A solid tungsten divertor for ASDEX Upgrade

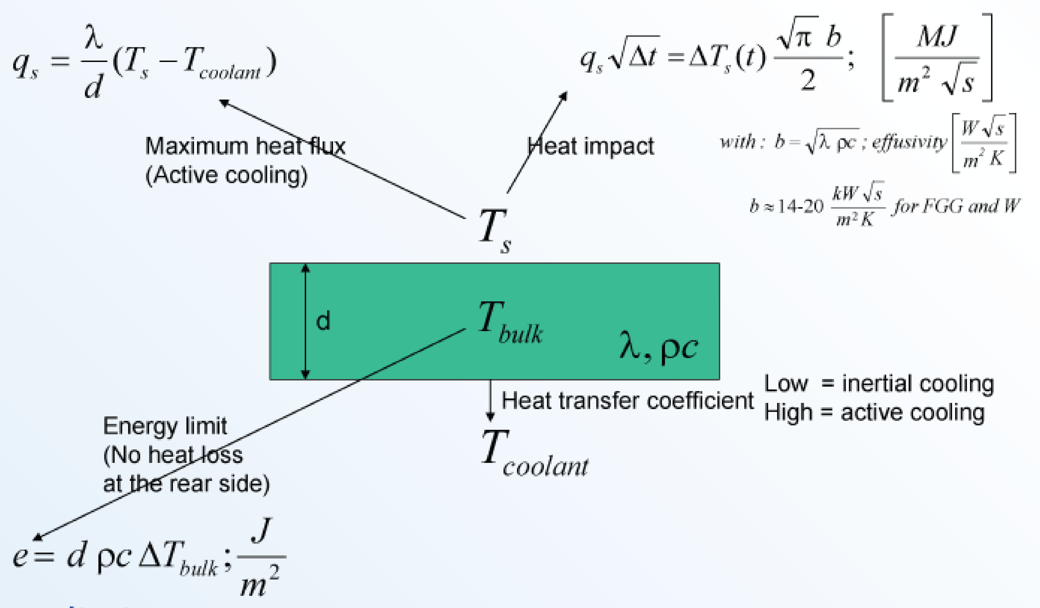
A. Herrmann, H. Greuner, N. Jaksic, B. Böswirth, H. Maier, R. Neu, S. Vorbrugg and the ASDEX Upgrade Team
Max-Planck-Institut für Plasmaphysik, EURATOM Association, Garching, Germany

ASDEX Upgrade

Motivation

- ASDEX Upgrade was changed stepwise from a full carbon to a full tungsten experiment.
- The full tungsten first wall is in operation since 2007.
- Coating of fine grain graphite with:
  - W-PVD (4µm, main chamber)
  - W-VPS (200 µm lower outer divertor)
  - W-CMSII (10 µm lower outer divertor, > 2008)
- Coatings have a lower heat receiving capability compared to carbon. This limits the operational parameters of ASDEX Upgrade.
- A solid tungsten divertor
  - restores the operational windows as for a graphite divertor.
  - allows the investigation of erosion and deuterium retention
  - is flexible for testing of different castelations (width, distance ...)
  - and target tilting/shadowing

Divertor limits



Energy limits

target material	Target data: 0.5 x target mass / g	Target data: Heat capacity (@ 500 C) J / (g K)	Maximum equilibrated temperature / °C: Single event	Maximum equilibrated temperature / °C: cyclic	Energy to a single target / MJ/tile: Single event	Energy to a single target / MJ/tile: Cyclic	Number of tiles	Energy to the divertor / MJ: Single event	Energy to the divertor / MJ: Cyclic
Graphite	470	1.50	550	300	0.38	0.20	128	48	26
Tungsten coated graphite	470	1.50	550	300	0.38	0.20	128	48	26
Solid tungsten	2703	0.15	1000	600	0.40	0.24	128	51	30

Heat impact factor

Target material	Target data (@ 500 °C): Mass density	Target data (@ 500 °C): Specific heat	Target data (@ 500 °C): Heat conductivity	Effusivity	Max. surface temperature	Heat impact factor
	kg / m**3	kJ/kg-K	W /m K	kW/(m**2 K)√(s)	°C	MW/m**2 √s
Graphite	1850	1500	70	14	2500	31
Tungsten coated graphite	1850	1500	70	14	1400	17
Solid tungsten	19300	150	130	19	2800	48

The heat impact factor for tungsten coated graphite restricts the discharge duration for high performance plasmas (> 10 MW/m2 stationary) to about 2.6 s,

Design criteria and conceptual design

Do we need an actively cooled divertor? - NO

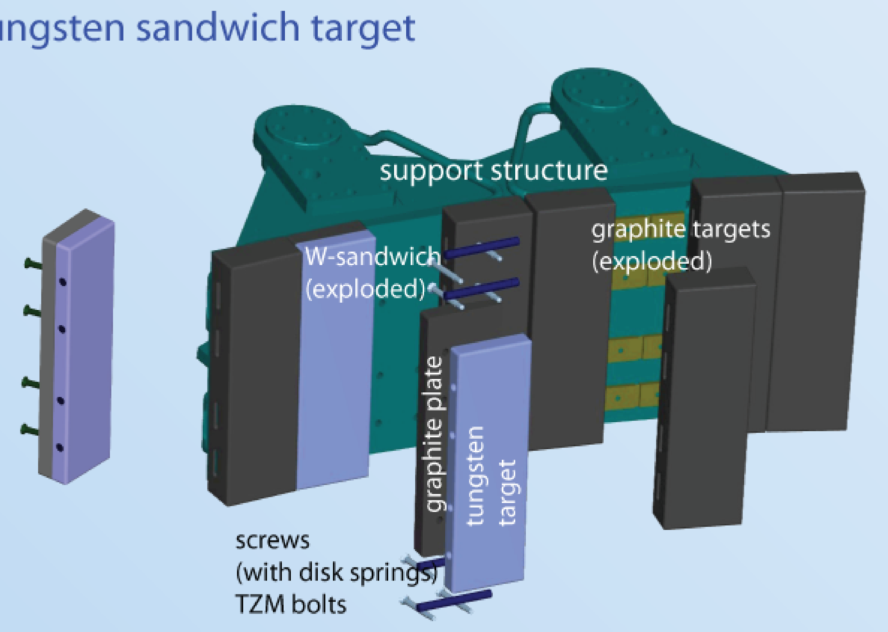
- Max. technical pulse length: 10 s
  - Heating of toroidal field coils
  - Energy consumption from fly wheel generators.
  - DAQ is designed to the technical pulse length.
- Max energy input: 10 s * 28 MW = 280 MJ
- Max tolerable plasma energy input of the present inertially cooled divertor:
  - 78 MJ ~ 8 s with 10 MW - standard operation
  - 144 MJ ~ 5 s with 28 MW - high power shots (single events)
- Problem with the tungsten coated divertor was the surface temperature NOT the energy limit.

Design criteria

The new Div-III should have:

- the same energy receiving capability as a graphite divertor of about 50 MJ
- a tolerable maximum heat load comparable to the uncoated graphite divertor
- compatibility to the existing support structure for the divertor target plates
- an optimized weight that allows handling with a minimum of in vessel tools.
- induced forces that are compatible to the existing support structure.
- a price that fits to the budget
- been realized in the near future

Tungsten sandwich target



- The 30 mm thick tungsten coated graphite tiles are replaced by a tungsten graphite sandwich structure.
- Sandwich: a 15 mm thick solid tungsten plate clamped together with a graphite plate of about 15 mm thickness to the exiting cooling structure.
- Target tilting is realized by shaping the graphite plate.
- Flat tungsten plate that to minimize the manufacturing effort and to maximize the flexibility of divertor shaping.
- Increased weight of the divertor plates from about 8 kg/sector to 40 kg/sector. (+20 kg support structure).
- Reduced thickness = reduced heat capacity: this is compensated by using TZM instead of SS = higher tolerable equilibrium temperature of 600 °C and 1000 °C for cyclic load and single events, respectively.
- The energy limit becomes for the solid tungsten sandwich divertor 30 and 50 MJ for cyclic and single loads, respectively.

Forces

- Divertor II with graphite targets is operated without (major) problems.
- Mechanical loads due to tungsten targets?
  - What is changing due to tungsten targets?
  - Model the divertor structure and calculate mechanical loads.
- Origin of mechanical loads:
  - Eddy currents/Disruptions
    - Worst case estimation (no material dependence)
    - Conventional.
  - Halo currents - NO difference to graphite
- FEM calculations : The divertor structure and the target clamping can withstand these loads.

Halo current

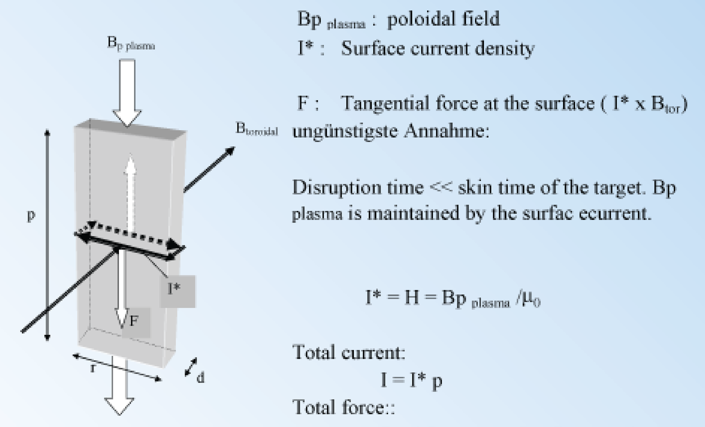
$$F_{halo} = I_{halo}\, B_{tor}\, l = 450kA/16 \times 3.5T \times 0.5m \approx 50kN$$

Eddy currents: worst case estimation - no material dependence

Force to a divertor tile

Input parameters

p - extension in poloidal direction (m)	0.24
r - extension in radial direction (m)	0.015
Btor (T)	3.5
d - extension in toroidal direction (m)	0.08
Bz (T)	0.2
mu0	1.26E-06
I=I* x p (kA)	38
Force (kN):	**2.0**
Torque (Nm):	**161**



Bp_{plasma} : poloidal field
I* : Surface current density

F : Tangential force at the surface (I* x B_{tor})
ungünstigste Annahme:

Disruption time << skin time of the target. Bp plasma is maintained by the surfac ecurrent.

$$I^* = H = Bp_{plasma}/\mu_0$$

Total current:

$$I = I^*\, p$$

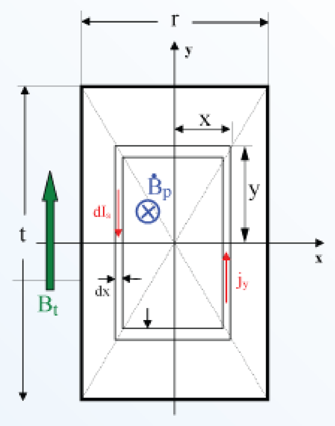
Total force::

$$F = I\, B_{tor}\, r = p\, r\, B_{tor}\, Bp_{plasma}/\mu_0$$

Eddy currents: conventional estimation - material dependent

Forces due to eddy currents

Input parameters	poloidal field: Graphite	poloidal field: W	poloidal field: Structure	radial field: W	radial field: Structure
r,p - extension perp. to dB/dt (m)	0.015	0.015	0.1	0.24	0.24
B_tor (T)	3.5	3.5	3.5	3.5	3.5
t - extension in toroidal direction (m)	0.08	0.08	0.4	0.08	0.32
dB/dt (T/s)	100	100	100	10	10
p,r - extension along dB/dt (m)	0.24	0.24	0.015	0.015	0.015
rho - el. Condcutivity (Ohm m)	1.0E-05	6.0E-08	7.0E-07	6.0E-08	7.0E-07
Output					
Force (kN):	**0.01**	**1.01**	**1.18**	**0.17**	**0.37**
Moment (Nm)	**0.03**	**5.71**	**44.12**	**15.12**	**33.18**



Modell

Total force to the halfe plate

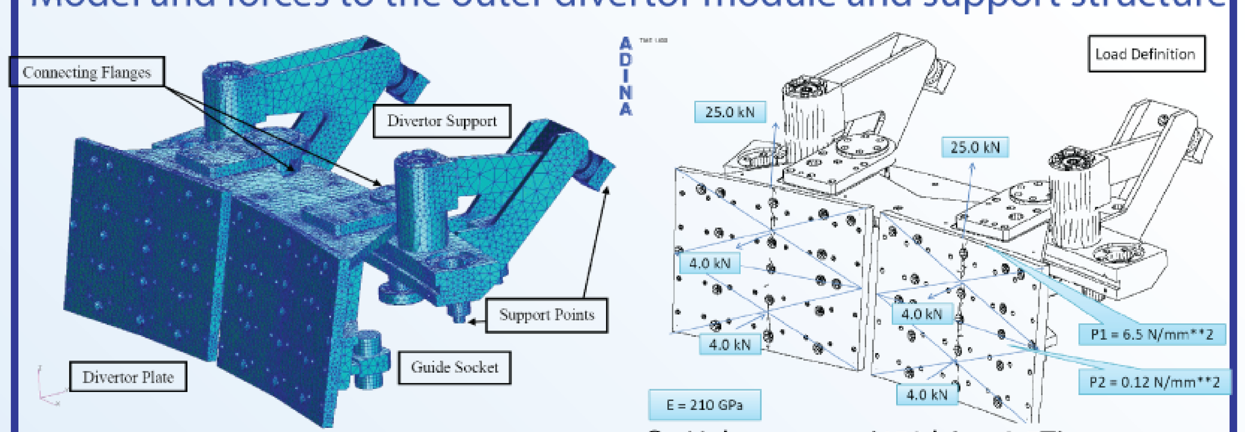
$$F_{tot} = B_t \cdot \dot{B}_p \cdot \frac{p}{\rho} \cdot \frac{t/r}{\left(1 + r^2/t^2\right)} \cdot \frac{r^3}{24}$$

Target clamping forces

- Preload force of 2x4 stacks of disc springs: 4.8 kN
- Rupture force of 2x4 M5 fastening screws: about 68 kN

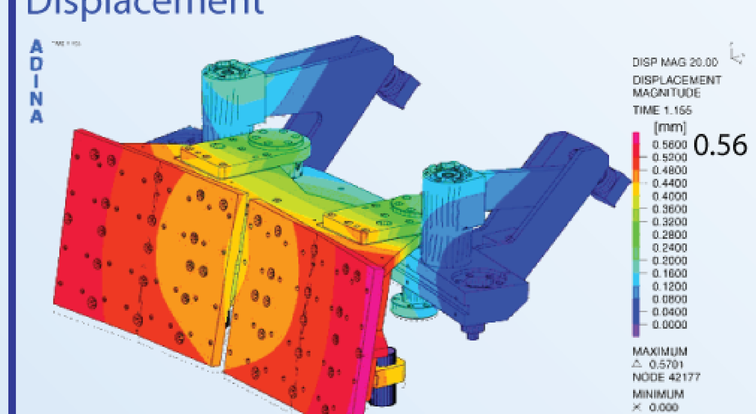
FEM modelling of the divertor structure

Model and forces to the outer divertor module and support structure



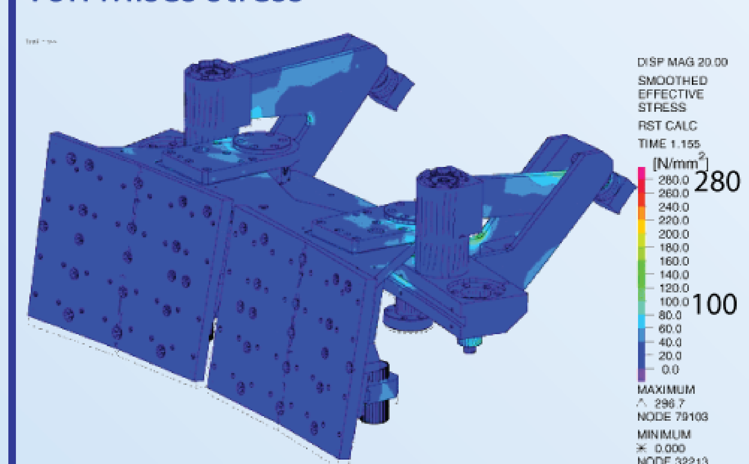
- Halo currents (450 kA @ 3.5T):
  - 2 x 2.5t poloidal load
- Eddy currents:
  - Torque to the front plate: 400 Nm.

Displacement



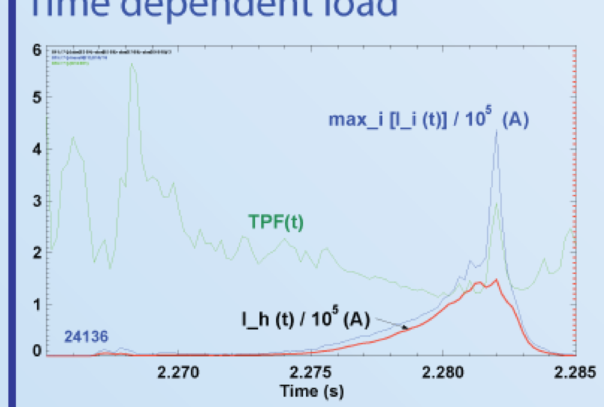
- The maximal displacement for this load case amounts 0.57 mm.
- The dashed lines in the figures mark the undeformed structure.

von Mises stress



- The average stresses in the structure are under 100 MPa.
- There are two hot spots with the peak stresses of ~ 298 MPa.
- The allowable stress for the stainless-steel at 20°C amounts approximately 400 MPa.

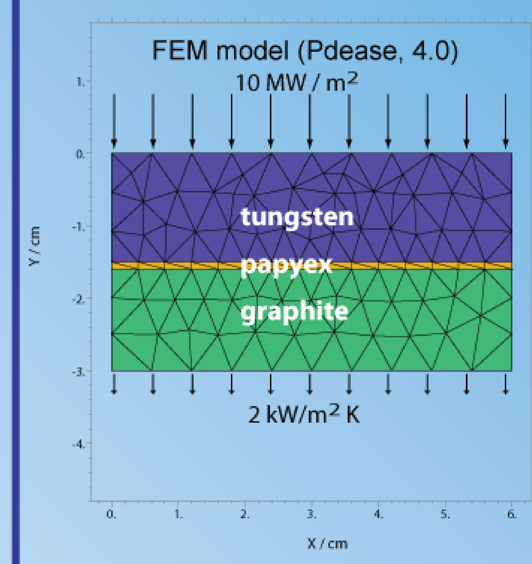
Time dependent load



- The maximal deflection of the structure amounts only ~0.1mm
- The disturbance of the structure caused by the load impulse, take place ~0.7 s only.
- The value of the dynamic maximal deflection is far below the values gained by the static analysis.
- The design values for the divertor plate and the related support structure gained in the static analyses covered entirely all other lad scenarios.

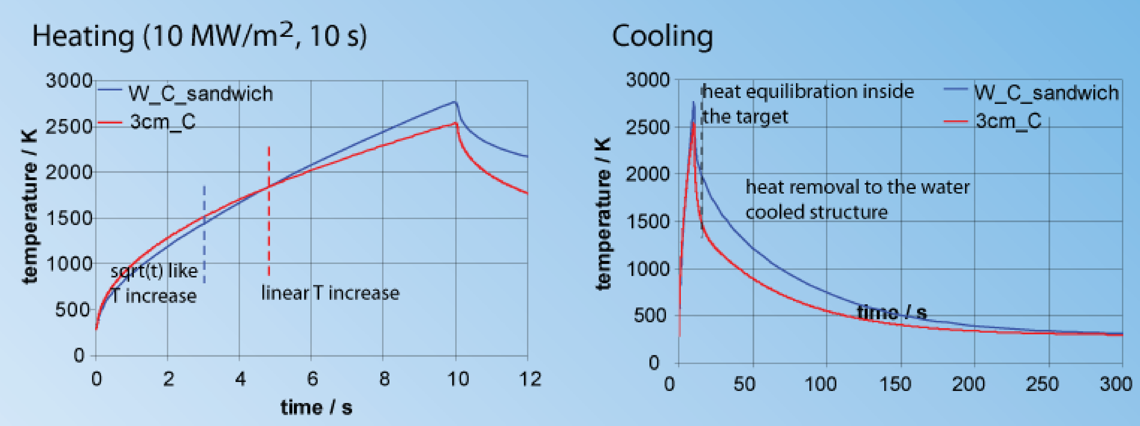
Thermal properties

Heating and cooling - 2D FEM



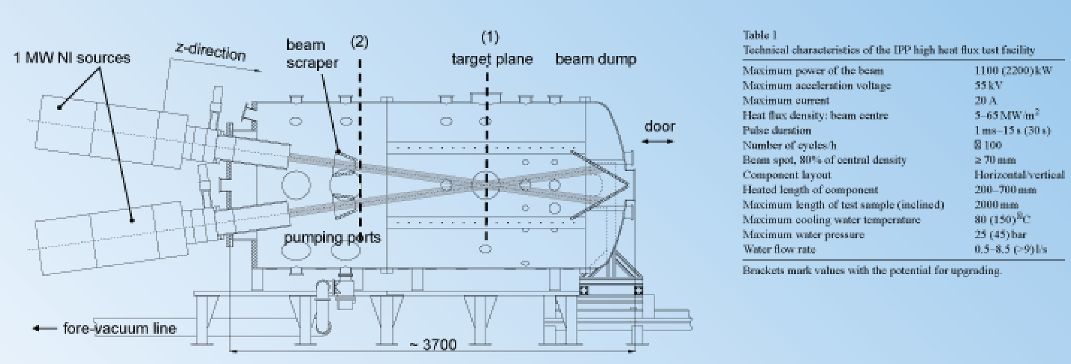
- The heat transmission between tungsten and graphite is low.
- No energy flow into graphite during the discharge.
- Heat resistance of the system is dominated by papyex (1mm) and the cooling (2 mm Papyex)
- Heat transmission coefficients:
  - 2 mm Papyex clamping: 2 kW/m² K
  - 15 mm graphite: 5 kW/m² K
- T increase becomes linear at about 3 s for the tungsten target.
- The maximum temperature is about 300 K higher compared to the graphite target.
- The T decay is slower
- The start temperature is reached at 5 min.

Temperature evolution



High heat flux tests in GLADIS

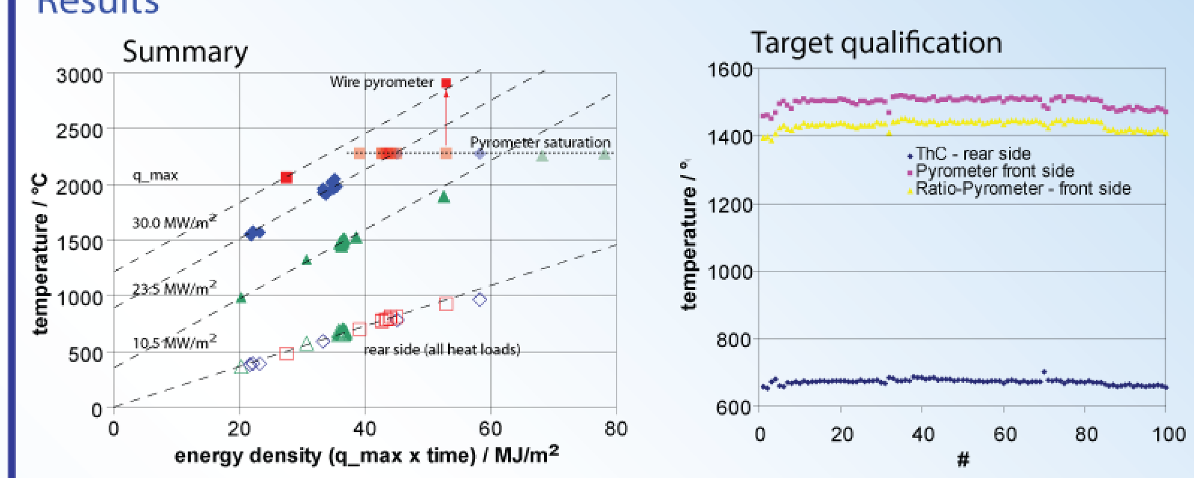
Garching Large Divertor Sample Test Facility - GLADIS



Aims of extensive target tests:

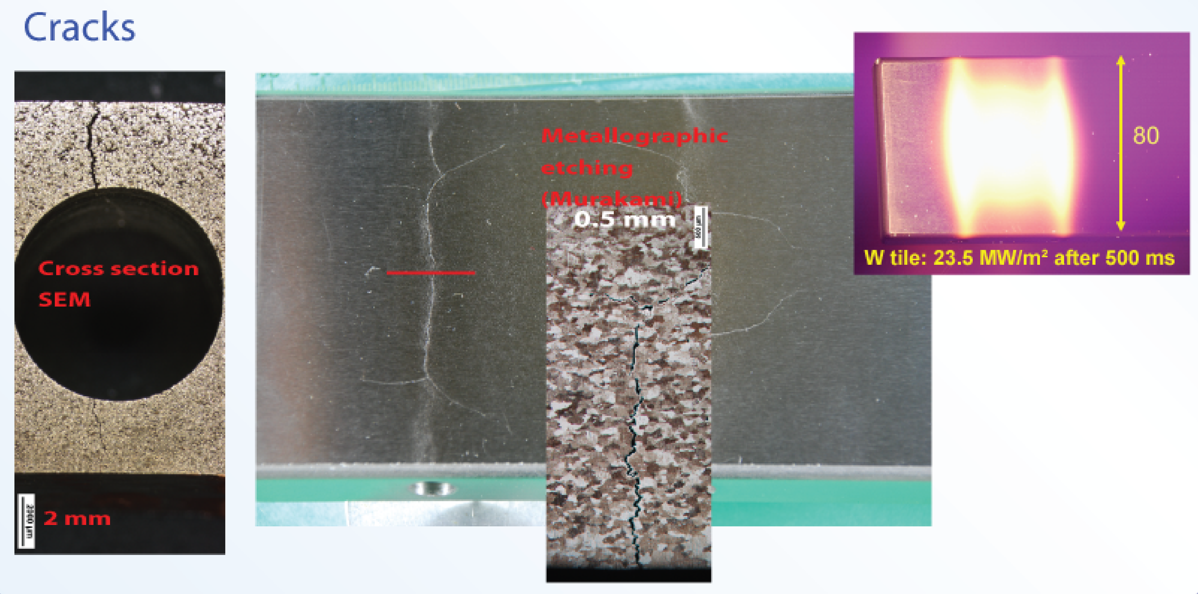
- Cyclic loading with 10.5 MW/m² for 3.5 s and 100 cycles ... representing the 'typical' ASDEX Upgrade divertor load for high power (10 -15 MW) discharges.
- Find out the damage level and the consequences of a target overload by increasing the pulse length and maximum heat flux.
- Increase the surface temperature above the melting limit for carbidized tungsten at about 2800°C.

Results



- Qualification tests:
  - Cyclic load 100 x 10.5 MW/m², T_{surf} = 1500°C no damage
- Damage level:
  - 10 MW/m² up to 7.5 s, T_{surf} > 2200 °C
  - 10 x 23.5 MW/m², 1.5 s cracks after #5
  - 23.5 MW/m² up to 2.5 s, cracks at 2.0 s
- Melting limit:
  - 30 MW/m² up to 1.8s, T_{surf}=2800°C, no melting, i.e. pure tungsten

Cracks



Summary

- ✔ Solid tungsten divertor compatible to the existing support structure.
- ✔ Mechanical loads
  - ✔ halo currents - no change
  - ✔ eddy currents - acceptable
- ✔ FEM calculation of induced stress (worst case) - stress is below 100 MPA.
- ✔ Investigation of thermal loads and heat receiving capability.
- ✔ Energy receiving capability - comparable to the graphite divertor
- ✔ FEM modelling (PDease) - Tmax and cool down time is comparable
- ✔ Tests in GLADIS - passes the qualification test,
- ✔ NO target loss at heat loads up to 30 MW/m2 for 1.8 s
- ✔ W sandwich test targets are installed in AUG for the 2011 campaign