

SMAUG EXPERIMENTS AT CERN'S HIRADMAT FACILITY FOR THE STUDY OF MATERIALS USED FOR PARTICLE BEAM WINDOWS

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Abstract

The SMAUG experimental campaign was conducted at CERN's HiRadMat facility to investigate the performance and limits of particle beam window materials to intense pulsed proton irradiation. Samples of glassy carbon, beryllium (grades I-220-H, S-200-FH, and PF-60), and silicon nitride (Si_3N_4) were exposed to 440 GeV/c proton beams with total intensities of up to 2.8×10^{15} protons per pulse and beam spot sizes ranging from $\sigma_{x,y} = 0.5$ mm to 0.25 mm. Three experimental configurations (SMAUG-1, -1.5, and -2) were used to reproduce operational beam conditions relevant to existing CERN accelerators and future facilities. Post-irradiation analyses included vacuum leak testing, optical microscopy, scanning electron microscopy, and three-dimensional surface topography measurements. FLUKA Monte Carlo simulations were performed to evaluate energy deposition in the irradiated materials. The results provide comparative performance data for beam window materials and support the selection of suitable solutions for high-intensity accelerator applications.

INTRODUCTION

Beam windows are essential components in high-intensity accelerators, providing vacuum separation while exposed to intense particle beams. Increasing beam brightness in future upgrades imposes stringent demands on window materials to endure extreme thermal and mechanical stresses while preserving vacuum integrity.

Past operational experience at CERN has shown that beam-induced damage or failure of window components can lead to significant downtime, increased radiation exposure risks for personnel and potential exposure to beryllium dust. Notably, two consecutive failures of PF-60 diffusion-bonded beryllium windows occurred at the TT66 HiRadMat facility [1] during experimental runs in 2021, when subjected to beam brightnesses of 5×10^{13} p⁺/mm² (Fig. 1). These incidents led to the establishment of a dedicated working group tasked with investigating the failure mechanisms and defining operational limits relevant to high-intensity proton beam applications.

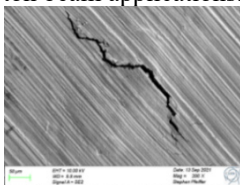


Figure 1: Microcrack on TT66 HiRadMat facility window, Beryllium PF-60 0.254mm.

The SMAUG experimental programme was initiated to evaluate candidate beam window materials under controlled, high-intensity proton beam conditions at the HiRadMat facility. In addition to benchmarking materials currently used in the CERN accelerator complex, the programme also investigated new applications, including the use of ultra-thin silicon nitride membranes as isolation barriers between hydrogen absorbers and vacuum in the final cooling section of a muon collider [2].

Throughout this paper, beam “brightness” refers to the peak intensity for a gaussian beam Eq. (1), expressed in protons per square millimetre.

$$Power_{Density(x,y)} = \frac{Protons\ Per\ Pulse}{2\pi\sigma_x\sigma_y} \quad (1)$$

EXPERIMENTAL SETUP

Configuration

The SMAUG-1 and SMAUG-2 experiments employed a common configuration consisting of eight window samples mounted in hermetically sealed flanges and arranged between alternating vacuum and air chambers (HELIOX for SMAUG-2), as shown schematically in Fig. 2. The assemblies were designed to allow independent leak testing of each window before, during and after the experiment.

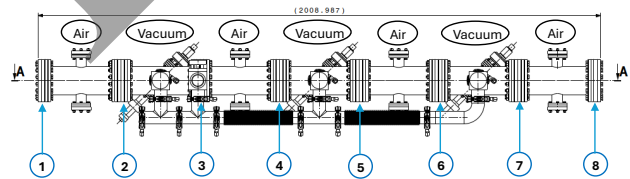


Figure 2: SMAUG 1 and SMAUG 2 experiment layout drawing indicating window positions.

SMAUG-1.5 was a parasitic experiment operated in parallel with another HiRadMat experiment. It consisted of a single vacuum chamber equipped with a 1 μm -thick Si_3N_4 membrane providing a beam aperture of 6 mm \times 6 mm upstream. A downstream window made of a 3 mm-thick glassy carbon disc with a $\text{\O}60$ mm aperture was used as a secondary window.

Sample Mounting and Alignment

All experiments were assembled, tested, and pre-aligned on the experimental TABLE 1 in the dedicated HiRadMat surface laboratory before installation in Station 2 (FP2) of the HiRadMat facility (CERN TNC). The table features a horizontal motor-driven baseplate that allows translation of

the setup to six independent beam impact sites, separated by 8.5 mm across the window surface. This enabled multiple irradiation scenarios on a single sample while maintaining reproducible alignment conditions.

Materials and Configurations

Table 1 summarises the materials, thicknesses, and window positions used in the SMAUG experiments. Glassy carbon (SIGRADUR G) was selected for its high sublimation temperature and low atomic number. Multiple grades of beryllium were included to benchmark performance against existing CERN beam windows. Ultra-thin Si_3N_4 membranes were tested for potential application in final cooling section of a muon collider isolation barriers between hydrogen absorbers and vacuum.

Table 1: Window Materials and Experimental Configurations

Material	Thickness [mm]	SMAUG	Window Position
GC [SIGRADUR G]	3	1	1, 2, 7, 8
		1.5	1
		2	2, 8
Be [PF-60]	0.254	1	3
		2	3, 6
Be [S-200-FH]	3	1	4, 6
		2	4
Be [I-220-H]	3	1	5
		2	5
Si_3N_4 [Silson]	0.001	1.5	1
		2*	1, 7

* Si_3N_4 membrane single membrane separated into six individual windows.

BEAM PARAMETERS

High-intensity proton beams from the CERN Super Proton Synchrotron (SPS) were extracted along the TT66 transfer line to the HiRadMat facility. All SMAUG experiments used a beam momentum of 440 GeV/c. The proton pulses consisted of 4×72 bunches, with Gaussian transverse profiles at the sample location.

Beam spot sizes ranged from $\sigma_{x,y} = 0.5$ mm to 0.25 mm, and average intensities of 5.8×10^{13} protons per pulse, corresponding to total pulse intensities of up to 2.8×10^{15} protons. SMAUG-1.5 demonstrated a wave-like affect after exposure to irradiation, selected pulses were delivered to SMAUG-2 sites 3 and 4 with an increased bunch spacing of 7 μs (compared to the nominal 0.25 μs) to investigate potential effects of bunch frequency on the Si_3N_4 membrane. A summary of the beam parameters used at each test site is provided in Table 2.

Table 2: Proton Beam Pulse List and Optics for SMAUG Experiments

Test site	Average beam pulse intensity [10^{13}]	No. of pulses	Beam optics [mm]
SMAUG 1			
1	4.6	5	0.5
2	4.6	50	0.5
3	3.7	5	0.35
4	3.7	50	0.35
5	4.6	5	0.35
6	4.6	50	0.35
SMAUG 1.5			
1	4.6	5	0.5
SMAUG 2			
1	3.5	5	0.4
2	3.5	50	0.4
3	5.8	5	0.25
4**	5.8	50	0.25
5	5.2	5	0.25
6	5.2	50	0.25

**bunch spacing increased from nominal 0.25 μs to 7 μs to evaluate if beam bunch frequency contributed to the wave-like effect.

FLUKA ANALYSIS

Post processing UCAP framework [3] was used to evaluate the beam spot sizes across all SMAUG experiments. FLUKA Monte Carlo simulations were performed to estimate the peak energy deposition in each irradiated window material [4]. The simulations used measured beam parameters, including spot size and intensity, together with material-specific thermal properties. The calculated energy deposition profiles were used to support the interpretation of experimentally observed surface modifications and damage thresholds (Fig 3.) [5].

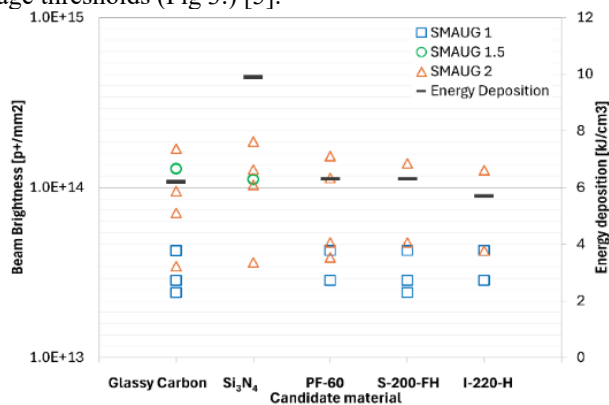


Figure 3: Results from post-experimental evaluated beam brightness and FLUKA simulation maximum energy deposition obtained from each candidate material.

POST EXPERIMENT ANALYSIS AND OBSERVATIONS

All samples were inspected prior to irradiation using optical microscopy to verify the absence of pre-existing defects. Following irradiation, global vacuum leak testing of the assemblies was performed, followed by individual leak tests of each window. Optical microscopy was carried out on all samples, while scanning electron microscopy (SEM) and three-dimensional surface topography measurements were performed on selected glassy carbon, beryllium and Si₃N₄ windows.

Glassy Carbon

The glassy carbon samples tested in all SMAUG experiments remained leak-tight after irradiation, with measured leak rates below 1×10^{-10} mbar·L·s⁻¹. No macroscopic damage was observed on the glassy carbon windows from SMAUG-1, SMAUG-1.5, or SMAUG-2 (window #8). In SMAUG-2, localised beam-induced surface depressions were observed on window #2 at test sites #5 and #6, corresponding to beam brightness values in the range of 1.7×10^{14} p⁺/mm². Topography measurements revealed that the depression depth increased linearly with the number of beam pulses at constant intensity. For identical irradiation conditions, the measured depth on the down-stream surface was approximately three times greater than on the up-stream surface (Fig. 4).

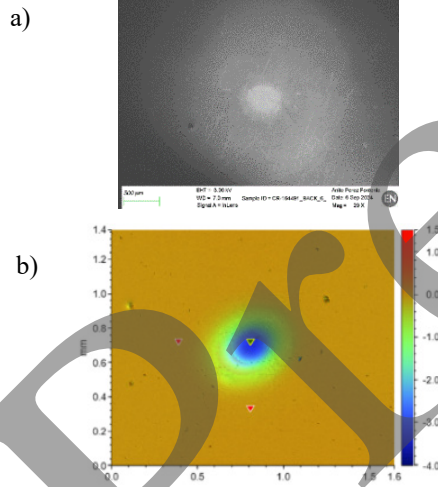


Figure 4: SMAUG 2, Glassy Carbon, Window 2, Test site 6, downstream surface. a): SEM image 29x magnification, b): Topography measurement [6].

Beryllium

For SMAUG-1 and -2 no microscopic damage was observed on I-220-H and S-200-FH samples. PF-60 samples exhibited more pronounced beam-spot markings under similar conditions. In SMAUG-2, the PF-60 window #3 developed an increasing helium leak rate after the 19th beam pulse. The leak rate continued to rise over subsequent exposures, leading to elevated vacuum pressure and necessitating isolation of the affected compartment. Post-experiment inspection confirmed fracture of the beryllium

membrane, attributed to accumulated thermo-mechanical fatigue under repeated beam loading.

Silicon Nitride

The Si₃N₄ membrane tested in SMAUG-1.5 remained leak-tight after irradiation, with measured leak rates below 1×10^{-10} mbar·L·s⁻¹. Optical and SEM inspections revealed a distinct beam-impact region characterised by a wave-like surface pattern, confirmed by three-dimensional topography measurements (Fig. 5). The observed deformation features are consistent with thermal decomposition and bond-reconfiguration mechanisms reported in the literature for silicon nitride ceramics at elevated temperatures [7] [8]. Si₃N₄ samples exposed to the highest tested beam brightness values, up to 4.2×10^{14} p⁺/mm², failed during the first irradiation pulse.

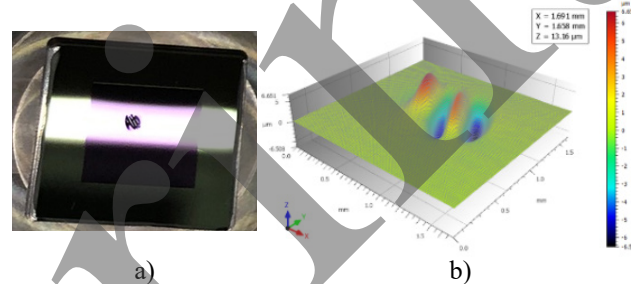


Figure 5: Beam-impact on SMAUG 1.5 Si₃N₄ membrane. a): Photo of beam-impact spot, b): Three-dimensional topography measurements [9].

CONCLUSION

The SMAUG experiments have provided for the first time a systematic comparative assessment of candidate particle beam window materials.

Glassy carbon demonstrated predictable sublimation behaviour and maintained structural integrity under the tested conditions, with damage scaling linearly with deposited energy.

Beryllium samples showed good resistance at moderate brightness levels, though fatigue-induced failure occurred in thin PF-60 membranes after repeated exposure. No beam-induced effects were microscopically observed on the I-220-H or S-200-FH beryllium samples, indicating high tolerance to proton beam of brightnesses up to 1.4×10^{14} p⁺/mm².

Silicon nitride membranes exceeded the beam intensity requirements foreseen for muon collider isolation barriers but failed at the highest tested brightness values. Plastic deformation was observed after repeated beam pulses at brightnesses of 1.1×10^{14} p⁺/mm².

The results indicate that glassy carbon represents a suitable and potentially safer alternative to beryllium for selected beam window applications in high-power pulsed proton accelerators. In addition, the experimental data support the use of numerical simulations to estimate material response and lifetime under intense beam operation.

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