The JET ITER-like wall project

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EFDA Associate Leader for JET
with contributions from G.Matthews, P.Coad and K-D.Zastrow
PPPL, 9 May 2005

The Joint European Torus (JET)

Plasma closest to ITER physics

Torus radius	3.1 m
Vacuum vessel	3.96m high x 2.4m wide
Plasma volume	80 m^3 - 100 m^3
Plasma current	up to 5 MA in present configuration
Main confining field	up to 4 Tesla

Unique technical capabilities :

- Tritium
- Beryllium

The JET ITER-like Wall Project

Contributions from G.F.Matthews (Project Leader),

E.Villedieu (Engineering team Leader), V.Riccardo (Deputy Engineering team Leader), T.Hirai (bulk W R&D Leader), H.Mayer (W coating R&D Leader), V.Philipps (Project Scientist), P.Edwards (Installation Manager), M.Way (DO coordinator), M.Cox (Project Sponsor)

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and many others

Part I - Programme Summary

Part II - Technical Description

Part III - Accompanying projects

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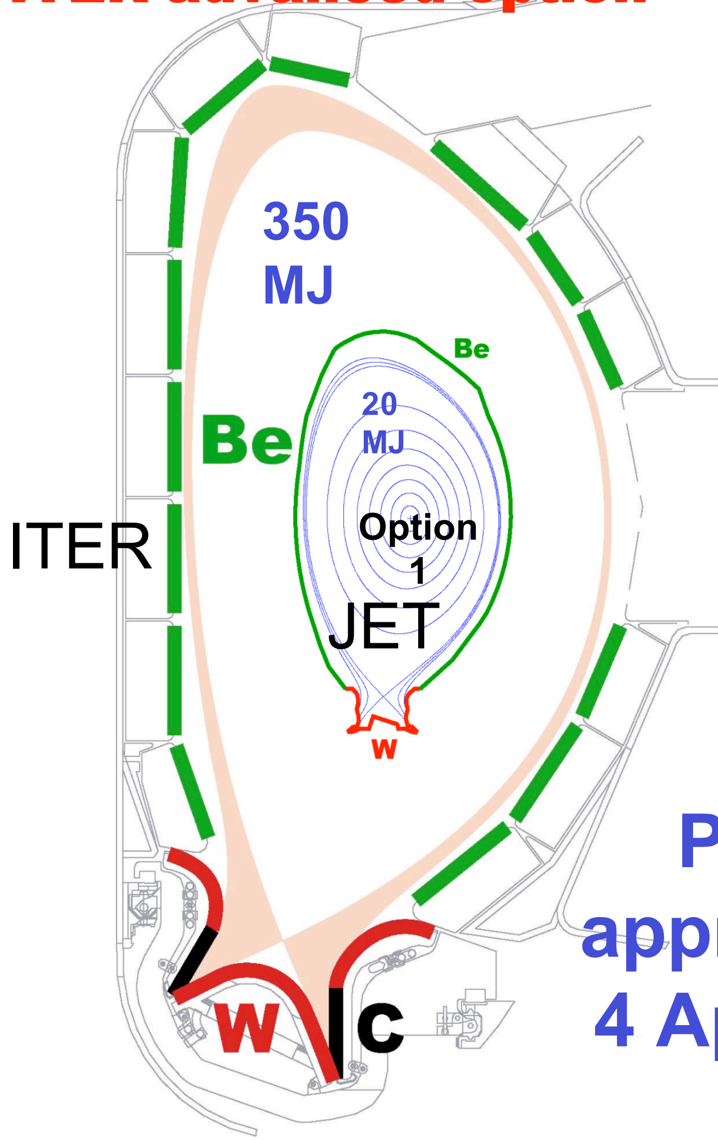
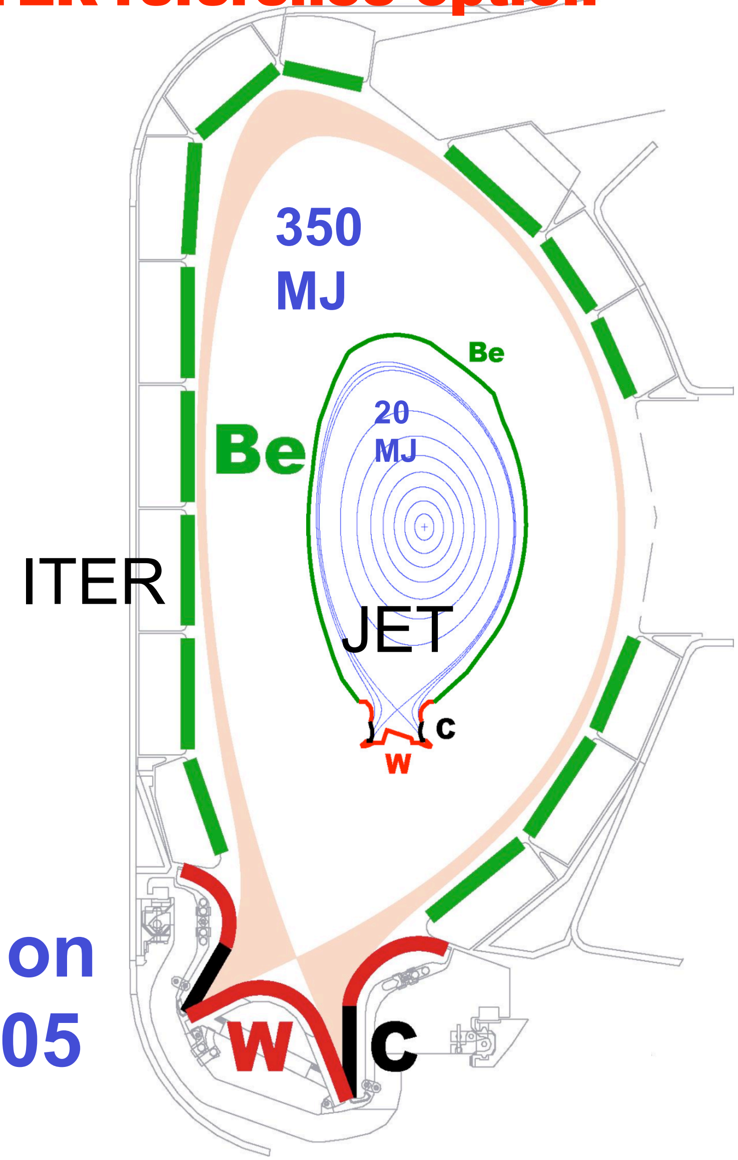
JET

Be wall / all W divertor -
JET Reference Option
⇨ ITER advanced option



Be wall / C + W divertor -
JET Fall back Option
⇨ ITER reference option



Project approved on 4 April 2005

Programme with the ITER-like wall

Construction over the period 2005-2008

Installation of Be wall and W divertor foreseen during a 1 year shutdown in 2008

+ NB Upgrade (from 25 to 24 MW) high frequency pellet injector for ELM mitigation and diagnostics

Experimental Campaigns in 2009-2010

foreseen to be interleaved with

Short Shutdowns for sample removals

Key Objectives

• Material erosion and migration with relevant mix of materials

• Tritium inventory control

•Wall lifetime

• Study of damage due to transients (ELMs and disruptions) e.g. melt layer loss studies

• control / mitigation techniques
⇨ Limit disruption / ELM damage

• *Reference Option (all-W divertor):* Operate without C - radiation

• *Option with C targets:* Test de-tritiation techniques

An essential stepping stone to ITER

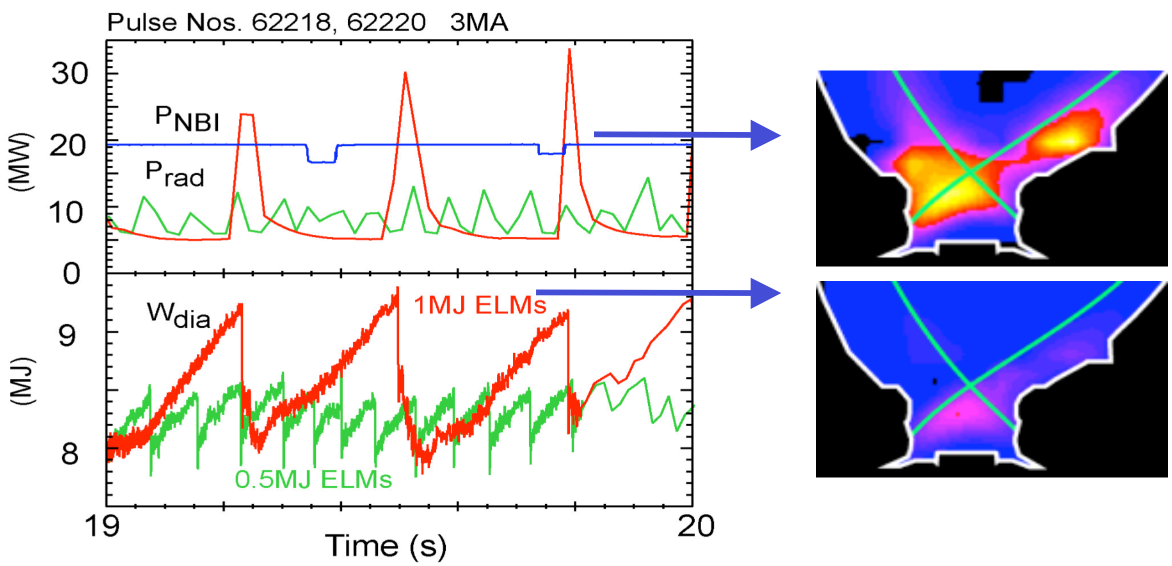
Demonstrate routine / safe operation of fully integrated ITER compatible scenarios at 3-5MA

⇨ power upgrade (40-45 MW overall power) to operate at high performance and high densities

ELM effects on the W (or C) divertor in JET

1-2MJ ELMs required to study melt layer effects on W target

achievable with 10-20MJ stored energy

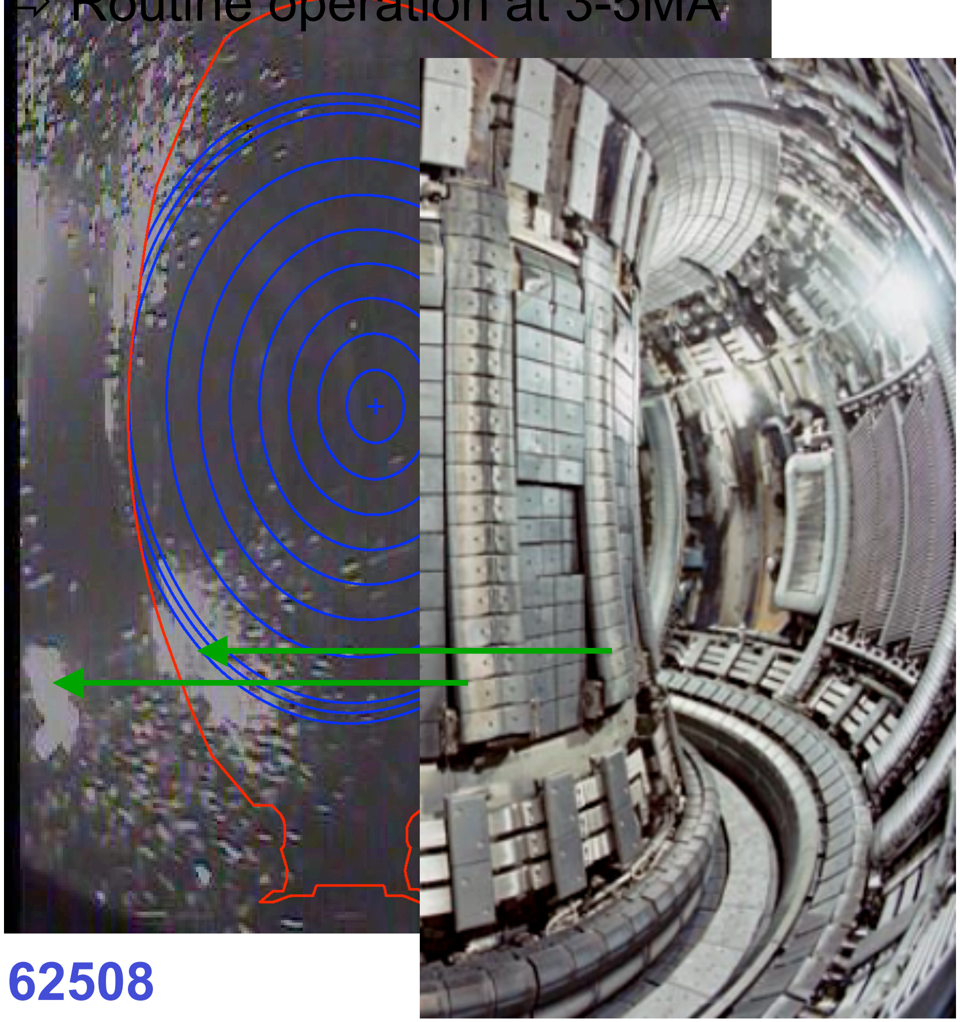


1MJ ELMs in JET → wall loads 10 – 40 $MJm^{-2}s^{-1/2}$
divertor Be-melting (~ 16 $MJm^{-2}s^{-1/2}$)
divertor C-ablation (~ 35 $MJm^{-2}s^{-1/2}$)

Studies of disruptions on a Be wall and W divertor

Disruption mitigation techniques

⇨ Routine operation at 3-5MA



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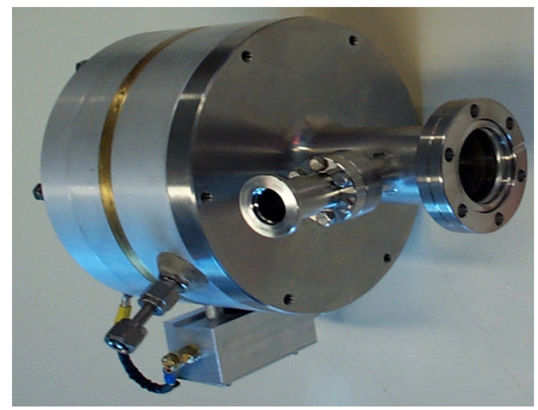
W_{th}= 3.5 MJ disruption on JET

fast mitigation valve currently being installed



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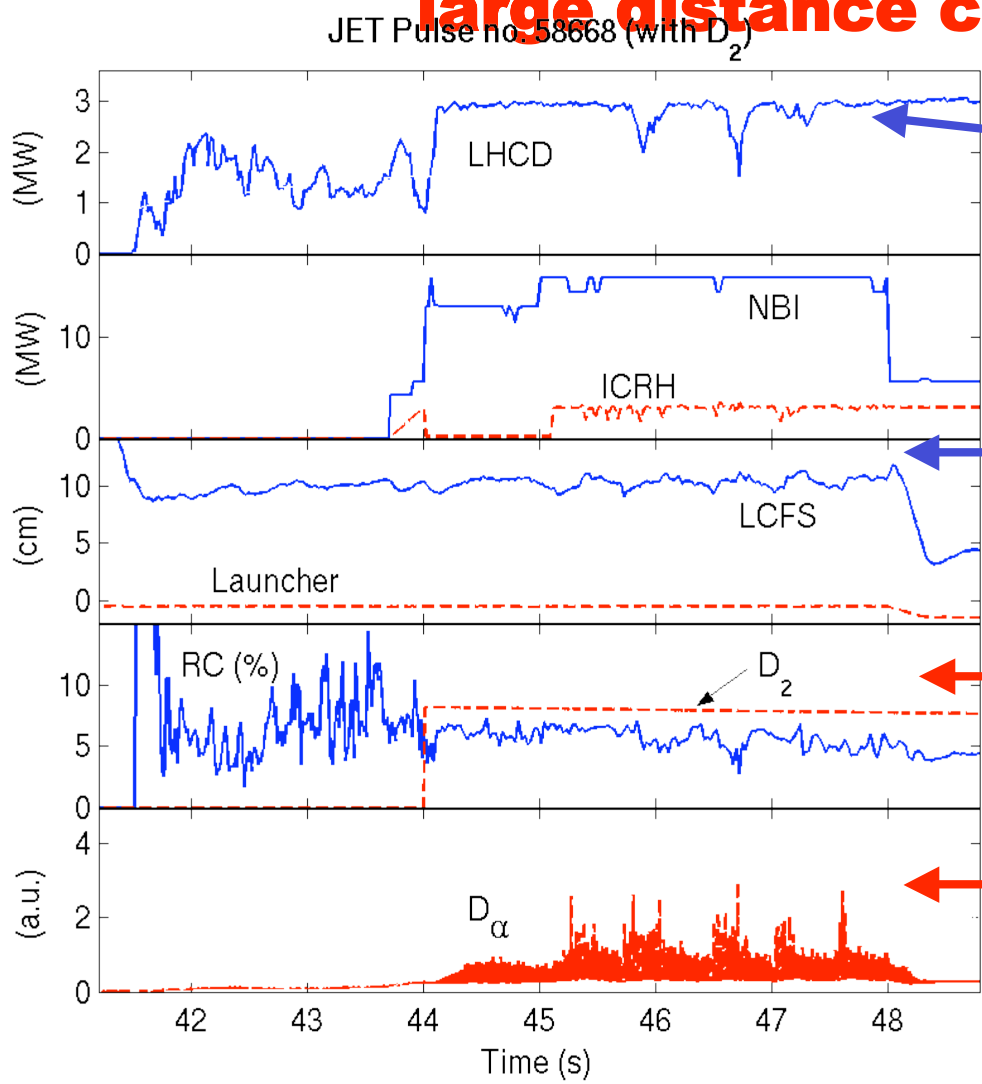
Further develop ITER-relevant large distance coupling (ICRH and LHCD)



3.0MW LHCD coupled

at 11cm distance between LCFS and launcher (ITER-relevant) in 2003

with D_2 injection (8×10^{21} el/s) near the coupler

in type I ELM plasma

Ekedahl/CEA, Noterdaeme/IPP-Garching, Mailloux/UKAEA, Tuccillo/ENEA

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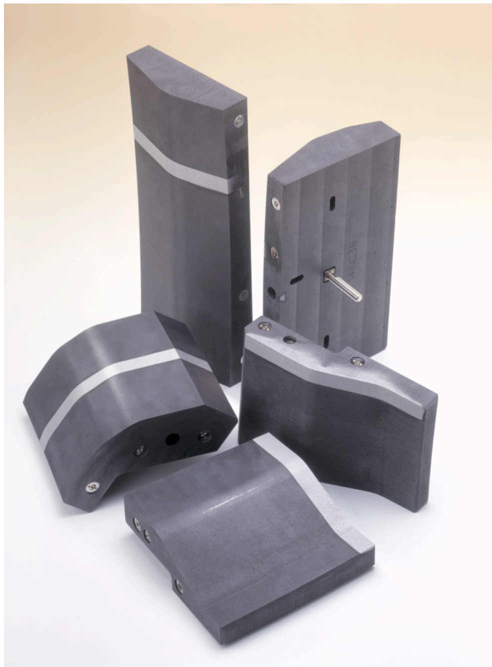
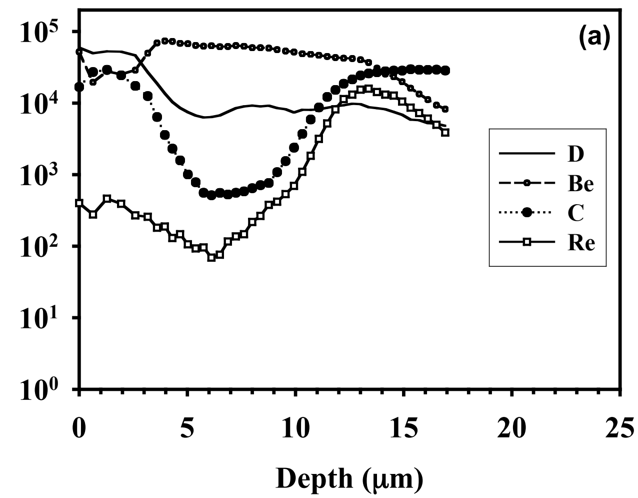
Fast shutdowns for sample removal



Surface analysis essential :

- Accurate estimate of D (or T) retention
- Full poloidal coverage
- Complete characterisation of substrate and deposits
  ⇨ SIMS, RBS, PIXIE, TOF/ERDA, electron microscopy…etc.

SIMS depth profile can resolve ~ 500 shots



Fast RH shutdown duration including Restart (ICH and NBI)

- 10 – 11 weeks interruption of experimental campaigns

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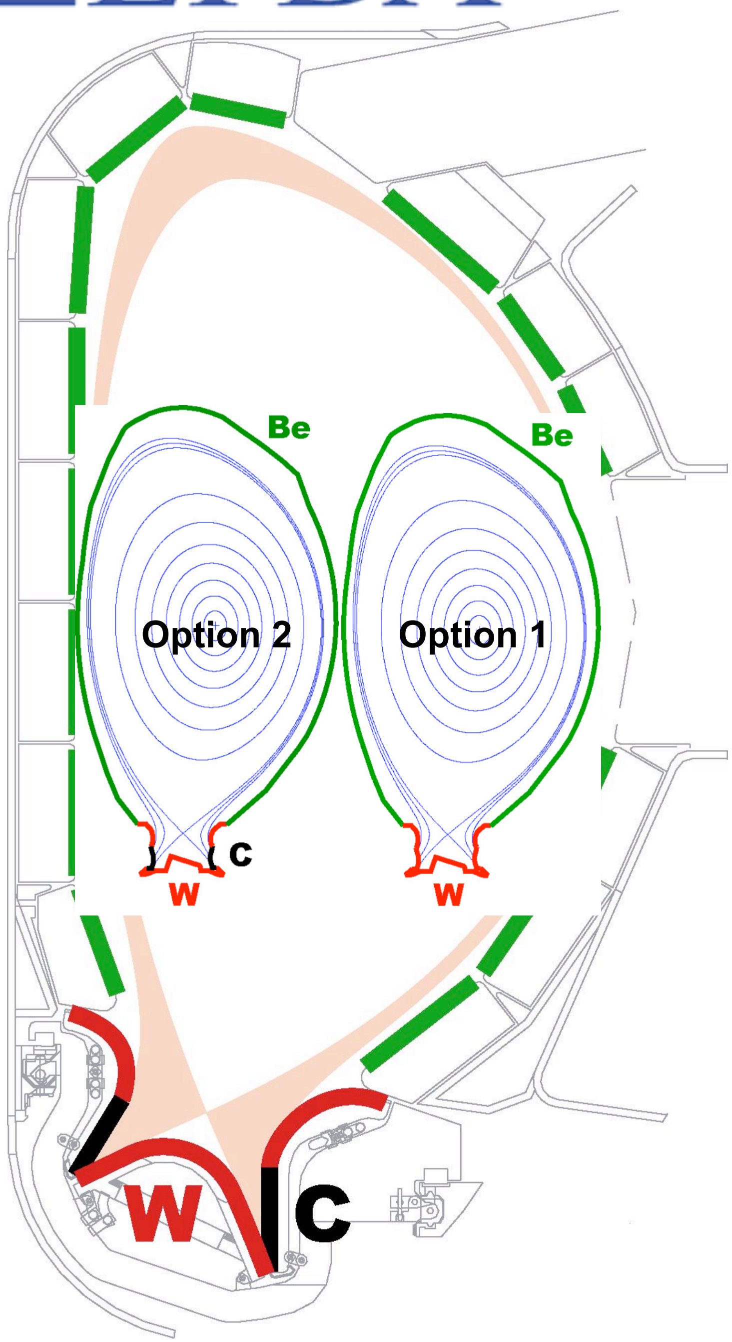
Wall and Divertor Materials



Main wall

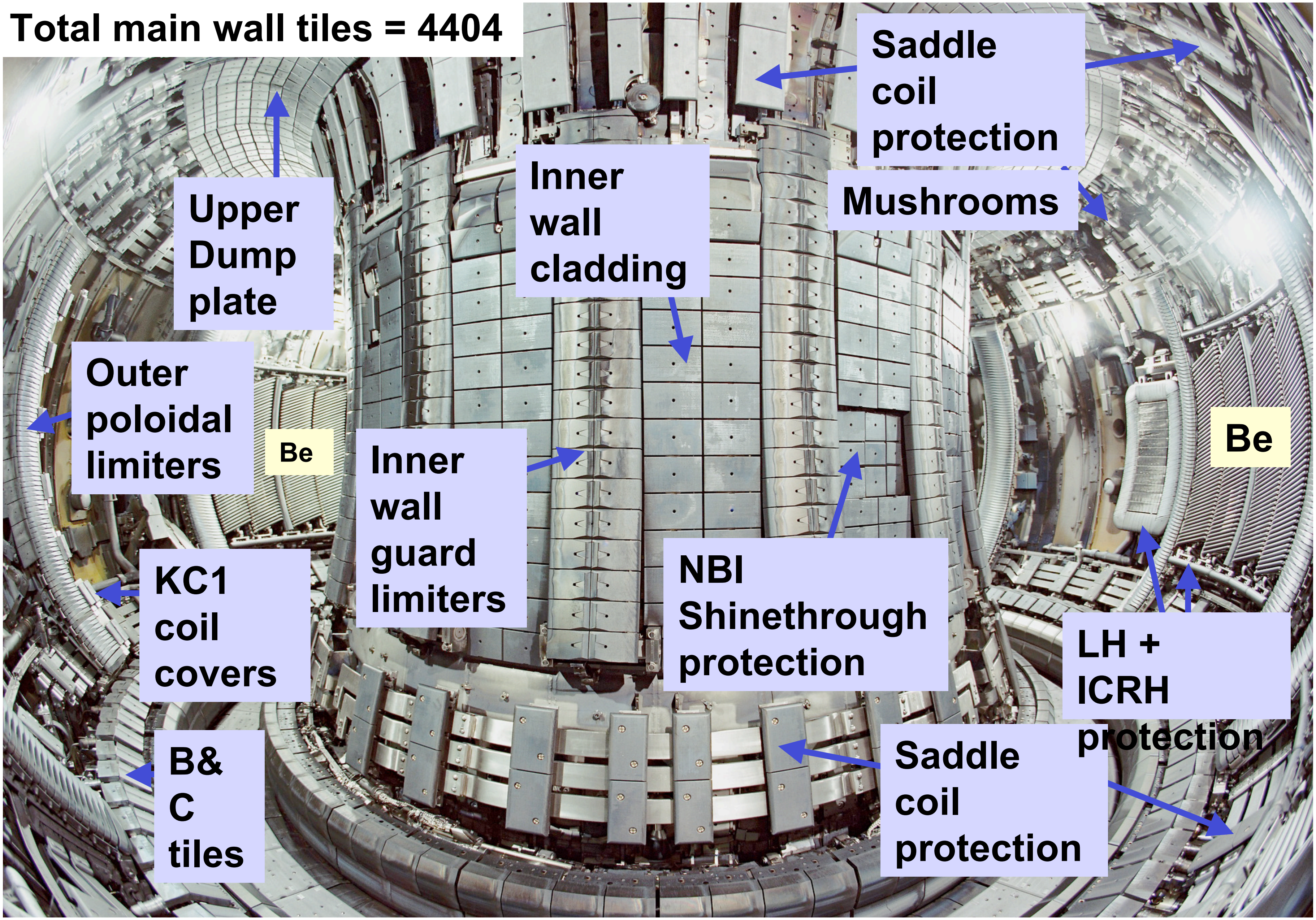
- **Bulk beryllium** where possible

Divertor

- Plan for **all W coated CFC** (Reference Option)
- *Fall-back Option:* ***CFC on targets***
- **Final decision on options in 2006**
  Depending on:
  ⇨ ITER needs
  ⇨ W Coating R&D outcome
  ⇨ Bulk W technology R&D

Be First Wall

Total main wall tiles = 4404



W Divertor options

Plan:

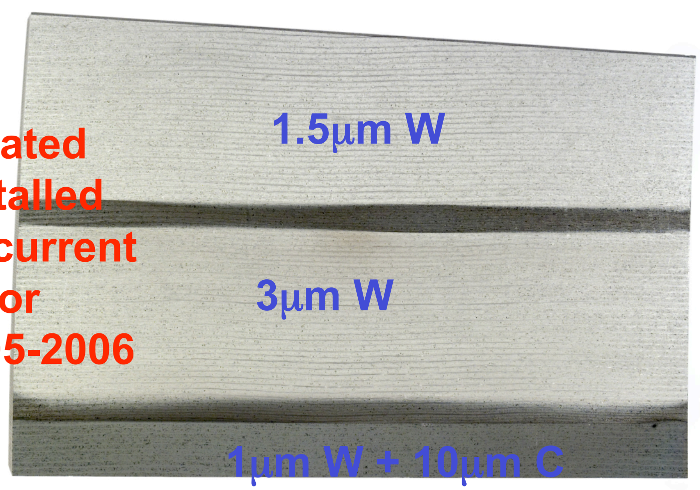
- Configuration - Final decision 2006
- Order a complete set of divertor tile replacements (marked in red)

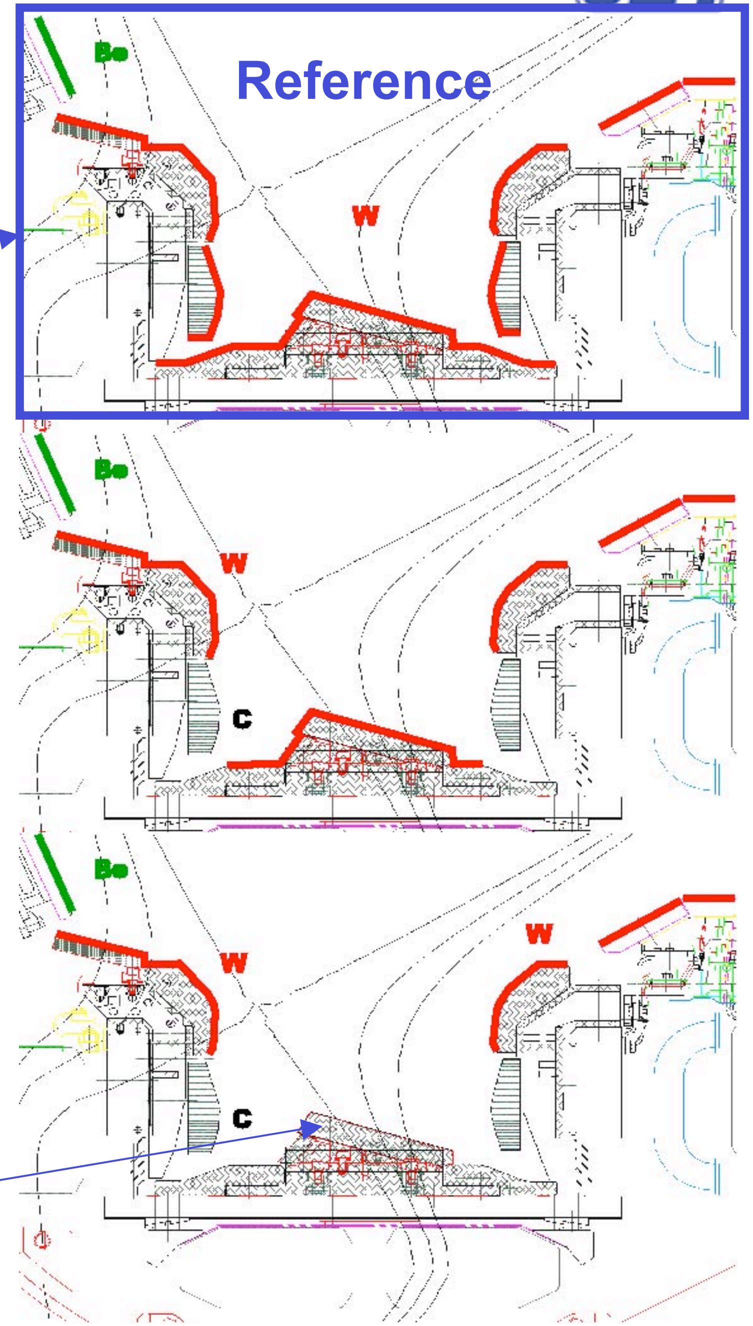
Refrence Technique: W-coating

- R&D (on-going)

  ⇨Optimise thickness / performance
  ⇨test industrially applicable thick coating

A few W-coated already installed during the current shutdown for tests in 2005-2006





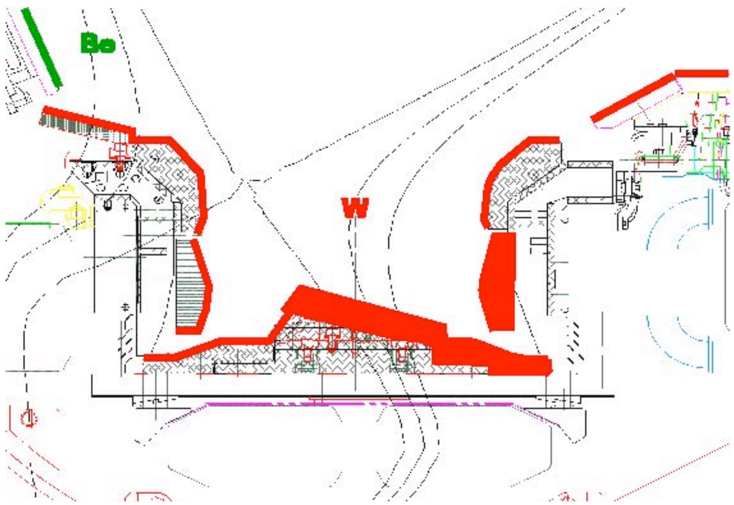
Development of bulk tungsten tiles for the Divertor

⇨*Coating performance and lifetime may be limiting*

Plan:

•R&D task on bulk W designs

⇨Procurement of prototype tiles and tests



• Engineering / physics analysis of which row(s) of outer tiles could be replaced.

Coordinated R&D programme on W coating and bulk W

involvement of several laboratories:

•Italy (ENEA), France (CEA), Germany (FZJ, IPP), UK (UKAEA), Belgium, Romania (MEC)

•Outcome March 2006

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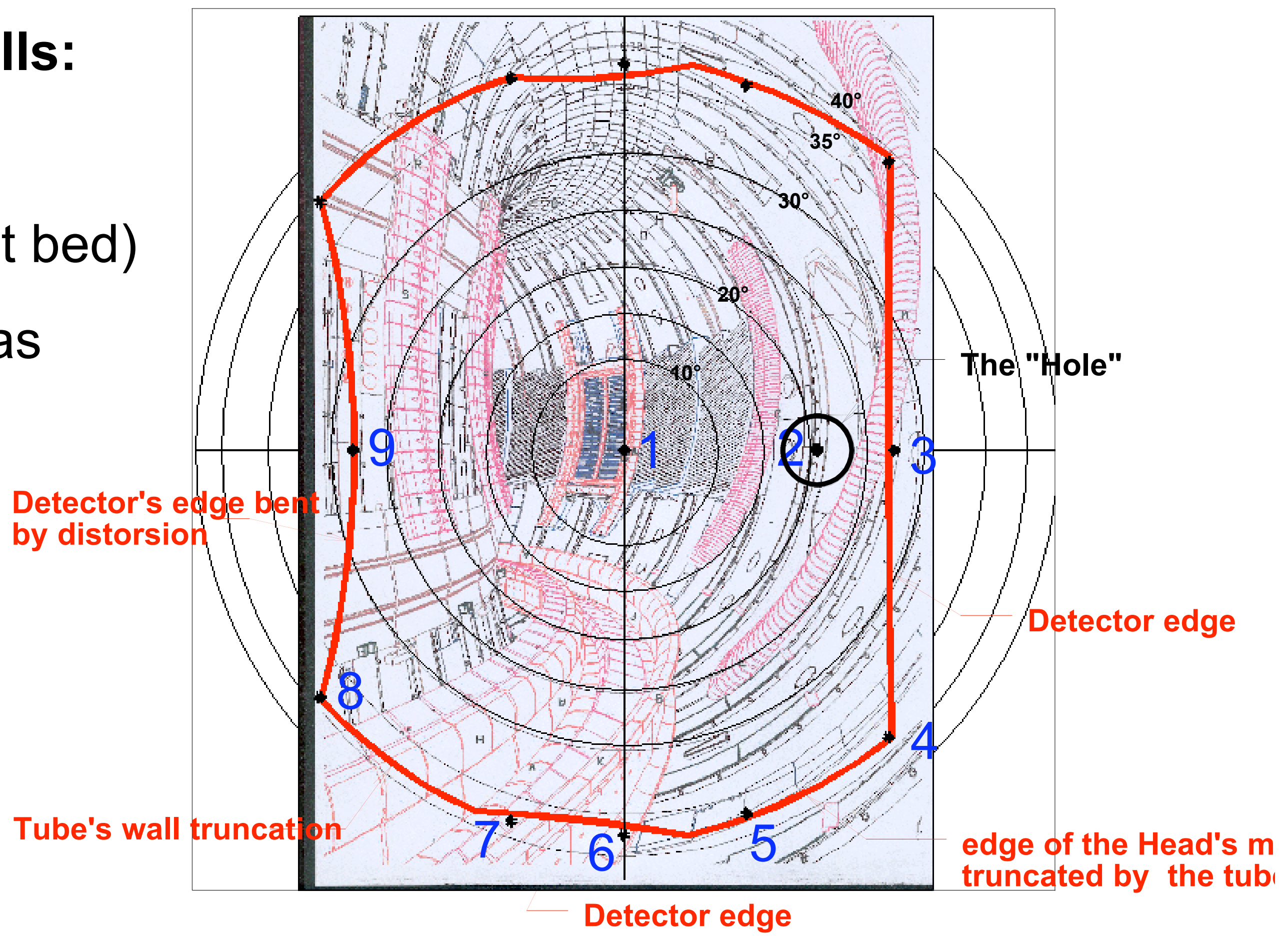
Wide angle IR diagnostic (operational end 2005)

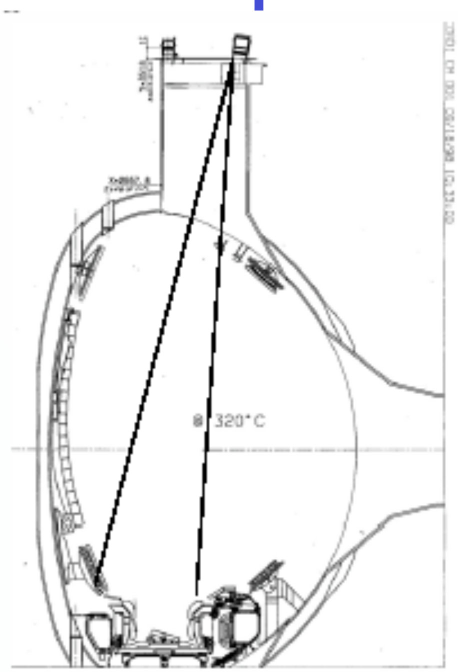
Issues for metallic walls:

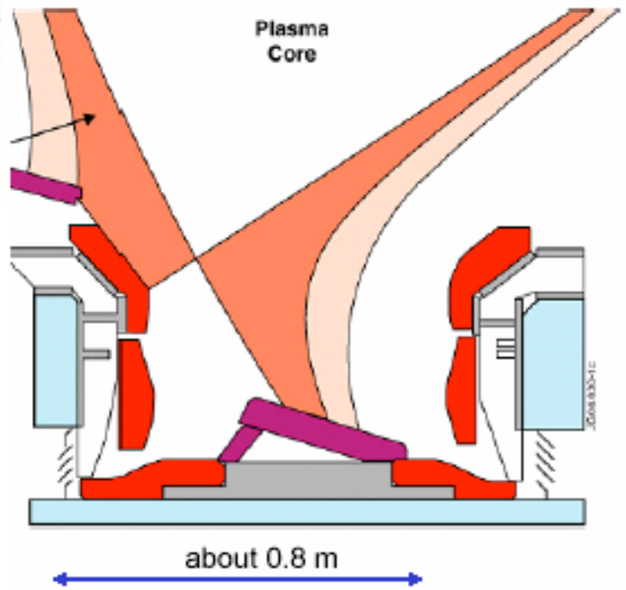
- Reflections (ASDEX)
- Be emissivity (NBI test bed)

⇨ TC array for key areas



Vertical IR upgrade (project under discussion; possible implementation in 2006)





Replace present camera to overcome several difficulties

- Mixing of spatial and temporal resolution
- Limited windowing capability, i.e. restricted temporal resolution
- Limited spatial resolution (128x128 pixels)

Unreliable electronics (upgraded)

Resolution of IR systems

	Existing vertical view	New vertical view 2006	Wide-angle view 2005
Spatial	10 mm	3 mm	10-20 mm
Min. exposure time	24 μs	4 μs	24 μs
Frame repeat period	2.56 s	3.2 ms	10 ms

(3.2 ms: 0.1 ms at lower spatial resolution)

Another IR project is under consideration for Tungsten tile temperature measurement (project under discussion; possible implementation in 2008)

Problem

Emissivity strongly dependent on temperature

→ two unknowns require two independent measurements

Proposed solution

Perform two measurements in different wavelength windows

Propose to use two filters with different transmission windows (window width ~ 1 μm)

System should be designed to analyse ELMs, disruptions, upper X-point

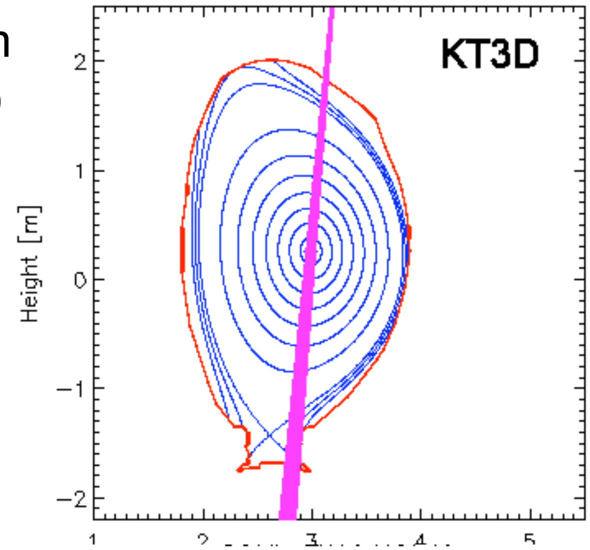
Spectroscopy upgrade for the beryllium wall and tungsten divertor (project under discussion)

Requirement to cover routinely from Z=2 (He) and Z=4 (Be) to Z=74 (W)

Several spectroscopy systems to be modified, upgraded or reinstated :

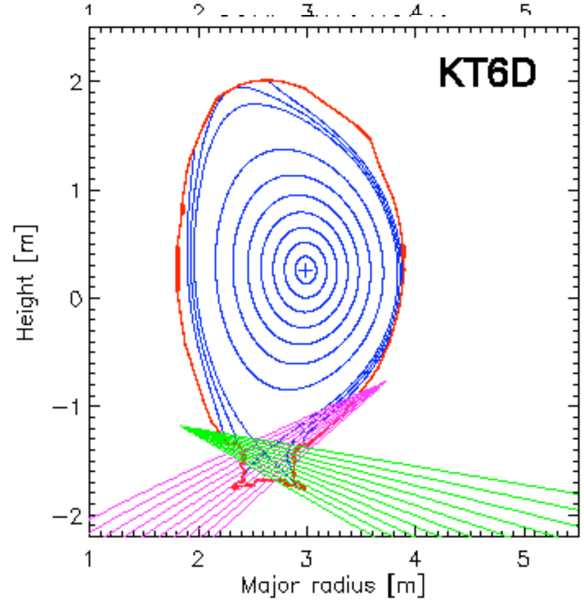
- *Visible*
- *UV*
- *VUV/XUV*
- *X-ray*

Capability to monitor 'standard' impurities will be retained in all cases



Visible/UV spectroscopy

- Outer divertor line of sight
- monitoring W in divertor



Visible spectroscopy

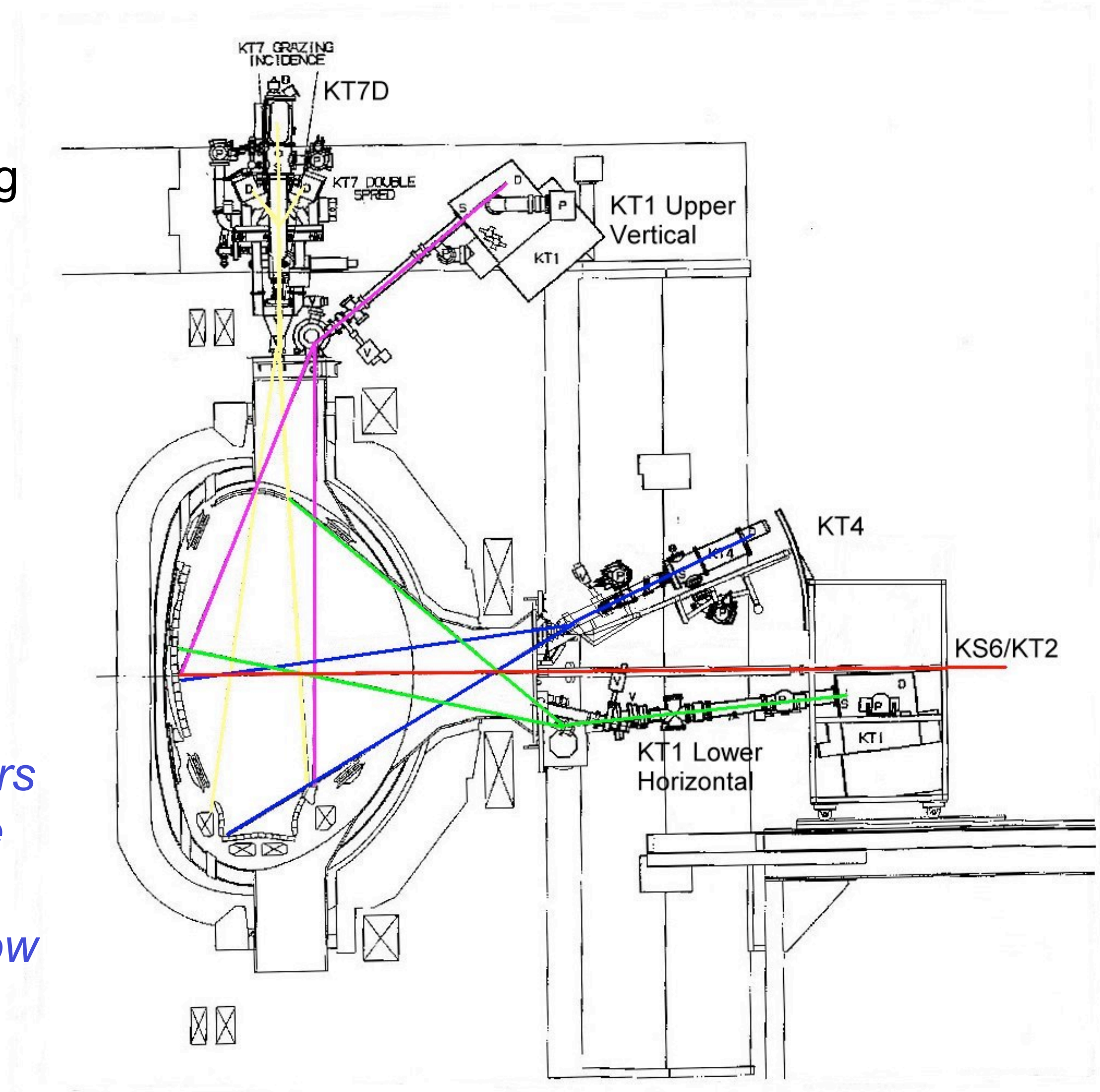
- Two divertor viewing periscopes
- Two spectrometers for C/Be sources

VUV/XUV spectroscopy

- Two spectrometers with scanning mirror system
- Upper inner wall/ vertical target plate & lower inner wall/divertor
- Diagnoses Be/W/C etc.

Several modifications under consideration:

- *Install new scanning system*
- *Upgrade or replace spectrometers to cover entire wavelength range*
- *New CCD detectors*
- *Reinstate visible channels to allow W/Be source measurements*



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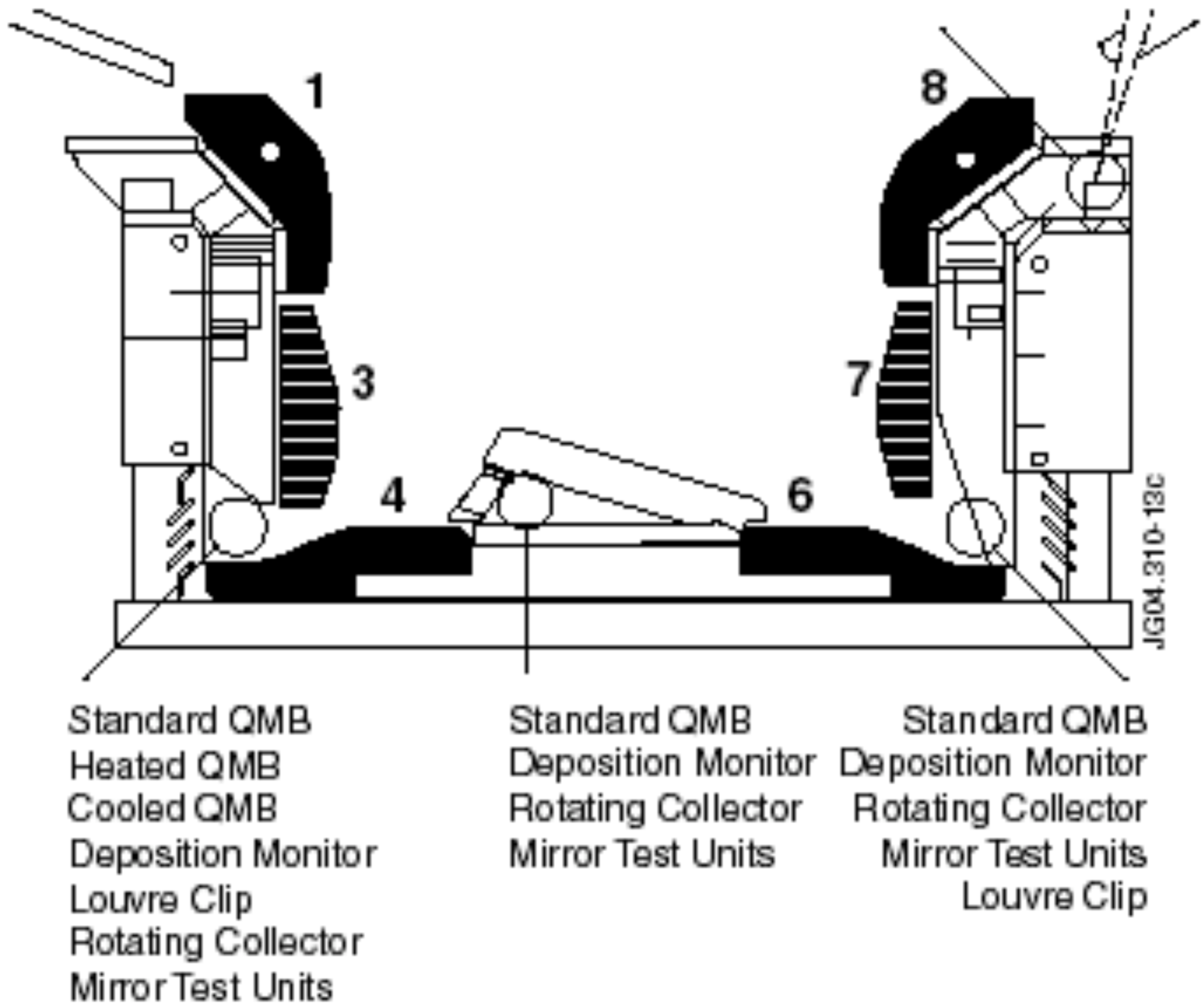
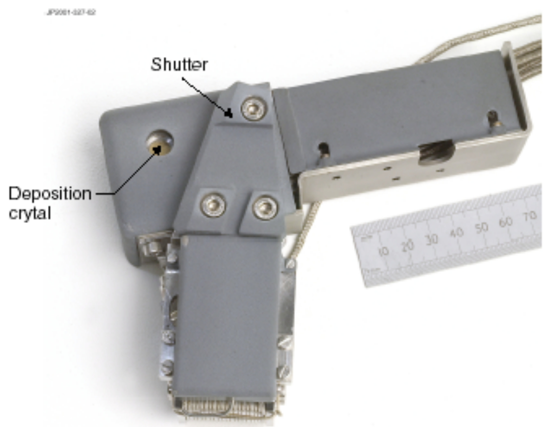
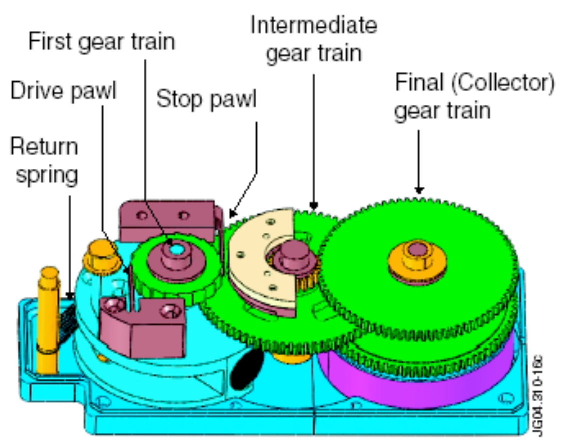
Refurbishment / Upgrade of Erosion/deposition diagnostics
Expected to be similar to diagnostics currently implemented



Erosion/deposition diagnostics
(Similar to diagnostics currently being implemented)

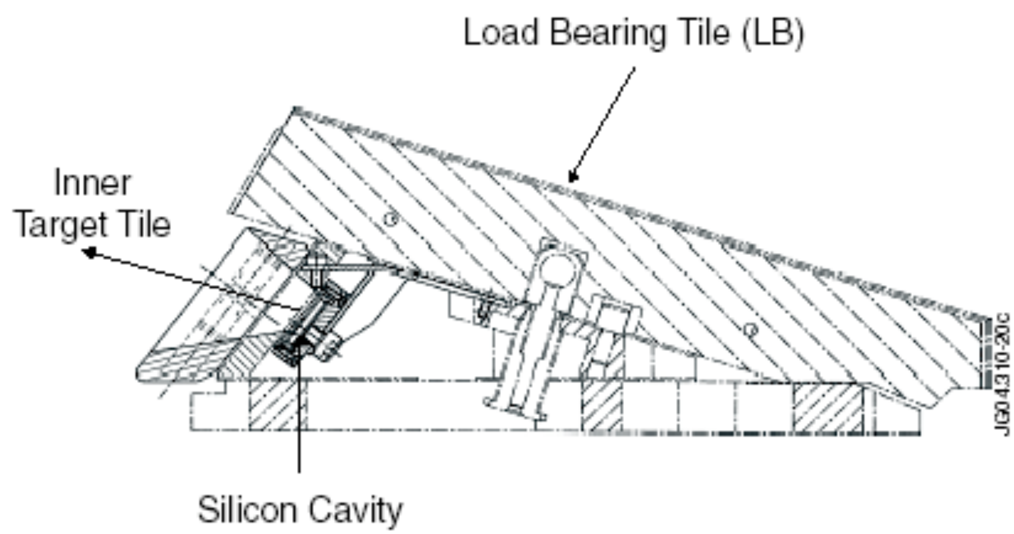


QMB detector



Rotating collector for time-resolved measurements

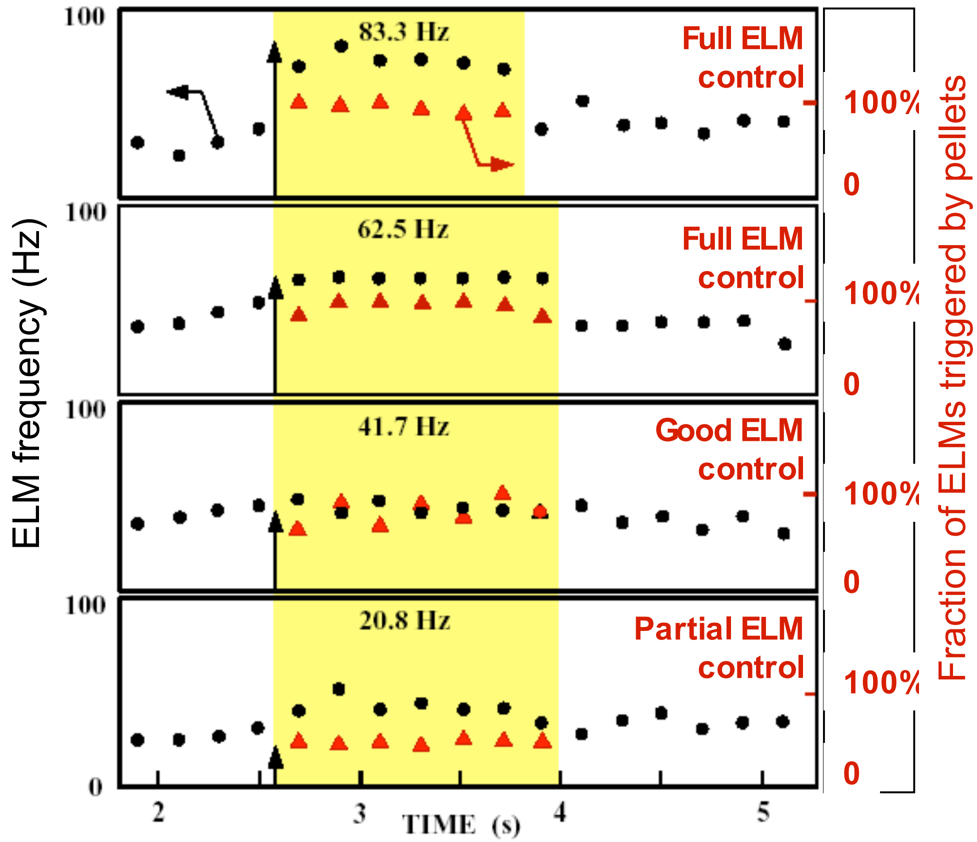
25 or 50 pulse time resolution



Deposition monitor (in silicon box with an entrance slit)b

High Frequency Pellet Injector Project (approved on 4 April 2005)

ELMs triggered by pellets on ASDEX Upgrade



- All ELMs triggered by pellets when pellet frequency above ~60Hz

Scientific rationale: ELM Pacing

- **Modest effect on confinement**
  Small pellets $W \propto f^{-0.16}$
  Gas puffing $W \propto f^{-0.6}$

- **Pellet controlled ELMs are similar to natural ELMs**
  Power load per ELM scales as $1/f_{ELM}$ in both cases

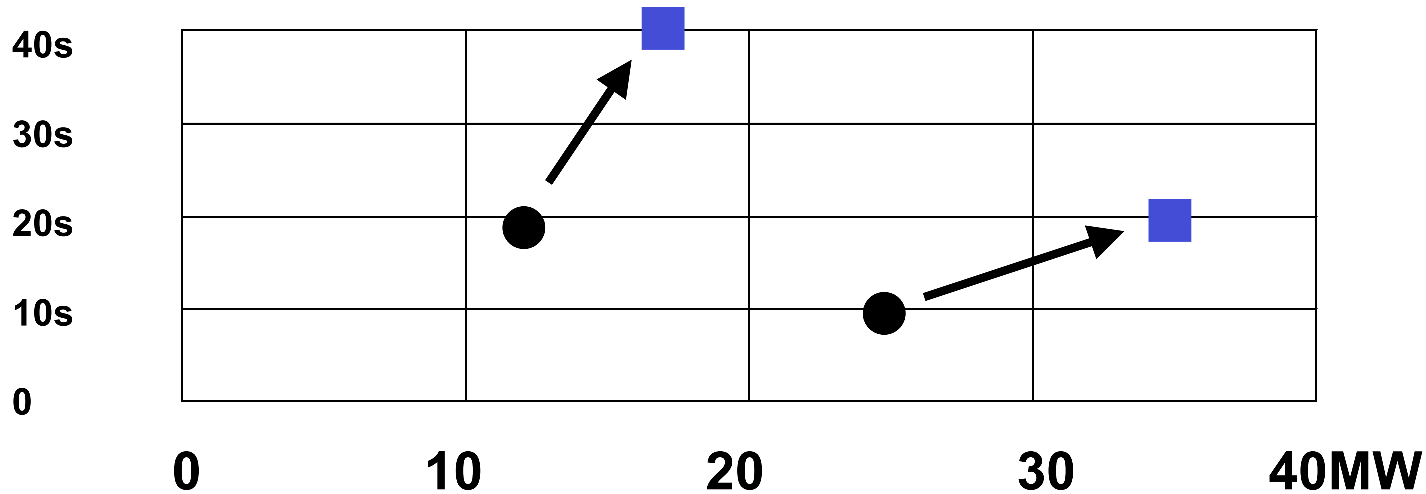
High Frequency Pellet Injector Project (approved on 4 April 2005)

Objective: ELM control & deep fuelling

	JET		ITER	
	Required for ELM control	Required for deep fuelling	Required for ELM control	Required for deep fuelling
Fuel	D_2	D_2, impurities (+DT/T_2 later?)	D2	D2, DT, T2, impurities
Number of pellets / pulse	unlimited	unlimited	unlimited	unlimited
Maximum frequency	10-60 Hz adjustable	1 - 15 Hz adjustable	16 Hz	16 Hz
Pellet speed at injector exit	50-200 m/s adjustable (LFS)	150-600 m/s adjustable (HFS)	300 - 500 m/s (LFS)	300 - 500 m/s (HFS)
Pellet size	1 - 2 mm^3 adjustable	35 - 65 mm^3 adjustable	33 ± 20 mm^3 17 ± 20 mm^3	92 ± 20 mm^3 50 ± 20 mm^3
Reliability	>98%	>98%	>98%	>98%

JET needs are close to ITER needs
Encouraging results obtained on TS (10 Hz) and on JT60-U (50 Hz) with a screw extruder system

Neutral Beam Power Upgrade (approved on 4 April 2005)



■ Upgrade of existing NB boxes to 16-17.5MW each, 20s, *co-injection only*

● 2005 NB (co-injection only), 2 boxes 25MW 10s, or 1 box after the other 12MW 2x10s, *co-injection only*

Safe operation with metallic wall of fully integrated ITER compatible scenarios at 3-5MA requires high density operation

⇨ strong incentive for NBI power upgrade

⇨ overall power ~ 34-35 MW (NB) + 10-12 MW (ICRH)

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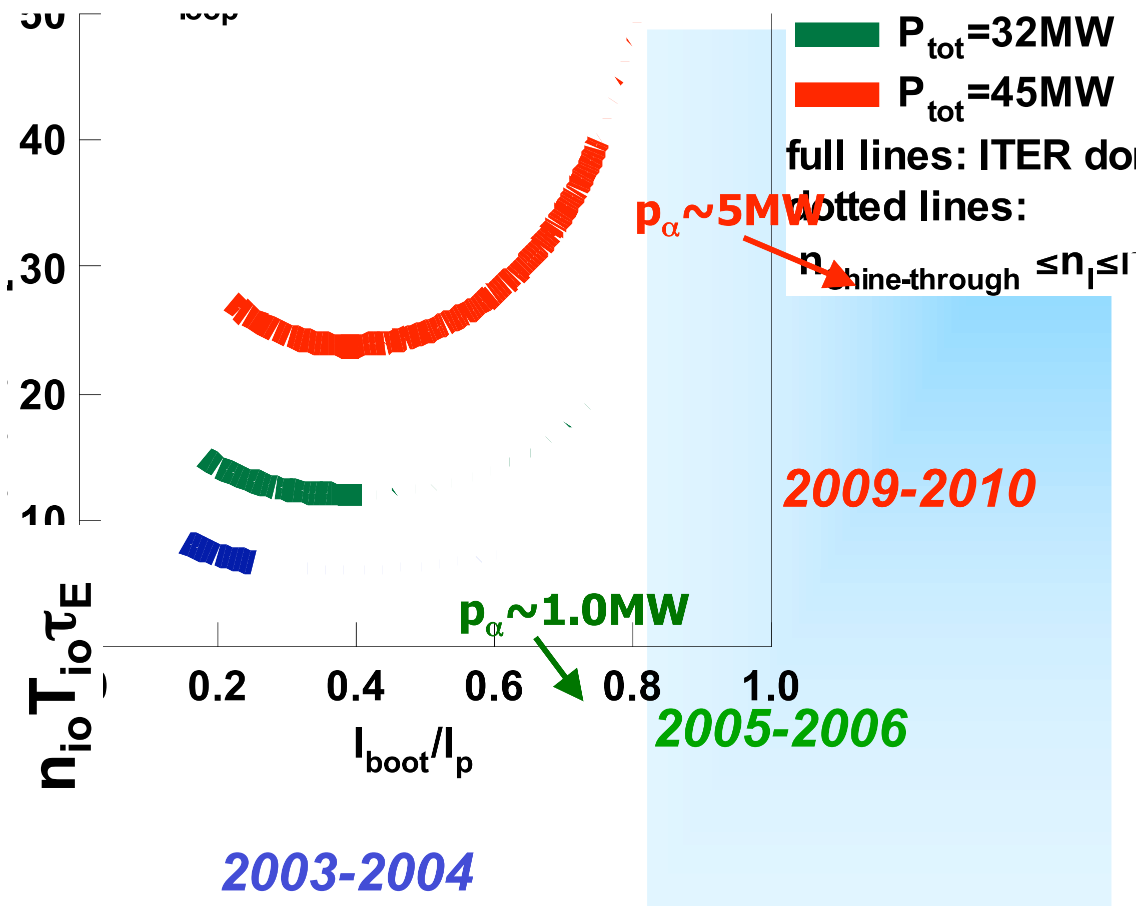
40-45 MW heating power will allow highly ITER relevant studies of plasma regimes e.g. High density bootstrap-dominated advanced regime in steady regimes



Full lines: $n_l \sim n_{GW}$ at q_{95} ~5 and β_N up to 3 (ITER Relevant domain)

Dotted lines: $n_l < n_{GW}$

- *simultaneous increase of I_{boot}/I_P and $nT\tau$*
- *high n_{edge} for metallic wall compatibility*

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D-T Integrated Experiment

DT qualification of ITER-relevant scenarios
Preparation for Burning Plasma Physics
ITER-relevant H&CD and Burning Plasma Diagnostics

D-T test of fully wall-compatible scenarios

Confirmation of reduced T-retention

NB Power Upgrade
PF system upgrade
Diagnostics

High Frequency Pellet injector (ELM pacing)

ITER-like wall (Be 1st wall, W(C) divertor)
Wall diagnostics

Plasma scenarios in ITER-like configurations

Plasma scenario-wall compatibility

ITER-like Wall experiment

Fully integrated optimised performance
Physics at high β_N, low (ρ^*, ν^*), $T_e \sim T_i$ and reduced rotation
Scaling of core and edge
Control of profiles n, T, j towards long pulse/S.S.

ITER relevant plasma control
Disruption and ELM mitigation
Management of core impurities

Reduce fuel retention (D and FTE)
Be and W erosion and migration
Mixed materials issues
Wall behaviour (Melt layer, vapour shielding etc.)
Detritiation
Radiative divertor scenarios in the absence of carbon

Proposed JET Programme 2007-2010

RESERVE

Vessel Conditioning / Preparation

Plan:

Eliminate any obvious C deposits prior to Be wall installation :

⇨ Extent of deposits currently being assessed

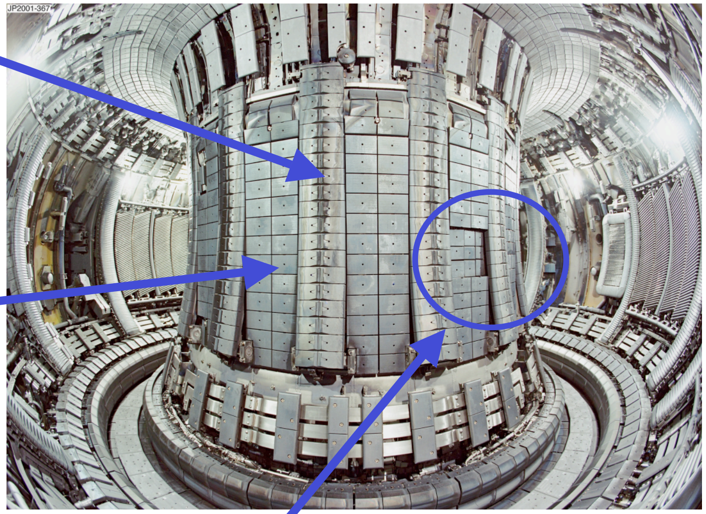
⇨ CO_2 pellet shot blasting used during MkI divertor installation

⇨ Flash lamp / laser cleaning also possible (used for de-painting)

Retain all four Be evaporators in current locations :

⇨ Required to maintain Be coating on inner wall cladding

⇨ Or in case of serious de-conditioning (e.g. air leak while hot)



Inner wall guard limiters (IWGL)
⇨ Except shinethrough protection

Plan: Bulk Be

Inner wall cladding (IWC)
⇨ Except shinethrough areas

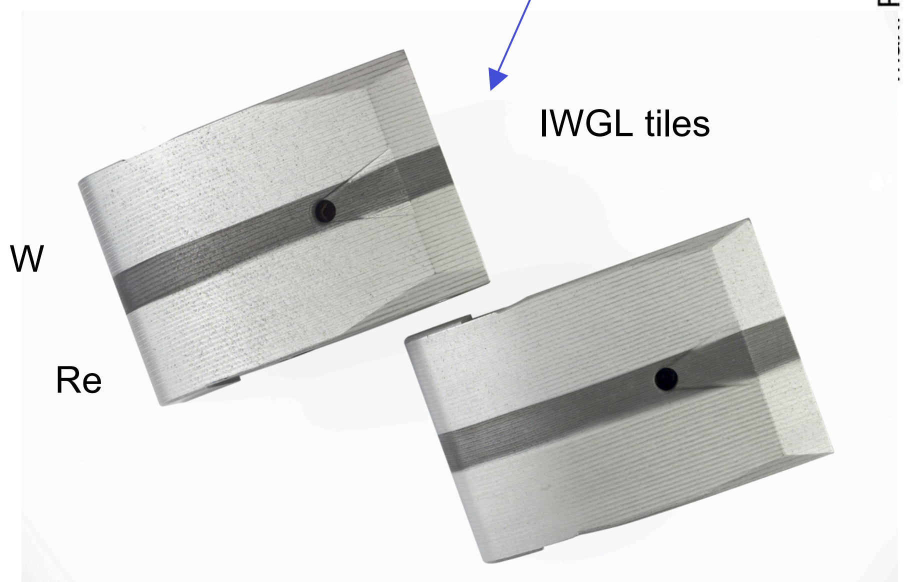
Plan: Inconel plates (Be coated)
⇨ Driven by cost and eddy current forces

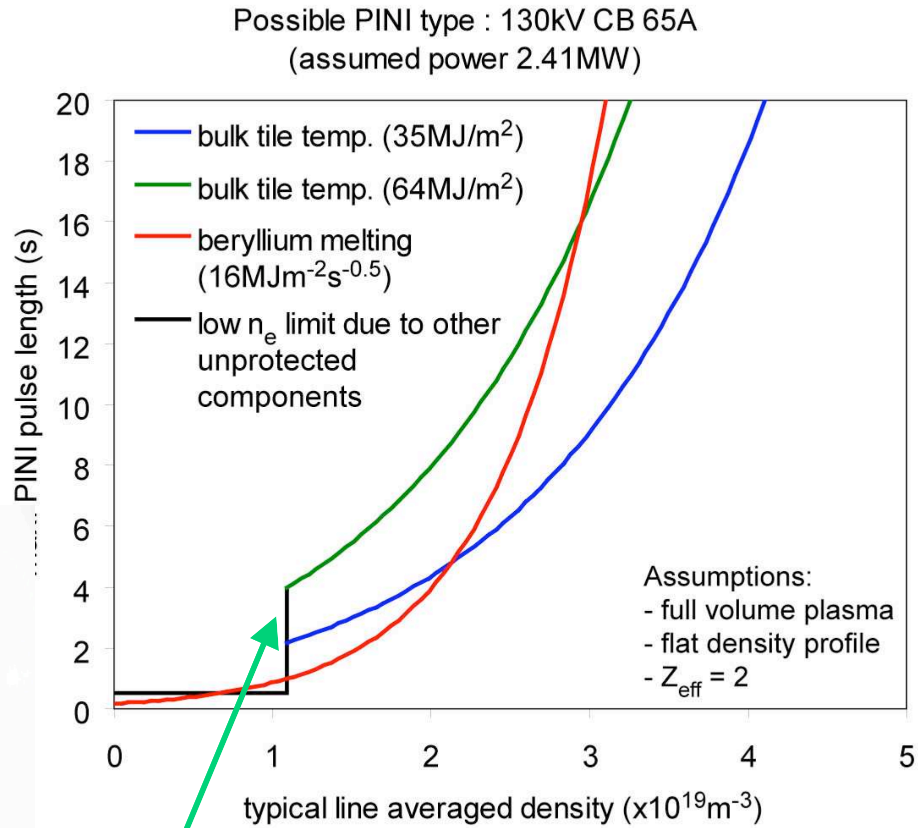
Inner wall NBI shinethrough protection (IWC + IWGL)

Plan: Re or W coated CFC
⇨ Driven by Integration Issues
(Be too restrictive for long pulse AT - de Baar)
⇨ Test tiles to be installed in JET this shutdown

Be shinethrough protection limits AT pulse length

- ⇨ Be not a problem for high density (fall back)
- ⇨ Proposal is W or Re coated CFC – in-situ test

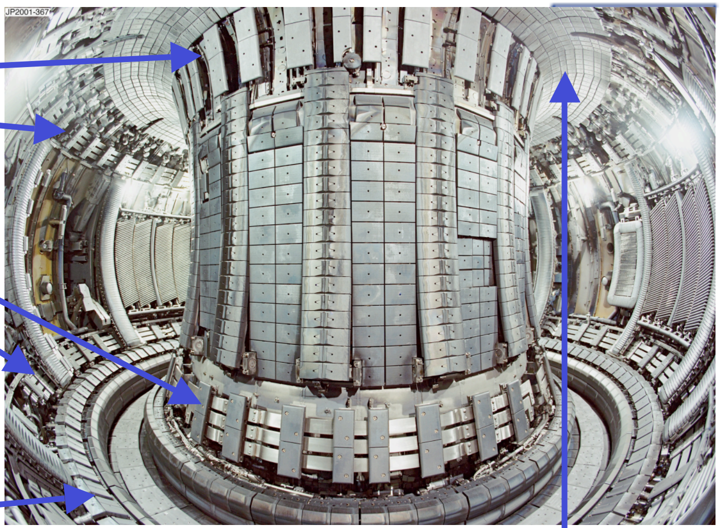




New higher energy design is proposed but not detailed

Saddle coil tiles

Plan: Bulk Be

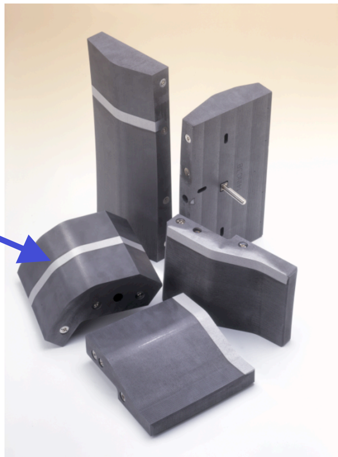


Outer protection B&C

Plan: W coated CFC (5μm)

⇨ITER like baffle geometry

⇨Used as surface marker in last campaign



Upper dump plate

Plan: Bulk Be

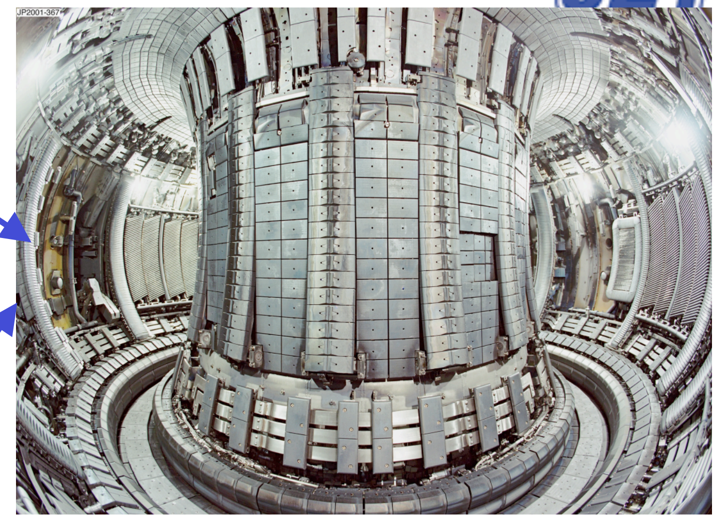
⇨Existing Be bi-directional design if upper X-point control not upgraded

⇨Uni-directional design would have the same tile envelope

Outer poloidal limiters

Plan: Bulk Be

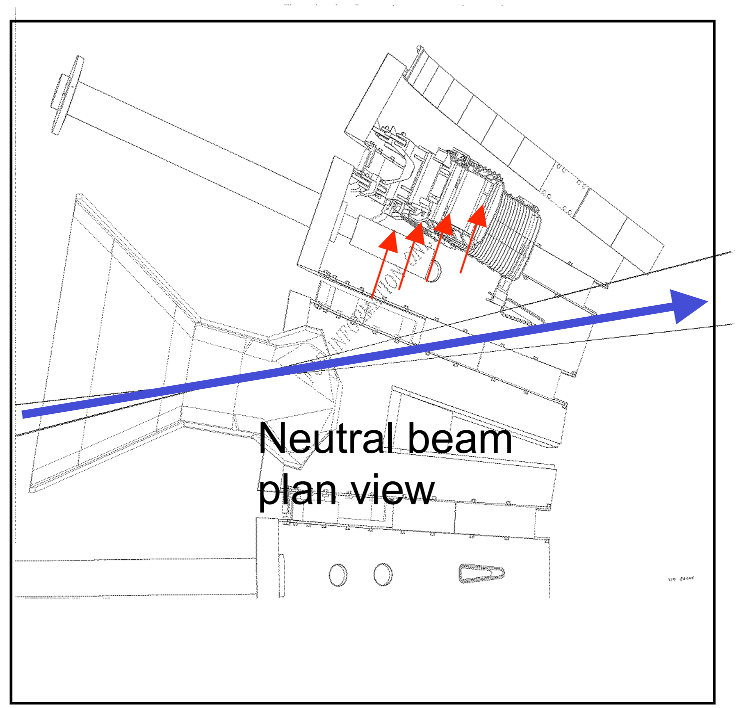
- ⇨ New design as ITER-like antenna
- ⇨ Eddy currents may limit tile size
- ⇨ ~ 50% better power handling
- ⇨ No impact on shutdown time (same beams, different carriers)

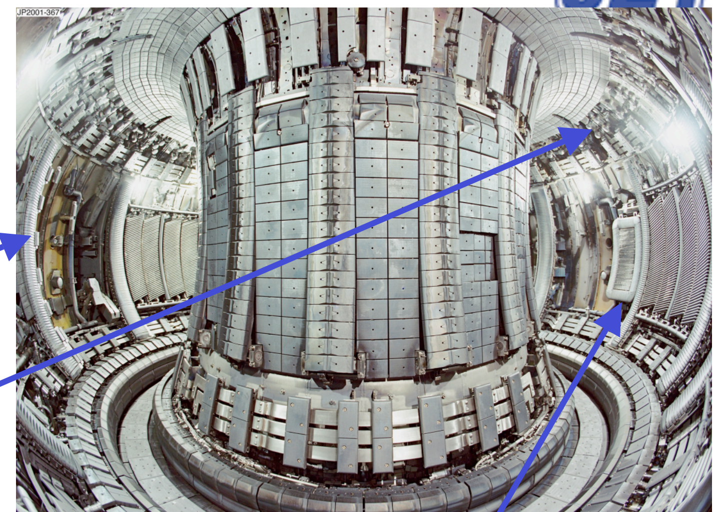


NBI re-ionisation protection

Plan: Re or W coated CFC

- ⇨ Be tiles too restrictive at high n_e
- ⇨ Test tiles to be installed in JET soon





Diagnostic protection tiles

Plan: Detailed analysis of requirements
⇨BN tiles might be used on fast magnetics

Mushrooms

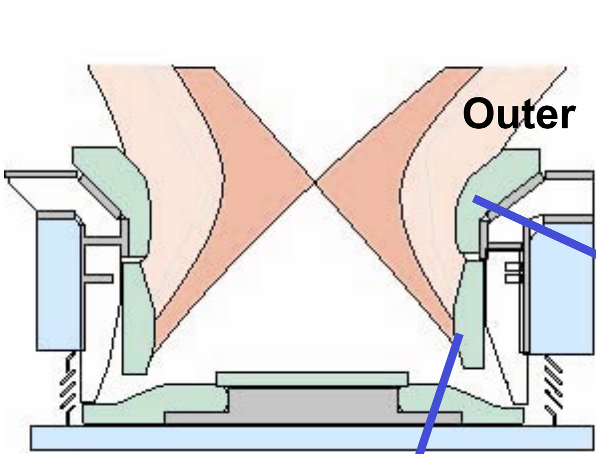
Plan: Replace only where necessary with Be coated inconel

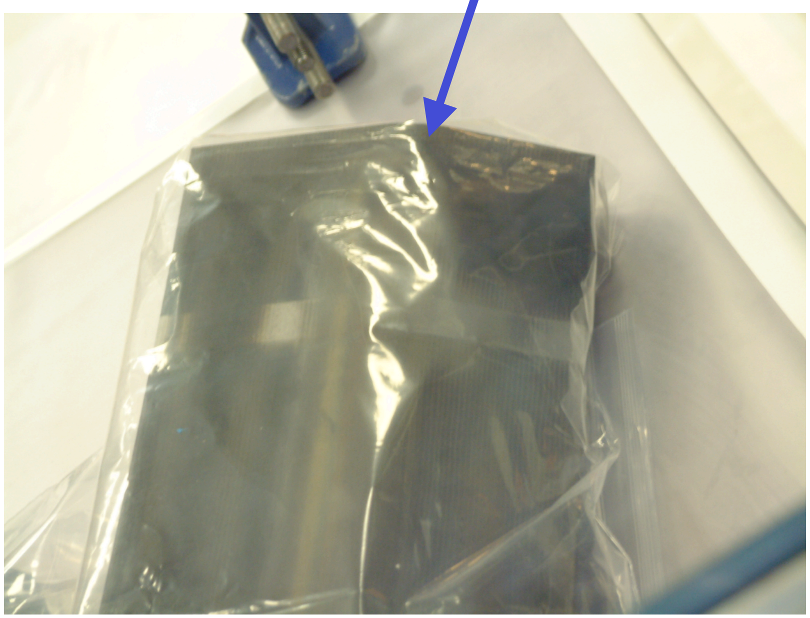
LH frame

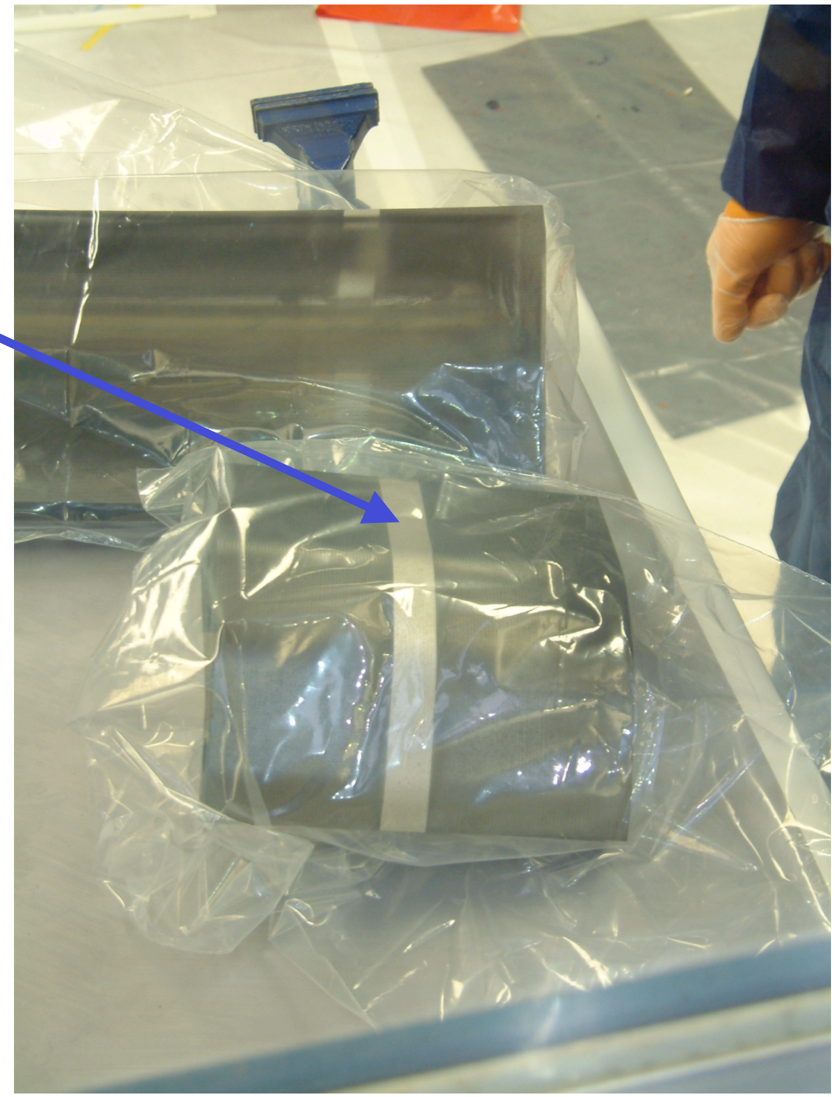
Plan: Bulk Be based on poloidal limiter design

3.5μm W stripes after 2 years in JET

⇨ Full surface analysis over next 6 months







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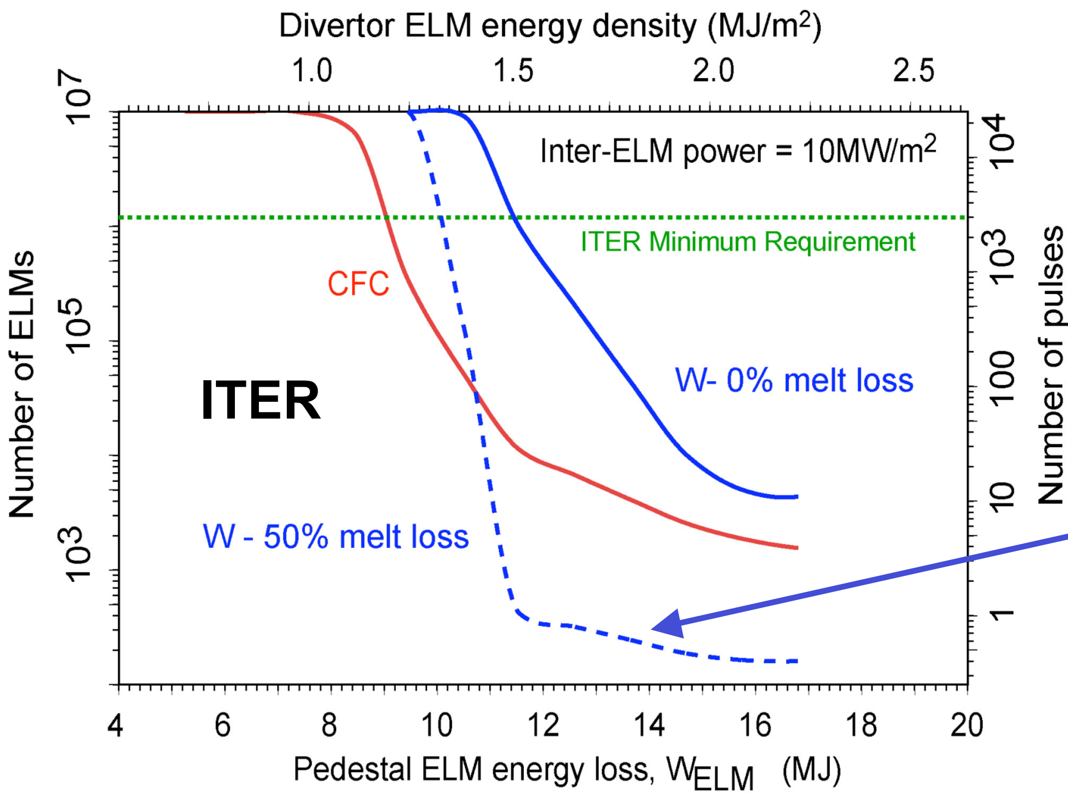
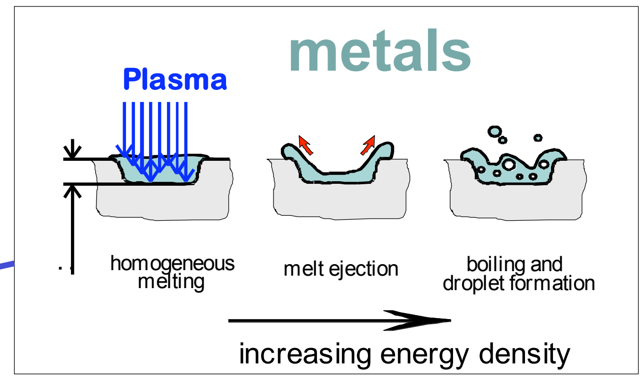
Rapid erosion by ELMs is a critical issue for ITER

⇨ Ablation / melt layer loss at the divertor target

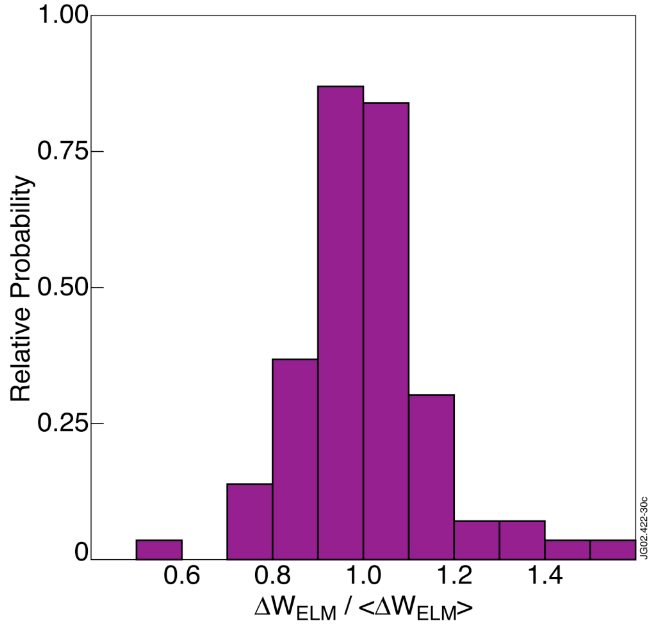




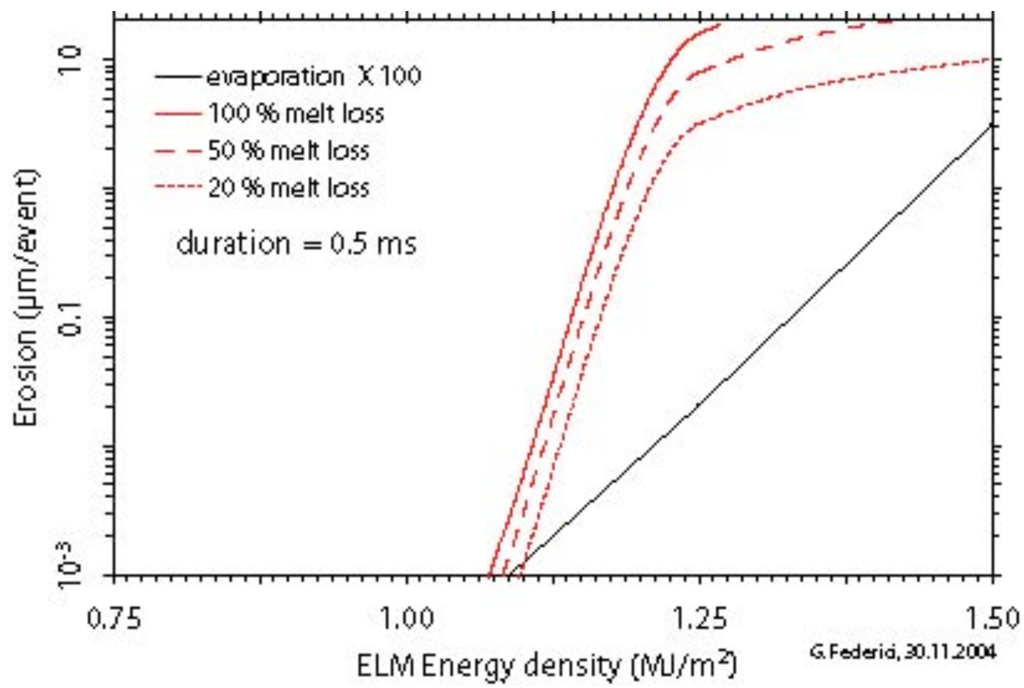
$\Delta W/W_{total}$ = 3%

ELM variability means thick coatings ~ 0.5mm or bulk W tiles required for melt layer study

ELM variability



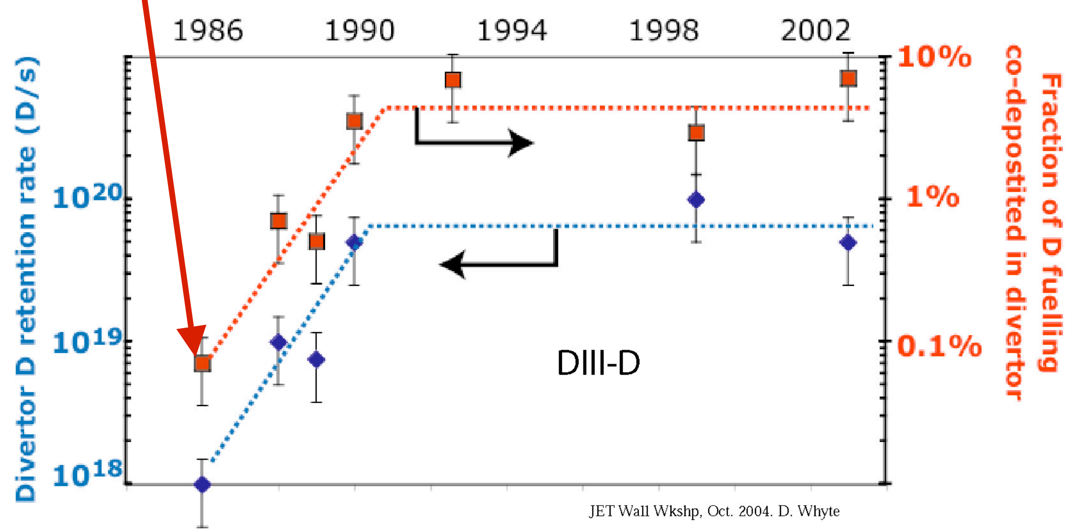
Erosion per ELM



Demonstrate low T retention in JET
Be Wall and W (or W + C) divertor

ITER would like
T retention < 0.1%

Only measurable in
JET by surface analysis



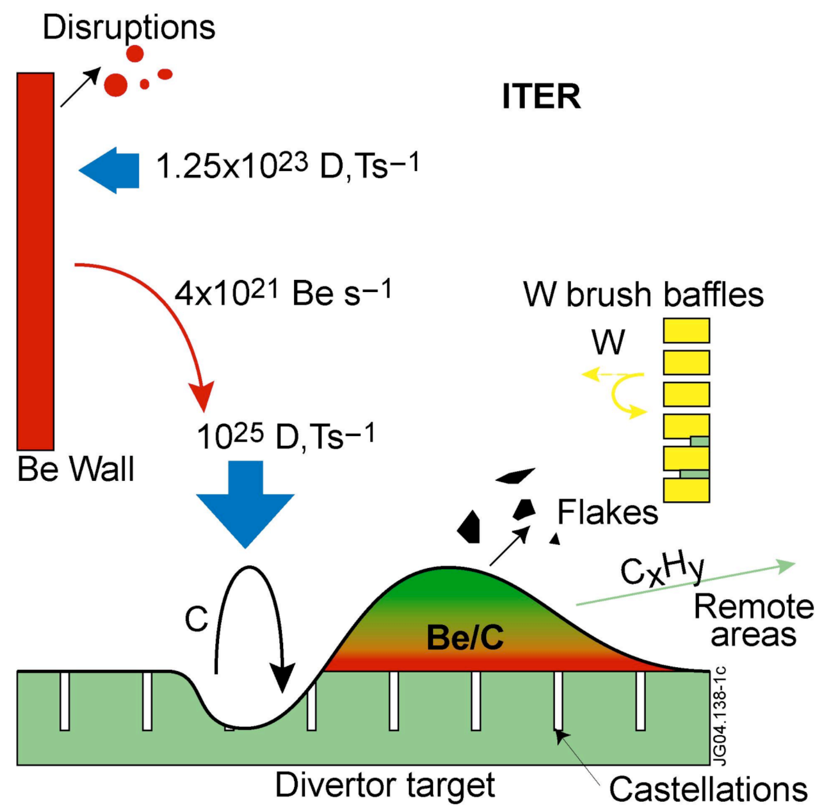
Introduction
of C in DIII-D

C coverage	9%	40%	100%		
Boronization	No	Yes			
Diagnostic	Run-period divertor tiles	Tritium retention	DiMES (detached)	13C	

Be wall / C + W divertor - Fall back

objectives would be:

- Material migration / lifetime
- Tritium retention / inventory control
- Damage due to transients / control



Tests of tritium removal strategies

Ex-situ

- **Photonic cleaning of sample tiles**
  ⇨ Flash lamp and laser – existing TF-FT tasks
- **Development of oxidation techniques**
  ⇨ Relevance depends divertor materials option chosen
  ⇨ GDC, Ozone and hot bake are being explored (TF-FT)

In-situ

- Photonic cleaning could be integrated with shutdowns for fast sample removal or with the final JET shutdown end 2010
- Oxidation methods carry some risk and should be left until the end of the primary wall evaluation programme.

Summary of scientific aims

Routine operation of JET with an ITER relevant wall at 3-5 MA in integrated scenarios with proven:

⇨ minimisation of T inventory (including T removal strategies)

⇨ Control of Impurities

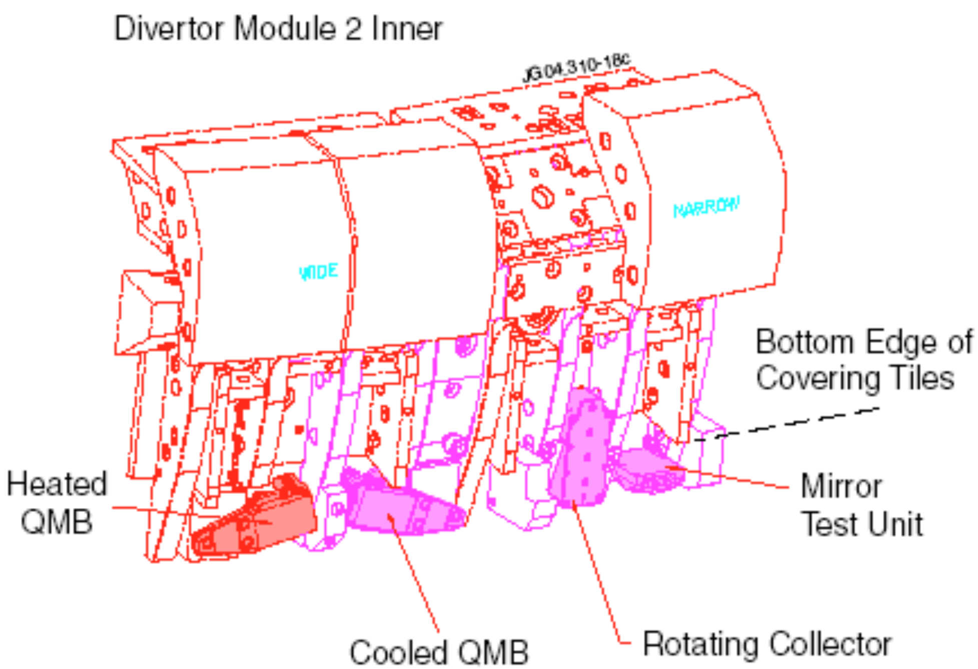
⇨ strategies for extended Wall lifetime

⇨ Heating with large gaps

⇨ Control of disruptions and disruption mitigation systems

An essential stepping stone to ITER

Erosion/deposition diagnostics

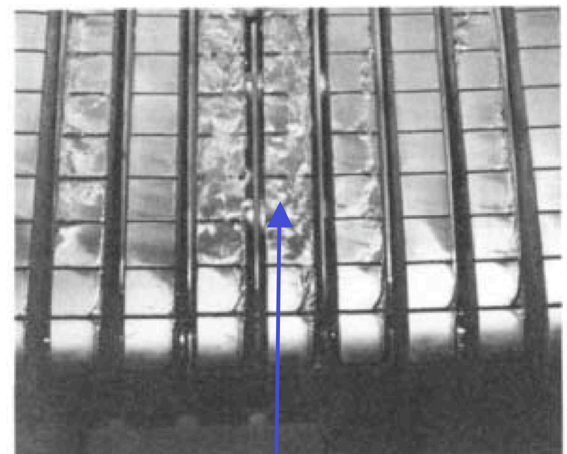


Arrangement of diagnostics in one module of inner divertor

- Mirror test units to assess changes in reflectivity, likely deposition in ITER divertor, eerosion in main chamber
- Two candidate mirror materials will be tested (molybdenoum and sainless steel)

Experimental Campaigns

- inductive scenario, AT and Hybrid operation on W target
  ⇨Test strategies to control W accumulation
  ⇨ Operate at high edge density (moderate ELMs)
  ⇨ Avoid Be melt damage if possible
- Heating and current drive with large gaps / low fast particle content
- Test disruption detection / mitigation schemes
- Push max pulse length / highest current
- Ultimately: Push JET scenarios to maximum stored energy / ELM size (melt-layer studies; mixed Be-W)
- Possibly: Tritium Campaign(s)



Significant main chamber Be melting tolerable

End campaigns with 2-4 weeks similar shots
⇨ Fast shutdown - remove samples