On the fracture toughness and structural integrity assessment of MPA CVD diamond in nuclear fusion devices

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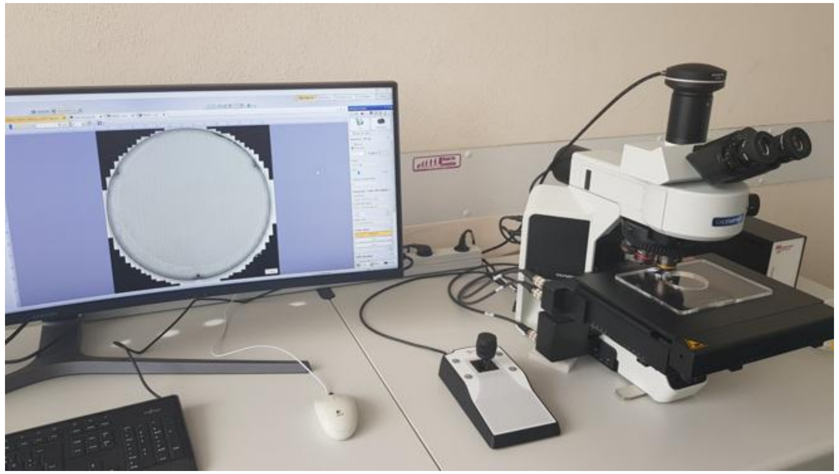
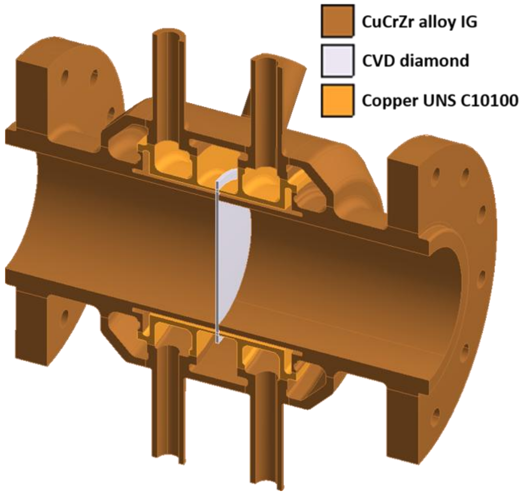
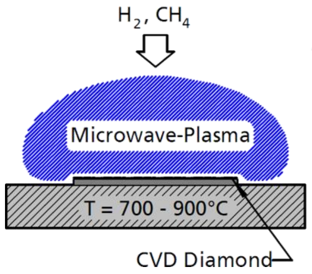
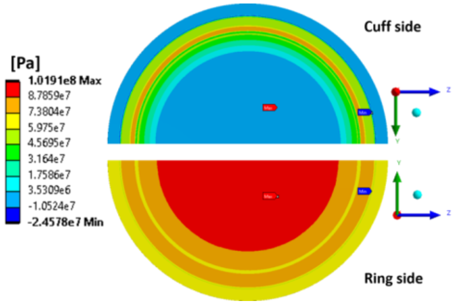
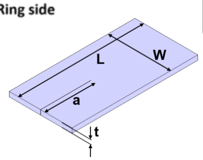
15.05.2025

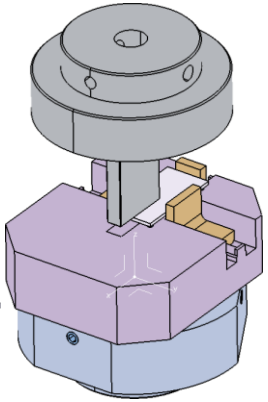






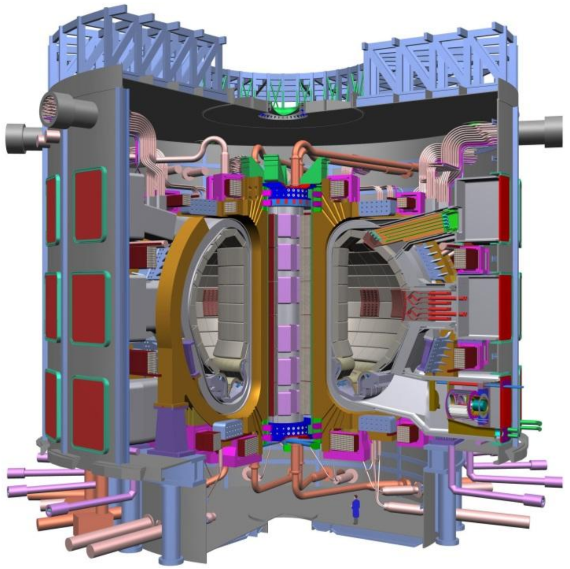


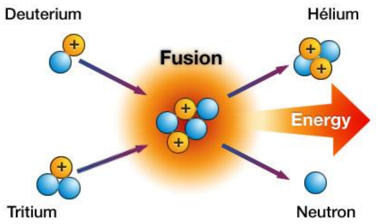




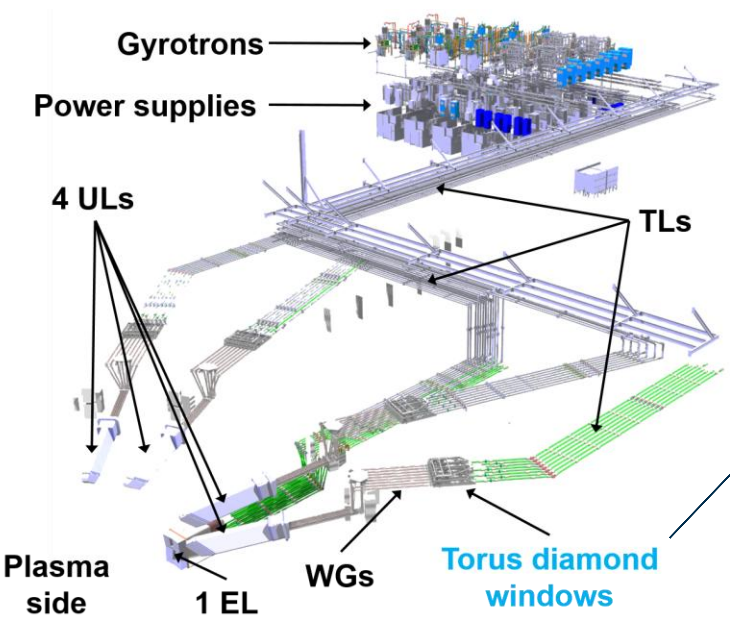
Content

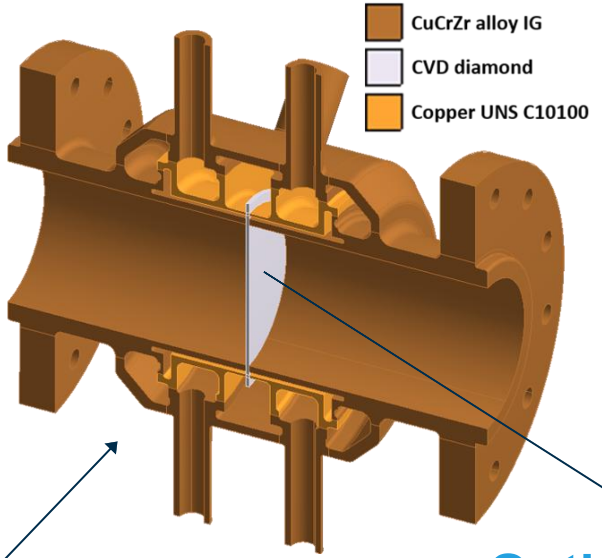
Context and motivation (ITER)



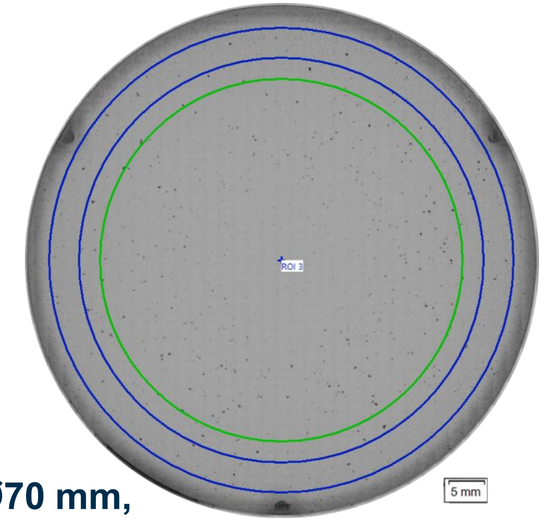


EC H&CD system





Optical quality polycrystalline MPA CVD diamond disk



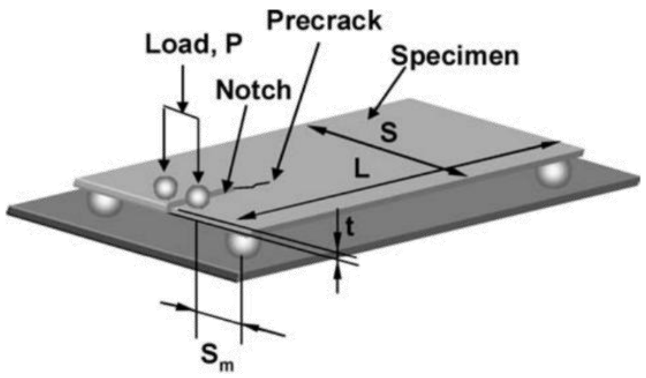
Ø70 mm,
1.11 mm

- Safety important role of diamond disks
- Failure to fracture
- Limited work in literature for fracture toughness

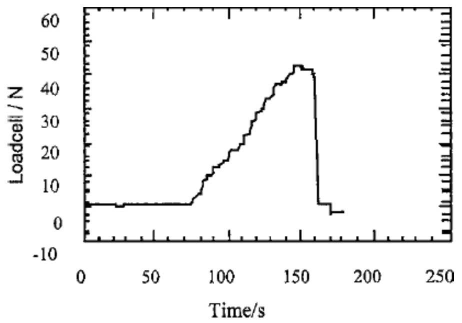
Fracture toughness (K_{IC}) of diamond - literature

Fracture toughness (MPa $m^{1/2}$)	Error (MPa $m^{1/2}$)	Type of diamond	Thickness (µm)	Shape	Dimensions (mm)	# of samples	Test method	Code	Papers no.	Year
6.3	**-**	**MPA CVD diamond**	**150 to 200**	**Disk**	**⌀25**	**2**	**Tensile test**	**E-399**	**10, 1**	**1995**
5.6	**0.4**	**MPA CVD diamond**	**150 to 200**	**-**	**-**	**8**	**Indentation**		**10**	**1995**
5.3	**1.3**	**MPA CVD diamond**	**400**	**-**	**-**	**11**	**Indentation**		**6**	**1991**
8.7	**0.3**	**MPA CVD diamond**	**880**	**Rectangular**	**13 x 18**	**-**	**Double torsion**		**8**	**1998**
8.3	**0.4**	**MPA CVD optical diamond**	**1000**	**Rectangular**	**13 x 18**	**5**	**Double torsion**		**3**	**2004**
8.5	**1**	**MPA CVD mechanical diamond**	**1000**	**Rectangular**	**13 x 18**	**2**	**Double torsion**		**3**	**2004**
6.5	1.2	Arc-discharge CVD diamond	244 (aver.)	Disk	⌀7 to ⌀16	5	Ball on ring		5	1992
7.6	1.8	Arc-discharge CVD diamond	244 (aver.)	Disk	-	4	Indentation		5	1992
8	-	Arc-discharge CVD diamond	485	Rectangular	2 x 10	9	Three-point	E-399	7	2000
9.2	-	Arc-discharge CVD diamond	485	Rectangular	2 x 10	8	Three-point	E-399	7	2000
4.6	-	Arc plasma jet CVD	300 to 700	Disk	⌀8	-	Ball on ring		13	1998
6	-	CVD diamond	300	-	-	-	Indentation		2	1994
6.8	1.1	Arc plasma jet/hot filament CVD	450	Rectangular	2,5 x 12	3	Three-point	E-399	12	2001
3.4	-	Natural diamond type Ia and IIa	-	-	-	9	Indentation		4	1981
13	-	PDC - cobalt phase	700 (aver.)	Rectangular	~15 x 30	5	Double torsion		11	1994

Double torsion (DT) method



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

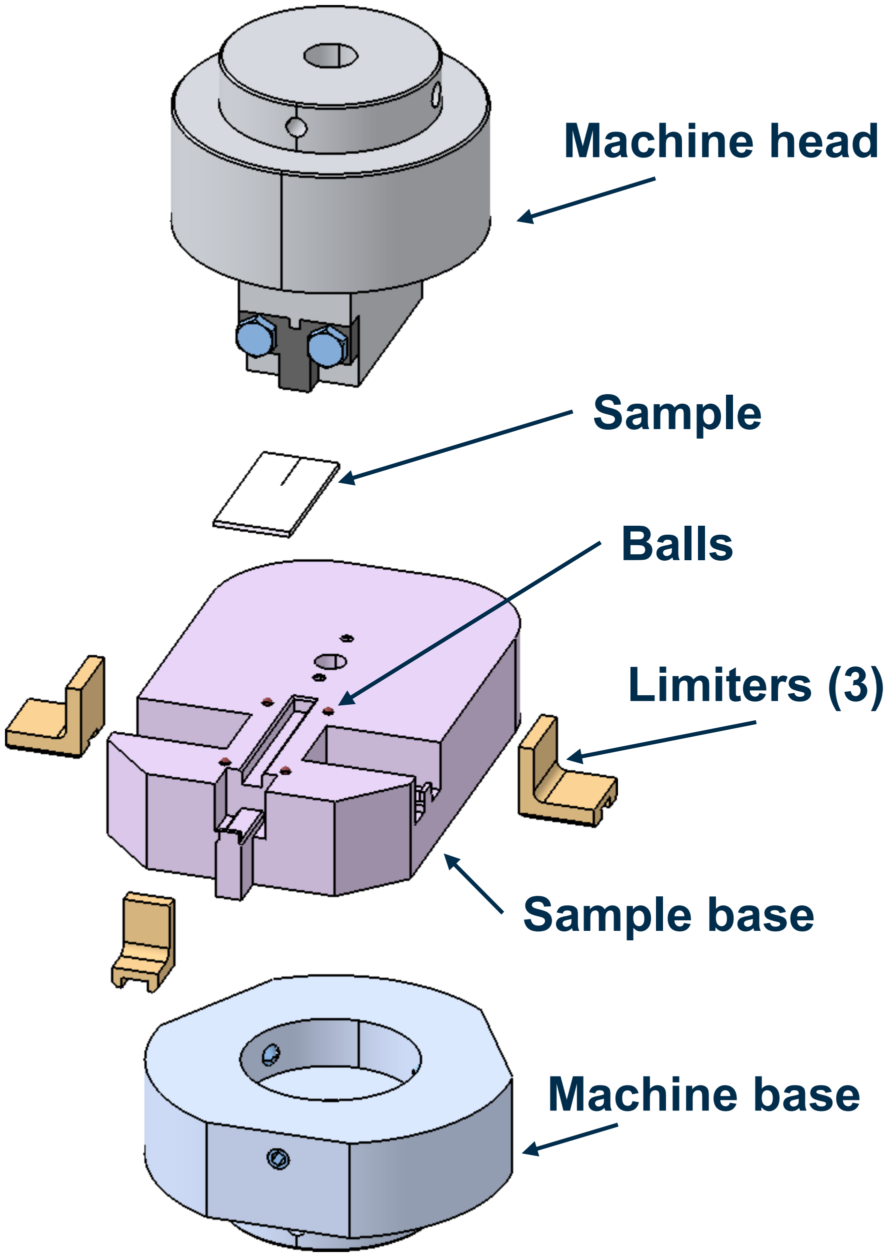


$$K = P S_m \left(\frac{3}{S t^4 (1 - \nu) \psi} \right)^{1/2}$$

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

At failure load, K = $\boldsymbol{K_{IC}}$ (**fracture toughness, MPa m$^{1/2}$**)

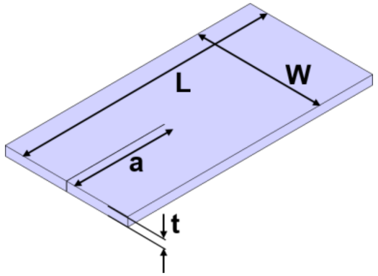
- Not yet standardized
- Applied to a very extensive range of materials: ceramics, glasses, composites, steels, diamond
- Relatively simple (specimen and loading)
- Planar configuration
- Symmetry and alignment are quite important in the experimental setup



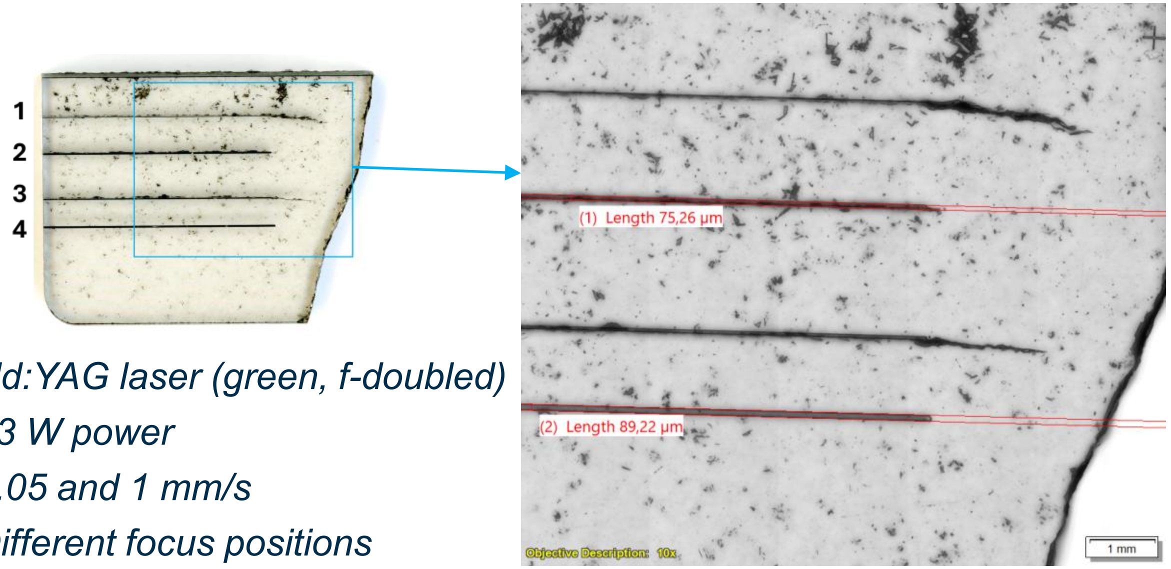
Diamond samples size and pre-crack

t (mm)	W (mm)	L (mm)	L/W	W/t
1.11	**15**	**30**	2.0	13.5

- Best compromise for samples size
- a/L ~ in the range 30% - 40%
- Pre-crack in diamond: preliminary laser cut studies

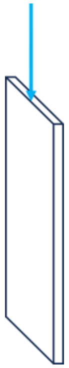


Laser cut from top

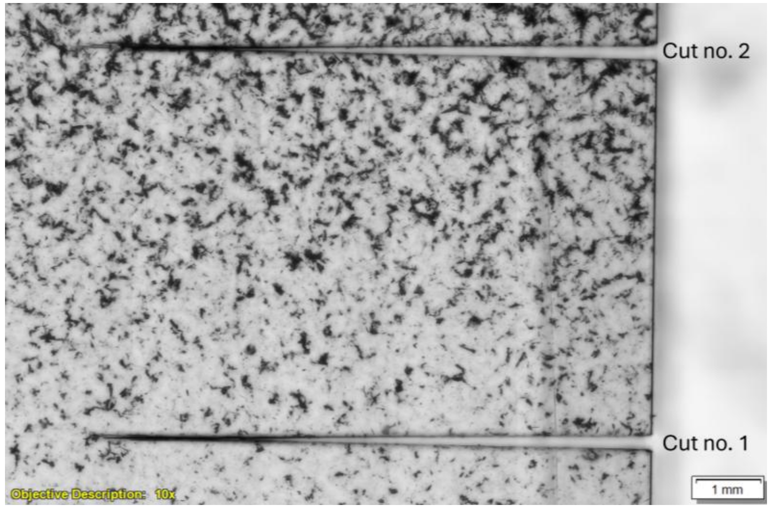


- *Nd:YAG laser (green, f-doubled)*
- *13 W power*
- *0.05 and 1 mm/s*
- *Different focus positions*

Laser cut from side



- *Nd:YAG laser (green, f-doubled)*
- *13 W power*
- *10 mm/s*
- *Cut length set to 8 mm*



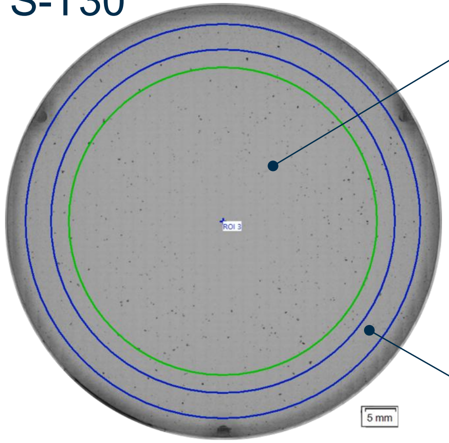
Promising way for pre-cracking

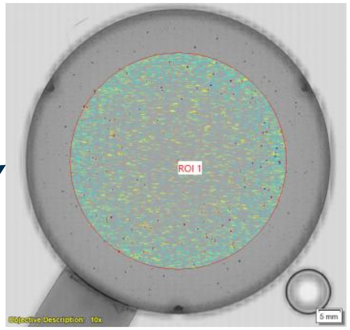
Microscopy activity

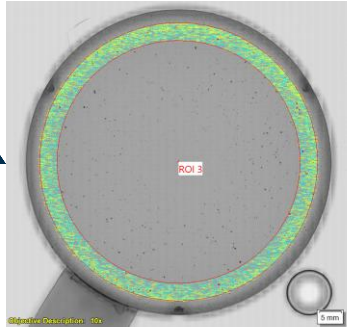
- Development of a specific procedure for **60 ITER disks** (Ø70 mm, 1.11 mm)
- Extended Focal Imaging (EFI)
  - A single image
  - Microfeatures info on disk surface

Aperture area

S-T30

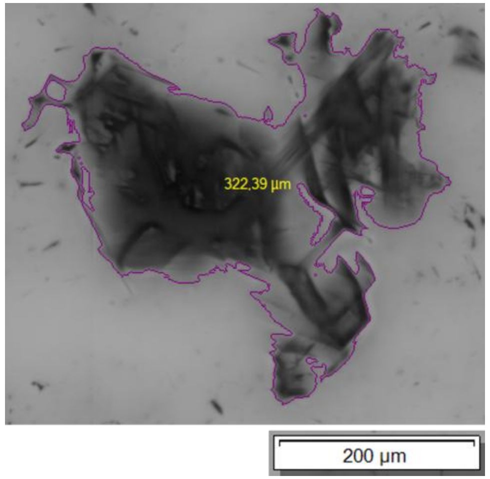






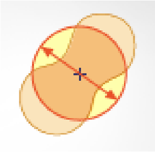
Brazing area

a = 322 µm



Brazing area

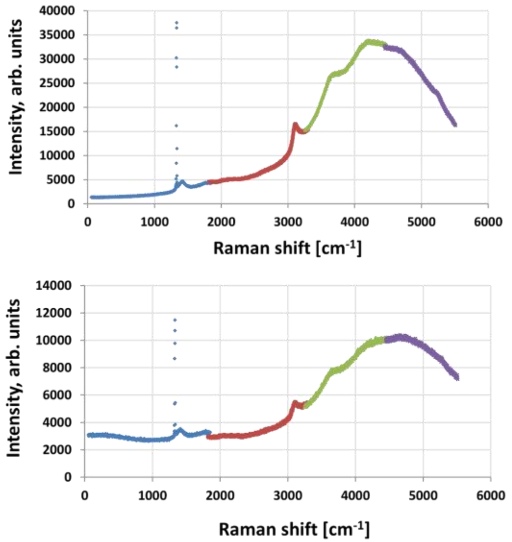
Disk/Ranges [µm]	100 - 150	150 - 200	200 - 250	250 - 300	300 - 600
S-T02	534	121	31	6	1
S-T03	299	53	12	4	1
S-T04	94	17	7	5	1
S-T05	447	82	21	7	0
S-T06	25	17	9	5	0
S-T17	1213	400	171	53	26
S-T09	326	71	11	4	2
S-T12	257	94	24	10	5
S-T08	164	27	15	10	1
S-T10	108	14	6	0	0
S-T13	82	13	4	2	1
S-T15	482	142	42	22	7
S-T16	80	10	1	1	0
S-T19	1422	580	255	102	64
S-T21	332	73	18	7	3
S-T23	1153	424	136	63	28
S-T14	264	69	14	4	1
S-T20	268	80	38	15	9
S-T24	1008	365	127	45	36
S-T27	452	101	27	4	1
S-T28	809	228	83	22	6
S-T30	40	15	6	10	1
S-T31	62	19	6	2	1
S-T33	85	21	6	0	1
Average	**417**	**127**	**45**	**17**	**8**

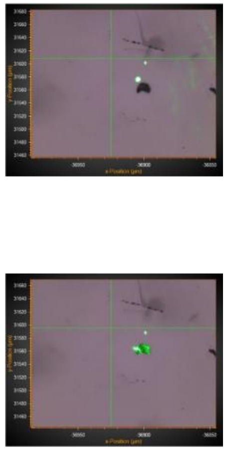


Equivalent Diameter Criterion

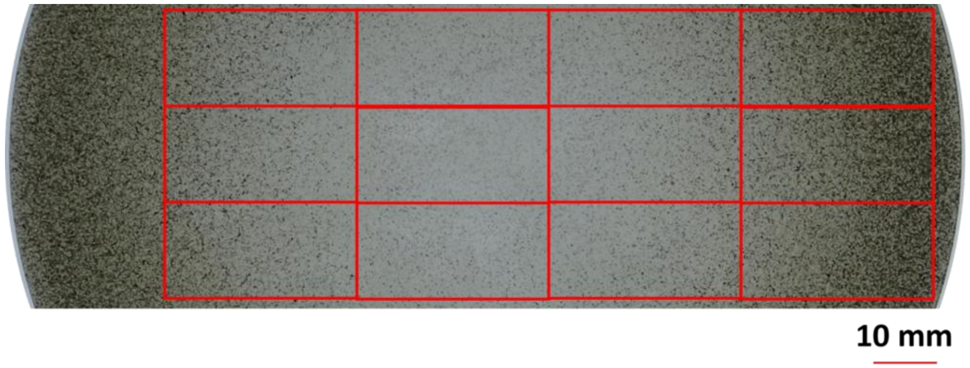
Diamond samples – characterization

- Loss tangent
- EBSD
- Raman
- XRD
- Polarimeter

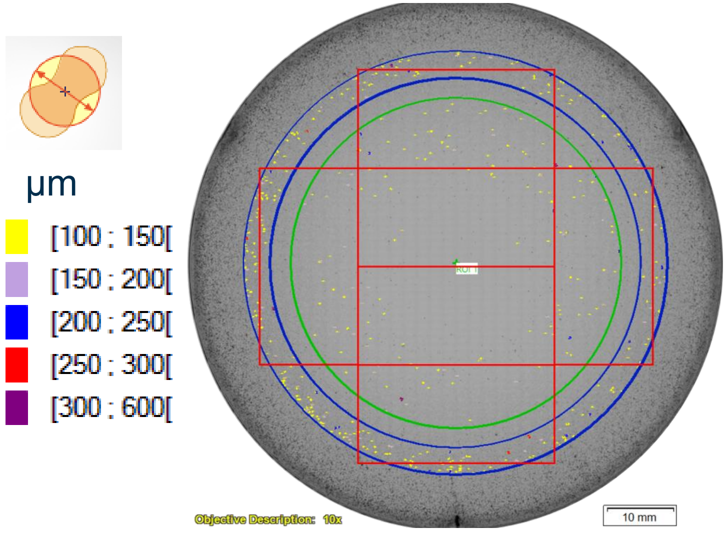




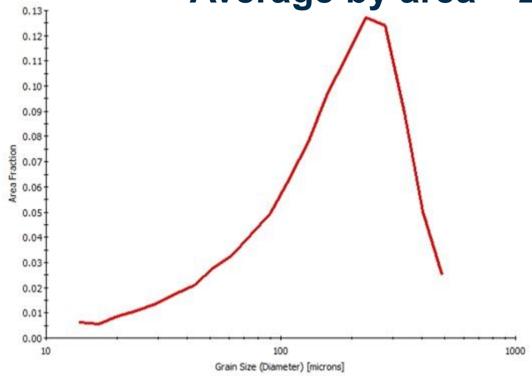
from Ø150 mm disk, thermal



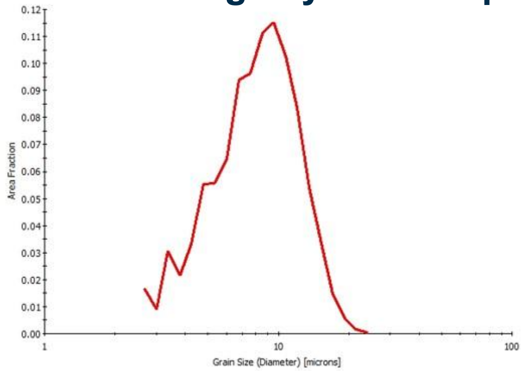
Ø80 mm disk, optical



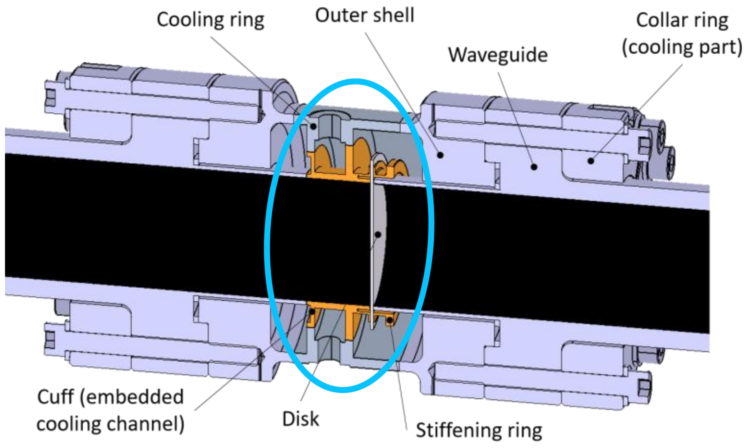
Grain size in GS
Average by number ~ 50 µm
Average by area ~ 200 µm

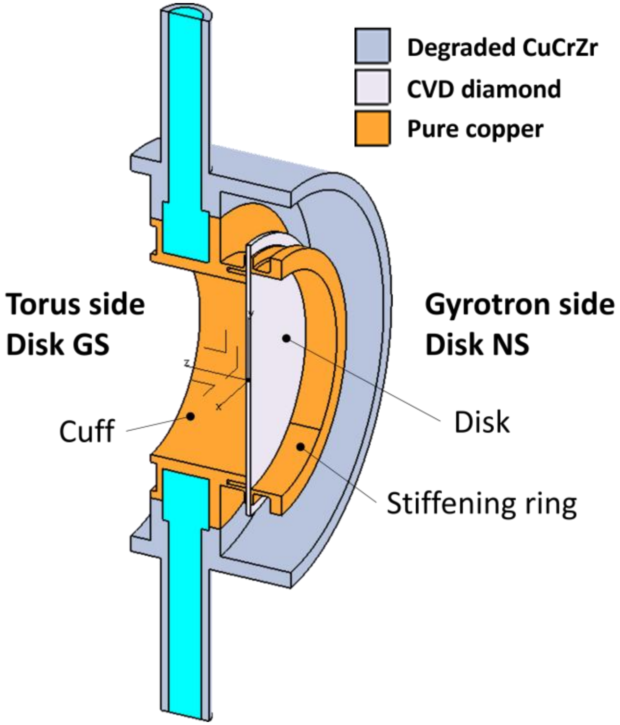


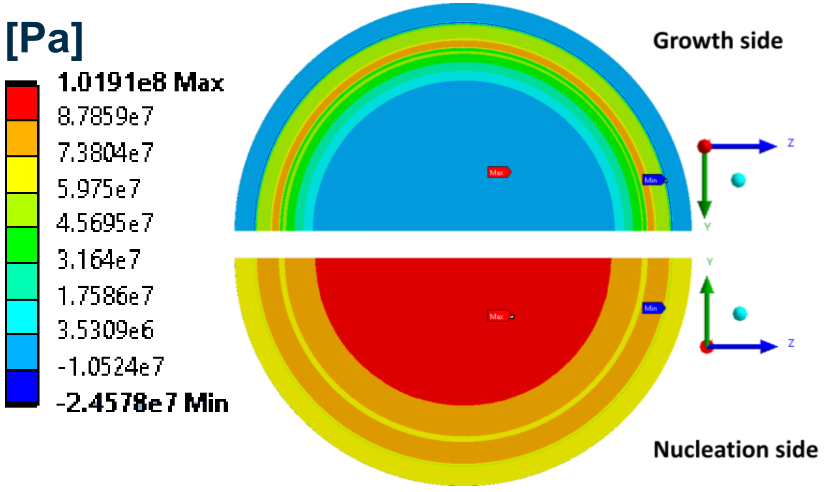
Grain size in NS
Average by number ~ 6 µm
Average by area ~ 9 µm

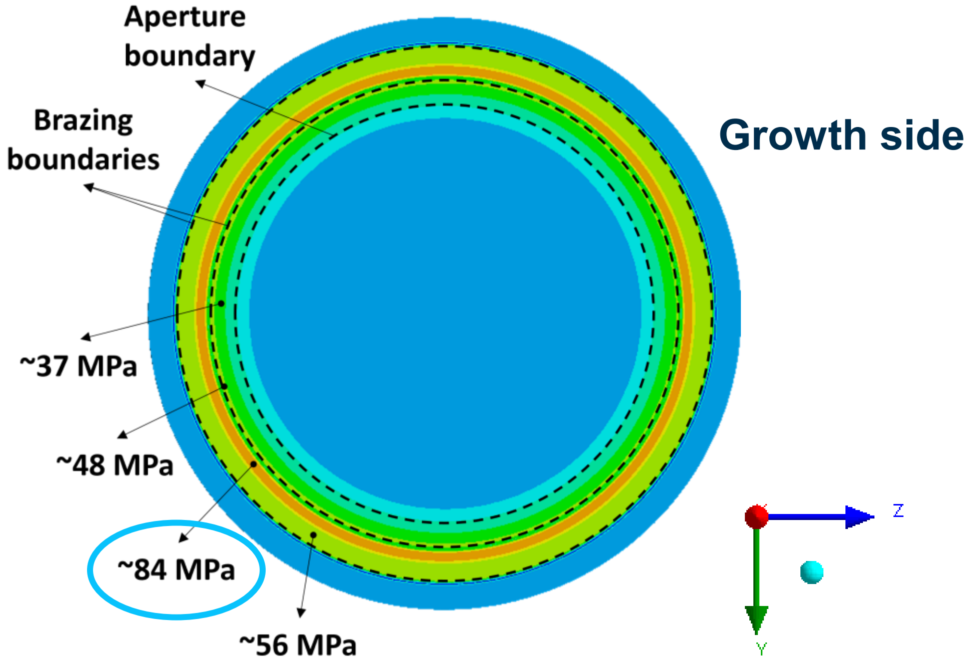


Numerical analyses



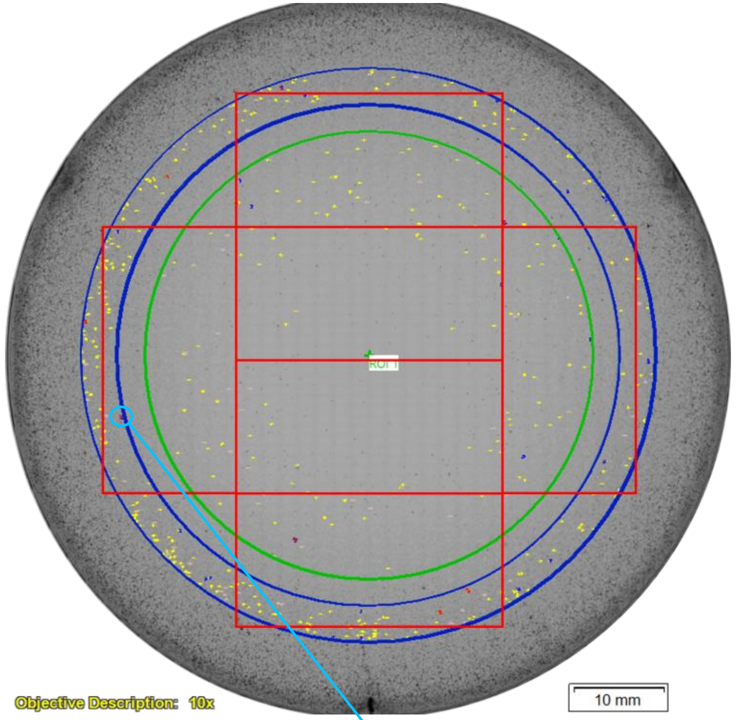


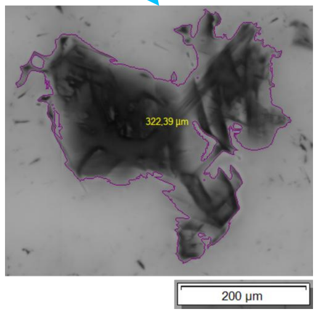


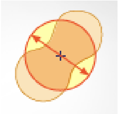


- Worst load scenario: NO + 2 bar event on torus side
- CFD conjugated heat transfer + structural analysis
- HE_{11} beam power of 1.31 MW, P_{abs} = 346 W
- Maximum stress in the disk lower than 150 MPa allowable limit
- Structural integrity assessment on growth side

Integrity assessment – first estimation

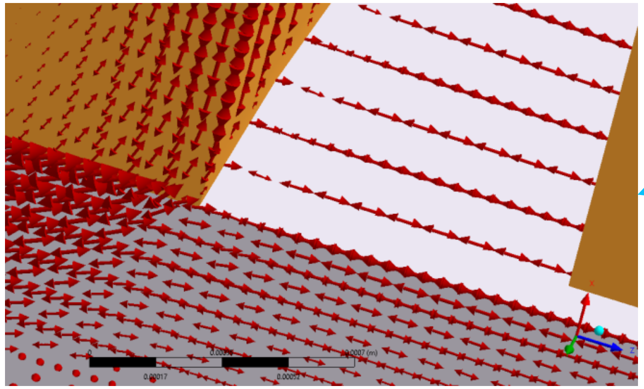


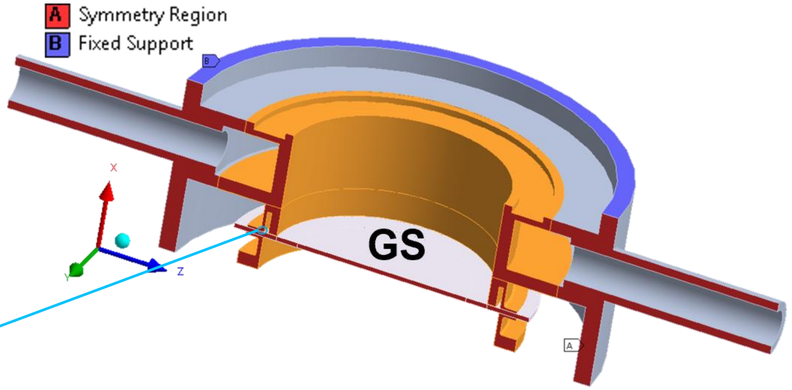




322 µm

Stress vector plot



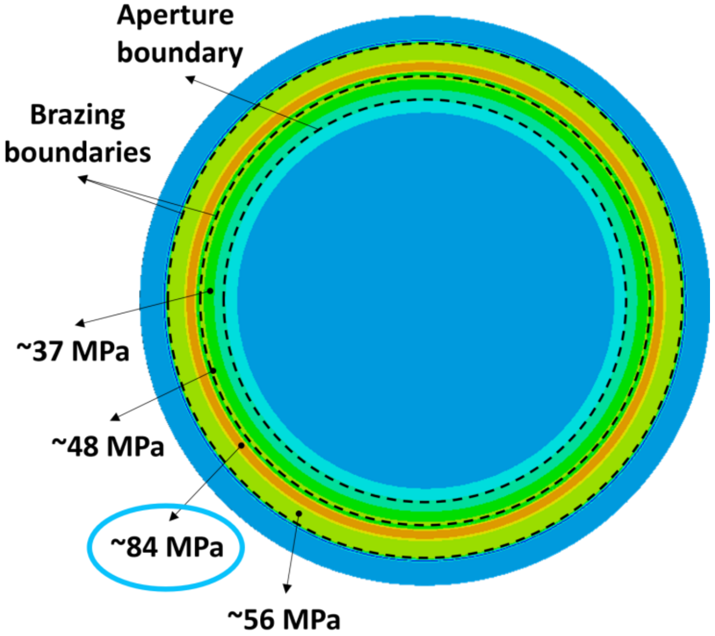


σ_0 ~ 84 MPa
a ~ 320 µm
β ~ 1 (first order)

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

$K_I \sim 2.6$ MPa $m^{1/2}$

$K_I \leq K_{IC}$



$K_{IC} \sim 8$ MPa $m^{1/2}$
(Davies, J. Mater. Sci, 2004)

Summary and outlook

- A mechanical characterization of MPA CVD diamond against crack propagation failure mode is required
- A procedure for microscopy investigation of the diamond disks was established
- Numerical analyses and a first integrity assessment were performed
- Characterization activities of the diamond samples are ongoing

- Generate drawings for the parts of the experimental setup
- Carry out the experiments
- Carry on the microscopy activity for the ITER disks

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.