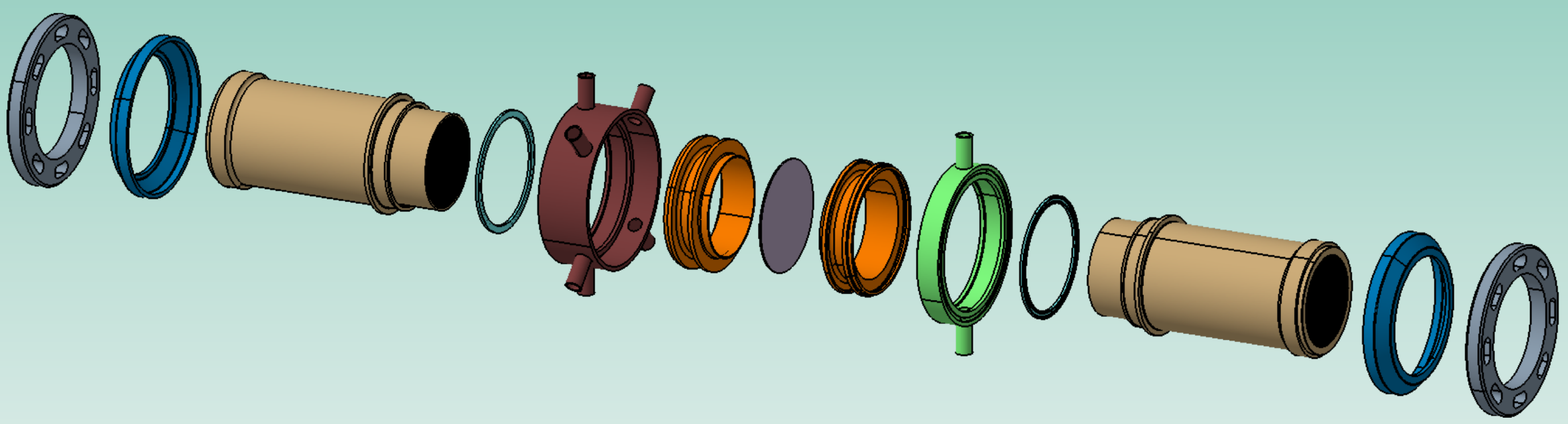
Dielectric diamond window for the ITER EC H&CD Upper Launcher: design, analysis and qualification

G. Aiello, M. Gagliardi, G. Grossetti, F. Mazzocchi, A. Meier, G. Saibene, S. Schreck, P. Spaeh, D. Strauss, A. Vaccaro and T. Scherer

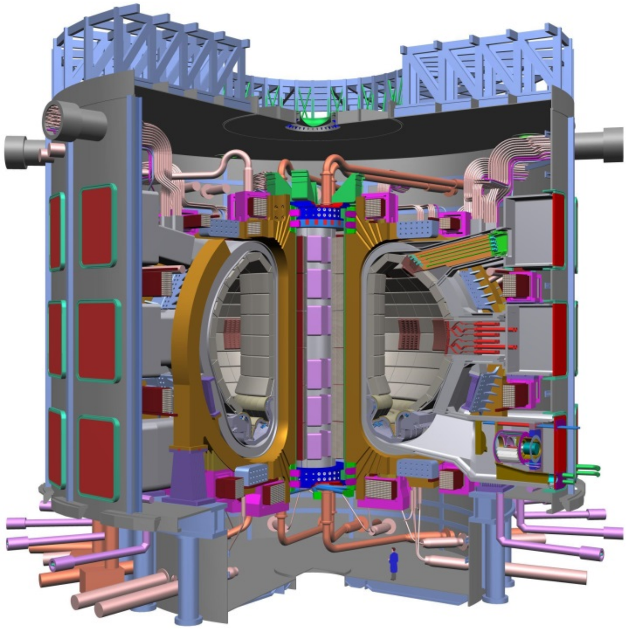
Institute for Applied Materials – Applied Material Physics (IAM-AWP)



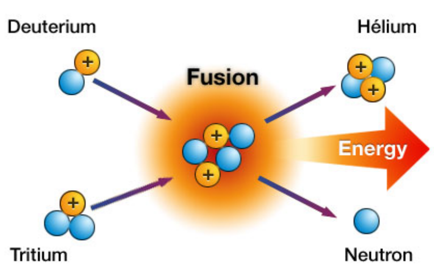
Outline

- ITER and EC H&CD system
- Design philosophy of the diamond window unit
- Design optimization and validation by FEM analyses
- Link dielectric measurements – FEM analyses
- Qualification program
- Assembling sequence of the window unit
- Conclusions and outlook

ITER – first fusion device to create net energy

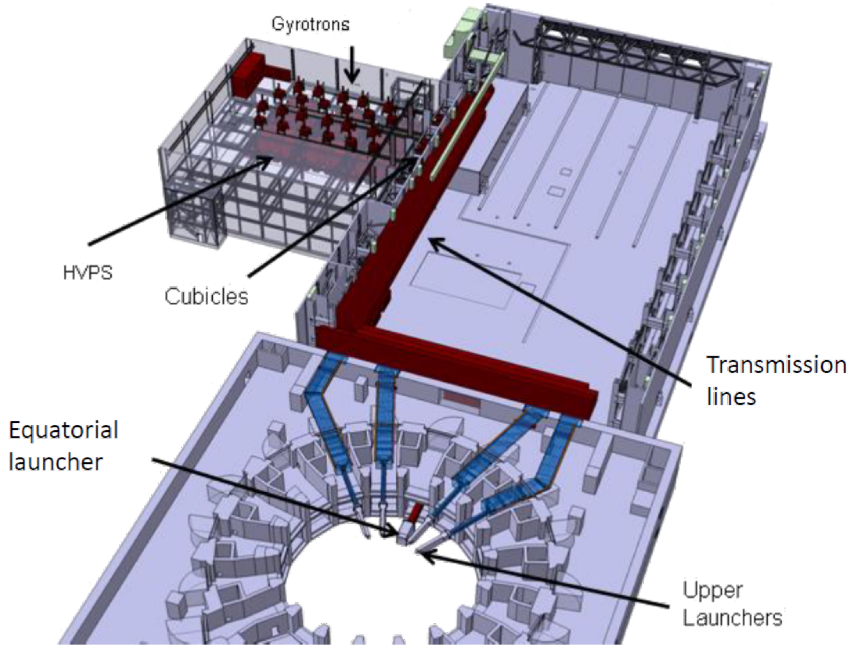


ITER is an experimental machine based on “tokamak” concept and designed to prove the feasibility of fusion as a large-scale source of energy.

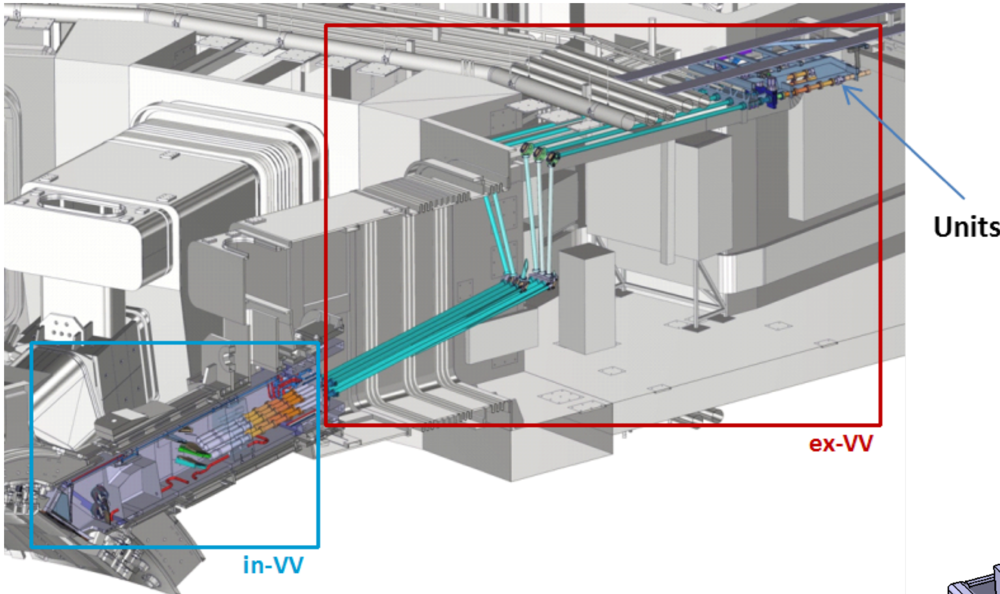


ITER EC H&CD System

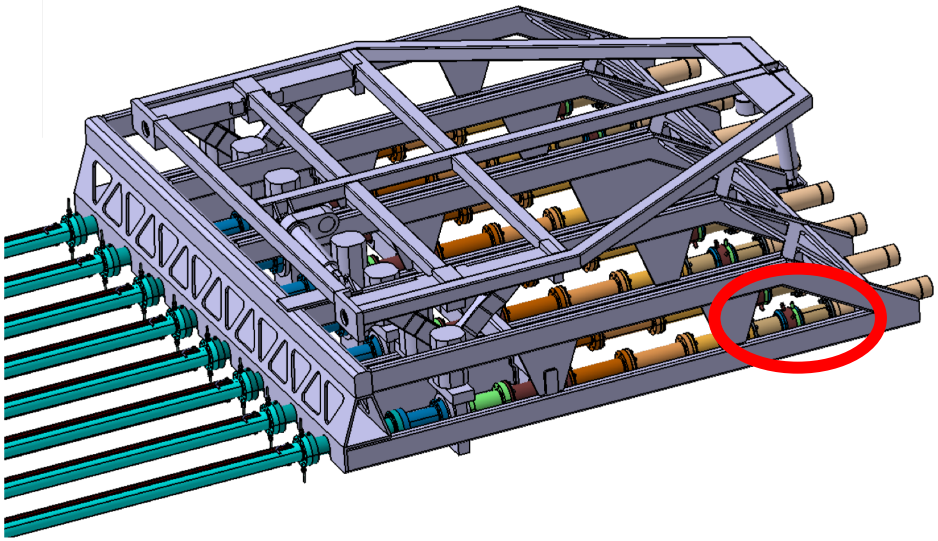
- To provide localized heating of plasma.
- To provide localized current drive for control of plasma instabilities.
- Twenty-four 170 GHz gyrotrons for a total installed power of 24 MW.
- 4 Upper Launchers, 4 x 8 beam lines up to 1.5 MW each.
- 1 Equatorial Launcher, 24 beam lines at 1 MW each.



Diamond window units in the Upper Launcher



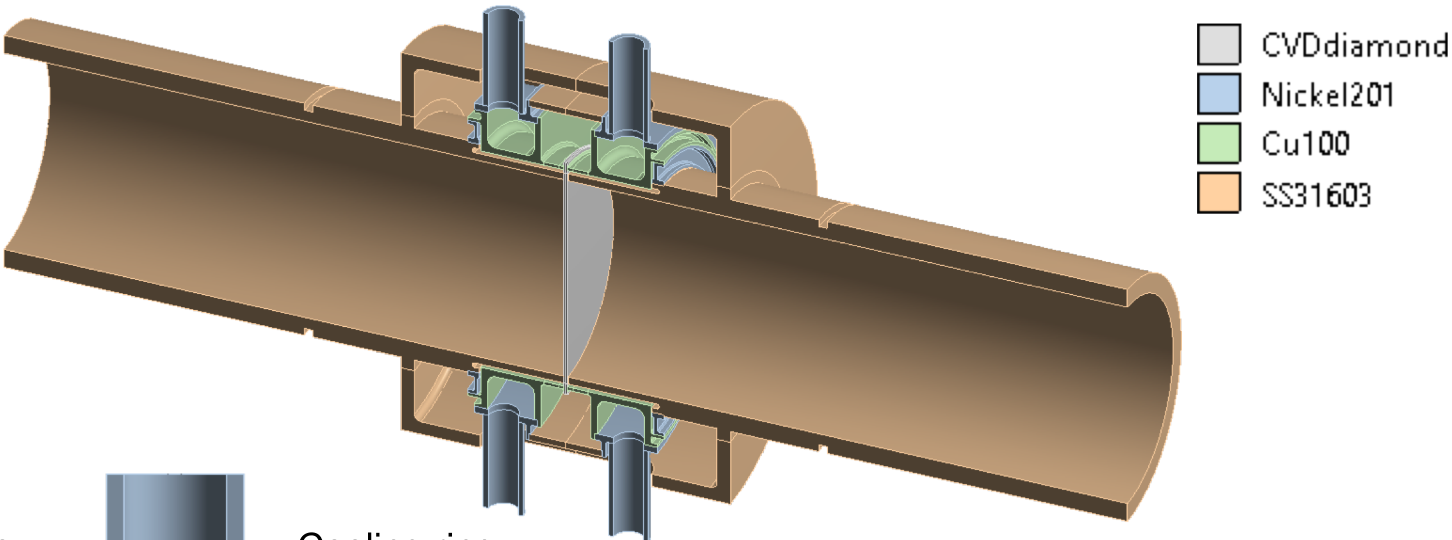
The Upper Launcher consists of an assembly of ex-vessel waveguides and an in-vessel port plug.

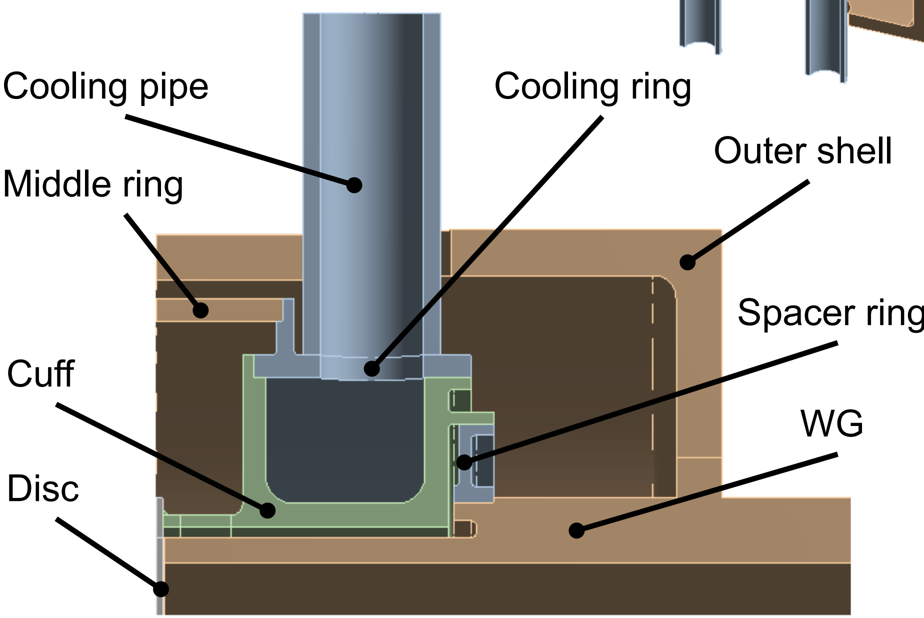


The window units are key components:

- Transmission of high power microwave beams.
- Part of the ITER first confinement system.
- Stringent ITER safety and quality requirements.

Design philosophy of the window unit

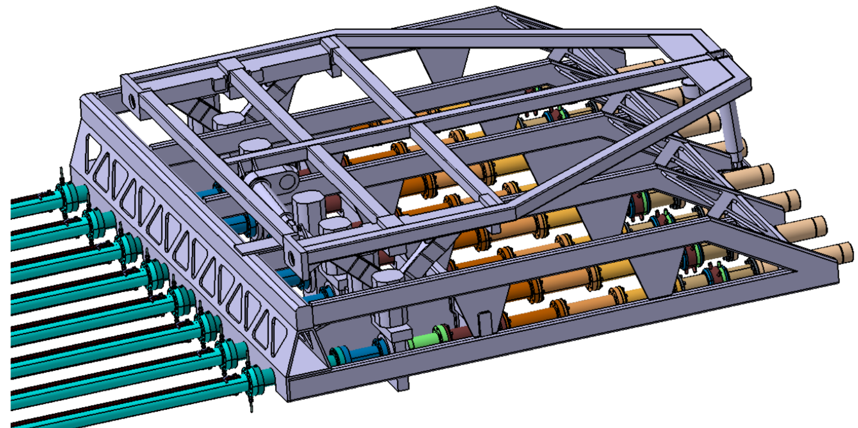


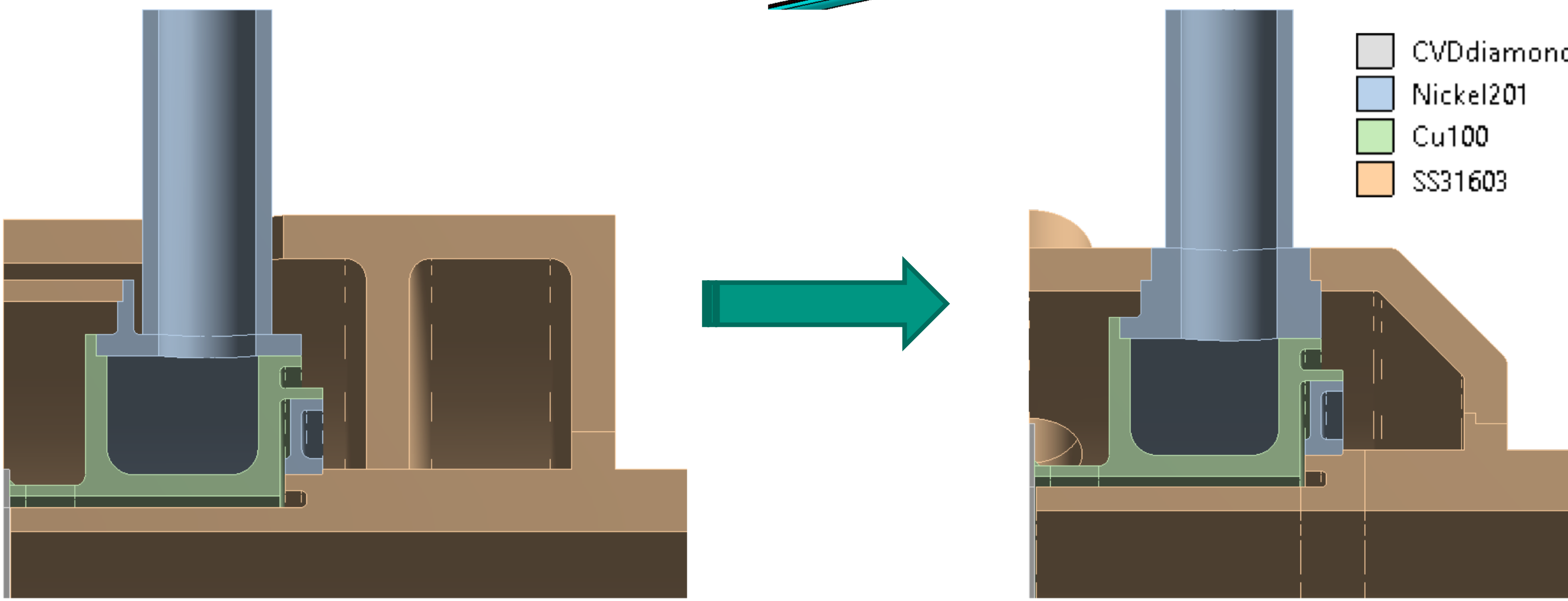


- Thin copper cuffs brazed to the diamond allowing indirect cooling of the disc.
- Rigid outer shell to withstand the external loads.
- Inserted corrugated WGs with inner diameter of 63.5 mm to suppress the parasitic oscillations.

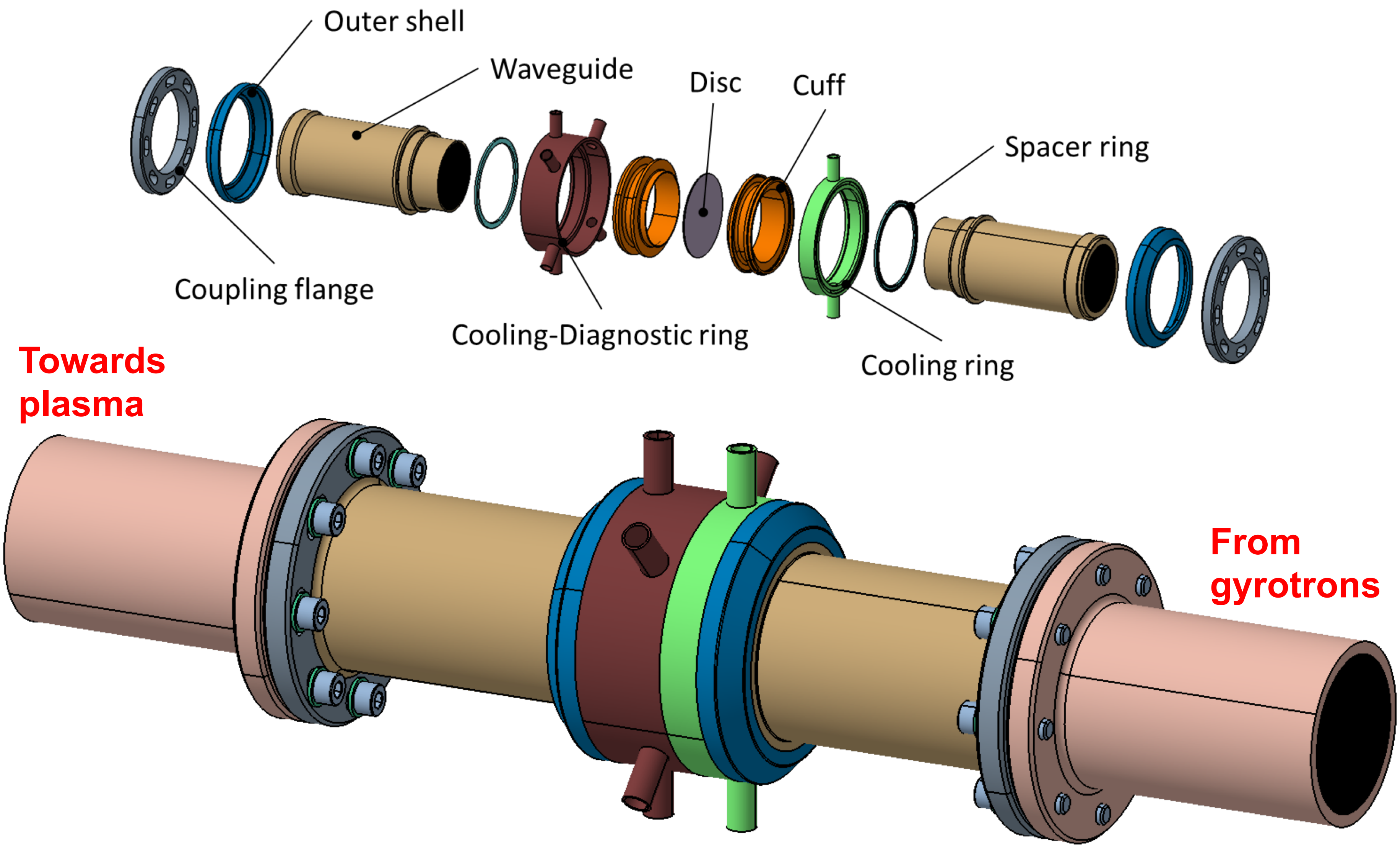
Design development – FEM analyses

- Lower seismic loads acting on the units.
- Design more compact and feasible to manufacture.
- Second tritium barrier and real-time monitoring of interspaces.





Exploded view of the unit design

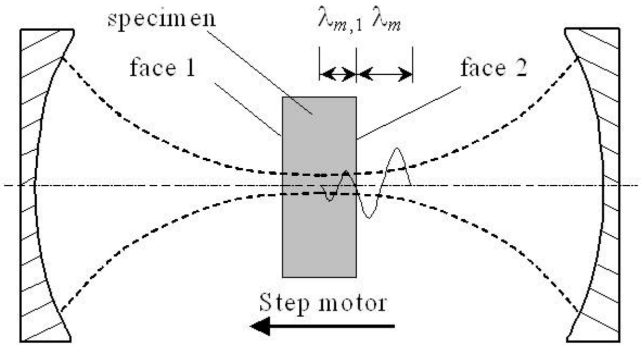


Measurements of tanδ in the diamond disc

- Fabry-Perot resonators are used to measure the dielectric properties of the diamond disc: ε_r and tanδ.
- The measured ε_r and tanδ are then used in the FEM analyses to model the power absorbed in the diamond disc during the beam transmission.

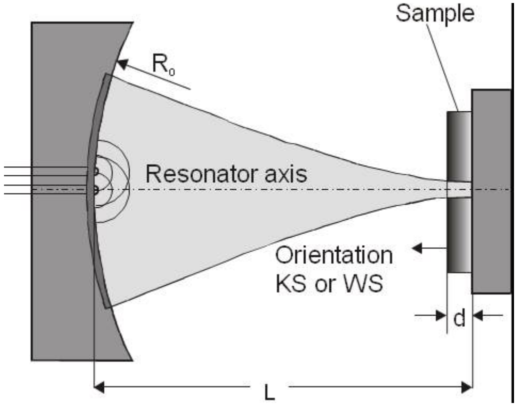
Spherical measurement setup

Determination of tanδ at the center of the diamond disc.

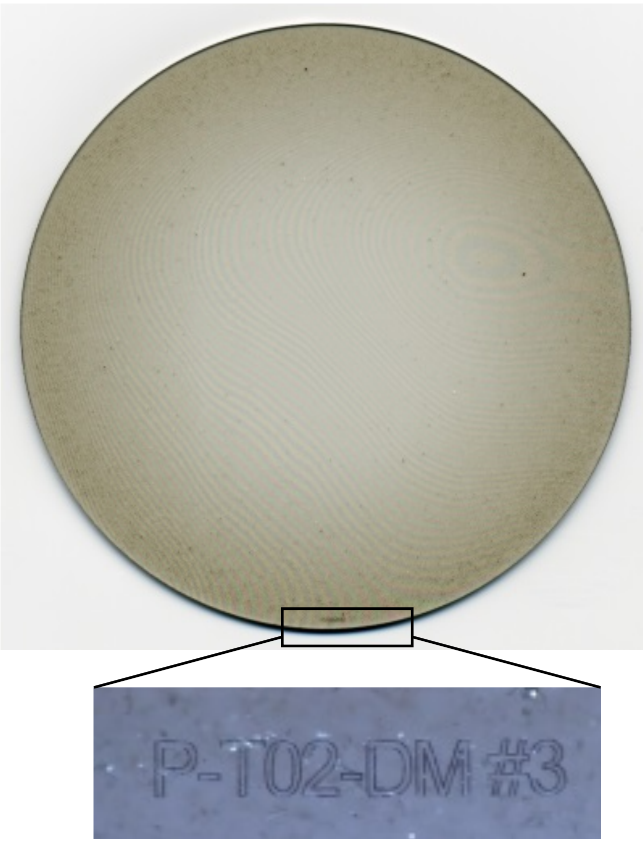


Hemispherical measurement setup

Determination of tanδ distribution over the diamond disc surface.



Typical results on bare diamond discs



Laser engraving
for identification

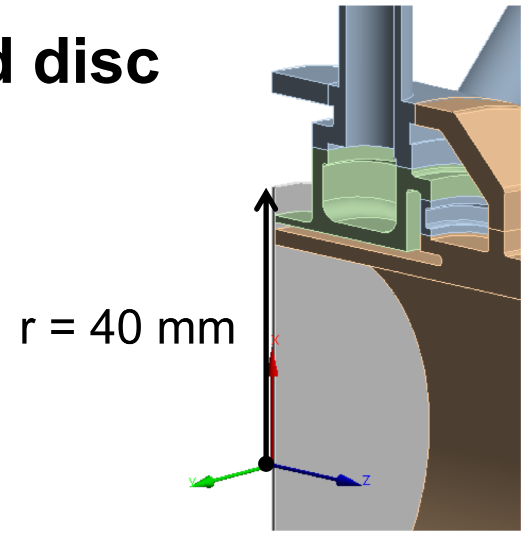
Parameter	T02-DM	T03-DM	Specification
diameter	79.95 mm	79.96 mm	80 mm (+0.2/−0.2 mm)
thickness (central)	1.1149 mm	1.1148 mm	1.11 mm (+0.005mm/ -0.000mm)
planarity *nucleation side* *growth side*	0.52 μm 0.66 μm	0.83 μm 1.43 μm	10 μm
Ra roughness *nucleation side* *growth side*	3.86 nm 2.11 nm	4.13 nm 3.91 nm	20 nm
permittivity ε_r	5.67	5.67	5.67
loss tanδ @ 170 GHz (mean D50)	$1.4 \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$	$3.5 \cdot 10^{-5} \pm 5 \cdot 10^{-6}$
loss tanδ @ 170 GHz (mean D90)	$2.6 \cdot 10^{-5}$	$2.5 \cdot 10^{-5}$	$6 \cdot 10^{-5} \pm 1 \cdot 10^{-5}$
Central loss tanδ	$(3.6 \pm 0.9) \cdot 10^{-6}$ @169.57 GHz	$(4.2 \pm 1.1) \cdot 10^{-6}$ @169.58 GHz	

Absorbed power in the diamond disc

$$P_{abs} = P_{beam} \cdot \frac{f}{c} \cdot \pi \cdot (1+\varepsilon_r) \cdot \tan\delta \cdot t$$

- P_{beam} = 1.31 MW (design value)
- f = 170 GHz
- ε_r = 5.67
- <u>tanδ = 2 × 10^{-5}</u>
- t = 1.11 mm

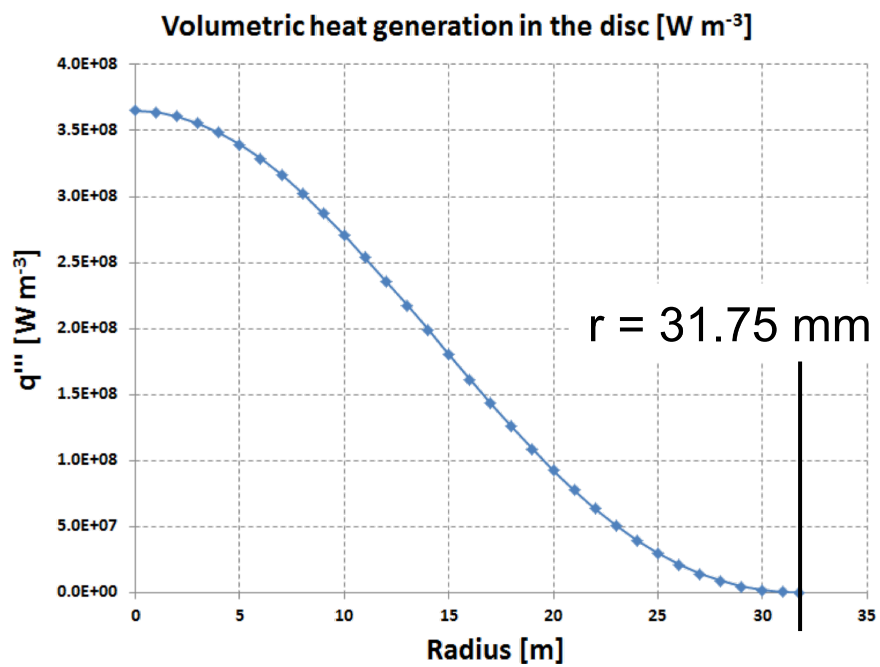
→ P_{abs} = 346 W



Power pattern according to HE_{11} mode beam, volumetric power density into disc:

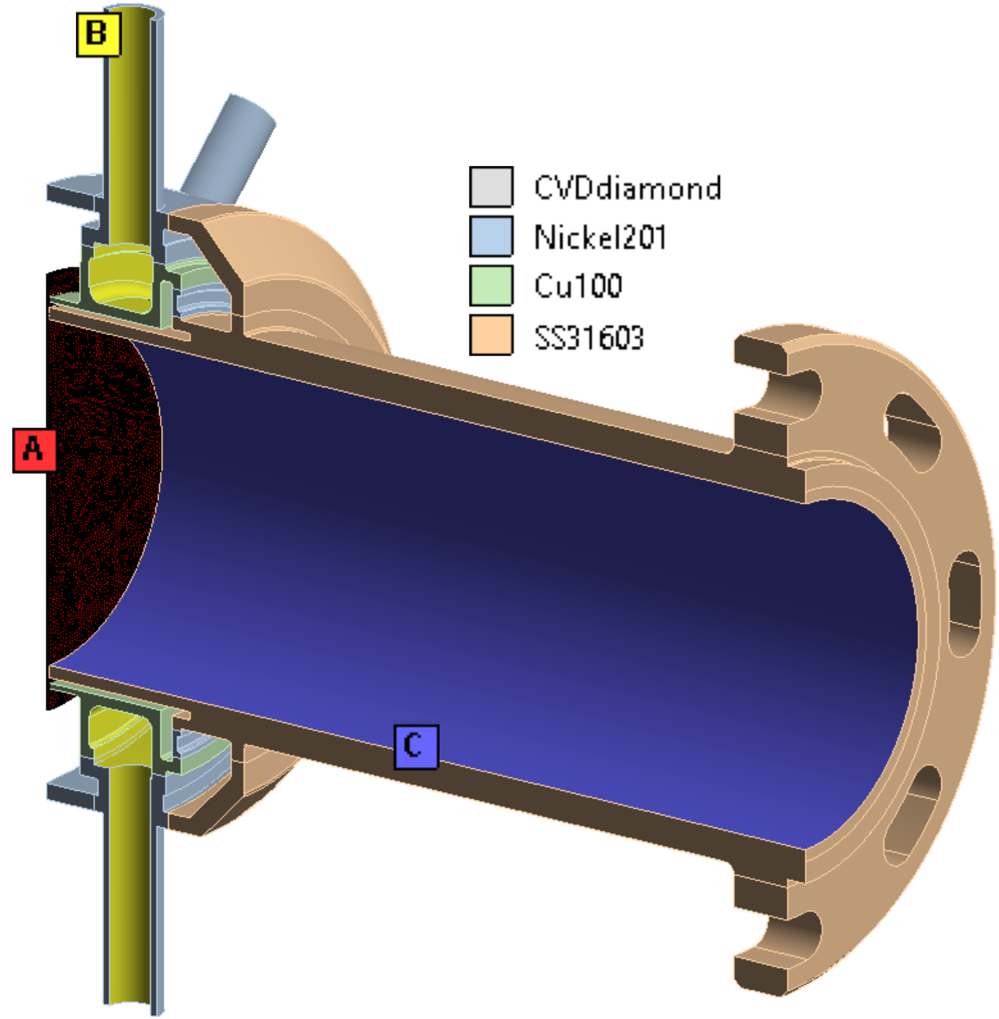
$$q'''(r) = A \cdot \left[J_0(x)\right]^2$$

$$x = 2.405 \cdot \frac{r}{a}$$

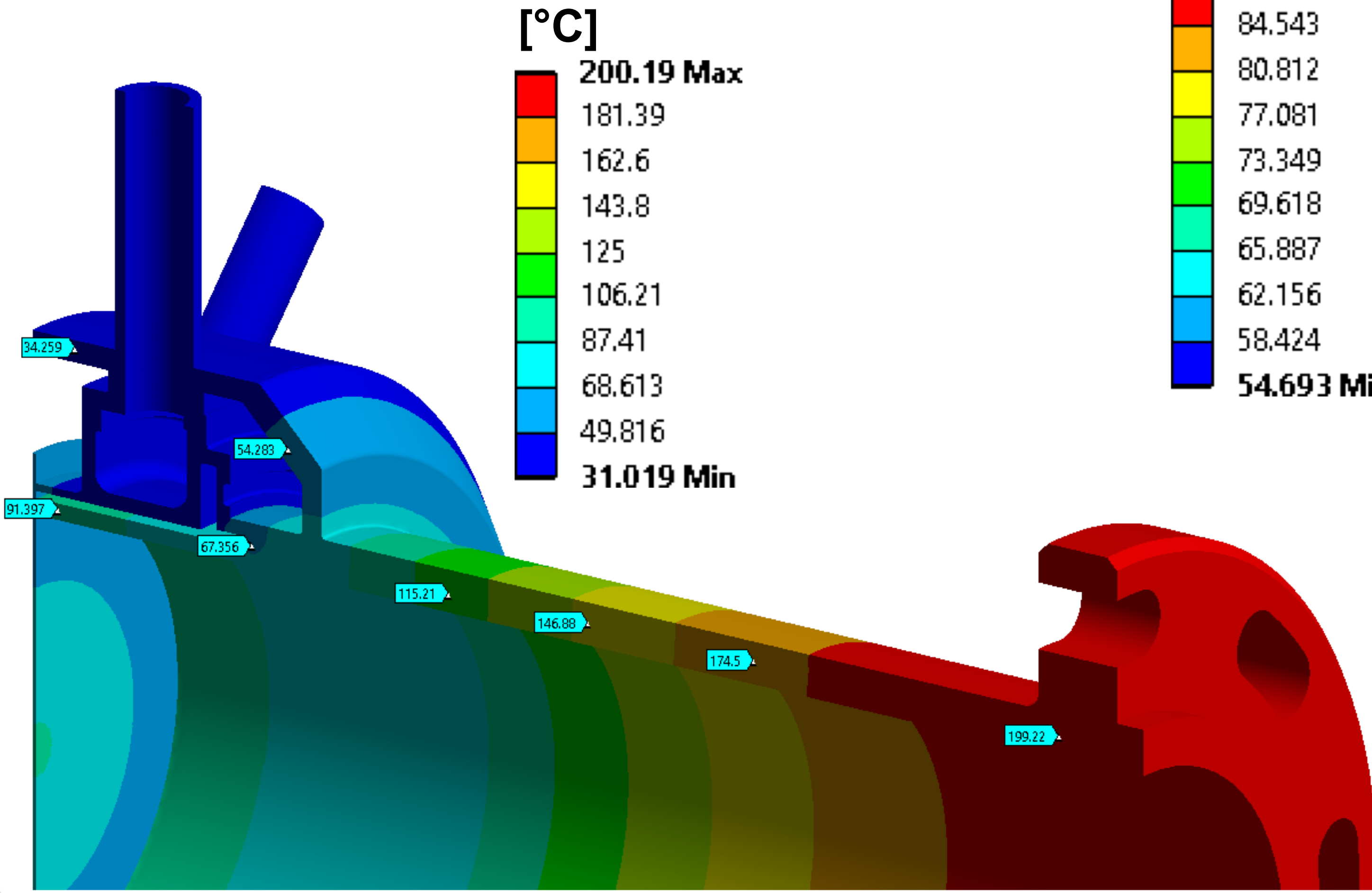


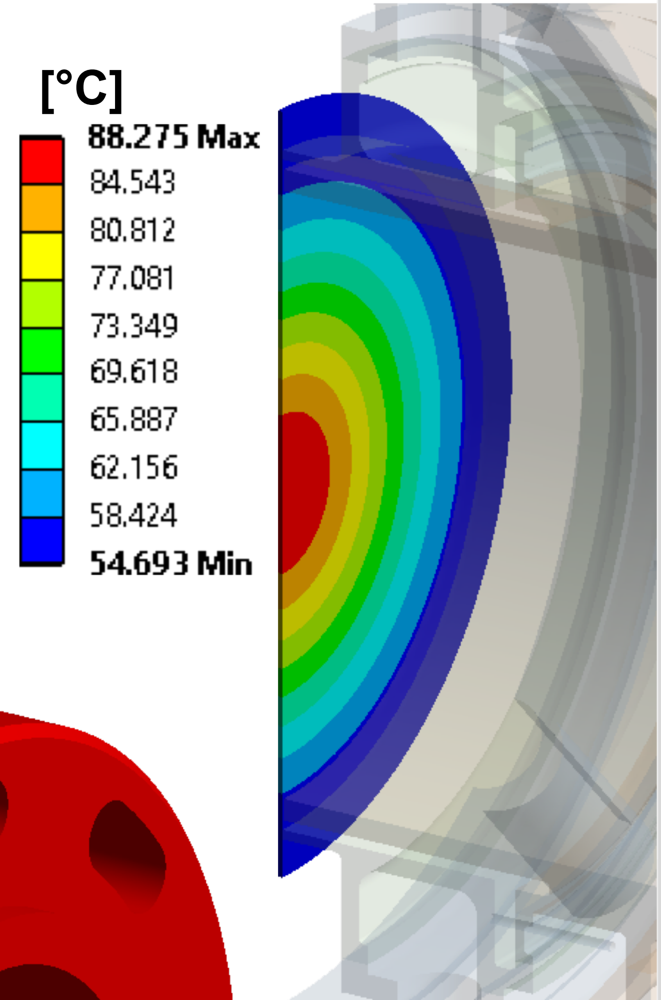
Design development – FEM thermal analyses

- **A** Volumetric heat generation due to power absorption is applied to the diamond disc.
- **B** Heat exchange coefficient is applied to the surfaces of the cooling channels: 3168 W m^{-2} $°C^{-1}$.
- **C** Heat flux is applied to the inner surface of the copper coated WGs: 1578 W m^{-2}.



Design development – FEM thermal analyses

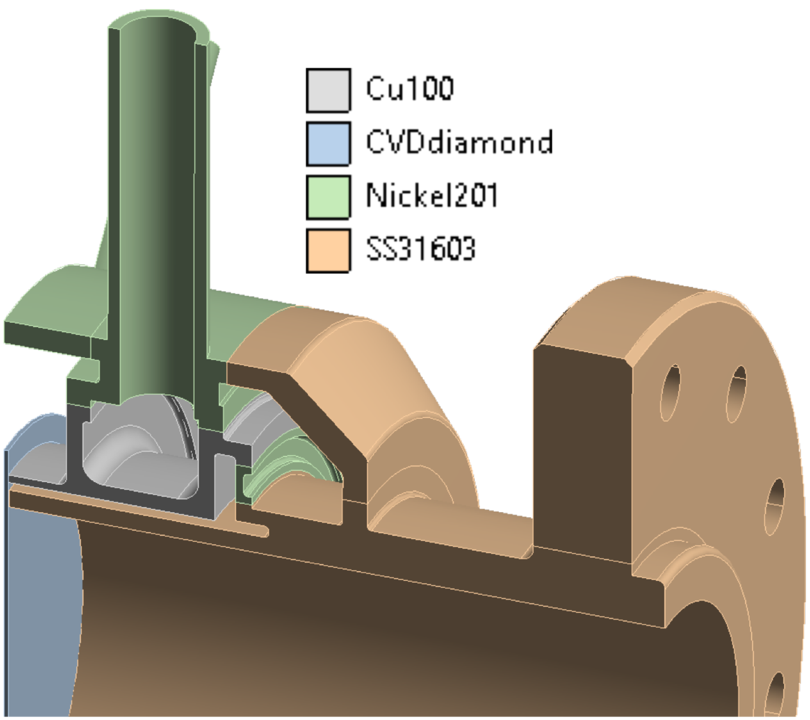




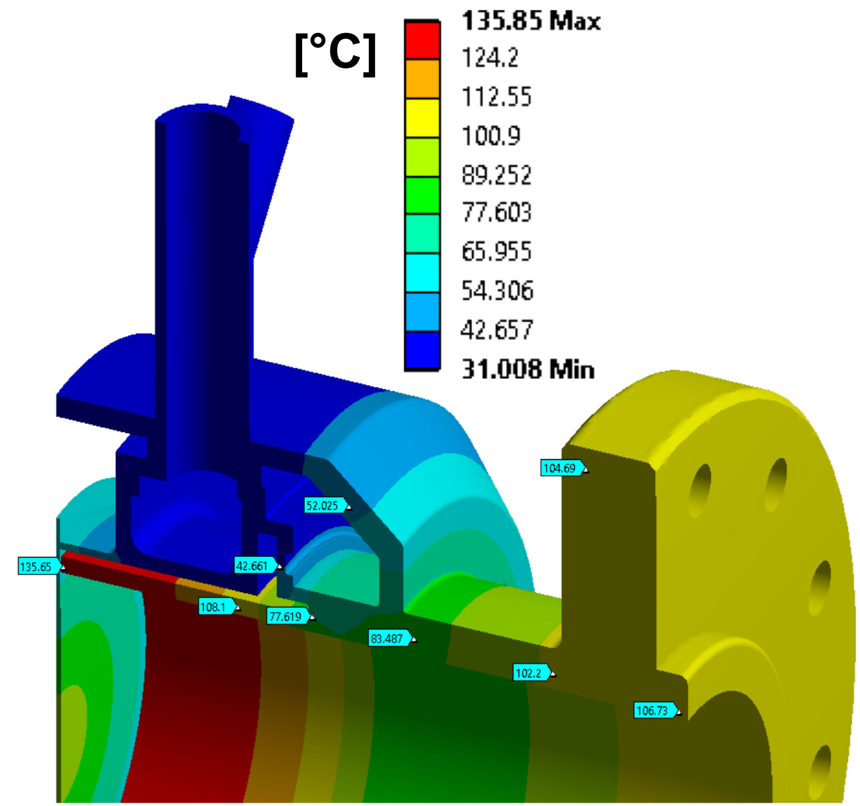
Design development – recent changes

- Reduction of the window unit length from 338.2 mm to 160.3 mm.
- Reduction of the inner diameter of the WGs from 63.5 mm to 50 mm.

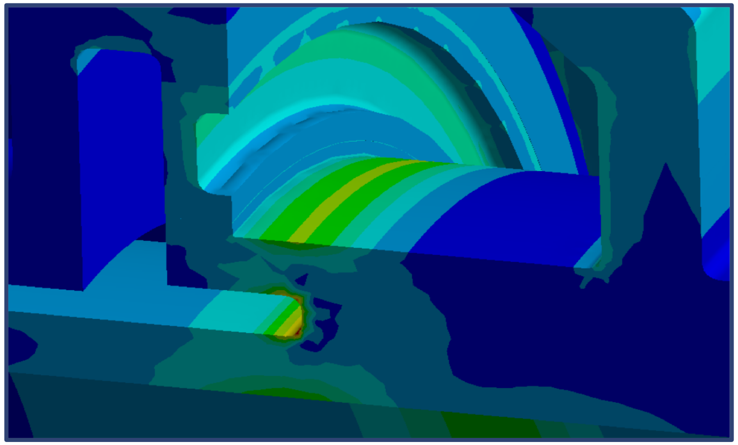
→ Heat flux to the WGs increased by 2.6 times: <u>from 1578 to 4071 W m^{-2}</u>.

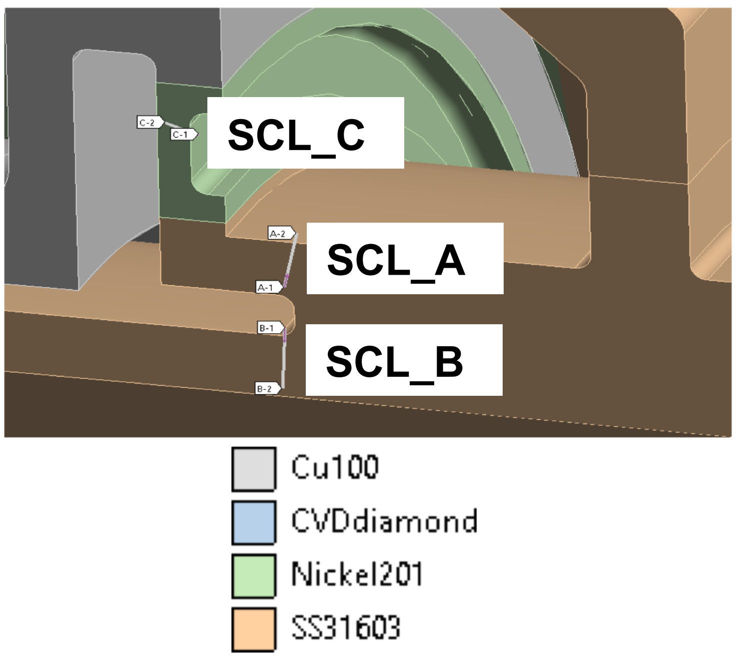


Re-run of thermal analysis →



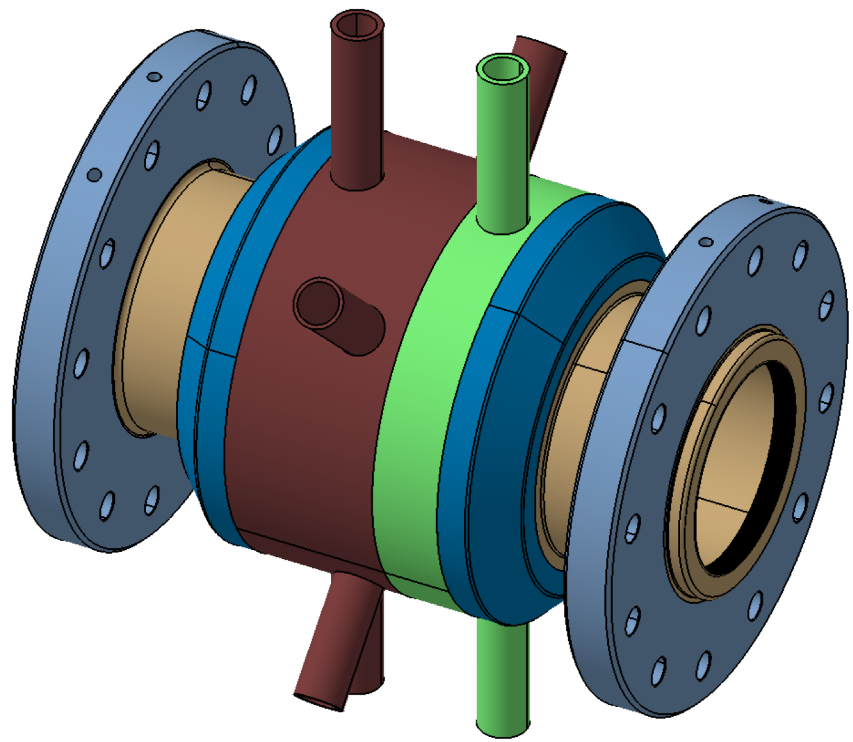
Design validation – FEM structural analyses





Check against ASME allowable limits

		Max (PL+Pb) [MPa]	Sm [MPa]	3*Sm [MPa]	PL+Pb ≤ 3*Sm
WG	SCL_A	149.88	115	345	Yes
WG	SCL_B	134.46	115	345	Yes
Spacer ring	SCL_C	80.22	46.2	138.6	Yes



Proposed new design

Window qualification program

- The window unit cannot be entirely covered by Codes & Standards.
- Functional, design, safety, operational, quality requirements (*Component Requirements Document*) and requirements related to the loading conditions (*Component Load Specification*) are being defined for the unit.

Window unit is qualified via

ASME code (III – NC, V, IX)

- Procedure and acceptance criteria for qualification of welded joints.
- Procedure and acceptance criteria for NDE of welded joints.
- Design criteria and allowable limits for the metallic parts.

Ad hoc program

- Dedicated testing program being developed in the context of F4E-OPE467.
- Design criterion based on the fracture mechanics method for the diamond disc.

Design criteria for metallic parts

Loading Category	Category I: Operational/Design Loading	Category II: Likely Loading	Category III: Unlikely Loading	Category IV: Extremely Unlikely Loading	Test Loading
Diamond window unit	Normal	Normal	Emergency	Faulted	Normal/test

Damage limits

Unit parts	Damage limits	Structural service criteria
Disc	Normal/Test	N/A
	Emergency	N/A
	Faulted	N/A
Cuffs	Normal/Test	ASME Level A
	Emergency	ASME Level A
	Faulted	ASME Level A
Cooling ring	Normal/Test	ASME Level A
	Emergency	ASME Level C

Correlation damage limits – ASME service levels

Structural service criteria	Stress intensity k factor
ASME Level A	1.0
ASME Level C	1.2
ASME Level D	2.0

ID	Design criteria
1	$P_m \leq kS_m$
2	$P_L \leq 1.5kS_m$
3	$P_L + P_b \leq 1.5kS_m$
4	$P_L + P_b + Q \leq 3S_m$
5	$P_L + P_b + Q + F \leq S_a$

- Mechanical load: criteria #1, #2 and #3.
- Mechanical + thermal load: criteria #1, #2, #3 and #4.
- Fatigue load: criterion #5.

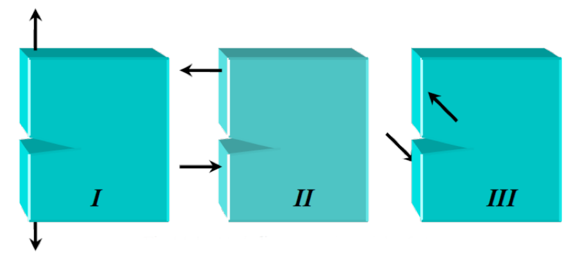
Design criterion for the diamond disc

Failure to fracture is the main failure mode to be considered for the diamond disc.

Stress intensity approach: $\mathbf{K_I \leq K_c}$

Stress intensity factor → K_I

Fracture toughness of diamond → K_c



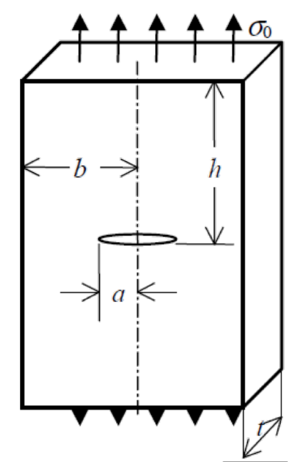
K_c = 5.3 ± 1.3 MPa $m^{1/2}$

(M.D. Drory et al., J. Am. Ceram. Soc., Vol. 74, No. 12, December 1991)

$$K_I = \beta \ \sigma_0 \sqrt{\pi \ a}$$

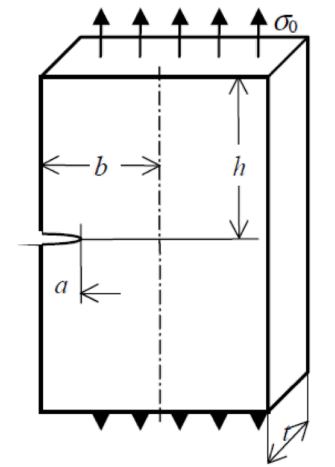
- β = factor depending on geometry element – crack
- σ_0 = reference stress in case of no crack
- a = length of the crack

(G. Petrucci "Lezioni di Costruzione di Macchine")



$$K_I = \sigma_0 \sqrt{\pi a}$$

(For a/b ≤ 0.4)



$$K_I = 1.12 \ \sigma_0 \sqrt{\pi a}$$

(For a/b ≤ 0.13)

Testing program for the window prototype

BARE DISC

- Geometrical check (d, D, surface roughness)
- Optical check (cracks, impurities)
- Mechanical check (bow)
- Tanδ check (disc area mapping and at center)

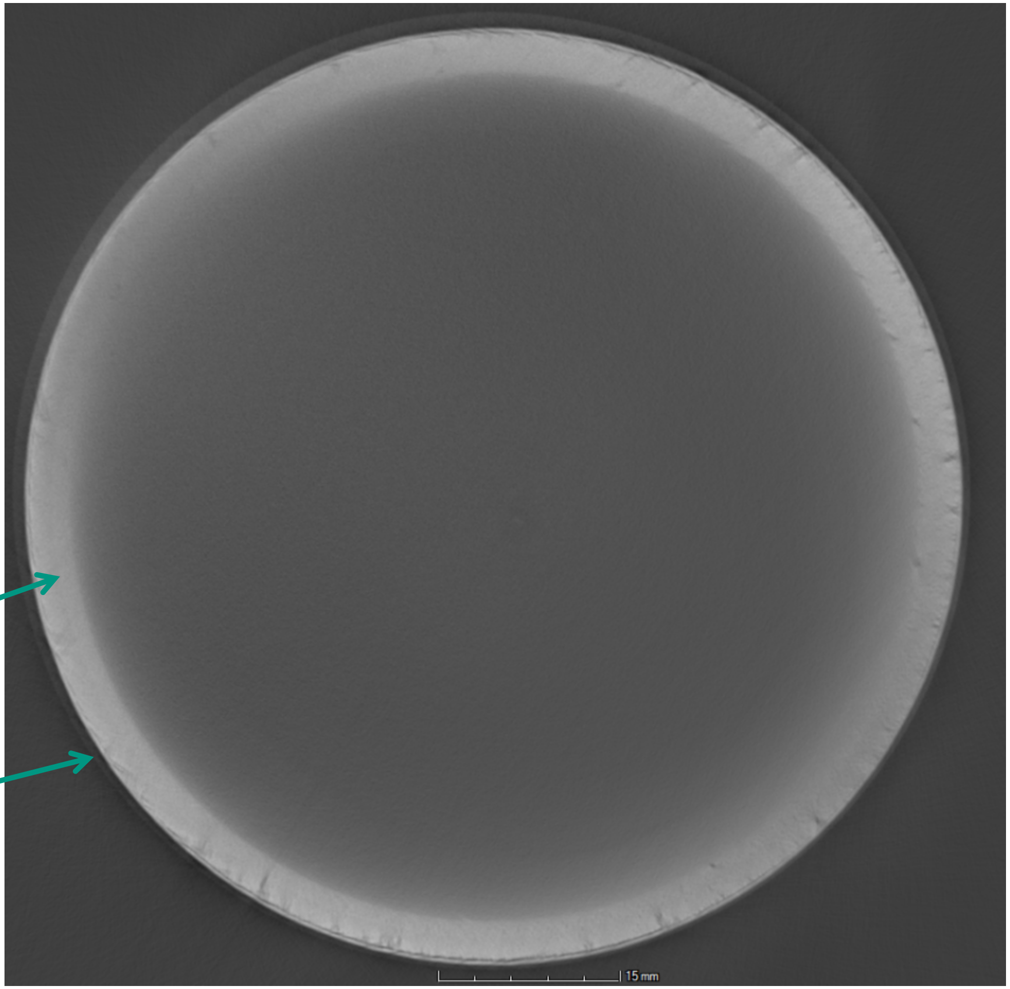
BRAZED DISC

- Geometrical check (e.g., cuffs centricity)
- Optical check
- Mechanical check (bow after brazing)
- Vacuum leakage check for braze
- Braze inspection (CT)
- Tanδ check at disc center

ASSEMBLY

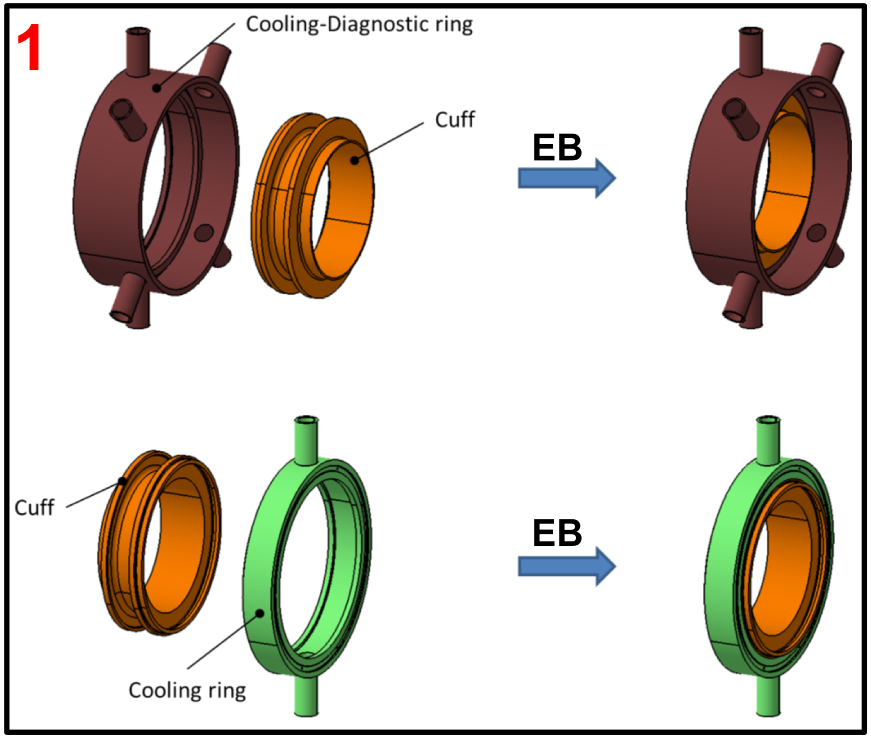
- Geometrical check
- Tanδ check at disc center
- High power MW test (short and long pulse)
- Vacuum leakage check for all joints
- Cooling pressure testing
- Permeation test by Deuterium
- Seismic test
- Overpressure test

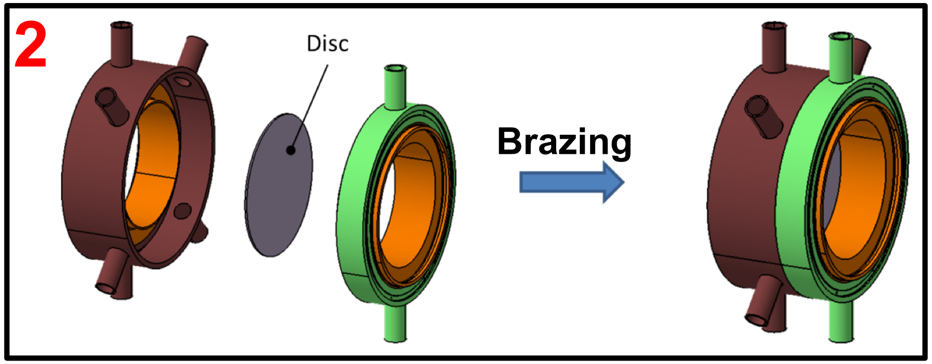
Brazed disc inspection at KIT by CT

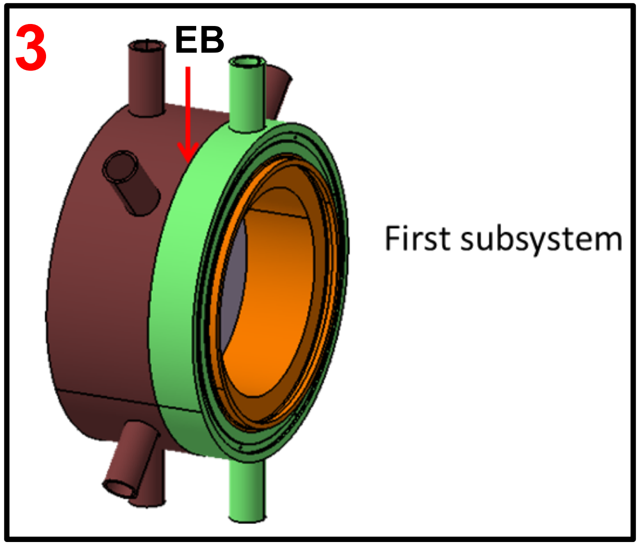


Top side of the diamond disc

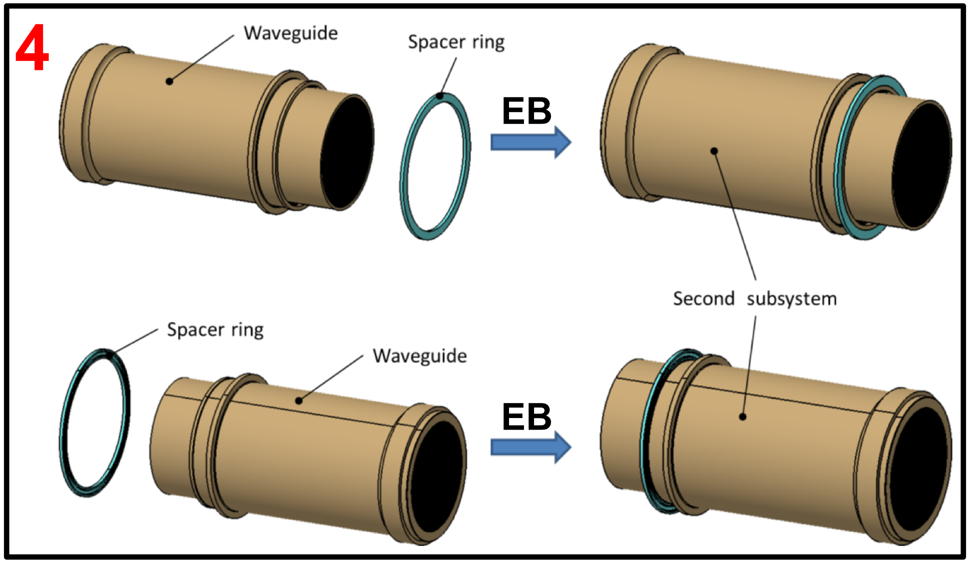
Assembling sequence of the unit

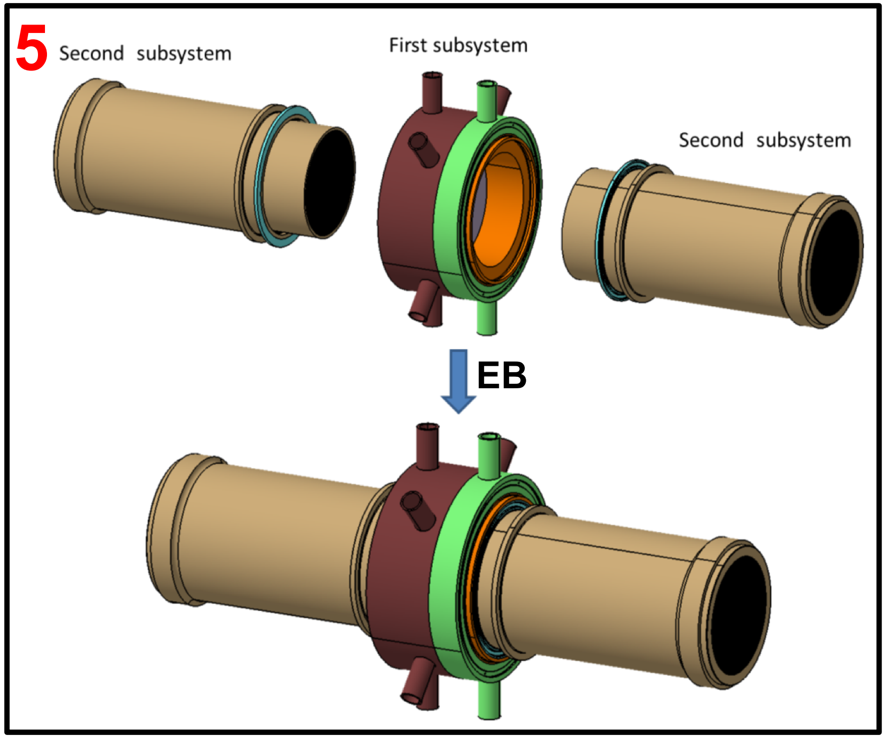




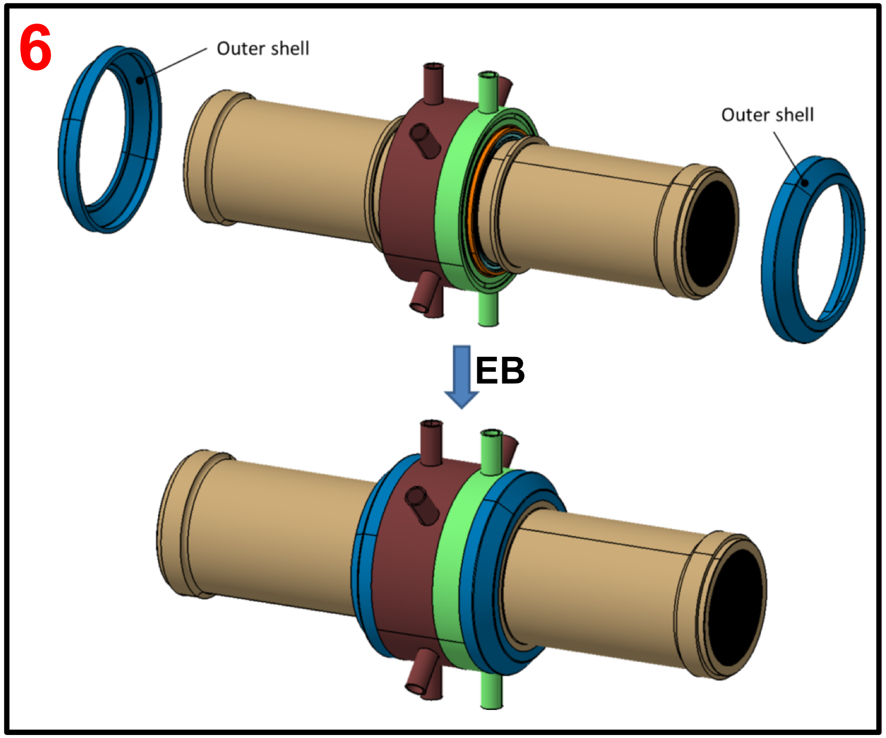


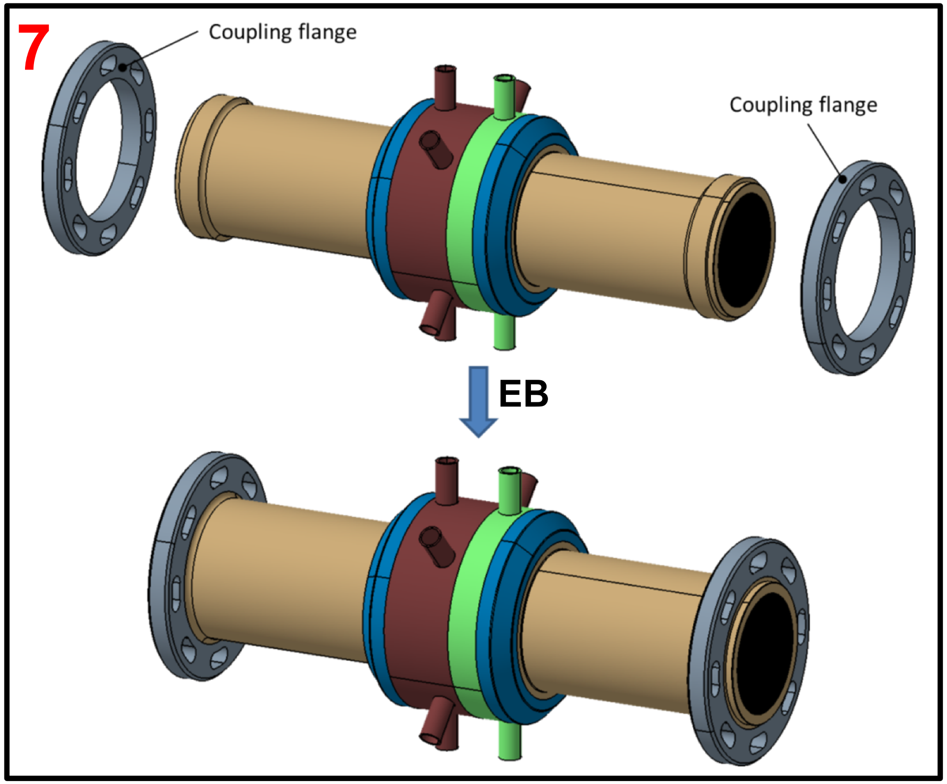
Assembling sequence of the unit





Assembling sequence of the unit





Conclusions and outlook

- The design of the window unit was developed and optimized by FEM analyses and in accordance with the ASME code.
- Dielectric measurements of the diamond disc provide input to the FEM analyses of the window unit.
- The window unit shall be qualified by the ASME code and a specific program (on going).
- Technical Specifications for the manufacturing of the window prototype are approaching the final phase in order to start the call for tender by F4E.

This work was/is partly supported by Fusion for Energy under the contract No. F4E-2010-GRT615 and F4E-2013-OPE467. The views and opinions expressed herein reflect only the author's views. Fusion for Energy is not liable for any use that may be made of the information contained therein.