ITER Divertor Design
HHF Components, ELMs, T-Retention

- **G. Janeschitz**[1], G. Federici[2], A. Kukushkin[2],
- A. Loarte[3], G. Saibene[3]

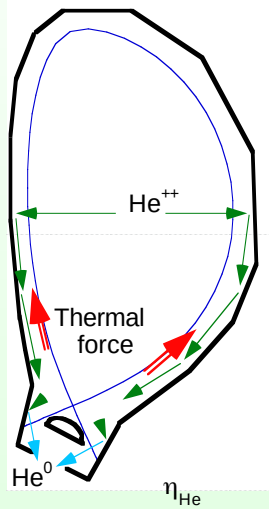
- 1 Forschungszentrum Karlsruhe EuratomAssociation
- 2 ITER International Team Garching
- 3 EFDA Close Support Unit Garching

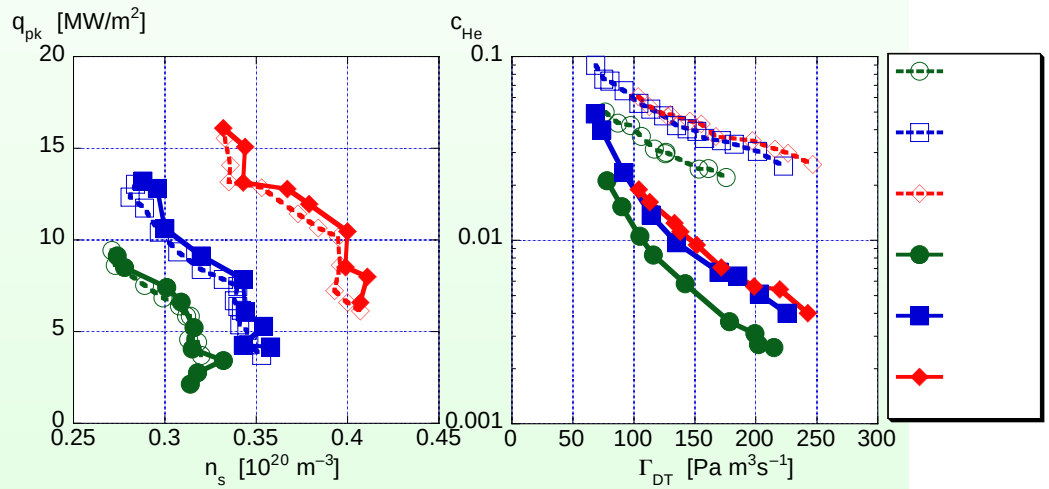
Outline

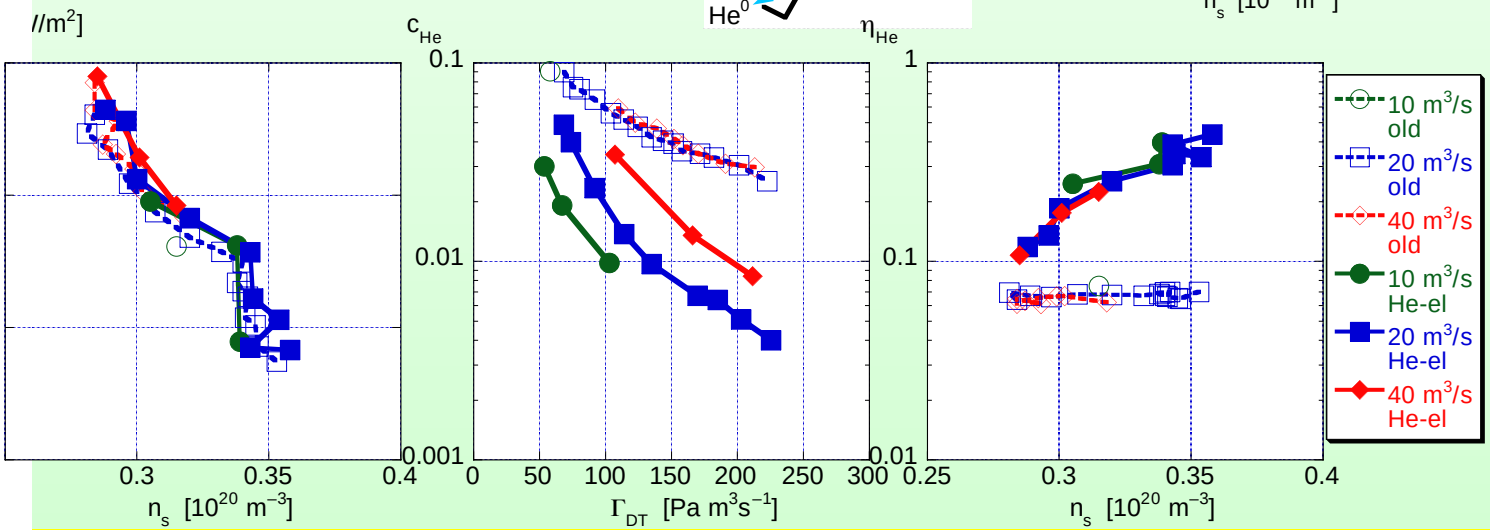
- **Divertor heatloads, He exhaust and HHF-Component design/R&D**
  - Steady state heatloads solved for ITER even for high power advanced modes
  - Pulsed heat loads (ELMs, Disruptions) are a concern
- **The ELM Issue and Composite Lifetime**
  - Plasma Facing Materials and Lifetime
- **First Wall erosion in ITER**
  - Plasma Facing Materials and Lifetime
- **Tritium co-deposition and dust**
  - CFC seems unacceptable even for ITER, W and W alloys are the choice for PFM
- **Summary**

Power and He exhaust predictions including D^+-He elastic collisions

- He streams towards the divertor in the outer SOL while it streams away from the divertor near the separatrix due to the thermal force







- **Elastic collisions increase the He conentration in t pumping duct du to an increae of t He atom energy**

=> Easier to cross h divertor plasma

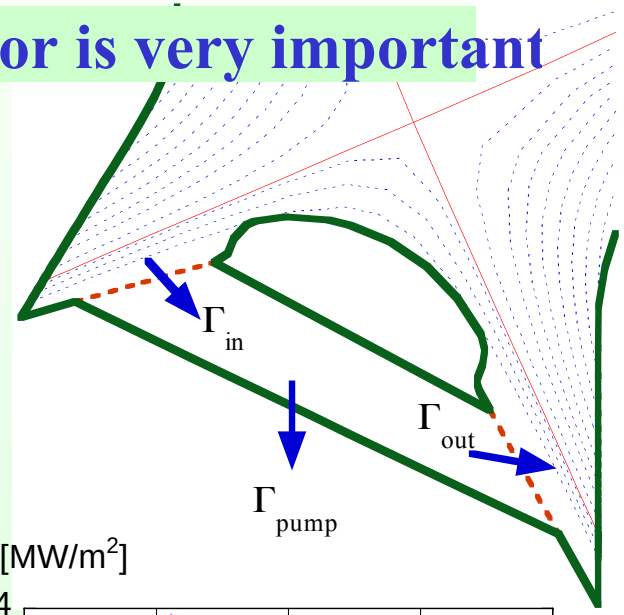
Changing the pumping speed and thus the throughput has no influence on He exhaust

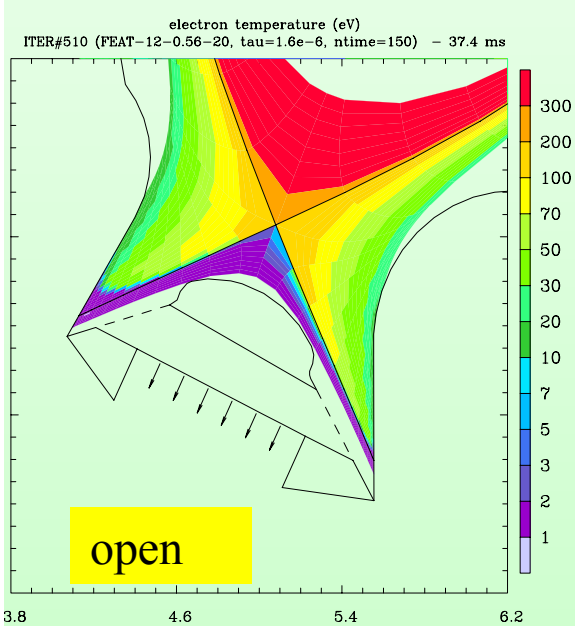
He exhaust only dependent on the upstream density =>Makes SOL control more flexible

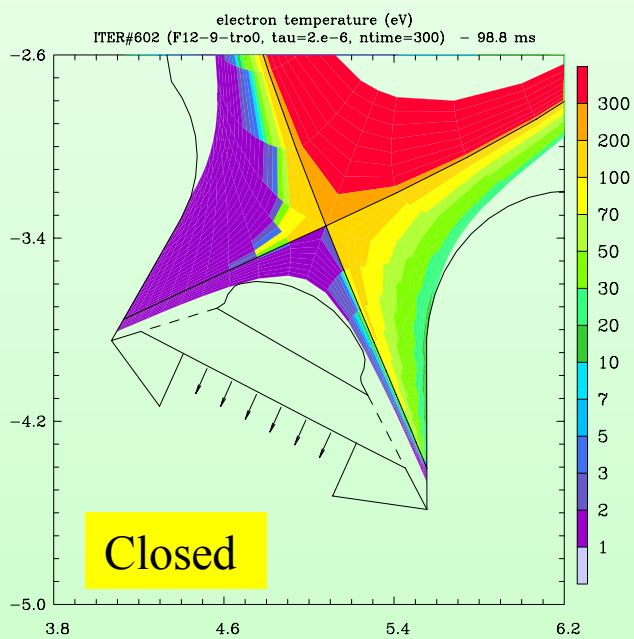
A large opening between inner and outer divertor is very important

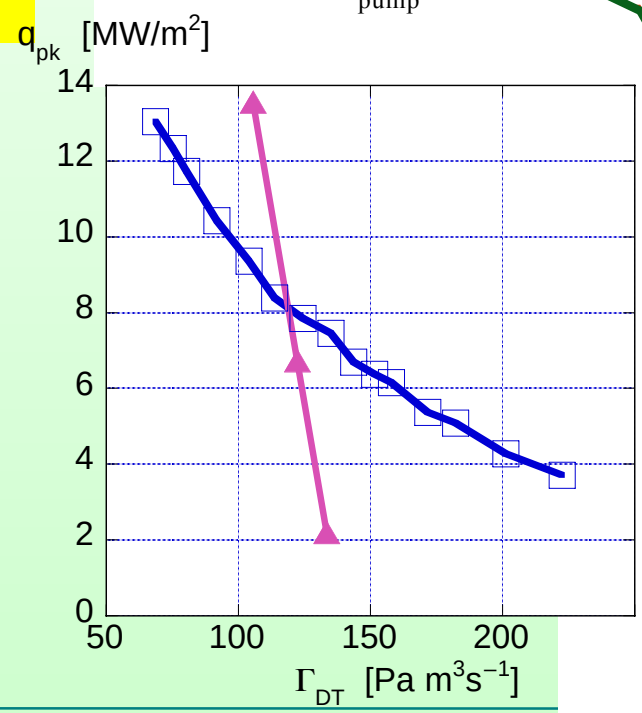
if a large probability for neutrals to cross the private region is provided increased neutral densities at the outer target and thus enhanced radiation losses can be achieved there while the inner target stays semi detached (otherwise degradation of H-mode !!)

- This is consistent with JET experiments in the MKII-GB with the septum installed
- In ITER 300 Pam^3s^{-1} are needed => consistent with the design

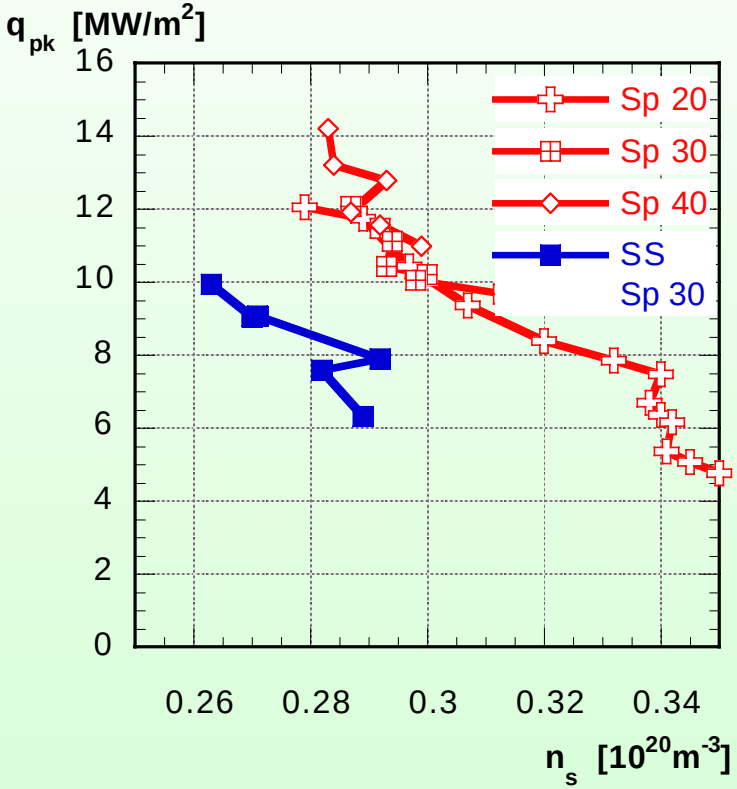


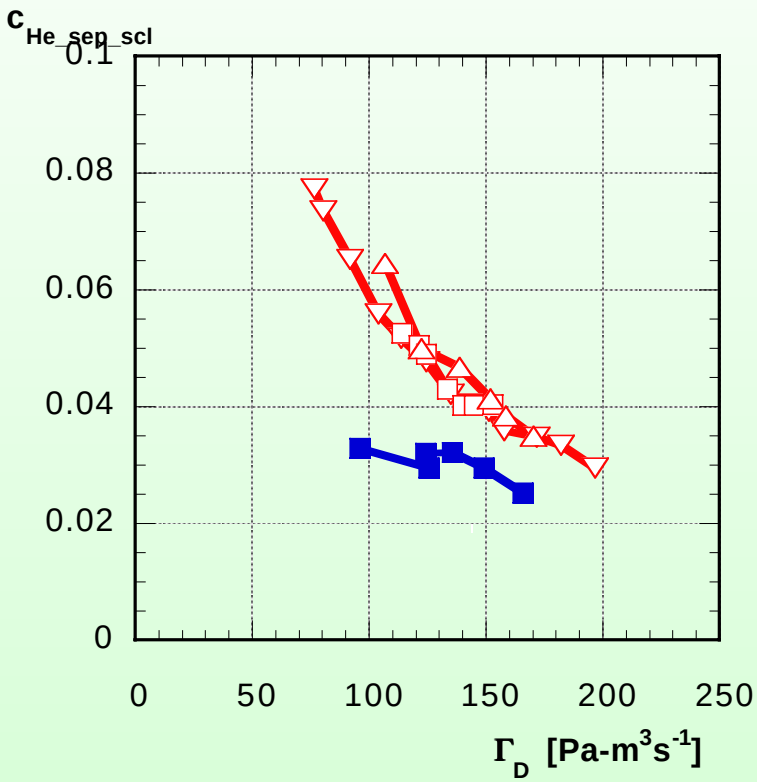






Is there a difference for Advanced Tokamak discharges ?





Due to the larger connection length in AT type of discharges (lower current) the upstream density at the same peak heatload is reduced by 15%

He concentration is lower due to lower production

In vessel Component assembly (VV, Blanket, Divertor)

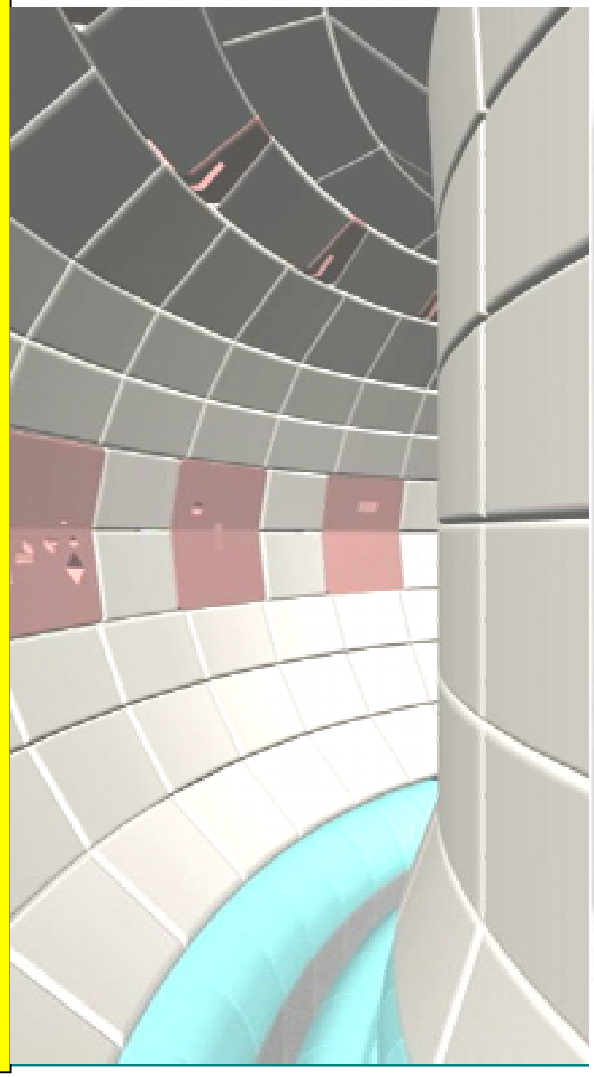
The VV is a double wall water cooled structure with steel ribs (in some places ferromagnetic) for shielding

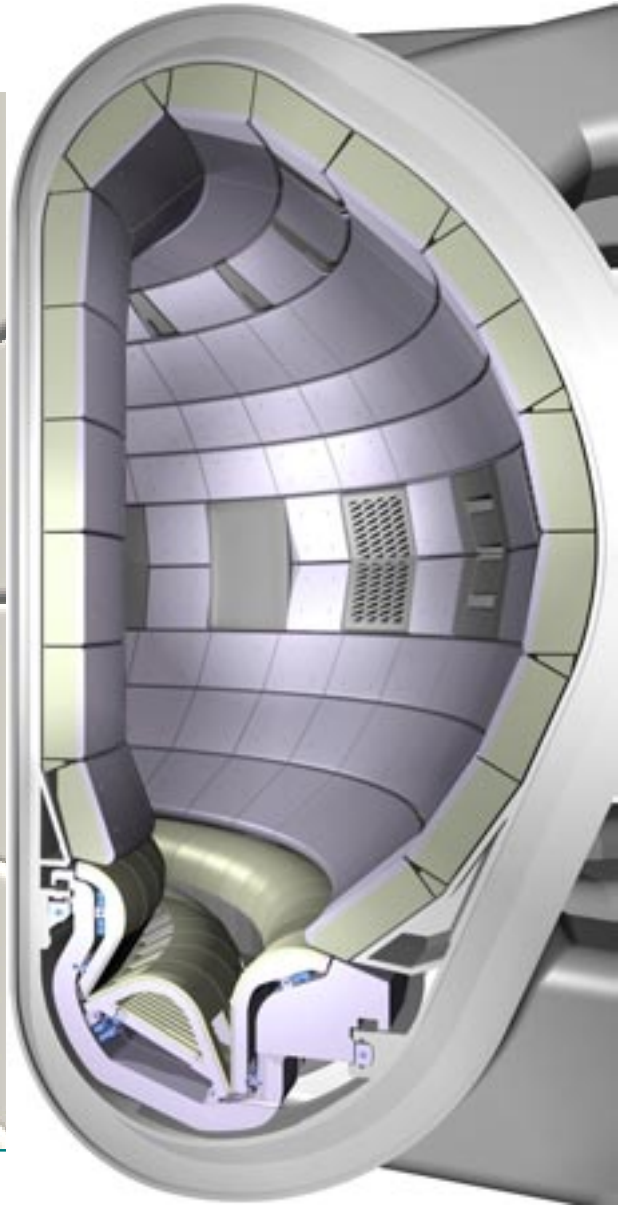
- It has to provide attachment points for the Blanket

The Blanket moduels are similar to the ones of ITER-98 but have a detachable First Wall (repair)

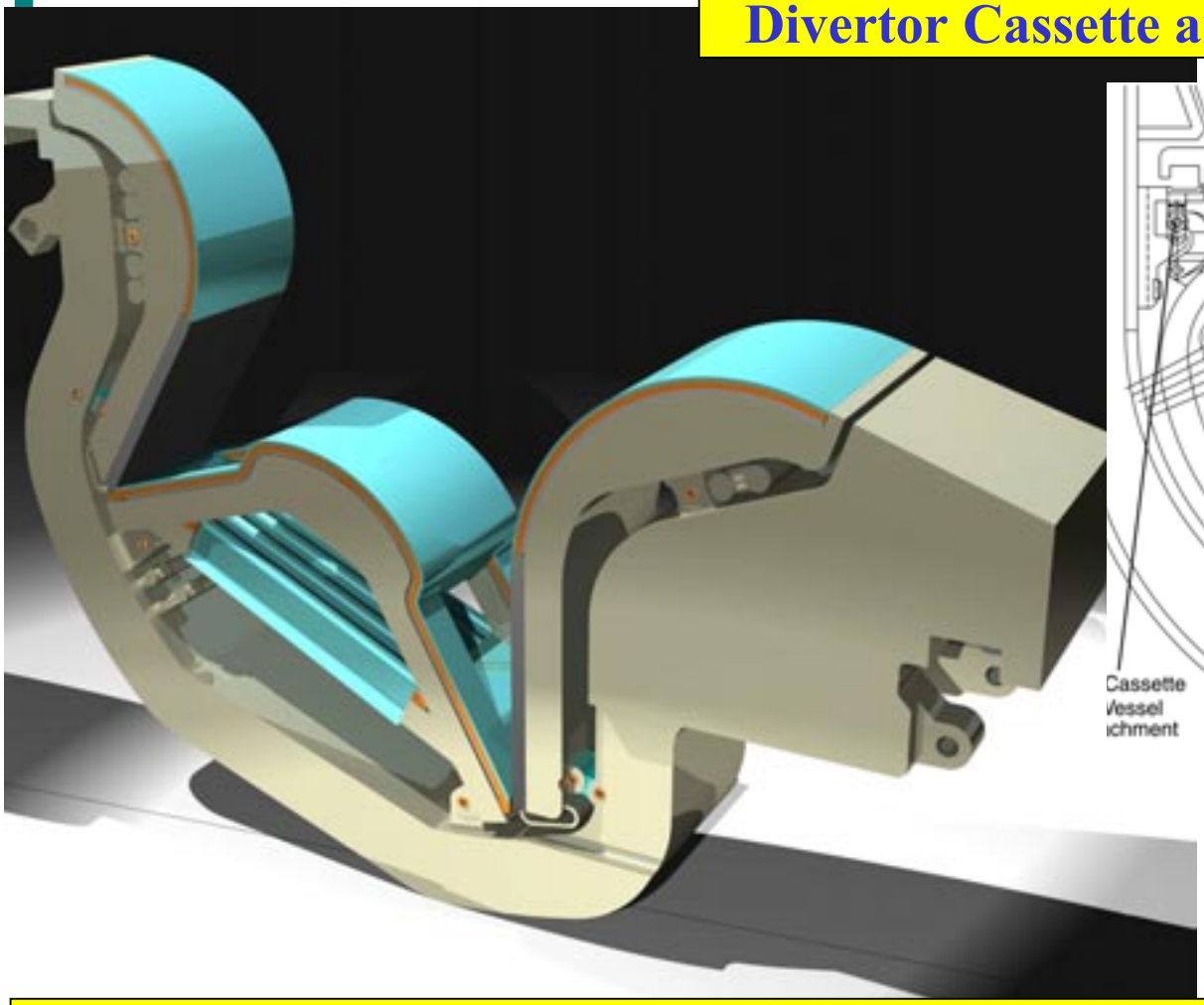
The divertor concept is similar to ITER-98 but includes now the baffles

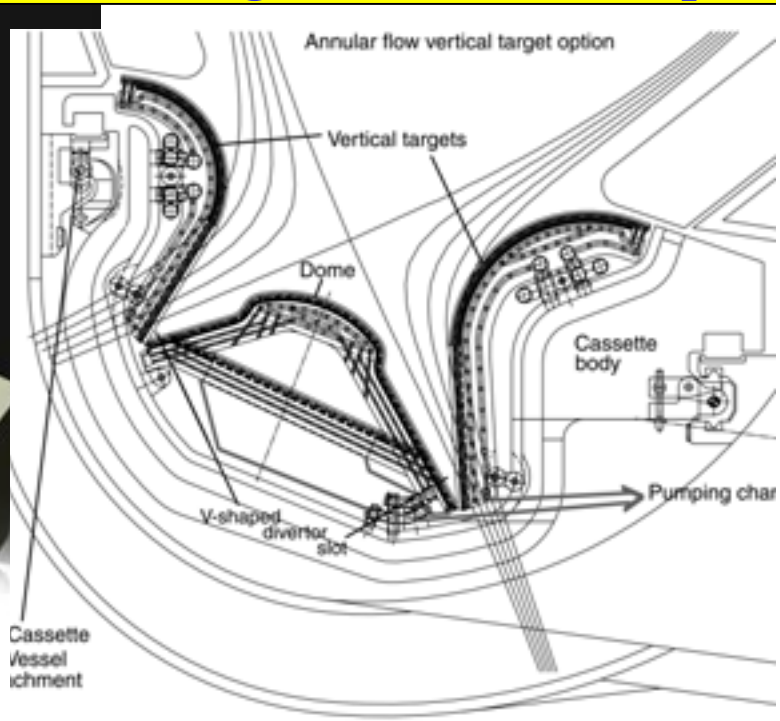
- Attachment locations and RH concept have slightly changed





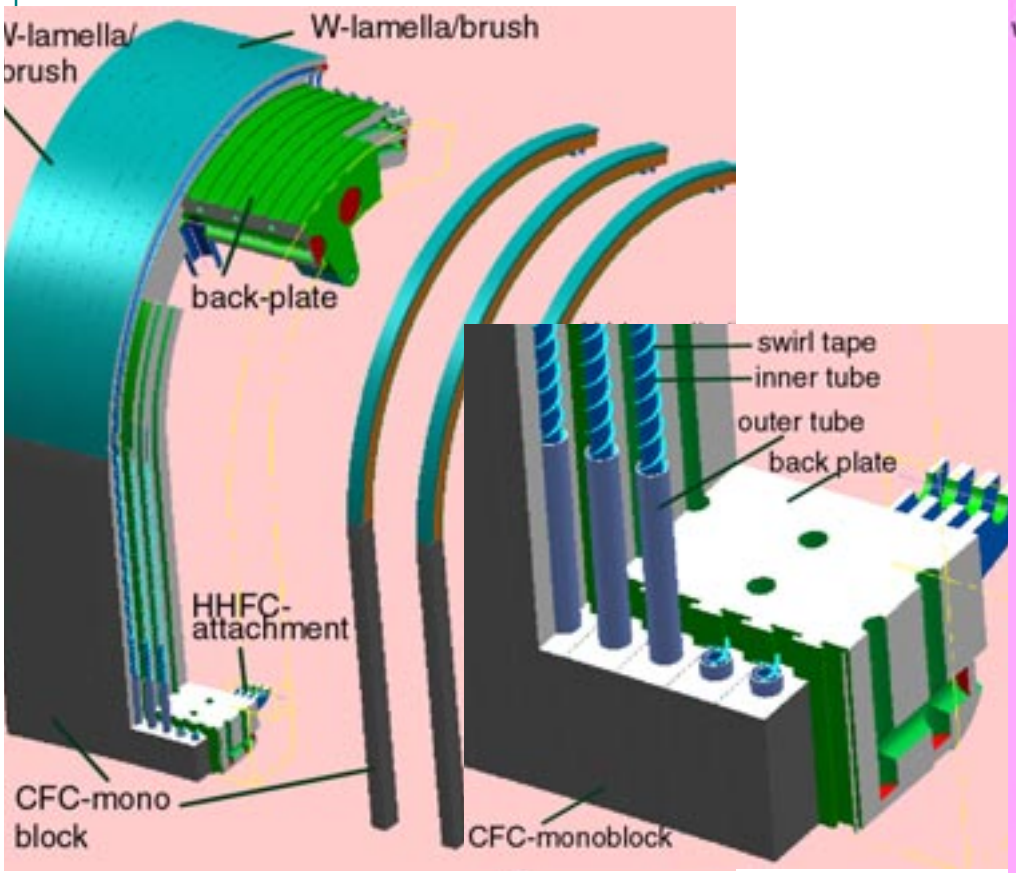
Divertor Cassette and High Heat Flux Component

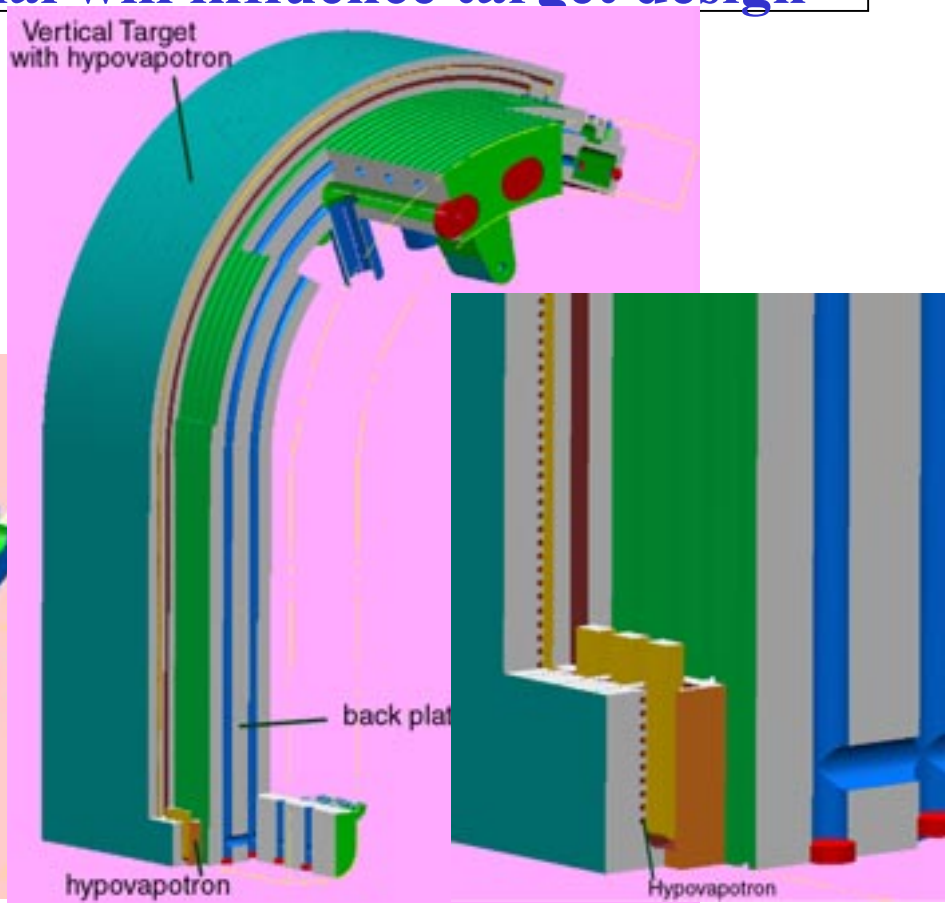




- Three HHF components (2 Vertical Targets, Dome and Liner) are mounted on a cassette body and can be changed in the Hot Cell
- Cassette is attached to 2 toroidal rails

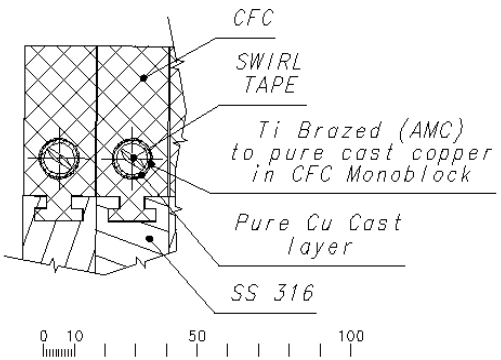
Choice of plasma facing material will influence target design

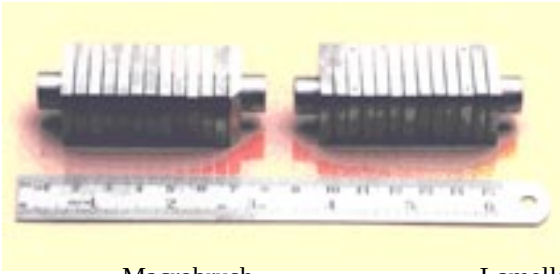


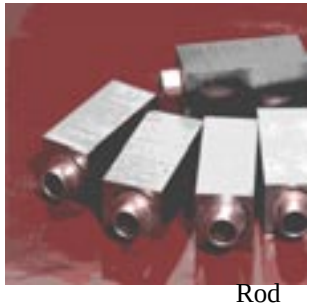


- If CFC monoblocks are chosen for the strike zone area (present reference) then a swirl tape or annular flow design is optimum
- If a W brush is chosen for the whole area of the Vertical Target a Hypovapotron will probably be the optimum heatsink design

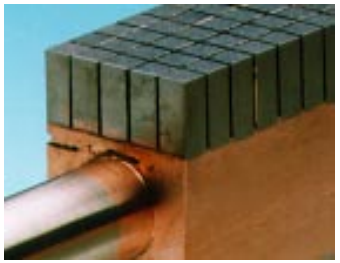
CFC Monoblocks and W brush / Lamella Mock Ups

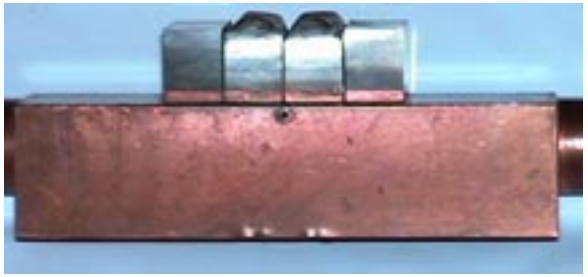


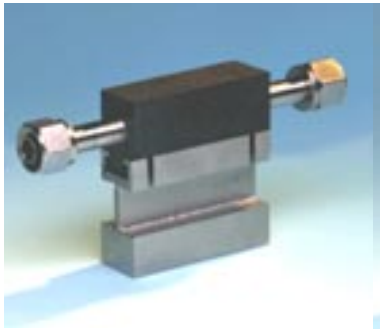




Macrobrush Lamellar Rod



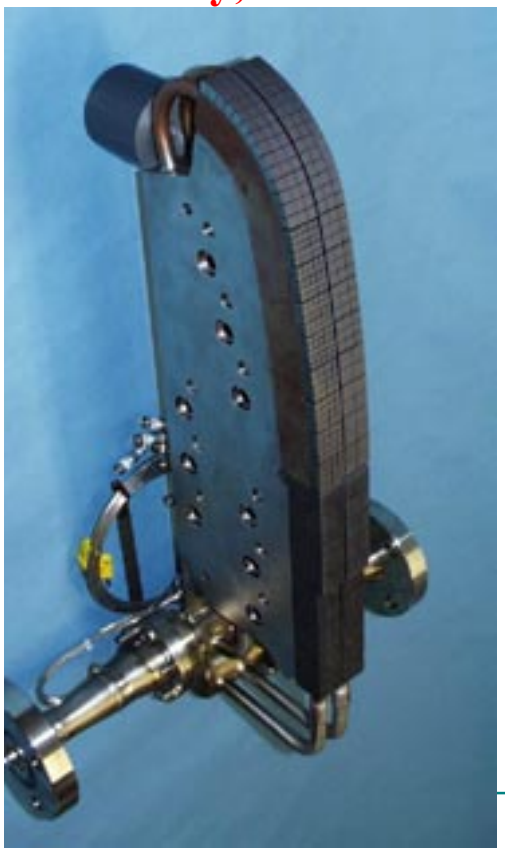




Qabs = 43MW/m2, 10-15s, 2 cycle
Qabs = 27MW/m2, 10s, 1500 cycle

Prototypical Vertical Target and cassette Mock-ups

- The medium scale mock up under high heat flux testing in the Le Creusot e-beam facility sustained:
- **1000 cycles at 15 MW.m-2 on the W macro-brush armour**
- **2000 cycles at 20 MW.m-2 on the CfC armour.**
- **Finally, the CfC armour was shown to survive > 30 MW.m-2 in a CHF test.**



Development of the High Heat Flux Components for ITER

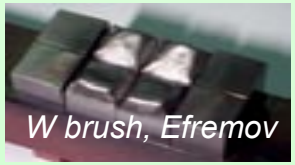
ITER EDA R&D program has provided significant progress in the development of the reliable Armour/Cu alloys joining technobgies:

CFC armour:

- CFC/Cu joints - monoblock design is able to withstand much higher heat flux than required for ITER (> 20 MW/m²);
- Flat CFC tiles could withstand ~ 18 MW/m² ;
- There are several joining technologies such as AMC and brazing which fulfil the requirements

W armour:

- Armour design (macrobrush, rods, monoblock) improves significantly the performance, e.g. :
  - W monoblock survived ~18 MW/m², 1000 cycles
  - W macrobrush ~27 MW/m², 1500 cycles

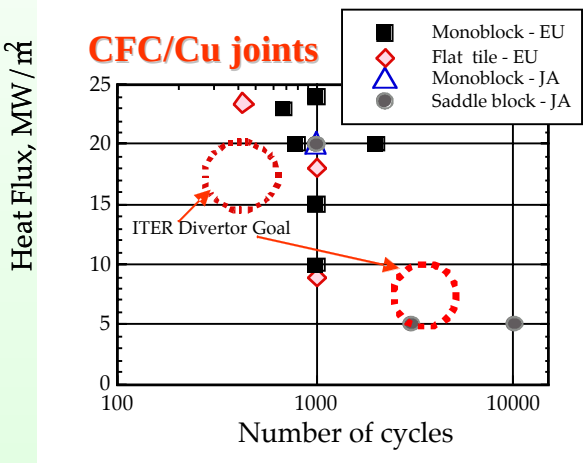


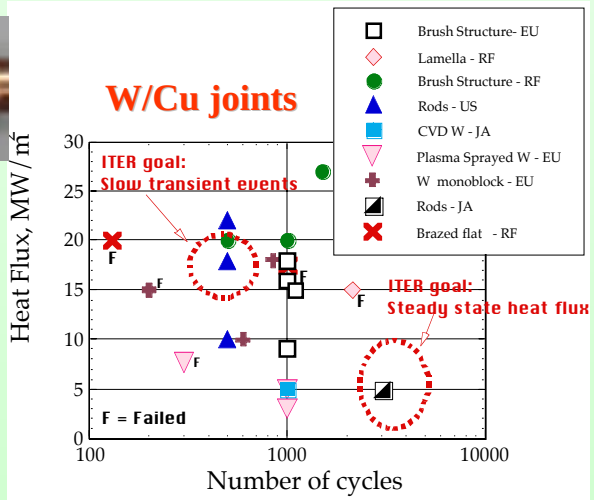
The results of these works demonstrates that W armoured components could withstand heat flux ~ 20 - 25 MW/m² (also with glanced heat flux)

Joining with heat sink (EU Party):

- Low Temperature HIP (~ 500-550°C) for joining Cast Cu to CuCrZr (goal - optimised properties) was demonstrated for W and CFC armour;

ITER EDA R&D



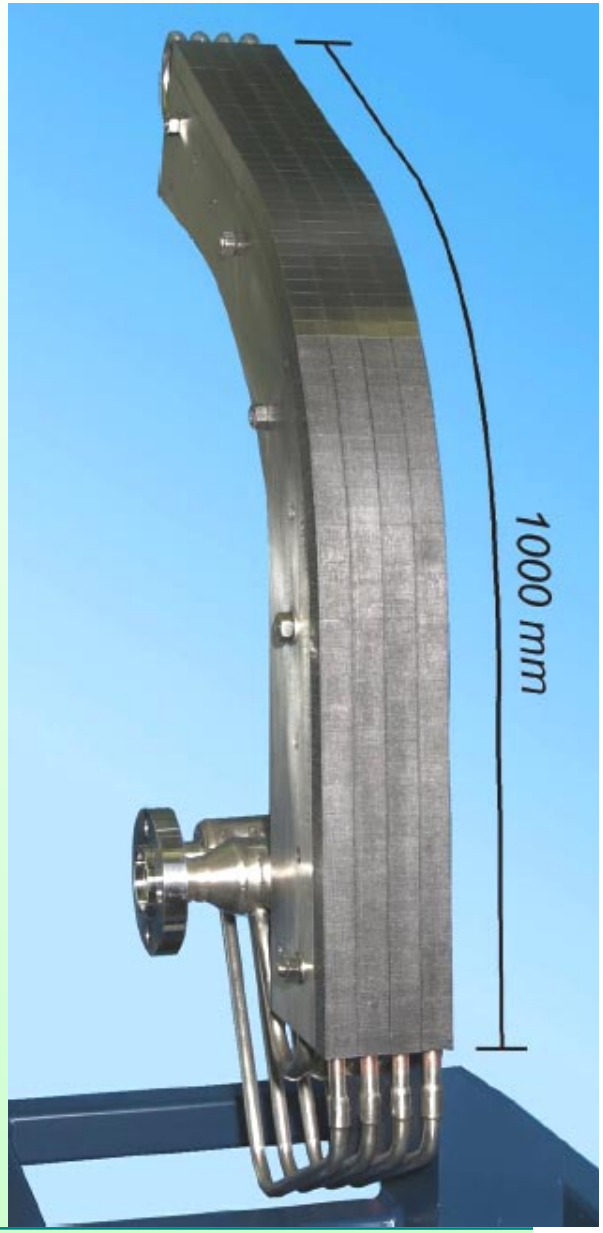


Vertical Target Full Size Prototype

The EU have fabricated a large prototypical target (see figure) using CFC monoblocks (lower part) and tungsten lamellae (upper part) attached to a CuCrZr tube via during 500°C HIP-ing a pure Cu interlayer. The HIP process maintains good CuCrZr mechanical properties

The RF use fast brazing of W tiles to a CuCrZr hypervapotron (suitable for an all tungsten target), again with a pure Cu interlayer.

The JA option is a CFC monoblock with brazed pure Cu interlayer brazed to the CuCrZr tube



Can the HHF-Components be manufactured with sufficent reliability

Quality Assurance: Experience has shown that the whole procurement must be Quality Assured.

- Prior to manufacture all materials must be specified and manufacturing procedures qualified;
- Material procurement must be monitored, particularly important for heat sink and armour materials – traceability material, furnace records, NDE & destructive testing of coupons etc.;
- Full qualification is needed for all procedures used by the Supplier prior to commencing manufacture;
- Manufacture & test full-scale prototype to qualified procedures;
- Monitor manufacturing process –witness tests;
- Apply Non Destructive Examination developed by R&D, ultrasonics, thermography, leak tests, high heat flux tests etc

Experience: with water cooled components subjected to high heat flux in a UHV environment has been gained in many tokamaks world-wide, but probably the biggest database is available from Neutral Beam Heating (NBH) systems.

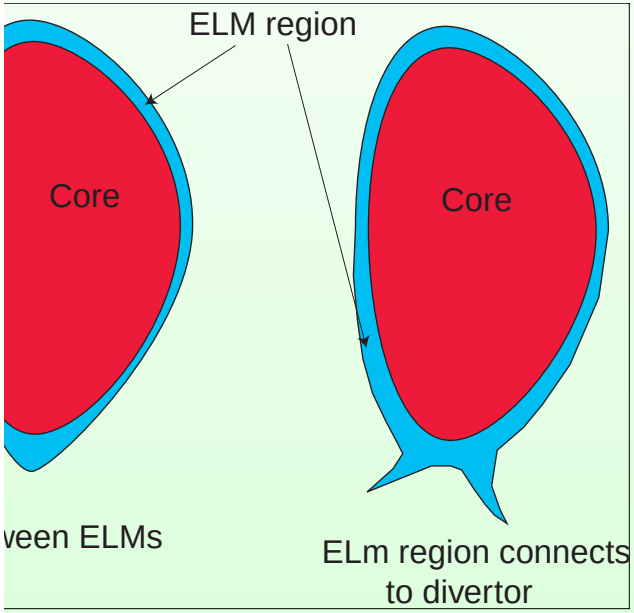
- In JET NBH more than 400 high heat flux components (hypervapotrons) were fabricated from CuCrZr and stainless steel. This represents a total of ~1000m of e-beam weld joints and 1000 CuCrZr to stainless steel brazed joints.
- In operation for almost 20 years (in many cases this means for more than 30,000 pulses) the hypervapotrons have been routinely subjected to heat flux cycles ~10MW/m2 in UHV. Their reliability allowed the systems to be used for injecting tritium into JET

The Type I ELM energy load issue

- **In an ITER or Demo H-mode discharge Type I ELMs can occur with ~ 1 Hz frequency**
  - Several 100 ELMs per ITER discharge and ~ $6x10^7$ ELMs in the required lifetime of a Divertor in the Demo Reactor (i.e. 2 years)
  - Evaporation and melting of the divertor target plates at each ELM must be avoided, otherwise the lifetime will be insufficient even for ITER
  - The energy threshold for eavporation and melting depends on the material, on the steady state power load and on the ELM duration
    - Most likely < than 1 MJm^{-2}
  - While extrapolations remain somewhat uncertain an understanding of the mechanisms of energy transport along fieldlines during ELMs is emerging
    - It is dominated by ion transport (not faster than ion sound speed)
    - ~ 200 to 300 μs in ITER; similar order of magnitude in Demo

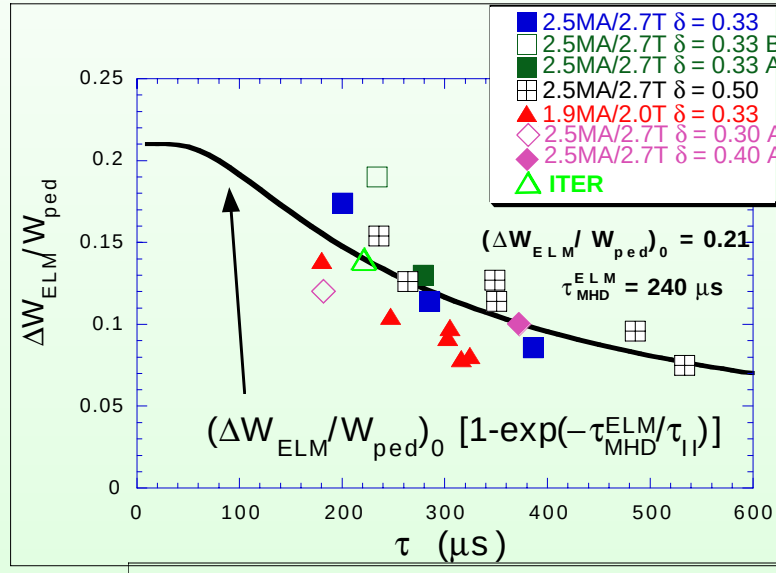
ELM energy loss is connected to parallel transport (G. Janeschitz et. al., PSI 20

a) Pedestal connects to Divertor (τ^{MHD}_{ELM})



b) Fast e- Losses create a new Sheath ($T_{e,ped}$)

c) The main Power Flow is determined by Ion Particle Transport



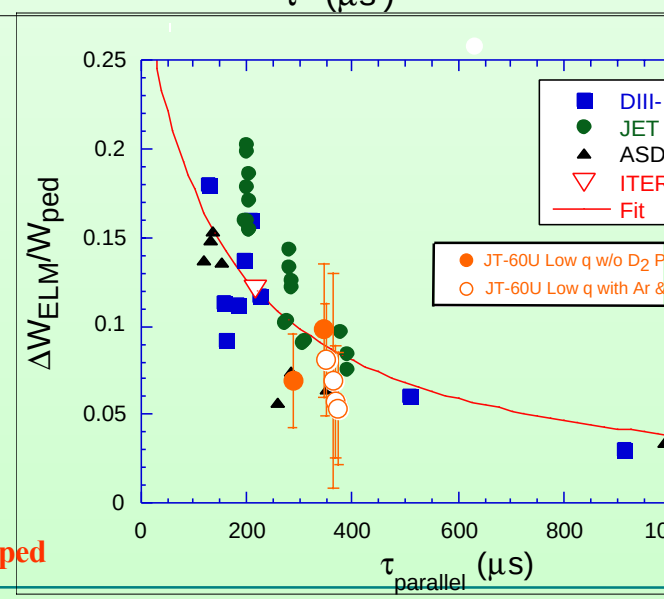
$$= \frac{2\pi R q_{95}}{c_{s,ped}} \left(1 + \sqrt{3/2}\ \nu^*_{ped} \right)$$

$$\frac{W_{ELM}}{W_{ped}} = \left| \frac{\Delta W_{ELM}}{W_{ped}} \right|_0 \frac{1}{\left(1 + \tau_{||}/\tau_{ELM}\right)}$$

Multimachine and JET data agree reasonably well

⇒Allows extrapolation to ITER and Demo

⇒ W_{ELM}~12% of W_{ped}

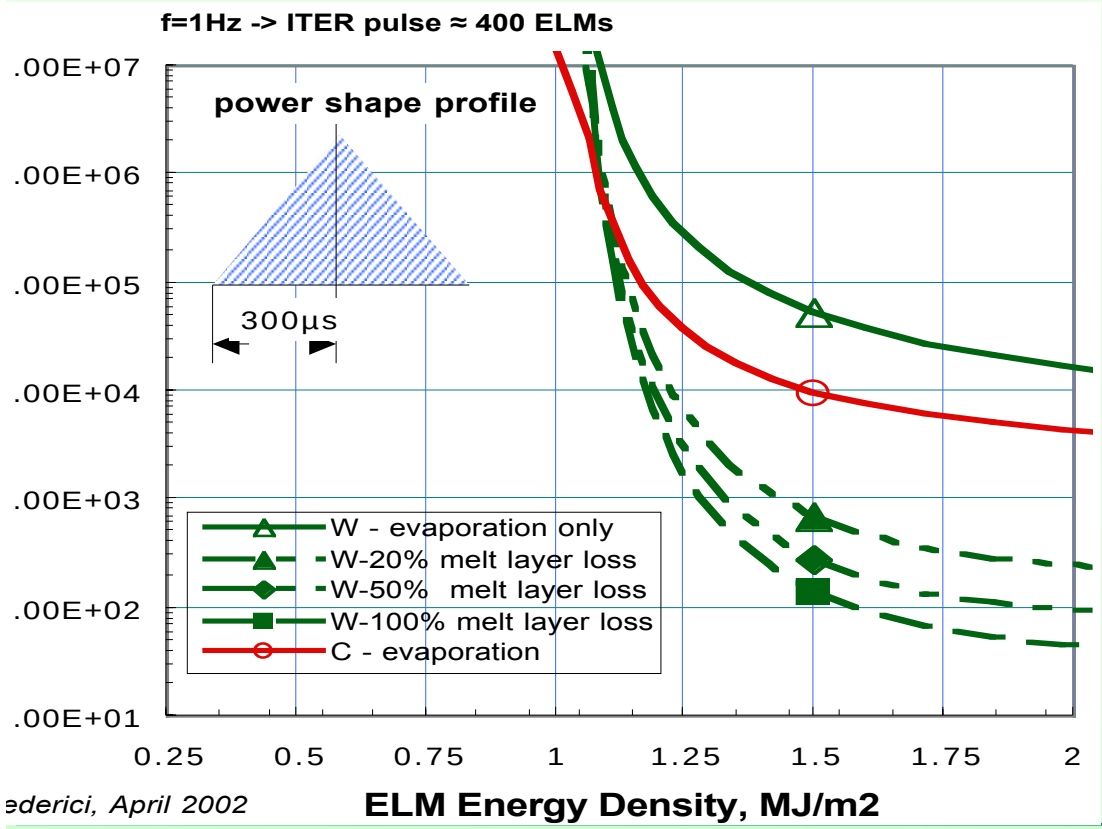


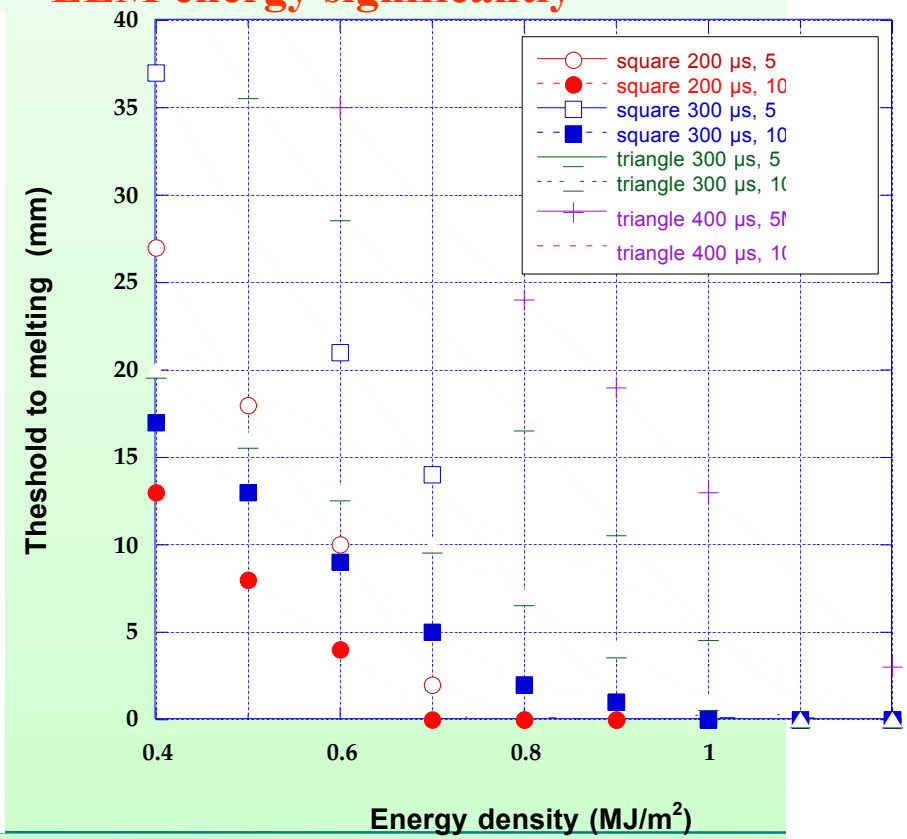
Allowable energy loss per ELM in ITER

The assumption is that the power shape profile during an ELM is triangular and that it has a rise time of 200 to 400 µs

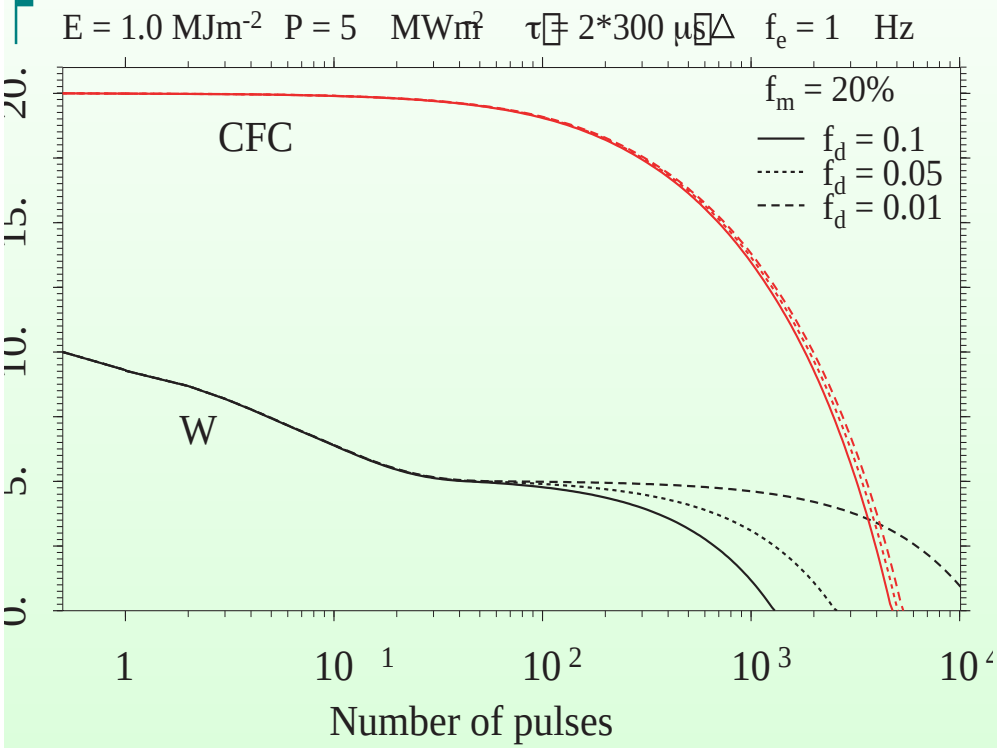
For a steady state power load of 5 MWm^{-2} the allowable ELM energy loss would be 1 MJm^{-2}

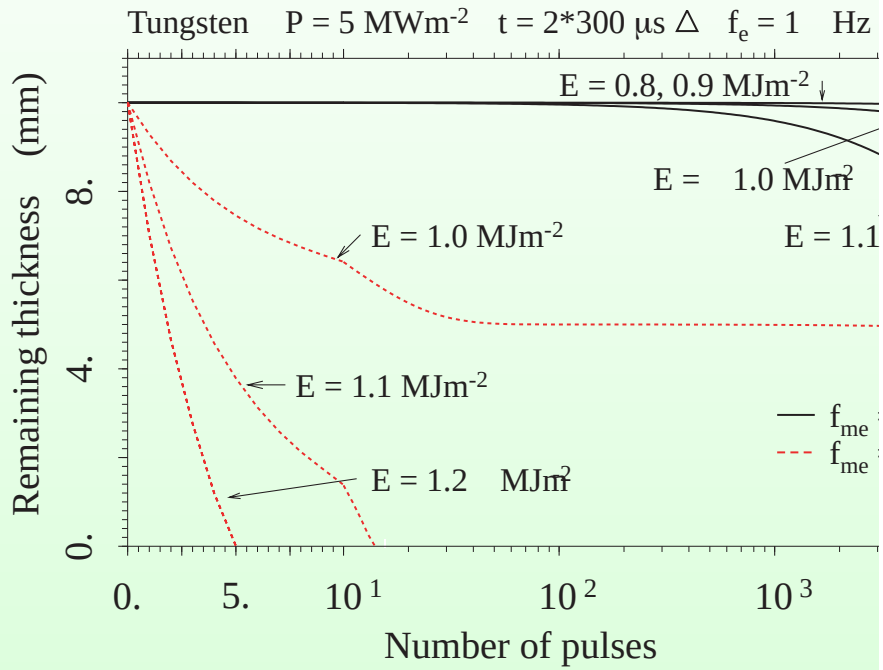
- **The maximum thickness of a W claddir is determined for 1 MJm^{-2} ELM energy load with 5 or 10 MWm^{-2} steady state power**
- **10 MWm^{-2} limits the thicknes and / or t ELM energy significantly**





Composite lifetime of the ITER Divertor targets





Lifetime for W and CFC assuming 1 MJm^{-2} ELM energy load (400 ELMs/ discharge) 1%,5%,10% of the discharges ending in disruptions, melt layer loss for W is 20%

Lifetime for both materials similar

- **Composite lifetime for a W target assuming ELM energys from 0.8 to 1 MJm^{-2}, no melt layer loss and 20% melt layer loss**
- **It shows that if one has a statistical distribution around 1 MJm^{-2} that the lifetime can be significantly lower**

Are Type I ELMs really compatible with ITER or Demo divertors ?

The energy stored in the ITER pedestal is ~ 100 MJ

- **The pedestal temperature is 3 to 4 keV => low collisionality !!**
- **The estimated energy loss per ELM is ~ 10 to 12 MJ**
  - **This prediction is based on the above explained physics ideas and has a large uncertainty !**

The ELM energy is deposited on a surface 1.5 to 2 times the one for steady state

- **This results in ~ 6 to 8 m^2**
- **With 1 MJm^{-2} allowable energy load we have ~ a factor 1.5 discrepancy**

The development of Type II ELMy H-mode is very important for ITER

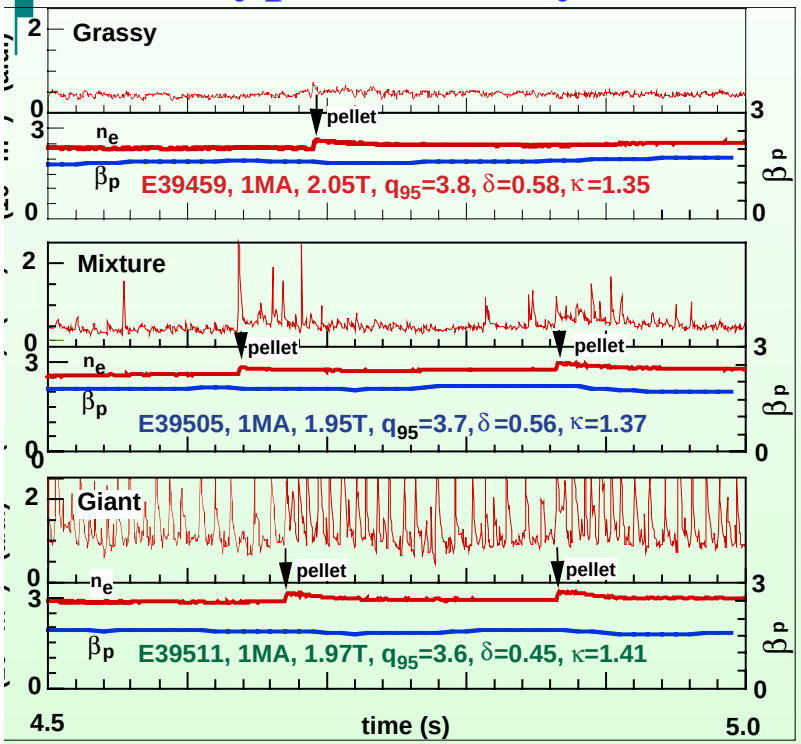
- **There is already ample evidence from various machines that this regime is achievable within the ITER shaping parameters**

In Demo the pedestal energy content will be in the order of 300 to 400 MJ !!!

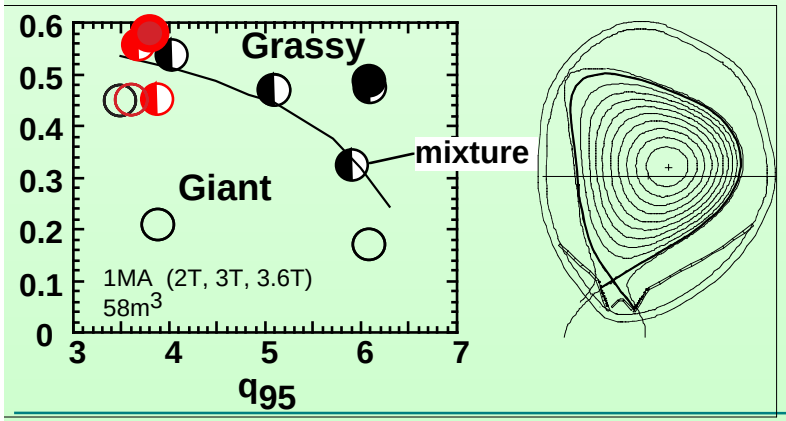
- **Considering the same physics the energy loss per Type I ELM will be ~ 30 to 50 MJ !!**

Considering that the deposition surface will be only ~ 10 m^2 and that the threshold w be lower than in ITER only Type II ELMs will be acceptable in Demo !!

Are Type II ELMy H-modes a realistic regime for ITER and Demo ?

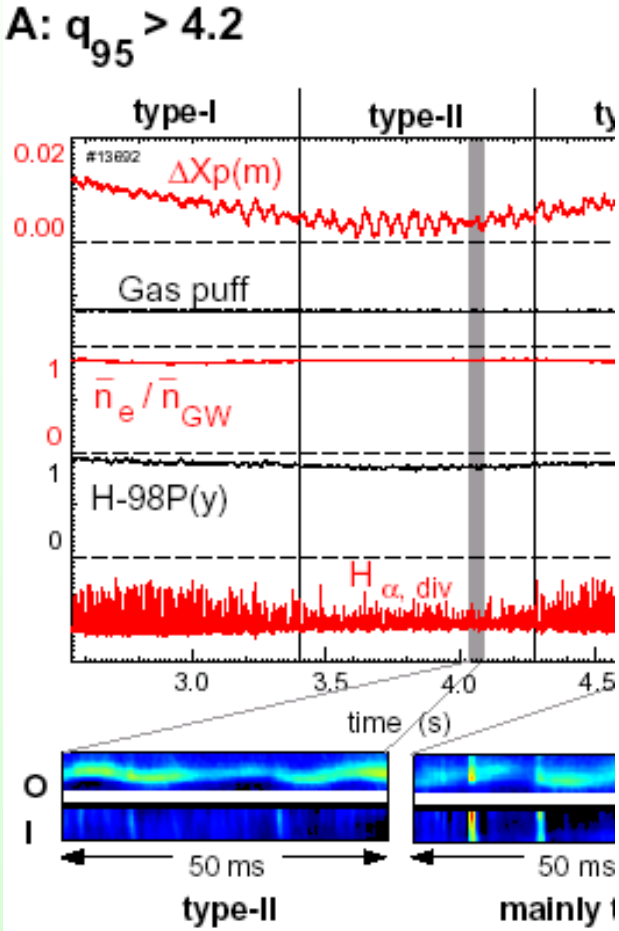


Increasing δ (shear)



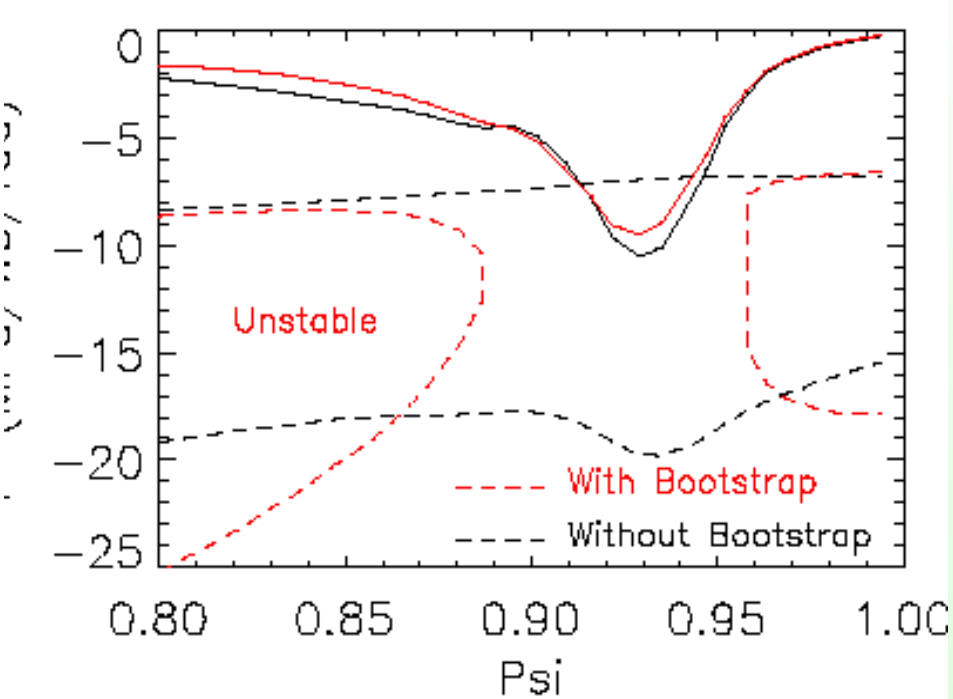
High triangularity, $q_{95\%}$ >3.5 and sometimes close to double null operation is the recipe for Type II ELMs

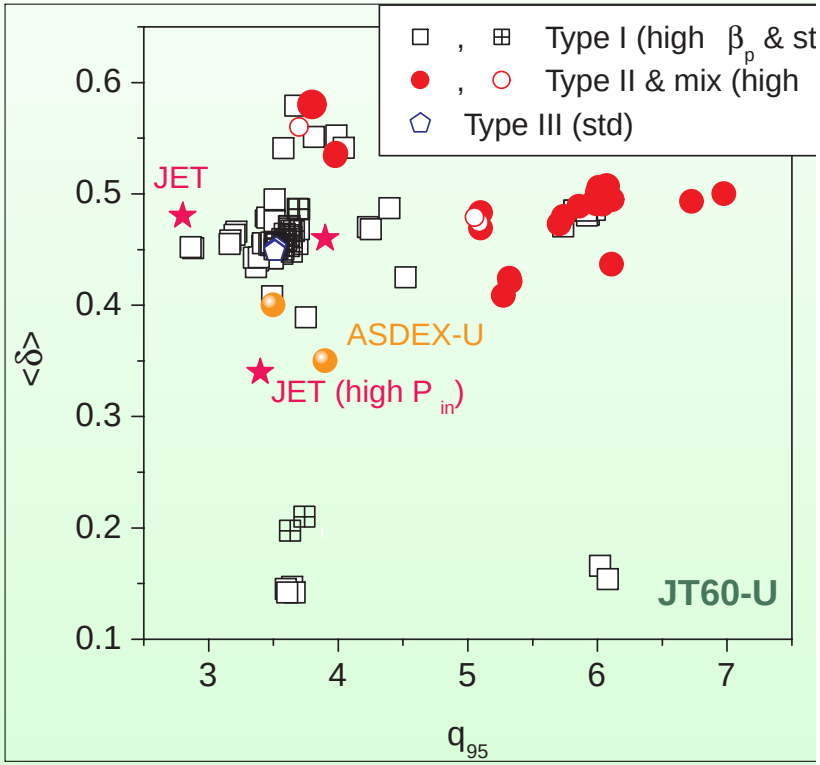
=> High edge shear !!



- **The ELM energy loss is reduced by a factor 2 to 5 when compared to Type I ELMs**
- **Certainly sufficient for ITER**
- **Marginal for Demo**

How can we achieve Type II ELMs





Type II ELMs are connected with second ballooning stability

- **High triangularity /elongation**
  - **High shear**

The second stability limit has to be violated near the separatrix otherwise a Type I ELM occurs

- **One possiblity is high density /recycling or gas puffing**

- **Limits operation window for ITER to higher $q_{95\%}$ => lower current !!**
- **Demo design could be optimized for this regime but may increase cost**

Erosion of the First Wall in ITER and in Demo

The erosion of a Be-clad FW is in the order of 0.1 nm/s

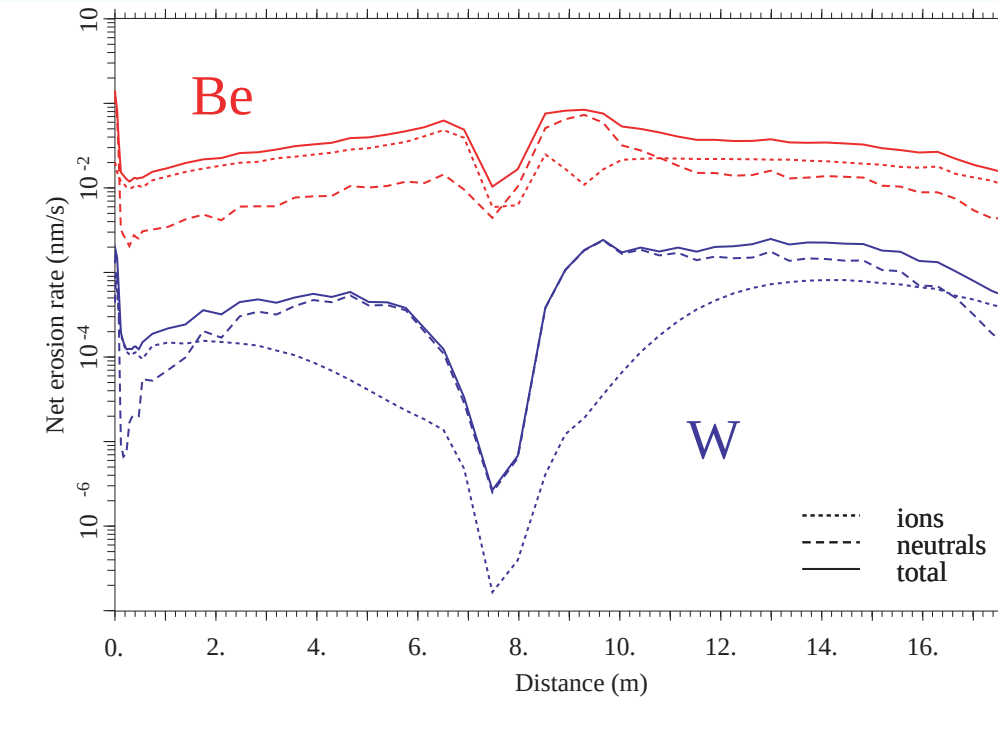
- **(0.5 to 1cm/ burn year)**
- By charge exchange neutrals and impurity ions

Erosion of a W-clad wall is negligible (<1mm / burn year)

VDEs will cause < 60 MJm^{-2} energy loads over < 0.3 sec

- Be melt layer loss < 0.4mm
- W melt layer loss < 0.7mm
- The Heat sink is better protected by Be (T-melt)

Killer pellet/ gas jet may provide mittigaion



➡ The erosion rate of Be is acceptable for a low duty-factor device such as ITER-FEAT and Be is the choic if VDEs are likely (1 cm Be can withstands ~20 VDE)

➡ For Demo only high Z such as W remain as realistic PFM for the FW !!!

Issues related to Dust produced from PFMs in ITER-FEAT

Fine dust (<10mm) from the three envisaged PFMs has safety implications

Limits for C-and Be-dust are related to an explosion

- we have to prove to the regulatory authorities that this limit is not reached

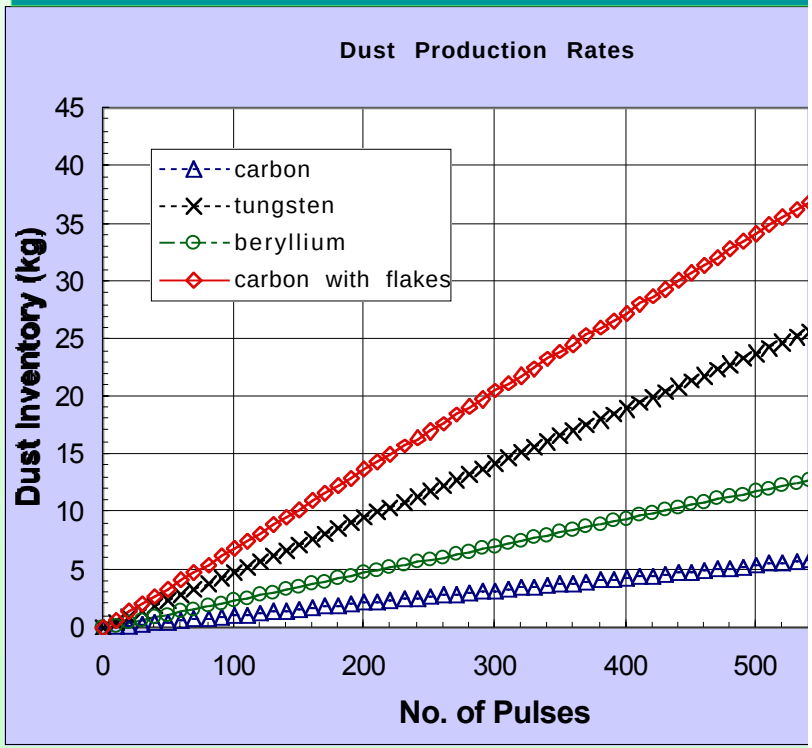
The limit for W-dust is related to the containment function of the ITER-FEAT building (is more flexible)

No reliable dust diagnostic exists to date

Crude estimates for dust production in ITER are shown here -->

- 10% of sputtered, 50% of evaporated material assumed + flakes for CFC)

Dust	Safety Issue	Limits (k
Beryllium	Reactivity with steam and H_2 Toxic	10-20 on surfaces
Carbon	Tritium retention Explosion with air	~100
Tungsten	Activation	100-400



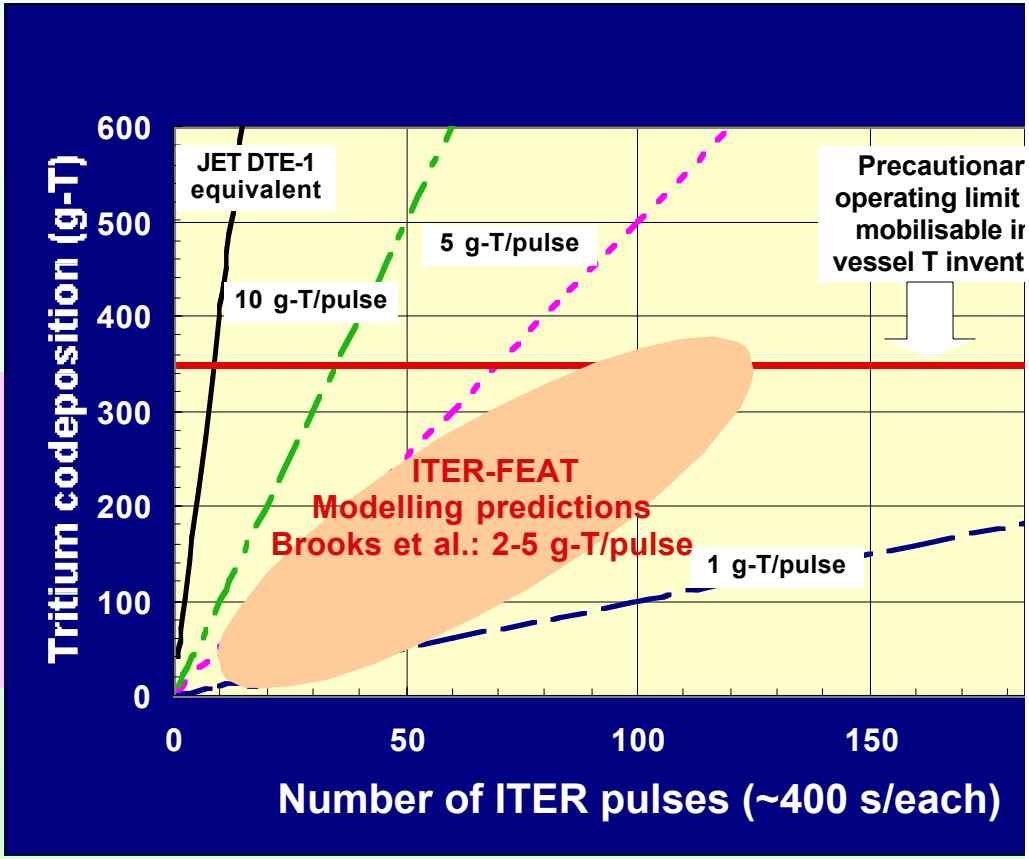
Co-deposited Tritium Removal Requirements

- Maintaining C in ITER has a strong impact on in-vessel T-inventory.

- A precautionary operating limit of 350 g-T (1000g in 1998 ITER design) is now set in ITER, based on safety considerations, for the mobilisable in-vessel tritium.

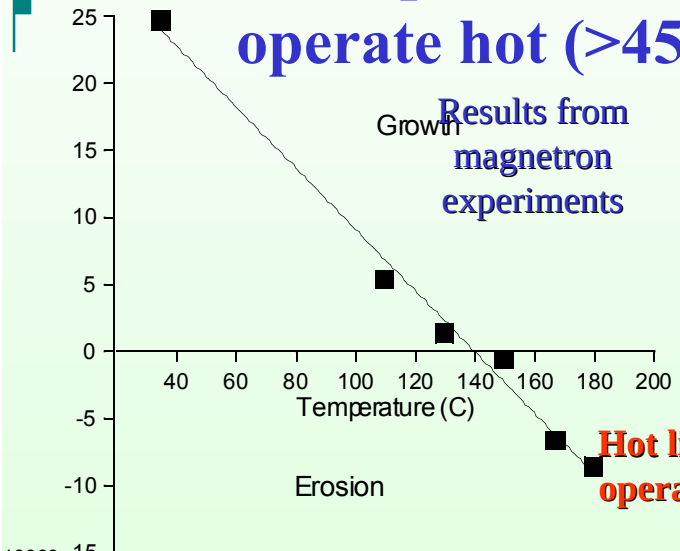
dep. rate T/pulse)	No. Pulses to reach limit 350 g-T
	350
	175
	70
	35

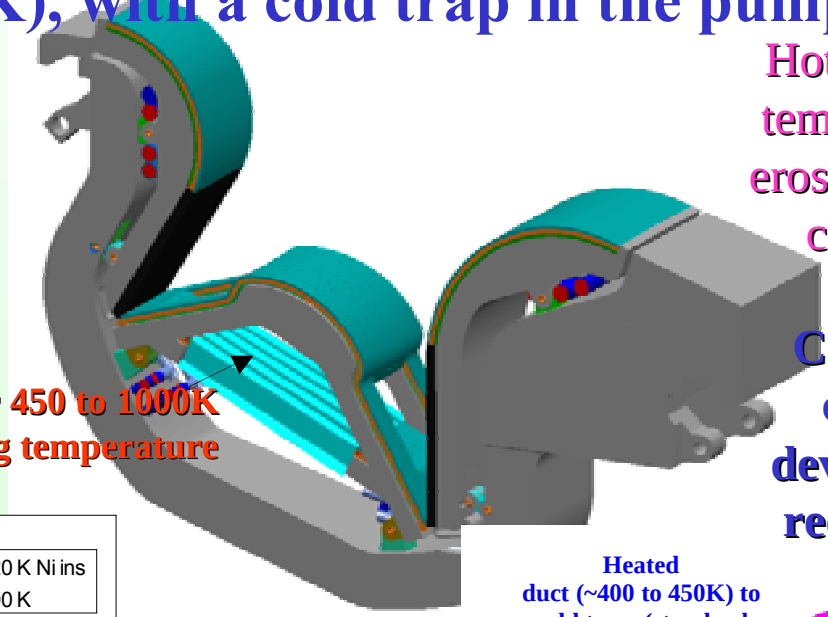
=>Codeposition prediction by Brooks (ANL): 2-5 g-T/pulse



A local Tritium trapping with regeneration (cold Trap), or an efficient cleanup metho
or only W may be feasible as Plasma Facing material in the ITER divertor !!!

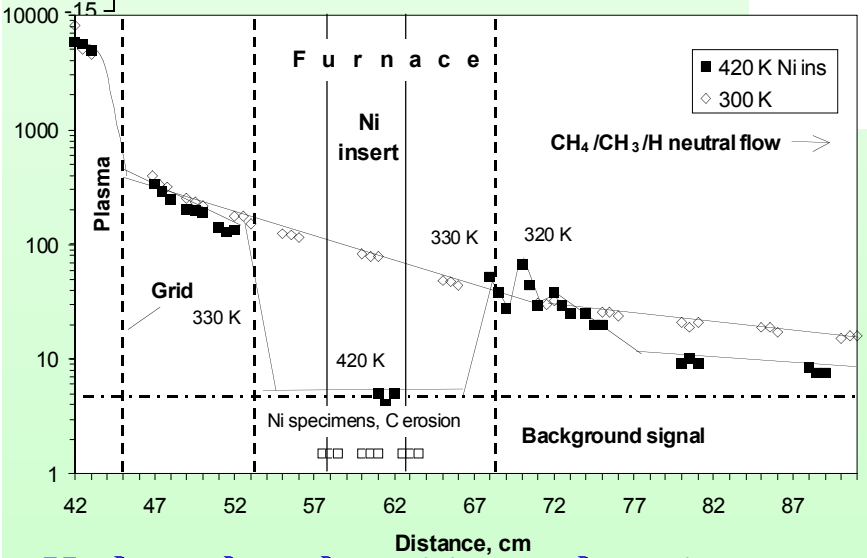
C/T co-deposition: To minimise deposition the Duct Surfaces must operate hot (>450K), with a cold trap in the pumping duct.



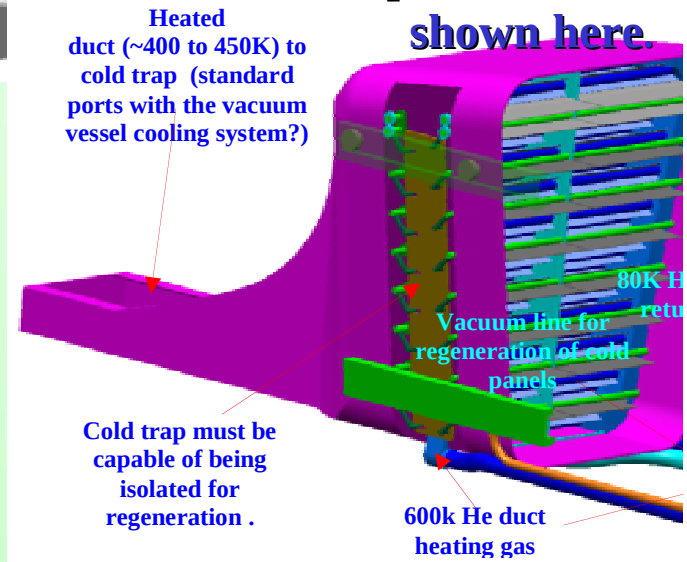


Hot liner operates in th temperature range of n erosion thereby providi clean plasma facing surfaces.

Cold trap design is currently under development but will require the features shown here.

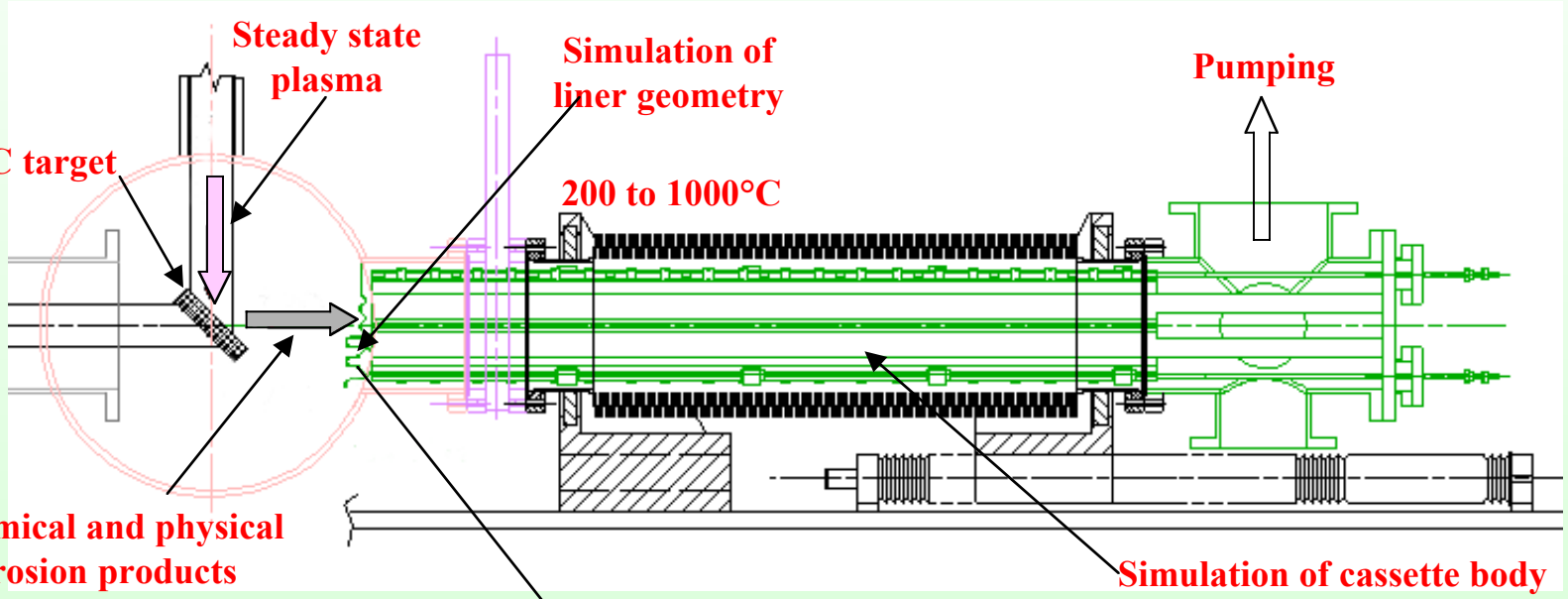


Results from radio frequency CH_4 discharge experiment



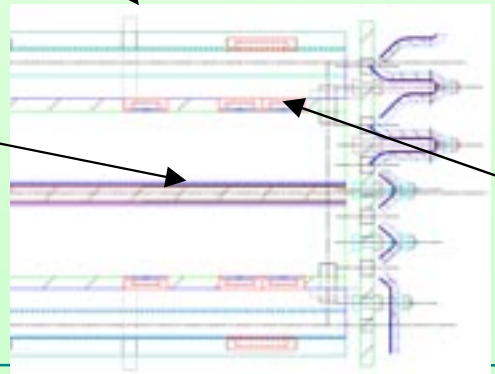
Hydrocarbon deposition and erosion versus temperature

Liner Simulation Experiment



100 to 150°C

Si waffers to measure total deposition



Cavities to monitor type of hydrocarbon species

Summary

- **Plasma wall interaction issues remain an active research area in relation to ITER and even more so in relation to a future Demo reactor**
  - The steady state power and He exhaust for ITER can be considered largely solved
  - For both machines ELMs are an issue, Type II ELMs seem to be a possible solution for ITER while they may be marginal for Demo
  - First wall erosion is no issue for ITER but becomes an issue in Demo resulting in W being the only choice for all PFM surfaces
  - Fine dust is a safety concern for ITER in particular for Be while this is less the case in Demo due to the use of W only
  - T- co-deposition is an unsolved problem for ITER when considering CFC targets; a cold trap and efficient cleaning methods may be a possible solution
- **The operation of ITER will be very important to understand these PWI issues to find solutions and to provide a solid knoledge basis for the design of a Demo reactor**