A beryllium material test experiment at CERN HiRadMat facility

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Outline

- Motivation and objectives of experiment
- Overview of HiRadMat facility
- Experimental specifications
- Numerical simulations
- Design overview and test matrix
- Online instrumentation
- Post-Irradiation-Examination (PIE) techniques
- Experiment status and conclusions

Motivation and objectives

Motivation: To help successfully design and reliably operate beryllium windows and targets for future high intensity particle accelerator facilities, by identifying failure mechanisms of beryllium under high intensity beam conditions

Objectives

- ☞ explore the onset of failure modes of various beryllium grades under controlled conditions at very high localized strain rates and temperatures
- ☞ identify potential thermal shock limits of different beryllium grades
- ☞ compare experimental measurements to highly non-linear damage/failure numerical simulations for validation of material models

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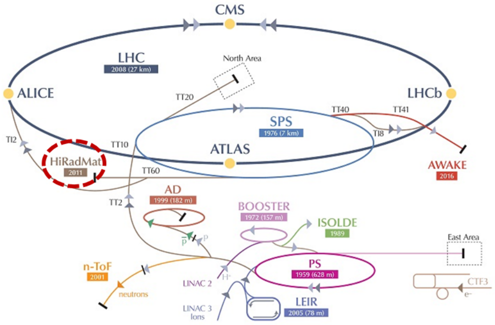
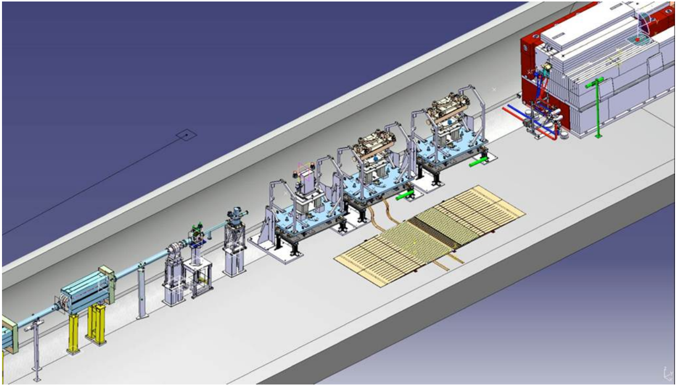
CERN's HiRadMat facility



- Proton beam energy: 440 GeV
- Max. intensity: 4.9×10^{13} ppp (288 bunches of 1.7×10^{11} ppb)
- Pulse length: 7.2 μs
- 1σ beam radius: 0.1 - 2.0 mm

HiRadMat experimental area



- 3 experimental test stands
- Remote installation of experimental tables
- 'Single-shot' experiments with annual limit $\sim 10^{16}$ pot

HiRadMat target area

Experimental specifications

Investigate beryllium windows/cylinders response to

- increasing proton beam intensity
  - ➥ 72, 144, 216, 288 bunches
- varying window thicknesses
  - ➥ 0.25, 0.75, 2 mm
- different beryllium grades/forms
  - ➥ PF-60, S-65F (VHP), S-200F (VHP), S-200FH (HIP)
- multiple beam pulses
  - ➥ 3 pulses of 144 bunches
- elastic/plastic stress waves
  - ➥ edge strain/vibration measurements of slugs/cylinders

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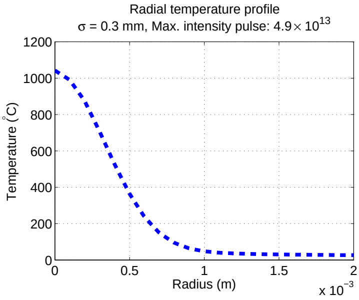
Numerical simulations

MARS energy deposition calculation[1]

- Beam σ_r = 0.3 mm selected to push beryllium specimens to its limit
- Temperature jump ∼1050°C for maximum intensity pulse
- Close to beryllium melting temperature (1280°C)
- Expect thermal shock due to large temperature gradient in material

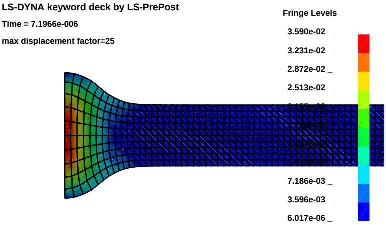


[1] Hartsell, B., "MARS energy deposition data for beryllium samples of HiRadMat experiment', 2014.

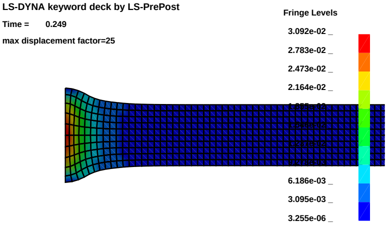
Beam induced stress and strain

- Temperature and strain rate dependent Be strength material properties [2]
- LS-DYNA elastic-viscoplastic material model (MAT 106)[3]

2D axisymmetric LS-DYNA model showing effective total strain
($4.9{\times}10^{13}$ protons, ΔT = 1050 $^\circ$C, 0.75 mm thick, beam centered on window)



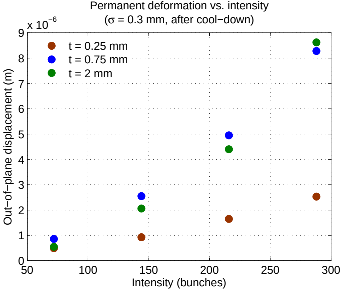
$t = 7.2\mu s, T_{max} \sim 1050^\circ C$
End of pulse



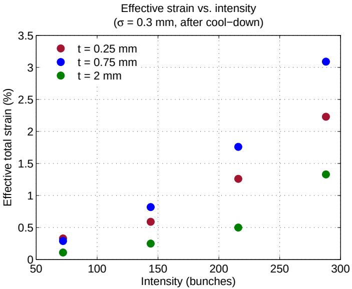
$t = 0.25s, T_{max} \sim 25^\circ C$
End of cool-down

[2] Montoya, D., et al., Comportement dynamique d'une nuance de beryllium, Journal de Physique IV, 1991, vol. 1, pp. 27-34.
[3] LS-DYNA Keyword User's Manual, Volume II, Material Models, LSTC, 05/19/14 (r:5442).

Surface deformation and plastic strain vs. intensity and thickness



Out-of-plane permanent surface deformation



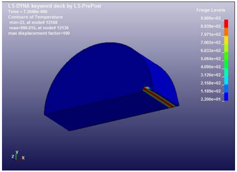
Maximum plastic strain

- Literature data predicts failure at plastic strains $\sim 2\%$ at RT
  - Be grade S-200F VHP[4]

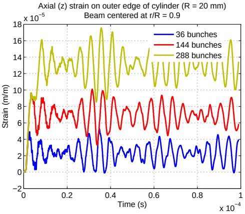
[4] Chaouadi, R. et al., "Tensile and fracture toughness test results of neutron irradiated beryllium", ITER Task T23, 1997.

Dynamic response of Be cylinders

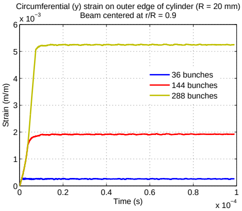
- Elastic/plastic strain response at the edge of the cylinder
- Beryllium slugs: R = 20 mm, L = 30 mm
- Beam incident at r/R = 0.9 (2 mm from edge)
- Strain and temperature gages mounted on cylinder edge



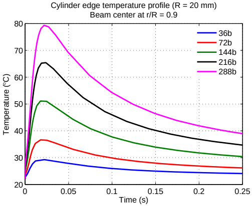
Temperature plot showing beam location



Axial strain



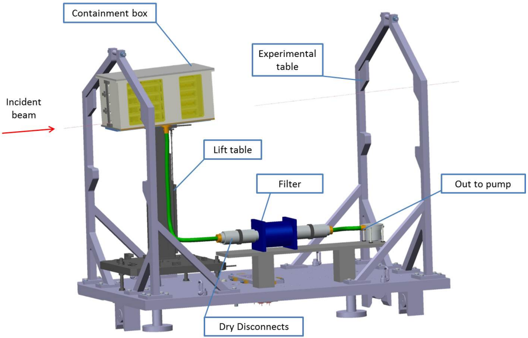
Circumferential strain



Temporal edge temperature

Design overview

Overall layout[5]



Main features of test rig

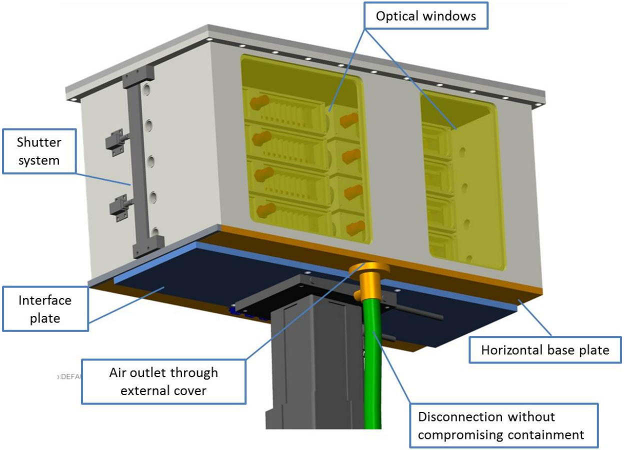
- Double containment
- Vertical lift table
- Optical viewports
- Pumping port and filter
- Quick-disassembly system

[5] Atherton, A. et al., "HRMT24 Experiment: test rig design", HiRadMat update meeting presentation, September 12th, 2014

Design overview

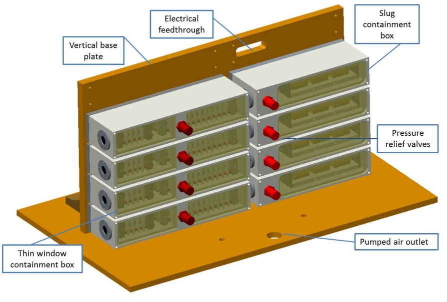
Containment box[5]

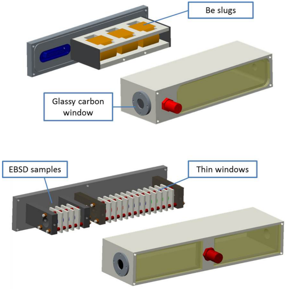
Dimensions ~ 0.60 m × 0.35 m × 0.30 m



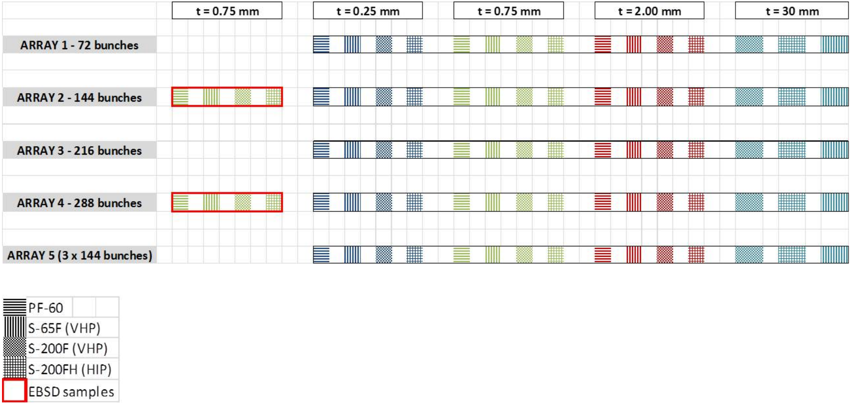
Design overview

Interior layout[5]

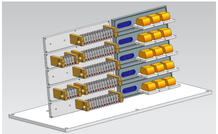




Test matrix



- ➛ Total proton on target $\sim 2.0\times10^{14}$



Online instrumentation

- Strain gages: positioned on beryllium slugs to measure
  - ➥ axial strain
  - ➥ circumferential strain
- Laser Doppler Vibrometer: to measure radial surface vibrations/displacements of slugs
- RTD sensors: to measure temporal temperature on surface of slugs
- Camera: to monitor any unforeseen events during the experiment

➠ *Experimental data from strain gages, LDV and RTD sensors will help validate numerical simulations*

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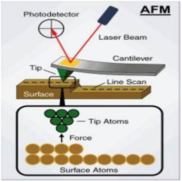
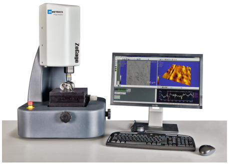
Post Irradiation Examination (PIE)

PIE at University of Oxford

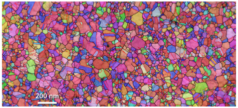
- Profilometer/AFM: to measure permanent surface out-of-plane displacements
- EBSD: pre-irradiation mapping of grain structure and possibly post-irradiation localized deformation/crack analysis
- SEM: surface evolution analysis
- 3D FIB-SEM: 3D analysis of crack morphology



Atomic Force Microscopy



Profilometer system



Electron Backscatter Diffraction

Summary of measurements

- ✓ Dynamic vibration and strain response
- ✓ Temporal temperature profile
- ✓ Out-of-plane plastic deformation profile
- ✓ Crack/failure detection and fracture surface morphology
- ✓ Localized deformation due to grain orientation
- ✓ Camera to capture unforeseen events

Experiment status

- Experiment proposal submitted in March 2014
- Proposal preliminary acceptance: June 2014
- Scientific and technical board review: Oct 2014
- Potential beam time for experiment: Spring 2015

Conclusions

- Exploratory study to probe damage mechanism of beryllium
- Compare damage mechanism and response of different beryllium grades
- Identify any primary failure mode for the various grades/conditions
- Attempt to benchmark macro-scale simulations and material strength models with experimental measurements

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