Melting of Tungsten by ELM Heat Loads in the JET Divertor

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…and JET Contributors

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EX/4-1, Fusion Energy Conference 2014, St. Petersburg

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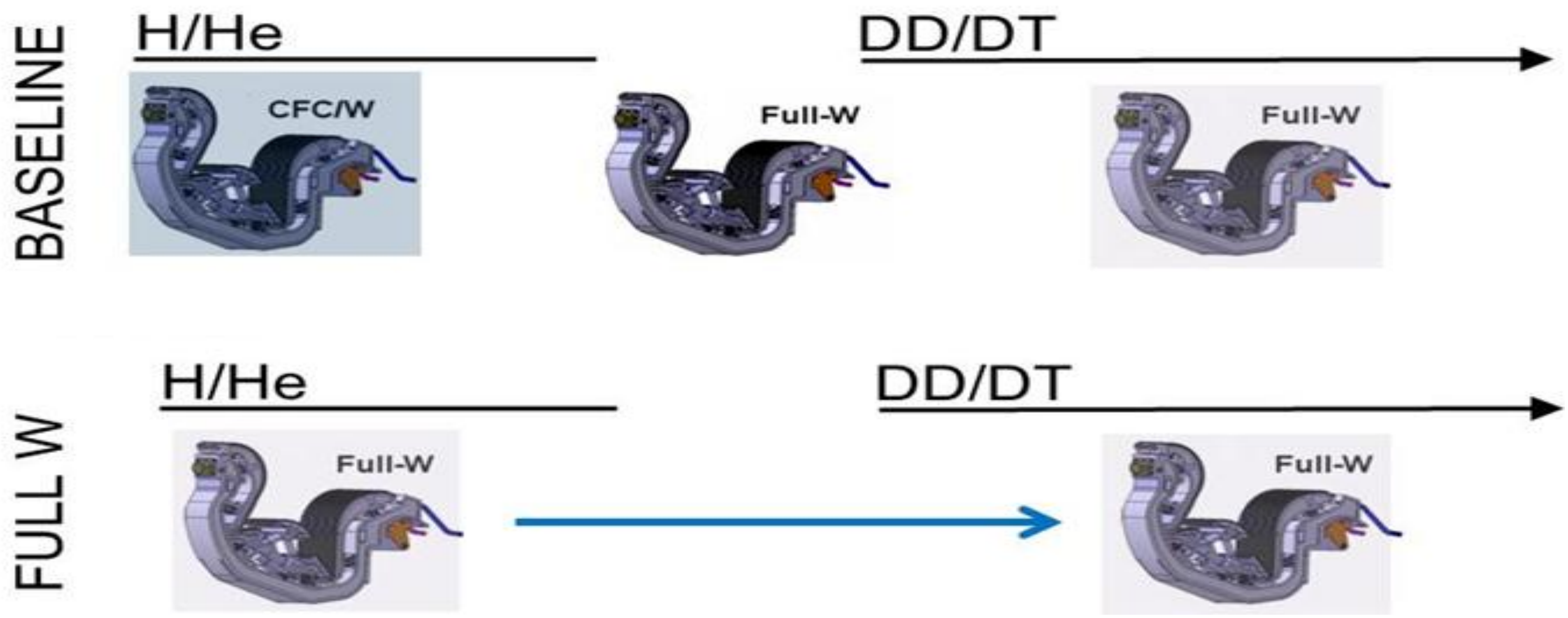
Outline

1. **Background**
2. The JET melt experiment
3. Simulation of the results
4. Conclusions and future plans

Decision on material for ITER first divertor



Risks for tungsten melting in early ITER operation had to be reviewed by IO

Bulk W melting well studied in medium sized tokamaks

Bulk melting can cause disruptions = dangerous for ITER

Bulk melting risk was considered low for ITER divertor due to tile shaping & protection systems

ASDEX-Upgrade
divertor manipulator

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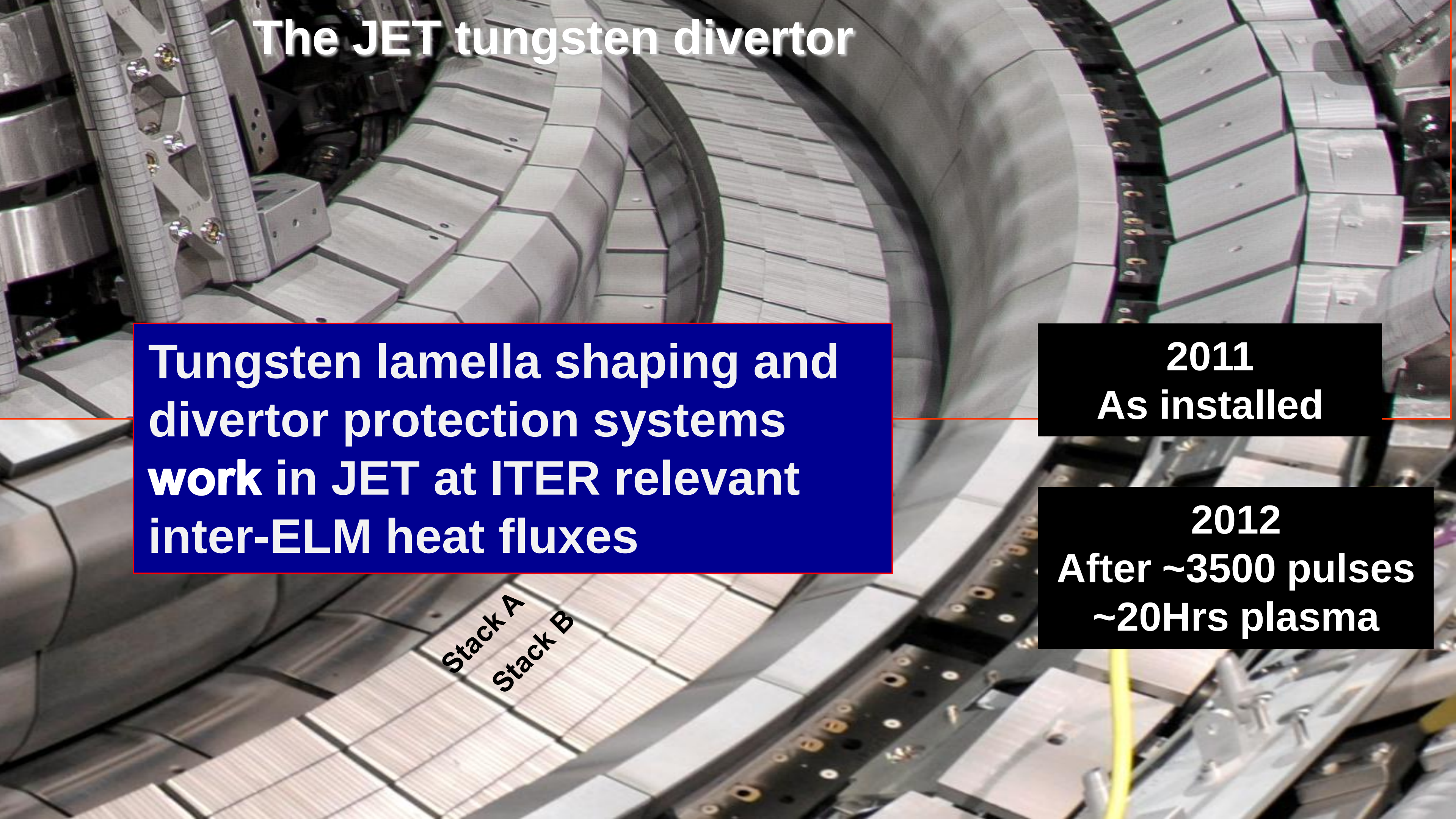
The JET tungsten divertor

Tungsten lamella shaping and divertor protection systems work in JET at ITER relevant inter-ELM heat fluxes



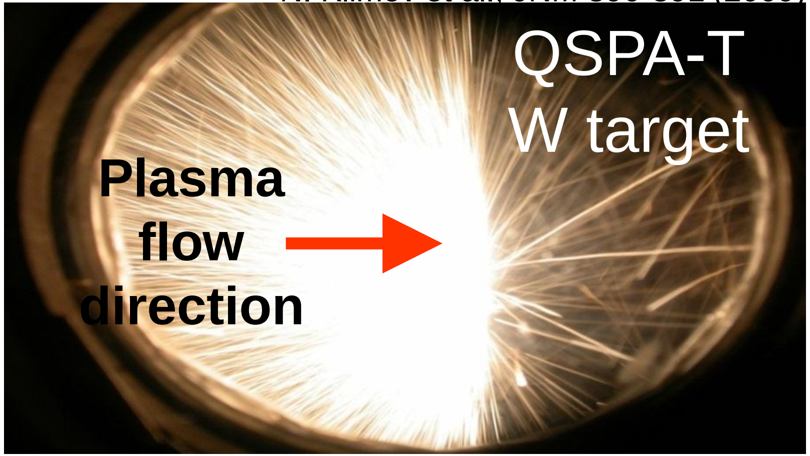
2011
As installed

2012
After ~3500 pulses
~20Hrs plasma

W melting by ELMs

QSPA ELM simulations looked worrying for ITER

N. Klimov et al., JNM 390-391 (2009)



…but plasma pressure lower and B higher in ITER (and JET)

⇨ stabilises surface waves

$q_{\perp}$ > 2.2 MJm^{-2}, t ~0.5 ms

≅ 3.8 MJm^{-2} for a 1.5 ms pulse

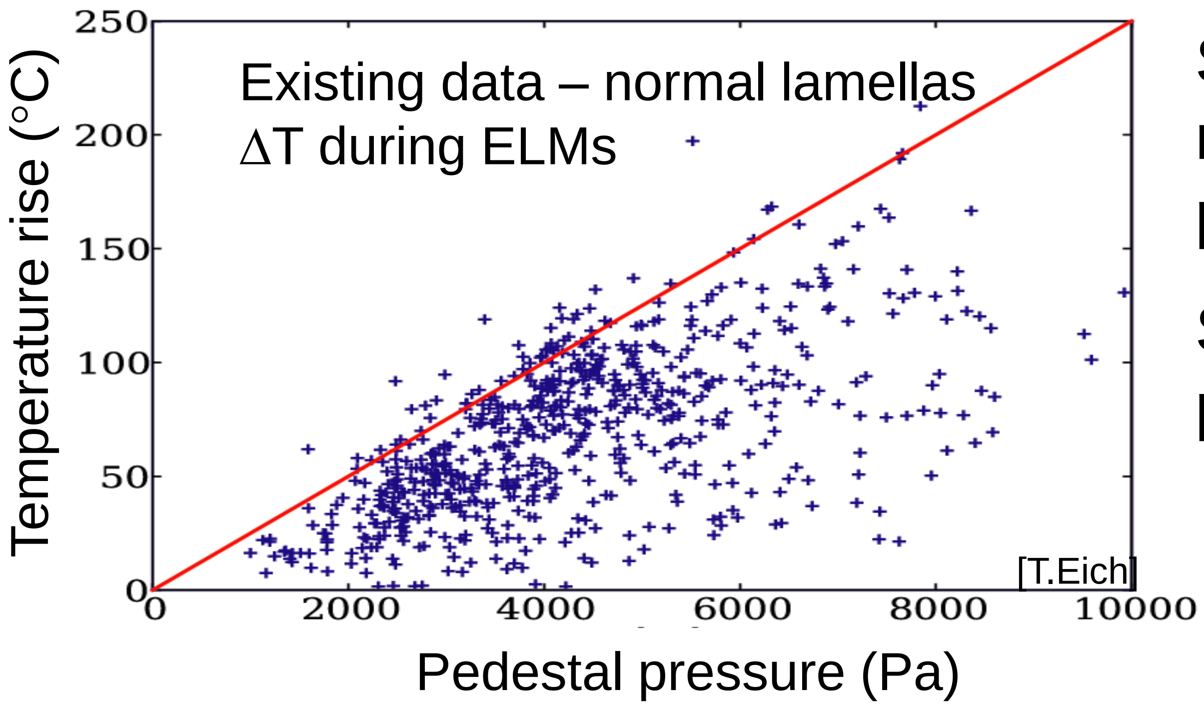
(ITER minimum τ_{TQ})

Extrapolation to ITER requires a benchmark for the MEMOS code

JET is capable of achieving a similar transient heat-flux at normal incidence

Typical temperature rise due to ELMs in JET

Geometric factor for a vertical edge ~ × 20



Surface ΔT depends mainly on pedestal pressure not ELM size!

So increase heating power or I_p to raise ΔT

ITER ~10^5 Pa

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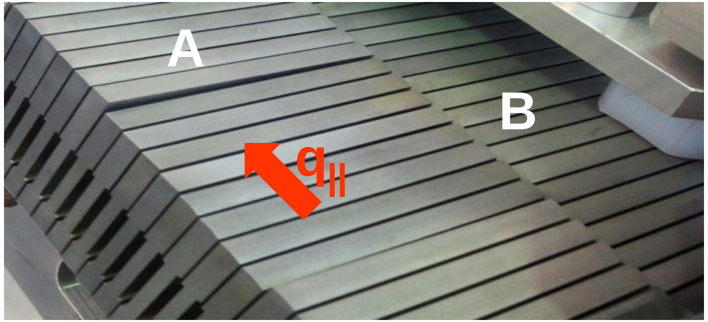
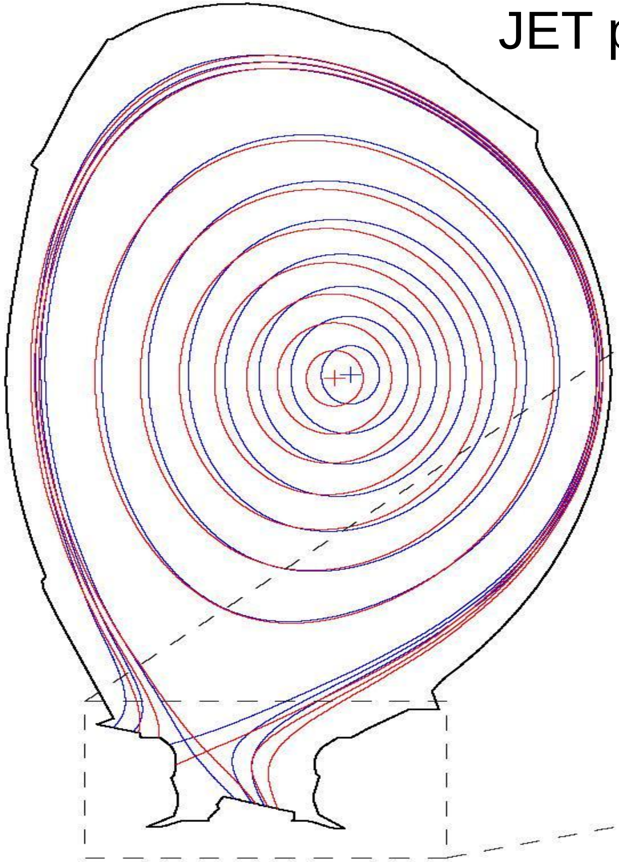
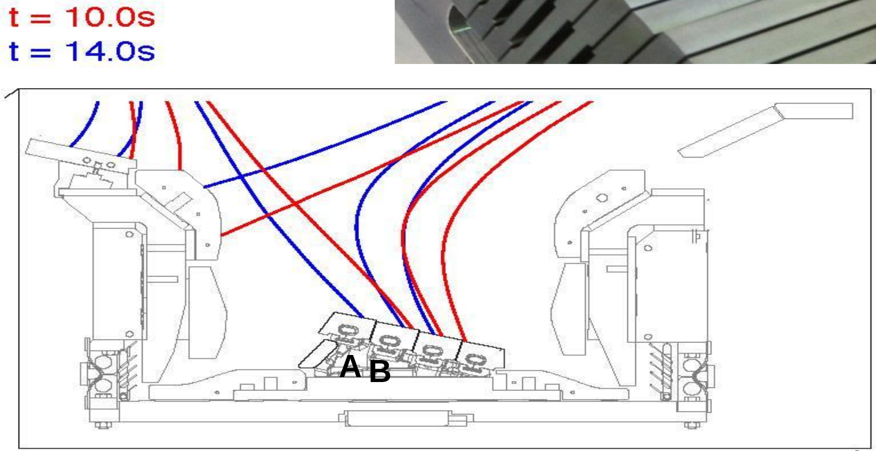
Exposing a tungsten edge in JET

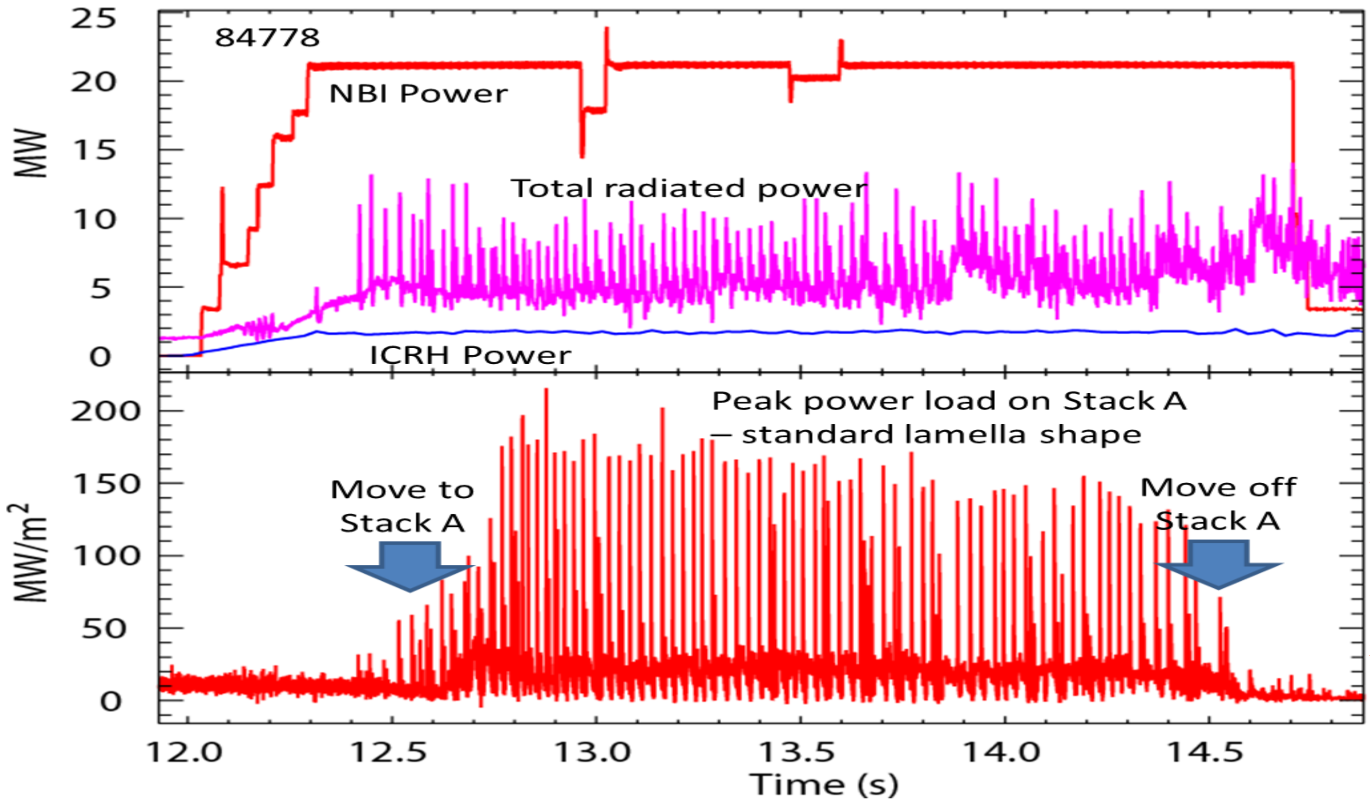
JET pulse 84779







Typical JET W melt pulse 3MA/2.9T 23MW



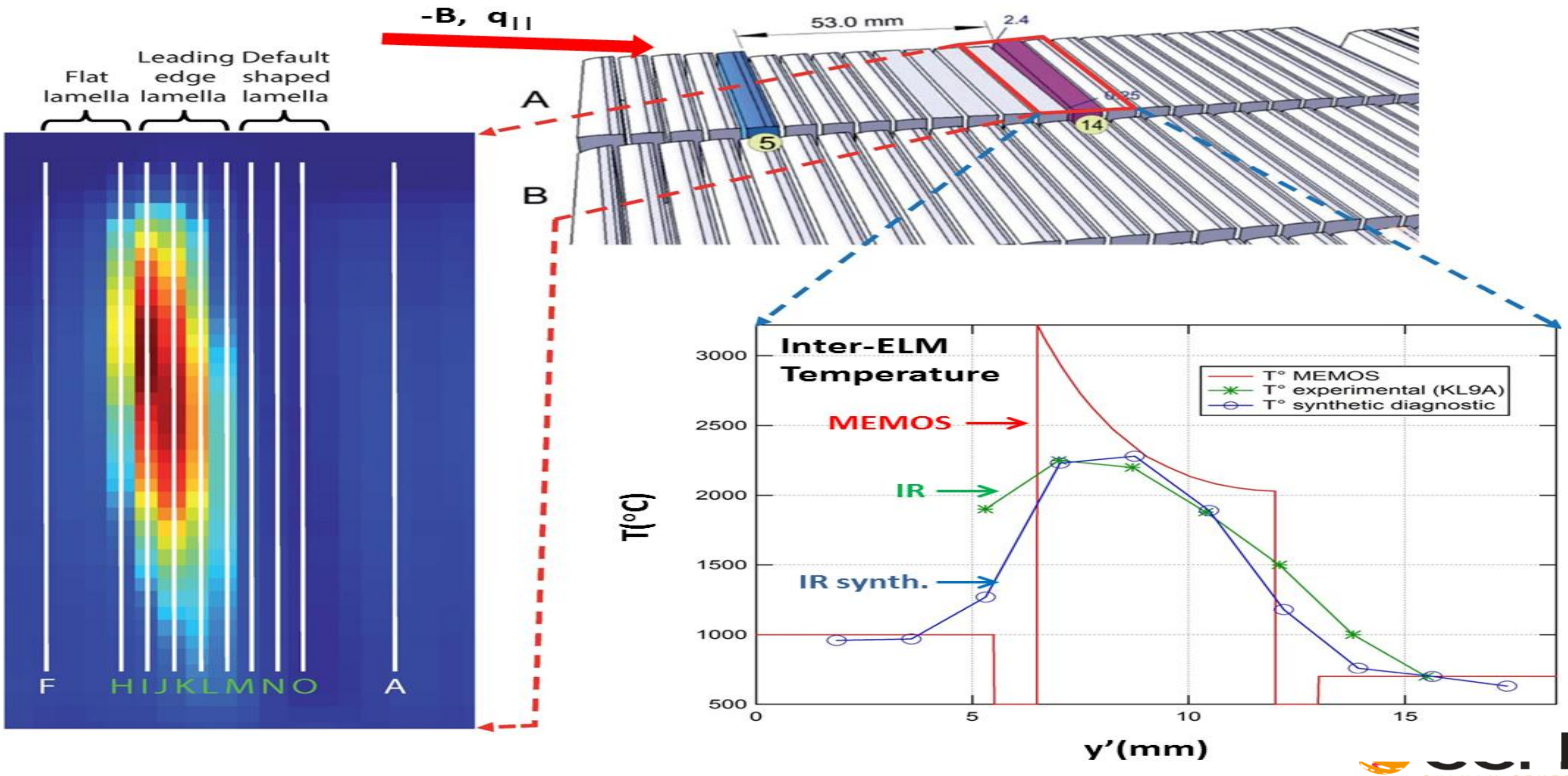
300kJ ELMs

$q_{||}$

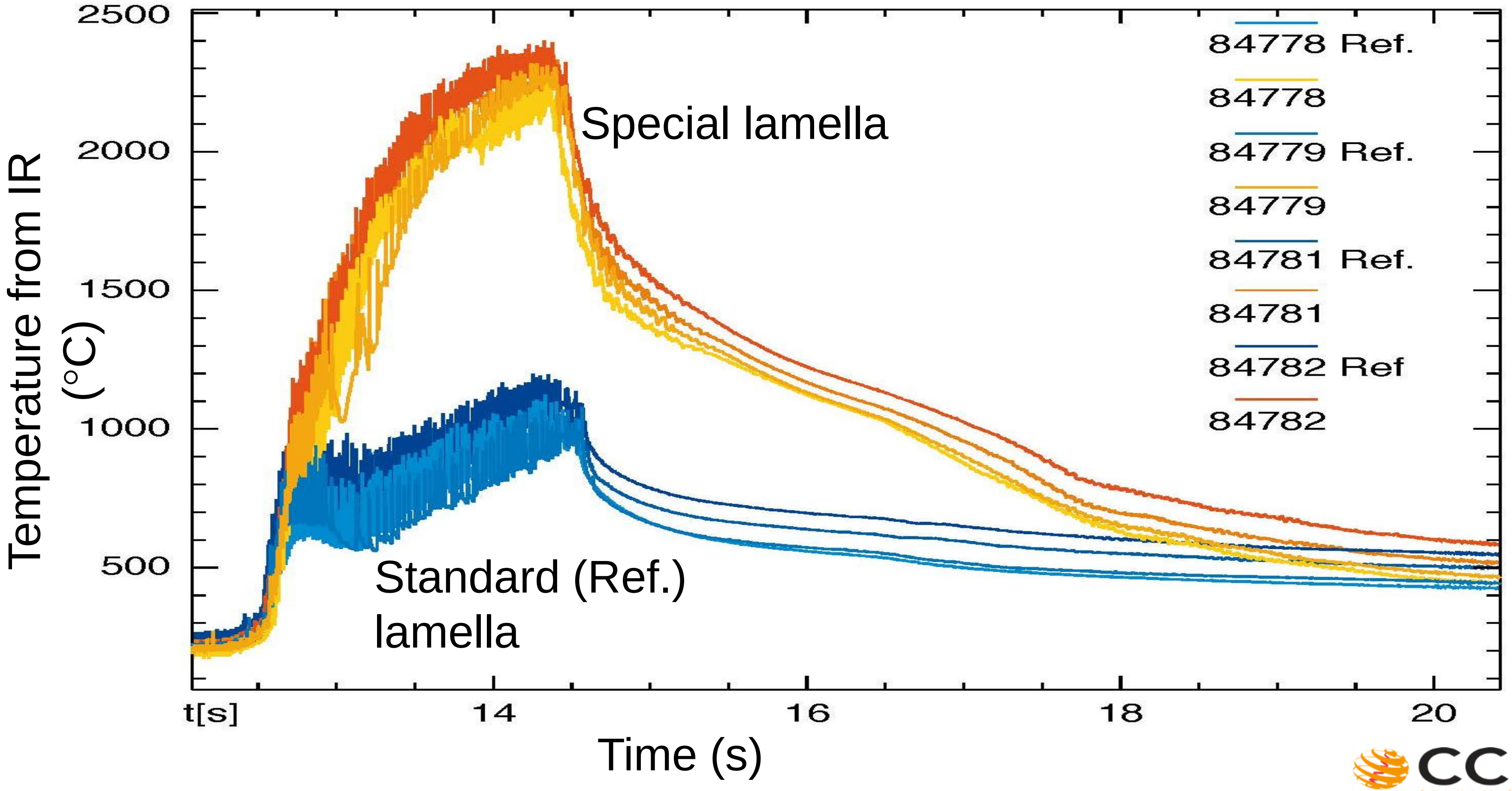
~3GWm^{-2}

~0.5GWm^{-2}

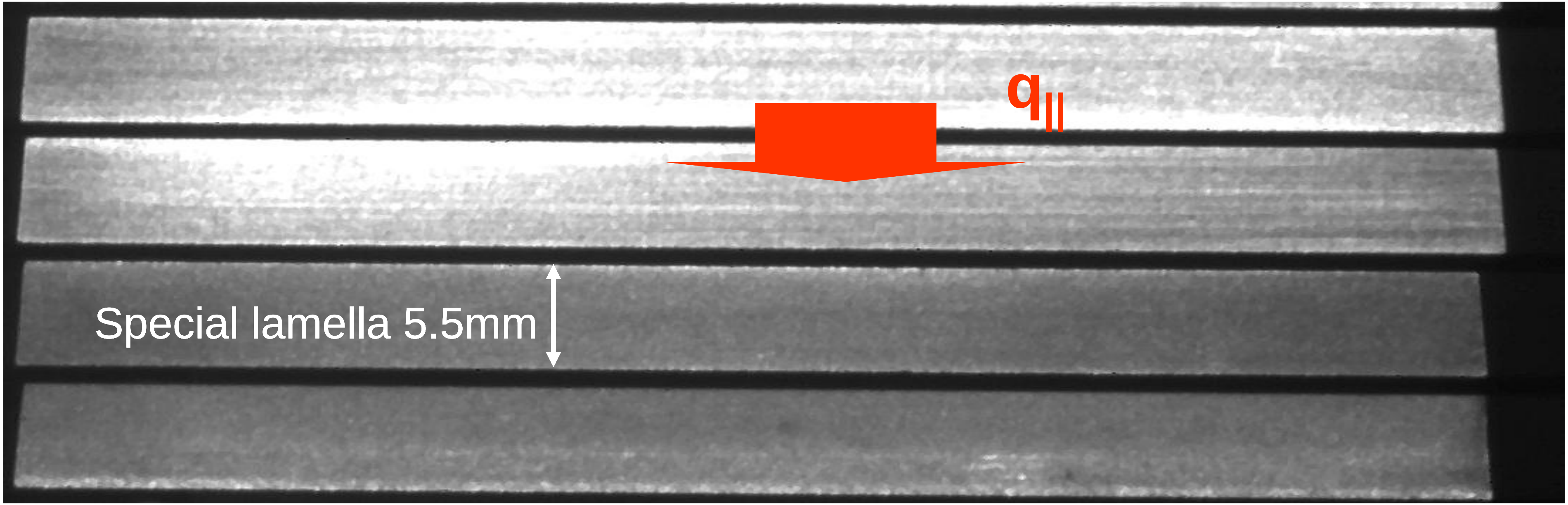
Limitations of the top IR viewing



Melt pulses are reproducible and no disruptions

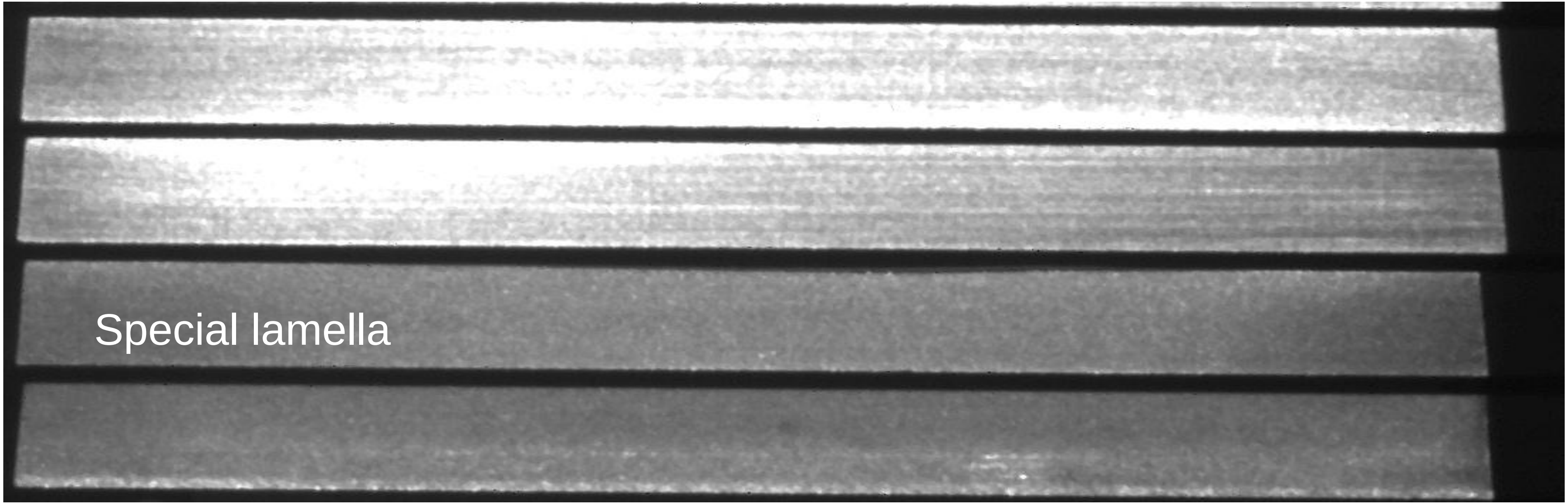


84686 – Before melting



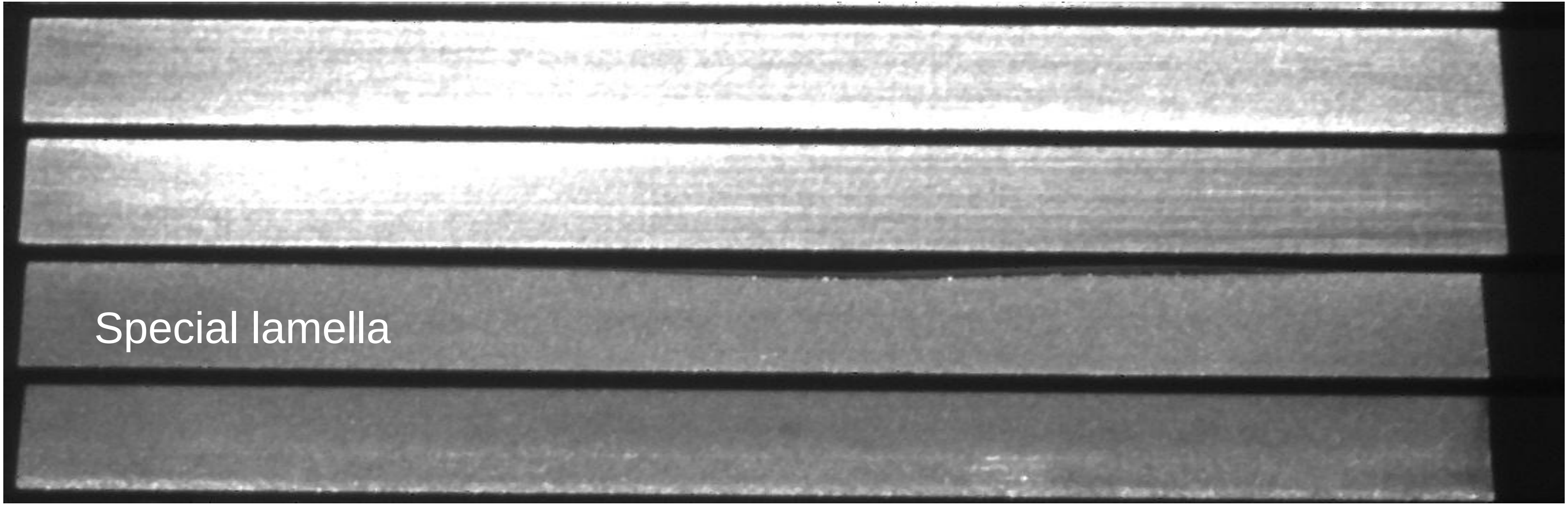
LFS HFS

After 84724



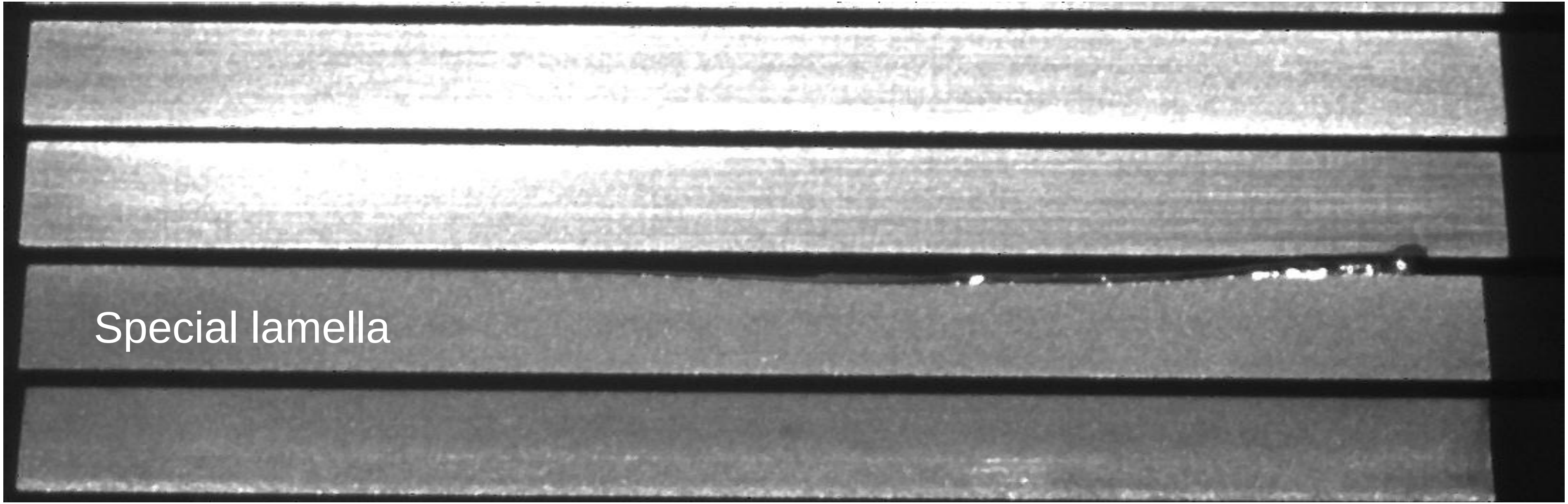
LFS HFS

After 84778



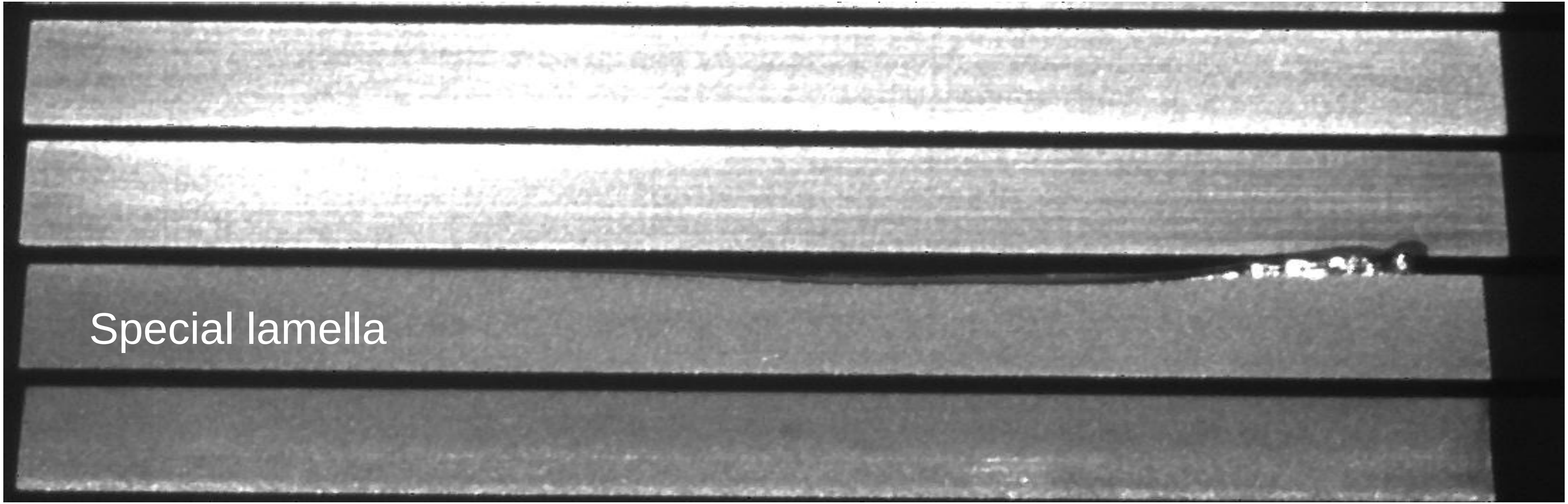
LFS HFS

After 84779



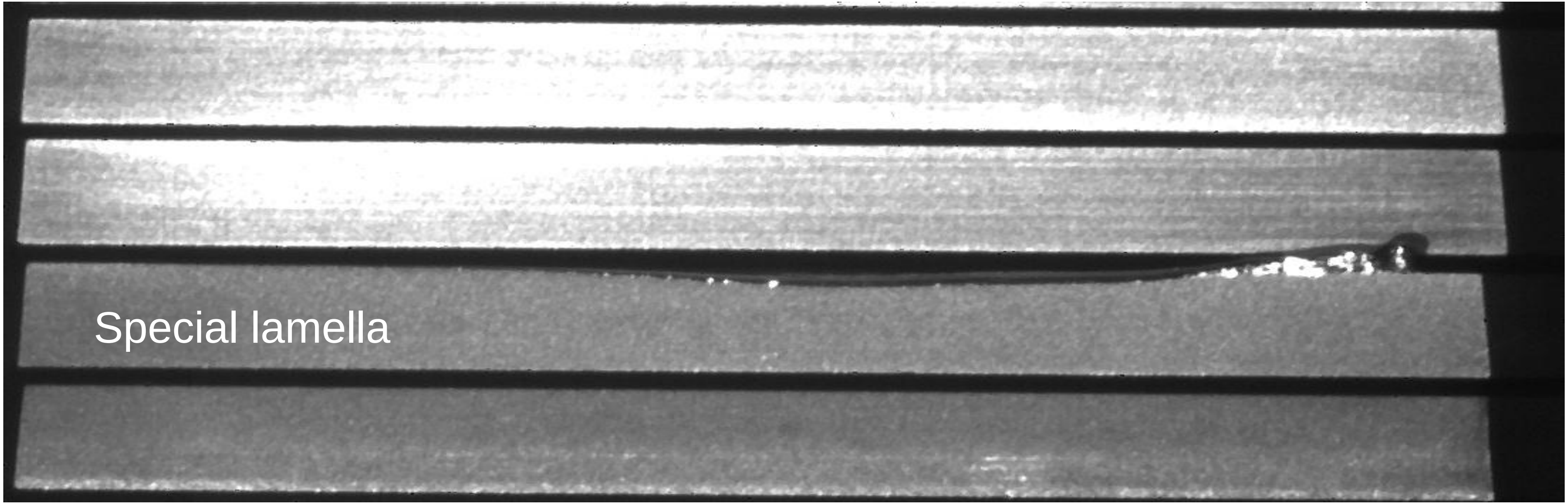
LFS HFS

After 84781



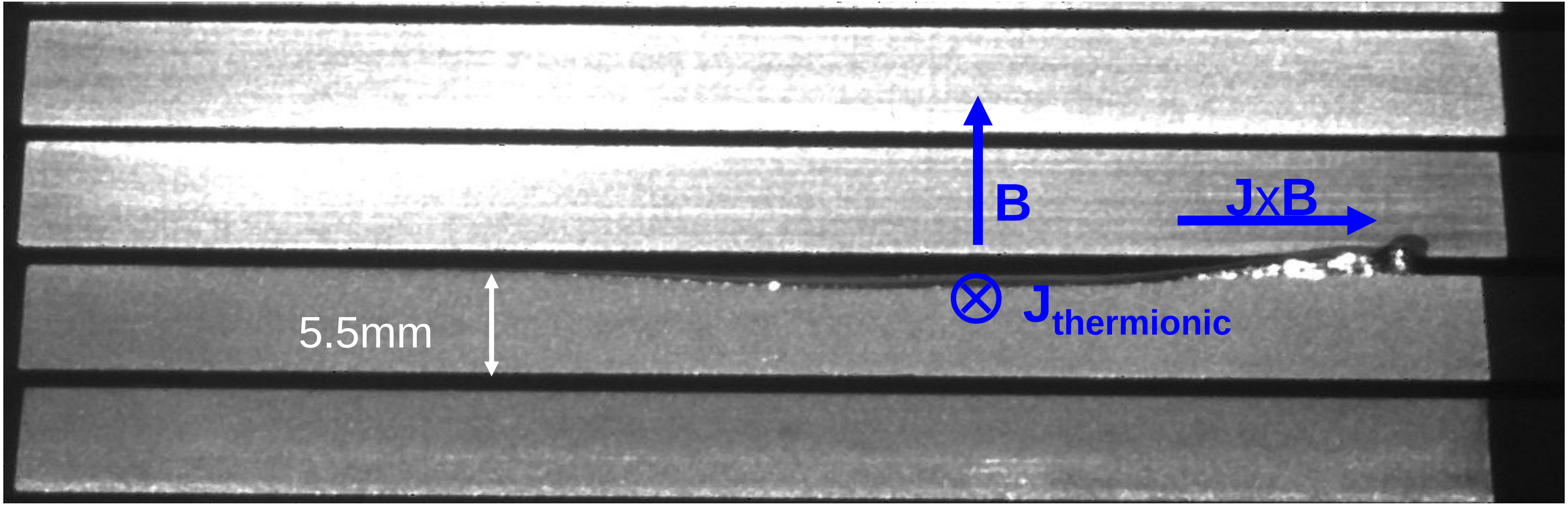
LFS HFS

After 84782



LFS HFS

After 84783

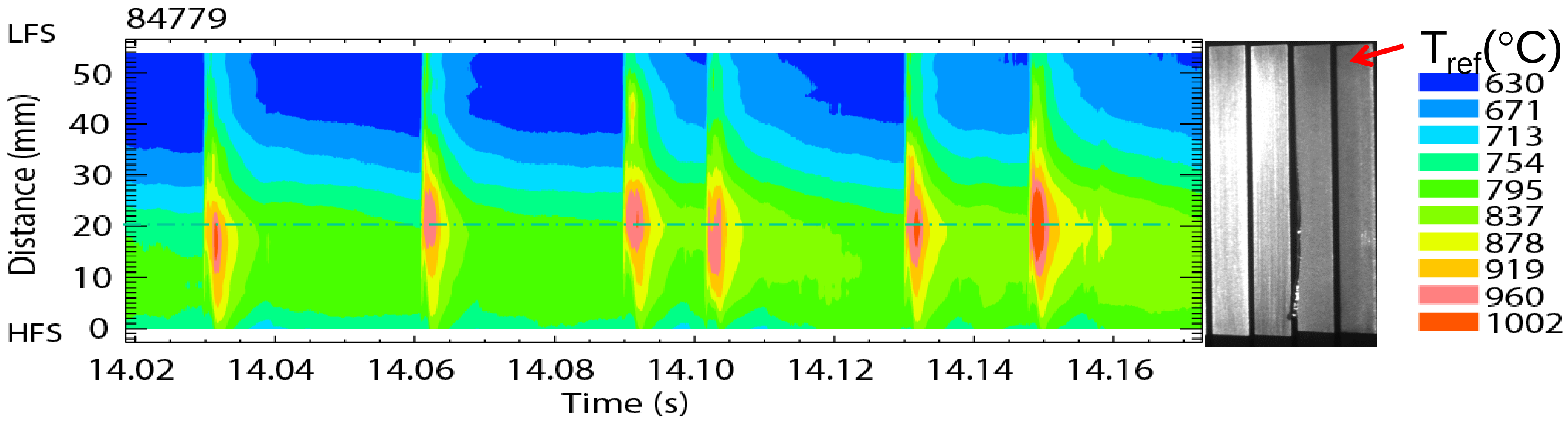


LFS HFS

Erosion: 150-300μm per pulse, 5-10μm per ELM (frequency 30Hz)

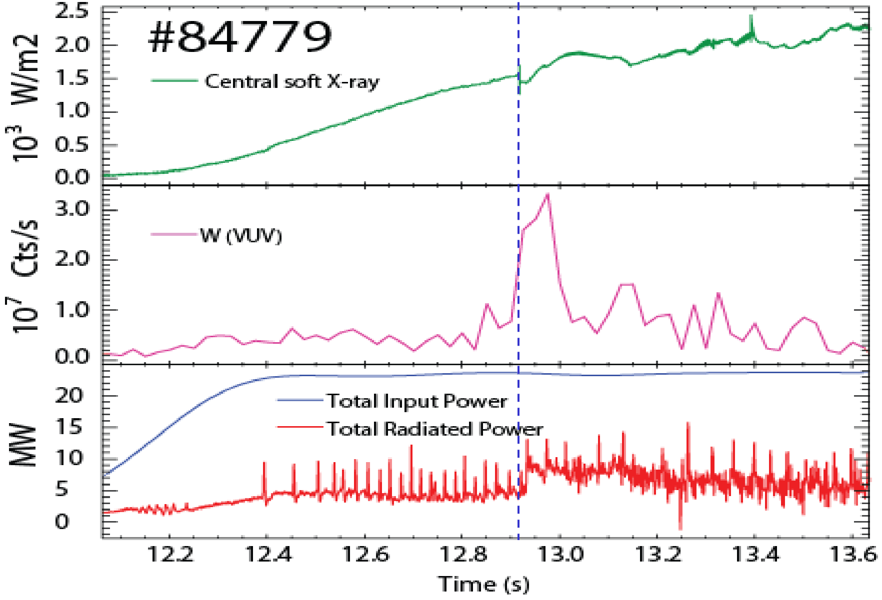
Total volume moved: ~$6mm^3$

Erosion centres on the ELM footprint

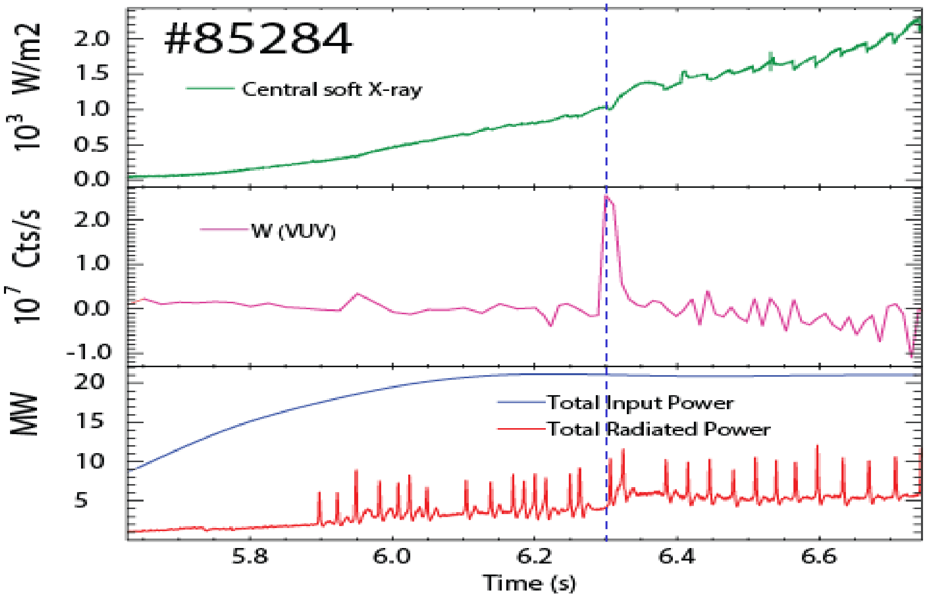


Indirect evidence for W droplet expulsion

W droplet event during melt pulse



Laser blow off with W target



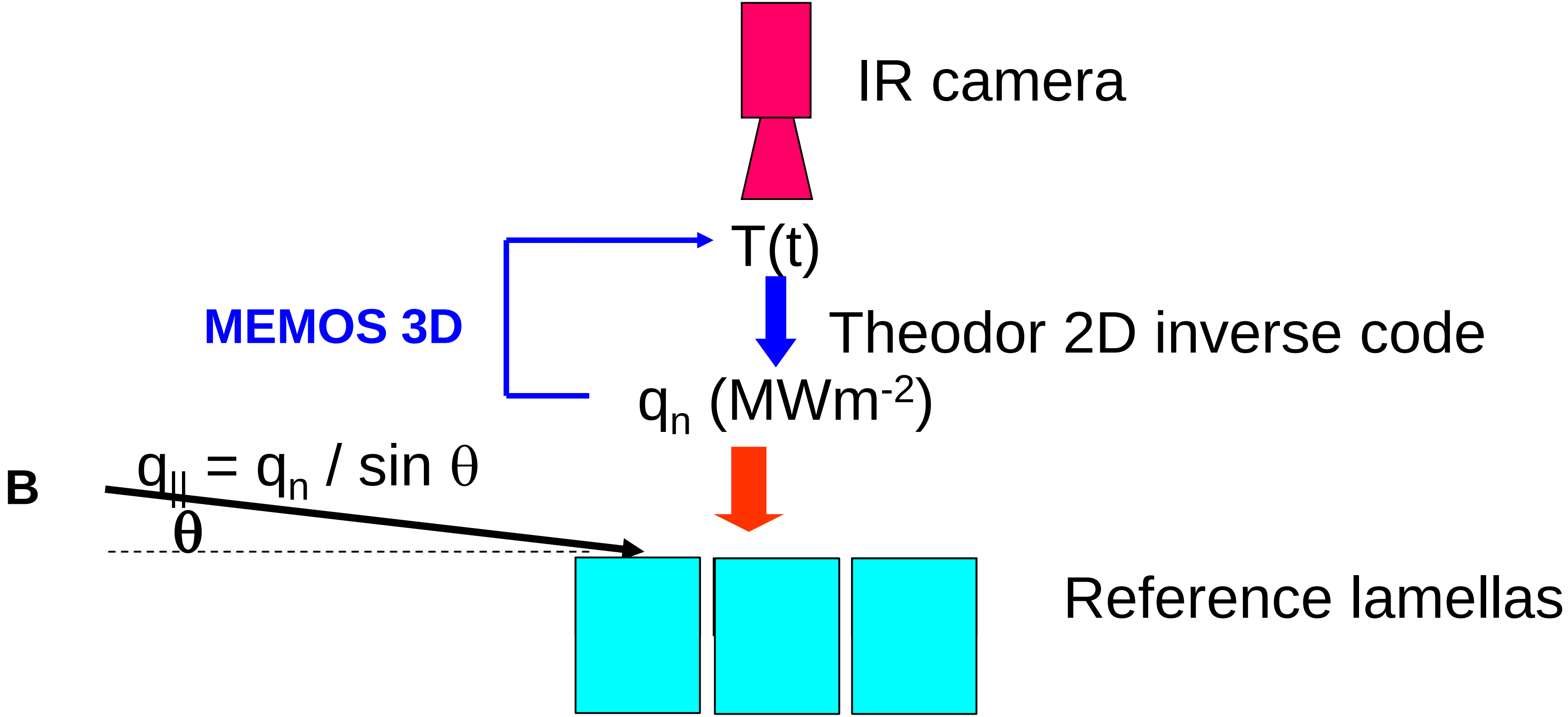
A few droplets reach the main plasma with diameters ~ 100μm

- Small perturbations only and <u>no disruptions</u>

Outline

1. Background
2. The JET melt experiment
3. Simulation of the results
   MEMOS = key tool used for ITER predictions
   Stefan problem in 3D geometry accounting surface evaporation, melting and re-solidification solved by implicit method
   - Surface power density vs time from IR is the input
   - Vapour shielding
   - Temperature dependent thermophysical data applied
   - Moving boundaries are attached to melt layers
   - All forces: Gradient of plasma pressure, gradient of surface tension, JxB, tangential friction force
   [Bazylev TH/P3-40]

Power density $q_{||}$ from reference lamellas



Power density on the special lamella

PIC model says:

f_s >0.6 during ELMs

f_s~1 inter-ELM and L-mode

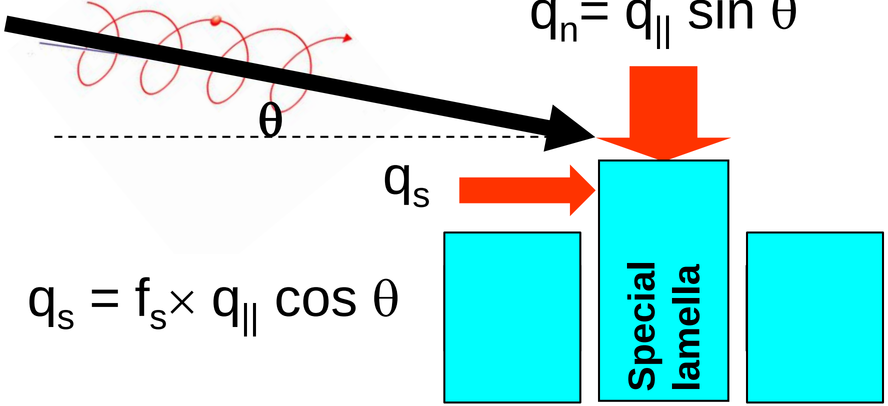
MEMOS input = q_n from IR (Theodor)

f_s iterated to match: evaporation rate,

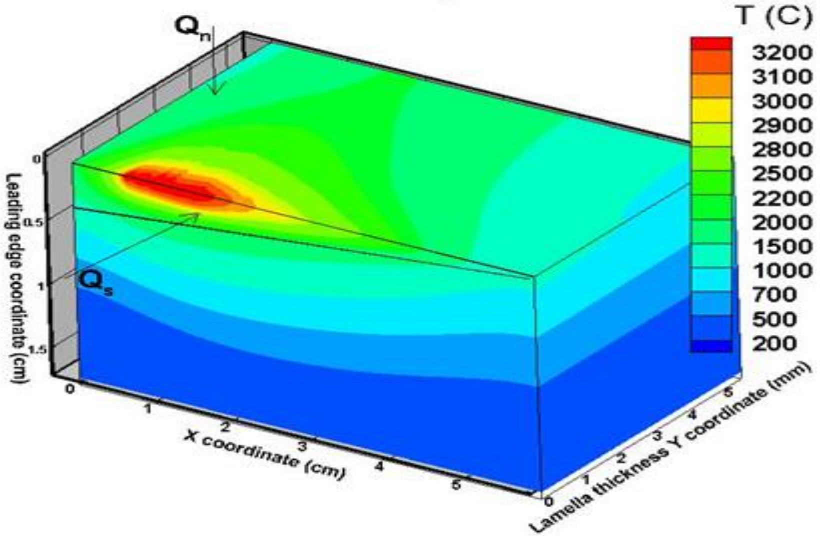
synthetic IR image and Planck radiation

$q_{||}$ from reference lamellas

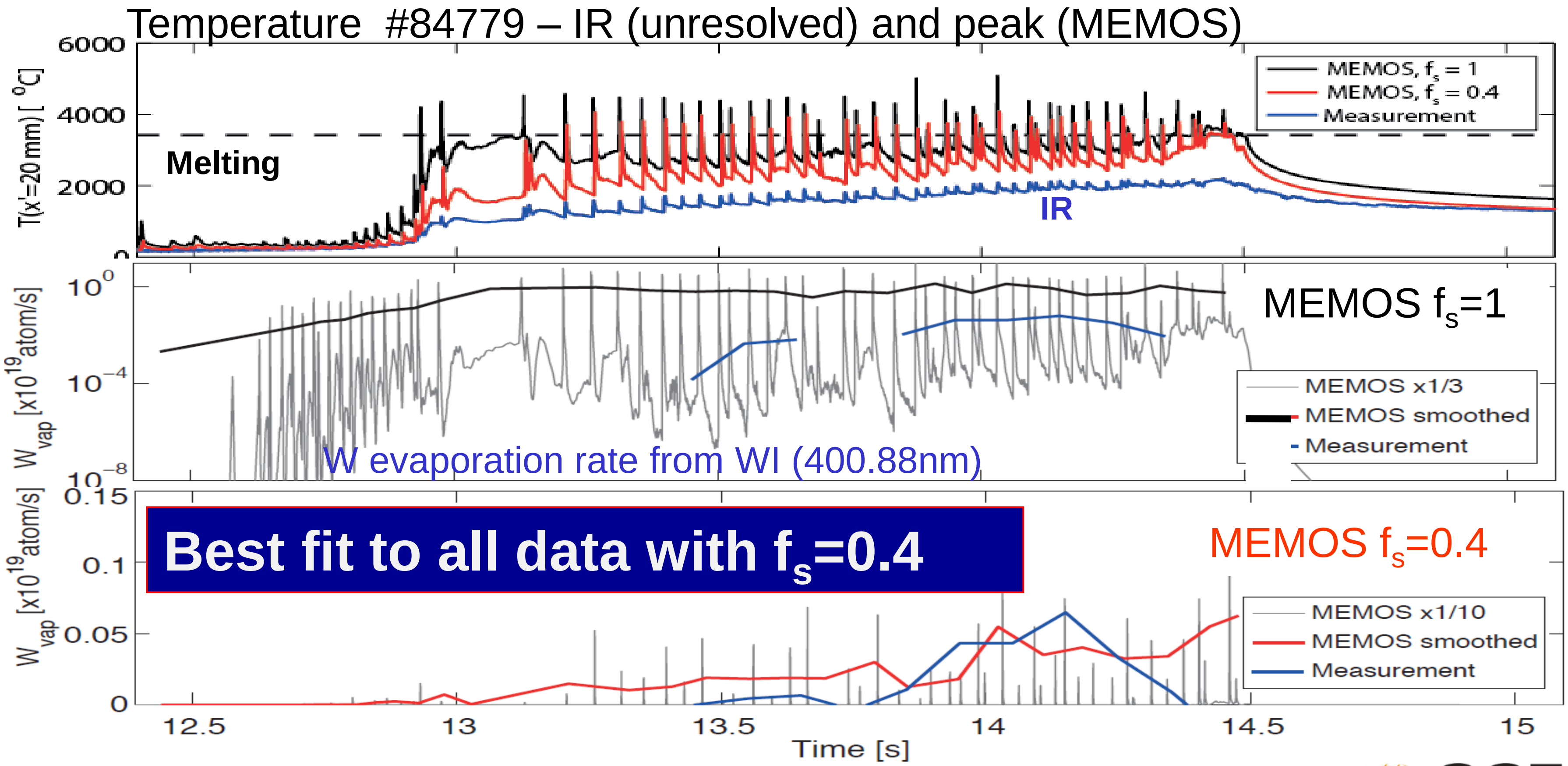
$q_n = q_{||} \sin\theta$



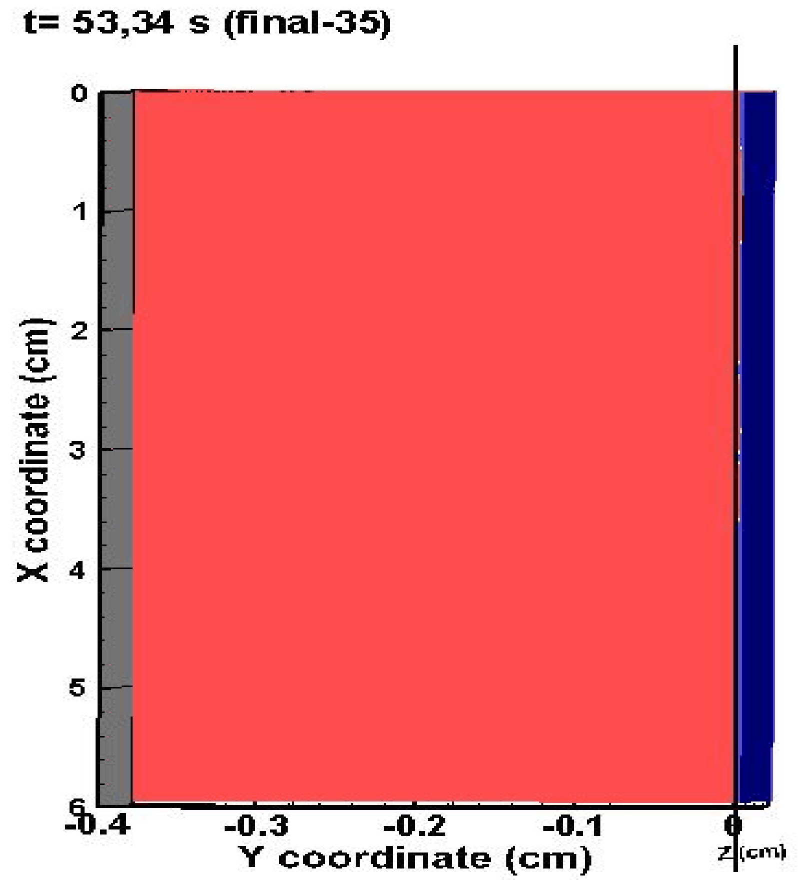
$q_s = f_s \times q_{||} \cos\theta$



f_s chosen to fit evaporation rate and Planck radiation



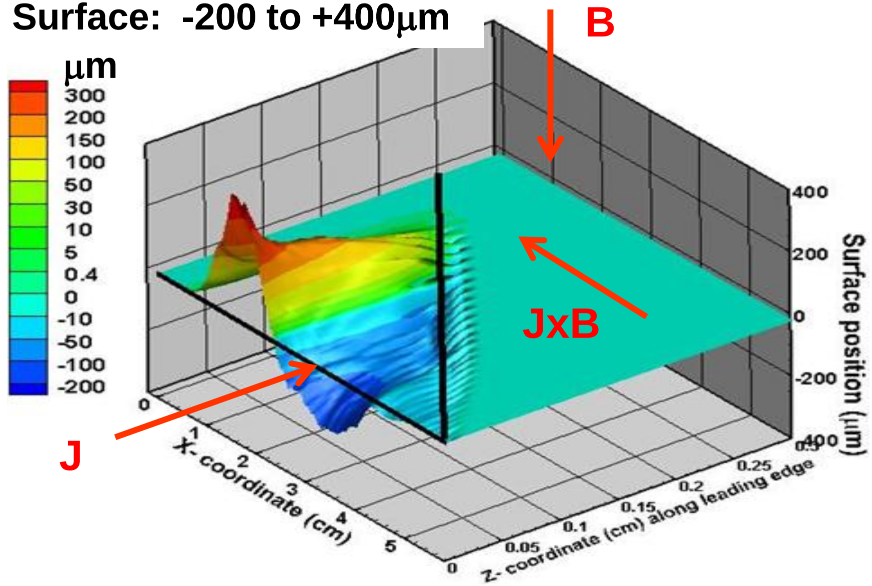
W melt evolution #84779 – MEMOS [Bazylev TH/P3-40]

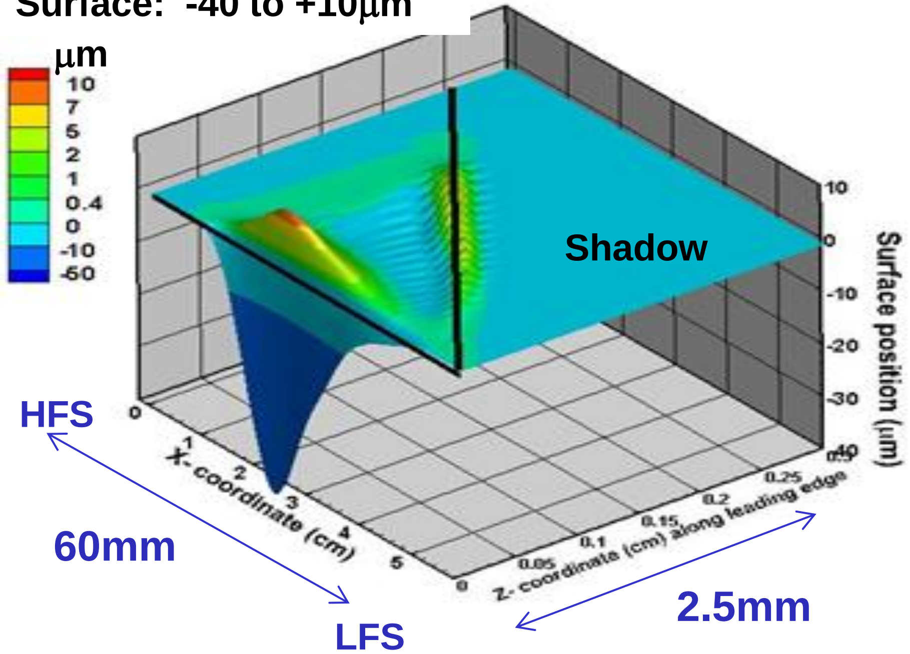


f_s=0.4

Hierarchy of forces – MEMOS [Bazylev TH/P3-40]

JET pulse #84779 - MEMOS





Plasma pressure (6kPa) + surface tension gradients + thermionic emission (JxB)

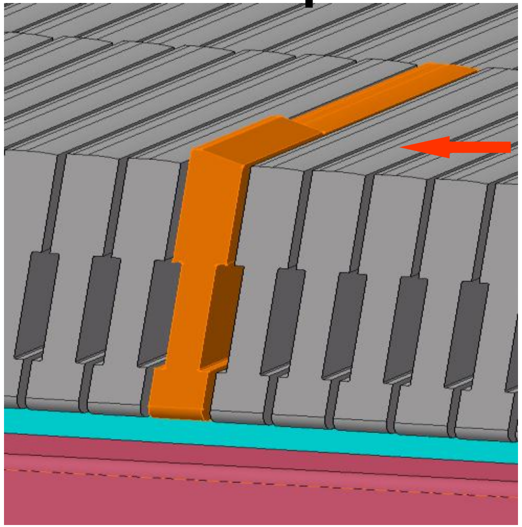
Plasma pressure (6kPa) + surface tension gradients

Conclusions

W melting by ELMs in JET provided important inputs to ITER:

- Shallow melts with a few small droplets ejected but no disruptions
- JET melt results are consistent with MEMOS assuming $J \times B$ dominant
- Unexpectedly large power mitigation factor found for exposed W edge

Future JET plans

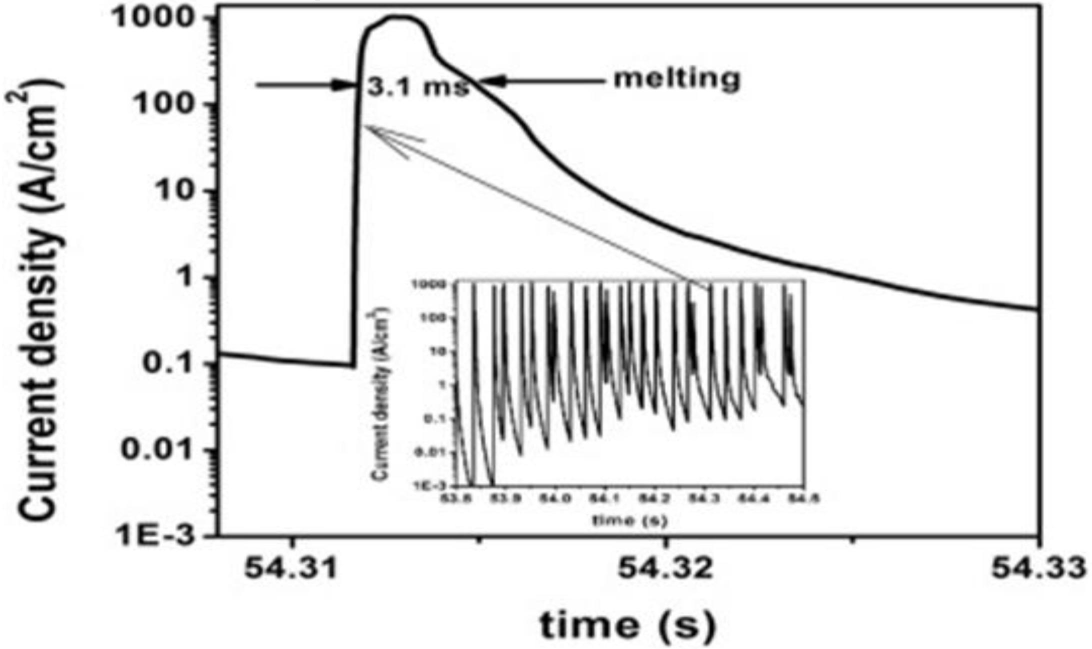


New lamella at 15°:

- Fully resolved IR temperature
- Grazing field angle / more ITER-like
- Simpler geometry

Thermionic emission during ELM - MEMOS

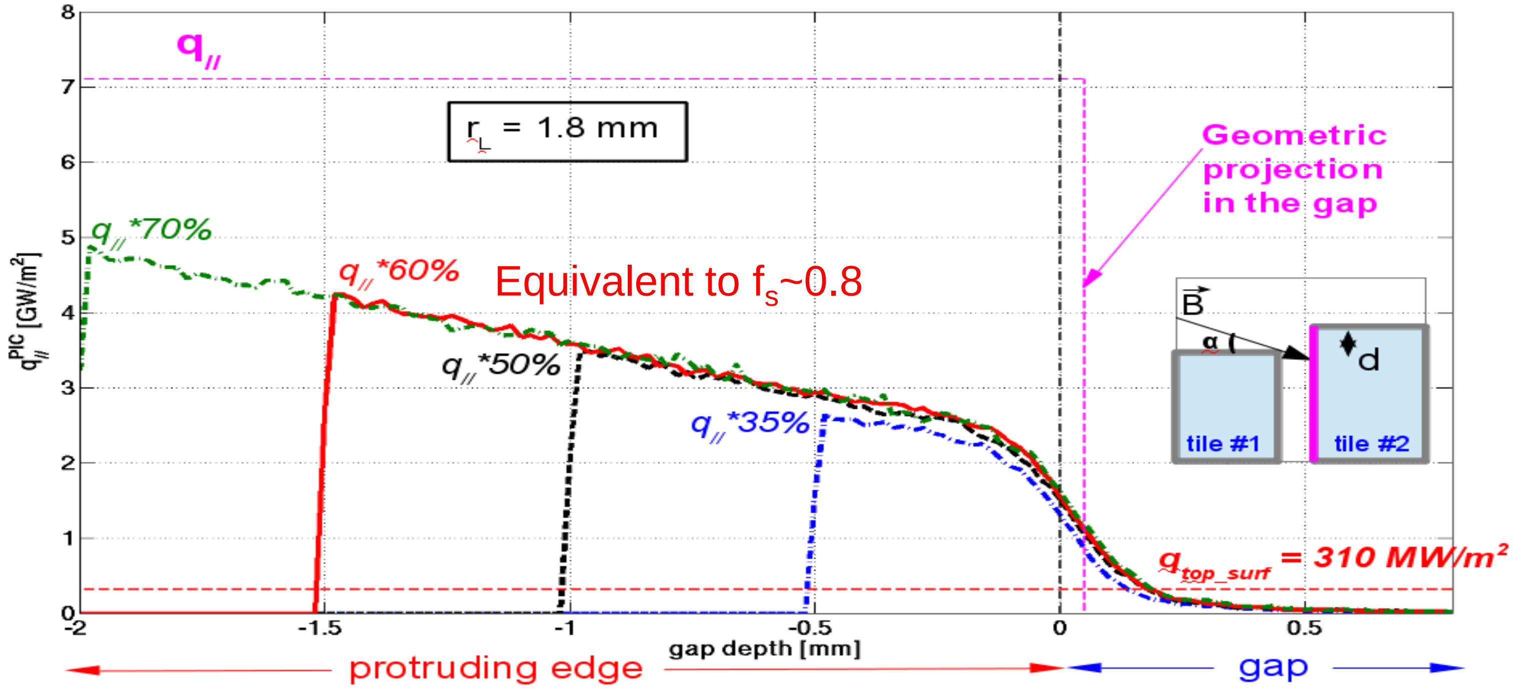
JET pulse #84779 - MEMOS



[Bazylev TH/P3-40]

Unlike JET experiment, suppression of thermo electron emission is predicted in ITER due to grazing field angles

Larmor radius smoothing - PIC code [Dejarnac NF]



- Calculated for ELMs only - insufficient to explain f_s=0.4 in H-mode

- No effect expected in L-mode where we find f_s=0.2

MEMOS suggests significant vapour shielding

…..but we are not able to prove it experimentally due to lack of a consistent physics model for f_s=0.4 in H-mode and f_s=0.2 in L-mode

#84779