Beryllium
-
(Experimental) Preparation for the JET ILW

S. Brezinsek
JET EFDA TaskForce E2
EU TaskForce Plasma-Wall Interaction

Be research – activities within EFDA

- EFDA TF PWI and JET-EFDA program focuses on ITER material mix
- Be is one of the main areas of interest
- Limited number of experiments, modelling activities and working groups
  - JET ILW – Be main chamber, Be migration, Be spectroscopy etc.
  - PISCES-B – guest scientist from EU (IPP/FZJ) (R. Doerner)
  - JULE-PSI plasma-generator in hot cells (FZJ in 2014/15)
  - JUDITH electron beam facility used for Be PFCs power load tests (FZJ)
  - IPP – Be mixed layer analysis, MD, WALLDYN modelling (W. Jacob)
  - FZJ – Be erosion, migration, spectroscopy and ERO modelling
  - VR, TEKES, CCFE, FZJ, IPP, CEK-MOL – post mortem analysis
  - TEKES, IPP, FZJ, universities - MD modelling with Be and mixed systems
  - MedC – production of Be tiles, layers, references etc.

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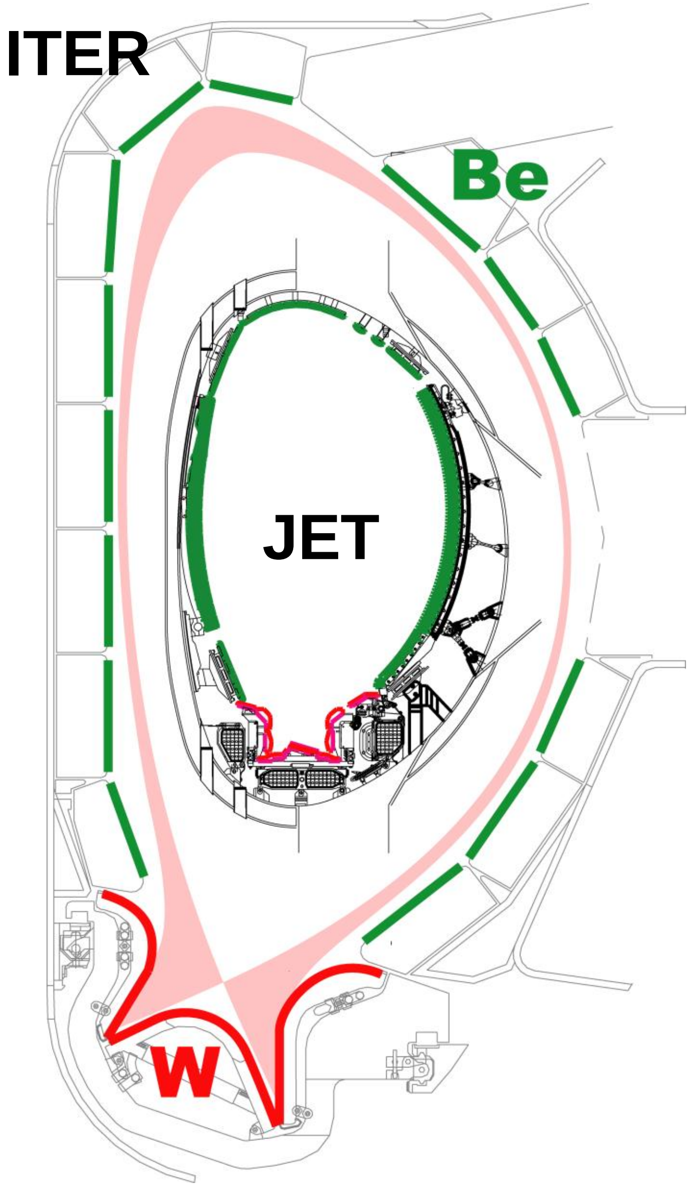
The Wall Combination for the DT Phase in ITER



Be wall and W divertor in JET

- **Material combination for the first time used**
- **Replacement of the wall in one shutdown**

- **"Carbon-free" environment**
  - **Reduced material migration to rem. areas**
  - **Reduced tritium retention**
  - **Loss of carbon as main radiator**

- **Change in operational space**
  - **Need for better plasma control**
  - **Need for heat load mitigation schemes**

NBI upgrade in JET

- **Parallel upgrade of neutral beam system**
  - **Maximum power from 20 to 34 MW**
  - **Maximum duration from 10 to 20 s**

Plasma-Wall Interaction Issues

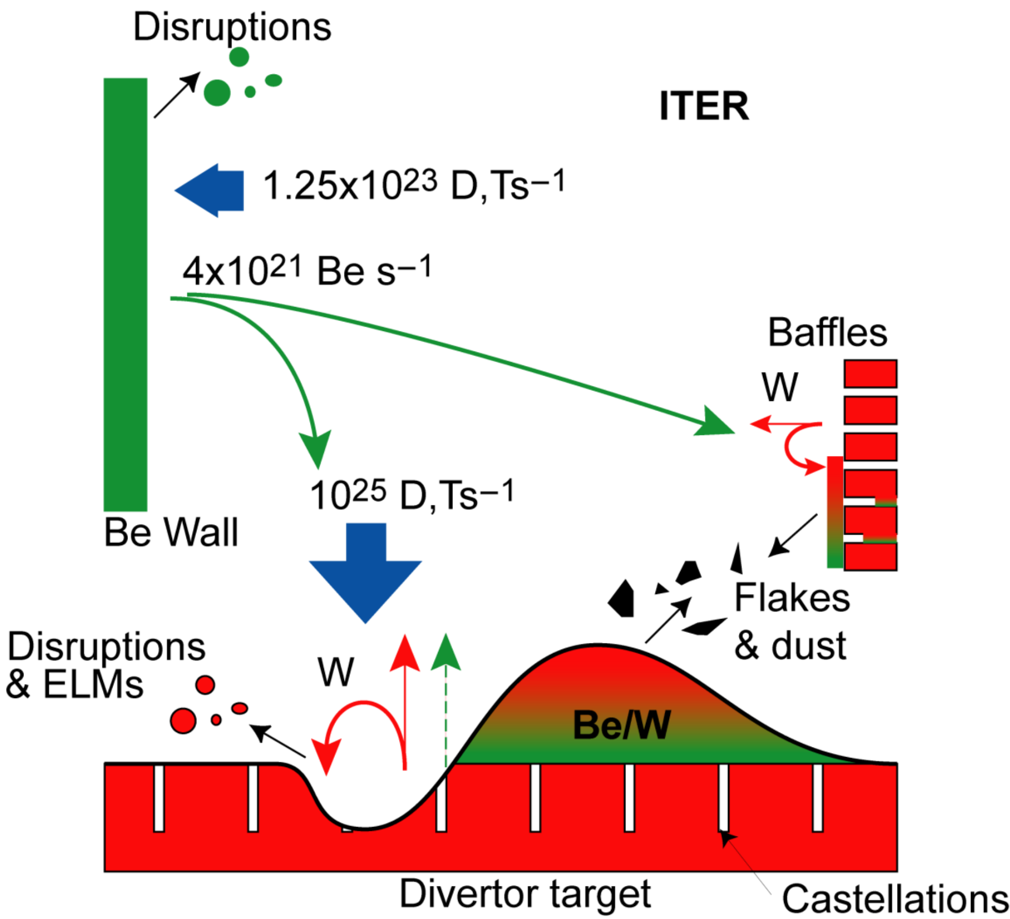
Important PWI questions for ITER will be addressed in JET with the ILW

Steady-state operation

- **Be wall erosion and transport**
- **Be-W material mixing**
- **Be:D layer formation and retention**
- **Re-erosion of (mixed) layers**
- **Material Transport to remote areas**
- **W erosion and prompt deposition**

Transients

- **Be/W Melt layer motion, loss and stability**
- **Metallic dust formation**



Integrated approach in developed plasma scenario – limited parameter studies

Scenario Compatibility

Scenario compatibility with the new wall has to be demonstrated:

- Adaption of magnetic shape – use of bulk W divertor
- Neutral beam shine through – minimum density requested

- Be concentration and plasma dilution– limit Be erosion by larger clearance
- First wall power flux –Be power handling

- W impurity production – below physical sputtering threshold
- W concentration in confined region – ELM flushing to release impurities
- W accumulation in core region – need for central heating

$\Rightarrow$ Semi-detached divertor operation favourable
$\Rightarrow$ Impurity seeded plasmas likely to be mandatory for high input power
$\Rightarrow$ Seeding species candidates: N_2, Ar, Ne

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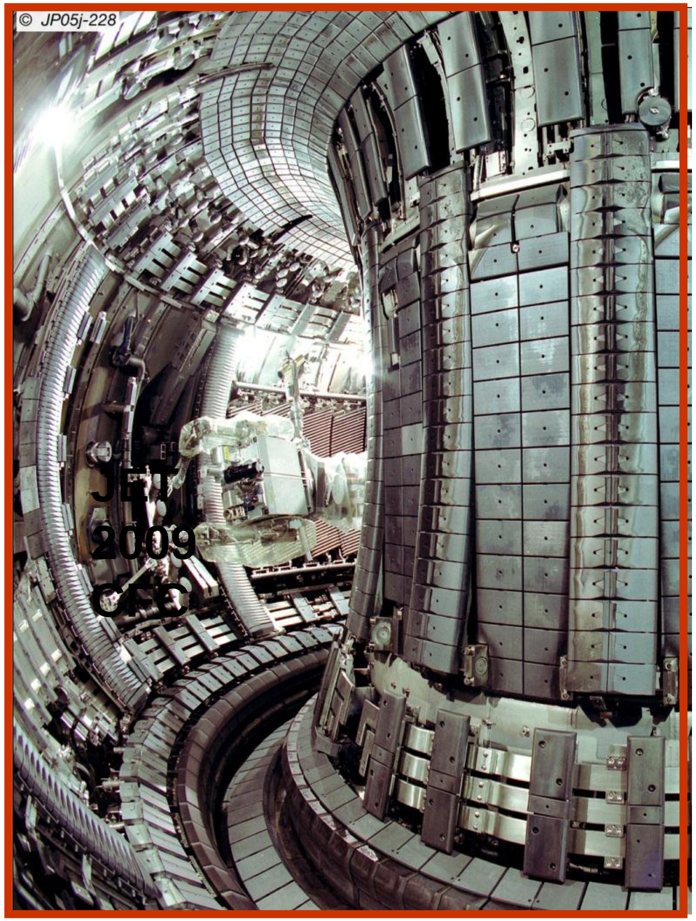
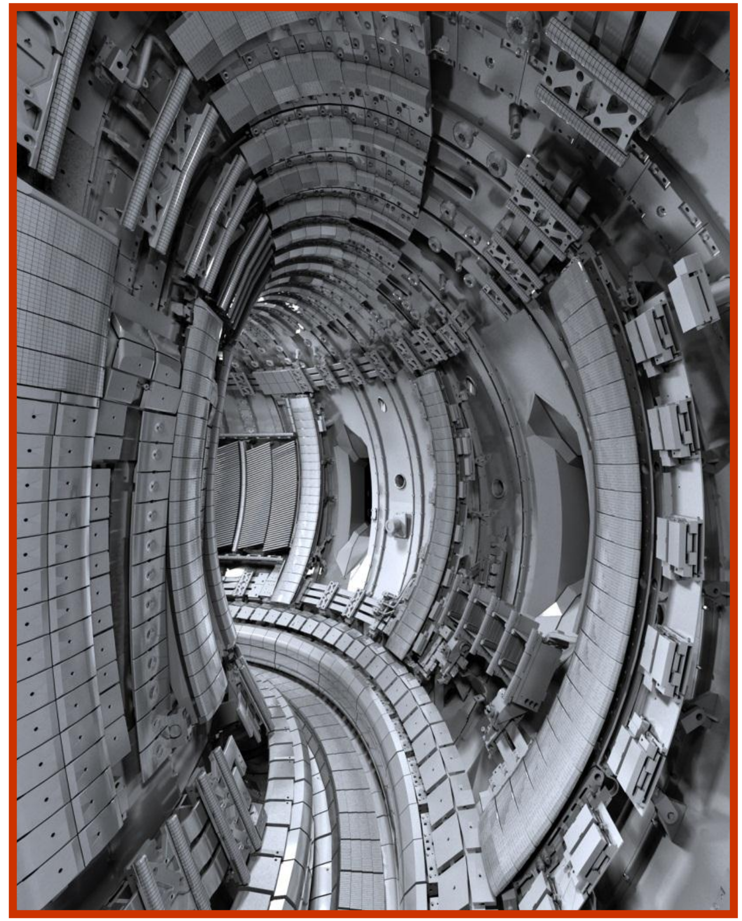
Replacement of Wall Components

JET (2009)
CFC and
Be layer
(evapor.)





JET (2011)
Be first wall
W divertor
(simulation)

- All plasma-facing components are only inertially cooled
- Power handling determined by material properties
- W-coated CFC tiles at neutral beam shine through areas

S. Brezinsek JNM 2011 (PSI)

G. F. Matthews Phy. Scripta 2009

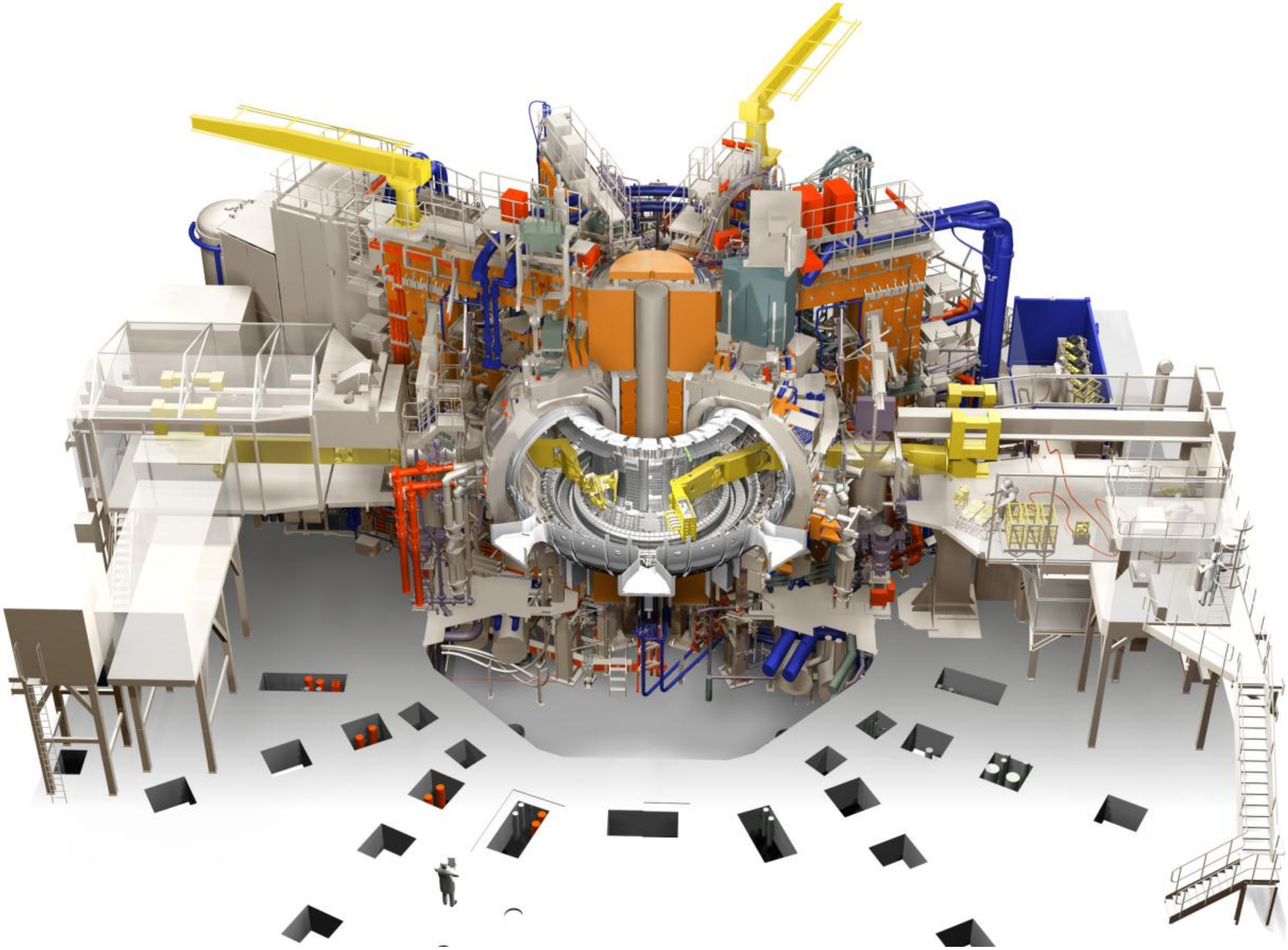
V. Riccardo Phy. Scripta 2009

ITER-like Wall Project Metrics

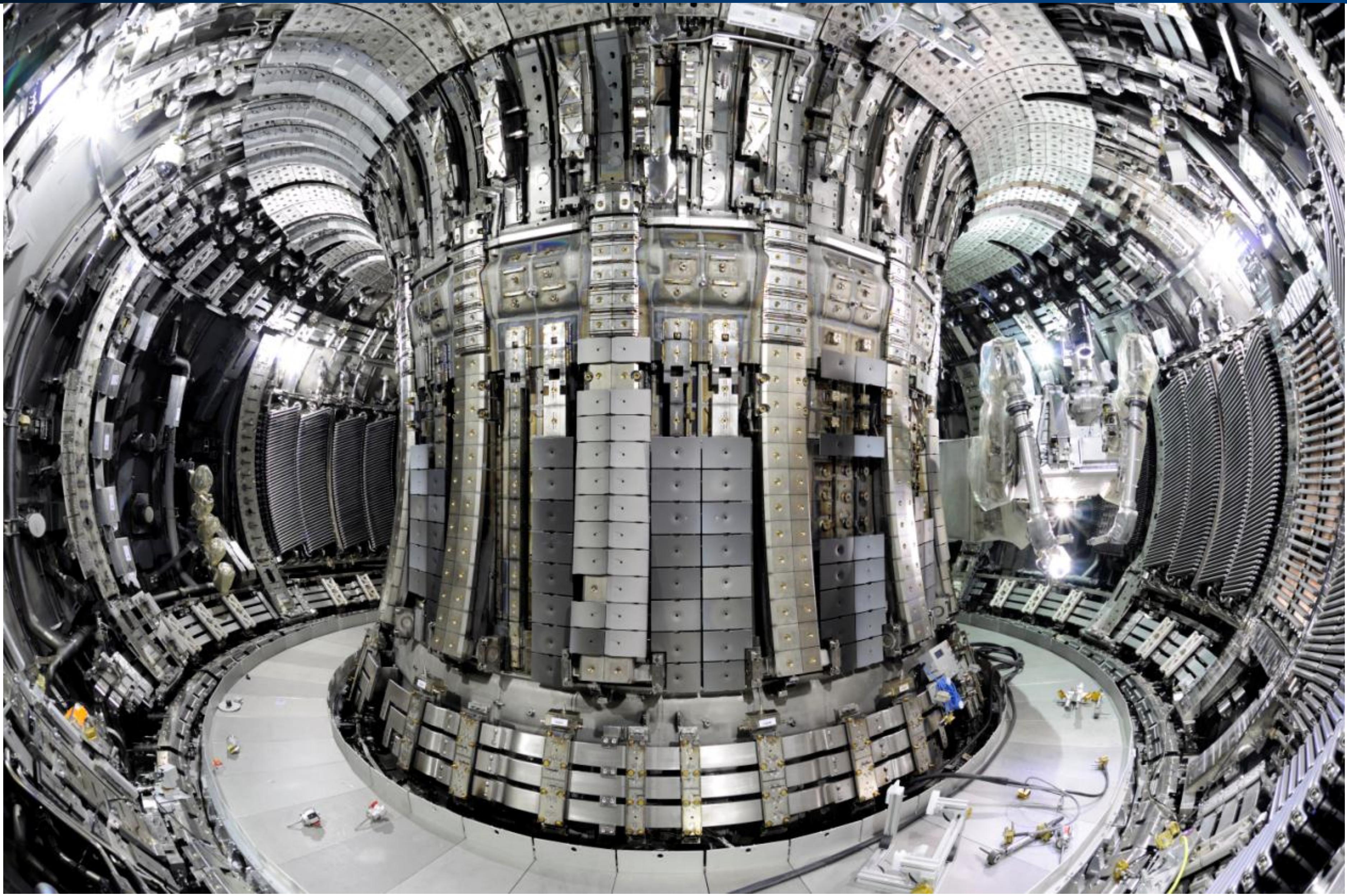
Number of installed items	**2880**
Number of individual tiles:	**5384 Be tiles (~2 tons Be / ~ 1m^3)** **1288 W-coated CFC tiles** **9216 W-lamellas (~2 tons W / ~ 0.1m^3)** **15828 total**
Total number of parts:	**82273 counting bulk W modules as one part**
Bulk W total parts:	**191664 including 100080 shims**

G. F. Matthews PFMC 2011

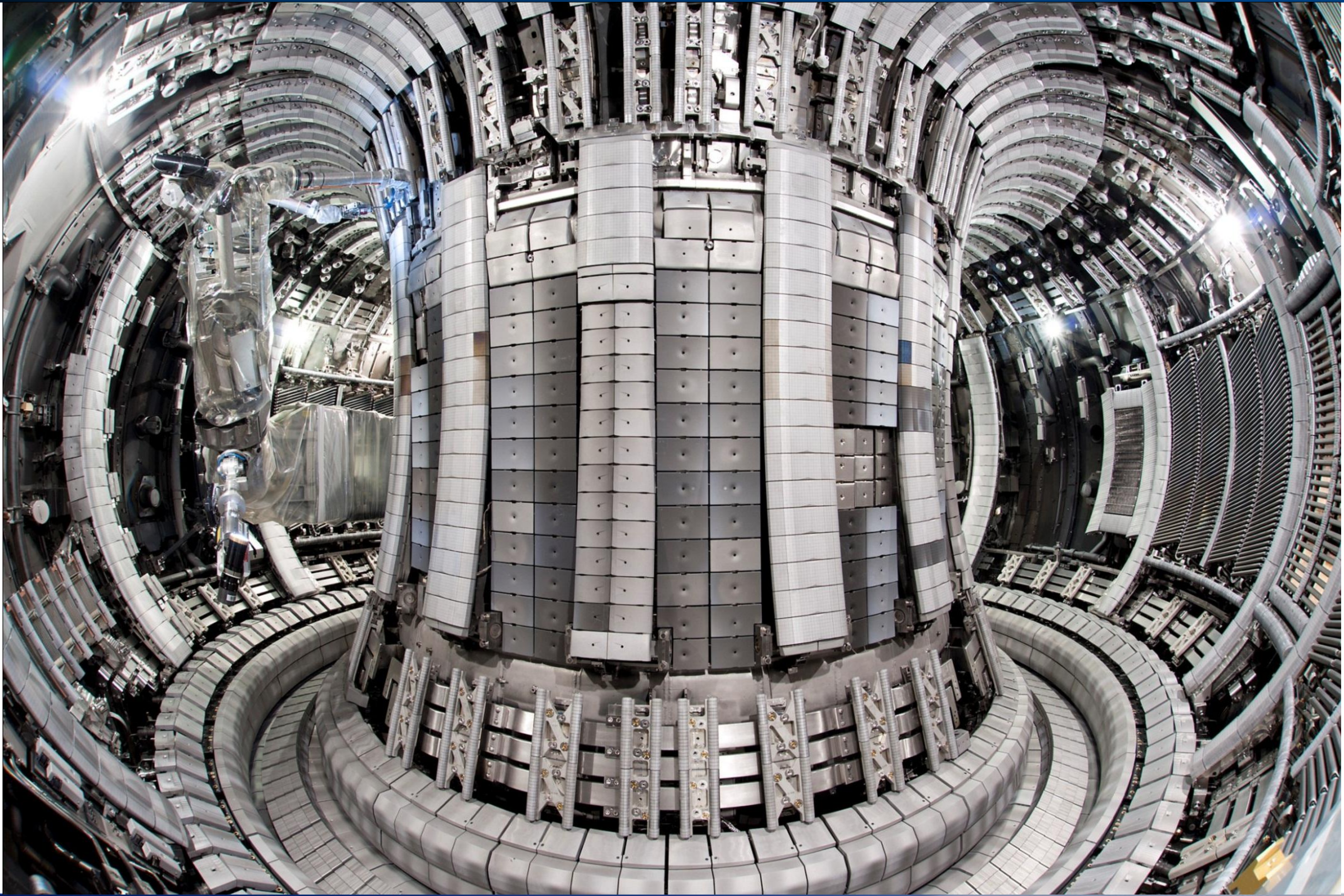
Remote Handling in JET



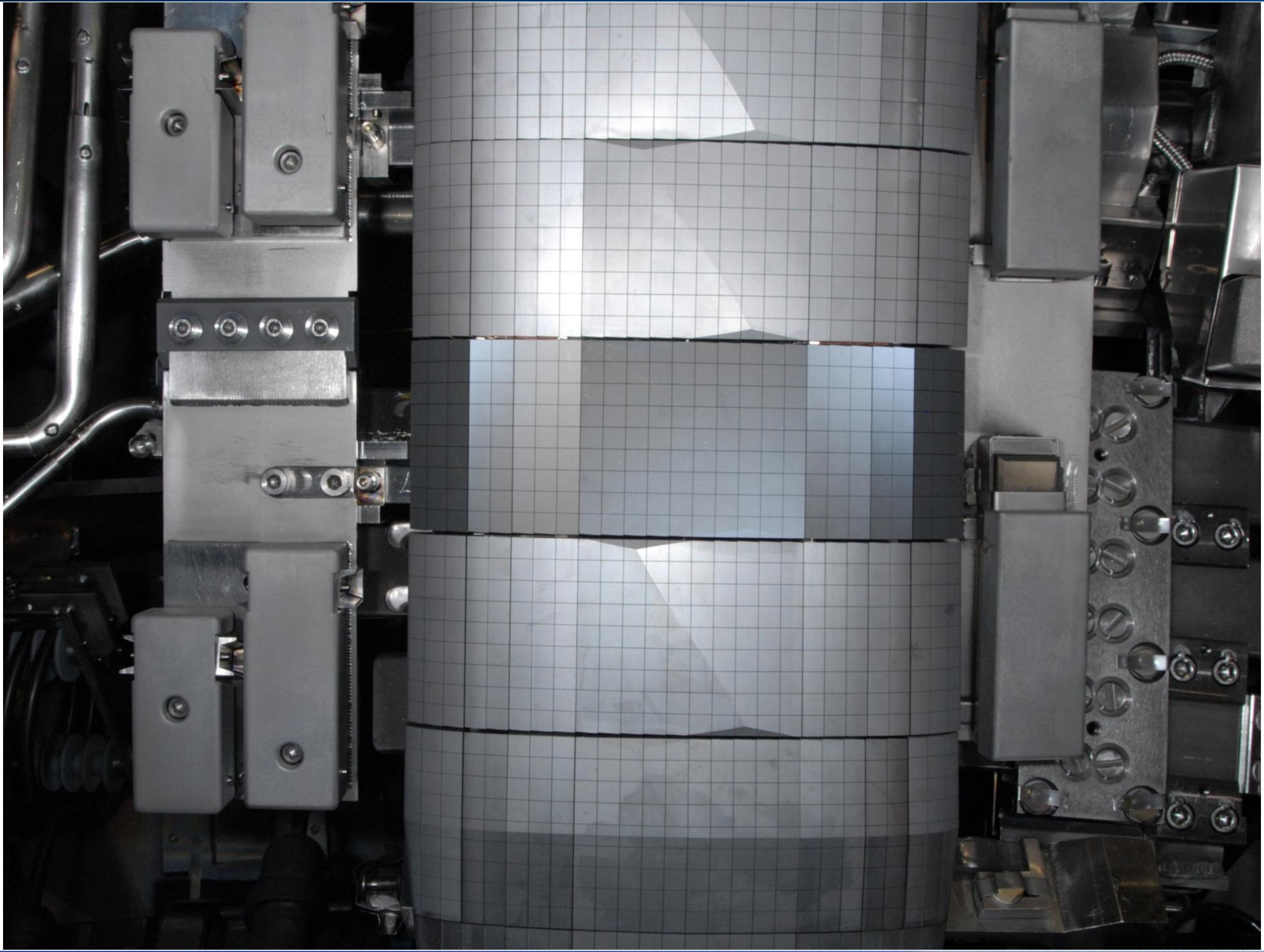
The JET Vessel: 19th September 2010



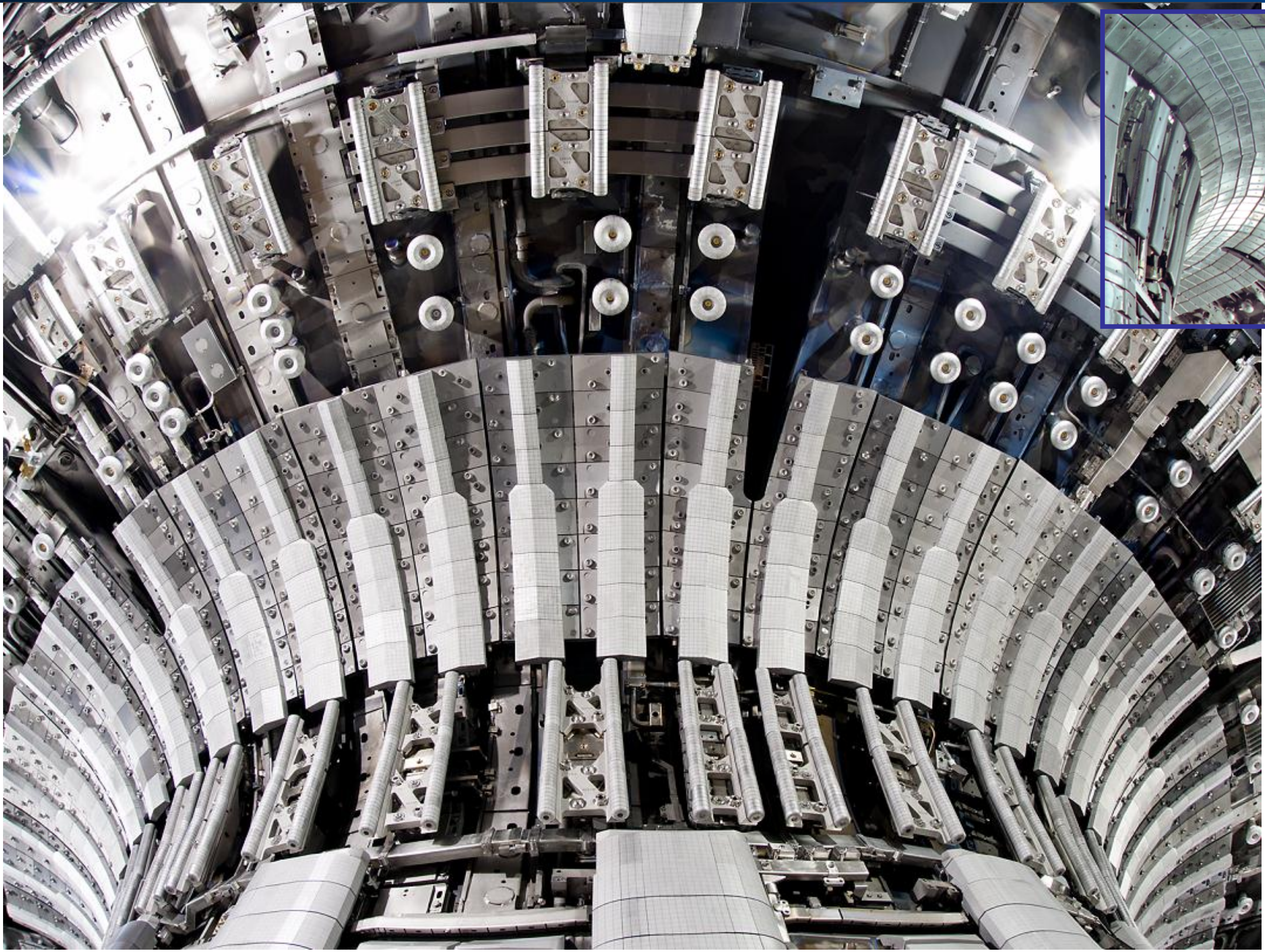
The ITER-like Wall completed: 8^{th} May 2011



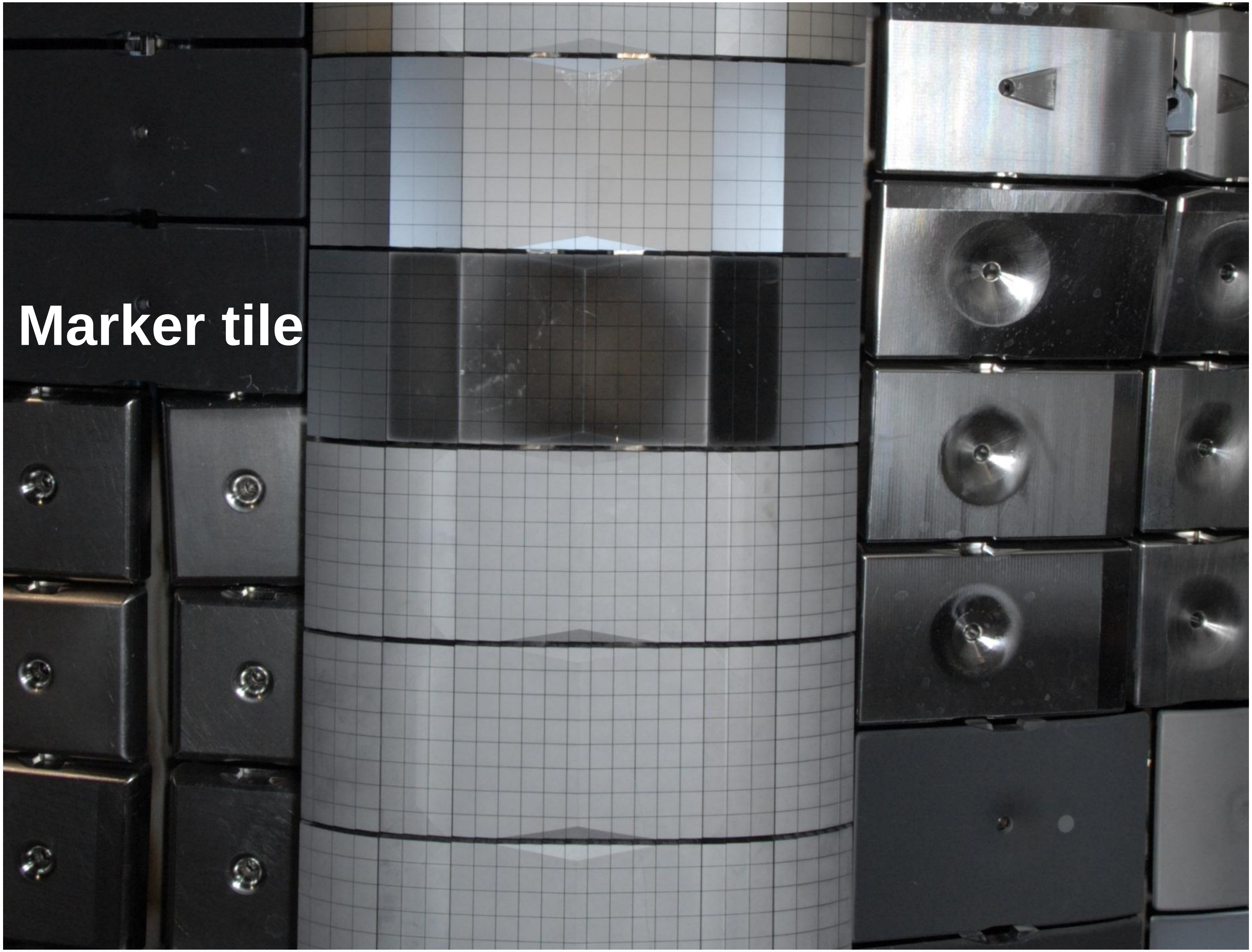
Poloidal Limiter (massive Be)



Ripped Upper Dump Plate (massive Be)



Inner Poloidal Limiter (massive Be)



W Divertor (top view)

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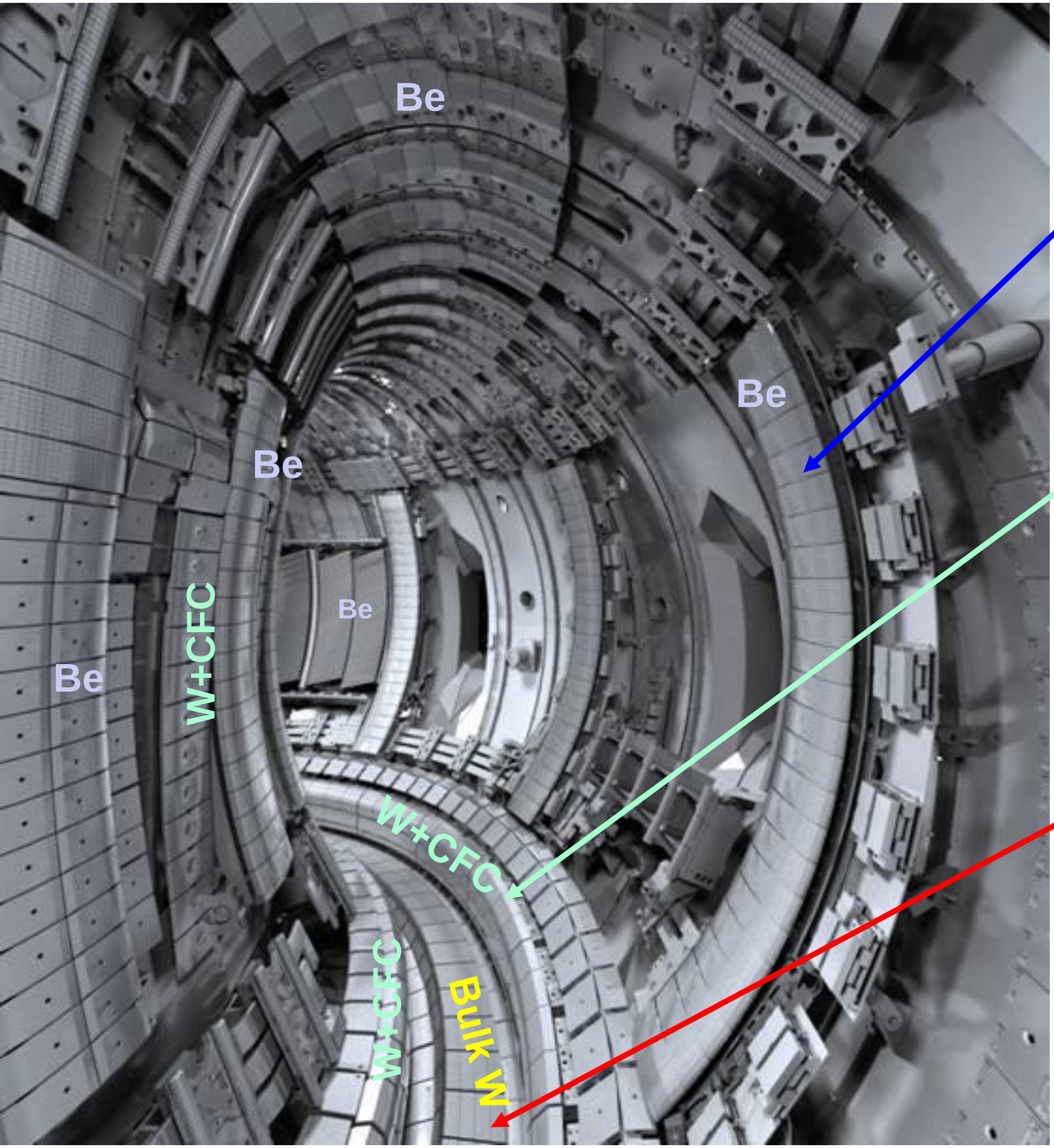
ILW: PFC Limits



Solid Be limiters
Surface temperature < 900^{o}C
22MJm^{-2}s$^{-1/2}$ (impact energy)

W-coating on CFC
Temperature <1200^{o}C
(carbidisation)
ELMs: ~5 MW m-2 s$^{-1/2}$

W stacks
Surface temperature limit
<1200^{o}C-2200^{o}C
20-35MJm^{-2}s$^{-1/2}$,
Fixings, 350^{o}C,
Energy limit ~60MJ/m^2/stack

What Should Be Measured?

- Source distribution at the wall and the divertor
  - Erosion fluxes: Be, W, BeD
  - Recycling flux: D, D_2
  - Impurity fluxes: C, O, N, Ar, He, Ne etc.
  - Bolometric reconstruction for total radiation in the divertor
- Impurity concentrations from the wall to the core
  - Fuelling efficiency and screening
  - Transport time
  - Bolometric reconstruction for total radiation
- Plasma parameters and ion fluxes in the divertor and main chamber
- Heat and power loads to the divertor and the main chamber
  - Profile information and decay length
  - Peak values

- Migration paths: net erosion and deposition
  - Net erosion rates of coatings
  - Net deposition rates in remote areas
  - Layer location and composition
  - Comparison of gross and net erosion (spectroscopy vs. QMBs)
  - Fuel retention

Different time scales involved:
Months –~ 120 x 500s (campaign); Experimental days –~500s; Discharges –~ms; ELM resolved ~µs

Edge Spectroscopy Systems

Spectroscopic observation of neutrals and low ionisation stages provide the impurity source distribution and the recycling flux

Fibre-coupled spectrometers and photomultipliers

- KS3 upgrade improves 'horizontal' and divertor spectroscopy
- KS8 upgrade for inboard/outboard source determination

Direct imaging spectrometers

- KT3 upgrade for complete outer divertor source profile

Endoscope systems

- KL11 will give useful inner and outer divertor source information and tomographic reconstruction
- KL1 refurbishment will give useful inner and outer wall source information

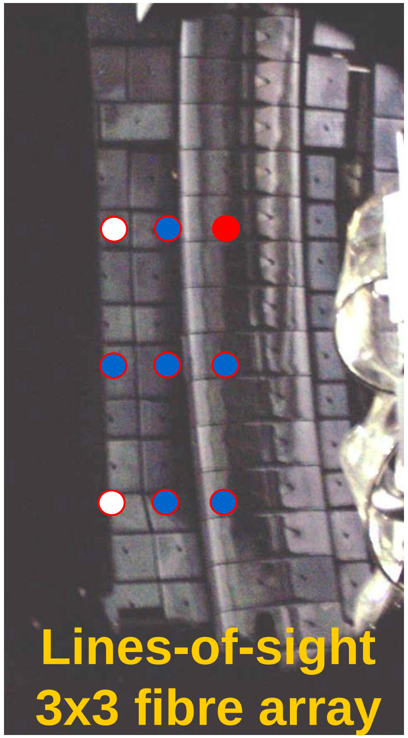
Visible channels – fibre-coupled – to VUV systems

- KT4/7 new visible views into divertor
- KT1 VIS upgrade for inner wall poloidal source profile

KS8 – Main Chamber Impurity Monitor

- *Compact Overview Spectrometer (COS) – # 24*
  - Particle fluxes monitor (impurities)
    - Atomic fluxes (Be, W, C, etc.)
    - Molecular fluxes (BeD, and if present CD, C_2)
  - Main chamber recycling flux (D, D_2)
  - Impurity source distribution
- *Echelle Overview Spectrometer (EOS) - #1*
  - Inner and outer wall impurity sources by Zeeman splitting analysis
  - Molecular properties

IWGL 7D planned
to be W-coated CFC



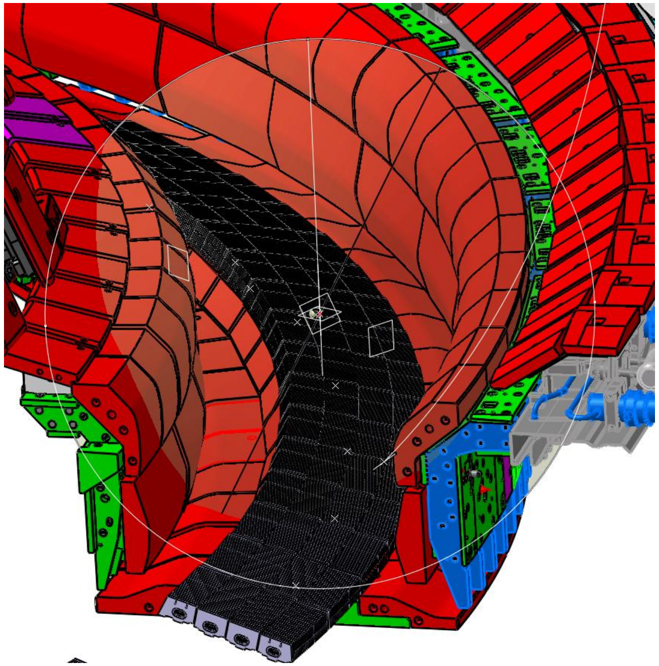
6 chords for COS
1 chord for EOS

COS
- 24 Czerny-Turner spectrometer
- Medium spectral resolution
- Wavelength span: 380-920nm
- Time resolution: typ. 100ms
  max. 5ms

EOS
- 1 Echelle spectrometer
- spectral resolution: R=20000
- Wavelength span: 363-720nm
- Time resolution: 125ms

KL11 - Divertor Endoscope for Spatial Information

View into Octant 2



- **Spatial resolution ≤ 3 mm at the object plane**
- **Suitable for tomographic reconstruction**
- **Suitable for impurity radiation pattern in the divertor**

Erosion – Deposition Diagnostics

Deposition monitors and marker tiles give information about net erosion and deposition

Quartz-micro balances (shot resolved)
- Net deposition or erosion rates in remote areas

Rotating collector probes (daily resolved – post mortem analysis)
- Robust techniques to measure deposition in remote areas

Sticking monitors (campaign integrated – post mortem analysis)
- Sticking probabilities and layer composition

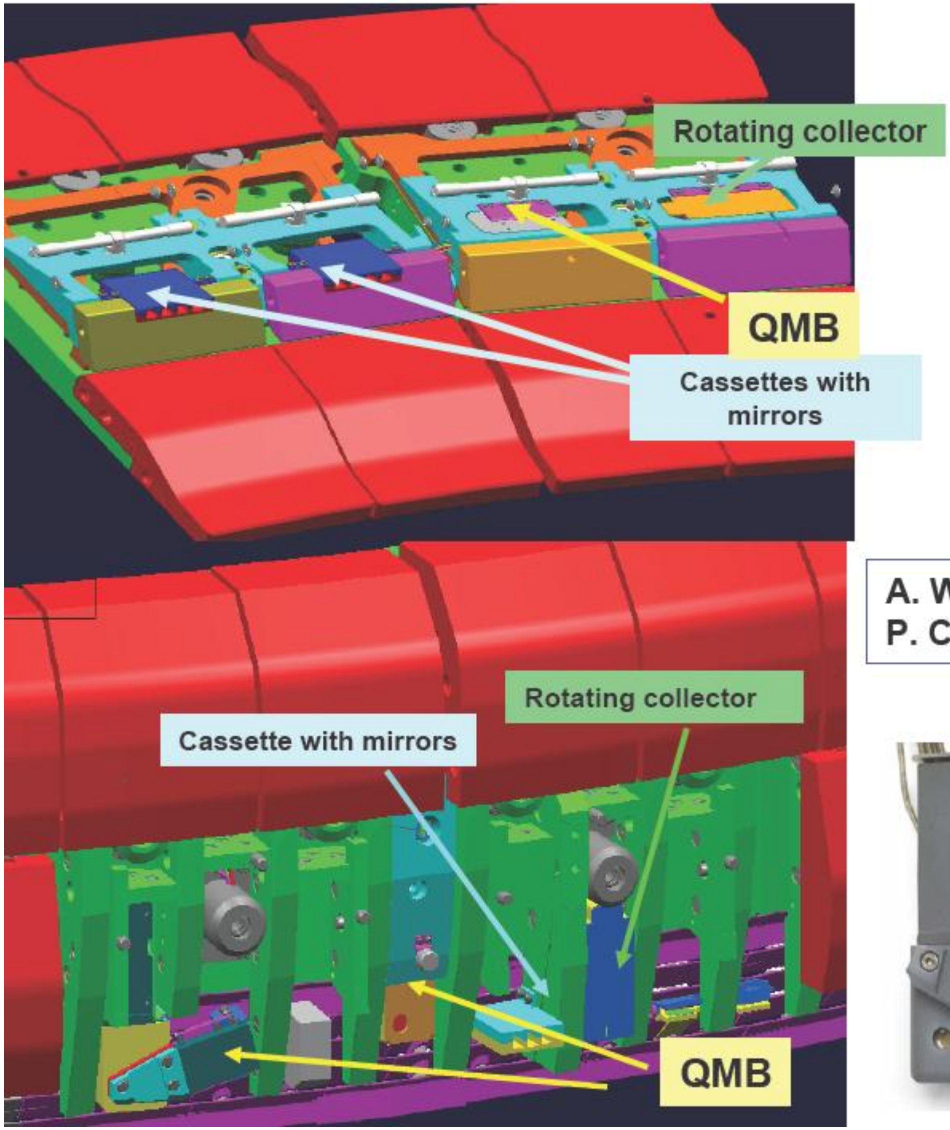
Marker tiles (campaign integrated – post mortem analysis)
- Erosion rates

Mirror cassettes (campaign integrated –post mortem analysis)
- Deposition rates and layer composition

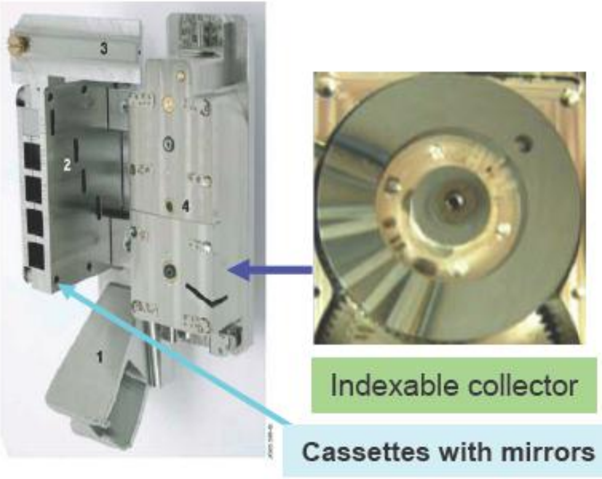
Post mortem analysis will also provide the final answer for fuel retention by determining the net transport to the inner divertor leg! Need of an intervention!

Erosion – Deposition Diagnostics

Divertor



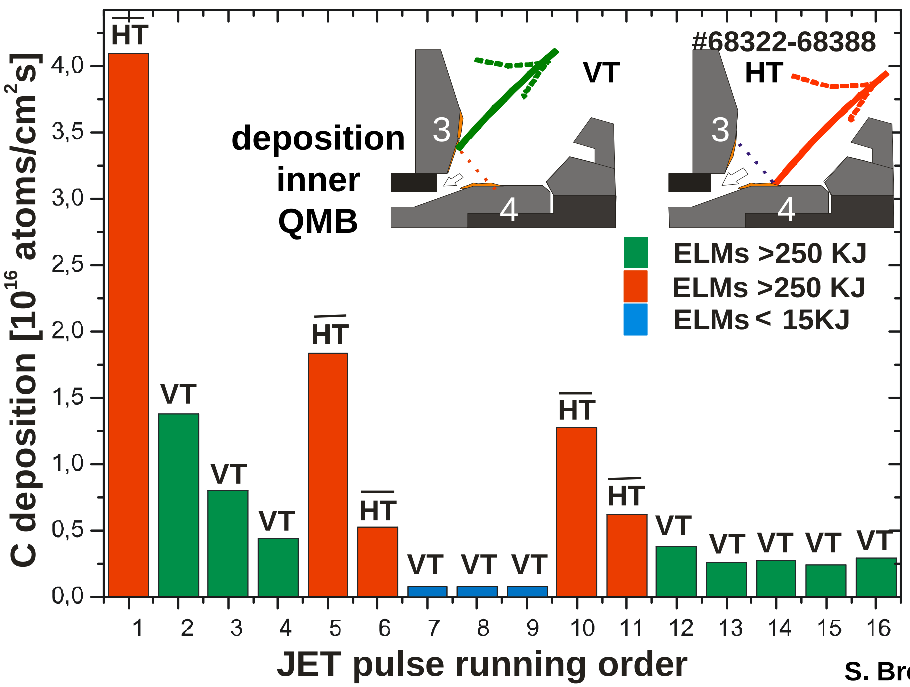
Main Chamber

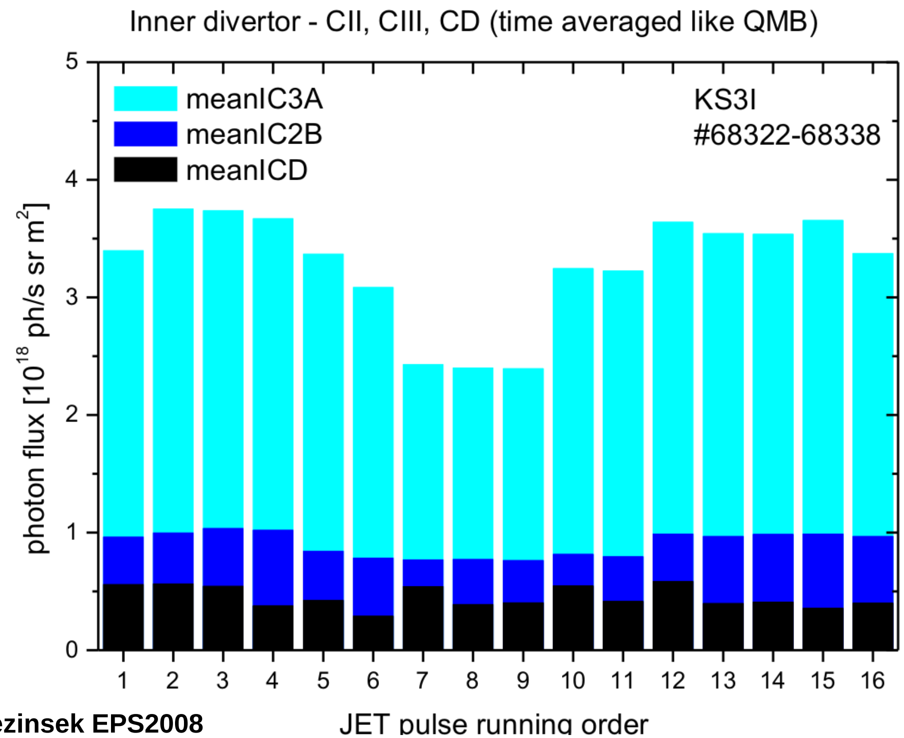


A. Widowson, M.Rubel, P. Coad – PFMC12

QMB and spectroscopy: Material Migration

- Magnetic configuration
- Power and heat load at the strike-points: steady state and transients
- Particle fluxes at the strike-points: ions and neutrals
- Local surface conditions: soft and hard carbon layers and CFC





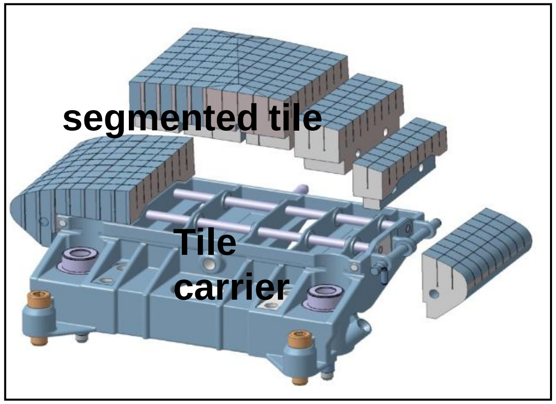
S. Brezinsek EPS2008

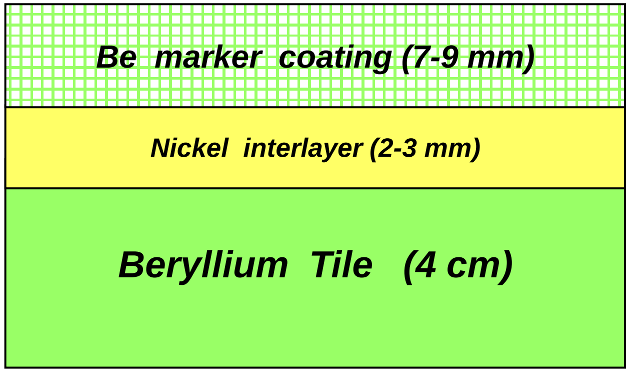
- Difference in carbon signals: Gross erosion vs. net erosion (=deposition on QMB)
- Quantify material transport to remote areas in the divertor

Brezinsek JNM PSI2010

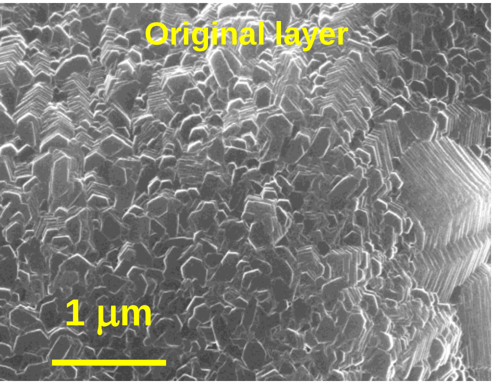
Beryllium Marker Tiles

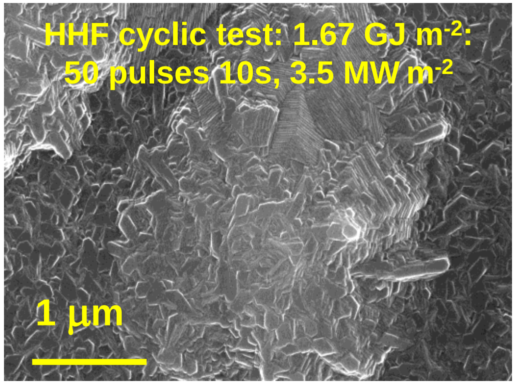
Be-Marker tiles developed to study net erosion at the main chamber limiters



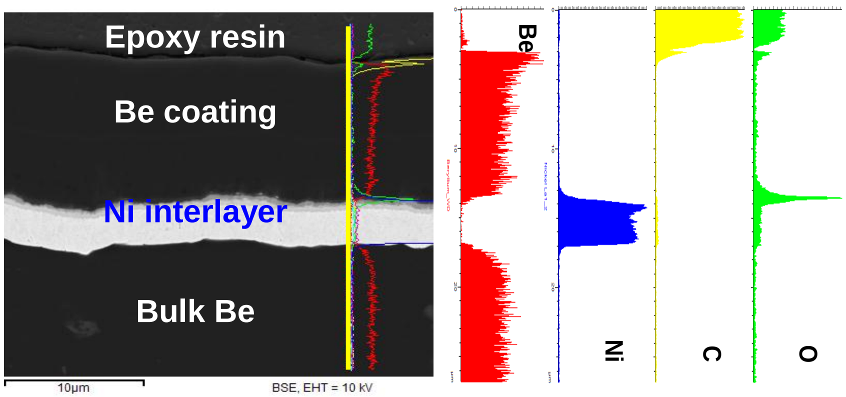


Micro-structure of Be layer





Micro-structure of marker after HHF test



Divertor: W coating techniques provides "natural" Mo marker!

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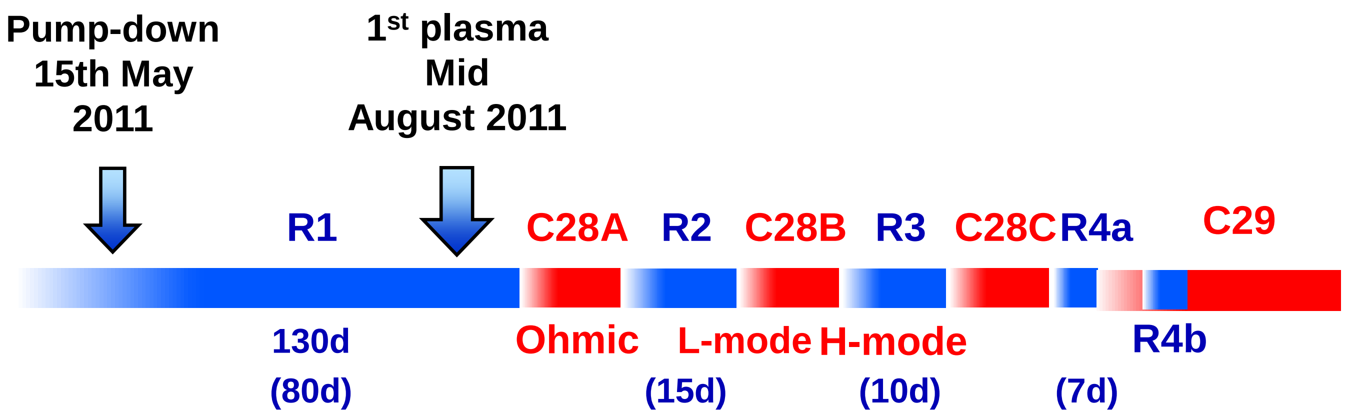
Program Blocks

- Initial scenario development
- H-mode development
- Hybrid development
- Intrinsic impurity characterisation & control
- W- Erosion
- Fuel retention
- Fuel recovery and conditioning
- Material migration and mixing
- Be power handling
- Detachment & divertor heat load mitigation
- Divertor power handling
- Pedestal & L-H threshold
- ELM physics and heat loads
- ELM mitigation
- Disruption studies
- Heating and fuelling
- Monitoring pulses

Program Sequence – ILW 2011/2012

Maximise operating time and optimise with respect to Headlines and ITER priorities

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2011								C28	C28	C28	C28	C29
2012	C29	C29	C30a	C30a	C30b	C30c			Shutdown			



- Restart blocks interleaved with Campaign C28 blocks
- Controlled start with scientific supervision
- C28-C29 (fixed timeline) and C30 (provisional plan)
- C30 to be consolidated in Nov 2011 in a general planning meeting

C28 Campaign

	Scenario Development	PSI Relevant Experiments
R1	1 limiter phase, X-point formation and low shape	
C28a	First ohmic scenario	Initial Be erosion, material mixing and retention
R2	More shapes + PPCC: HT3, V5, SFE PIW end-to-end tests First NBI box, ICRH, LH	Monitoring pulse preparation L-mode detachment Limiter plasma and heat loads Intrinsic impurity composition C/Be migration study Fuel retention using AGHS in L-mode First disruption studies First Be & W power handling
C28b	L-mode qualification First H-mode attempts	
R3	WALLs energy limits Second NBI box + advanced limit setting Increased ICRH + ECT VDE tests	Monitoring pulse preparation W-erosion (steady-state vs. ELMs) W-screening peaking and control Particle balance with N injection C/Be migration study Fuel retention using AGHS in H-mode Material migration to remote areas Characterisation of heat load including ELMs Bulk W tile power handling Detachment studies Disruption studies and MGI (incl. heat loads)
C28c	H-mode qualification with ILW Baseline H-mode at 2.5MA (1st)	

C29 Campaign

	Scenario Development	PSI Relevant Experiments
R4A	Power handling and power system qualification	
C29	Baseline H-mode at 2.5MA L-H threshold Vertical target configuration Quasi-double null configuration Detachment control and seeding control	Monitoring pulse preparation Impurity seeding studies C/Be migration to remote areas Fuel retention using AGHS (including sweeping) Fuelling and seeding studies Type III ELMy H-mode Divertor characterisation including detachment
R4B	Hybrid plasma development	ELM physics and charactrisation W-erosion (steady-state vs. ELMs) W-screening peaking and control ELM mitigation techniques Characterisation of heat load including ELMs Bulk W tile power handling Disruption studies and MGI (incl. heat loads)
C29		W-bulk melting references

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Questions related to the Be first wall

- Be erosion: Absolute yields? Angular dependence? Impurity composition?
- Be erosion: Role of BeD? At JET observed only after strong Be evaporation
- BeN formation? Erosion yield?
- Be re-erosion yields?
- Be/W alloys and Be/C mixture formation? Transients?

=> Multidimensional parameter space: fluxes, temperatures, energies, composition

- Be and BeD spectroscopy: photon emission rates (2 eV -100 eV)?
- Role of destruction process of BeD? Recombination into BeD?

=> Multidimensional parameter space: fluxes, temperatures, energies, composition

- Be retention dominated by co-deposition
- Retention in Be/N, Be/C mixtures etc.

=> Multidimensional parameter space: fluxes, temperatures, energies, composition

Dedicated data needed to interpret experimental results …
… experimental results as input for predictive modelling for ITER.

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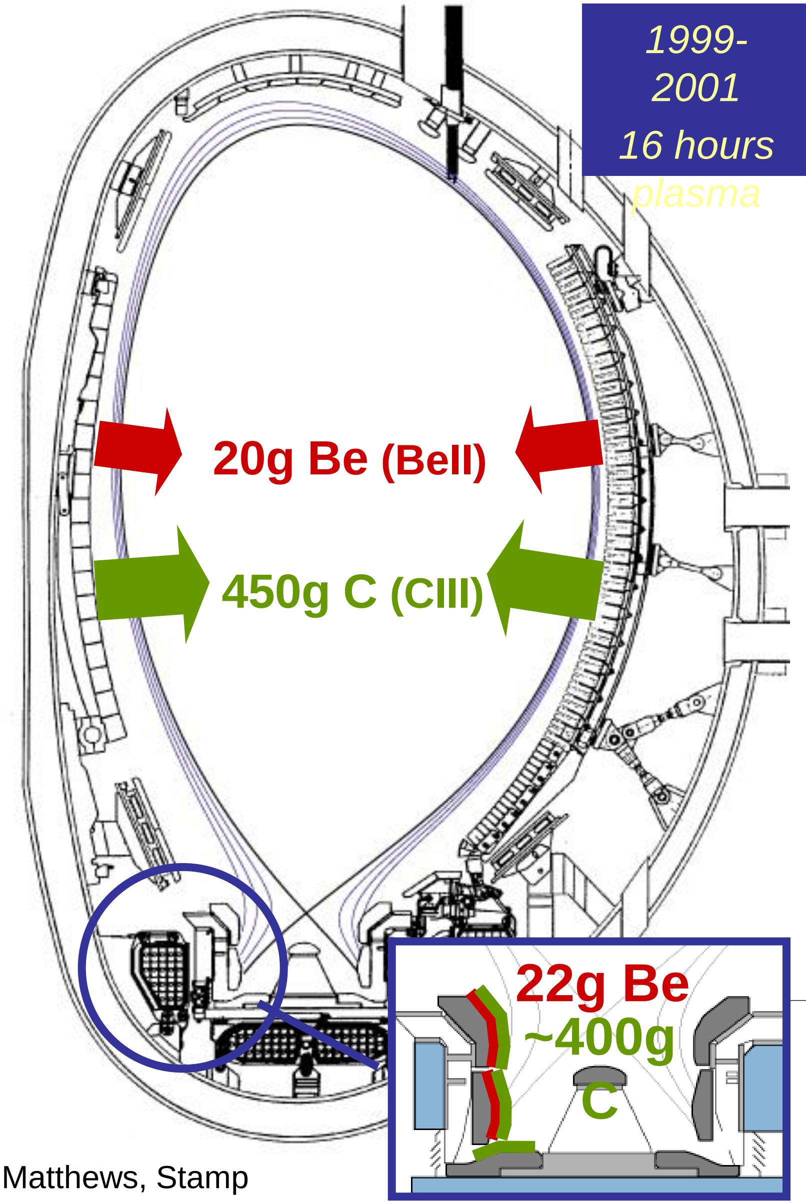
Material Migration



Matthews, Stamp

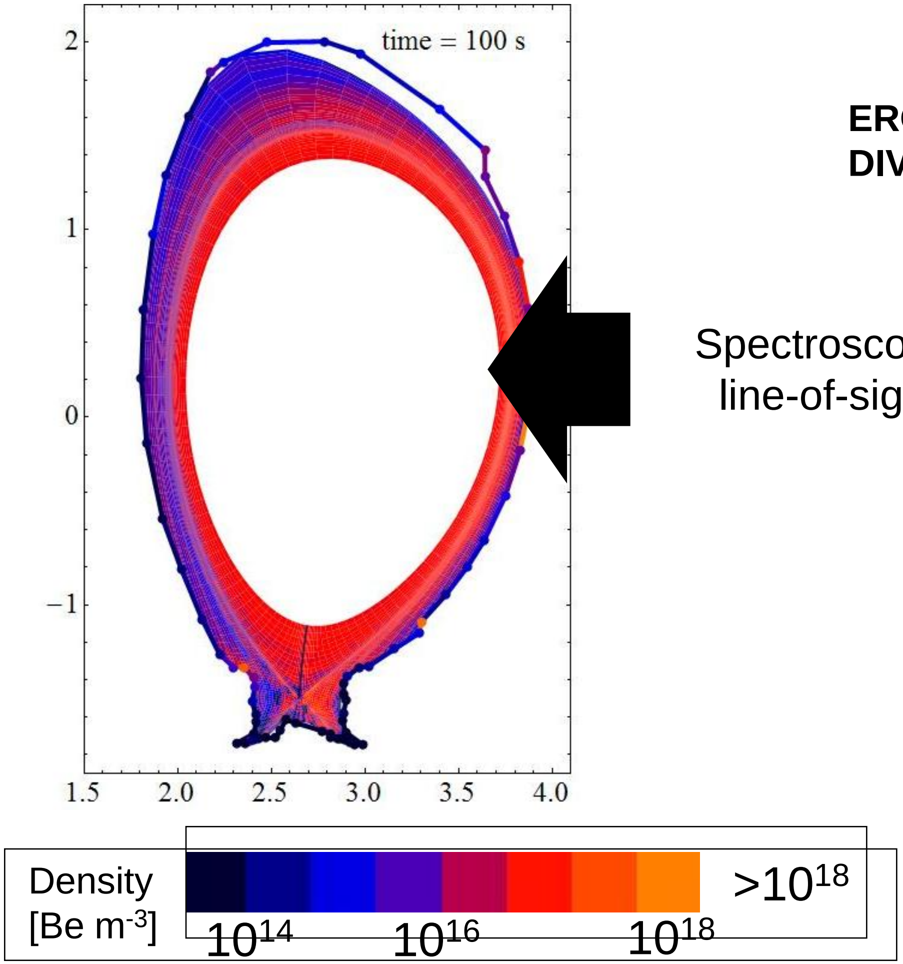
JET with C/Be material mix:

- Ion and neutral bombardment to the PFCs
- Main chamber is the dominant erosion source
- Material (C and Be) is transport to the inner divertor due to SOL flows
- Multiple step process (C) and transport to remote areas
- Low Be content in remote areas

JET with Be/W material mix:

Does the migration pattern change without C?
How strong is C reduced?
Flux ratio of Be to C?
Impact of seeding gases?
Transport to remote areas?
Source strength of W sputtering by impurities?

First experiment: Evolution of Be Wall Sources



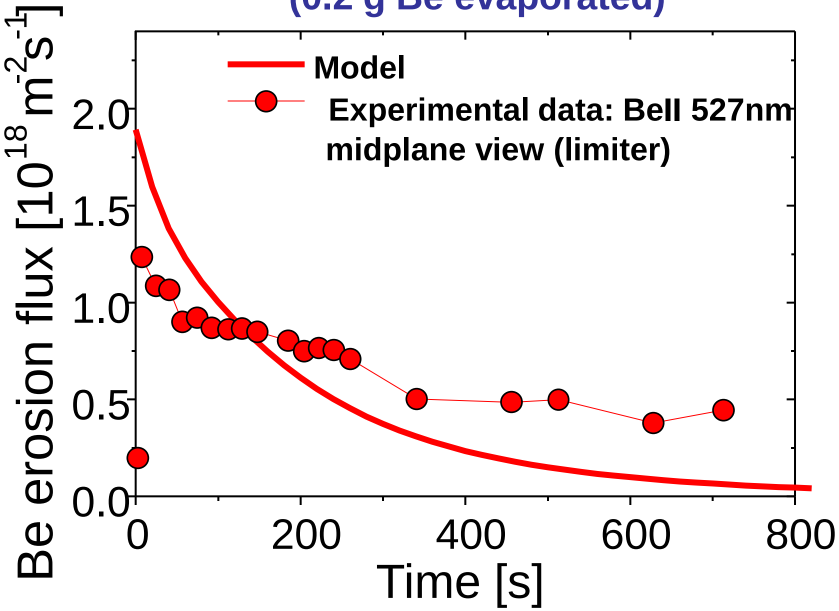
ERODEP
DIVIMP

Spectroscopic
line-of-sight

Reference Experiment

Be erosion fluxes in L-mode

(0.2 g Be evaporated)



DIVIMP-ERODEP Modelling

Reinelt JNM PSI2010

- **First ILW experiment: Be and W mixing in the inner divertor leg**
- **ERODEP-DIVIMP modelling – needs input for mixing matrix, erosion yields…**

Initial Experiment: Experimental Proposal

Ex-1.1.2: First wall Be erosion and Be/W mixing in divertor

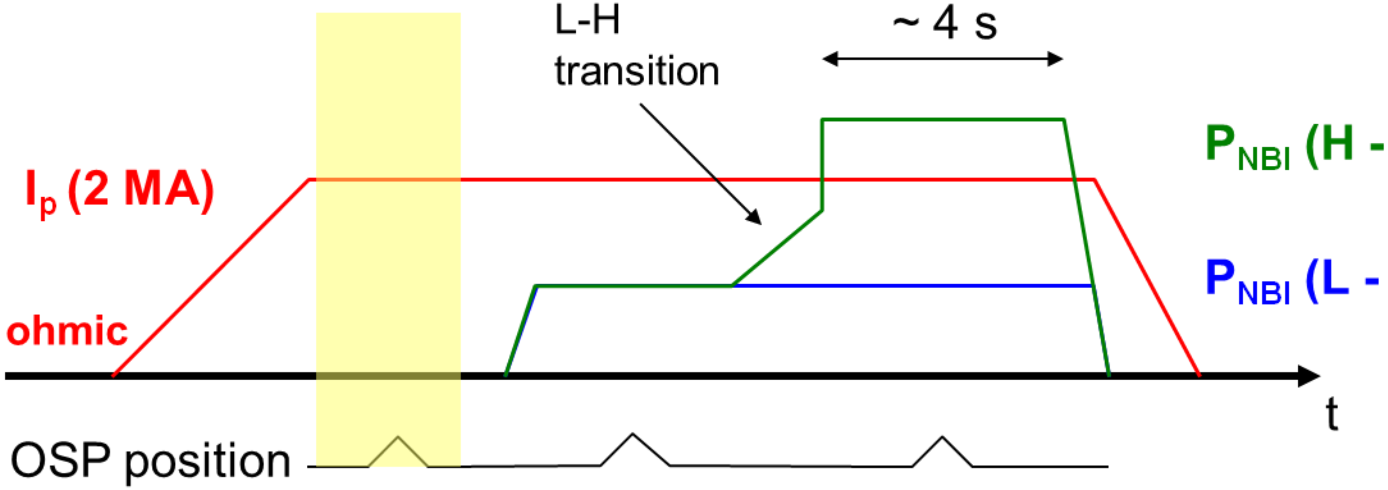
- Initial experiment with "new" plasma-facing components
- Period of identical simple ohmic plasmas till steady-state conditions reached => inner divertor covered by Be (expect. time ~500s)
- In-situ determination of Be and W sources via spectroscopy
- Initial quantification of reduction in C fluxes and increase of Be fluxes
- In-situ determination of Be transport to remote areas via QMBs
- Gas balances with AGHS to document wall recycling and fuel uptake

Additional Be migration experiments:

- Transport to remote areas
- Be tracer experiment (^{11}Be)
- Be probe experiment
- Be vs. C erosion, deposition and redeposition
- Two weeks of identical plasmas before tile intervention

Follow-up Experiment: Monitor Discharge

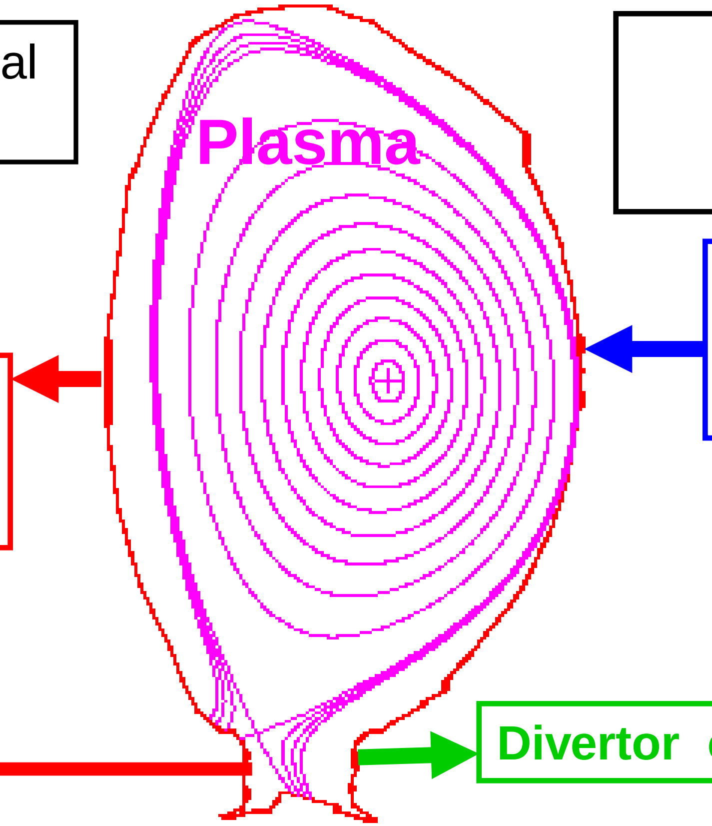
- Regular monitor/reference discharge (once per day/week)
  - **Reference pulse to monitor changes in wall conditions, impurity fluxes and concentrations with time and plasma conditions**
  - **must be robust and easy to execute**
  - **configuration identical to “first" ILW experiment**
  - **plasma evolves with campaigns by addition of reference phases: limiter phase, ohmic phase, L-mode, H-mode phase(s)**
  - **each reference phase with min. 3s duration**
  - **reference phases with different ROG/RIG**
  - **small strike-point sweep at end of phases for LP and spectroscopy**



Gas Balance Studies at JET - ILW

Repeat sets of identical discharges

Regenerate cryogenic pumps before and after expt.
→ collect total pumped gas



T. Loarer
PFMC 2009

Injection = Pumped + Short Term Ret + Long Term Ret

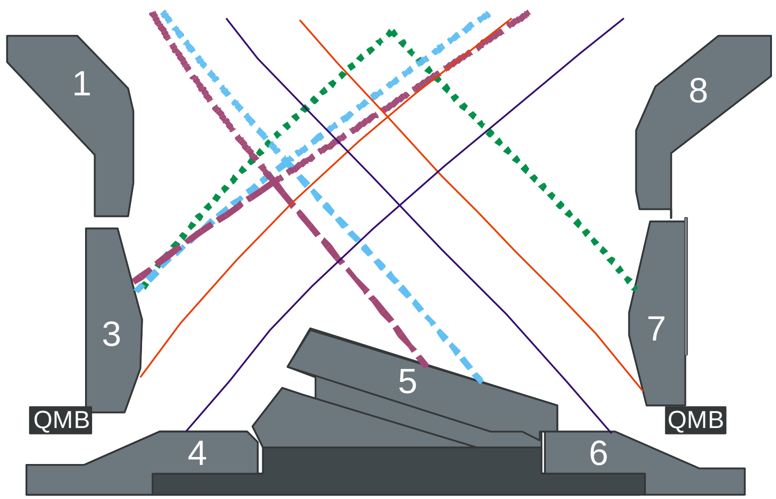
Total recovered from cryo-regeneration:
Pumped + **intershot outgassing** over ~800s (assumed equal to **Short Term Ret**)

Loarer JNM PSI2010

References for Material Migration Studies

Intrinsic carbon transport

Migration in comparable plasma and surface conditions

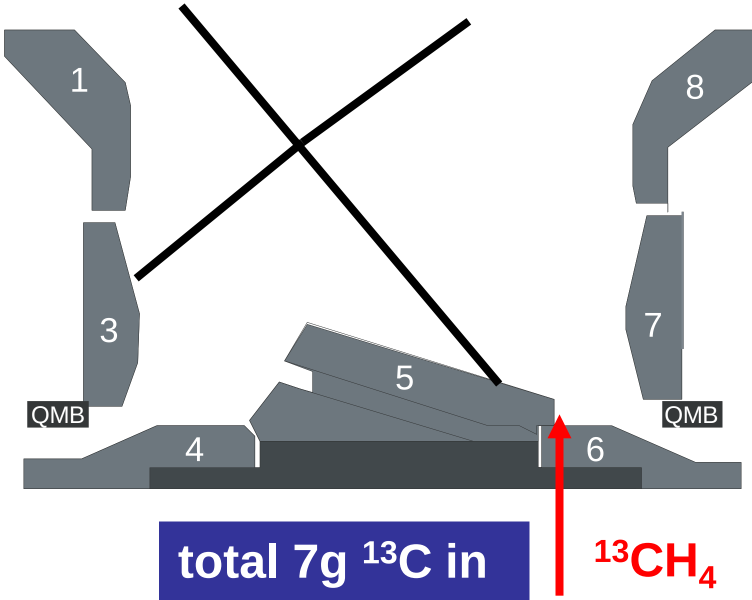


S. Brezinsek and H.G. Esser et al.

	inner QMB	outer QMB
OSP on tile 5	0.30 nm/s	0.58 nm/s
OSP on tile 5	0.66 nm/s	0.21 nm/s
OSP on tile 6	4.71 nm/s	-0.28 nm/s
OSP on tile 7	1.46 nm/s	0.37 nm/s
OSP on tile 7	0.58 nm/s	0.45 nm/s

Carbon tracer experiment

- **ILW reference plasma in H-mode**
- **Injection into outer divertor**
- **With ILW – SiH_4**



total 7g ^{13}C in 30 discharges

M.Rubel and P. Coad et al.

- **1/3 of $^{13}CH_4$ pumped by divertor cryo**
- **Post-mortem analysis ongoing**

Brezinsek JNM PSI2010 **Likonen JNM PSI2010**

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- Definition of the JET work program 2011/12
- Questions related to the Be first wall
- Examples: the very first experiment - Be migration and mixing
- Be data needs for ERO

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Be data needed for the ERO code

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Be data necessary for ERO

ERO applications involving Be

1. ERO for ITER divertor
2. ERO for ITER Be first wall
3. PISCES-B – ERO benchmark
4. Outlook: JET ILW

Former: Bohdansky*Yamamura
Recently: Eckstein 2007 fit

Data for fit: SDTrimSP, MD,
still many uncertainties, empirical data is difficult for interpretation

Be data

1. Sputtering yields, including angular part
2. Be chemical erosion (Be-H molecules)
   - Be-H release from surface
   - Be-H dissociation, charge exchange, spectroscopy, …
3. Be atomic data (ionization, spectroscopy)
4. Be/C/W mixed layers
   - Carbide/alloy formation
   - Influence on sputtering/retention

Recently available

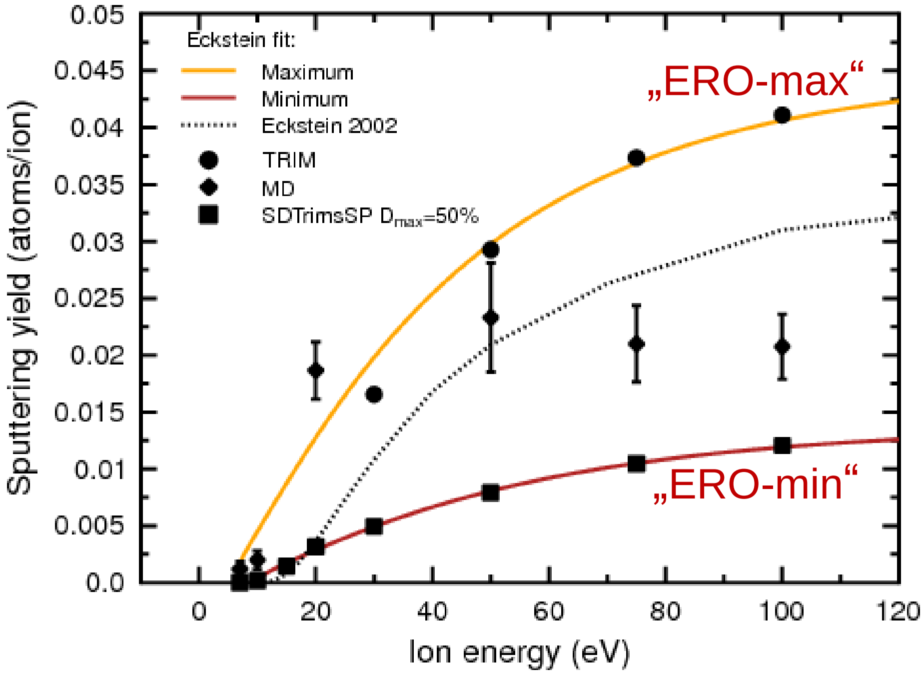
Support from R.Janev

ADAS, including MS

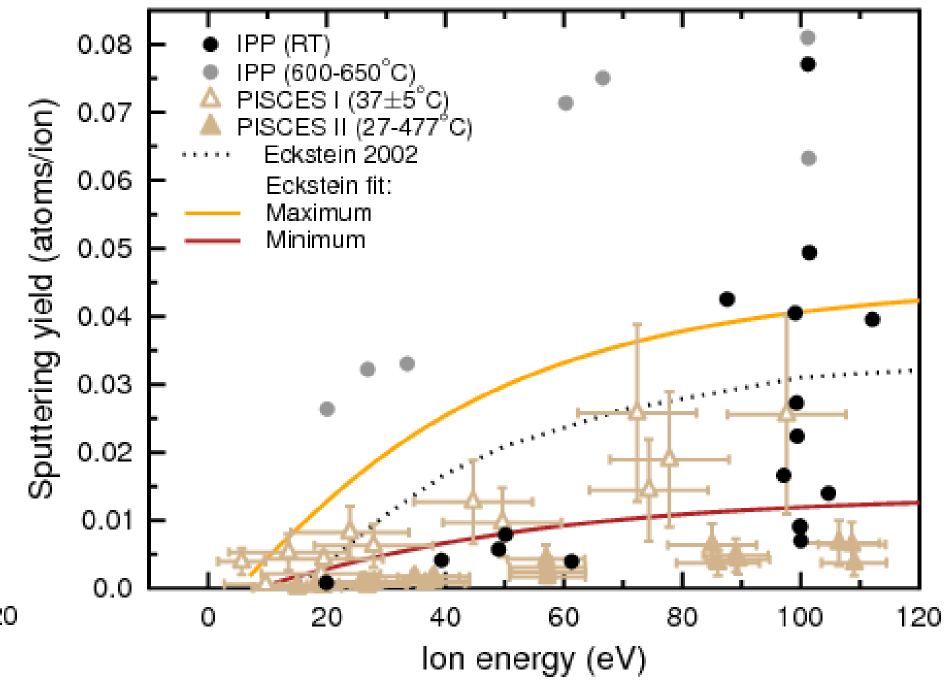
Many experiments, some modelling done (e.g. ERO for PISCES-B). Still, open and complicated issue

Be sputtering yields – extreme assumptions

Be by D$^+$ sputtering



Be by D$^+$ sputtering



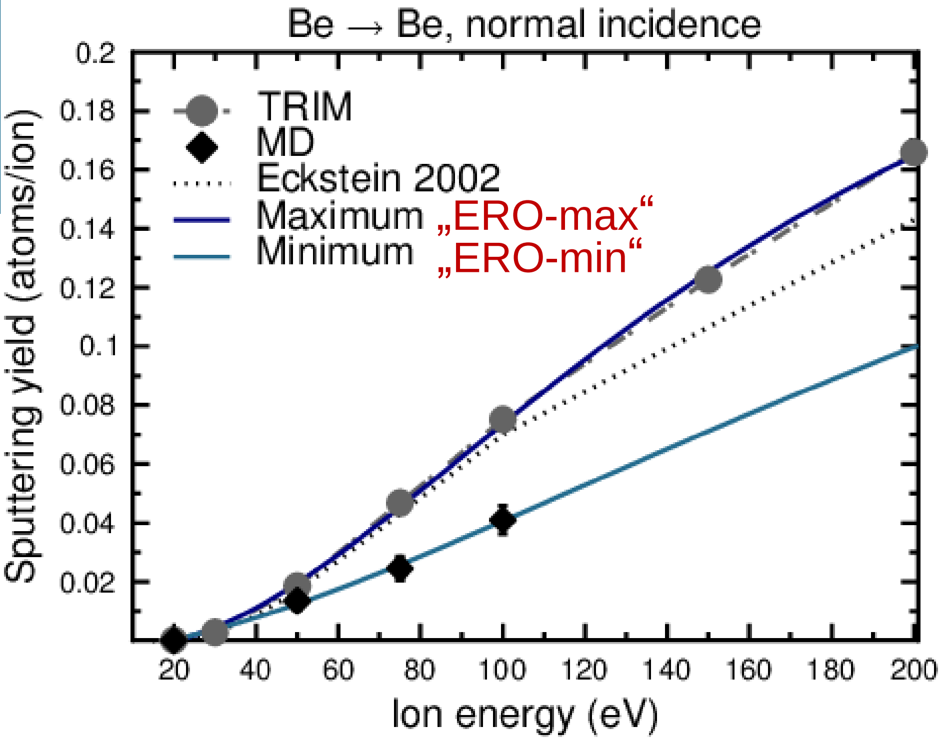
Only the 'calculated' data are included!
1) "maximum" – static TRIM + MD
2) "minimum" – SDTrimSP with 50% of D (reasonable limit)

Experimental data too much scattered!
1) Large deviations: no sense to analyse shape of curves
2) Various effects are difficult to separate

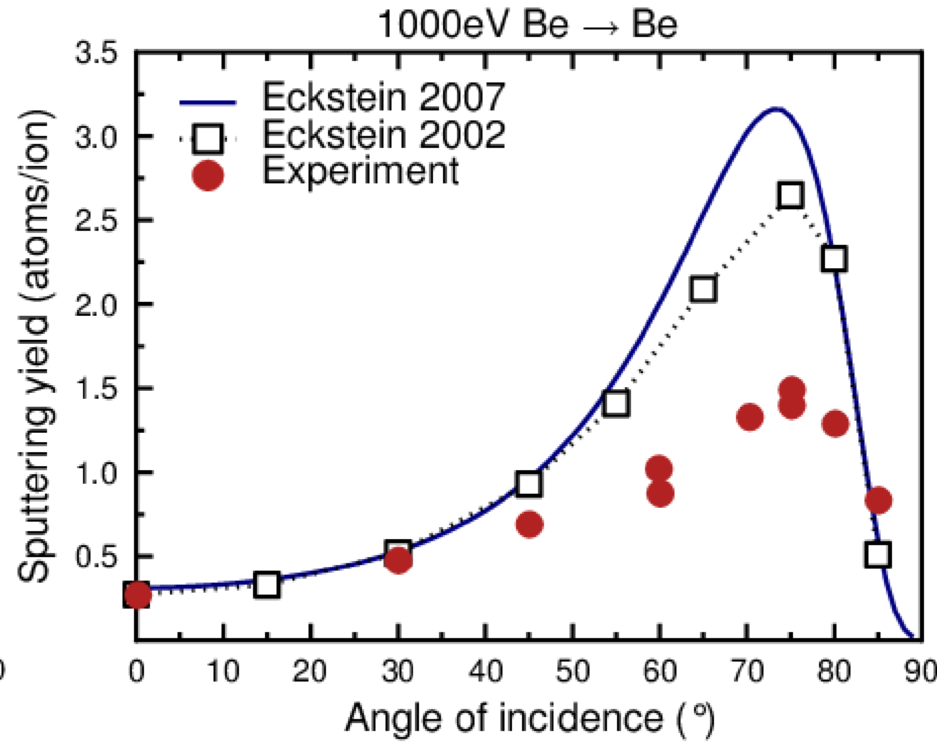
Normal incidence! Angle dependence should be taken into the account!

Be sputtering yields – self sputtering

Normal incidence



Angular dependence

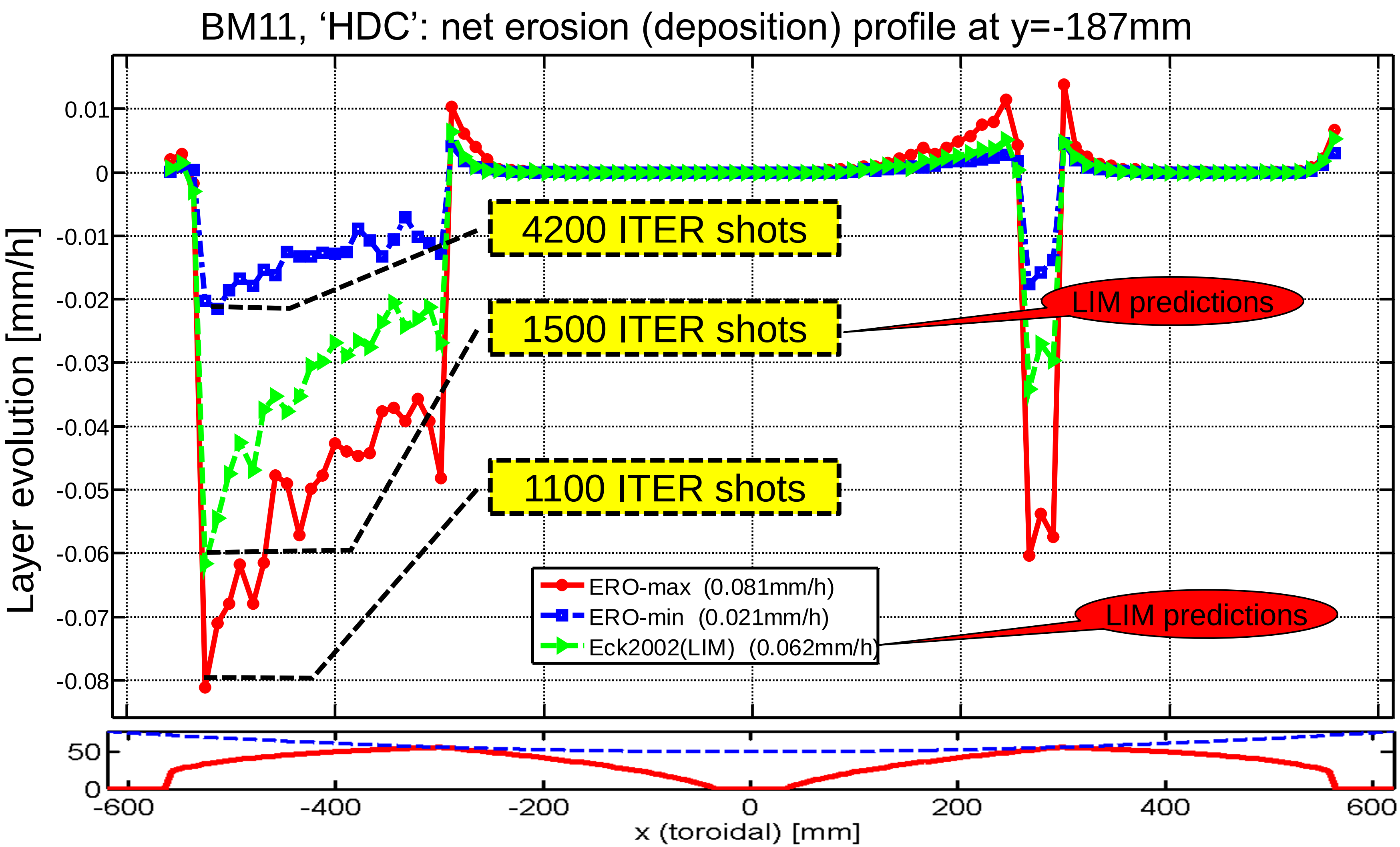


Estimation based on calculated data as for Be by D^+ sputtering

Angular part is essential!

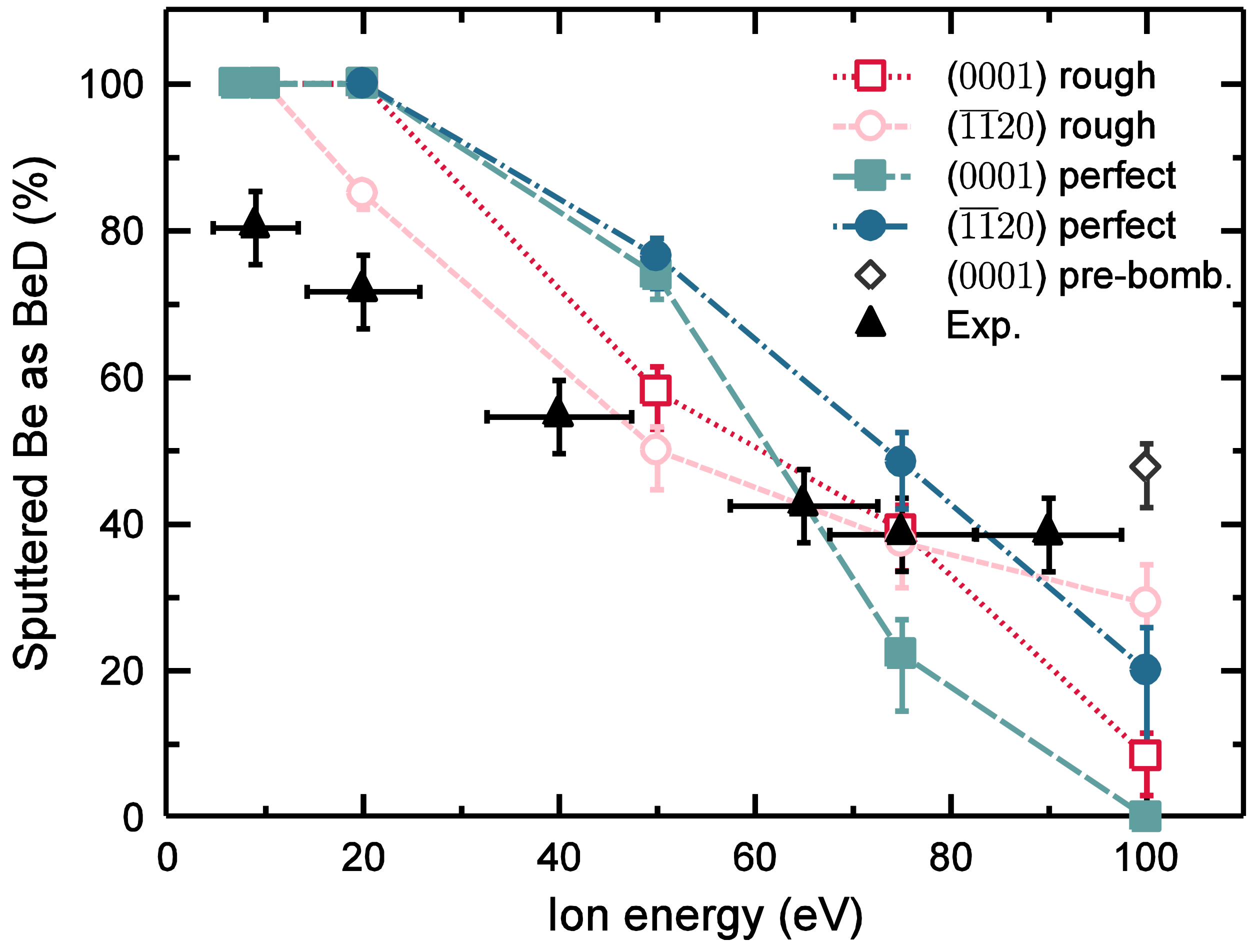
For following BM simulations ERO uses Eckstein 2007 fit.

Sputter yields assumptions and net erosion for ITER



Important uncertainty, though less important as plasma prameters.

Be sputtering yields – BeD fraction



Dependence on surface temperature? Other uncertainties? . . .

Model and data for BeH and products transport in plasma – under development