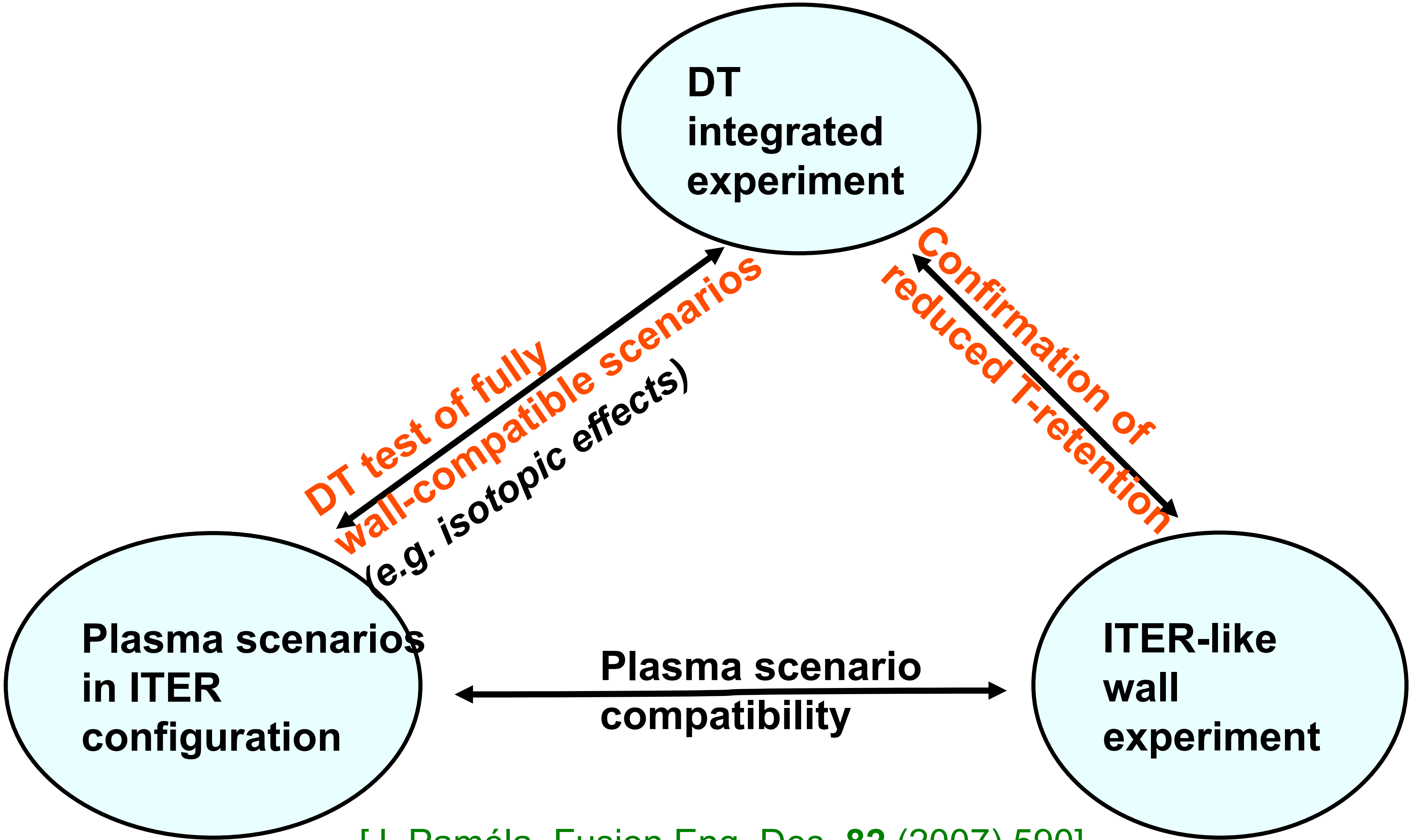
Francesco Romanelli
on behalf of JET contributors

Overview of the JET results

Acknowledgments:
L. Horton, D. Borba, G. Sips
and JET Task Force Leaders

25th Fusion Energy Conference Saint Petersburg, 13-18 October 2014

The JET programme in support of ITER



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

DT

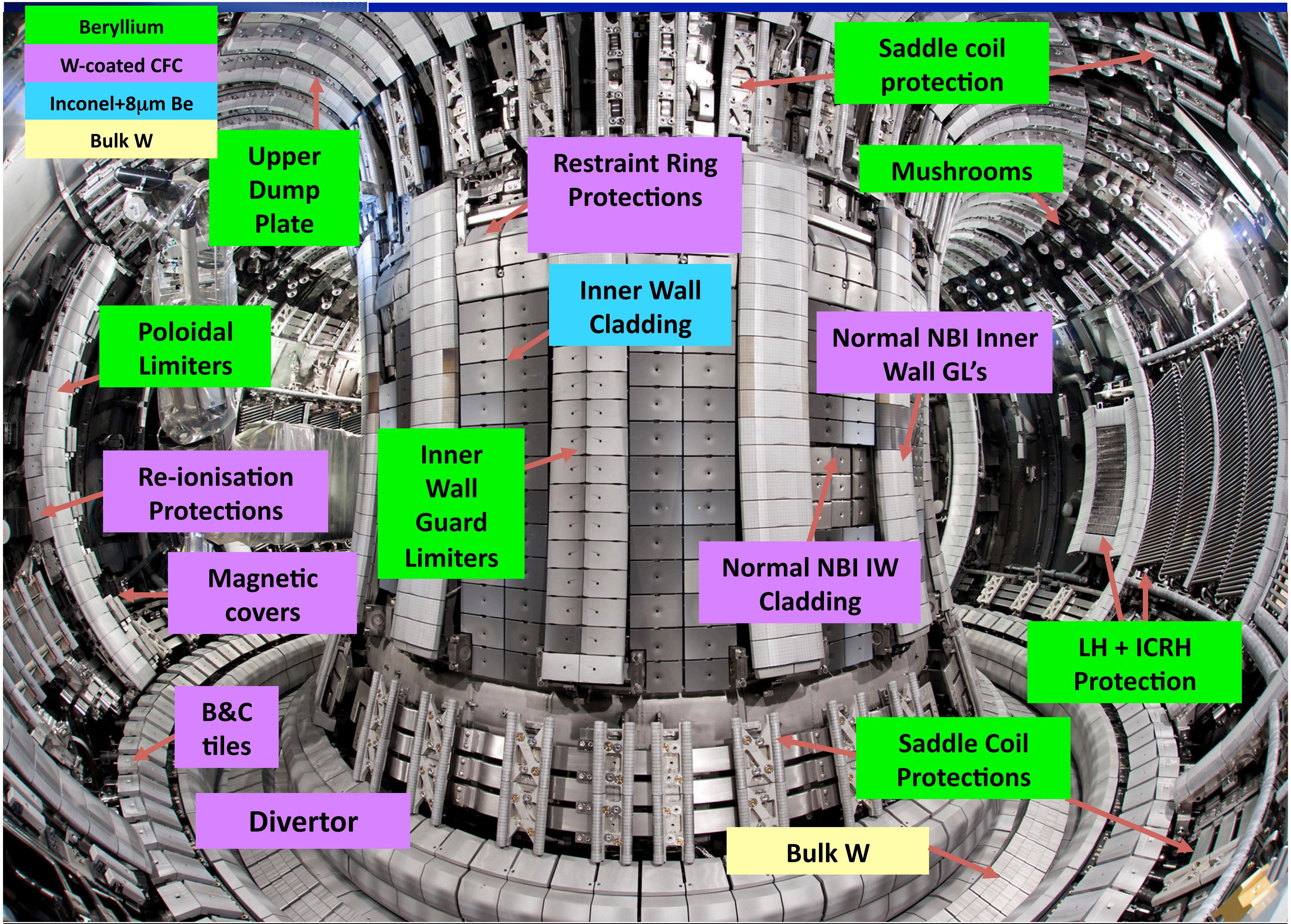
The JET programme in support of ITER is now completing the characterization of the ITER-like wall and progressing towards the DT experiment.

Plasma scenarios in ITER configuration

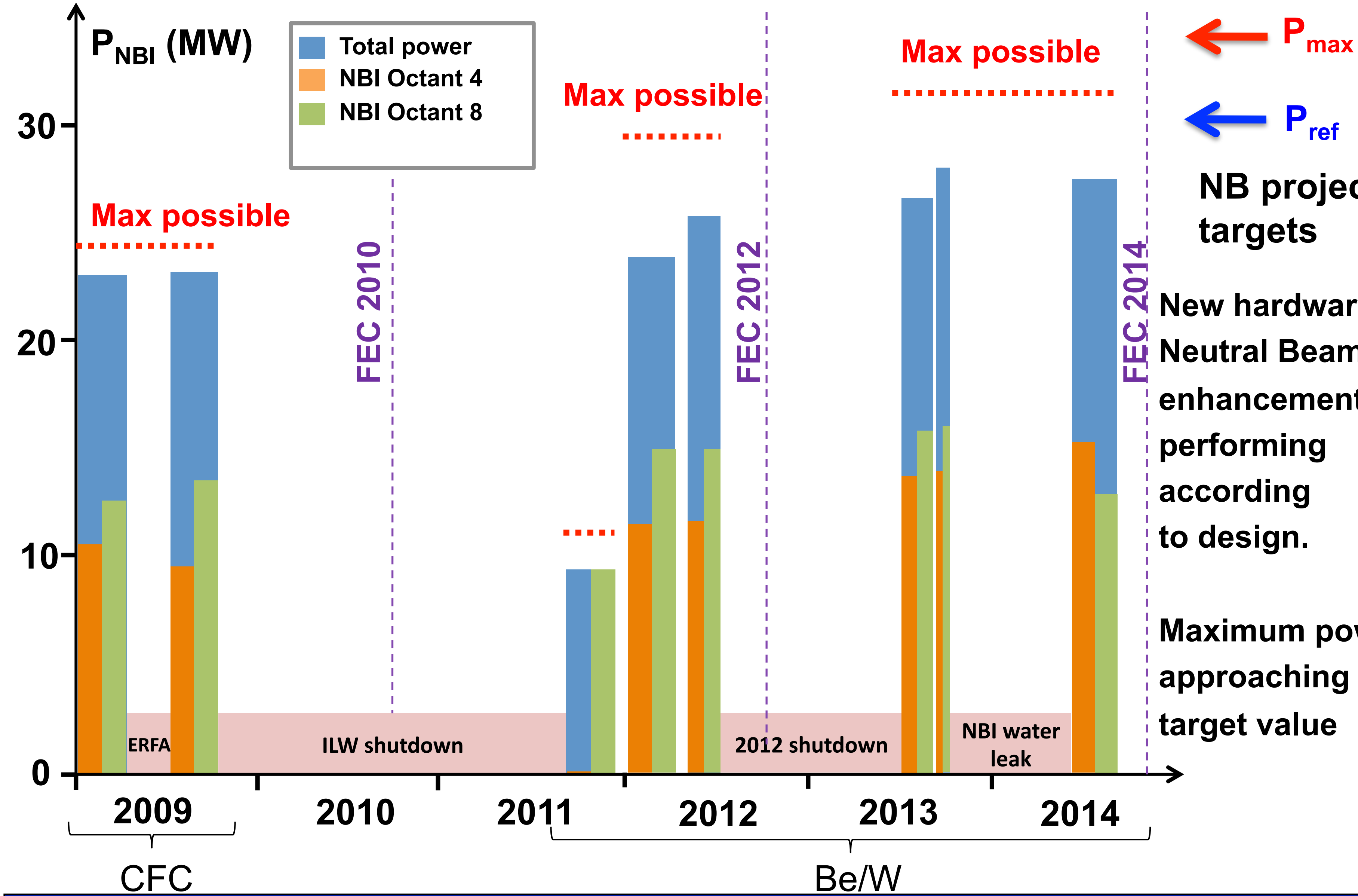
Plasma scenario compatibility

ITER-like wall experiment

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


Beryllium
W-coated CFC
Inconel+8μm Be
Bulk W
Upper Dump Plate
Restraint Ring Protections
Saddle coil protection
Mushrooms
Inner Wall Cladding
Poloidal Limiters
Normal NBI Inner Wall GL's
Re-ionisation Protections
Inner Wall Guard Limiters
Normal NBI IW Cladding
Magnetic covers
LH + ICRH Protection
B&C tiles
Saddle Coil Protections
Divertor
Bulk W

The JET programme in support of ITER



NB project targets

New hardware of Neutral Beam enhancement performing according to design.

Maximum power approaching target value

The JET programme in support of ITER

	JET-CFC (2009)	JET-ILW → 2014
I_p	4.5MA	4.0MA
P_{NBI}	23.2MW	28MW
P_{ICRH}	8.7 MW (+ ILA)	6 MW
NBI input	185MJ	230MJ
Pulse rate*	18 /day	17.5 /day

**: Successful physics pulses*

After 3 years of operation with the ITER-like wall:

- System capabilities at a similar level compared to the carbon wall.
- Higher NBI power and input energy

Main limitation: Surface temperature (Be and W), to avoid melt damage.

→ Substantial increase in real-time protection systems (as required in ITER):

✓ Infra Red protection of PFC's
✓ Closed-loop use of Massive Gas Injection for disruption mitigation
✓ Disruption avoidance and plasma termination scenarios

The JET programme in support of ITER

	JET-CFC (2009)	JET-ILW → 2014
I_p	4.5MA	4.0MA
P_{NBI}	23.2MW	28MW
P[illegible]	8.7 MW (+ ILA)	6 MW

After 3 years of operation with the ITER-like wall:

- System capabilities at

JET experience with Be+W shows the need of a careful preparation (as now integrated in the ITER research plan with the choice of the W divertor from the beginning) to achieve continuous improvement in the plasma performance.

✓ Closed-loop use of Massive Gas Injection for disruption mitigation
✓ Disruption avoidance and plasma termination scenarios

Outline

- JET programme in support of ITER
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  - Tungsten Melt Experiment
  - Material Migration & Retention
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  - Progress to maximum fusion performance
- Conclusions and perspectives

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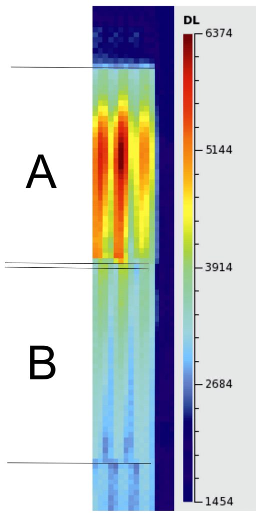
2013 programme focussed on the support to an ITER decision on the day-one W divertor

- One lamella on stack A intentionally misaligned
- IR measurements on the top surface.

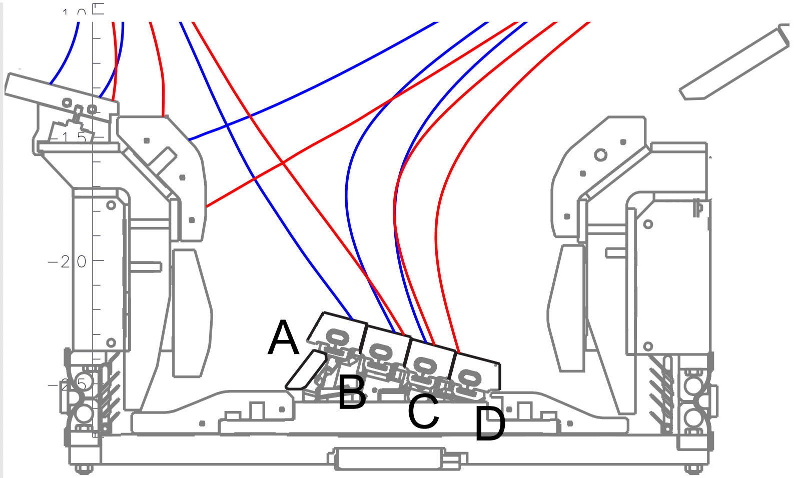
- Modelling of lamella temperature evolution by conduction through supporting structure

- Note: the temperature on the vertical surface is not resolved. New stack to be installed in the next shutdown.

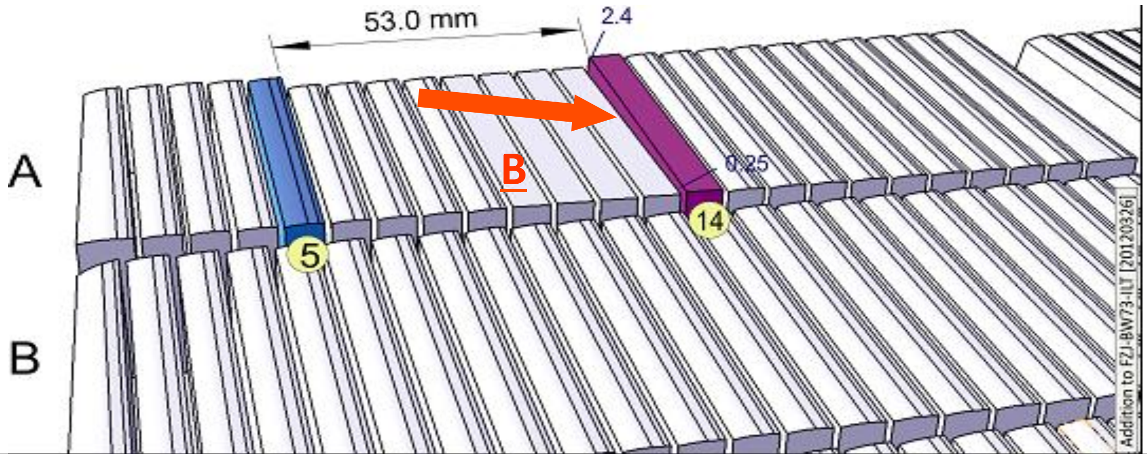
82703, t =56.178s, T_{max} = 236°C



– KL9B –
[NBI ~10MW, 2s]

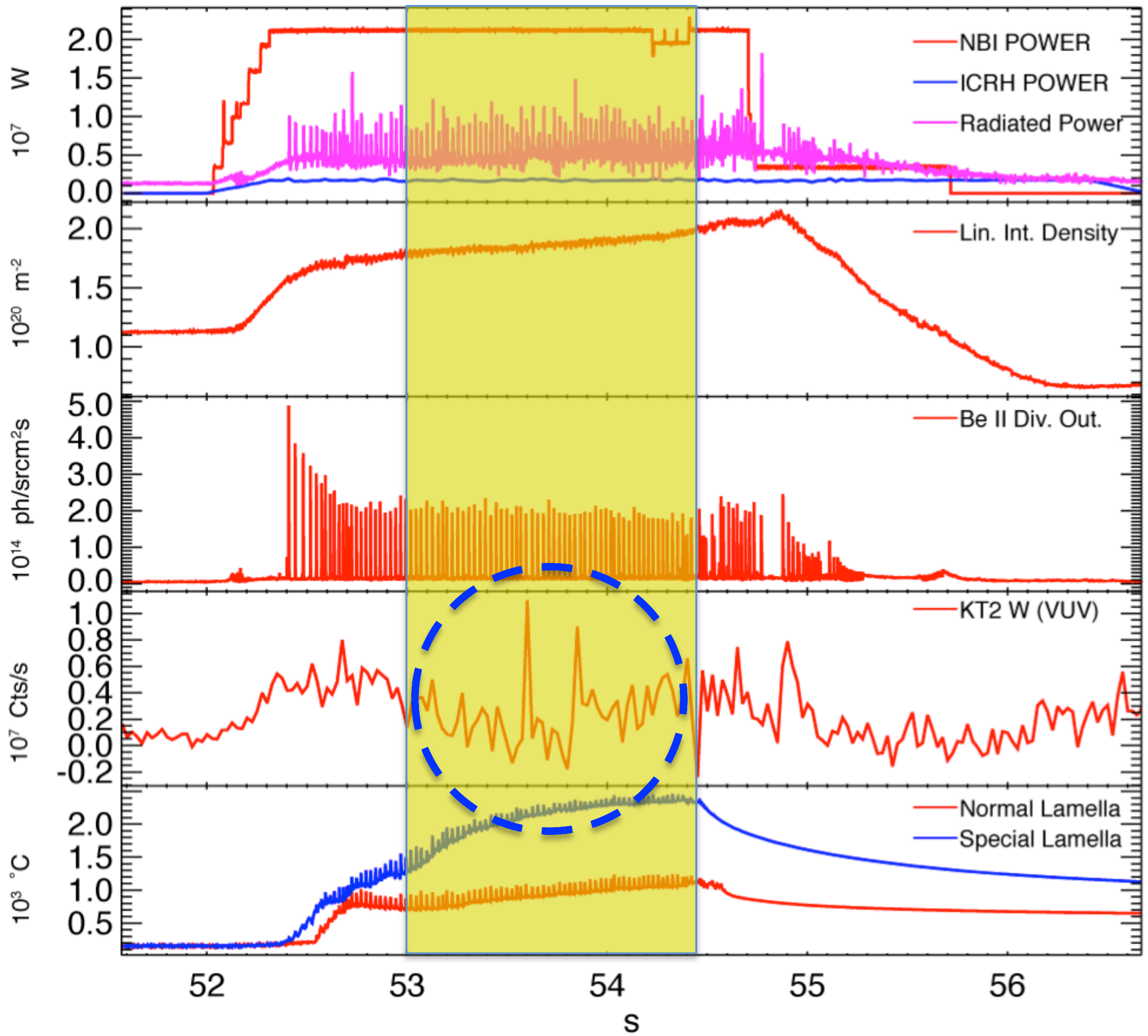


[G. Matthews EX/4-1 Wednesday, J. Coenen, PSI 2014]



Shallow W-melting does not impact JET operation

#84782



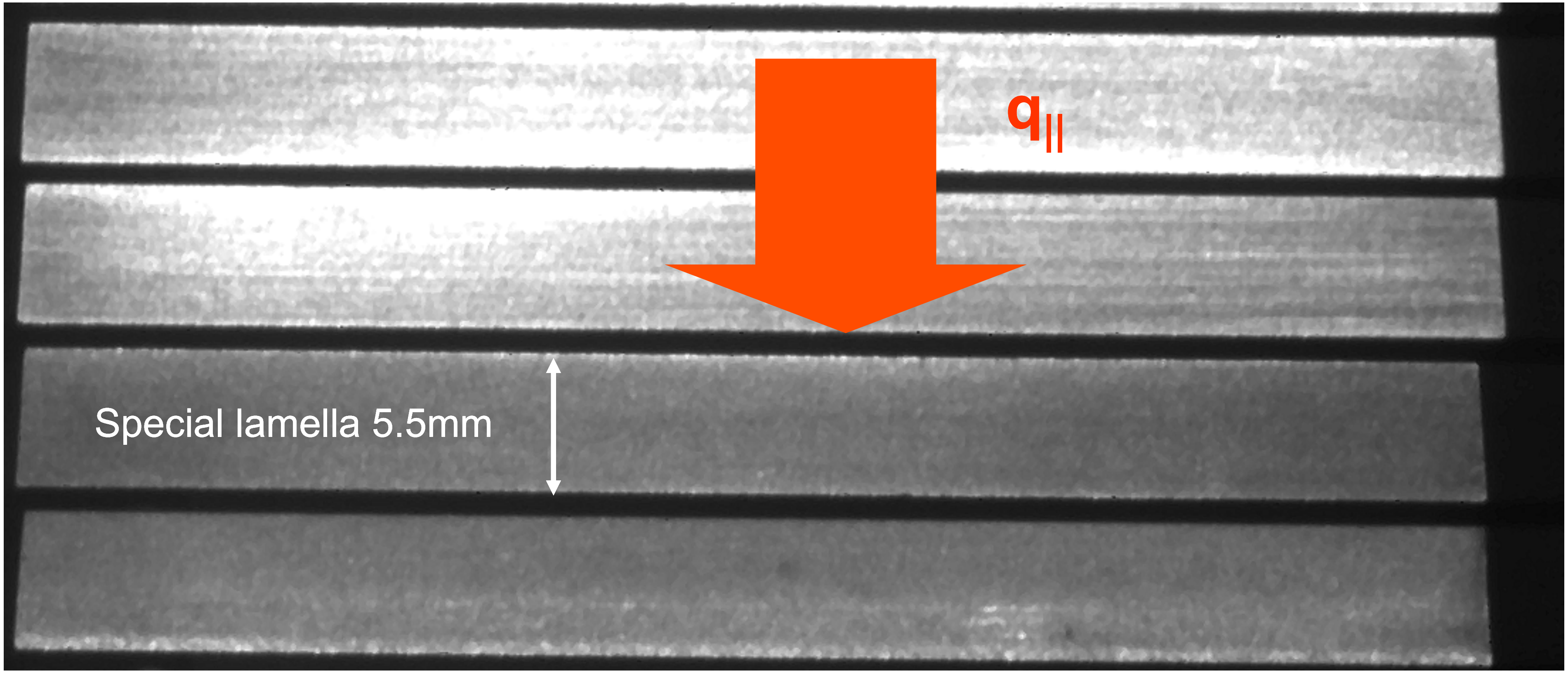
- Strategy: 1s heating to raise bulk lamella temperature to facilitate shallow melting by ~300 kJ ELMS

  $q_{||} = 0.5 – 1.0\ GW/m^2$

- Results consistent with melting followed by resolidification.

- Small W events associated with the occasional expulsion of droplets **but no impact on JET operation**!

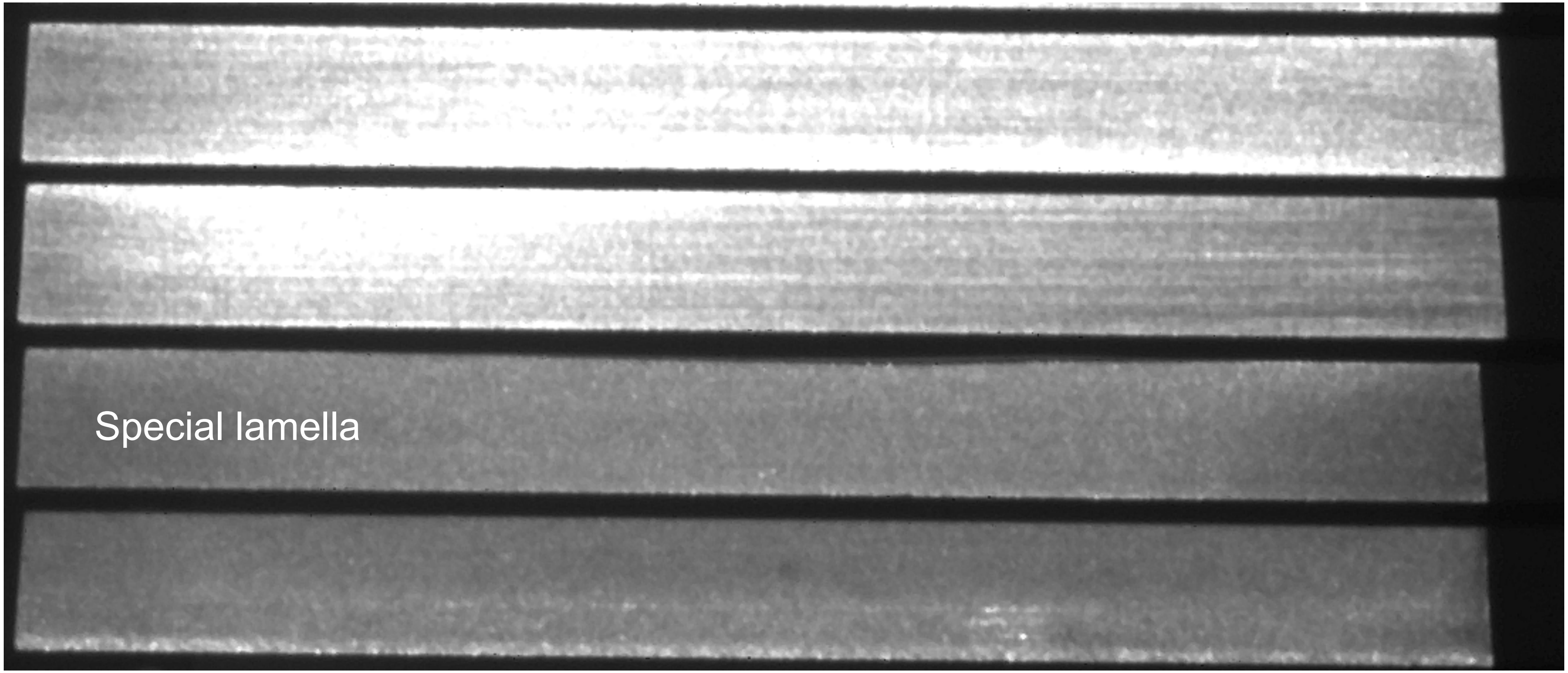
84686 – Before melting



Low
Field
Side

High
Field
Side

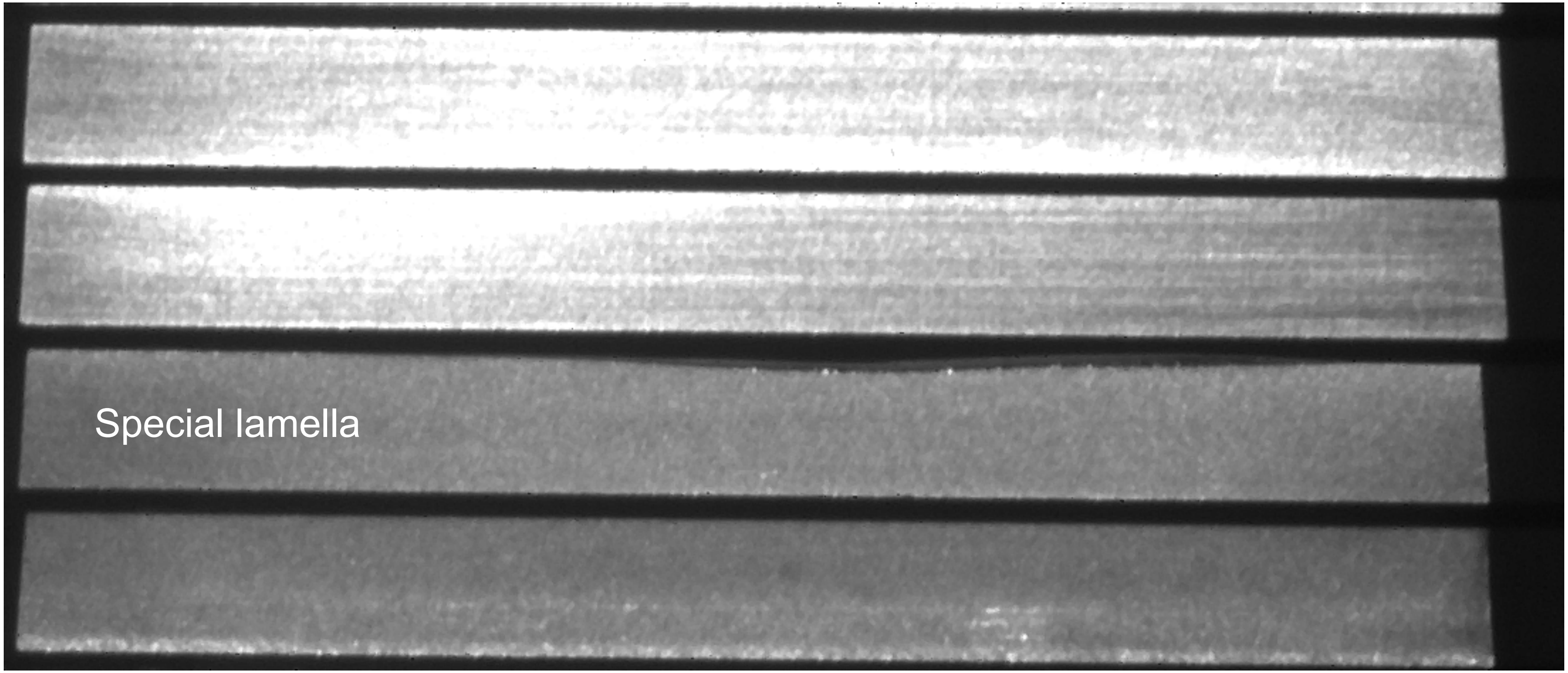
After 84724



Low Field Side

High Field Side

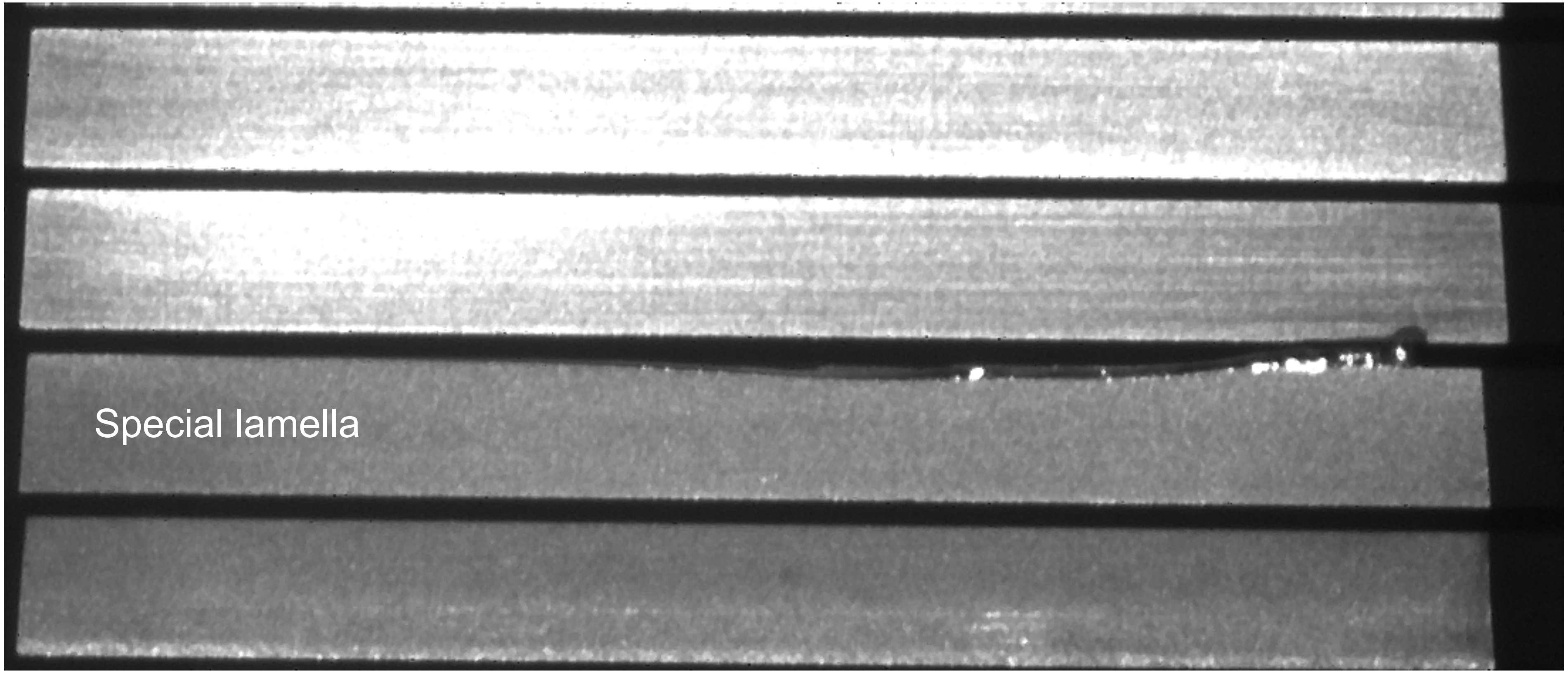
After 84778



Low
Field
Side

High
Field
Side

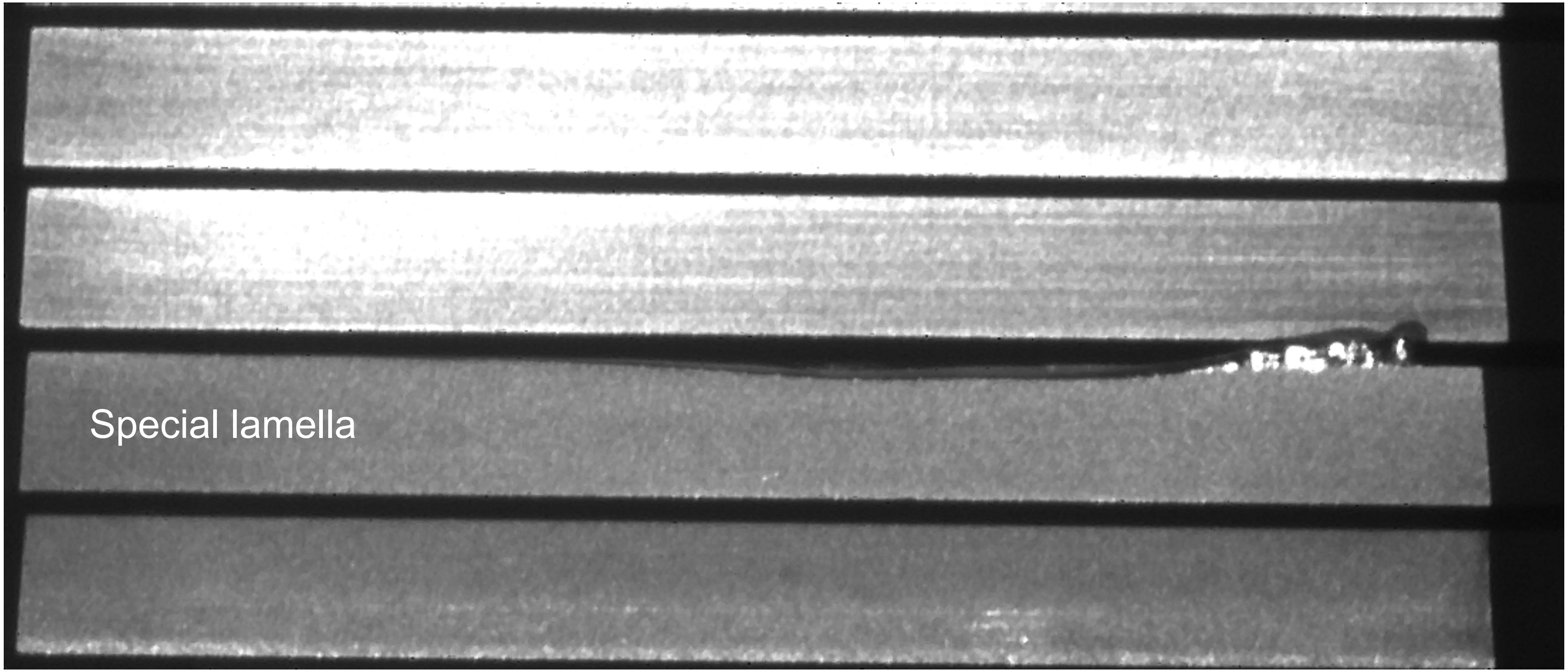
After 84779



Low
Field
Side

High
Field
Side

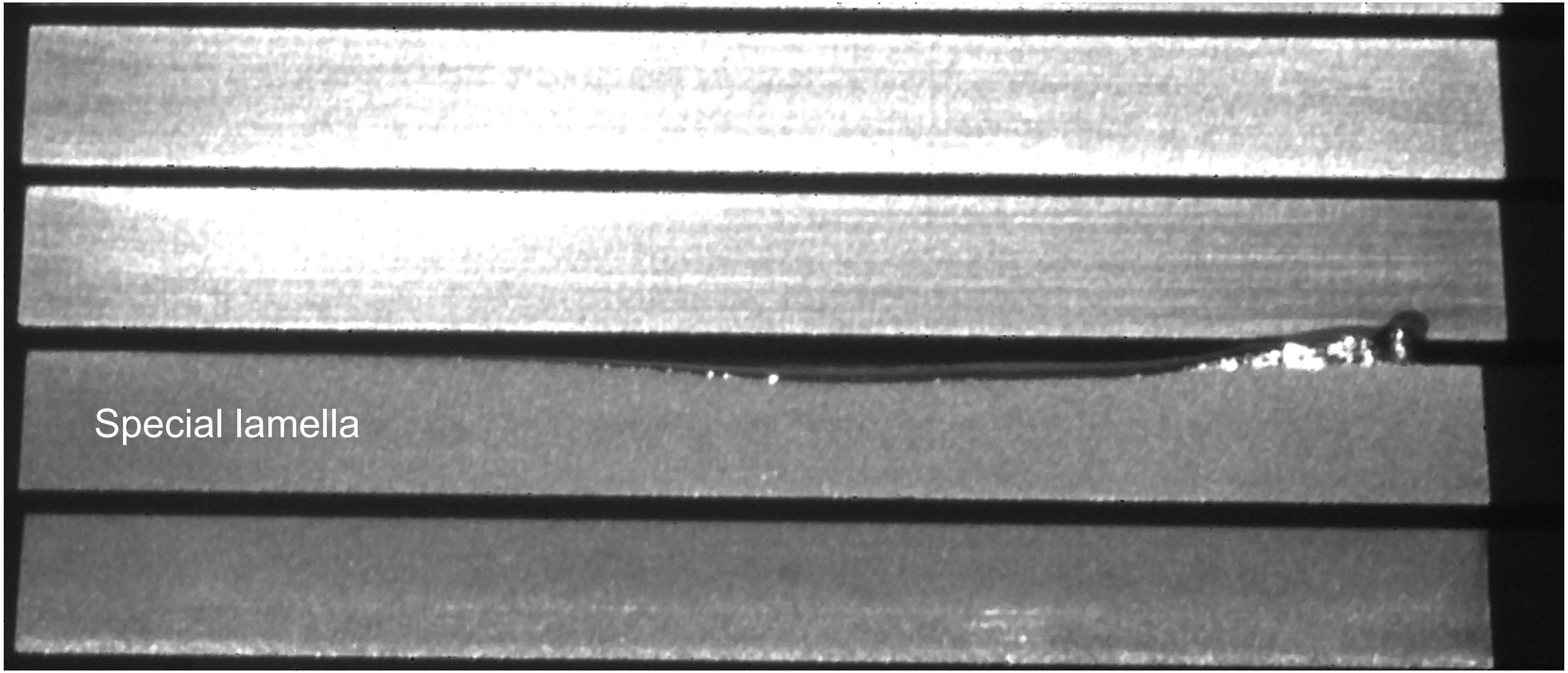
After 84781



Low
Field
Side

High
Field
Side

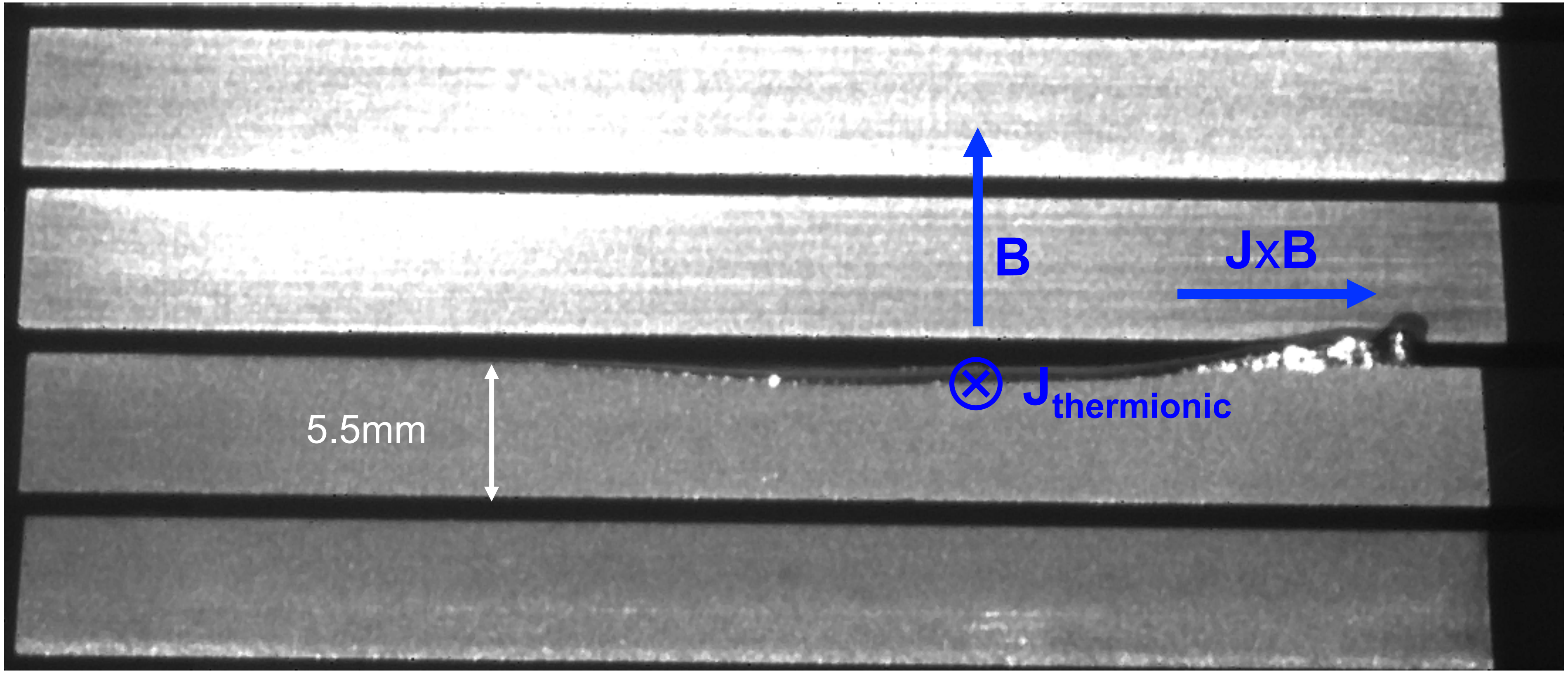
After 84782



Low
Field
Side

High
Field
Side

After 84783

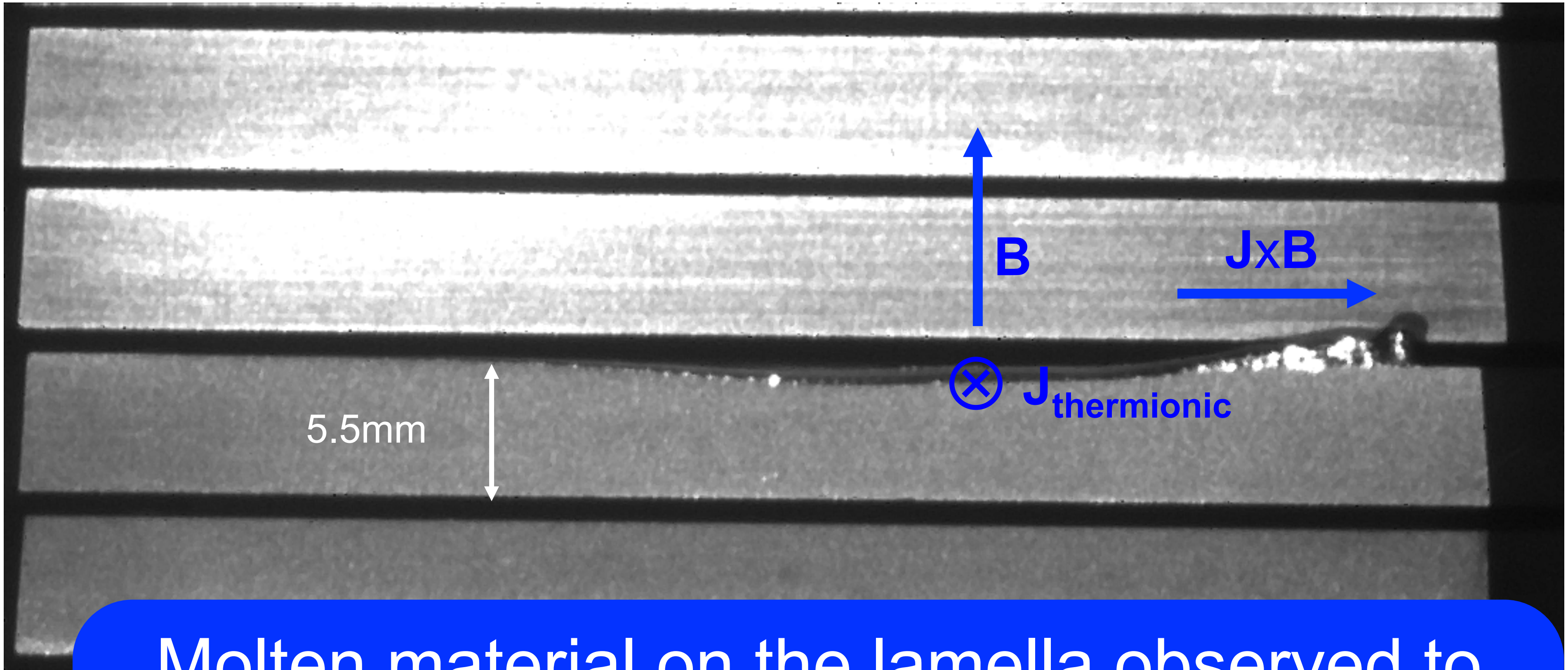


Low
Field
Side

High
Field
Side

Erosion: 150-300μm per pulse, 5-10μm per ELM (frequency 30Hz)
Total volume moved: ~6mm^3

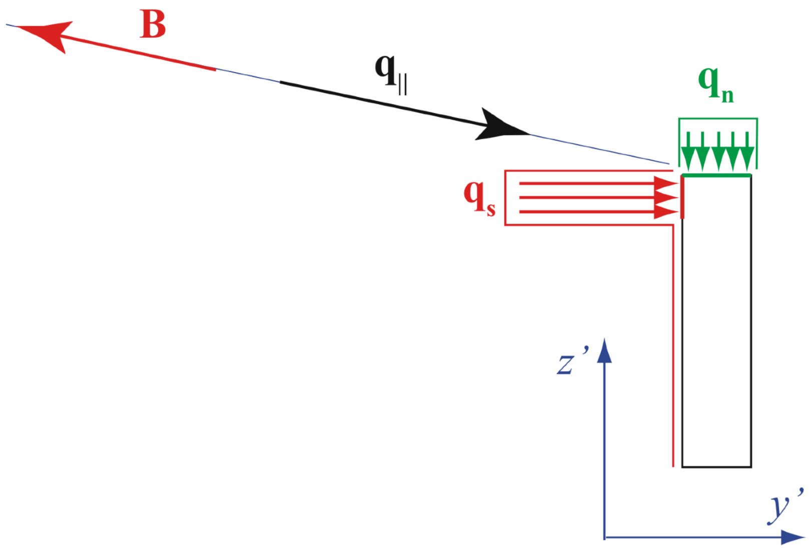
After 84783



Molten material on the lamella observed to coalesce and grow, which increases the risk for longer pulse duration above the melt threshold.

Side heat load lower than expected

Matching the experimental measurements requires mitigation factors instead of pure geometrical assumptions



$q_n = q_{perp} * f_n$; $f_n = 1$

$q_s = q_{||} * f_s$; $f_s = 0.4$

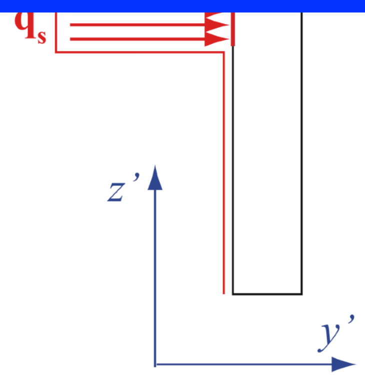
Vapour shielding included

Larmor radius smoothing not sufficient

Side heat load lower than expected

Matching the experimental measurements requires
mitigation factors instead of pure geometrical

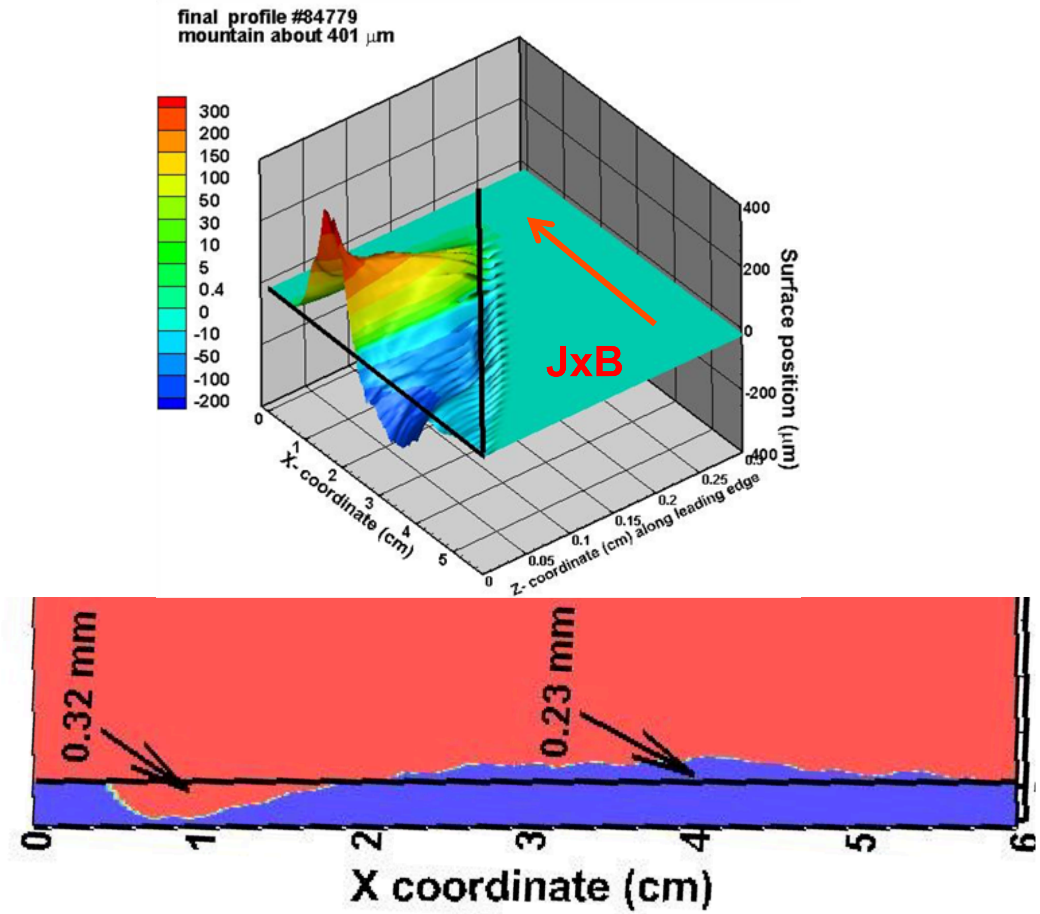
Potentially positive implications for ITER, which may be less sensitive than previously feared to exposed edges created by chipping of mono-block edges or components outside tolerance



Vapour shielding included

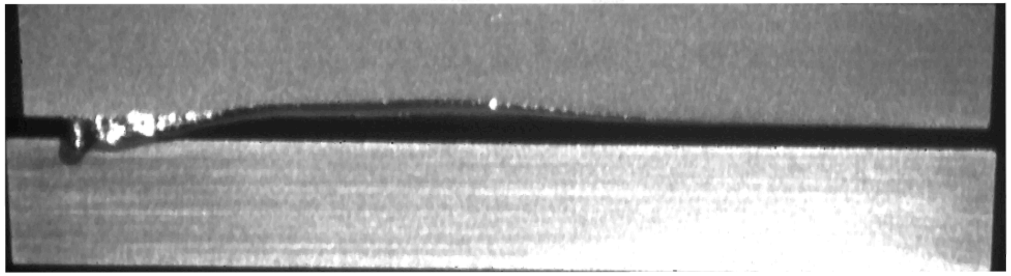
Larmor radius smoothing not sufficient

Modelling of Melt layer



- The melt layer motion is modelled correctly by MEMOS by including the mitigation factors and the JxB force.

[Bazylev TH/P3-40]



1 mm after seven pulses

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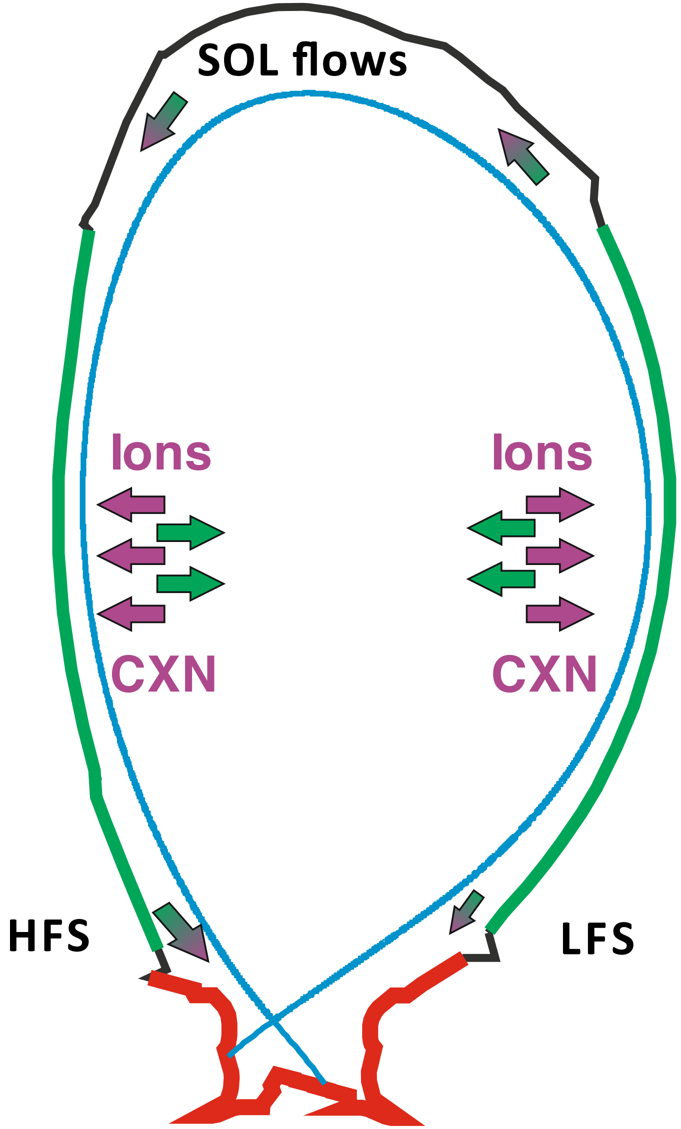
Material Migration

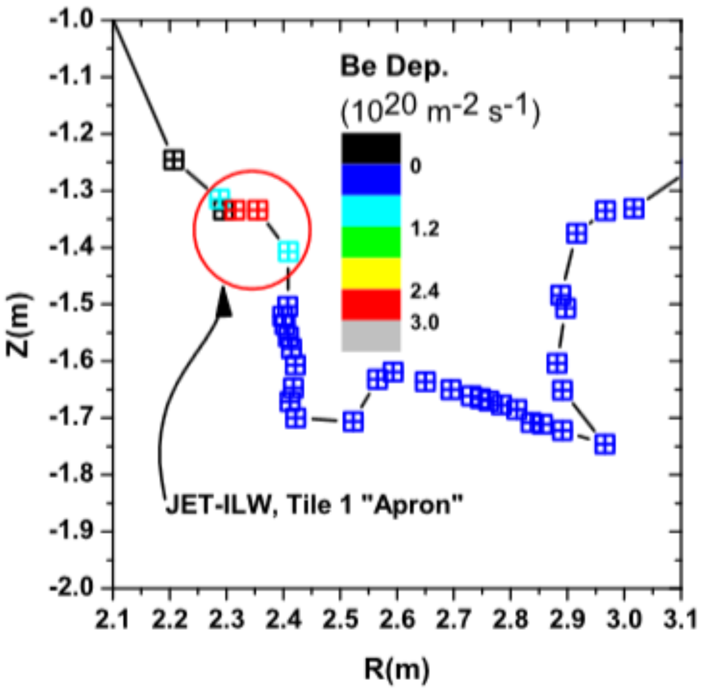
- Sputtering at inner wall and limiter at low impact energies (<10 eV)
- At low energy, Be sputtering yield (JET-ILW) is lower than total C sputtering yield (JET-C)
- Spectroscopy and *ex situ* analysis revealed a factor 4-5 smaller primary source
- Absence of chemical erosion by low energy particles in case of ILW!
- Majority of Be transported in SOL towards inner divertor



[S. Brezinsek, EX/P5-26]

ITER fuel retention predictions

- Measured long-term fuel retention by post-mortem analysis is below 0.25%
- WallDYN code validated by gas balance and post-mortem analysis in JET-C and JET ILW
  - WallDYN confirms material migration path in JET in divertor configuration



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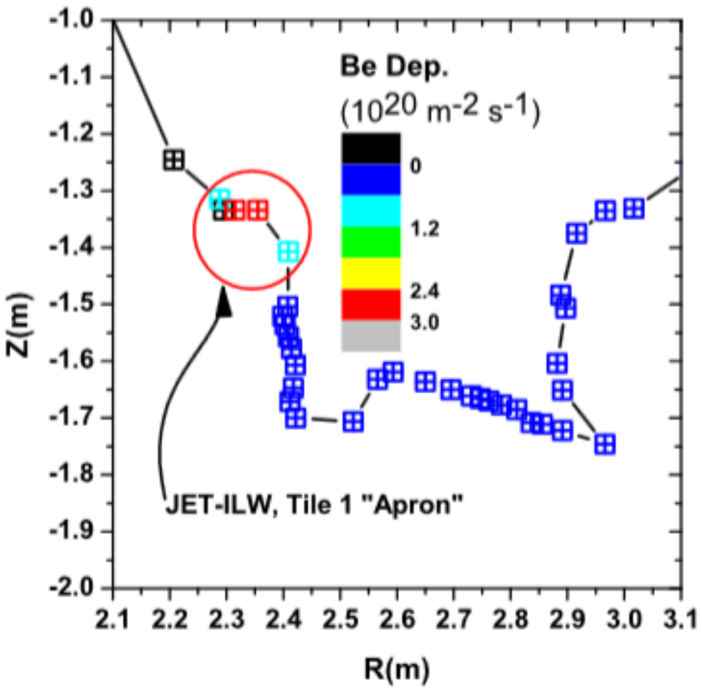
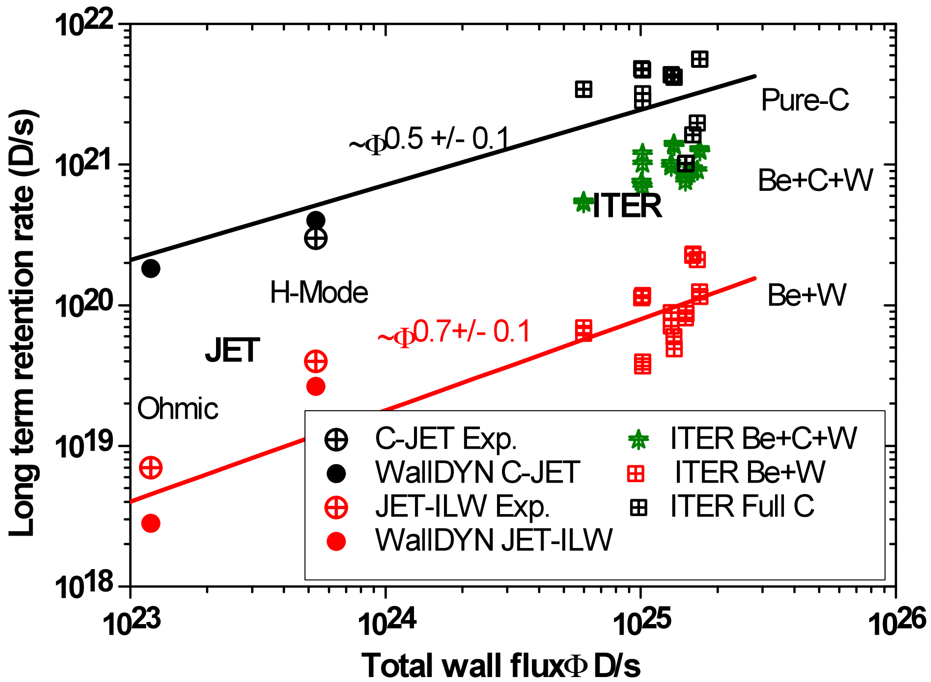
  - WallDYN confirms fuel retention rate (absolute values) in JET-C and JET-ILW

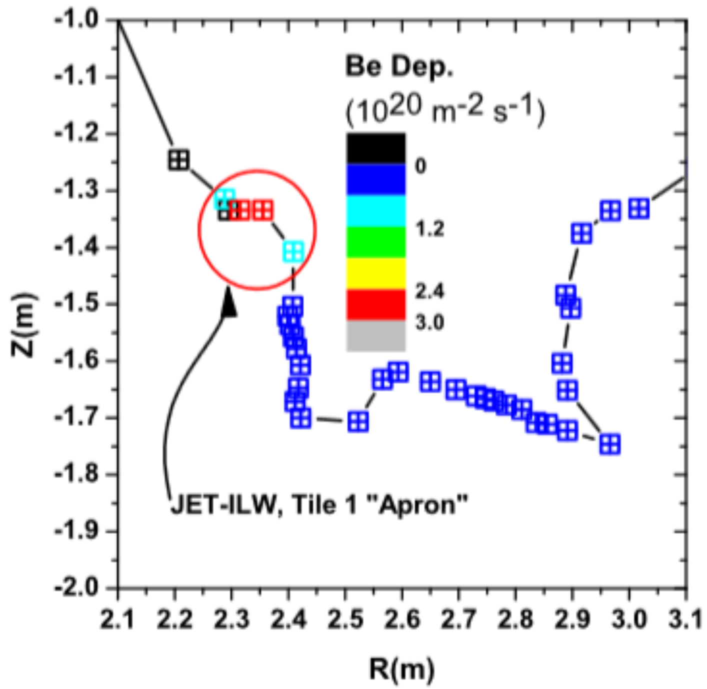


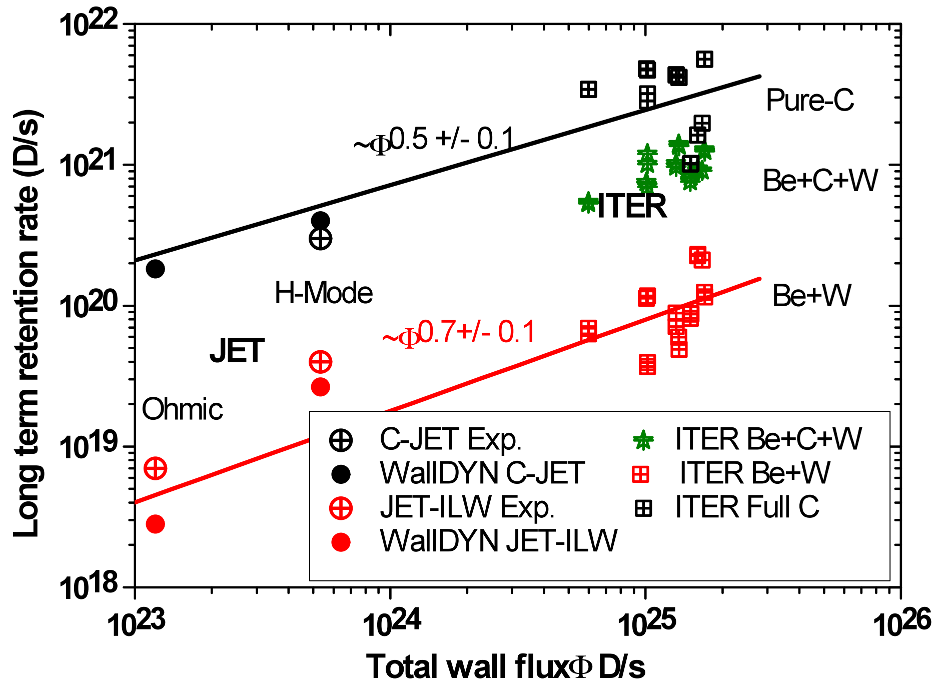


[K. Schmid, EX/P5-32, K. Heinola, PSI 2014]

ITER fuel retention predictions

ITER with Be+W walls 3000-20000 full power DT discharges before reaching the maximum tritium inventory.





[K. Schmid, EX/P5-32, K. Heinola, PSI 2014]

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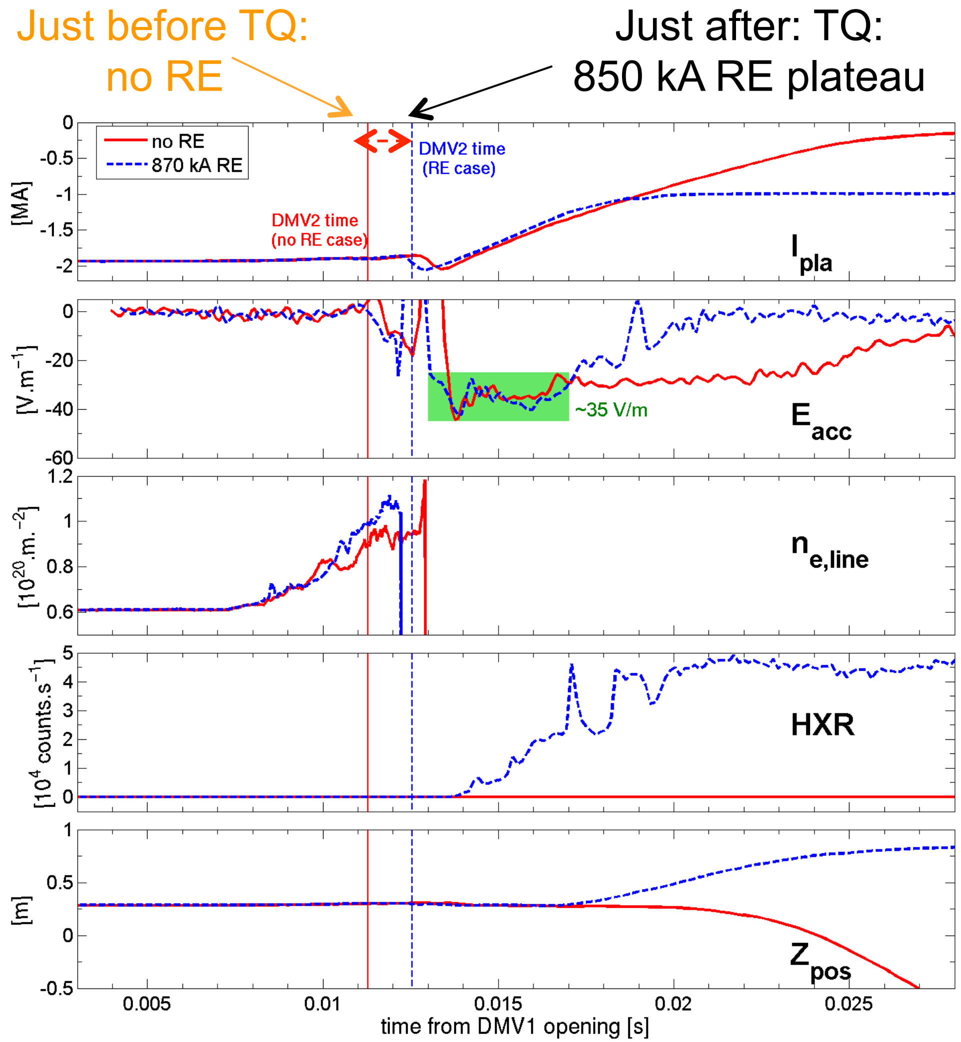
Runaway Electron suppression

- Runaway electron beams are not normally produced with the ILW. They can be generated and studied using massive Ar injection above some threshold value
- Runaway avoidance is possible using a second MGI as long as it comes before the thermal quench
- Thereafter, runaway beam suppression using high-Z MGI was found to be ineffective (Ar, Kr and Xe have been tried)



[C. Reux, EX/5-2 Thursday]

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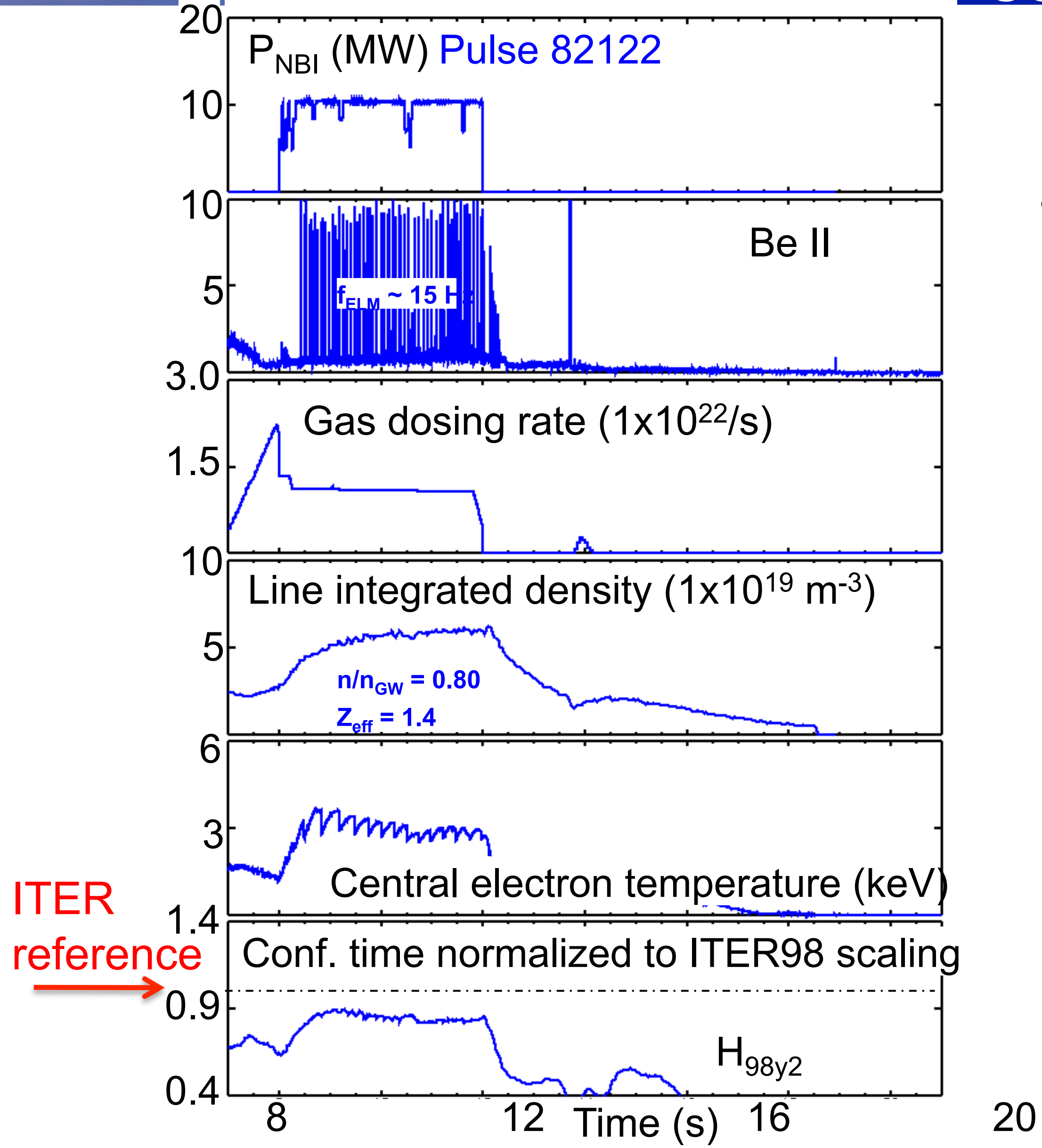
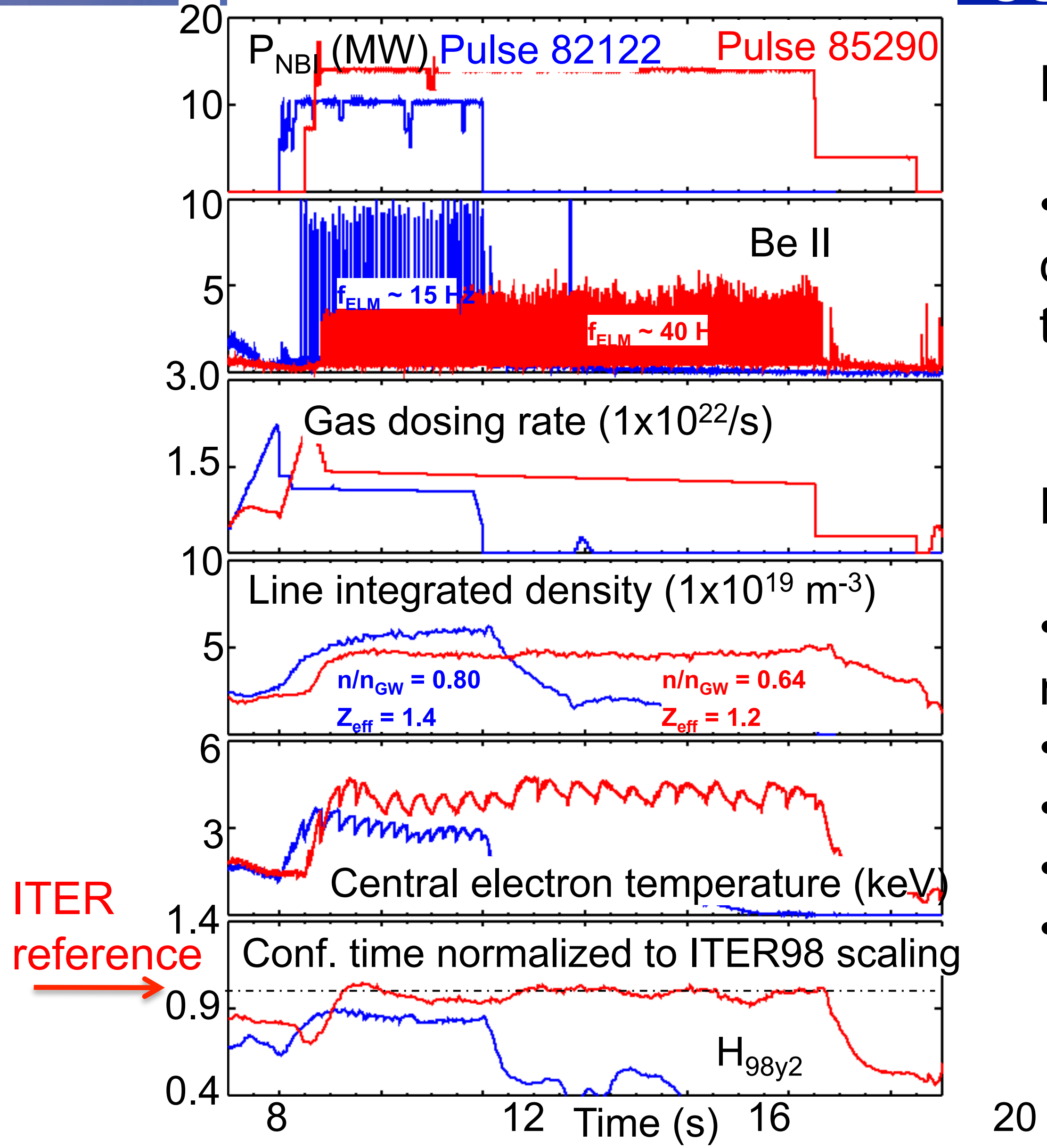
ITER-relevant energy confinement re-established



FEC 2012

- W-accumulation avoided by controlling ELM frequency through gas fuelling

ITER-relevant energy confinement re-established



FEC 2012

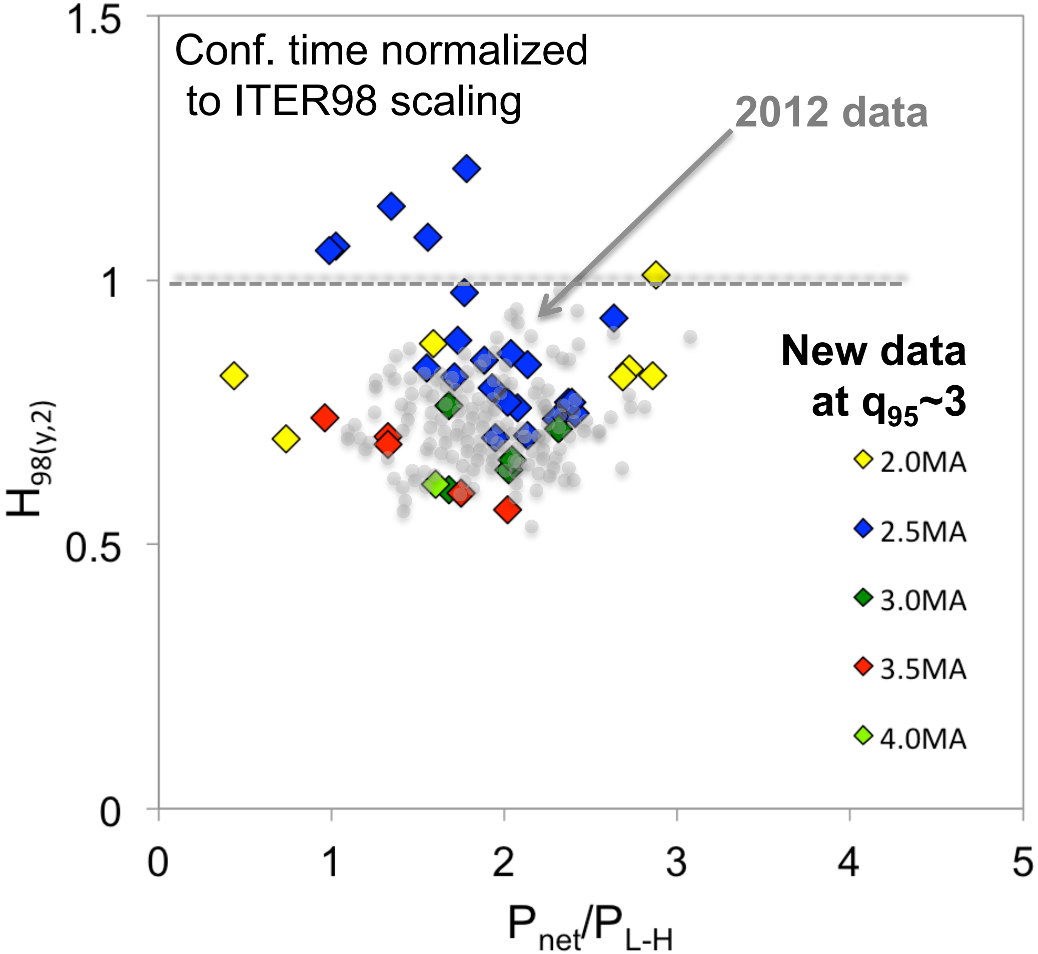
- W-accumulation avoided by controlling ELM frequency through gas fuelling

FEC 2014

- Strike point optimised for maximum pumping
- Higher ELM frequency
- Long pulse operation (10s)
- T_{e0} ~ 4.5keV
- H_{98} =1 for > 9s

[E.Joffrin EX/P5-40]

ITER-relevant energy confinement re-established

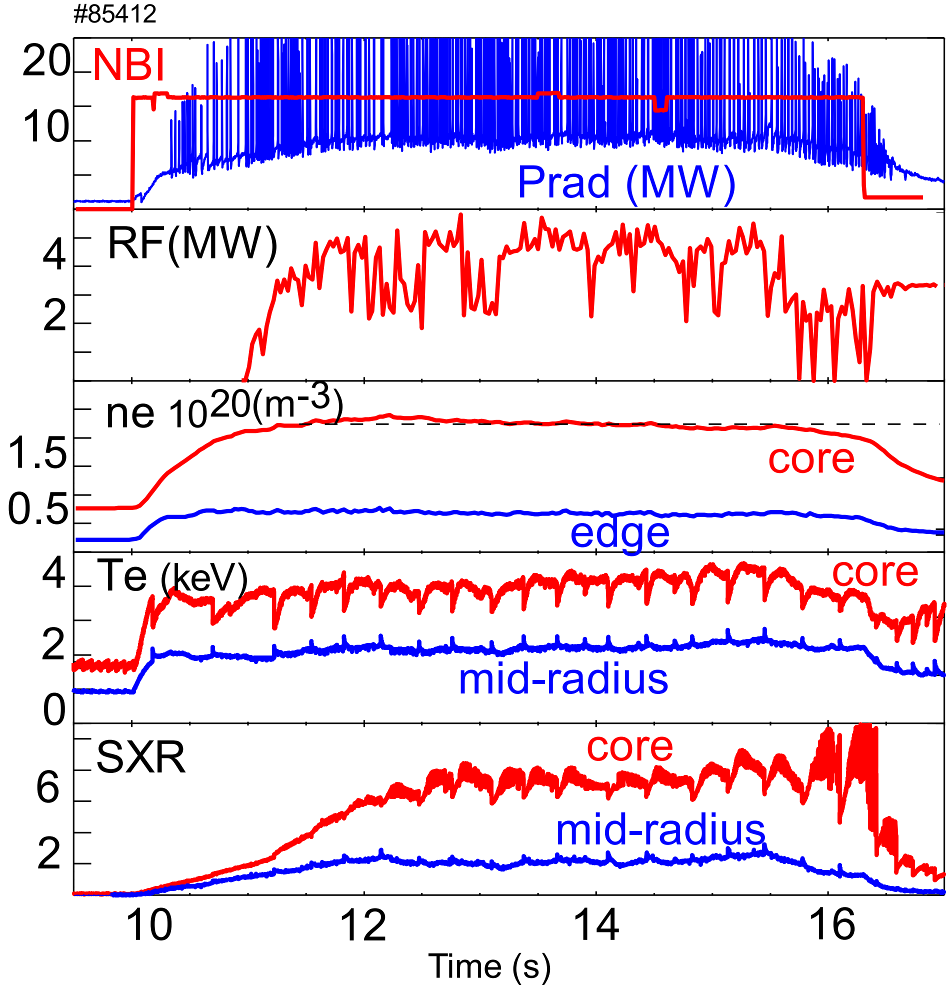


Input power normalized to the threshold power for H-mode access

Optimisation, including placing the divertor strike point so as to maximise pumping, allows access to the ITER targets of H_{98}=1 and β_N=1.8

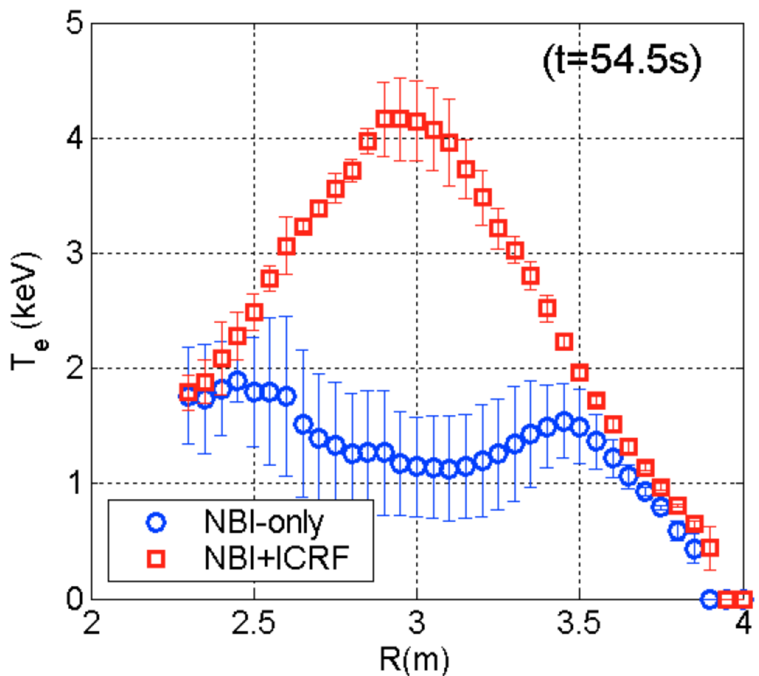
→ Also at ITER levels of input power of P_{NET}/P_{LH} ~1-2

W control by ICRH successful



W accumulation determined by inward neoclassical convection due to density peaking of main plasma

[M. Valisa EX/6-1 Thursday]

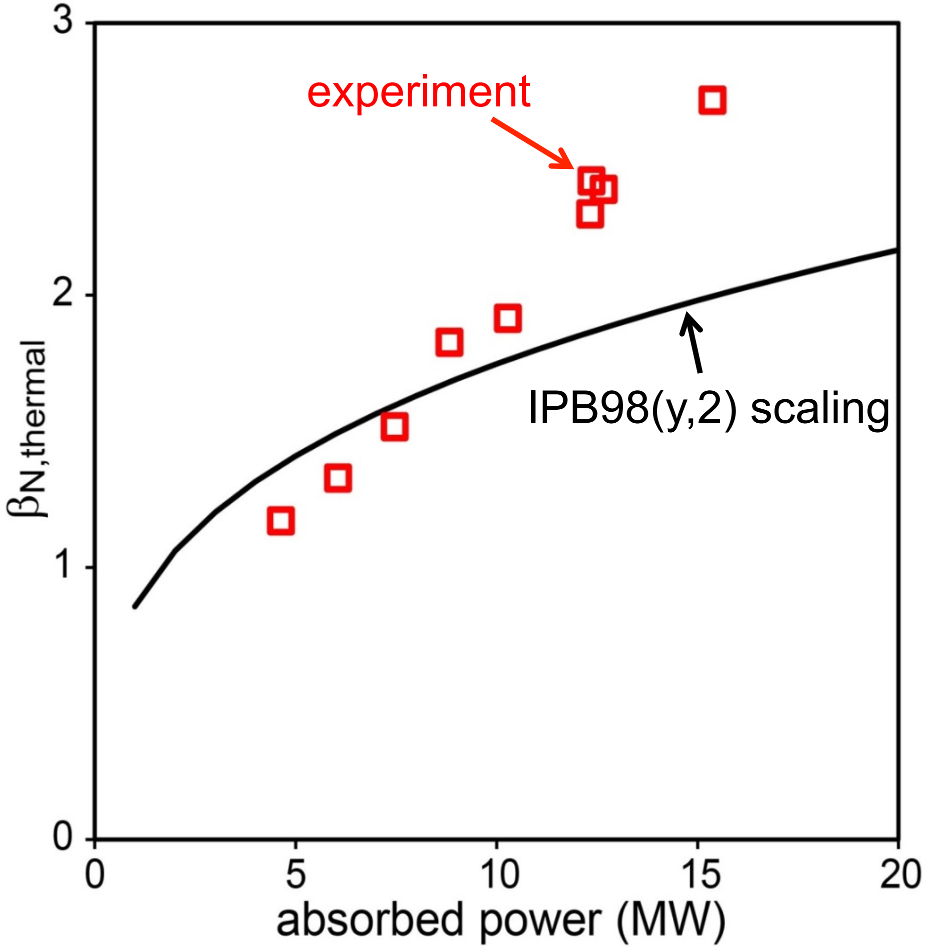


[M. Goniche, EPS 2014,

E. Lerche EX/P5-22]

Weak confinement degradation with power

Power scan with JET ITER-like wall at constant: I_P, B, M_{eff}, n_e, a,

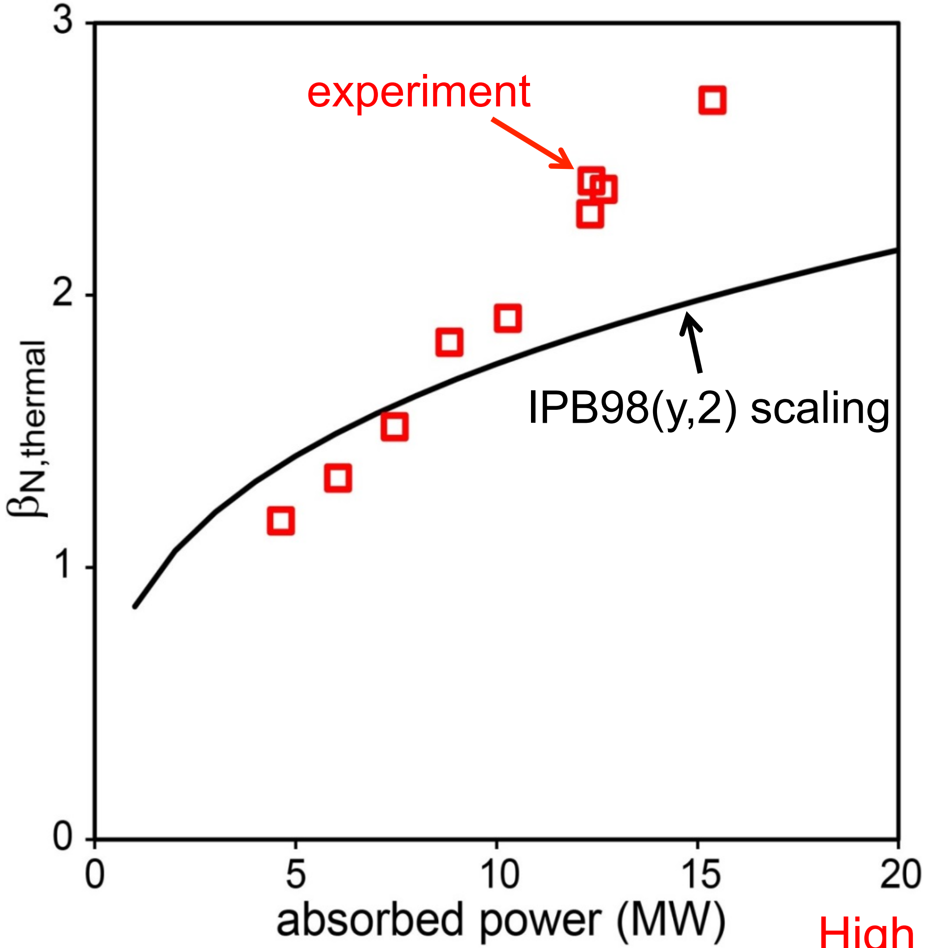


[C. Challis, Ex/9-3 Friday]

- Power scan performed in type I ELMy H-mode with low level gas injection shows weaker confinement degradation with power than expected from the IPB98(y,2) scaling
- Rapid increase in β with heating power due to:
  - Increase in core temperature consistent with transport modelling including fast ion effects [J. Garcia, TH/5-2 Thursday]
  - Increase in density peaking correlated with collisionality
  - Increase in pedestal pressure consistent with peeling-ballooning modelling [C. Maggi, EX/3-3 Wednesday]

Weak confinement degradation with power

Power scan with JET ITER-like wall at constant: I_P, B, M_{eff}, n_e, a,



[C. Challis, Ex/9-3 Friday]

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  - Increase in density peaking correlated with collisionality
  - Increase in pedestal pressure consistent with peeling-ballooning modelling [C. Maggi, EX/3-3 Wednesday]

High δ experiments with C-wall atypical. Possible role of neutrals. [E.De la Luna, EX/P5-29]

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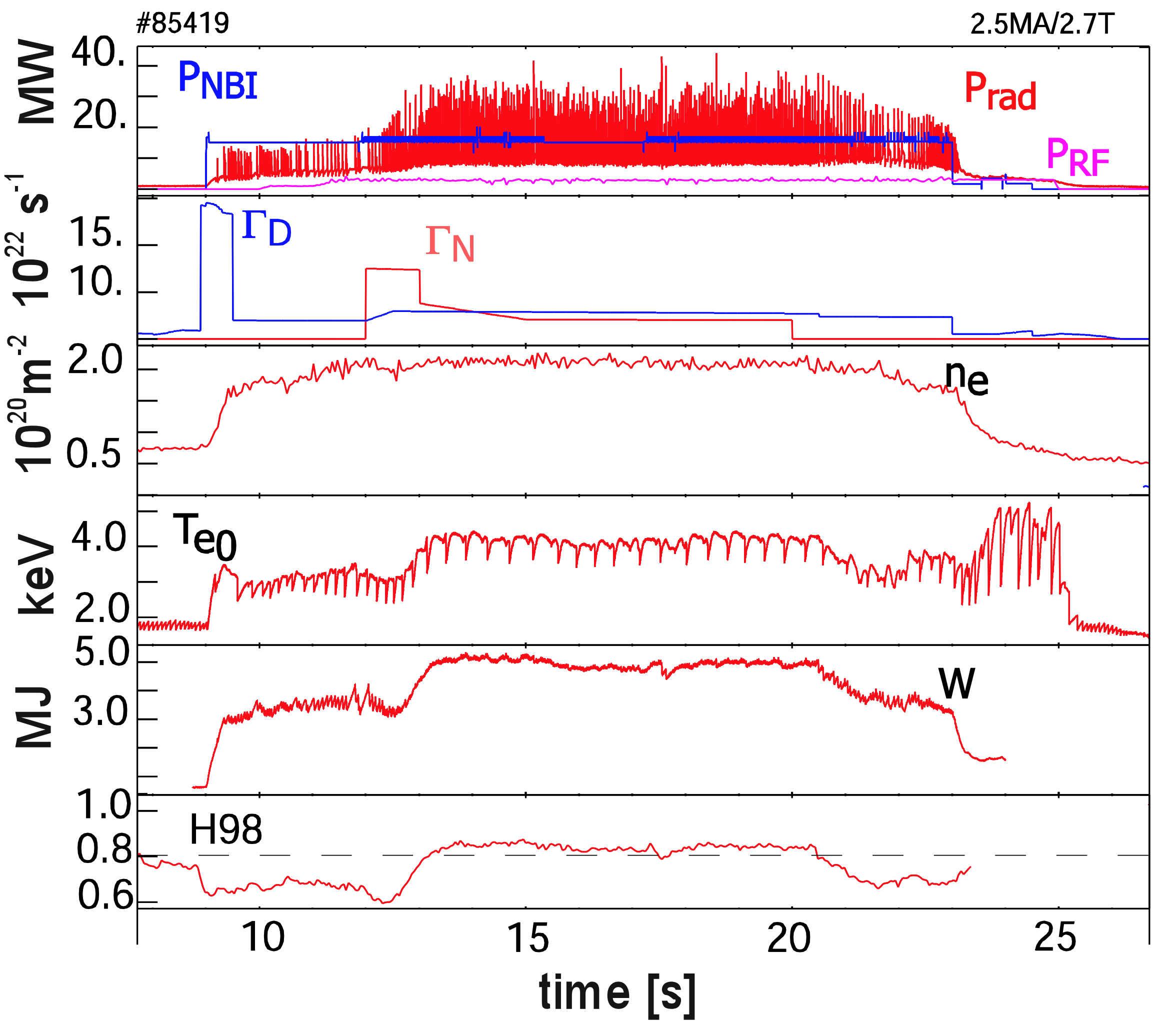
Integrated performance with N-seeding and divertor compatibility



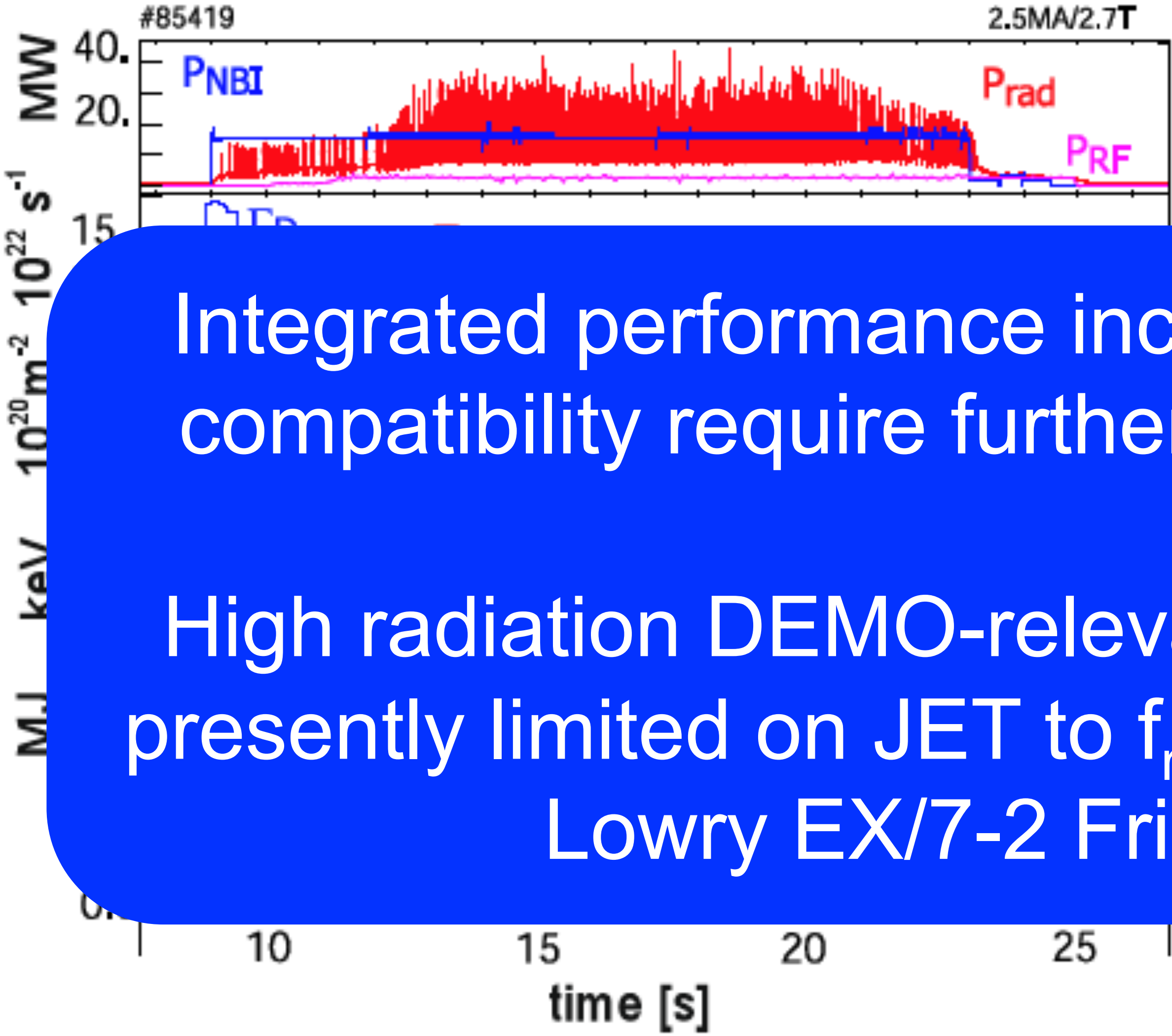
[C. Giroud, EX/P5-25]

- Semi-detached divertor operation in both legs
- No feed-back required
- Stationary conditions ~7s=26×τ_E

		ITER
▪	H_{98}~ 0.85	1.0
▪	β_N~1.6	1.8
▪	f_{GW}~ 0.85	0.85
▪	Z_{eff}~ 1.6	1.6
▪	$\Delta W_{ELM}/W_{ped}$~4%	1%

- **Similar scenario to be developed with Ar or Ne for DT campaign**

Integrated performance with N-seeding and divertor compatibility



- Semi-detached divertor operation in both legs
- No feed-back required

Integrated performance including divertor compatibility require further development

High radiation DEMO-relevant discharges presently limited on JET to f_{rad}=75% (see C. Lowry EX/7-2 Friday)

- **Similar scenario to be developed with Ar or Ne for DT campaign**

[C. Giroud, EX/P5-25]

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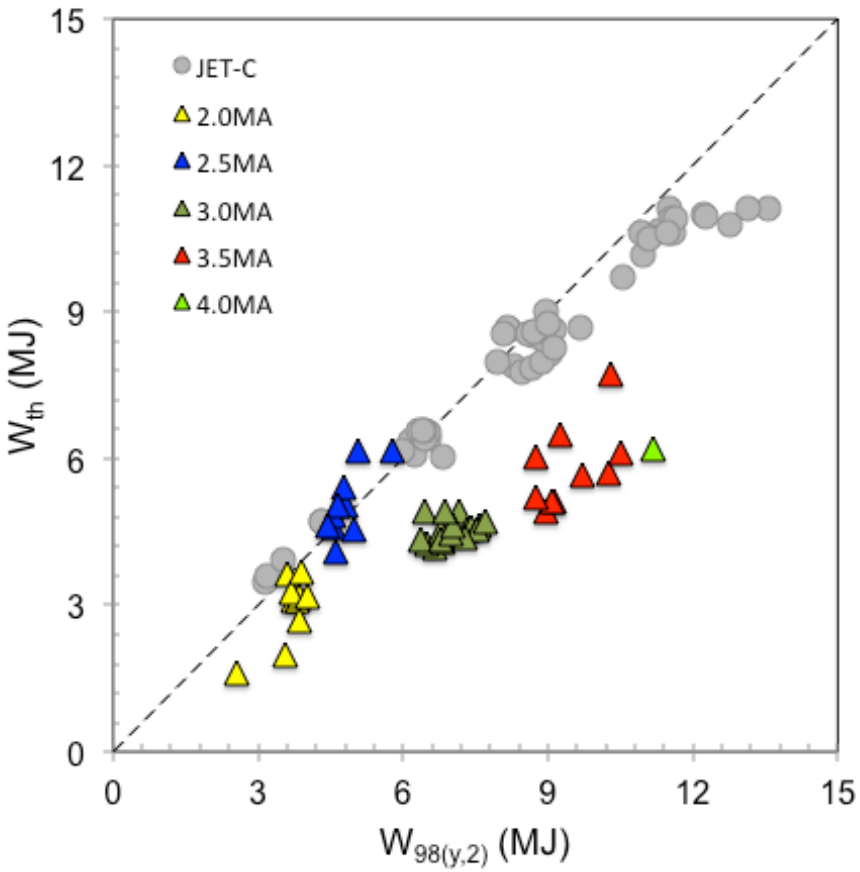
Progress to maximum performance



Maximum performance in JET is still being optimised but suffers from:

- Lack of power to reach moderate / high β at full current
- Power handling limits that require divertor sweeping – away from the position of maximum exhaust
- Minimum gas (or ELM frequency) to control W accumulation

[I. Nunes, EX/9-2 Friday]

Progress to maximum performance

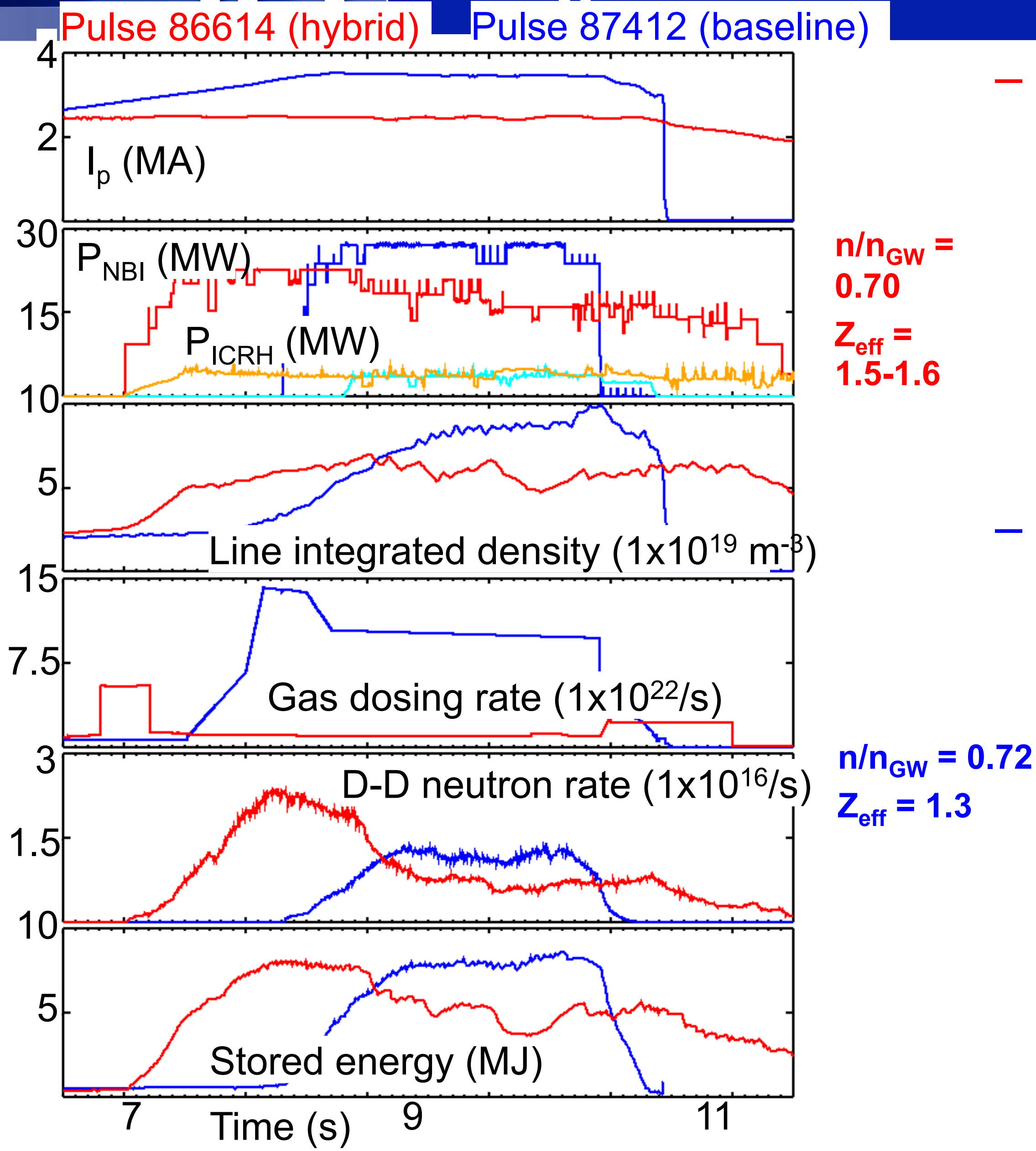
Maximum performance in JET is still being optimised but suffers from:

Further optimisation will be a primary goal in 2015 and is driving upgrades planned for the 2014/15 shutdown:

- **Re-instate ITER-like Antenna to increase central heating for W control**
- **Relocate High Frequency Pellet Injector to facilitate ELM pacing (also DEMO-relevant [P. Lang, SOFT 2014])**

[I. Nunes, EX/9-2 Friday]

Progress to maximum performance



- Hybrid: 2.5MA/2.9T (q_{95}=3.7): Transient good confinement phase of ~1 s Limited by MHD and divertor compatibility (low gas fuelling rate).
- Baseline: 3.5MA/3.3T (q_{95}=3): Stationary plasmas. Limited by very high gas dosing rates (to minimise risk of disruption) and temperature limit on divertor.

Progress to maximum performance

	Hybrid		Baseline	
	2014	DT extrapolation	2014	DT extrapolation
I_p (MA)	2.5 →	3.5	3.5 (4) →	4.5
B_t (Tesla)	2.9	3.85	3.4	3.85
q_{95}	3.8	3.65	2.9	2.9
P_{NBI} (MW)	24 →	34	27 →	34
P_{ICRH} (MW)	4	5	4	5
W_{dia} (MJ)	7.5	12	8	12
Duration (s)	1	5	2-3	5
Limitation	MHD	TF I^2t	T_{surf} of divertor	TF I^2t
P_{fus} (MW)	(7)	15*	(4)	13**

: Extrapolated from JET-C data* * 8MW for H_{98}=0.8*

Projection do not include alpha power and isotope effect on confinement.

Compatibility with divertor operation still to be achieved for long pulse operation.

Progress to maximum performance

	Hybrid		Baseline	
	2014	DT extrapolation	2014	DT extrapolation
I_p (MA)	2.5	3.5	3.5 (4)	4.5
Limitation	MHD	TF I^2t	T_{surf} of divertor	TF I^2t
P_{fus} (MW)	(7)	15*	(4)	13**

: Extrapolated from JET-C data* * 8MW for H_{98}=0.8*

Plasma operation with the ITER-like Wall:

- Is ~ready for T-T operation in 2017 (retention, isotope scaling, RF studies)
- Needs further development of ITER scenarios at high performance in 2015

Projection do not include alpha power and isotope effect on confinement.

Compatibility with divertor operation still to be achieved for long pulse operation.

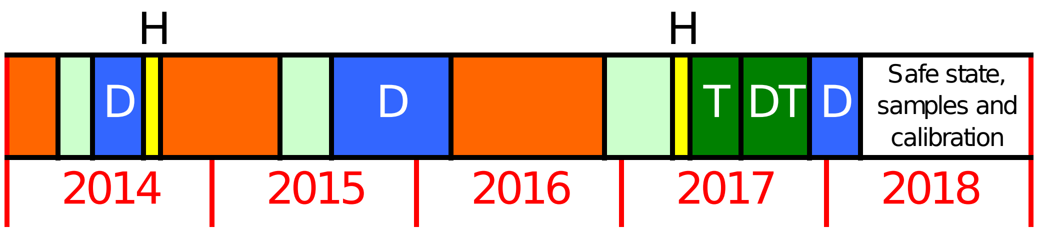
Outline

- JET programme in support of ITER
- Operation of JET with the ITER-like wall (ILW)
  - Tungsten Melt Experiment
  - Material Migration & Retention
  - Disruptions and Runaway Electrons
- H-mode physics in an all-metal environment
  - H-mode optimization with the ILW
  - Stationary N-seeded discharges
  - Progress to maximum fusion performance
- Conclusions and perspectives

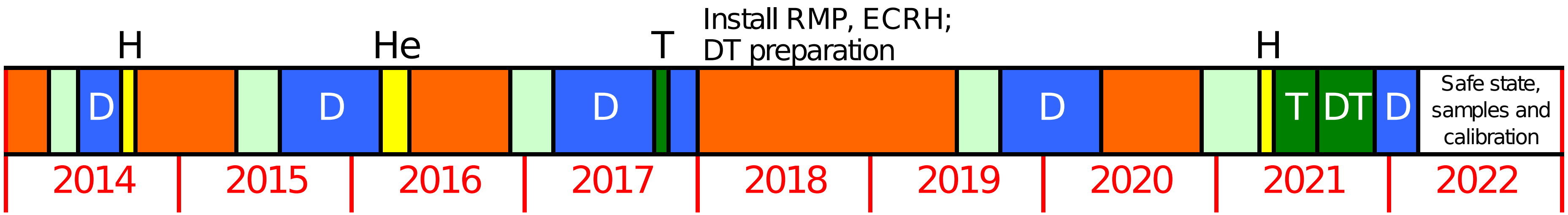
JET Forward Programme

There are two possible scenarios for the future use of JET:

Reference Scenario:



Alternative Scenario:



*Details of the Alternative Scenario are not yet agreed

Conclusions

- Operation with shallow W melting have been demonstrated on JET. Agreement with MEMOS predictions.
- Retention/migration path reproduced by WallDYN. More than 3000 full DT shot on ITER to reach maximum T inventory.
- High-confinement H-mode have been re-established at 2.5MA by optimizing the magnetic configuration.
- Divertor compatible regimes established with N-seeding. Confinement optimization in progress.
- The preparation of the DT campaign in 2017 has started and the demonstration of high (equivalent) fusion gain discharges will be the main objective of the 2015-16 JET programme.

Other JET contributions at this conference

L. Aho-Mantila Assessment of Scrape-off Layer Simulations with Drifts against L-mode Experiments in ASDEX Upgrade and JET

I Bolshakova Experimental Evaluation of Stable Long-Term Operation of Semiconductor Magnetic Sensors in ITER-Relevant Environment

C. Bourdelle L to H mode transition: Parametric dependencies of the temperature threshold

W.A. Cooper Equilibrium and Fast Particle Confinement in 3D tokamaks with toroidal rotation

E. Delabi e Overview and Interpretation of L-H Threshold Experiments on JET with the ITER-like Wall

D. Douai Experimental and modelling results on wall conditioning for ITER operation

A. Garcia-Carrasco Comprehensive First Mirror Test for ITER at JET with ITER-Like Wall

S. Gerasimov JET and COMPASS Asymmetrical Disruptions

M. Groth Steps in validating scrape-off layer simulations of detached plasmas in the JET ITER-like wall configuration

GMD Hogeweij Interpretation of W evolution in JET and AUG and implications for ITER

GTA Huijsmans Non-linear MHD Simulations for ITER

P. Jacquet Maximization of ICRF power by SOL density tailoring with local gas injection

A Jarvinen Comparison of H-mode plasmas in JET-ILW and JET-C with and without impurity seeding

F. Jenko Can gyrokinetics really describe transport in L-mode core plasmas?

A.B. Kukushkin Theoretical Model of ITER High Resolution H-alpha Spectroscopy for a Strong Divertor Stray Light and Validation Against JET-ILW Experiments

M. Lennholm Real-Time Control of ELM and Sawtooth Frequencies: Similarities and Differences

V. Leonov Simulation of the Pre-Thermal Quench Stage of Disruptions during Massive Gas Injection and Projections for ITER

T. Loarer Plasma isotopic change over experiments in JET under Carbon and ITER-Like Wall conditions

J.R. Martin-Solis Formation and termination of runaway beams in tokamak disruptions and implications for ITER

S. Moradi Core micro-instability analysis of JET hybrid and baseline discharges with carbon wall

V. Plyusnin Parameters of Runaway Electrons in JET

M. Rubel An Overview of Erosion-Deposition Pattern in JET with ILW

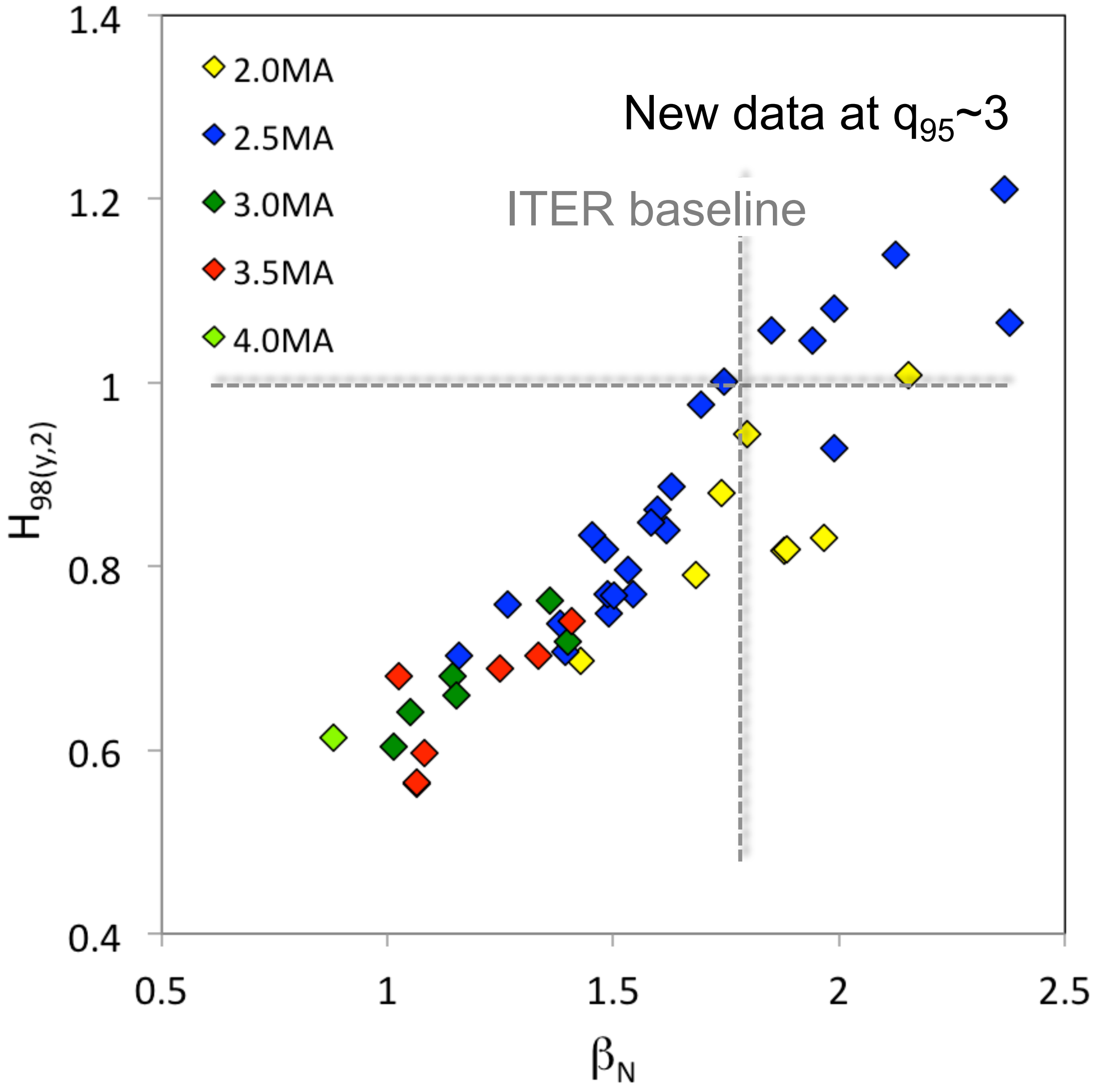
A.C.C. Sips Progress in Preparing Scenarios for ITER Operation

S. Varoutis Simulation of neutral gas flow in the JET subdivertor and comparison with experimental results

T. Wauters ICRF Discharge Production for Ion Cyclotron Wall Conditioning on JET

R. Zagorski Integrated core-SOL-divertor modelling for ITER including impurity: effect of W on fusion performance in H-mode and hybrid scenario

Plasma Energy Confinement



Optimisation, including placing the divertor strike point so as to maximise pumping, allows access to the ITER targets of H_{98}=1 and β_N=1.8