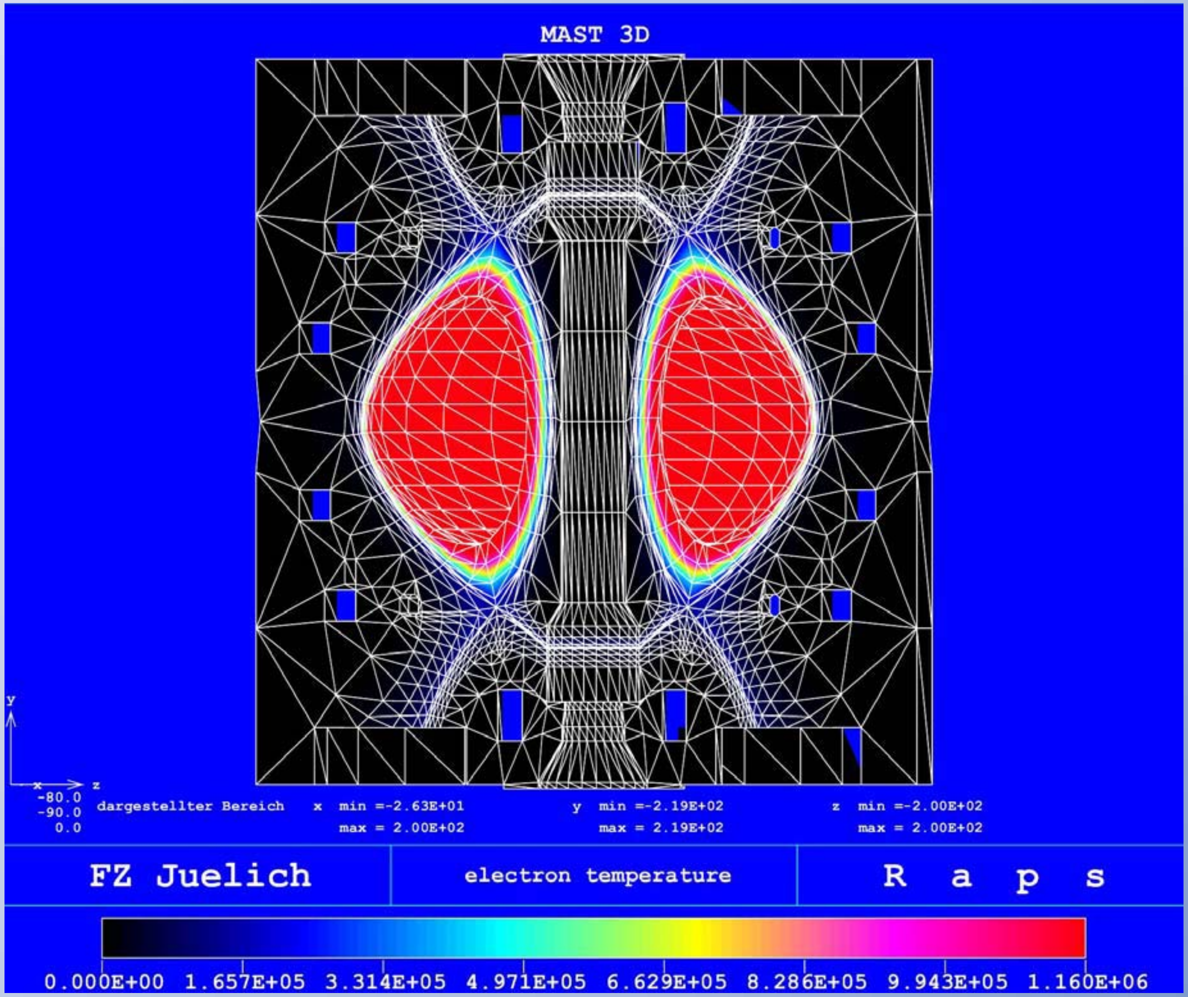
H_2: are $H_2(v)$ "metastable" or QSS species
In C_xH_y brake-up: which are QSS?

A sound mathematical procedure
(from combustion and flame science):
The Intrinsic Low Dimension Manifold (ILDM) technique.
(but: very cumbersome to implement in transport codes)
Based on spectral analysis of reaction system.

See :
Dauwe, Tytgadt, Reiter: "Automatic reduction of the hydrocarbon reaction
Mechanisms in fusion edge plasmas, JUEL-4299, Nov. 2006, ISSN 0944-2952
and: www.eirene.de/recentreports

Example: MAST (UK)

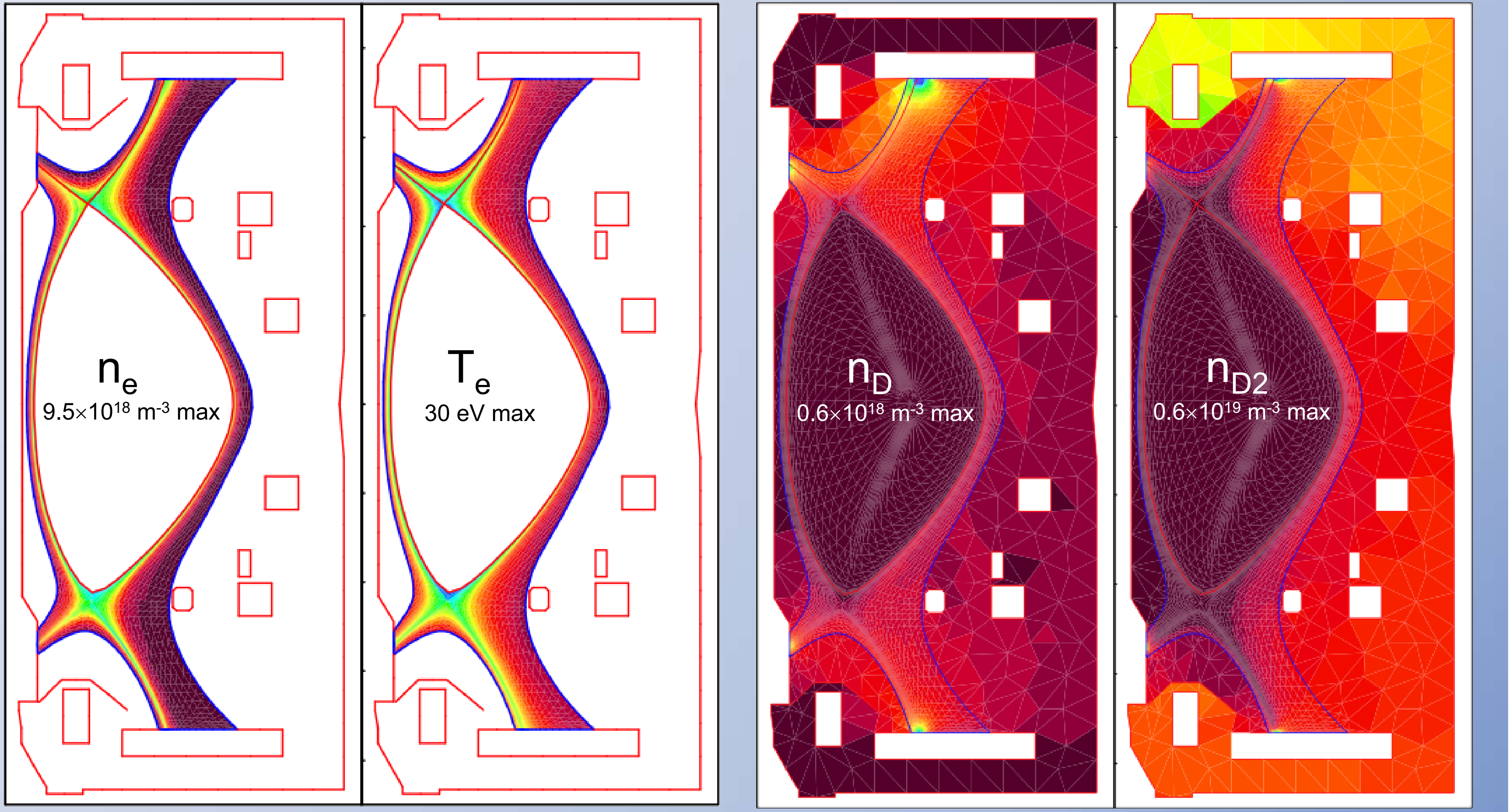




Plasma temperature in K

Courtesy: S. Lisgo

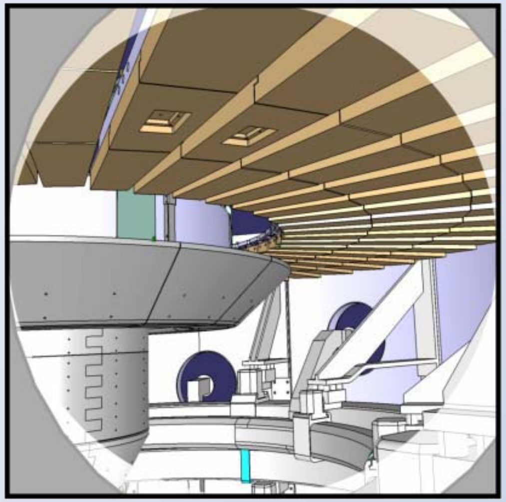
Consistent Plasma-Gas-Radiation fields in MAST edge

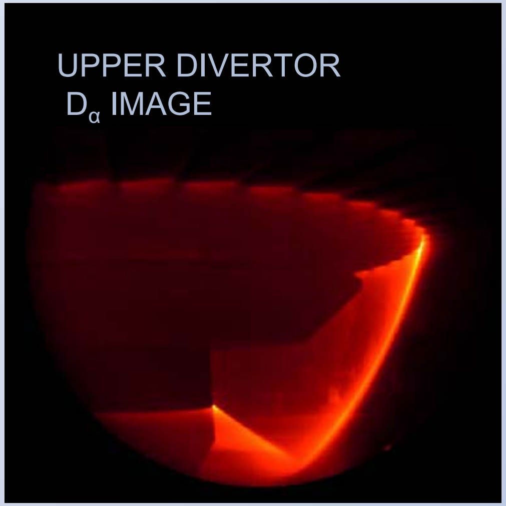


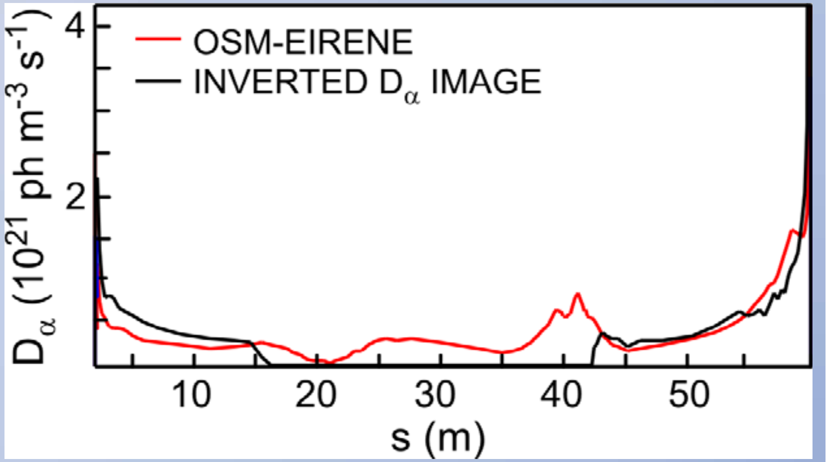
Plasma flow (experiment + OSM Modelling)

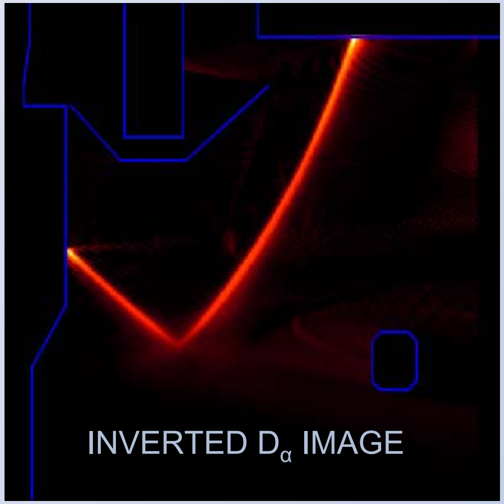
Gas flow (atomic and molecular) EIRENE

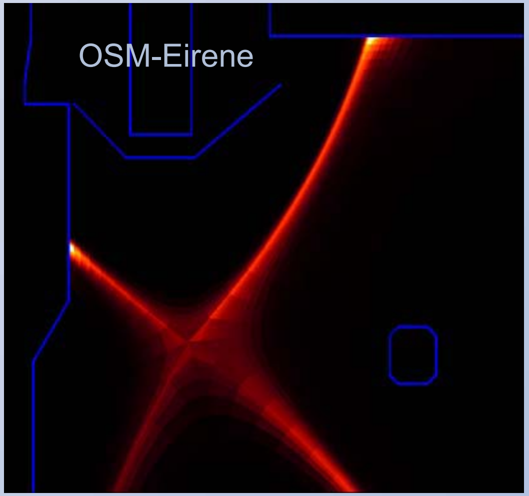
Courtesy: S.Lisgo et al., MAST Team, EPS 2007

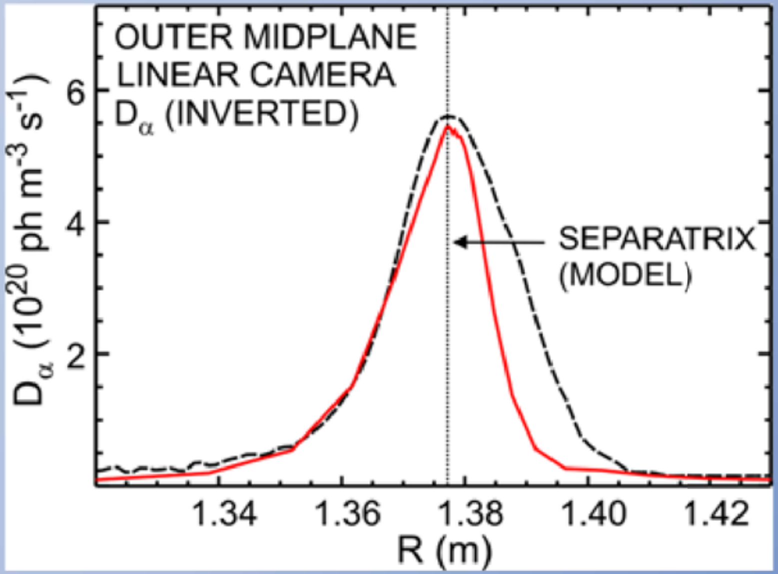








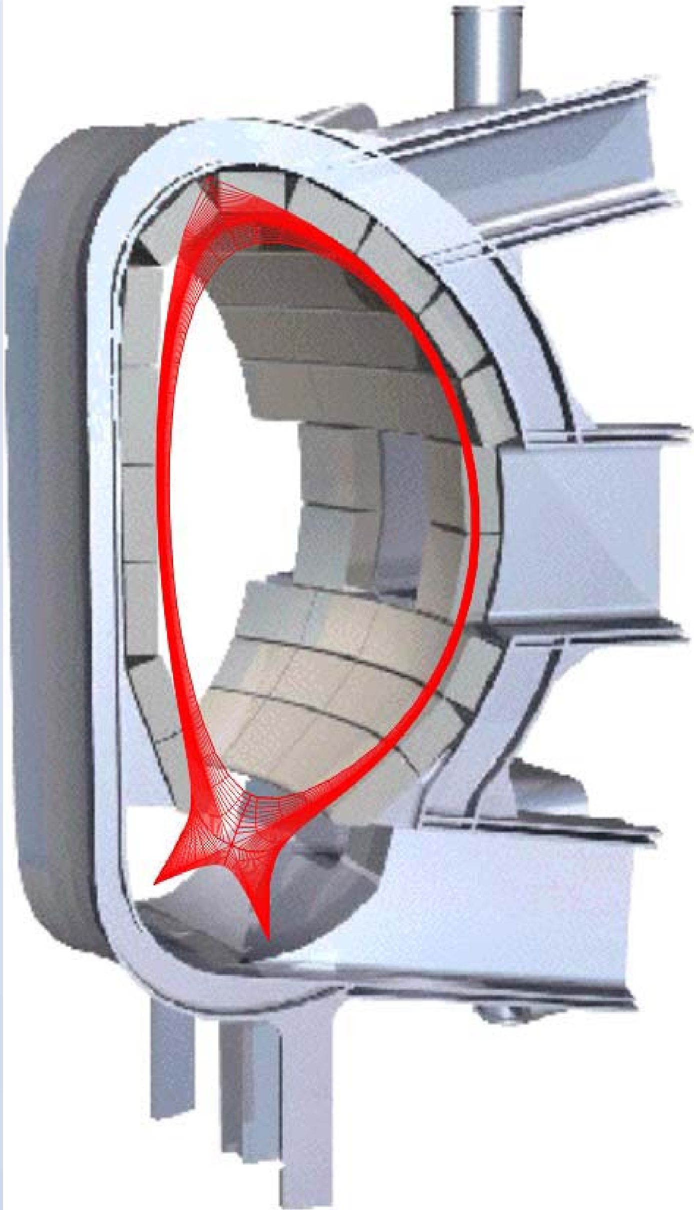


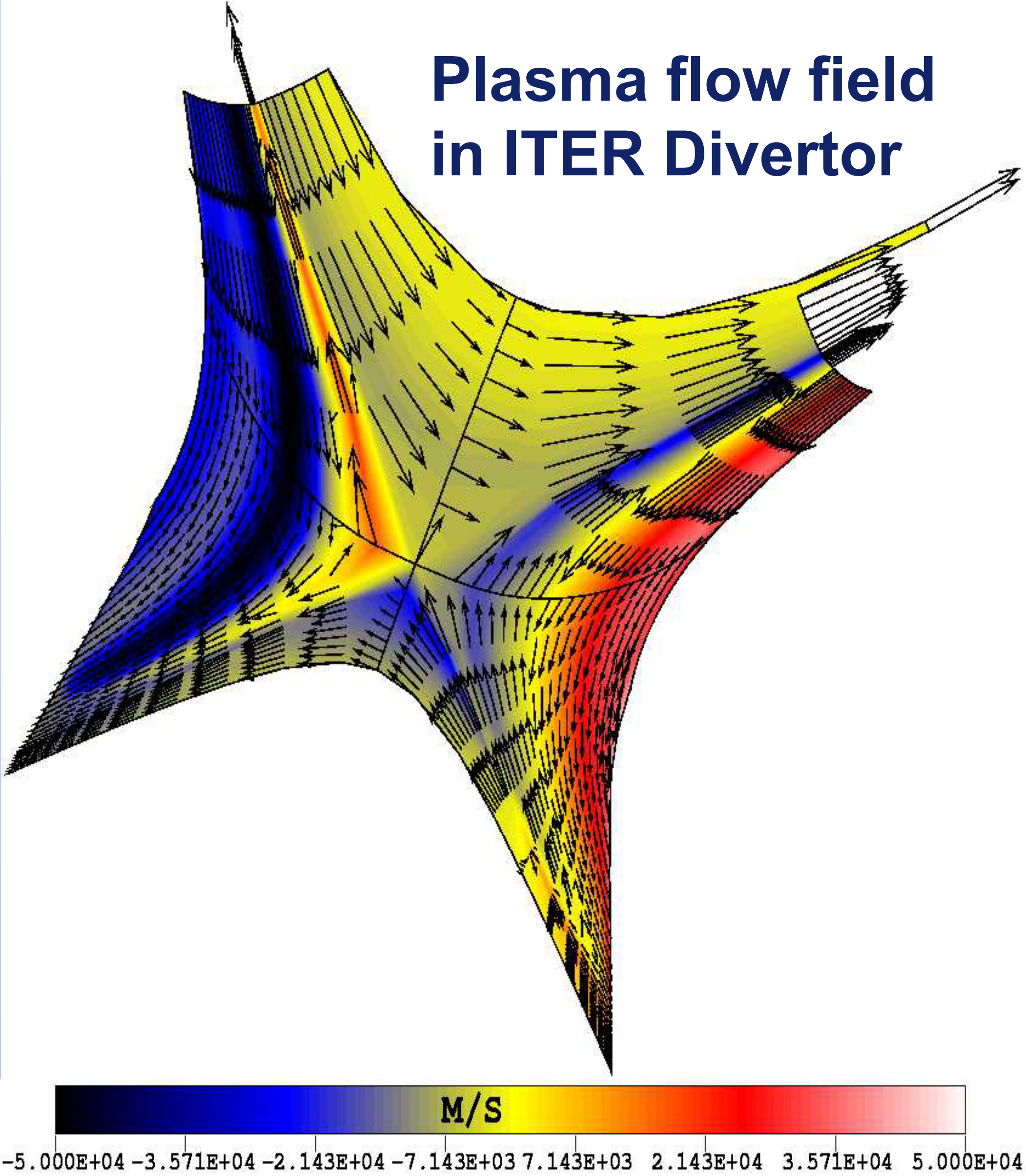


Spectroscopy → OSM transport modelling → CR plasma chemistry modelling→
→ Quantitative comparison → experimental validation of tokamak edge chemistry

Courtesy: S.Lisgo et al., MAST Team, EPS 2007

Transport-Simulations for ITER



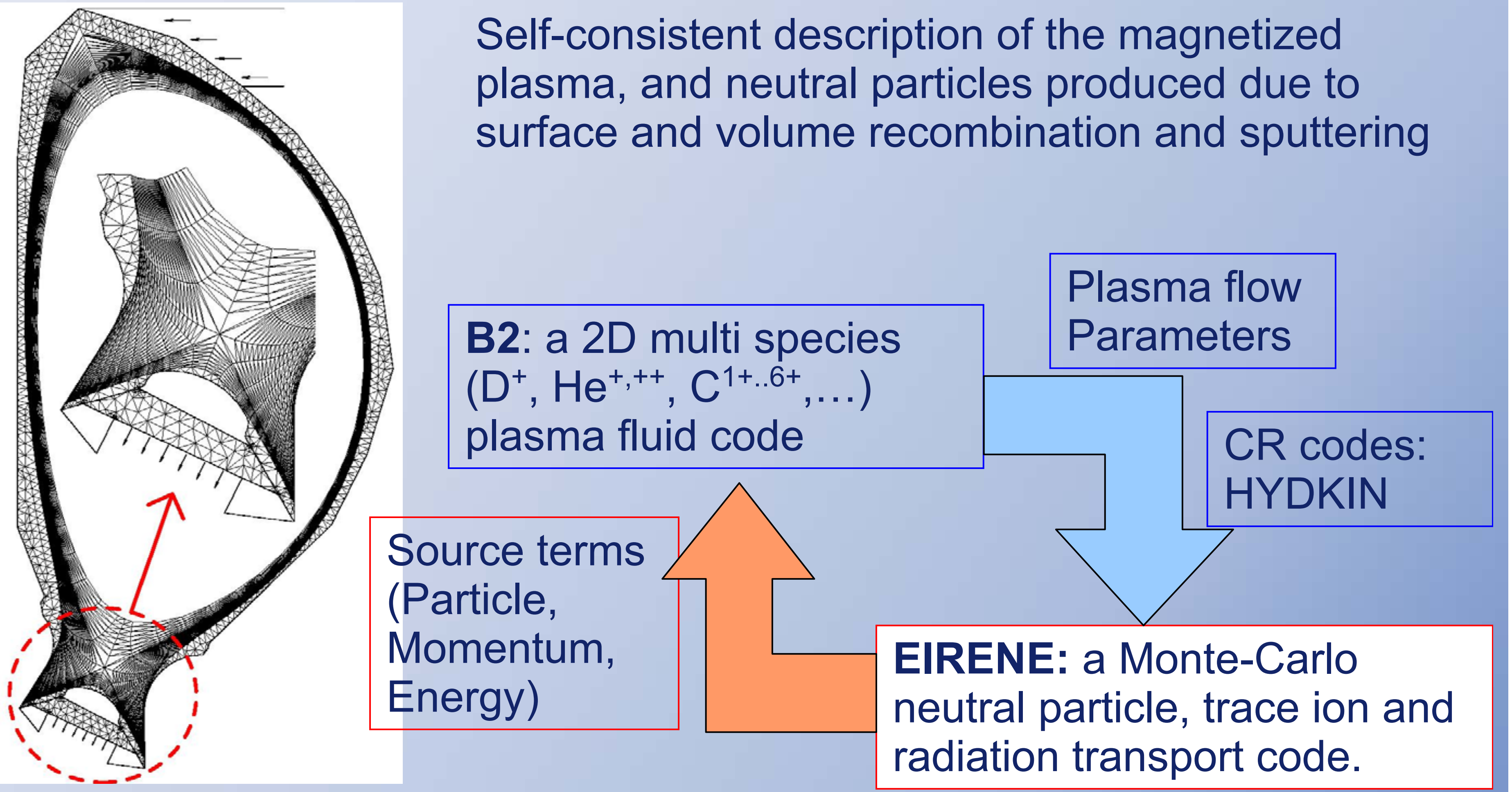


Plasma flow field in ITER Divertor

Numerical tool for the edge plasma science: B2-EIRENE code package (FZJ-ITER)

Reiter, D., et al., Fusion Science and Technology **47** (2005) 172.

Self-consistent description of the magnetized plasma, and neutral particles produced due to surface and volume recombination and sputtering



B2: a 2D multi species (D^+, $He^{+,++}$, $C^{1+..6+}$,…) plasma fluid code

Plasma flow Parameters

CR codes: HYDKIN

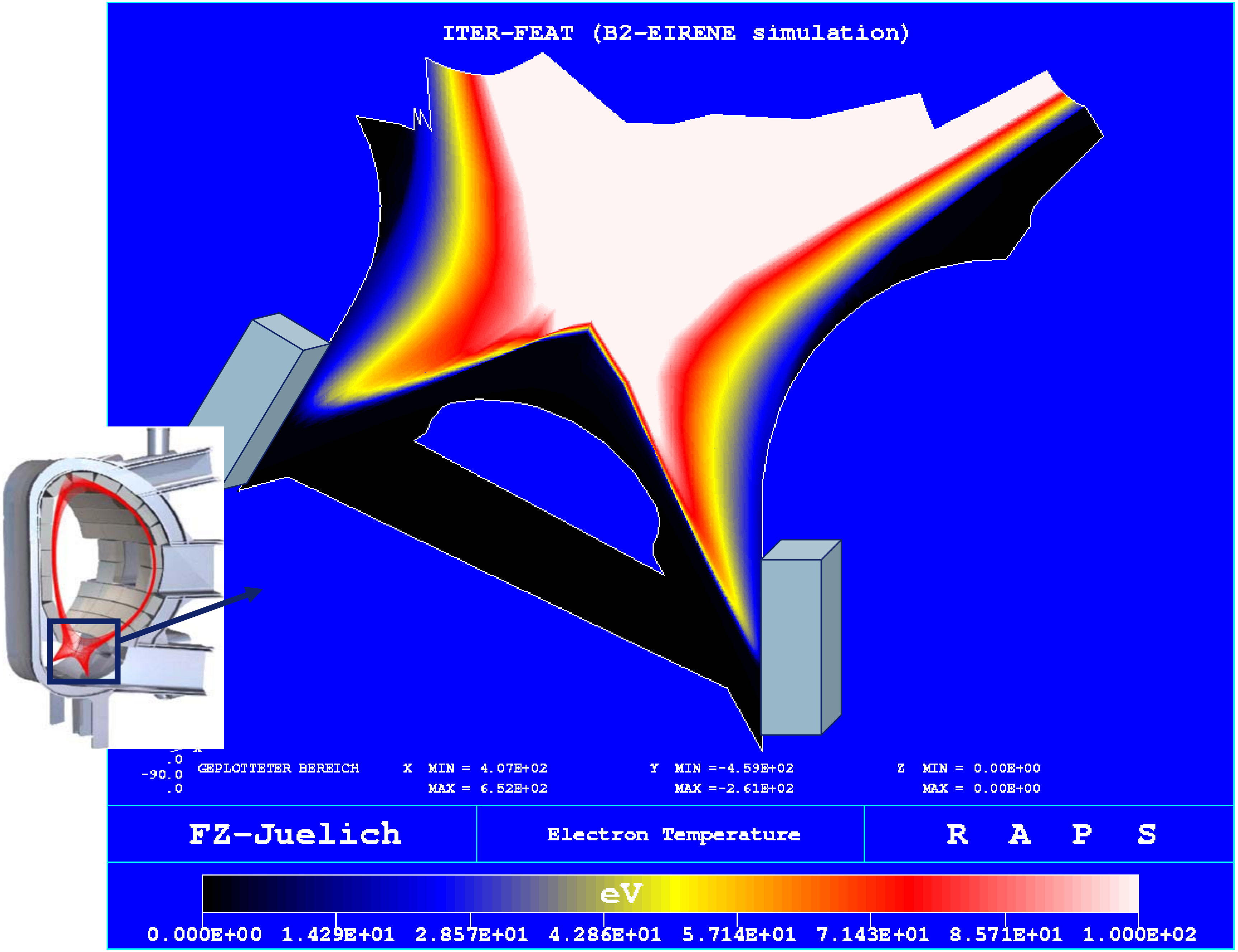
EIRENE: a Monte-Carlo neutral particle, trace ion and radiation transport code.

Source terms (Particle, Momentum, Energy)

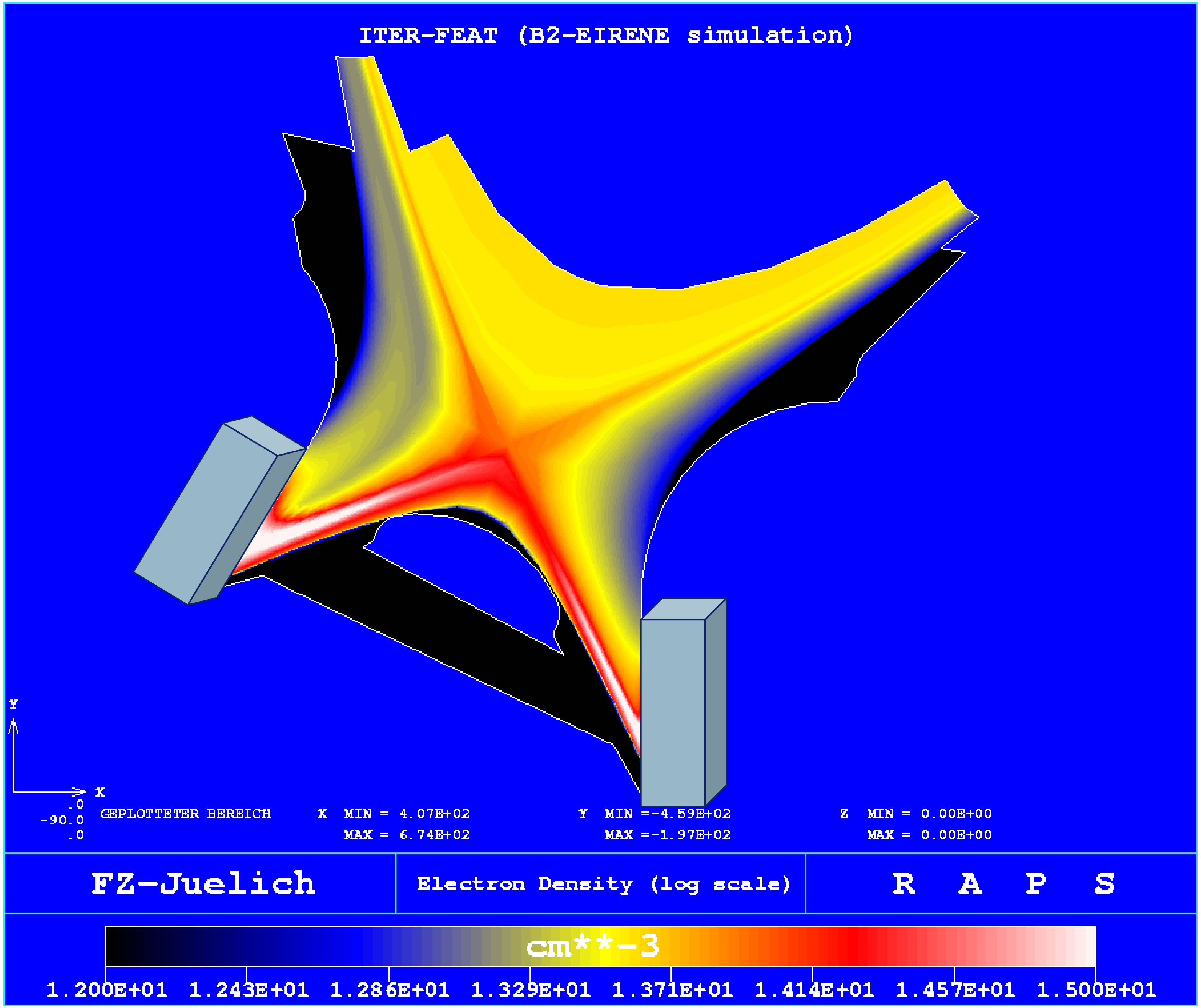
Computational Grid

see www.eirene.de

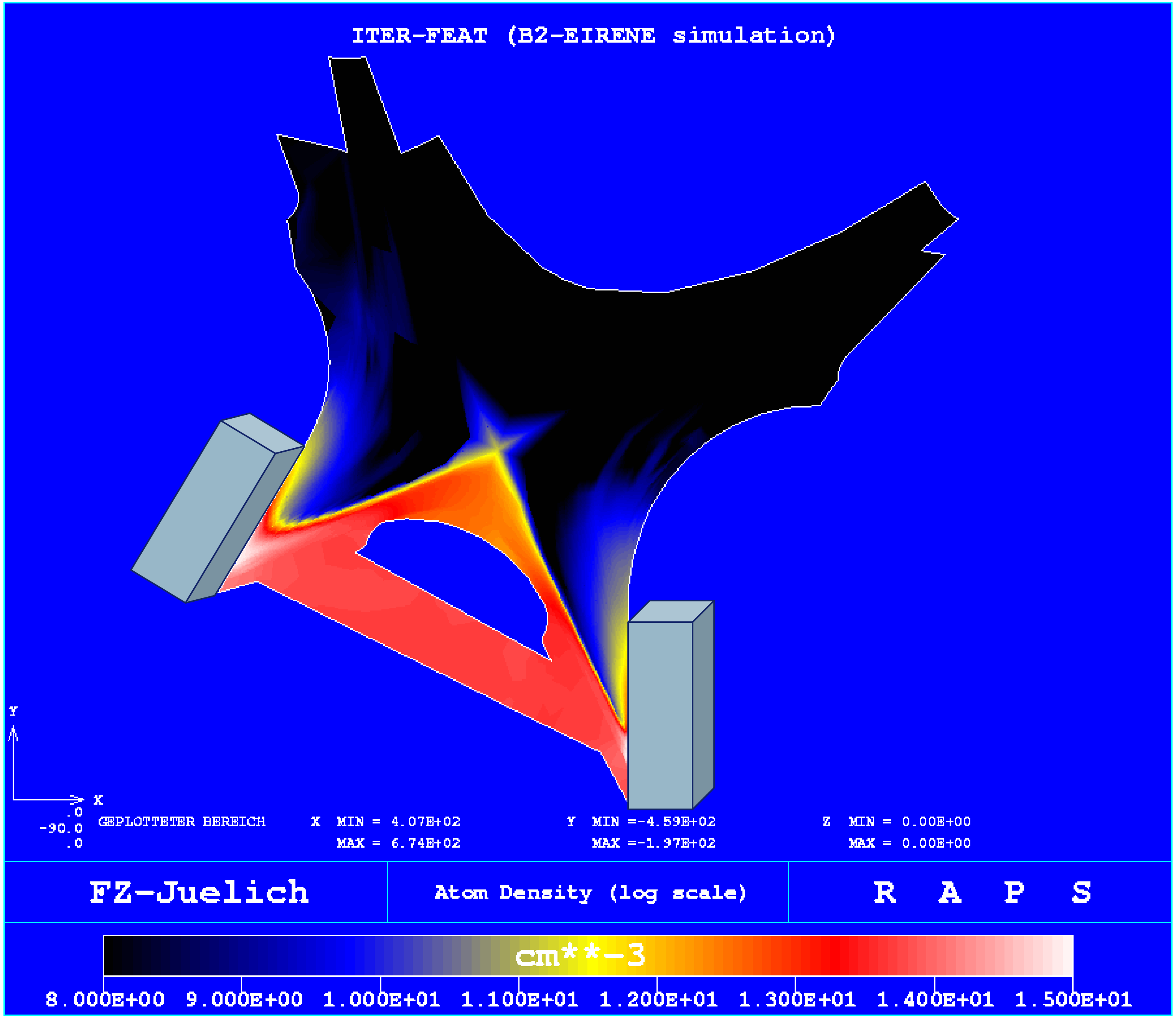
ITER, B2-EIRENE simulation, fully detached, T_e field



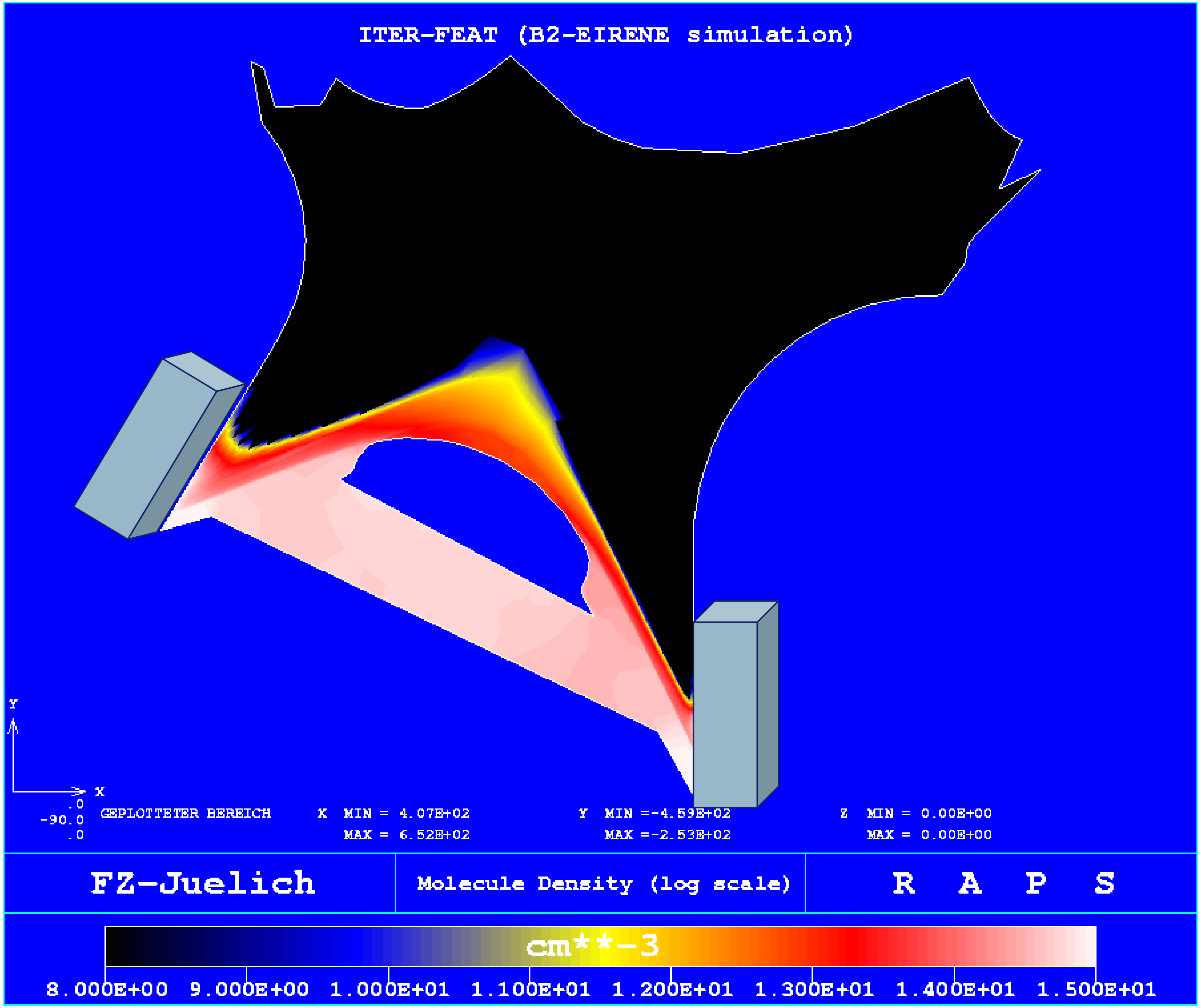
ITER, B2-EIRENE simulation, detached, n_e field



ITER, B2-EIRENE simulation, detached, n_A field

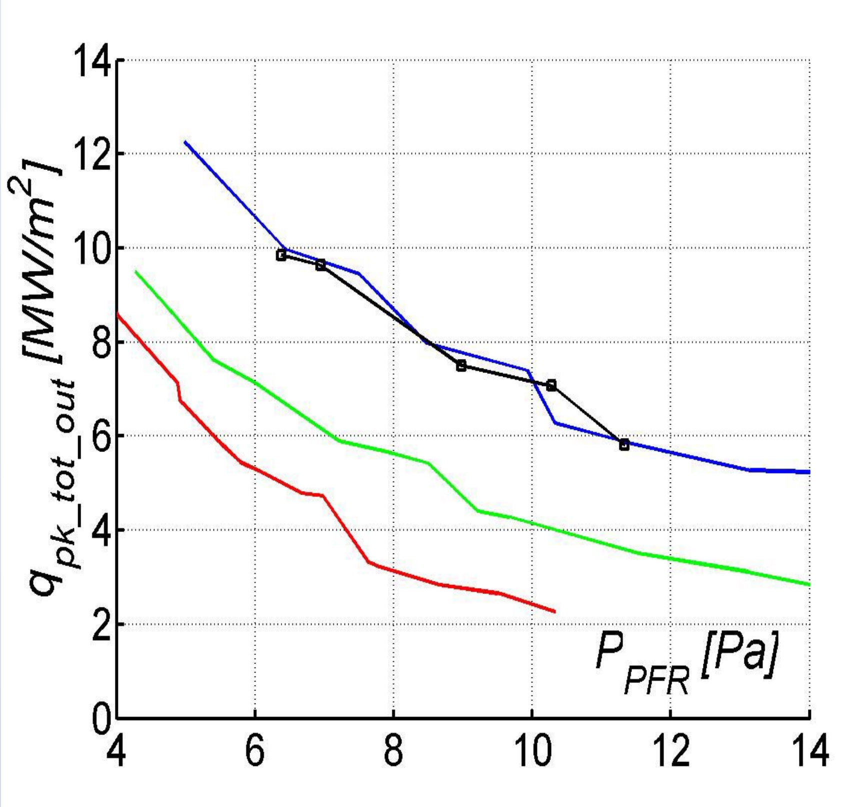


ITER, B2-EIRENE simulation, detached, n_{H2} field



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

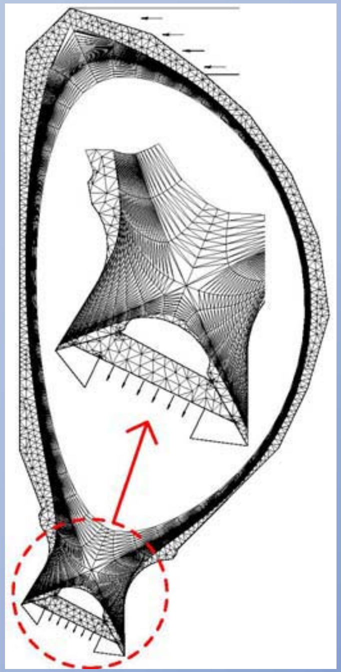


— **1996**
(ITER physics basis1999)

— **2003, neutral - neutral collisions**

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

— **2005, + photon opacity**



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

ITER design review 2007-2008:
“Dome“ re-design now considered

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

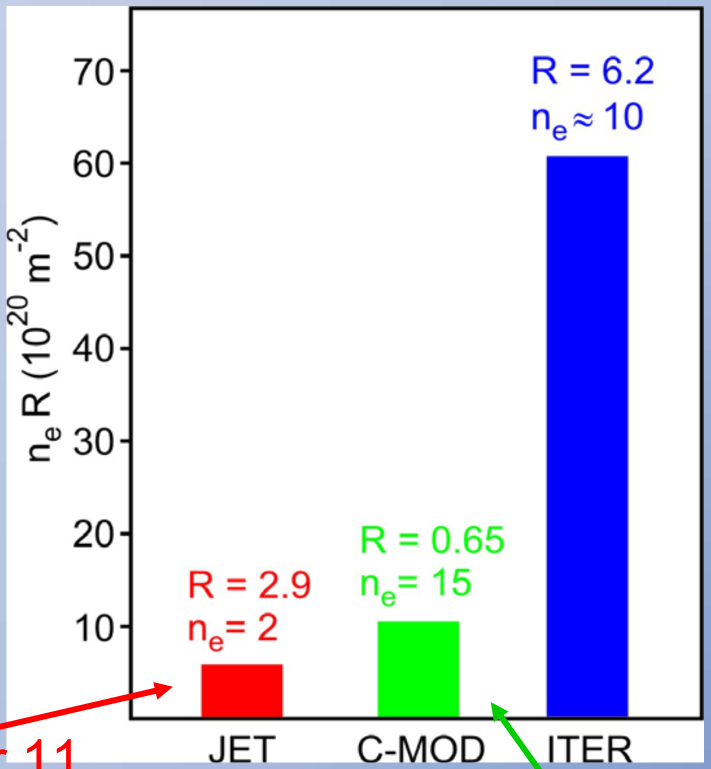
- gas-plasma friction,
- recombining plasmas,
- plasma cooling (radiation)

Current hypothesis: in the “detached state” is the divertor dynamics and chemistry is controlled by “Collisionality”

(inv. Knudsen number)

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

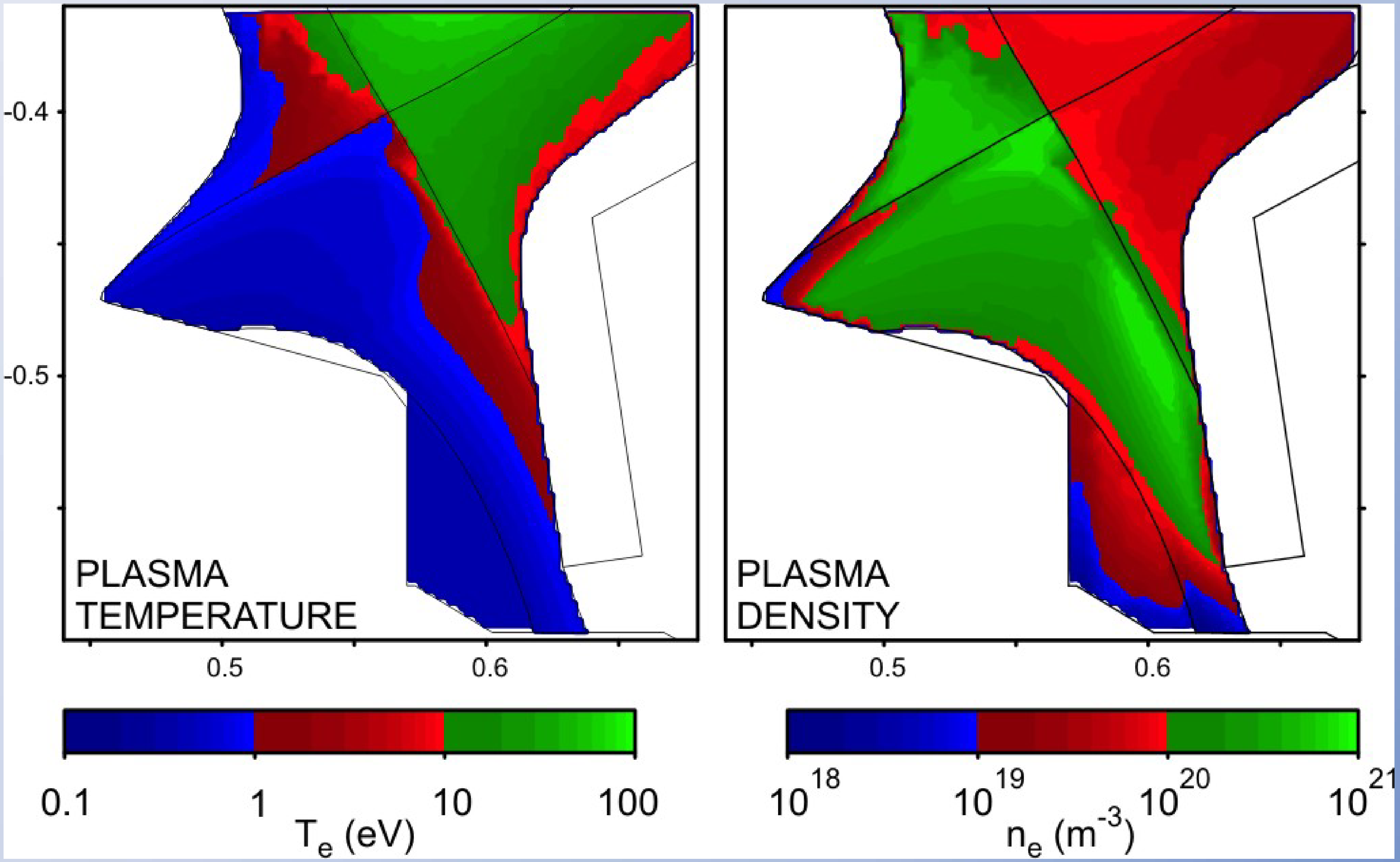
Alcator C-Mod (MIT)
10 times smaller than ITER
similar shape
higher density

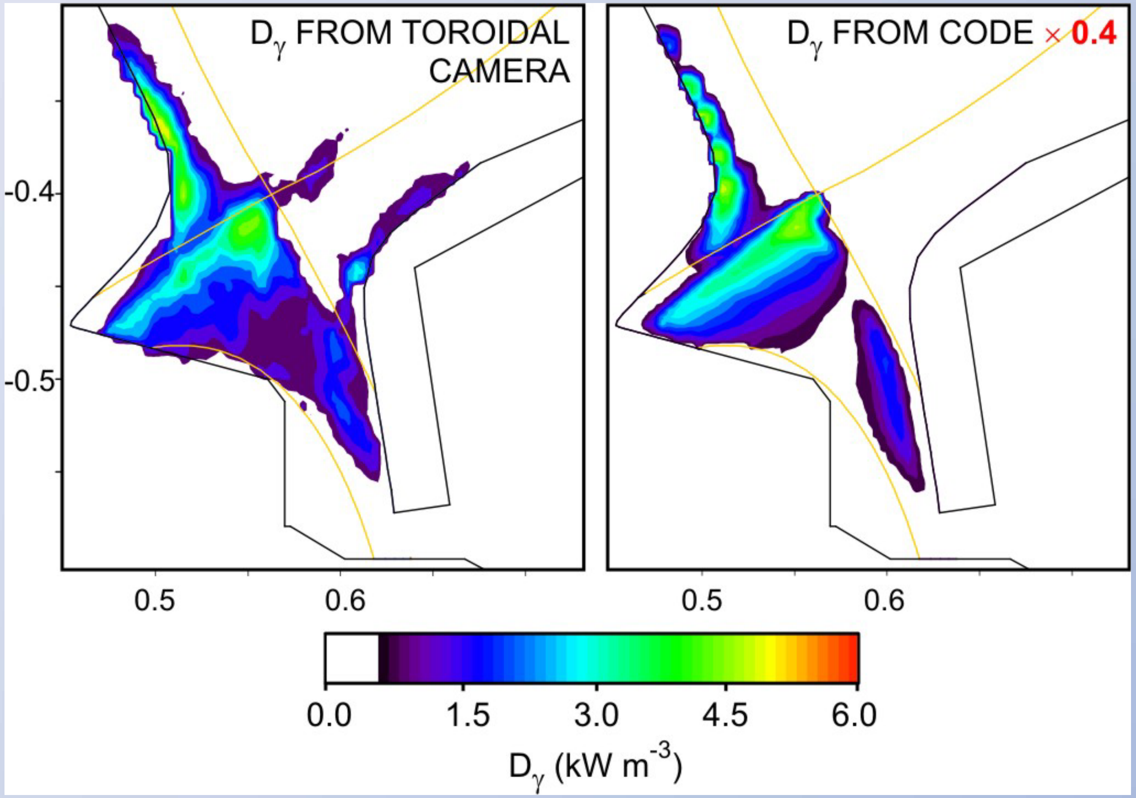


Factor 11 away

Factor 6 away

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)





D_γ (from D, D_2, D^+,D_2^+):

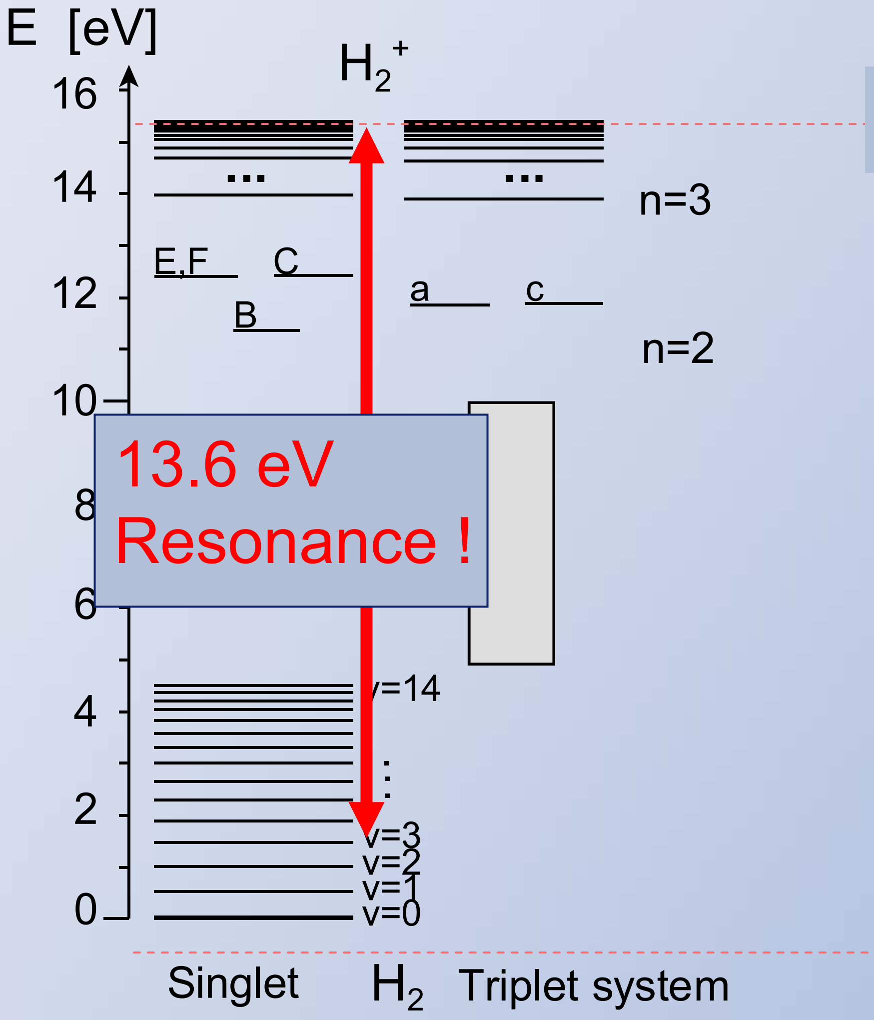
Profile matched, but high by factor 2

Calibration? Atomic Data? Plasma reconstruction?

Results very sensitive eg. to T_e profile

H_2 molecule, status in present divertor code

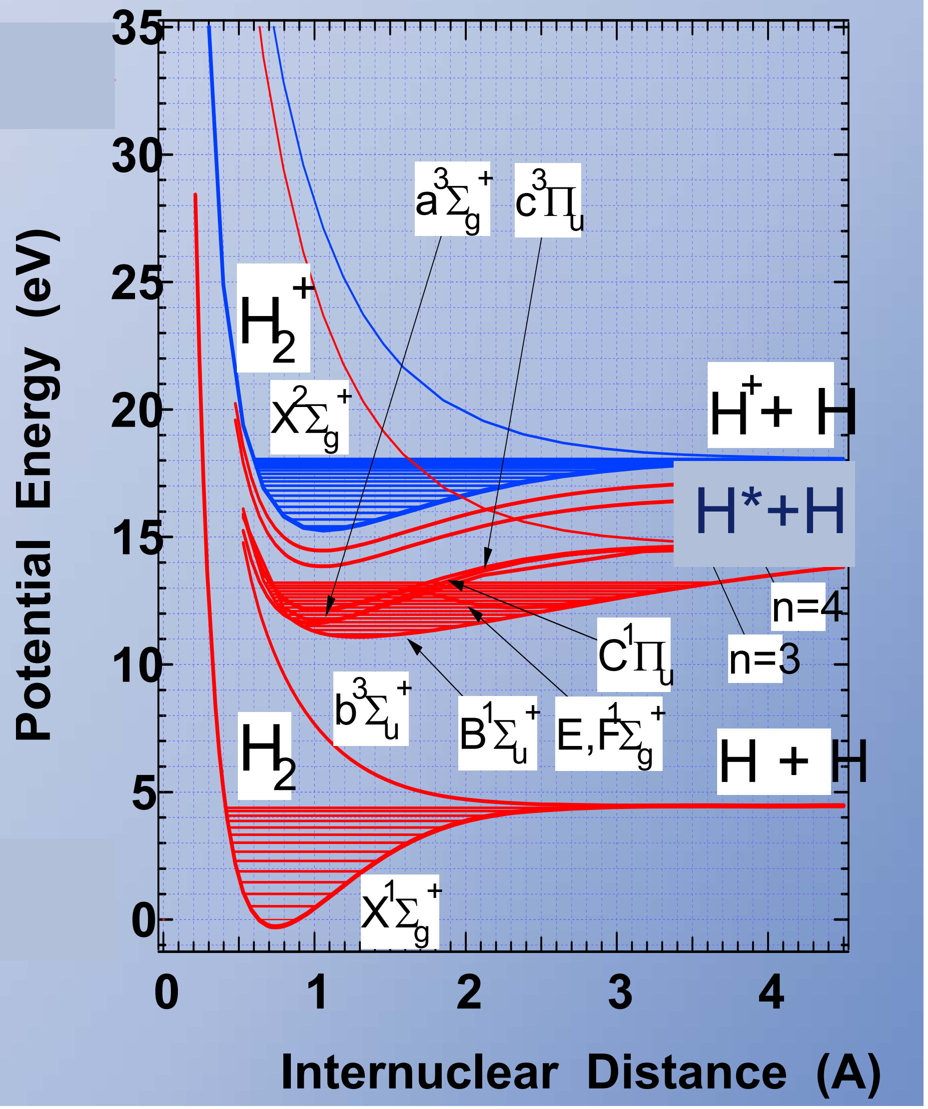
compiled 1997



13.6 eV
Resonance !

More complete models available, still need to be integrated

compiled 2005

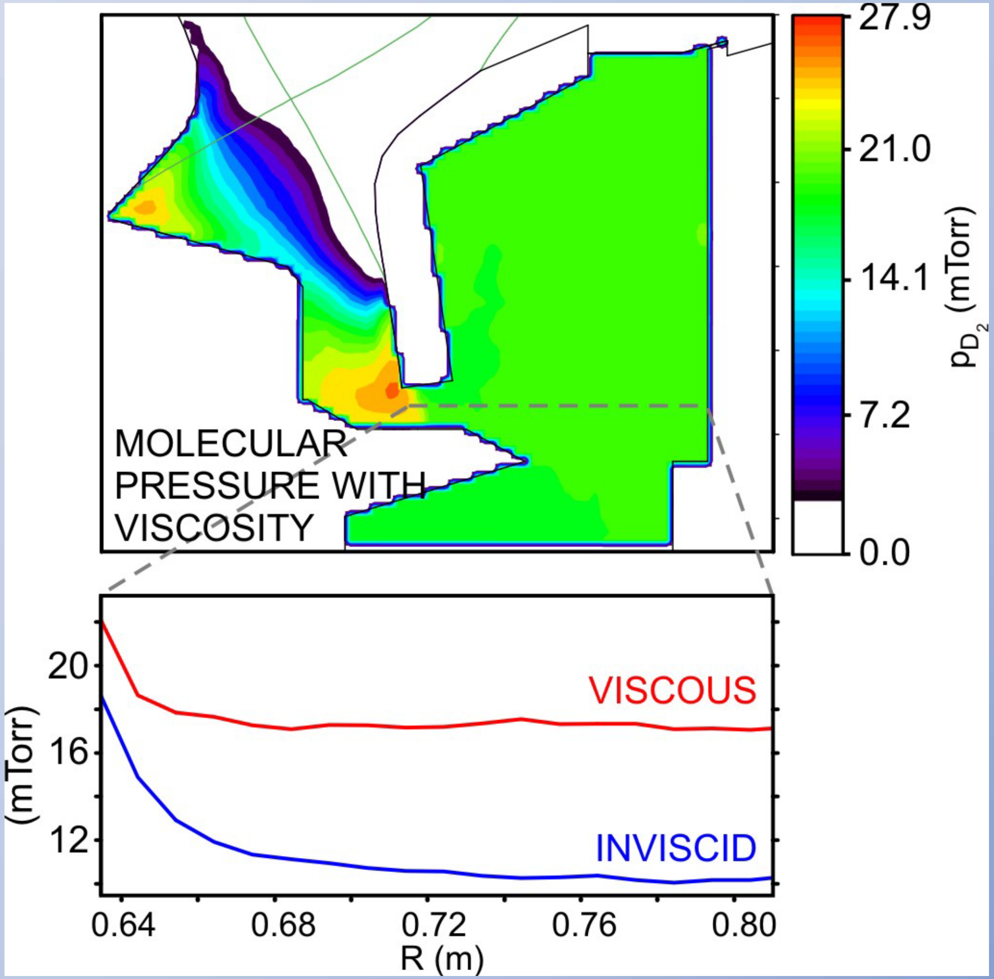


Critical for particle throughput (convection):

Neutral Plenum Pressure

Exp:	25 mTorr
Calc 2D (2000)	3 mTorr
Calc 2D (2003)	27 mTorr

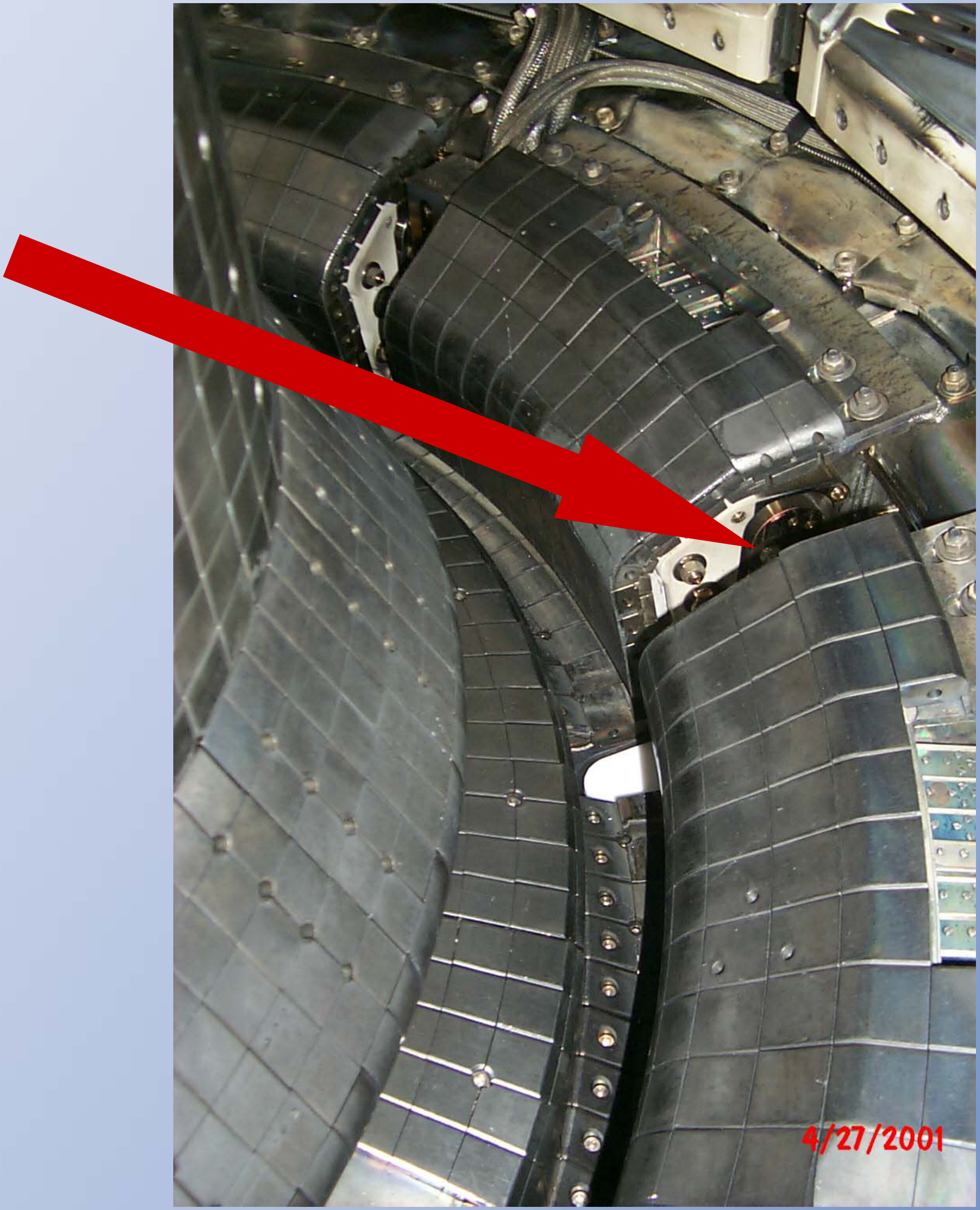
(better A&M data,
better Plasma data,
better codes)



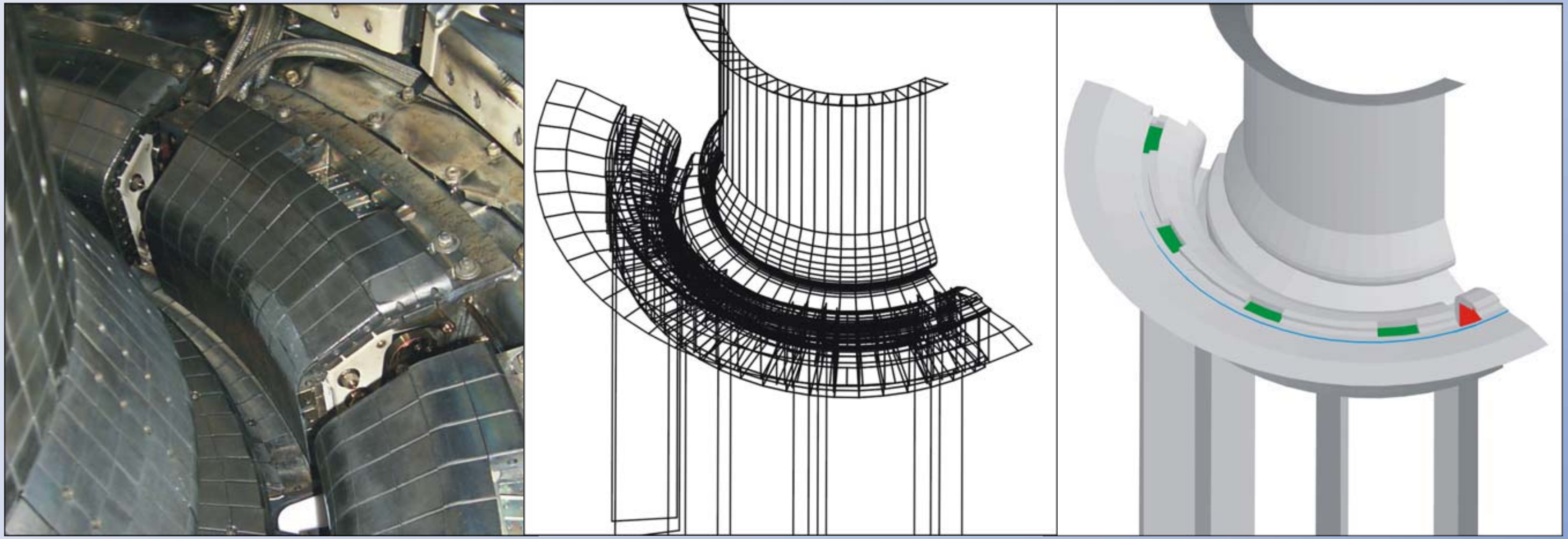
Very good match: code - experiment
But:
Is there further edge physics that we are sure must be operative?

Additional leakage pathways:

2D → 3D
(see later)



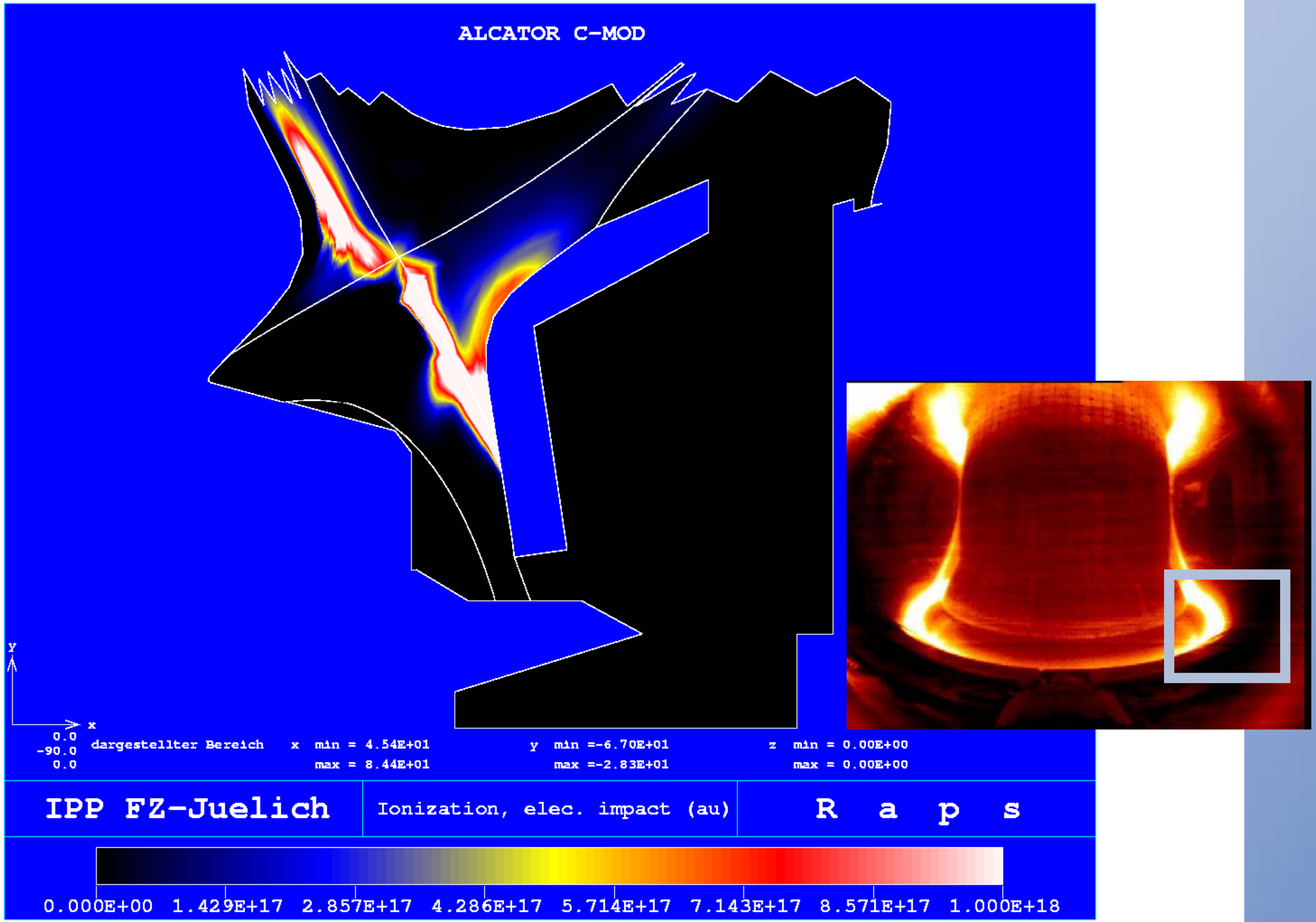
3D Neutral Gas, A&M and PSI Modelling



3D divertor structures (toroidal gap and gussets, bypass and poloidal gap)

→strong toroidal variations in the divertor neutral pressure

Ionization by electron impact on neutral gas

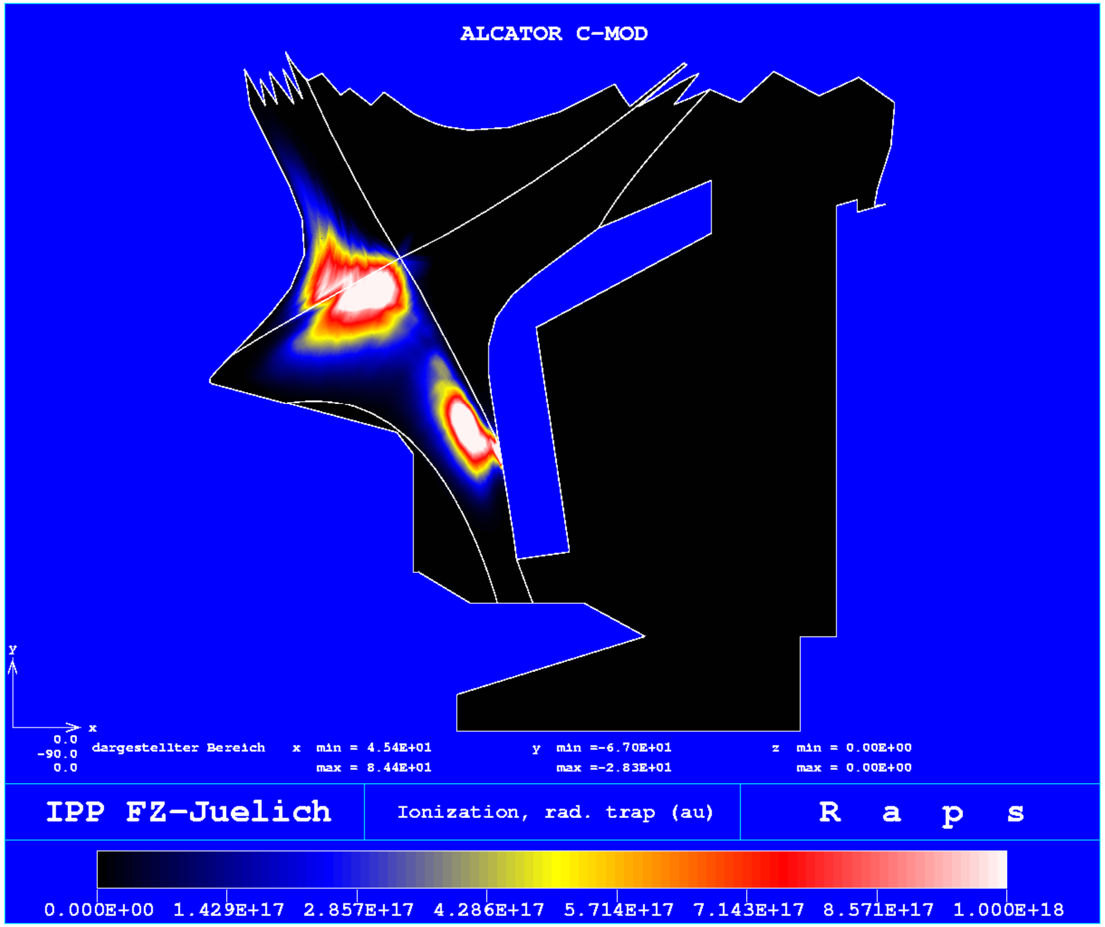


Radiation transfer: opacity of Ly-lines

(though completely elementary, has long remained unnoticed in edge modelling)

$h\nu + H(1) \rightarrow H^*$, $H^* + e \rightarrow H^+ + 2e$

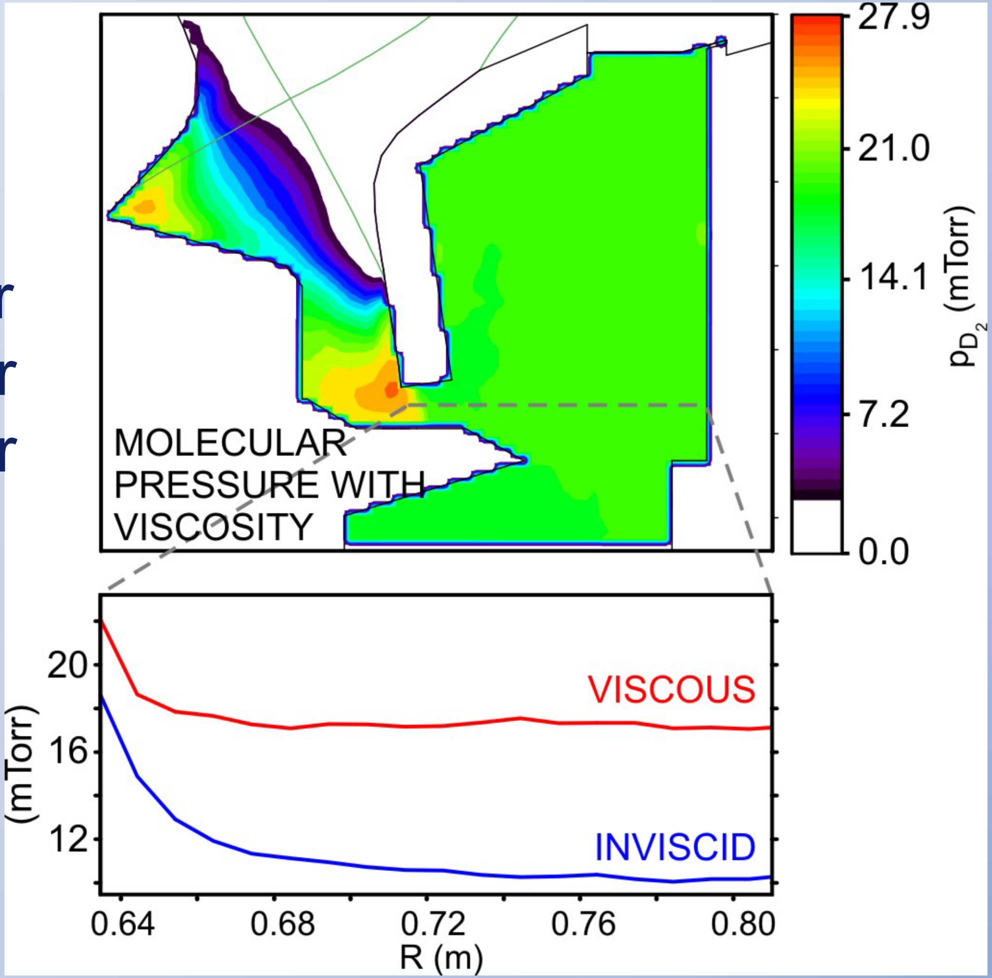
(additional path for ionization in dense, low T_e divertors)



Neutral Pressure

Exp: 25 mTorr
Calc 2D (2000) 3 mTorr
Calc 2D (2003) 27 mTorr
(better A&M data,
better Plasma data)

However
Ly-opacity: 17 mTorr
3D: 11 mTorr

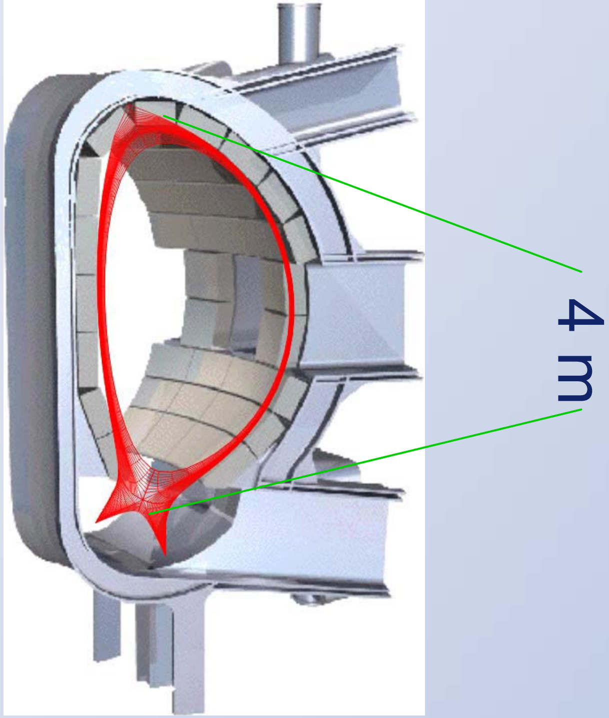


Model validation in the presence of many free parameters:

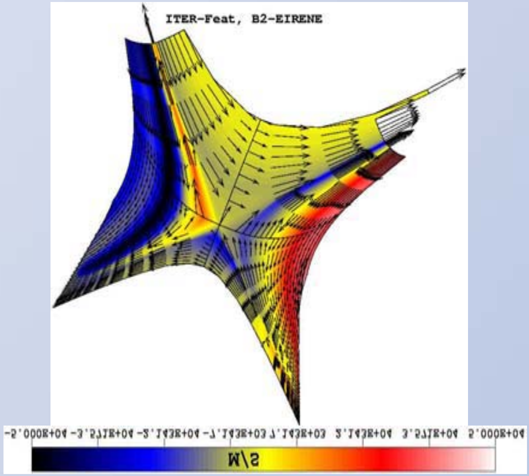
include ALL edge physics that we are sure must be operative
even while our capability to confirm these directly remains limited

Radiation transfer module: verification and validation using HID lamps

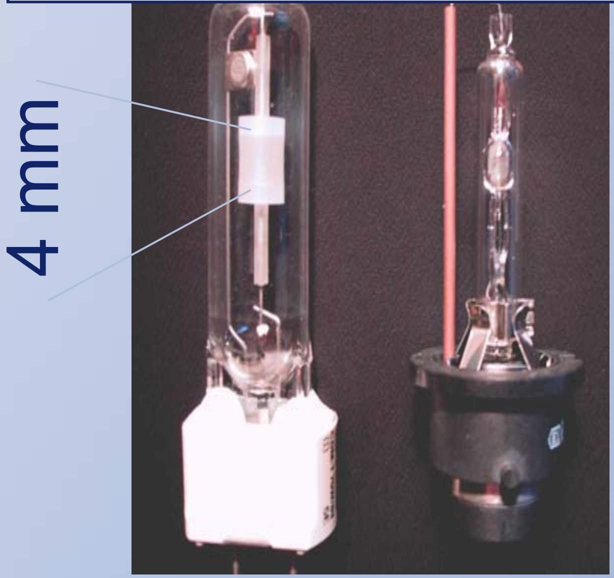
ITER



B2-EIRENE



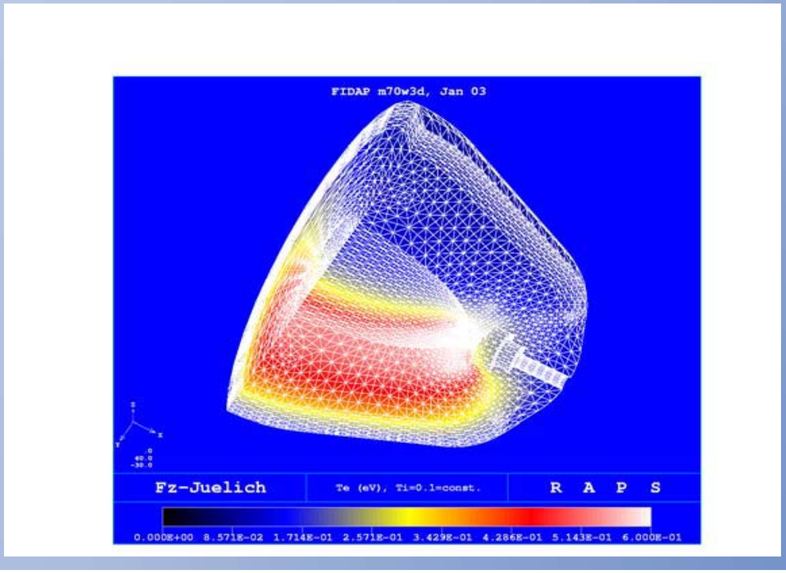
High Intensity Discharge Lamps



D2-36 W
Automotive
Material:Quartz

CDM-75 W
Shop-Lighting
Material:PCA

FIDAP-EIRENE



2D → 3D

- Extending edge models towards predictive quality is a theoretical and experimental task

- Going from 2D CFD to 3D CFD is a computational physics task

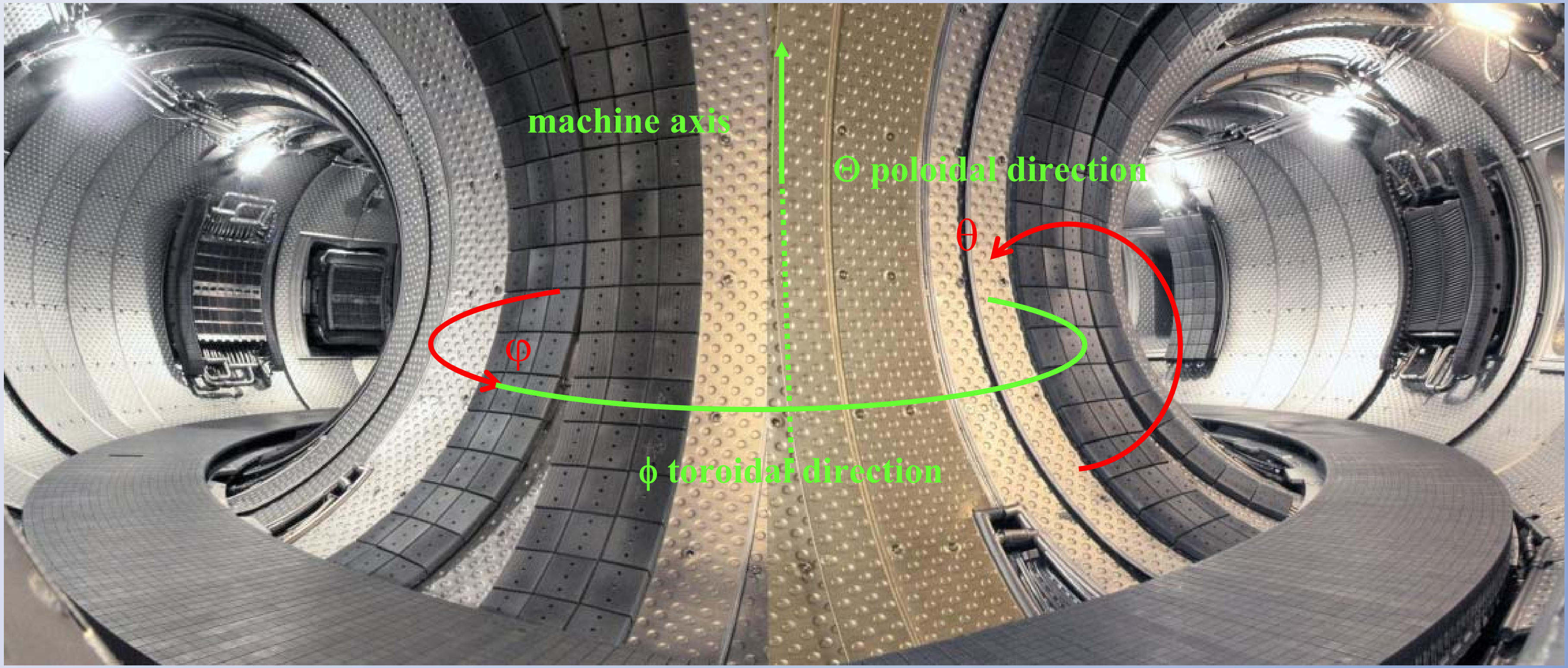
0 3D recycling, reaction-diffusion problems: in hand

1: smooth particle hydrodynamics+ random walks (ITER, W7X, LHD)

2 Edge ergodization (TEXTOR-DED, DIIID: C-Coils, ELM-mitigation)

Tore Supra

Interior view of Tore Supra

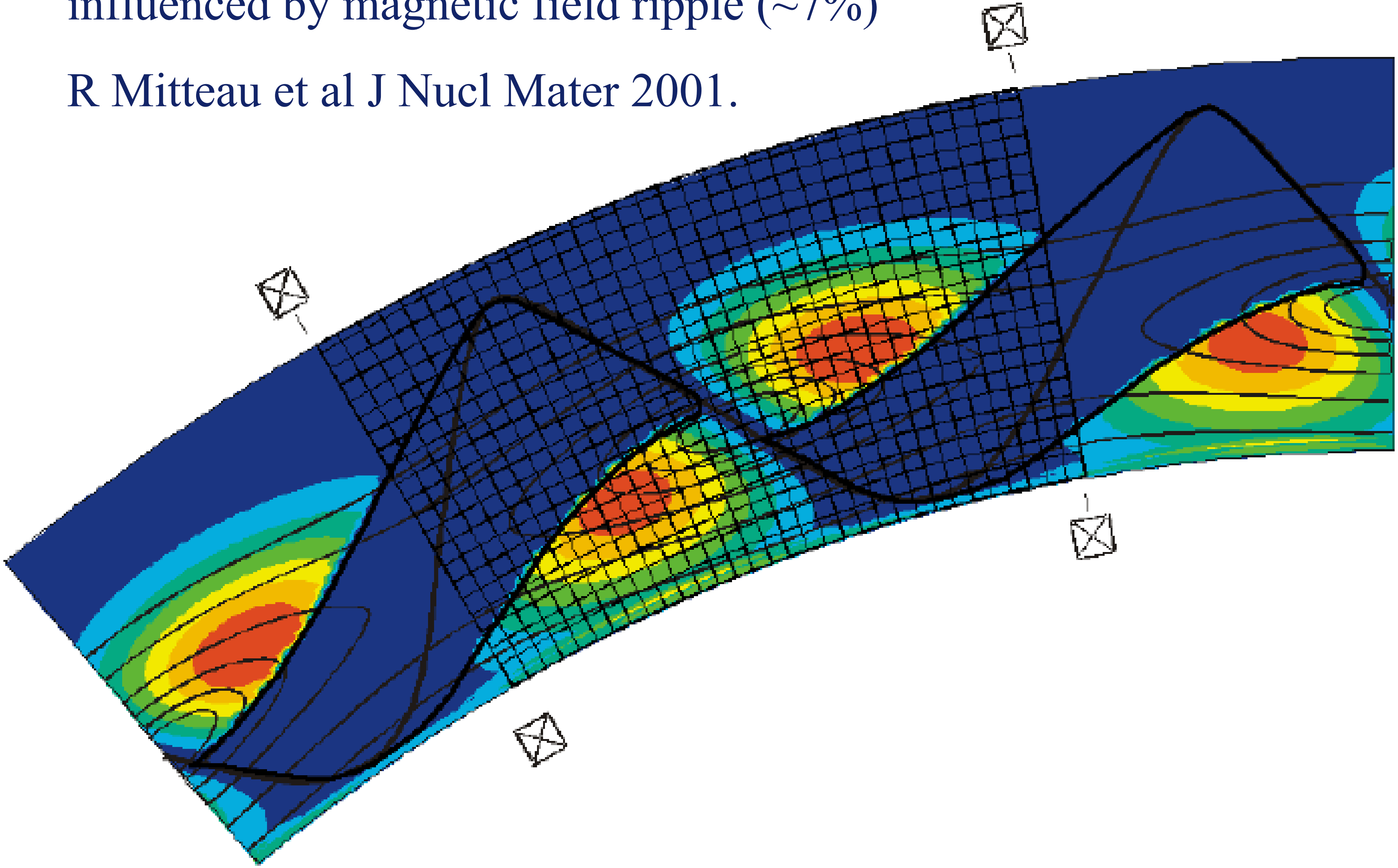


Full toroidal limiter CIEL

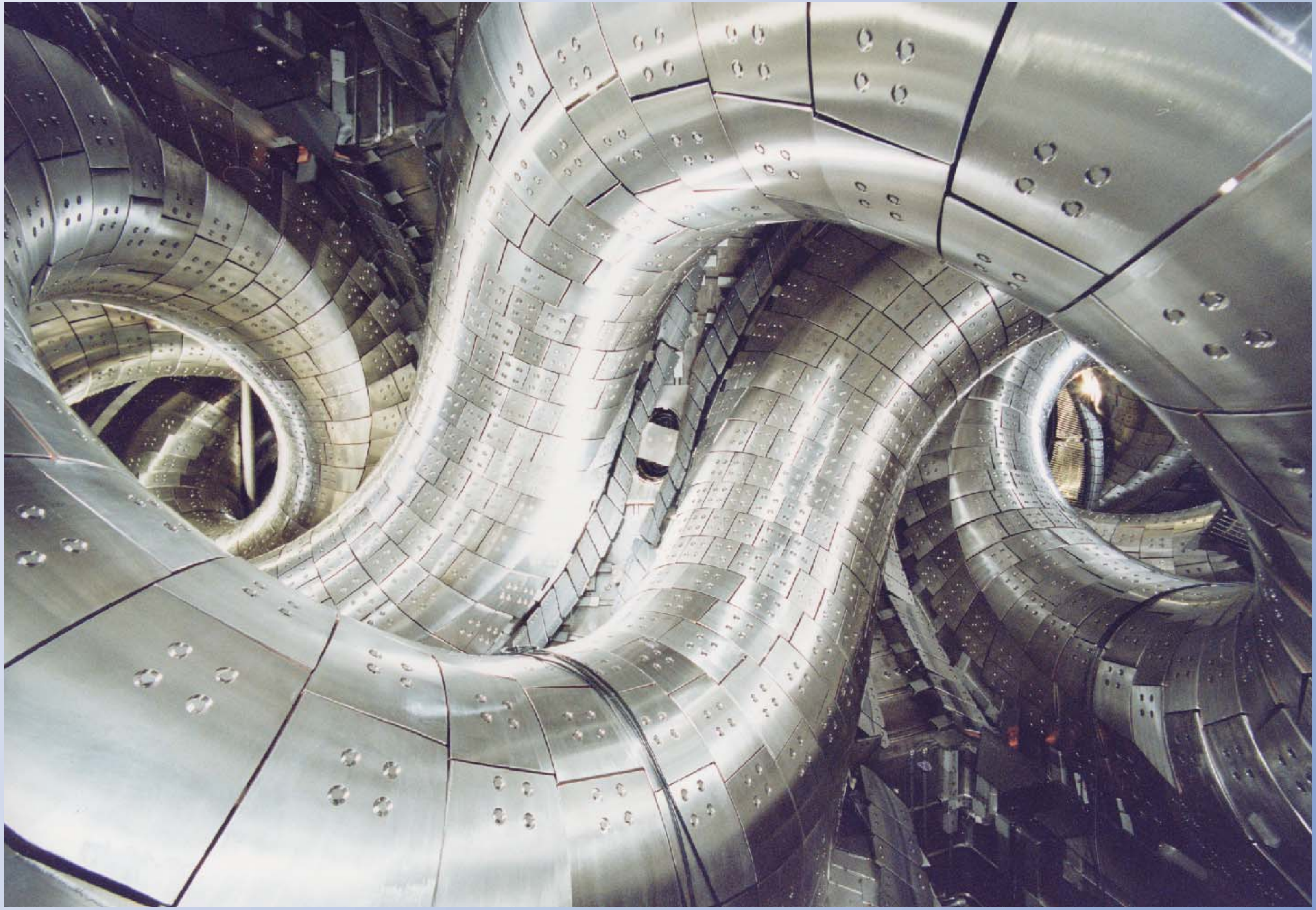
dépôt de flux LPT avec **TOKAFLU/OMBRAGE**

Tore Supra heat, particle flux deposition is strongly influenced by magnetic field ripple (~7%)

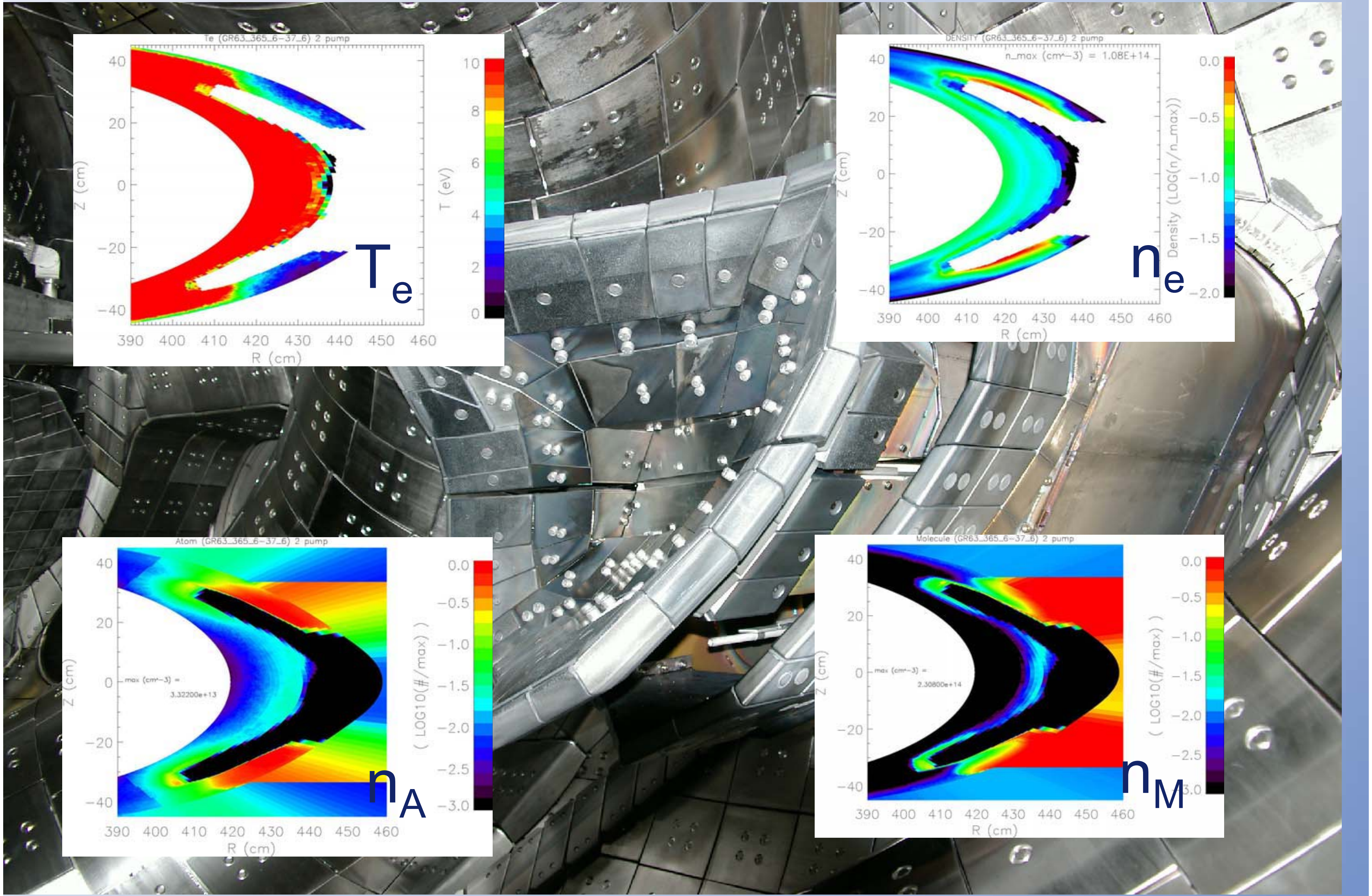
R Mitteau et al J Nucl Mater 2001.



Large Helical Device (LHD), Toki, Japan

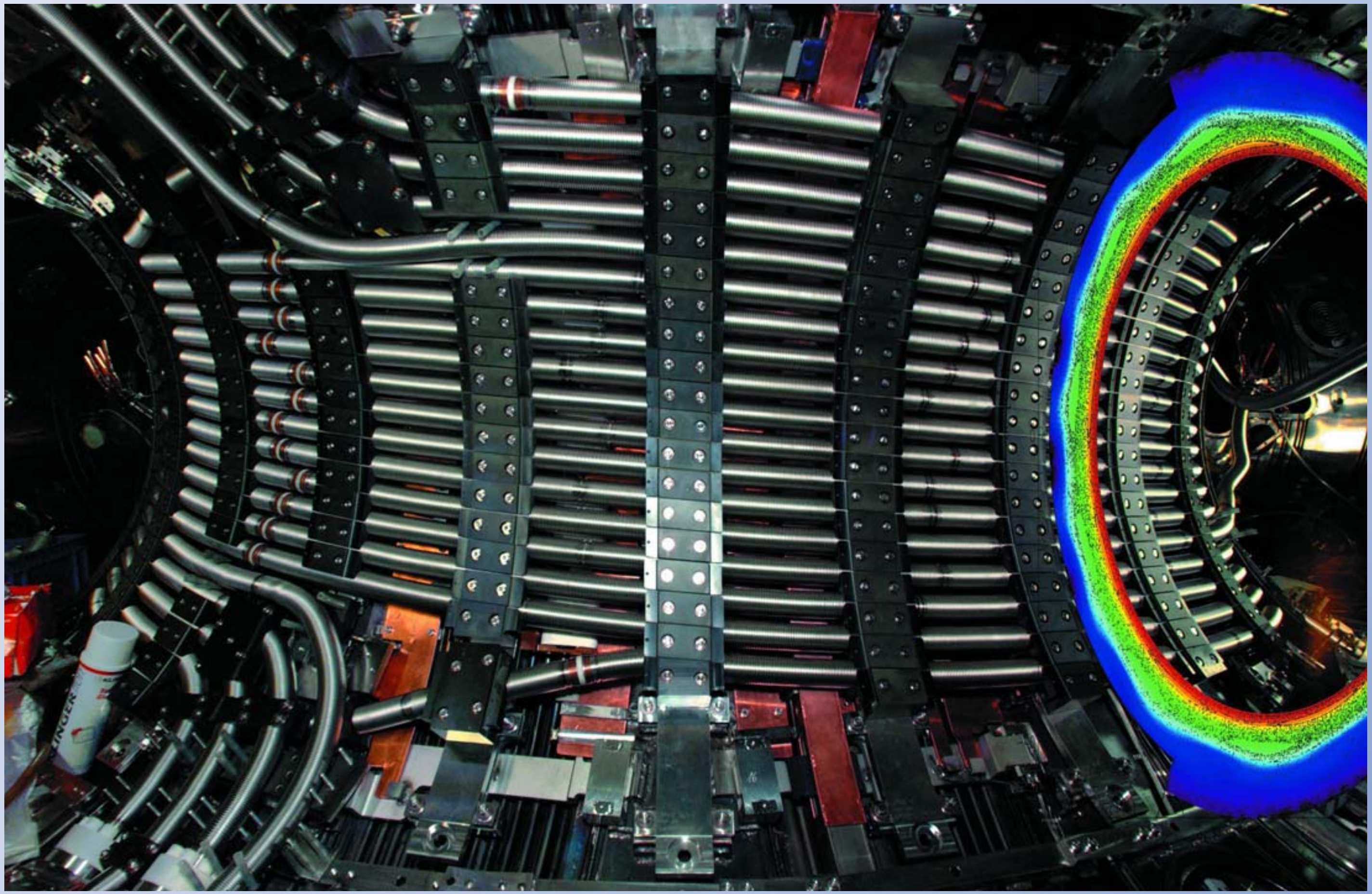


3D LHD Plasma Edge Simulation (Kobayashi, Reiter, Feng, 2005)

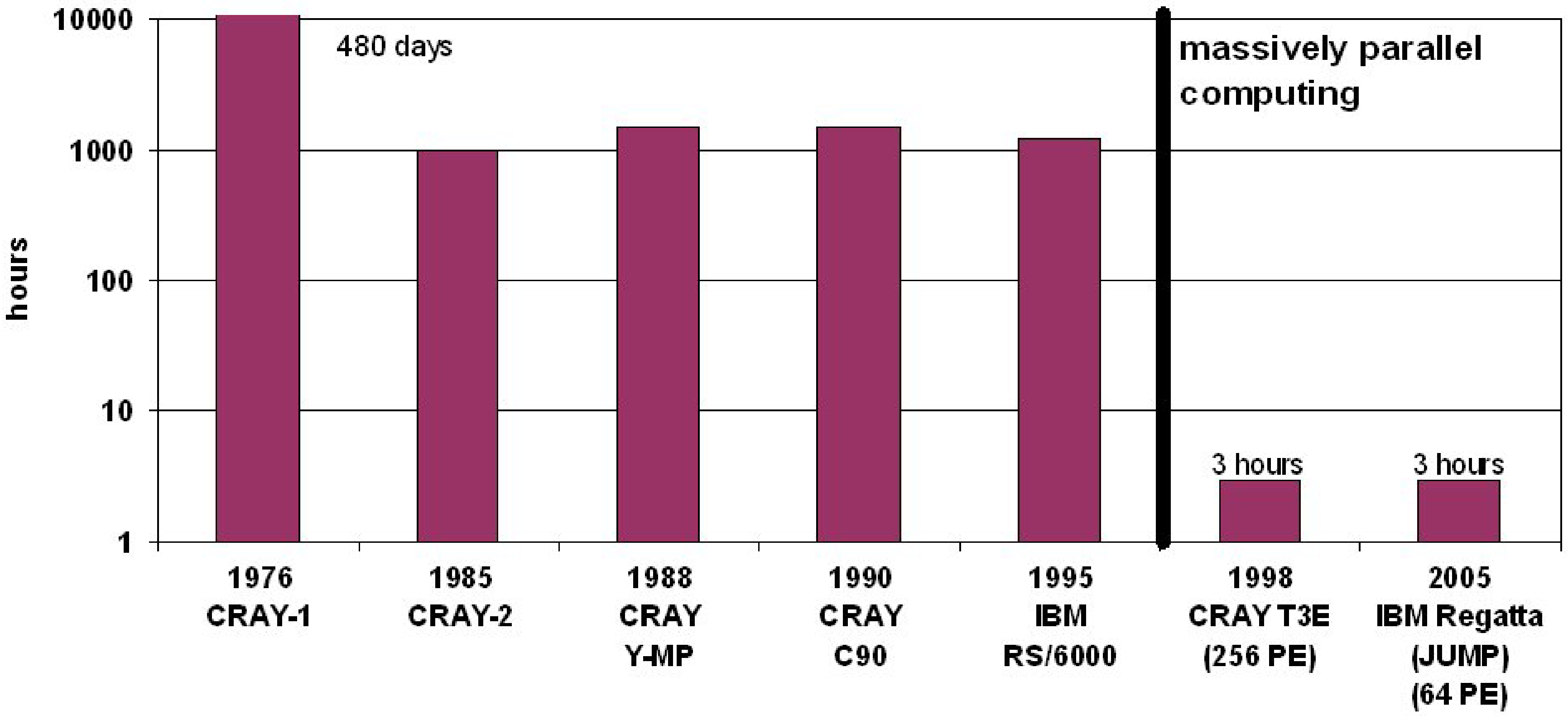


Prediction: high source upstream, high flow speed, low T near target

TEXTOR-DED: smooth particle hydrodynamics
Monte Carlo for non convective terms
interpolated cell mapping for stochasticity



Typical runtime for a 3D edge modelling job
(TEXTOR-DED case, single transport equation)



0.5 Million particles
256 processors

grid size 20 x 20 x 40
600000 iterations

Conclusions/Outlook

Similar to previous steps: progress to ITER is based mainly on experimental and empirical extrapolation

guided by theory and aided by modelling

Present goal:

include all of edge physics that we are sure must be operative (opacity, A&M physics, surface processes, drifts…, even while our capability do confirm these directly remains limited.

Present upgrading:

- **low temperature plasma chemistry**
- **consistent wall models**
- **drifts and electrical currents in the edge**
- **2D →3D**
- **coupling to first principle edge turbulence codes**
- **code integration: Core- ETB – edge (ELM modelling)**

Summary: Edge Theory and Modelling

Where are we? A reality check

Compare with aircraft aerodynamics

Things in Common:

- Both use fluid models/codes as primary analysis tool
- In both cases one can get fairly far with 2D (ITER design) but in the end: 3D is needed
- Both involve a powerful controlling fluid-solid interaction/interface
- Both involve turbulence in an important way
- Both are applied sciences:
  What, Why, How   (how can we make this application work?)

Summary: Edge Theory and Modelling

Where are we? A reality check

Compare with aircraft aerodynamics

The differences:

- Aero: involves 2 states of matter. The Edge: minimum 3, sometimes all 4
- Aero: involves no B or E fields, no currents, Maxw. Eq. play no role.
  Edge: Maxwells eqs. as important as fluid eqs.
- Sub-sonic aero: largely incompressible flow. Our fluid is compressible
- Aero: one fluid. We: many fluids (electrons, ions, impurities…)
- Aero: no exchange of matter. For us: the exchanges are dominating
- Aero: some unsteady effects, but no equivalent to our powerful effects: ELMs…
- Aero: 2D flow field can be studied in small, cheep, wind tunnels,
  done 1000‘s of times over 100 years
  We need 2D (3D) fluid field for all fluids, around the entire edge (when? cost?)

Summary: Edge Theory and Modelling

Where are we? A reality check

Computational aircraft aerodynamics is still an active field of research.

Edge plasma: orders of magnitude more complex,
orders of magnitude less R&D

If computational edge plasma science would be “largely in hand”,
it would be a miracle.

A major computational edge plasma science effort is needed,
in order to avoid major code failures in the ITER design and operation

The JET divertor design philosophy

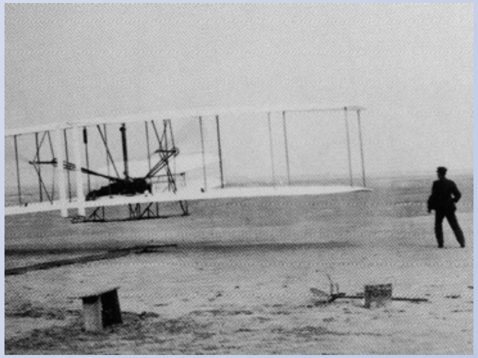
Michael Pick has used to describe the design of the JET divertor:

> *"The only way to do research is to tell the complete truth. And the truth is that research is often based partially on intuition, which is a perfectly acceptable basis for research in the face of a lack of evidence and verified predictive models.*
>
> *We built the divertor based on what we thought would be a reasonable solution, based on simple extrapolation,*
> *models and intuition, leaving open the possiblities to change."*

Still true for ITER, despite significant progress in edge plasma science and in predictive quality of models

- One and a half decade ago we lacked a credible solution to the divertor problem.
- With the discovery of the cold, detached, radiating divertor in the 1990s, we now have (the makings of) a divertor solution for high power magnetic confinement devices.

We now have enough understanding of „WHAT“
(JET, Tore-Supra, D-IIID, ASDEX, LHD, W7AS,…..)
to proceed with the „HOW“ (to build ITER,…)
Very little on the „WHY“ question still, see lecture III
But we are ready to go: Bring on ITER!



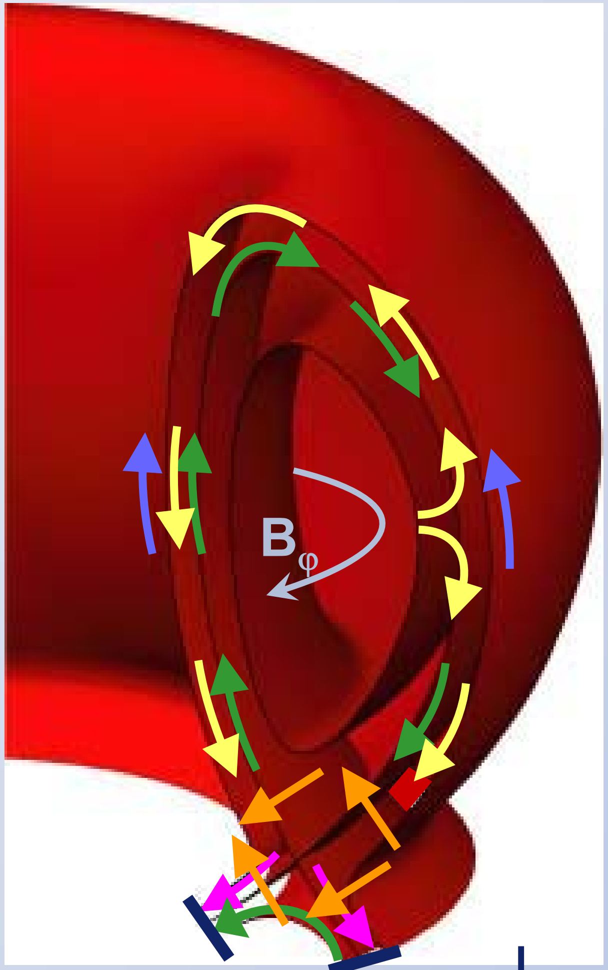
Compare to similar situation after first flight of Wright brothers

The End

Reserve slides

Motivation – understanding SOL flows

Simplified – flow components in poloidal plane only



FWD B_φ $B\times\nabla B \downarrow$

$E_r xB$, ∇pxB →

$E_\theta xB$ →

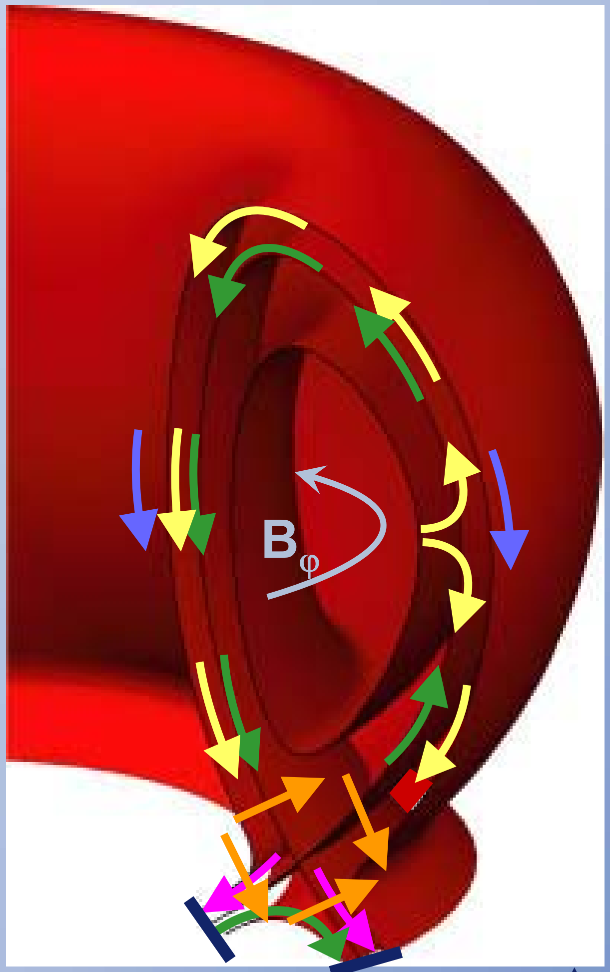
Poloidal

Pfirsch-Schlüter →

Divertor sink →

Ballooning →

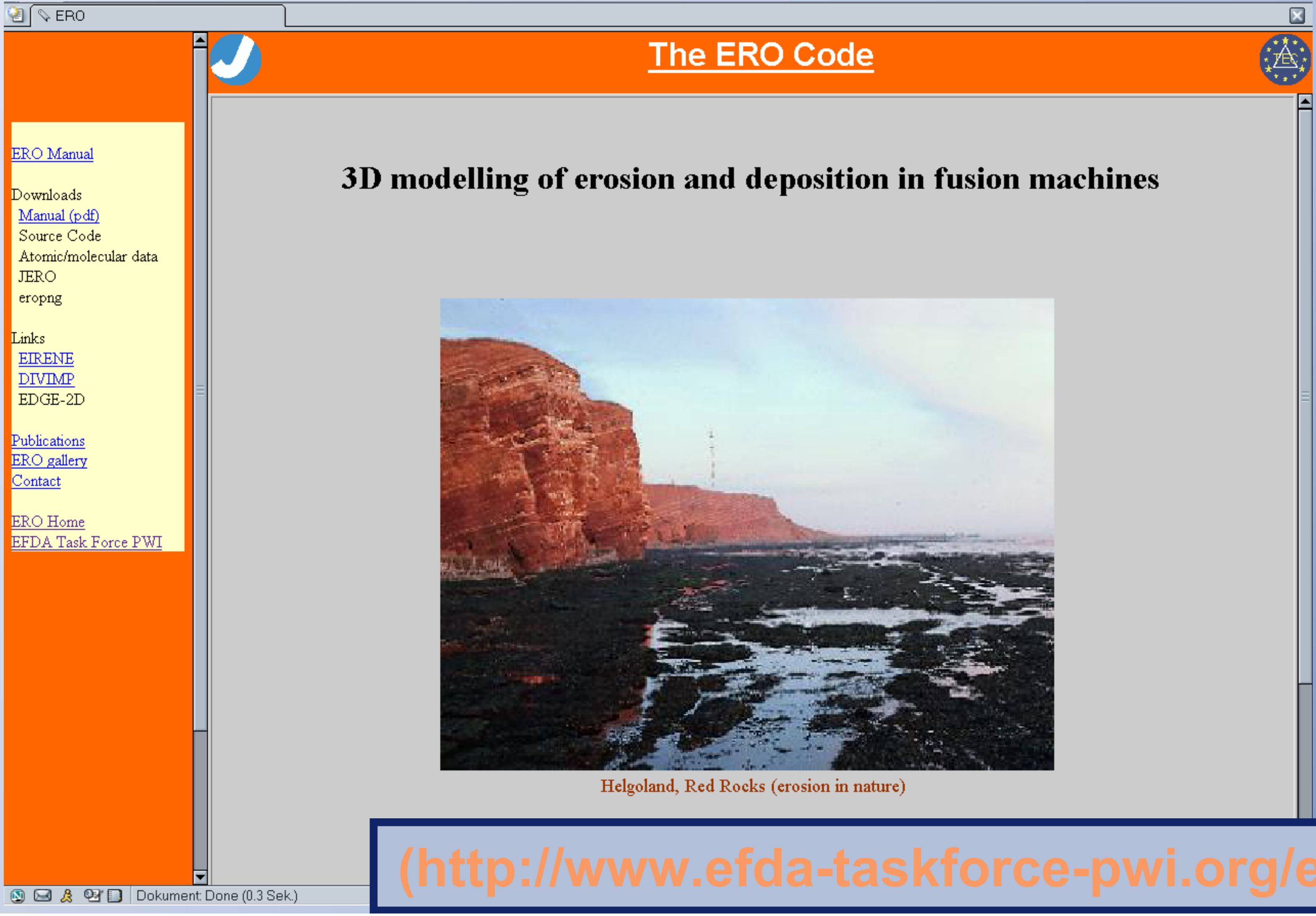
Parallel



REV B_φ $B\times\nabla B \uparrow$

IV.) Applications of ERO

The ERO webpage – still under development …



The ERO Code

3D modelling of erosion and deposition in fusion machines

Helgoland, Red Rocks (erosion in nature)

(http://www.efda-taskforce-pwi.org/ero/