



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

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

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EFJET ITER-like Wall Project at JET

G.F. Matthews (I-01)



Demanding conditions at the outer strike point



7 MW/m² uniformly on the whole conical surface (frustum), for <10 s. Reaches easily 10 MW/m² locally, or more, with due account of gaps and actual wetted fraction

> Iack of active cooling M. Missirlian (I-04)

dB/dt ≤100 T/s during abnormal events ("disruptions"); halo currents <19 kA /module (a tile pair)</p>

purely metallic

R. Mitteau (I-05)

Limits \rightarrow scenario development to reach the goals of the scientific programme

<u>N.B.</u> the full divertor row named "tile 5" or W-LBSRP is about 4 m² large, but the plasma footprint on the tile typically extends to ~20mm only in poloidal direction



Bulk W tile

Top to bottom description





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)</p>



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 $\Delta t_{cooling} \sim 2700-3600s$

Power handling in first approximation through definition of max. temperatures, esp. $T_{W.surf}$

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



thermal shocks: G. Pintsuk (0-12)



Tungsten: yield strength



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

 $T_{Wsurf,max} = \{ 1200^{\circ}C, 1600^{\circ}C, 2200^{\circ}C \}$



Bulk W tile: physics (shadowing)

Magnetic field: angles of incidence





- Tolerances take *O*(gyro-radius) into account
- Sover $(\theta_{\prime\prime}, \theta_{\perp})$ pairs to approach the CFC case

ЕГДА в

- Physical sputtering \rightarrow out of present scope, bulk material
- Melting \rightarrow 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

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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.

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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





 $T_{max, carrier} = 600^{\circ} C$

ON after pulse (pyrometer view)



Tile carrier (wedge): Gap Gun survey



Courtesy M. Woollard

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Clamping scheme (*tensegrity*)



Combine clamping and integrity of the tungsten stack







W-LBSRP



• Test of shallow wing in MARION completed

- $T_{W \ tile, \ max}$ < 1955°C (2050°C at 66MJ/m²) all TC measurements estimated ±7%

- *T*_{Inconel carrier, max} > 600°C excursions too large (up to ~10%)

- $T_{springs, max} = 317-349^{\circ}C$ for the nominal E_{dep} of 60 MJ/m²

→ Stay ~10% below 60MJ/m² which is now a hard limit >250 pulses in total >230 pulses with $E_{deposited}$ > 38 MJ/m² >180 pulses with $E_{deposited}$ > 55 MJ/m²







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):

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

and

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

where $\theta_{\perp} = 14.96R_{strike} - 36.683$, and $\alpha = 0.7$ degrees. Scaled to Q=60 MJ/m², 10s pulses, 2700s pause.

The following parameters were specified

$$- \lambda_{m} = 5 \text{ mm}, \mathbf{B}_{\phi,m}/\mathbf{B}_{p,m} = 0.335;$$

- the central dowel in the adaptor (and wedge) is at R=2.667m

- $R_{\text{start}}-R_{\text{end}}=100^{\circ}\cos(16.8^{\circ})=96$ mm.



Various cases of energy deposition (scenarios)







60MJ on stack 3, 150MJ total (sweeping over 2+3+4)





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Conclusions



- High rate of change of the magnetic field + high heat loads + fully metallic + inertial cooling \rightarrow 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 $E_{dep} < 60 \text{MJ/m}^2$ 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 $(heta_{\prime\prime}, heta_{ot})$





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News	Overview
Key dates	The objective of the Symposium on Fusion Technology (SOFT) is to exchange information on design, construction and operation of fusion experiments and on the technology for present fusion machines, the next step and future power plants. With the construction of ITER now starting, fusion research is making a big step forward. ITER, with its demanding requirements, is expected to be a major topic on this symposium. SOFT includes oral and poster presentations as well as an industrial and R&D exhibition.
Overview	
Conference programme	
Contribution upload and Abstract submission	The expected attendance is up to 1,000 delegates from all over the world, active in university and research laboratories on subject dayling with furing devices, generically with the construction of ITEP as well as in inductibility analysis to the second s
Fusion technology forum	engineers, developers, users and students are offered an opportunity to exchange views, visions and experience and to establish
Organizing committees	nuclui business contacts.
Transport and	Language
Accommodation	The working language of the SOFT is English.
Venue	Fusion Expo
Social programme	Here's a link to fusion expo.
Previous SOFTs	

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