Brewster-angle diamond window for microwave application

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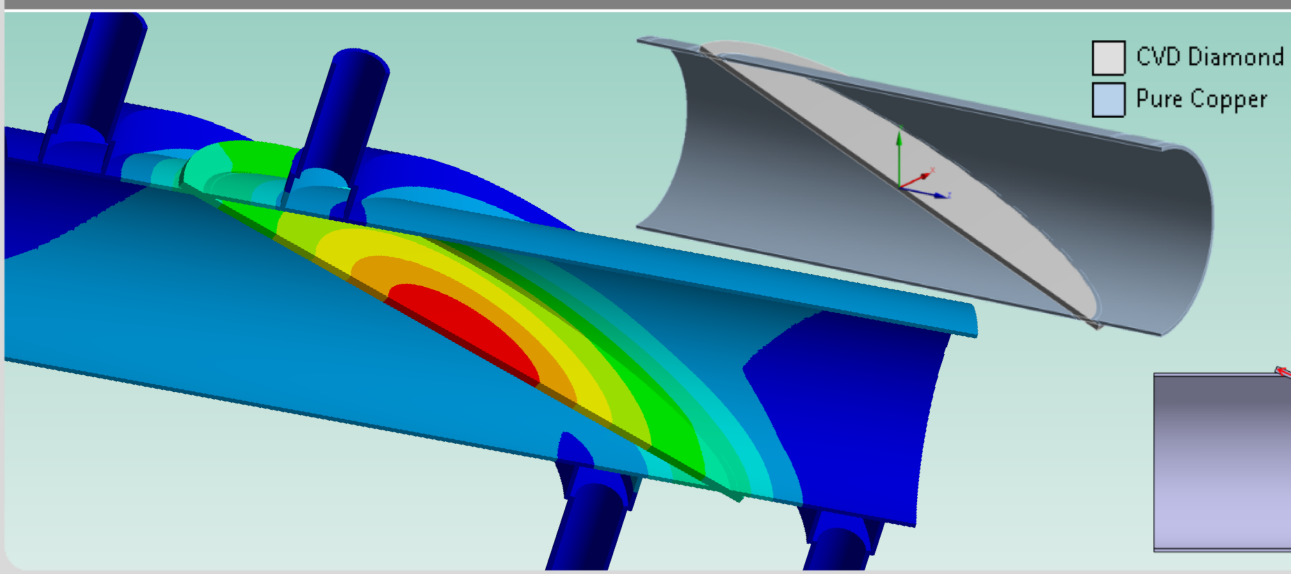
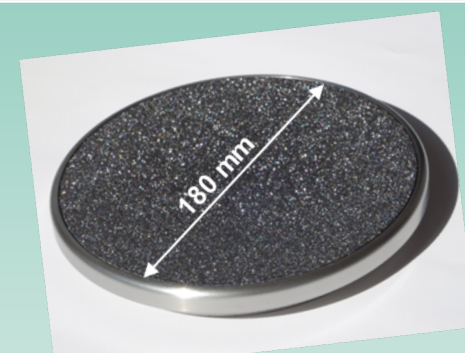
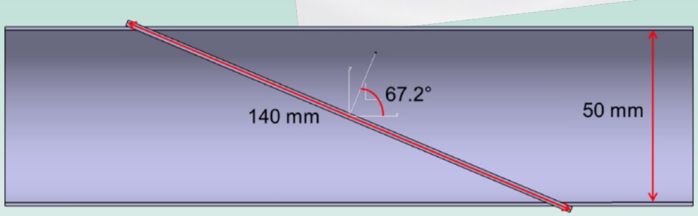


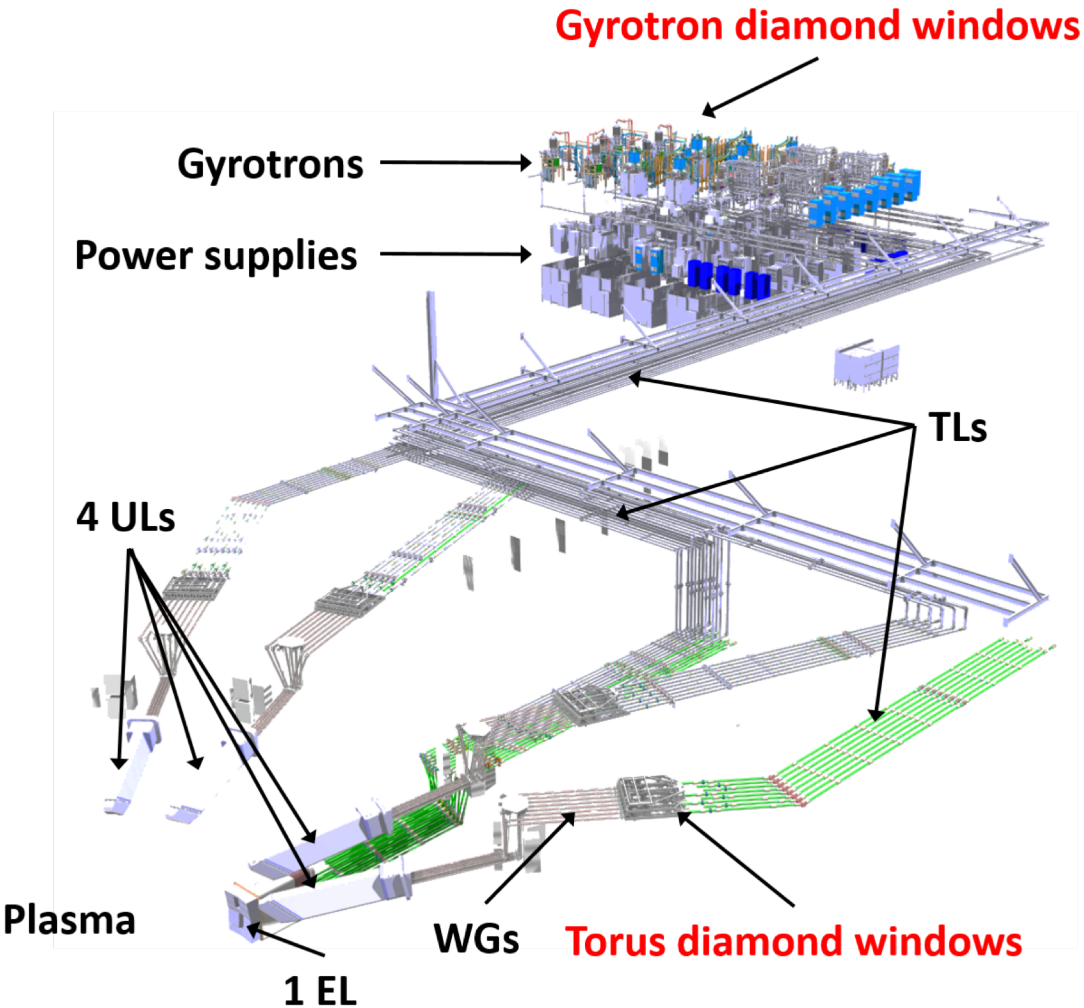




Outline

- EC HCD system
- Towards EU DEMO1
- Diamond window concepts
- The Brewster-angle diamond window and challenges
- Development of large-size diamond disks
  - Diamond joining by hot filament method
  - Growth experiments of 180 mm disks in microwave plasma reactors
- Indirect cooling layouts and analysis
- Conclusions and outlook

EC HCD system (example from 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)

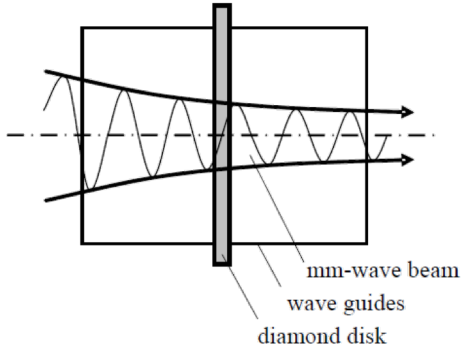
Towards DEMO gyrotrons

	ITER	EU DEMO1
Center frequency	170 GHz	170/204 GHz
RF output power	1 MW	2 MW
Overall efficiency	50 %	≥ 60 %
Pulse length	> 2 h	1 h
Tunability range (in case of frequency-steering)	-	± 10 GHz in steps of 2-3 GHz
RAMI level	Experimental reactor	Demonstration power plant

- EUROfusion Work Package HCD: R&D focused on gyrotrons
- Specific diamond window solutions in case of frequency step-tunability

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

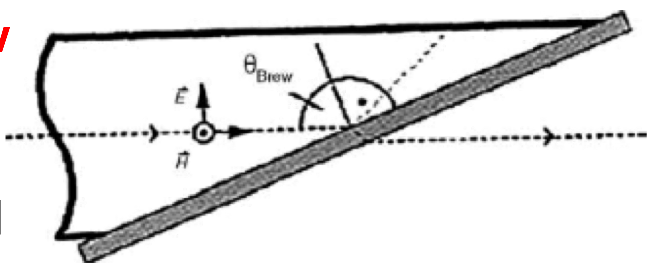
Torus window → n=3, d=1.11 mm

Gyrotron window → n=5, d=1.85 mm

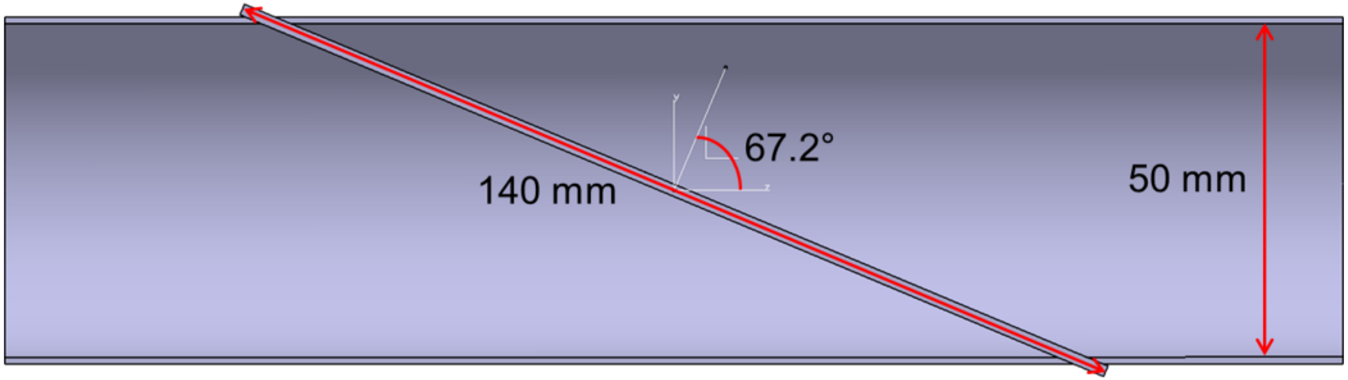
- Deploying a beam at different frequencies in the plasma (DEMO)
  - Broadband window solutions for multi-frequency gyrotrons: single disk matching different wavelengths (e.g., 136/170/204/238 GHz for 1.85 mm)
  - Broadband window solutions for step-tunable gyrotrons: e.g., the **diamond disk Brewster-angle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

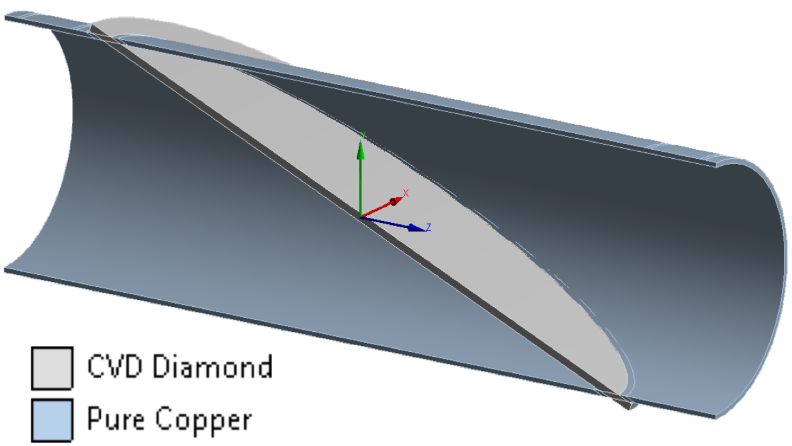
$$\theta_B = \tan^{-1}\sqrt{\varepsilon_r}$$

θ_B=67.2° for diamond



The Brewster-angle diamond window



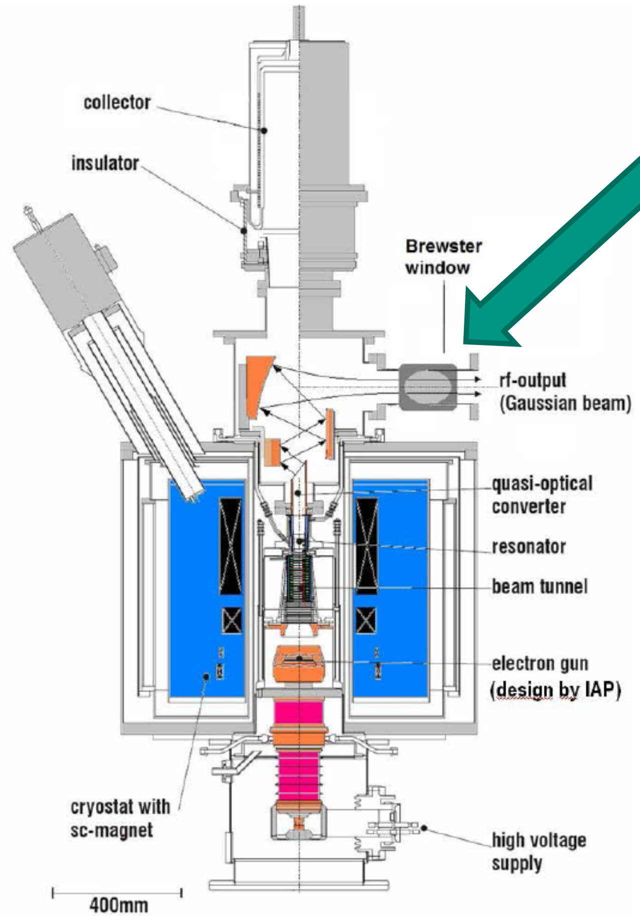


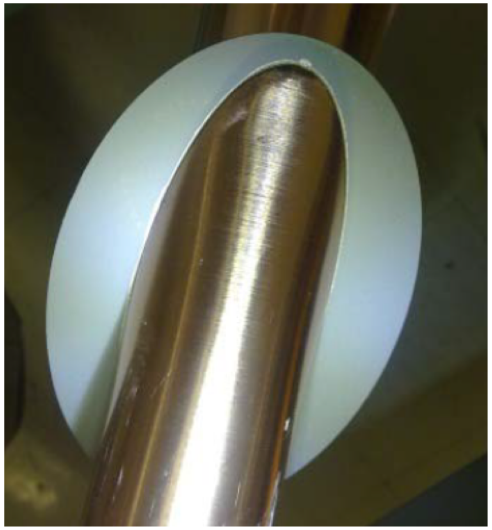
Target: window suited for long pulse gyrotron operation at 2 MW power

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

Operation in a high power gyrotron (2014)





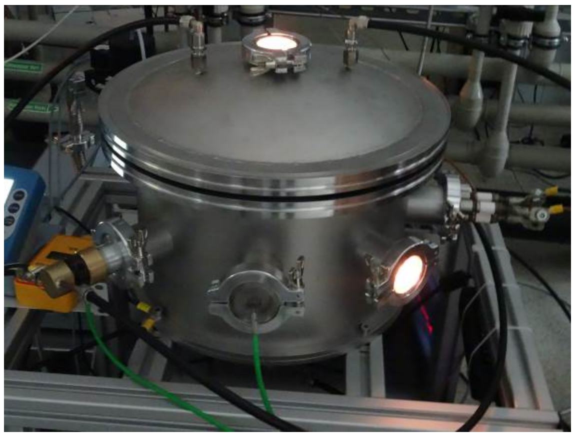
- Elliptical diamond disk of **139 mm major axis** and 1.7 mm thickness
- Waveguide with **inner diameter of 49 mm**

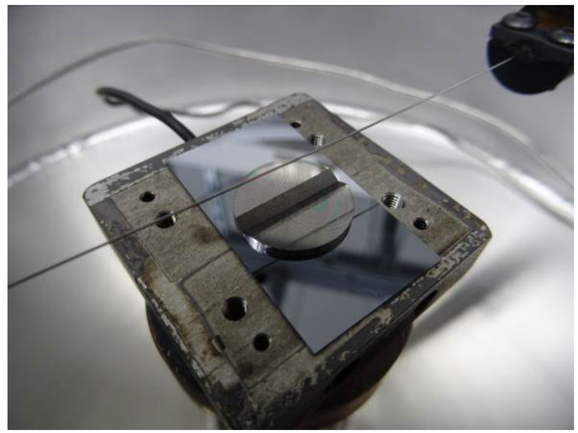
The operation of the Brewster window concept was successfully shown for a high power gyrotron (~1 MW) working in the short pulse regime (< 10 ms) **without any cooling** of the diamond window

G. Gantenbein et al., First operation of a step-frequency tunable 1-MW gyrotron with a diamond Brewster angle output window, IEEE Trans. Electron Devices, vol.61, no.6, pp.1806-1811, 2014

Diamond joining by hot filament (W) method

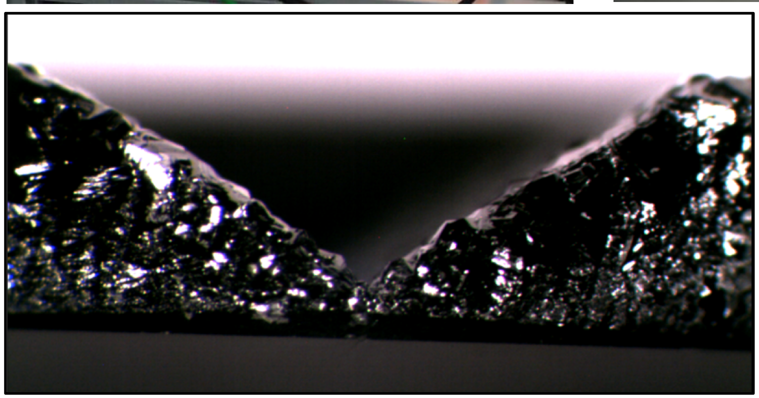
Join diamond fragments in a small scale by overgrowing the joint gap with diamond to obtain large diamond disks





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 microwave plasma reactor

#	Name	Thickness [µm]	Result	Quality
1	ERIV821	392	Broken	Optical
2	ERIV831	410	Broken	Optical
3	ERIV 843	461	Broken	Optical
4	ERIV 852	449	Unbroken	Optical
5	ERIV 863	379	Unbroken	Optical
6	Neptun12	537	Broken	Thermal
7	Neptun13	1651	Broken	Thermal
8	Neptun14	1695	Broken	Thermal
9	ERIV898	1672	Broken	Optical
10	Rhea12	1634	Broken	Thermal
11	Pandora9	1828	Broken	Thermal
12	Saturn11	2050	Unbroken	Thermal
13	Neptun19	1557	Unbroken	Thermal

- Today's microwave plasma reactors are able to deposit diamond on substrates of 120-150 mm diameter
- The growth of 180 mm diameter disks of optical quality represents a **new field for diamond manufacturers**
- Growth test experiments for parameter optimization at Diamond Materials GmbH
- 13 growth runs with optical/thermal quality and increasing thickness of the (unpolished) disks
- Adopted specific solutions for the substrate holder

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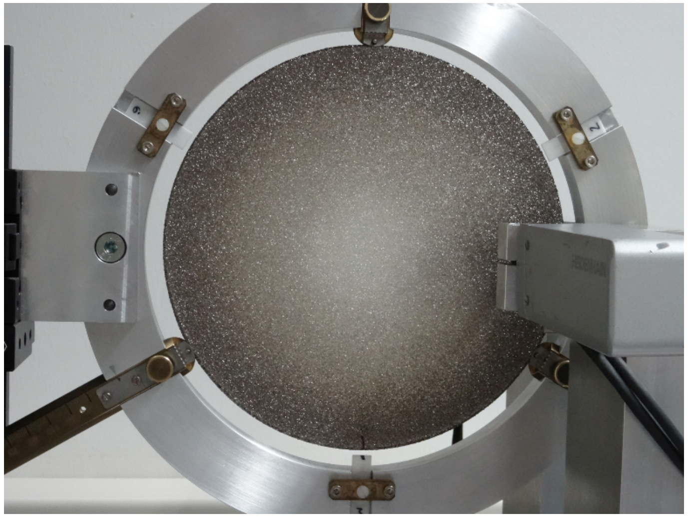
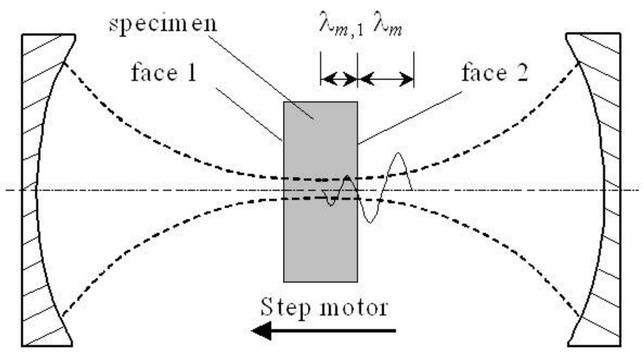
For the very first time, a crack-free diamond disk of thermal grade with 180 mm diameter and ~2 mm average unpolished thickness was produced

Diamond Materials
Advanced Diamond Technology



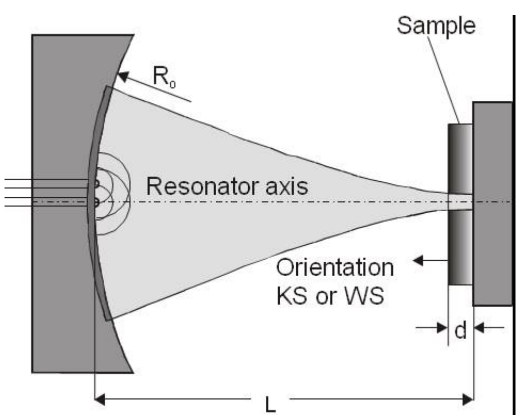
Measurements of tanδ in the diamond disks

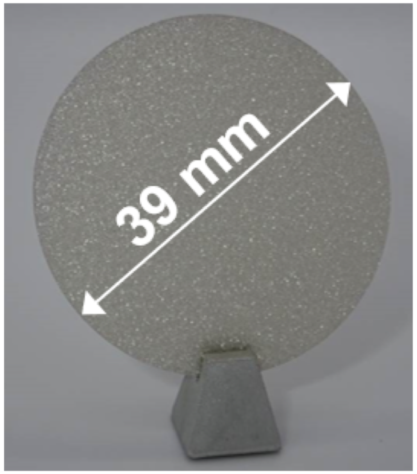
Spherical measurement setup



Fabry-Perot resonators have been already used to measure the loss tangent at the center of the optical quality cracked 180 mm disks and also of the fragments resulting by the broken 180 mm disks

Hemispherical measurement setup

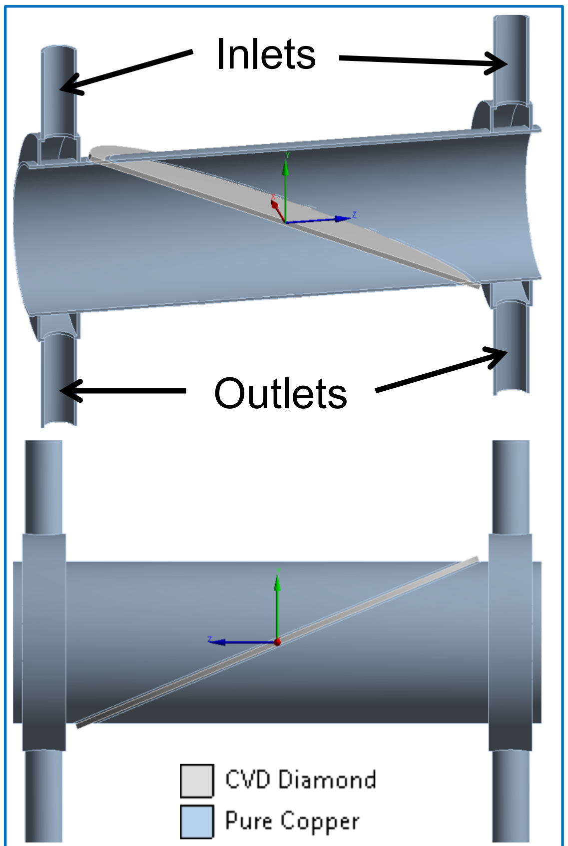




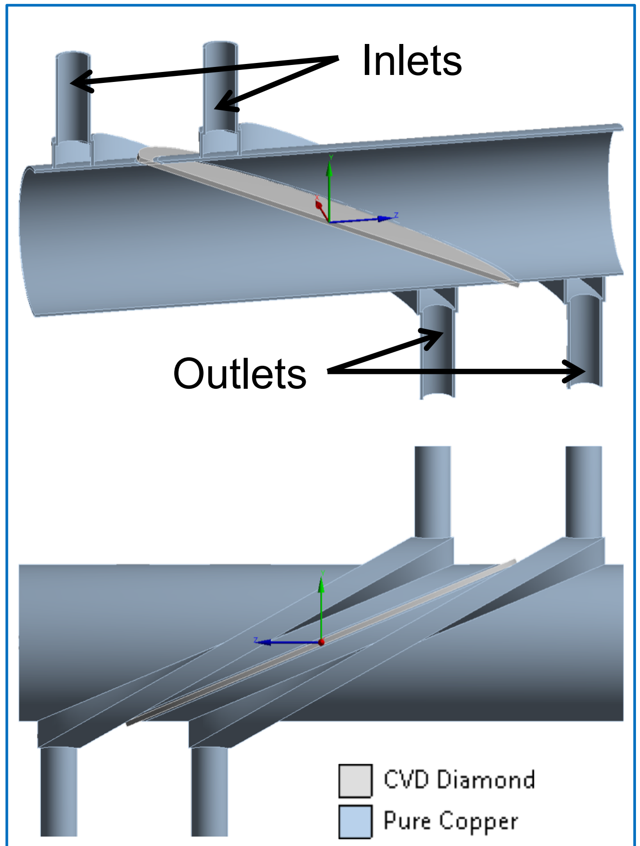
tanδ < $1 \cdot 10^{-4}$
(unpolished disk)

Indirect cooling: investigated layouts

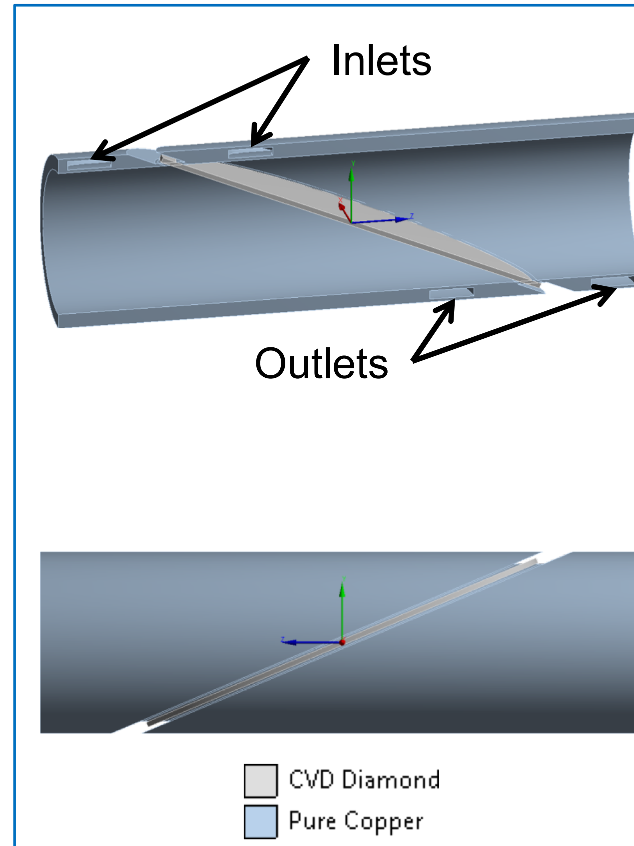
Cylindrical channels



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

Analysis setup

- Thermal and structural analyses
- Different scenarios
- Elliptical disk 140*75 mm, 1.7 mm thick
- Cylindrical waveguide, diameter 50 mm

Scenarios	Absorbed power in the disk [W]
2 MW @170 GHz	1094
1.5 MW @240 GHz	1159
2 MW @240 GHz	1545

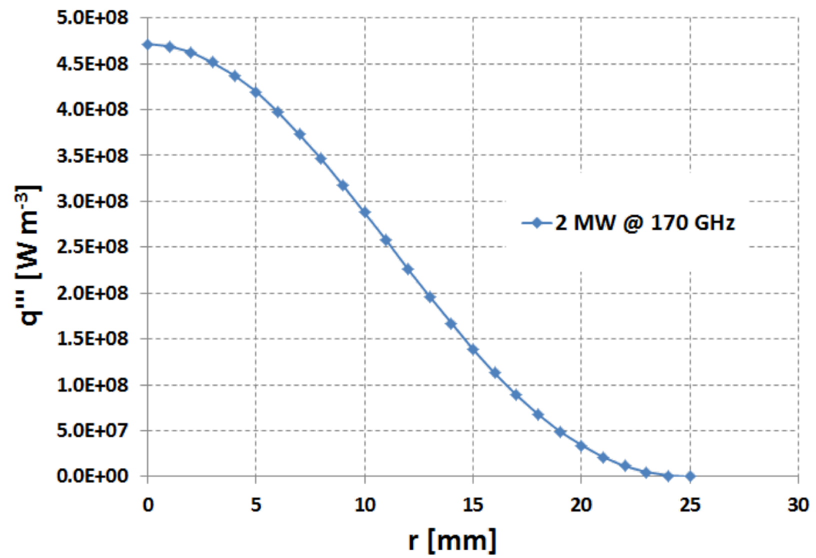
$$P_{abs} = P_{beam} \cdot \frac{2\pi\nu\sqrt{\varepsilon_r}\tan\delta}{c} \cdot \frac{t}{\sin(\theta_B)}$$

$\varepsilon_r = 5.67$, $\tan\delta = 3.5 \times 10^{-5}$
$t = 1.7$ mm, $\Theta_B = 67.2°$

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

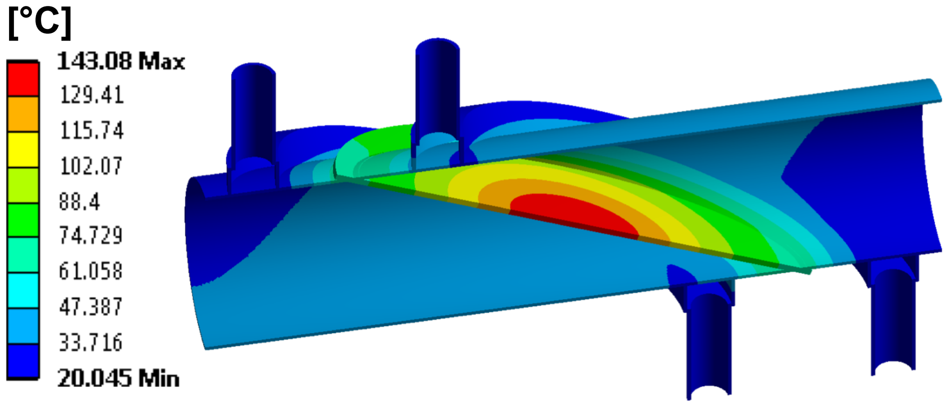
$$x = 2.405 \cdot \frac{r}{a}$$

HE$_{11}$ mode beam, volumetric power density into disk

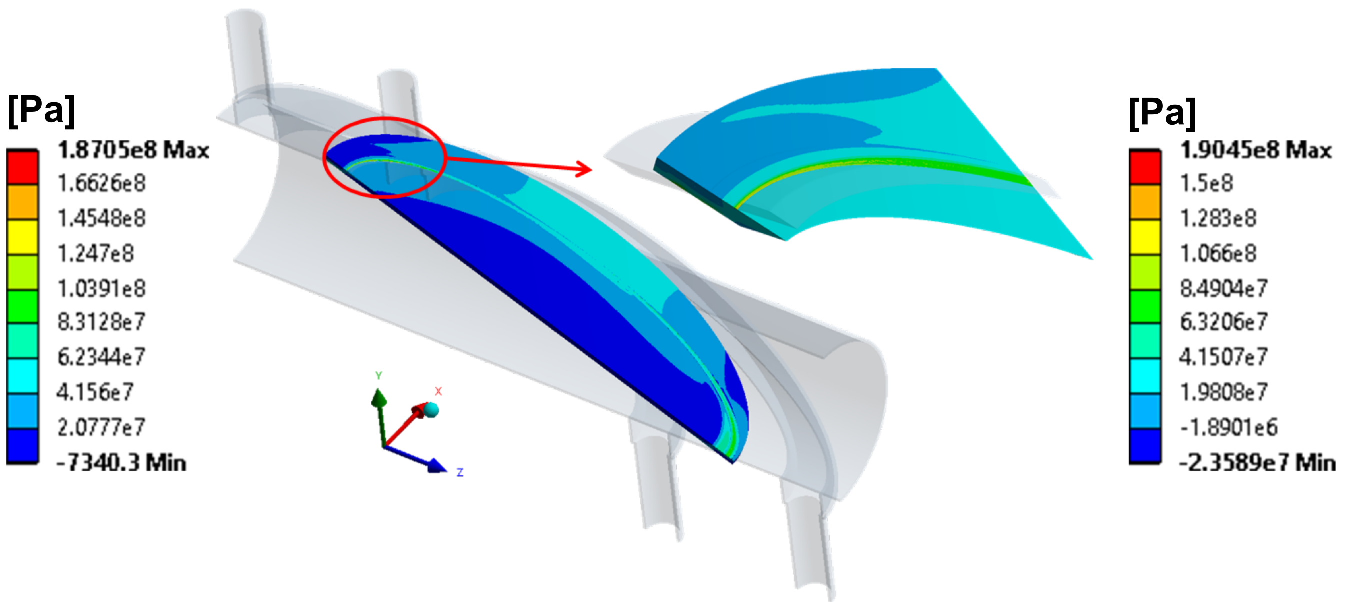


Analysis results for 2 MW @ 170 GHz

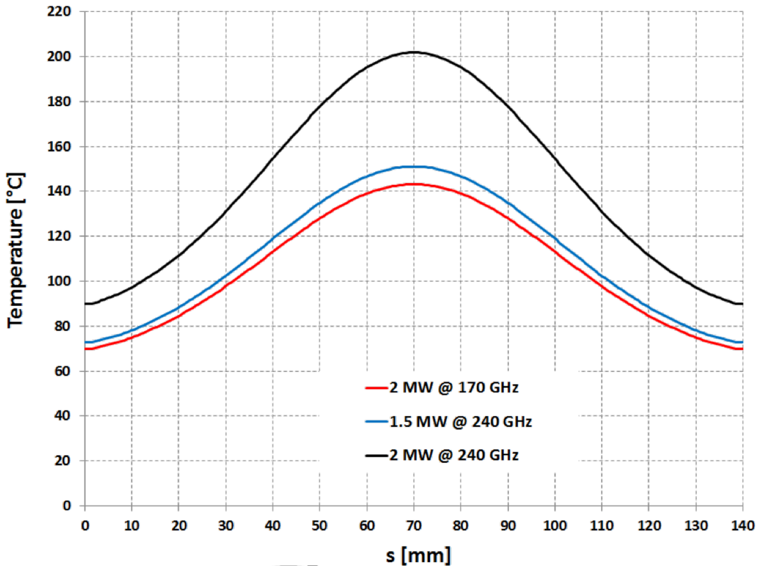
Thermal analysis

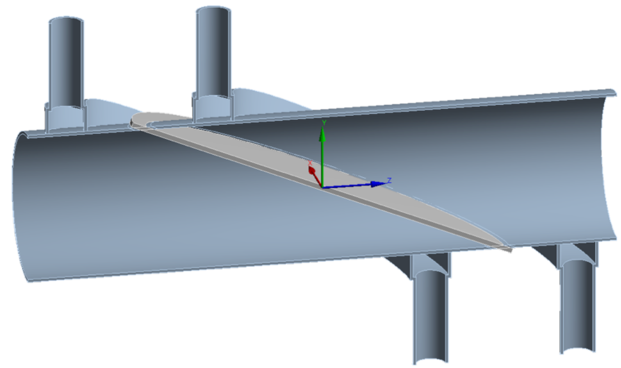


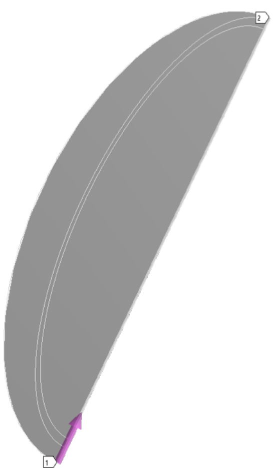
Structural analysis

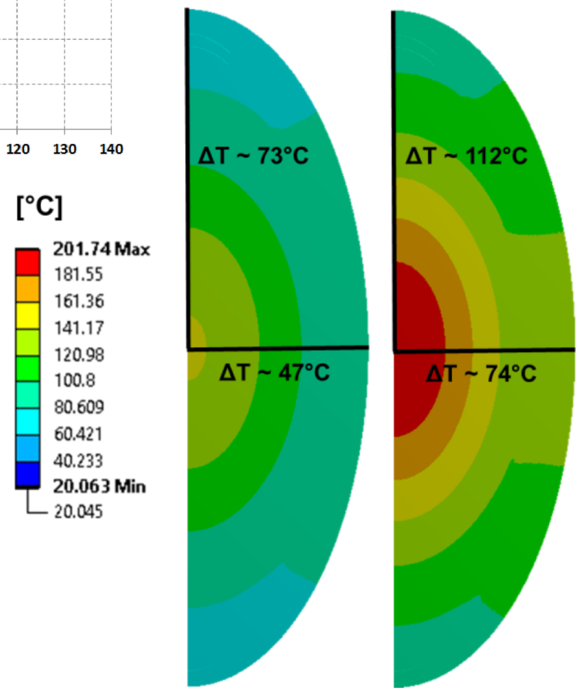


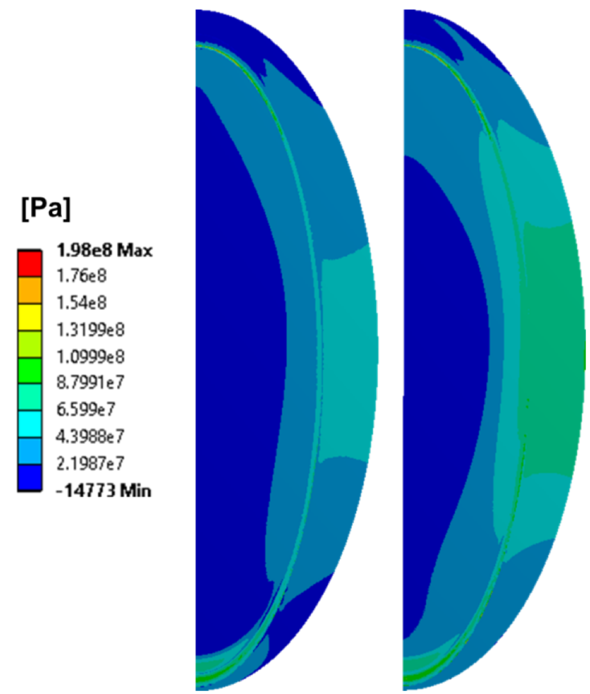
Analysis results for the different scenarios











2 MW power beam at… 170 GHz 240 GHz 170 GHz 240 GHz

Conclusions and outlook

- The Brewster-angle diamond window is an elegant and compact window solution for long pulse step-tunable gyrotron operation at 2 MW
- For the very first time, a crack-free diamond disk of thermal grade with 180 mm diameter and ~2 mm average unpolished thickness was produced
- Different indirect cooling layouts for Brewster window were investigated and cooling channels following the skewed position of the disk are required
- Several growth and polishing test experiments shall be carried out in order to produce 180 mm / 2 mm crack-free optical grade diamond disks
- Experiments on joining the disk to the waveguides shall be also performed

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