Detailed Design of a Solid Tungsten Divertor Row for JET in Relation to the Physics Goals

Ph. Mertens

and all contributors to the ILT-Project
(procurement of the bulk W divertor row)

Institute of Energy and Climate Research IEF-4 (Plasma Physics)
and IEF-2, Association EURATOM-FZJ

Demanding conditions at the outer strike point

Outer strike point (OSP), an heavily loaded place

- $7\ MW/m^2$ uniformly on the whole conical surface (frustum), for <10 s. Reaches easily $10\ MW/m^2$ locally, or more, with due account of gaps and actual wetted fraction

  ◀ lack of active cooling

  M. Missirlian (I-04)

- *dB/dt* ≤100 T/s during abnormal events (“disruptions”); halo currents <19 kA /module (a tile pair)

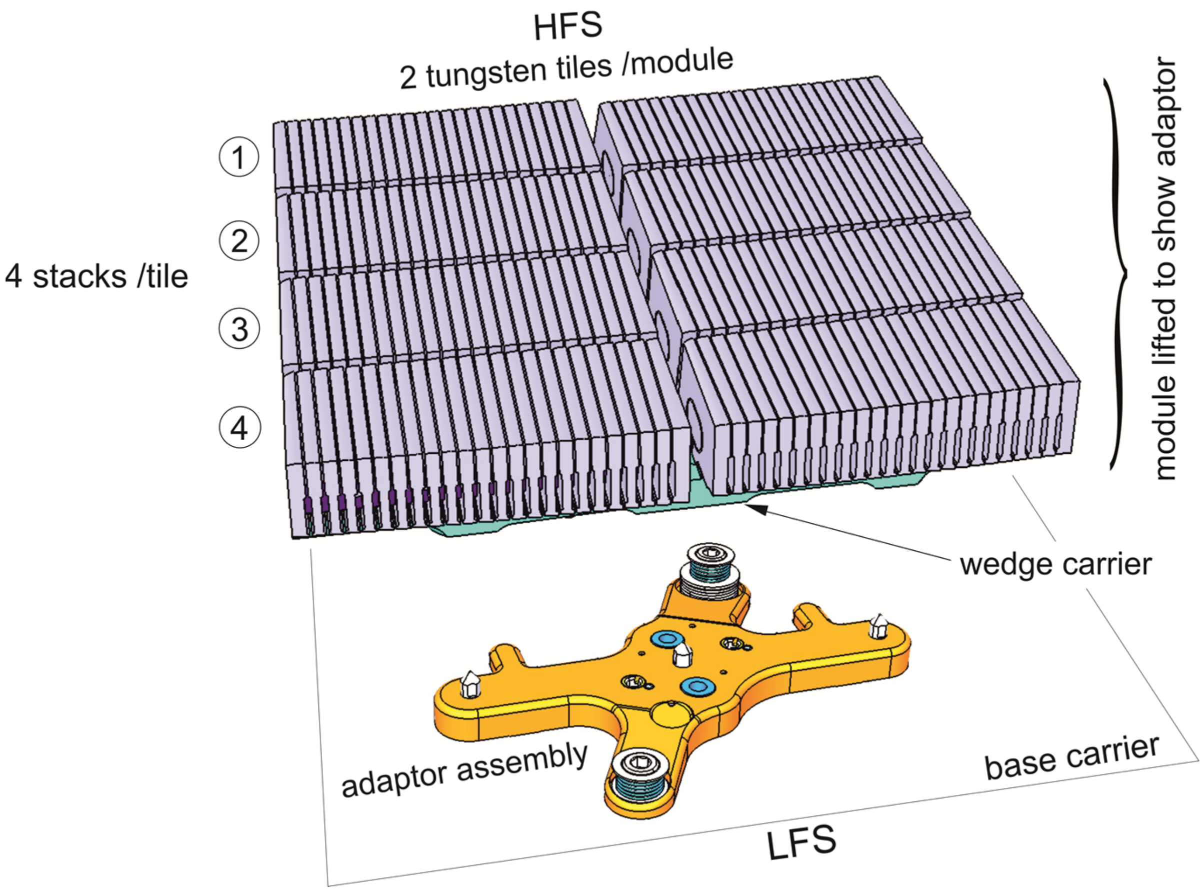
  ◀ purely metallic

  R. Mitteau (I-05)

- Limits → scenario development to reach the goals of the scientific programme

N.B. the full divertor row named “tile 5” or W-LBSRP is about 4 m^2 large, but the plasma footprint on the tile typically extends to ~20mm only in poloidal direction

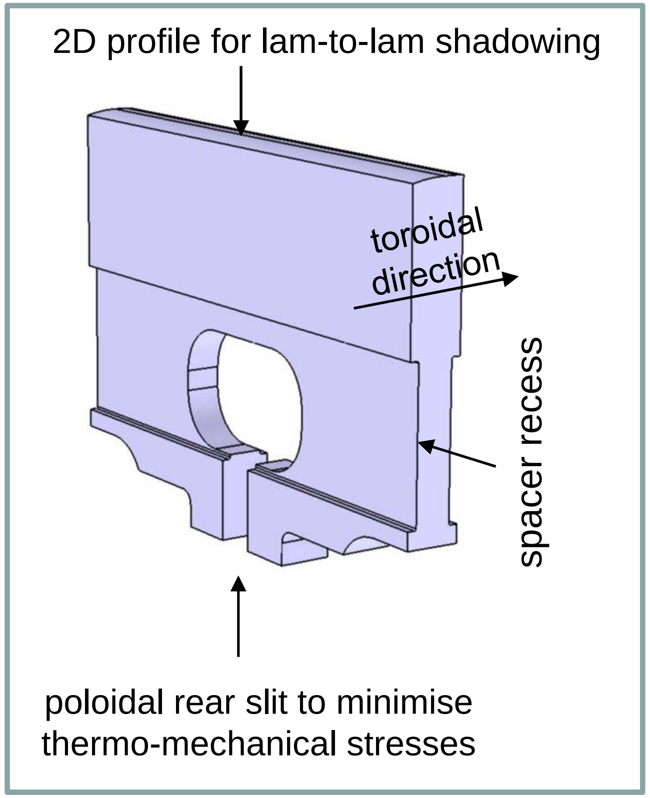
Top to bottom description



- chronological order
- mimic the former, 3D shaped CFC tile to get close to its performance
- challenge, esp. with "not so adequate" properties of tungsten
- from original requirements: bolt down a simple tile as strongly as possible…

Standard tungsten lamellae

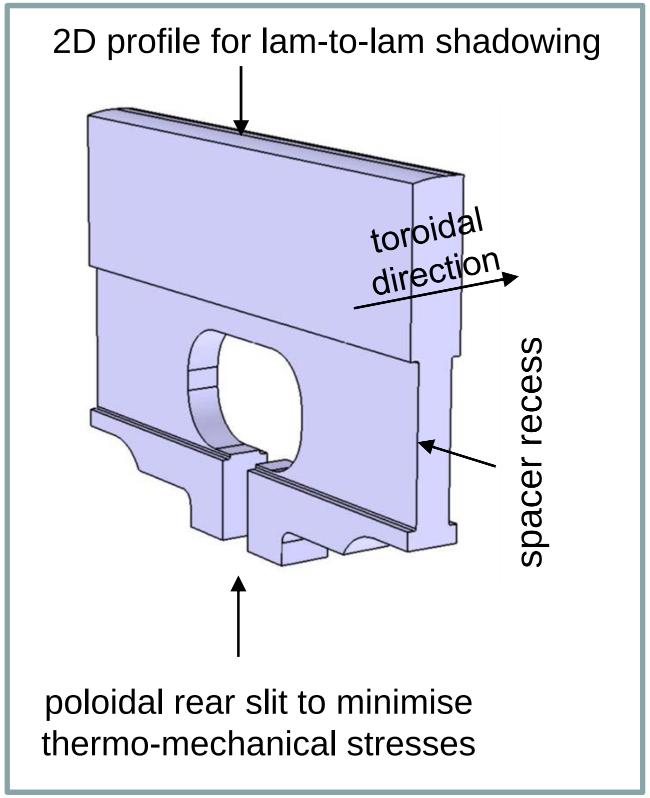
- Segmentation of the tile for thermo-mechanical and electromagnetic reasons

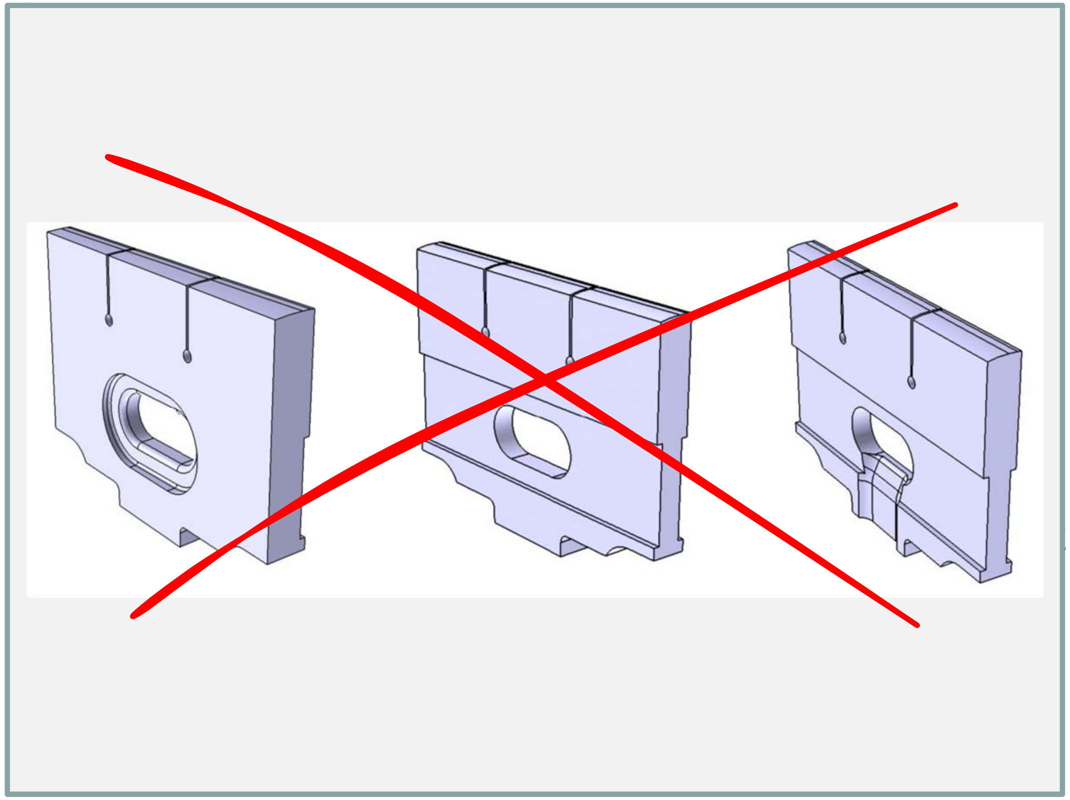


- Lamella height determined by heat capacity (vertical temperature gradient, internal stresses, maximal temperature of carrier)
- Lamella length also from thermo-mechanical considerations
- Lamella thickness determined by realistic toroidal castellation
- Appropriate cuts, both toroidal and poloidal, prevent large eddy current loops
- Path provided at the bottom for the high halo current (<120 A /lamella)

Standard tungsten lamellae

- Segmentation of the tile for thermo-mechanical and electromagnetic reasons





Tungsten lamellae: *physics*

- Amount of tungsten has an impact on total tolerable energy E_{dep} and on the cooling time
  - mass > 2100 kg
  - c_p, ε_W, … ; observed $\Delta t_{cooling}$ ~ 2700-3600s
- Power handling in first approximation through definition of max. temperatures, esp. $T_{W,surf}$

thermal shocks: G. Pintsuk (**O-12**)

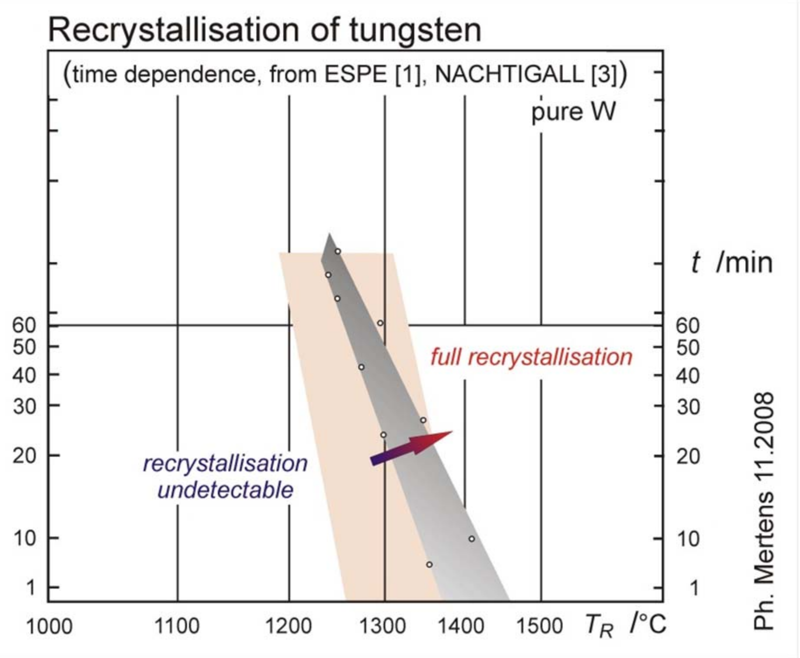
- Material strength
- Why so complicated?

irradiation: Y.Ueda (**I-09**)

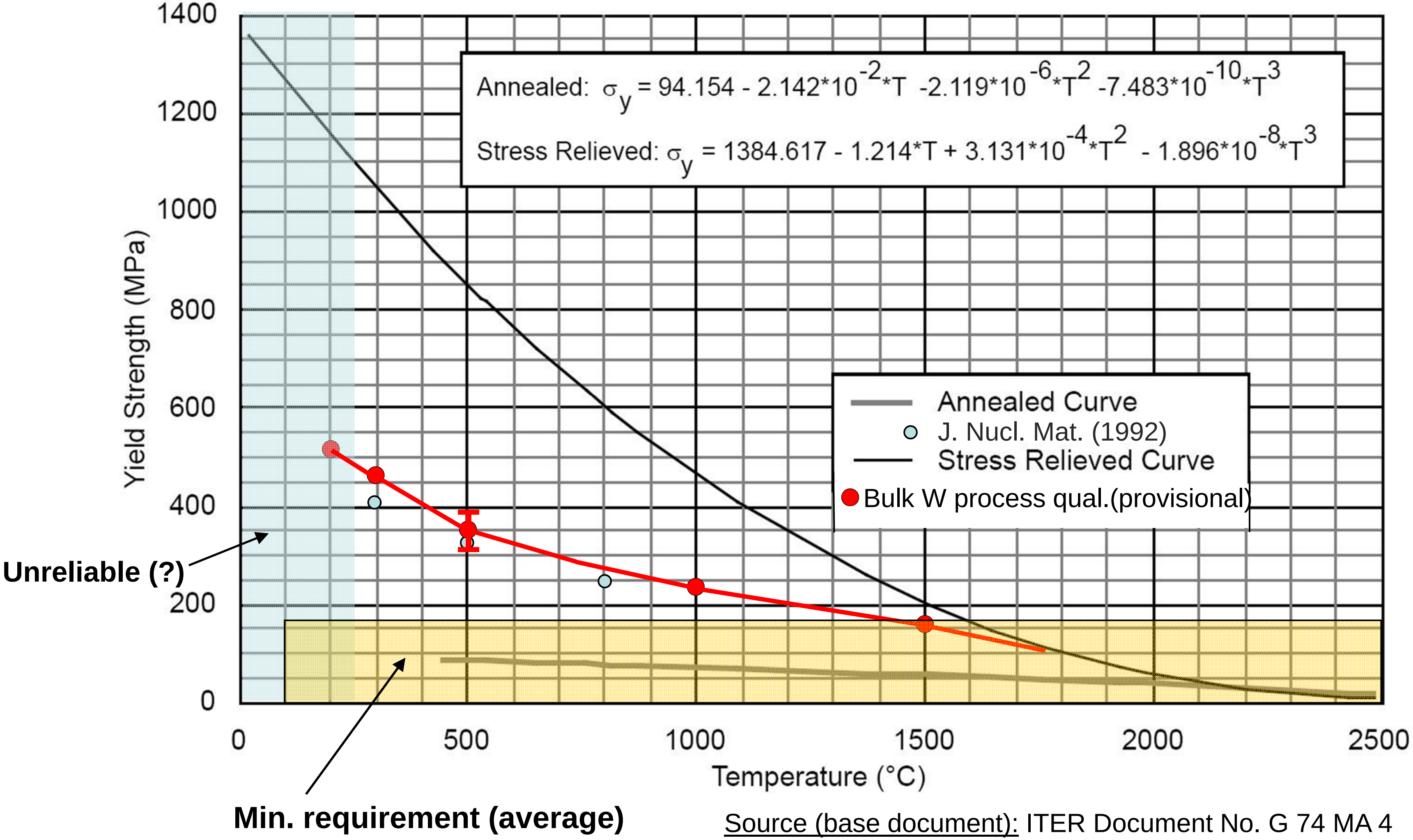
Tungsten material rather unfavourable:

- refractory metal: $R_{p0.2}$ (yield strength) not ok
- excursions through DBTT at low T temperature, re-crystallisation threshold at high temperature
- use in compression only (σ_1<150 MPa)

▶ accounts for complexity

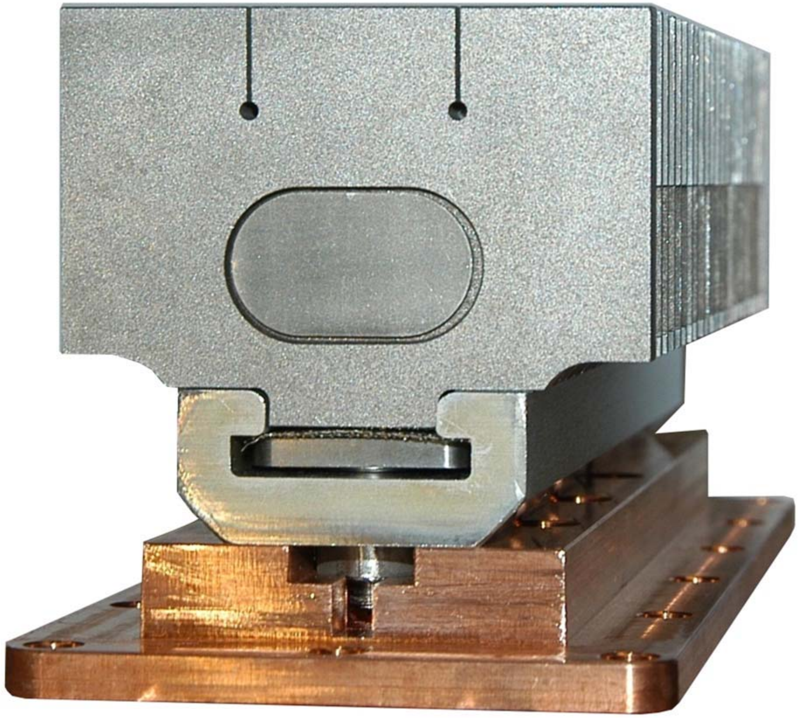


Tungsten: yield strength

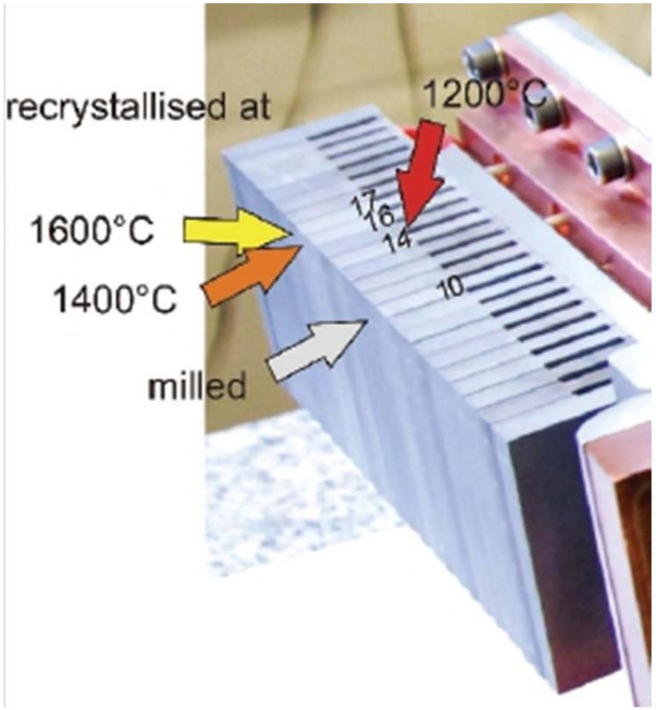


Source (base document): ITER Document No. G 74 MA 4

Tungsten lamellae: stacks



Prototype stack for exposure in the JUDITH-2 e-beam facility

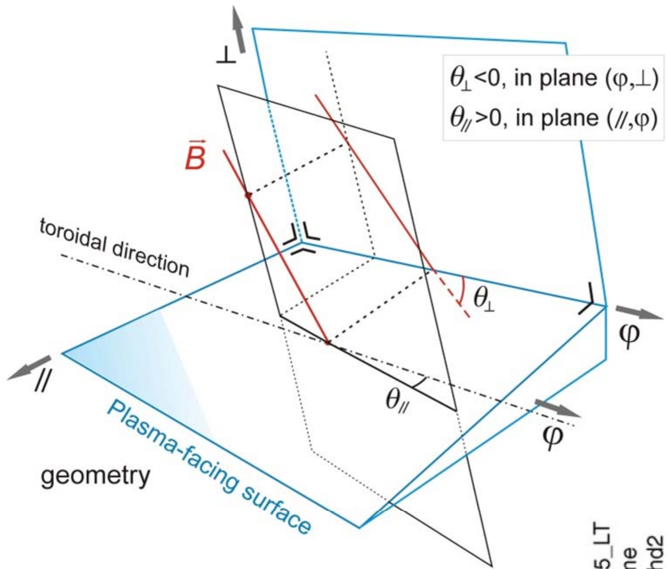


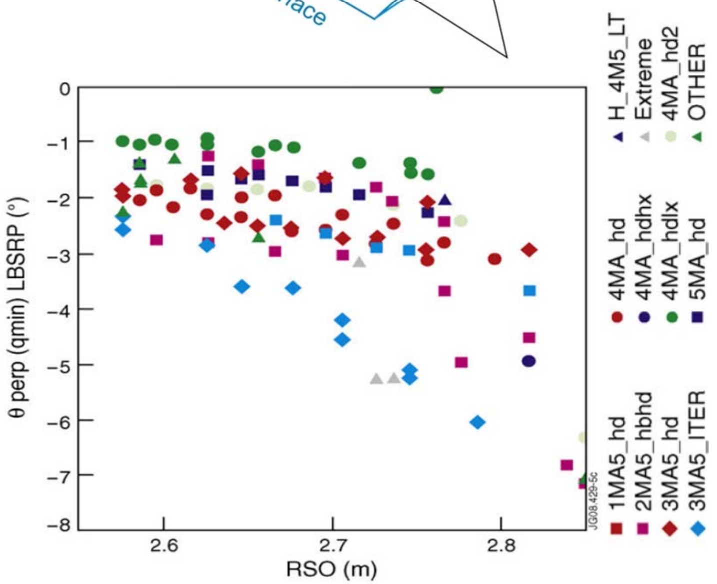
Sequence of special lamellae for exposure in the MARION ion/neutral beam facility

$$\boxed{T_{Wsurf,max} = \{\ 1200°C,\ 1600°C,\ 2200°C\ \}}$$

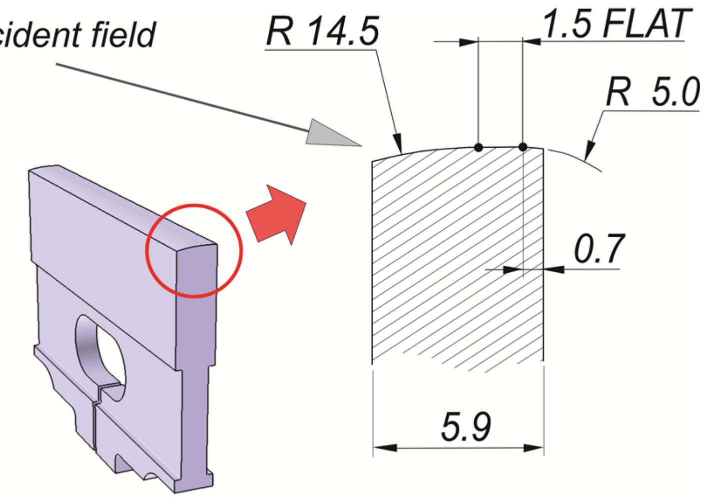
Bulk W tile: *physics (shadowing)*

Magnetic field: angles of incidence





LWF:



$$\mathrm{TWF} = \frac{1}{\cos\alpha_x}\left[1 - \frac{h_x + g_x \sin\alpha_x}{(L_{\mathrm{tile}} + g_x)(\sin\alpha_x + \sin\theta_\perp)}\right]$$

- 2D profile optimised for $\theta_\perp$ ~1°-3°
- Tolerances take *O*(gyro-radius) into account
- Cover $(\theta_{//},\theta_\perp)$ pairs to approach the CFC case

Bulk W tile: *physics (other effects)*

- Physical sputtering → out of present scope, bulk material
- Melting → J.W. Coenen(**I-20 on Friday**), K. Krieger (**I-21**); tried to consider in present design
- Monitor W spectroscopically in front of the *tile 5* divertor row

Ionization of W atoms and W^+ ions by electrons

L Vainshtein[1], I Beigman[1], Ph Mertens[2]‡, S Brezinsek[2], A Pospieszczyk[2] and D Borodin[2]

[1]P.N. Lebedev Physical Institute RAS, Leninskiy prospekt 53, 119991 Moscow, Russia

[2]Institute of Energy and Climate Research - Plasma Physics, Forschungszentrum Jülich GmbH, Association EURATOM-FZJ, Partner In the Trilateral Euregio Cluster, Jülich, Germany

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Abstract. Ionization cross sections and rate coefficients of the atom W and the ion W^+ by electron impact are calculated for the electron energies from thresholds to 300eV. The Coulomb-Born method with exchange and normalization (by the reduced K-matrix method) is used. The contribution from excitation of autoionizing levels to the single ionization as well as of inner shell ionization to the double ionization is also calculated.

Results for W^+ are compared with experimental data and were found to be in agreement within 15%. A similar accuracy is expected for the W atoms.

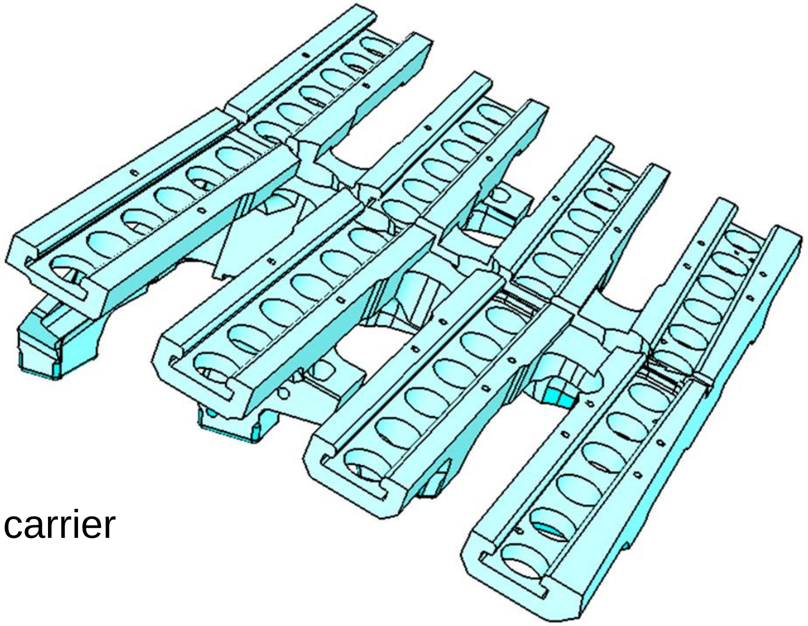
PACS numbers: 95.30.Ky, 95.30.Dr, 52.25.Vy, 52.25.Ya, 28.52.Fa

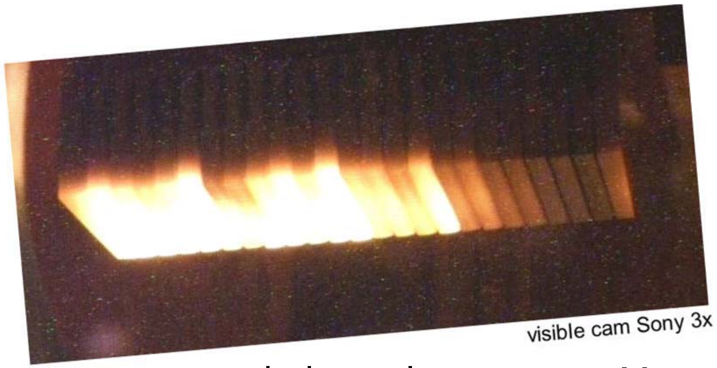
Tile carrier (wedge)

- Wedge shape given (tilt 16.8°)
- Deep cuts prevent eddy current loops
- Best possible material within budget: Inconel alloy 625
- Pre-loaded; dimensional tolerances for the tungsten tile:

  0.3mm plasma-facing surface to base carrier

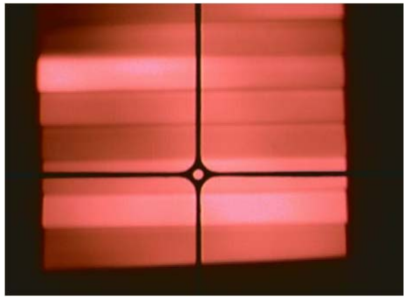
  +/- 50µm lamella-to-lamella





during pulse

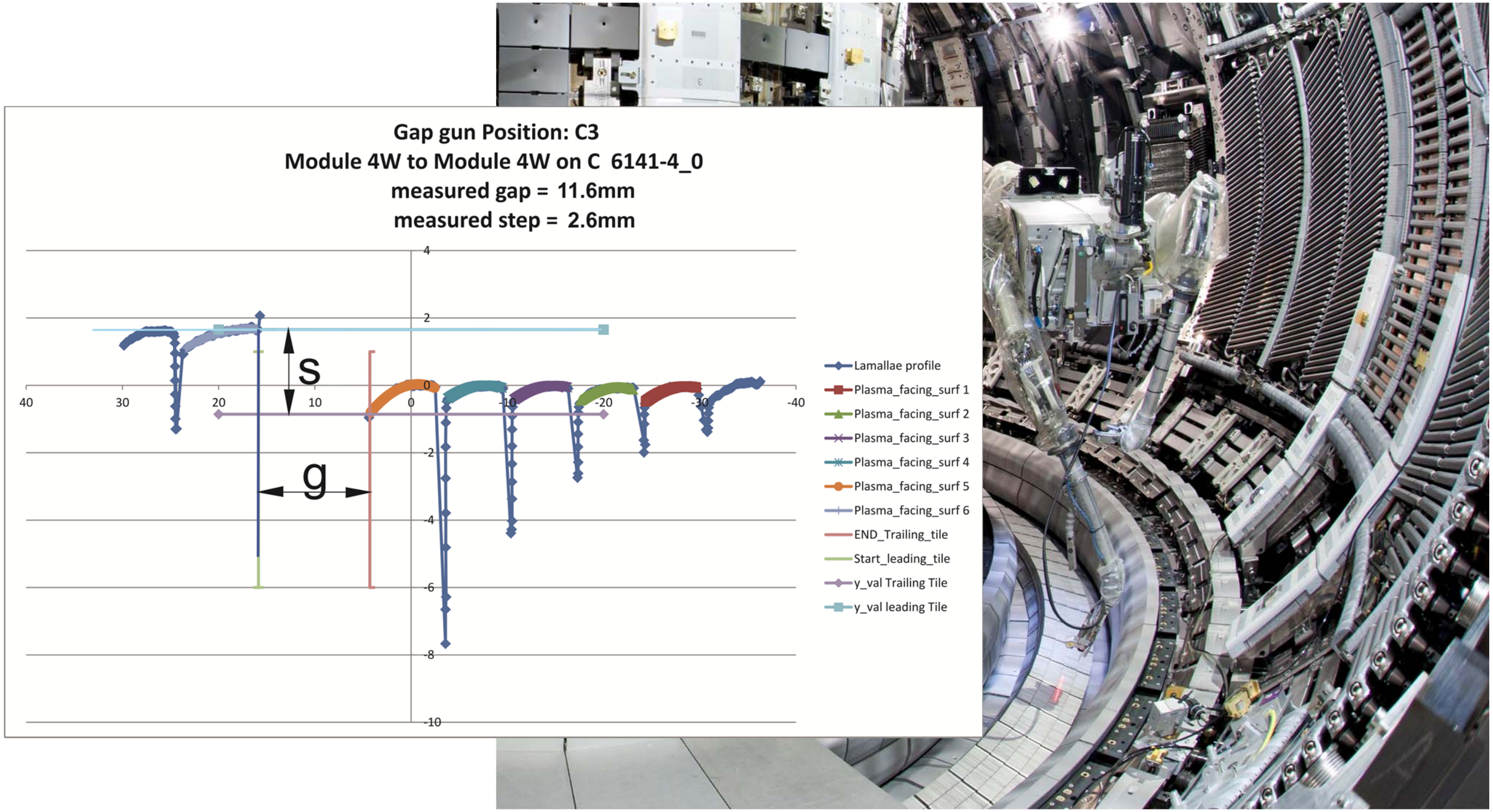
MARION



after pulse (pyrometer view)

$T_{max,carrier}$ =600°C

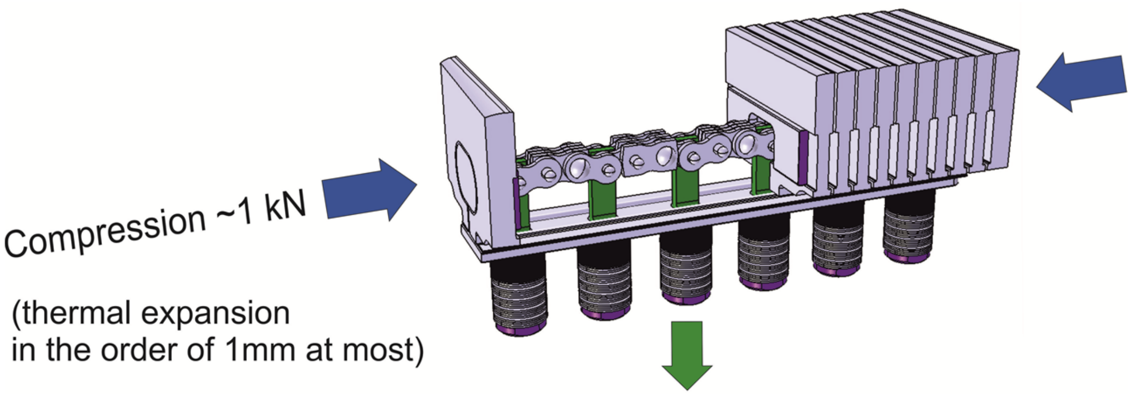
Tile carrier (wedge): Gap Gun survey



Courtesy M. Woollard

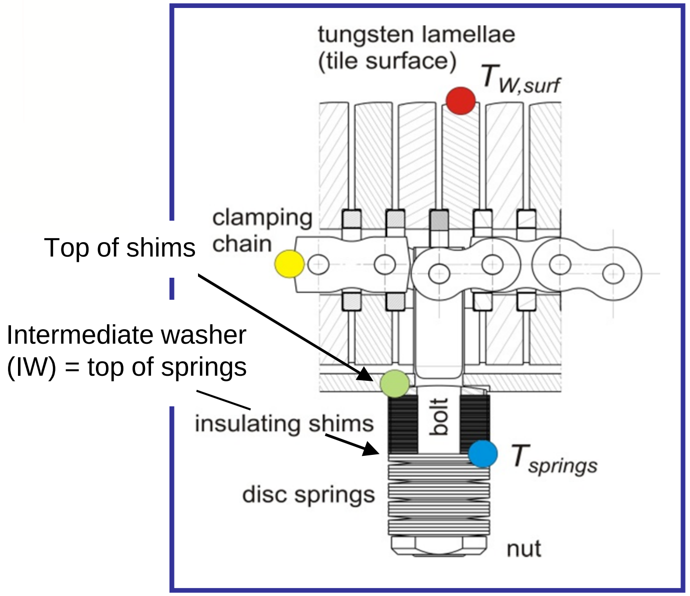
Clamping scheme (*tensegrity*)

- Combine clamping and integrity of the tungsten stack



- Tungsten in compression only
  (to the largest extent)

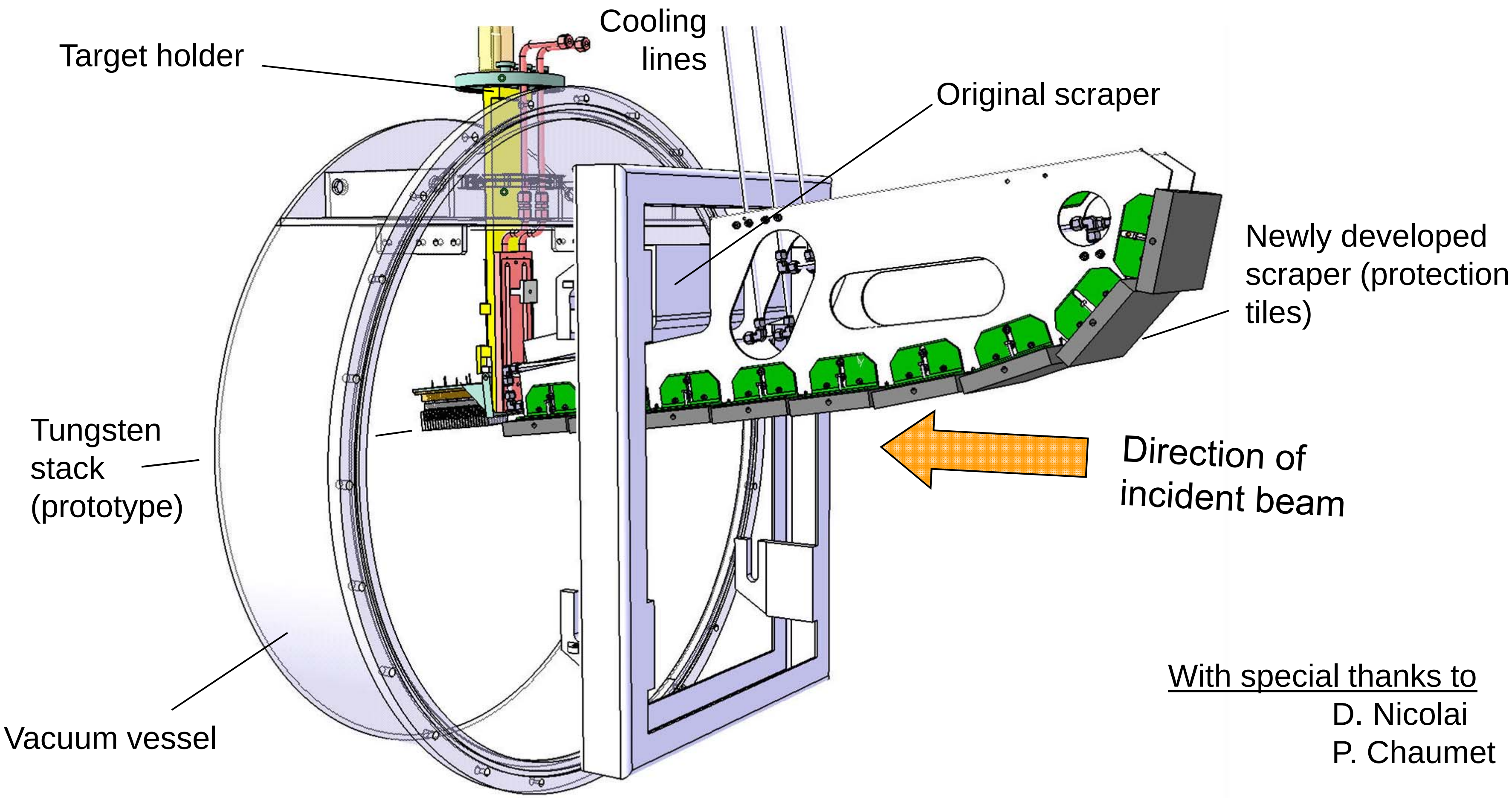
- <u>Limits shifted slightly to the supporting structure</u>



$$\boxed{T_{springs,max} = 330°C}$$

Test in the MARION facility

JÜLICH FORSCHUNGSZENTRUM



With special thanks to
D. Nicolai
P. Chaumet

W-LBSRP

- Test of shallow wing in MARION completed

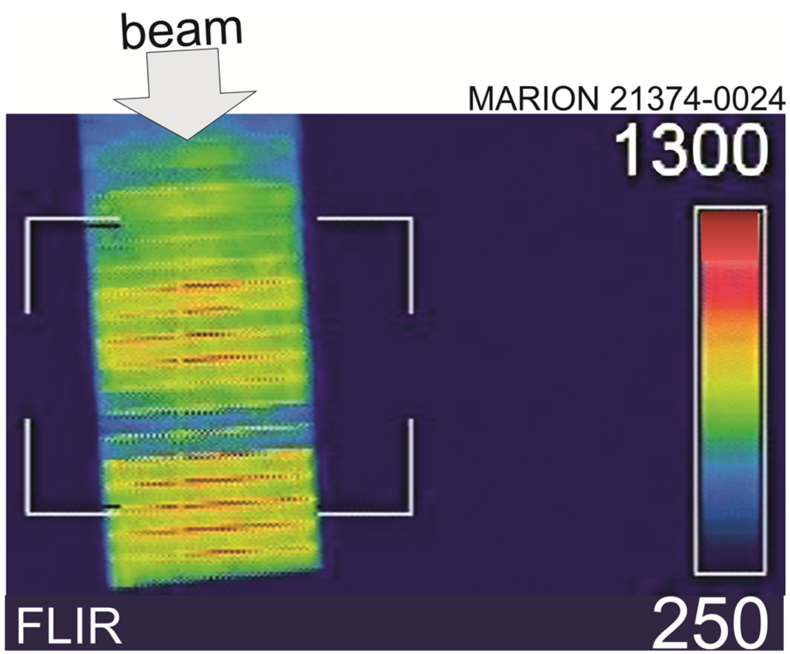
>250 pulses in total
>230 pulses with $E_{deposited}$ > 38 MJ/m^2
>180 pulses with $E_{deposited}$ > 55 MJ/m^2

- $T_{W\ tile,\ max}$ < 1955°C (2050°C at 66MJ/m^2)
  all TC measurements estimated ±7%

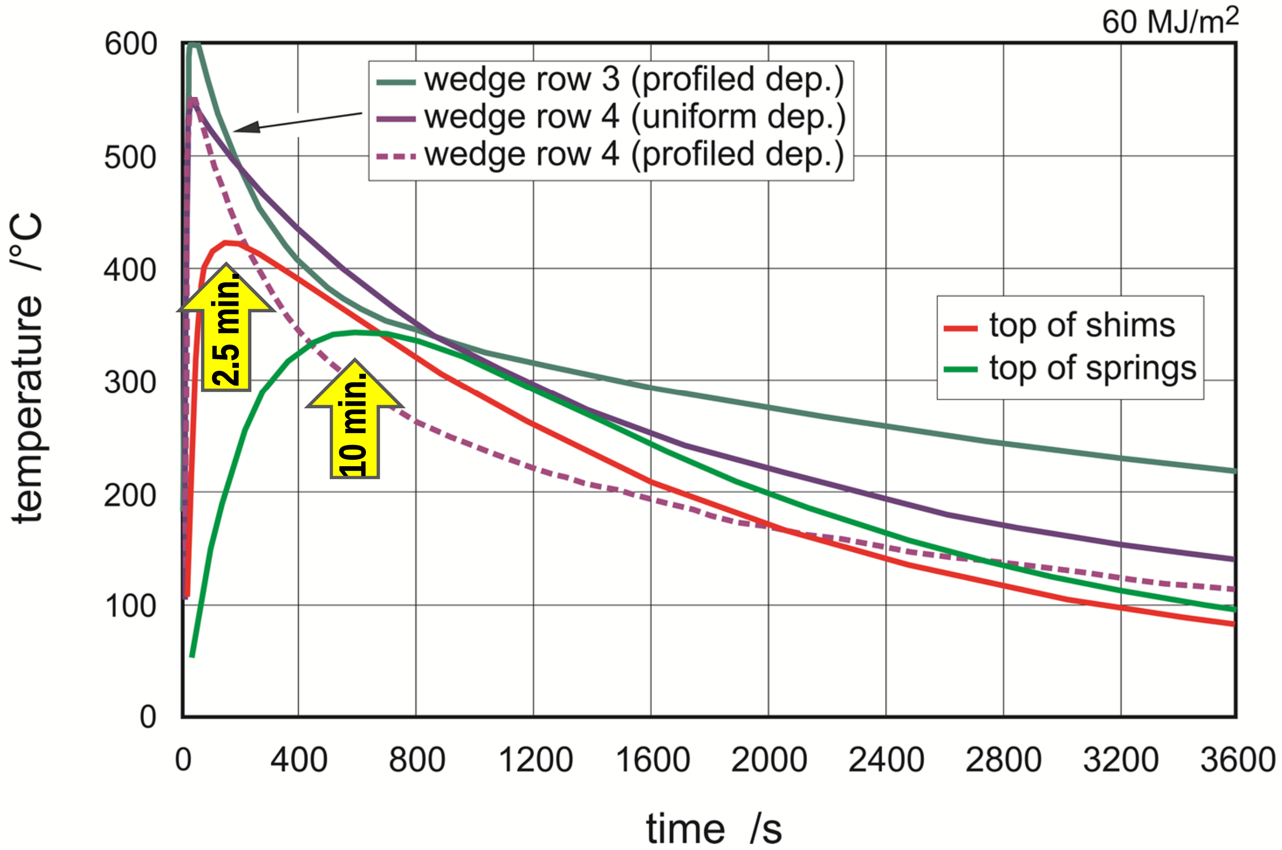
- $T_{Inconel\ carrier,\ max}$ > 600°C
  excursions too large (up to ~10%)

- $T_{springs,\ max}$ = 317-349°C
  for the nominal E_{dep} of 60 MJ/m^2

→ Stay ~10% below 60MJ/m^2
which is now a hard limit



Evolution of the temperature after the plasma pulse (t =0 is end of pulse)



More to the physics goals (esp. *scenarios*)

Realistic deposition profiles (poloidal extension):

$$q\left(MWm^{-2}\right)=\frac{3}{4\lambda_m}\frac{B_{\phi,m}}{B_{p,m}}\frac{1}{2\pi R_{strike}}\frac{\sin(\alpha+\theta_\perp)}{\cos\theta_\perp}\exp\left(\frac{-1.044(R-R_{strike})}{\lambda_m}\frac{B_{\phi,m}}{B_{p,m}}\tan\theta_\perp\right)$$, in the SOL

and

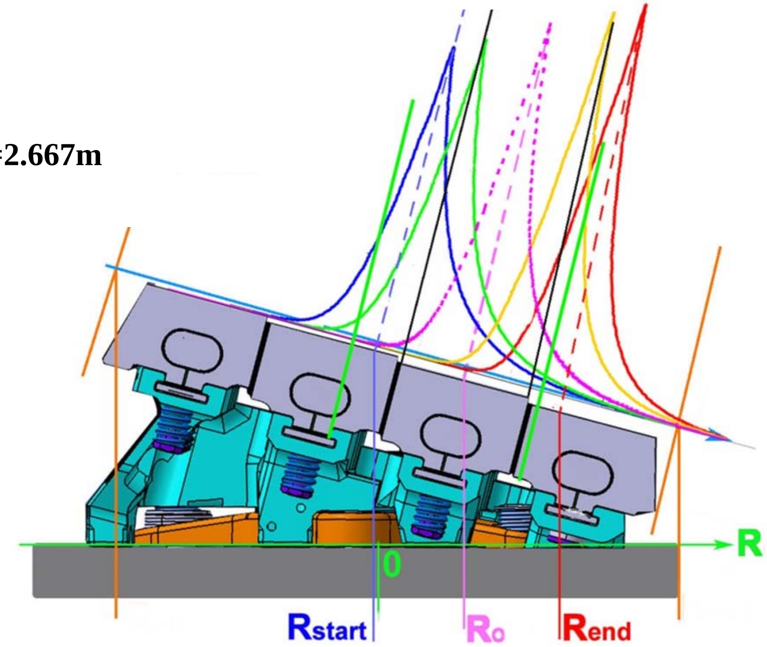
$$q\left(MWm^{-2}\right)=\frac{3}{4\lambda_m}\frac{B_{\phi,m}}{B_{p,m}}\frac{1}{2\pi R_{strike}}\frac{\sin(\alpha+\theta_\perp)}{\cos\theta_\perp}\exp\left(\frac{3.132(R-R_{strike})}{\lambda_m}\frac{B_{\phi,m}}{B_{p,m}}\tan\theta_\perp\right)$$, in the private

region,

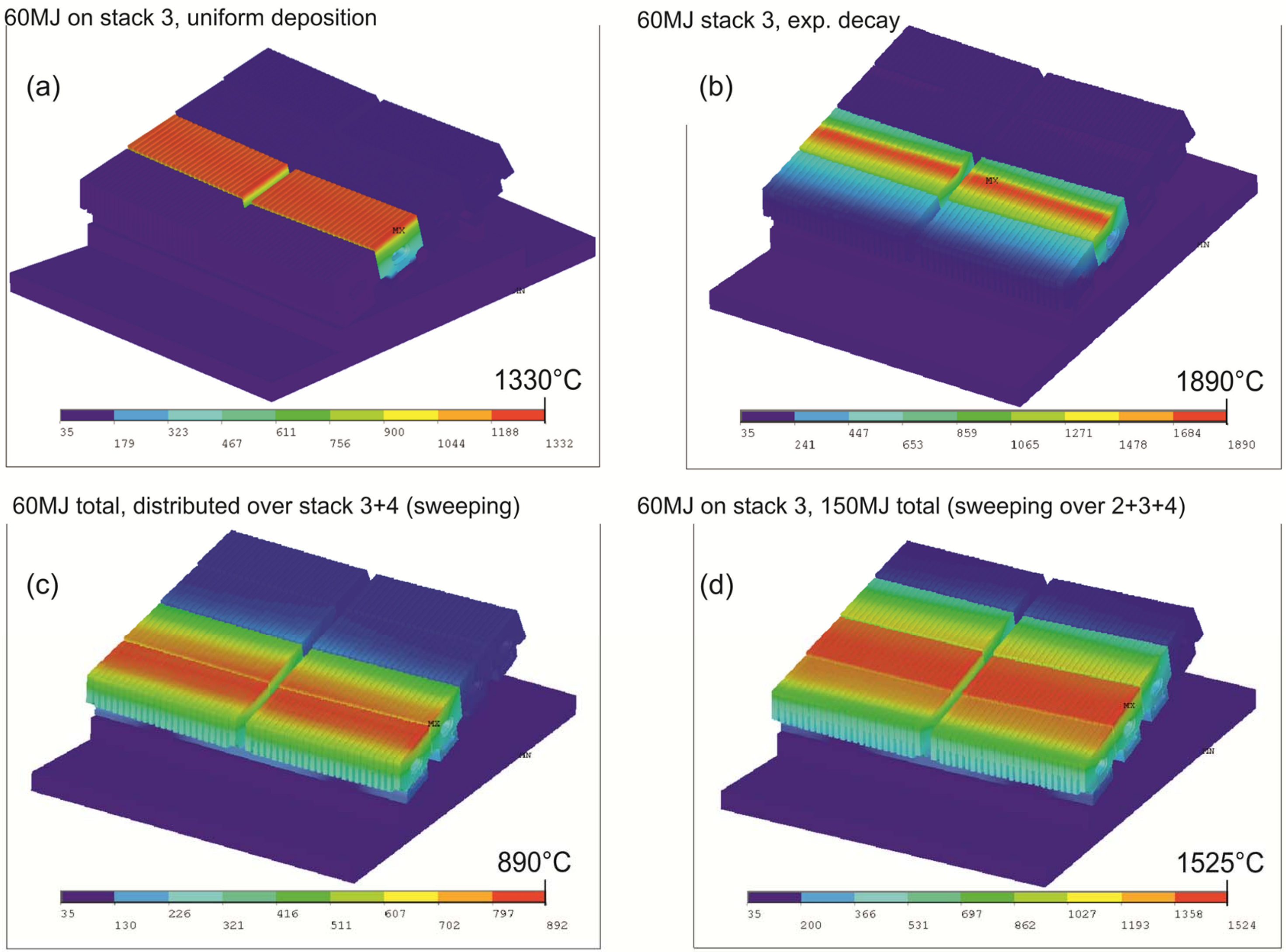
where $\theta_\perp = 14.96R_{strike} - 36.683$, and α=0.7 degrees. **Scaled to Q=60 MJ/m^2, 10s pulses, 2700s pause.**

The following parameters were specified

- λ_m =5 mm, $B_{\phi,m}/B_{p,m}$ =0.335;
- the central dowel in the adaptor (and wedge) is at **R=2.667m**
- R_{start}-R_{end}=100*cos (16.8°)=**96mm**.



Various cases of energy deposition (*scenarios*)



Conclusions

- High rate of change of the magnetic field + high heat loads + fully metallic + inertial cooling
  → avoidance of (worst case) disruptions (Lehnen **I-23**), strict observance of operational limits

- Strict observance of operational limits difficult : diagnostic requirements and T_{max} after plasma pulse!

- Recommended scenarios include sweeping and a radiative fraction f_{rad} ~0.65

- The limit on the deposited energy density E_{dep} <60MJ/m^2 is a coarse indication:

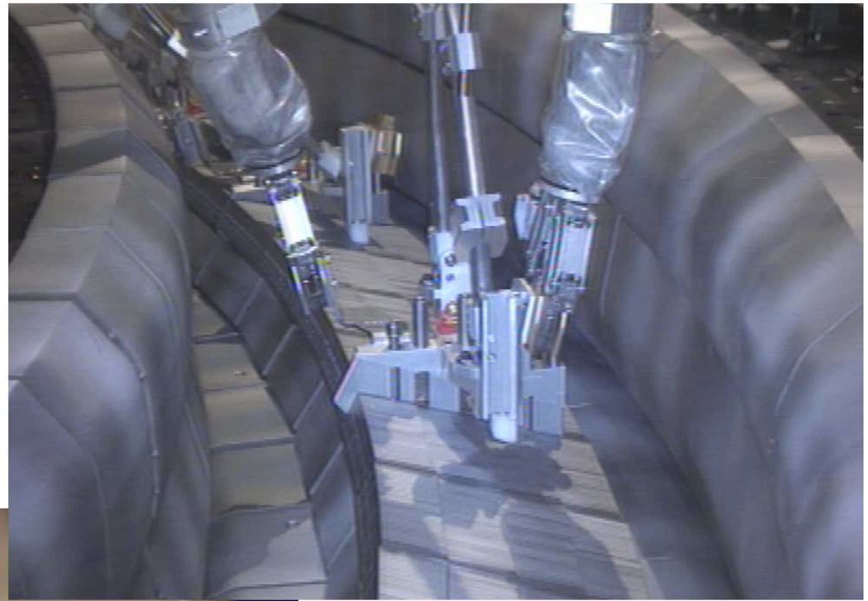
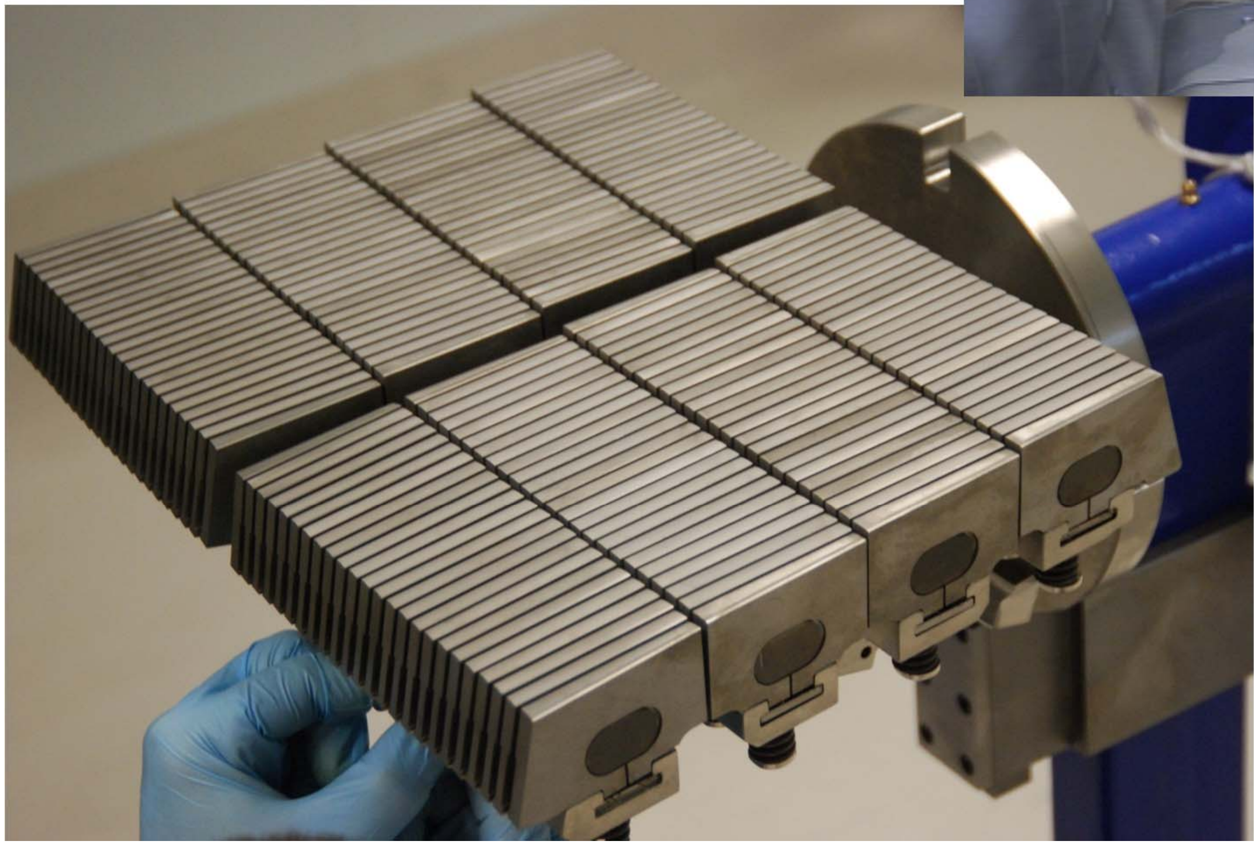
  - the time span of deposition for a given energy is very important <2s $T_{W,surf}$ (tungsten tile) high, but beneficial for carrier, cooling time…

    >10s low $T_{W,surf}$ high, but…

  - similarly, the effects of sweeping depend on poloidal extension and on the goal (more E_{dep}, lower tungsten temperature…)

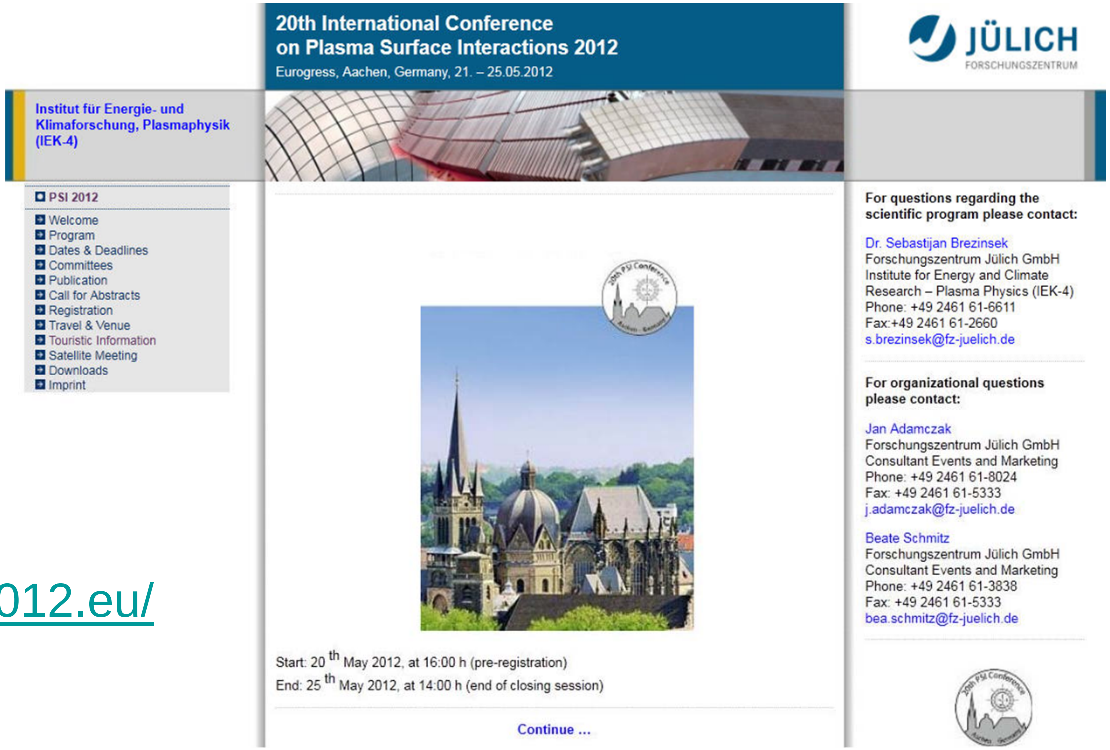
  - keep an eye on the impact on the cooling time (including influence of initial conditions)

- Caution with extreme values of $(\theta_{//},\theta_{\perp})$

PSI 2012: http://fz-juelich.de/psi2012/

Aachen



SOFT 2012: http://www-soft2012.eu/

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