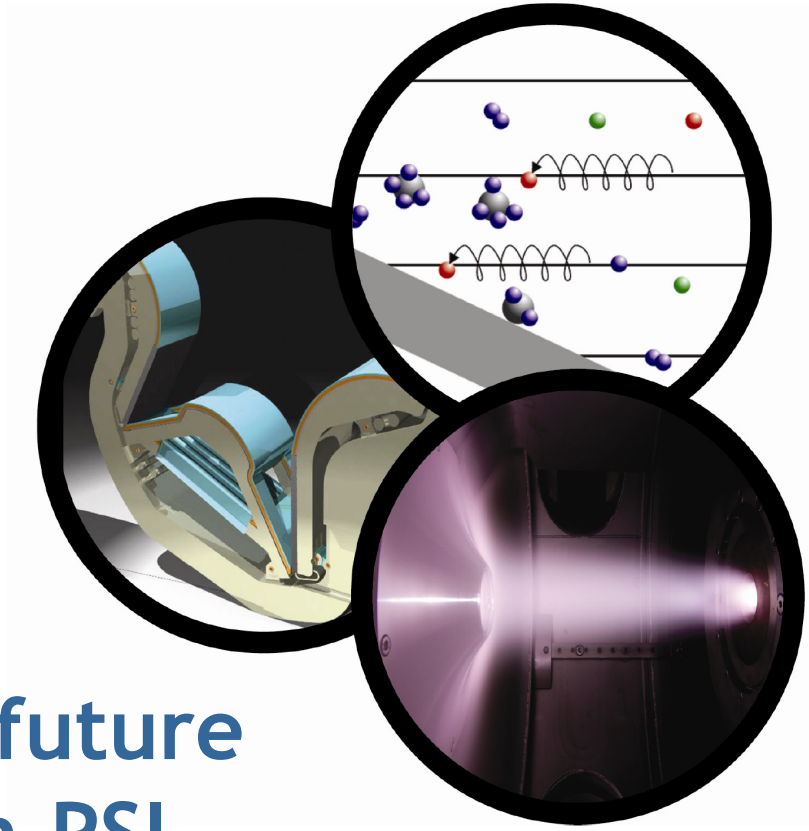


An advanced plasma generator in support of future fusion reactors: Magnum-PSI

Jürgen Rapp

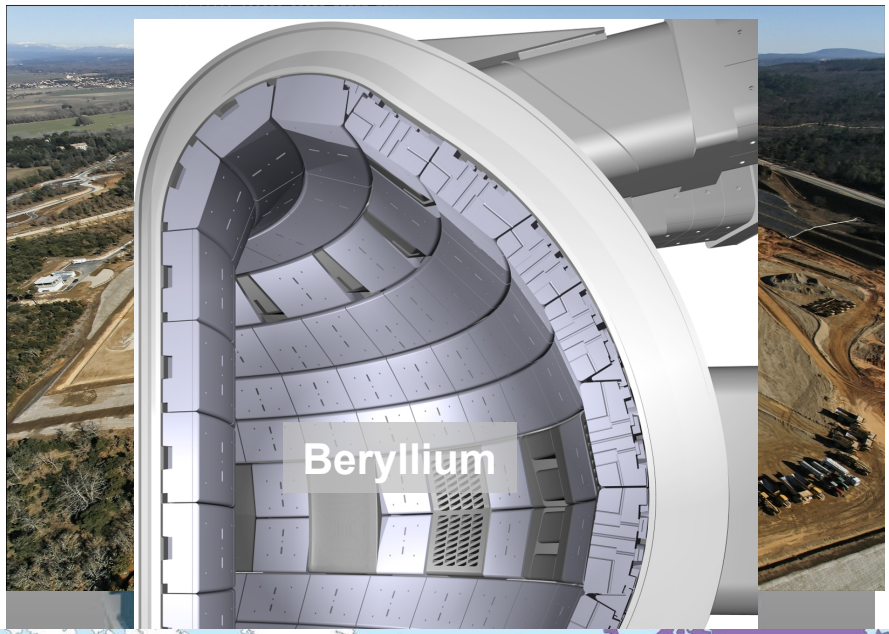
New era has started

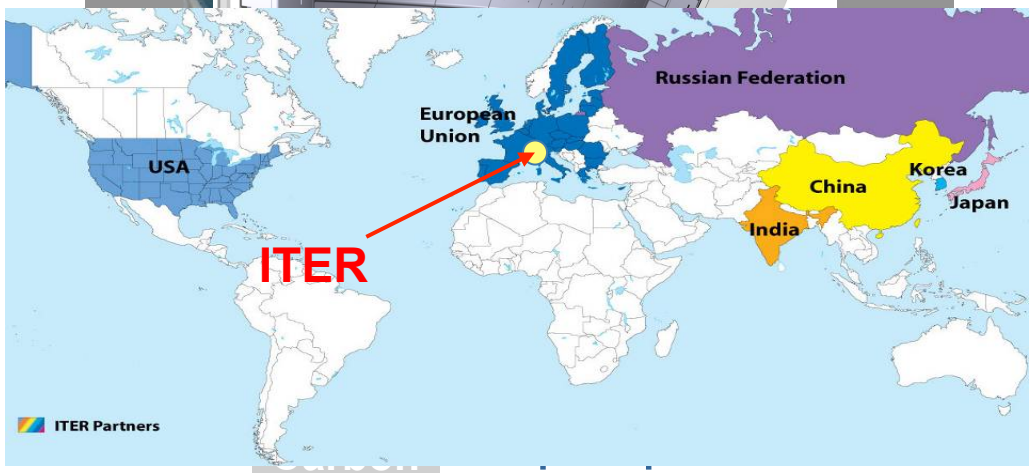
ITER in construction

DEMO in study stage
(conceptual design in Japan, Korea, US, China)

ITER will demonstrate for the first time a thermonuclear burning plasma

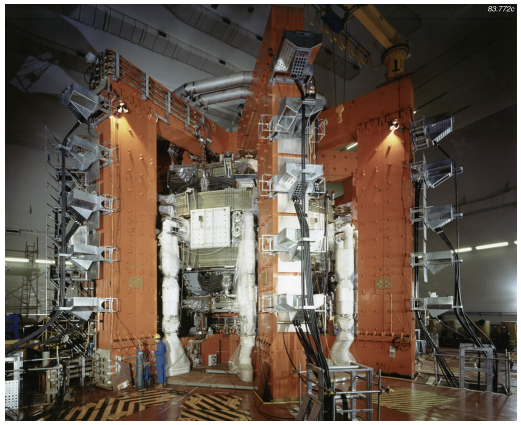
The wall components will define the quality, economy and hence the success of the device



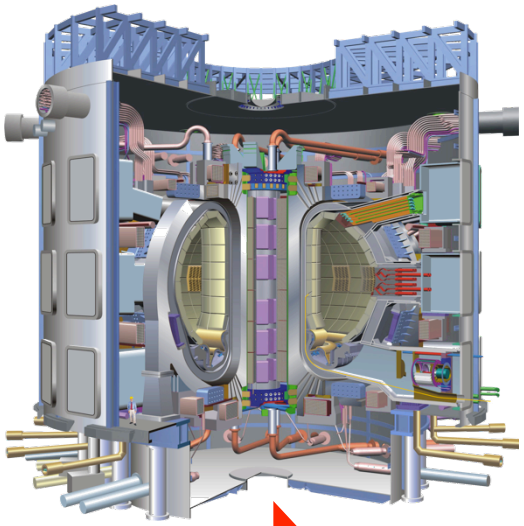


Challenges for PFCs: particle fluxes

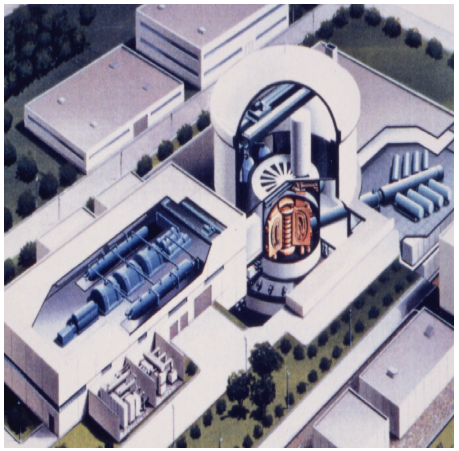
JET



ITER



DEMO



50 times higher ion fluxes

5000 times higher ion fluen up to 5 times higher ion fluence

1000000 times higher neutron fluence gher neutron fluence

Challenges: thermal loads

HWR

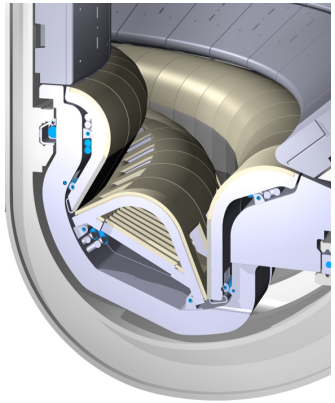
Re-entry vehicle

Ariane 5/Vulcain 2

~1 <10 85 2000

Power load [MW/m^2]

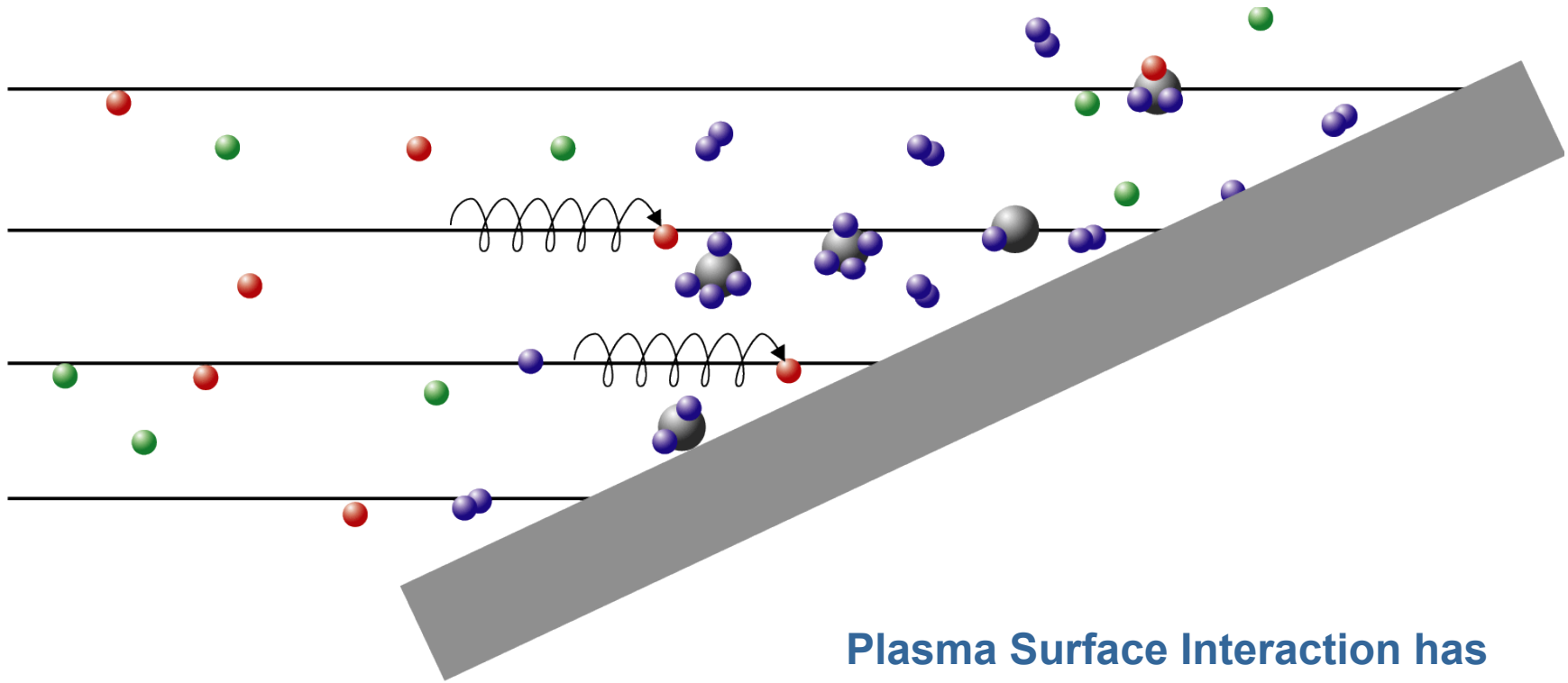
Rolls Royce Trent 900



ITER steady-state

ITER transients

Plasma surface interactions



Plasma Surface Interaction has impact on quality by

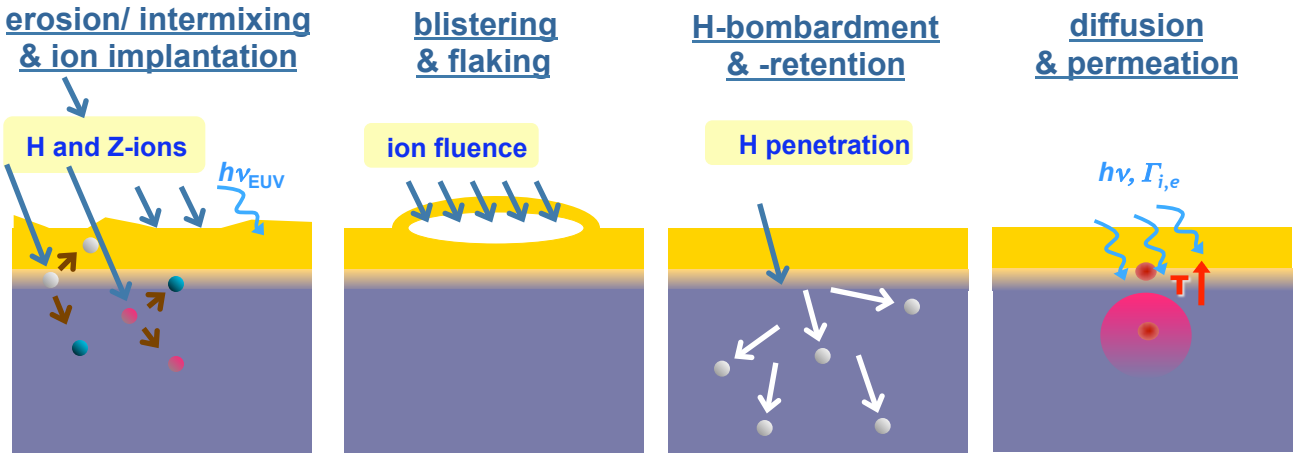
- Degradation of SPECS (heat load capability.....)
- Lifetime of components (erosion, impurity contamination.....)
- Contamination of device by eroded material

Plasma surface interactions

Complex systems with many species and layers

H, D ions plus low-Z and high-Z ions:

He, C, (Be), W, N, Ne, Ar



Extreme conditions change materials considerably

Irradiation by neutrons and helium will enhance surface modification !

Effect of irradiation on PFCs

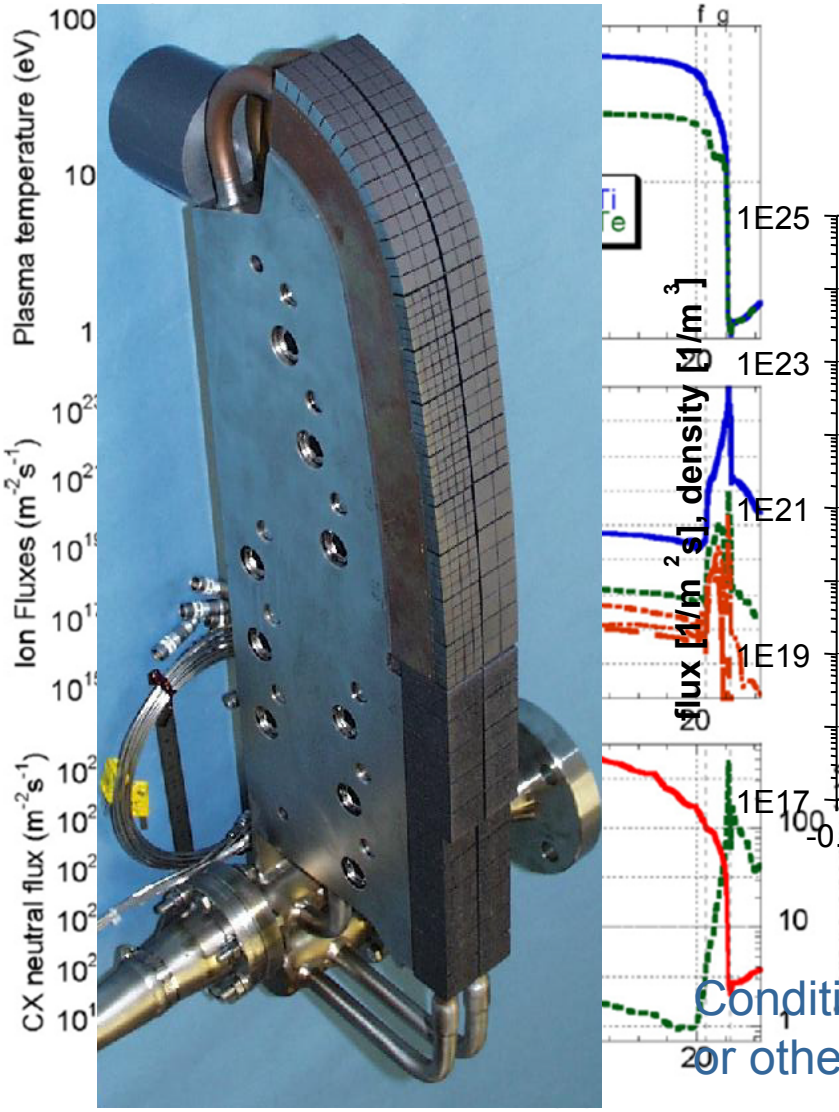
- Thermal conductivity (in particular for carbon based materials)
- Chemical composition (e.g. transmutation)
- Interstitials, vacancies, clusters of those, dislocation loops, voids
- Hydrogenic retention
- Micro-structural changes (e.g. swelling)
- Mechanical properties (e.g. DBTT, He embrittlement)

Damage and transmutation productions for different materials for a neutron fluence of 1 MWa/m^2

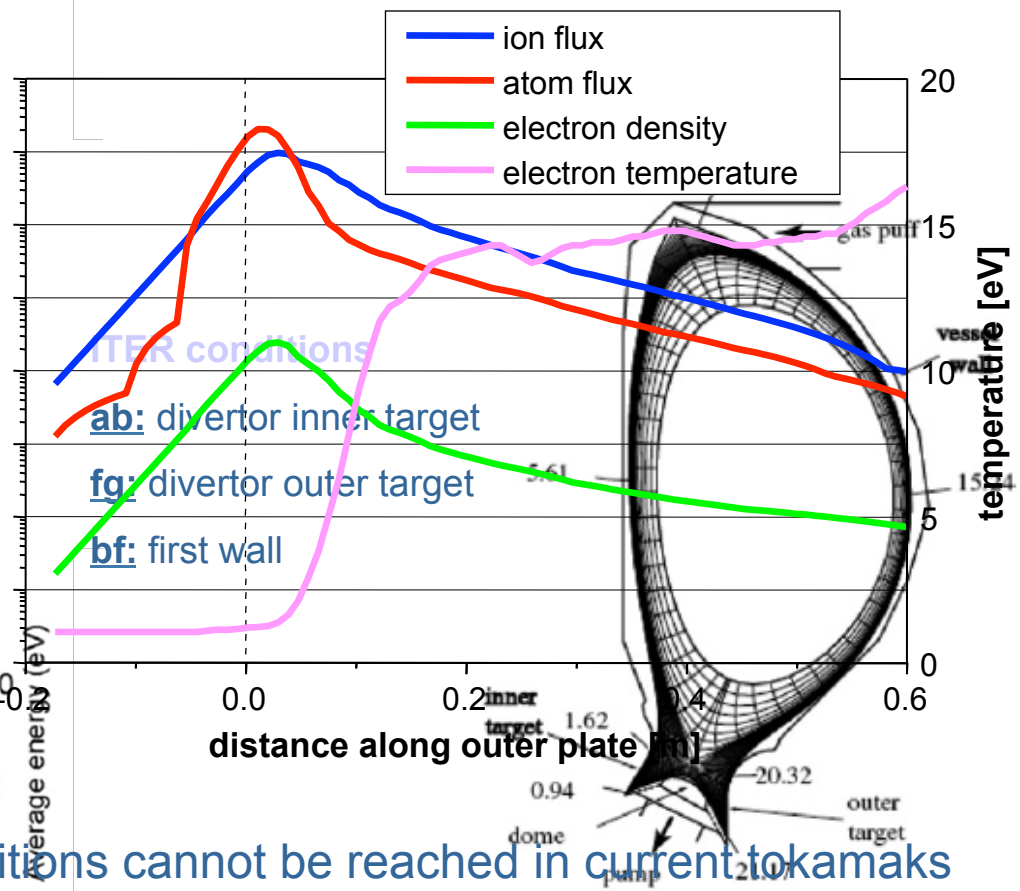
Material	dpa	He (appm)	H, D, T (appm)	Others (%)
Be	3.5	3500	~50 (T)	–
C	4.5	1500	0.2	–
W	3.5	2	0.1	Re: 3, Ta: 0.8, Os: 0.2
Ferritic steel	8.3	150	300	Reducing of W, some Re, Os
V	8.5	50	160	–

Barabash et al., J. Nucl. Mater. 2003, 313-316, 42

Conditions in ITER



B2-Eirene simulation for ITER, including impurities (A.S. Kukushkin)



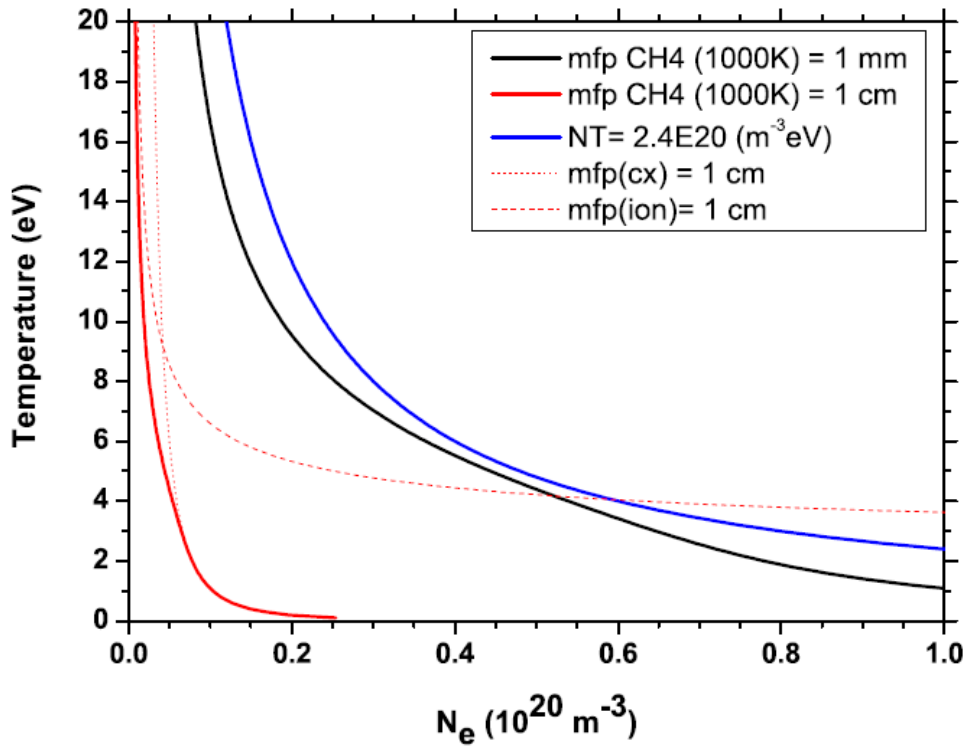
Conditions cannot be reached in current tokamaks or other devices: Design of Magnum-PSI

Design Criteria of Magnum-PSI

- Future fusion reactor plasma conditions
  - high density + low Te, high pressure requires cascaded arc source
- Ensure system size is larger than typical length scales of important physics processes (e.g. confinement of dust particles)
- Mimic real geometries (large targets, shallow angle between magnetic field lines and target surface)
- Reactor relevant heat fluxes (material test stand)
- Add new data to data from existing devices (complementary to existing devices)
- Good diagnostic access
- Surface analysis without breaking vacuum (fast transfer to a target station and good vacuum in target station)

Mean-free path of hydro-carbons

For temperatures higher than lines, hydro-carbons have mean-free path lower than indicated

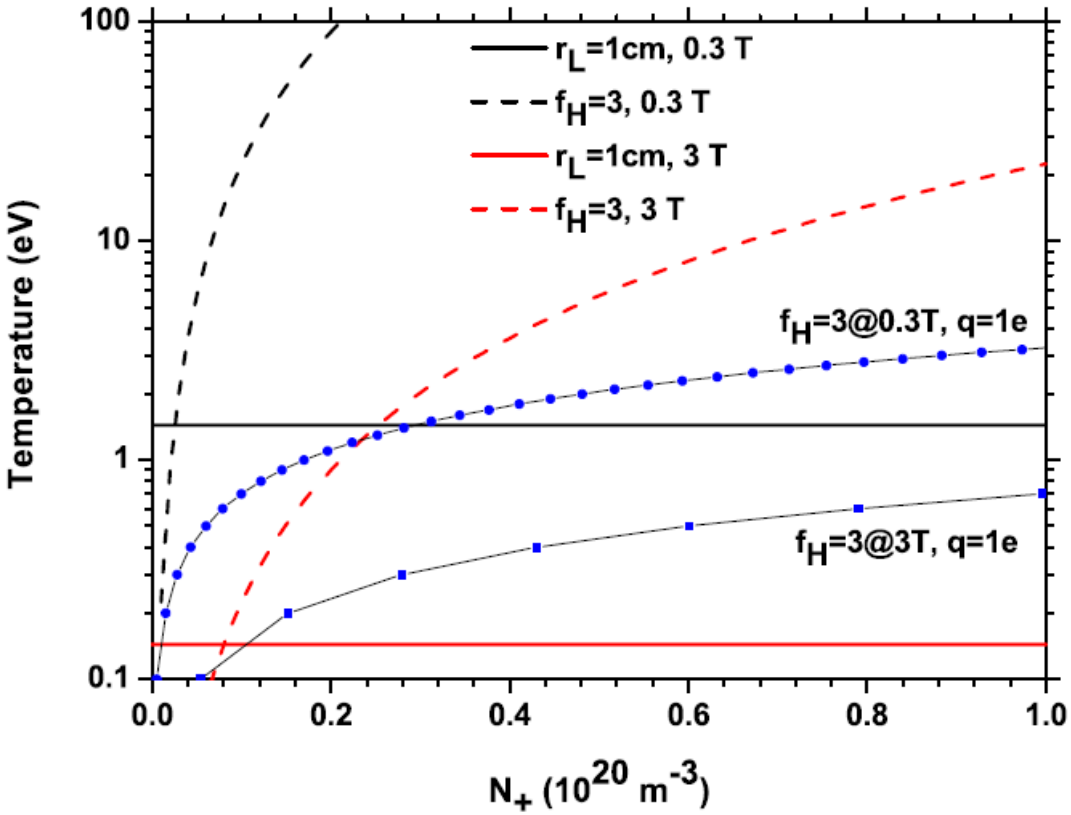


- for Magnum-PSI CX processes determine mean-free path
- Confinement of hydro-carbons should be no big problem

Confinement of dust particles

Spherical particles with floating potential of twice the plasma temperature

For temperatures higher than lines, particles are confined



- Larmor radius is good even for low magnetic fields
- Hall factor determines confinement of dust particles (momentum loss to neutrals and ions)

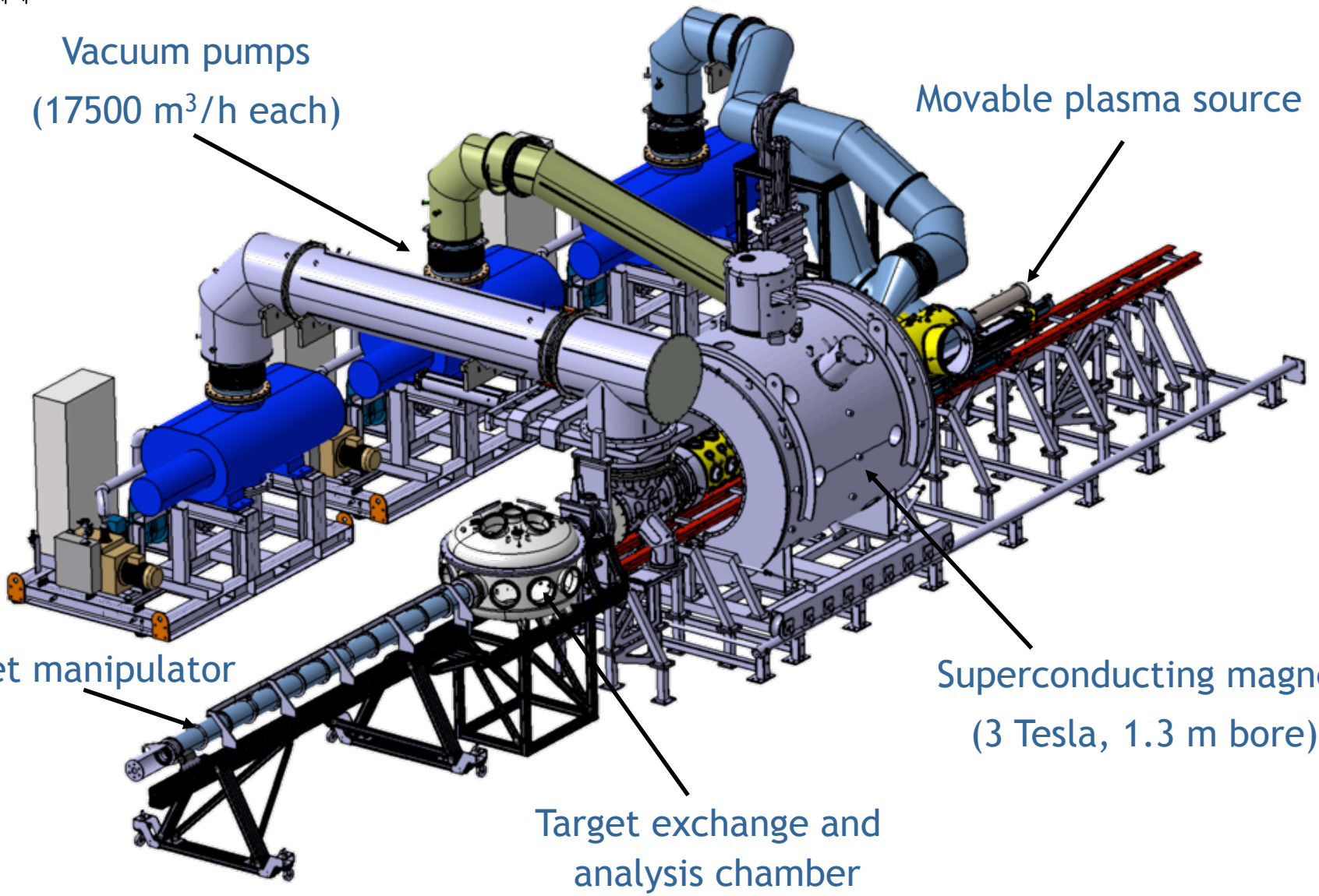
➢ High field of 3T is necessary to confine dust particles with diameter of 20nm

Design Criteria

	Magnum	PISCES
T_i target [eV]	0.1-10	<20
T_e target [eV]	0.1-10	<40
n_i target [m^{-3}]	10^{19}-10^{21}	10^{17}-10^{19}
Pressure target [Pa]	< 3	<1
Ion flux target [m^{-2} s^{-1}]	10^{24} (⊥); 10^{25} (‖)	10^{23}
Power flux target [MW/m^2]	10 (⊥); ~100 (‖)	<10
Power flux transiently [MJ/m^2]	2	0
B [T]	3	0.05
Pulse length [s]	steady state	steady state
Beam diameter [cm]	10-1.5	20-3
Target size [cm]	60 x 12	
mfp of CH4 [cm]	1-0.01	10-1
dust particle size [nm]	60-0.6	0

- Magnum-PSI will be able to investigate the strongly coupled PSI regime

Overview of Magnum-PSI



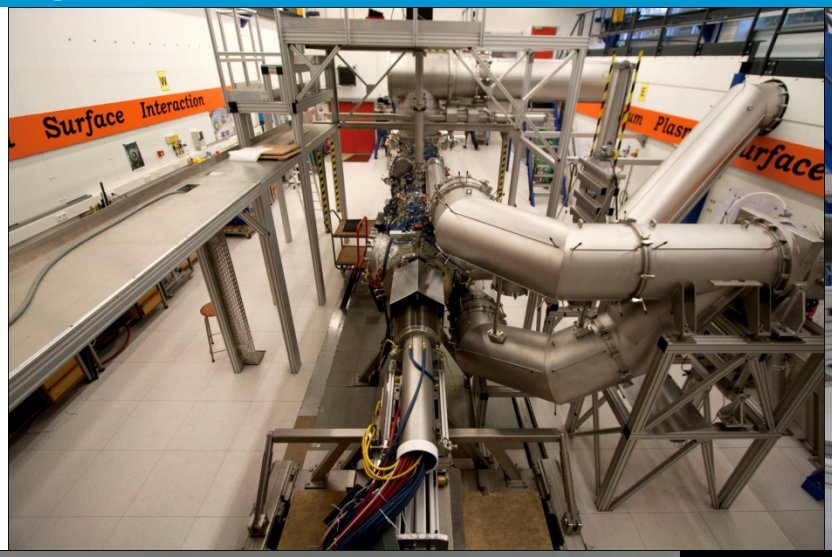
Magnum-PSI

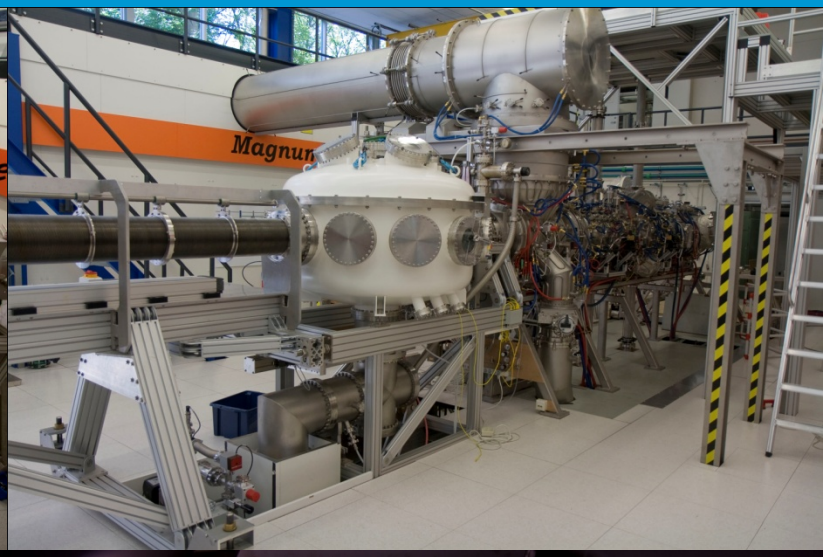
2

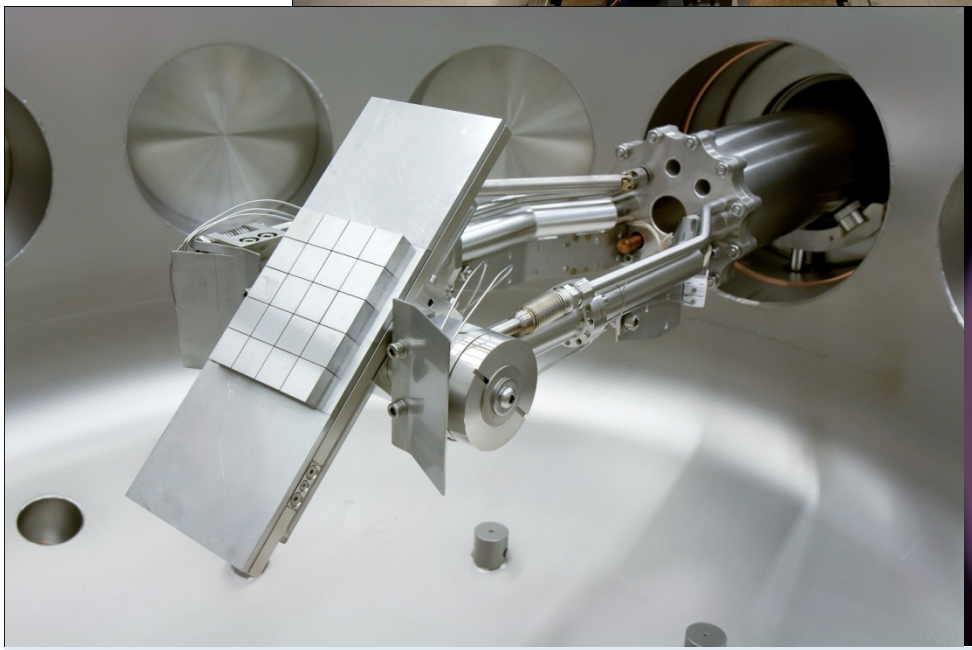
0

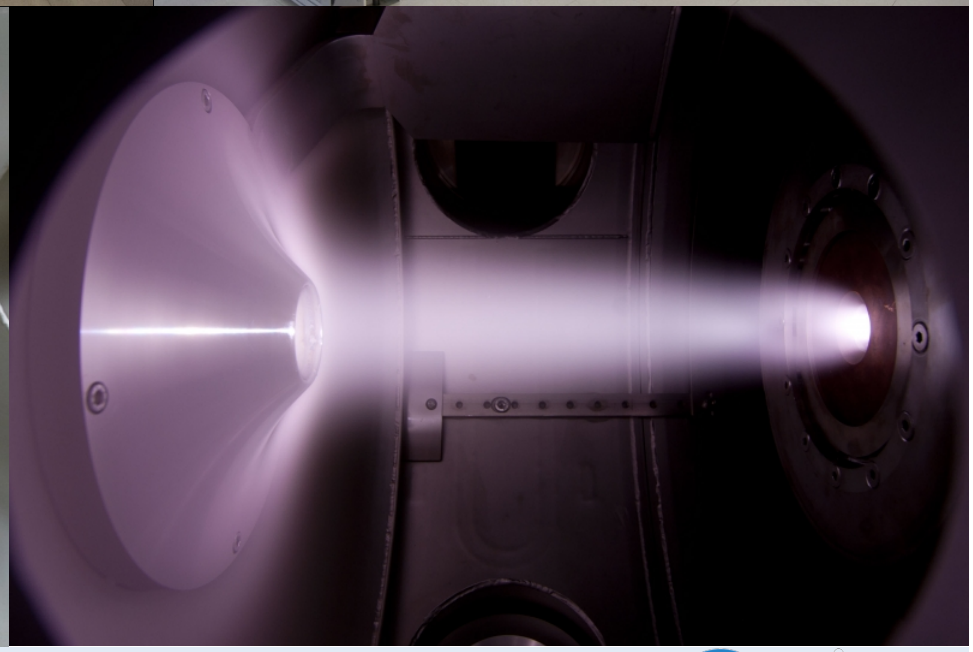
1

0

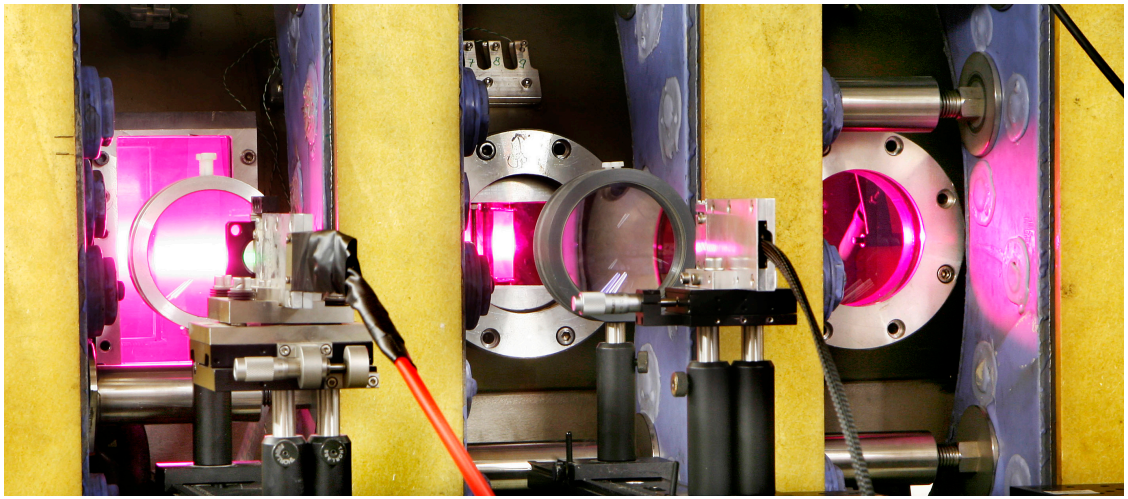


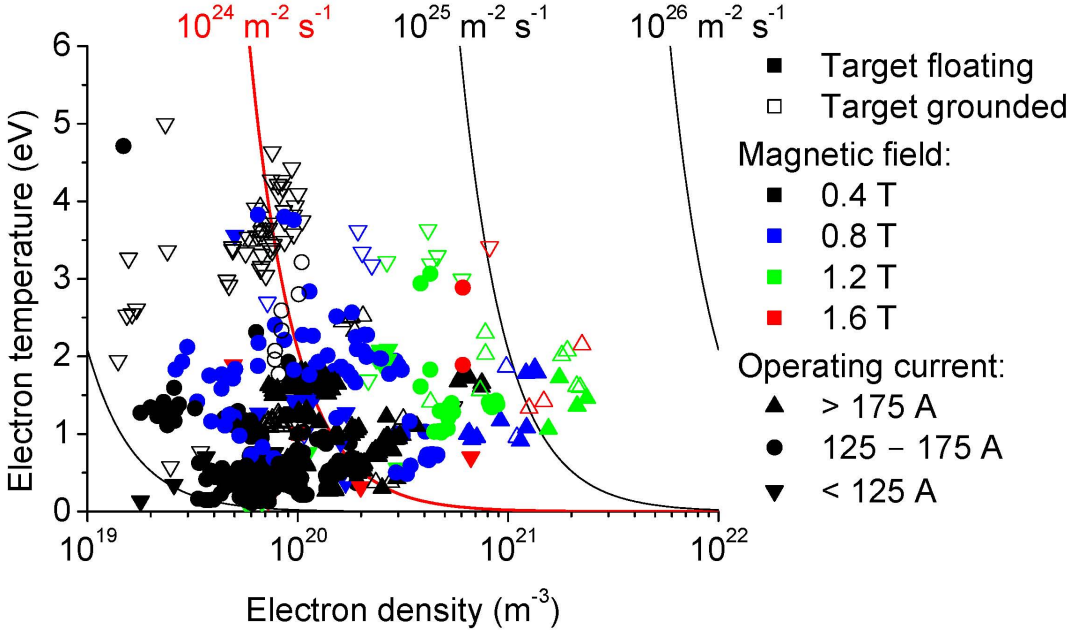






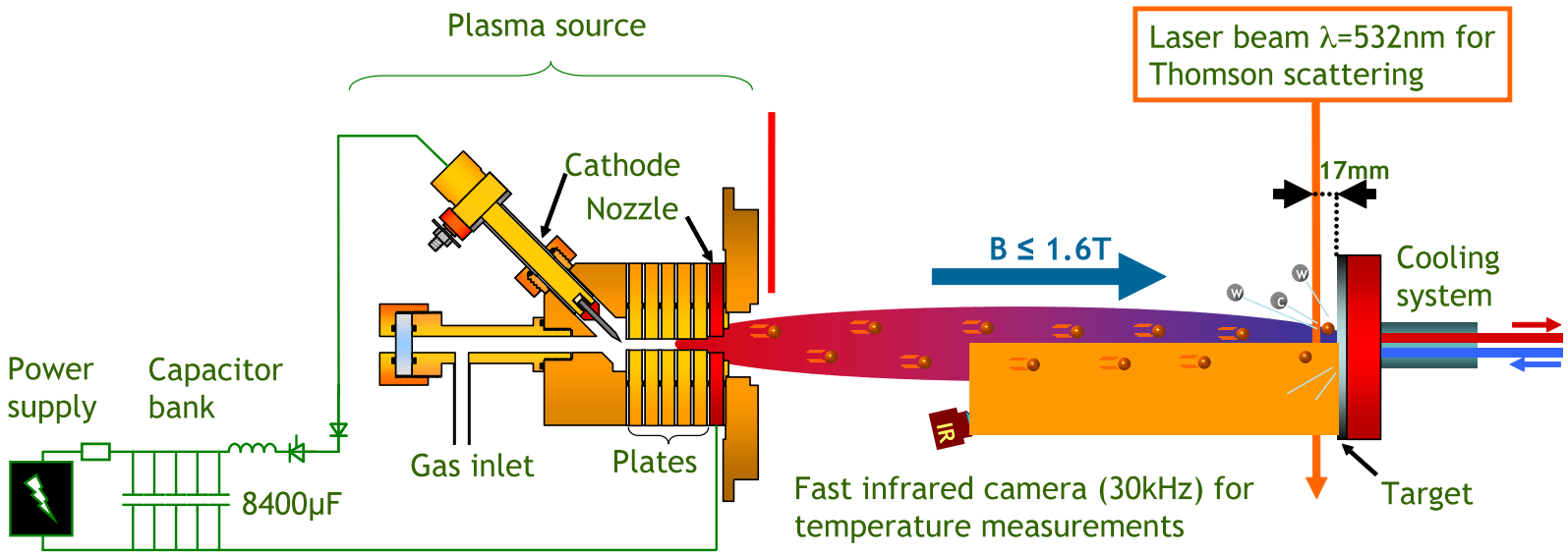
Forerunner experiment Pilot-PSI





Transient heat/particle pulses in Pilot-PSI

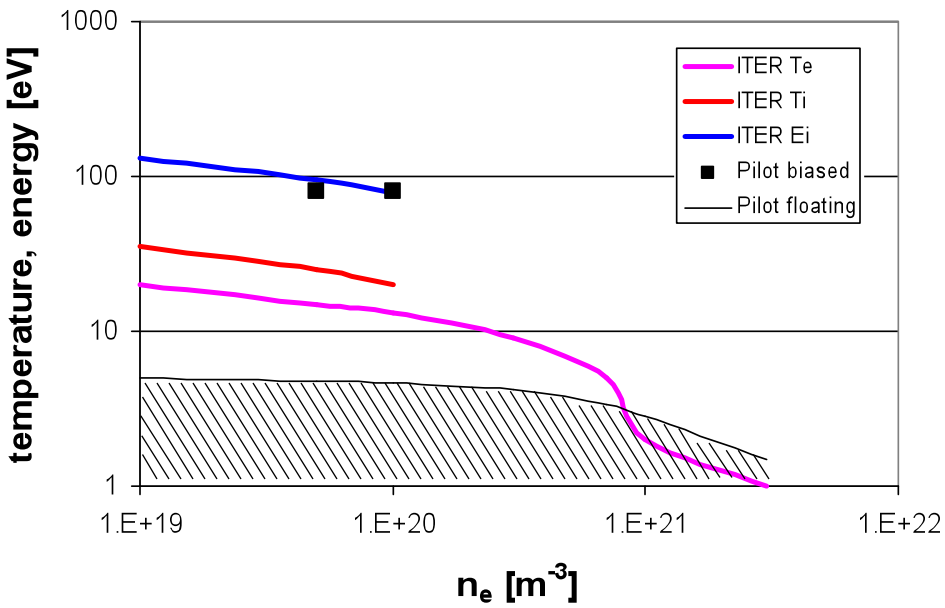
- Plasma source modified to allow very high power operation
- In parallel to DC power supply, discharge current transiently increased by discharging capacitor in source



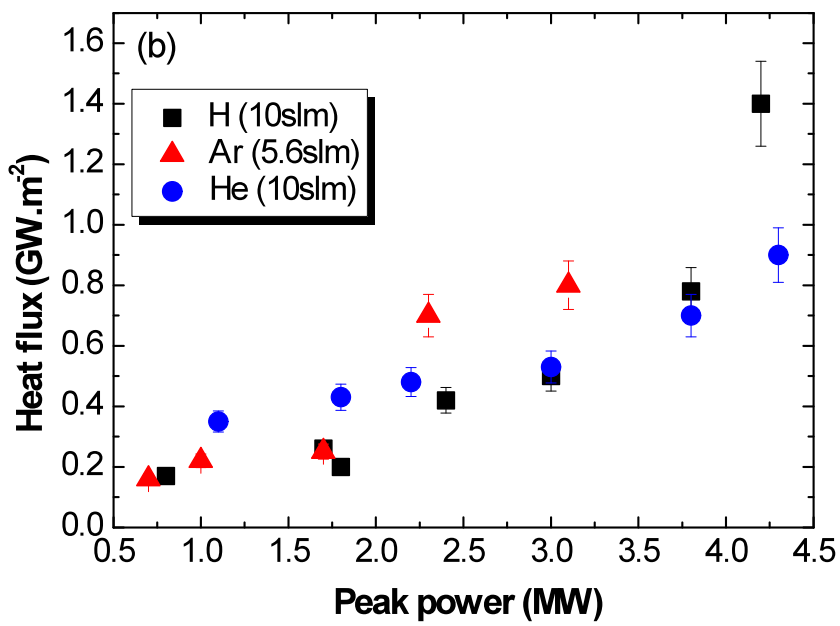
Pulsed plasma superimposed on steady-sate plasma
Pulsed bias system being developed (-100V reached)

Operation domain proven on Pilot-PSI

Quasi steady state conditions for Pilot-PSI



Pulsed source operation for ELM simulation in Pilot-PSI



Operation domain of linear plasma generators is compatible with ITER plasma parameters in front of divertor and main chamber wall PFCs

Specification of Magnum-PSI

	Magnum	Pilot achieved	Pulsed CA achieved
Power [kW]	270	135	4500
Pressure source [Pa]	10^4	10^4	
Pressure target [Pa]	< 3	1-10	
T_i target [eV]	0.1-10	0.1-5	
T_e target [eV]	0.1-10	0.1-5	~ 6
n_i target [m^{-3}]	10^{20}-10^{21}	10^{21}	~ 2 x 10^{22}
Ion flux target [m^{-2} s^{-1}]	10^{24}-10^{25}	2 x 10^{25}	
Power flux target [MW m^{-2}]	10	30 (80)	1400
B [T]	3	1.6	1.6
Beam diameter [cm]	10-1.5	1.5	2.0
Pulse length [s]	steady state	4	0.0005
Extra heating [kW]	50	0	0
Target size [cm]	60 x 12	2.5	2.5

Single arc high performance

From thesis W. Vijvers:

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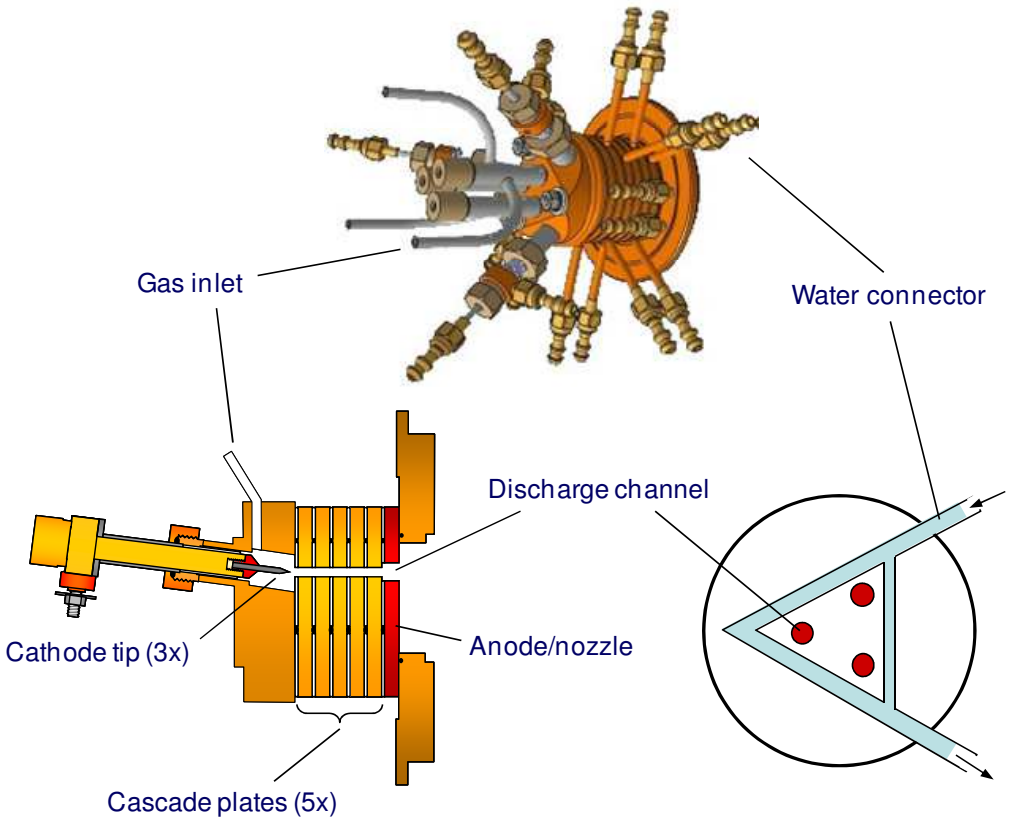
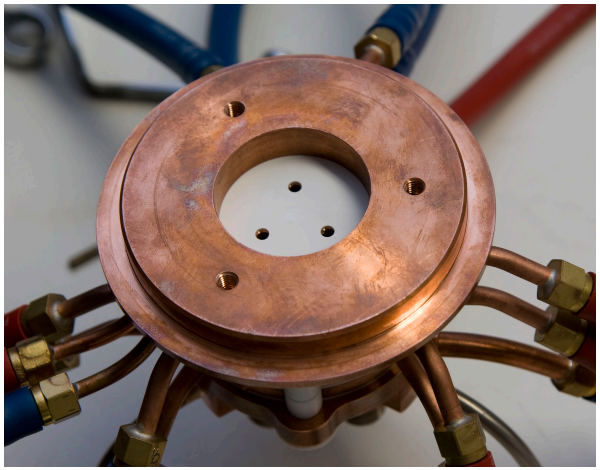
Quantity	Requirement	Result	Difference	
Ion flux density	$10^{24}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$	$2 \cdot 10^{25}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$	$20\times$	✓
Total flux	$4 \cdot 10^{21}\,\mathrm{s}^{-1}$	$2 \cdot 10^{21}\,\mathrm{s}^{-1}$	$\frac{1}{2}\times$	~✓
Temperature	1-3 eV	2 eV		✓
Beam width	10 cm	2 cm	$\frac{1}{5}\times$	-
Gas efficiency	20%	~40%	$2\times$	✓
Energy efficiency	10%	12%	$1.2\times$	✓

Table 6.1: Overview of Magnum-PSI requirements and experimental results obtained with the 7 mm diameter, 18 mm long source described in chapter 5.

Plasma source development: multiple beams

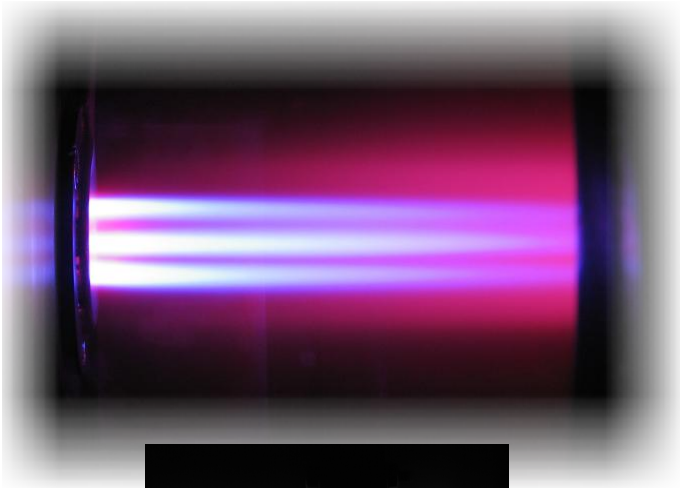


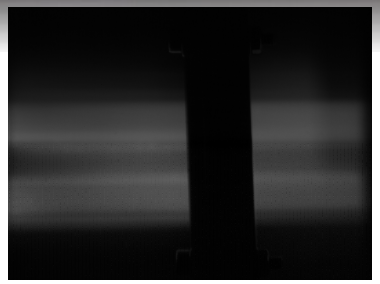


- Multiple channels, because limit on diameter (pressure)
- Cooling design challenging
- Channels operate independently
- Hydrogen operation sensitive to details of source construction

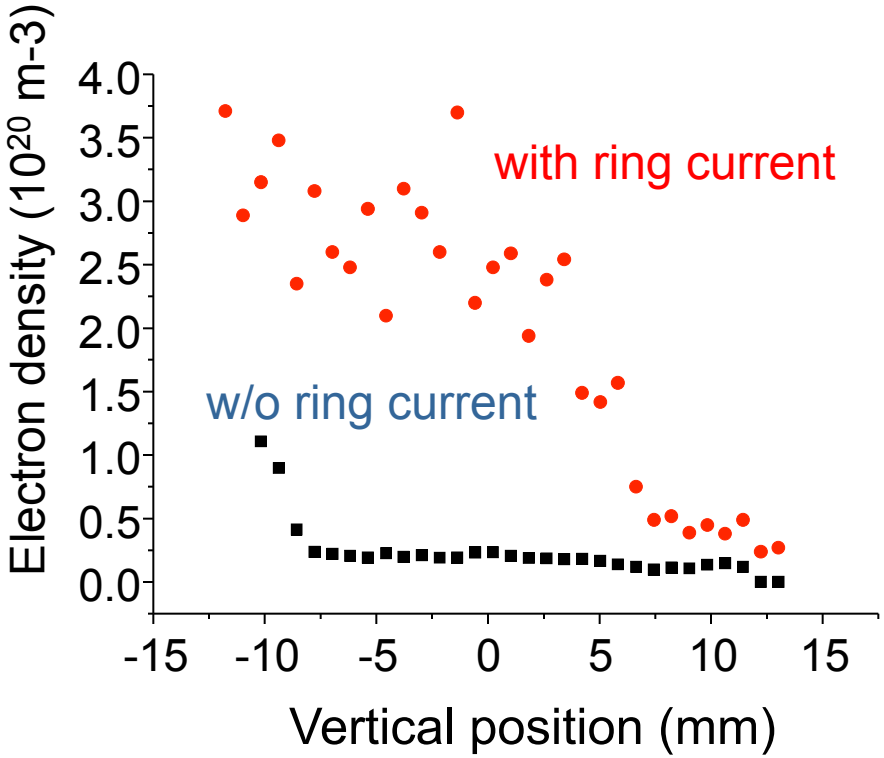
Mixing of multiple hydrogen beams

H plasma w/o ring





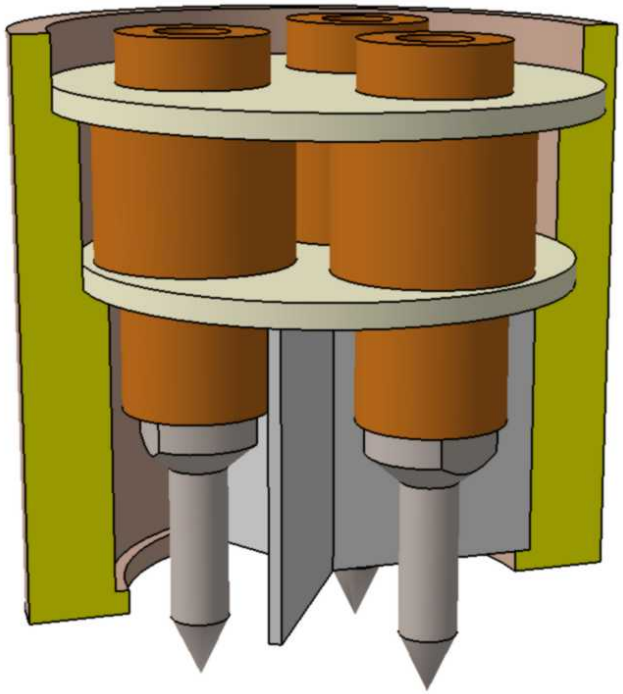
Absolute numbers!

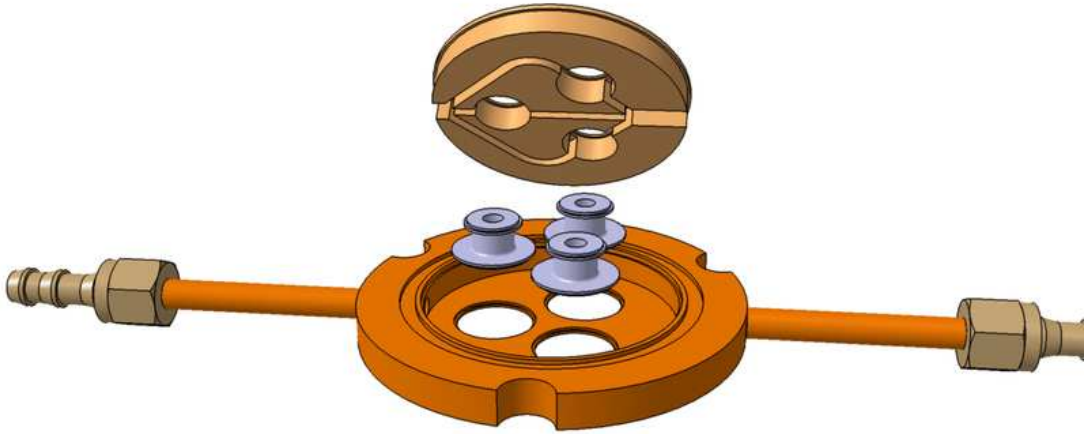


Mixing by ring electrode

New 3channel concepts

Pure H is difficult due to high power loads.
New 3channel source under development
with better cooling



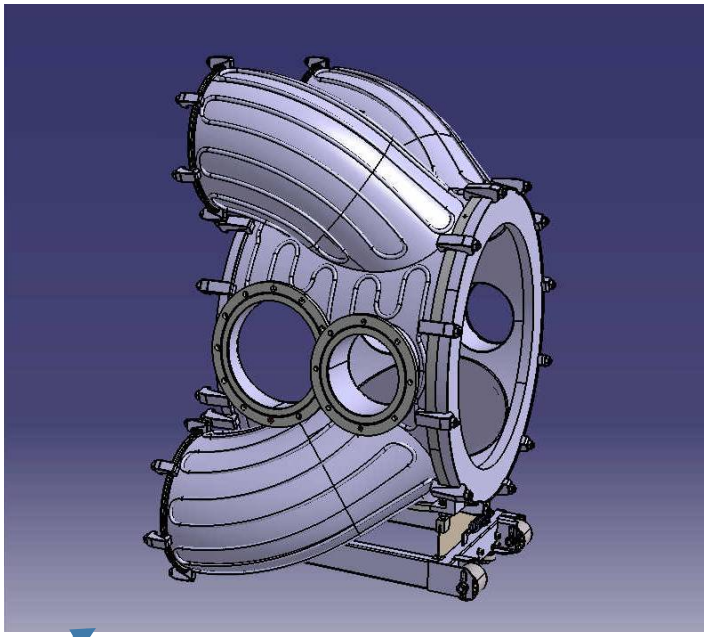


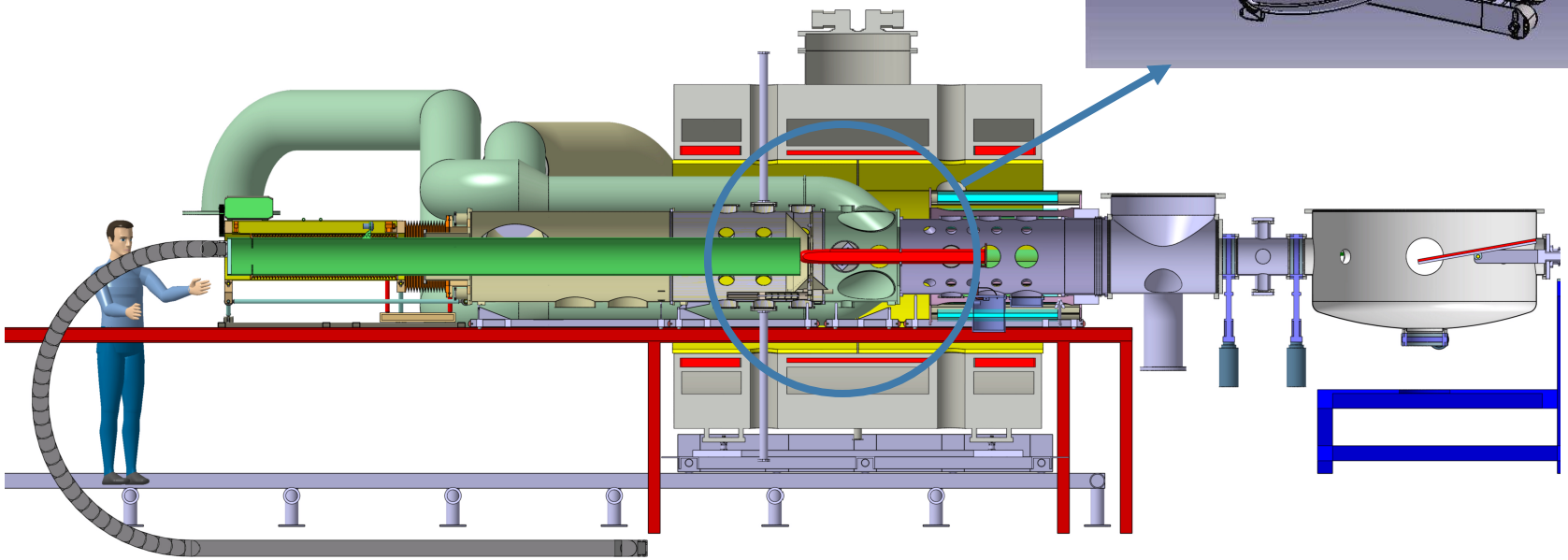
Magnum-PSI: RF heating

Two frequency ranges are considered:

- Lower Hybrid range (2.45 GHz)
- Ion Cyclotron range (5-50 MHz)

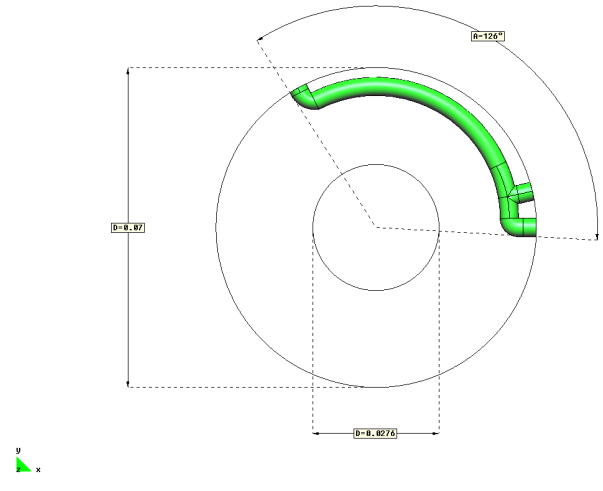
Collaboration with ERM/KMS Brussels and Politecnico di Torino, Italy

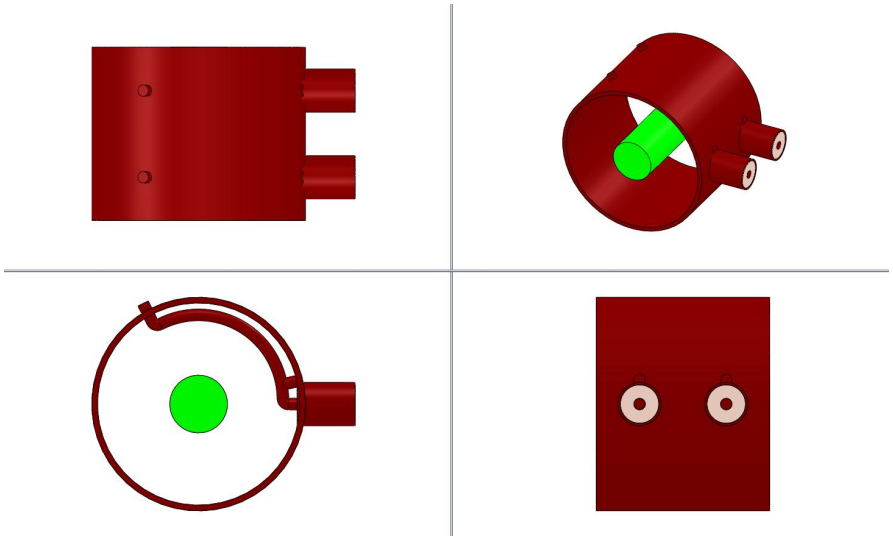




Magnum-PSI: Lower Hybrid heating

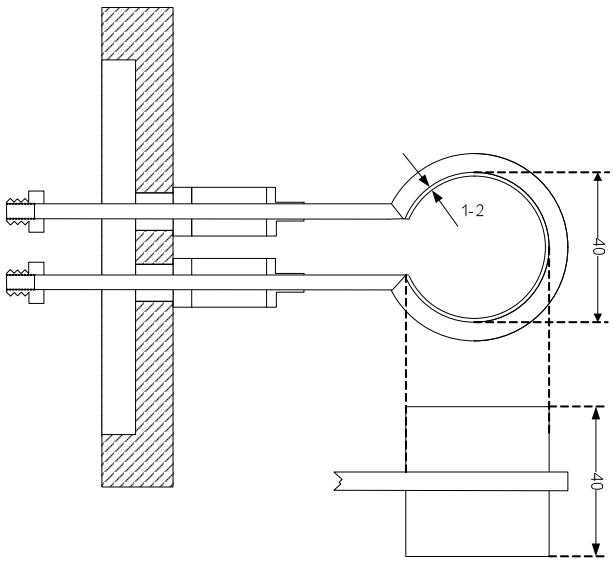
- ~ 800 MHz – 2.5 GHz (2.45 GHz preferred)
- Array antenna of 2 elements. Each element is water cooled.
- Designed using CST Microwave Studio.
- Optimized element parameters: length, stub location, radius and distance from metallic cylinder.
- Reflection coefficient after optimization: -2.5 dB at 2.45 GHz.





Magnum-PSI: Ion Cyclotron Heating

- ~ 5-50 MHz
- TOPCYL design (cylindrical version of TOPICA (TOrino Politechnic Cyclotron Antenna) code), including plasma model
- TOPCYL validation on PILOT-PSI measurements
- First test with a single loop antenna were performed on Pilot-PSI
- Final design is double-loop antenna
- Tests with double-loop antenna are imminent

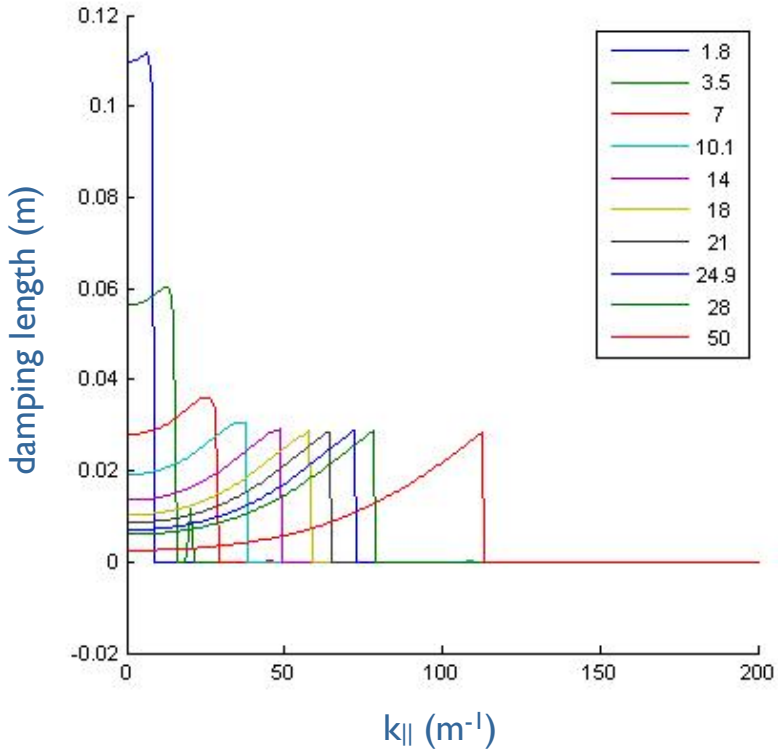


non-optimized test antenna without TOPCYL

Magnum-PSI: Ion Cyclotron Heating

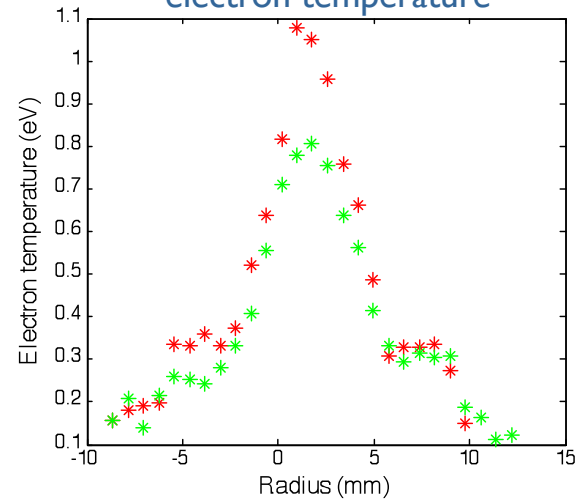
preliminary result @ 18.2 MHz

Pilot setting: 2 slm H_2, 150 A, 0.8 T

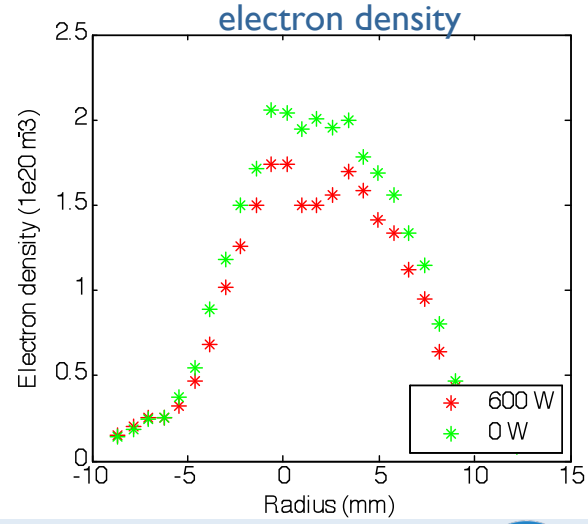


Thomson scattering

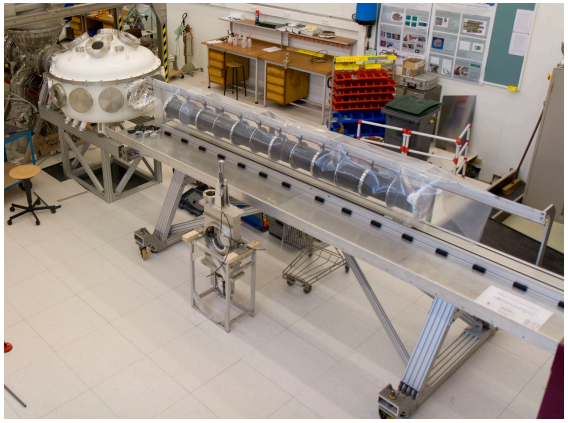
electron temperature

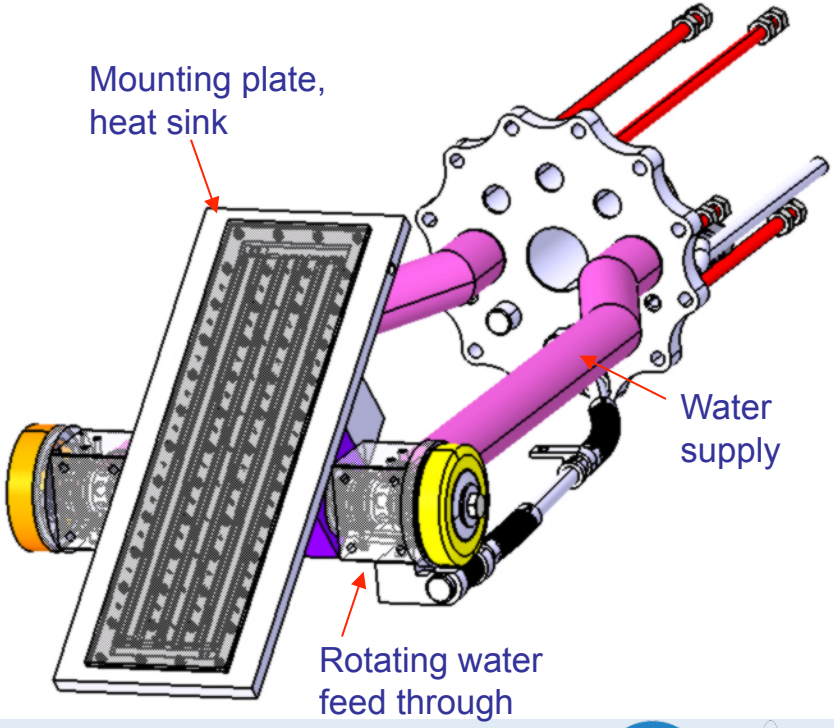


electron density



Magnum-PSI: Target station

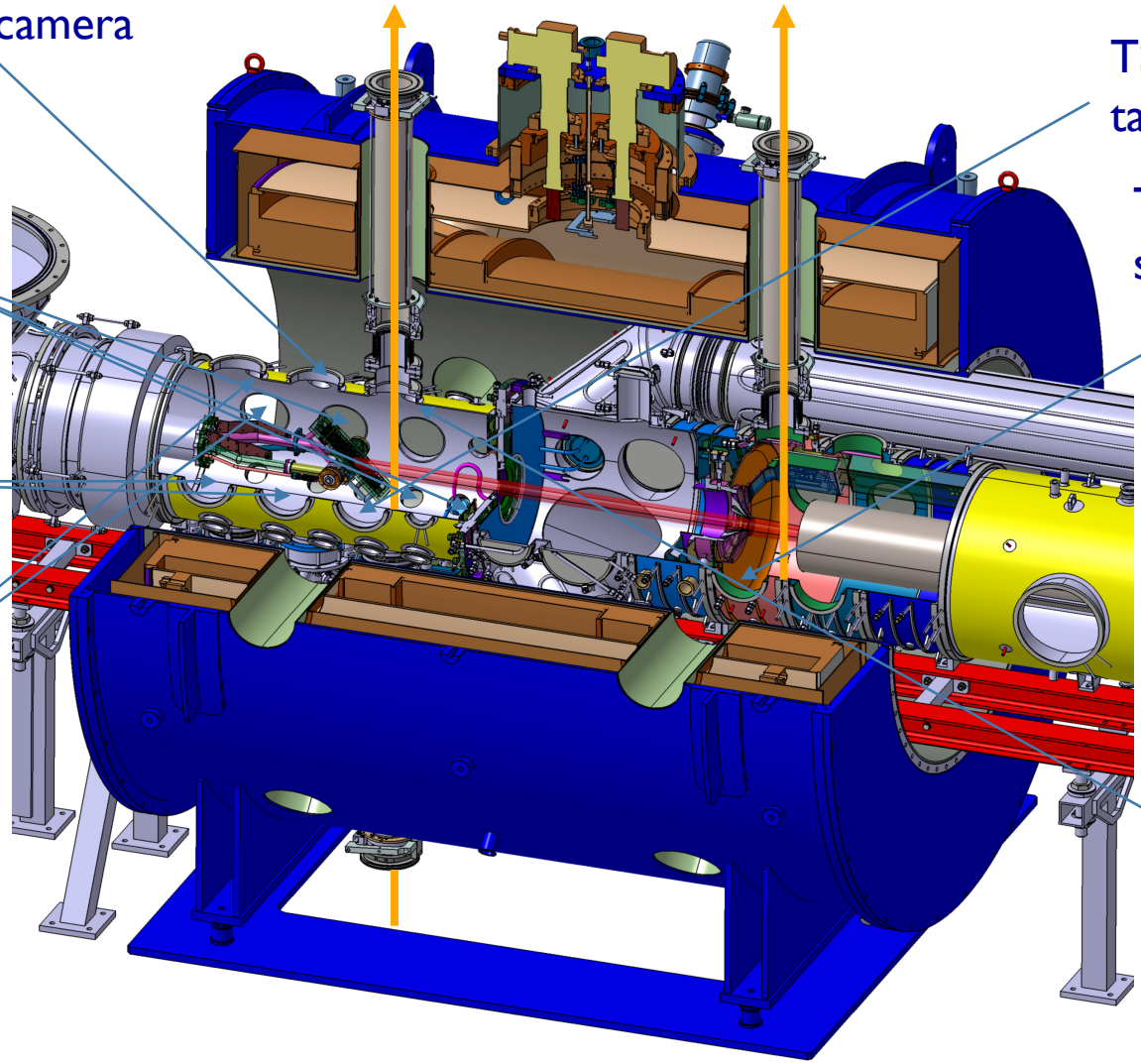




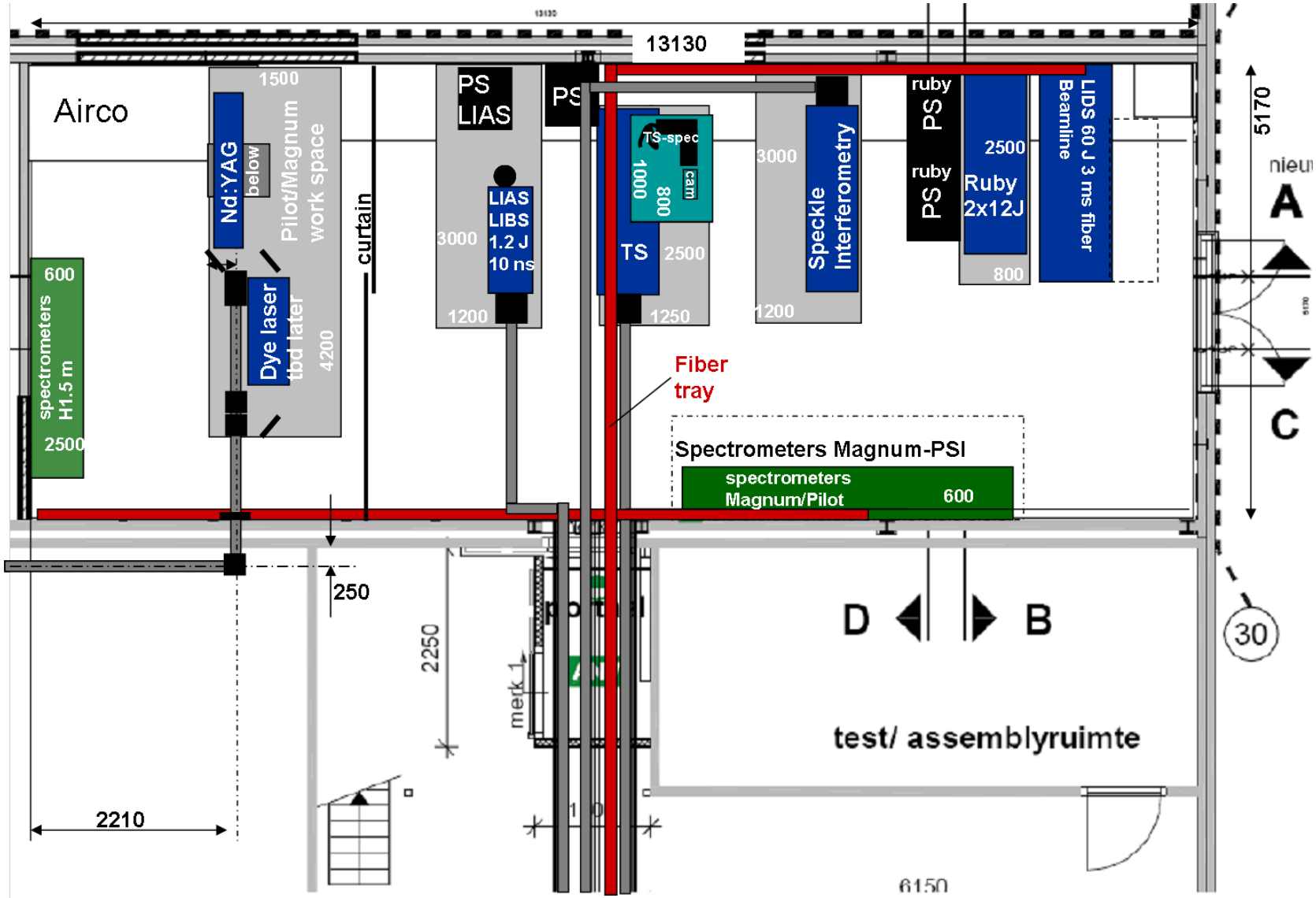
Target weight: 100 kg
Target size: 600 x 120 mm

Installation and commissioning completed

Magnum-PSI: Diagnostics

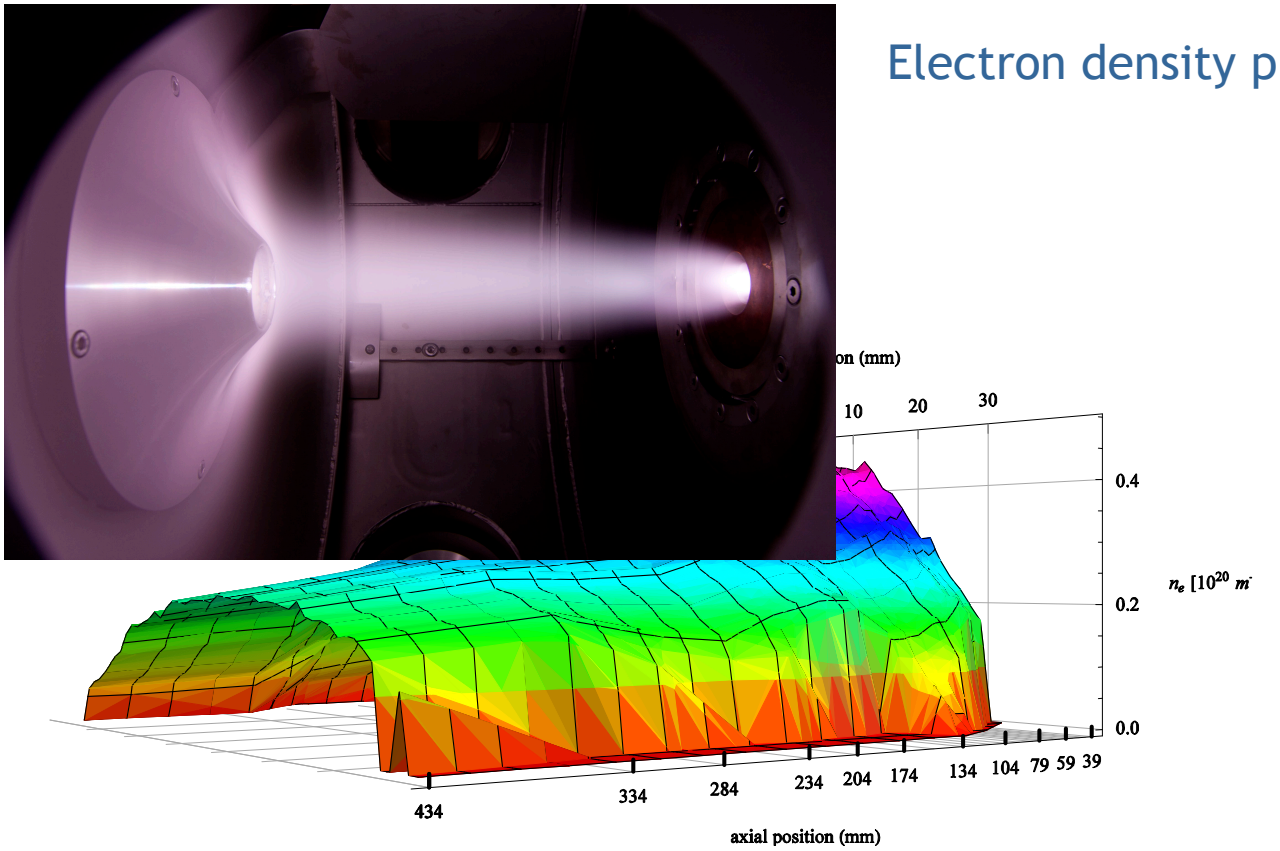


Magnum-PSI: Diagnostics



Diagnostics

Electron density profile Ar plasma



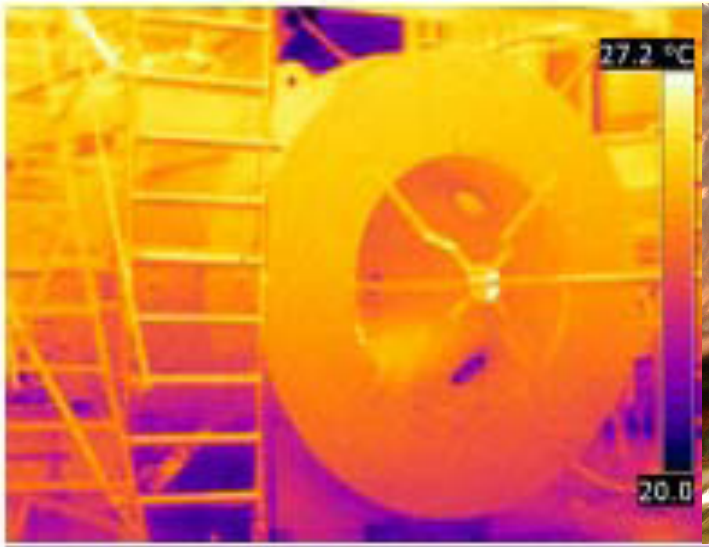
Diagnostics for MAGNUM-PSI (in-situ)

Done	Calorimetry (source and target) Pressure gauges Residual gas analysis Current and voltage measurements Monitoring cameras
First stage (by 1.7.2011)	Thomson scattering High resolution spectroscopy (T_i, v_{rot}, v_{axial}) Wide spectral range spectroscopy Multi-wavelength pyrometer LIDS, LID-QMS, LIAS, LIA-QMS, LIBS QMB Fast imaging camera Fast IR camera
Second stage (by 1.1.2012)	Laser induced fluorescence (LIF) Speckle Interferometry
Third stage (after 1.1.2012)	Cavity Ring Down spectroscopy Langmuir probes in target Dust diagnostic (MIE scattering)

Status of magnet

- Factory acceptance test failed May 2010
- Disassembly revealed several thermal problems
- Expert group meeting August 2010
- FOM steering committee September, December 2010

Problems diagnostics ports



Compressed super insulation

Status of magnet

Repair of magnet:

- Renew wiring plate
- Proper soldering of all connections
- Additional stabilization copper in grooves
- Improve clamping of SC wires
- Add additional voltage taps
- Better super-insulation
- Improved tolerances
- Smaller diagnostics ports

Status March 2011

Impact of delay on Scientific Programme

- Next factory acceptance test of magnet in April 2011
- Delivery of magnet to Rijnhuizen in May 2011
- Start of scientific exploitation of Magnum in July 2011

- Relocation of institute is starting in Jan 2015
- Relocation of Magnum-PSI core device is proposed for end of 2015
- **~4.5 years** of Magnum operation is still possible on Rijnhuizen site

Summary of capabilities of Magnum-PSI

- Simulation of ITER and DEMO divertor conditions (partial detached conditions)
- $T_i \sim T_e$ thermal
- 10^{24} m^{-2} s^{-1} also on inclined target (factor of 100 higher than any other device)
- Superimposed high frequencey (10 Hz) transient heat and particle fluxes to simulate sub-threshold ELMs (~2 GW m^{-2})
- Neutral flux in same range as ion flux to target (determined by recycling)
- Large targets (user defined, up to ITER mock-up size), 60 x 12 cm, 100 kg, no Be, no activated targets
- Minimal angle between surface and field (defined by max target size) ~ 3°
- High fluence (everything is water cooled)
- High surface temperature
- 30 sec transfer from exposure position to target station
- Target station pressure (~10^{-7} mbar) -> 1-2 minutes before one atomic layer

Experimental Programme

Hydrogen retention in plasma facing components

Pilot-PSI

Erosion/re-depostion
Lifetime of plasma facing components

PSI Diagnostics development

Magnum-PSI

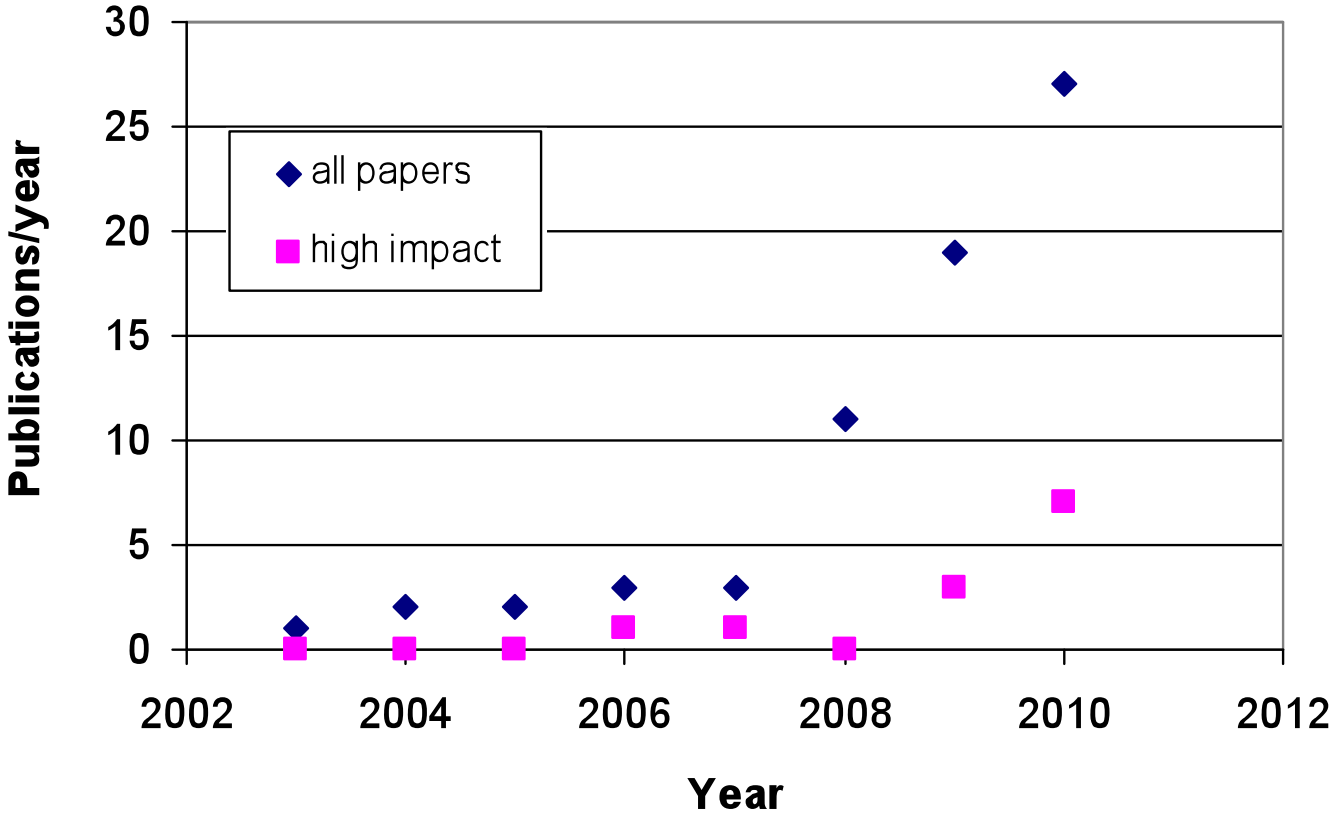
Material transport and dust

Physics of low T_e, high n_e plasmas

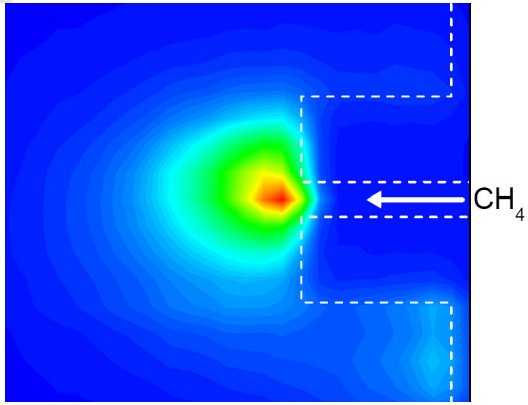
Surface and Material Science

Computational models: interpretation and prediction

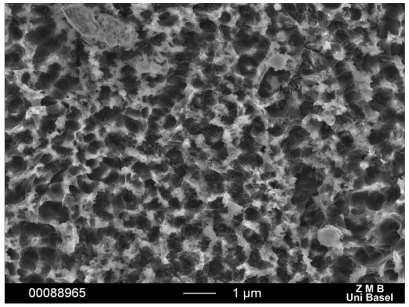
Scientific Output of PSI, 2003 – 2010

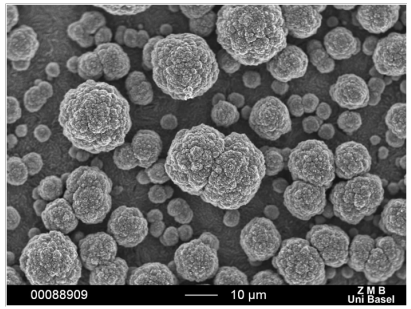


2010 highlights

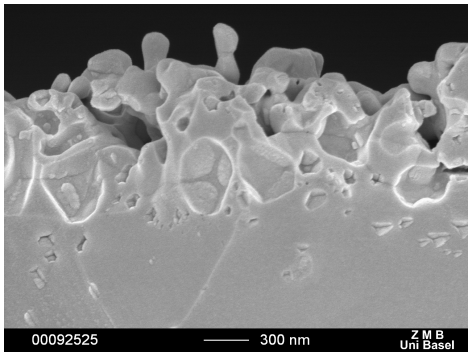


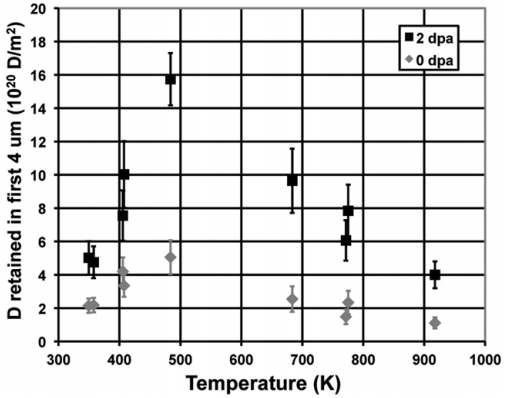
CARBON

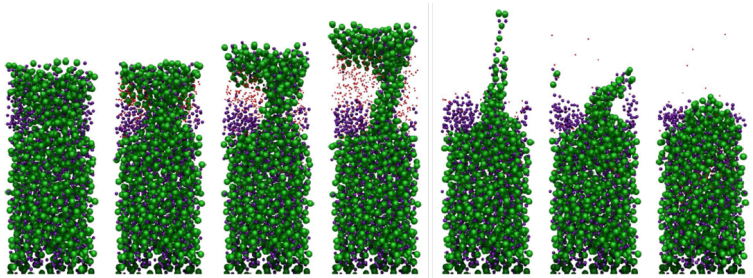


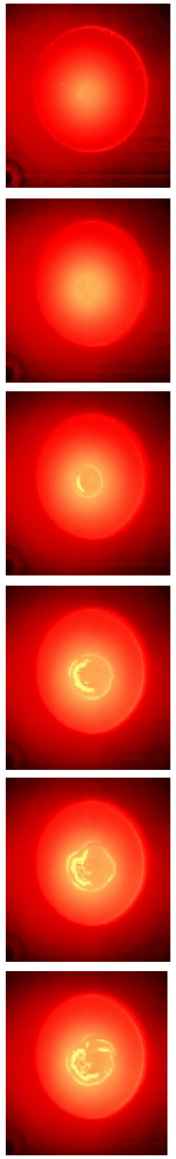


TUNGSTEN



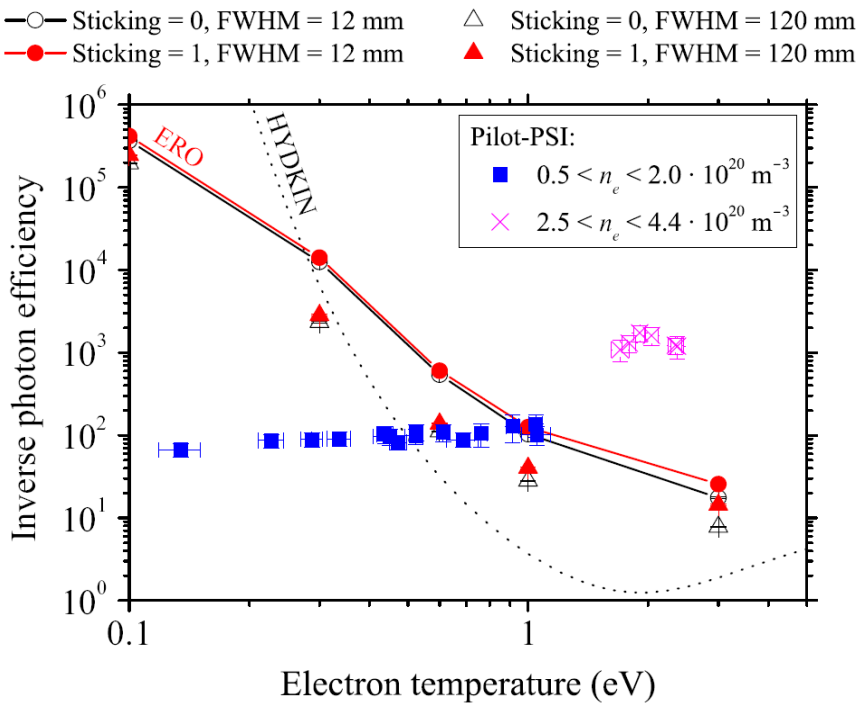


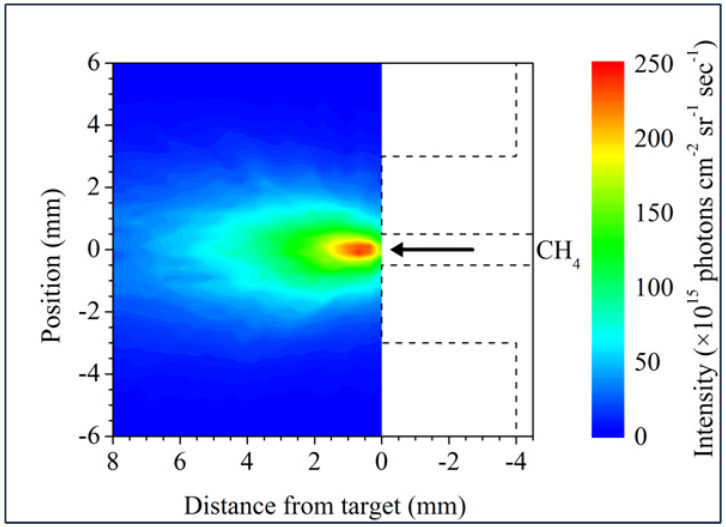




Break-up of methane

Comparison of chemical erosion of carbon targets with ERO simulations





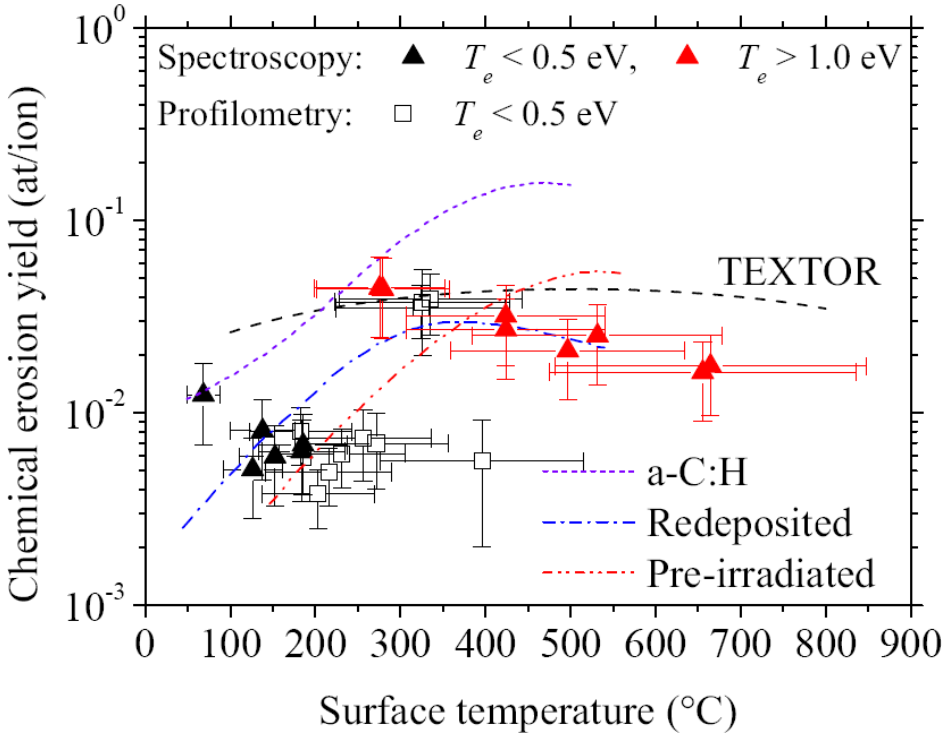
- Importance of charge exchange and dissociative recombination for break-up of methane in those low temperature plasmas

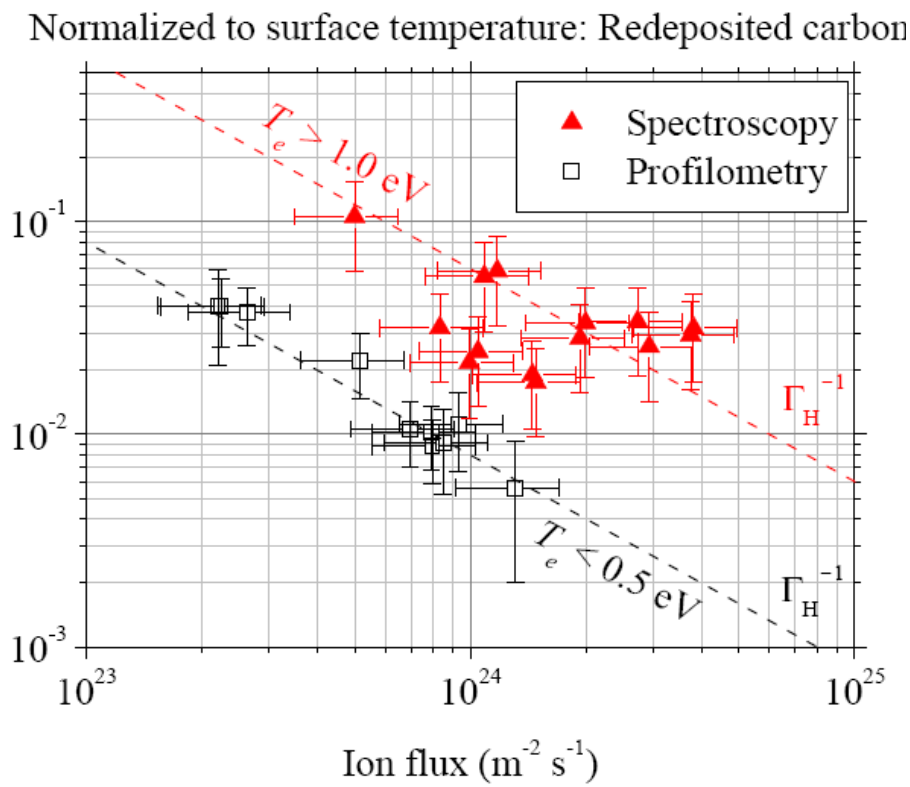
Westerhout et al. Appl. Phys. Lett. 95 (2009) 151501

Westerhout et al. Nucl. Fusion 50 (2010) 095003

Carbon chemical erosion

Chemical erosion of carbon targets at ITER-like ion fluxes

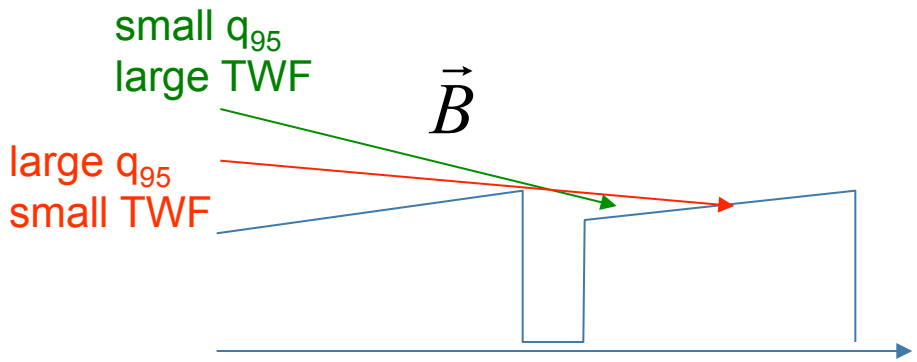


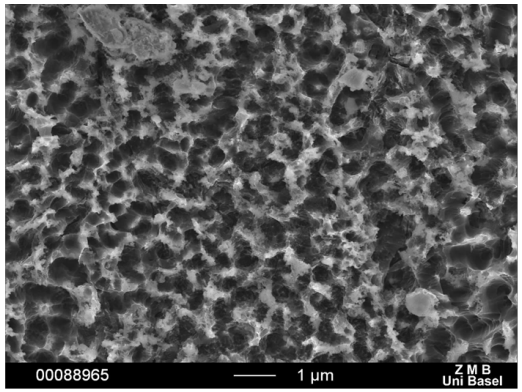


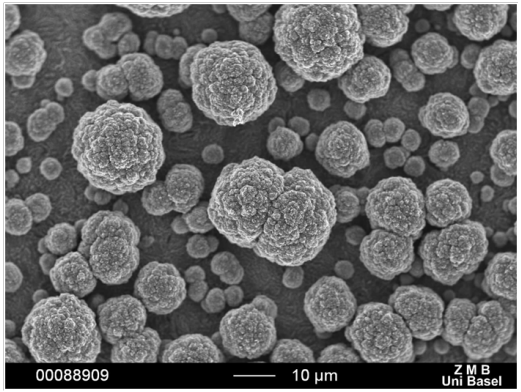
Westerhout et al. submitted to Nucl. Fusion

Carbon erosion, re-deposition

- Flux dependence for chemical erosion is based on limited hydrogenation rate
- Re-deposition leads to effectively higher surface area and hence saturation at higher flux densities
- Next step: investigation of real target geometries





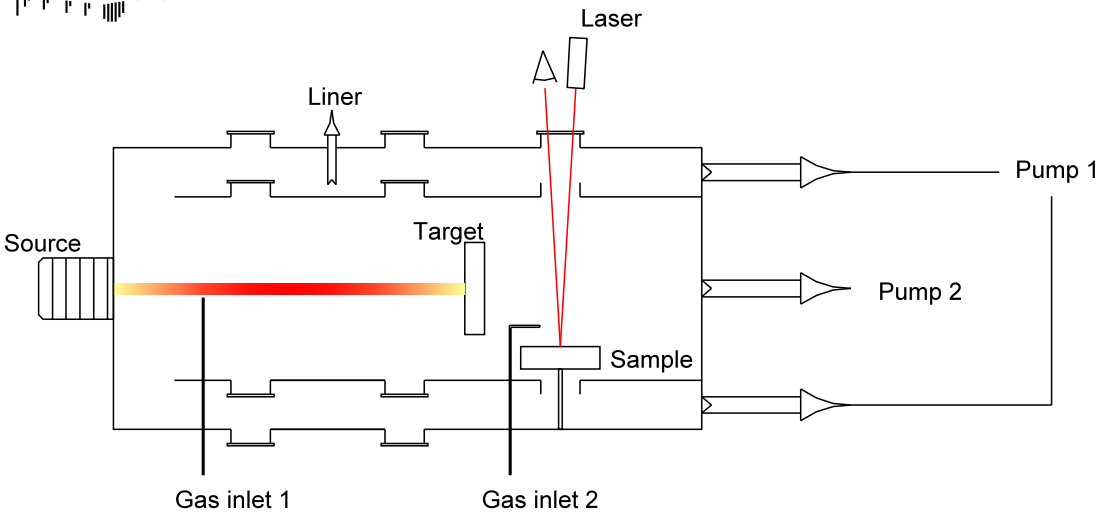


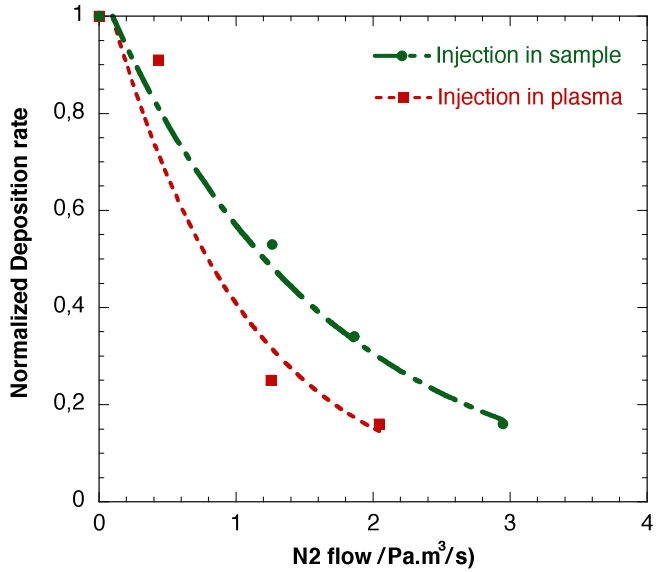
➢ requires high fluxes with thermal plasma (no biasing)

- Formation of nm-size dust particles in plasma?

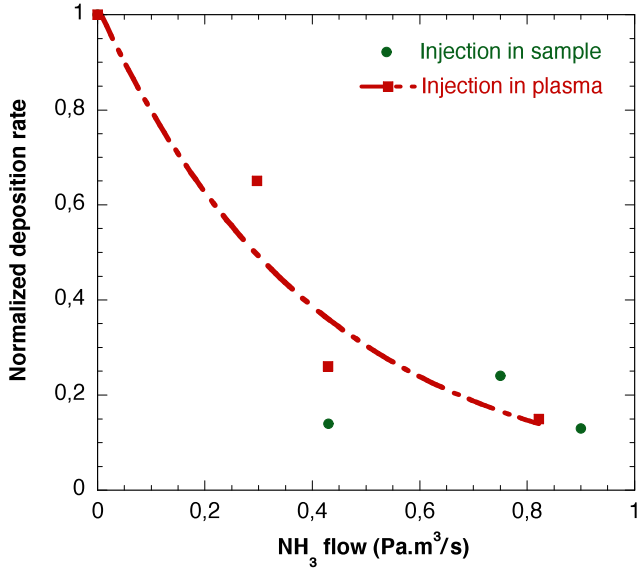
➢ requires high magnetic field and thermal plasma

Scavenger techniques





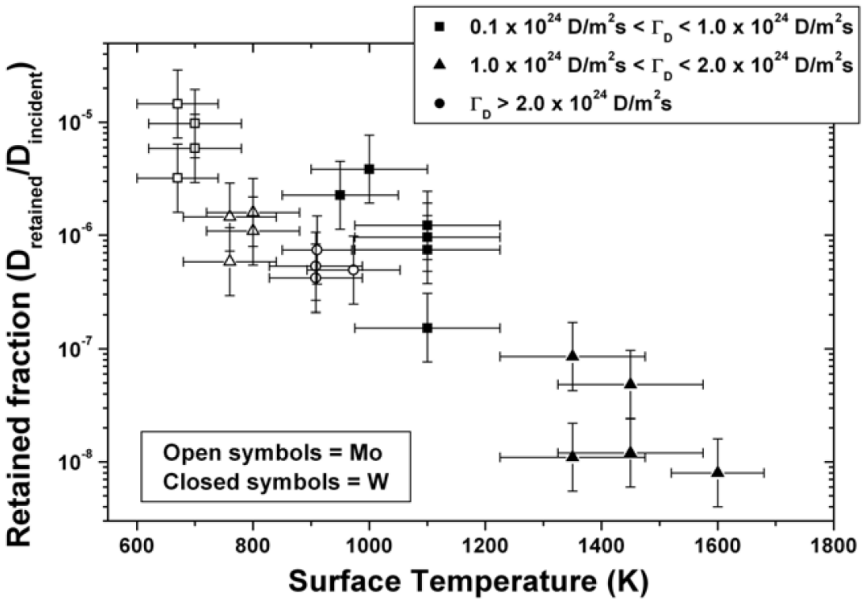
- Ammonia injection in the plasma afterglow is able to efficiently suppress film formation in remote areas, as required for tritium inventory control in a Fusion Reactor under carbon PFC scenarios.



Tabares et al. Phys. Rev. Lett. 105 (2010) 124007

Hydrogenic retention

Hydrogen retention in refractory metals

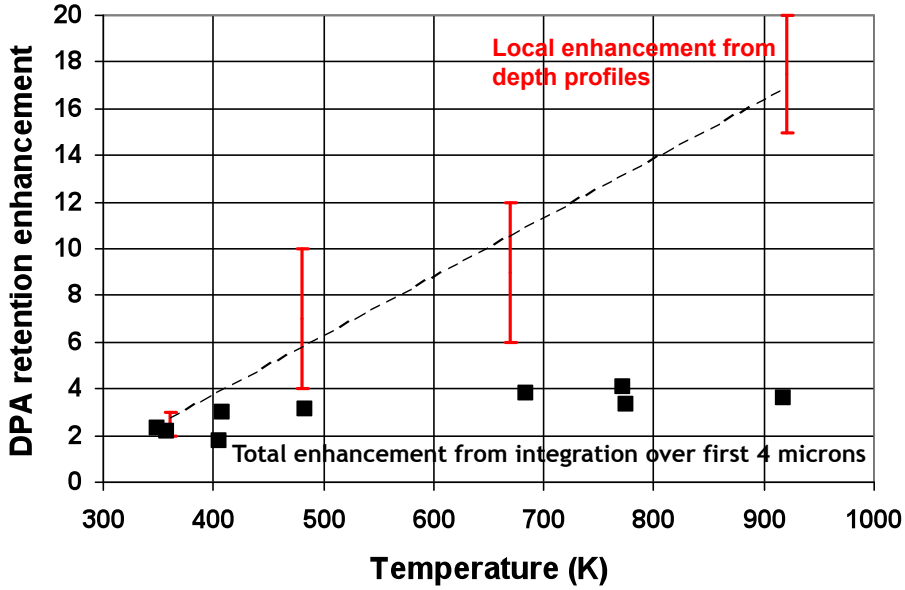


- Retention is low (<10^{-5})
- Retention falls strongly with surface temperature

Wright et al. Nucl. Fusion 50 (2010) 055004

DPA retention enhancement

(0.5-2 dpa by 12 MeV W irradiation)



- Retention in W can be enhanced up to a factor of 20 by irradiation of 2 dpa

Wright et al. Nucl. Fusion 50 (2010) 075006

Hydrogenic retention

To be investigated still:

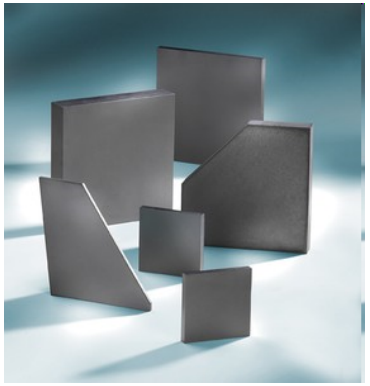
- Flux dependence (super-saturation), fluence dependence
- Temperature dependence during irradiation
- Dynamics of vacancies and interstitials
- Effect of grain size
- Nano-composite materials
- Nano-structured alloys

- Effect of bulk irradiation (neutron irradiated material) far beyond grain boundaries
- Simultaneous irradiation with plasma exposure to study synergistic effects of vacancy dynamics and hydrogen trapping/diffusion/permeation

Plasma-facing material research

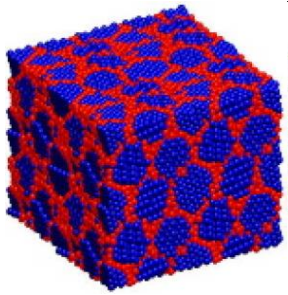
Materials of interest

- Diamond, SiC

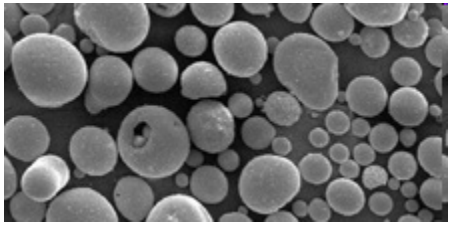


- Be proxies like Al and Mg

- Liquid metals like Li, Ga and maybe Al?
- Special tungsten alloys, nano-structured tungsten alloys



- Nano-composites
- Self healing materials



Role of advanced plasma generators

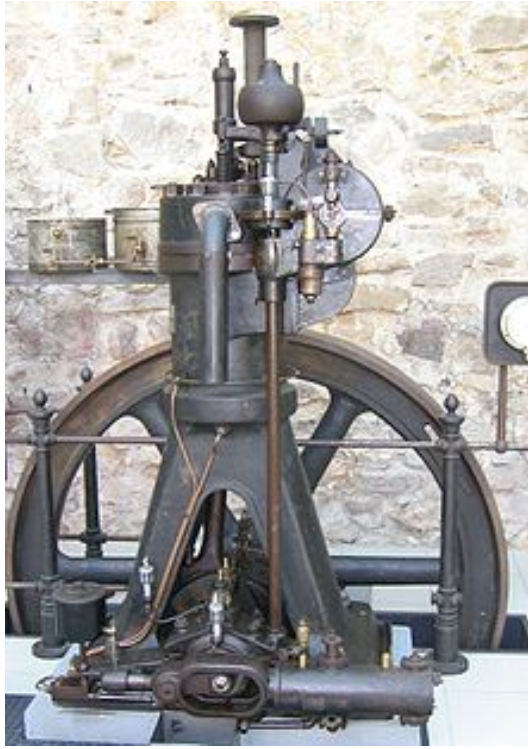
- Testing of next generation materials (maybe metamaterials)
- Qualification of plasma facing components under reactor relevant conditions, in particular nuclear conditions
- Development of science for high density divertor plasmas
- Development of alternative power exhaust solutions
  - liquid metal targets
  - pebble divertors
  - novel gas targets
- Finding optimal operation point for power exhaust, which is acceptable for divertor, materials and fusion performance (in iteration with magnetic fusion devices)
  - impurity production
  - surface, material temperature
  - divertor geometry
  - plasma composition

Hist. Similarities: Diesel engine development

- Rudolf Diesel's first design was rejected by engineers at MAN (Augsburg).

  The pressure in excess of 100 bar was too high. Engineers thought it was impossible to build an engine, which could withstand the forces -> challenge for materials
- In second design Diesel reduced pressure to 44 bar (intuitively to the minimum pressure required for self ignition), which was build.
- First Diesel engine had to be helped to run (coupled to a steam machine).
- Set backs happened with overheating problems.

  Diesel was determined to solve problems.



Summary and Conclusions

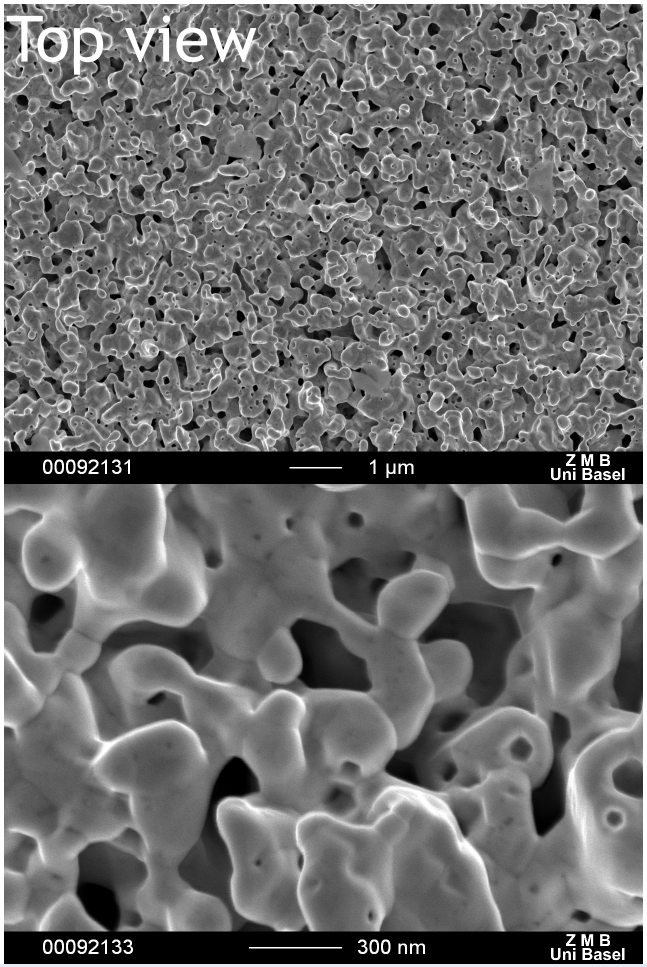
- Magnum-PSI will be available for scientific exploitation from July 2011 onwards (delay of ~2 years, due to super-conducting magnet)
- Magnum-PSI will be build to cost, and specifications eventually
- Magnum-PSI is cost effective
  - 13.4 MEuro investment; ~0.8 MEuro annual operation costs
  - Comparison ITER-like wall project on JET: 55 MEuro investment; 60 MEuro operation cost for one year exploitation
- Magnum-PSI can address many PSI issues for ITER and beyond (e.g. fluxes, fluence, strongly coupled PSI regime, PFC testing...)

- PSI in nuclear environment is completely new field and needs to be addressed for future fusion reactors ->> PMTS

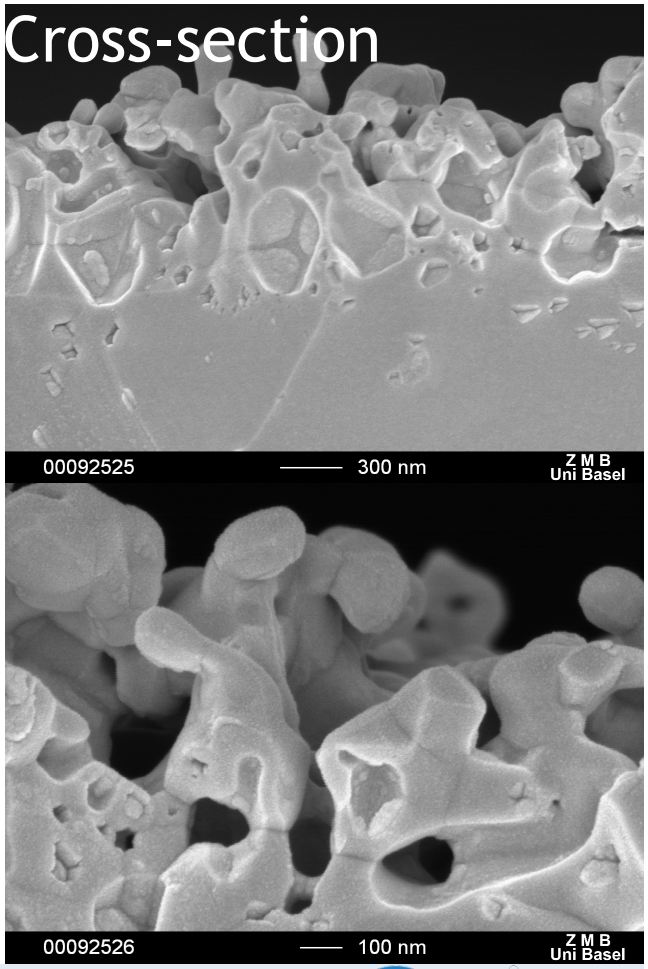
Highlights: He ions on W surface

W target, high flux region

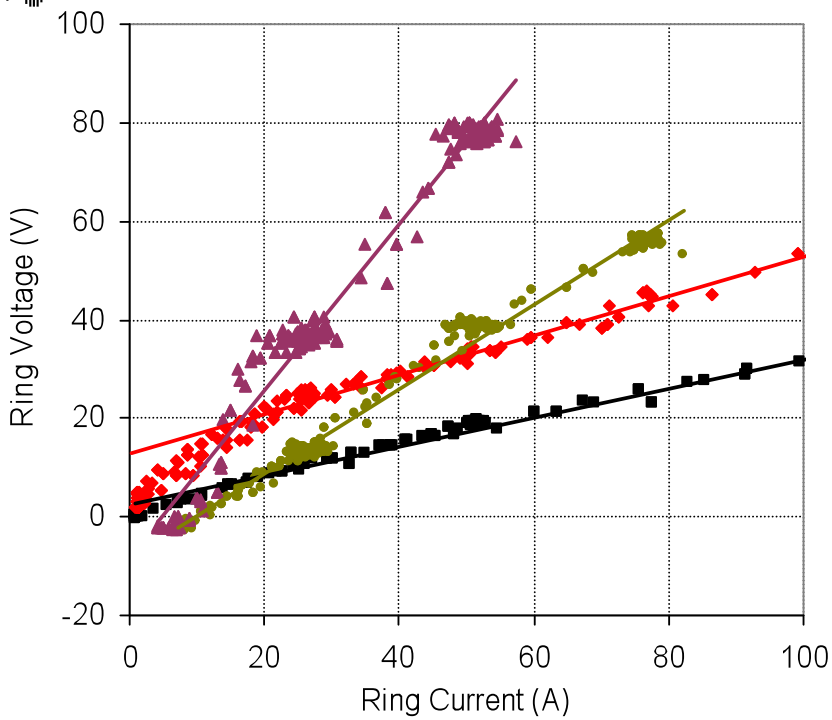
1500 C, 500 s, 2.4x10^{26} He^{+}/m^{2}, 50 eV He^{+}

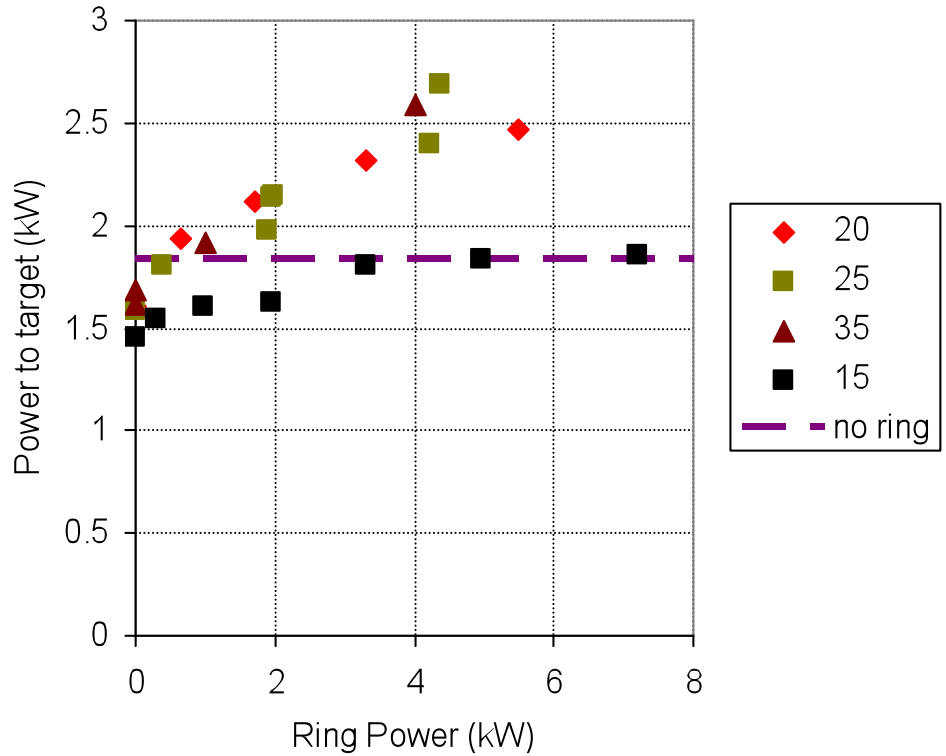


- Many pinholes observed on the surface
- Nanostructure starts protruding from the surface
- Evidence of bubble coalescence and swelling
- Grain structure?



Remote anode





- Alignment of ring and source causes differences in offset
- Two regimes, most pronounced for 20 mm ring: first increasing plasma diameter

- ring diameter comparable to plasma diameter doesn't allow to deposit extra power in the plasma
- energy efficiency of ring power up to 17% (6% without ring)

Improving impurity levels and reliability

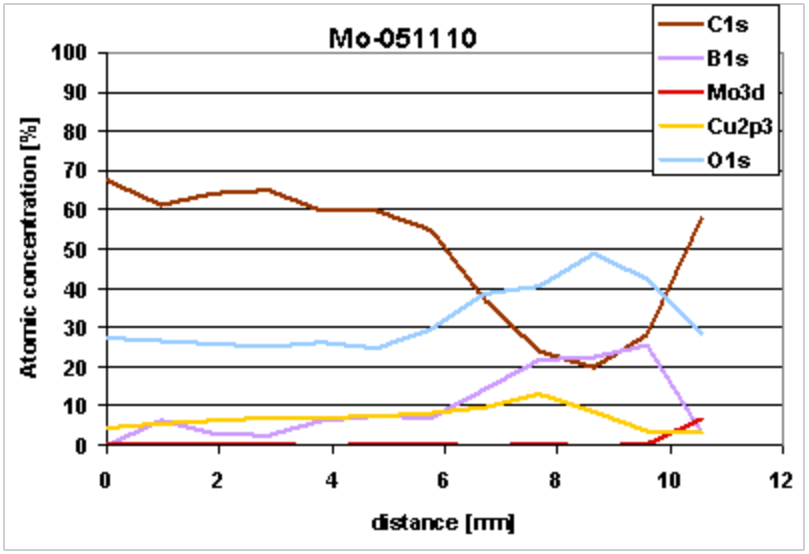
- Variation of inner diameter of BN rings:

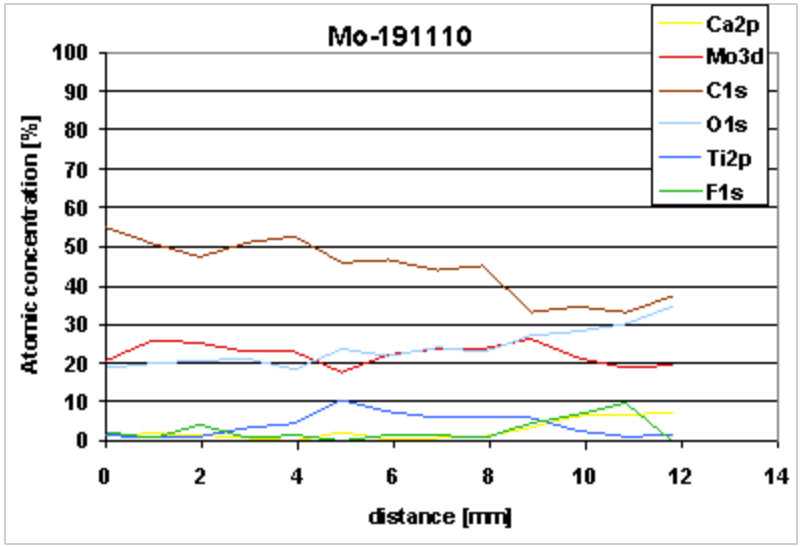
The BN plates diameter was increased to 20 mm to avoid contact between the BN and the plasma in the source:

- No sparks or arcs for the most critical conditions are observed for this source in contrast to the rest of the used sources.
- The XPS analysis of the samples exposed to the plasma produced by this source don't show any B or Cu traces even at the most critical conditions.
- The source does not appear to be damaged at all after the experiments.
- The Pin of this source is lower than for the rest of the sources for the same plasma current. The Power to the wall is lower as well and the % Power loss to the wall is lower at least for the higher magnetic fields (1.2 T and 1.6 T).

No B or C with wide BN ring

- Normal source produces B and Cu
- 20 mm BN ring gives no detectable Cu and B



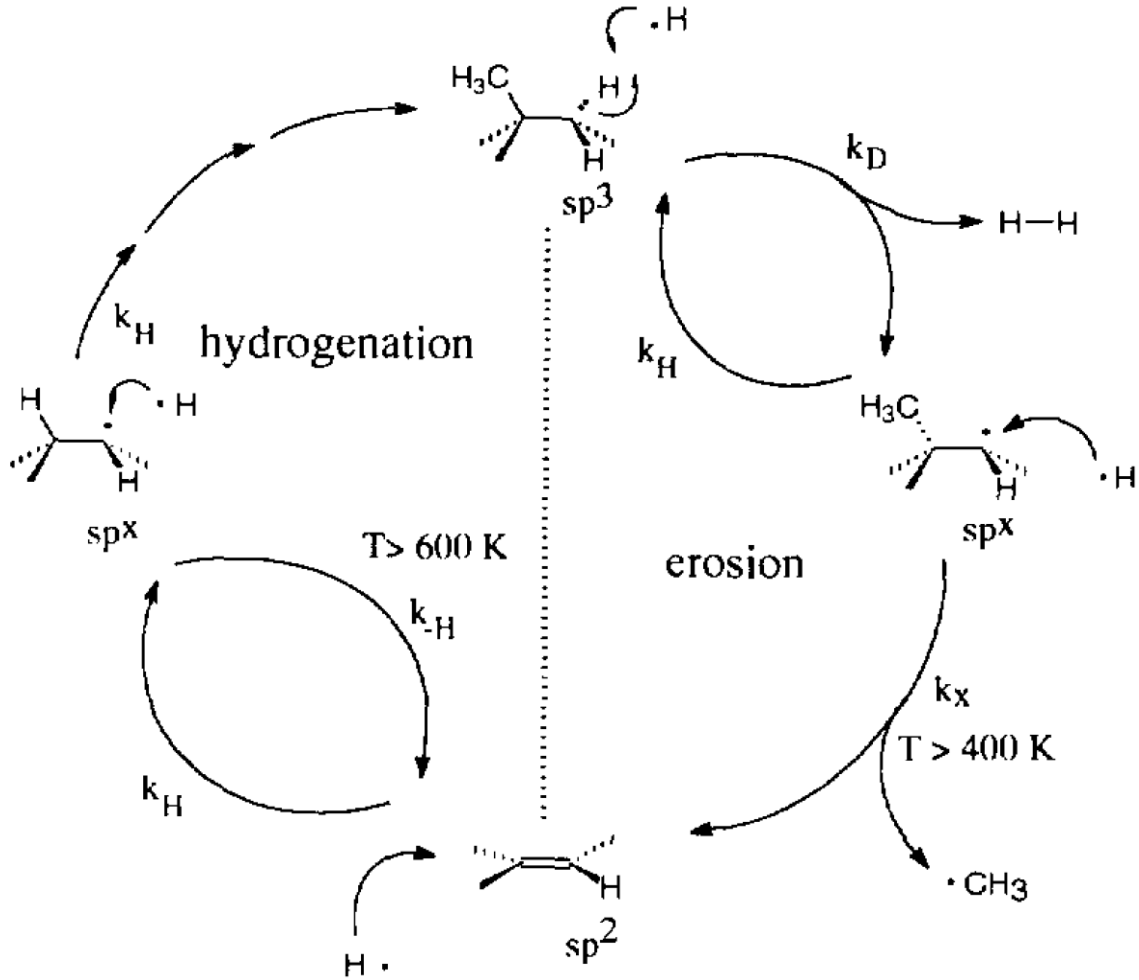


W erosion

- The standard source was used with different parameters to quantify the W erosion by optical spectroscopy:
  - No W is observed in front of the source even in the more critical conditions (1.6T, 250 A, 3 slm).
  - No W is observed even looking at the W tips from the back of the source in the more critical conditions (1.6T, 250 A, 3 slm).
  - No W is observed via XPS in the samples exposed to the plasma.

Carbon erosion, re-deposition

- Hydrogenation



PSI Department

Groups within Plasma Surface Interaction department:

- Computational Plasma Physics – Low Temperature (CPP-LT)
  Wim Goedheer
  - *Modelling of plasma jet, erosion, dust, molecular dynamics.....*

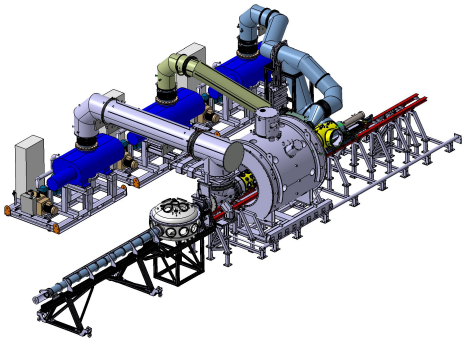
- Low Temperature Plasma Physics & Heating (LTPP&H)
  Gerard van Rooij
  - *Physics of plasma jet, sheath physics, physics of source, RF heating.....*

- Plasma Surface Interactions – Experimental (PSI-E)
  Gregory De Temmerman
  - *Erosion/re-deposition, material migration, mixed layers, transients.....*

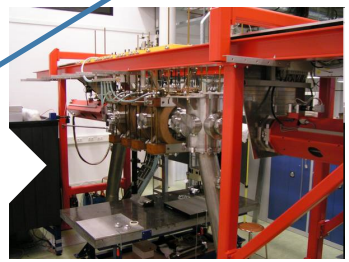
- Plasma Surface Interactions – Operations (PSI-O)
  Pedro Zeijlmans van Emmichoven
  - *Operation of Magnum-PSI and Pilot-PSI....*

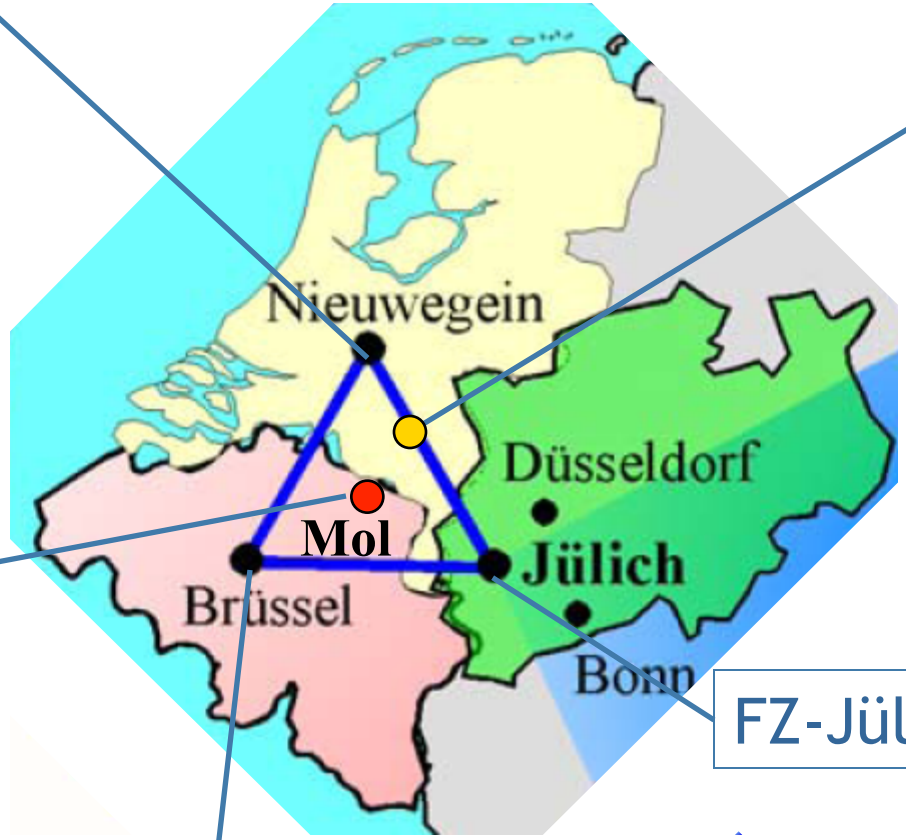
International positioning: TEC

FOM-Institute Rijnhuizen

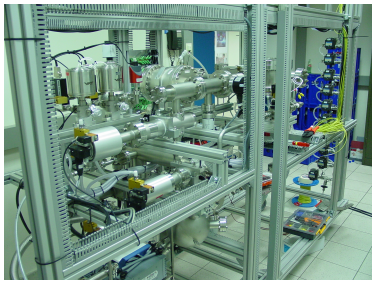


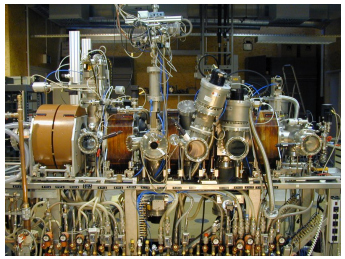
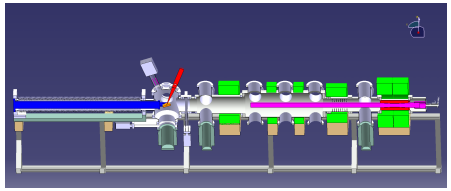
TU Eindhoven





SCK CEN Mol



ERM/KMS Brussels

FZ-Jülich