Hydrogen surface interaction over many orders of magnitude in flux and power

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FOM

TU/e

CPS
CENTRUM
VOOR PLASMAFYSICA EN
STRALINGSTECHNOLOGIE

FOM Institute for Plasma Physics Rijnhuizen

- National homebase for Fusion in The Netherlands
- Joint research program in fusion with FZ Jülich and RMA Brussels: TEC
- Focus on: PSI (new), Mesoscopic structures, Plasma diagnostics, ECRH

Rijnhuizen in winter:

Oil price skyrocketing and confined,

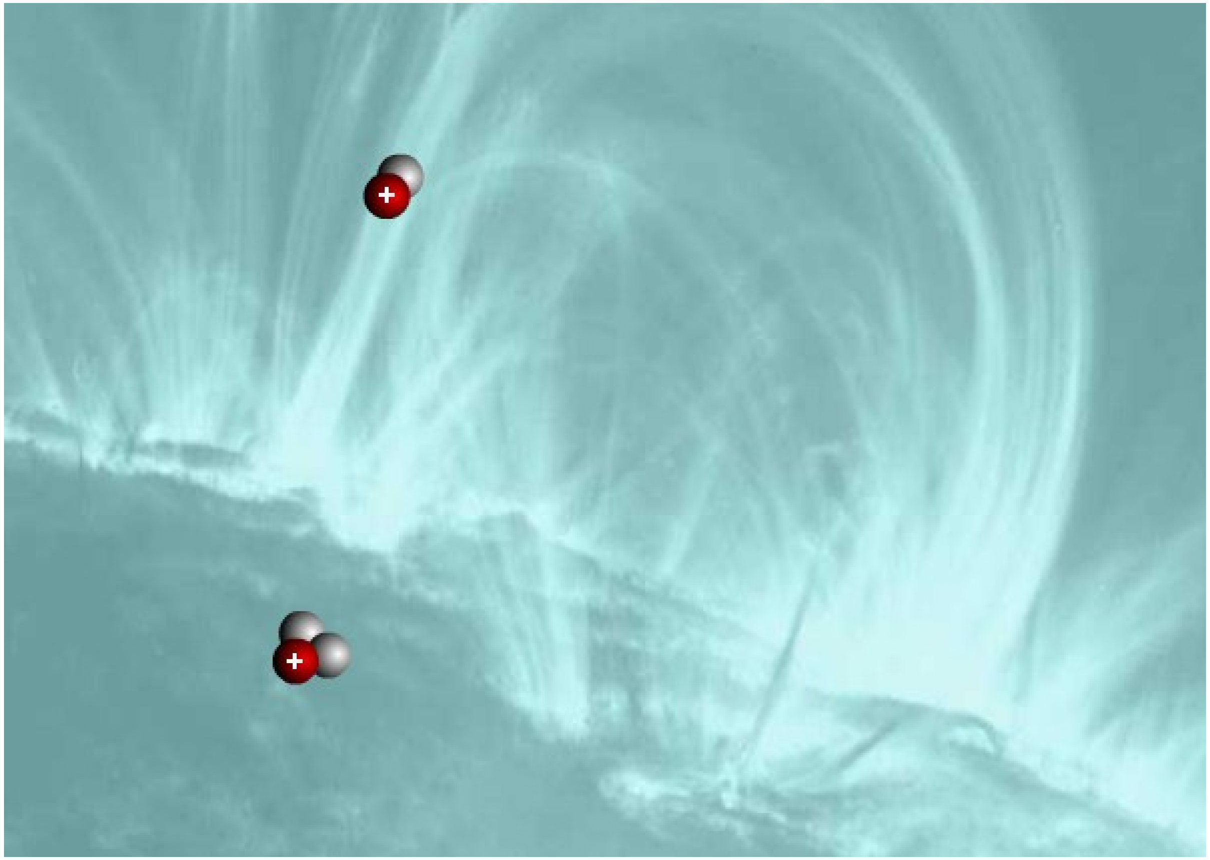
politically controlled supply

CO_2 emission and climate change

Fusion Energy:

let’s build a sun on earth

Nuclear fusion: ${}^{2}D + {}^{3}T \rightarrow n + {}^{4}He$

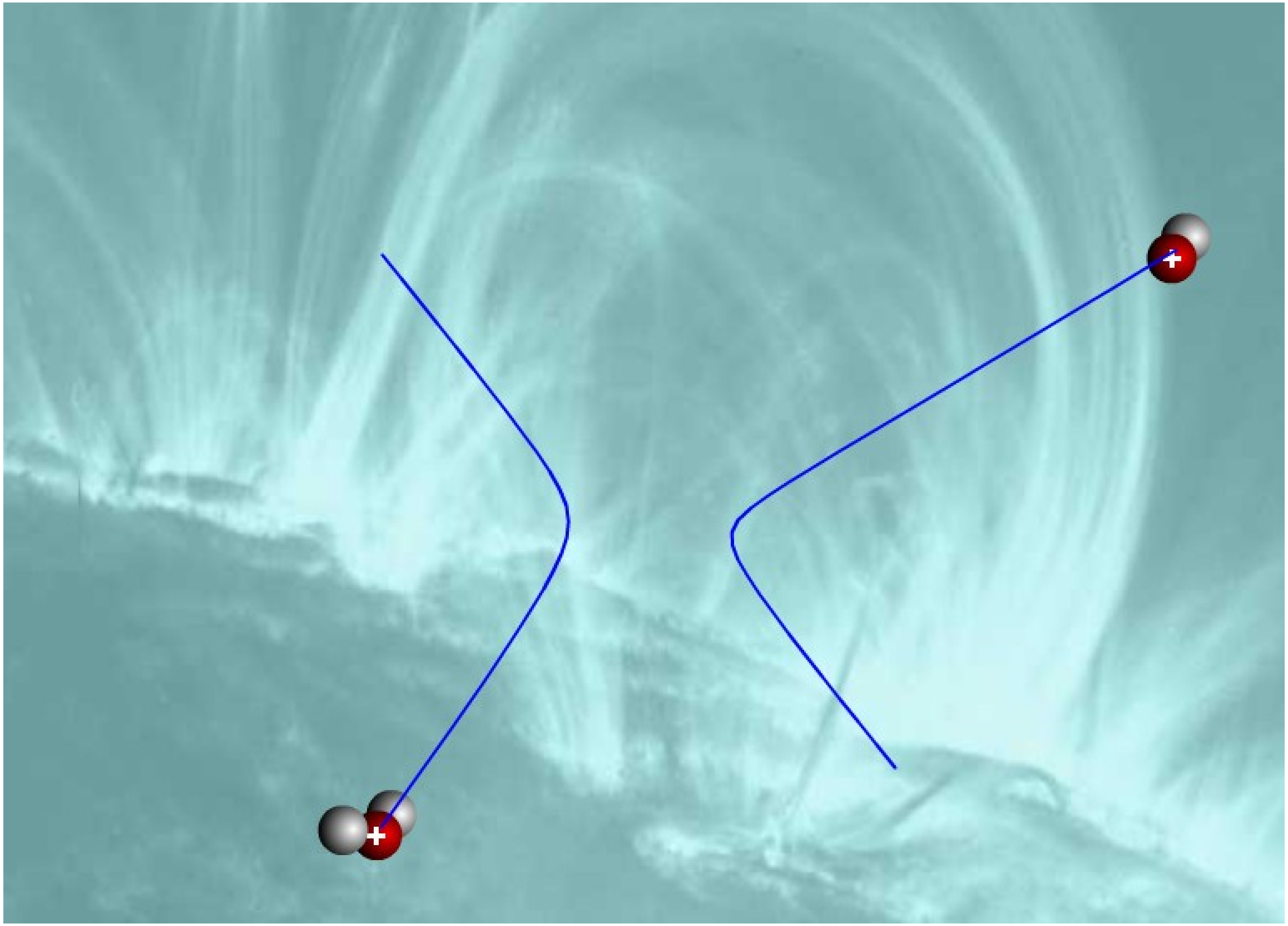


No chain reaction: no runaway danger

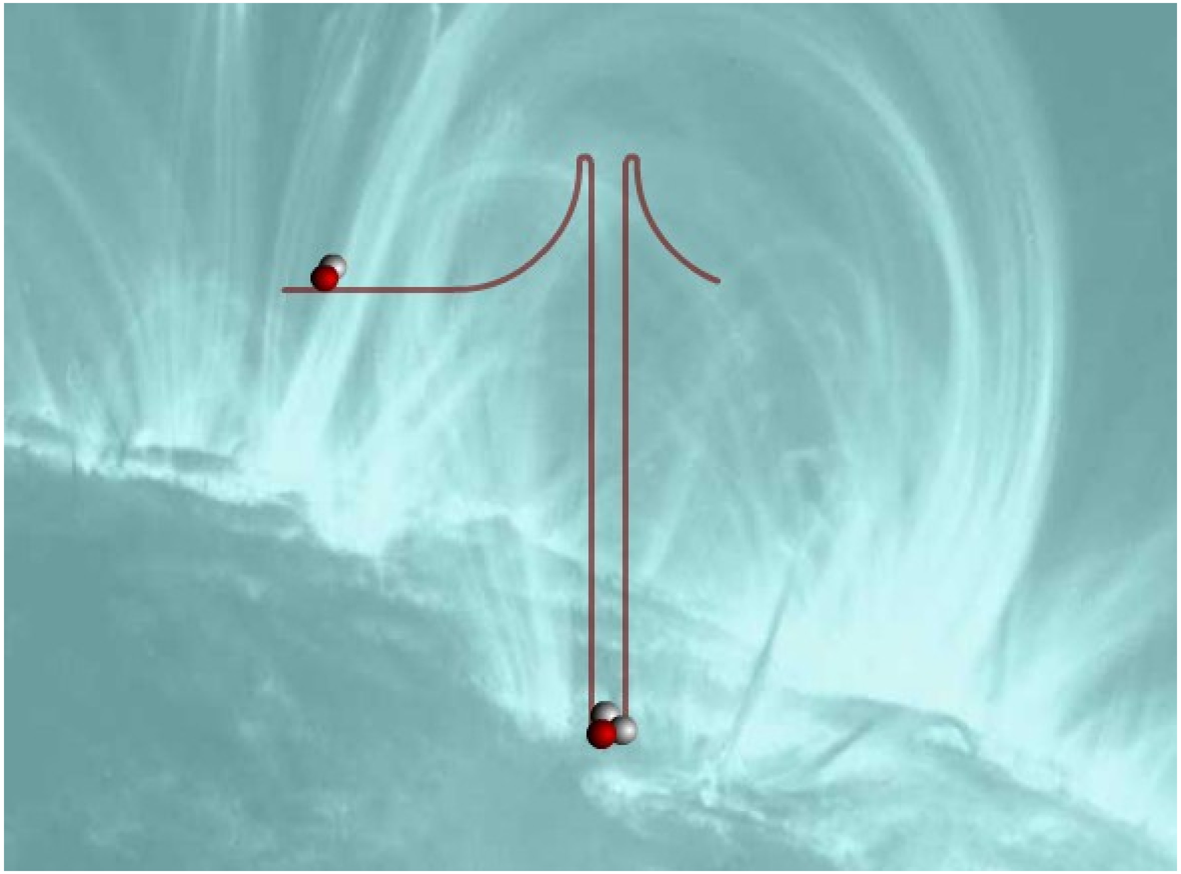
Total reaction: ${}^{2}D + {}^{6}Li \rightarrow 2\ {}^{4}He +$ 22.4 MeV.

Compare: $2\ CO + O_2 \rightarrow 2\ CO_2 + 10$ eV

Coulomb repulsion between the reacting ions

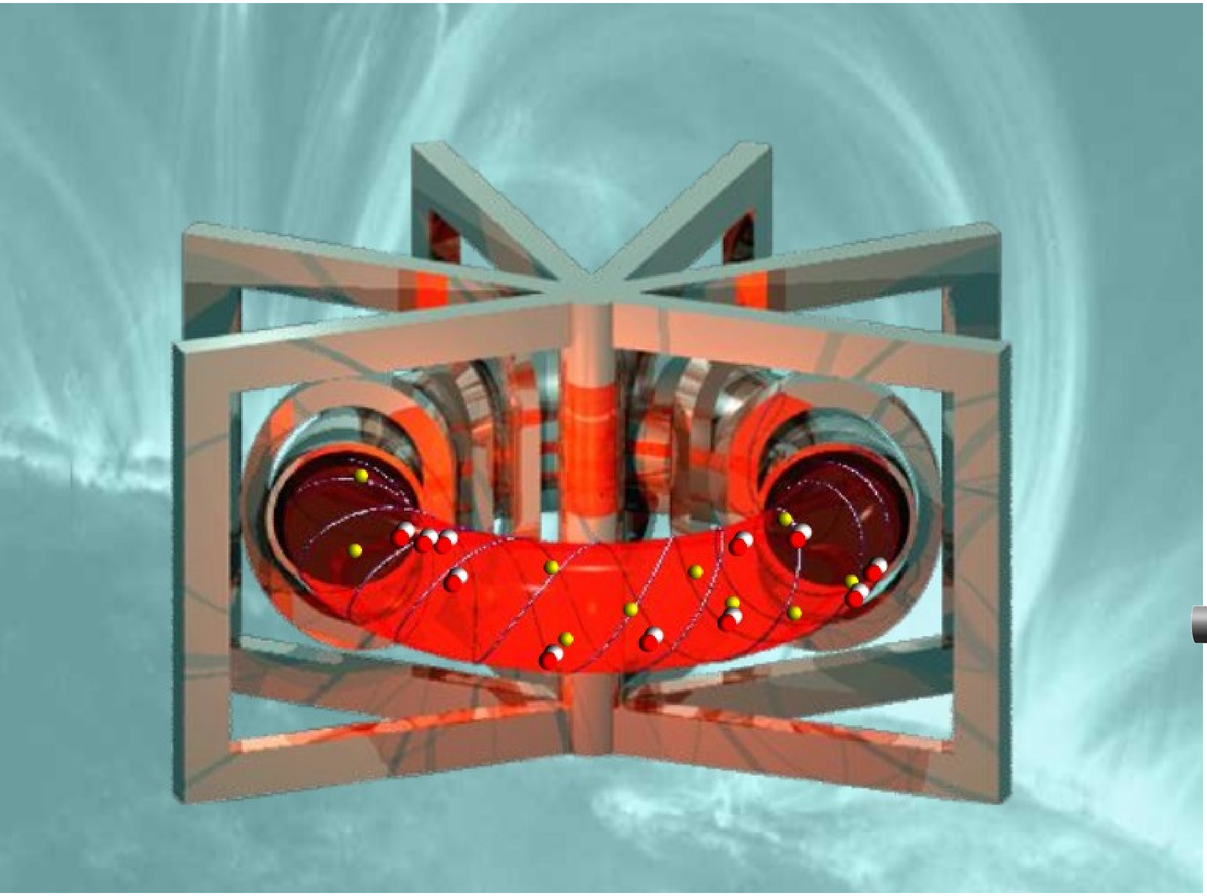


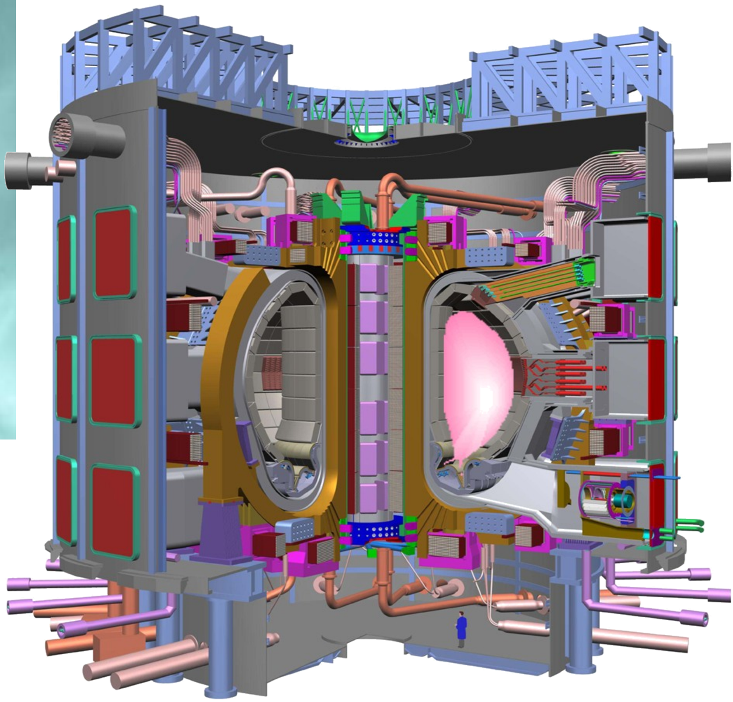
Coulomb barrier and nuclear attraction



Overcoming the barrier requires 20.000 eV (> 200 000 000 ^{o}K)

The reactor geometry: the Tokamak





Waste from fusion power plants

Fusion does not produce greenhouse gases

The only gas produced by the fusion process itself is helium. This is a harmless and inert gas already present in the earth's atmosphere. A 1000 MW fusion power plant would only produce about 250 kilograms of helium each year, whereas a comparable coal-fired power plant produces about seven million tons of carbon dioxide every year. The operation of a fusion power plant does not produce greenhouse gasses.

China opens one of those every week!!

Waste from a 1000 MW power plant per year

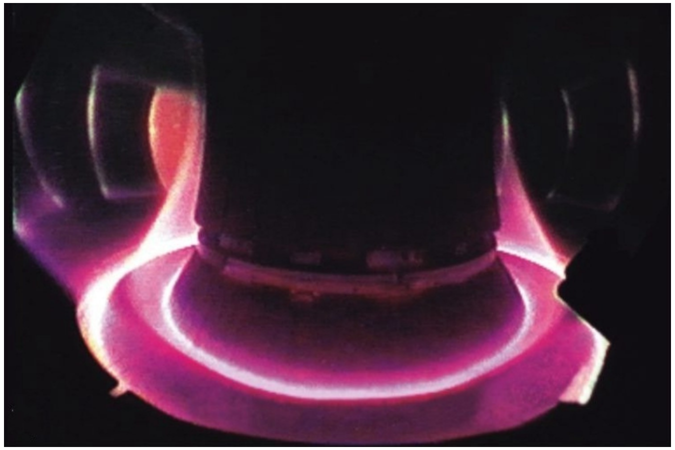
Coal	7.200.000 tons CO_2 5.800 tons SO_2
Gas	3.600.000 tons CO_2
Fission	32 tons of spent fuel
Fusion	250 kilograms of helium

This cd-rom was partly financed by the European Commission

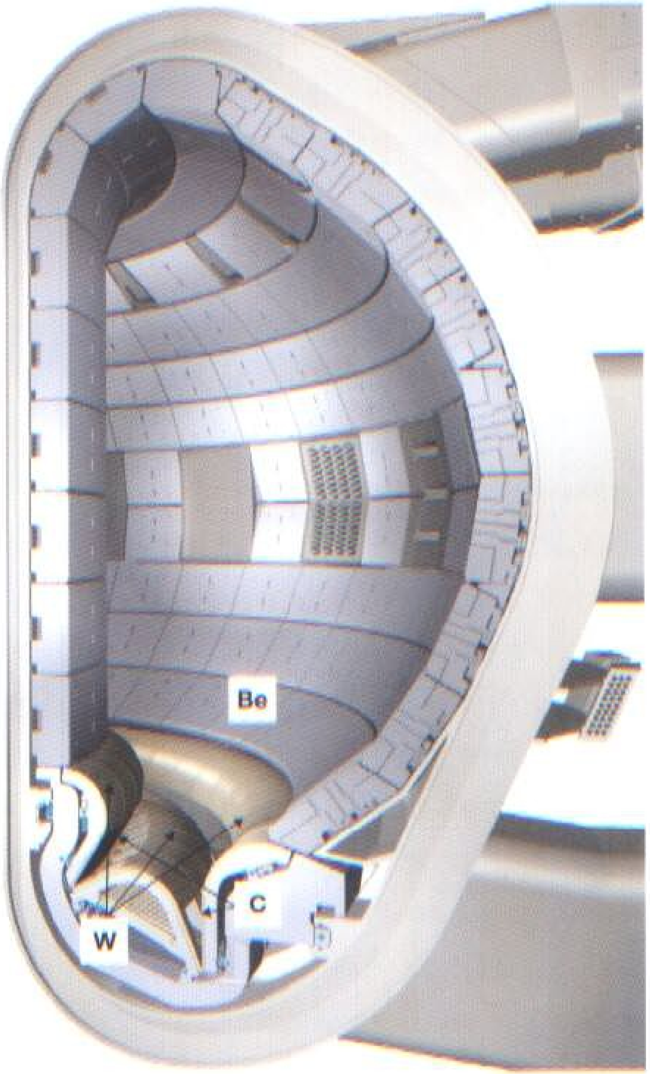
EFDA • European Fusion Development Agreement

email • info@efda.org

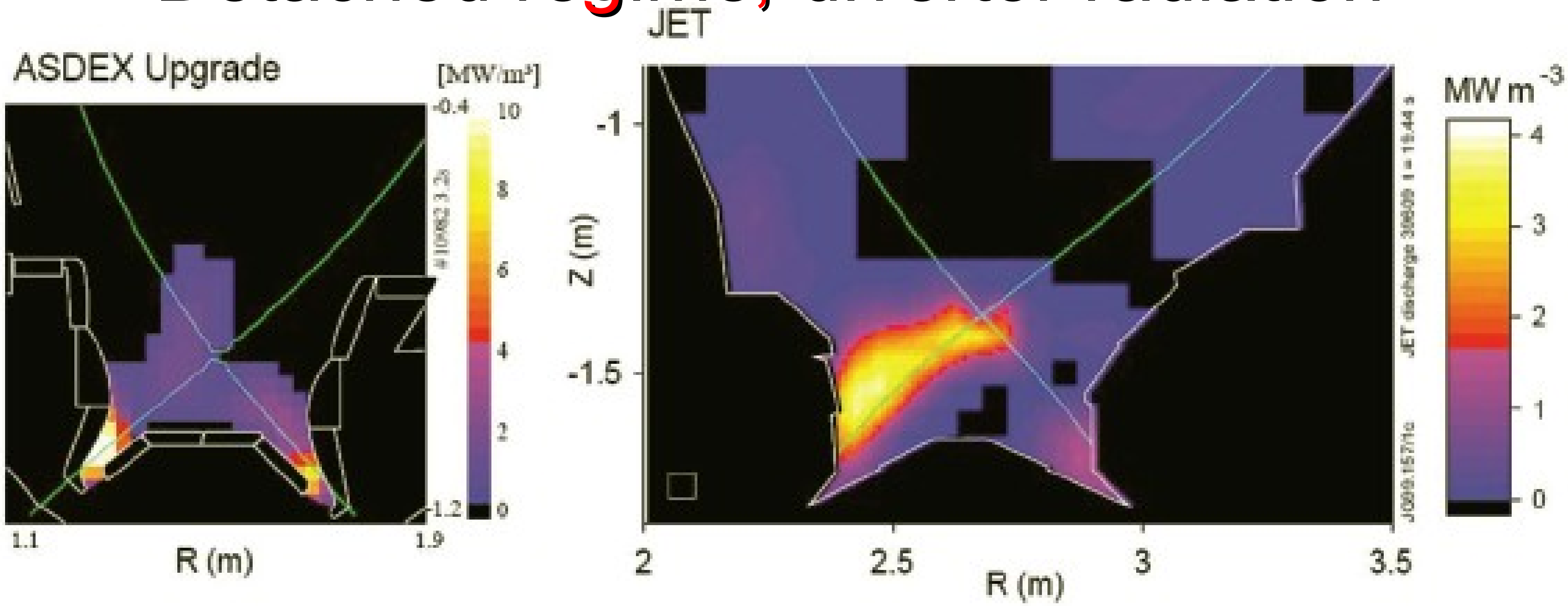
Plasma Wall Interaction in tokamaks



Divertor in ASDEX upgrade
and ITER



Detached regime, divertor radiation



- Field and plasma lines hit divertor surface at a few degrees: 200 rotations before hitting it
- Carbon radiation cooling plasma before the surface (detached), not at the surface (attached)
- Low energy plasma, at or below threshold for physical sputtering
- Self regulating, self protection
- Gas puffing helps
- from: Kallenbach, et al. Plasma Physics and Controlled Fusion 41 (1999) B177

Walls in ITER

Why does the plasma hit the wall:

$^4He^{++}$ ash and power disposal, gas cleaning.

Where does the plasma hit the wall?

Limiters

confinement

Divertors

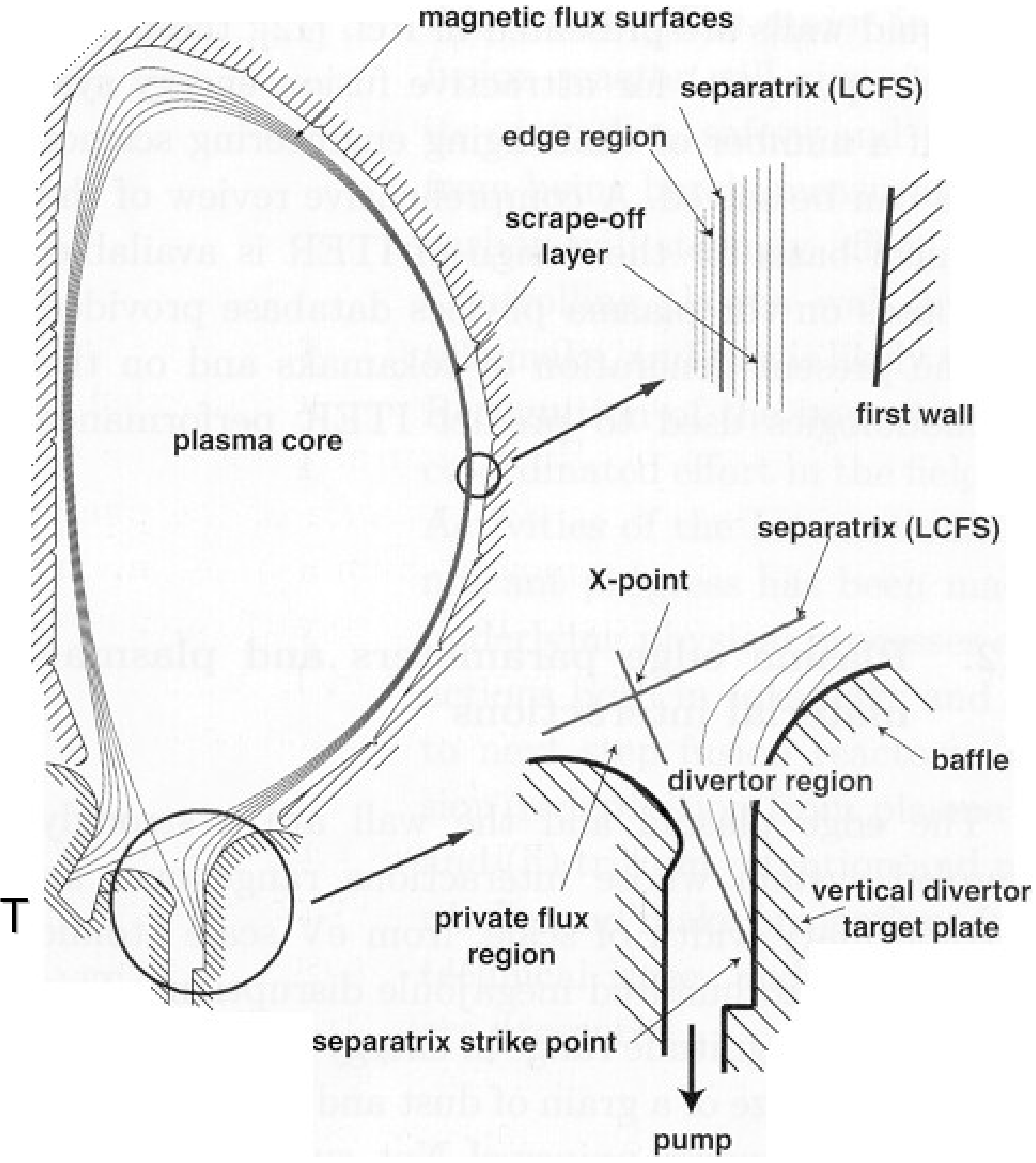
1) power exhaust: the detached plasma is radiatively cooled by gas collisions

2) control impurity level of the core

3) 'ash tray', He ion removal and D-T recycling

All plasma facing surfaces:

elm's, disruptions, accidents



Federici, et al. Nuclear Fusion 41 (2001) 1967

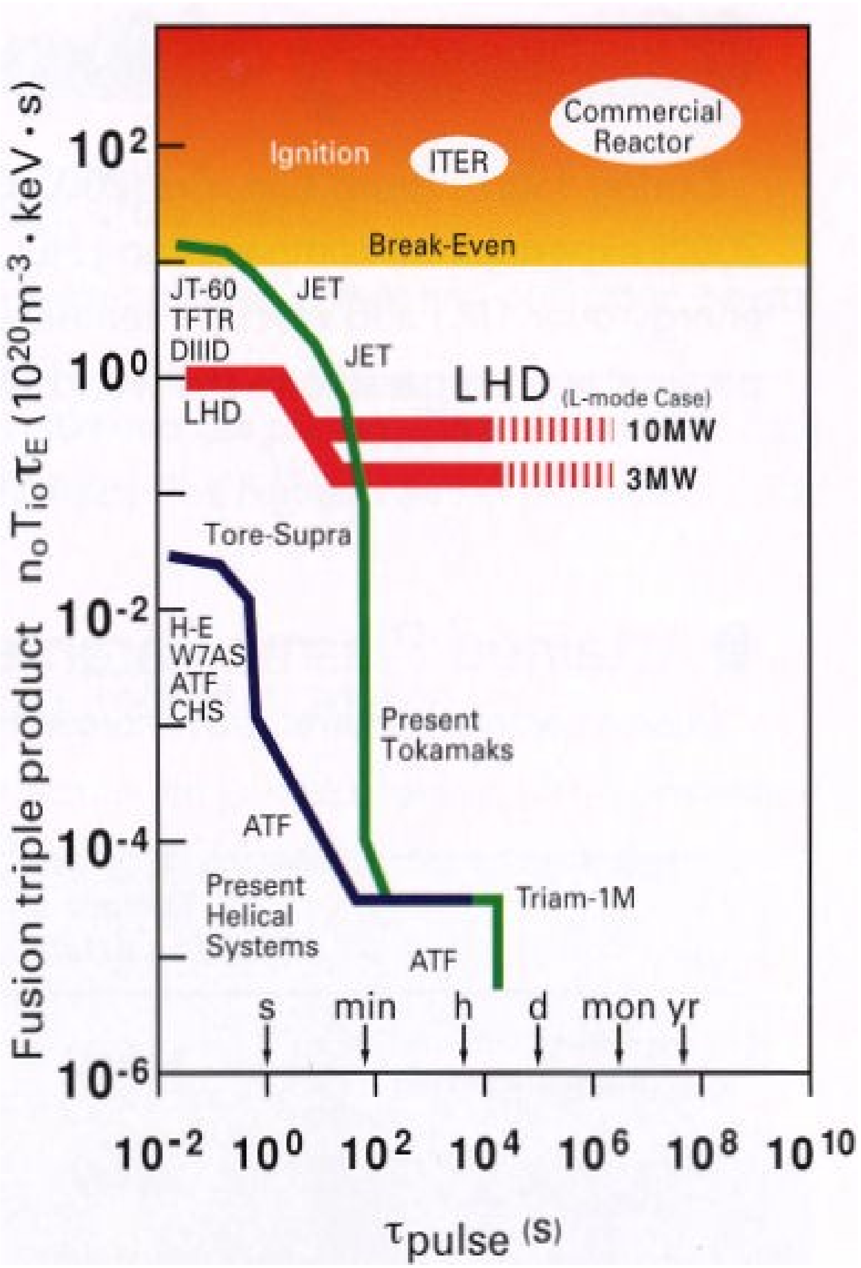
Power and pulse duration:

most experiments went for peak triple product in ‘short’ pulses, limits wall erosion

Future devices have both power and long pulses

Much research on hydrogen surface interaction is needed for the long pulse regime

From: www.nifs.ac.jp



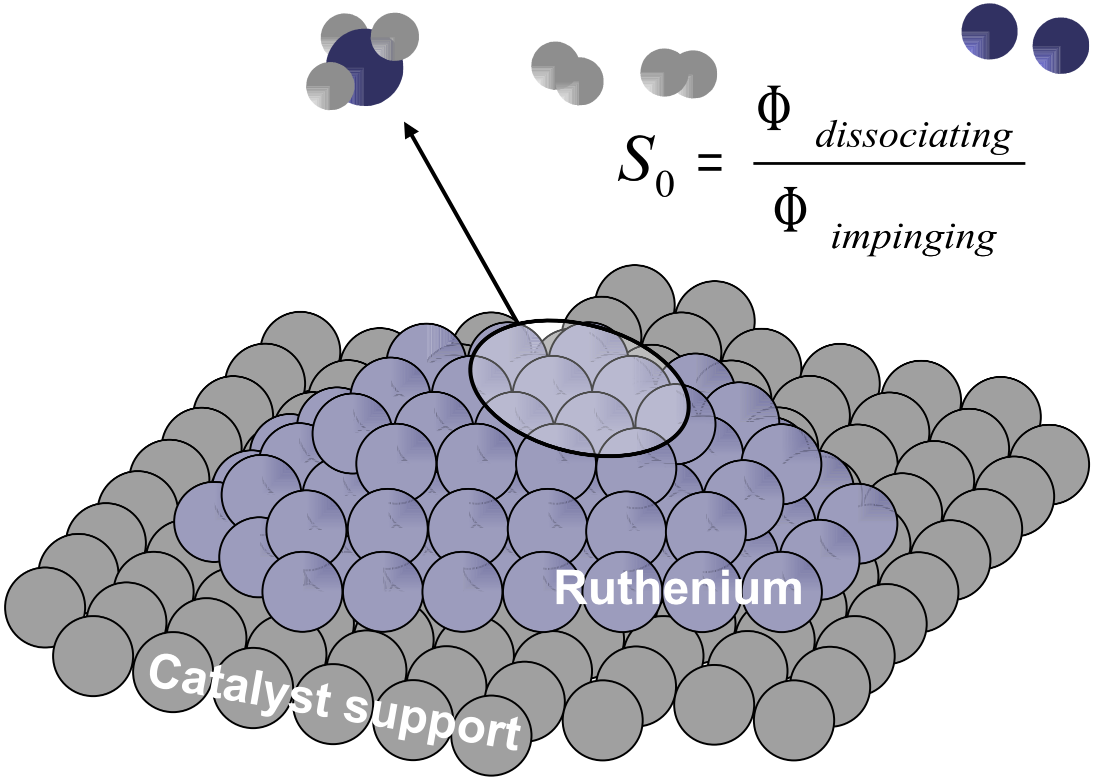
A simple (?) system at low flux: Comparing theory and experiment in dissociative adsorption of H_2 on Ru(0001)

Are experiments still required in theoretically well-developed fields e.g. gas-surface dynamics?

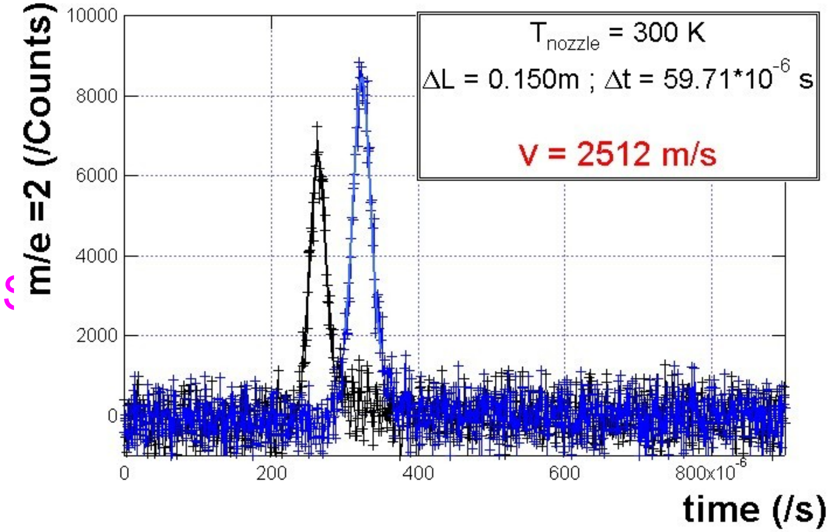
Irene Groot, Hirokazu Ueta, Janneke van der Niet
Geert-Jan Kroes, Roar Olsen, Marc T.M. Koper,
Aart W. Kleyn, Ludo Juurlink
Leiden University
Einsteinweg 55, 2333 CC Leiden, the Netherlands

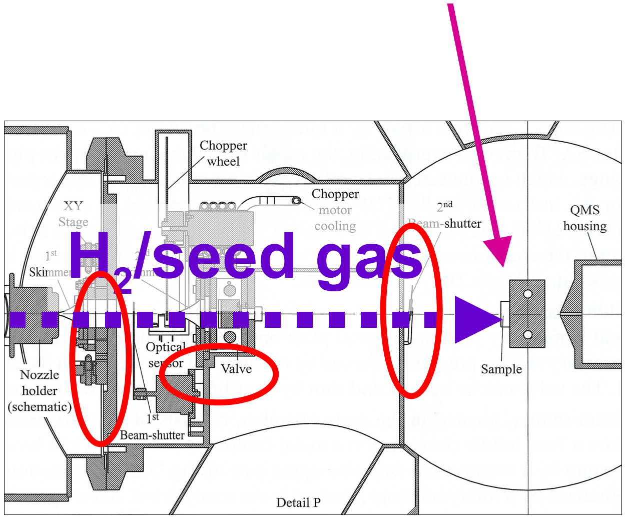
1. Modeling of reaction kinetics
2. Understanding of heterogeneous catalysis

Dissociation Probability, S_0



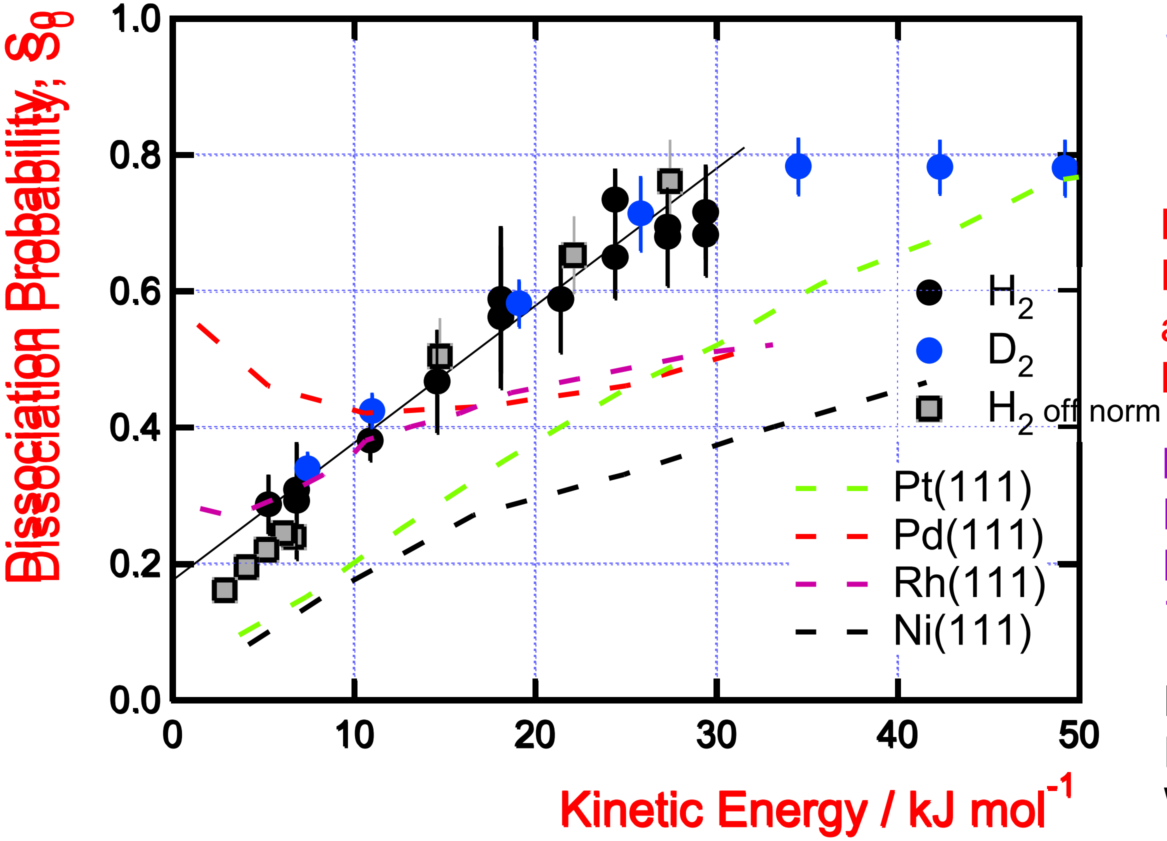
$$S_0 = \frac{\Phi_{dissociating}}{\Phi_{impinging}}$$



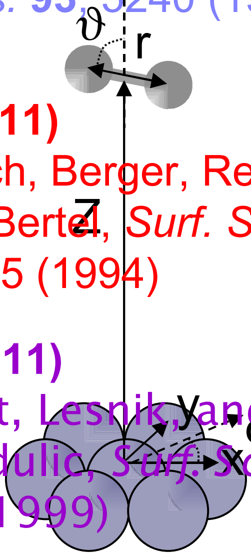


- Cleaning Ru(0001)
  - Sputtering
  - Oxygen treatment at 1200 K
  - Sputtering
  - Annealing at 1500 K
  - Verify cleanliness and surface order
- King and Wells measurement of S_0
- Time-of-Flight

- [illegible] surfaces?
- How does S_0^0 vary with kinetic energy?



Pt(111)
Luntz, Brown, and Williams, *J. Chem. Phys.* **93**, 5240 (1990)

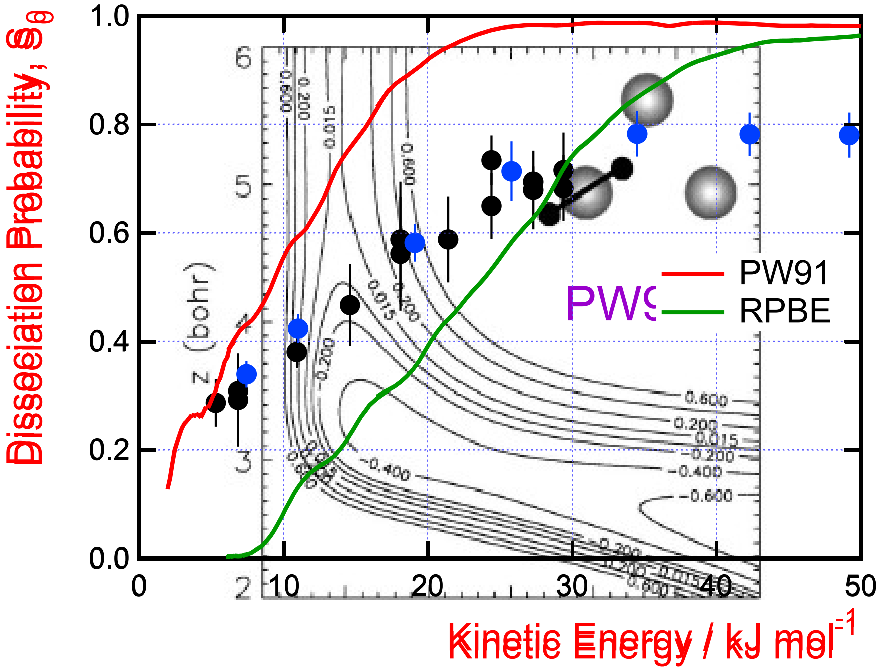


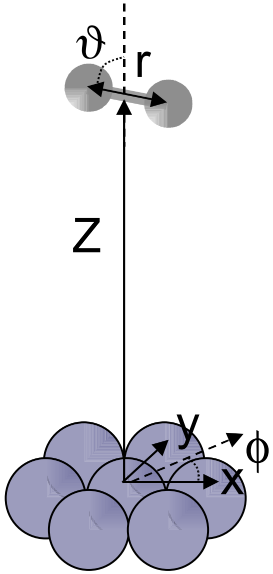
Pd(111)
Resch, Berger, Rendulic, and Bertel, *Surf. Sci.* **316**, L1105 (1994)

Rh(111)
Beult, Lesnik, and K.D. Rendulic, *Surf. Sci.* **429**, 71 (1999)

Ni(111)
Rendulic, Anger, and Winkler, *Surf. Sci.* **208**, 404 (1989)

1. Mostly [illegible]



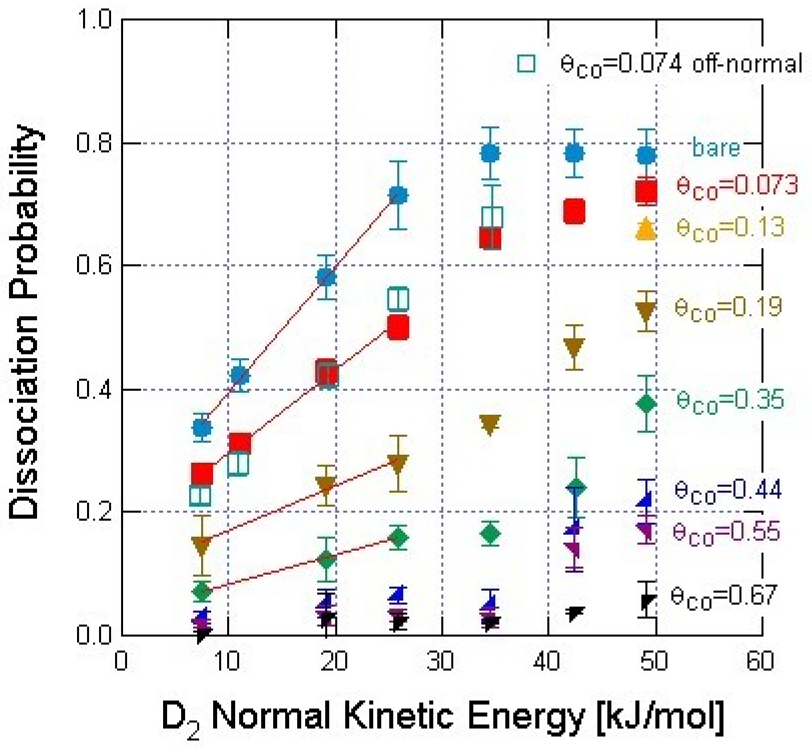


Vincent *et al.*,
J. Chem. Phys. **123** (6), 044701, 2005

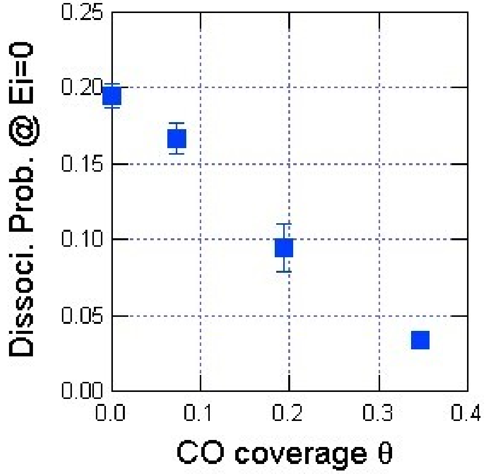
- 6D quantum-dynamics calculations
- two different PESs based on PW91 and RPBE functionals

Experiment	Theory
• low/non-activated pathways	• minimum activation barrier
• broader activation barrier distribution	• narrower activation barrier distribution
• $S_{0,max} = 0.8$	• $S_{0,max} = 1$

Ru(0001) The dependency of the dissociation probability on D_2 kinetic energy and CO coverage

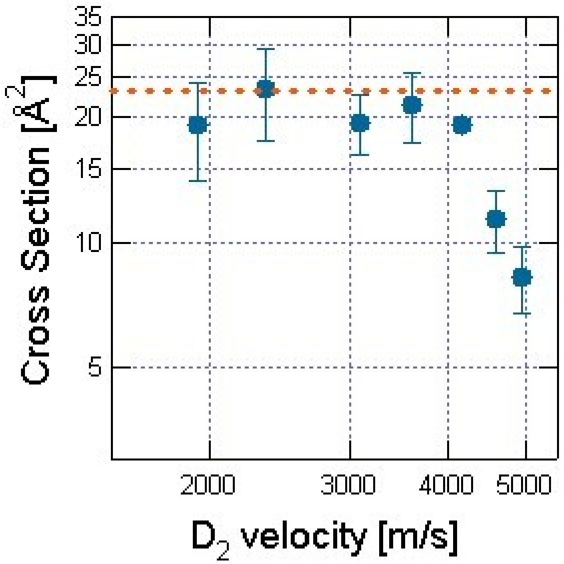


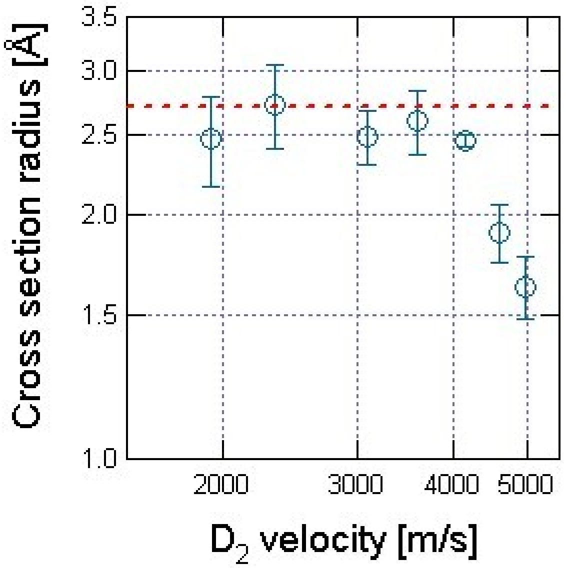
- Surface temperature; 180 K
- D_2 kinetic energy are controlled by nozzle temp. & gas mixing ratio with H_2
- CO were dosed by backfilling at T_S < 200 K and quantified using integrals from TPD.

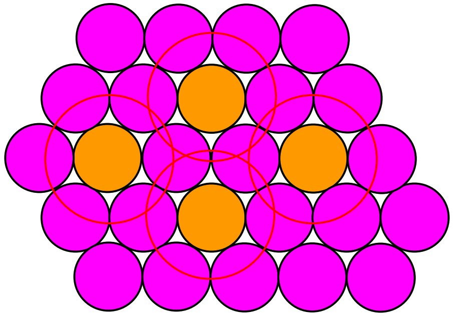


- **D_2 dissociation on CO/Ru (0001) is mainly an activated process.**
- **There is non barrier site for D_2 dissociation which implies a-top of Ru surface.**

The dependence of the cross section for site blocking on D_2 velocity







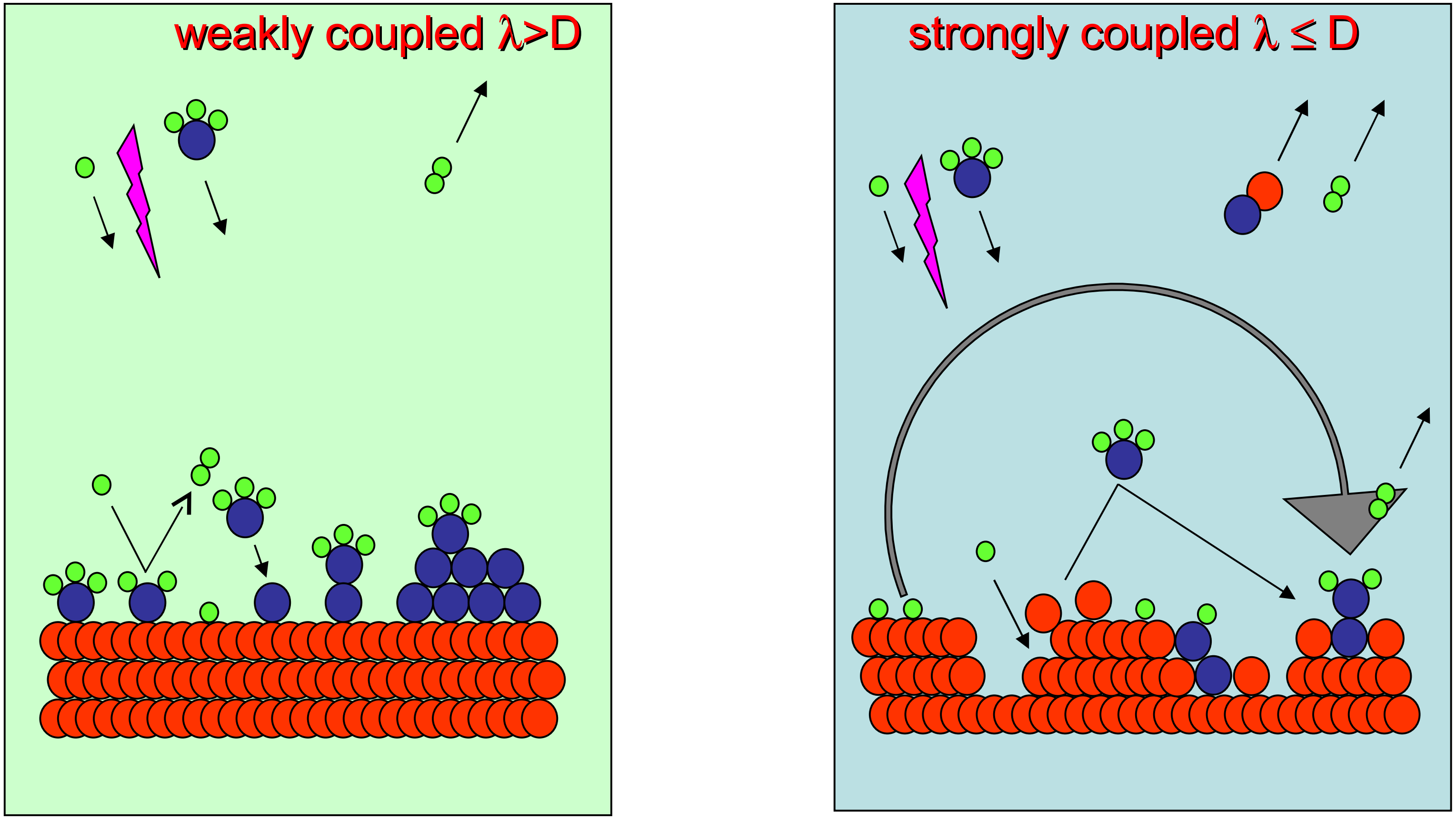
- For 2000 ≤ v_{D2} ≤ 4000 m/s, size of cross section are almost constant.
- Cross section are slightly smaller than area of Ru-Ru nearest distance.
- For D_2 high velocity, CO’s site-blocking capability decreases rapidly.

Low flux region

- The sticking probability of H_2 on surfaces like Ru(0001) and stepped Pt is not fully understood.
- Simplest omissions in theory like e-h pair excitation of phonon excitation are unlikely to decrease the sticking probability
- Does DFT fail to give the right barriers?
- Site blocking by CO at high velocities is not simple geometric and not understood
- Is required for understanding of issues like catalysis and hydrogen storage

Plasma and radical surface interaction

two extreme cases:



weakly coupled λ>D

strongly coupled λ ≤ D

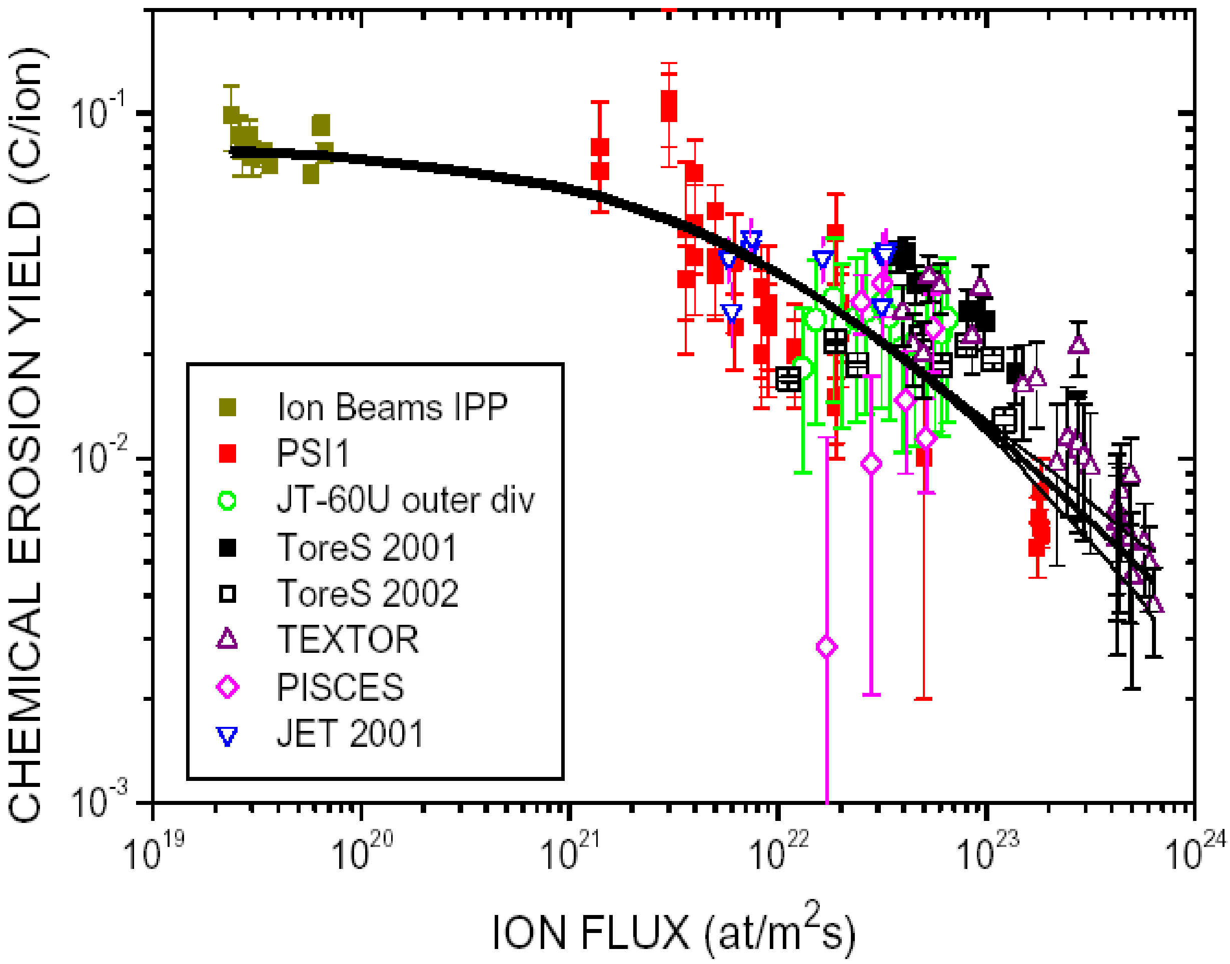
Particles produced disappear

Particles produced are returned

In both cases the effective temperatures and radical densities can be tuned, leading to strong synergistic effects, creating unique chemistry

Kleyn, Koppers, Lopes Cardozo, Vacuum 80 (2006) 1098

Chemical erosion yields of carbon by hydrogen is non-linear in the flux



Erosion seems small but wall load in ITER per shot is 10^4 times higher than in current machines!

Roth et al. J. Nucl. Materials 337-39 (2005) 970.

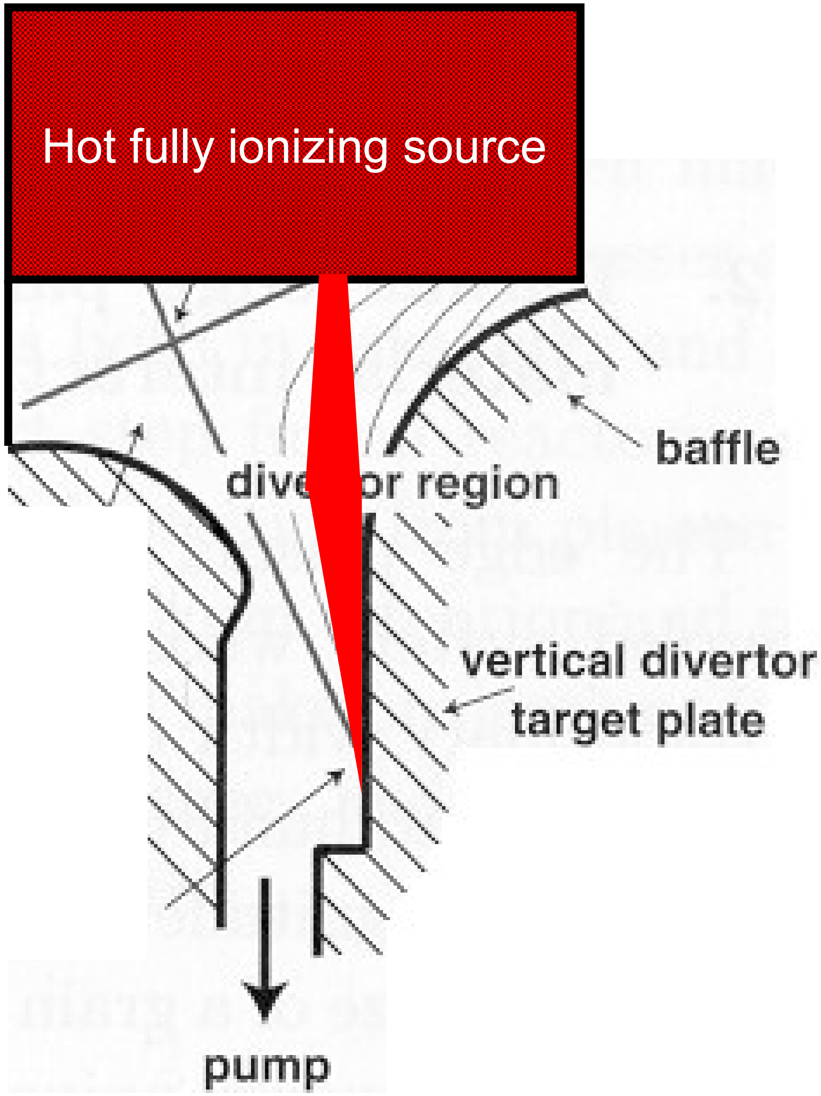
Experiment on walls in ITER

Diagnostic access is difficult; ITER is expensive.

Divertor region cools plasma from 10 keV to 1 eV, issues:
  Surface stability in steady state
  Surface stability during disruption
  Tritium retention
  10 MW m^{-2} power load

Needed for PSI studies:
  High flux: 10^{24} $m^{-2}s^{-1}$
  High magnetic field: 3 T
  Continuous operation
  Diffusion and migration measurements
  Surface dynamics and analysis

How: same target, different plasma generator.
But: plasma generators with T > 100 eV, high density and degree of ionization do not exist
B Field lines almost parallel to divertor, but perpendicular to source



Federici, et al. Nuclear Fusion 41 (2001) 1967

Association Euratom-FOM

Erosion and deposition of C in Pilot-PSI

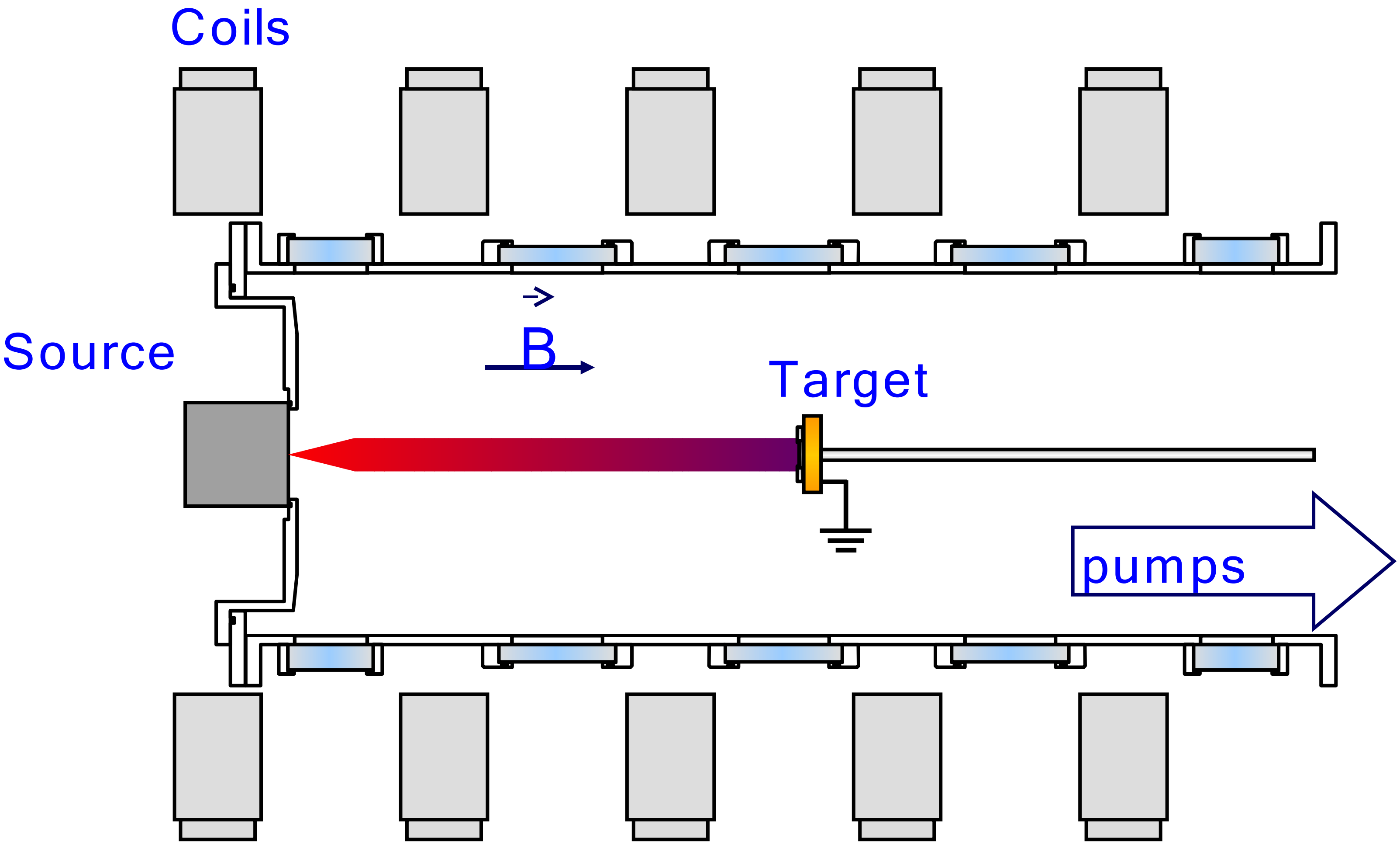
The Pilot-PSI and Magnum-PSI team:
Gerard van Rooij, J. Westerhout, G. Wright, W.A.J. Vijvers, A.E. Shumack, H.J. van der Meiden, R.S. Al, H.J.N. van Eck, B. de Groot, W.R. Koppers, M.J. van de Pol, P.R. Prins, L.W. Veldhuizen, A.W. Kleyn, W.J. Goedheer, N.J. Lopes Cardozo

Massachusetts Institute of Technology : D.G. Whyte

TU/e technische universiteit eindhoven : R. Engeln, D.C. Schram

: Forschungszentrum Jülich (TEC): S. Brezinsek

Experimental: Pilot-PSI



Coils

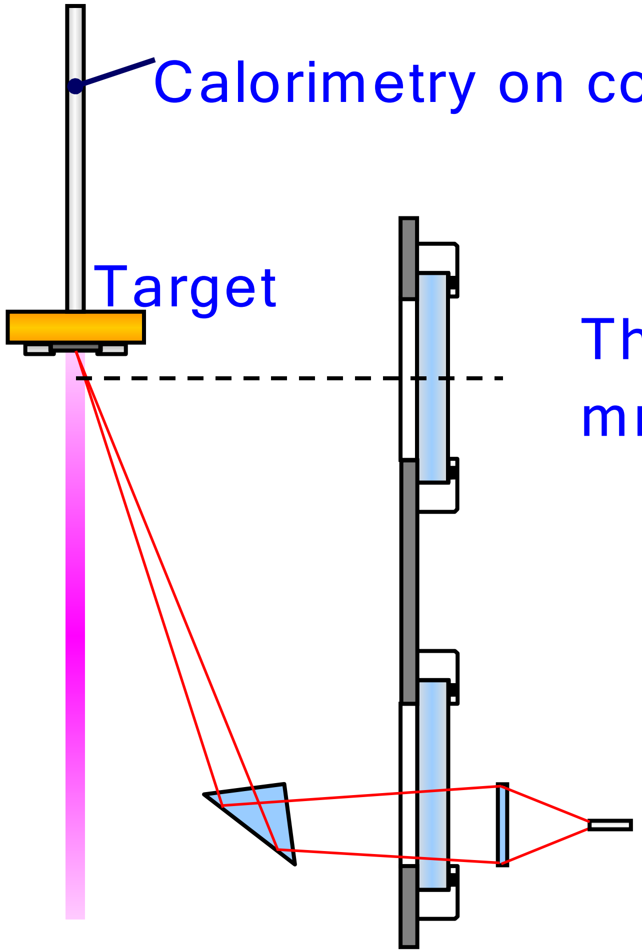
Source

$\vec{B}$

Target

pumps

Experimental: Diagnostics



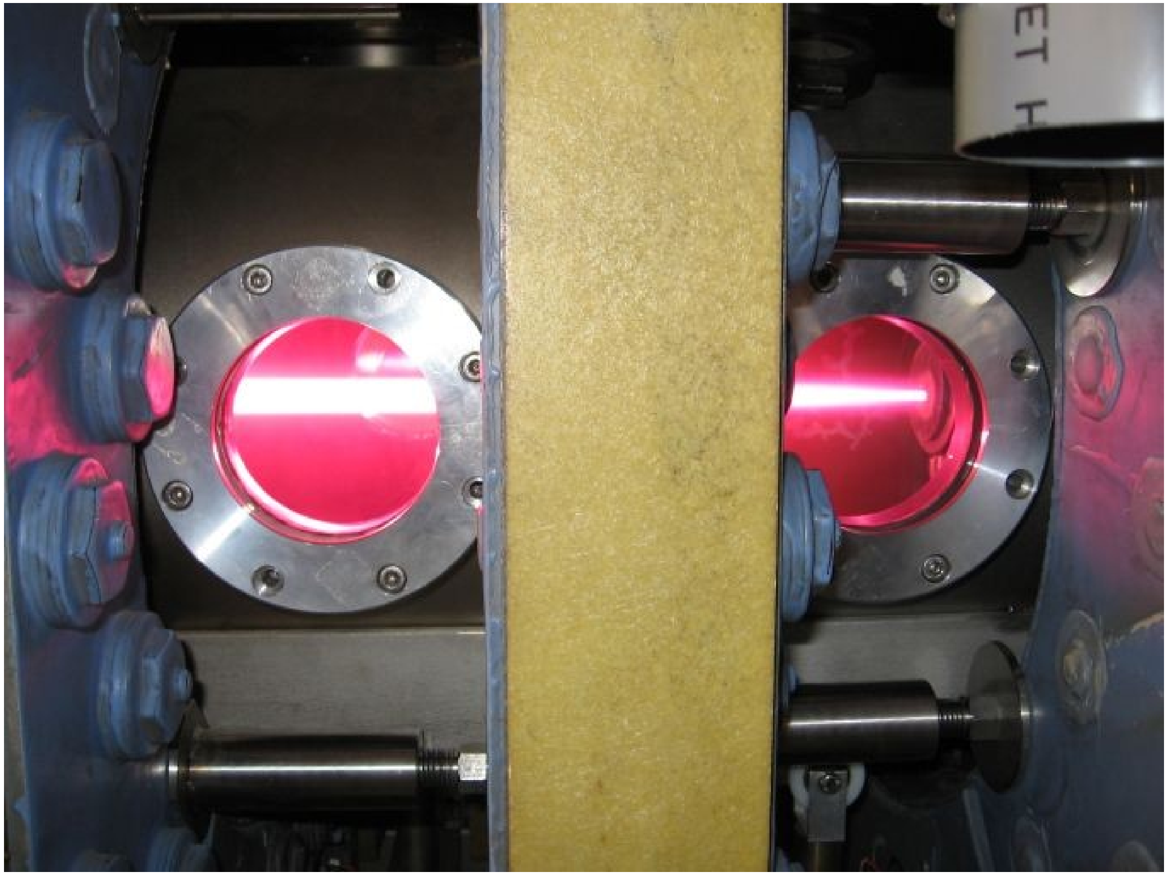
Calorimetry on cooling water

Target

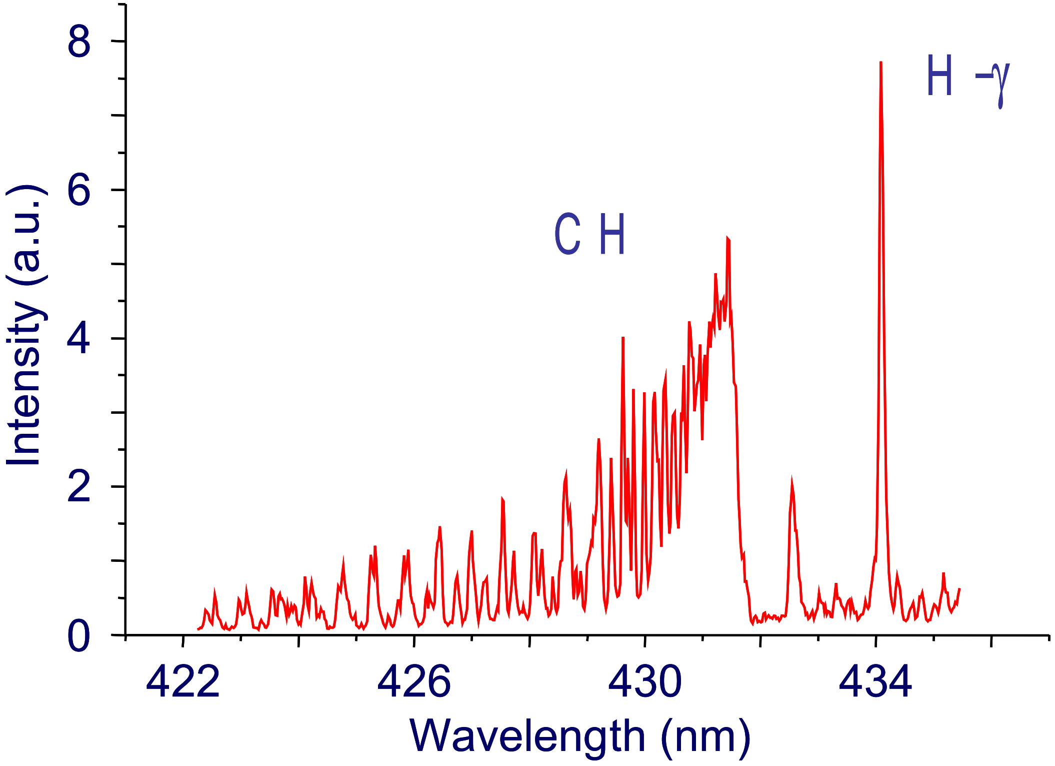
Thomson Scattering at 17 mm in front of target

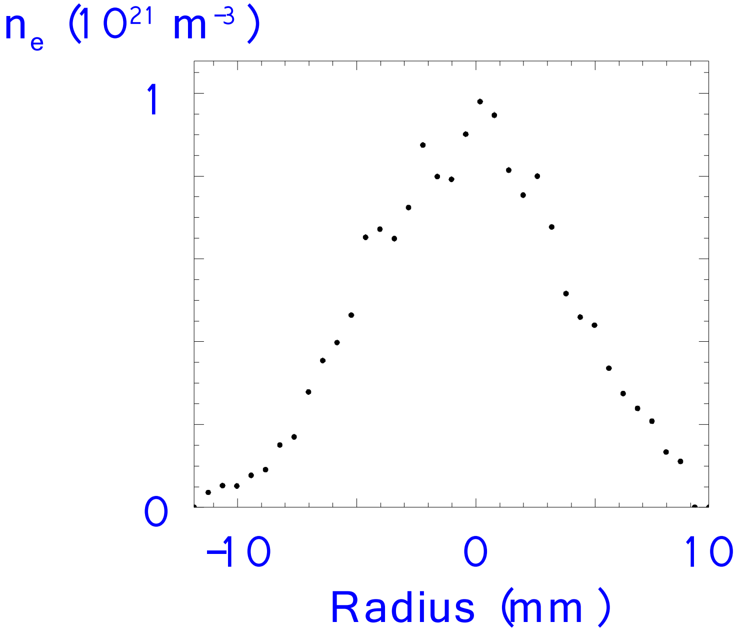
CH spectroscopy

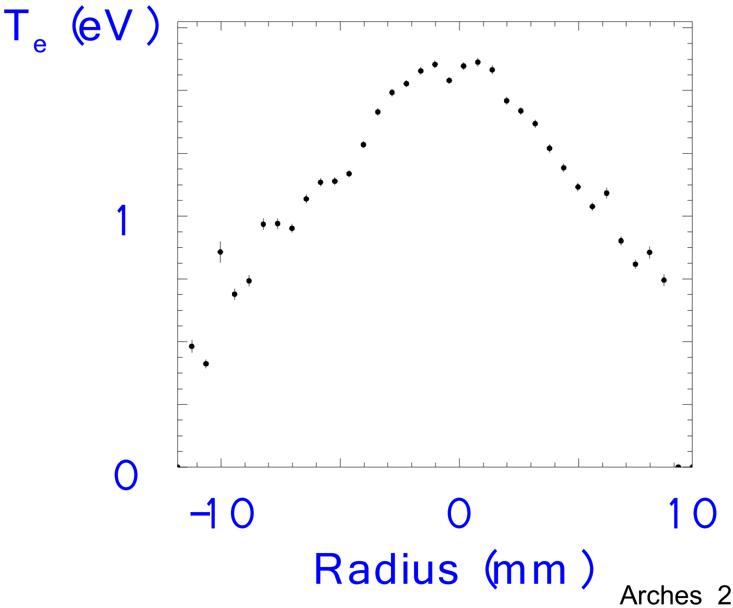
Experimental: target exposure



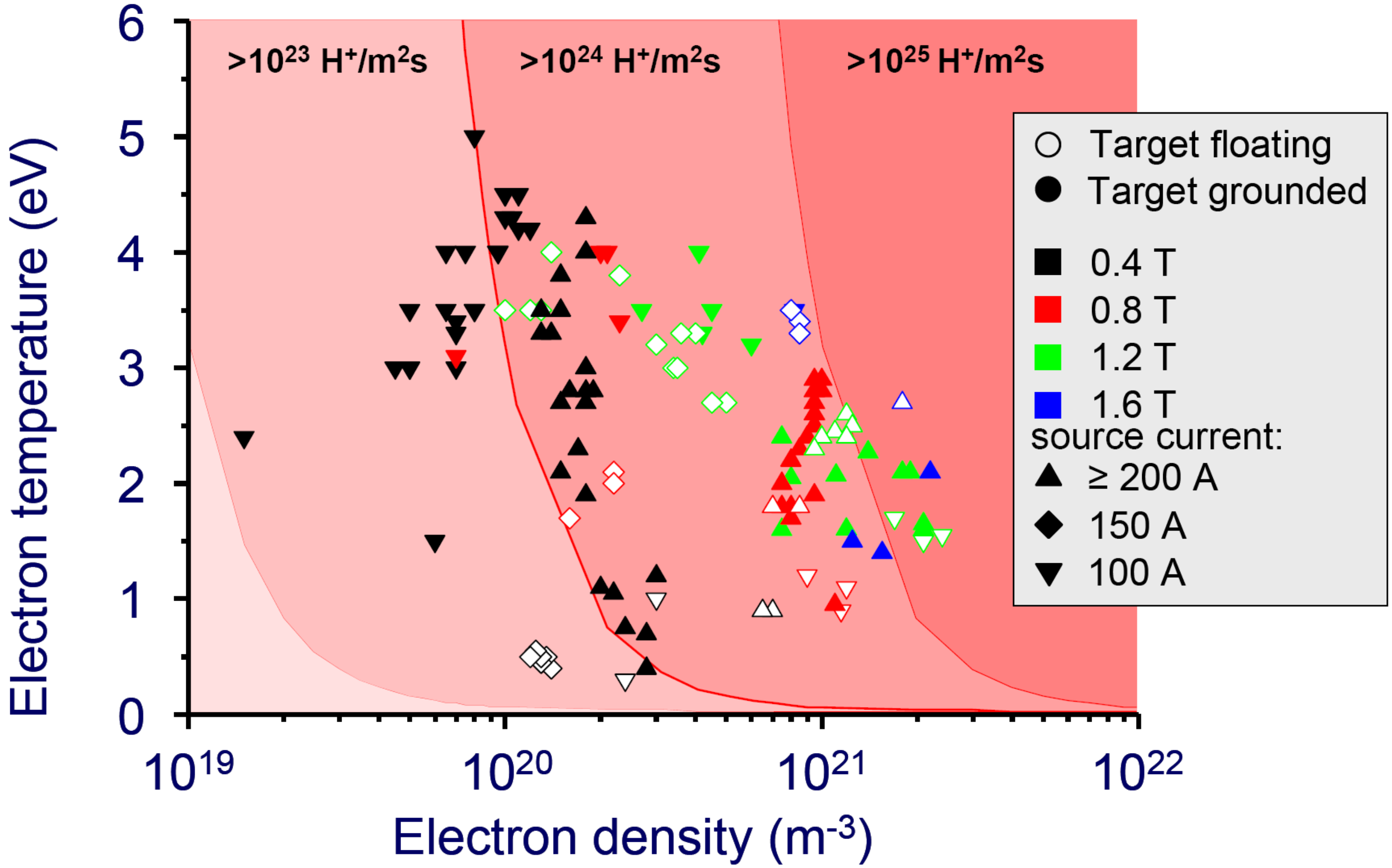
Results: Thomson Scattering and Emission Spectroscopy





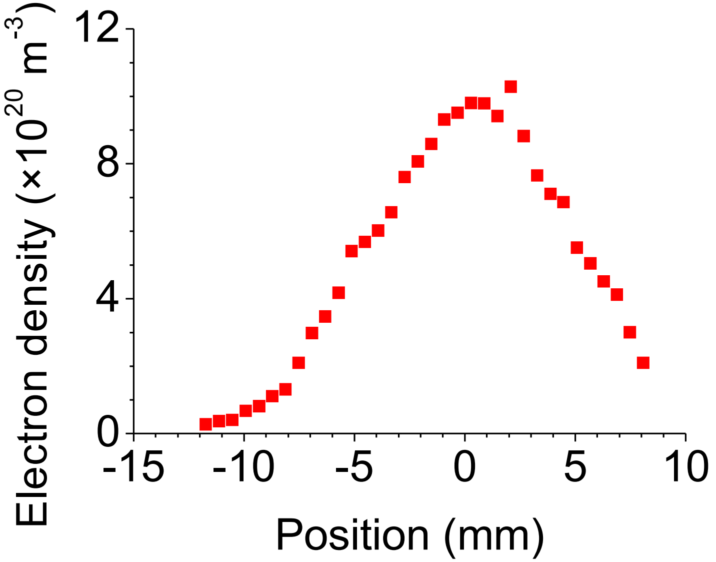


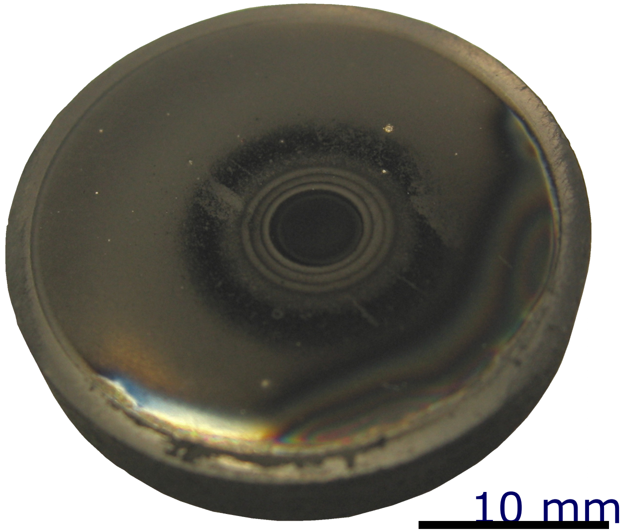
Results: conditions at target

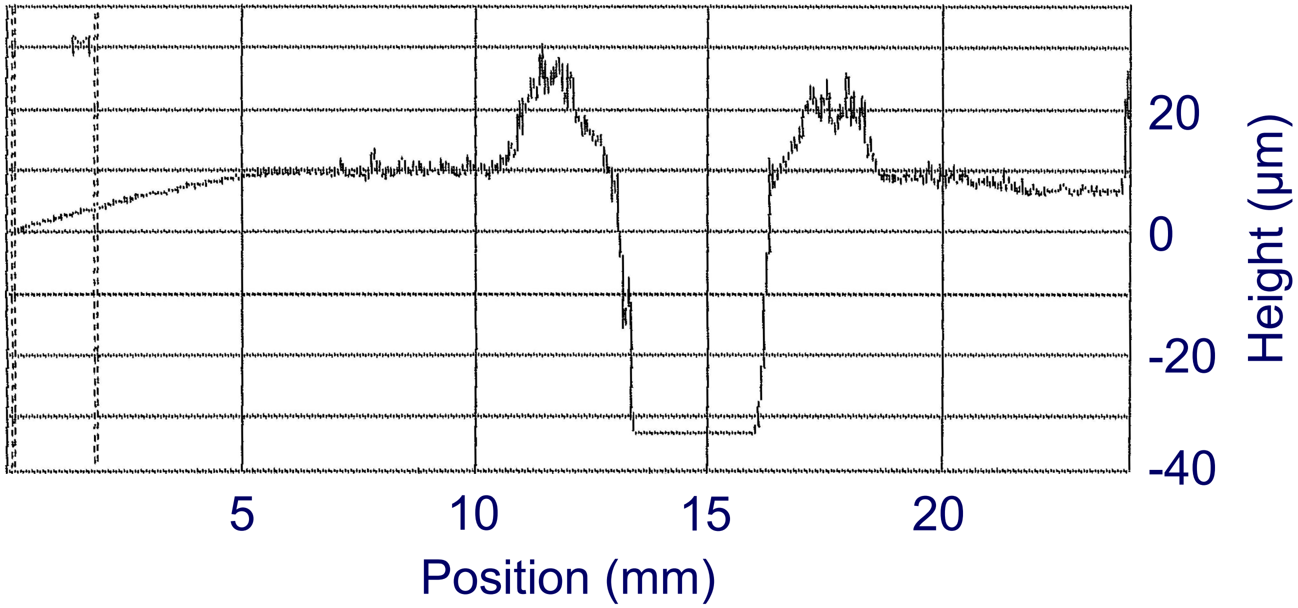


van Rooij, Veremiyenko, Goedheer, de Groot, Kleyn, Smeets, Versloot, Whyte, Engeln, Schram,, Lopes Cardozo, Appl. Phys. Lett., 2007, 90, 121501

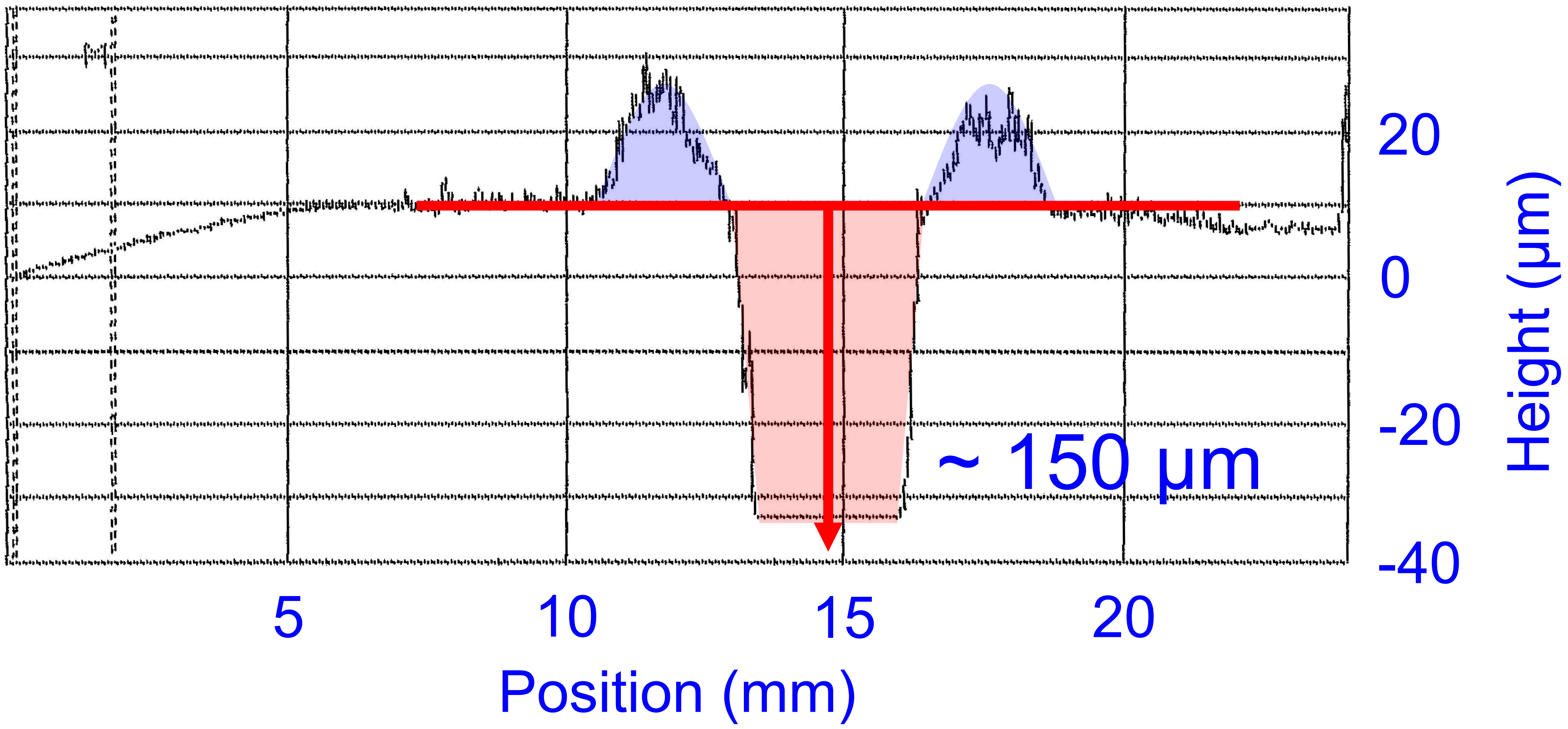
Results: erosion/deposition profile







Results: erosion/deposition profile

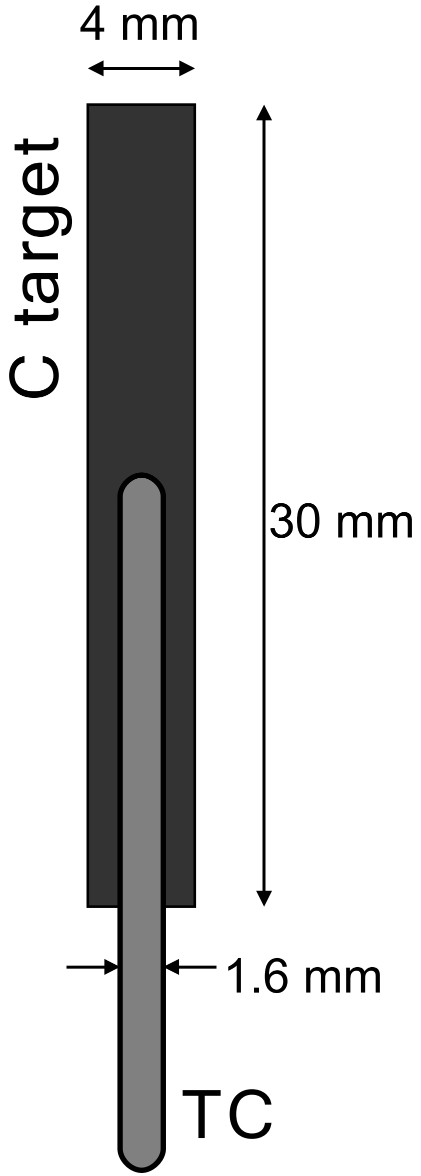


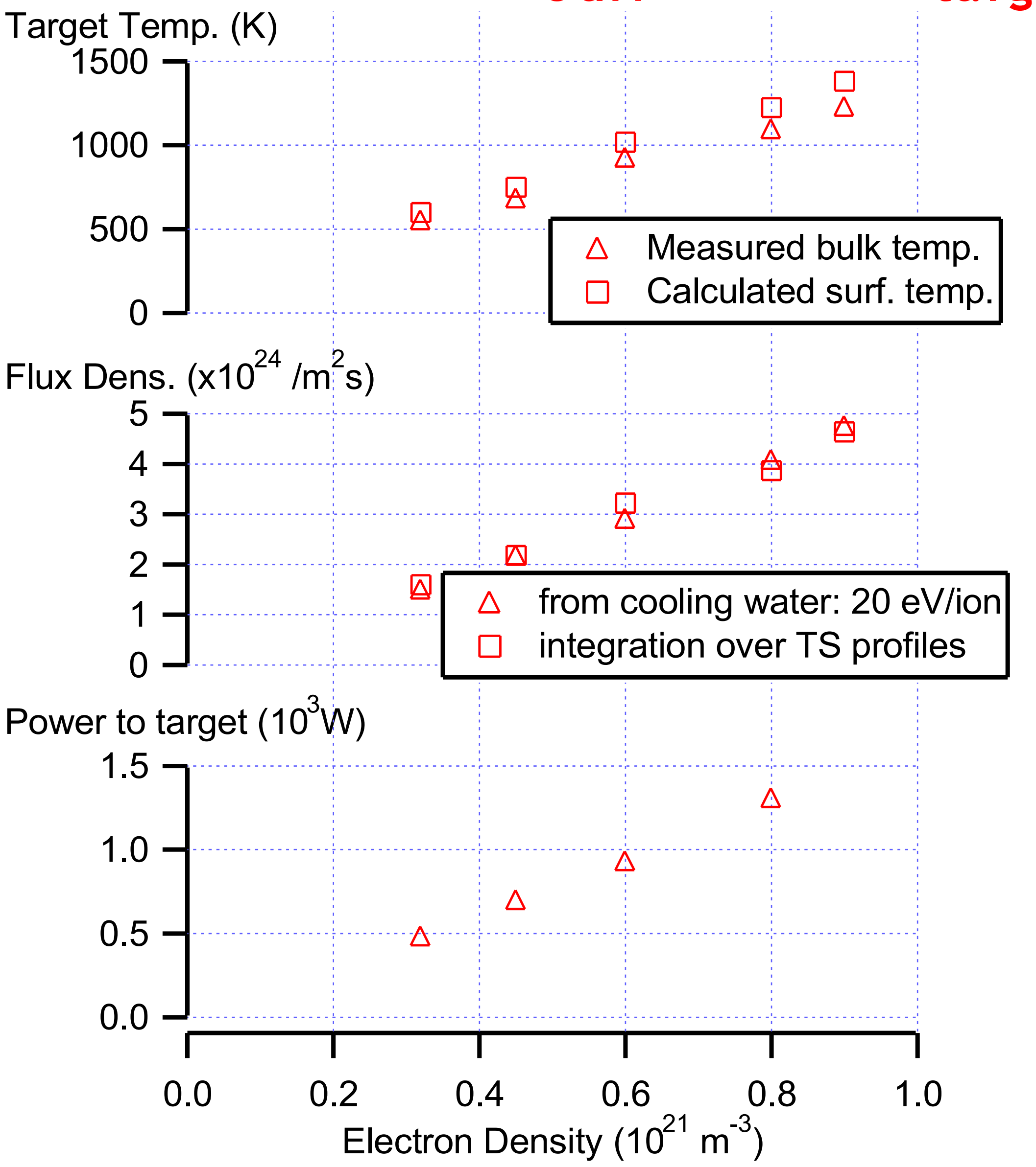
Erosion ≈ 0.94 mm^3

Deposition ≈ 0.47 mm^3

→ 50% redeposition (Vol.% !)

Results: comparing Γ, T_{surf} and P_{target}





Conclusions

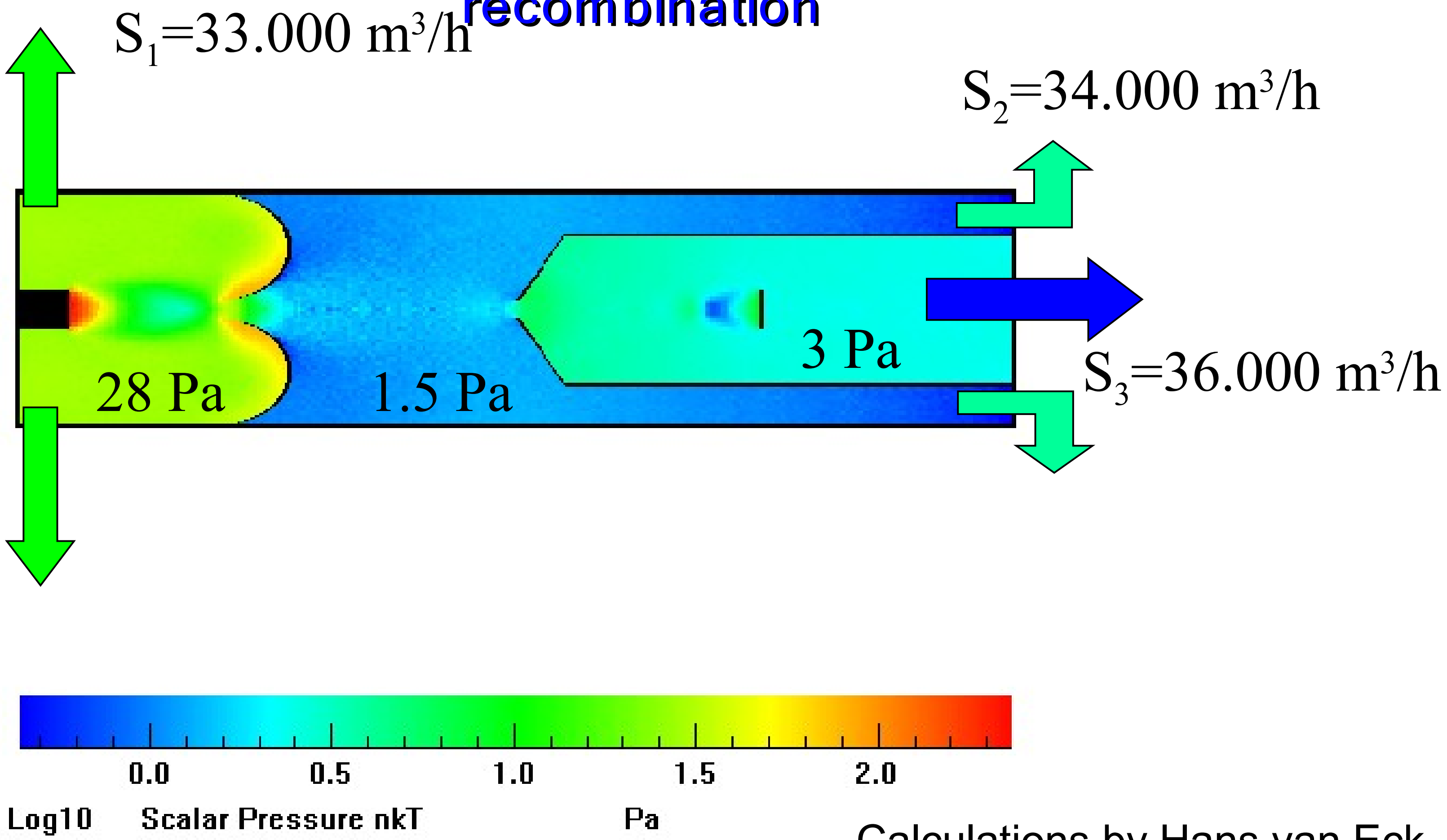
- Exposures at flux densities of $1-5 \cdot 10^{24}$ m^{-2}s^{-1} demonstrated
- Calculated sheath flux agrees with power to target
- Flux sets surface temperature up to ~1400 K
- Up to 50 vol.% redeposition observed
- (Preliminary) chemical erosion yield drops by factor 50 by elevating surface temperature from 600 to 1400 K

BUT:

- Pressure at target high with respect to ITER
- Only normal incidence, small target
- Magnetic field (<1.6 T pulsed)
- Need to design new machine: MAGNUM-PSI

Does differential pumping work beyond the molecular flow regime:

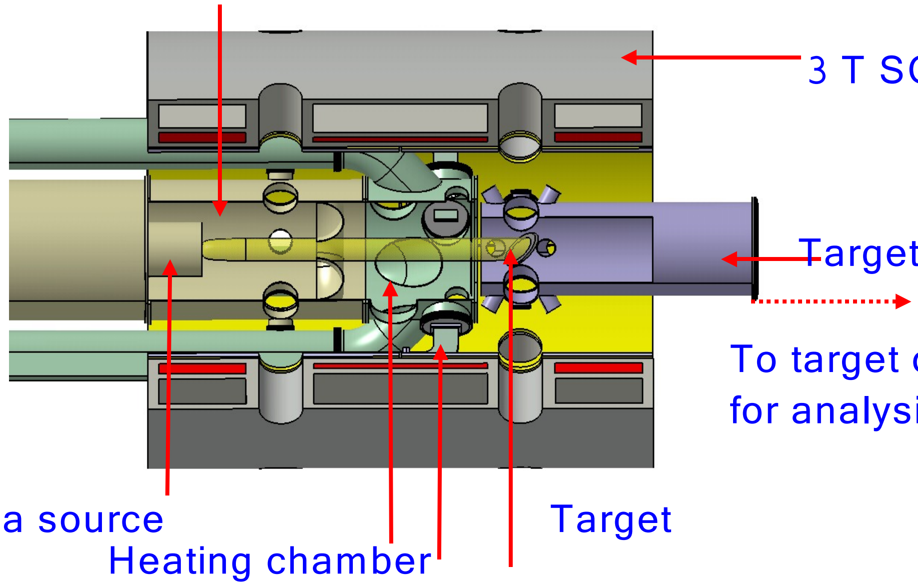
75 slm Argon and 7.5 slm source in 3rd stage, to simulate recombination

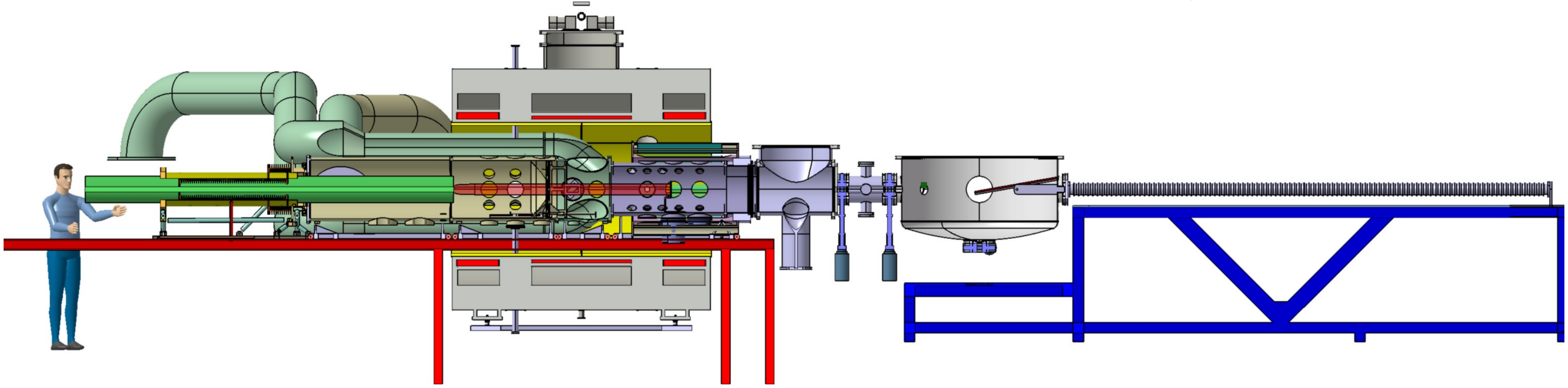


Calculations by Hans van Eck

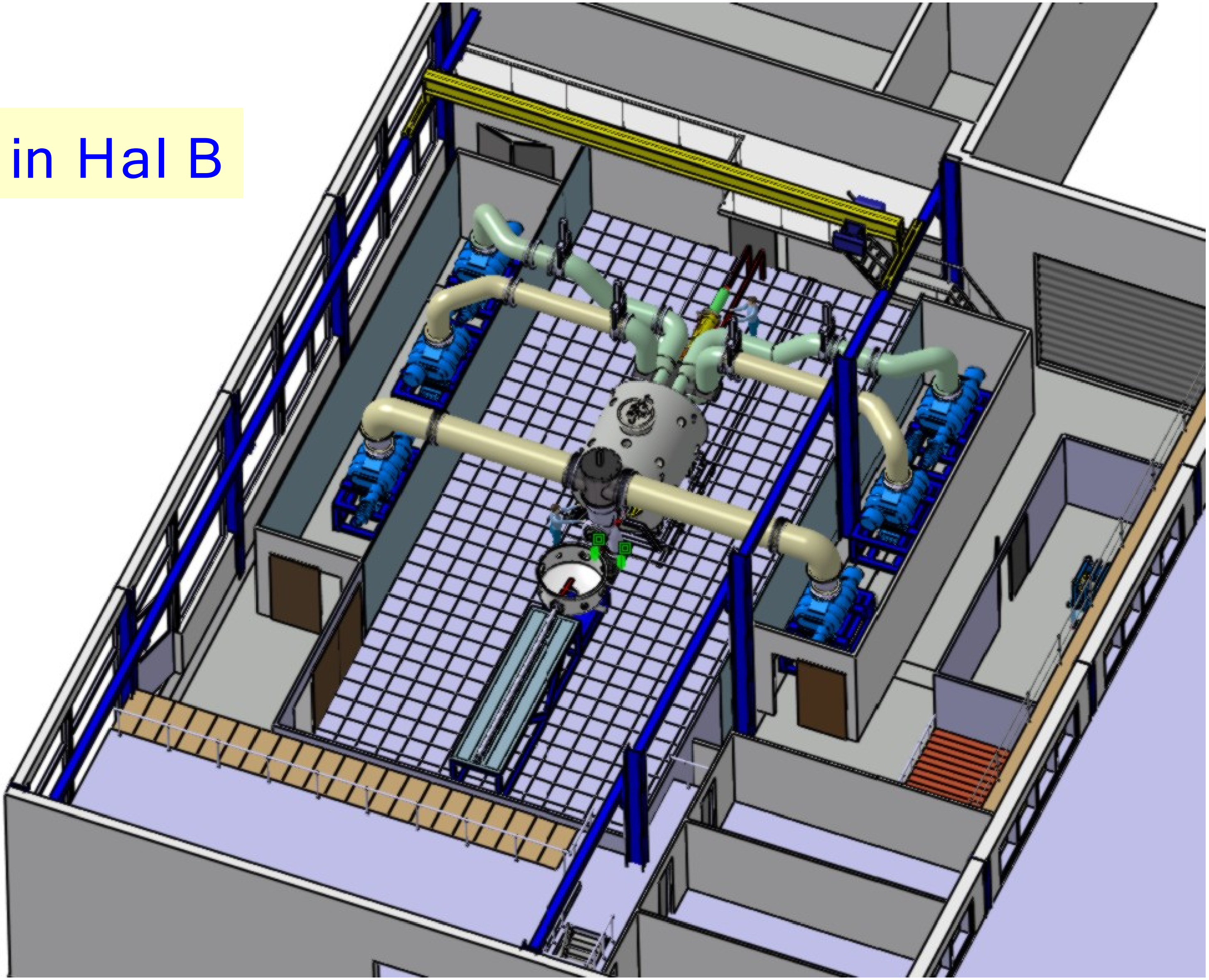
Design Magnum-PSI

3T, steady state
10 cm diameter beam





Pumps in Hal B



Conclusions:

- Hydrogen surface interactions still not fully understood at low flux
- Plasma-surface interaction in ITER can be modeled outside ITER; items to be studied:
- Detached divertor region cooling plasma from 10 keV to 1 eV
- Surface stability in steady state
- Surface stability during excessive plasma load
- Hydrogen retention and removal
- Behaviour of multicomponent ITER wall (C, W, Be)
- 10 MW m^{-2} power load, like the surface of the Sun!

Lots of opportunities for novel research in a number of fields

See: Kleyn, Lopes Cardozo, Samm, Physical Chemistry Chemical Physics 8 (2006) 1761.