Francesco Romanelli
on behalf of EFDA-JET contributors

Overview of the JET results with the ITER-like Wall

Acknowledgments:
L. Horton, F. Rimini, G. Sips,
A. Malaquias and JET Task
Force Leaders

24th Fusion Energy Conference San Diego, 8-13 October 2012

EFDA JET

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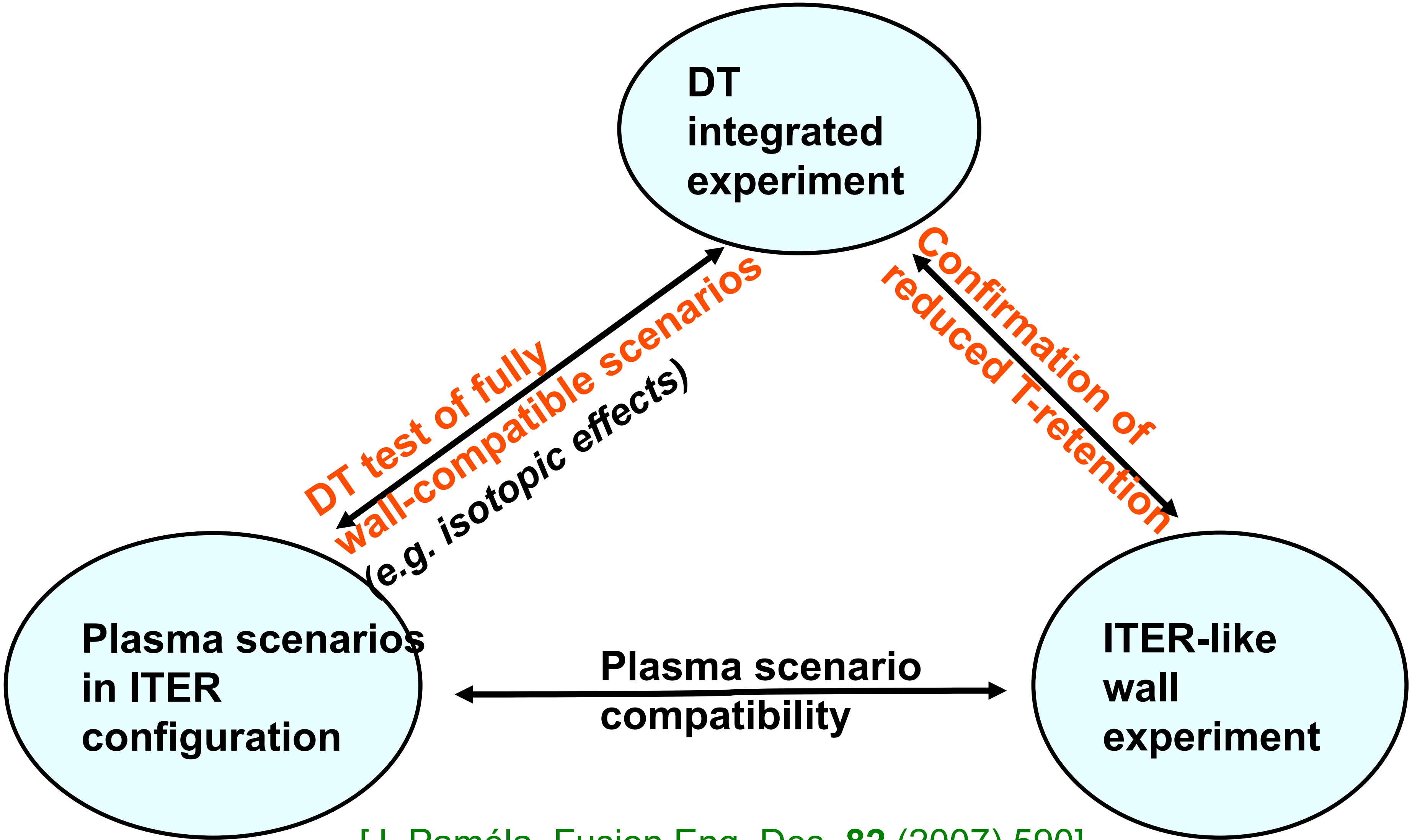
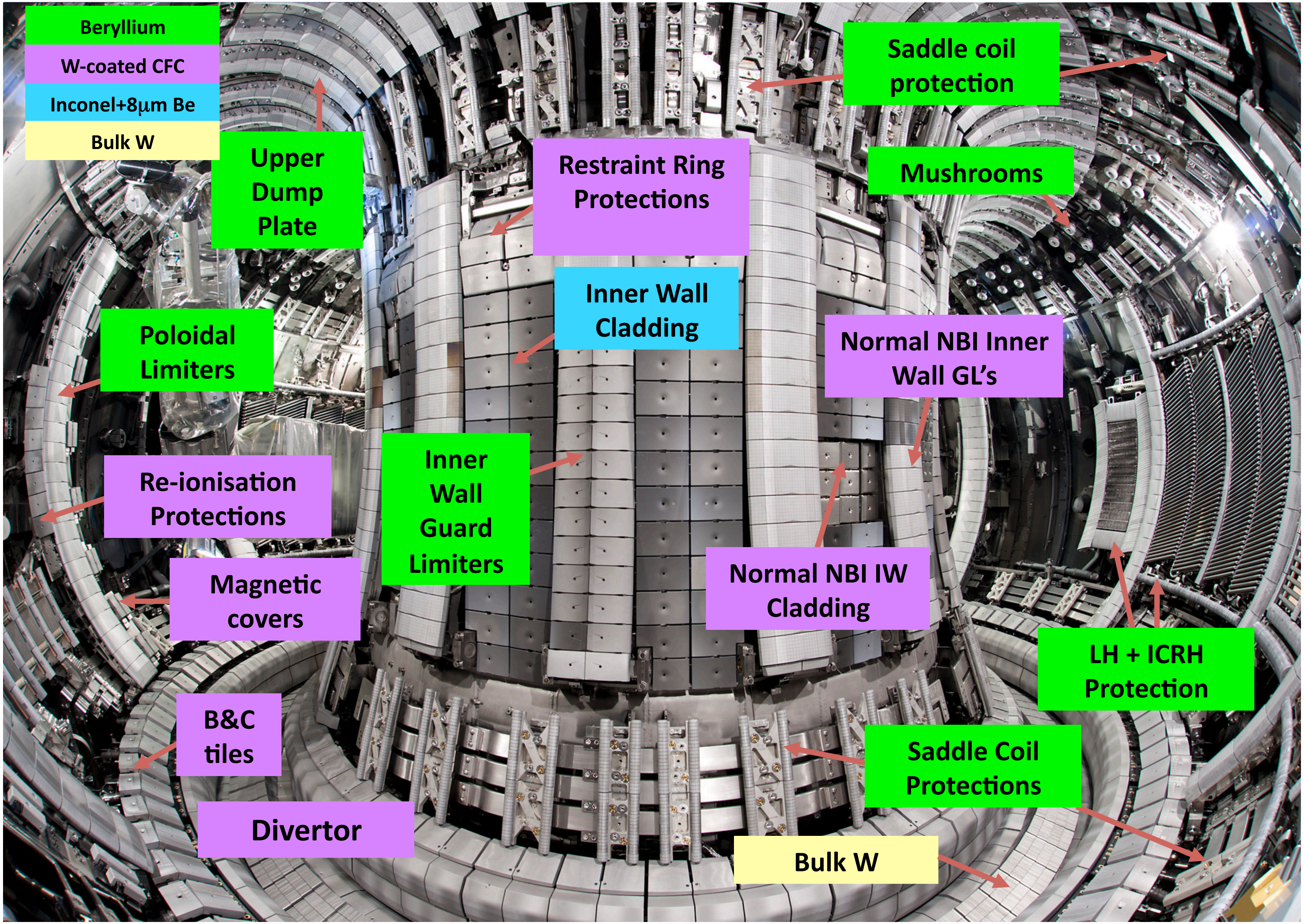
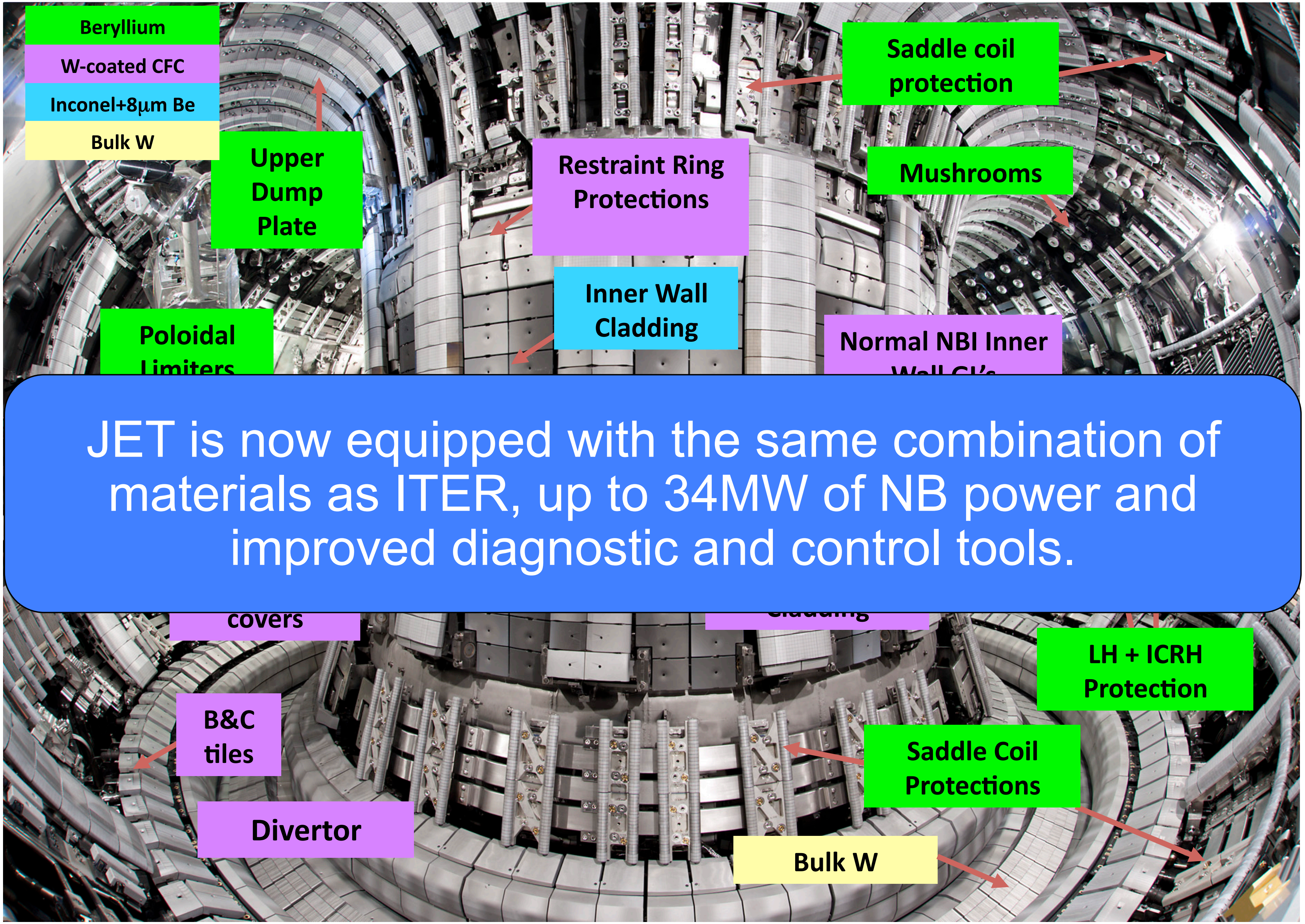
The JET programme in support of ITER has started the exploitation phase



[J. Paméla, Fusion Eng. Des. **82** (2007) 590]



ILW = 2880 installable items, 15828 tiles (~2 tonnes Be, ~2 tonnes W)



JET is now equipped with the same combination of materials as ITER, up to 34MW of NB power and improved diagnostic and control tools.

ILW = 2880 installable items, 15828 tiles (~2 tonnes Be, ~2 tonnes W)

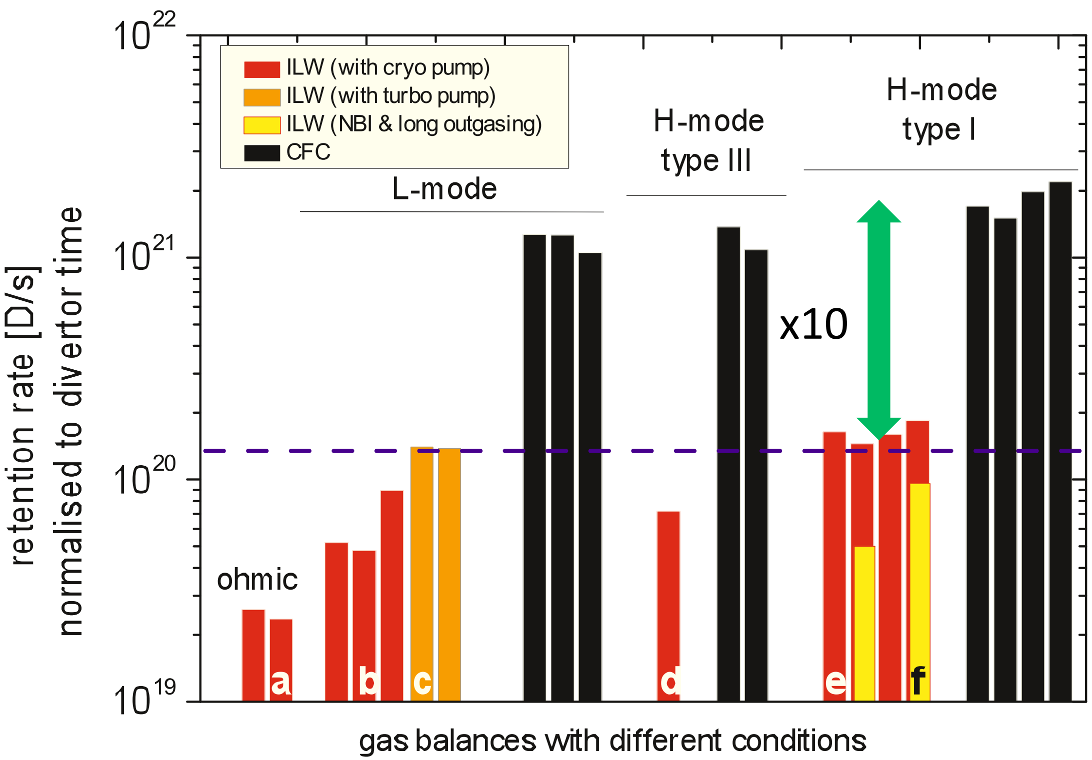
Outline

- JET programme in support of ITER
- Operation of JET with the ITER-like wall (ILW)
  - Fuel retention
  - Plasma breakdown
  - Impurity content
  - Disruptions
  - PFCs power handling and protection
- H-mode physics in an all-metal environment
- Conclusions and perspectives

Fuel Retention with the ILW is in line with the ITER requirements

- Measured fuel retention is more than an order of magnitude lower with the ILW, consistent with predictions made before the wall was installed.

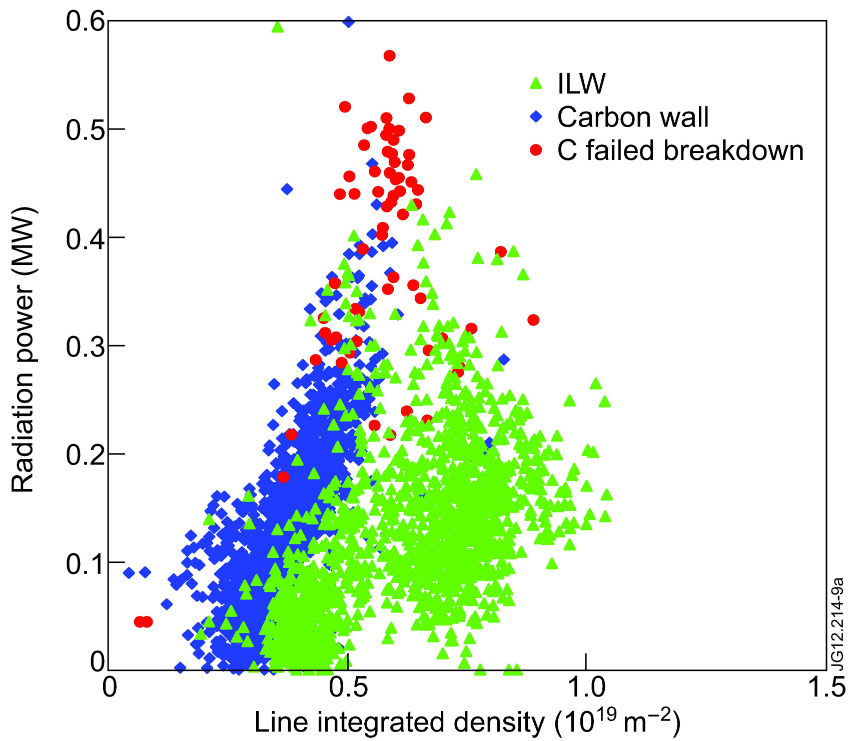
- Residual retention consistent with co deposition in Be layers.



[Brezinsek, EX/4-1]

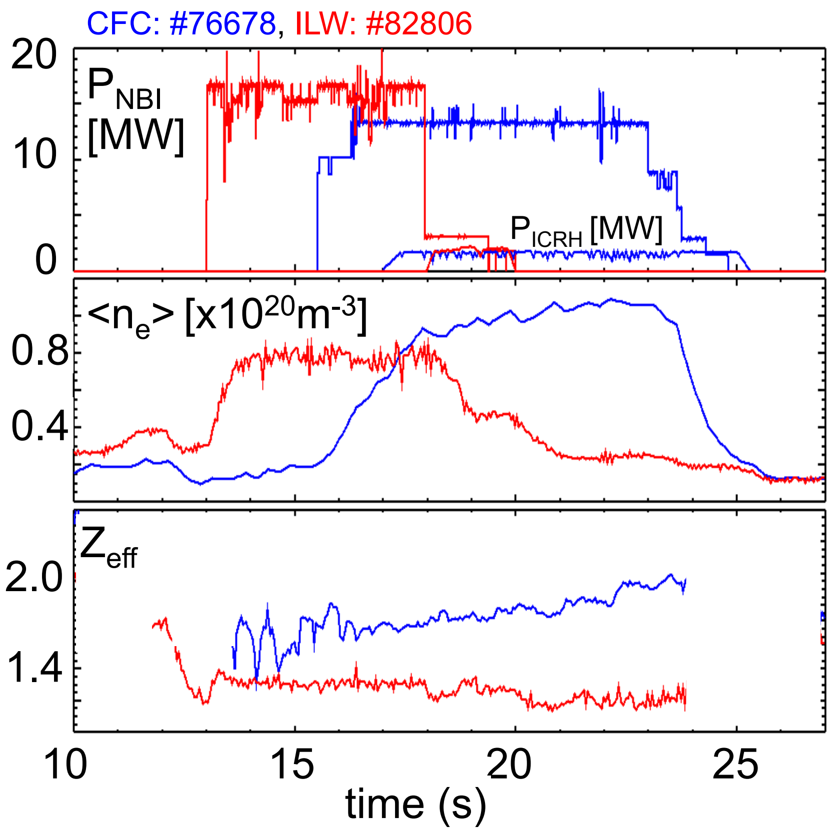
Better wall conditions with the ILW lead to more robust plasma breakdown

- 1MA/15s plasmas established at the first attempt during the 2011 restart.
- Non assisted breakdown demonstrated down to 0.35V/m (ITER value).
- Lower radiation level at higher density achieved making the breakdown more robust.
- Unlike the C-wall, no de-conditioning event following disruptions have been observed with the ILW. No need for GDC or Be evaporation during operation



[de Vries, EX/4-2]

ILW plasmas exhibit lower Z_{eff} than C-wall plasmas



[Groth, TH/3-1]

[Mayoral, EX/4-3]

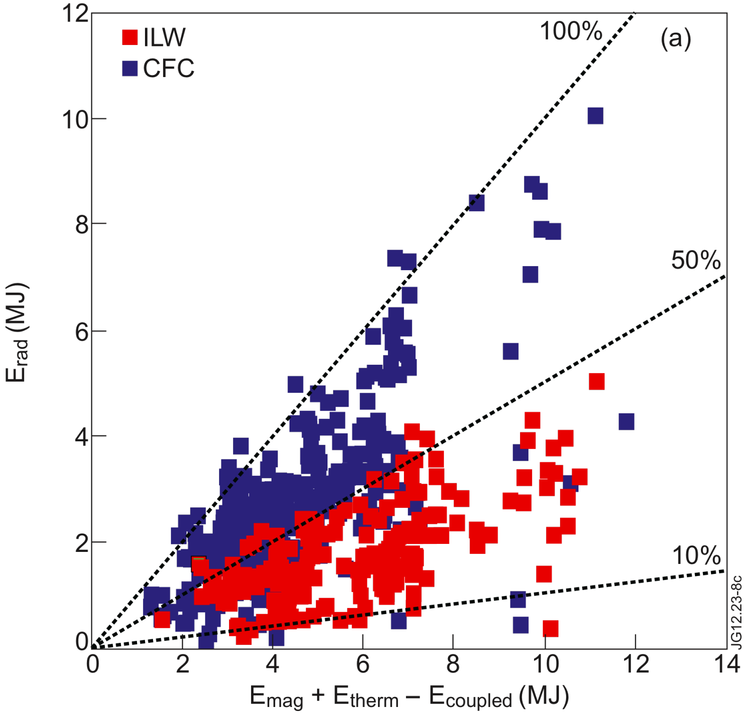
[Puetterich, EX/P3-15]

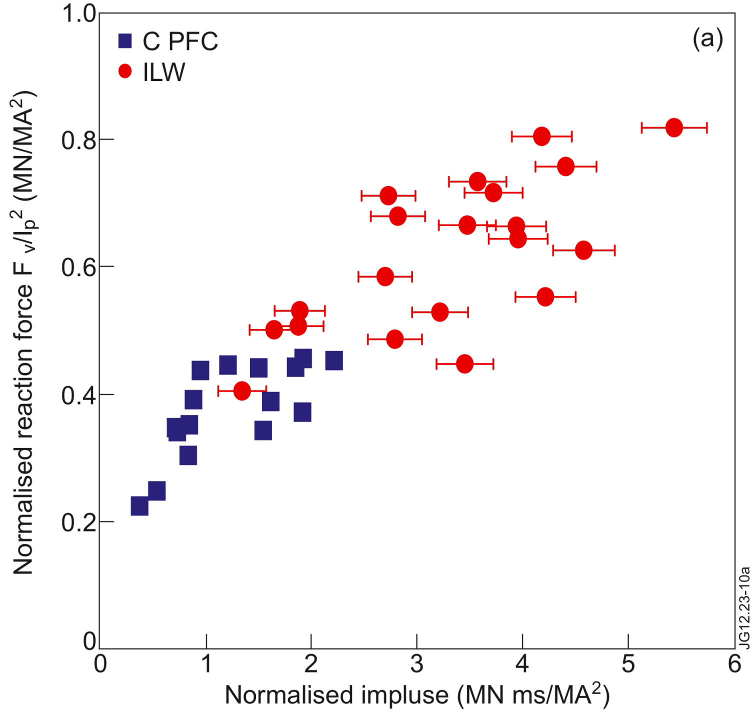
[Coenen, EX/P5-4] [van Rooij, EX/P5-5]

- H-mode plasmas typically have Z_{eff} ~ 1.2-1.4
- Carbon concentration decreased by a factor 20. Beryllium now the dominant intrinsic impurity.
- Beryllium and tungsten erosion are consistent with physical sputtering
- Inner/outer divertor legs detach at the same upstream density and 30% below the L-mode density limit.
- Higher W concentration observed with ICRH but sources not yet identified

Massive gas injection required to mitigate disruptions with the ILW

- The dynamics of disruptions are very different with the ILW
  - ➢ Higher plasma purity ➞ lower radiation during disruption
  - ➞ slower current quench
  - ➞ higher heat loads and halo currents
  - ➞ higher reaction forces on the vessel
-

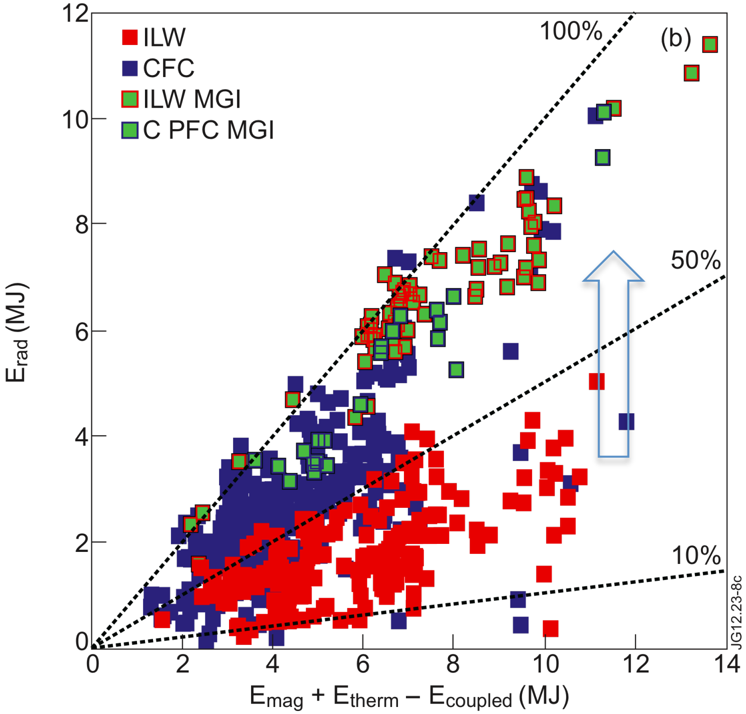


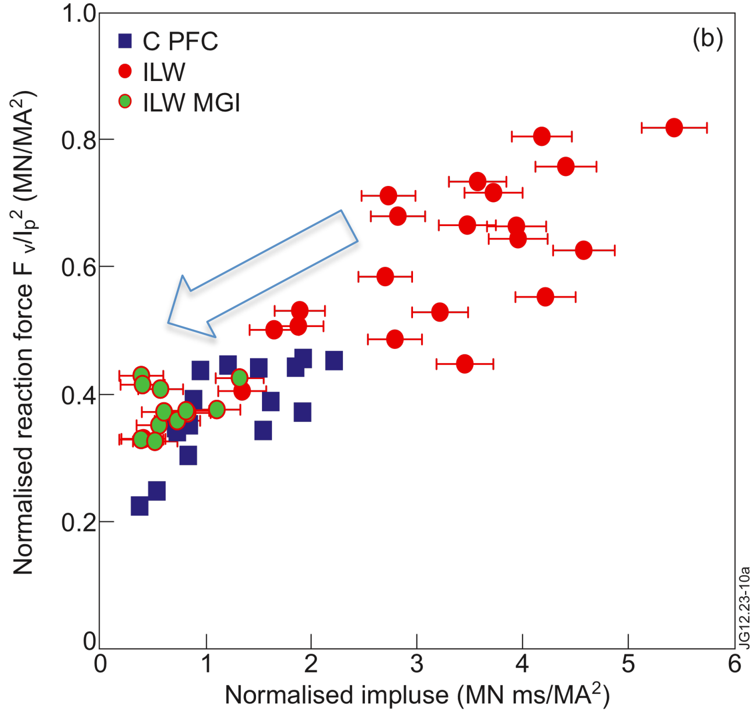


[Lehnen, EX/9-1, Murari EX/P8-4, Plyusnin EX/P8-5]

Massive gas injection required to mitigate disruptions with the ILW

- Massive gas injection as a disruption mitigation tool is now mandatory for JET experiments at or above 2.5 MA.
- With the mitigation, the forces and power loads resulting from disruptions are returned to the level observed with C wall





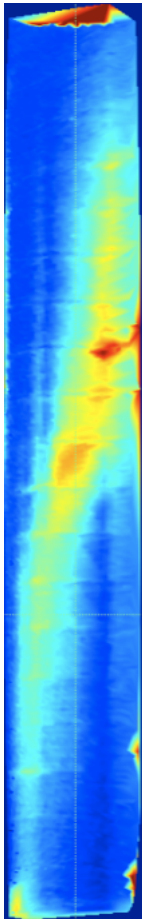
[Lehnen, EX/9-1, Murari EX/P8-4, Plyusnin EX/P8-5]

Component Power Handling have been confirmed by initial ILW operation

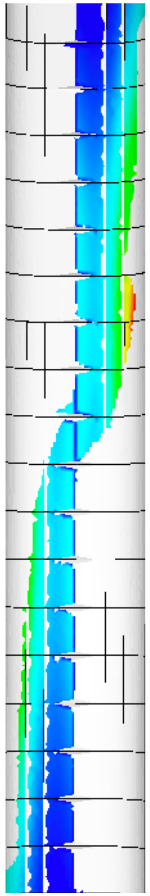
- Careful shaping of the Be limiters validated
- Details of the measured and calculated power footprints are being compared: limiter & plasma model

➢ **Validation for ITER**

- Integrated protection system for the ILW implemented with CCD IR cameras covering 66% of the wall and 43% divertor
- Some local damage to due off-normal events and prolonged heated limiter tests



Experiment



Model (PFCFLUX)

[Nunes, FTP/2-1Rb]

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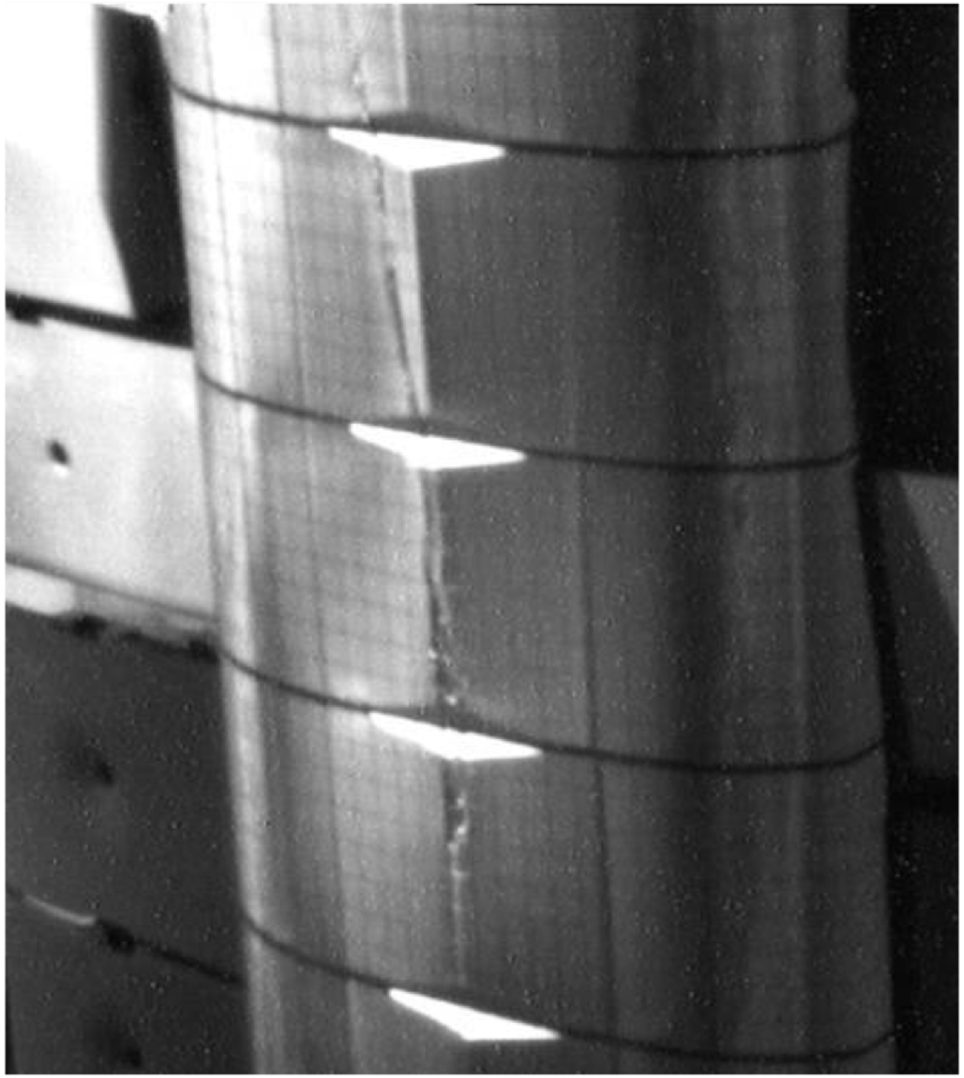
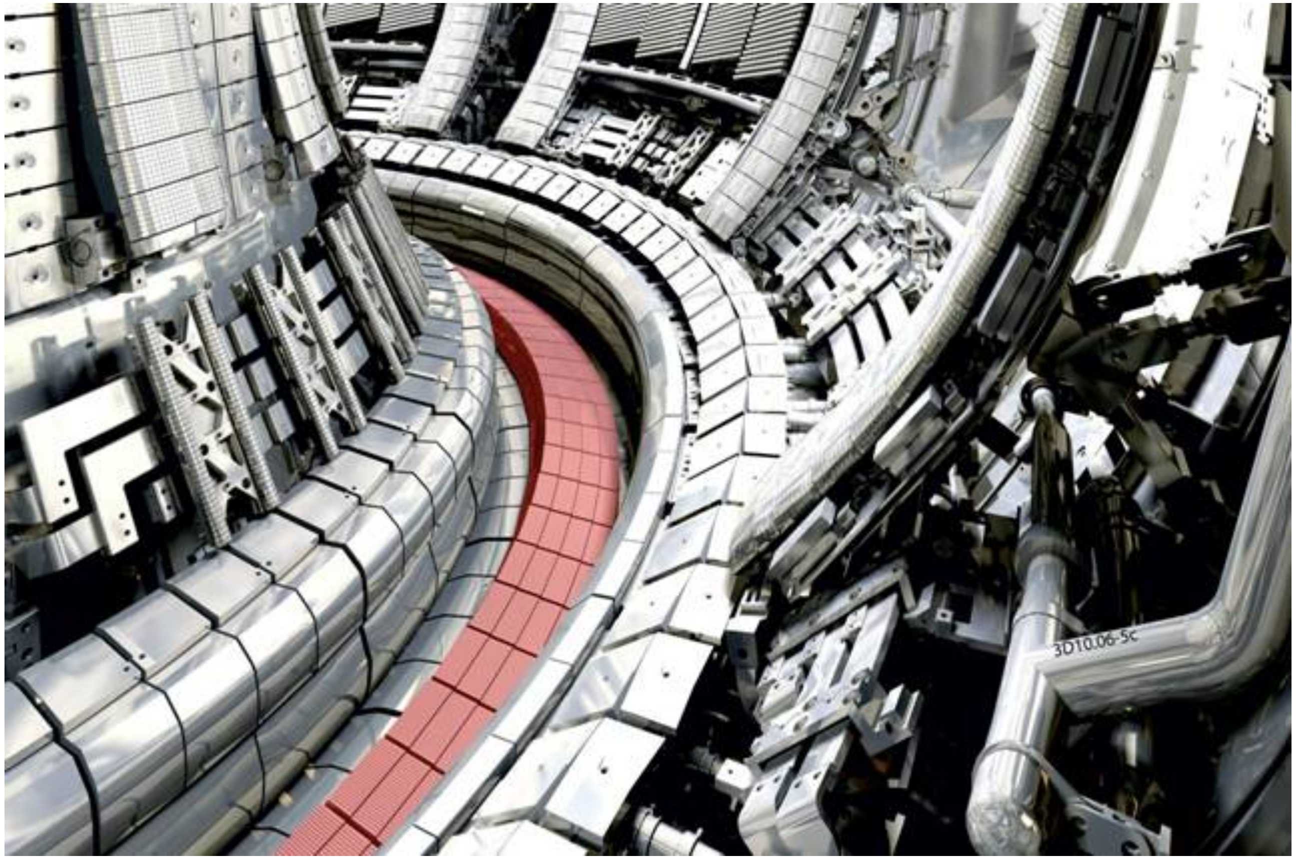


[Nunes, FTP/2-1Rb]

W divertor successfully tested

The bulk tungsten divertor is designed for a maximum local temperature of the plasma-facing tungsten of 2200° C and a maximal energy deposition of 60 MJ/m^2

[Mertens, EX/P5-24]



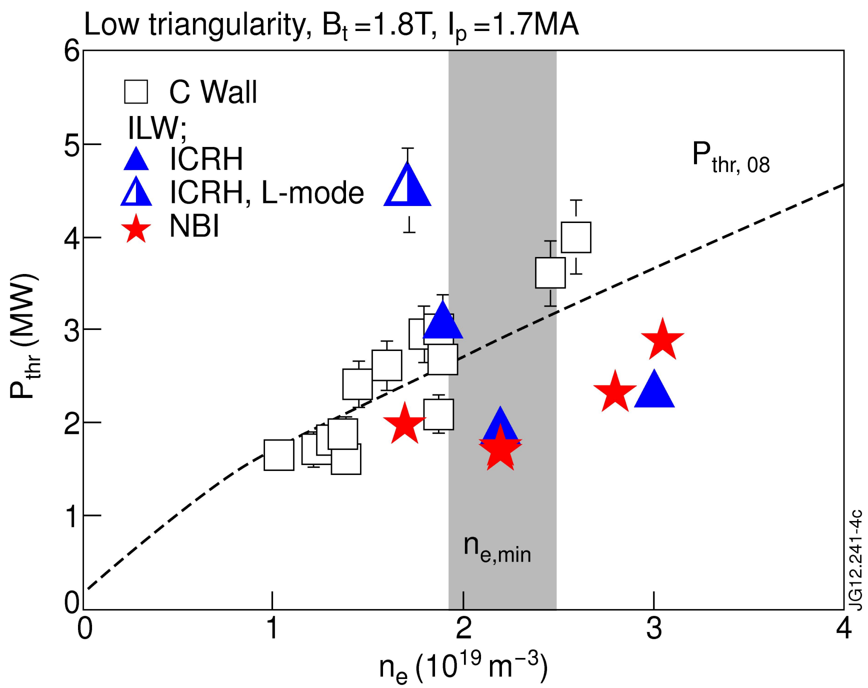
Routine operation performed at 30MJ/m^2 and T_{surf} up to 1000° C.

Good agreement with the model calculation

Outline

- JET programme in support of ITER
- Operation of JET with the ITER-like wall (ILW)
- H-mode physics in an all-metal environment
  - L-H power threshold
  - Baseline H-mode scenario
  - Hybrid H-mode scenario
  - ELM mitigation
- Conclusions and perspectives

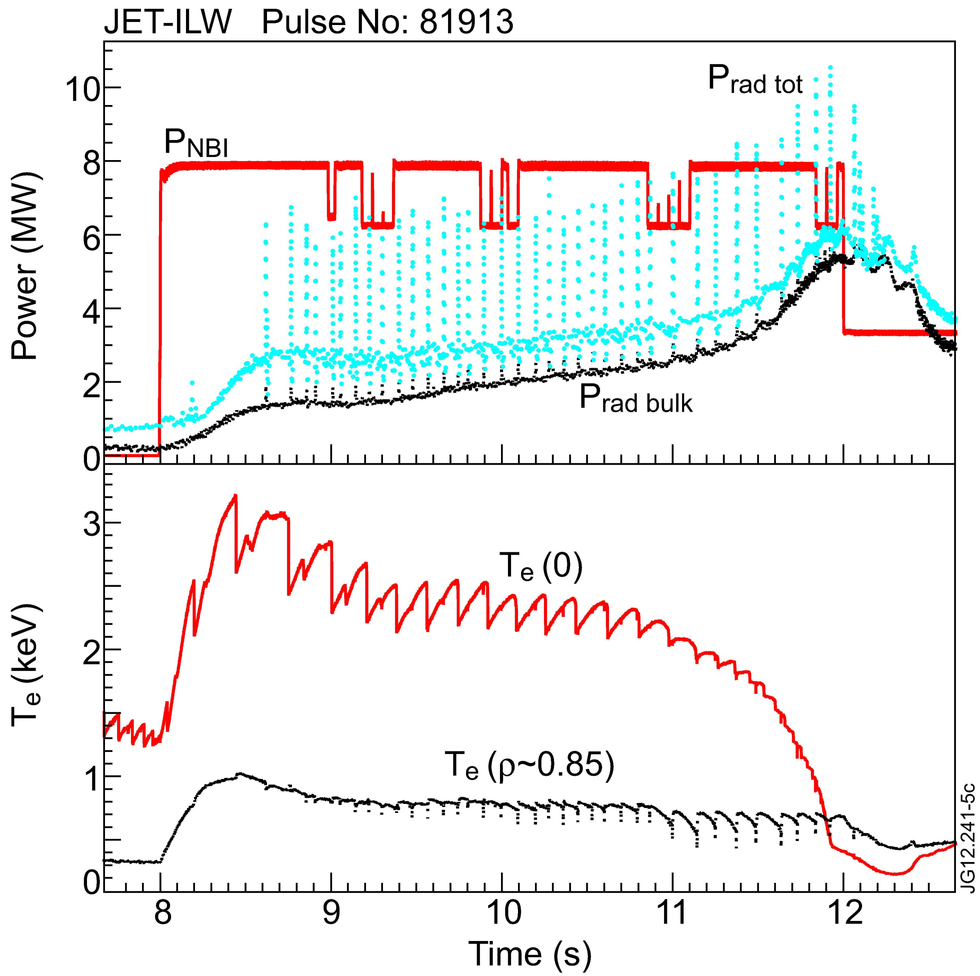
L-H power threshold not consistent with the ITPA scaling



- With the old C-wall P_{thr} was consistent with the multi-machine ITPA scaling down to low density.
- With the ILW P_{thr} is 30% lower at high density while it increases at low density below a critical value (as with the MkII-GB).
- Same trend after subtracting radiation inside the separatrix

[Beurskens, EX/P7-20]

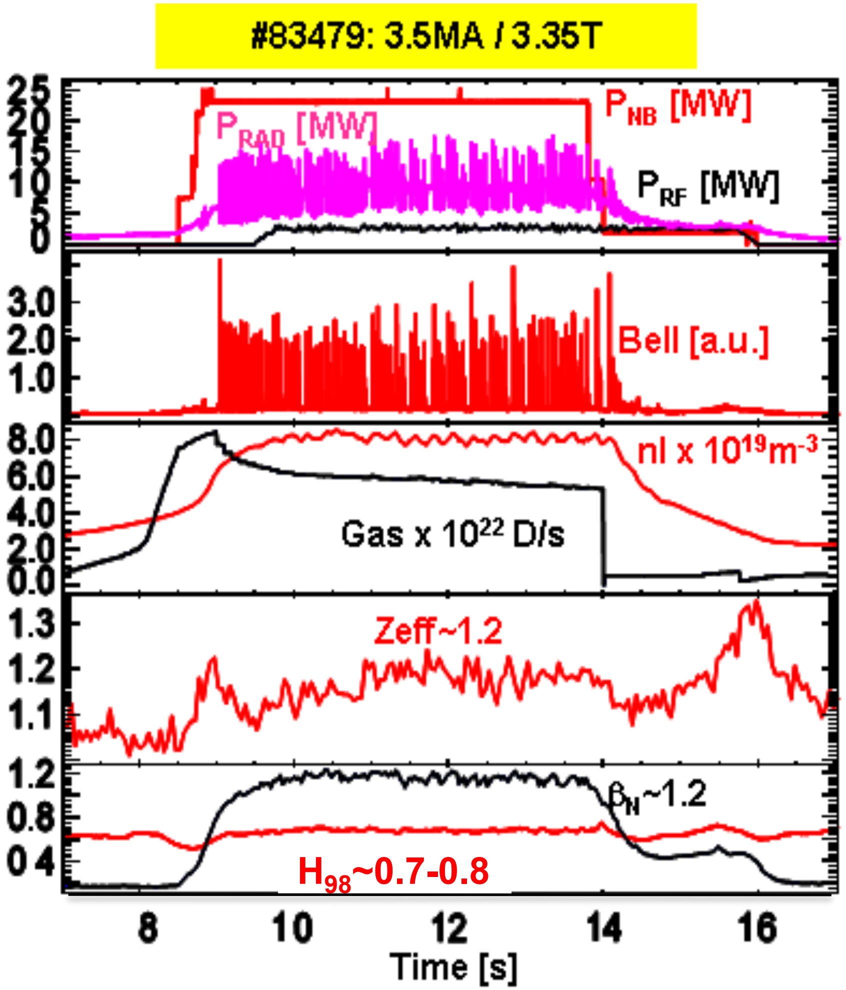
Establishing stationary H-mode requires avoiding W accumulation



- In H-mode, below a certain ELM frequency the tungsten density peaks in the plasma centre, resulting in a loss of sawteeth and a central temperature collapse.

[Joffrin, EX/1-1]

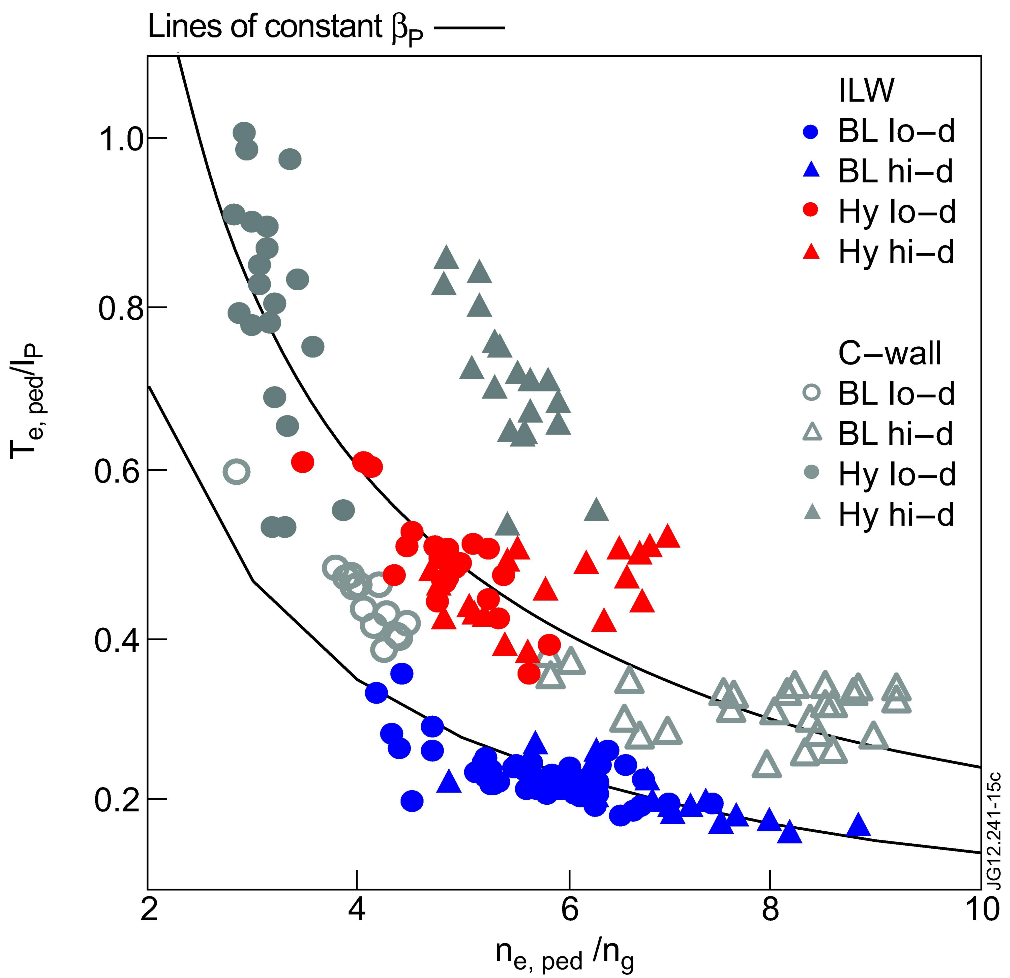
Stationary H-mode established with the ILW up to 3.5MA and 27MW



[Joffrin, EX/1-1]

- •Injected power corresponds to 1.5 P_{th}
- •Strike point sweeping implemented to reduced the temperature on the bulk tungsten tile (<1200°C)
- •Strong gas fuelling used to achieve high frequency ELMs and avoid W accumulation.
- •Confinement strongly affected by the gas. H_{98}~0.7-0.8

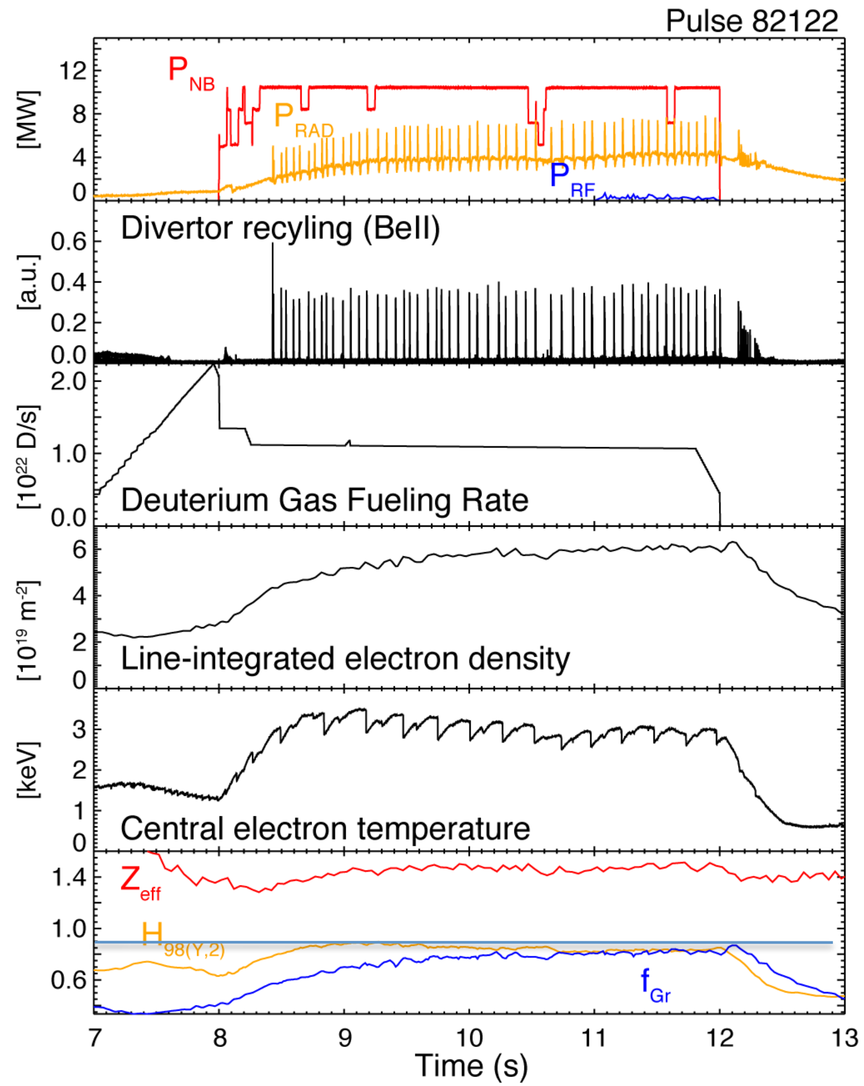
Reduced H-mode confinement is associated with the edge transport barrier



[Joffrin, EX/1-1]
[M. Beurskens, Ex/P7-20]

- The reduced confinement is due to lower pedestal temperatures with the ILW and is propagated across the plasma by transport stiffness
- Largest difference in pedestal properties observed at high δ.
- Understanding and improving these initial results is a priority for future experiments

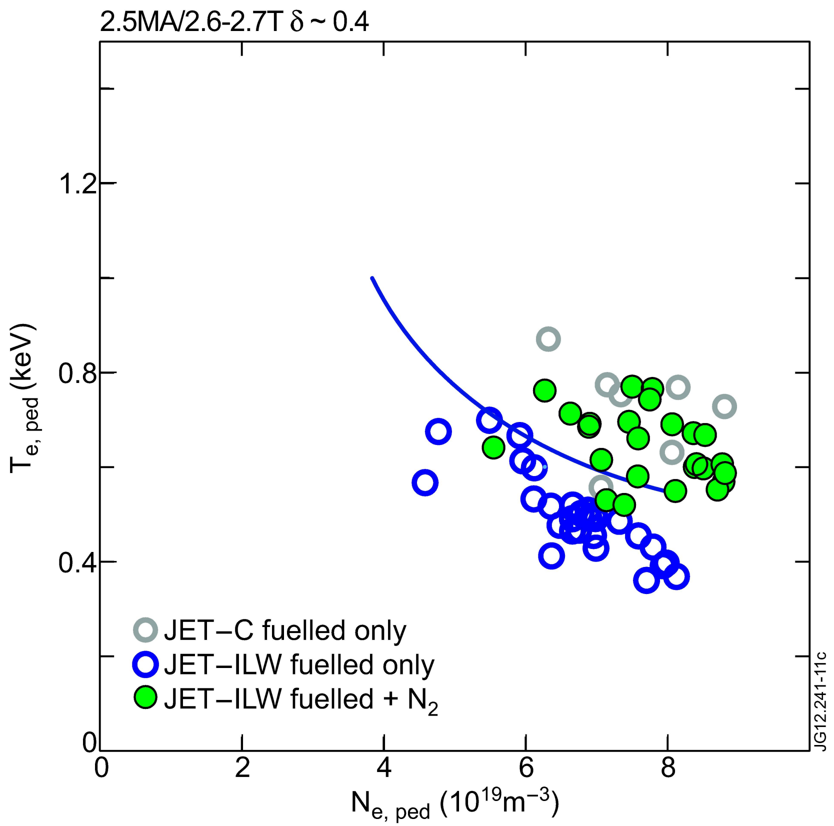
To preserve H_{98}, frequent ELMs and moderate fuelling must be achieved simultaneously



- When high-frequency Type-I ELMs are achieved using high input power (rather than using high gas fuelling rate) confinement improves.
  - H_{98}~0.9
  - f_{Gr} ~ 0.9
  - Z_{eff} ~ 1.2 – 1.4

[Joffrin, EX/1-1]

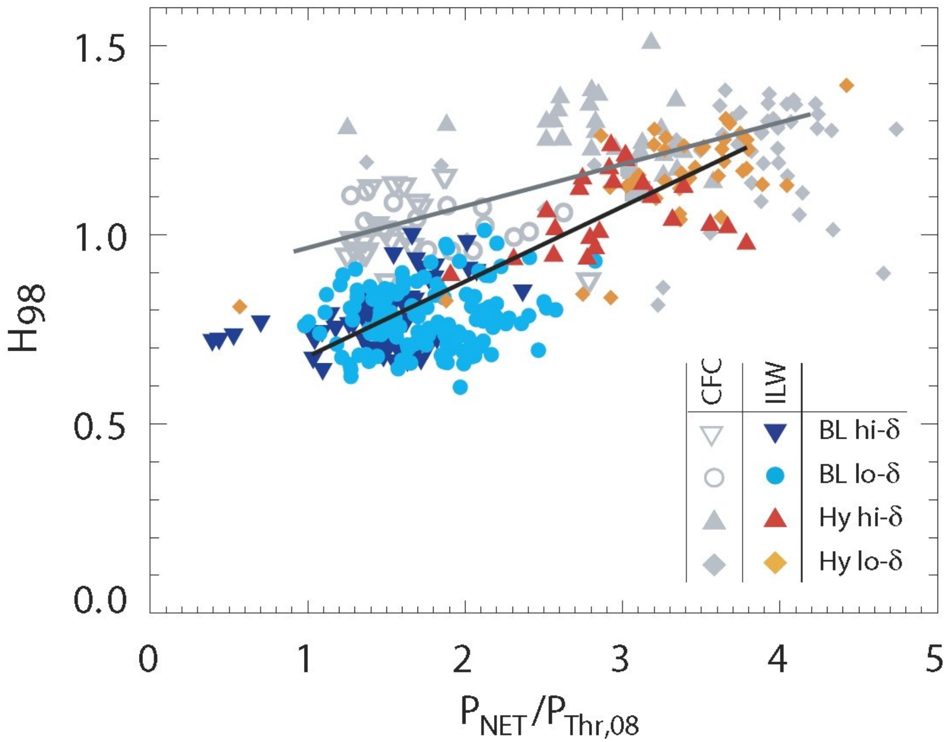
Nitrogen seeding leads to increased confinement



- Nitrogen seeding has been tested primarily in high δ configurations
- Increased pedestal temperature & density, decreased ELM frequency lead to increased confinement!
- This effect not observed in low δ
- Plasmas still prone to impurity accumulation.

[Giroud, EX/P5-30]

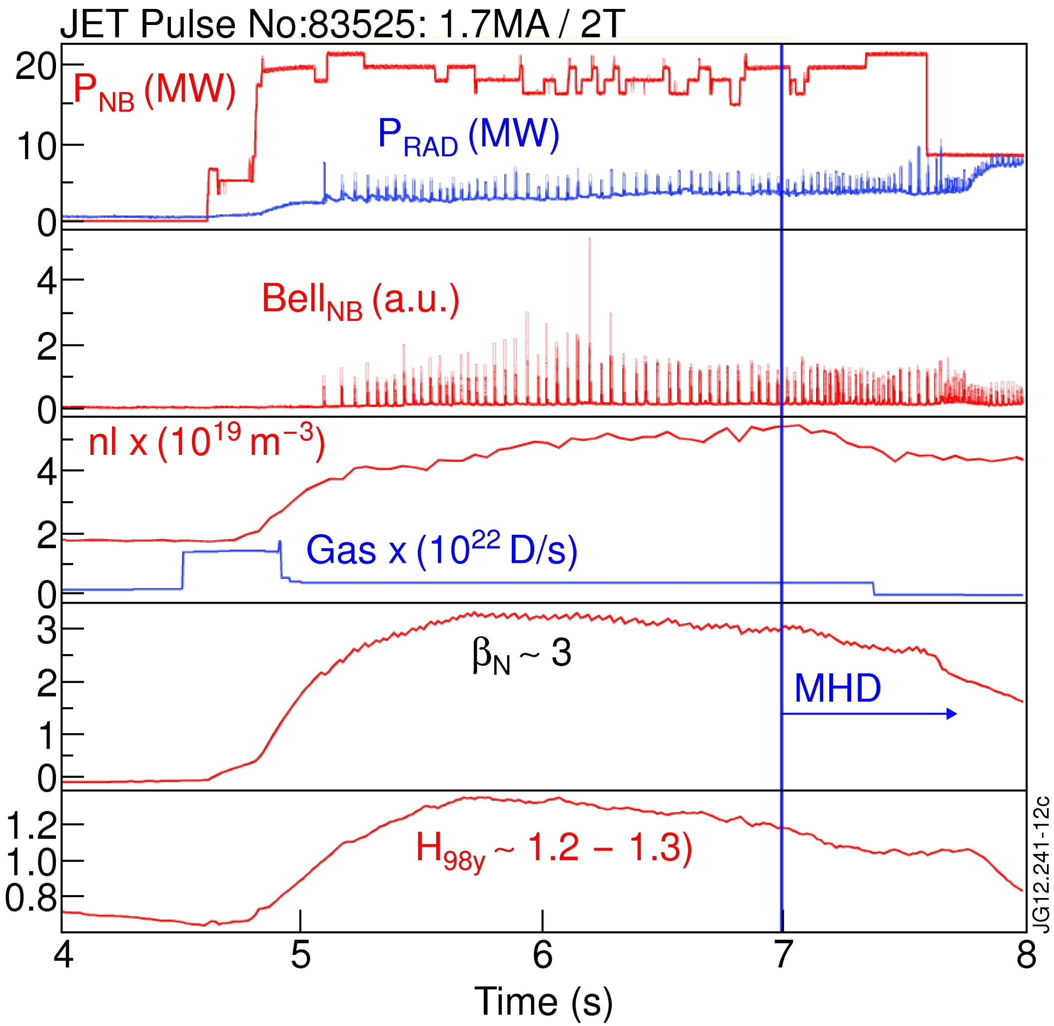
To recover H_{98} more input power is required



[Beurskens, EX/P7-20]

- Up to ~2.5MA, H_{98}~1 can be achieved at P_{net}/P_{thr}>2
- However, input power above 30MW could not be used during the last Campaigns.
- Up to ~40MW will be used in the next Campaigns to test whether H_{98}=1 can be recovered at high current.

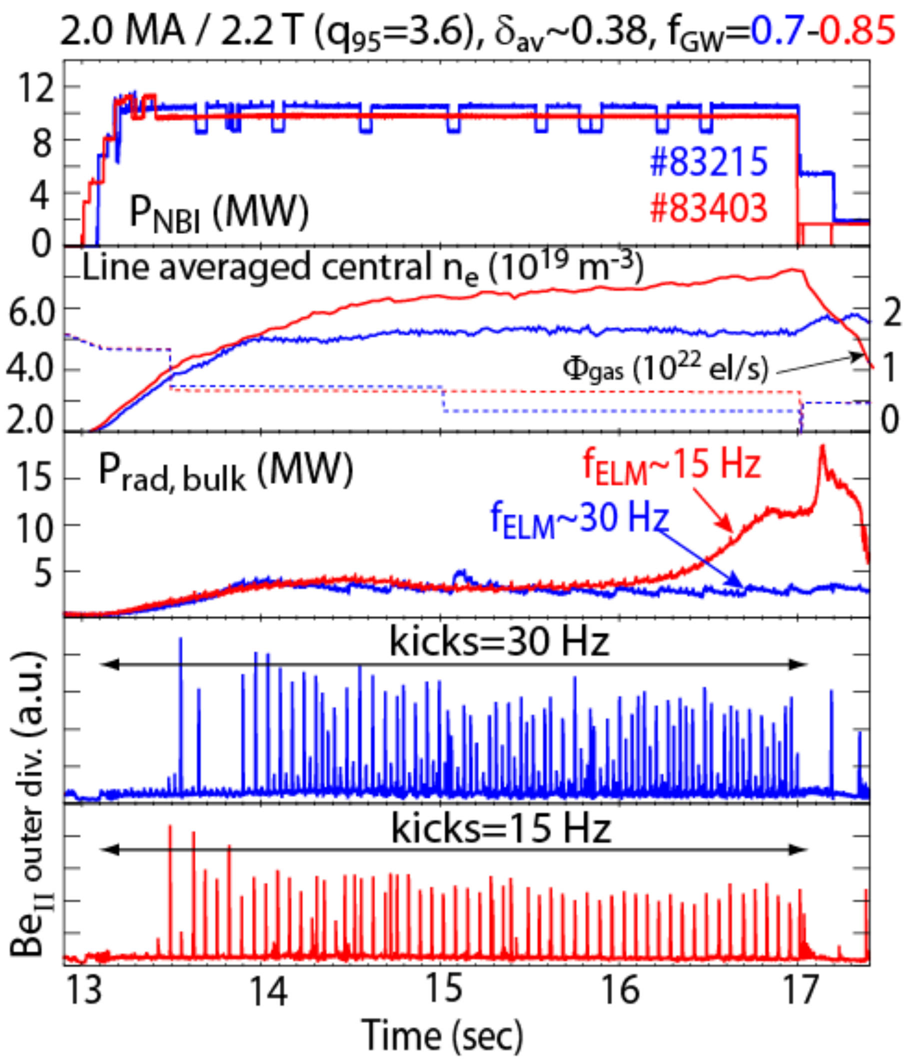
Hybrid H-modes have been re-established with the ILW



- C-wall hybrid discharges in high δ configurations have been transiently reproduced.
- **H_{98}~1.2-1.3 at β_N~3 achieved, similar to the C-wall**
- Duration of high performance phase typically limited by MHD

[Joffrin, EX/1-1]

ELM pacing



[Lang PD, de la Luna, EX/6-1]
[Liang, EX/P4-23]

- **Vertical kicks:** increase in f_{ELM} can help in reducing W core accumulation in gas fuelled H-mode plasmas in JET with Be/W wall

- Planned to be used routinely in 2013

- **Pellets:** ELM sustainment in baseline scenario – *"fuelling size"* from LFS at 15 Hz
  f_{ELM} can be increased 4.5x,

- Good launcher performance, guide tube improvements planned for 2013

Outline

- JET programme in support of ITER
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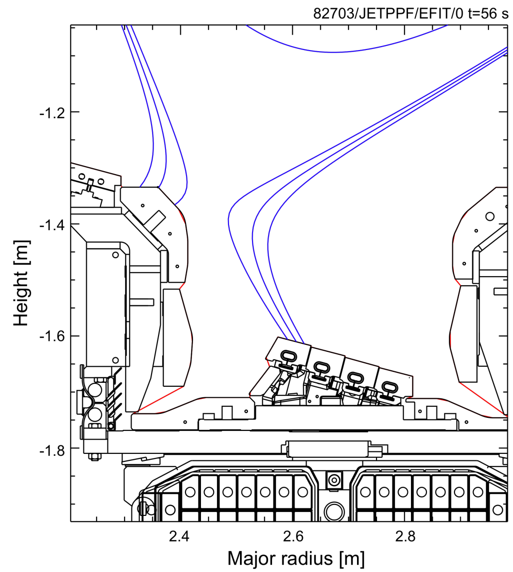
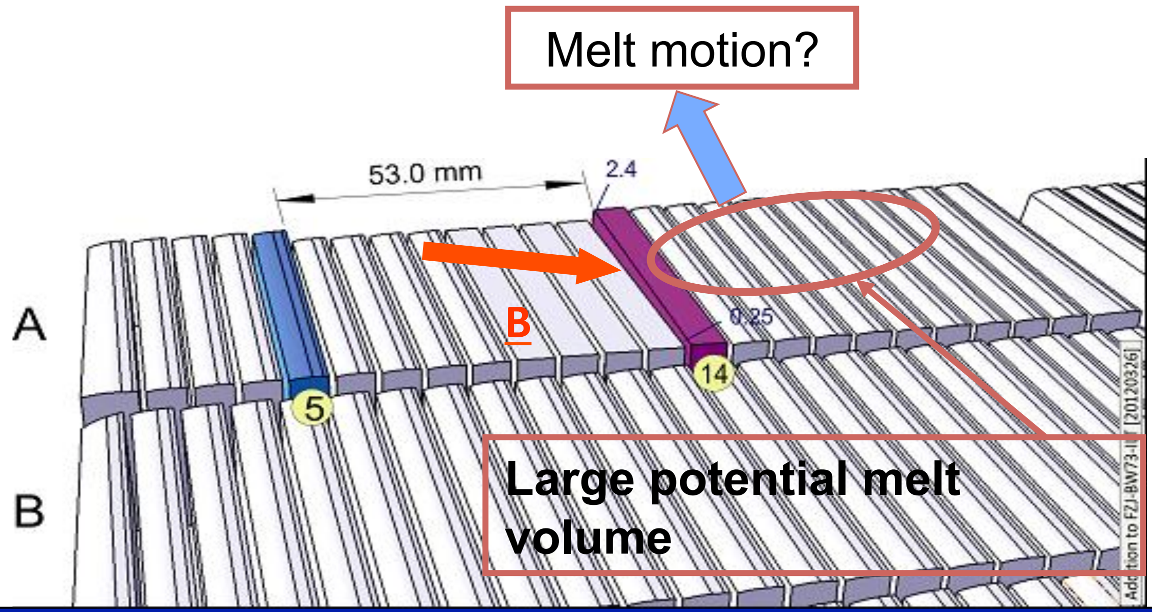
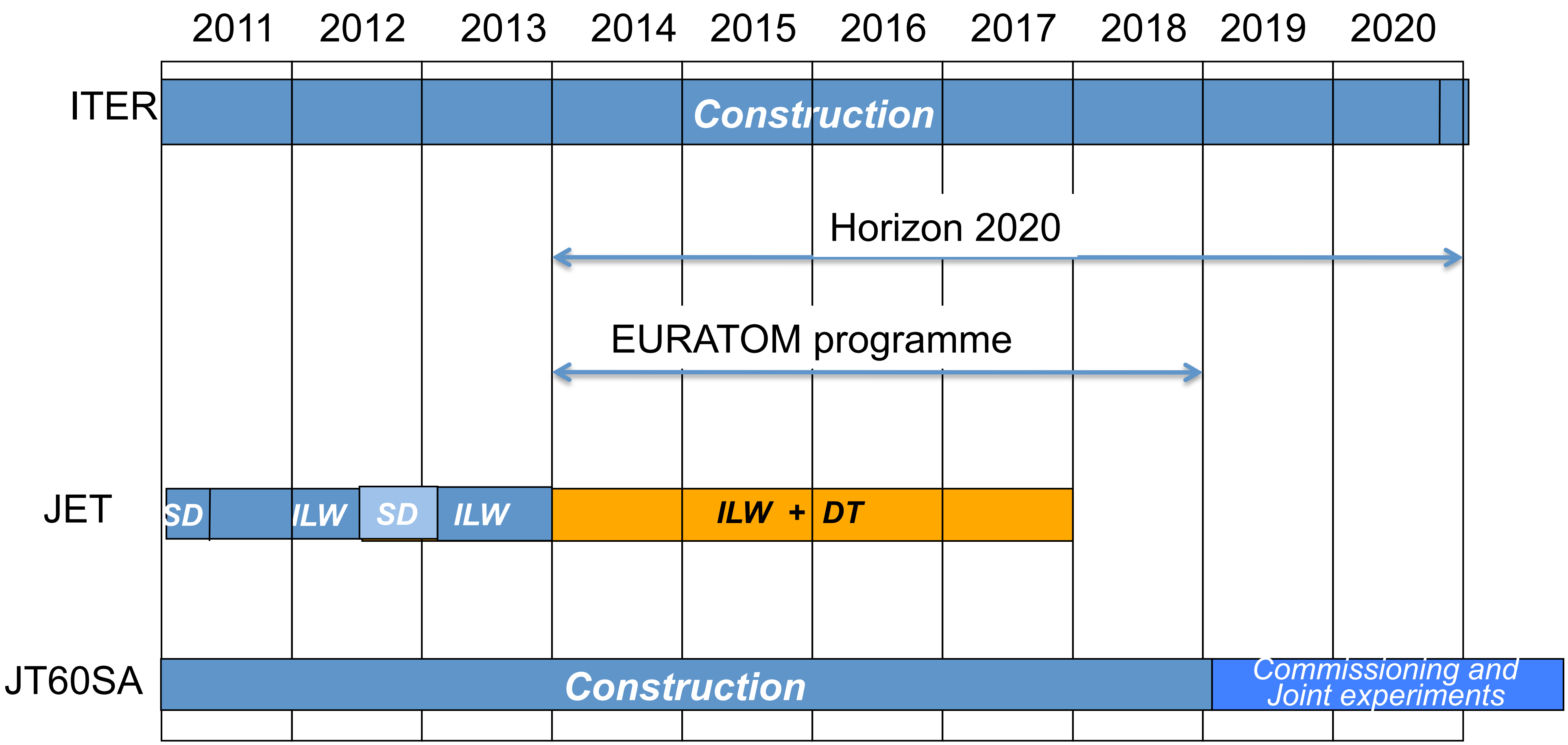
- H-mode physics in an all-metal environment
- Conclusions and perspectives

- 2013 JET Campaigns have the main goal of establishing
  - Operation after shallow W melt events
  - Optimization of H-mode performance





Long term JET plan depend on the success of the internationalization process*



SD = Shut down

Launched **Proposed** *Under further discussion*

* *see A. Wagner Panel on Strategic Orientation*

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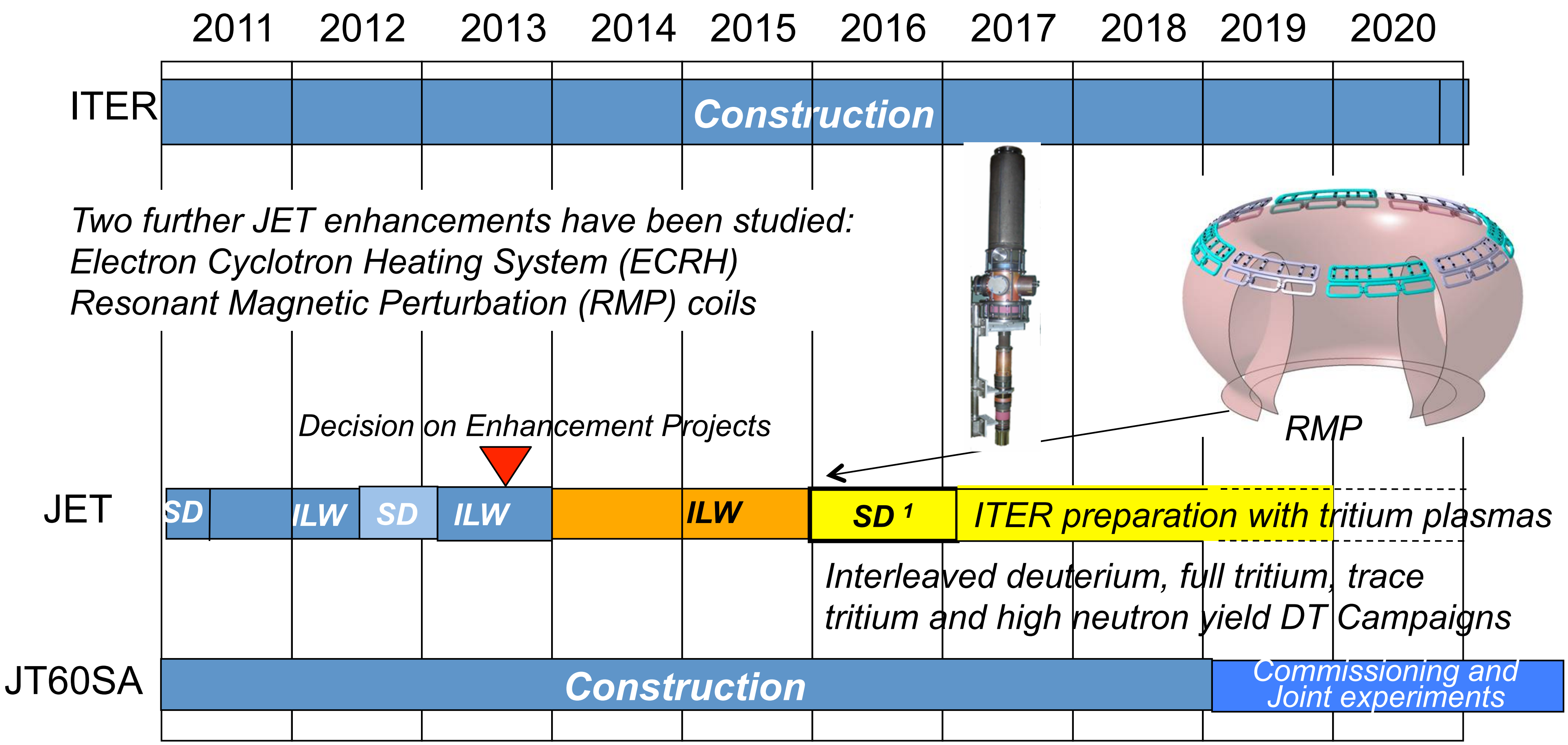

SD = Shut down **Launched** **Proposed** *Under further discussion*

[1] *Exact duration to be quantified*

** see A. Wagner Panel on Strategic Orientation*

Long term JET plan depend on the success of the internationalization process

JET ELM Control Coils

Conceptual design started in collaboration

with Institute for Plasma Research, India

Summary

The first JET results with the ILW have demonstrated that fuel retention in line with ITER requirements and good machine conditions are achievable.
The next step is the demonstration of operation after shallow W melt events and reproducible high-confinement regimes.
On the longer term a DT Campaign is envisaged.

JET contributions at this conference

Eich	Scaling of the Tokamak near Scrape-off Layer H-mode Power Width and Implications for ITER	ITR/1-1
Joffrin	Scenario development at JET with the new ITER-like wall	EX/1-1
Sharapov	Energetic Particle Instabilities in Fusion Plasmas	OV/4-3
Tuccillo	On the use of Lower Hybrid waves at ITER relevant density	ITR/P1-09
Parail	Self-consistent simulation of plasma scenarios for ITER using a combination of 1.5D transport codes and free boundary equilibrium codes	ITR/P1-10
Sips	Demonstrating the ITER base-line operation at q95=3	ITR/P1-11
Tala	Tokamak Experiments to Study the Parametric Dependences of Momentum Transport	ITR/P1-19
Kallenbach	Multi-machine comparisons of divertor heat flux mitigation by radiative cooling	ITR/P1-28
Budny	PTRANSP tests of TGLF and predictions for ITER	ITR/P1-29
Chapman	Assessing the Power Requirements for Sawtooth Control in ITER through Modelling and Joint Experiments	ITR/P1-31
Gohil	Assesment of the H-mode power threshold requirements for ITER	ITR/P1-36
Bazylev	Modelling of Material Damage and High Energy Impacts on Tokamak PFCs during Transient Loads	ITR/P1-39
Kalupin	The European Transport Solver: an integrated approach for transport simulations in the plasma core.	TH/P2-01
Giruzzi	Model validation and integrated modelling simulations for the JT-60SA tokamak	TH/P2-03
Litaudon	Modelling of Hybrid Scenario: from present-day experiments toward ITER	TH/P2-05
Rafiq	Physics Basis and Validation of MMM7.1 Anomalous Transport Module	TH/P2-13
Weisen	Non-diffusive Momentum Transport in JET H-mode Regimes: Modeling and Experiment	TH/P2-17
Falchetto	The European Integrated Tokamak Modelling (ITM) Effort: Achievements and First Physics Results	TH/P2-25
Saarelma	Pedestal modelling based on ideal MHD and gyrokinetic stability analyses on JET and ITER plasmas	TH/P3-10
Puetterich	Tungsten Screening and Impurity Control in JET	EX/P3-15
Liang	Mitigation of Type-I ELMs with n =2 Fields on JET	EX/P4-23
Nave	Scales of Spontaneous Rotation in the JET Tokamak	EX/P3-31
Schneider	Analysis of temperature and density pedestal in a multi-machine database	EX/P4-02
Brezinsek	Fuel Retention Studies with the ITER-likeWall in JET	EX/4-1
de Vries	Comparison of plasma breakdown with a Carbon and ITER-like wall	EX/4-2
Groth	Impact of carbon and tungsten as divertor materials on the scrape-off layer conditions in JET	TH/3-1
Mayoral	On the challenge of plasma heating with the JET metallic wall	EX/4-3
Nunes	Be tile power handling and main wall protection	FTP/2-1Rb
Coenen	Longterm Evolution of Impurity Composition and Transient Impurity Events with the ITER-like Wall at JET	EX/P5-04
van Rooij	Characterization of Tungsten Sputtering in the JET divertor	EX/P5-05
Douai	Overview of the International Research on Ion Cyclotron Wall Conditioning	EX/P5-09
Mertens	Power Handling of the tungsten divertor in JET	EX/P5-24
Giroud	Nitrogen seeding for heat load control in JET ELMy H-mode plasmas and its compatibility with ILW materials	EX/P5-30
Arnoux	Scrape-off layer porperties of ITER-like limiter start-up plasmas at JET	EX/P5-37
De La Luna	The effect of ELM mitigation techniques on the access to high H-mode confinement (H98~1) on JET	EX/6-1
Beurskens	L-H power threshold, confinement, and pedestal stability in JET with a metallic wall	EX/P7-20
Lehnen	Impact and mitigation of disruptions with the ITER-like wall in JET	EX/9-1
Plyusnin	Latest Progress in Studies of Runaway Electrons in JET	EX/P8-05
Murari	Latest Developments in Data Analysis Tools for Disruption Prediction and Disruption Physics.	EX/P8-04
Lang	ELM pacing and trigger investigations at JET with the new ITER Like Wall	PD