Numerical analyses of the W7-X ECRH gyrotron diamond output window and overview on the residual stress analysis of MPA CVD diamond disks

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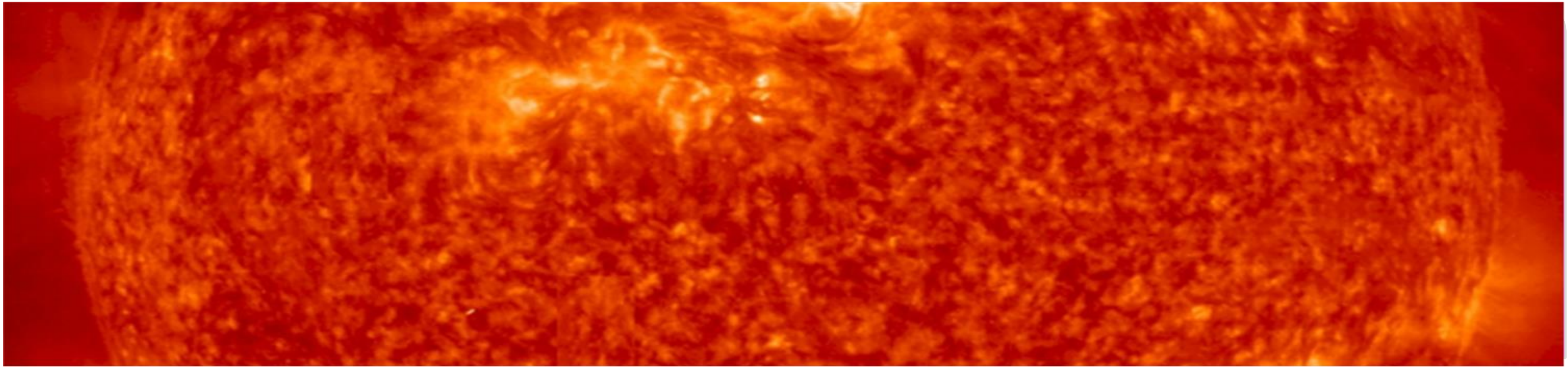
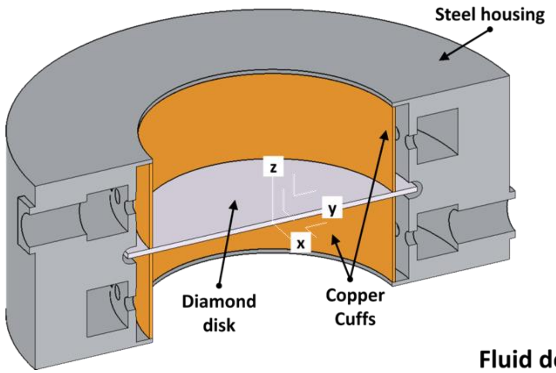


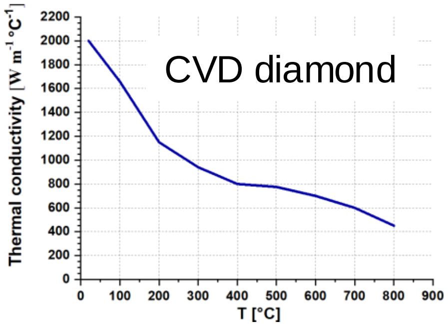
Outline

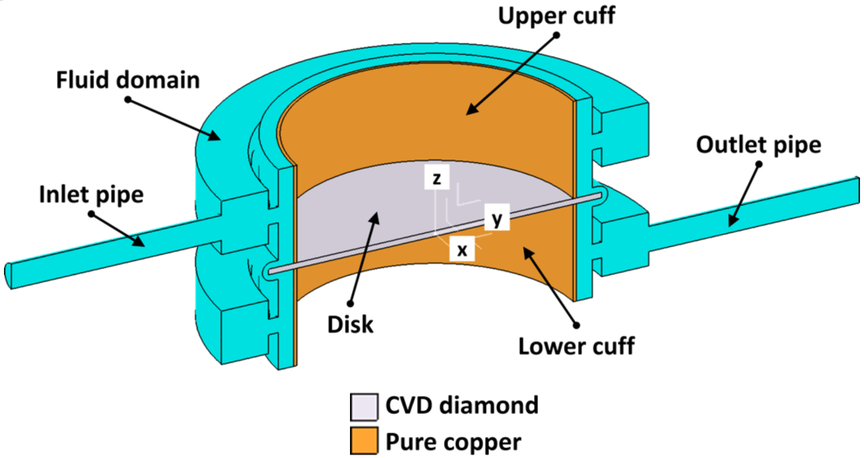
- W7-X gyrotron diamond output window
  - Performance at 1.5 MW operation
  - Performance at 2 MW operation
- Initial intrinsic stress analysis in MPA CVD diamond
  - Polarimeter
  - Raman
  - XRD
- Summary and outlook

Previous window design and analyses at 1.5 MW



$$q'''(r) = \frac{2\,P_{abs}}{\pi\, w_0^{\,2}\, t}\, e^{-2\frac{r^2}{w_0^{\,2}}}$$



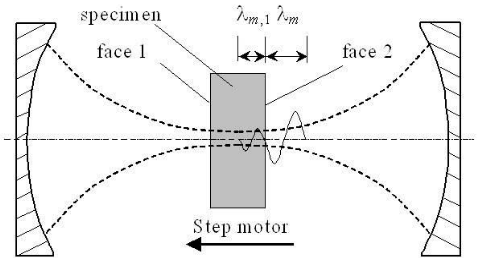


CFD and structural analyses

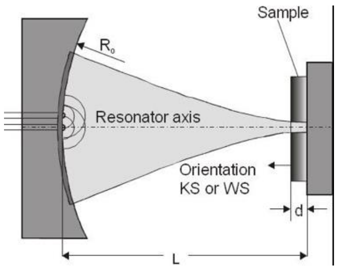
- Gaussian mm-wave beam with 20 mm radius
- Symmetry
- Temperature dependent material properties
- 0.2 kg s^{-1} at inlet (25°C) at inlet and 0 Pa at outlet
- Runs with <u>different absorbed power values</u>
- Runs with <u>water</u> and <u>silicon oil</u> DC 200(R) 5cSt

Loss tangent measurements

Spherical setup



Hemispherical setup



$$P_{abs} = \frac{P_{beam}\,\pi\,f\,t\,tan\delta\,(1+\varepsilon_r)}{c_0}$$

	tanδ [x 10^{-5}]	absorbed power [W]
Conservative assumption	5.68	1500
Disk 89DB1	4.55	1201
D90, average on 25 bare disks	3.49	921
D50, average on 25 bare disks	2.10	555

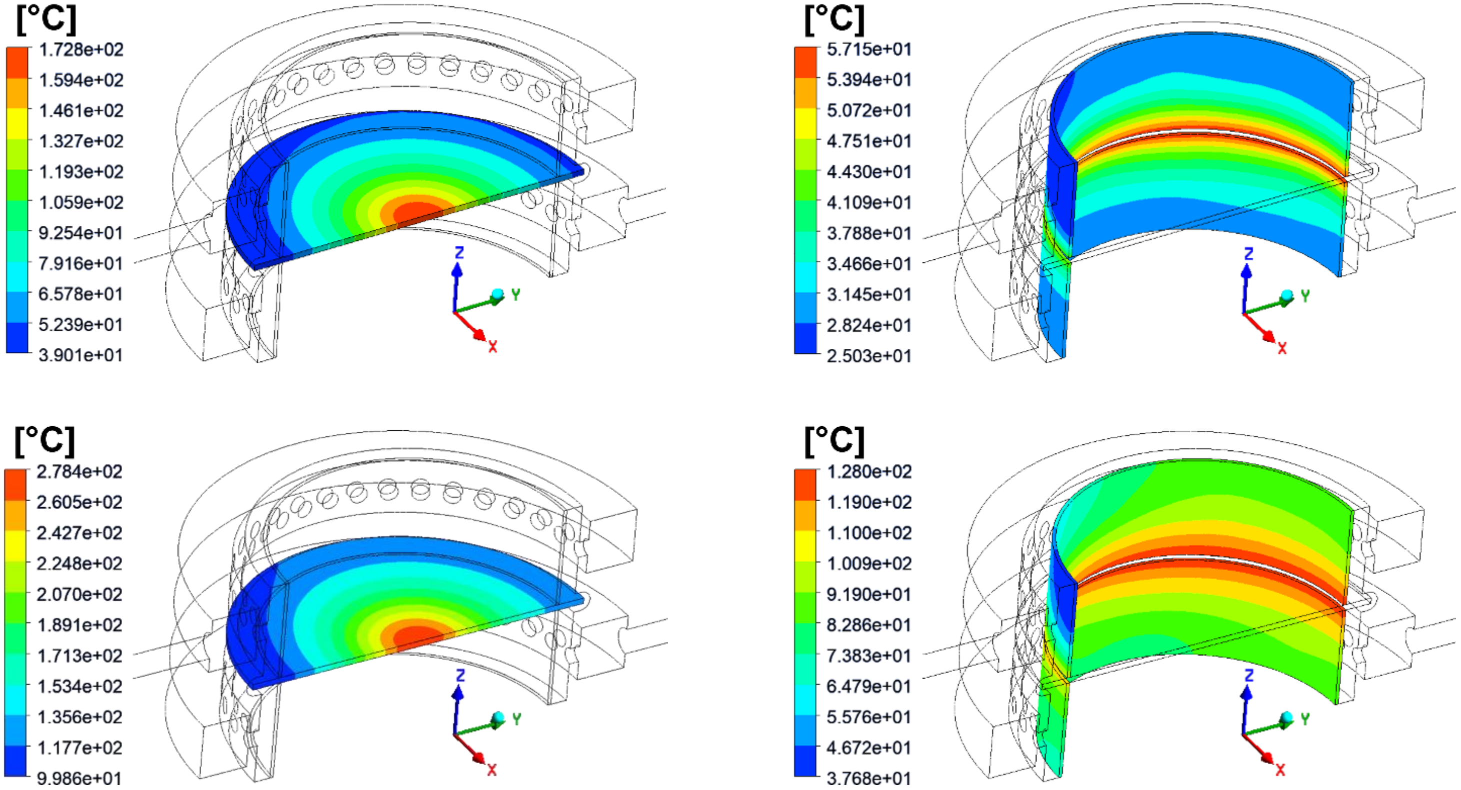
- Fabry-Perot resonators at KIT to measure the tanδ of the diamond disks
- Input to numerical analyses to model power absorption in disks
- Margin against potential degradation factors of the disk quality

- P_{beam} = 1.5 MW
- f = 140 GHz
- ε_r = 5.67
- t = 1.8 mm

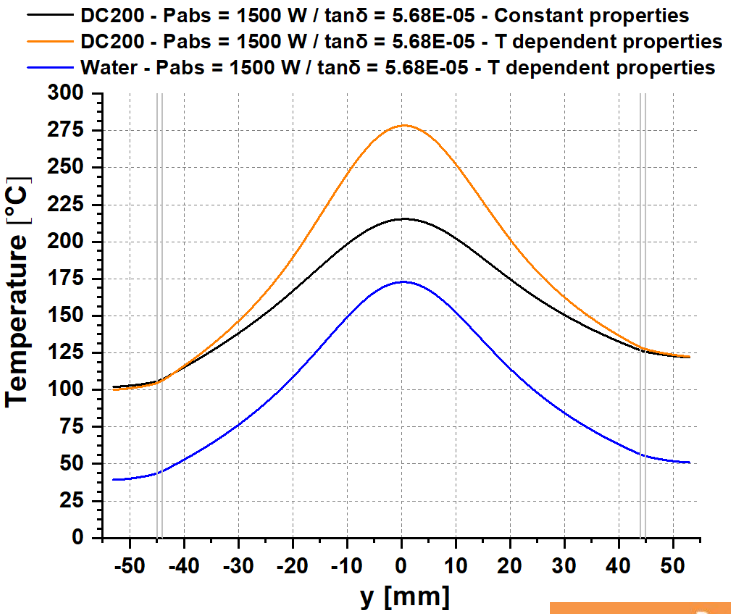
CFD analysis results at 1.5 kW absorption

Water

Oil (DC200)



CFD analysis results at 1.5 kW absorption

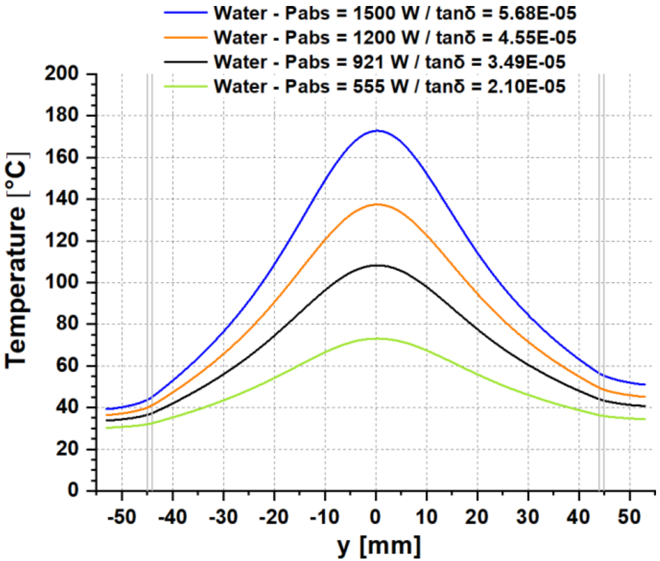


- 250°C is the limit assumed for diamond
- **Oil-cooling** is not an option for the window at 1.5 kW absorption
- **Water-cooling** shall be used at high power operations
- **Temperature dependent properties** shall be used

	density [kg m^{-3}]	dynamic viscosity [Pa s]	specific heat [J kg^{-1} K^{-1}]	thermal conductivity [W m^{-1} K^{-1}]
Water	997	8.90×10^{-4}	4182	0.607
DC200	915	45.8×10^{-4}	1639	0.142

Coolant	*Pressure drop [bar]*	*ΔT fluid inlet-outlet [°C]*	*Max T in disk [°C]*	*Max T in cuffs [°C]*	*ΔT disk edges [°C]*	*Power fraction removed by diamond [-]*	*Power fraction removed by copper [-]*
Water	0.15	1.75	172.8	57.2	11.8	58%	42%
Oil	0.20	4.47	278.4	128.0	22.4	48%	52%

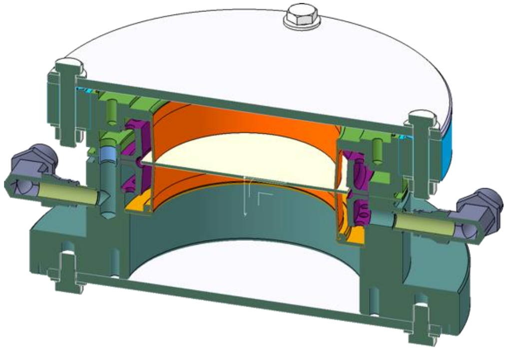
Parametric study for loss tangent



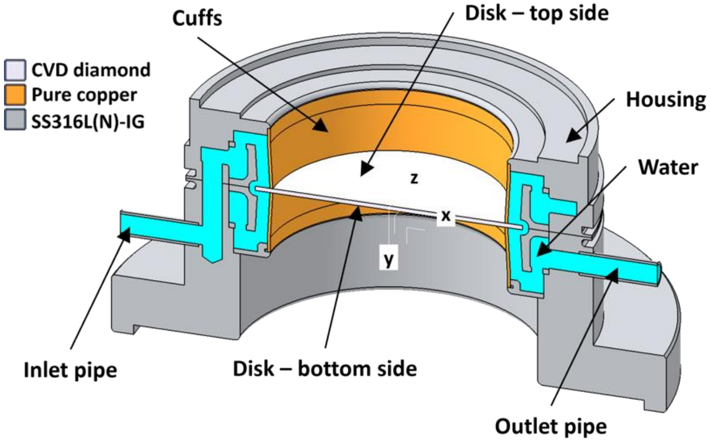
- **Water-cooling** provides by far significant temperature reserve margins, even at higher values of absorbed power
- **High reserve margins** are important to counteract potential factors leading to a degradation of the microwave transmission capability of the diamond disk

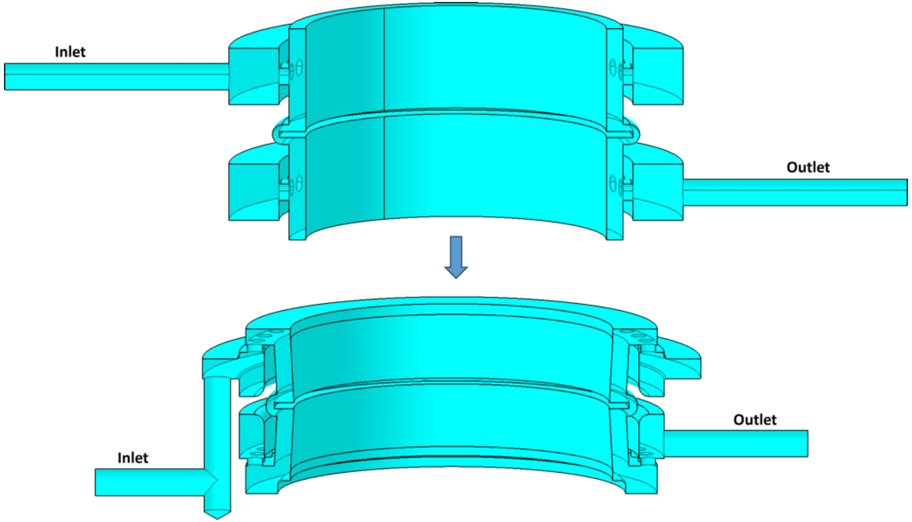
Absorbed power in disk [W]	Water		DC200	
	Max T in disk [°C]	Reserve margin [°C]	Max T in disk [°C]	Reserve margin [°C]
1500	172.8	77.2	278.4	-
1200	137.4	112.6	213.1	36.9
921.4	108.2	141.8	159.3	90.7
554.5	73.11	176.9	100.7	149.3

Current window design and analyses at 2 MW



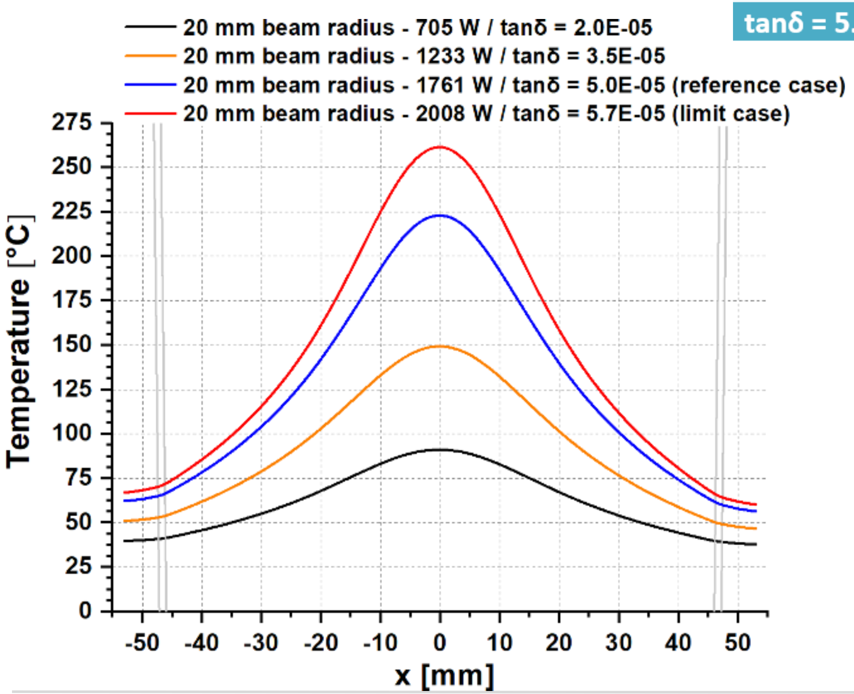
- CFD with different combinations of tanδ and beam radius
- Operational limits of the window
- Structural with the complete window assembly and both thermal and other operational loads





CFD analysis results

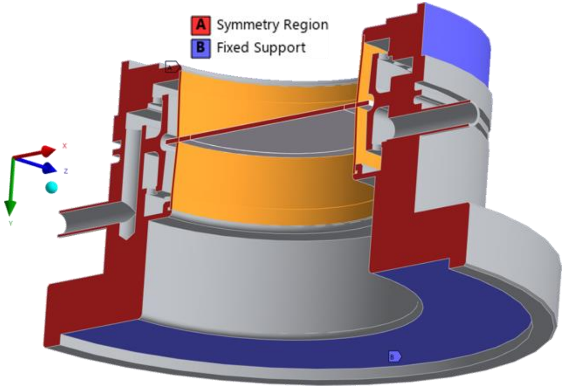
	r_{beam} = 17 mm	r_{beam} = 20 mm	r_{beam} = 23 mm
tanδ = 2.0e-5 / P_{abs} = 705 W	97.2	91.1	85.9
tanδ = 3.5e-5 / P_{abs} = 1233 W	162.3	149.3	138.6
tanδ = 5.0e-5 / P_{abs} = 1761 W	245.6	223.0	203.0

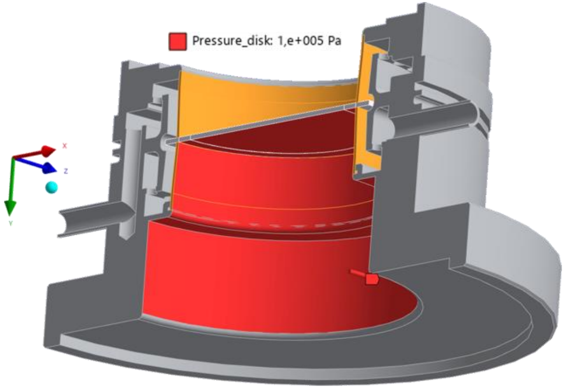


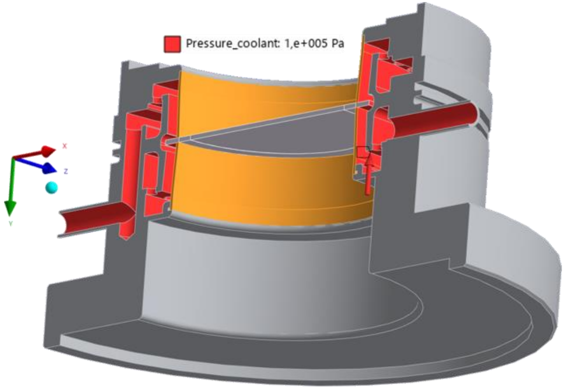
- Major symmetry in temperature distribution
- Going to higher values of absorbed powers, a greater beam radius may play a significative role in keeping low the maximum temperatures
- Maximum value of tanδ that might be still tolerated at 2 MW operation is 5.7E-5

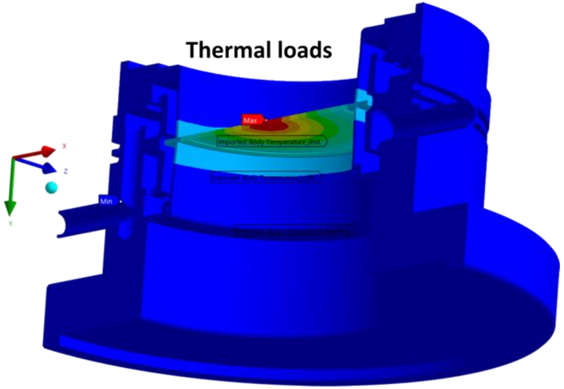
Structural analysis - setup

- Reference case
  (r_{beam}=20 mm and tanδ=5.0E-5)
- Metallic housing is included
- Plastic steady-state analysis
- Thermal loads
- Coolant pressure of 1 bar
- Atmospheric pressure acting on the bottom side of the disk



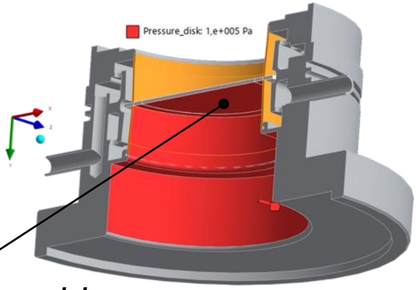






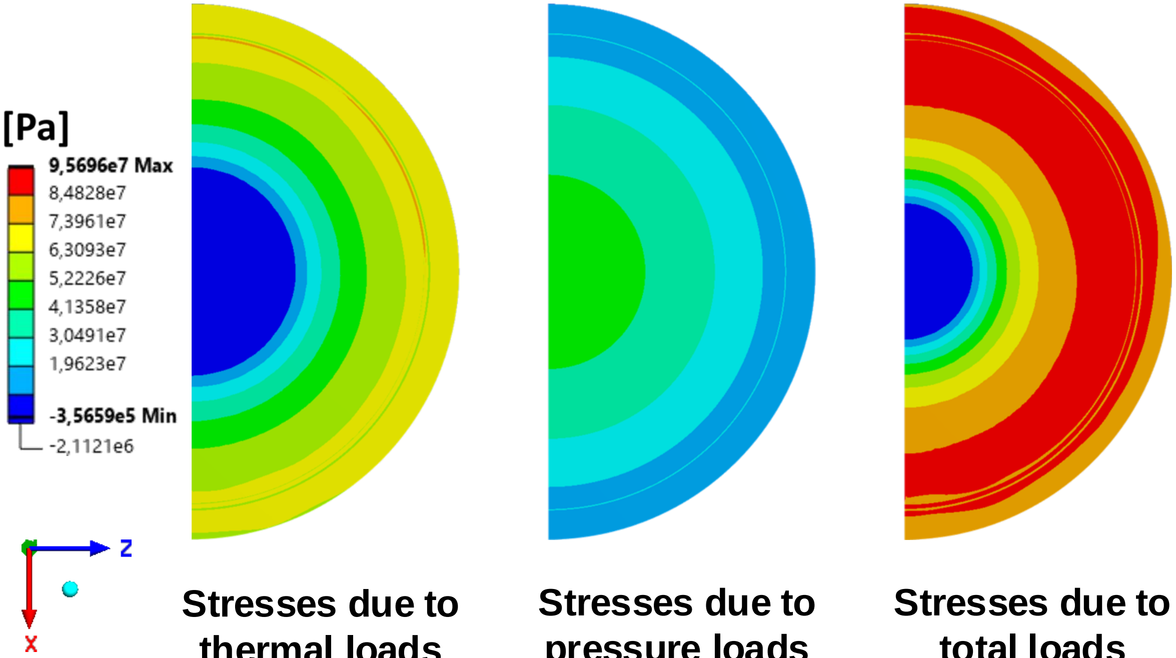
Structural analysis - results

- Maximum principal stresses are shown (tensile component)
- Thermal loads lead to a compressive stress of ~120 MPa
- Pressure loads lead to a tensile stress of ~ 47 MPa
- Thermal loads rule the total stress distribution



Disk bottom side

Top side



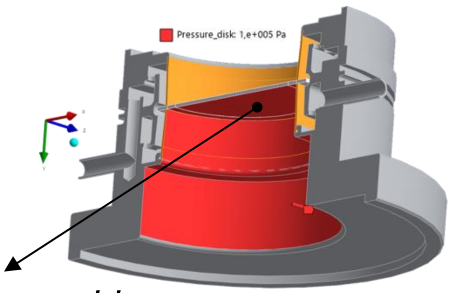
Stresses due to thermal loads

Stresses due to pressure loads

Stresses due to total loads

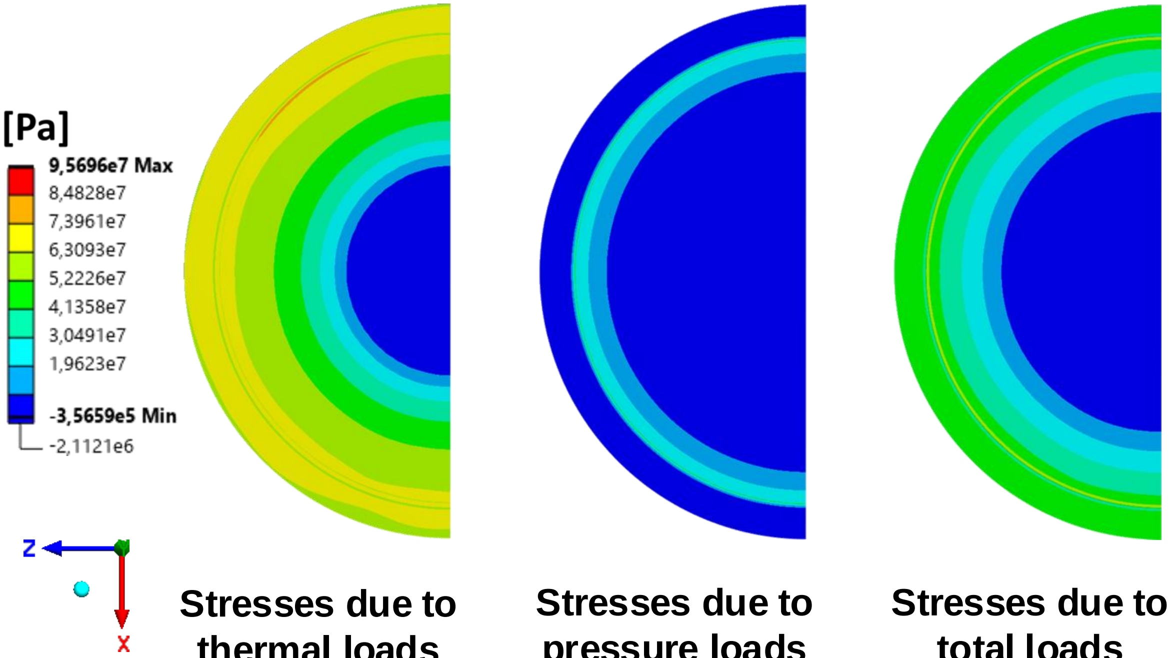
Structural analysis - results

- On the bottom side, stresses relax when pressure loads are added to the thermal ones
- Stresses can be safely accepted with respect to the 150 MPa allowable limit
- Bow of the disk is ~ 45 µm



Disk bottom side

Bottom side



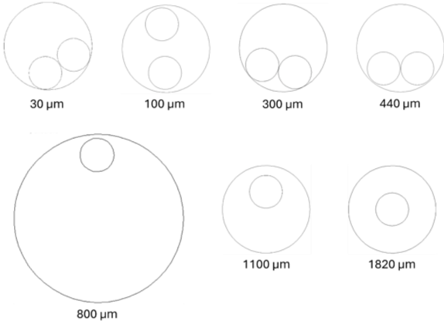
Stresses due to thermal loads

Stresses due to pressure loads

Stresses due to total loads

Intrinsic stress analysis in diamond

Procurement of a 1.11 mm, Ø 80 mm optical quality CVD diamond disk and Ø 30 mm optical quality samples at various thickness

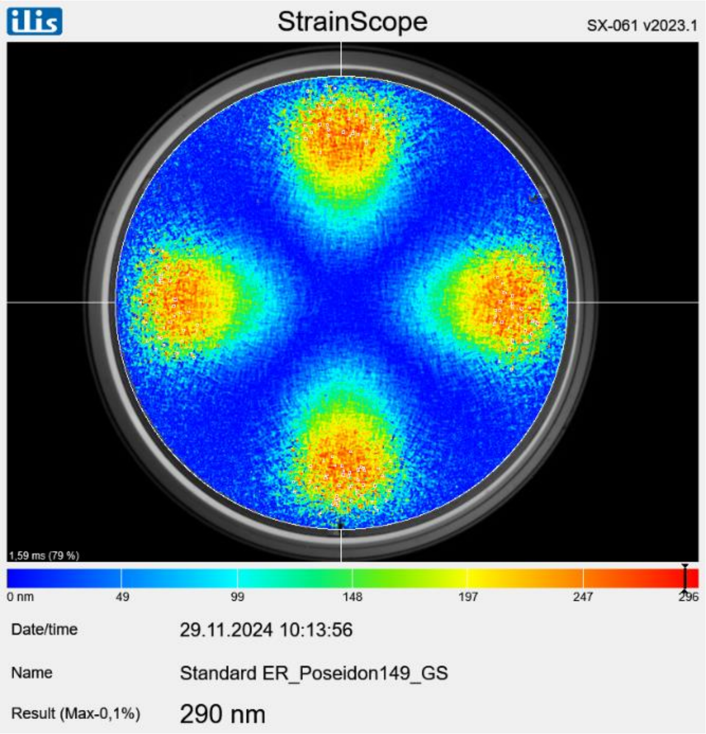


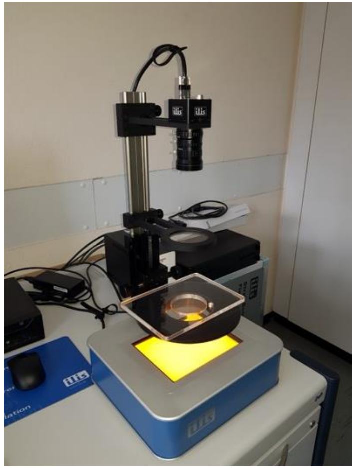
Measurements by
- Polarimeter
- Raman
- X-ray diffraction (XRD)

Nominal thickness (µm)	30	100	300	440	800	1100	1820
Sample identification number	SN-1214 SN-1215	SN-1191 SN-1192	SN-1195 SN-1196	SN-1212 SN-1213	SN-1153	SN-1157	SN-1151
Central thickness (µm)	29.6 (SN-1214) 30.4 (SN-1215)	107.4 (SN-1191) 107.5 (SN-1192)	302.0 (SN-1195) 302.1 (SN-1196)	450.5 (SN-1212) 450.6 (SN-1213)	817.2	1118.3	1811.7
Total thickness variation (µm)	3 (SN-1214) 1.5 (SN-1215)	0.39 (SN-1191) 0.52 (SN-1192)	6 (SN-1195) 6.3 (SN-1196)	4.5 (SN-1212) 2.4 (SN-1213)	3.0	3.6	2.7

Measurements by polarimeter

- $\sigma_1 - \sigma_2 = \delta / t \cdot C$
  - σ_1, σ_2 principal stresses (MPa)
  - δ, retardation (nm)
  - t, thickness (mm)
  - C, stress-optical coefficient (TPa^{-1})
- Output in terms of retardation
- Measurements with a specific linear polarization (angular shift of the visible cross)
  - max stress difference in outer region
  - axial-symmetry, stress dependence on disk radius

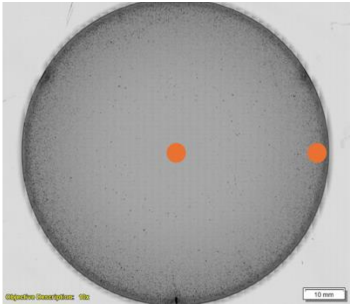


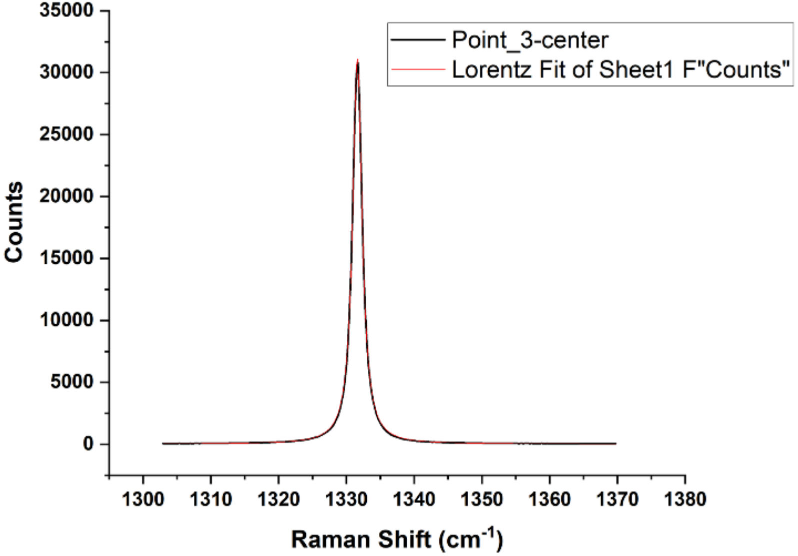


StrainScope® Flex

Measurements by Raman

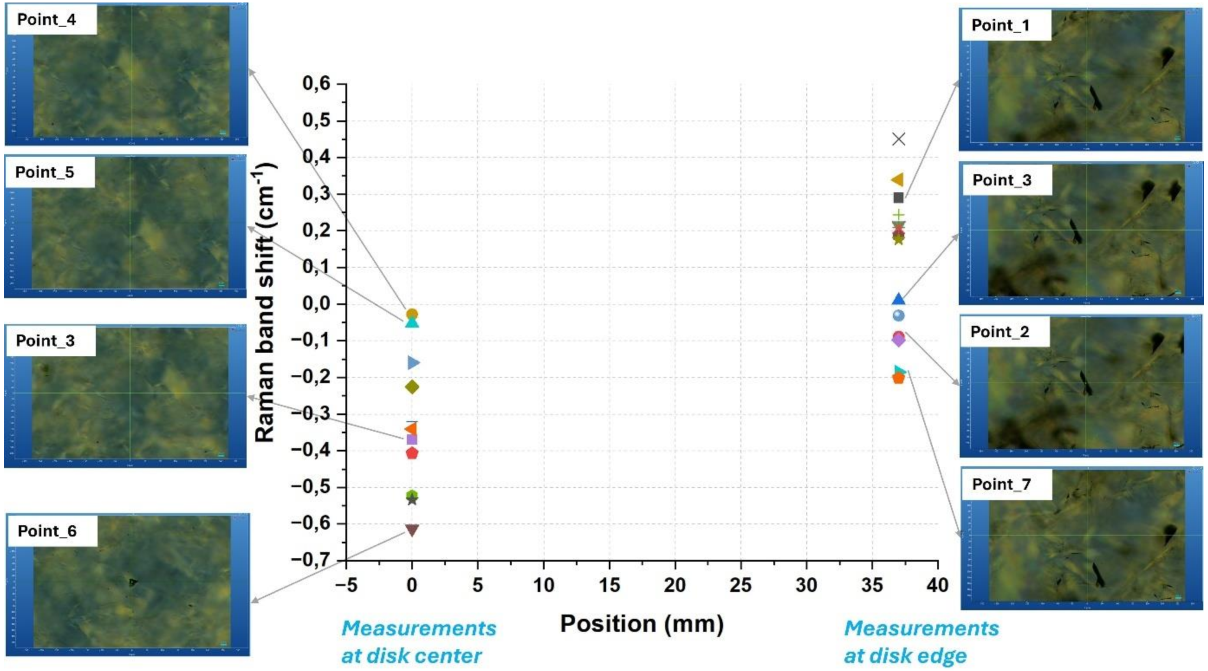
- LabRam HR Evolution Raman Spectrometer
- Diamond line is at 1332 cm^{-1}
- Residual stresses cause shift of Raman peak
- $\nu_s - \nu_r = \alpha\,\sigma$
  - ν_s, measured frequency of Raman peak (cm^{-1})
  - ν_r, frequency of stress-free material (cm^{-1})
  - α, coeff. of stress-induced frequency shift ($cm^{-1}\,GPa^{-1}$)
  - σ, stress (GPa)
- Output in terms of shift of the Raman band position
- Initial measurements:
  - two specific regions at center and outer on GS
  - 532 nm, 10% power, 2400 g/mm, x10, 50µm aperture
  - 5 times acquisition of 3s each, Lorentz fitting





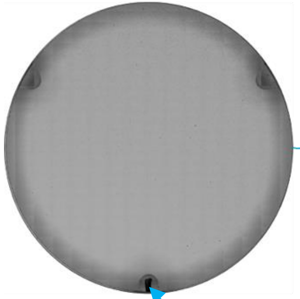
Measurements by Raman

- Image for each measurement point (using a polarizer)
- Shift to lower (upper) frequencies relates to tensile (compressive) stresses
- Tensile stress appears at center while tensile and compressive stress in the outer region
- Large variation of the shift, indicating a large variation of stress among the points

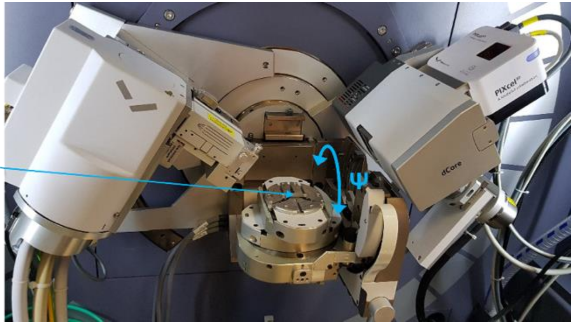


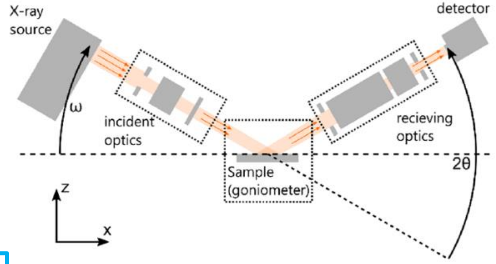
XRD residual stress analysis

- XRD $\sin^2\Psi$ method on GS and NS of 300, 440, 800, 1100 and 1820 µm samples
- Empyrean diffractometer (Panalytical)
- Cu Kα radiation
- (331) diffraction peak with 2θ = 140.6°
- Sampling central area of 3 mm x 3 mm
- ϕ - 1 direction of measurements around surface normal (black mark at bottom, ϕ = 0°)
- Ψ - 36 tilt angles from -67° to 67°
- Modified Lorentzian shape function to determine peak position
- A plot d - $\sin^2\Psi$ is generated
- Stress is obtained from the straight-line slope (least squares regression) and material elastic constants



Black mark



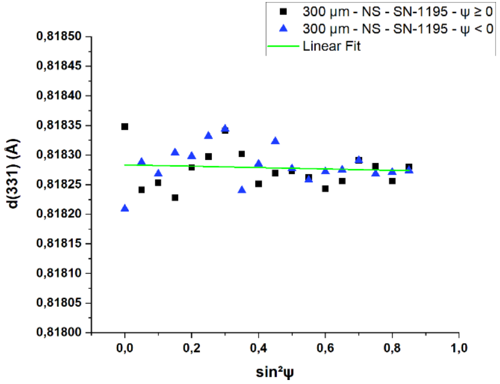


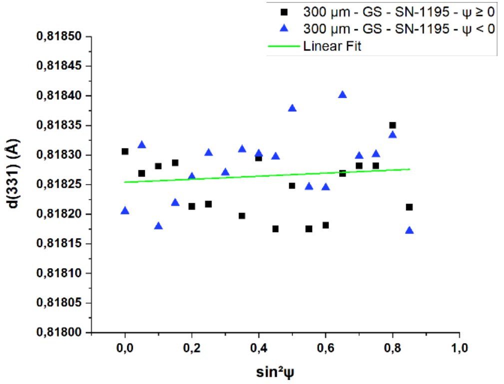
$$\sigma_\phi = \left(\frac{E}{1+\nu}\right)_{(hkl)} \frac{1}{d_{\phi o}} \left(\frac{\partial d_{\varphi\psi}}{\partial \sin^2\psi}\right)$$

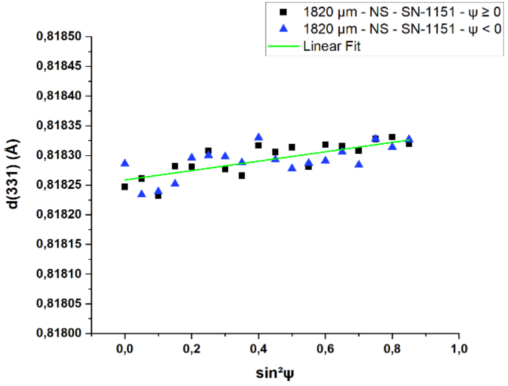
ϕ rotation angle about surface normal

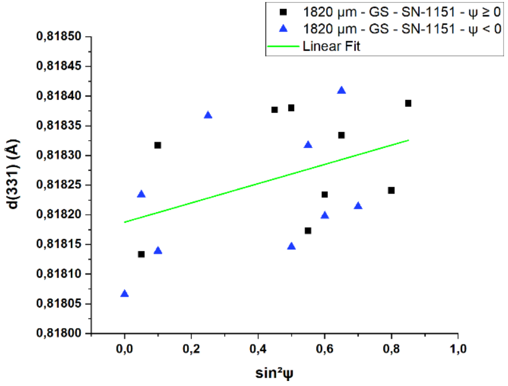
Ψ inclination angle of the sample

XRD residual stress analysis





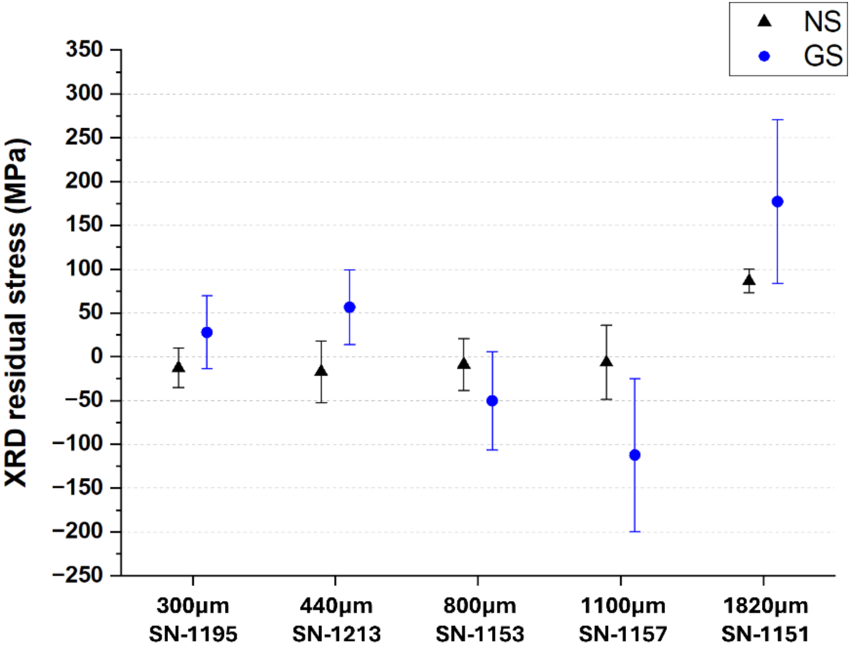




- Larger scatter on the GS with respect to NS
- At 1100 and 1820 µm on the GS, only about half of the measuring points was possible to use
- Causes shall relate to the columnar growth and presence of large grains
- $\sin^2\Psi$ method might be applicable only to NS
- However, some techniques might improve the measurements by increasing the number of contributing grains (e.g. slightly oscillating the sample)

→ feasible at KIT Campus South

XRD residual stress analysis



- No defined trend as a function of thickness and also between NS and GS
- Large value of standard deviation (reported also in literature – maybe due to texture and columnar growth)

Sample	Sample side	Stress (MPa)	Standard deviation (MPa)
300 µm - SN-1195	NS	-12,8	22,5
	GS	27,8	41,5
440 µm - SN-1213	NS	-17,1	35,3
	GS	56,5	42,6
800 µm - SN-1153	NS	-8,8	29,3
	GS	-50,3	56,4
1100 µm - SN-1157	NS	-6,5	42,3
	GS	-112,2	87,5
1820 µm - SN-1151	NS	86,4	13,3
	GS	177,1	93,3

Summary & outlook

- Numerical analyses verified the performance of the W7-X gyrotron diamond output window at 2 MW operation by water cooling
- Temperature dependent properties shall be used to obtain a real picture of the window performance at these power levels
- Initial measurements of residual stress in CVD diamond by polarimeter, Raman and XRD show that useful information can be obtained on the distribution and nature of the stresses
- Systematic investigation of the stresses over the area of the diamond samples

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