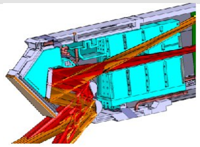


Design of the ITER ECRH Upper Launchers

D. Strauß, Institute of Materials Research I, FZK

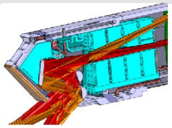
ECRH Upper Launcher in ITER – main challenges

Diamond windows

Numerical design tools

Materials, manufacturing and testing

Summary



Based on the work of:

G. Aiello[1] , R. Bertizzolo[2] , W. Bongers[4] , A. Bruschi[3] , R. Chavan[2] , S. Cirant[3] , A. Collazos[2] , M. de Baar[4] , B. Elzendoorn[4] , D. Farina[3] , U. Fischer[1] , J. Gafert[5] , F. Gandini[3] , G. Gantenbein[1] , A. Goede[4] , T. Goodman[2] , G. Hailfinger[1] , M. Henderson[6] , R. Heidinger[1] , W. Kasparek[7] ,K. Kleefeldt[1] , J.-D. Landis[2] , W. Leonhardt[1] , A. Meier[1] , D. Mellein[1] , A. Moro[3] , P. Platania[3] , E. Poli[5] , G. Ramponi[3] , D. Ronden[4] , G. Saibene[8] , F. Sanchez[2] , O. Sauter[2] , T. Scherer[1] , A. Serikov[1] , C. Sozzi[3] , P. Spaeh[1] , D. Strauss[1] , V.S. Udintsev[2] , A. Vaccaro[1] , H. Zohm[5] , C. Zucca[2]

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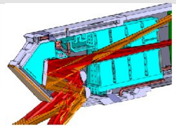
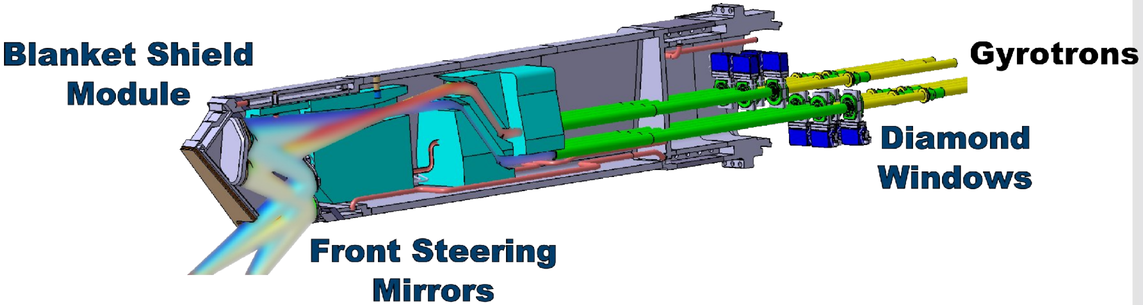
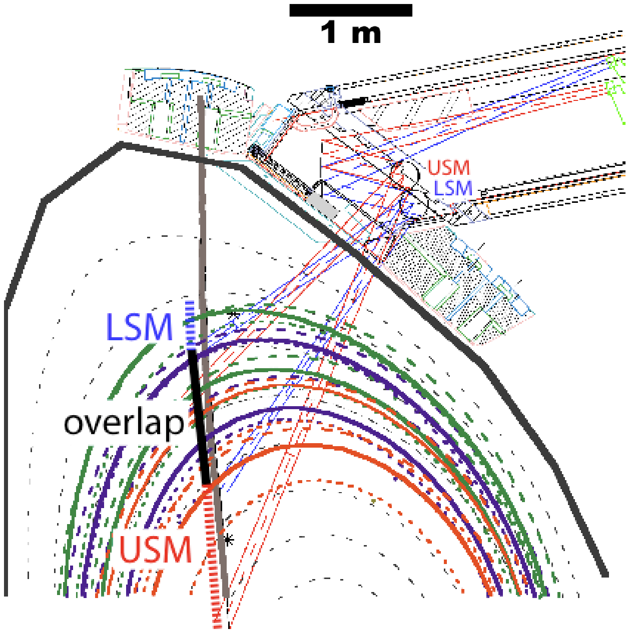


The four ITER ECRH Upper Launchers

- 20 MW via 4 Upper & 1 Equatorial Launcher for Heating & Current Drive
- In-line switching diverts power to UL/EL
- UL stabilize MHD instabilities such as neoclassical tearing modes & the sawtooth instability

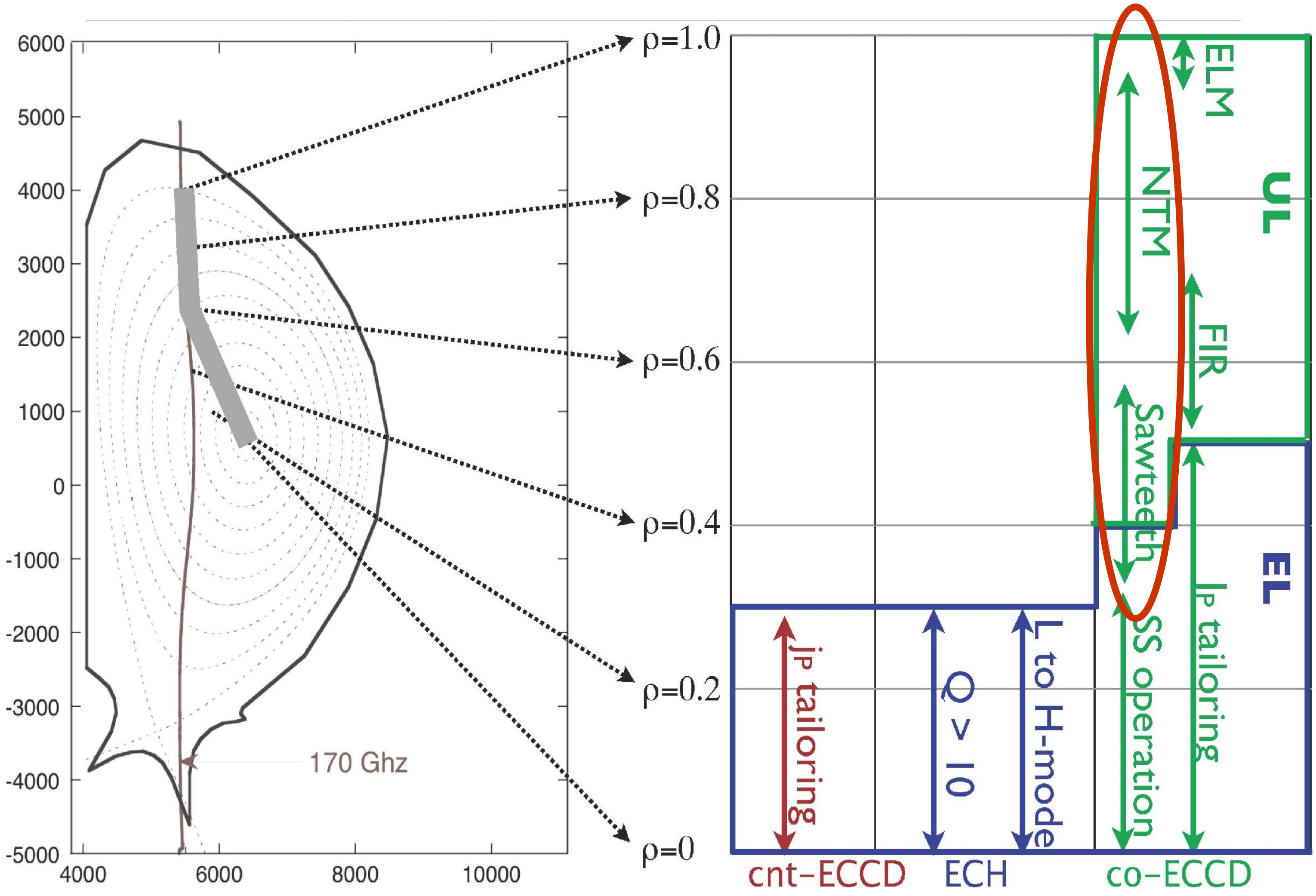




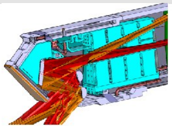
Challenges:

- Plasma stabilization
  - **Instabilities:** ***Tokamak plasmas are instable***
  - **Local current drive:** ***focus (20mm) on instabilities***
  - **Front Steering Mirror:** ***wide angular targeting***
- Withstand normal operation conditions
  - **Erosion:** ***Beryllium coated multilayer first wall panel***
  - **Cooling:** ***high heat loads close to plasma***
  - **Shielding:** ***limit dose rate and helium production***
- Withstand emergency events
  - **Plasma disruptions:** ***extreme Lorentz forces***
  - **High leverage:** ***upper port + plug length ~10m***
  - **Limited deflection:** ***small gap to neighbouring blankets required***

Physics Mission of the ECRH in ITER



Wide angle steering for stabilization of NTMs and the sawtooth instability.



Actual challenges for the UL

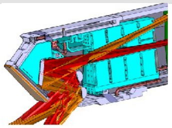
Boundary conditions significantly hardened:

  - **Upward VDE redefined (15MA, 36ms LCQ vs. 40ms LCQ).**
  - **Minimum gap to neighboring blankets reduced to <13mm (20 mm).**
  - **Port plug size reduced.**
  - **Physics performance requirements increased (transition to QO system).**

- **Plasma stabilization:**
  - **Transition mitre-bend to quasi-optical design.**
  - Redefined cut-out in Blanket Shield Module.

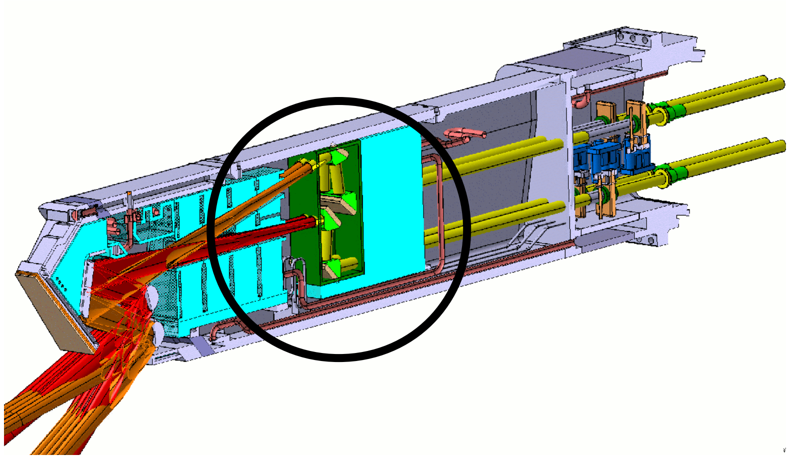
- **Normal operation:**
  - **Refine load simulation – BSM, mirrors.**
  - **Refine cooling simulations.**
  - **Prototyping.**

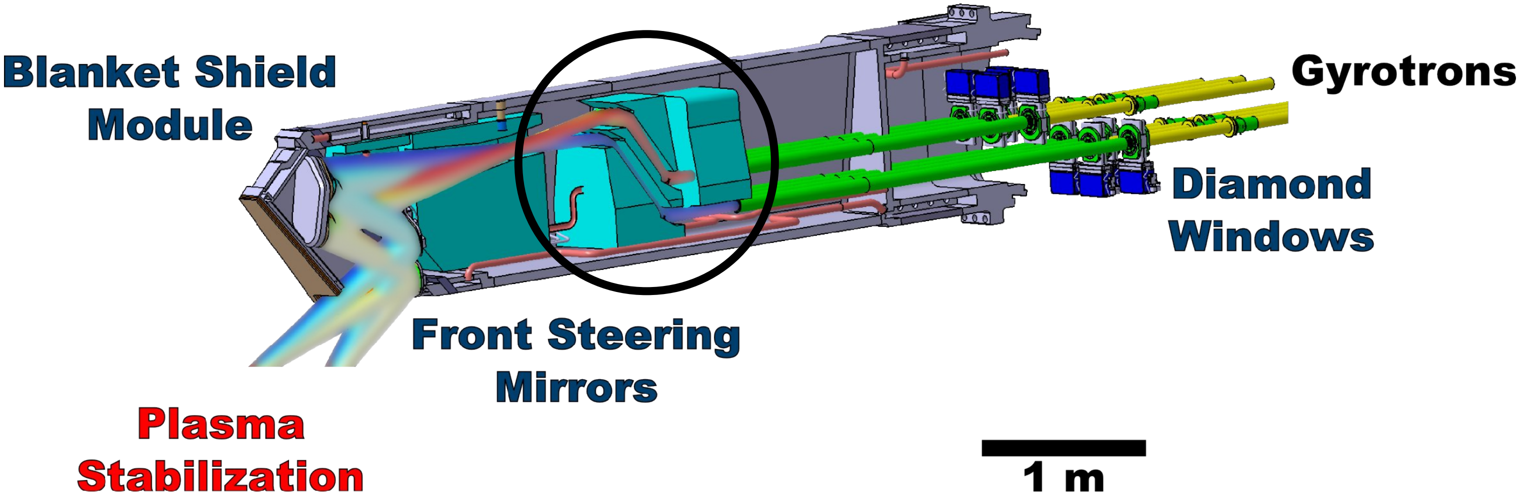
- **Disruption mitigation:**
  - **Increase stiffness: main frame redesign.**
  - **Reduce eddy current induction: shield block redesign.**
  - **Current path shaping: segmented shield blocks.**

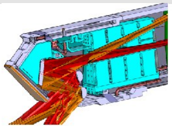


Plasma stabilization: Transition mitre-bend to quasi-optical design

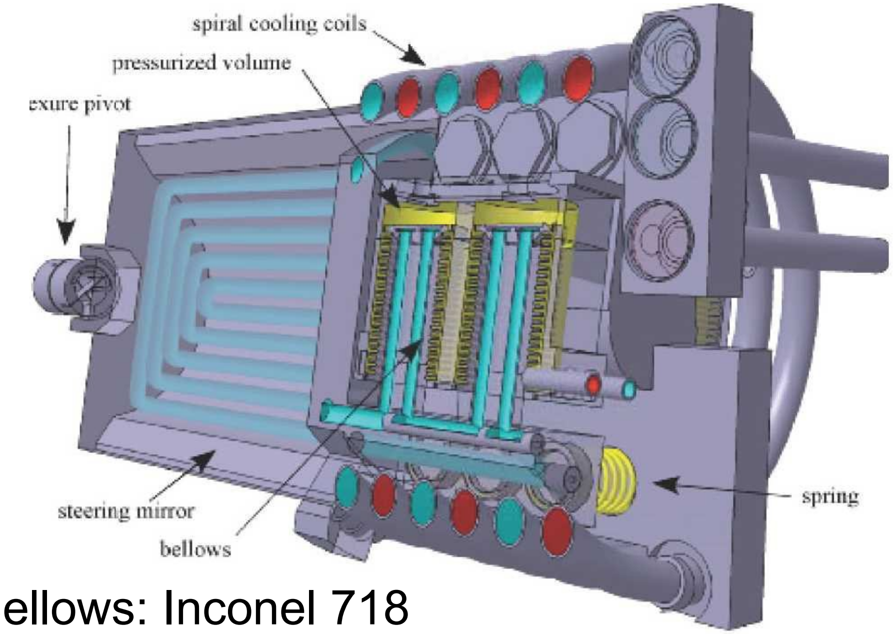
- Main advantages of the QO system:
  - Reduced losses (~1.8% vs. ~3.8%).
  - Less stray radiation.







Regular operation: steering mirrors

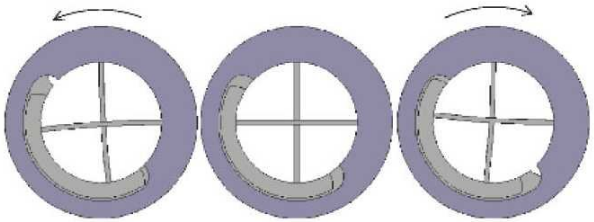


Bellows: Inconel 718

Pneumatic system:

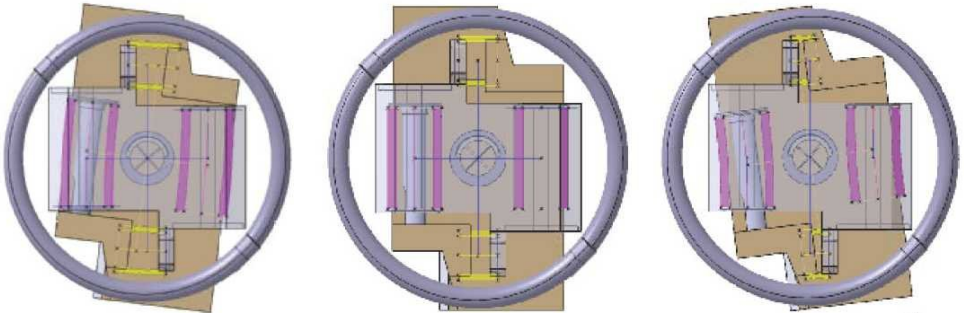
- Frictionless and backlash free
- Accurate rotational control $\leq 0.1^\circ$ or ~2 to 4mm (<3.5% degradation in j_{CD})
- flexure pivot replaces bearings
- Bellows 'piston' replaces push-pull rods

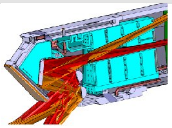
Flexure pivot concept



Pneumatic actuator concept

$P_{bellows}$~2bar $P_{bellows}$=nominal $P_{bellows}$~13bar





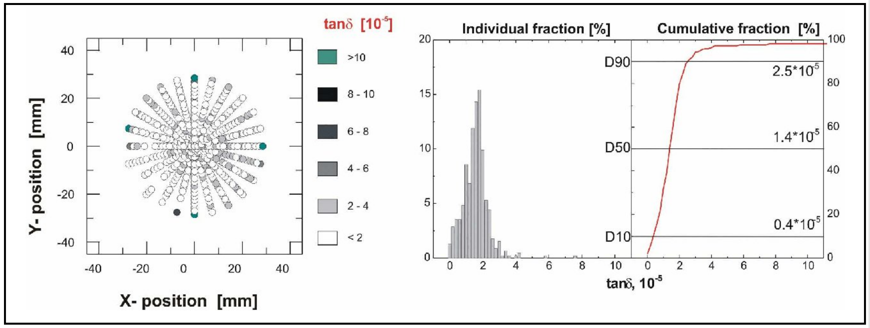
Regular operation: diamond windows

Diamond Windows are a key technology for high power ECRH

- **ultra low loss tangents (tanδ ≈ 10^{-5} → 1 mm diamond absorbs 100 W of 1 MW beam power).**
- **outstanding thermal conductivity and Young modulus.**

CVD Diamond Disk

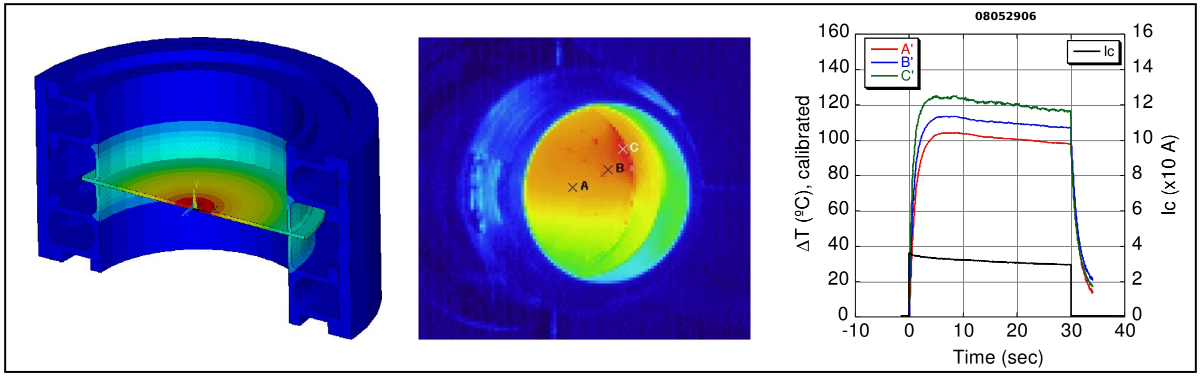
Diamond Window



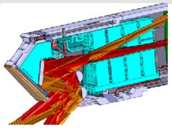
Exemplary loss tangent measurement

CVD Diamond outlook:

- Surface engineering
  → lower losses (DEMO)
- Brewster windows
  → tuneable gyrotrons

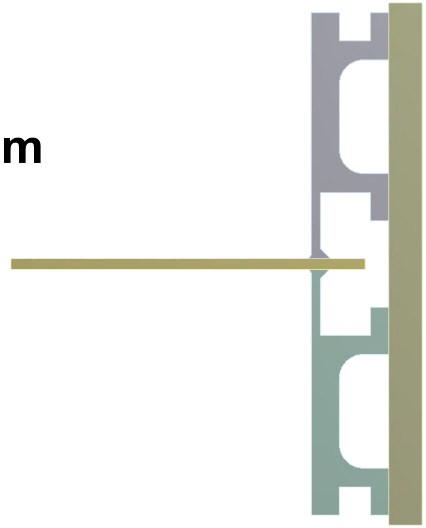


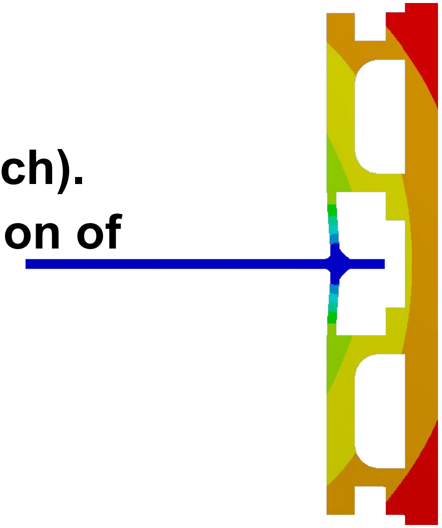
Simulated ideal gaussian beam (left, T_{max}=125°C) vs. IR mapping/influence of RF mode composition



Diamond/Metal Joining Techniques

- Joining options:
  - Mechanical (not suitable as first Tritium barrier).
  - Diffusion bonding Al-braze.
  - Chemical bonding Ag-(Cu)-braze.
- Brazing Technique:
  - Apply braze.
  - Join components.
  - Heat up + braze.
  - Cool down.
  - Thermal stresses (expansion mismatch).
  - Stress reduction by plastic deformation of the cuff or the braze.

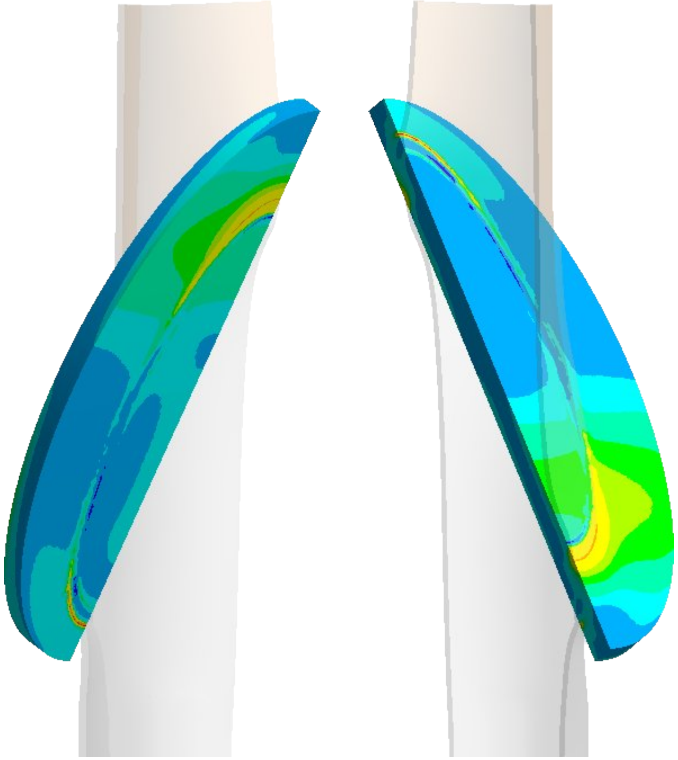




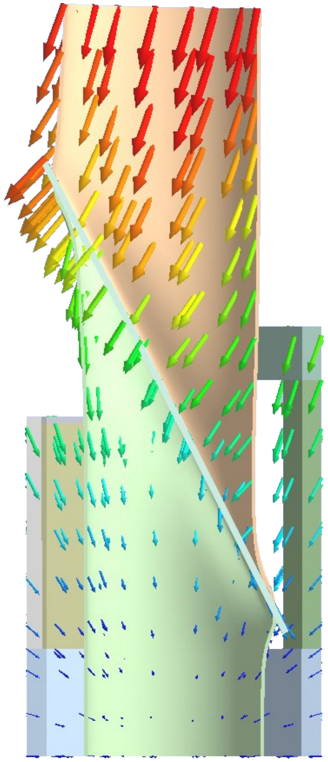
Thermal expansion ratio: $a_{Cu} / a_{Diamond} = 19$

Outlook: Brewster window brazing

Cu–cuffs: partial plastic deformation

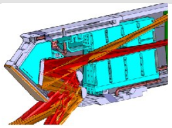


Residual stresses in the disk



central cuff axis shifted

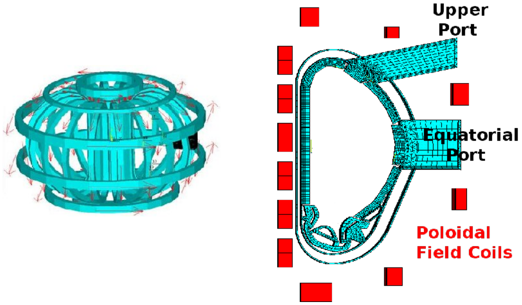
First successful brazing experiments with Quartz, Al_2O_3 and a small diamond disk.
Diamond window prototype in preparation.



Design tool development

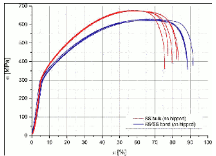
- ***Limited prototype testing*** covers only a small subset of ITER relevant conditions
- ***Numerical simulations*** cross checked with experiments ***for design development***

Electromagnetic analysis

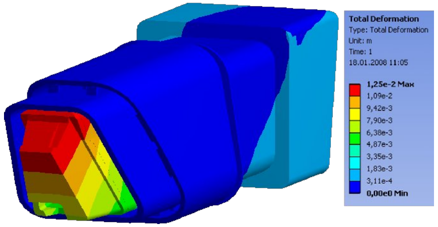


Eddy current induction during plasma disruptions and generated Lorentz forces

Structural analysis

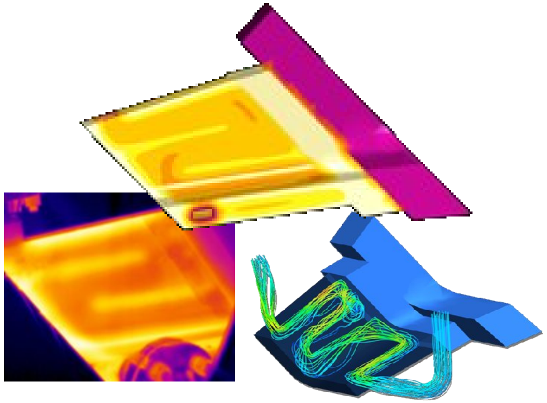


Material property checks of joints beyond ITER materials handbook



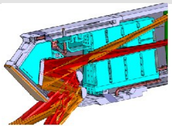
Plasma disruptions & launcher deflection

Computational Fluid Dynamics



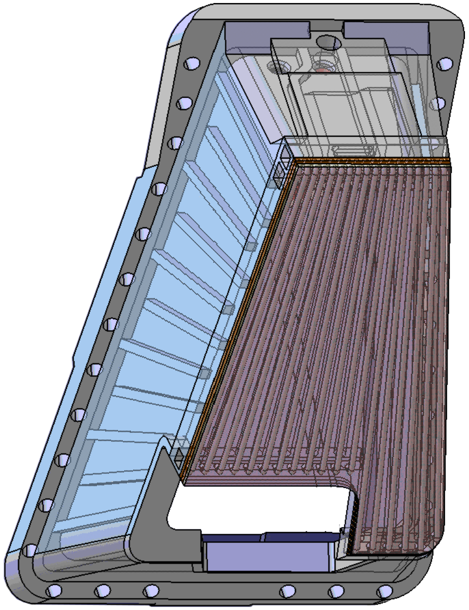
Experimental IR thermography, CFD heat profile and coolant flow paths

The way towards final design requires optimized tools.



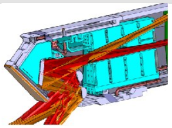
Manufacturing

- **Design complexity is constrained by:**
  - **Manufacturing route availability.**
  - **Costs.**
  - **Limited material choice.**
  - **Joint properties beyond ITER materials handbook.**
- **Prototypes:**
  - **Manufacturing route checks and solid cost estimations.**
  - **Tensile tests of joint quality.**
- **Testing:**
  - **Verification of numerical design tools.**
  - **Development of acceptance test schemes.**



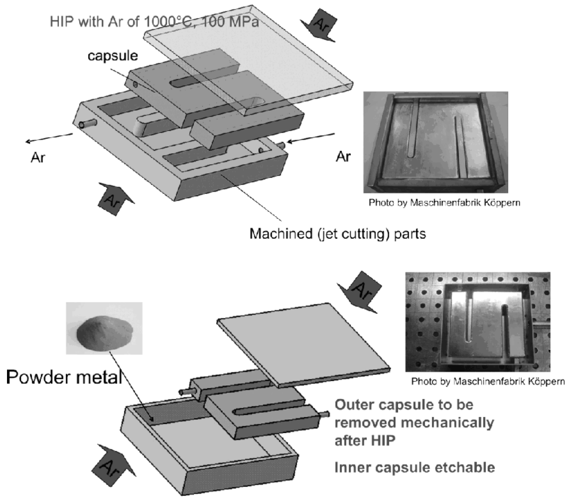
Example Blanket Shield Module:

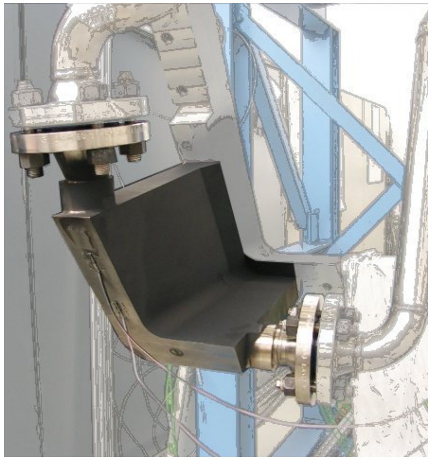
- Complex rectangular double wall cooling channels.
- Complex cut-out for mm-waves.
- Multilayer first wall panel: Be-Cu-Steel-Cu-Steel.



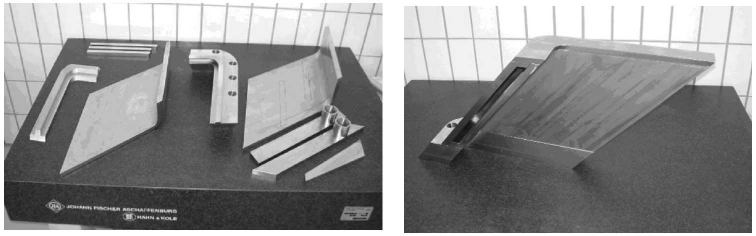
Prototypes

- **Manufacturing routes**
  - Brazing
  - Welding
  - Hot Isostatic Pressing (HIP)
- **Challenges:**
  - Joint properties
  - Manufacturing cost/time estimates
  - Tolerances

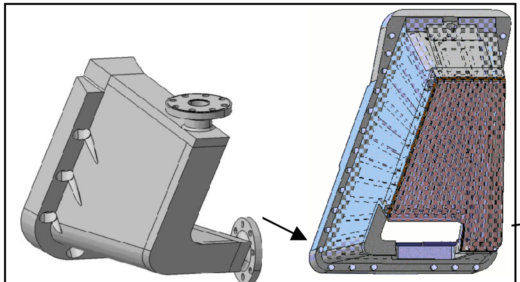




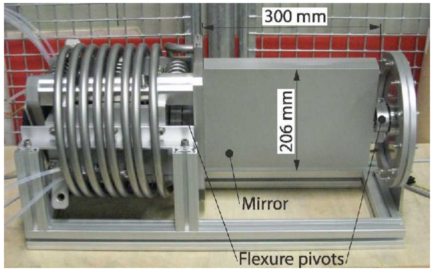
Corner mock-up manufacturing by HIP + prototype testing



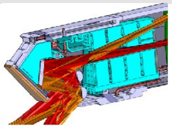
Corner mock-up manufacturing by brazing



Double wall structure & corner mock-up

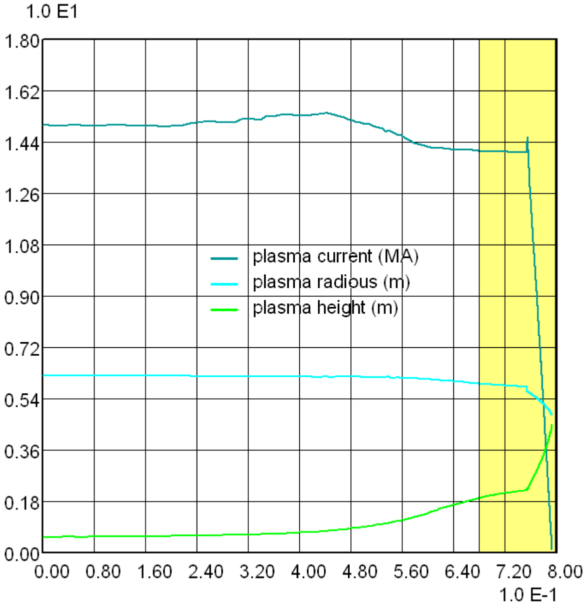


Front steering mirror prototype

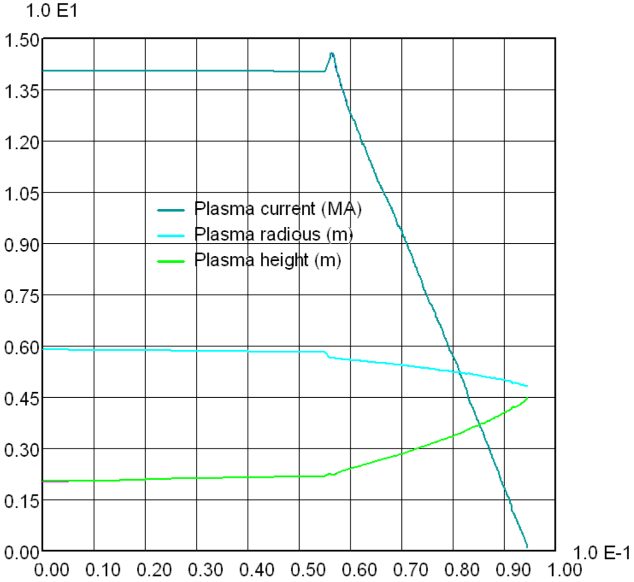


Plasma disruption mitigation

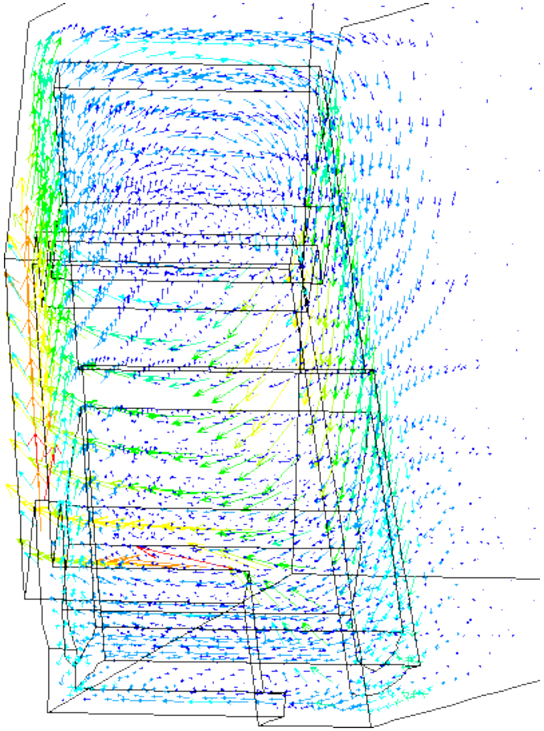
- **Worst case scenario for UL: upward VDE (vertical displacement event) with fast linear current quench (recently upgraded to 15MA, 36ms).**
- **Eddy current induction.**
- **Lorentz forces: current loops x magnetic field.**
- **Problem: peak stresses and <u>gap</u> to neighbouring components.**

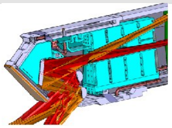


The Upward VDE. The whole simulation.



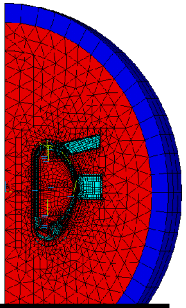
The current quench phase of the Upward VDE. Only this phase has been analyzed. The first slow phase gives no significant contribution to the EM loads of the in vessel components.



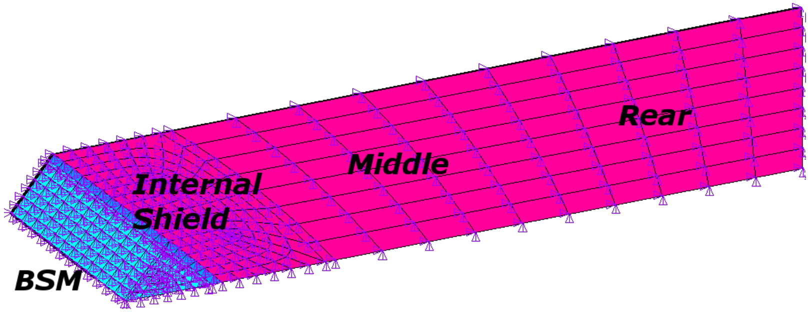


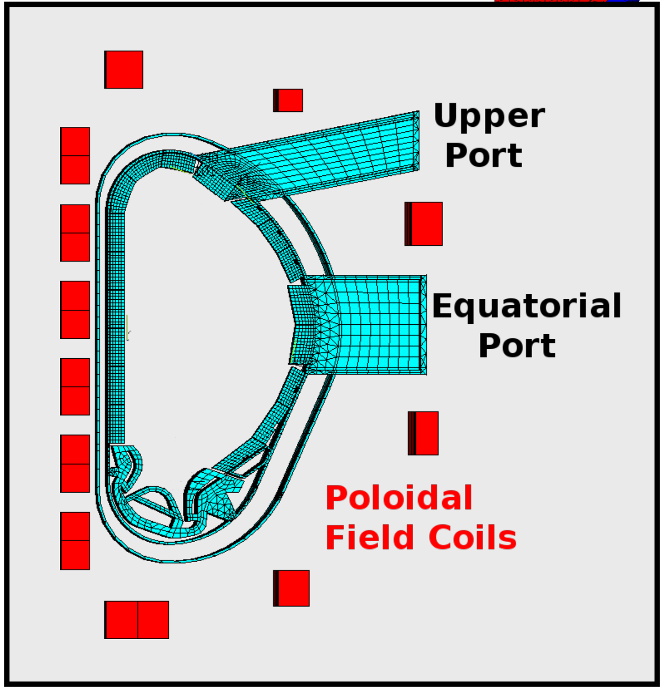
ECH UPP model of EM loads

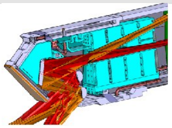
- **Base model (ANSYS):**
  - **10° of the torus (***half modeled UP***), toroidal field introduced in post-proc.**
  - **Plasma disruption simulated by** *virtual coils* **in front of the VV.**
  - *Good reproduction* **of EMAS simulations (M. Roccella, ITER_D_222SNE).**



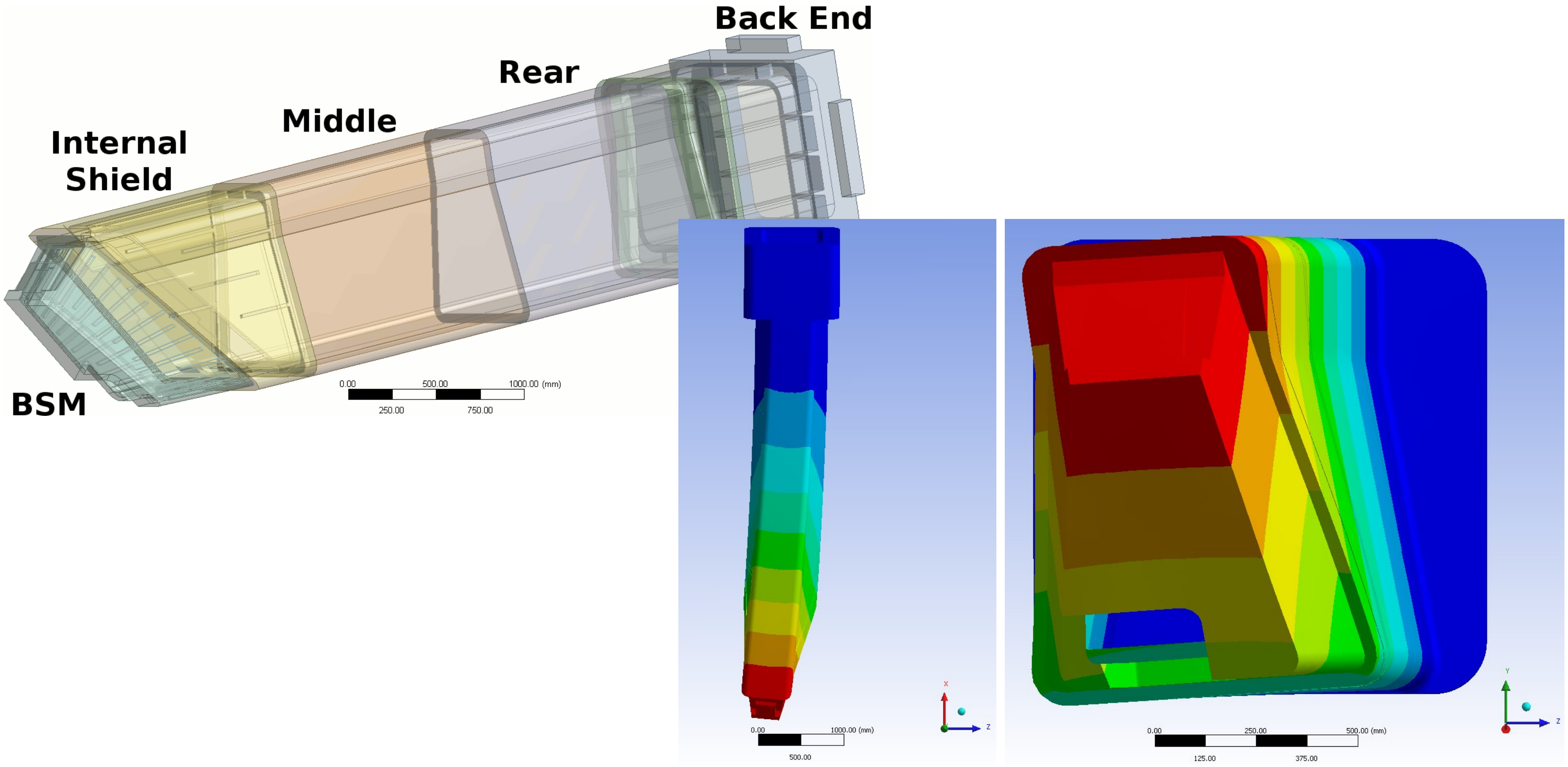
- **Extended model:**
  - *full UPP* **for asymmetric details. Consistent results with base model (M. Roccella 2005).**
  - **Available disruption data (15MA, 40ms - LS 2005):** *upward VDE with fast linear decay*.
  - **Upgrade to new reference scenarios in work – ITER EM benchmarking.**





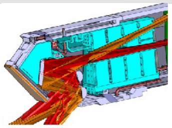


Load mapping and static deflection

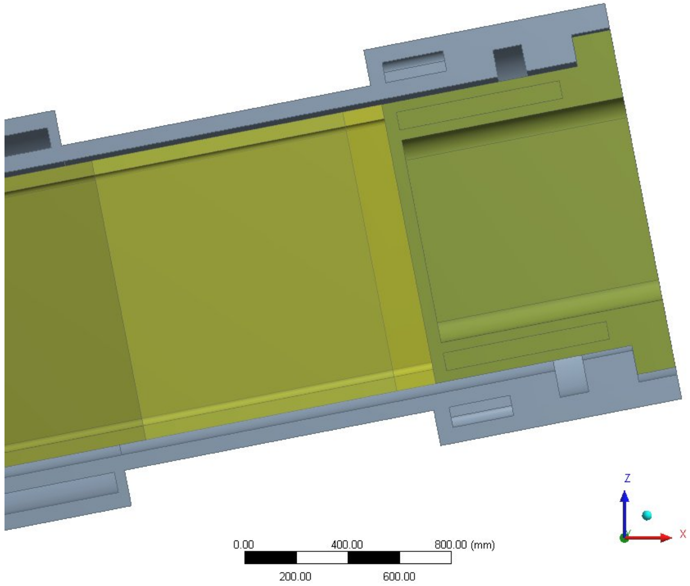


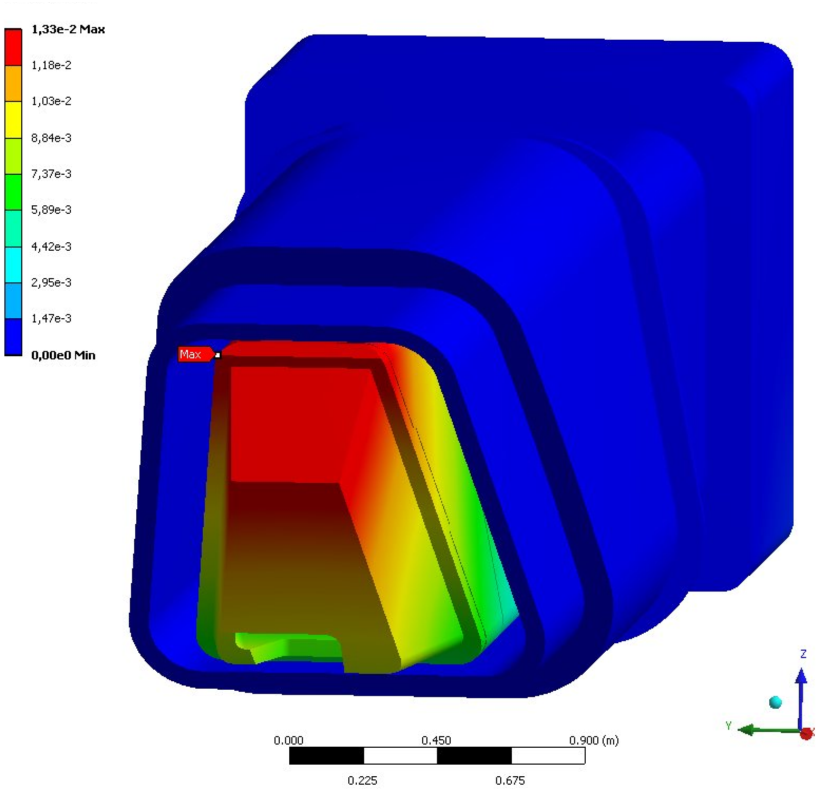
Maximum UPP deflection (10.8 mm) at the upper area of the BSM and the flange to the main frame. It results from

- 80% bending - poloidal moment + toroidal force.
- 20% tilting - radial moment.

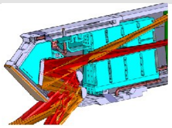


Deflections including port extension

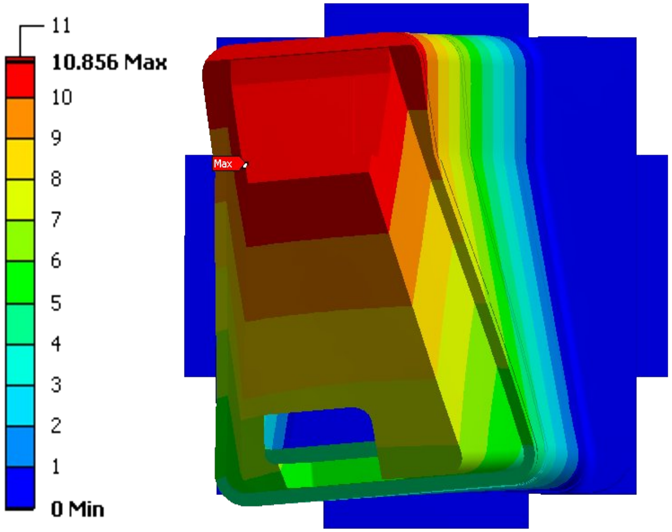




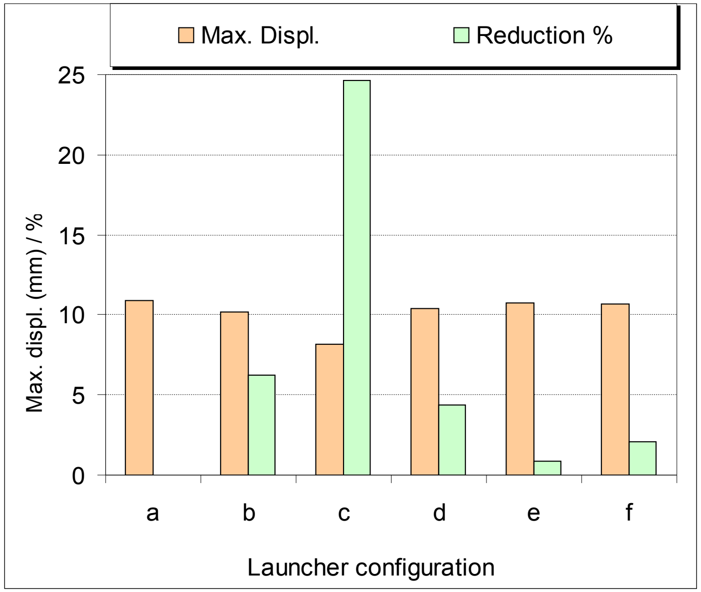
- **13 mm deflection including the port extension (static).**
- **Leverage: UPP + Port ~ 10 m, gap to neighbouring components 13 mm.**
- **Additional disruption upgrade (~10%) and dynamic amplification.**
- **Plug deflection has to be further decreased.**

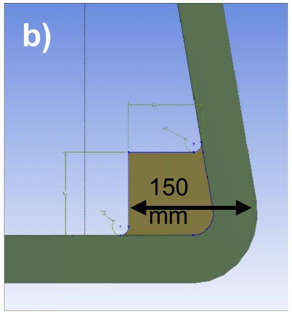


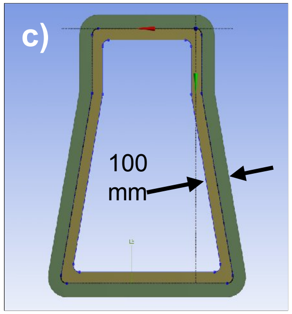
Structural stiffening of the Upper Launcher

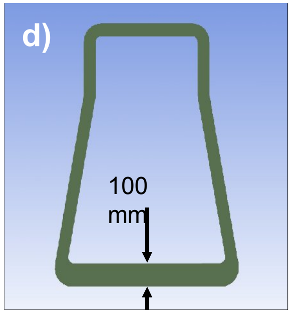


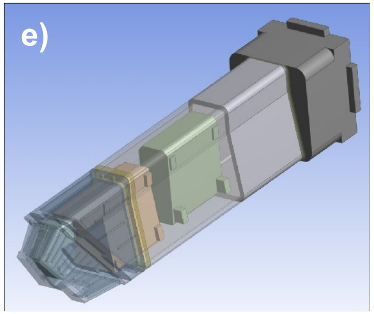
a) (reference)

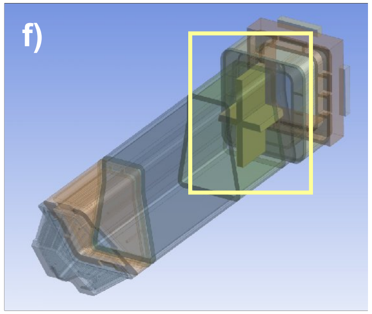


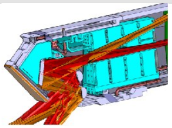










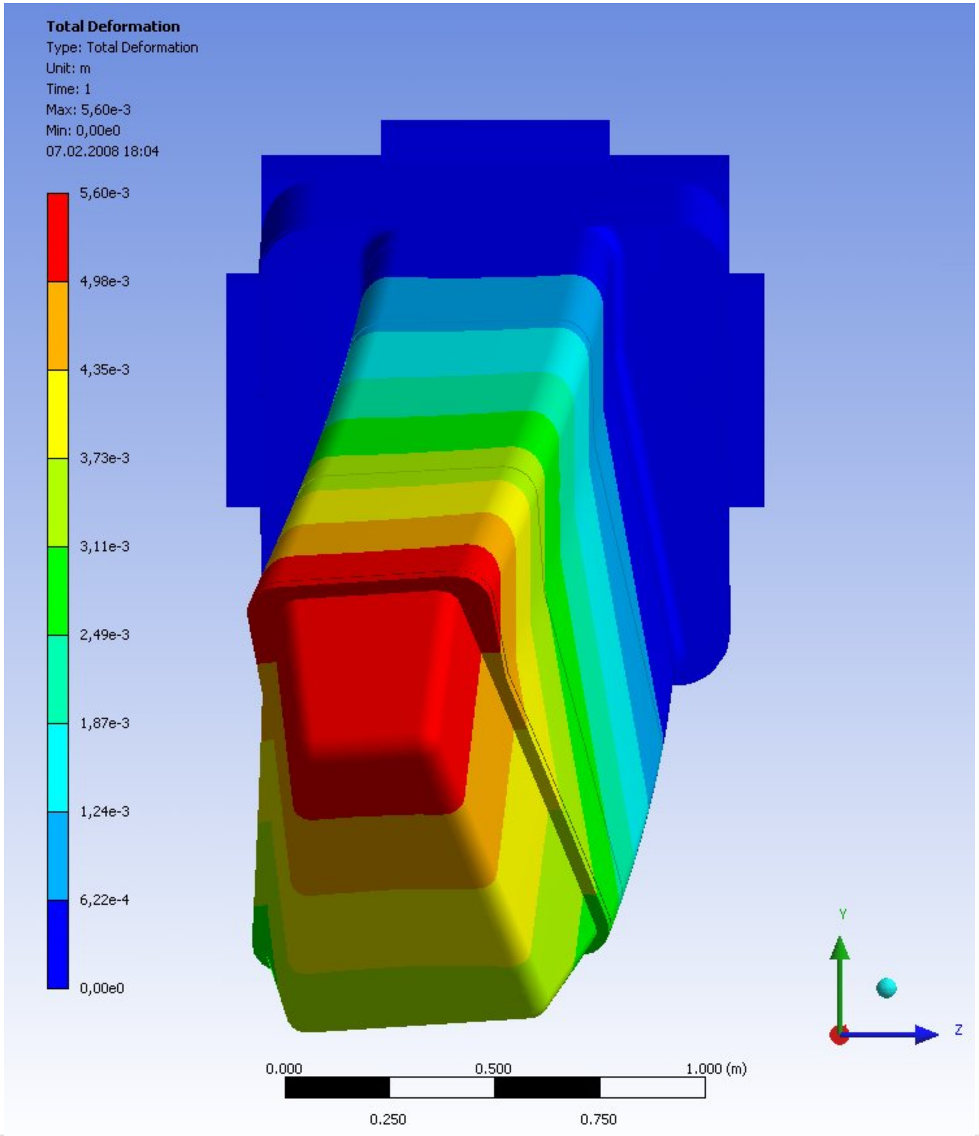


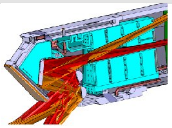
Extreme stiffening – physical limits

- EM loads from the standard plug model (not massive).
- Deflection analysis with loads applied to a completely massive plug.
- Deflection reduction from 10.8 mm to 5.6 mm.
- port deflection +2 mm.
- VDE upgrade +10%.
- Dynamic amplification

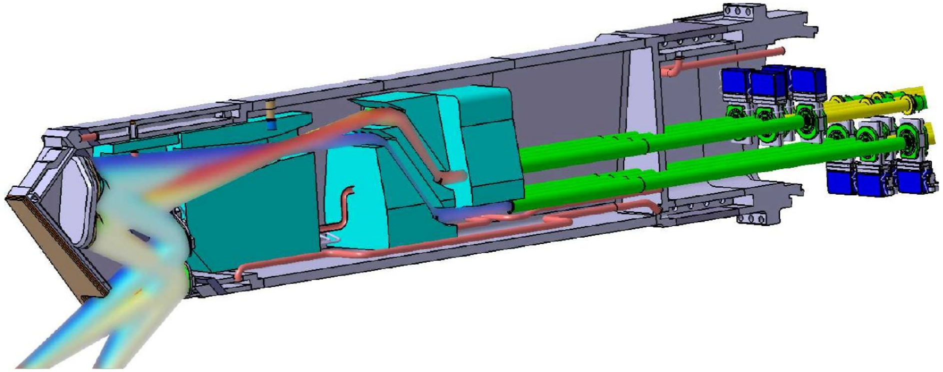
→ 10 mm.

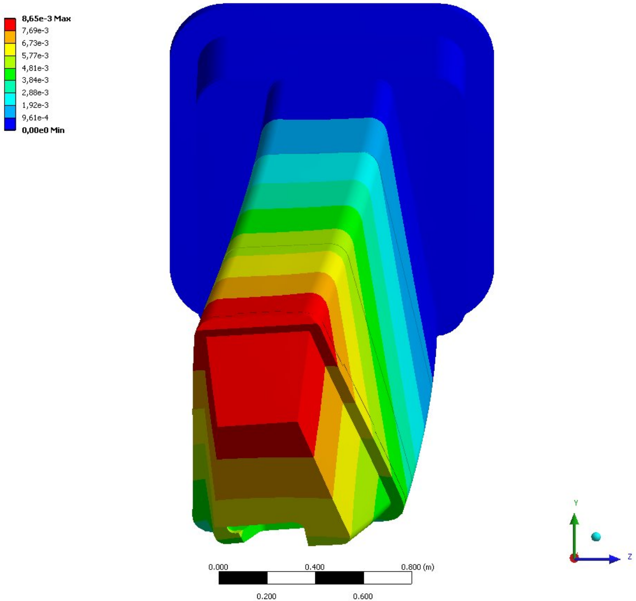
→ More gap required.





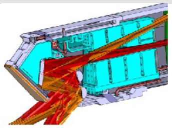
EM Load reduction by improved shield block design - empty port plug study





- **Standard** ECH model configuration: **10.8 mm** deflection (BSM nearly empty, rest of the plug filled with shielding).
- **Empty plug: 8.6 mm** deflection (no shielding).
- No shielding not realistic:
  - Shift as much shielding as possible to the rear.
  - Optimized shield block design (segmentation) to avoid net torque.

Conclusion: for the ECH plug (BSM already nearly empty) an optimized shield block design can lower the deflection by up to 20%.

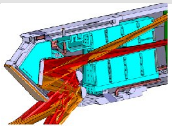


Fulfilling the gap requirement

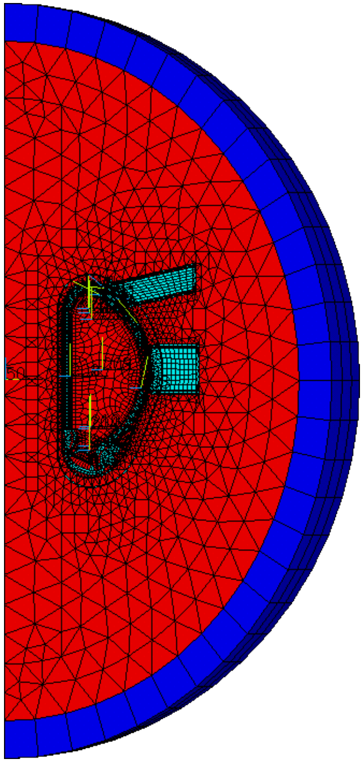
A tolerable deflection during plasma disruptions can be reached combining different optimizations:

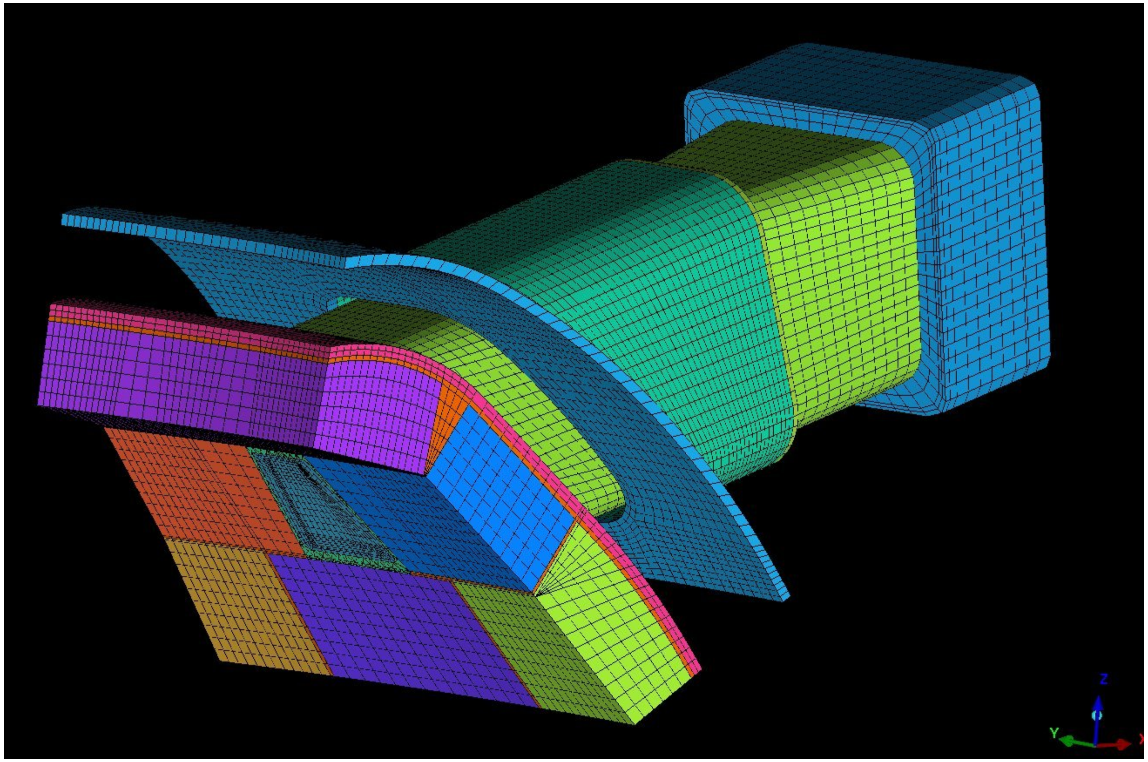
- ***Structural stiffening***.
- Advanced ***shield block design*** for reduced eddy currents induction in the regions with high magnetic fields.
- ***Current path shaping*** by the introduction of segmentation, slits and optimization of fixations for reduced Lorentz force generation.

With the optimizations the UPP come close to the physically possible. Further improvements require redesign (e.g. reduced leverage).

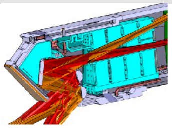


Outlook disruption mitigation



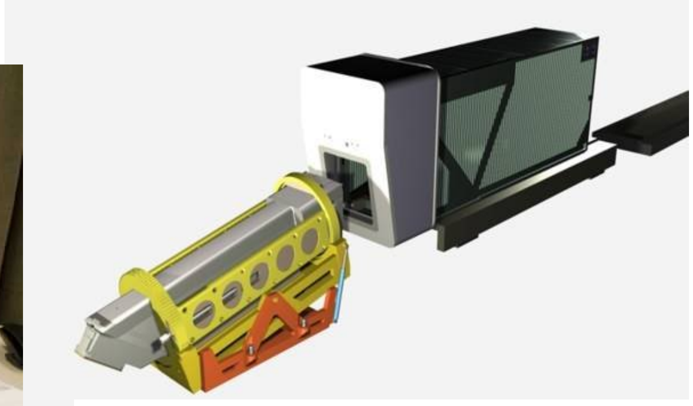


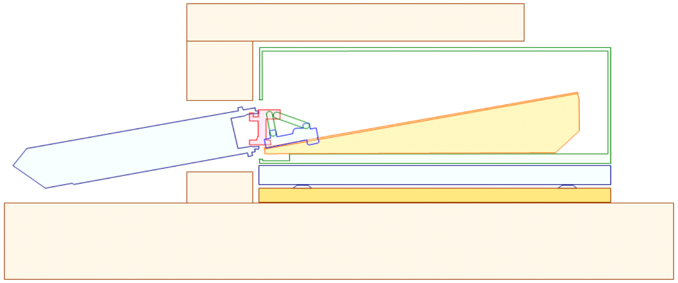
- Global torus segment model with updated disruption scenario.
- New local submodel model of upper launcher and surroundings.
- -> Tool for detailed design of local stresses, mirrors, fixations etc.



Virtual Reality studies of Remote Handling

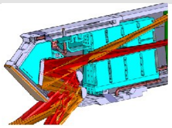
- Software oriented analysis of assembly/maintenance procedures
- Framework: CATIA models of Port Plug and ITER Hot Cell
- First studies of Plug acceptance and BSM removal





Hand over at location hot cell

A good design has to be compatible with remote handling tools and procedures.



Conclusions

- Preliminary design nearly finished.
- Path towards final design:
    - Design tool upgrade in progress.
    - Cross check design tools with prototype tests
    - Detailed design of quasi-optical system.
    - Adaptation of structural components to new boundary conditions & QO design.
- Procurement outlook:
    - Prototyping and testing started.
    - Check of manufacturing routes.
    - Find qualified suppliers & check procurement schedule.