SMAUG 2 – HRMT Users Day

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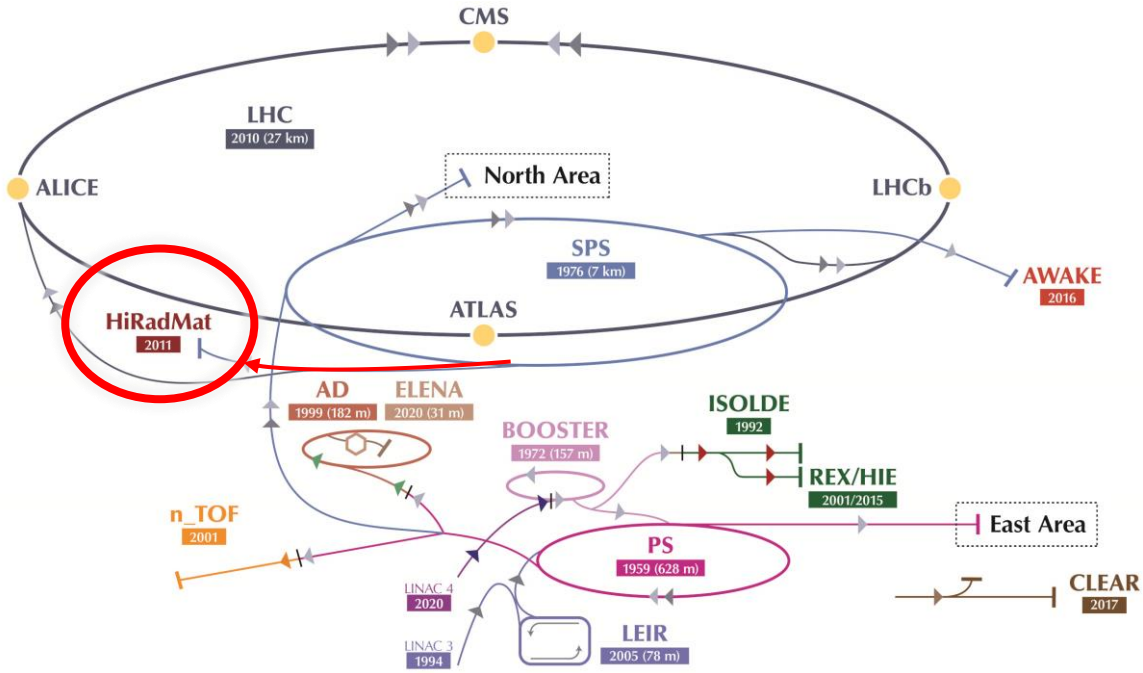
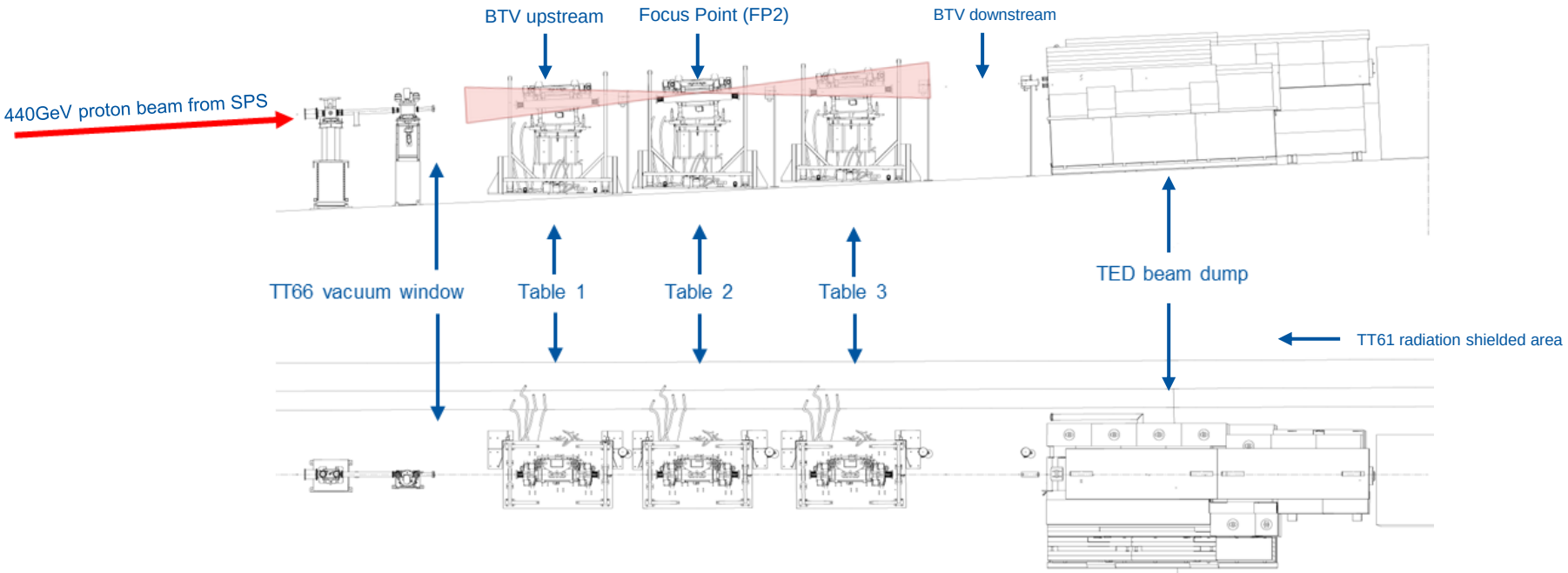
Overview

- Background to experiment
  - HRMT#26
  - HRMT#59 - SMAUG (1)
  - HRMT#62 - Baby SMAUG (1.5) (Parasitic experiment)
- HRMT#66 – SMAUG (2)
  - Experiment overview
  - Experimental results & observations
- Conclusion

HiRadMat Facility



HiRadMat Facility (High-Radiation to Materials)



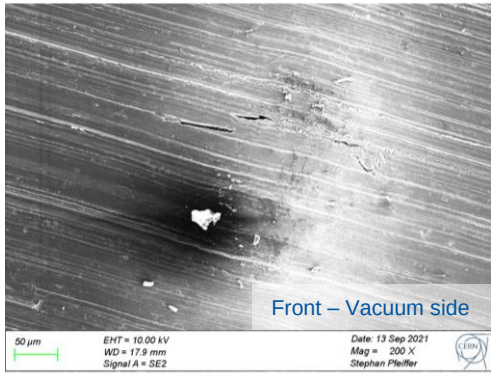
High-intensity proton LHC-like beam pulses with adjustable beam parameters are delivered to the facility which can be focused onto three experimental tables

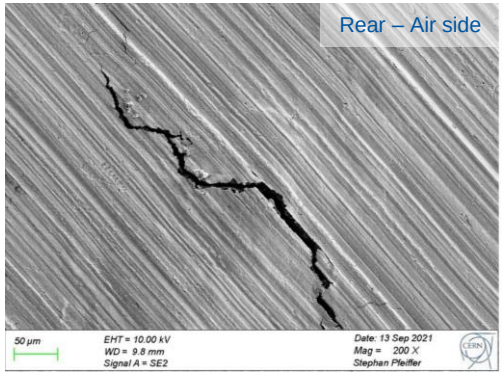
Background

Motivation: Failure of two Beryllium windows in HiRadMat 2021 – windows were not studied at higher LIU intensities. After ~50 high brightness beam shots each

Beryllium PF-60 with niobium coating (0.254mm)

- ✓ Beryllium originally selected due low Z properties.
- ✓ High transparencies with respect to the proton beam.
- ✓ Good mechanical properties
- ▪ Toxic material
- ▪ Difficult to procure





Fracture propagates from air side to vacuum side.

Crack develops in the direction of the rolled structure.

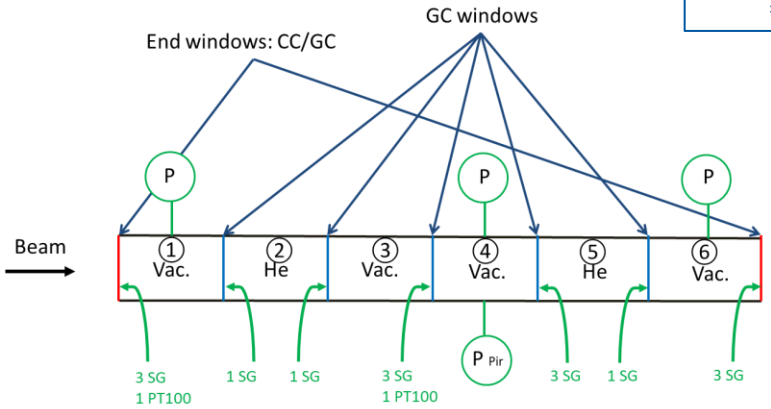
Temporary solution to displace vacuum window by 1.5 m upstream to reduce beam brightness

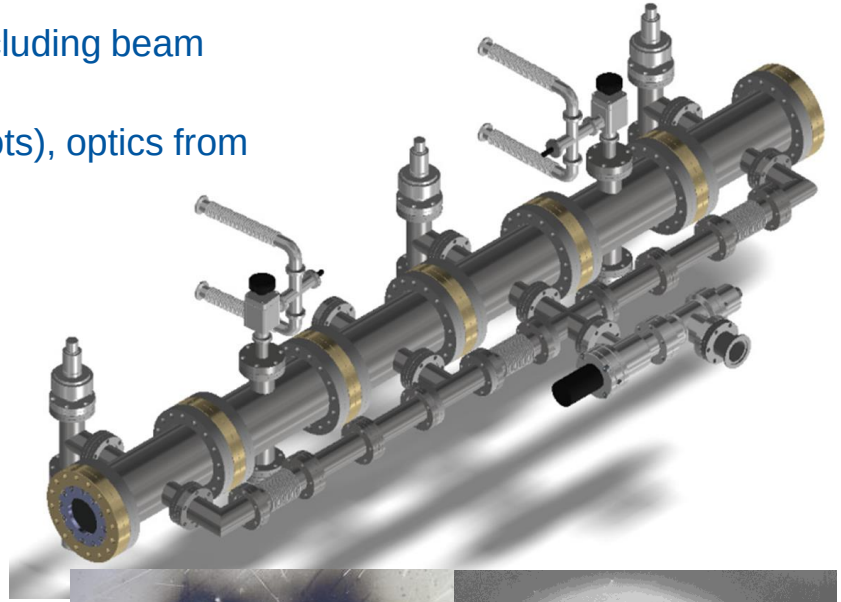
HRMT #26 - Glassy Carbon study

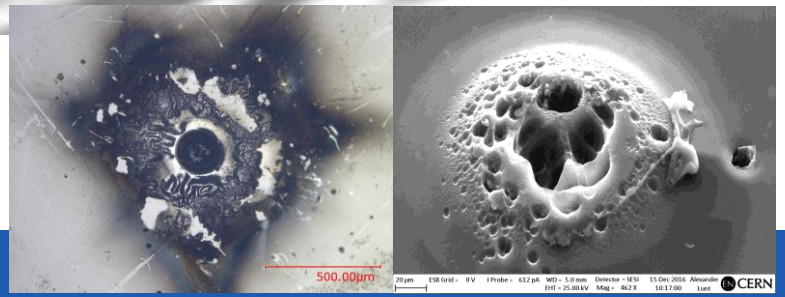
L. Baudin & C. Garion

- Development of material for vacuum structures – including beam windows
- Maximum beam shot intensity = $3.7e^{+13}$ p (for 5x shots), optics from sigma 2mm to sigma 0.25mm.
- Maximum energy deposition density of 4.1kJ/mm^3

Total number of protons on single site = $1.33E^{+15}$







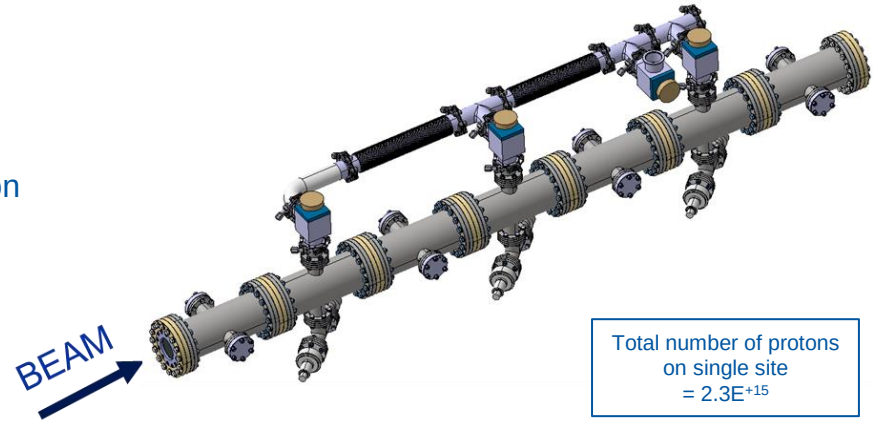
SMAUG 1 recap

- Study of beam windows material.
- Maximum beam spot intensity = $4.6e^{+13}$ p (for 50x shots), optics of sigma 0.35 mm.
- Maximum energy deposition density of 3.8kJ/mm^3

Experimental position	Window #	Material	Thickness (mm)
1	GC #03	Glassy carbon	2
2	GC #04	Glassy carbon	2
3	PF-60 #01	Beryllium PF-60	0.254
4	S-200-FH #01	Beryllium S-200-FH	3
5	I-200-H #01	Beryllium I-220-H	3
6	S-200-FH #02	Beryllium S-200-FH	3
7	GC #05	Glassy carbon	2
8	GC #02	Glassy carbon	2

# spot	Beam size	Brightness FP2 [p+/mm^2]	# shots at 288 bunches
1	0.5	$9.2E^{+13}$	5
2	0.5	$9.2E^{+13}$	50
3	0.35	$1.4E^{+14}$	5
4	0.35	$1.4E^{+14}$	50
5	0.35	$1.8E^{+14}$	5
6	0.35	$1.8E^{+14}$	50

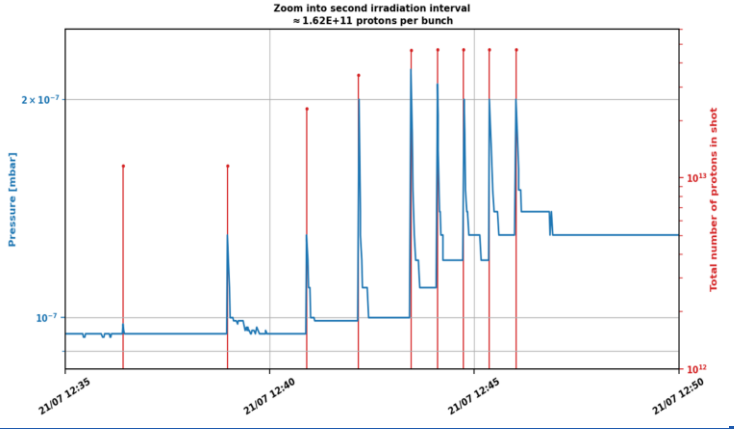
- Optical microscopy: clear marks at shots 2, 4 & 6 on Glassy Carbon and Be alloyed sample; clear marks of point 4 and 6 on PF-60.
- SEM confirms no cracks initiation and propagation.
- Glassy Carbon windows installed during TT66 YETS23 (HRM-V-EC-0002)

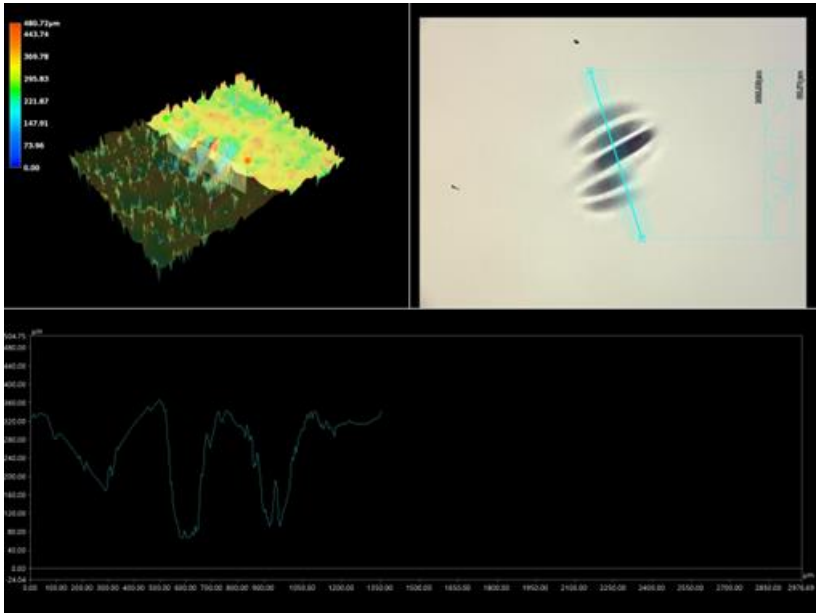


Total number of protons on single site = $2.3E^{+15}$

SMAUG 1.5 recap

- Si_3N_4. (6mm x 6mm 1µm membrane)
- Glassy Carbon (Ø80mm x 2mm)
- Maximum energy deposition density of 6.0kJ/mm^3
- Both glassy carbon and Si_3N_4 leak tight
- Indentation visible after venting Si_3N_4. No observed damage on glassy carbon



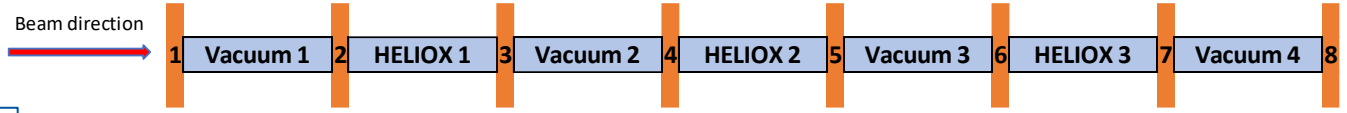


Total number of protons on single site = 5.94E^{+15}

SMAUG 2 concept

- Continued testing of materials for proton beam physics.
- Higher beam intensities.
- Six individual test sites:
  - Positions 1 & 2 – to recreate the same conditions as failure of beryllium PF-60 TT66 windows
  - Positions 3 & 4 – to offset beam train frequency to analyze Si_3N_4 ‘wave’.
  - Positions 5 & 6 – maximum beam intensity to test the limits of all windows – Beryllium/Si3N4/Glassy Carbon.

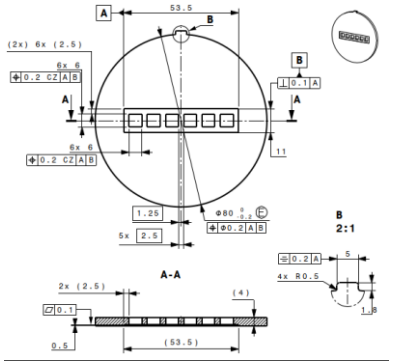
Window	Material	Supplier	Geometry
1	Si_3N_4	Silson Ltd.	1µm thick membrane, 6 windows 6mmx6mm
2	Glassy Carbon Sigradur G®	HTW GmbH	2mm Ø80 disc (beam aperture Ø60mm)
3	Beryllium PF-60	Materion	0.25mm diffusion bonded to DN63CF flange
4	Beryllium S-200-FH	Materion	3mm Ø80mm disc (beam aperture Ø60mm)
5	Beryllium I-220-H	Materion	3mm Ø80mm disc (beam aperture Ø60mm)
6	Beryllium PF-60	Materion	0.25mm diffusion bonded to DN63CF flange
7	Si_3N_4	Silson Ltd	1µm thick membrane, 6 windows 6mmx6mm
8	Glassy Carbon Sigradur G ®	HTW GmbH	2mm Ø80 disc (beam aperture Ø60mm)



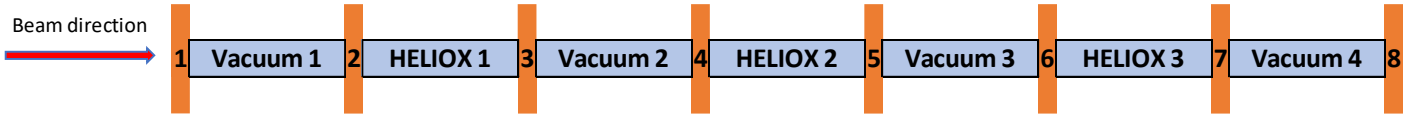
Proton beam experimental request:
- Scientific board approval
- Technical board approval
- Safety file

SMAUG 2 design

- 8 windows – 4 vacuum chambers and 3 HELIOX chambers.
  - HELIOX tracer gas - He 80%, O2 20%. Monitoring with leak detector.
- 6 test spots – horizontal motion table.
- PLC automated valve control.
- All windows individually tested before final assembly.
- Fiducialisation at surface (BA7) before plug and play in TNC.



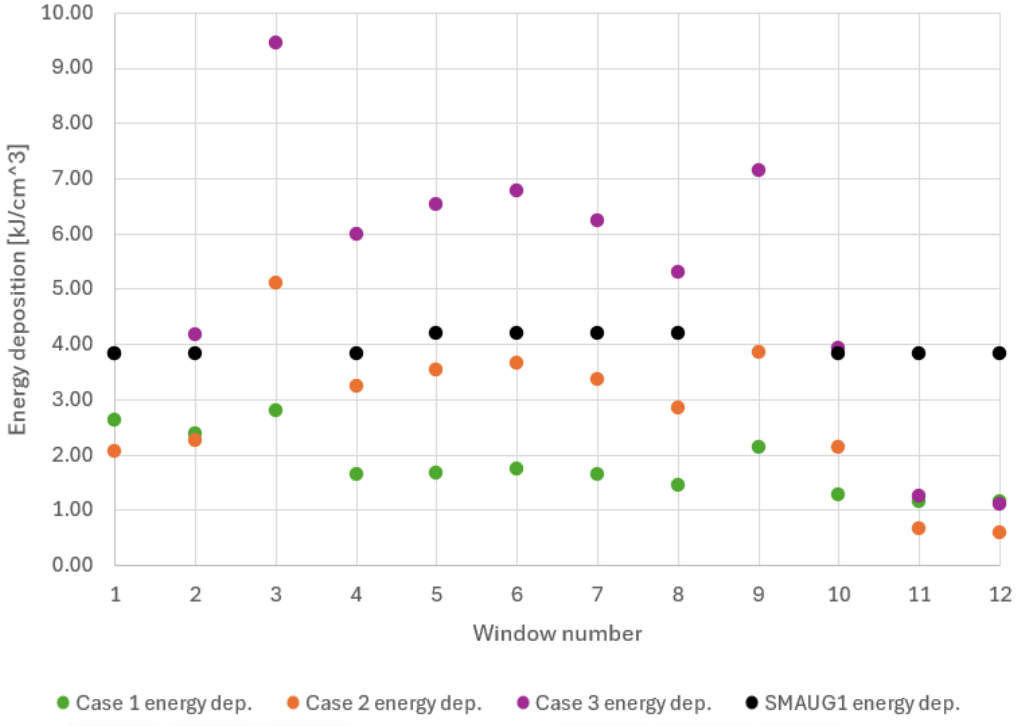
Si3N4 window with 6 individual sites (spots), membrane glued to S/steel plate



Pulse List & FLUKA

	Position	Shots	Bunches	Beam size [µm]	Brightness FP2 [E^{+14} p+/mm^2]
Case 1	Spot 1	5	288	0.4 x 0.4	1.08
	Spot 2	50	288	0.4 x 0.4	1.08
Case 2	Spot 3	1	144	0.25 x 0.25	1.90
	Spot 4*	1	144	0.25 x 0.25	1.90
Case 3	Spot 5	5	288	0.25 x 0.25	2.76
	Spot 6	50	288	0.25 x 0.25	2.76

*increased train spacing – frequency shift

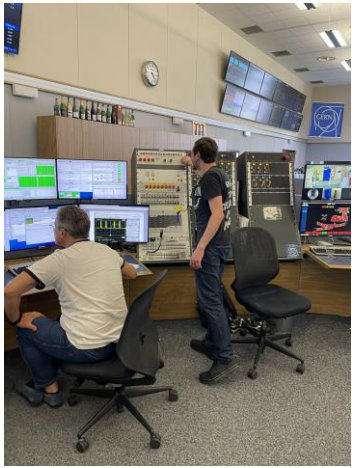


Data supplied courtesy of A. Lund & S. Niang

Window pos.	1	2	3	4	5	6	7	8	9	10	11	12
Material	BTV GC		Si_3N_4	GC	PF-60	S200FH	I220H	PF-60	Si_3N_4	GC	BTV GC	

*FLUKA data pre-experiment – to be updated from TWISS

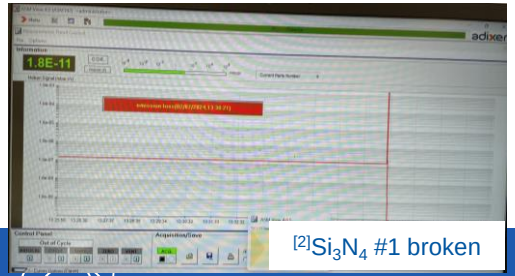
Experimental week



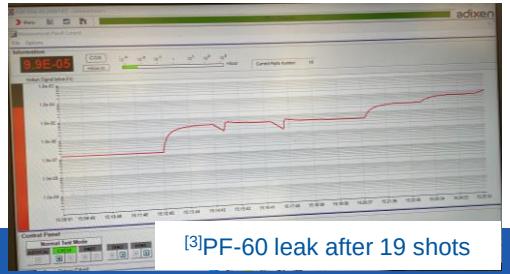
Shot position	No. pulses	Optics [µm]	Average intensity	Total intensity
1	5	0.4 x 0.4	3.48e+13	1.74e+14
2	50	0.4 x 0.4	3.52e+13	1.76e+15
3	1	0.25 x 0.25		2.99e+13
4[1]	1	0.25 x 0.25		2.97e+13
5[2]	5	0.25 x 0.25	5.55e+13	2.78e+14
6[3]	51	0.25 x 0.25	5.48e+13	2.80e+15

[1]Pulse 4 = 7µs spacing

Total number of protons sent to experiment: 5.18E+15



[2]Si_3N_4 #1 broken

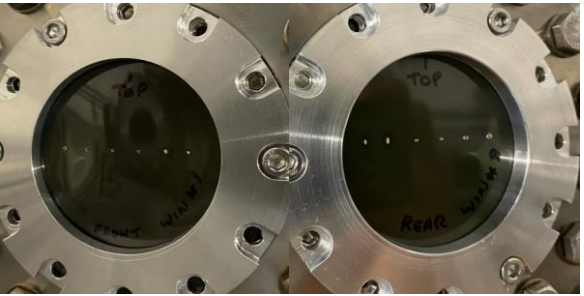


[3]PF-60 leak after 19 shots

Pulse list achieve in 2 days – thanks the outstanding efforts of SPS Operations and BE-EA

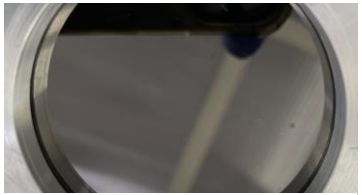
Post experiment observations

- Disassembly in 867/R-P48 bunker.
- Leak detection of assembly and individual windows.
- Observations:

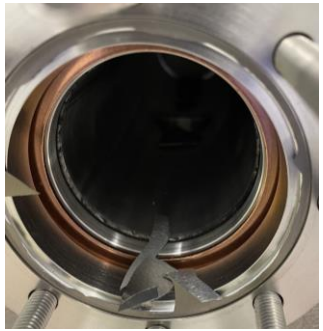


Gafchromic film shows focused beam upstream and divergence downstream

Window #1 Si_3N_4 – spots 5 & 6 broken

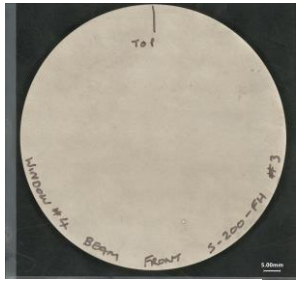


Window #2 GC – spots 5 & 6 beam traces



Window #3 PF-60 – window broken by vacuum forces.

Clean-up in accordance with HRM-V-SYP-0001 and HSE expert

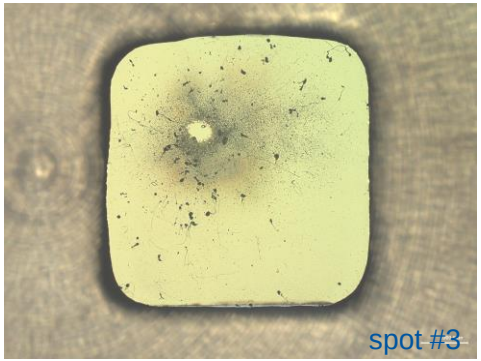


Window #4 & #5 Be – no beam traces

Analysis Si_3N_4

Window #1

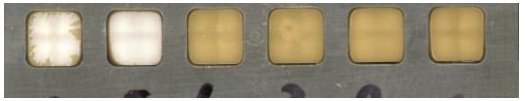
- Maximum energy deposition density of 9.46 kJ/mm^3
- 1st shot at higher intensity broke window
- Deposition of Gafchromic on spots #3 & #4



Window #7

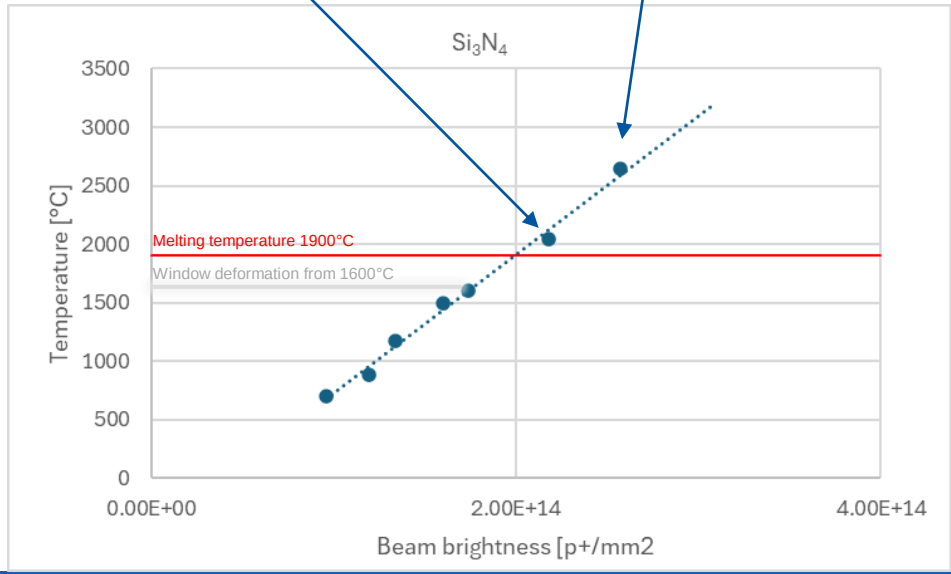
- No damage
- Maximum energy deposition density of 7.2 kJ/mm^3

*FLUKA data pre-experiment – to be updated from TWISS



Window #1 – positions 5 & 6 broken

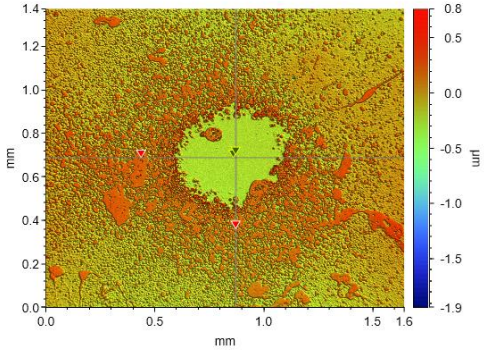
Window #7 – no damage

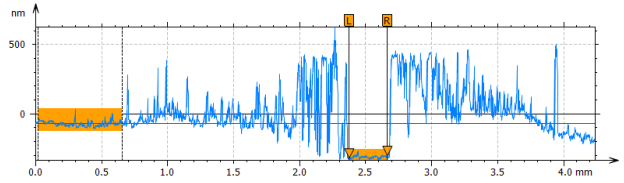


Analysis Si_3N_4

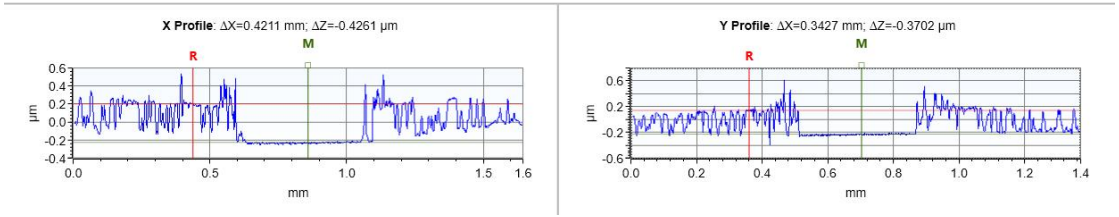
Window #1

- Spot #3 rear, interferometer measurements – no significant surface deflection.
- Surface roughness from Gafchromic deposition.





Parameters	Unit	Step 1
Maximum height	nm	264.7
Minimum height	nm	197.0
Mean height	nm	240.7

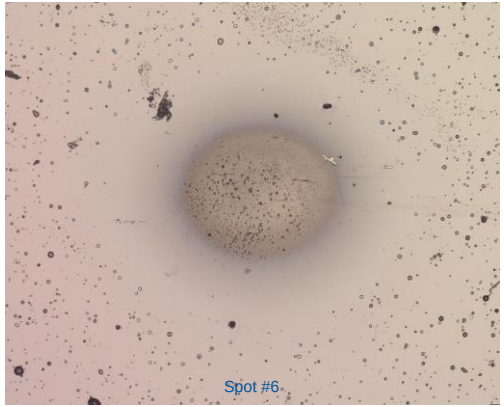


Measurements of SMAUG 1.5 Si_3N_4 window still to be performed

Analysis Glassy Carbon

Window #2

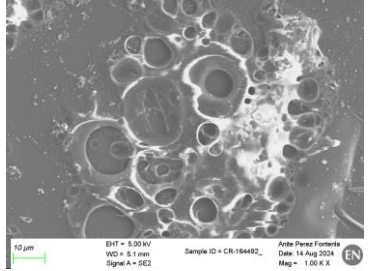
- Maximum energy deposition density of 6.0kJ/mm^3
- Craters observed on front face and rear face – on spots #5 & #6.



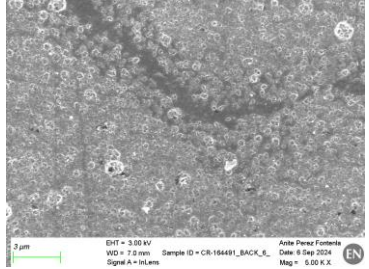
Window #8

- Maximum energy deposition density of 3.9kJ/mm^3
- No damage
- Deposition of Gafchromic on spots #5 & #6

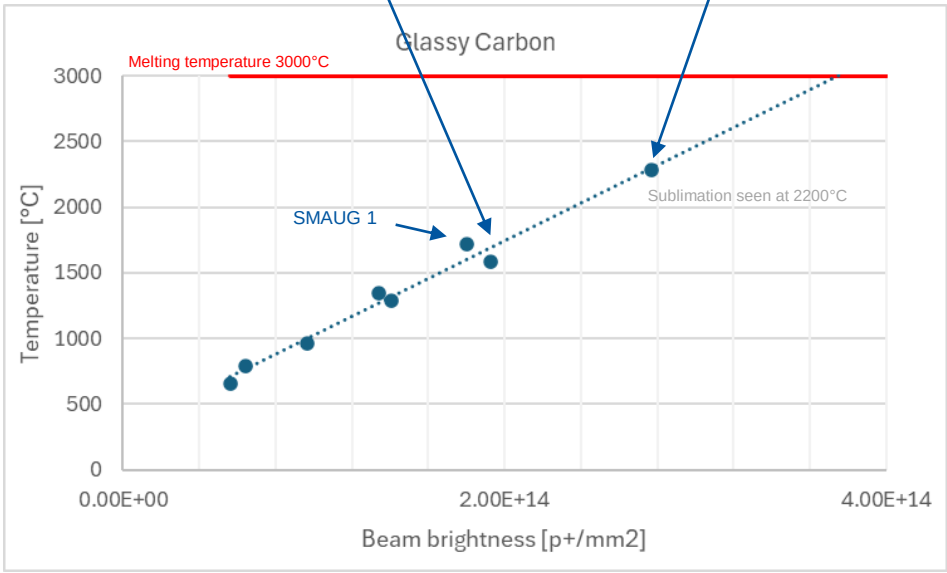
*FLUKA data pre-experiment – to be updated from TWISS



Window #8 – Gafchromic deposition



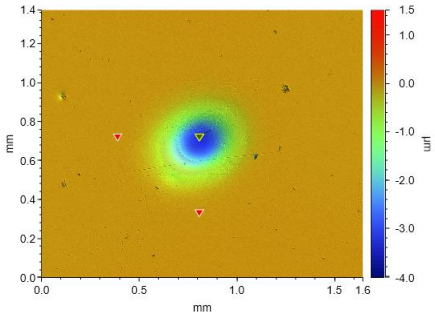
Window #2 – rear spot #6



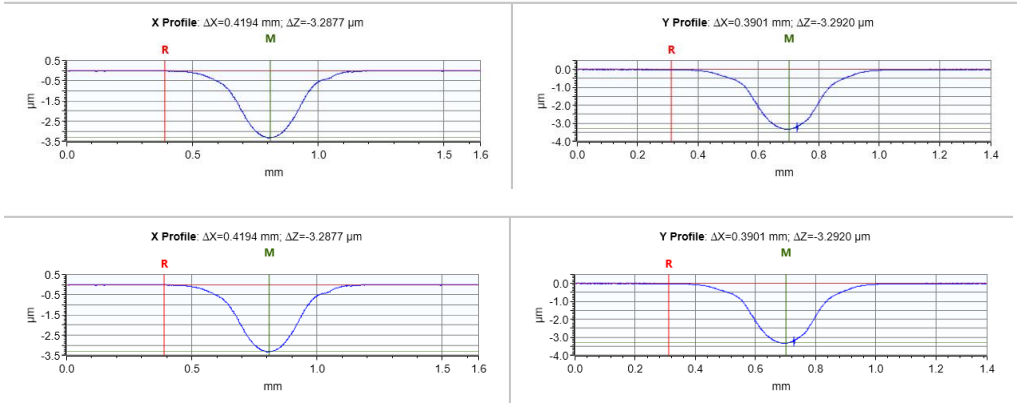
Analysis Glassy Carbon

Window #2

- Maximum energy deposition density of 6.0kJ/mm^3
- Higher sublimation rate seen on the rear of the window



Window #2
Rear
Site #6



Window #2		ΔZ [µm]	ΔX [µm]	ΔY [µm]
Spot #5	Front	0.21	459	444
	Rear	0.35	582	537
Spot #6	Front	1.60	672	581
	Rear	3.29	728	631

Initial analysis indicate a sublimation rate of 3mg/shot (rear side at brightness 2.77E^{+14} p$^+$/mm^2)

- Advanced interferometer measurement techniques still to be performed.

Analysis beryllium PF-60

Window #3

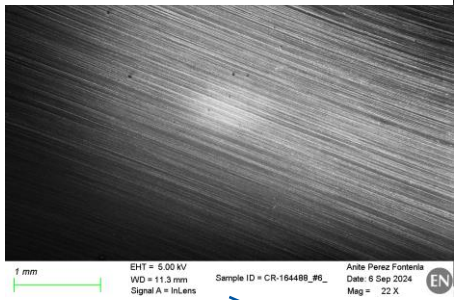
- Leak developed with high intensity beam
  - 19th shot 4.3e^{-6} mbar·l·s^{-1}
  - 20th shot 2.6e^{-5} mbar·l·s^{-1}
  - 21st shot 6.4e^{-5} mbar·l·s^{-1}
  - 22nd shot 1.3e^{-4} mbar·l·s^{-1} – vacuum valve closed
  - Window broken due to vacuum forces
- Maximum energy deposition density of 6.5kJ/mm^3

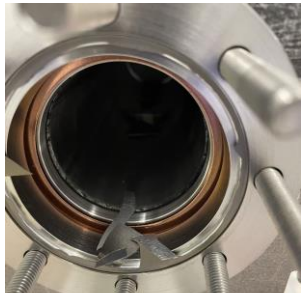
Window #6

- Leak tight (Q_{BG}<1e^{-10} mbar·l·s^{-1}).
- Beam impact visible - believed to be due to chemical composition change.
- Maximum energy deposition density of 5.3kJ/mm^3

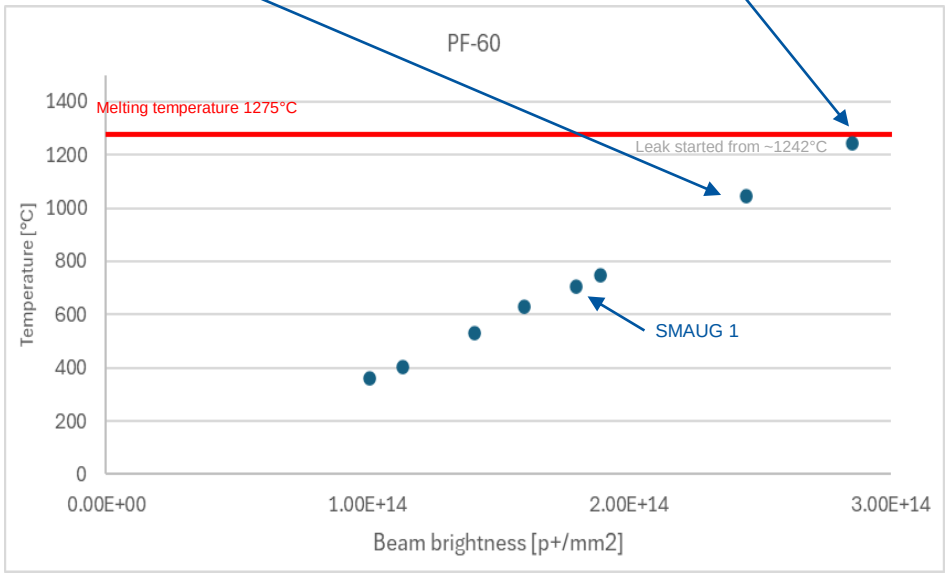
*FLUKA data pre-experiment – to be updated from TWISS

Window #6 Spot #6





Window #3 failure



Next steps…

- FLUKA update to include focal point offset from BTV measurements (TWISS data).
- Interferometer measurements of Si_3N_4 from SMAUG 1.5.
- Continued studies of Si_3N_4 for Muon Collider application.
- Two papers planned:
  - SMAUG experiments
  - Si_3N_4 for Muon Collider applications
- SMAUG 3…?

Conclusions

- Glassy Carbon is outperforming the original beryllium PF-60 material.
- Sublimation rate of GC in the region of 3mg/shot at Beam Brightness levels of $2.77E^{+14}$ p^{+}/mm^{2}*
- Si_3N_4 performing above simulated expectations. The ripples (SMAUG 1.5) caused by plastic deformation causing a ‘bubble’.
- PF-60 failure due to fatigue from high intensity beams

*to be confirmed after advanced TWISS analysis and FLUKA update

Aknowledgements

- Thanks
- Merci
- Ευχαριστώ
- Grazie
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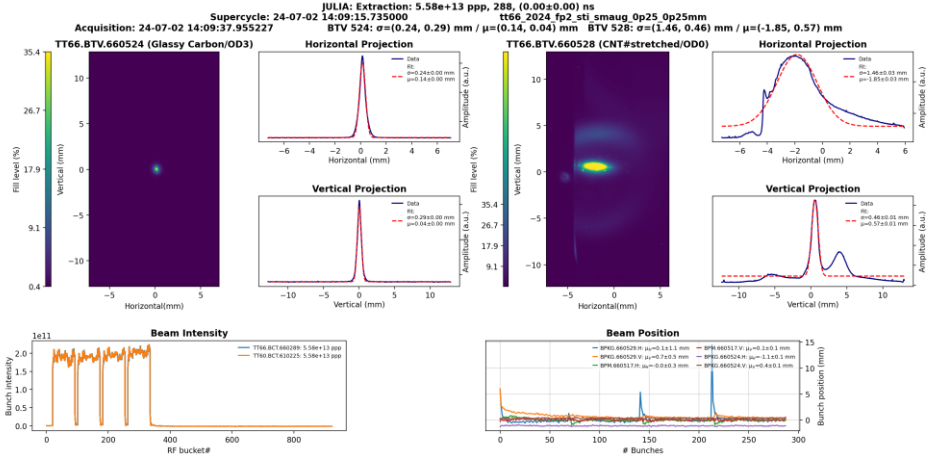
A. Ebn Rahmoun, N. Solieri, A. Lund,
A. T. Perez Fontenla, B. Descargues,
E. Soria, F. Philippon, D. Manousou,
SPS Operations Team.

Spare slides

Initial observations – Gafchromic film

All 6 Pulse sites clearly visible and represent beam intensities

Round beam trace upstream, indicating more focused beam. Elliptical beam tract downstream – focal point of experiment was towards the front of the experiment



Case 1	From	To	Shots	Avg. total intensity	Std. dev.	%RSD	Avg. number of bunches	Avg. bunch intensity
Pre shots	01/07/24 17:22:25	01/07/24 17:27:49	5	3.483E+11	2.734E+11	0.79	288 (constant)	1.505E+11
Experiment	24-07-01 17:54:49	24-07-01 18:44:19	50	3.519E+11	2.326E+11	0.66	288 (constant)	1.521E+11

Case 2	From	To	Shots	Avg. total intensity	Std. dev.	%RSD	Avg. number of bunches	Avg. bunch intensity
Experiment	24-07-02 11:48:16	24-07-02 11:59:58	4	2.968E+13	2.353E+11	0.79	144 (constant)	2.061E+11

Case 3	From	To	Shots	Avg. total intensity	Std. dev.	%RSD	Avg. number of bunches	Avg. bunch intensity
Pre shots	24-07-02 13:34:32	24-07-02 13:37:57	2	5.497E+13	3.885E+11	0.71	288 (constant)	1.909E+11
Leak observed in window 1, between sector 1 & 2								
Experiment	24-07-02 14:09:15	24-07-02 15:24:54	27	5.498E+13	5.277E+11	0.96	288 (constant)	1.910E+11
Experiment	24-07-02 16:49:22	24-07-02 17:54:21	28	5.490E+13	5.119E+11	0.93	288 (constant)	1.906E+11
Total	24-07-02 14:09:15	24-07-02 17:54:21	55	5.494E+13	5.258E+11	0.96	288 (constant)	1.9075E+11

Total number of protons sent to experiment: 5.18E+15

Window #1 Si_3N_4 #2

Vacuum failed

Pulses #1 & #2 – No visible impact marks

Pulses #3 & #4 – Impact mark can be seen

Pulse #5 – Failed after 1st Pulse
Pulse #6 – Failed (probably 1st Pulse but unable to verify)

Window #1 Si_3N_4 #2

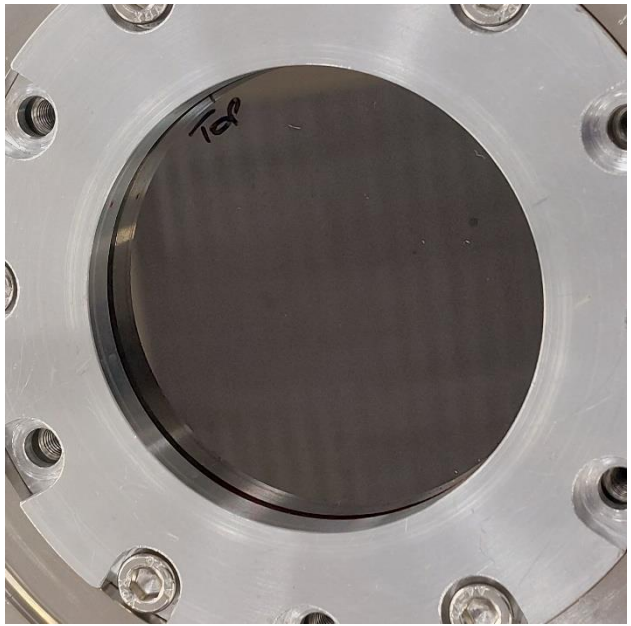
Vacuum failed

Pulses #1 & #2 – No visible impact marks

Pulses #3 & #4 – Impact mark can be seen

Pulse #5 – Failed after 1st Pulse
Pulse #6 – Failed (probably 1st Pulse but unable to verify)

Window #2 Glassy Carbon #8



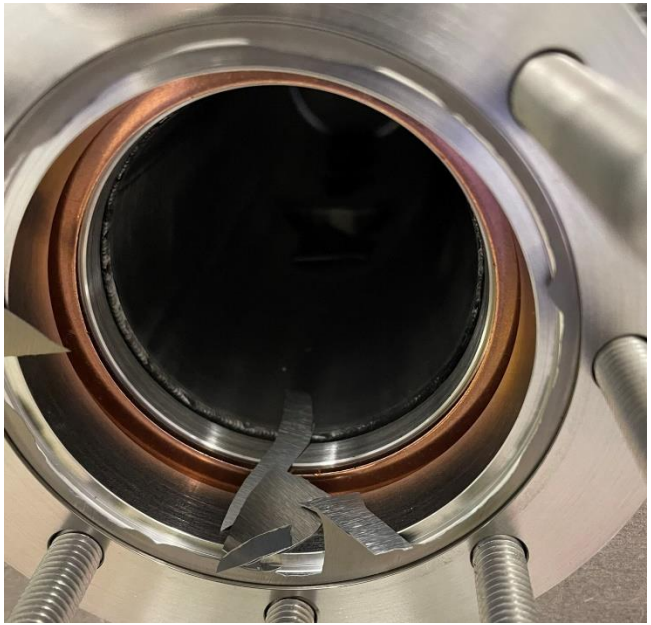
Window leak tight

Pulses #1, #2, #3 & #4 – No visible impact mark

Pulse #5 – Barely visible impact mark on back face

Pulse #6 – Visible impact mark on back face

Window #3 PF-60 #2

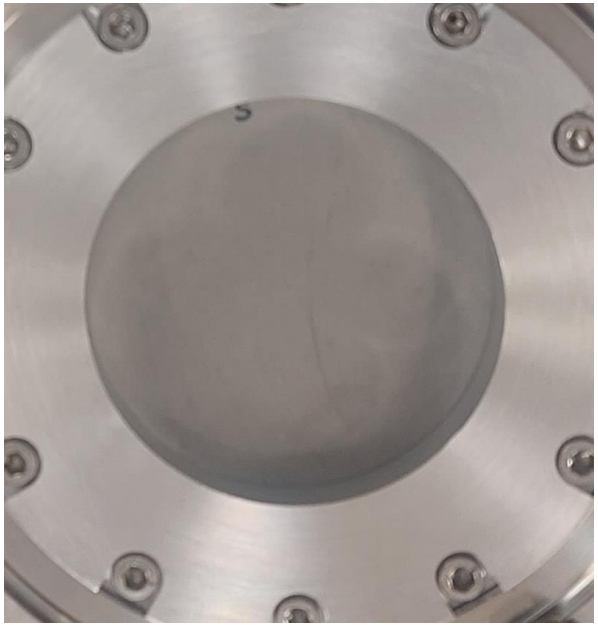


Vacuum failed Pulse #6, leak rate increased in steps during each Pulse

– after 19 Shots Q_{LR} = 4.3e^{-6} mbar·l·s^{-1}
– after 20 Shots Q_{LR} = 2.6e^{-5} mbar·l·s^{-1}
– after 21 Shots Q_{LR} = 6.4e^{-5} mbar·l·s^{-1}
– after 22 Shots Q_{LR} = 1.3e^{-4} mbar·l·s^{-1}
– Vacuum chamber closed after shot #22

Inspection in 867/R-P48 found vacuum forces fully broke the PF-60 material

Window #4 S-200-FH #3



Window leak tight

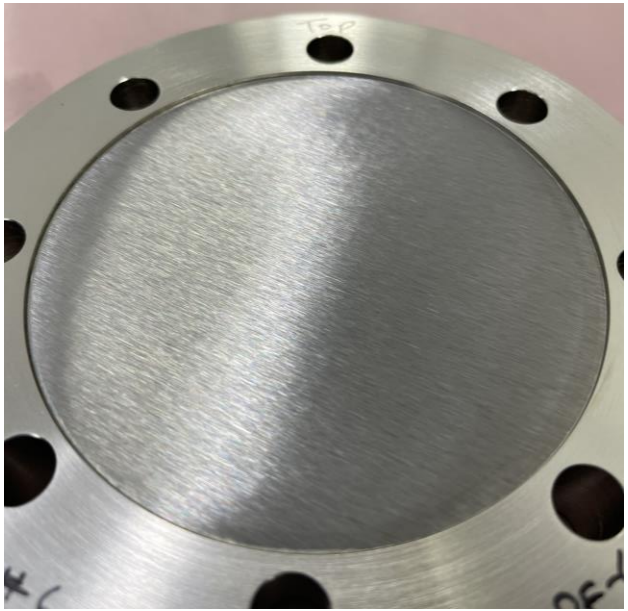
Pulse #1, #2, #3, #4, #5 & #6 - No visible impact marks

Window #5 I-220-H #3

Window leak tight

Pulse #1, #2, #3, #4, #5 & #6 - No visible impact marks

Window #6 PF-60 #3



Window leak tight

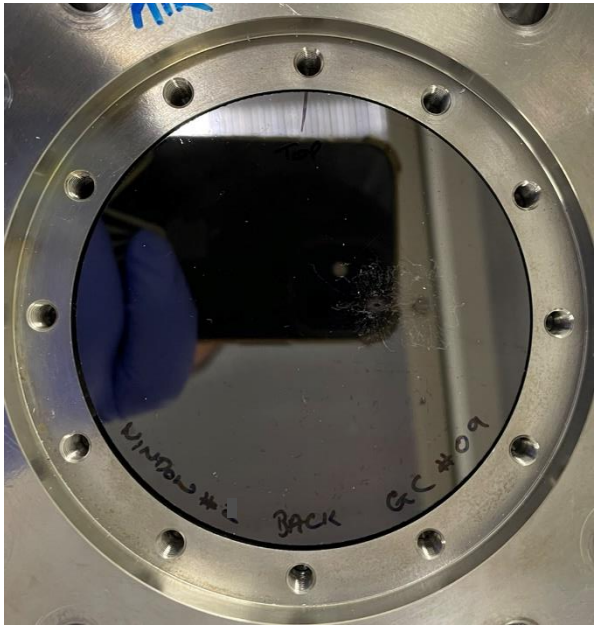
Pulse #1, #2, #3, #4, #5 & #6 - No visible impact marks

Window #7 Si_3N_4 #3

Window leak tight

Pulse #1, #2, #3, #4, #5 & #6 - No visible impact marks

Window #8 Glassy Carbon #9

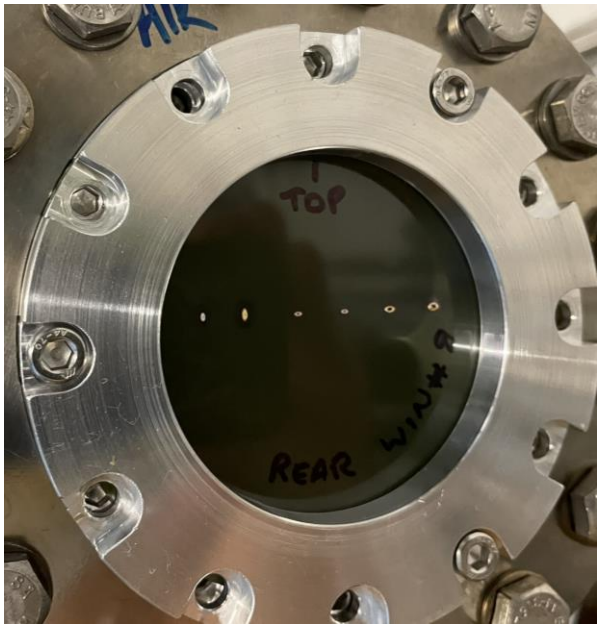


Window leak tight

Pulse #1, #2, #3 & #4 – No visible impact marks

Pulse #5 & #6 – Impact mark on back face (possibly from Gafchromic film?)

Downstream Gafchromic



All 6 Pulse sites clearly visible and represent beam intensities

Elliptical beam trace in horizontal plane, indicating more defocused beam