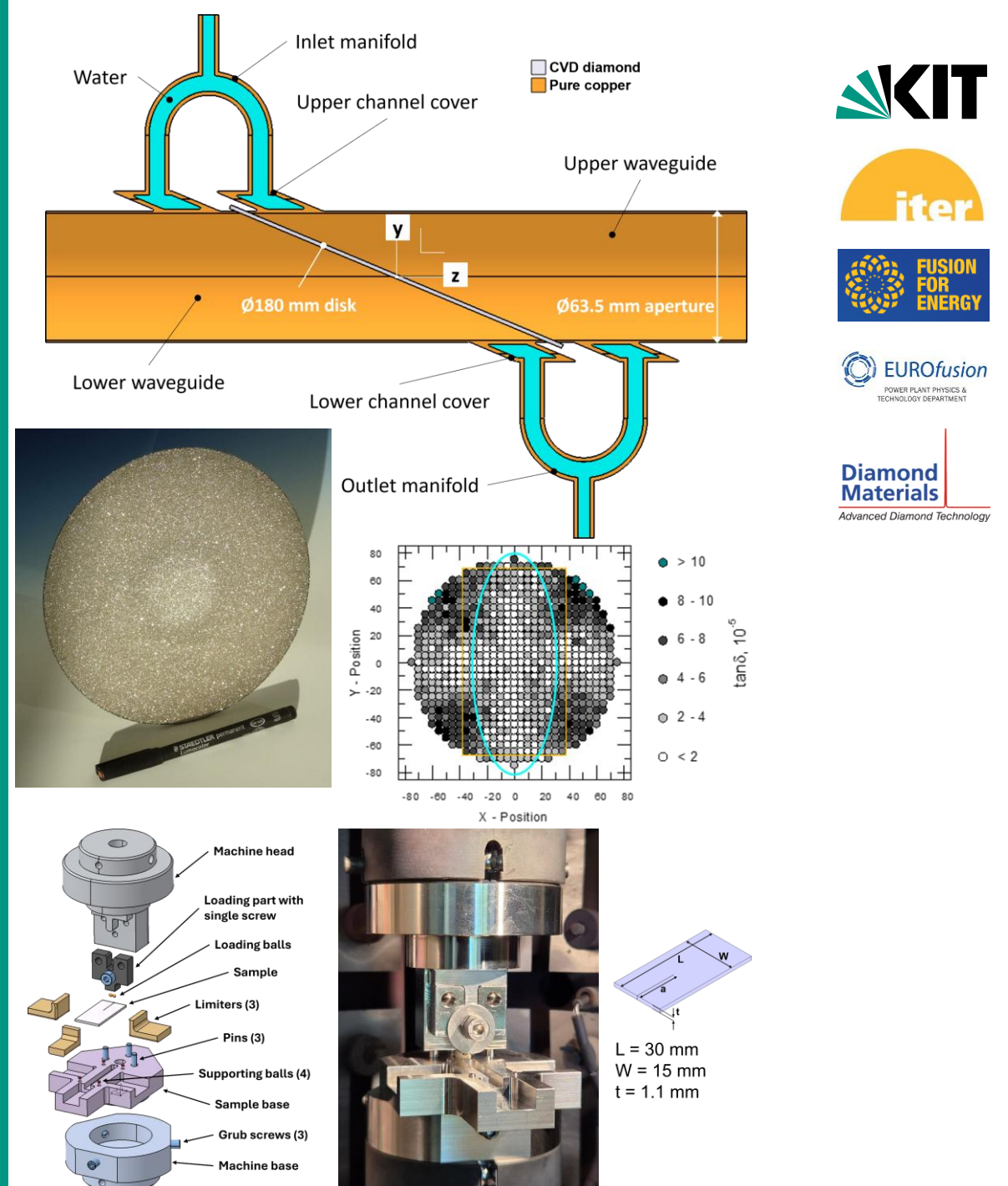


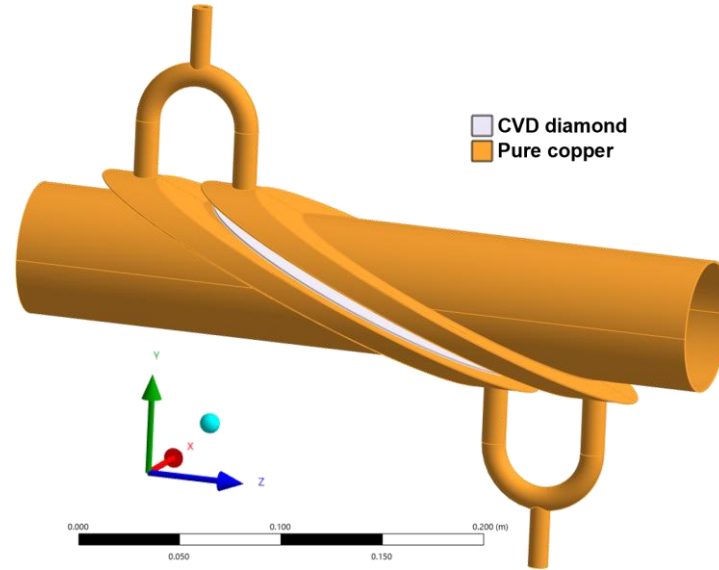
Numerical analyses of a Brewster-angle window featuring the largest diamond disk to date and an overview of integrity assessment against fracture failure

G. Aiello, A. Meier, T. Scherer, S. Schreck, D. Strauss
21.10.2026

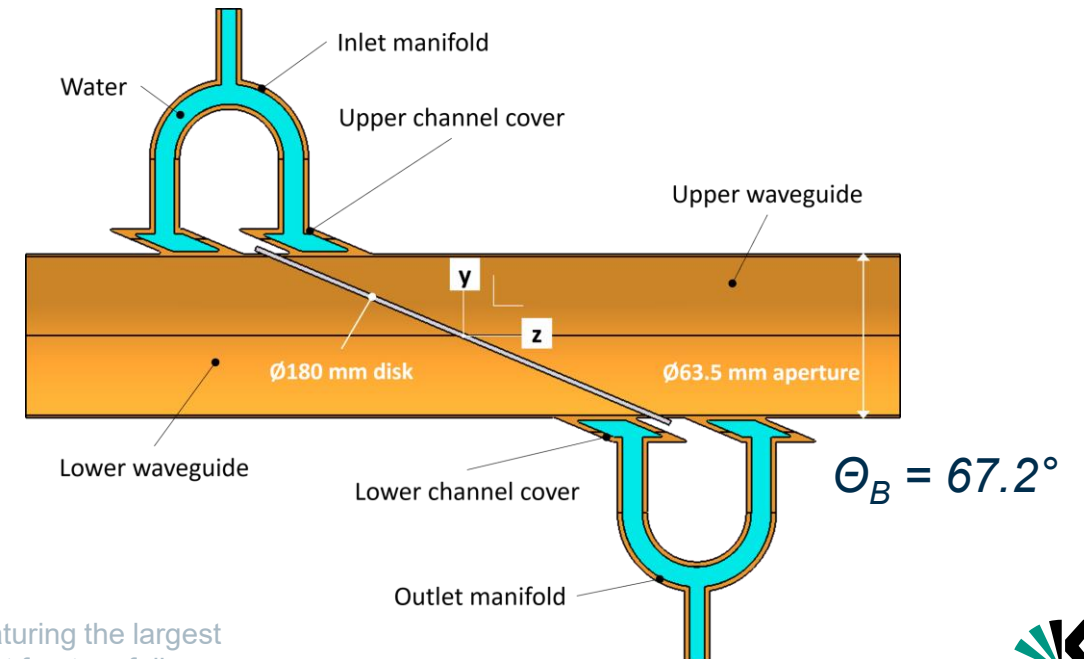
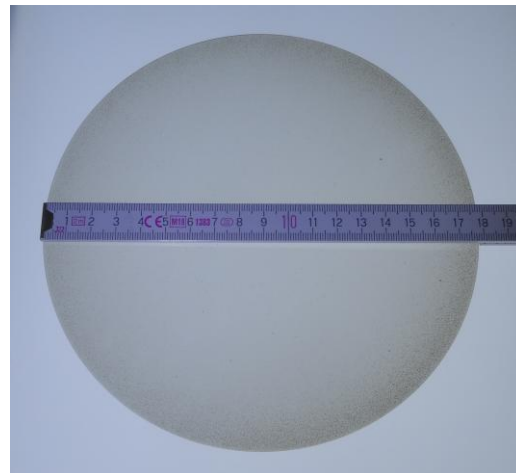
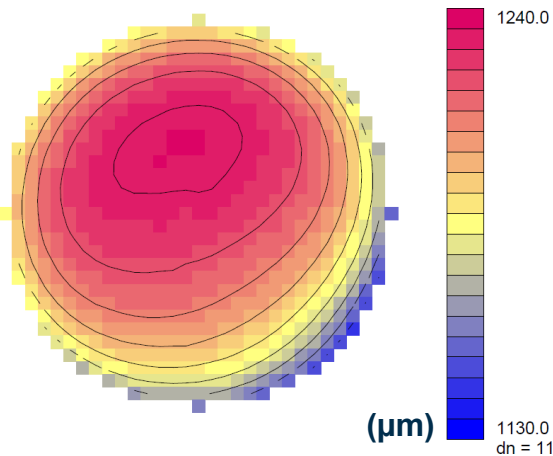


1. Context and motivation
2. The Ø180mm optical diamond disk
3. Impact assessment of loss tangent distribution as input for the analyses
4. Design verification of the window
5. Fracture toughness experiments
6. Fracture failure assessment
7. Summary and outlook

Context and motivation

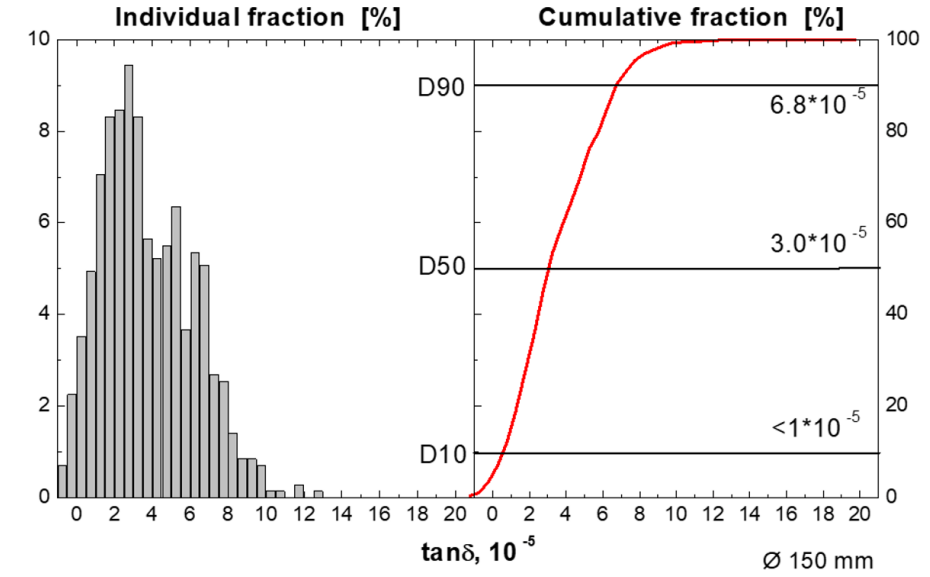
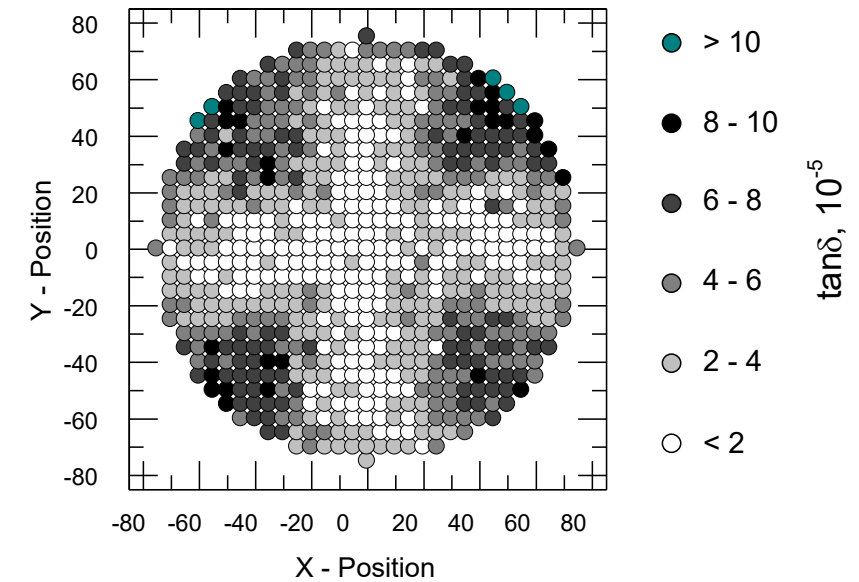
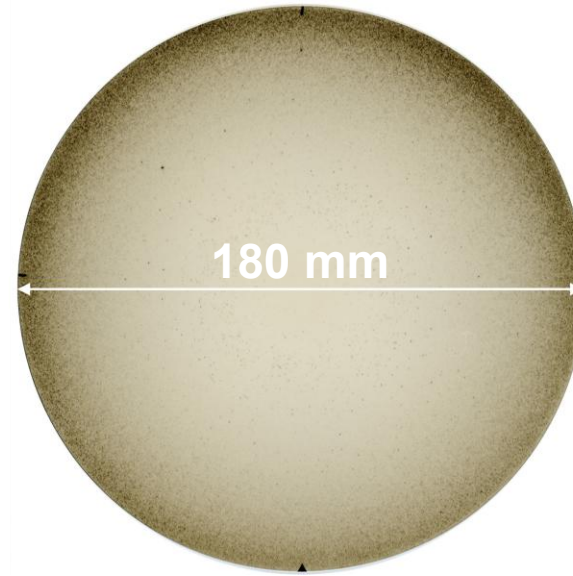


- CVD diamond Brewster-angle window is the compact solution for high power, CW, EC frequency-steering gyrotrons
- First-of-its-kind optical grade diamond disk was manufactured with $\varnothing 180$ mm
- The disk is ~ 1230 μm thick at center, in the range 1100 – 1150 μm at edge (2 mm thickness was the target)

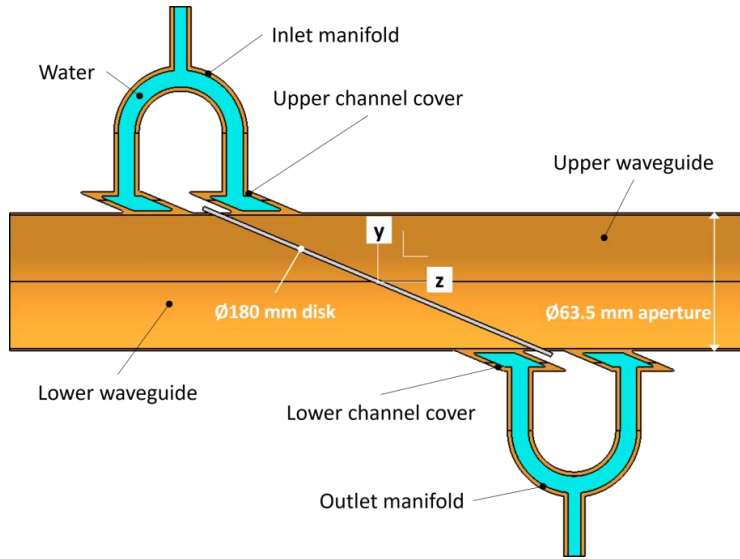


Numerical analyses

- Thermal, structural analyses
- Entire model of the window (no symmetry)
- Diamond disk with 1.1 mm thickness (lower bound value), 180 mm major axis and 95 mm minor axis
- Beam scenario: 2 MW @ 204 GHz
- Normal operation (NO): thermal loads, gravity and 10 bar coolant pressure
- Gaussian beam on EC gyrotron side (NO)
- HE_{11} mode beam on EC torus side (NO, overpressure with 1 and 2 bar)
- Macro for $\tan\delta$ distribution input
 - measurement at 102.4 GHz over $\varnothing 150$ mm disk area
 - one disk side polished, growth side
 - consideration of thickness variation

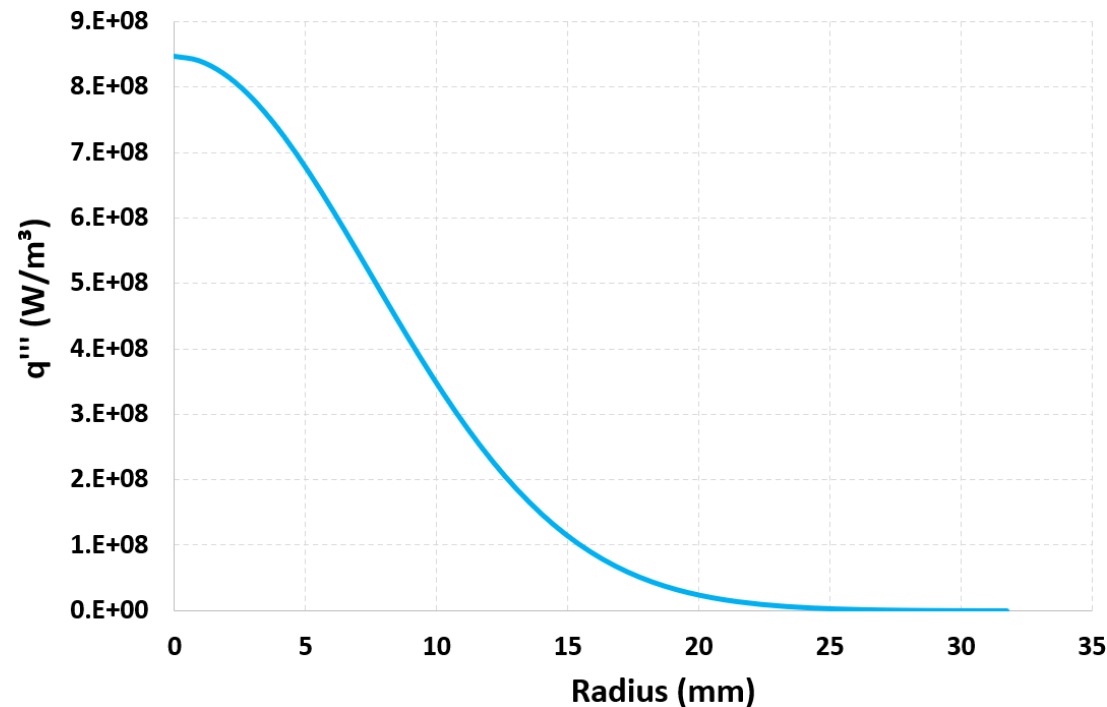


Previous analysis with uniform $\tan\delta$ value input



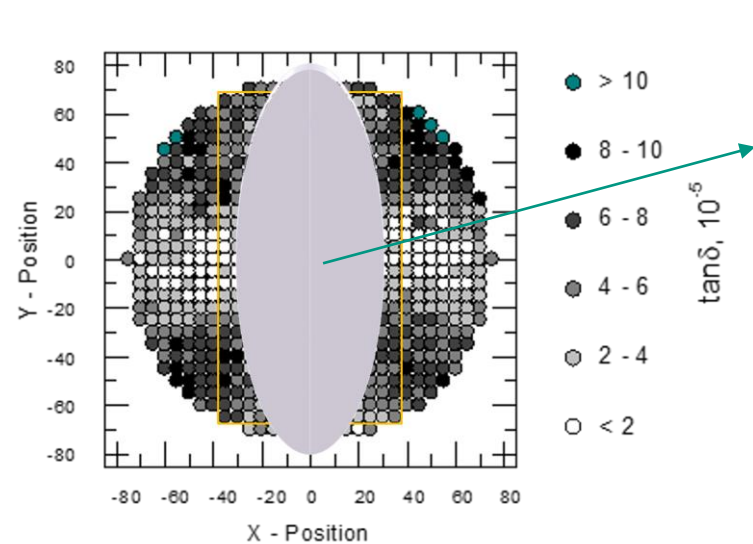
$$P_{abs} = \frac{P_{beam} 2 \pi \nu \sqrt{\epsilon_r} \tan\delta t}{c \sin(\theta_B)}$$

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

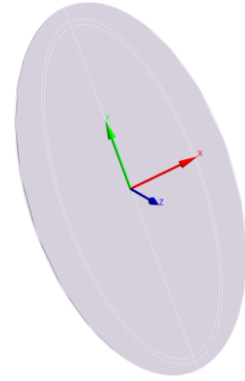


- 2 MW @ 204 GHz
- Beam radius $w_0 = 15$ mm
- Disk thickness $t = 2$ mm
- Uniform $\tan\delta = 3.5 \times 10^{-5}$ ($P_{abs} = 1546$ W)
- Heat generation load applied to disk as volumetric power density along radius according to a Gaussian beam

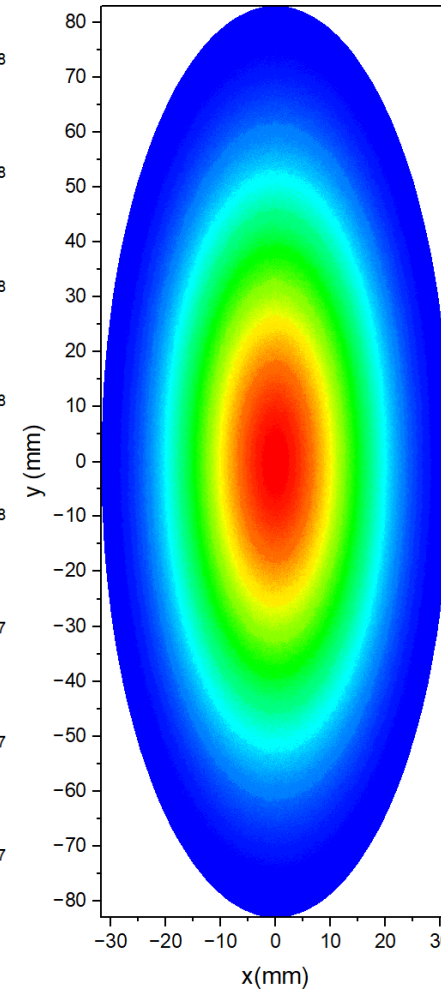
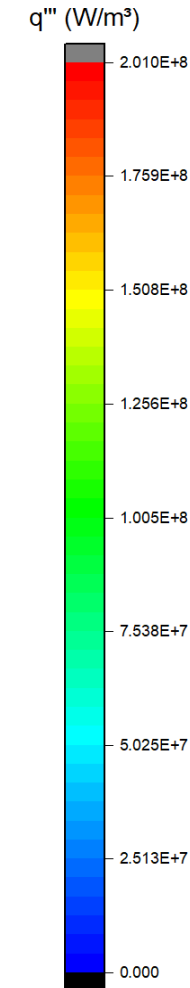
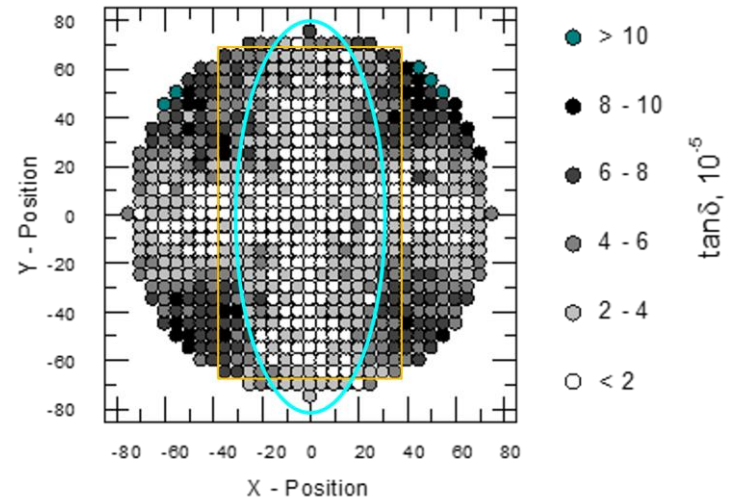
HE₁₁ mode: tanδ distribution input vs. uniform tanδ value



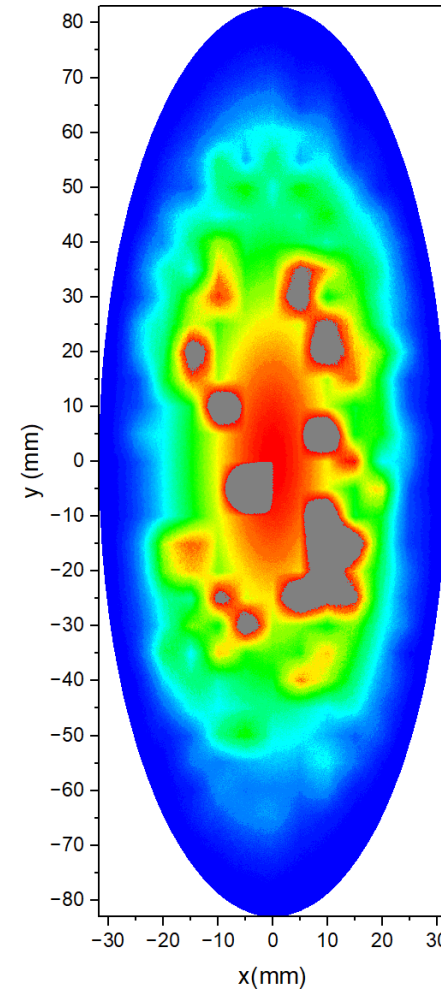
Region of the disk faced by the beam



- tanδ values from mapping are used to calculate the P_{abs} in each mesh element of the disk
- More realistic picture of the window performance
- Impact assessment performed by thermal and structural analyses with two tanδ values: 2×10^{-5} and 3×10^{-5}



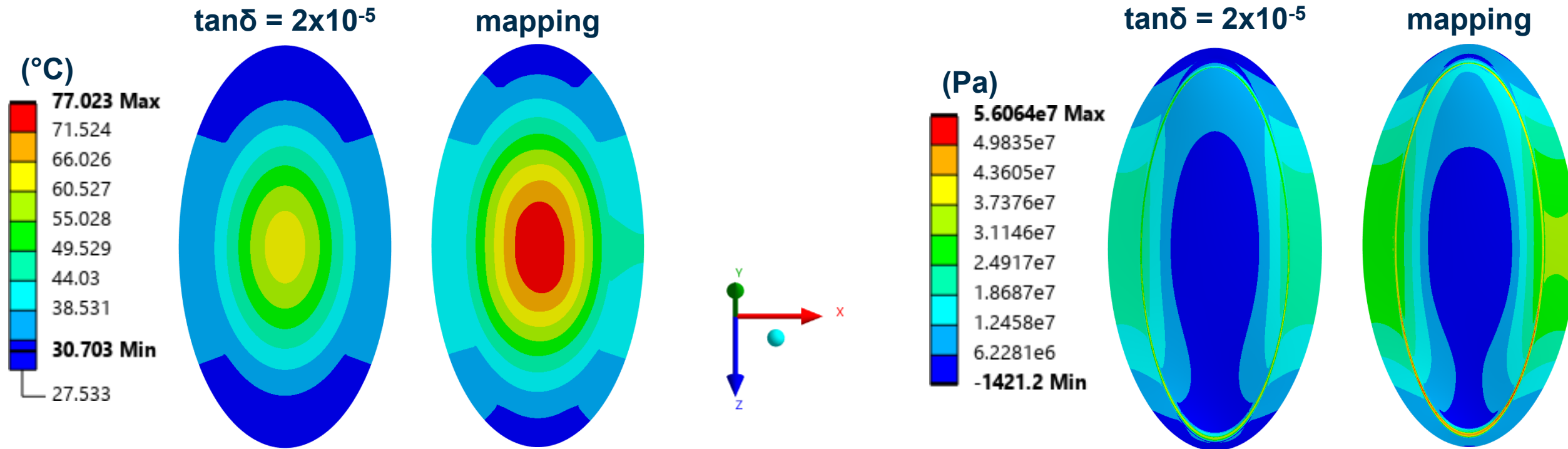
tanδ = 2×10^{-5}



tanδ mapping

HE₁₁ mode

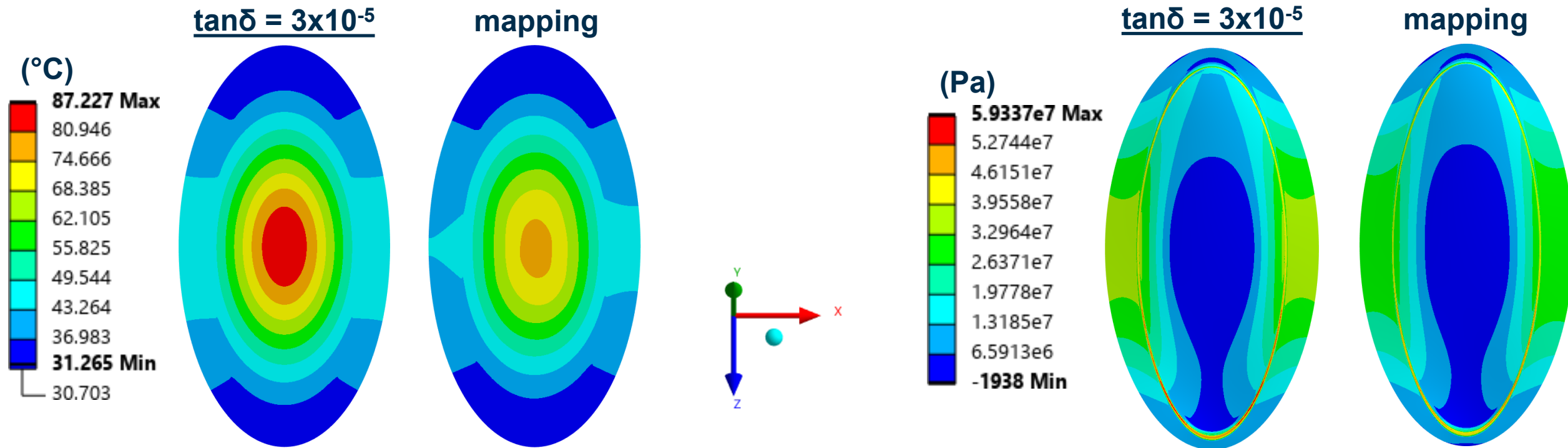
HE₁₁ mode, $\tan\delta = 2 \times 10^{-5}$ vs. $\tan\delta$ mapping input



- Thermal analysis with water at 20°C, $h = 5000 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$ (average from CFD analysis)
- Structural analysis with thermal loads only
- $P_{\text{abs}} = 486 \text{ W}$ by $\tan\delta = 2 \times 10^{-5}$, $P_{\text{abs}} = 670 \text{ W}$ by mapping (**184 W** difference)
- Max T and stress **lower** in $\tan\delta = 2 \times 10^{-5}$ case by $\sim 13^{\circ}\text{C}$ and $\sim 14 \text{ MPa}$, different distribution

HE₁₁ mode

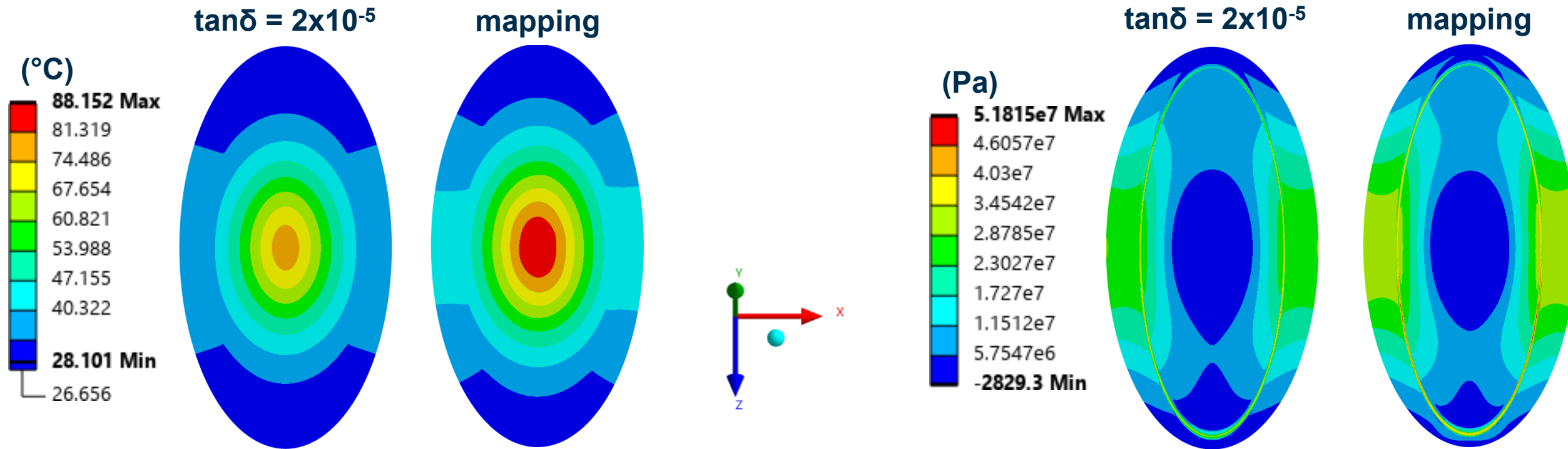
HE₁₁ mode, $\tan\delta = 3 \times 10^{-5}$ vs. $\tan\delta$ mapping input



- Thermal analysis with water at 20°C , $h = 5000 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$ (average from CFD analysis)
- Structural analysis with thermal loads only
- $P_{\text{abs}} = 729 \text{ W}$ by $\tan\delta = 3 \times 10^{-5}$, $P_{\text{abs}} = 670 \text{ W}$ by mapping (**59 W** difference)
- Max T and stress **greater** in $\tan\delta = 3 \times 10^{-5}$ case by $\sim 10^{\circ}\text{C}$ and $\sim 3 \text{ MPa}$, different distribution

HE₁₁ mode

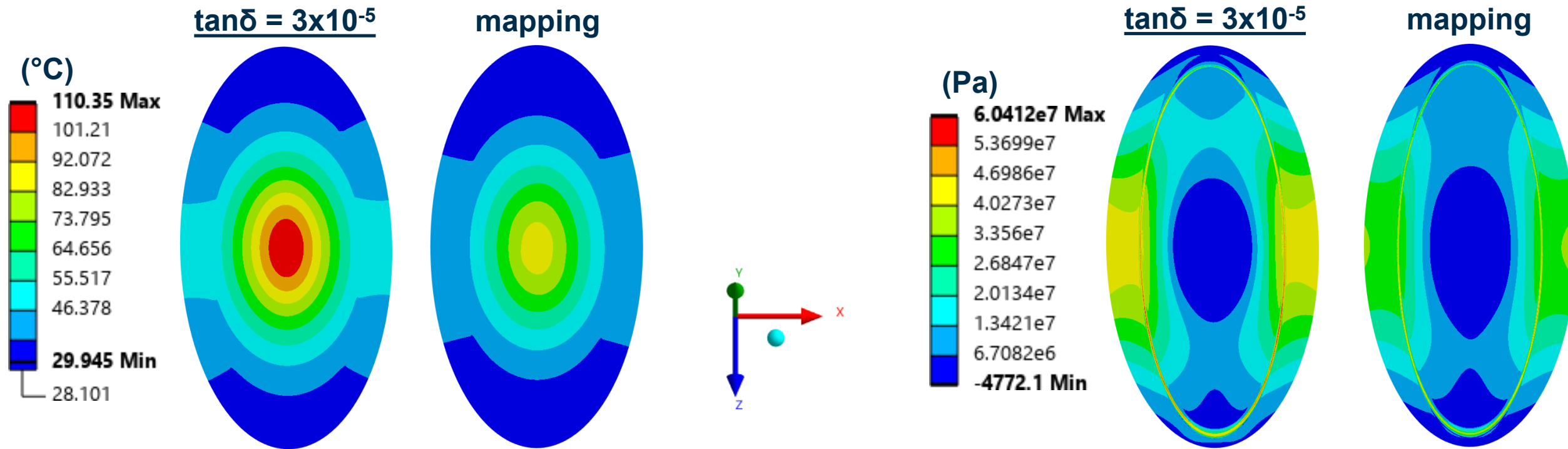
Gaussian mode, $\tan\delta = 2 \times 10^{-5}$ vs. $\tan\delta$ mapping input



- Thermal analysis with water at 20°C, $h = 5000 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$ (average from CFD analysis)
- Structural analysis with thermal loads only
- $P_{\text{abs}} = 486 \text{ W}$ by $\tan\delta = 2 \times 10^{-5}$, $P_{\text{abs}} = 589 \text{ W}$ by mapping (**103 W** difference)
- Max T and stress **lower** in $\tan\delta = 2 \times 10^{-5}$ case by $\sim 10^{\circ}\text{C}$ and $\sim 8 \text{ MPa}$, different distribution

Gaussian mode

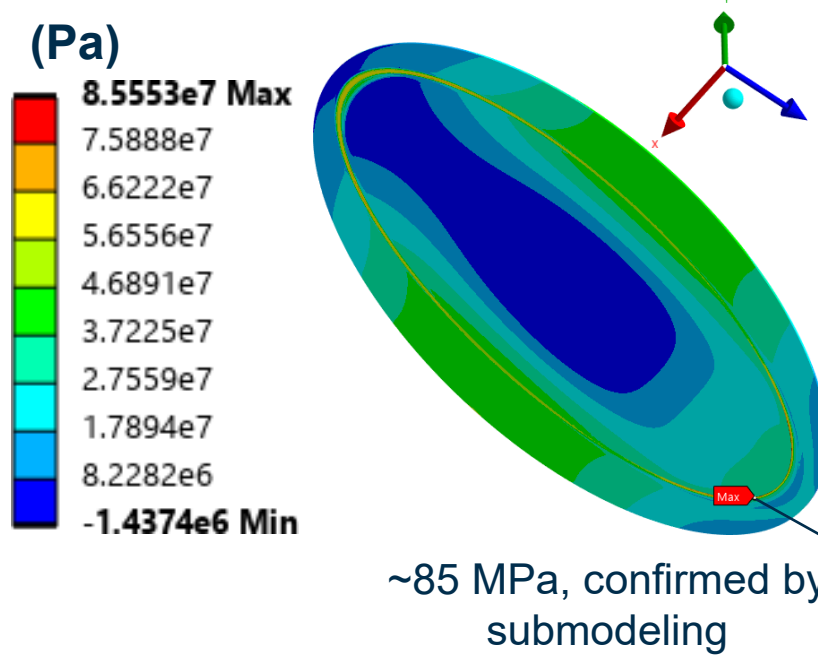
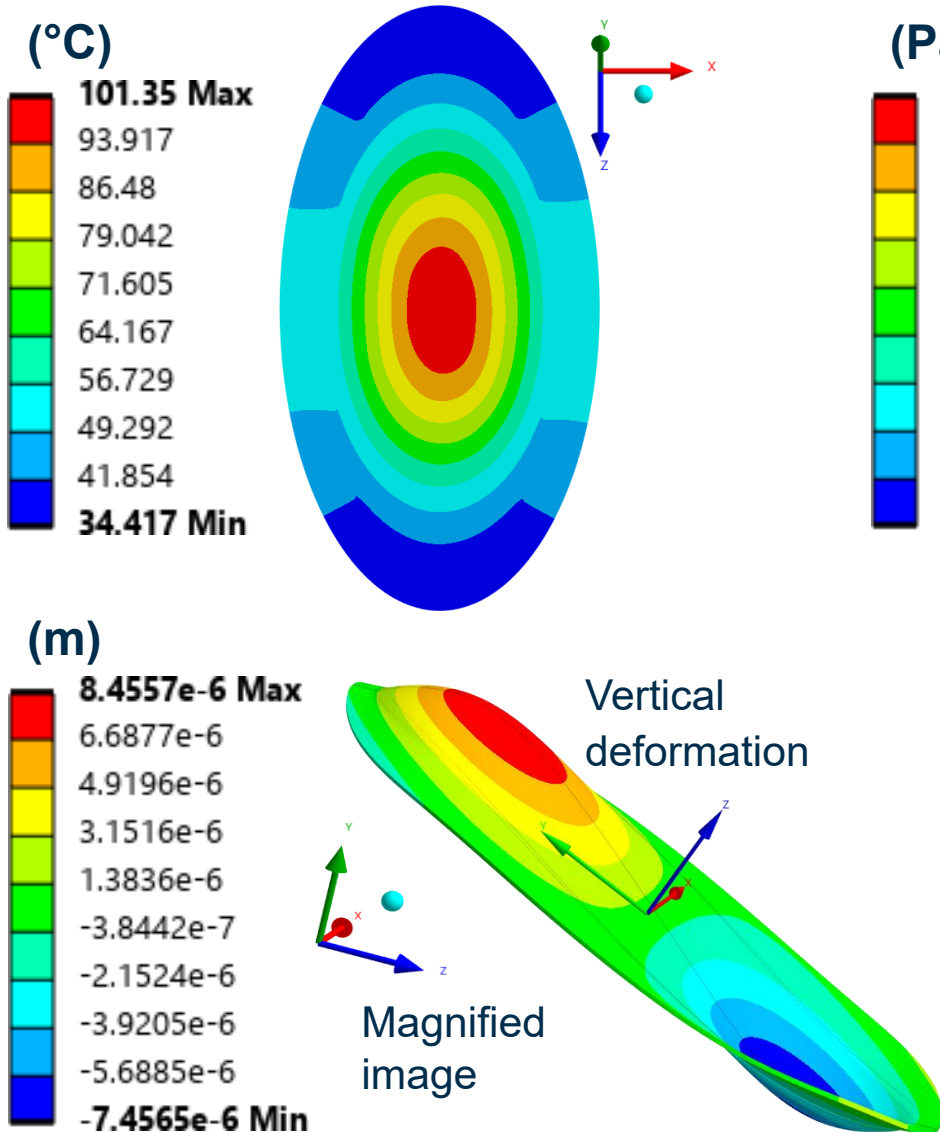
Gaussian mode, $\tan\delta = 3 \times 10^{-5}$ vs. $\tan\delta$ mapping input



- Thermal analysis with water at 20°C, $h = 5000 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$ (average from CFD analysis)
- Structural analysis with thermal loads only
- $P_{\text{abs}} = 729 \text{ W}$ by $\tan\delta = 3 \times 10^{-5}$, $P_{\text{abs}} = 589 \text{ W}$ by mapping (**140 W** difference)
- Max T and stress **greater** in $\tan\delta = 3 \times 10^{-5}$ case by $\sim 22^\circ\text{C}$ and $\sim 8 \text{ MPa}$, different distribution

Gaussian mode

Design verification, HE₁₁ mode beam, mapping + 1x10⁻⁵ (I)

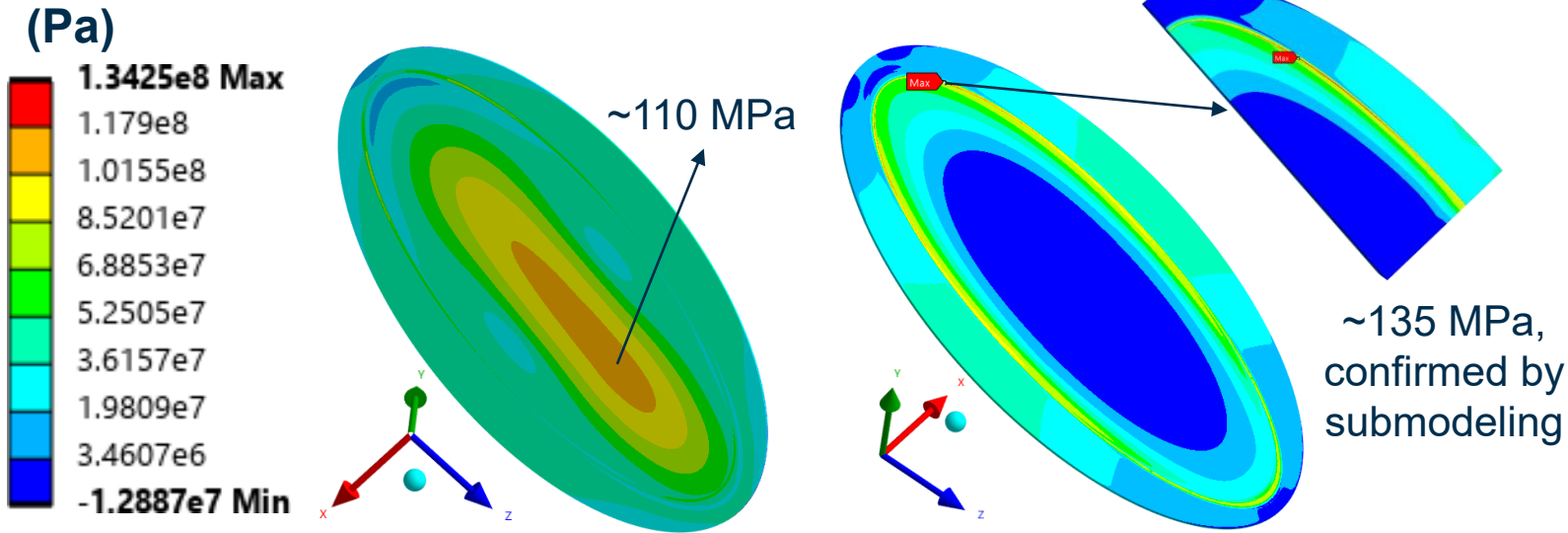


- tanδ mapping is used for a better picture of the window performance
- tanδ = 1x10⁻⁵ is added as safety margin against potential tanδ degradation
- **Normal Operation (NO)**
 - thermal loads, gravity, 10 bar coolant pressure

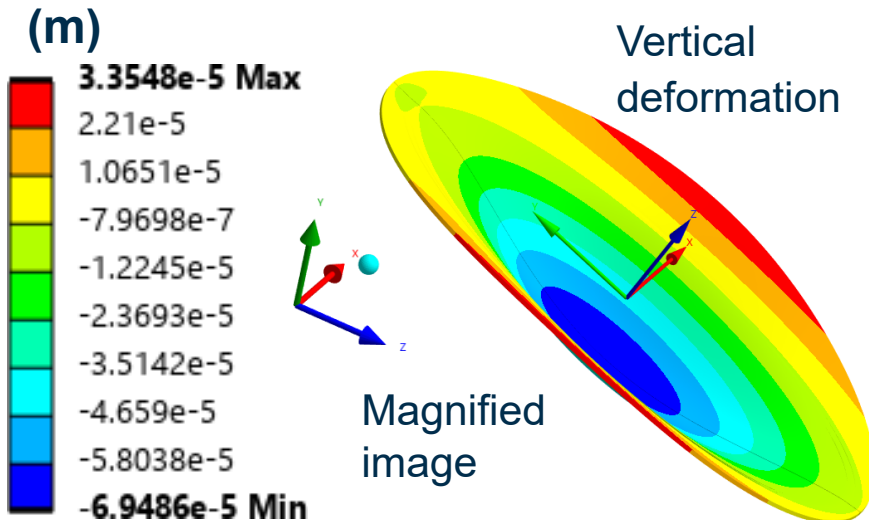
- $P_{abs} = 913 \text{ W}$
- Water at 20°C
- As expected, anti-symmetrical distribution of stress and deformation

HE₁₁ mode

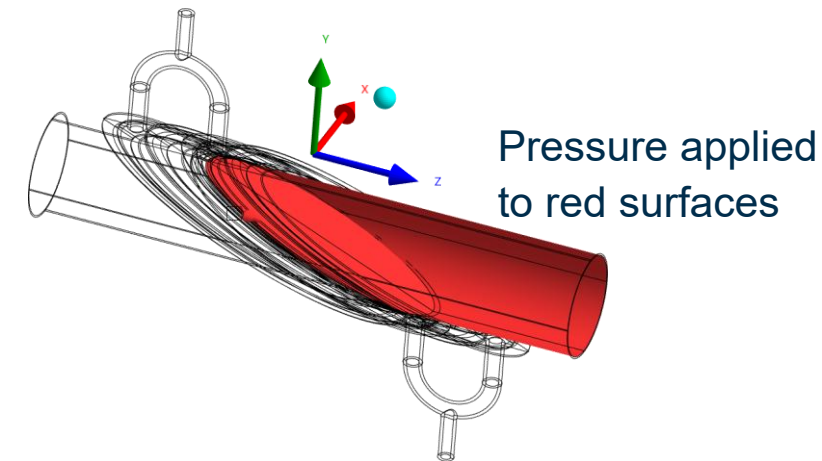
Design verification, HE₁₁ mode beam, mapping + 1x10⁻⁵ (II)



- tanδ mapping is used for a better picture of the window performance
- tanδ = 1x10⁻⁵ is added as safety margin against potential tanδ degradation
- **NO** (thermal loads, gravity, 10 bar coolant pressure)
- **NO + 1 bar** overpressure

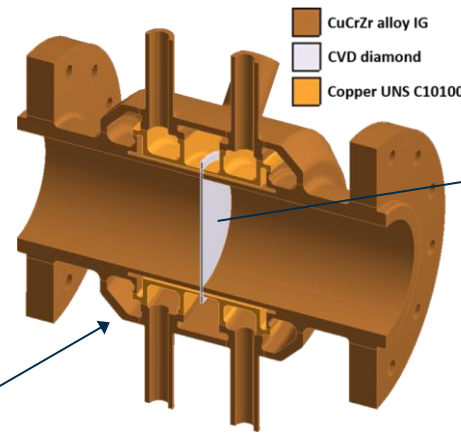
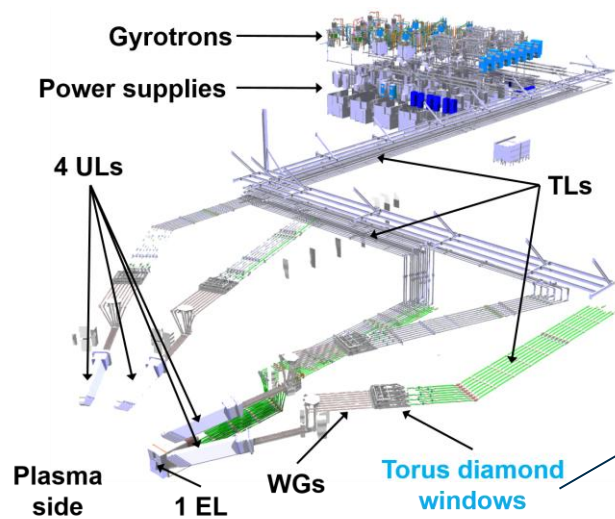


- Max stress is ~135 MPa, lower than the limit (150 MPa)
- The window design was verified according to the analysis assumptions
- Stress at tensile side > 200 MPa by 2 bar overpressure

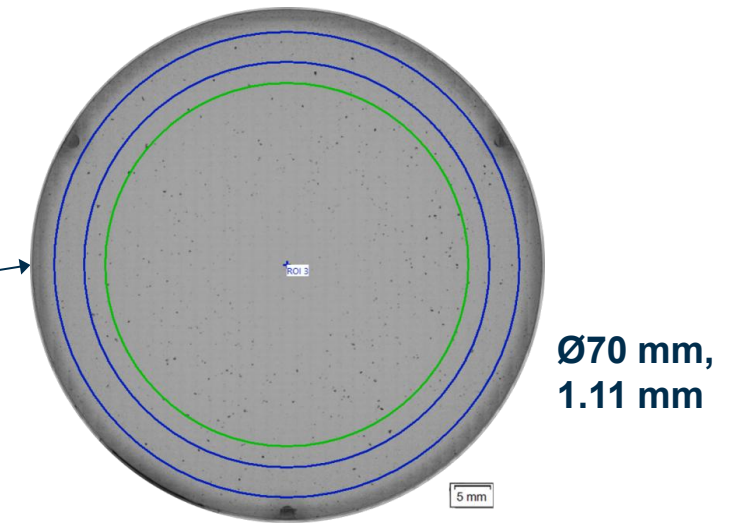


HE₁₁ mode

Fracture failure in the diamond disks



ITER EC H&CD
torus window

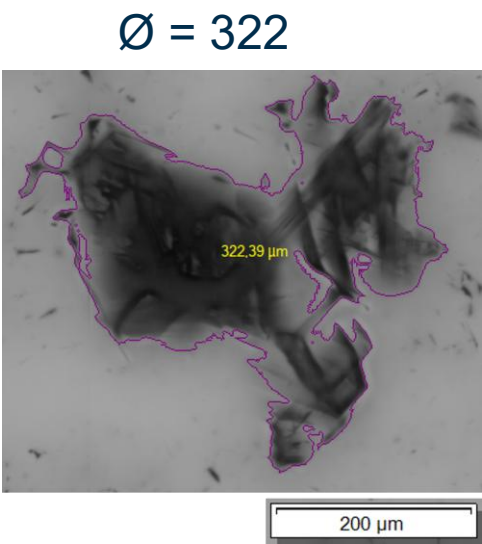
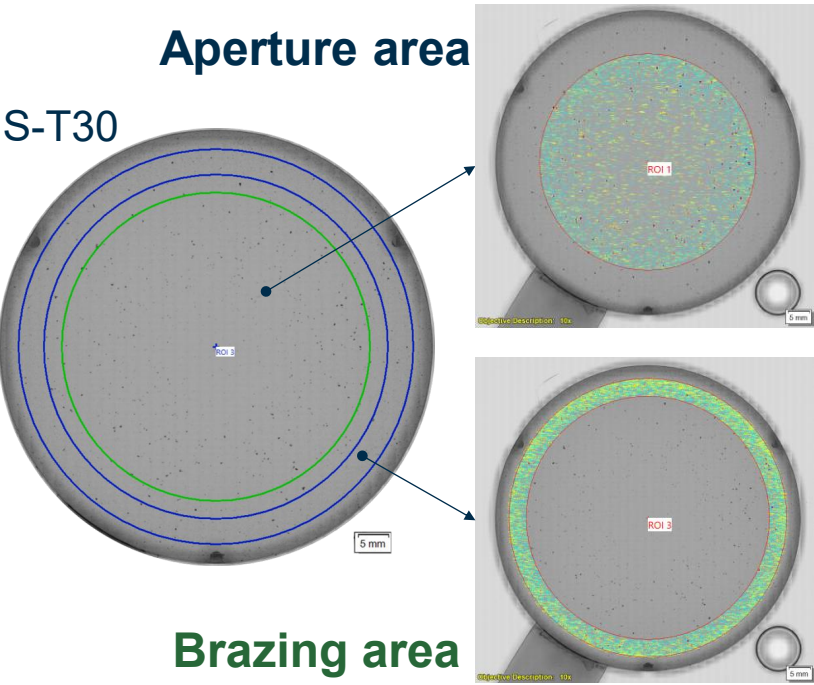


Fracture toughness (MPa m ^{1/2})	Error (MPa m ^{1/2})	Type of diamond	Thickness (µm)	Shape	Dimensions (mm)	# of samples	Test method	Code	Year
6.3	-	MPA CVD diamond	150 to 200	Disk	ø25	2	Tensile test	E-399	1995
5.6	0.4	MPA CVD diamond	150 to 200	-	-	8	Indentation		1995
5.3	1.3	MPA CVD diamond	400	-	-	11	Indentation		1991
8.7	0.3	MPA CVD diamond	880	Rectangular	13 x 18	-	Double torsion		1998
8.3	0.4	MPA CVD optical diamond	1000	Rectangular	13 x 18	5	Double torsion		2004
8.5	1	MPA CVD mechanical diamond	1000	Rectangular	13 x 18	2	Double torsion		2004
6.5	1.2	Arc-discharge CVD diamond	244 (aver.)	Disk	ø7 to ø16	5	Ball on ring		1992
7.6	1.8	Arc-discharge CVD diamond	244 (aver.)	Disk	-	4	Indentation		1992
8	-	Arc-discharge CVD diamond	485	Rectangular	2 x 10	9	Three-point	E-399	2000
9.2	-	Arc-discharge CVD diamond	485	Rectangular	2 x 10	8	Three-point	E-399	2000
4.6	-	Arc plasma jet CVD	300 to 700	Disk	ø8	-	Ball on ring		1998
6	-	CVD diamond	300	-	-	-	Indentation		1994
6.8	1.1	Arc plasma jet/hot filament CVD	450	Rectangular	2,5 x 12	3	Three-point	E-399	2001

- Safety important role of diamond disks on EC torus side
- Qualification of the disks based on $\tan\delta$ measurements only
- Failure to fracture is the main failure mode of the disks
- Limited work in literature for the fracture toughness parameter of MPA CVD diamond

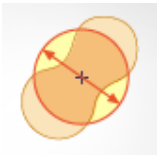
Microscopy activity

- Development of a specific procedure for **60 ITER torus disks** (Ø70 mm, 1.11 mm)
- Extended Focal Imaging (EFI)
 - A single image
 - Microfeatures info on disk surface



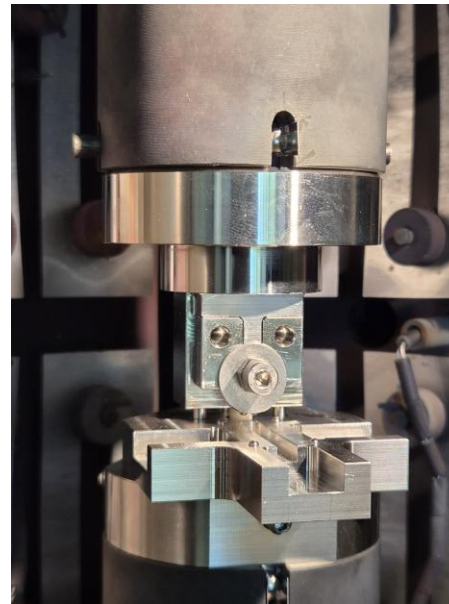
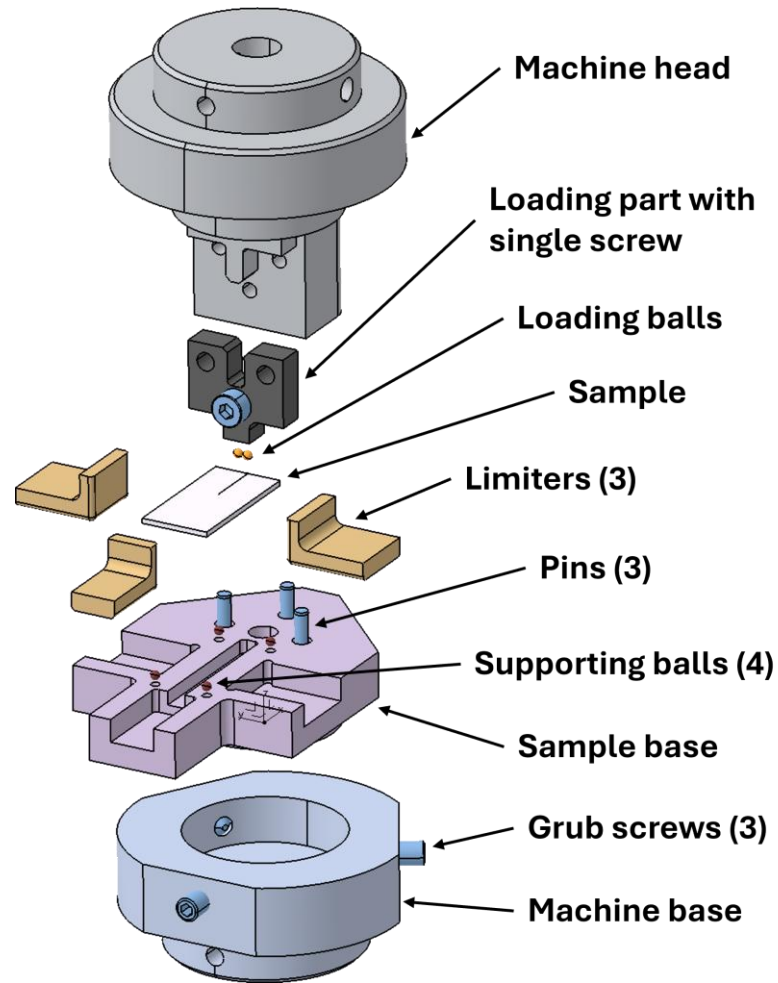
Brazing area

Equivalent diameter criterion



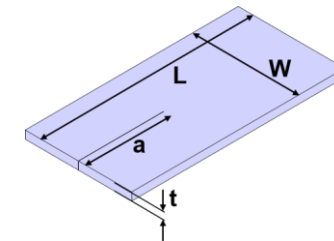
Disks/Ranges (μm)	100 - 150	150 - 200	200 - 250	250 - 300	300 - 600
S-T02	565	134	43	8	5
S-T03	321	62	14	4	2
S-T04	100	16	8	5	1
S-T05	475	85	32	7	1
S-T06	27	17	9	4	0
S-T17	1230	422	192	67	43
S-T09	342	82	14	5	3
S-T12	261	102	25	13	5
S-T08	164	27	15	10	1
S-T10	108	14	6	0	0
S-T13	82	13	4	2	1
S-T15	482	142	42	22	7
S-T16	80	10	1	1	0
S-T19	1422	580	255	102	64
...	...	...	...	...	...
S-T38	239	52	19	5	4
S-T40	793	206	73	29	26
S-T44	288	71	13	4	3
S-T25	1543	718	346	161	227
S-T39	180	46	7	3	1
S-T41	287	69	16	8	1
S-T45	467	149	43	19	10
S-T46	160	32	9	2	0
S-T47	529	119	37	12	5
S-T42	62	14	4	6	0
S-T48	177	34	7	6	1
S-T49	40	23	1	1	1
S-T50	172	31	12	4	2
S-T52	485	101	21	2	3
S-T54	56	17	7	2	1
S-T43	87	8	1	0	0
S-T53	248	38	13	1	1
S-T55	1068	302	82	27	10
S-T56	27	3	0	0	1
S-T60	276	49	12	0	2
S-T61	27	5	0	0	0
S-T51	212	30	7	3	1
S-T57	456	101	21	8	1
S-T58	689	222	82	24	14
S-T59	385	57	18	7	2
S-T62	57	7	3	1	0
S-T63	144	30	10	3	1
Average	361	103	37	14	11

Double torsion method



Diamond samples ID	Critical load (N)	K_{Ic} (MPa m ^{1/2})	Angular deviation (°)
Thermal #1	-158.9	9.2	6.3
Thermal #3	-153.5	8.9	4.0
Thermal #5	-150.7	8.8	10.3
Thermal #8	-148.3	8.5	7.9
Thermal #11	-163.3	9.6	8.0
Thermal grade average	-154.9 ± 5.4	9.0 ± 0.4	
Optical #2	-138.2	8.0	7.4
Optical #3	-139.9	8.1	9.3
Optical #4	-136.9	7.9	1.3
Optical #5	-137.4	7.9	8.6
Optical grade average	-138.1 ± 1.2	8.0 ± 0.1	

- Fracture toughness (K_{Ic}) of diamond measured at KIT
- Double torsion method
- Custom test setup developed in-house (no C&S available)
- Consistency with ITER disks
- Ad hoc pre-cracking solution for diamond specimens
- Good agreement with the limited literature data for optical grade diamond

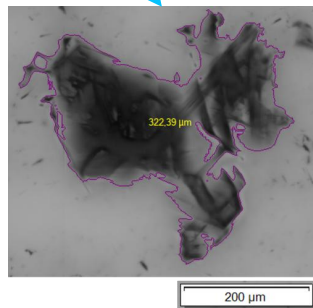
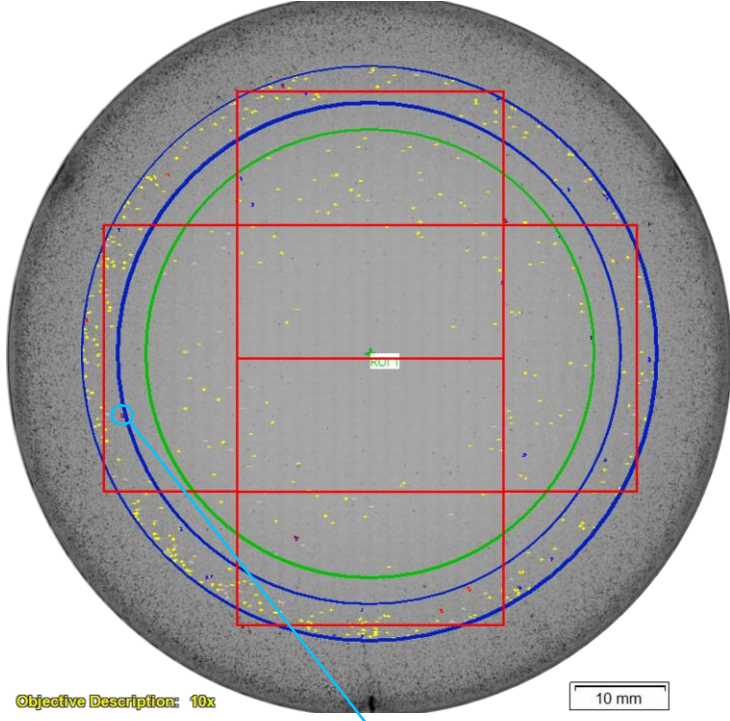


$L = 30 \text{ mm}$
 $W = 15 \text{ mm}$
 $t = 1.1 \text{ mm}$
 $a \sim 11 \text{ mm}$

$$K_{Ic} = P_c S_m \left(\frac{3(1 + \nu)}{W t^4} \right)^{1/2}$$

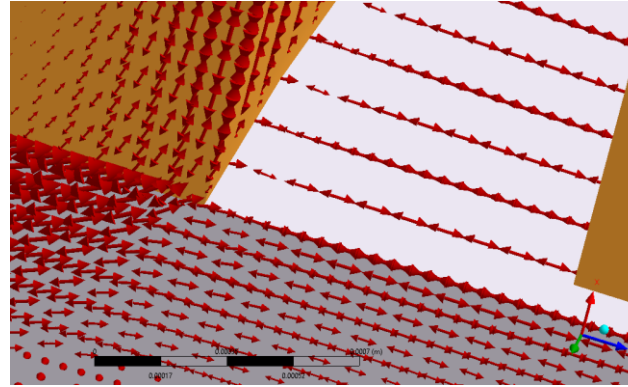
P_c – critical load
 S_m – moment arm
 ν – Poisson's ratio

Preliminary structural integrity assessment



Ø ~ 320 μm

Stress
vector plot



$$\sigma_0 \sim 84 \text{ MPa}$$

$$a \sim 160 \text{ μm}$$

$$\beta \sim 1 \text{ (first order)}$$

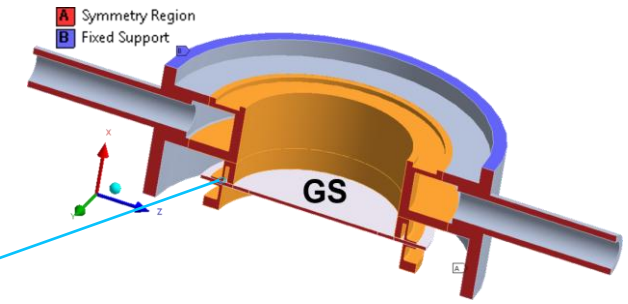
$$K_I = \beta \sigma_0 (\pi a)^{1/2}$$

$$K_I \sim 1.9 \text{ MPa m}^{1/2}$$

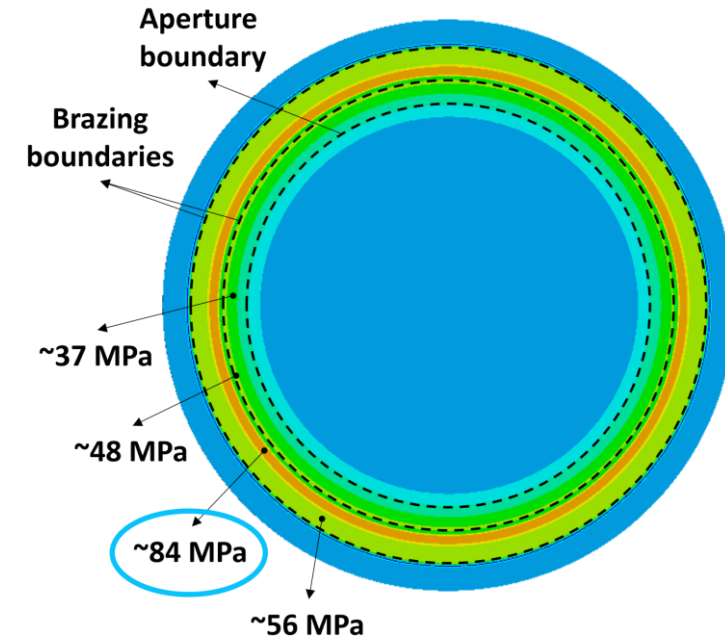
$$K_{Ic} = 8.0 \pm 0.1 \text{ MPa m}^{1/2}$$

$$K_I \leq K_{Ic}$$

No crack propagation occurs



Maximum principal stress on disk growth side for normal operating conditions + 2 bar



Conclusions and next steps

- Brewster-angle window design was successfully verified for the manufactured 1.1 mm thick, Ø180 mm diamond disk
 - Measured $\tan\delta$ distribution in the disk as input to the analyses enables a more realistic assessment of window performance
 - Structural integrity assessment of the diamond disks shall be based on fracture mechanics
-
- Raman spectroscopy and polarimetry for characterization of the large diamond disk
 - Continuation of structural integrity assessment of diamond disks
 - Detailed microscopy activity of the fractured diamond specimens to investigate crack paths

Thanks for your kind attention!



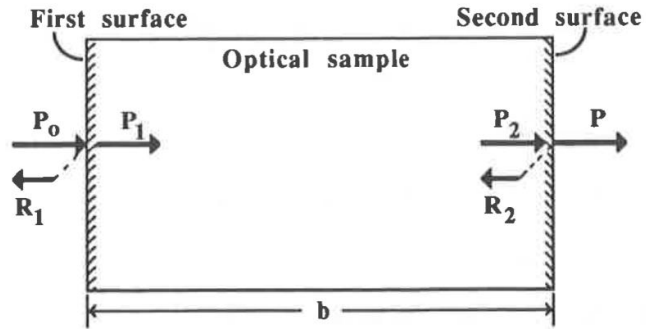
This work has been supported by Fusion for Energy under the contract No. F4E-OFC-842-SC03. The views and opinions expressed herein reflect only the author's views. Fusion for Energy and ITER Organization are not liable for any use that may be made of the information contained therein. This work has been carried out also within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No. 101052200 — EUROfusion). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

The authors are grateful to Diamond Materials GmbH & Co. KG for providing the diamond disks and to IAM – MMI institute at KIT for conducting the experiments of fracture toughness at their laboratories.

Backup slides



Loss tangent measurements

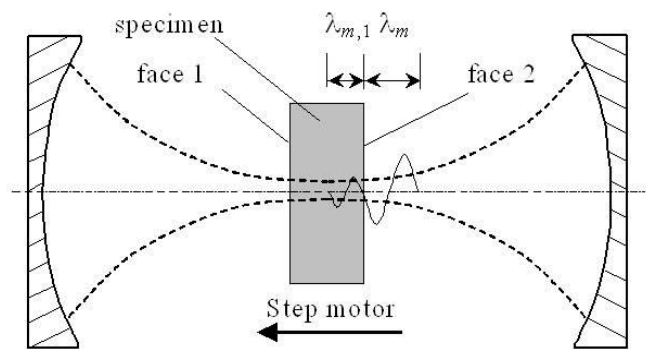


$$\frac{P_2}{P_1} = e^{-\alpha b}$$

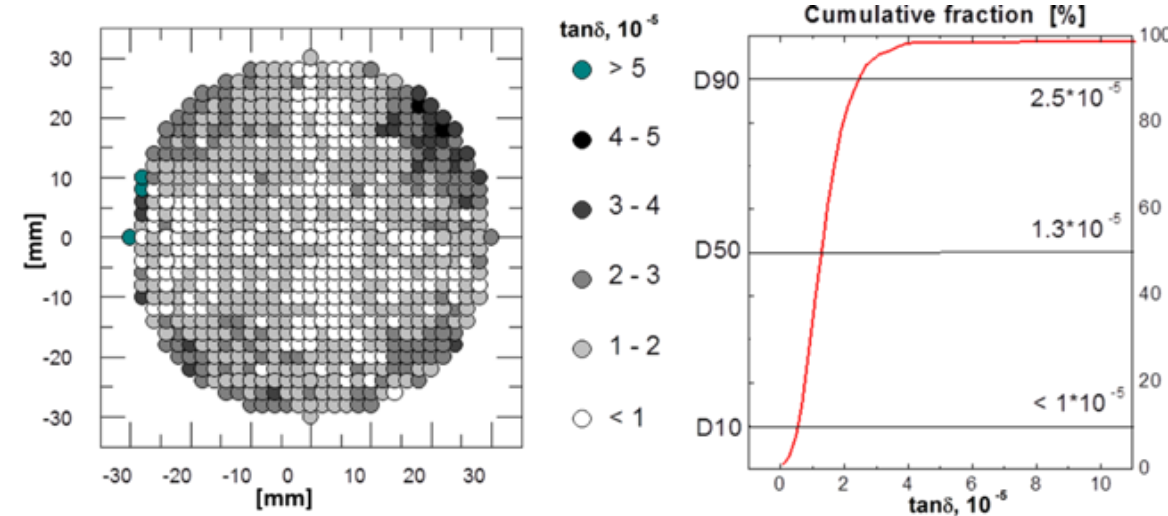
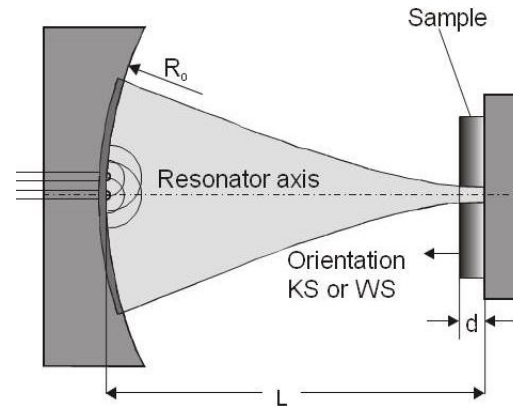
$$\frac{P_2}{P_1} = e^{-\left[\left(\frac{2\pi}{\lambda}\right)\tan\delta\right]b}$$

- Fabry-Perot resonators to measure the $\tan\delta$ of the diamond disks
- Parameterization of $\tan\delta$ distribution
- Acceptance criteria for ITER disks:
 - $\tan\delta = 3.5 \times 10^{-5}$ for the D50
 - $\tan\delta = 6.0 \times 10^{-5}$ for the D90

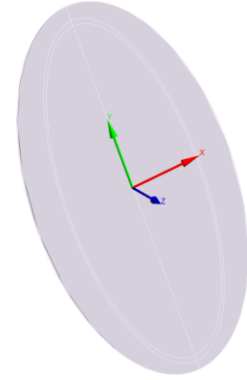
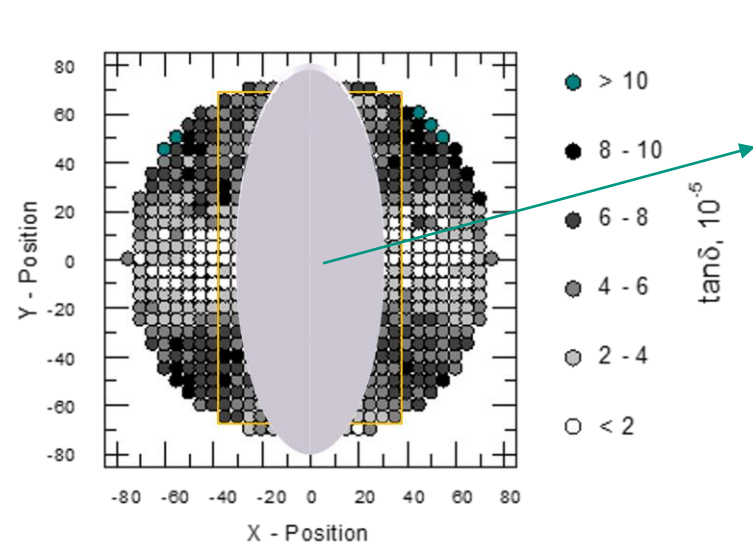
Spherical setup



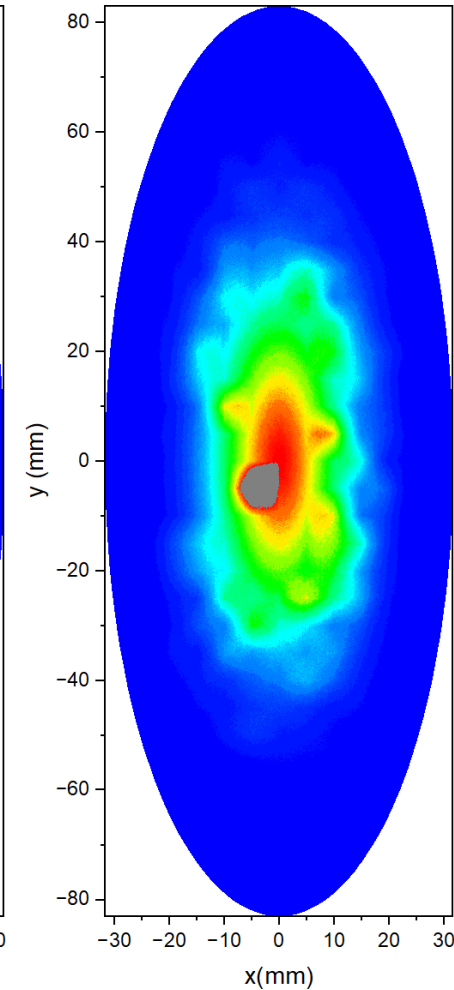
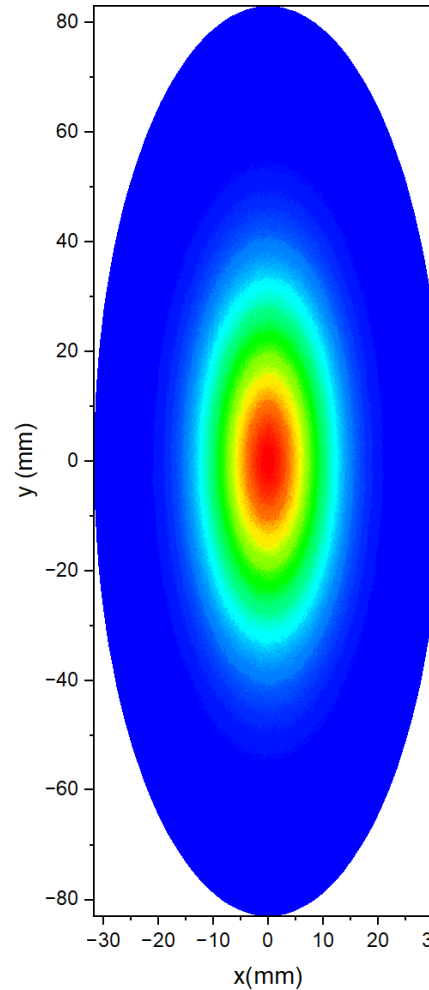
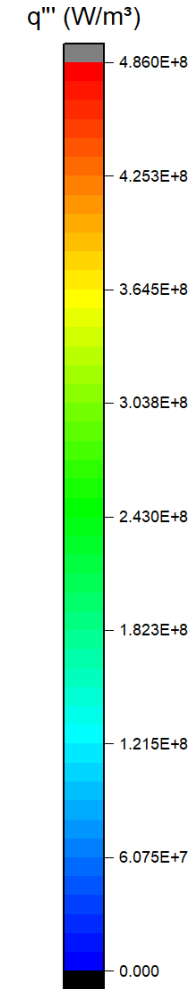
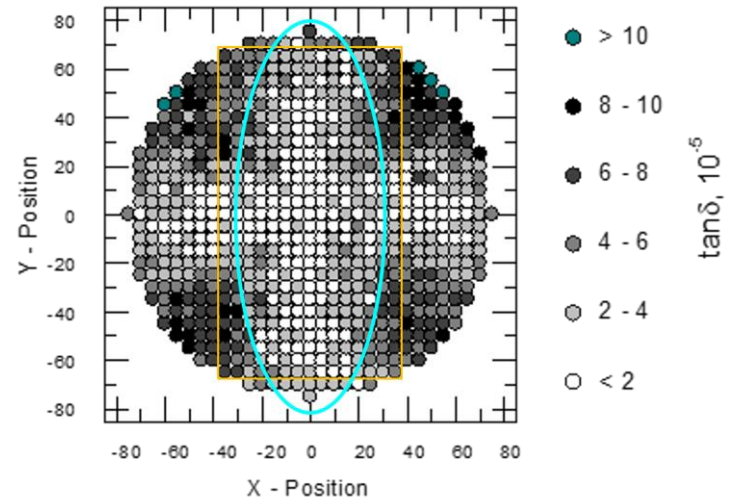
Hemispherical setup



Gaussian: $\tan\delta$ distribution input vs. uniform $\tan\delta$ value

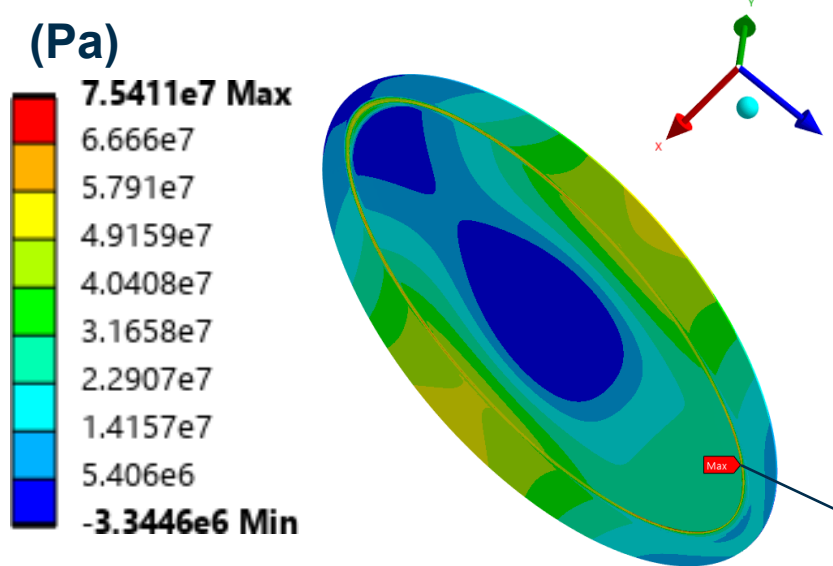
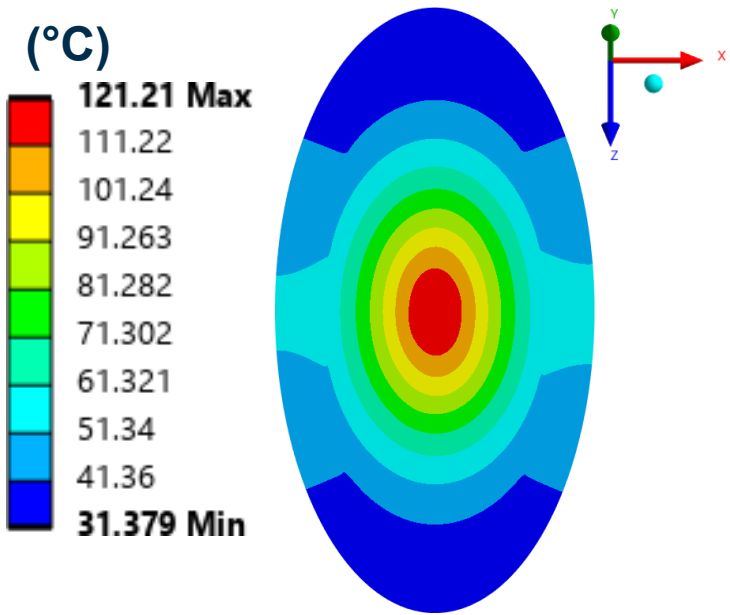


- $\tan\delta$ values from mapping are used to calculate the P_{abs} in each mesh element of the disk
- More realistic picture of the window performance
- Impact assessment performed by thermal and structural analyses with two $\tan\delta$ values: 2×10^{-5} and 3×10^{-5}

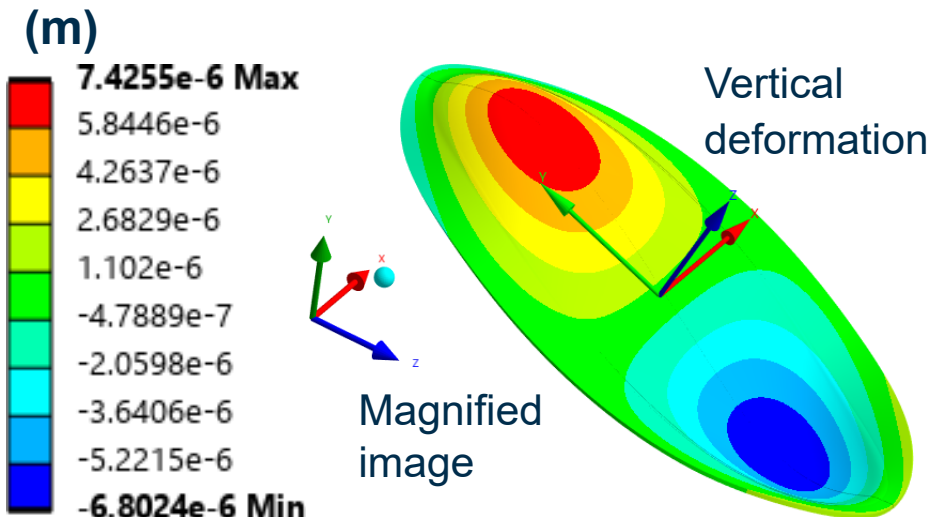


Gaussian mode

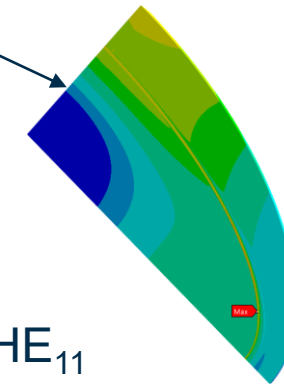
Design verification, Gaussian beam, mapping + 1×10^{-5}



- tanδ mapping is used for a better picture of the window performance
- tanδ = 1×10^{-5} is added as safety margin against potential tanδ degradation
- **NO** (thermal loads, gravity, 10 bar coolant pressure)



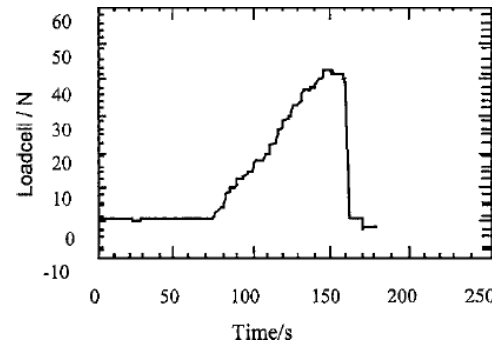
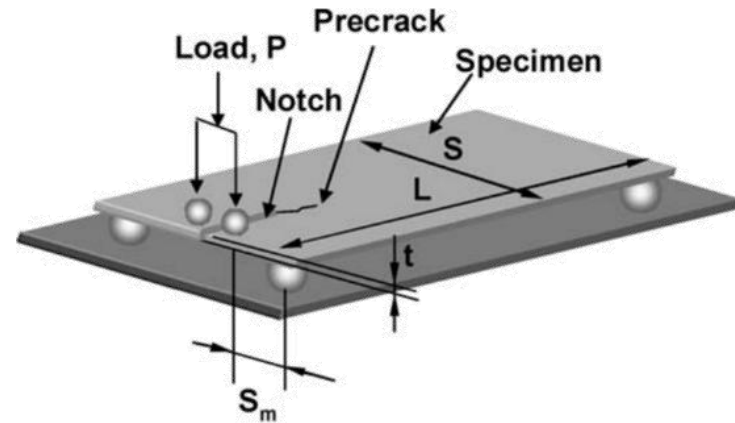
- $P_{abs} = 832 \text{ W}$ (~80 W less than HE₁₁ case, T higher of ~20°C)
- Water at 20°C
- The window design was verified according to the analysis assumptions



Max stress of
~75 MPa, confirmed
by submodeling

Gaussian mode

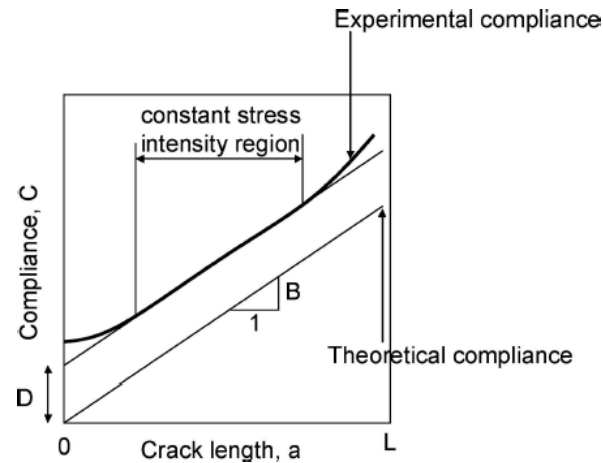
Double torsion method: the choice



Plane strain

$$K = P S_m \left(\frac{3}{S t^4 (1 - \nu) \psi} \right)^{1/2}$$

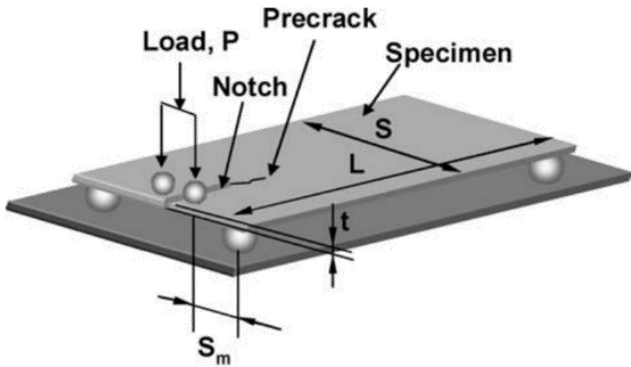
$$\psi = 1 - 0.6302\tau + 1.20\tau \exp(-\pi/\tau)$$



- Method to determine K_{Ic} and slow crack growth behaviour (SCG curve)
- The method has not been standardized yet
- However, applied to a very extensive range of materials: ceramics, glasses, composites, steels, diamond (CVD, PDC)
- Key features:
 1. A relatively simple method (specimen and loading)
 2. K_I independent of crack length for a certain range (linear crack length – compliance relationship)
 3. Ideal method for opaque materials
 4. Relative stability of crack extension for SCG studies

A. Shyam et al., J. Mater Sci 41, 2006

Double torsion method: some aspects

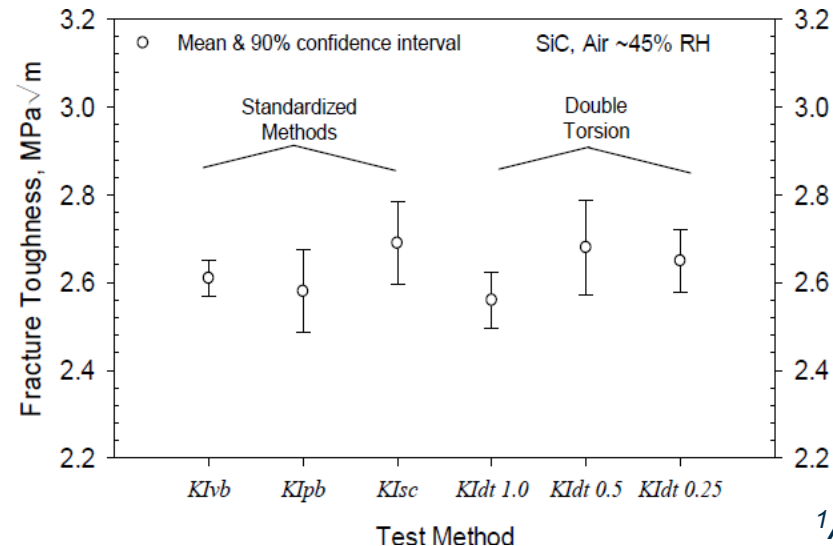


Assumptions in DT testing

- Mode I loading (good agreement¹ with mode I values by other techniques)
- Torsion bars deform independently with no contact stresses and negligible deflection beyond the crack tip
- Symmetric torsion loading and sample geometry about the crack plane

Key points for DT testing

- Pre-crack tip in the constant K region
- Very thin samples (with respect to width)
- A well aligned loading fixture (no guiding grooves on the samples)



Good agreement²
between ASTM
C1421 and DT
testing for various
thickness of α SiC
(R-flat as diamond)

¹A.G. Evans, *J. Mater Sci* 7, 1972

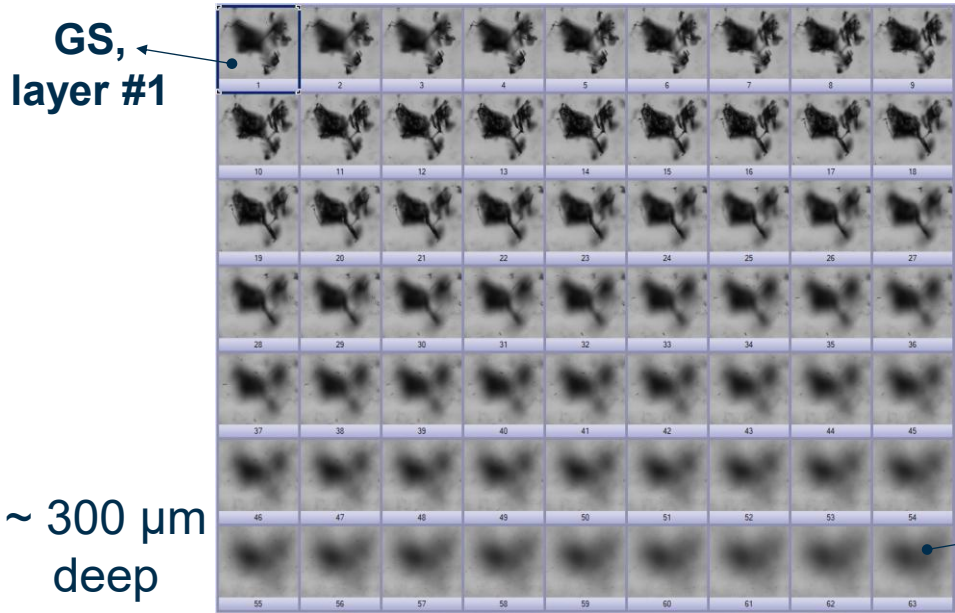
²J.A. Salem et al., 42nd ICACC, 2018

Microscopy – procedure - ITER

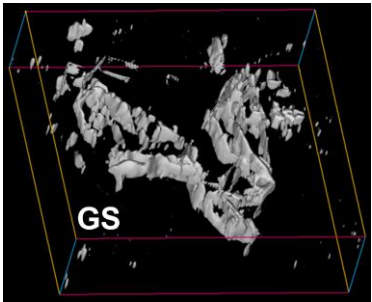
- Development of a specific procedure for **60 disks** (Ø70 mm, 1.11 mm)
- 2 types of scans on the entire disk

Multi-layers

- A z-stack of images
- Microfeatures depth info



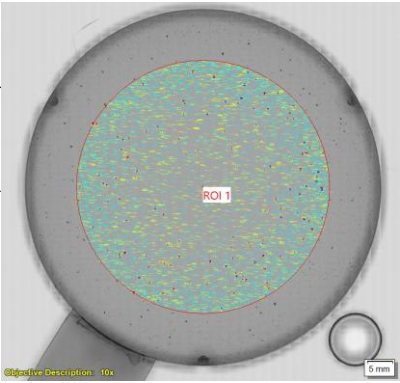
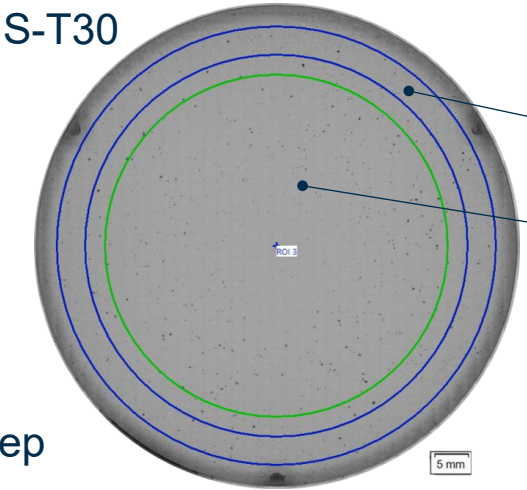
Microcrack ~ 300 µm deep



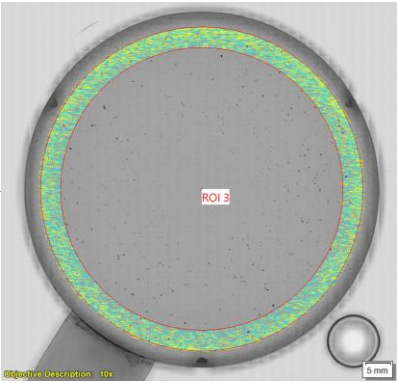
NS, layer #63

Extended Focal Imaging (EFI)

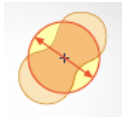
- A single image
- Microfeatures info on disk surface



Aperture area

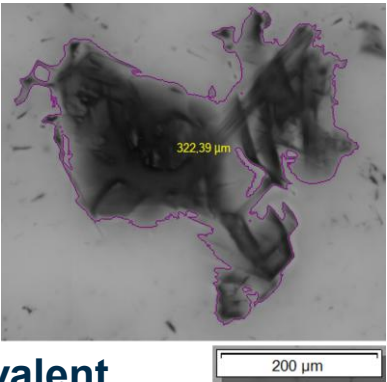


Brazing area



322 µm

Equivalent Diameter



447 µm

Maximum Extension

