PSI Investigations in the JET full W divertor (ITER-Like Wall)

S. Brezinsek

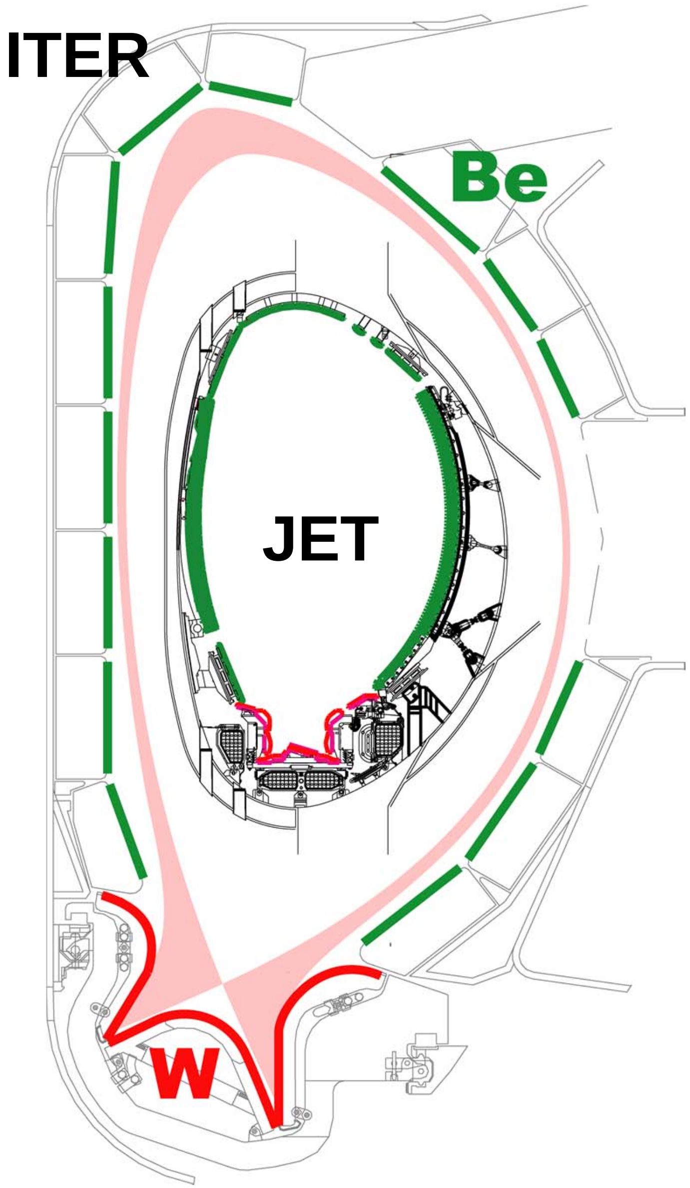
for TFE, E1, E2, S1 and JET EFDA contributors

JÜLICH FORSCHUNGSZENTRUM

Outline

- ITER-Like Wall at JET
- Operational space of ILW components
- Strategy of preparatory work
  - Development of compatibility tools to control heat loads and transients
  - Reference plasmas for direct comparison of graphite and metallic wall
- Plans for ILW exploitation

The Wall Combination for the DT Phase in ITER



Be wall and W divertor in JET

- Material combination for the first time used
- Replacement of the wall in one shutdown

- "Carbon-free" environment
  - Reduced material migration to rem. areas
  - Reduced tritium retention
  - Loss of carbon as main radiator

- Change in operational space
  - Need for better plasma control
  - Need for heat load mitigation schemes

NBI upgrade in JET

- Parallel upgrade of neutral beam system
  - Maximum power from 20 to 34 MW
  - Maximum duration from 10 to 20 s

Plasma-Wall Interaction Issues

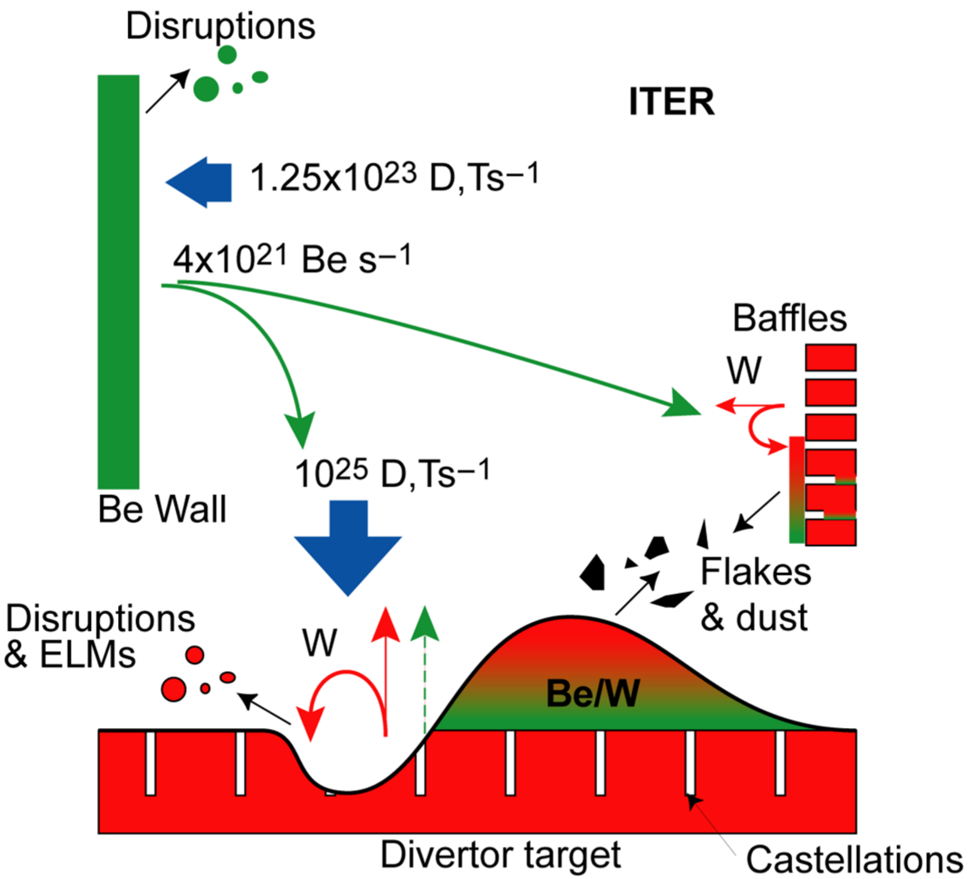
Important PWI questions for ITER will be addressed in JET with the ILW

Steady-state operation

- **Be wall erosion and transport**
- **W erosion and prompt deposition**
- **Be-W material mixing**
- **Be:D layer formation**
- **Fuel retention**
- **Re-erosion of (mixed) layers**
- **Material Transport to remote areas**

Transients

- **Be/W Melt layer motion, loss and stability**
- **Metallic dust formation**



Matthews et al.

Role of remaining impurities: residual C and O

Scenario Compatibility

Strong link between plasma wall interaction and scenario compatibility

- **Adaption of magnetic shape – use of bulk W divertor**
- **Neutral beam shine-through – high density operation needed**
- **W impurity production – low plasma temperature in divertor necessary**
- **W sputtering by ELMs – ELM control to reduce sputtering (and flushing)**
- **W accumulation in core region – need for central heating (ICRH)**

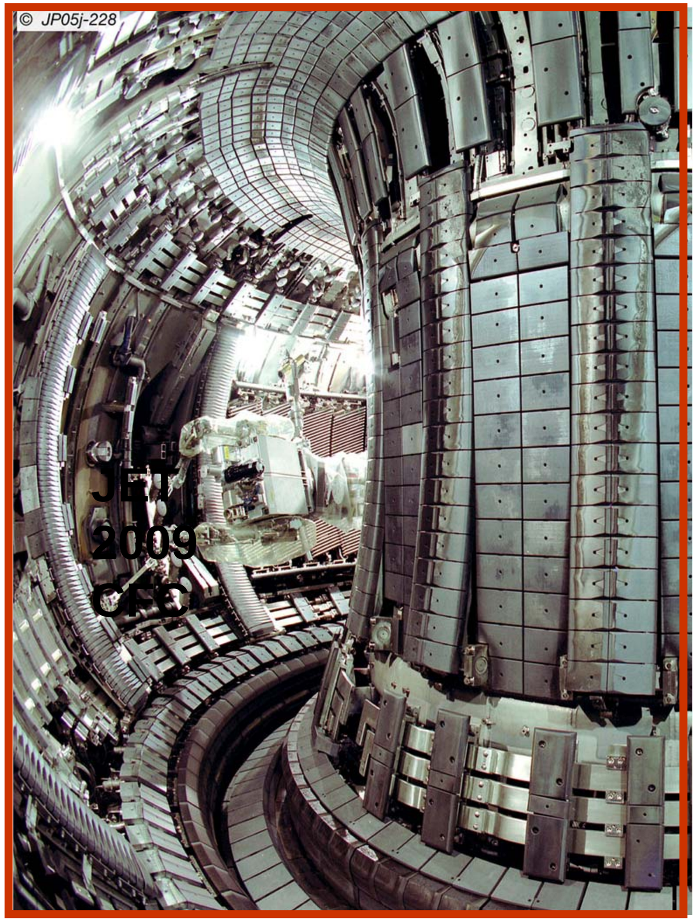
=> High recycling or semi-detached divertor operation favourable/needed
=> Impact on confinement and plasma energy content

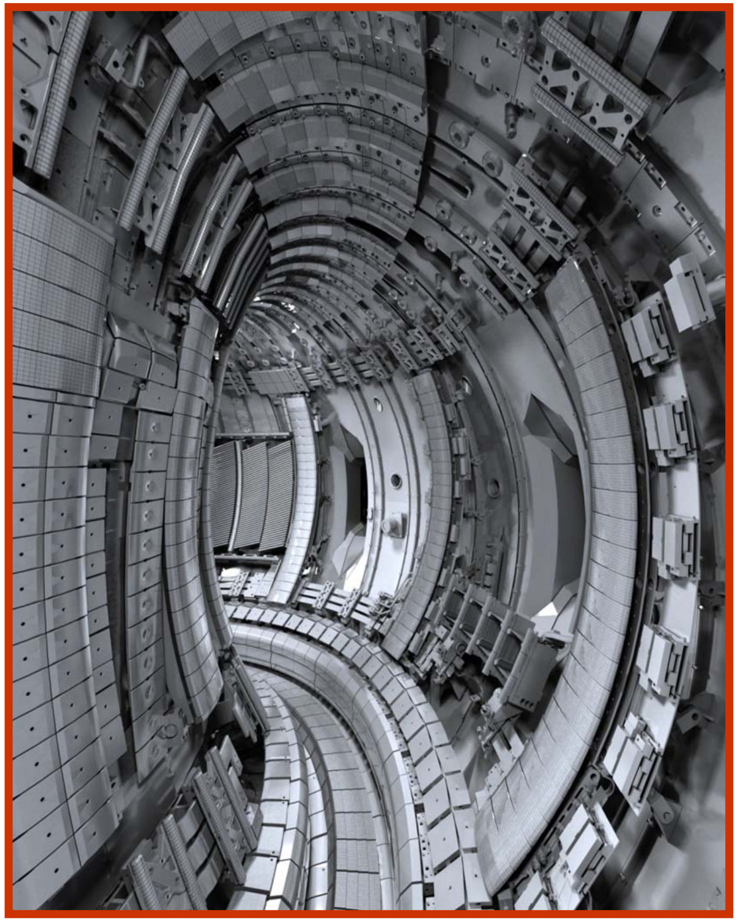
Outline

- ITER-Like Wall at JET
- Operational space of ILW components
- Strategy of preparatory work
  - Development of compatibility tools to control heat loads and transients
  - Reference plasmas for direct comparison of graphite and metallic wall
- Plans for ILW exploitation

Replacement of Wall Components

JET (2009)
CFC and
Be layer
(evapor.)





JET (2011)
Be first wall
W divertor

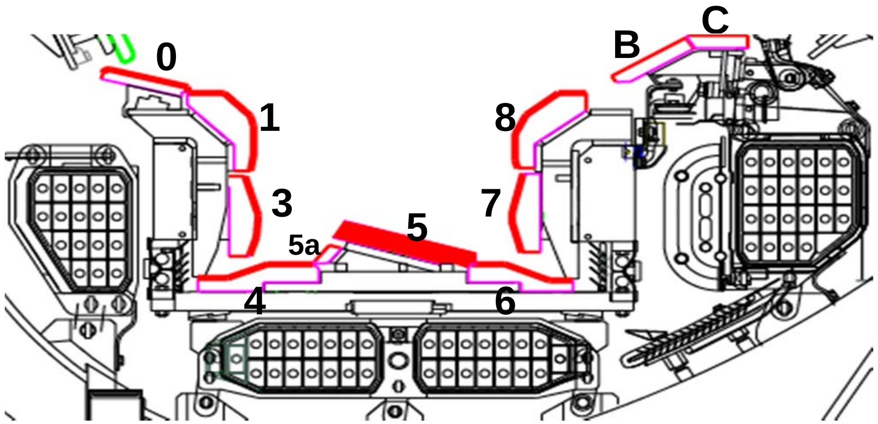
ILW main chamber

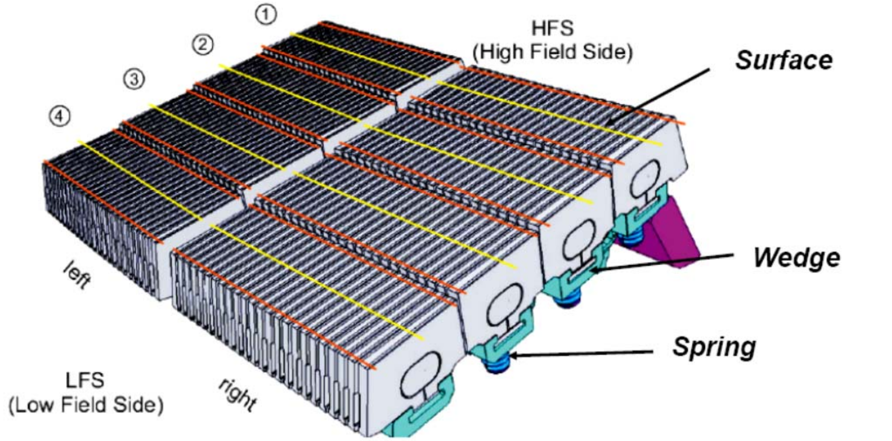
- Massive Be tiles on main chamber limiters
- Be-coating on Inconel recessed areas
- W-coating on CFC in NBI shine-through area

ILW divertor

- W-coated CFC tiles in the divertor
- Bulk W tile with lamella structure used as outer divertor target plate

Operational Space of ILW Components (Divertor)



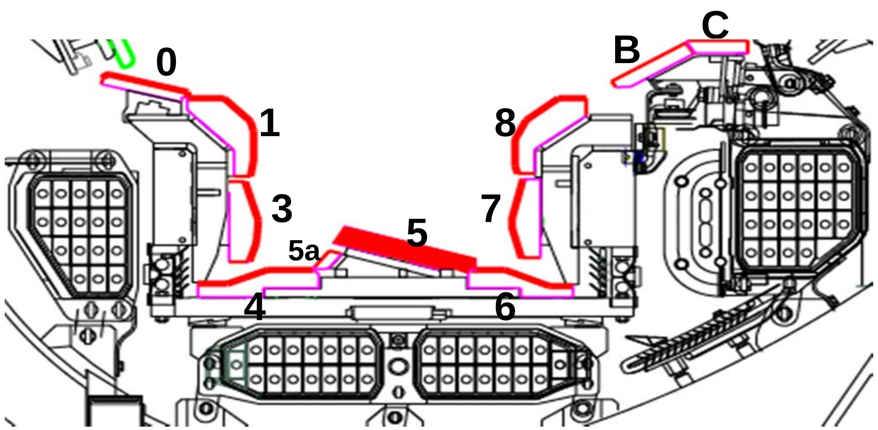


CPM Ph. Mertens

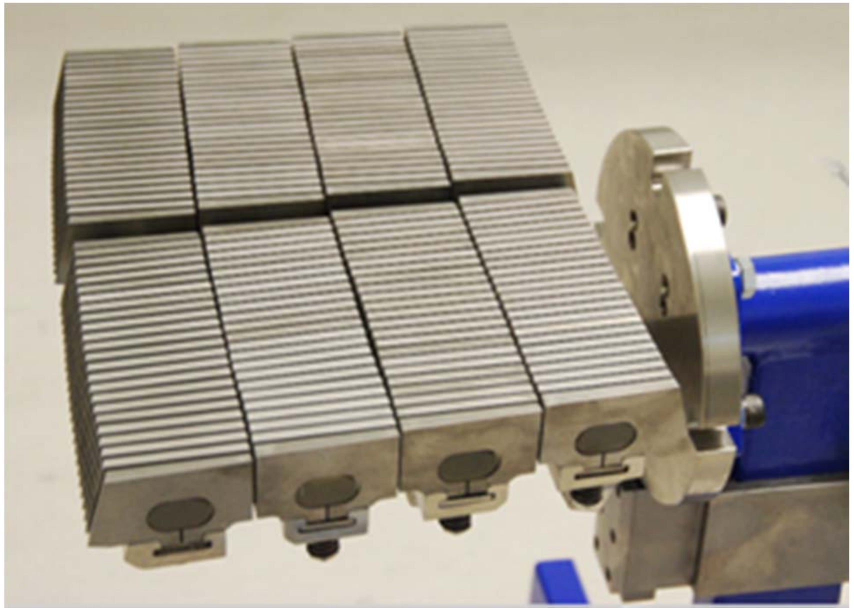
Bulk W tile (tile 5) – design and realisation by FZJ

- **“Shape” pre-defined from CFC divertor tile 5. No active cooling!**
- **Bulk W tile for outer divertor segmented in 4 stacks with 24 lamellae each**
- **Energy limit per stack of ~60MJ determined by substructure**
  - **limit depends on wetted fraction area => configuration dependent!**
- **Power limit of the surface temperature => W recrystallisation phase 1: 1200°C and final phase: 2200°C**
- **Cool-down time important => Reduction of plasma repetition rate**
- **Complex operational instructions to avoid melting of substructure**

Operational Space of ILW Components (Divertor)



CPM Ph. Mertens

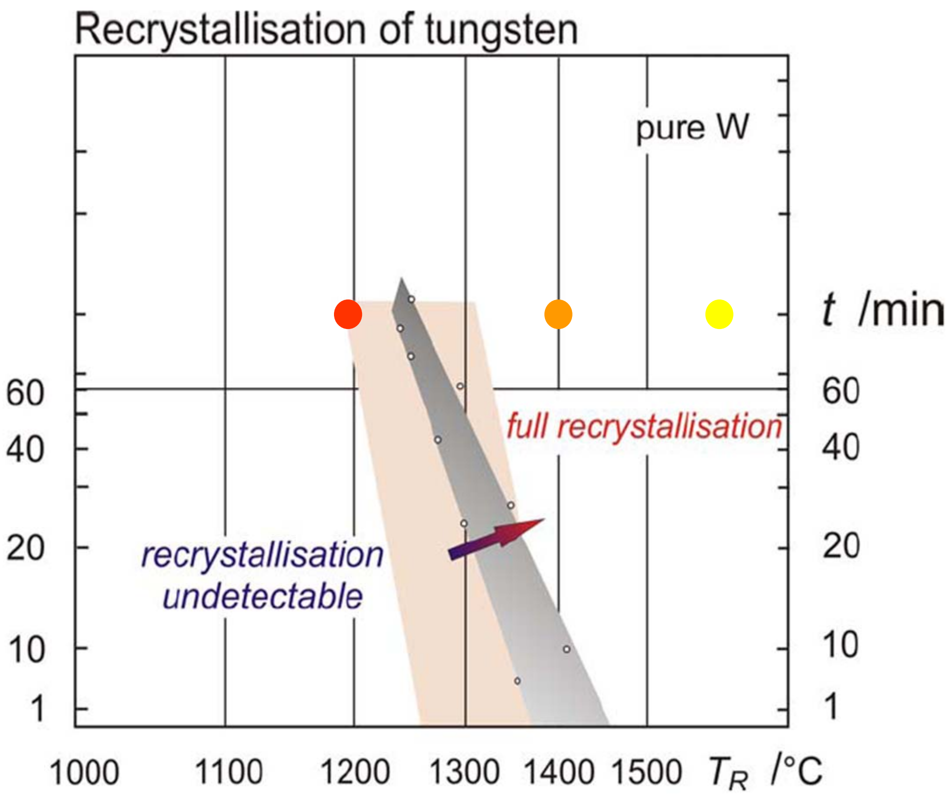


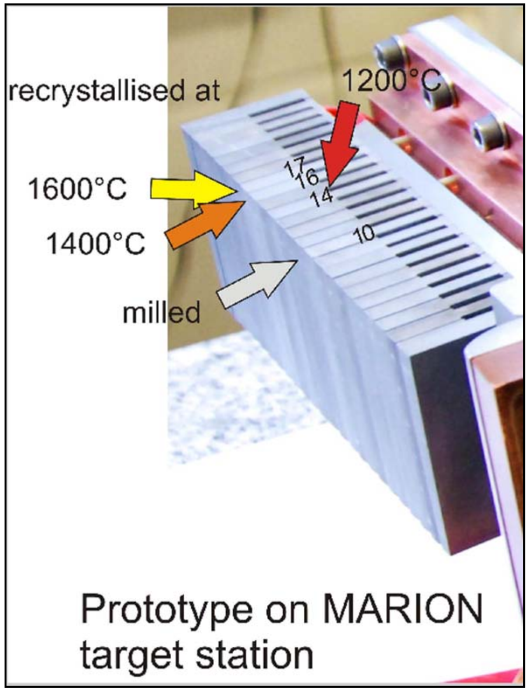
Bulk W tile (tile 5) – design and realisation by FZJ

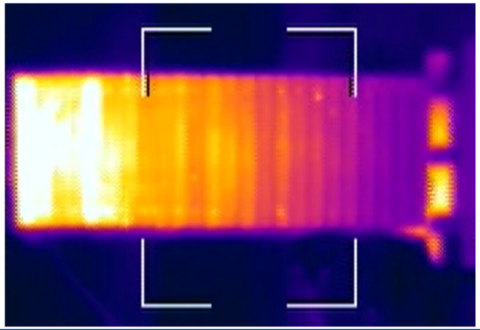
- "Shape" pre-defined from CFC divertor tile 5. No active cooling!
- Bulk W tile for outer divertor segmented in 4 stacks with 24 lamellae each
- Energy limit per stack of ~60MJ determined by substructure
  - limit depends on wetted fraction area => configuration dependent!
- Power limit of the surface temperature => W recrystallisation phase 1: 1200°C and final phase: 2200°C
- Cool-down time important => Reduction of plasma repetition rate
- Complex operational instructions to avoid melting of substructure

Operational Limit Tests / W-Recrystallisation

MARION - Testing at 60MJ for steady-state operation in ion beam facilitiy



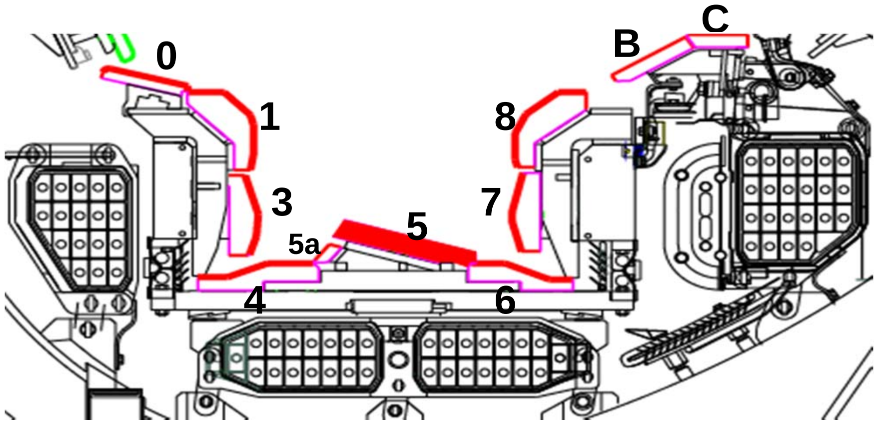




Ion
Beam

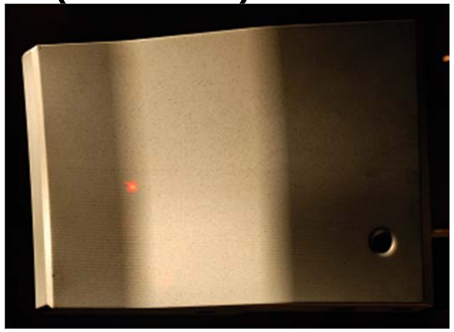
Recrysallisation is not expected to be a limitation!

Operational Space of ILW Components (Divertor)

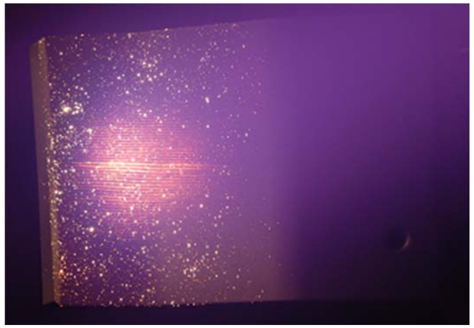


CPM H. Maier

Tile 4 in GLADIS (ion beam)



No damage in cycling up to 1600°C



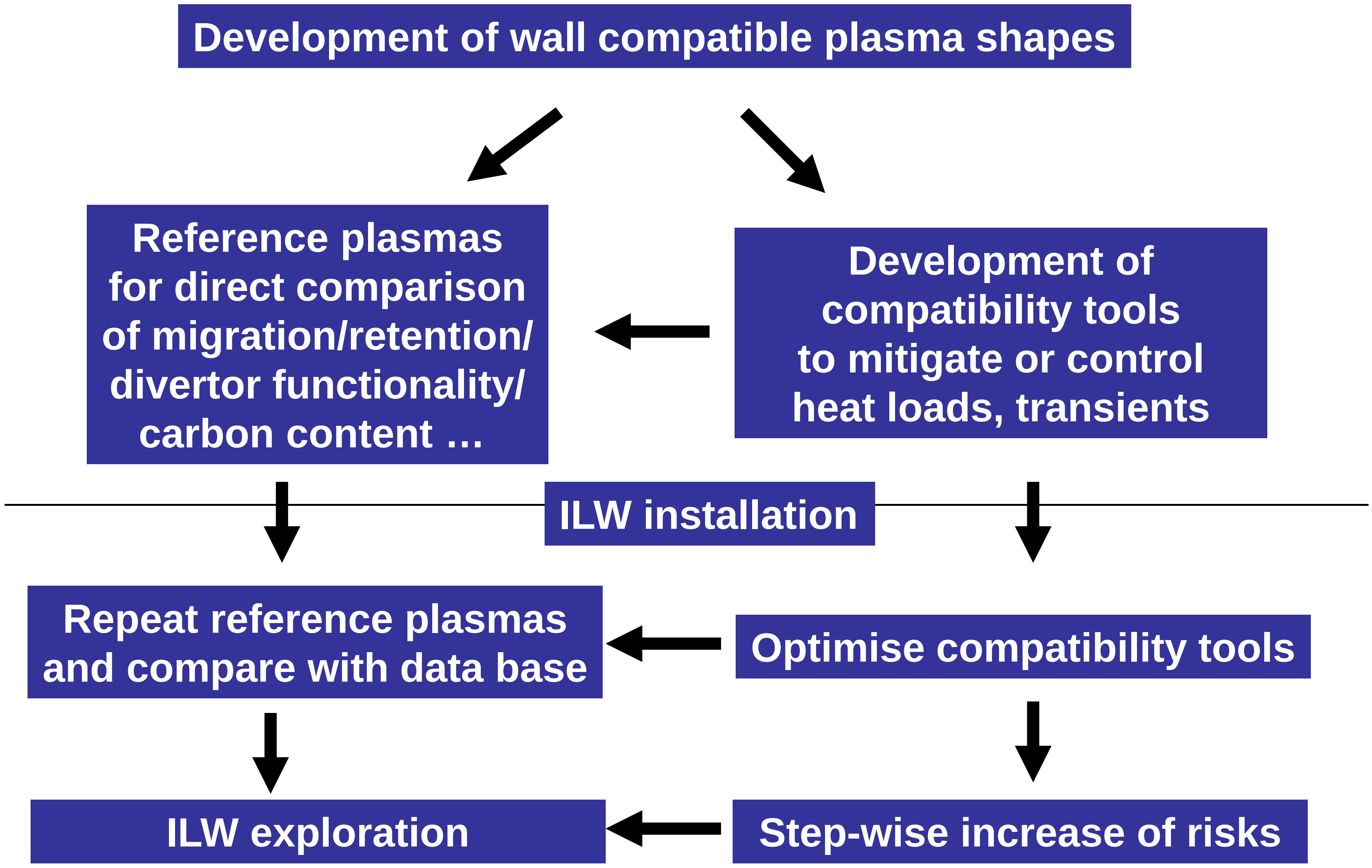
W-coated CFC tiles – test and qualification IPP

- W coating on standard 2D Dunlop CFC at JET (project requirement)
- No active cooling!
- Expected lifetime of 25µm W-coating for tile 6&7 ~100000s
  extrapolation from test coatings of 3 µm thickness in previous campaigns
- (Additional) limitations by carbidisation and inhomogeneous erosion
- Energy limit of W-coated CFC tiles is 90 MJ/m^2
- Power limit of W-coated tiles - phase 1: 1200°C, phase 2: 1600°C
- Limitations with respect to multiple ELM energy load: ~125kJ/m^2 (?)
  but depends on starting value (preliminary)

Outline

- ITER-Like Wall at JET
- Operational space of ILW components
- Strategy of preparatory work
  - Development of compatibility tools to control heat loads and transients
  - Reference plasmas for direct comparison of graphite and metallic wall
- Plans for ILW exploitation

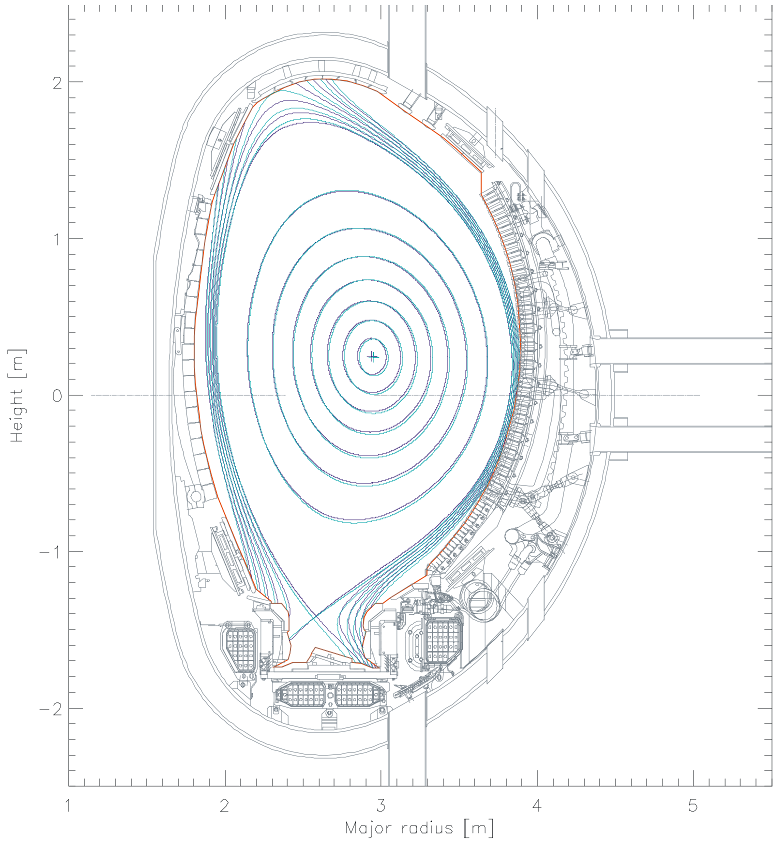
Strategy of Preparatory Work



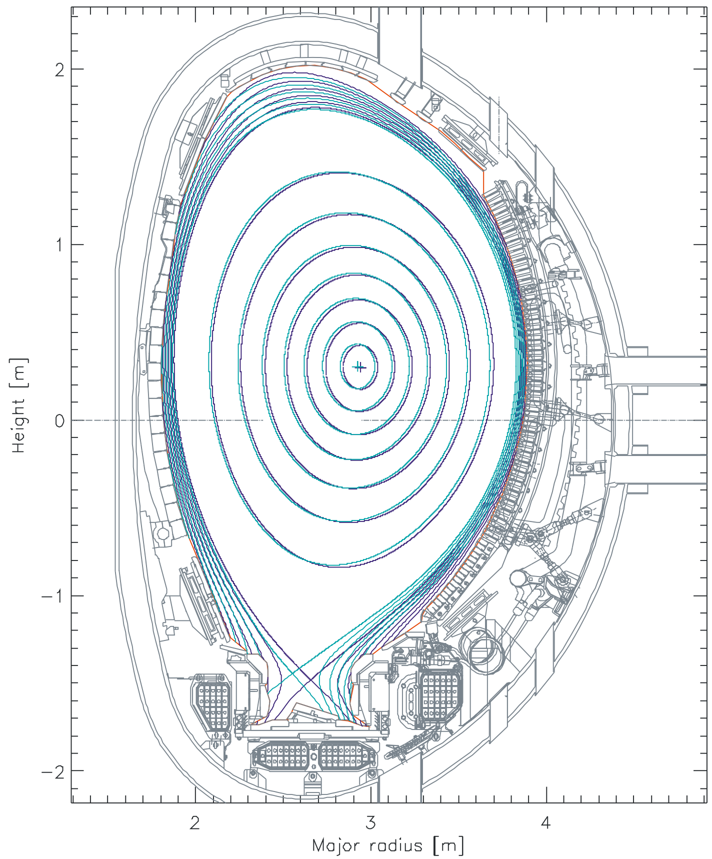
Plasma shape

- Shift of the outer-strike point from tile 6 to tile 5 (bulk W with ILW)
- Change in pumping capability / proximity inner strike point and tile 1

high triangularity (δ=0.42)



low triangularity (δ=0.27)



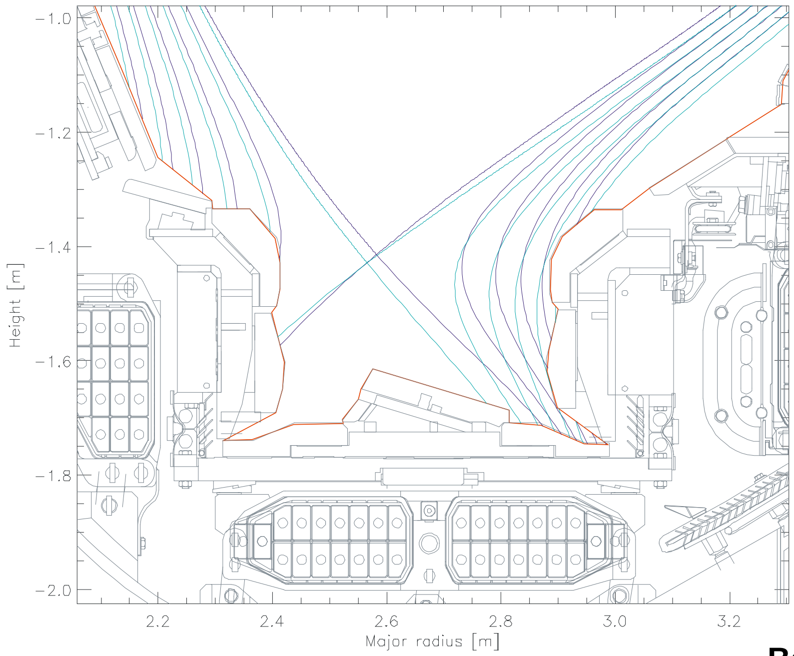
Baseline scenario: P. Lomas, I. Nunes et al.

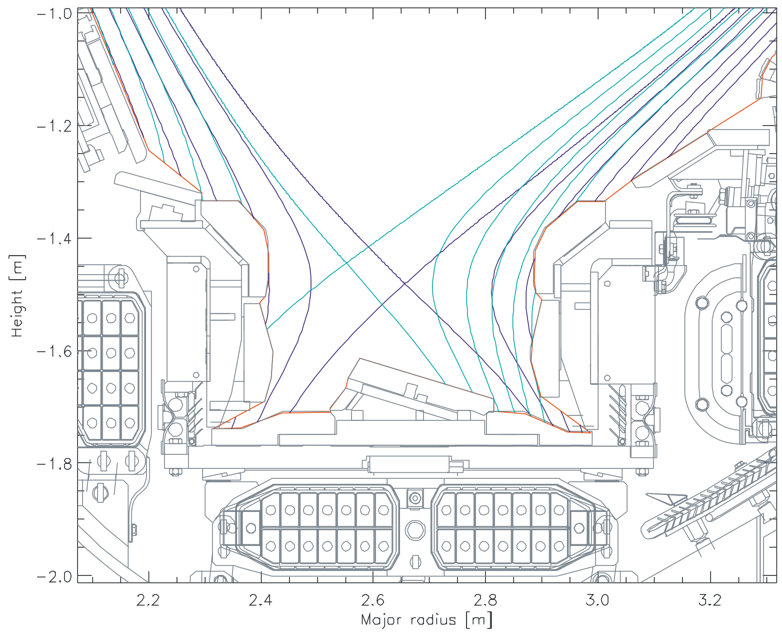
- Majority of preparatory experiments and reference plasmas in similar shapes

Plasma shape

- Shift of the outer-strike point from tile 6 to tile 5 (bulk W with ILW)
- Change in pumping capability / proximity inner strike point and tile 1

high triangularity (δ=0.42) **low triangularity (δ=0.27)**





Baseline scenario: P. Lomas, I. Nunes et al.

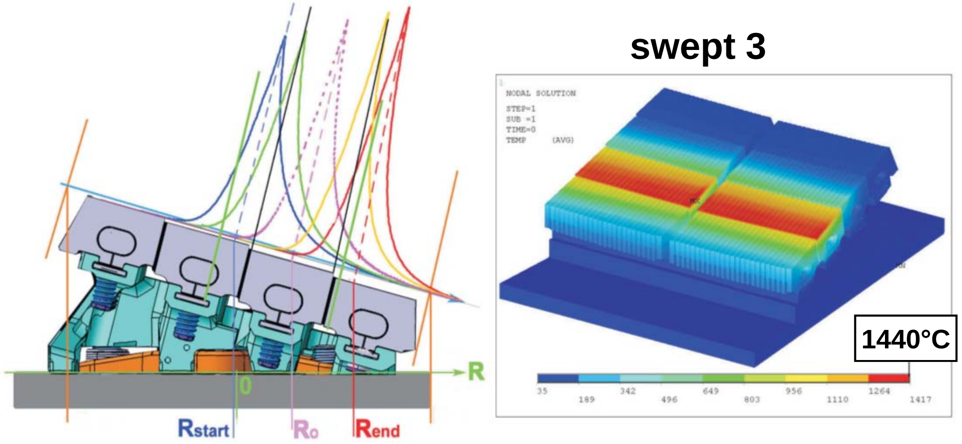
- Majority of preparatory experiments and reference plasmas in similar shapes

Strategy of Preparatory Work (in CFC divertor)

- Development of tools to control heat loads, transients and erosion
  - Techniques to reduce Inter-ELM heat load
  - Techniques to reduce ELM heat load
  - Techniques to reduce W erosion
  - Techniques to mitigate disruptions
- All techniques developed in the first step independent from each other, but combinations have been applied in the later phase of preparation.

Strike-point Sweeping to Redistribute Load

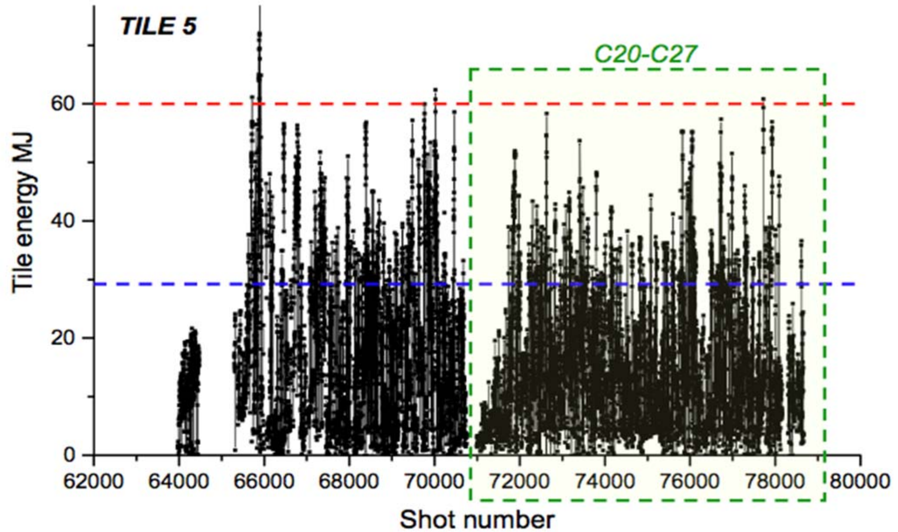
▪ Thermal modelling of energy load



Scenario	Maximal Energy (/MJ) deposited over						Temperature (W)
	stack 1 (HFS)	stack 2	stack 3	stack 4 (LFS)	tile 6	total	*Tsurf* max. *(approx., 1st pulse)*
uniform 3	0.0	0.0	60.0	0.0	0.0	60.0	1330°C
static 3	0.0	0.3	60.0	14.4	0.2	74.9	1890°C
swept 3	0.0	9.3	60.0	32.3	1.9	103.5	1440°C
swept 2+3+4	0.4	30.0	60.0	53.8	5.8	150.0	1400°C

Ph. Mertens PSI

▪ Tile 5 energy load in 2006-2009



Energy (MJ)	# pulses (%)
0-30	3797 (64%)
30-60	1997 (33%)
>60	169 (3%)
Total	5963

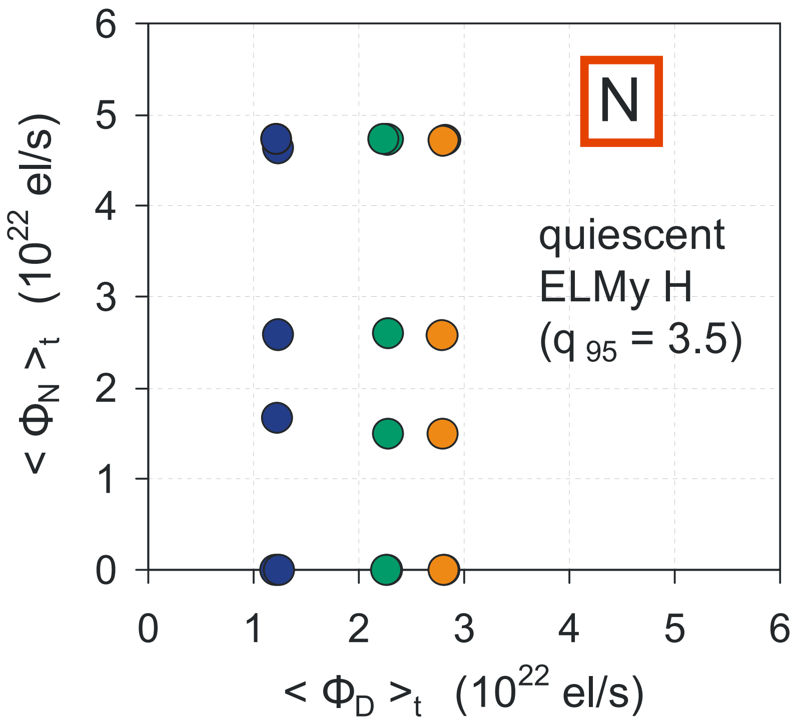
↓ need for sweeping

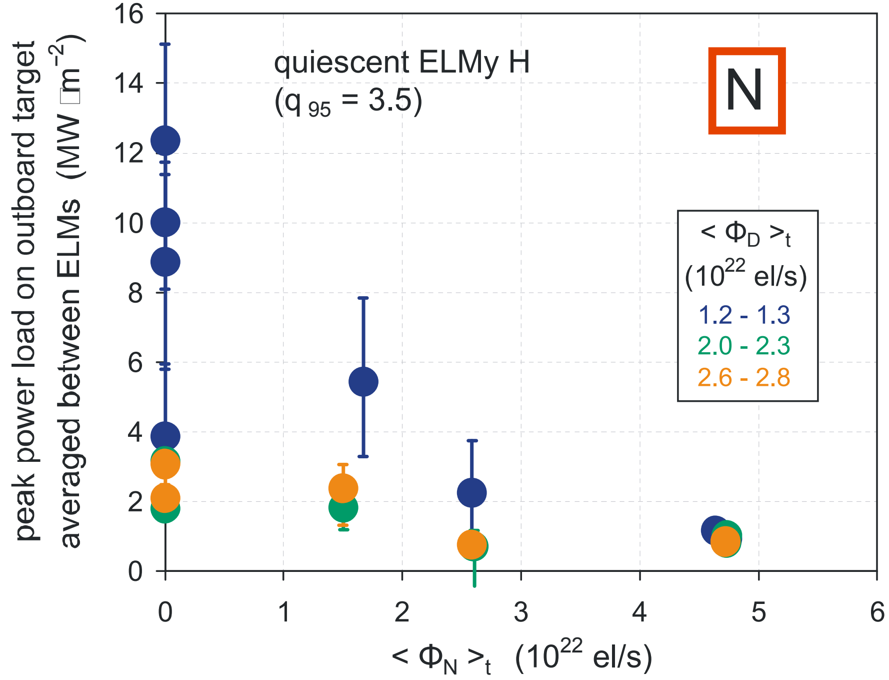
▪ **Modelling inline with ion beam tests on real W stacks for ILW**

▪ **Sweeping required for highest input powers**

Impurity Seeding Experiments

▪ Impurity seeding for radiation cooling and steady-state heat load mitigation



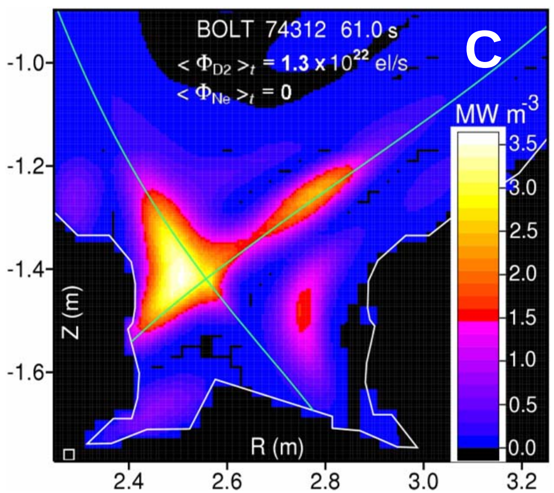


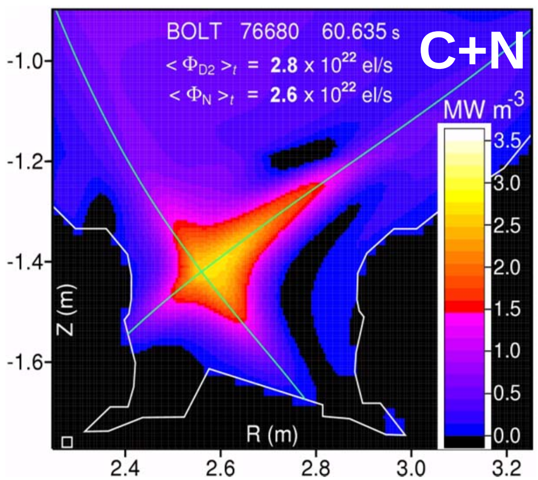
G.P. Maddison PSI

- **Matrix scans in D fuelling and N (Ne) seeding**
- **D fuelling tends to raise plasma density, while seeding generally lowers it**
- **Outboard inter-ELM peak heat load declines substantially**
- **Clear shot-to-shot legacy effect of nitrogen**

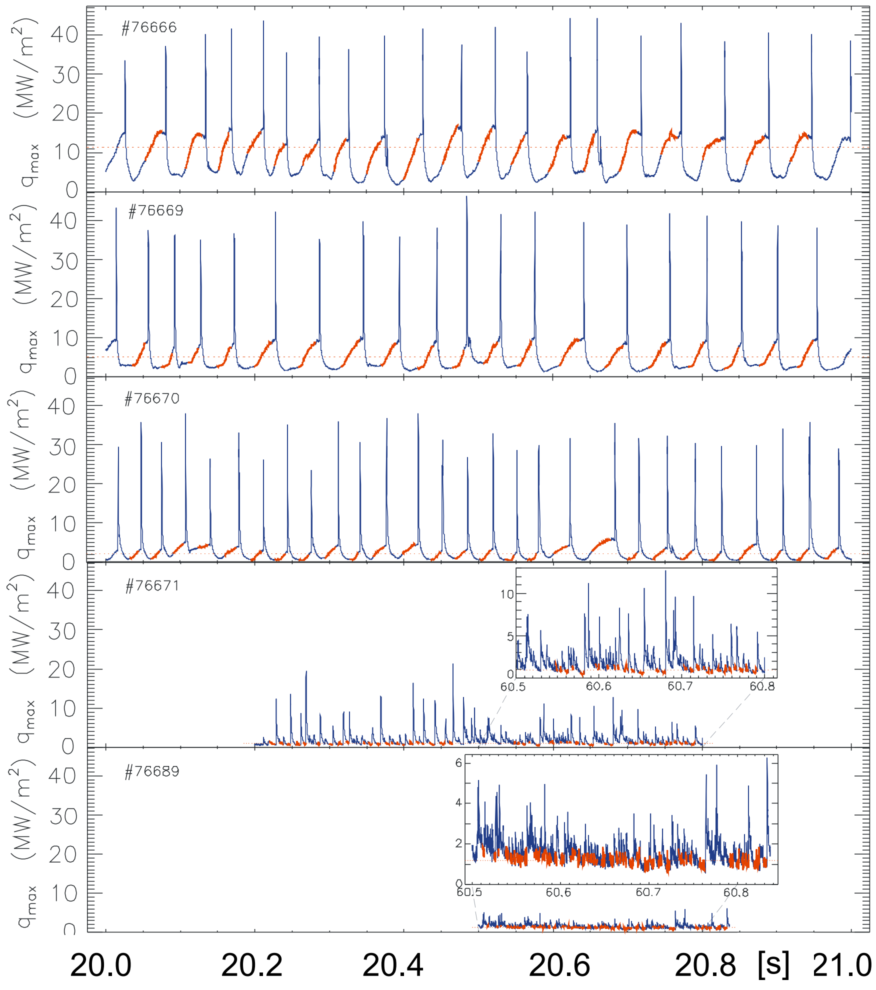
Impurity Seeding Experiments with N

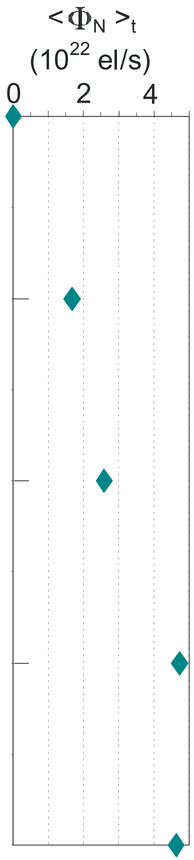
Radiation distribution in the divertor





Impact of nitrogen seeding on ELMs





nitrogen legacy effect

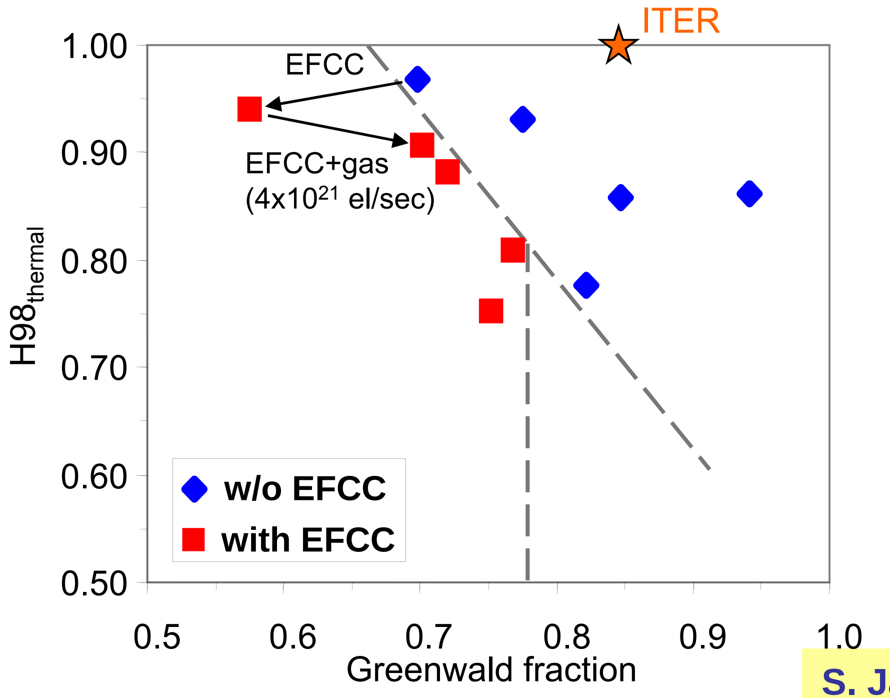
ELM energy and ELM heat load drops

ELM Control Techniques

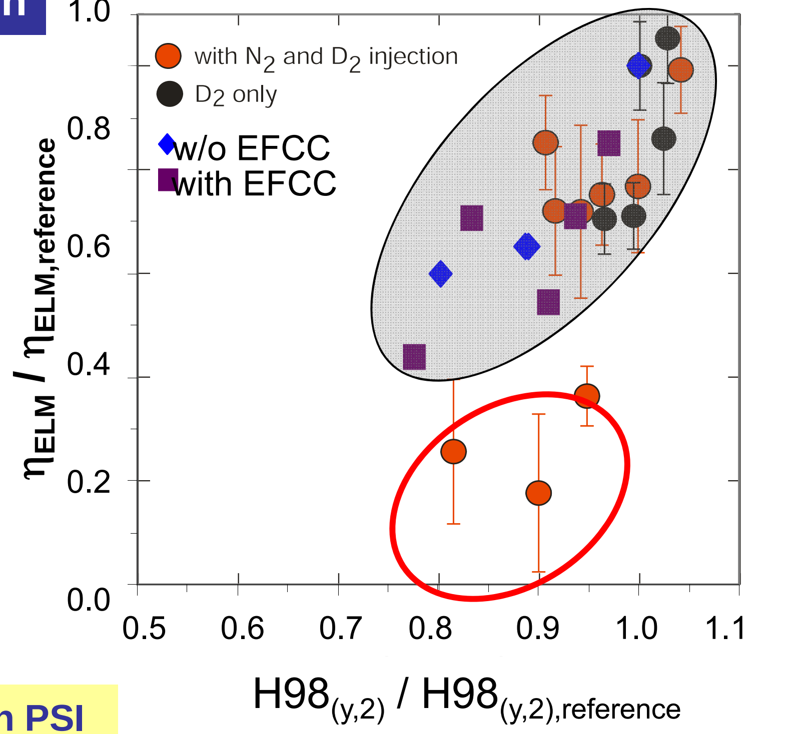
- **Three techniques have been compared at JET:**

(i) magnetic perturbation **(ii) vertical kicks** **(iii) deuterium & nitrogen fuelling**

All techniques: Increase of ELM frequency
Density pump put
Moderate confinement degradation



S. Jachmich PSI



- ELM pacing capabilities of kicks and EFCCs limited in fuelled plasmas **(control backup)**

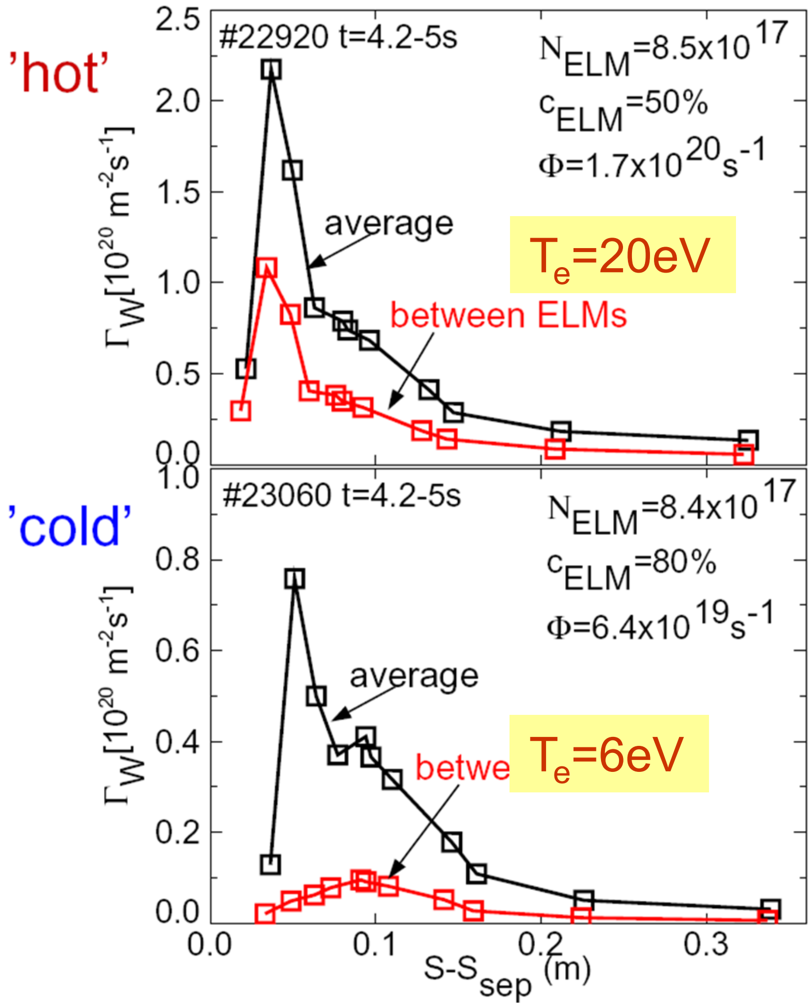
W Source Control in the Divertor

Experience from AUG full tungsten divertor
- **Absence of C radiation => "hot" divertor**
- **W erosion during ELM phases dominates**

Means to reduce W sputtering in JET
- **Radiation cooling**
- **ELM size control**

Optimal operation
- **Detached divertor plasma in the outer divertor with "mild" ELMs**
- **Natural detachment of the outer target by deuterium fuelling** ***S. Brezinsek et al. JNM 2009***
- **Semi-detachment due to fuelling and nitrogen seeding** ***J. Rapp et al. NF 2010***

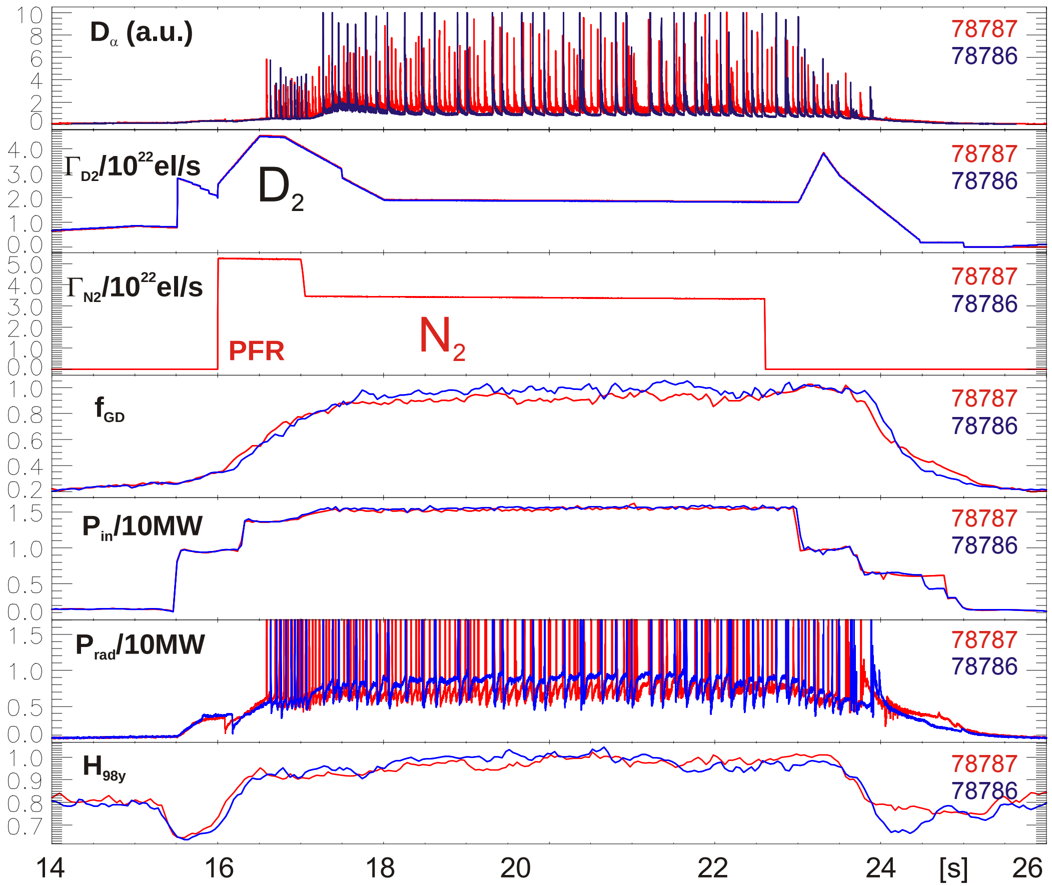
Experience from ASDEX Upgrade



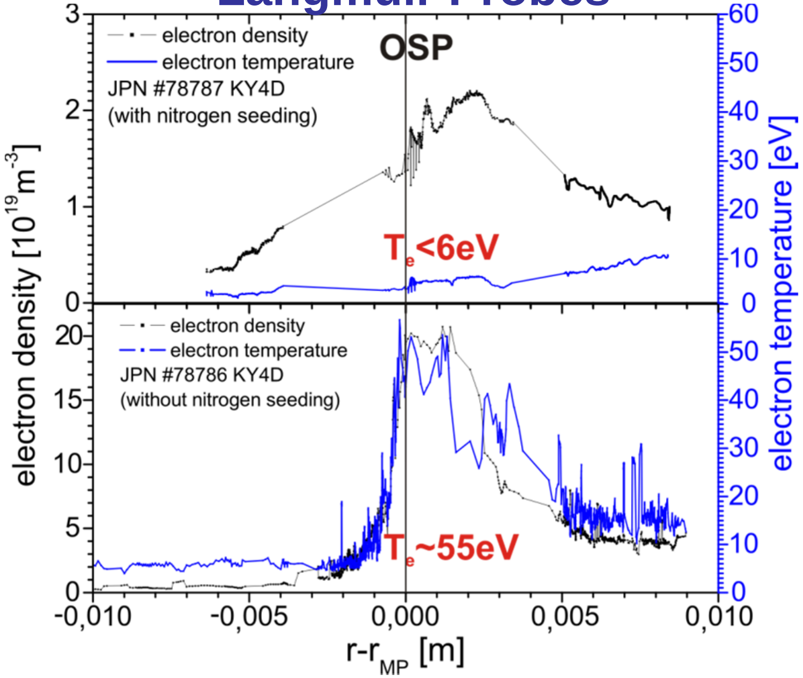
R. Dux et al. PSI2008

Detached and Recombining Plasma

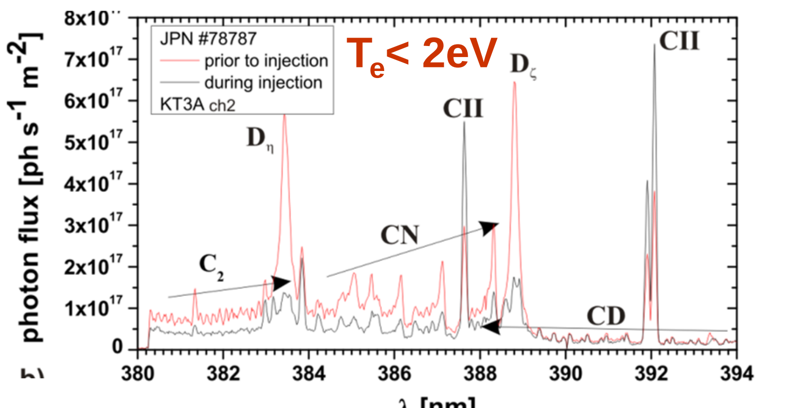
- Detachment and recombining plasma due to strong D_2 fuelling and N_2 seeding.
- ELM energy load acceptable



Langmuir Probes



Balmer recombination lines ratio

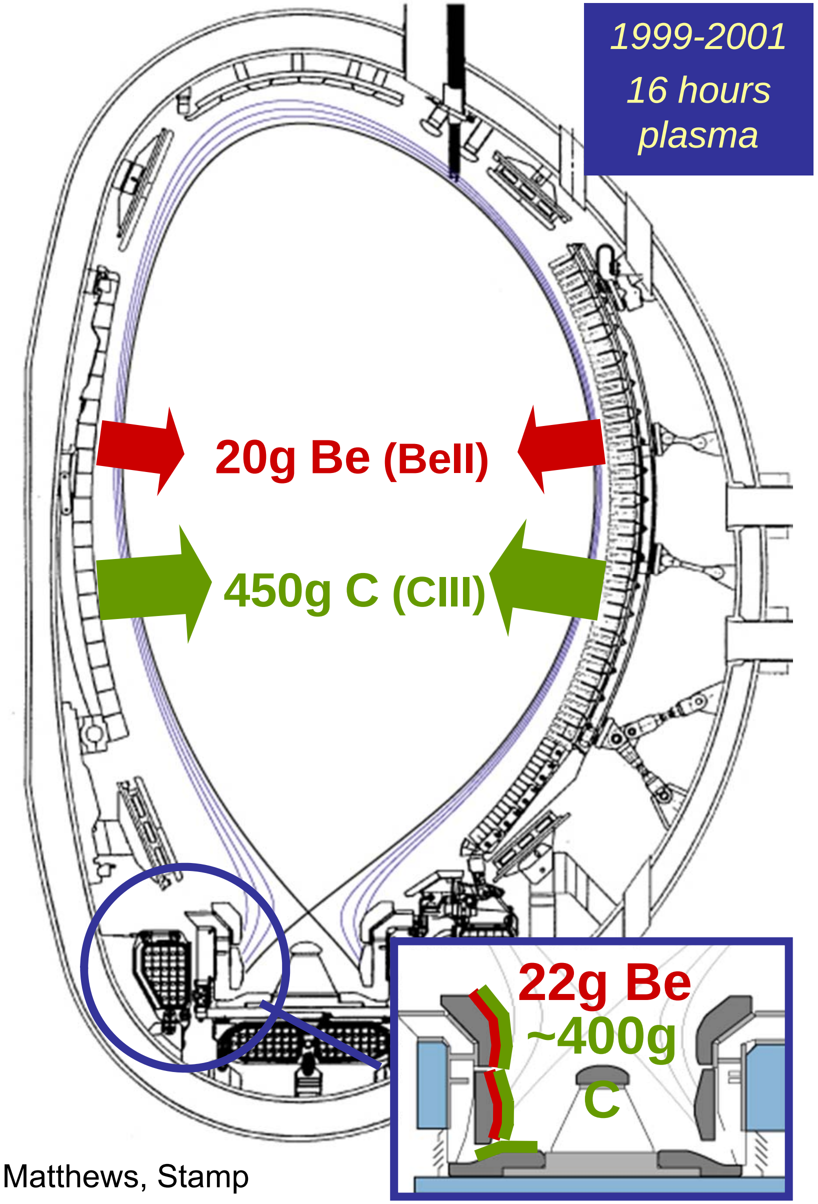


S.Brezinsek ICFRM 2009

Strategy of Preparatory Work (in CFC divertor)

- Reference plasmas for direct comparison of graphite and metallic wall
    - Global material migration
    - Migration to remote areas
    - Fuel retention data base
    - Divertor functionality and SOL properties
    - ICWC wall conditioning
- References were taken in the first period of operation with moderate input power without any control techniques, but combinations have been applied in the later phase of preparation

Material Migration (Global)



Matthews, Stamp

JET with C/Be material mix

- Ion and neutral bombardment to the PFCs
- Main chamber dominant erosion source
- Material transport to the inner divertor due to SOL flows (deposition zone)
- C transport to remote areas in steps
- Low Be content in remote areas
- Outer divertor in balance (MKII GB)
- C transport to remote areas in outer divertor observed (MKII HD)

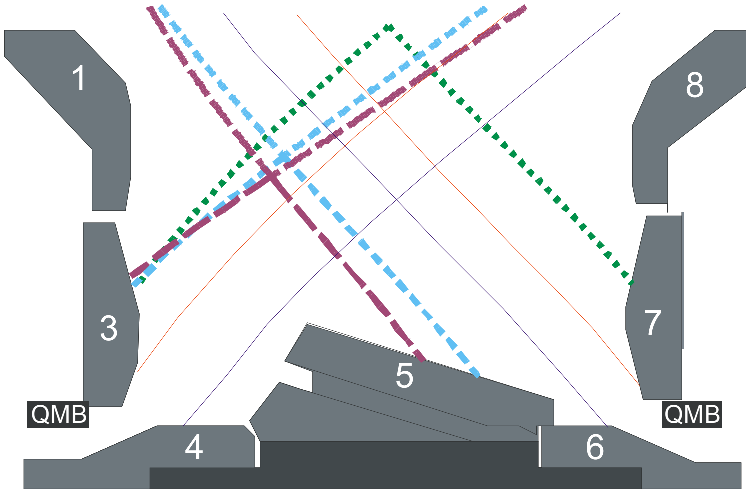
Database for migration / ILW comparison:

- New configurations and a large set of new diagnostics
- Variations in input power, plasma parameters, gas rate, regime etc.
- Reference discharges document the C/Be influx, concentration and migration

References for Material Migration Studies

Intrinsic carbon transport

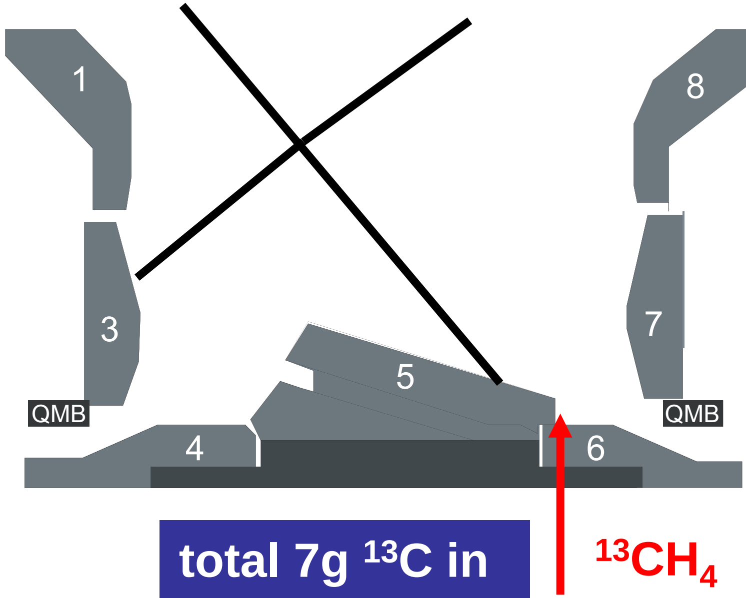
Material migration in outer divertor leg with comparable plasma and surface conditions



	inner QMB	outer QMB
OSP on tile 5	0.30 nm/s	0.58 nm/s
OSP on tile 5	0.66 nm/s	0.21 nm/s
OSP on tile 6	4.71 nm/s	-0.28 nm/s
OSP on tile 7	1.46 nm/s	0.37 nm/s
OSP on tile 7	0.58 nm/s	0.45 nm/s

Carbon tracer experiment

- **ILW reference plasma in H-mode**
- **Circ. injection into outer divertor**
- **Gas balance analysis in parallel**



total 7g ^{13}C in 30 discharges

M.Rubel and P. Coad et al.

- **1/3 of $^{13}CH_4$ pumped by divertor cryo**
- **Post-mortem analysis ongoing**

S. Brezinsek PSI **J. Likonen PSI**

Gas Balance Studies at JET

Repeat sets of identical discharges

Regenerate cryogenic pumps before and after expt.
→ collect total pumped gas

Calibrated Particle Source (Gas, NBI, pellets…)

Wall Retention Long & Short Term

Divertor cryo-pumps

T. Loarer
PFMC 2009

Injection = Pumped + Short Term Ret + Long Term Ret

Total recovered from cryo-regeneration:
Pumped + **intershot outgassing** over ~800s (assumed equal to **Short Term Ret**)

Dedicated series of experiments: L and H mode in 2007-2009 (ILW references)

Data Basis for Fuel Retention

Plasma HT3R	Injection (Ds^{-1})	Heating phase (s)	Long term retention (Ds^{-1})	Divertor phase (s)	Long term retention (Ds^{-1})	Normalisation to L-mode
L-mode early X	$\sim 1.7\times10^{22}$	75	2.40×10^{21}	170	1.05×10^{21}	0.83
L-mode late X	$\sim 1.8\times10^{22}$	81	2.04×10^{21}	126	1.27×10^{21}	1.00
Type III	$\sim 1.7\times10^{22}$	72	2.40×10^{21}	126	1.37×10^{21}	1.08
Type I	$\sim 1.7\times10^{22}$	32	2.83×10^{21}	50	1.70×10^{21}	1.33

- Long term retention in carbon-dominated JET depends on plasma scenario
- Increase of retention from L-mode to moderate type I ELMy H-mode by 33%
- Moderate impact of the limiter phase in the fuel retention experiments

Additional data sets provide similar retention rates: $\sim 1\text{-}2\text{x}10^{21}$ Ds^{-1}
- L- und H-mode in new LT configuration
- H-mode plasma with ELM control (vertical kicks)
- H-mode plasma including cleaning discharges for fuel recovery
- H-mode plasma with impurity seeding (nitrogen)
- H-mode plasma with tracer injection

Outline

- ITER-Like Wall at JET
- Operational space of ILW components
- Strategy of preparatory work
  - Development of compatibility tools to control heatloads and transients
  - Reference plasmas for direct comparison of graphite and metallic wall
- Plans for ILW exploitation

Plans for ILW Exploration

Scientific headlines

Characterisation of the ILW
Exploration of ITER operating scenarios with the ILW
Physics issues essential to the efficient exploitation of ILW

Exploitation plan

- Scientific experiments will begin with the very first plasma followed by progressive exploitation of all systems to their full capabilities
- Expansion of operational domain interspersed by periods of commissioning and interventions
- Step-wise increase of input power to minimise risks
  - Ohmic restart to document initial material migration and mixing
  - L-mode campaign, low power H-mode and standard H-mode
- Repetition of plasmas to document changes in wall conditions
- Accepted proposals presented at planning meeting 11/2010

Next Steps

The needs to operate within the new plasma-facing components limits define to a certain extend the range of PSI investigations required to characterise and explore the ILW!

Second part of investigations is purely scientific driven to obtain input for predictions for ITER!

- **Plasma operation at high density ⇔ divertor characterisation**
- **Impurity seeding ⇔ radiation distribution**
- **ELM pace-making techniques ⇔ power and heat load studies**

- **Material migration and mixing studies (references)**
- **Fuel retention at fuel removal studies (references)**
- **Material limit experiments**

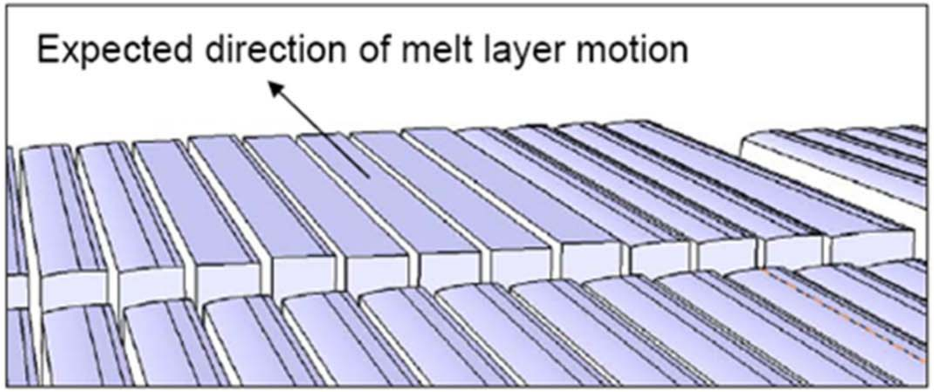
- **… more than 200 proposals for 3 years**

First plasma in July 2011

Example Proposal : W Melting Experiment

Suggested arrangement

- 16 lamellae are squared, at reference level
- 6 lamellae are squared, and displaced vertically



Yellow arrows indicate ref. level