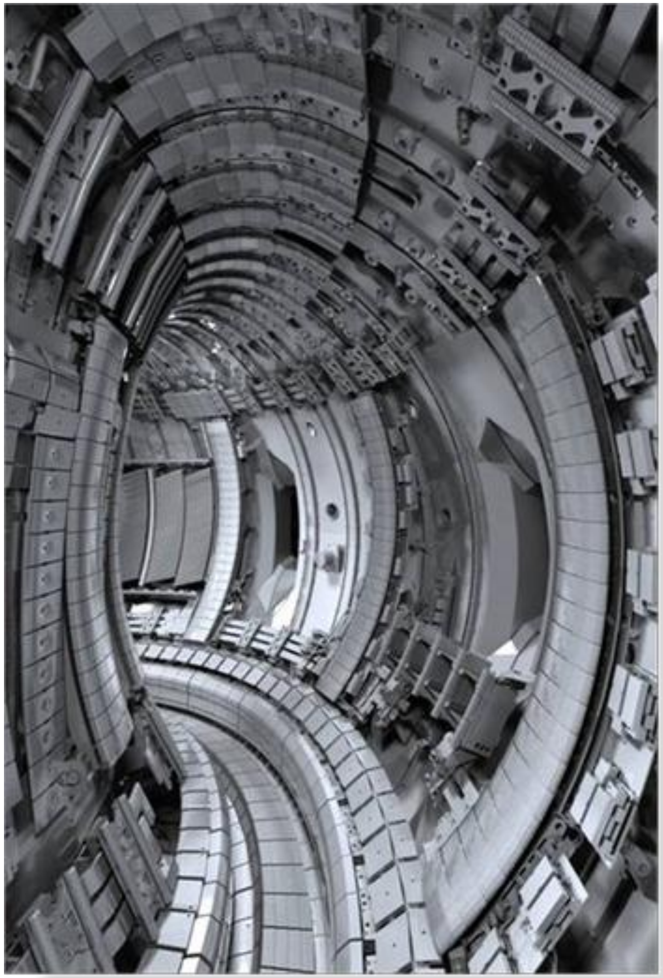
- **JET Enhanced Performance 2** – ITER like wall and others
- **‘SK ring’ for GOLEM** – status and plans
- **FTTF practica** – status, troubleshooting

JET Enhanced Performance 2

- JET – largest present day tokamak
- only one able to operate with Tritium
- closest to ITER present day integrated approximation
- Recent JET enhancements:
  - ITER like wall
  - NBI enhancement
  - several other small projects (pellet injector, **Hall probes**, real time control, …)

JET EP2 enhancements

ITER like wall (ILW)



Neutral beam enhancement (20s)

Parameter	Gas species			
	H_2	D_2	T_2	^4He
Max. beam energy (keV)	90	125	118	120
Max. power per PINI (MW)	1.0	2.16	2.2	1.56
Max. power per NIB (MW)	8.0	17.3	17.6	12.5
Max. total power (MW)	**16.0**	**34.6**	**35.2**	**25.0**

- Significant power in H_2 and He (but no time to exploit in 2011 or 2012)

Various diagnostic and other enhancements

- Magnetics, TAE antennas, edge diagnostics, spectroscopy, EFCC, pellet injector, ILW viewing and protection

Graphite has been used to optimise plasma requirements

- Plasma operation/performance
- Resistance against power transients and operational failures

Additional requirements must be fulfilled for future devices

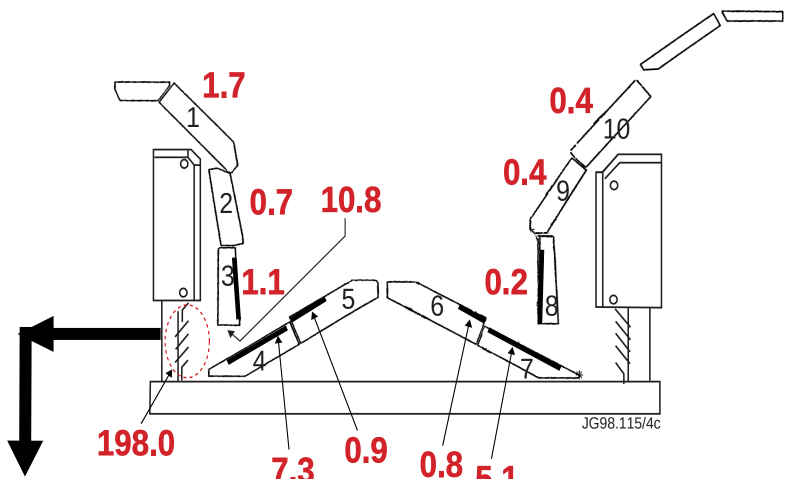
- Lifetime (low erosion) (Demo)
- Low T uptake (ITER)
- Neutron compatibility (Demo)

T retention: C walls

Injected: 13000 TBq

Inner wall
7.6

Outer poloidal
limiter 18.7

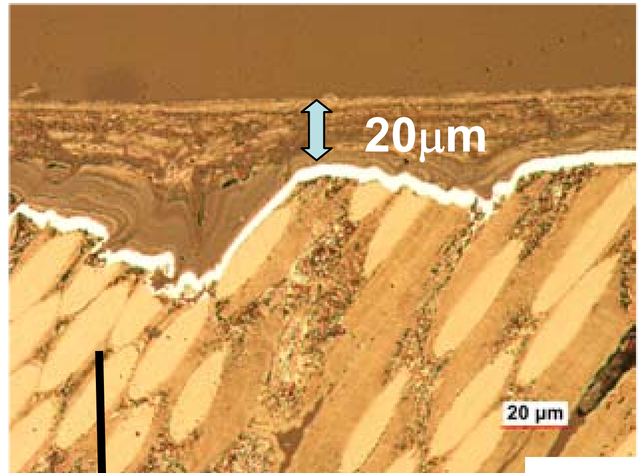


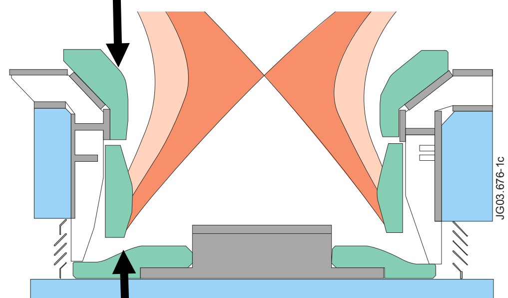
Missing: 1200 TBq in flakes on floor

T Content in TBq

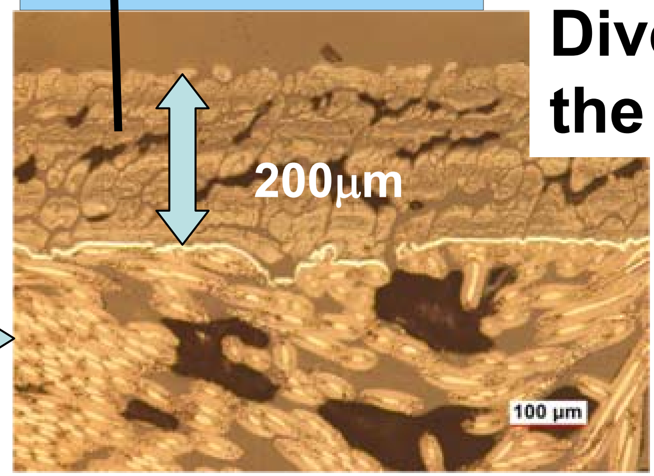
from 35gT → 3.7g in vessel after D plasma and venting

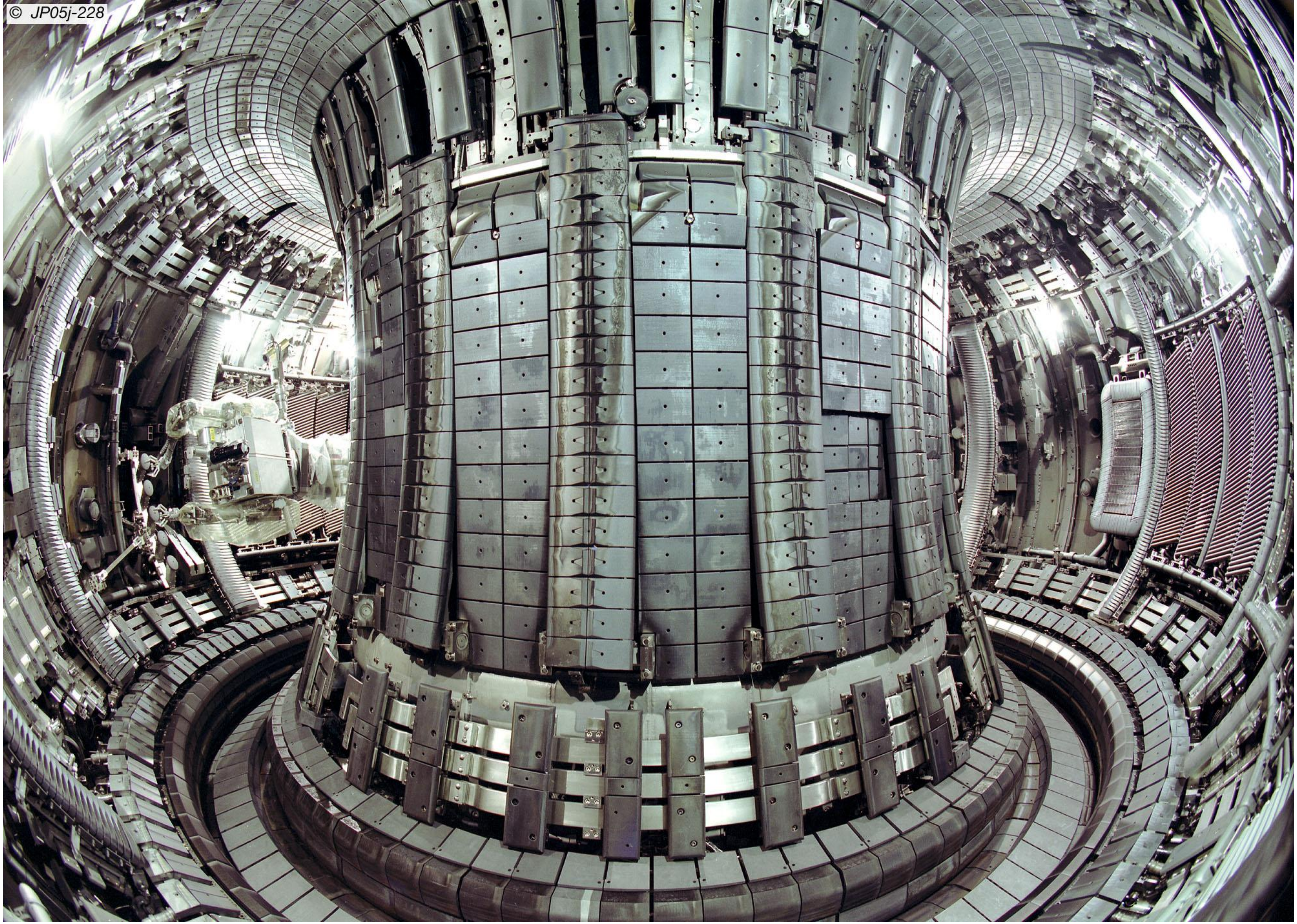
JET T experiment





Fuel retention is mainly by codeposition with C in the Divertor, mainly the inner





More than 5000 tiles to replace – 2 tons of Be

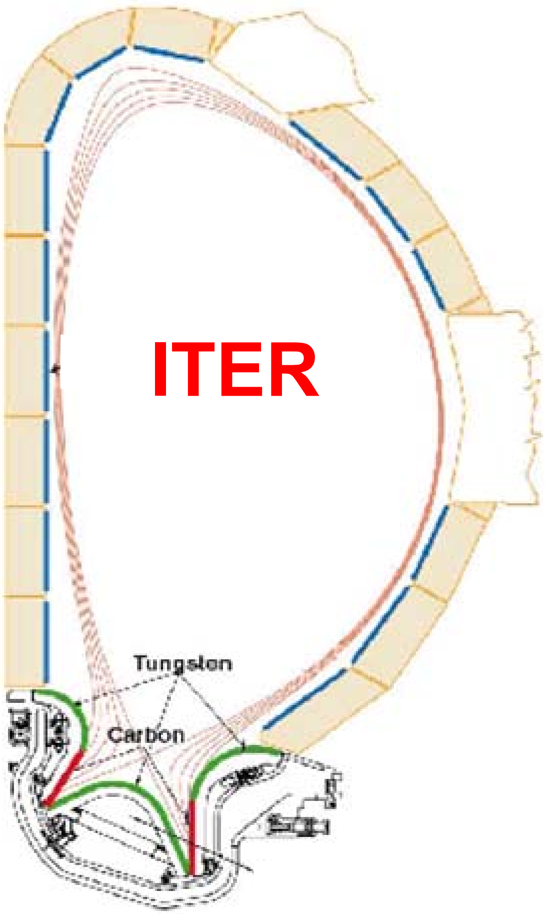
Avoid graphite in ITER

Forbidden in DEMO

Main step:

Transition from graphite (non melting) to a metallic (melting) wall

ITER strategy



Beryllium first wall
plasma performance
large erosion & melting

Graphite divertor
Tolerable against transients
large erosion & T retention

DT phase

Tungsten divertor
Fulfil T retention limit
Prepare future devices
melting in uncontrolled events

Requirements from plasma (Be) and wall side (W)

JET ILW will gain experiences for the ITER material combination for the DT phase

a full (bulk) Be first wall and a full W divertor (no carbon)

Many outstanding issues

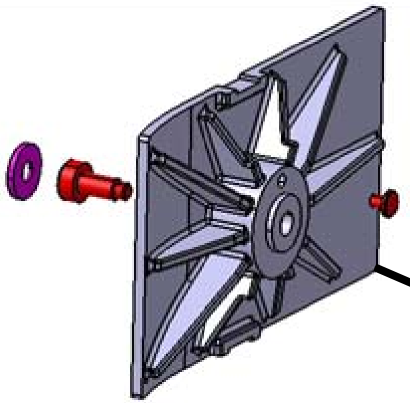
- Operational experiences & plasma performance
- Various dedicated issues

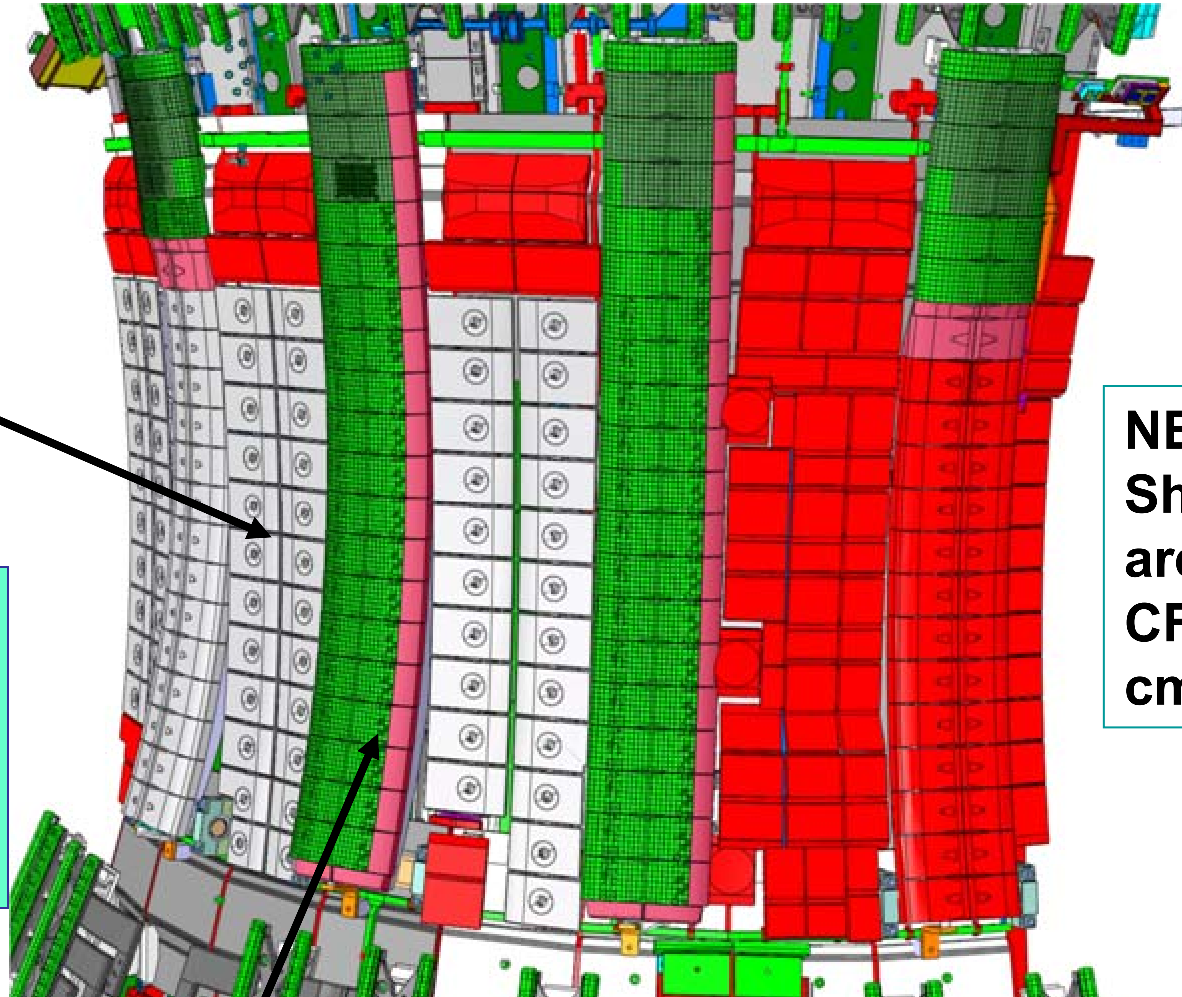
↓

Demonstration of tolerable T retention

talks by R. Pitts, E. Tsitrone and others

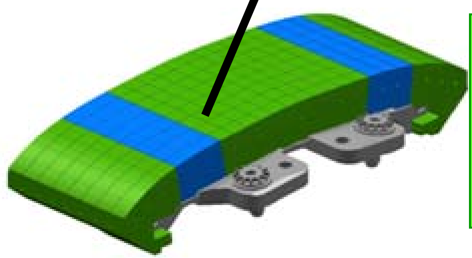
Main Wall configuration





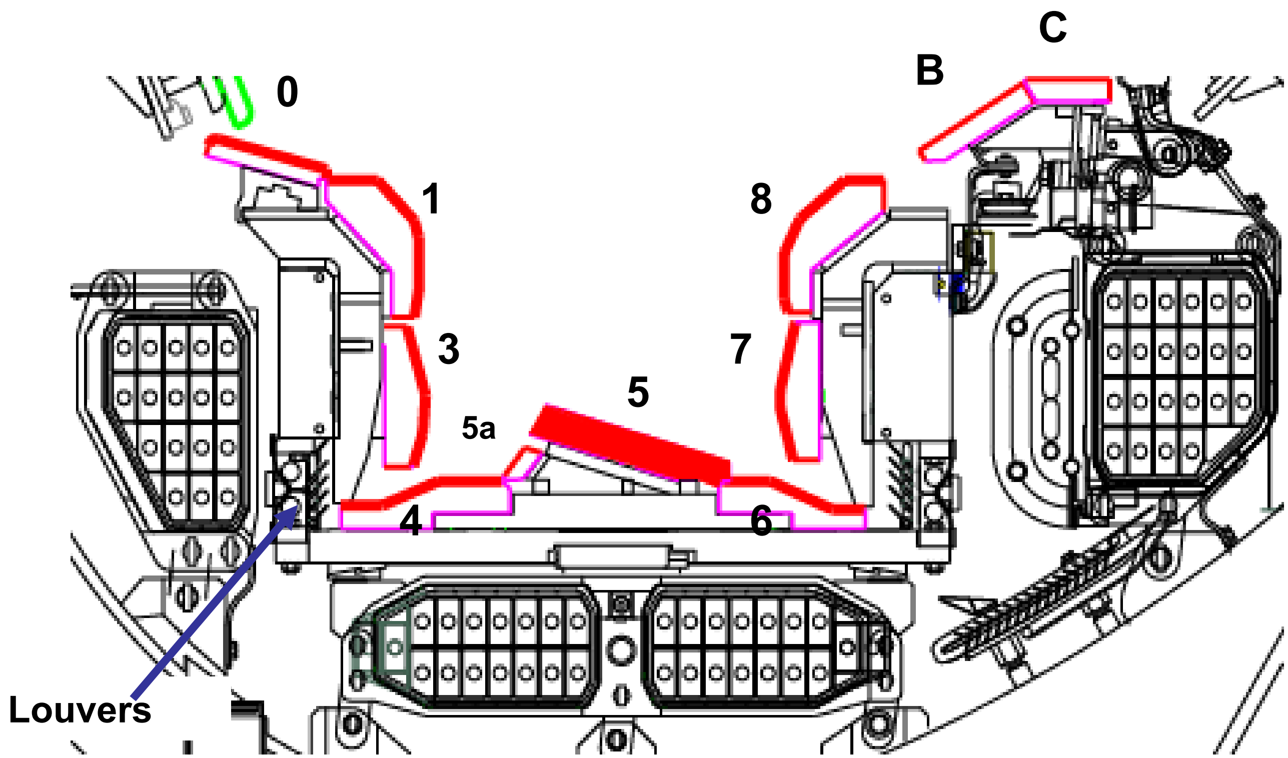
Be coated inconel in between Limiters (8 µm, low flux area)

NBI Shinethrough area W-coated CFC (10µm), 3 cm recessed



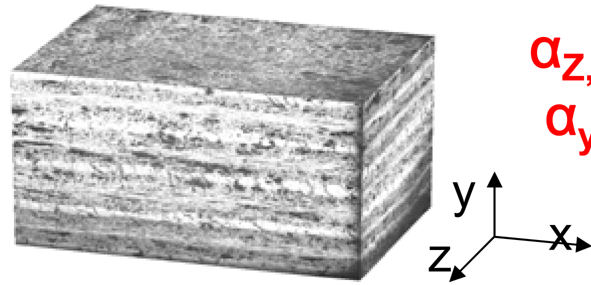
Outer and inner Bulk Be limiters, take most of the first wall particle power loads

Divertor configuration: mainly W coating on CFC + bulk W tile 5 (outer target in high triangularity)



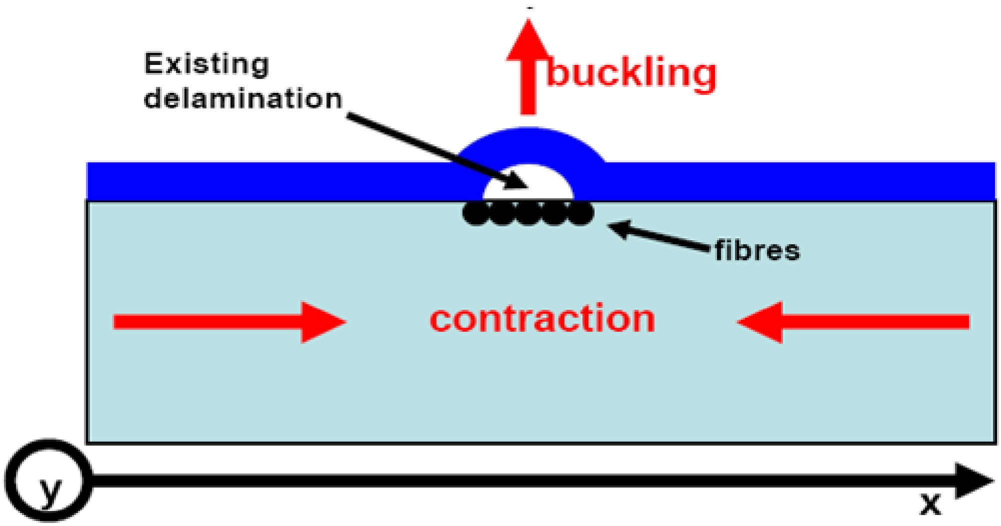
Large R&D needed to qualify W coatings on *existing JET 2D CFC tiles*

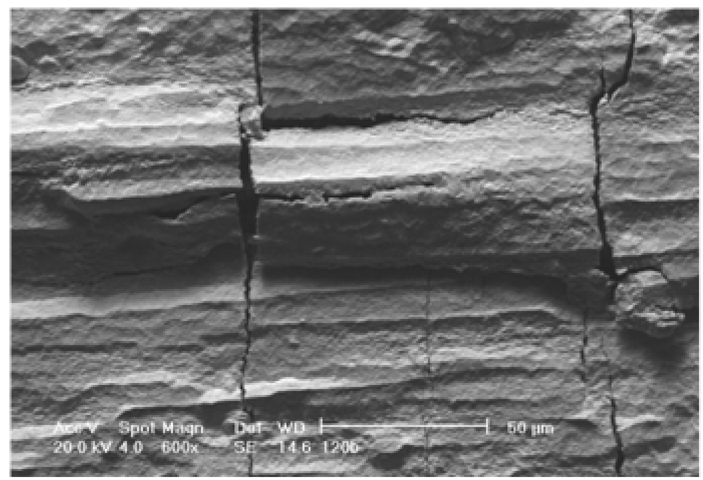
JET Dunlop CFC: 2 D CFC with strongly anisotropic thermal properties



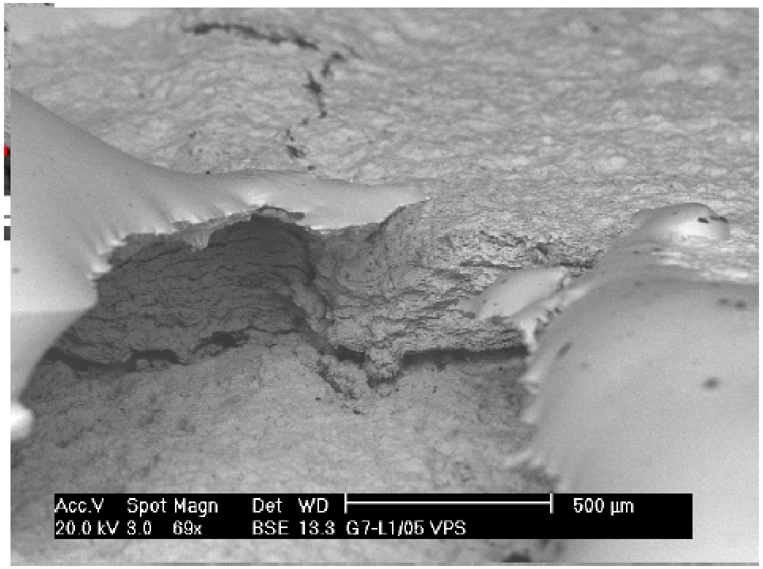
$\alpha_{z,x}$: 0 -1
α_y : 10-12 ($10^{-6}K^{-1}$)

High conductance





Cracking of W layer not to avoid, but delamination must be



A delamination failure can progress fast due to reduced thermal contact

Local hot spots, melting

Final selection:
W- coatings (25 µm) with Mo interlayer produced by Combined Magnetron Sputtering & High Voltage Ion Implantation (CMSII)

no delamination /failures in HHF tests of tiles as delivered

NILPRP Romania (Bucharest)

What are Neutral Beams used for?

Neutral Beams (NB) are used on almost every fusion research facility for:

a) Plasma heating

Fast neutral beam particles injected into plasma are ionised by ion or electron impact ionisation or by charge exchange

Once charged, the fast ions become trapped in the magnetic field and circulate, losing energy to the plasma ions and electrons by electrostatic collisions

b) Plasma diagnostics – CXRS, MSE

Various plasma parameters are determined by spectral analysis of light emission generated by collisions of fast neutrals with plasma

c) Current drive

Injected neutral flux can be used to drive plasma current – important for future devices using high energy neutral beams

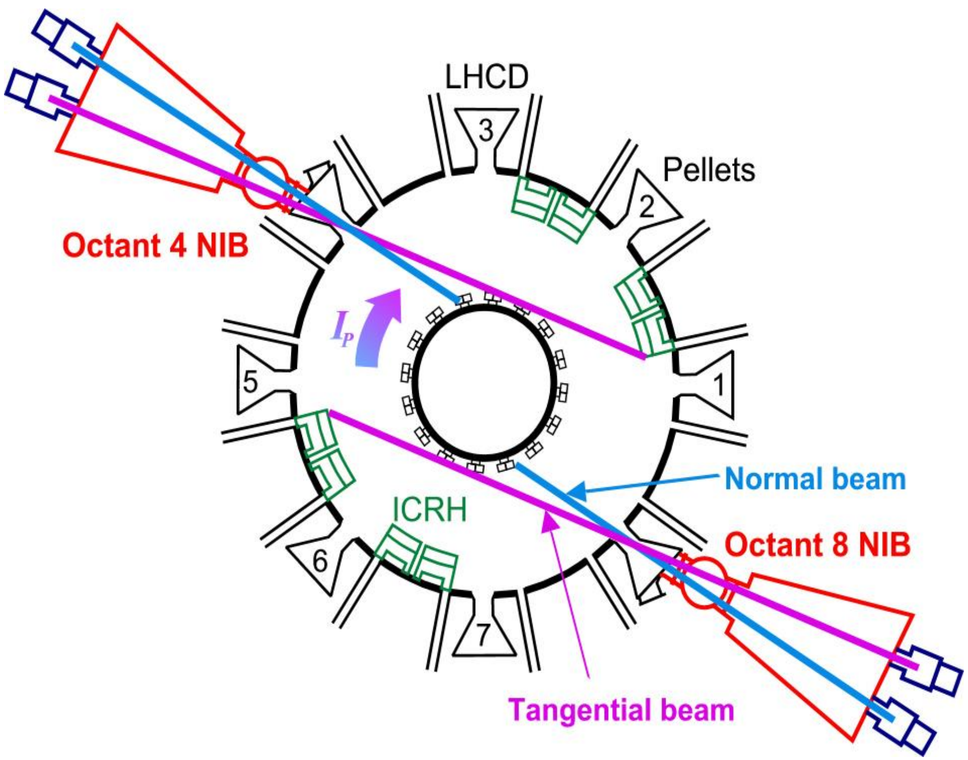
d) Rotation drive

Injected neutral flux imparts momentum, increasing the plasma rotation – important for plasma stability

There is high demand for neutral beam power:

Neutral beams are required on >90% plasma pulses on JET and MAST.

JET NBI System Layout (1)



Layout of JET heating and fuelling systems.

There are two **N**eutral **I**njector **B**oxes (**NIBs**) on the JET tokamak.

Each NIB can be equipped with up to 8 **P**ositive **I**on **N**eutral **I**njectors (**PINIs**).

Four PINIs on each NIB are grouped into two banks:

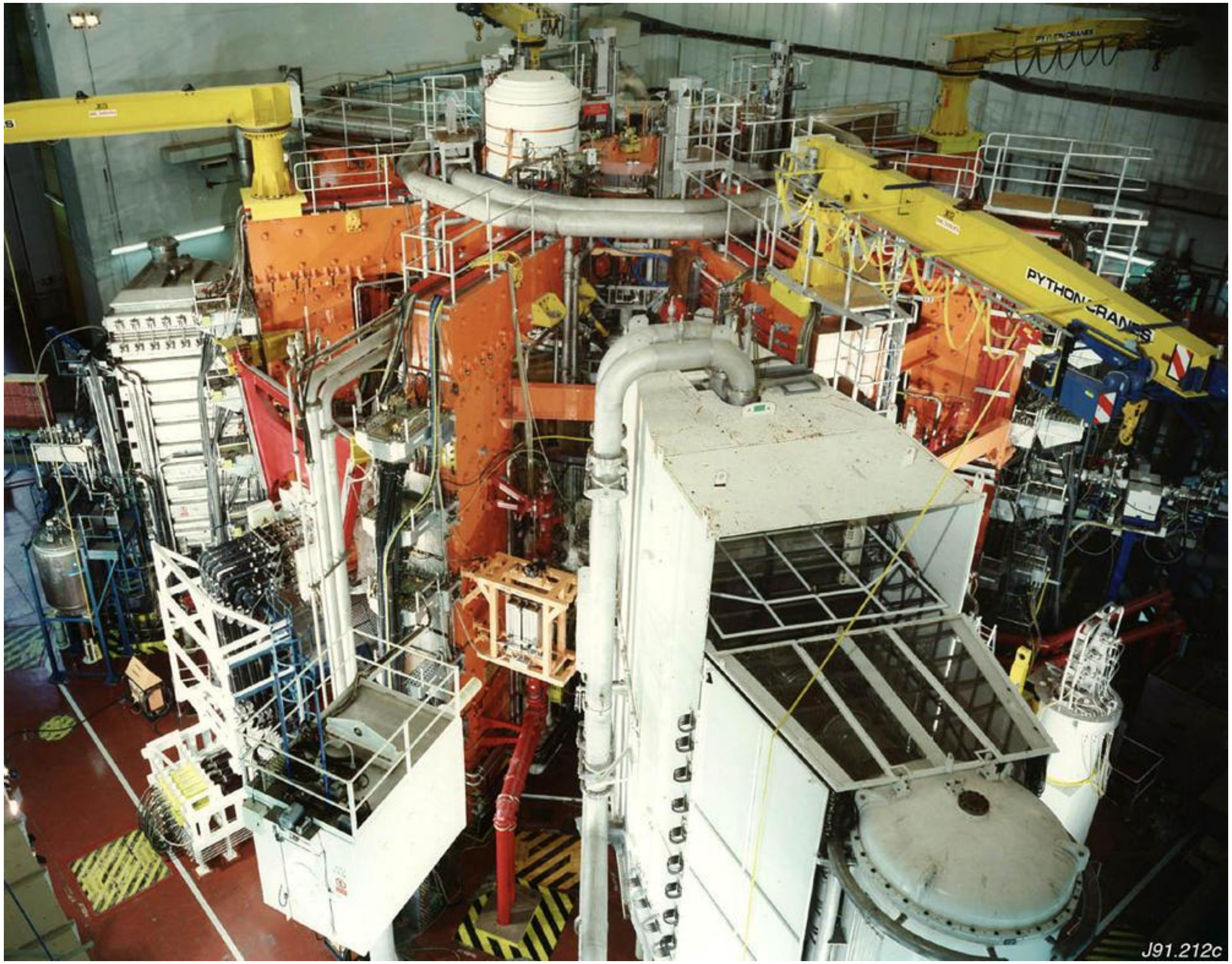
Tangential bank (R_T=1.85m): two passes through the plasma.

Normal bank (R_T=1.31m): one pass through the plasma.

PINIs and beamline components are designed for **20s pulse duration**, only 10s up till 2009.

Total deuterium neutral beam power in 2011 will be**: 34MW (maximum)**, up from 24MW in 2009.

JET NBI System (2)



JET machine and Octant 4 Neutral Injector Box

EP2 NBE Goal & Implementation

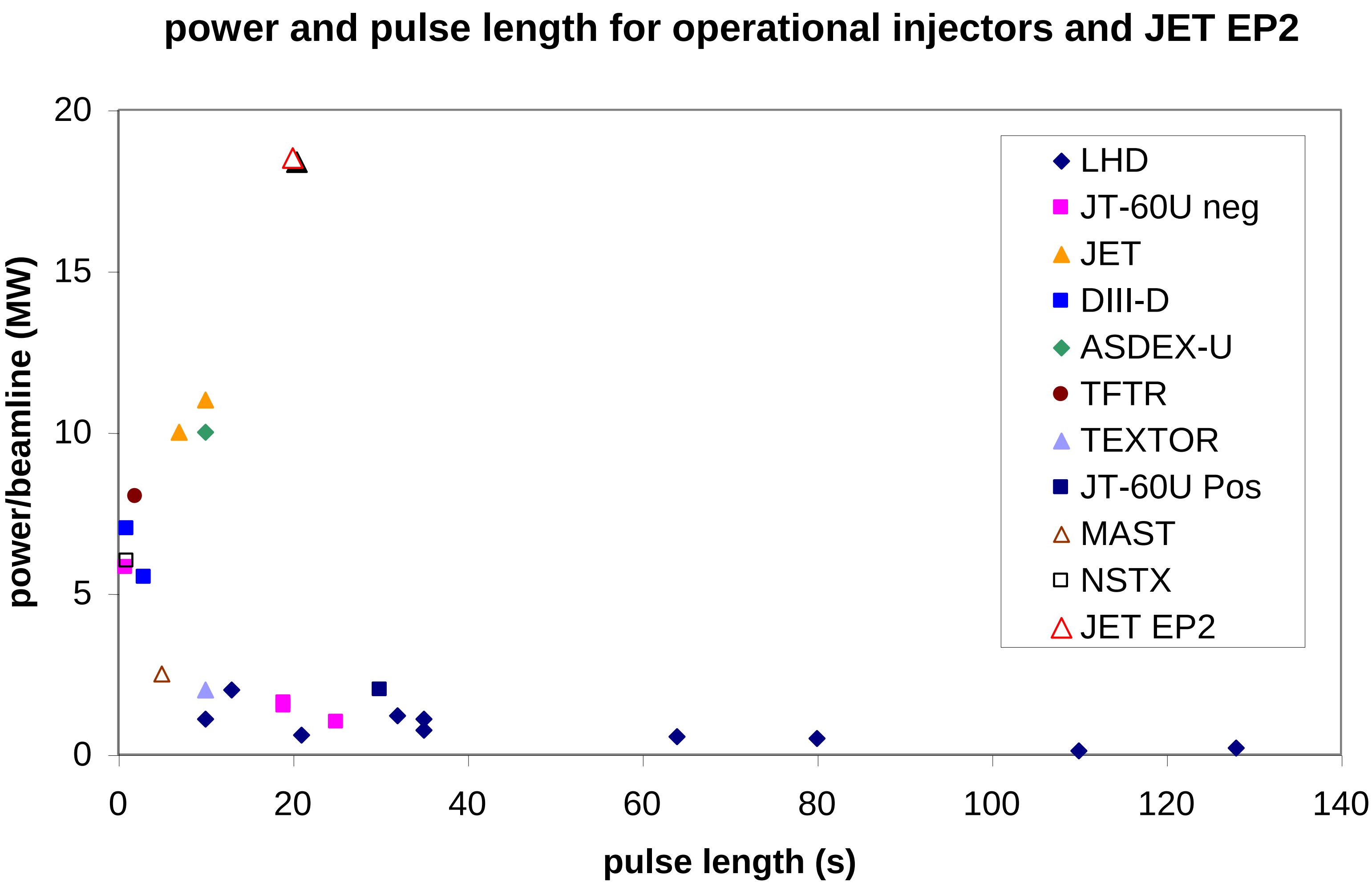
The aims of the EP2-NBE Project (approved in 2005) were:

- To increase the deuterium NB power to at least 34 MW
- To increase the beam pulse length at full power to 20 s (40 s at half power)
- To improve NB reliability and availability

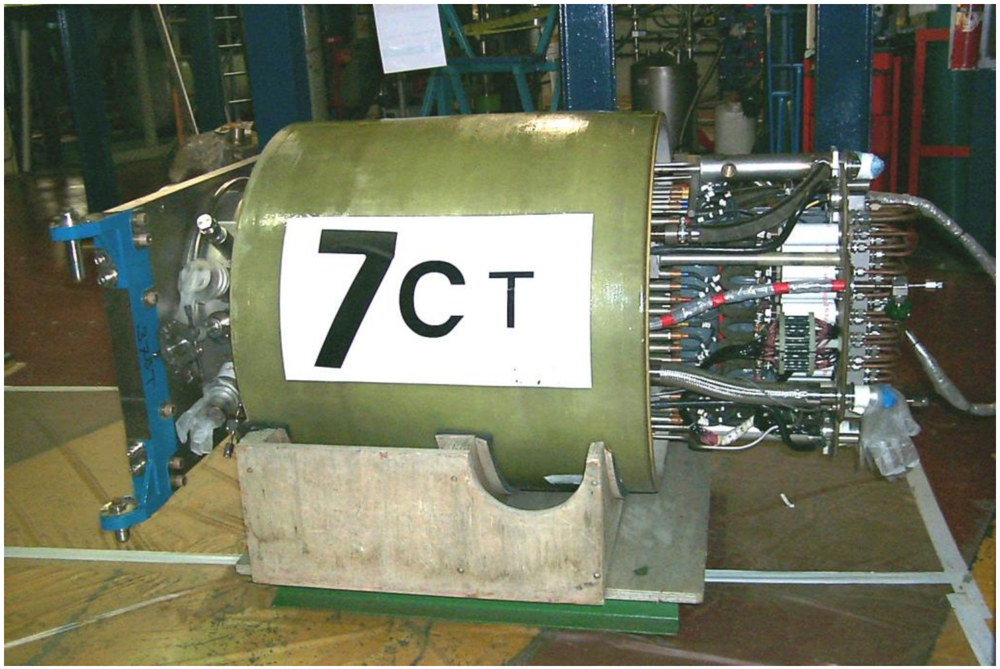
This has been achieved by:

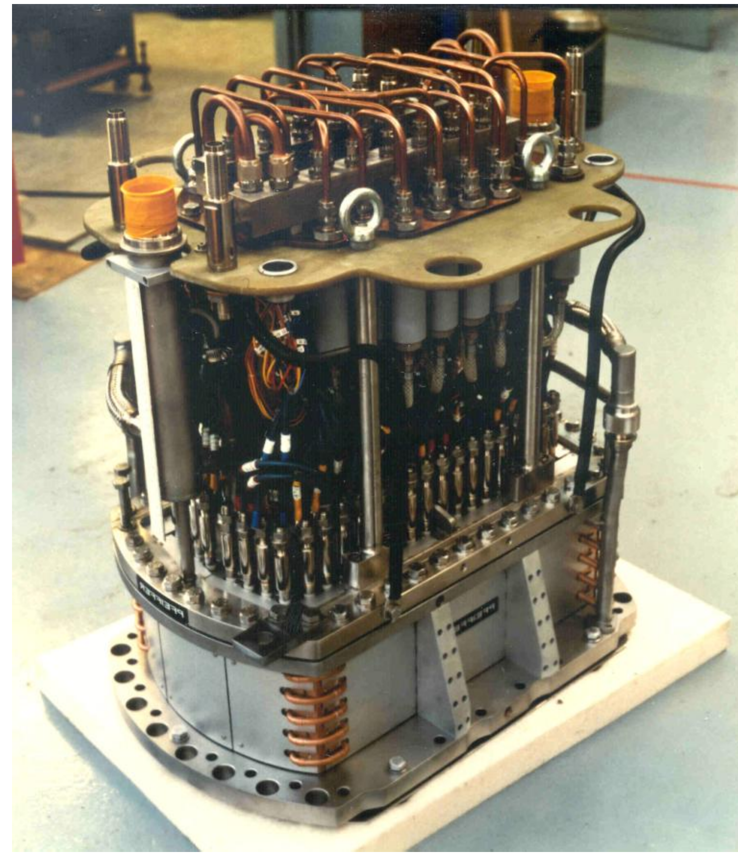
- Changing PINI ion sources to **Chequerboard** type producing more molecular ions that are easier to neutralise, and re-optimising the accelerators for **125kV/65A** deuterium beam operation
- Modifying some Central Column beamline components to cope with four-fold increase in fractional and molecular residual ion power and pulse length increase
- Replacing a number of beamline components with upgraded designs, e.g. actively cooled Duct Scrapers
- Replacing the high voltage power supplies serving 8 PINIs with four new 130kV/130A HVPS modules

Beam-Lines of the World



NBI Principles – Ion Source (2)

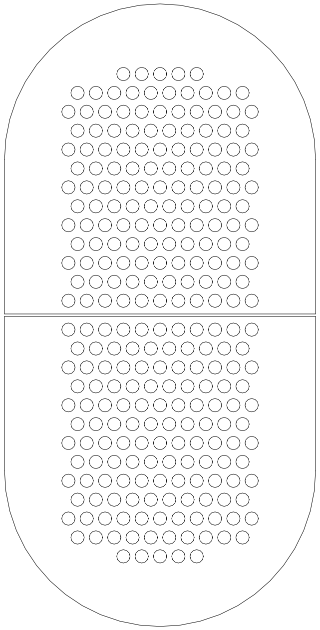




JET Positive Ion Neutral Injector - PINI

PINI ion source.

NBI Principles – Accelerator (3)

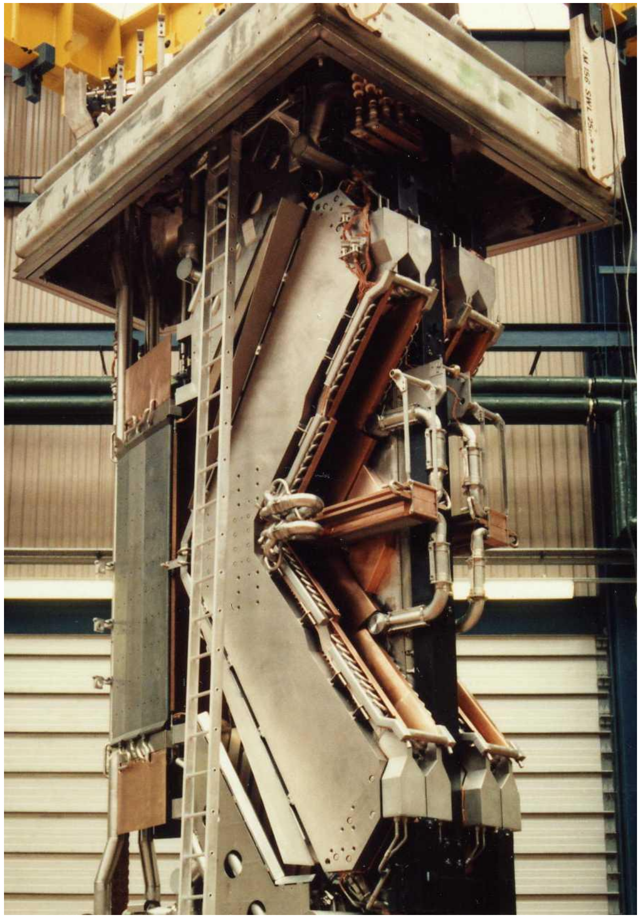


Central aperture of each grid half has zero offset. Offset is increasing towards the edges of the grid halves.

Grid alignment is critical: Error of **0.1 mm** in horizontal alignment can move the beam sideways by **3.6 cm** over **8 metre** distance!

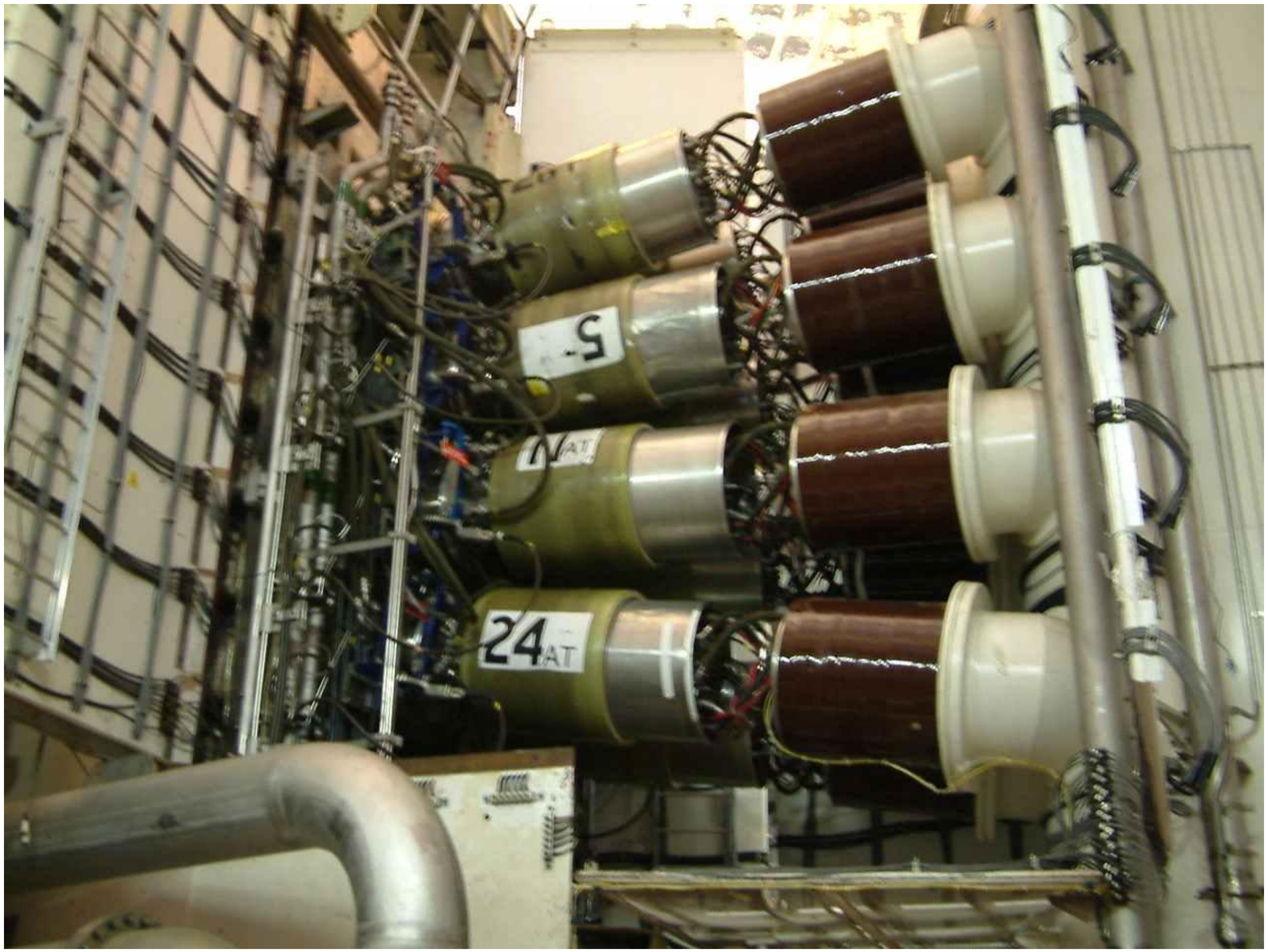
NBI Systems & Components (4)

JET Neutral Injector cryopump.



JET Neutral Injector Central Support Column (deflection magnets, ion dumps, calorimeters).

NBI Systems & Components (5)



NBI Systems & Components (1)

Ion beam current:	up to 60 A (per PINI)
Ion current densities	up to 240 mA/cm^2
Beam acceleration voltage	up to 160 kV
Total extracted power (ions):	up to 8 MW (per PINI)
Total neutral beam power:	up to 2 MW (per PINI)
Peak power density:	up to 300 MW/m^2

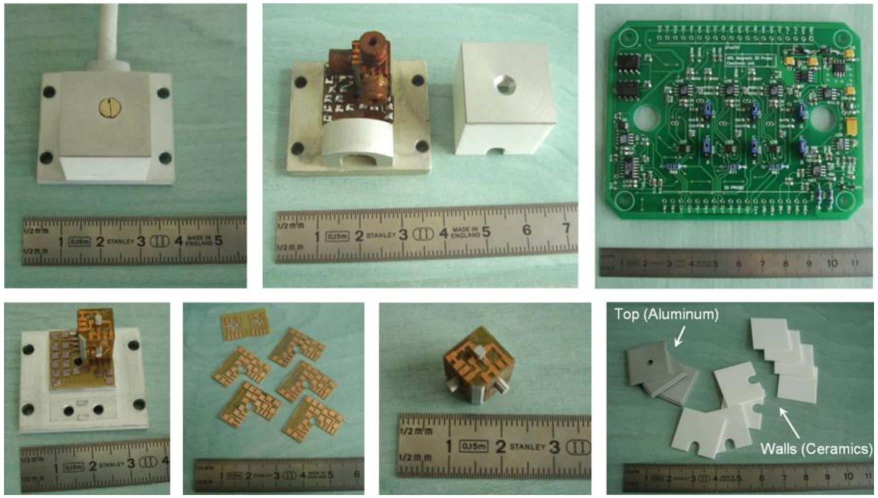
Large and complex power supplies:	tens of MW
Large vacuum vessels:	tens of m^3
High gas flows:	hundreds of mbar×l/s
Huge pumping speeds:	millions of l/s
Most of beam components water cooled:	thousands of m^3/h
Fast and complex control, feedback & safety system:	thousands of signals

EP2 ex-vessel Hall probes

Six 3D Hall probes will be installed in 2009 within JET EP2 project RHP.

- **ENEA (CREATE)** – project leader, support structures for probes
- **MSL Ukraine** – delivery of probes
- **IPP.CR** – commissioning, performance evaluation

One of the JET ex-vessel Hall probes developed within EP2 enhancement project RHP at various stages of manufacturing process.



JET relevance:

- Enhance database for iron core modelling
- Enhance data for equilibrium reconstruction
- Measures of magnetic flux density at ex-vessel locations might be required for NBI

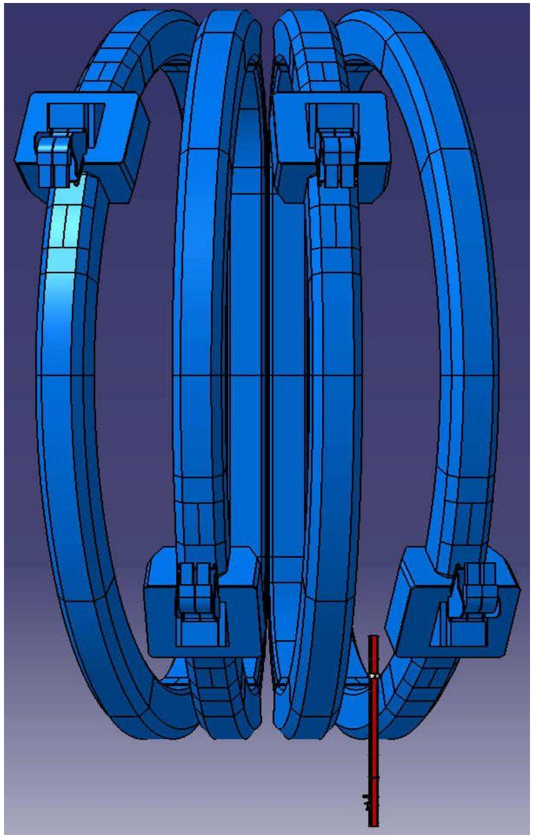
ITER relevance:

- Gain further experience in using direct field measurements for magnetic diagnostics
- Test innovative hard radiation Hall probes in neutron environment with fusion spectrum

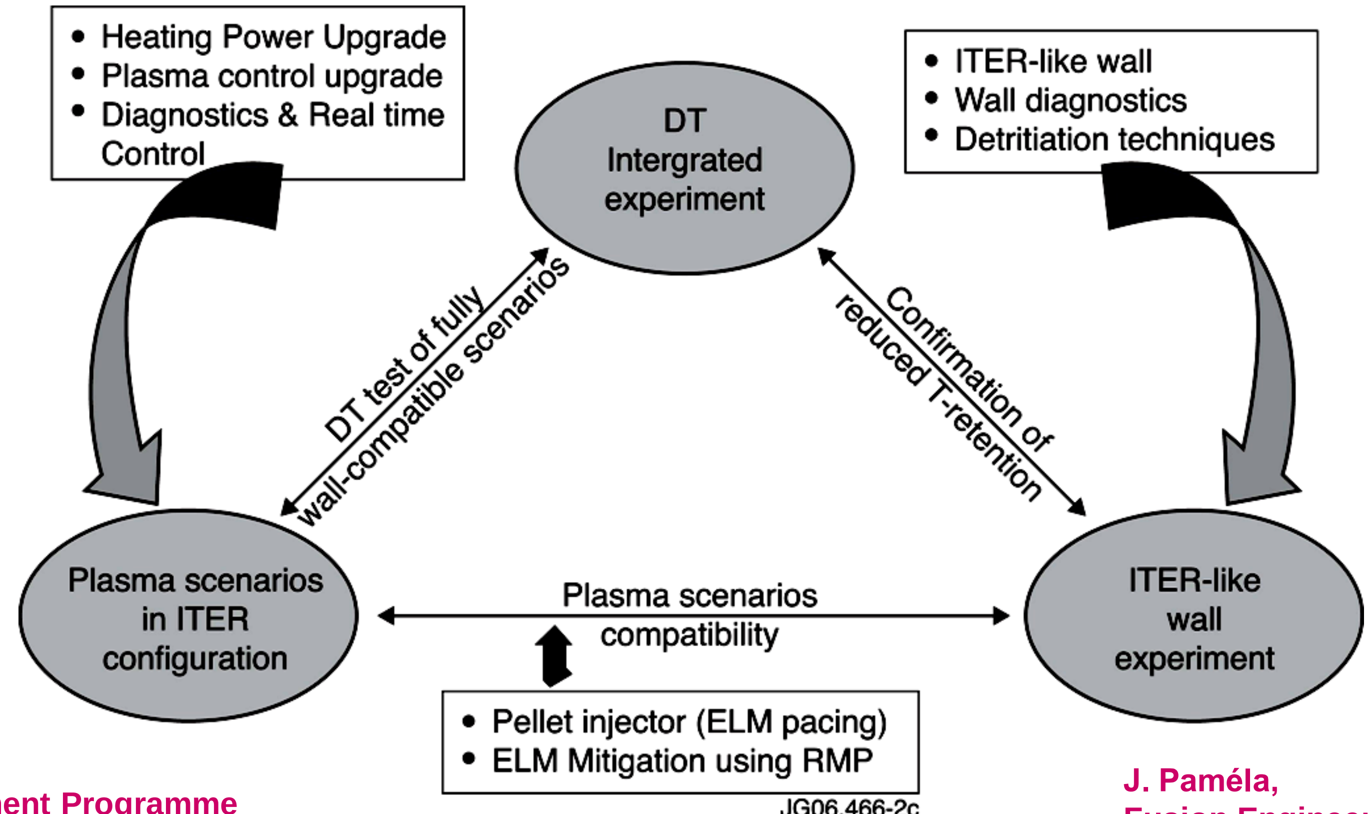
EP2 ex-vessel Hall probes

Two manipulators, each containing 3 probe heads, with control electronic boxes shortly before installation on JET.

Locations of three 3D magnetic probes with respect to JET TF coil structure.



Context for Campaigns of 2011-2012



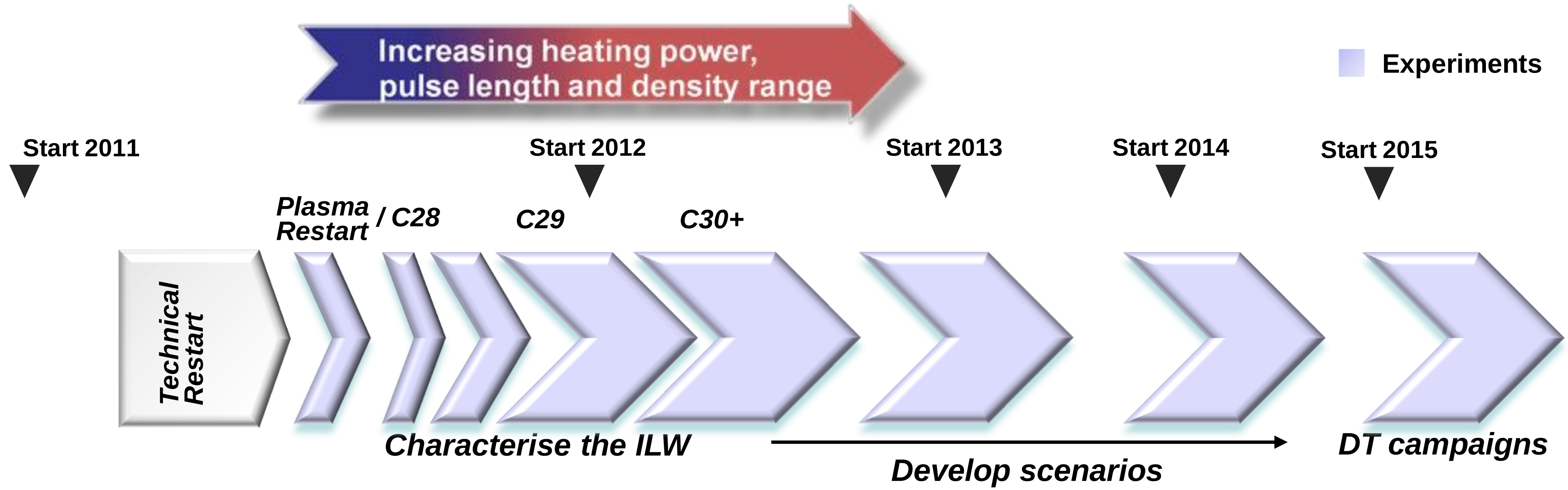
EP2 Enhancement Programme

J. Paméla,
Fusion Engineering Design, 2007

Coherent approach in a multi-annual "JET programme in support of ITER" based on the full exploitation of the ILW

Phase I: Experimentation with an ITER-like-Wall (2011-2012)
Phase II: Develop plasma scenarios approaching ITER relevant conditions (2013)
Phase III: Integrated experimentation in deuterium-tritium (2014-2015)

Five-year road map for JET



Fusion Facilities Review, 2008

- Phases I&II: Characterise ILW and develop scenarios towards ITER parameters (higher performance) + physics issues (2011-2013)
- Logical sequence of Restart and experiments (staged/phased approach, key deliverables, long term view)
  → **Specific experiments need to be done early**
- Phase III: Prepare and execute a DT campaign (2014-2015)

Programme Focus and Structure

- **JET has a very challenging task**
  - To cover **all** scientific areas (diversity in Programme Headlines), provide timely input to ITER, provide input on PWI issues, prepare for D-T operation
  - To coordinate experiments with other devices, international partners
- **Headlines for the Experimental Programme of 2011**
  - Characterisation of the ITER-like Wall (ILW)
  - Exploration of ITER operating scenarios with the ITER-like Wall
  - Physics issues essential to the efficient exploitation of the ILW and ITER

Key results expected from JET during 2011-2012
(substantiate case for Day 1 all W-divertor on ITER)
→ Experiments need to be elaborated at 2nd GPM
for full exploitation of ILW

Experiments need to be efficient and focussed
to achieve desired results and output
→ Priorities and sequence for 2011 and 2012 need to be established

JET component of EFDA Workprogramme: Headlines for 2011 Experimental Programme

1. **Characterisation of the ITER-like Wall**
   - 1.1 Fuel retention and material migration
   - 1.2 Material limits and long term samples
   - 1.3 Transient and steady state power loads

2. **Exploration of ITER operating scenarios with the ITER-like Wall**
   - 2.1 Develop plasma scenarios.
   - 2.2 Assess plasmas scenarios
   - 2.3 Explore scenarios in domains closest to ITER dimensionless parameters

3. **Physics issues essential to the efficient exploitation of the ILW and ITER**
   - 3.1 Divertor and Scrape-Off Layer physics
   - 3.2 Confinement, pedestal and ELM physics
   - 3.3 Disruptions, MHD and fast particle physics
   - 3.4 Diagnostic issues for ITER

Longer-term programme plan: Preparations for 2012-2013

Campaigns of 2012

- Establish preliminary timeline of experiments (2nd GPM)
- Prepare JET Workprogramme for 2012 in first half 2011
- Review 2012 Campaigns in November 2011 (after C28)
- Define future Campaigns at JET, covering period up to DT in 2015

Campaigns of 2013

- Demonstrate plasma operation closest to ITER parameters and related physics issues + full exploitation of EP2 enhancements
- Consider H/He campaigns, reversed ∇B, TF ripple, W-bulk melt experiments….. (not done in 2011-2012)

Longer-term programme plans: Milestones towards DT (2014-2015)

(JET Science Meeting: 8 November 2010)

- DT Campaign is final Phase of ILW programme performed with W/Be wall
  Solid W tile 5 may be exchanged for W-coated carbon tile in 2013/2014
- Full NB power at 35MW + 5MW from ICRH must have been shown to be available and compatible with ILW (for at least 5s) at high plasma current
- High performance scenarios must have been developed in DD (3.5-5 MA), including operation up to 4T (performance and ICRF heating schemes)
- LHCD could be used (in contrast to DTE1)

DT campaign in 2014-2015 would require significant preparation, starting as soon as possible, with the development of plasma scenarios that aim for high absolute performance whilst also being compatible with the ILW