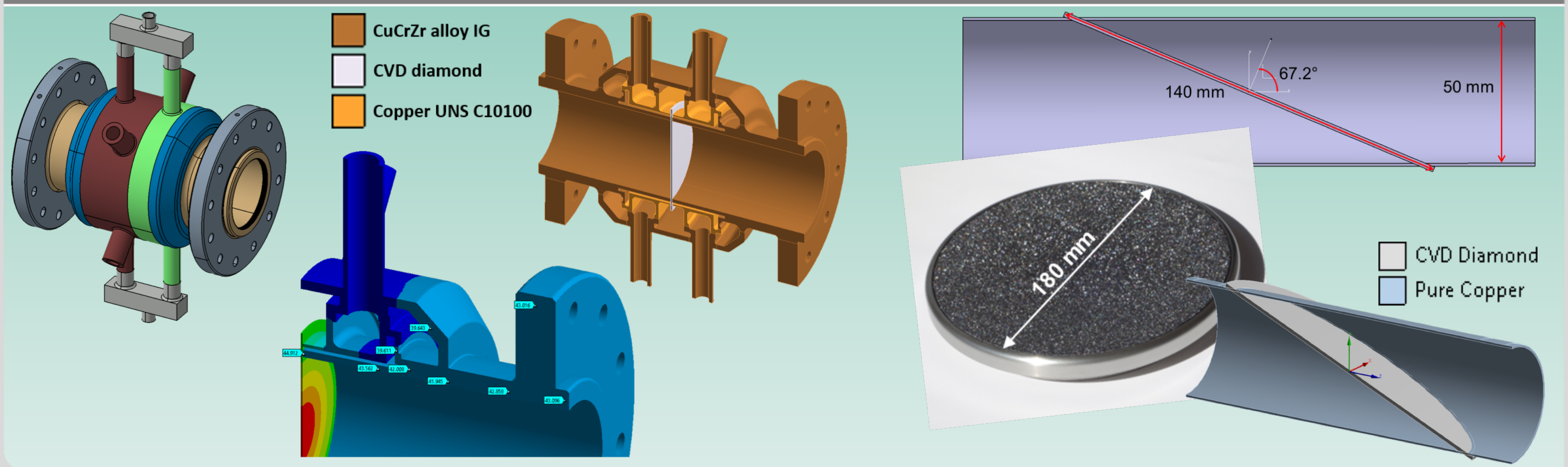
Diamond window technology for EC heating and current drive – state of the art

G. Aiello, T. Scherer, K. Avramidis, N. Casal, T. Franke, M. Gagliardi, G. Ganbeinbein, M. Henderson, J. Jelonnek, A. Meier, G. Saibene, S. Schreck, D. Strauss, M. Thumm, M.Q. Tran, C. Wild, E. Woerner

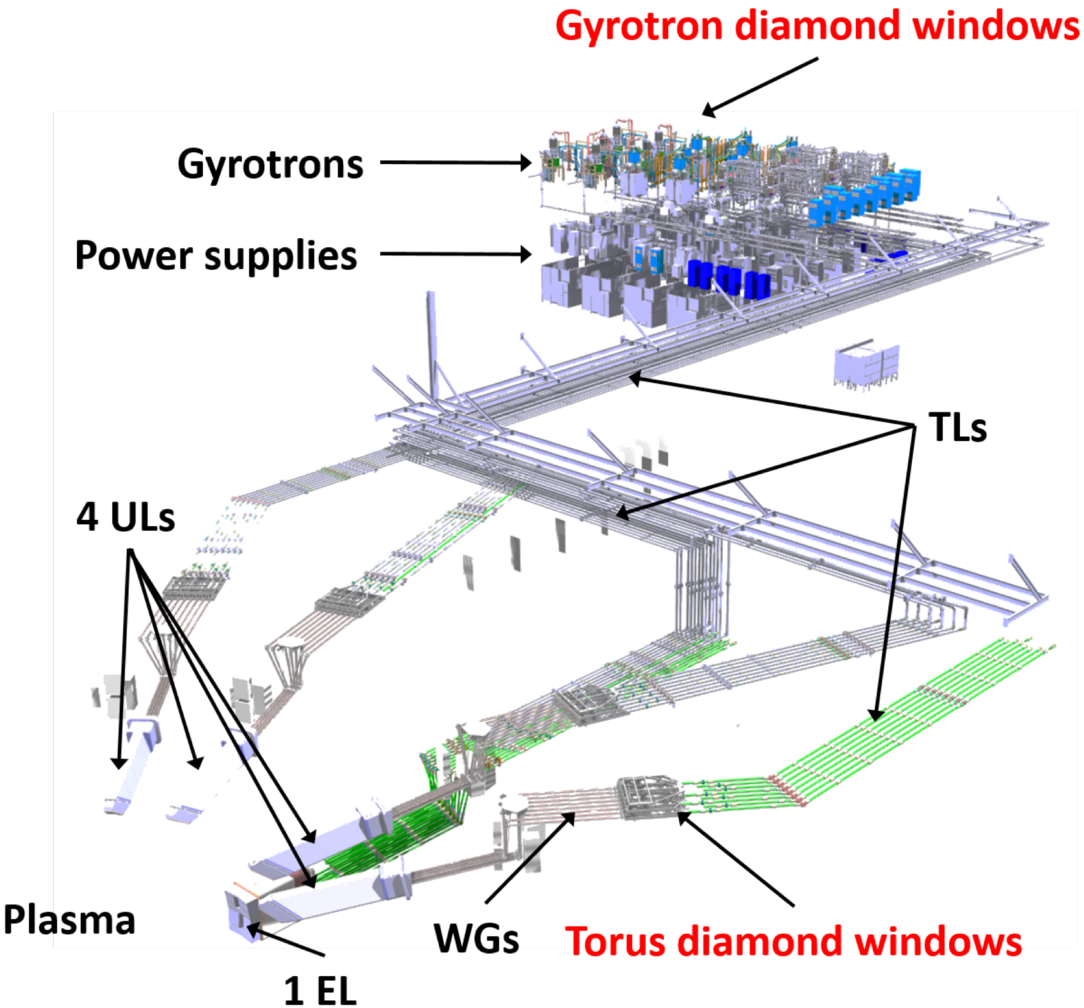
Institute for Applied Materials – Applied Material Physics (IAM-AWP)



Outline

- EC H&CD system
- Diamond window concepts
- Why diamond?
- The ITER torus diamond window
  - Design
  - Optimization by FEM analyses and codes
  - Loss tangent measurements
  - Qualification program
- The Brewster-angle diamond window (DEMO)
  - Challenges
  - Large-size diamond disks
  - Indirect cooling layouts
- Conclusions and outlook

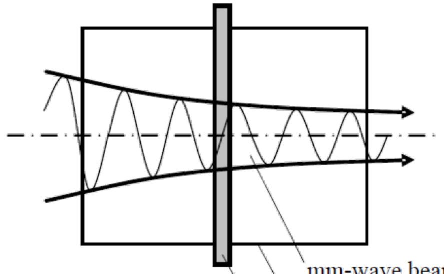
The context: EC system (ITER)



- Microwave beams of 1-1.5 MW
- Localized plasma heating
- Control of plasma MHD instabilities
- Gyrotron diamond windows: vacuum boundaries
- Torus diamond windows: vacuum and confinement boundaries (in particular tritium)

Two different ways for EC power deposition

- Sweeping of a fixed frequency beam by moveable mirrors across the plasma cross section (ITER EC UL)



$$d = n \cdot \frac{\lambda_m}{2}$$

$$\lambda_m = \lambda_0 / \epsilon_r^{1/2}$$

170 GHz, ε_r=5.67

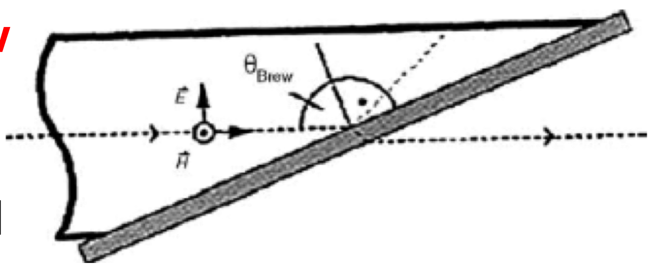
Torus window → n=3, d=1.11 mm

Gyrotron window → n=5, d=1.85 mm

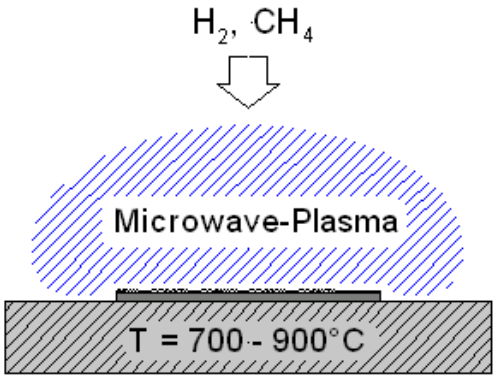
- Deploying a beam at different frequencies in the plasma (DEMO)
  - Broadband window solutions for multi-frequency gyrotrons: single disk matching different wavelengths (e.g., 136/170/204/238 GHz for 1.85 mm)
  - Broadband window solutions for step-tunable gyrotrons: e.g., the **diamond disk Brewster-angle window** (ideally, no reflection for all frequencies)

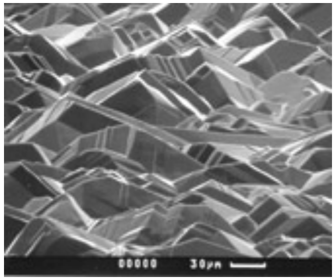
$$\theta_B = \tan^{-1}\sqrt{\epsilon_r}$$

θ_B=67.2° for diamond



CVD diamond: why?





- Diamond growth by Microwave Plasma Assisted (MPA) CVD
- Growth rate of 0.1 to 10 µm/h
- Grinding / Polishing to the required thickness

Material	BeO p.c.	Silicon Au-doped s.c.	SiC (6H) p.c.	Diamond p.c.
Thermal cond. *k* [W/mK]	260	150	330	**2000**
Failure resistance *R'*	10.3	284	40	**772**
RF power transmission capacity P_T	0.06	106	0.63	**106**

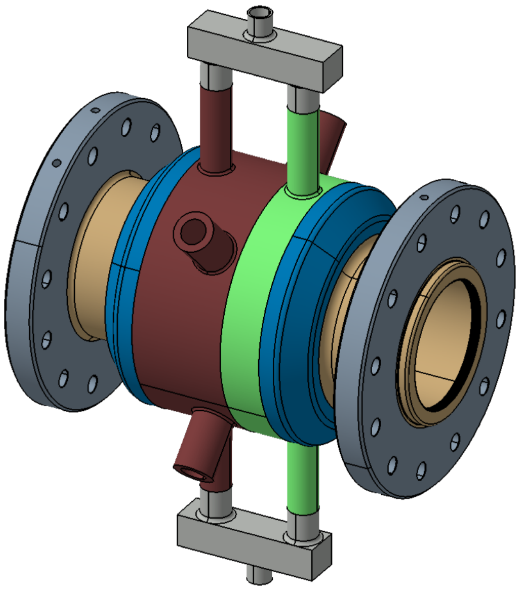
$R' = k \cdot \sigma_B \cdot (1-\nu)/(E \cdot \alpha)$

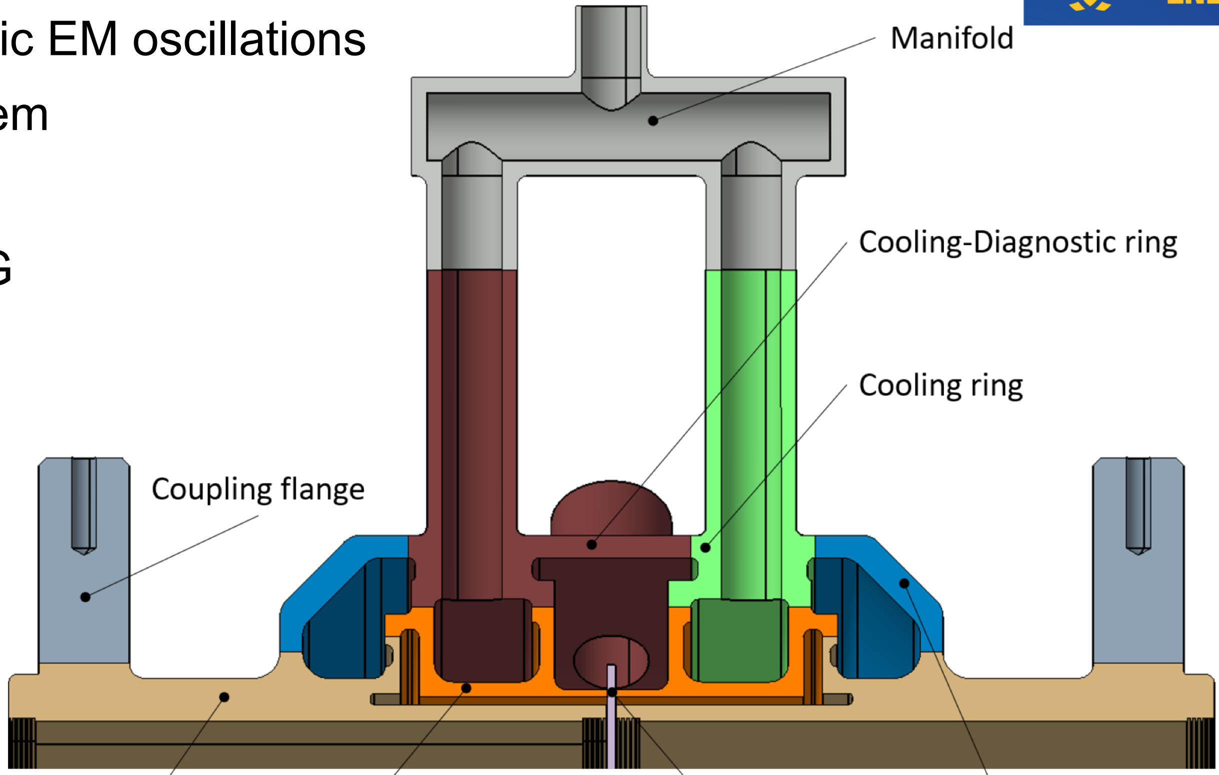
$P_T = R' \cdot \rho \cdot c_p/((1+\varepsilon_r) \cdot \tan\delta)$

M. Thumm, State-of-the-Art of High Power Gyro-Devices and Free Electron Masers, 2017

The EC ITER torus diamond window

- Inserted WGs to prevent the generation of parasitic EM oscillations
- Indirect cooling system
- Rigid outer frame
- 100 µm gap disk-WG
- Corrugated WGs

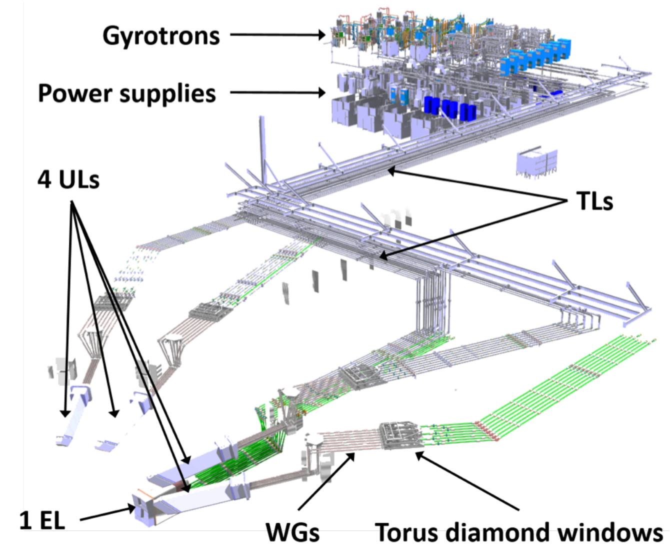


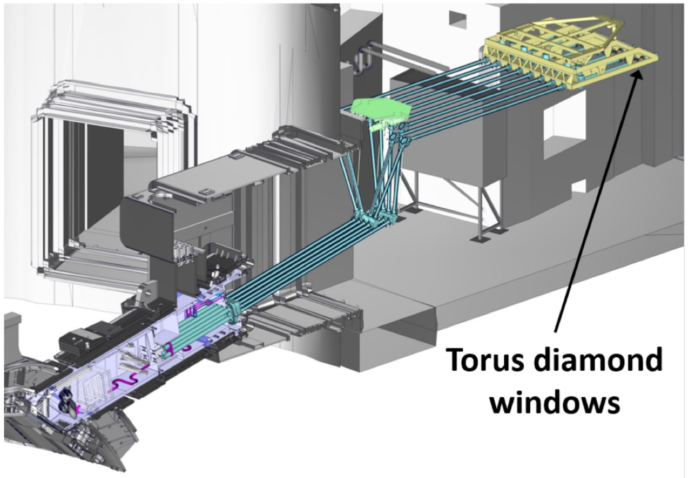


- Length: ~ 160 mm
- Outer diameter (incl. pipes): 170 mm
- Inner diameter WGs: 50 mm

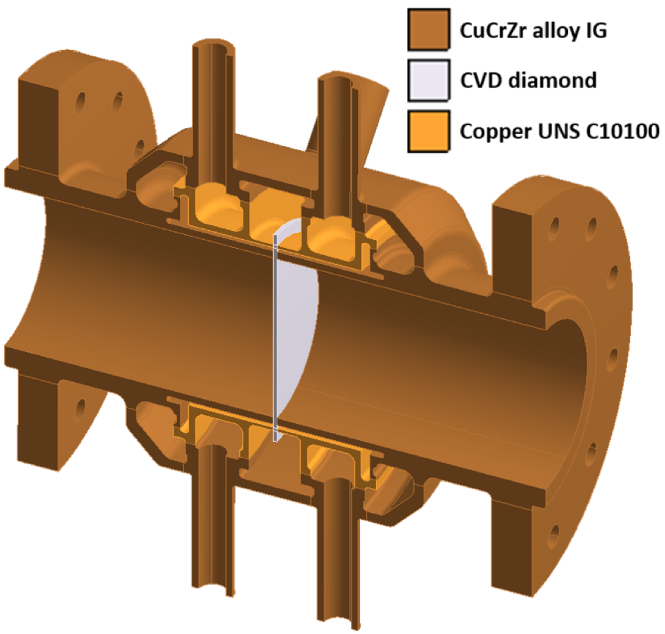
ITER torus window: status

- Mature design ready to start prototyping and testing activity
- Manufacturing of 3 prototypes
- **Final Design Review (FDR) of the window assembly in 2019-2020**
- Design developed for the UL 32 windows (F4E responsibility)
- Same design adopted for the EL 24 windows (JAEA responsibility)
- **Successful FDR of the diamond disk in December 2017** (long procurement time for the 56 disks)

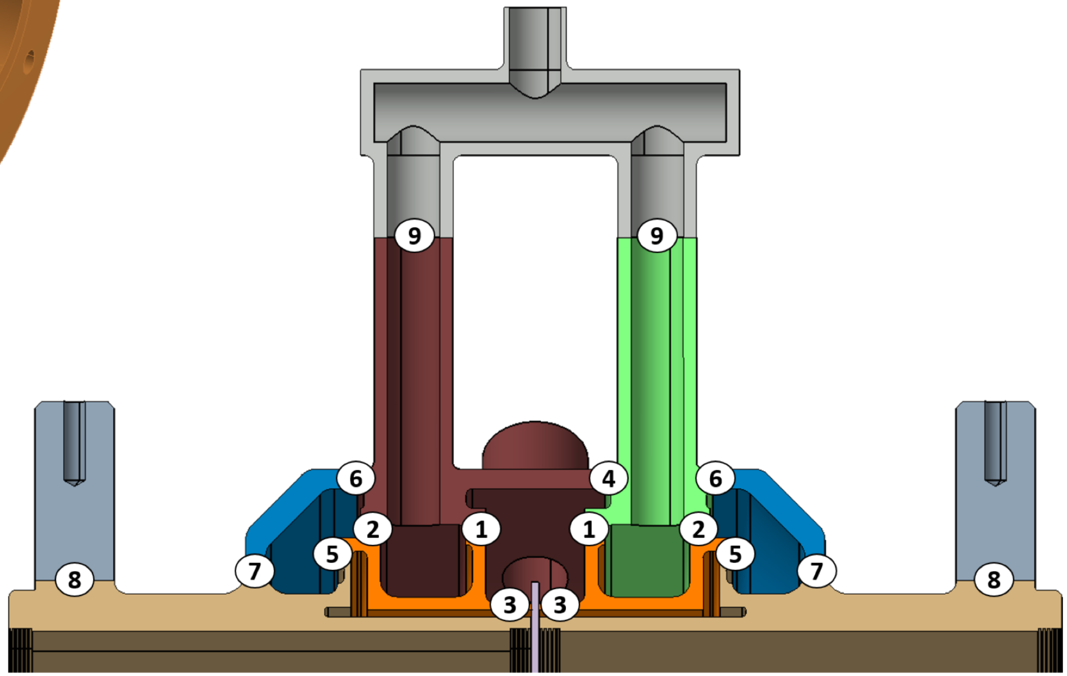




ITER torus window: materials and joints



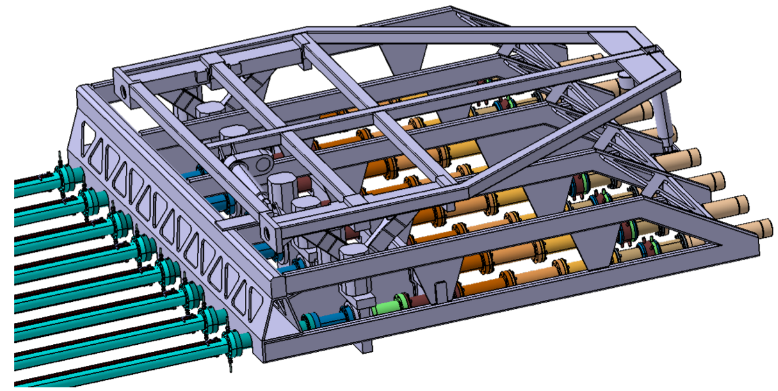
- Optimization work by FEM analyses and codes
- ASME III-NC code for design, manufacturing, assembling and qualification
- Unique component as brittle material is arranged in a metallic housing with a non-standard technique
- Ad-hoc qualification program (supporting analyses)

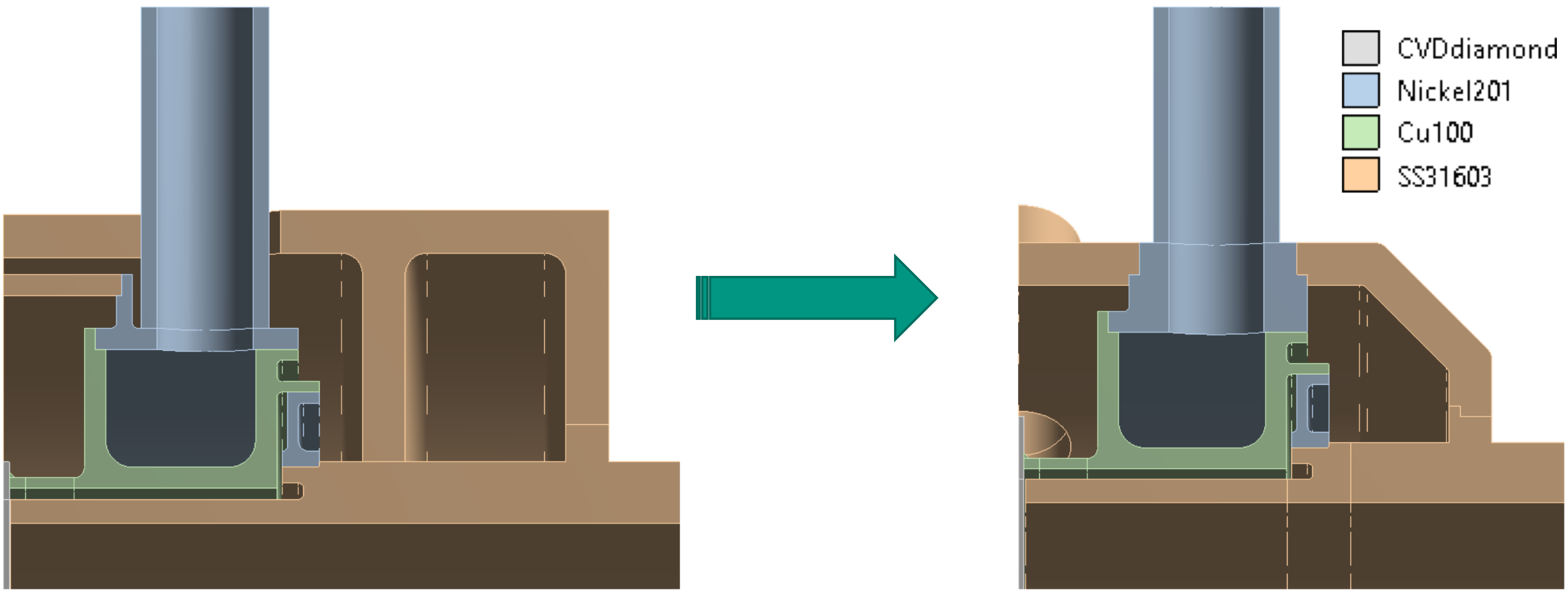


- EB welding
- Brazing for joints #3
- Orbital TIG welding for joints #9

ITER torus window: optimization by FEM analyses

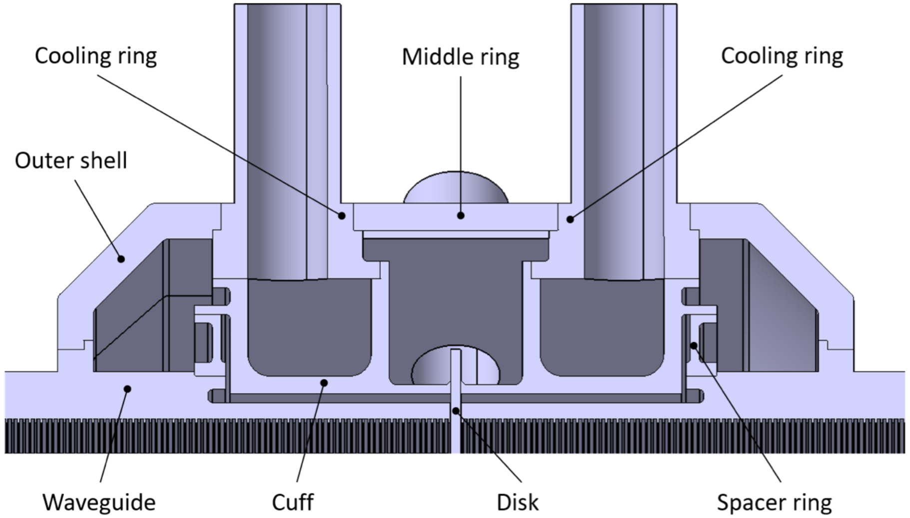
- Design driver: SL-2 + VV baking
- Lower seismic loads
- Design more compact and feasible to manufacture
- Additional confinement barrier and real-time monitoring of interspaces

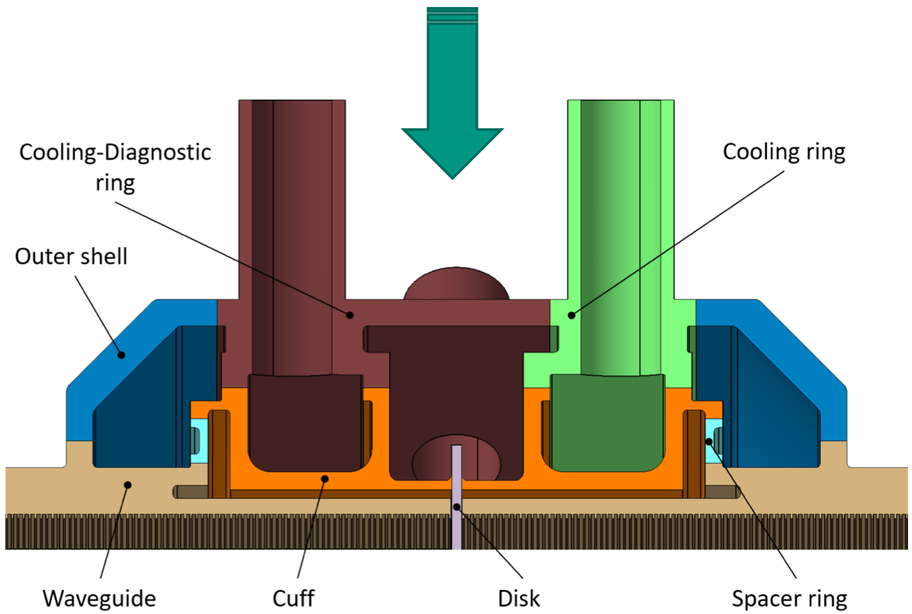




ITER torus window: optimization by ASME III-NC

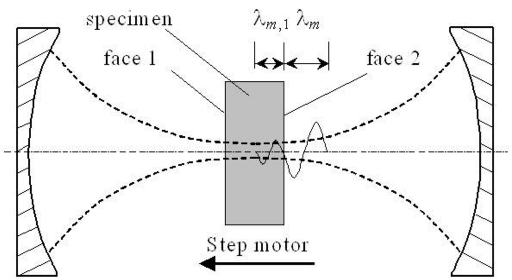
- Complete joint penetration
- Full fusion in the joints
- Joints fully radiographed
- Minimum number of joints (especially after the brazing)
- More margin for the extent of the heat affected zone (HAZ)



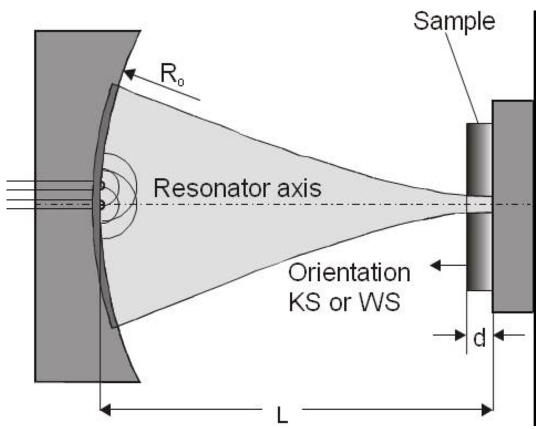


G. Aiello et al., Design evolution of the diamond window unit for the ITER EC H&CD upper launcher, submitted to the Fusion Eng. Des., 2018

Loss tangent measurements in the diamond disk

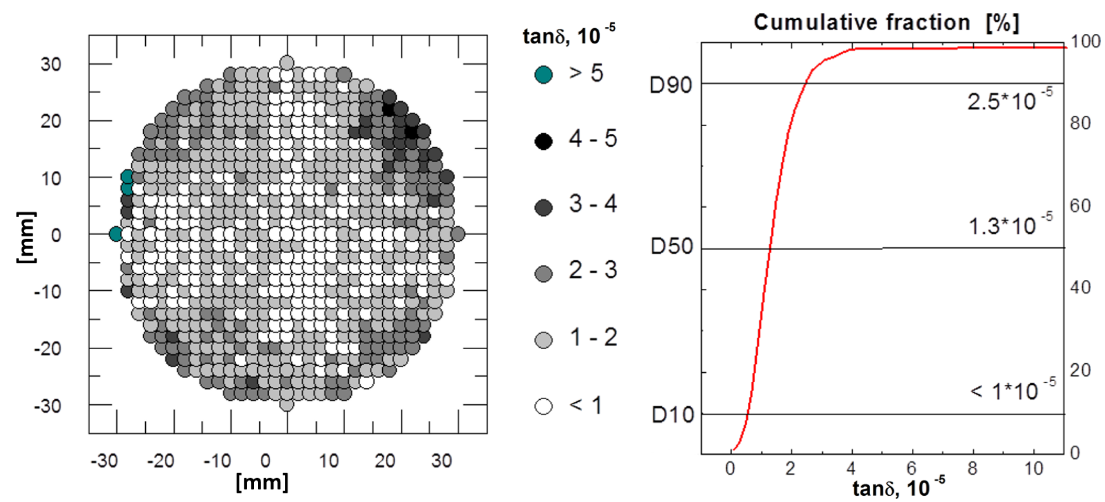


Spherical resonator



Hemispherical resonator

- Mandatory test for disk acceptance in the qualification program of the window
- Acceptance criterion for D50: $3.5 \cdot 10^{-5}$
- Acceptance criterion for D90: $6.0 \cdot 10^{-5}$
- Input to calculate the EC power absorbed in the disk



Tanδ at 170 GHz in the bare disk: accepted for integration in the window prototype!

FEM thermo-structural analyses: setup

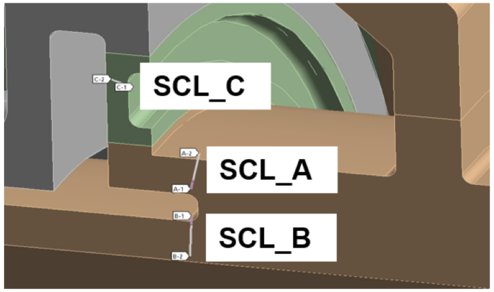
$$P_{abs} = P_{beam} \cdot \frac{f}{c} \cdot \pi \cdot (1+\varepsilon_r) \cdot \tan\delta \cdot t$$

- P_{beam}=1.31 MW
- f=170 GHz
- ε_r=5.67
- tanδ=$2 \cdot 10^{-5}$
- t =1.11 mm

P_{abs}=346 W

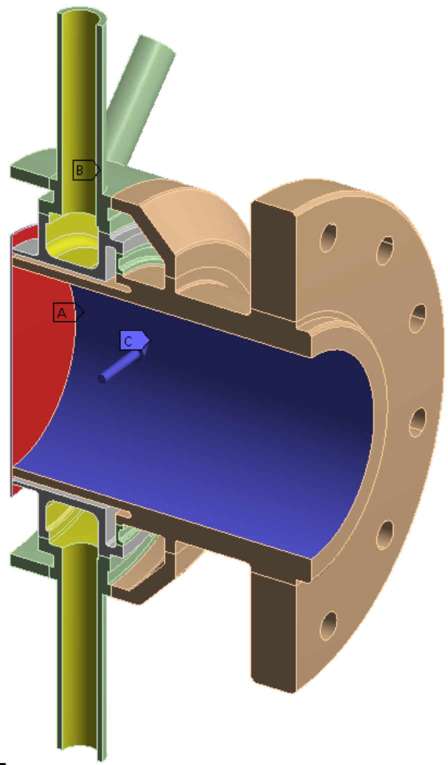
HE_{11} mode

$$q'''(r) = A \cdot \left[J_0(x)\right]^2 \qquad x = 2.405 \cdot \frac{r}{a}$$



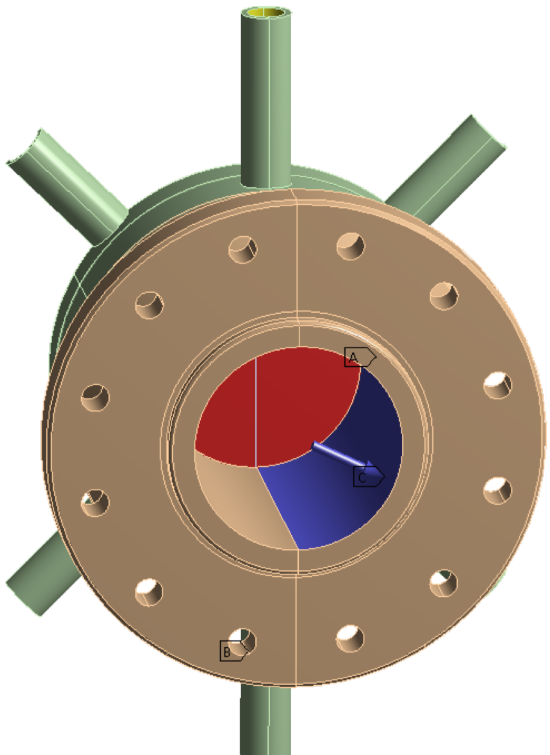
$3S_m$ rule

Normal operation



A LoadedBody
B Convection: 31. °C, 3167.5 W/m²·°C
C Heat Flux: 4070.7 W/m²

Hot spot case

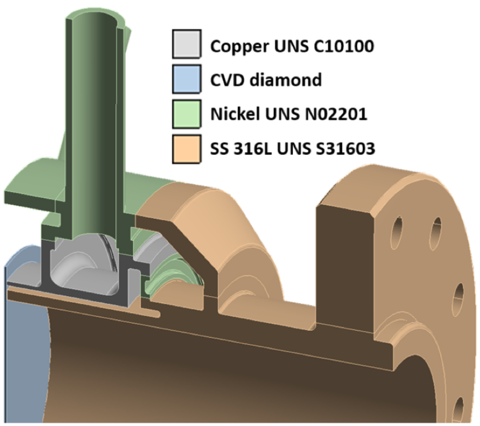


A LoadedBody
B Convection: 31. °C, 3167.5 W/m²·°C
C Heat Flux: 10421 W/m²

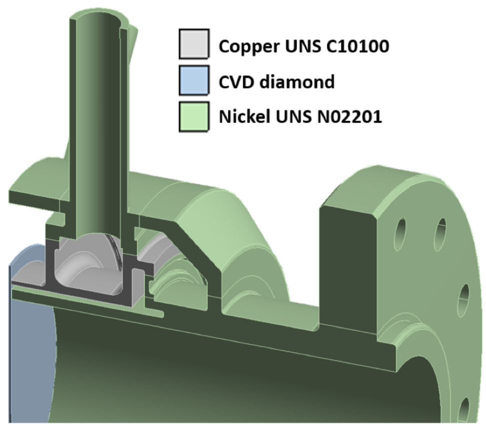
FEM thermo-structural analyses: assessment

ITER project decision: reduce the inner diameter of the TLs from 63.5 to 50 mm

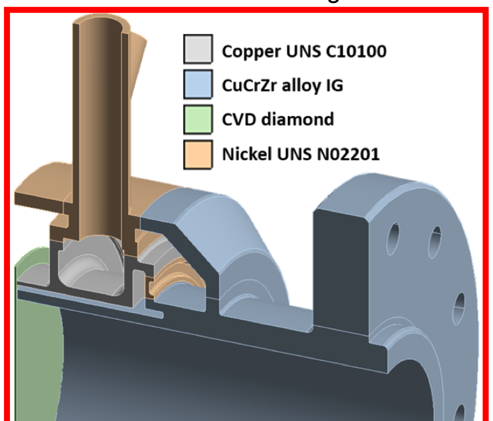
→ For Cu-coated WGs, power density in the WGs increased by 2.6 times!



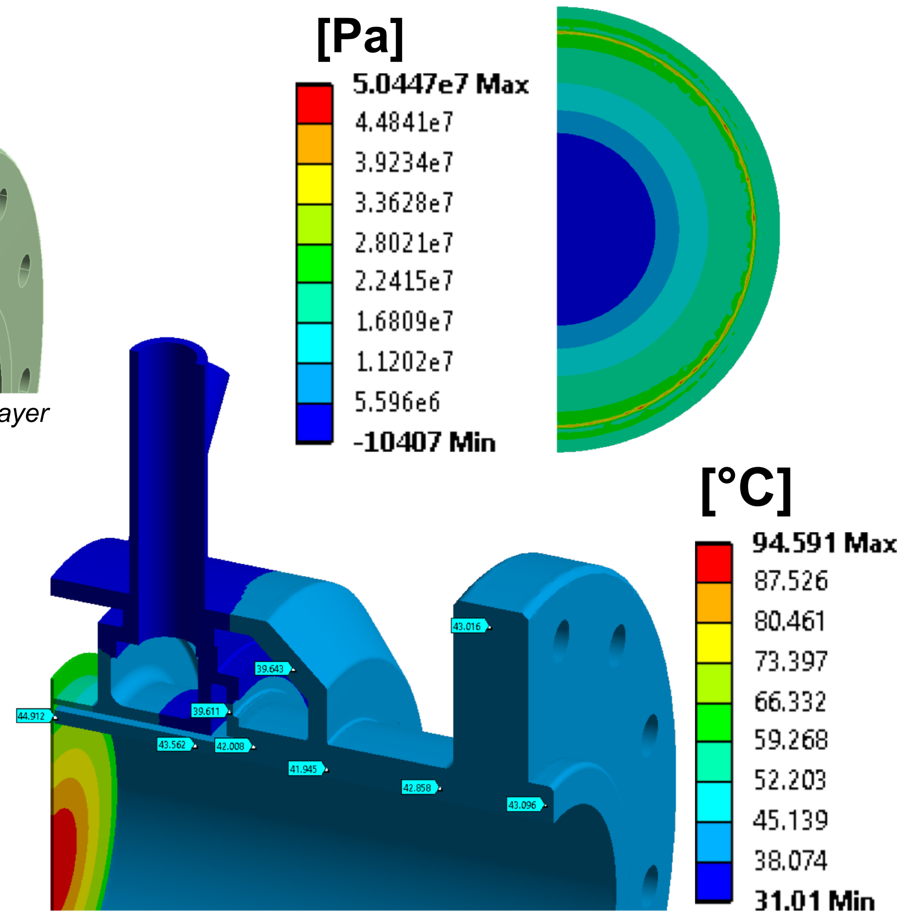
Configuration #1: steel WGs + Cu layer



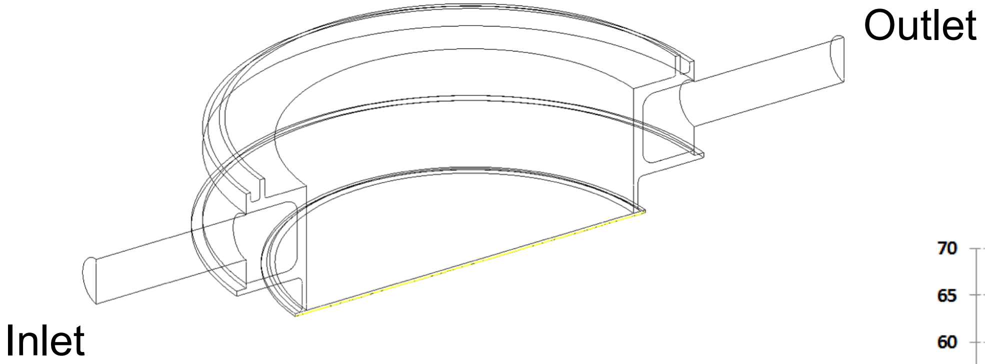
Configuration #2a: nickel WGs + Cu layer
Configuration #2b: nickel WGs

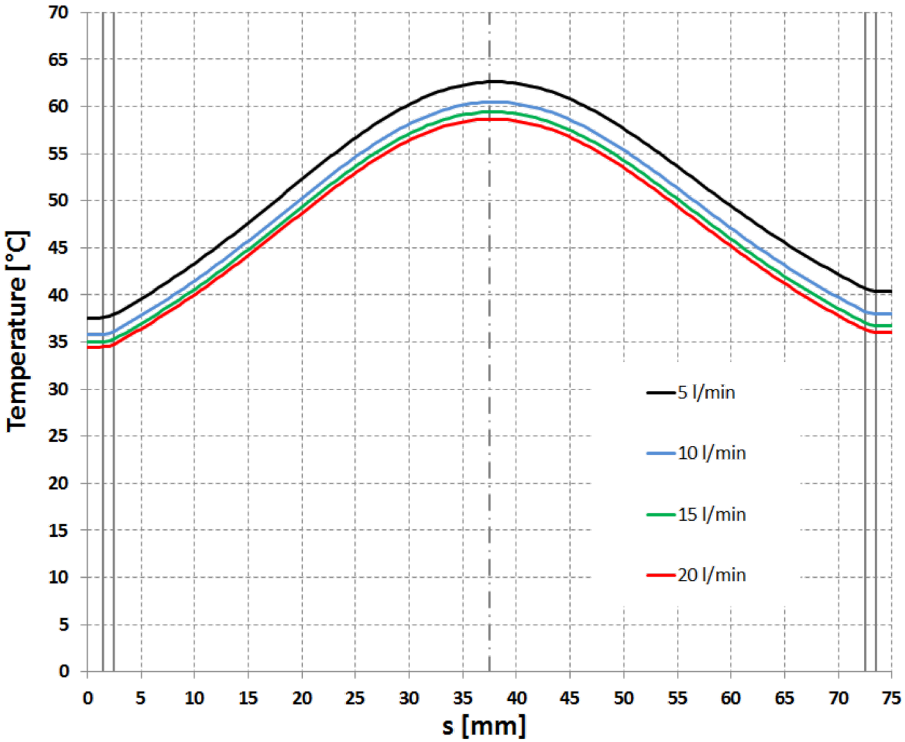


Configuration #3: CuCrZr alloy IG



Sensitivity analysis for disk cooling





- 1.11 mm disk thickness
- Very stable thermal performance with regards to variations of the inlet mass flow rate
- Temperature increased by only 4°C

Window qualification program

- The window unit cannot be entirely covered by Codes & Standards
- Functional, design, safety, operational, quality requirements and requirements related to the loading conditions are being defined for the window
- The EC 56 windows shall be qualified by → **ASME code** / **Specific qualification program**
- The prototyping and testing activity shall be the base to define the specific qualification program (e.g., the definition of the acceptance criteria)

Testing program for the window prototype

BARE DISK

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

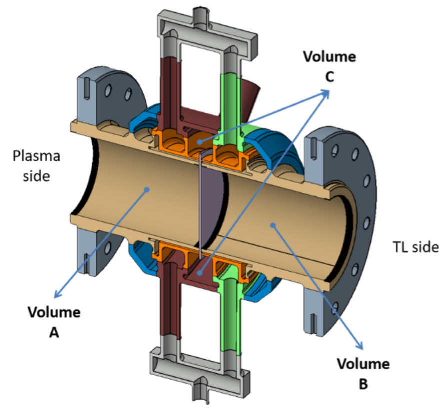
BRAZED DISK

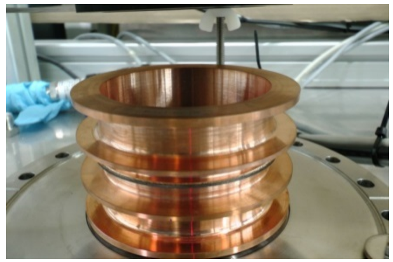
- Geometrical check (e.g., cuffs centricity)
- Optical check
- Mechanical check (bow after brazing)
- Vacuum leakage check for braze
- Tanδ check at disk center

ASSEMBLY

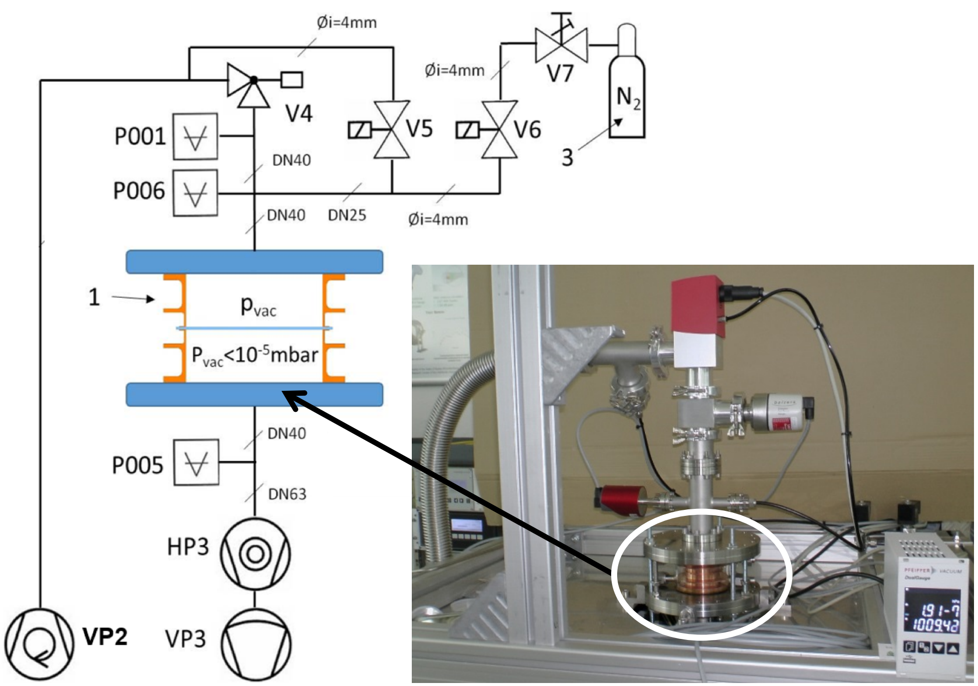
- Geometrical check
- Tanδ check at disk center
- High power MW test (short and long pulse)
- Vacuum leakage checks for all joints
- Cooling pressure testing
- Permeation test by Deuterium
- Seismic test
- Overpressure test

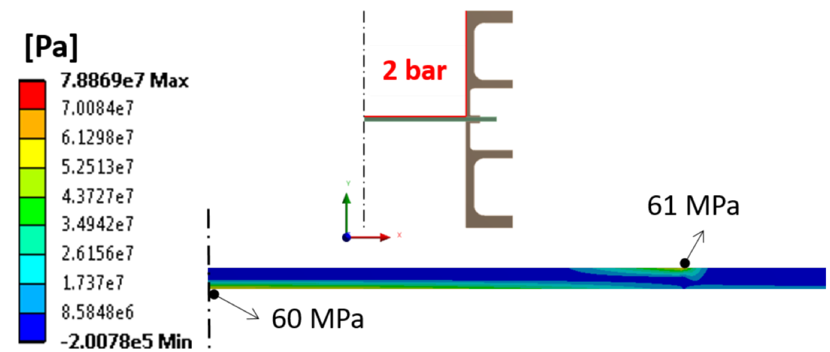
Pressure tests mock-up: cyclic and 2 bar test





ID test	ΔP_{win} [bar]	Number of cycles from Table 2	Number of cycles to be applied in the tests	Allowable leak rates provided by Table 2	Orientation of the disc mock-up in the setup
A	+0.12	675	1700 (x2.5)	≤ $1 \cdot 10^{-9}$mbar•l/s	GS to variable pressure
B	-0.10	48	120 (x2.5)	≤ $1 \cdot 10^{-9}$mbar•l/s	NS to variable pressure
C	+1.0	1	21	≤ $1 \cdot 10^{-9}$mbar•l/s	GS to var. pres.
D	-1.0	2	23	≤ $1 \cdot 10^{-9}$mbar•l/s	NS to var. pres.
E	+2.0	1	1	≤ $1 \cdot 10^{-2}$mbar•l/s (at 2 bar pressure gradient)	GS to var. pres.

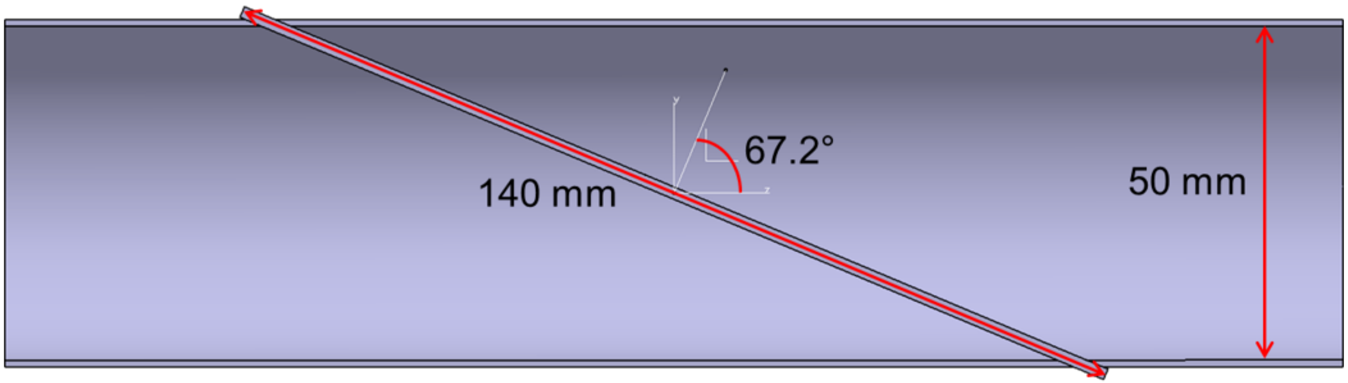


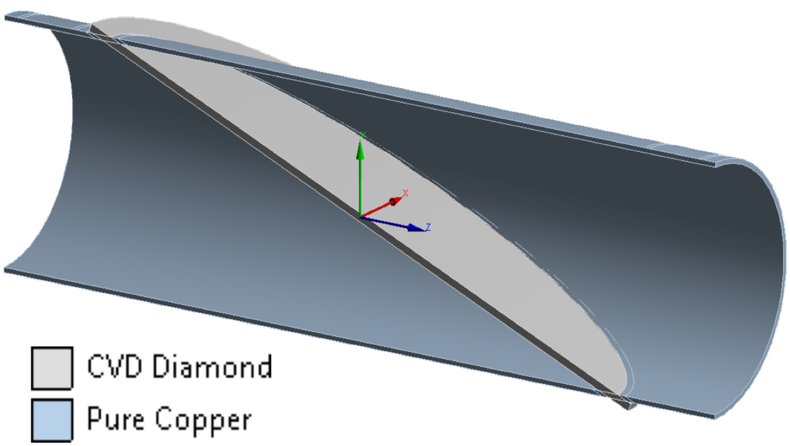


Successful 2 bar overpressure test:

validation of the 1.11 mm disk (FDR)

The Brewster-angle diamond window (DEMO)





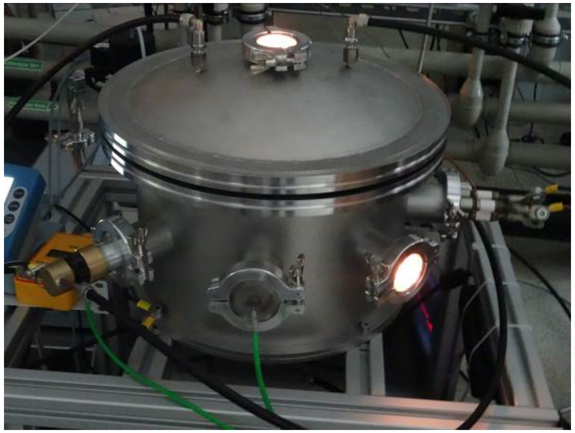
Target: window suited for long pulse gyrotron operation at 2 MW power

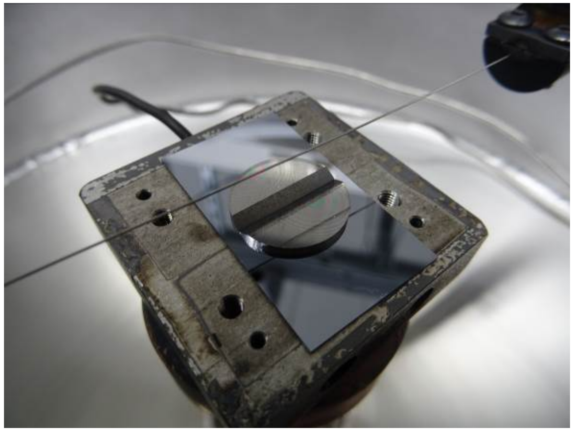
Challenges:

- Produce very large-size (**Ø 180 mm, 2 mm**) disks suited for 63.5 mm WG, compatible with 2 MW transmission
- Join the disk to the waveguides (skewed position of the disk)
- Design an effective cooling layout

Diamond joining by hot filament (W) method

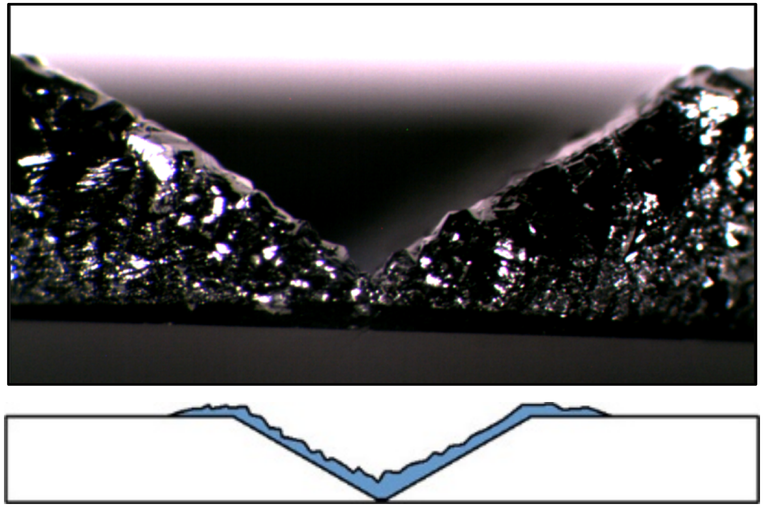
Join diamond fragments in a small scale by overgrowing the joint gap with diamond to obtain large diamond disks





Optical grade CVD diamond disk

Diameter: **18 mm**
Thickness: **1000 µm**
Surfaces: Polished, Ra < 10 nm
Joint edges with 60° angle



Result after 150 h of diamond deposition: the two plates grew together and formed a solid compound!

…however this is not the path towards large diamond disks…

180 mm disk growth in the plasma reactor

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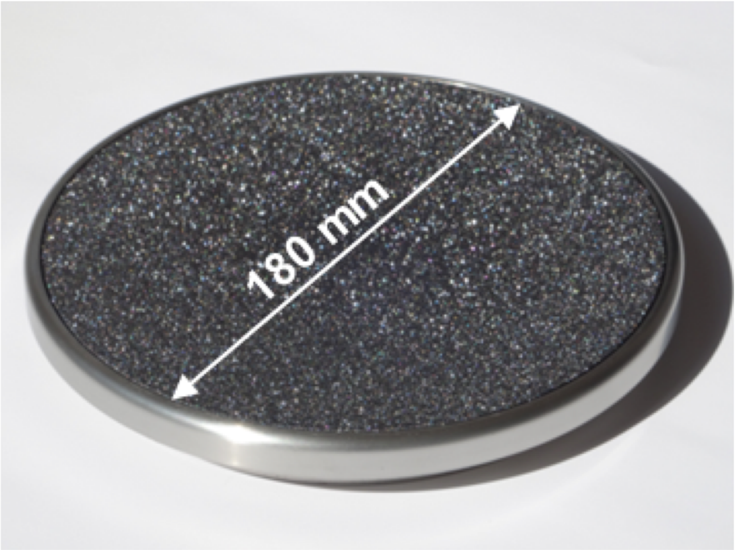
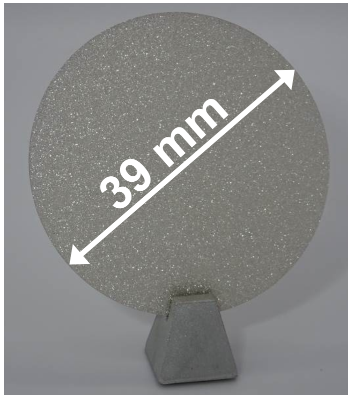
Diamond Materials
Advanced Diamond Technology



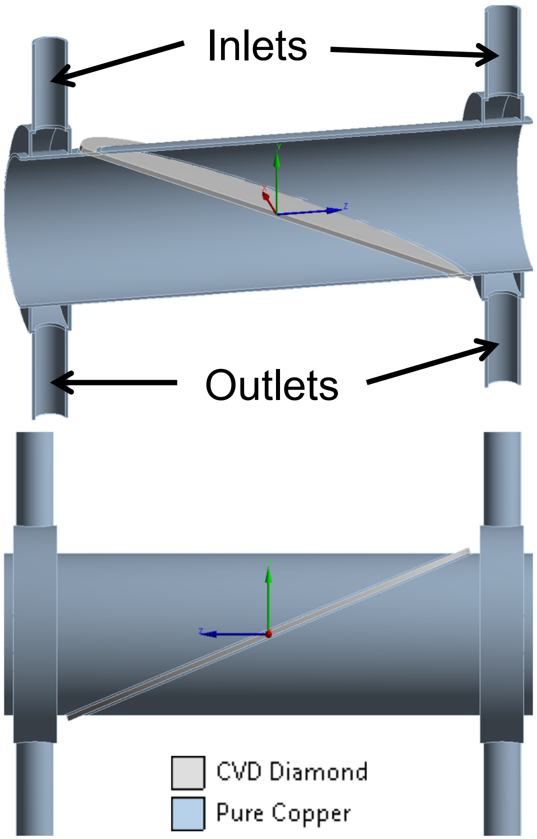


tanδ < 1·10^{-4}

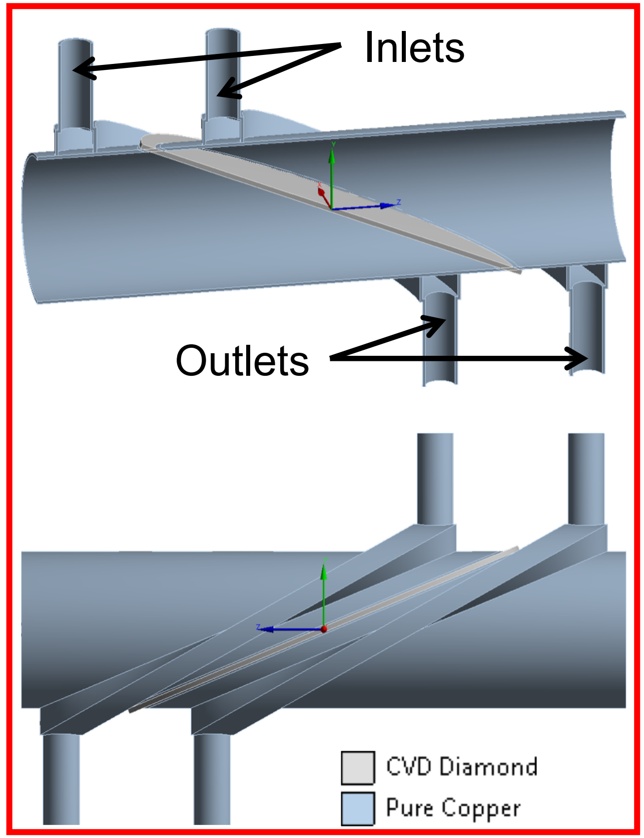
- Growth test experiments for parameter optimization
- Two runs of 400 and 350 h produced the very first 180 mm diamond disk at a thickness of 300 to 450 µm
- After dissolving the silicon substrate, both disks broke and loss tangent was measured in a 39 mm disk fragment
- Depositions runs aiming to a **180 mm, 2 mm disks** are ongoing
- **New field for diamond manufacturers**

Indirect cooling layouts

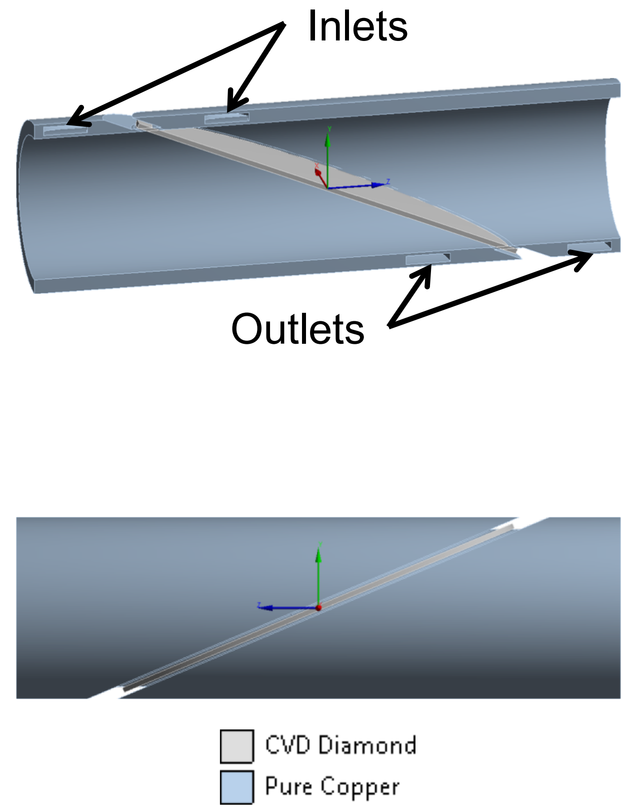
Cylindrical channels



Outer elliptical channels



Inner elliptical channels



G. Aiello et al., Cooling concepts for the CVD diamond Brewster-angle window, 42nd IRMMW-THz Conference, IEEE 2017

Conclusions

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- The development and the current status of the diamond window concepts for the EC H&CD applications both in ITER and DEMO were discussed
- The ITER torus window has a sufficient mature design to start the prototyping and testing activity in view of the FDR in 2019-2020
- Many efforts are addressed to the development of a Brewster-angle diamond window for long pulse step-tunable gyrotron operation at 2 MW

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