JET Enhancements Programmes: key steps in preparation of ITER

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on behalf of all participants to the EFDA-JET Enhancement Programmes

Some challenges for ITER

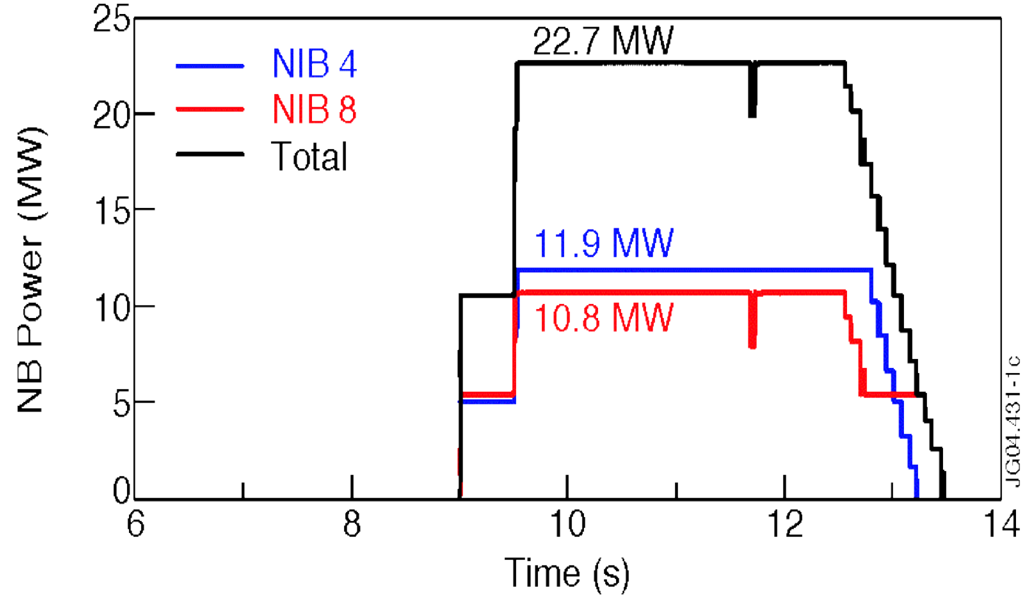
	Issues	Relevant JET enhancements
Large ELMs	• Plasma-wall compatibility • Coupling RF power • Vertical control	• NB & ICRH power upgrades • ELM resilient RF coupling • Plasma control upgrade • ITER-like wall • Diagnostics • *(Ergodisation coils)*
Disruptions	• Risk of damage to first wall	• Disruption mitigation valve • Diagnostics
DT operation	• New burning plasma physics • Tritium retention • Difficult environment for diagnostics	• Burning Plasma Diagnostics • ITER-like wall
Steady state	• Profile control	• Extended heating pulses • Diagnostics and Real-Time Control

Outline

- Enhancement Programme 1 (EP1) 2000-2006
- Enhancement Programme 2 (EP2) 2004-2008
- Conclusion

EP1: JET Neutral Beam Heating Upgraded in 2003 and 2004

- Increase of power obtained by increasing the beam current per source from 30A to 60A
- Achieved by installing new **switch mode** power supplies, each rated at ***130kV/130 A,*** on one of the 2 NB boxes



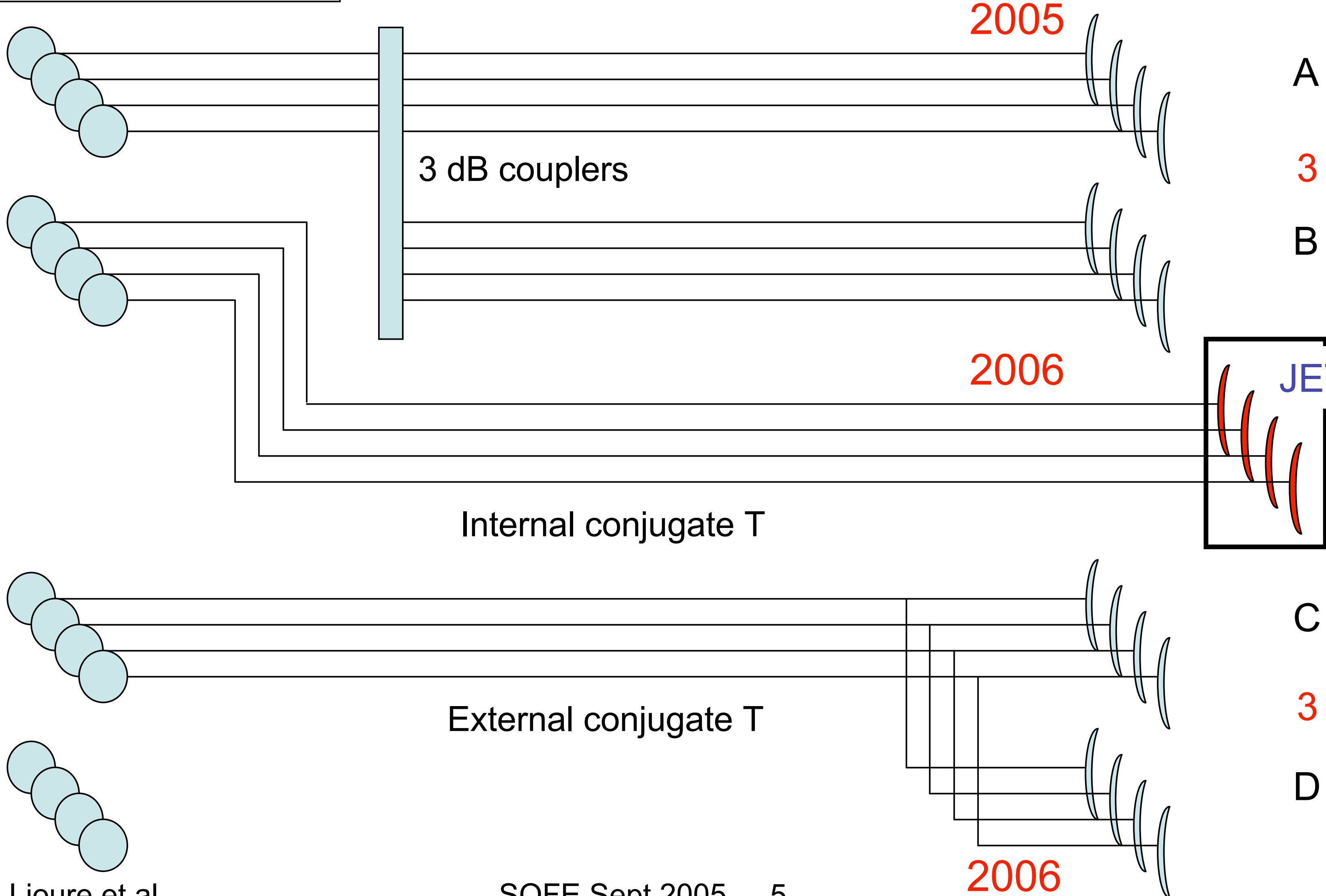
⇒ **A record JET NB power (D^0) of 22.7MW** was achieved on 22/1/04

⇒ **up to 25 MW maximum power expected end 2005 after an upgrade of the neutralisers**

EP1: ICRH

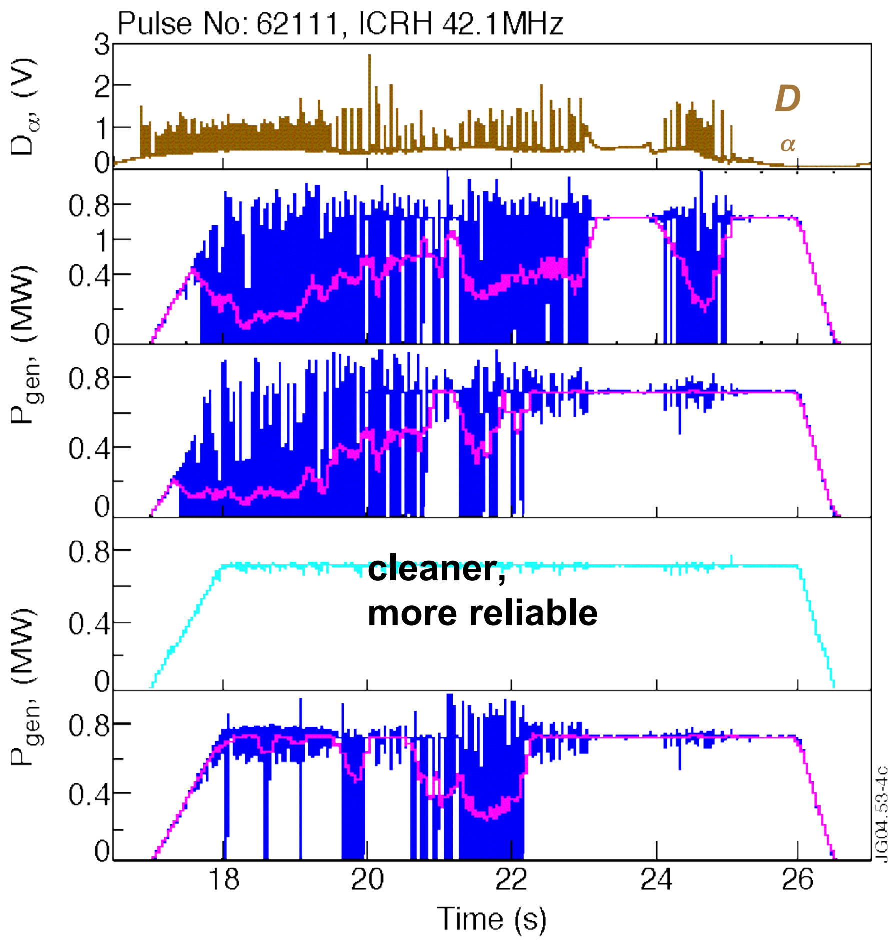
Reliable Power into H / L

From 4 / 10 MW today with standard connections of Antennas A,B,C&D to 12 / 15.2 MW



EP1: Proof of Principle of ELM Resilience with (External) Conjugate T ICRH Antenna Scheme

I. Monakhov et al., to be published in Fusion Engineering and Design)



ELMy Plasma

⇐ *module 'A' - conventional matching*

⇐ *module 'B' - conventional matching*

⇐ ***amplifier 'C' - conjugate-T matching***

Higher average power, less strain on generators

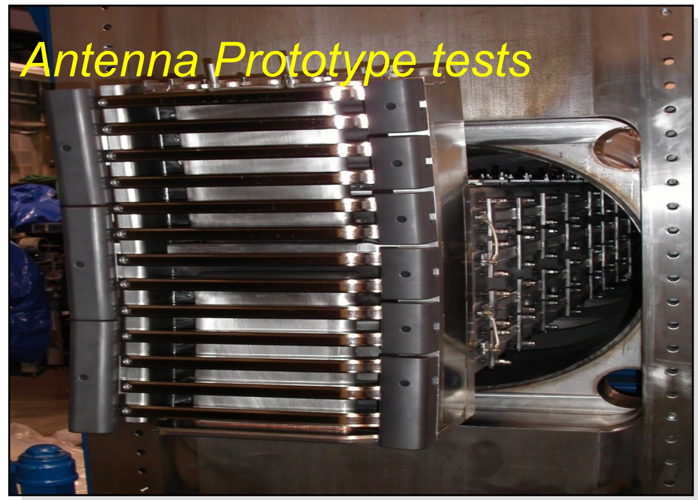
⇐ *module 'D' - conventional matching*

EP1: ITER-like ICRH antenna

Under construction: partly installed, operation in 2006

- ELM resilient Conjugate-T with Internal Matching
- High Power Density: ~8 MW/m2 in the range of 2-4 Ω/m
- ~7MW additional power

Transmission lines



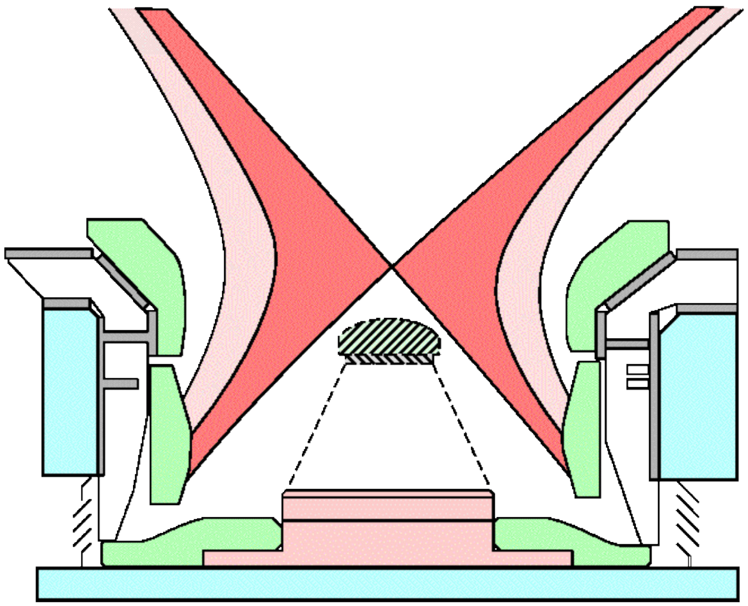
HPP test

US contribution from ORNL and PPPL

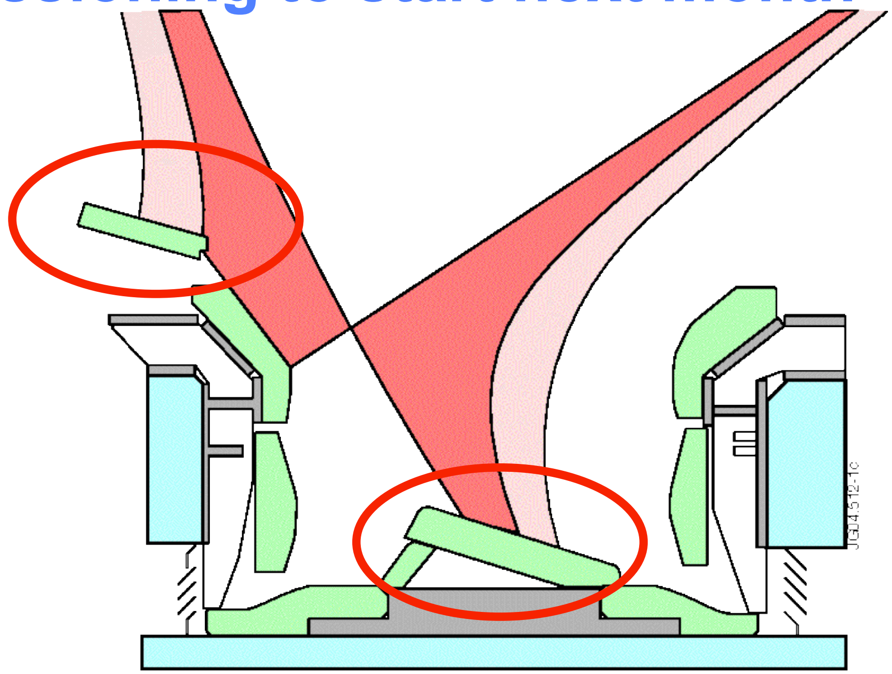
Main Port bellows

EP1: modified divertor (MkII-HD)

Increased power handling with ITER-like plasma shapes/ installed in 2005, commissioning to start next month



MkII-SRP divertor since 2002



From 2005: MkII-HD (high δ)

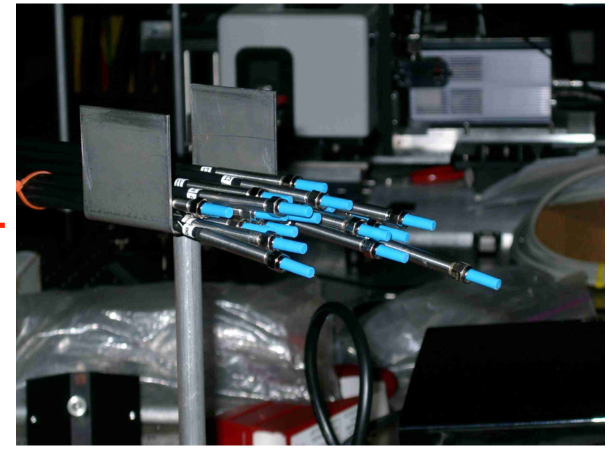
- ***40 MW capability***
- ***ITER-like δ at 3.5 - 4 MA***

Core diagnostics (EP1, 2005)

HRTS double vacuum window

GA

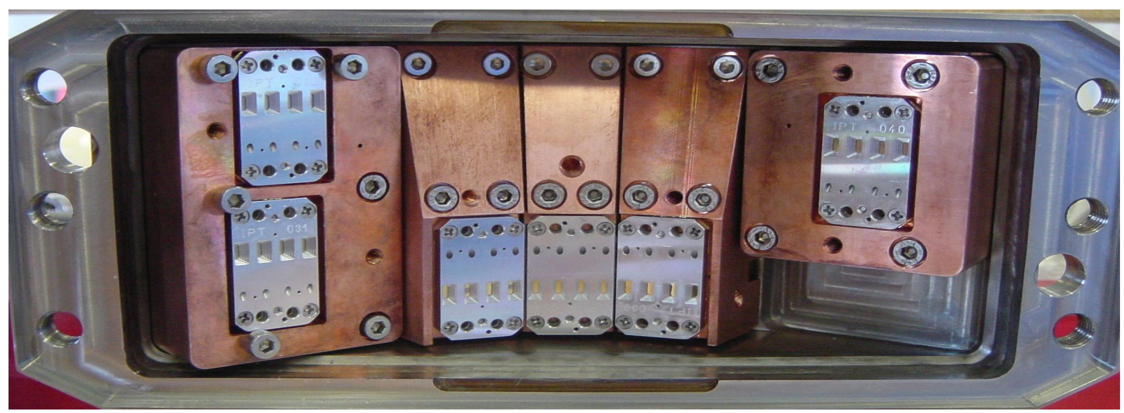
Fibres for CXRS



ORNL

US contribution from :

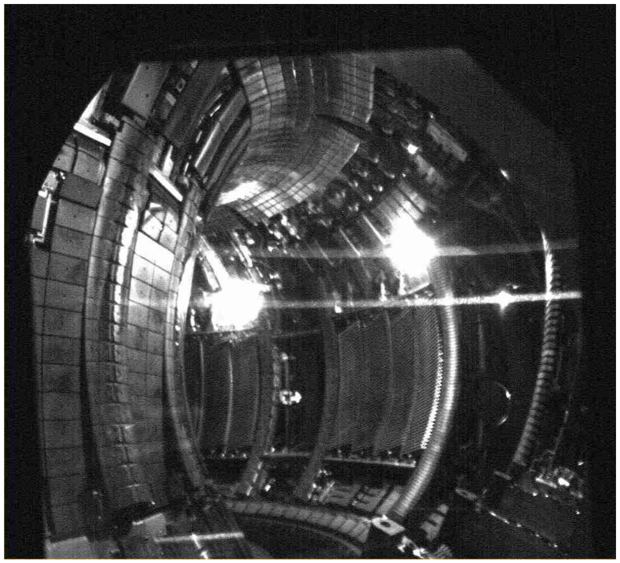
PPPL



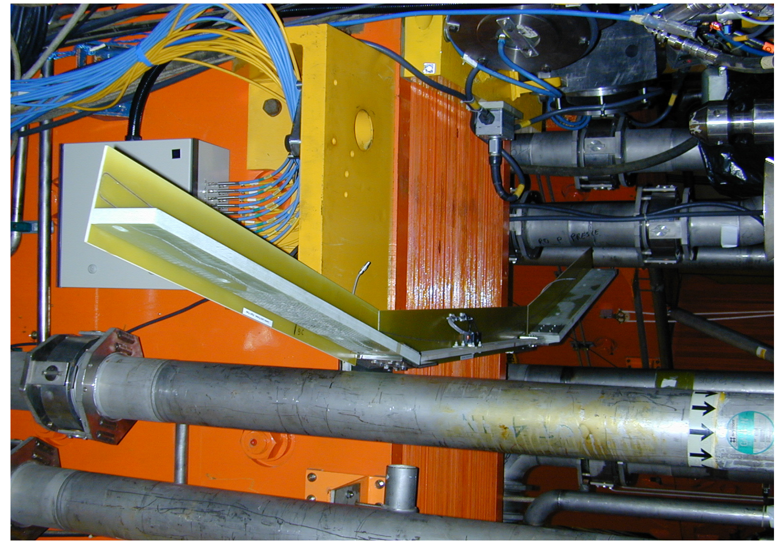
MWA launcher and ECE oblique

Bolometers

Edge diagnostics (EP1, 2005)



Wide angle IR camera



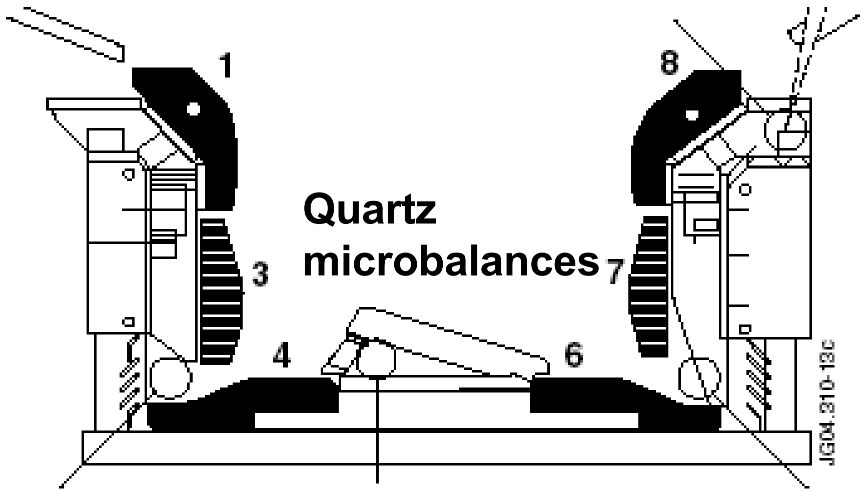
Ex-vessel magnetics

US contribution from :

MIT

Boards for fast acquisition

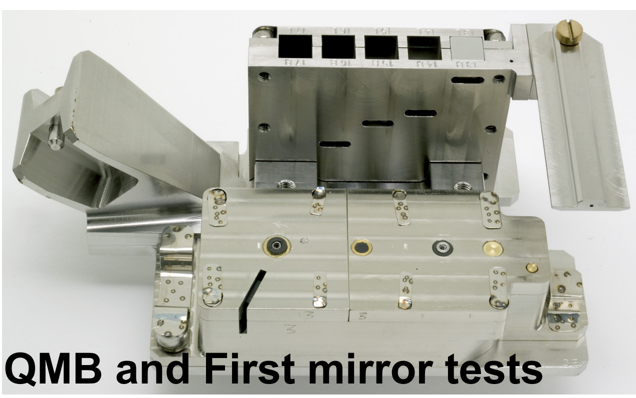
Wall diagnostics and protection (EP1, 2005)



Standard QMB
Heated QMB
Cooled QMB
Deposition Monitor
Louvre Clip
Rotating Collector
Mirror Test Units

Standard QMB
Deposition Monitor
Rotating Collector
Mirror Test Units

Standard QMB
Deposition Monitor
Rotating Collector
Mirror Test Units
Louvre Clip

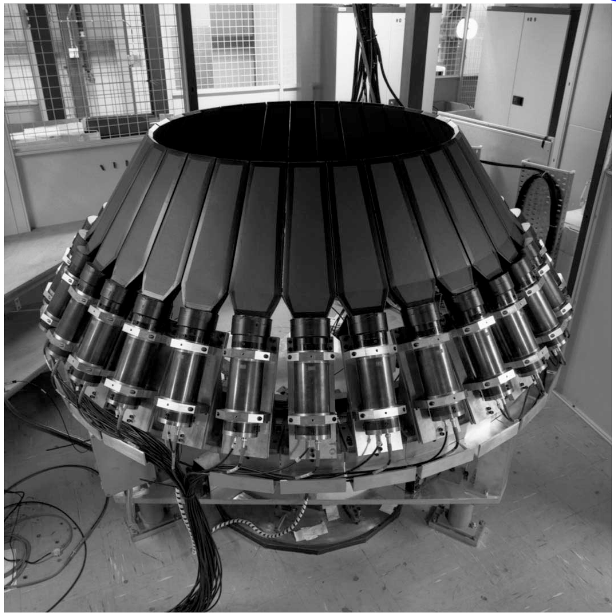


QMB and First mirror tests

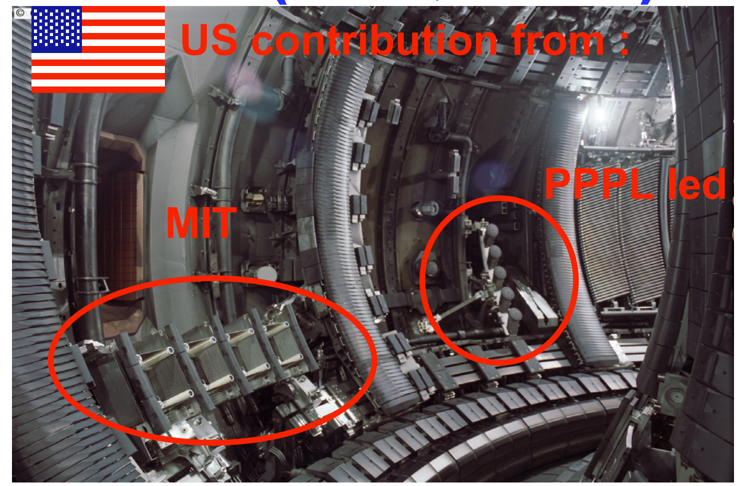
Halo current sensors

Disruption mitigation valve

Burning plasma diagnostics (EP1, 2005)



New Time of Flight, Optimised Rate 2.5 MeV neutrons spectrometer



TAE and Lost α Faraday cups in vessel

Magnetic Proton Recoil, upgrade 2.5 and 14MeV neutrons

Lost α scintillator probe

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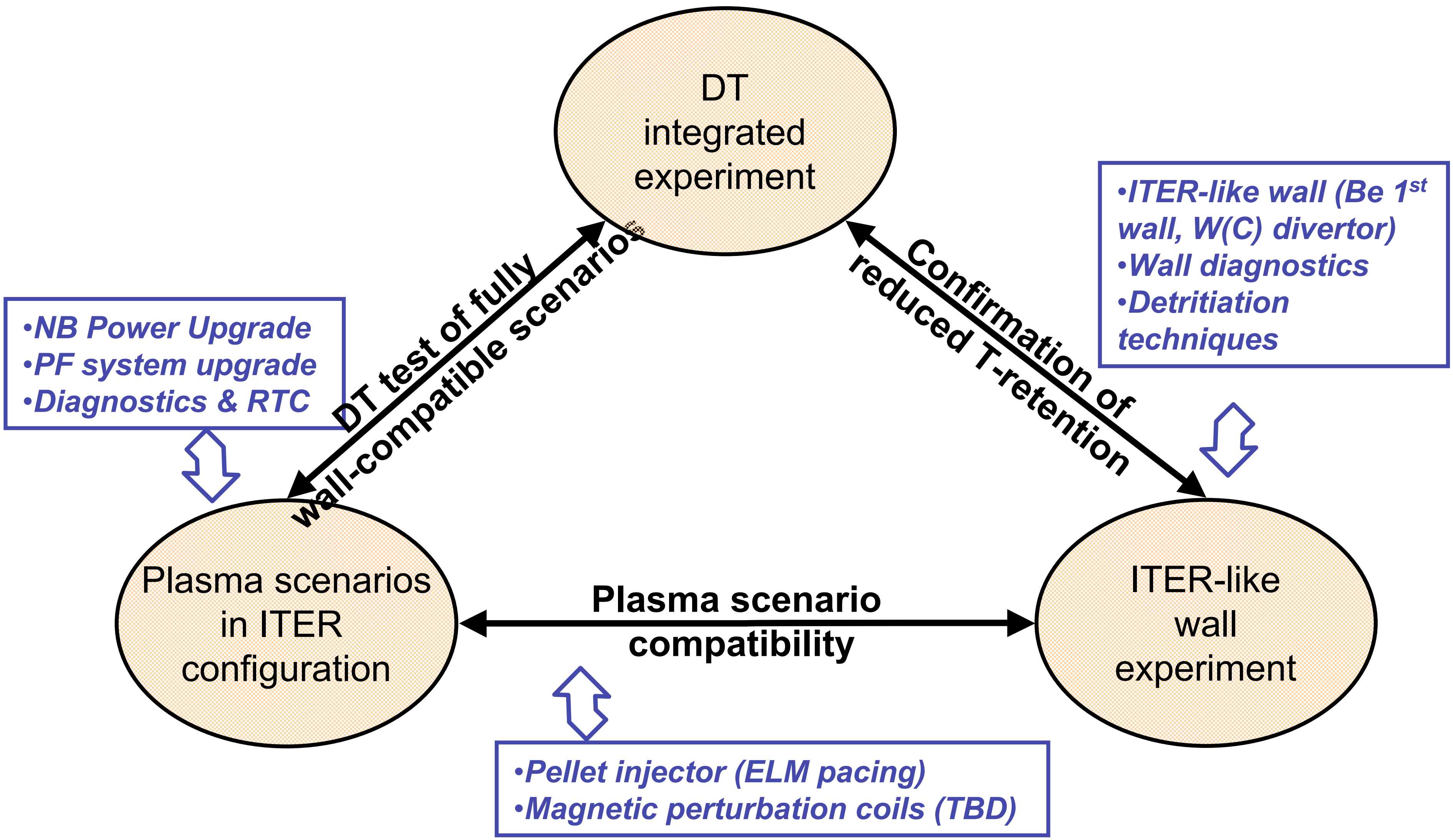
Status of EP1 projects

Divertor	Installed
NB upgrade	Completed
3dB coupler on ICRH system,	Installed
Diagnostics	15 diagnostics presently under commissioning, for use in 2005/6 campaigns

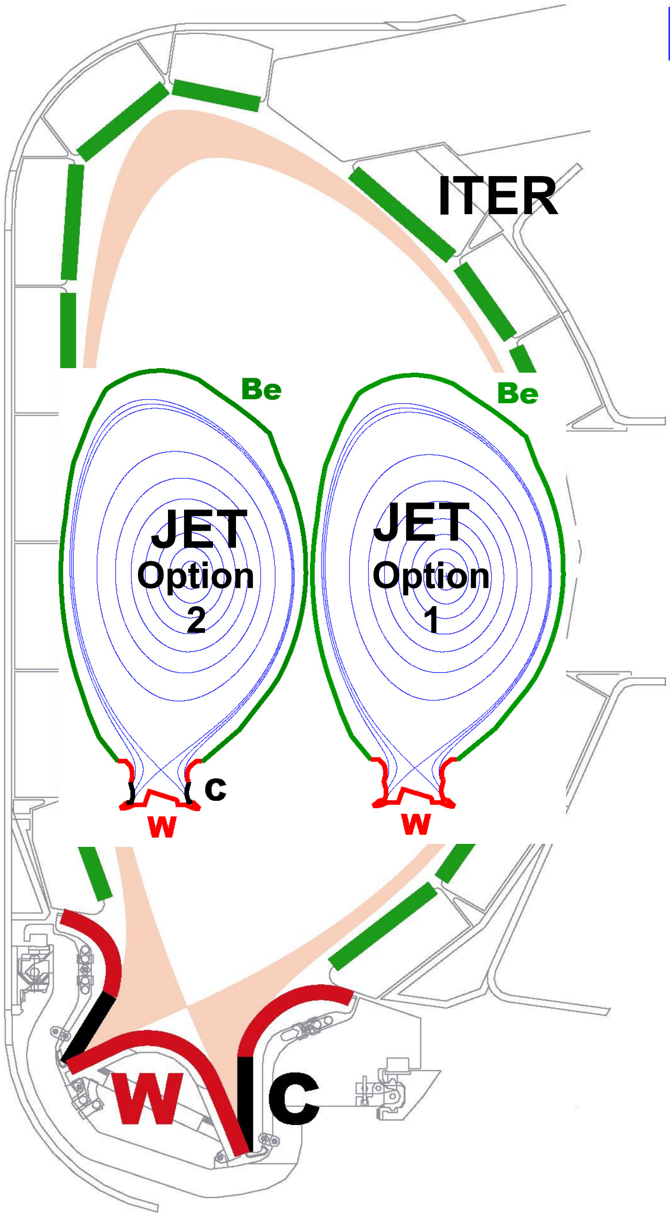
Installation in 2006:

- ITER-like ICRH antenna
- Conjugate-T on 2 pairs of ICRH antennas
- Part of magnetics
- 1 of 2 TAE antennas

EP2 : Proposed JET Programme 2007-2010



EP2: ITER-like Wall experiment



Main wall

- **Bulk beryllium** where possible

Divertor

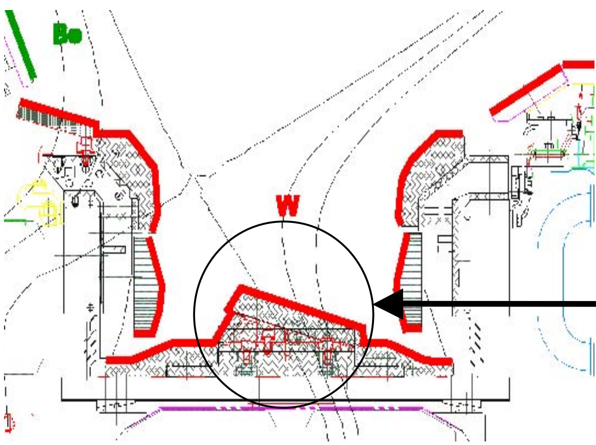
- Plan for **all W coated CFC**
  (Reference Option)
- *Fall-back Option:* ***CFC on targets***
- **Final decision on options in 2006**
  Depending on:
  ⇨ ITER needs
  ⇨ W Coating R&D outcome
  ⇨ Bulk W technology R&D

EP2: Project oriented R&D programme on W for the divertor

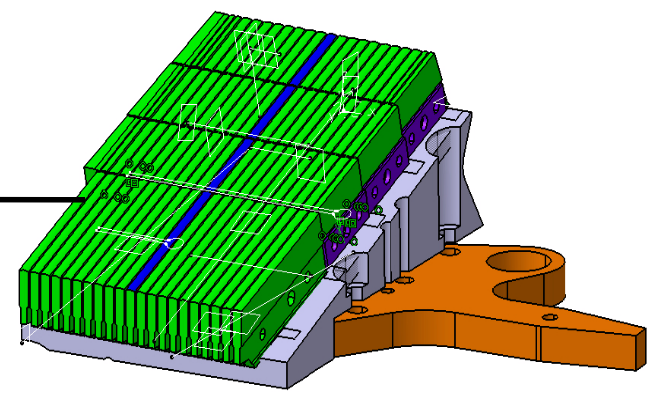
Depending on the position (different erosions), coatings with different thickness might be necessary.
Two coatings are being investigated:

Thin coatings: 4 & 10 μm

Thick coatings: ~ 200 μm

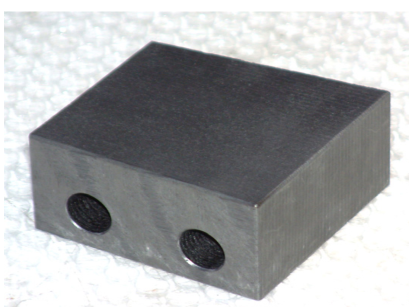


Coating performance and lifetime may be limiting, therefore R&D is performed on bulk W tile design

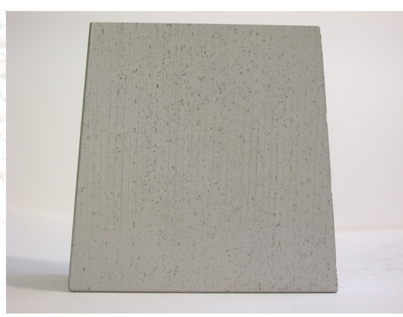


Lamellae concept:
W-lamellae on an Inconel basis

W-coated CFC sample
(4 μm W + ~ 0.3 μm Re interlayer)



before coating



after coating

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CEA | IPP | FZJ | ENEA | MEC | TEKES | VR

EUROPEAN FUSION DEVELOPMENT AGREEMENT

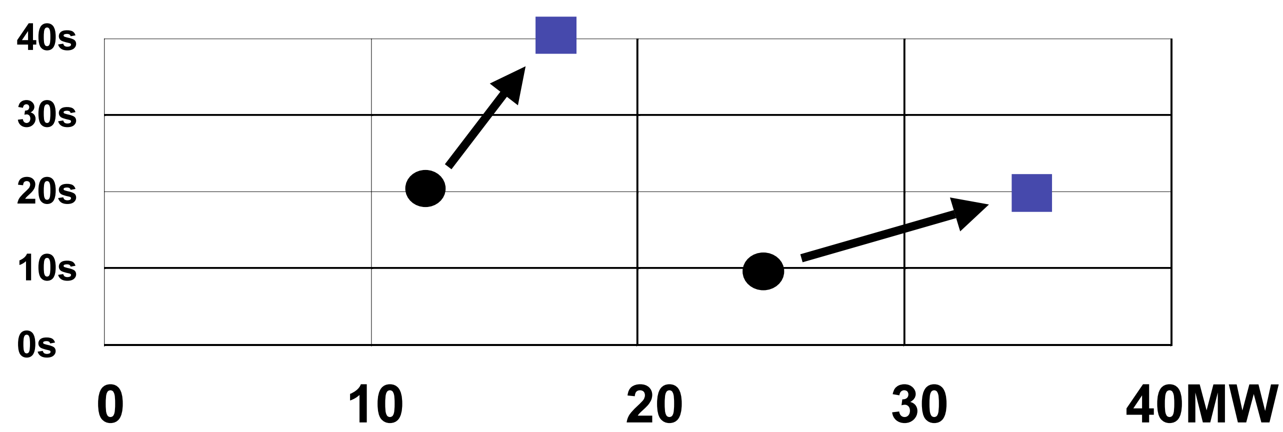
EP2: Increase Neutral Beam Power and Pulse Length

Motivation

- **Full exploitation of the pulse length capability of the JET machine**
- **Progress, in particular, the hybrid and advanced scenarios, which require full or partial current profile control**

The power increase is obtained by a combination of changes:

- **modifying all 16 ion sources to deliver a higher molecular ion yield, resulting in higher overall neutralisation efficiency**
- **increasing beam current from 60A to 65A**
- **increasing the voltage of the six remaining 80kV beam sources to 125kV**



UKAEA

■ >2008: Upgrade of Oct 4 and 8 to 16-17.5MW each, 20s

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

EP2: High frequency pellet injector for ELM control and deep fuelling

CEA UKAEA

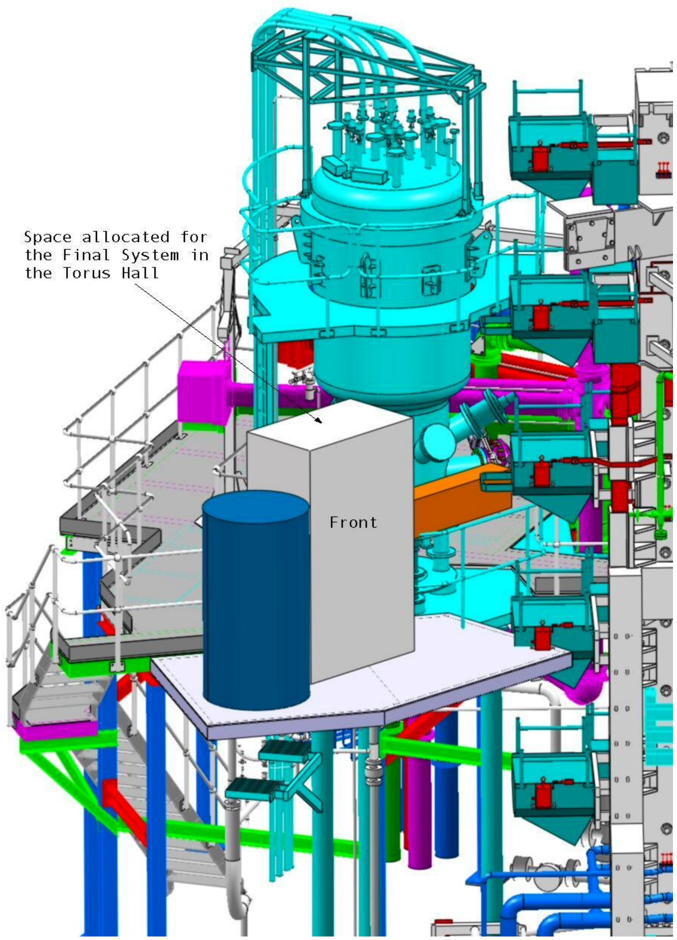
Motivation

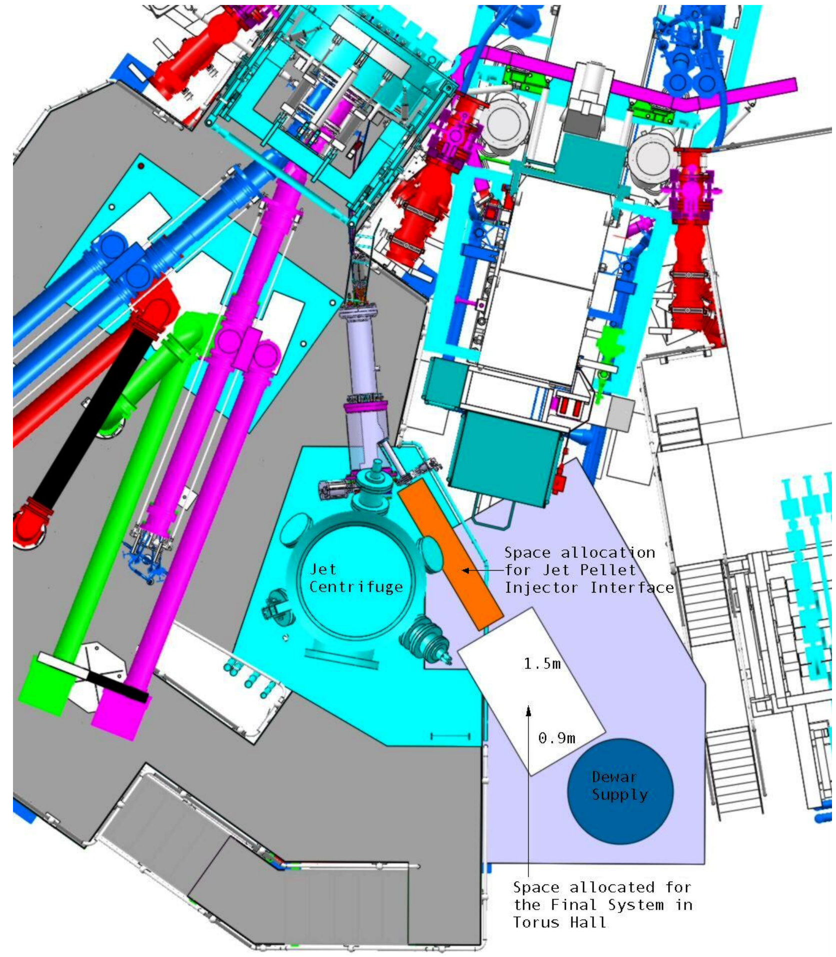
- ELM mitigation by full control of the ELM frequency
- Obtained with pellet injection frequency ~ 1.5 to 3 times the natural ELM frequency
- In JET the natural type-I ELM frequency is typically 10 Hz but can reach 20 to 25 Hz for high plasma densities.

llet sizePellet velocity on frequency< 2 $mm^3$50

Technical objectives of the new system

EP2: High frequency pellet injector for ELM control and deep fuelling (installation layout)





EP2: Diagnostics

Diagnostics for the ITER-like wall

- Edge and wall diagnostics (erosion, co-depositions, temperature. Same diagnostics as in EP1)
- Spectroscopy : Beryllium and Tungsten in core and edge plasma
- Upgrade of the top view IR-system (fast events in divertor: procurement of a new state of the art IR camera, 3mm at 50 _s, from AUG experience)
- Cellular Nonlinear Network technology (image processing applied to IR thermography)

FZJ UKAEA IPP ENEA

Diagnostics for the new pellet injector

- New fast camera (wide angle view) for ablation studies: at least 100 kHz, CMOS technology

CIEMAT HAS IST CEA

EP2: Diagnostics

Burning plasma diagnostics *(exploiting JET DT/DT-related capabilities)*

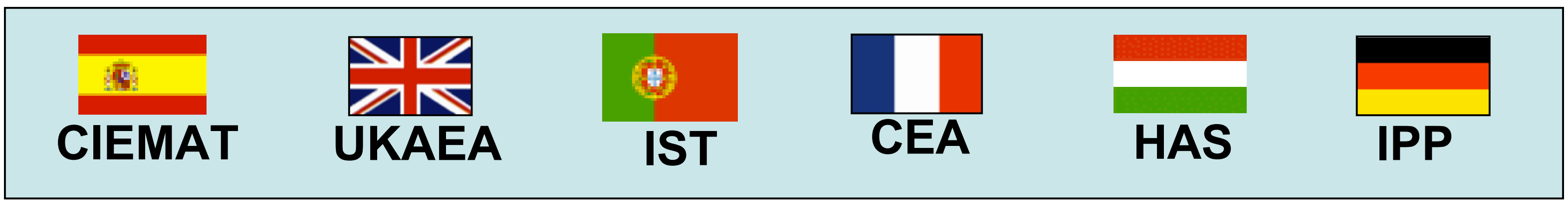
- Compact neutron spectrometer with organic scintillators
- Neutron measurements using artificial CVD diamond detectors
  (further developments of ITER-relevant technologies)
- Data acquisition systems for neutron & γ-diagnostic enhancements
- Upgrade of γ -ray spectrometers
- Neutron Attenuators for γ -ray cameras: vital for the survival of the camera in ITER conditions
- Neutral Particle Analyser detector development and upgrade
- UV measurements using single artificial CVD diamond detectors
- Radiation hard hall probes: ITER-relevant technology
- Fast wave reflectometer (tbc)

MEC | IST | UKAEA | ENEA | VR | TEKES | IPP-CR | Ukraine

EP2: Diagnostics

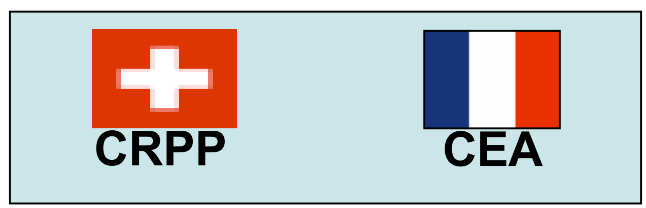
Profile (edge) and control diagnostics

- ECE extension (upgrade of the KK3 Heterodyne Radiometer)
- Edge LIDAR detector and digitiser upgrade: new oscilloscope and new detectors; objectives ≈ 1cm spatial resolution (equivalent to 6cm in ITER)
- Real time control related diagnostic upgrades: for magnetics
- Upgrade of Li-beam Intensity



Advanced Physics diagnostics

- Magnetics for MHD (tbc)



EP2: Plasma Control Upgrade (Vertical Stabilisation)

Motivation

Avoidance of ELM triggered Vertical Displacement Events

Practical benefits
❖Robust operation. Fewer leaks
❖Higher elongation

Operation at low/lower $\nu*$
❖Core $\nu*$ closer to ITER. Scaling ELM size with $\nu*$
ϖ Study of ablation/melting erosion with 1-2MJ ELMs

Impact on ITER
ϖ Understanding effect of ELM on boundary shape, vertical speed
ϖ Test of VS controller and design methodology for ITER

ENEA
UKAEA
CEA
IPP
IST

Conclusion

⇒ JET Scientific Capabilities enhanced by EP1 / Experimental Campaigns to start end November 2005

⇒ Second major enhancement programme under way since the start of EFDA (EP2)

Objectives:

- ⇒ scientific and technological tests in preparation of ITER operation
- ⇒ reduce costs and optimise operation on ITER

Target: installation in 2008 for operation from 2009 onwards

⇒ Quality of US contributions to EP1 highly appreciated

EP2 offers a number of opportunities for further US-EU collaborations