BeGrid2 - Target and beam window material experiment at CERN's HiRadMat facility

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Outline

- Motivation and objectives of the experiment
- CERN HiRadMat facility overview
- Summary of BeGrid experiments and PIE work
- BeGrid2 experiment
  - Specifications
  - Test matrix
  - Numerical simulations
  - Design overview
  - Experiment implementation and PIE
- Conclusion

Motivation for experiment

- A follow-up experiment to BeGrid (HRMT24) to further understand the thermal shock response of conventional and novel materials used for accelerator beam windows and particle production targets

- Help successfully design and operate windows and targets for future high intensity multi-MW accelerator facilities, without having to compromise particle production efficiency

- Understand and compare the failure mechanisms, dynamic limits and flow behavior of the various material specimens exposed to high energy high intensity proton beams available at the HiRadMat facility

Objectives of the experiment

I. Build upon the previous BeGrid (HRMT24) experiment to expose Beryllium to even higher beam intensities than what was achieved in HRMT24

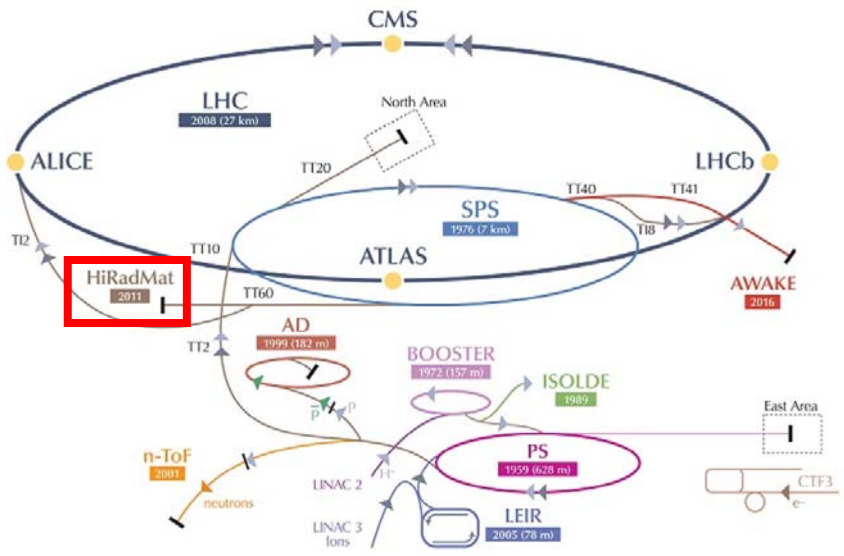
II. Identify thermal shock response differences between non-irradiated and previously irradiated material specimens (Be, C, Ti, Si)

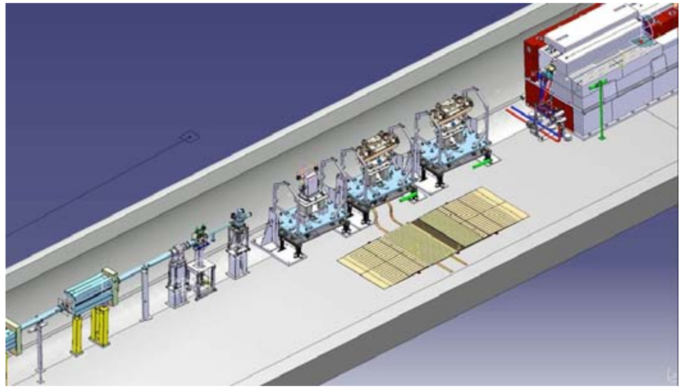
III. Include novel materials such as metal foams and electrospun fiber mats to evaluate their resistance to thermal shock and suitability as target materials

IV. Real-time measurement of the dynamic thermo-mechanical response of graphite slugs in an effort to benchmark numerical simulations (and for online diagnostics)

V. Study the effects of stress resonance on thin beam windows (under consideration)

CERN’s HiRadMat facility

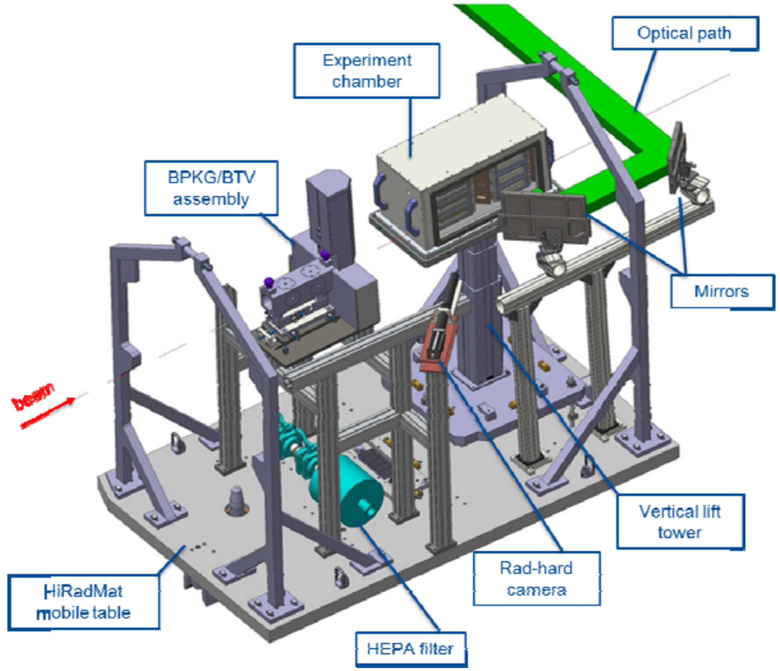


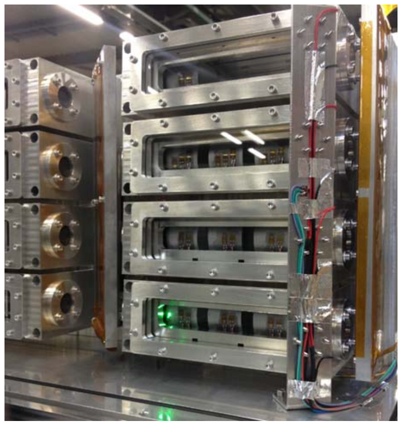


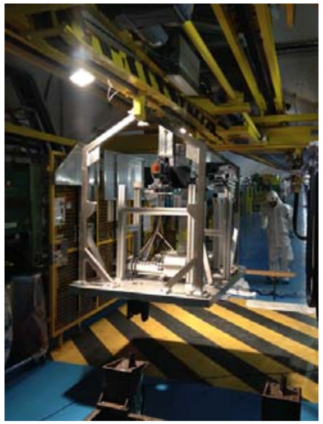
Beam Parameters	
Beam energy	440 GeV
Max. bunch intensity	1.2×10^{11}
No. of bunches	1 - 288
Max. pulse intensity	3.5×10^{13} ppp
Pulse length	7.2 μs
Gaussian beam size	1σ: 0.1 – 2 mm

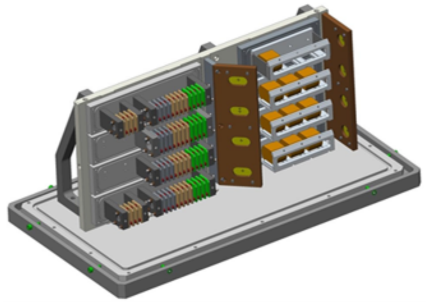
BeGrid - HRMT24 (2015)

- Experiment successfully completed in 2015
- Consisted of four arrays of thin Be discs and slugs of various thicknesses and grades
- PIE of thin discs performed at University of Oxford
- Real-time measurements of temperature, strain and displacement from surface of slugs









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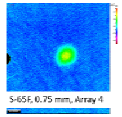
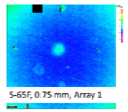
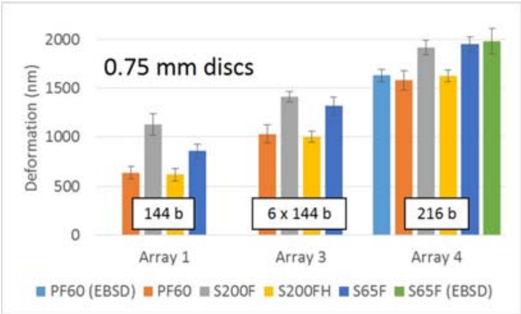
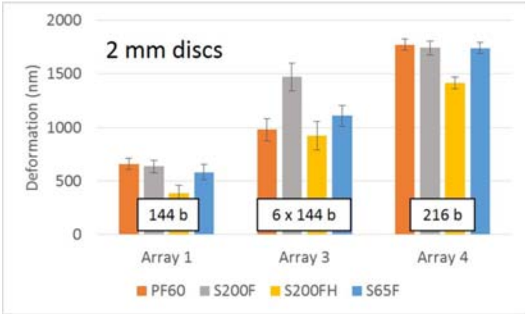
BeGrid - HRMT24 results

Profilometry maps of thin Be discs

- S200FH showed lowest plastic deformation
- S200F showed higher plastic deformation
- Observed plastic ratcheting in Array 3
- No cracks were observed with optical microscopy

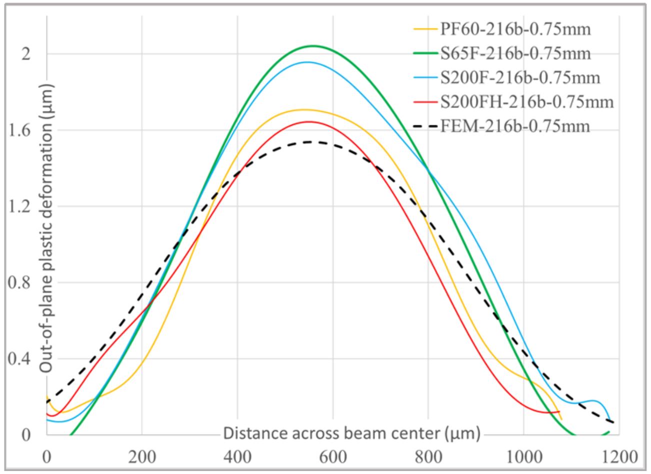







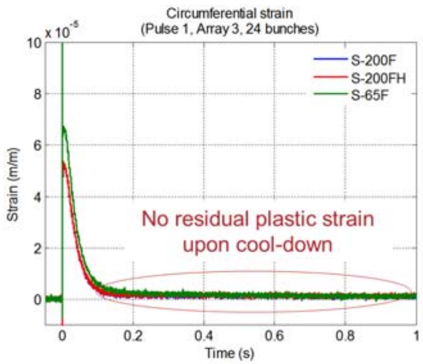
Be S200FH Johnson-cook model validation:

JC parameters specifically developed by SwRI to model experimental results

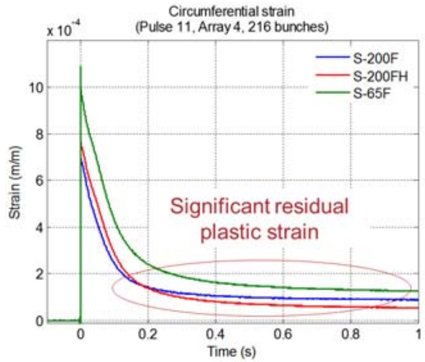


Relatively good agreement between simulation and experimental measurement for 0.75 mm thick Be S200FH disc

Strain response of Be slugs



Array 3 – 24 bunches
3.196×10^{12} POT



Array 4 – 216 bunches
2.792×10^{13} POT

Experimental issues

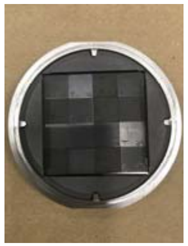
- Large variations of beam sigma on target
- Array 4 did not receive the desired maximum beam intensity
  - Due to larger beam sigma and lower ppb
  - Peak ΔT: 650 °C instead of desired 1000 °C

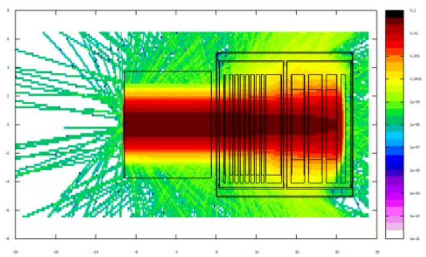
BeGrid2 (2018) experimental specification

- Four specimen arrays exposed to varying beam pulse intensities
  - Maximum beam pulse intensity higher than achieved in HRMT24

- Various material specimens and grades, of varying thicknesses
  - Beryllium, graphite, glassy carbon, titanium alloys, silicon, CfC, WGr, foam materials (C, W, SiC), and electrospun fiber mats (Al_2O_3, ZrO_2)

- Previously proton-irradiated specimens
  - Beryllium, graphite, glassy carbon, titanium alloys, silicon
  - Specimens irradiated at BNL BLIP with 180 MeV protons for about 8 weeks



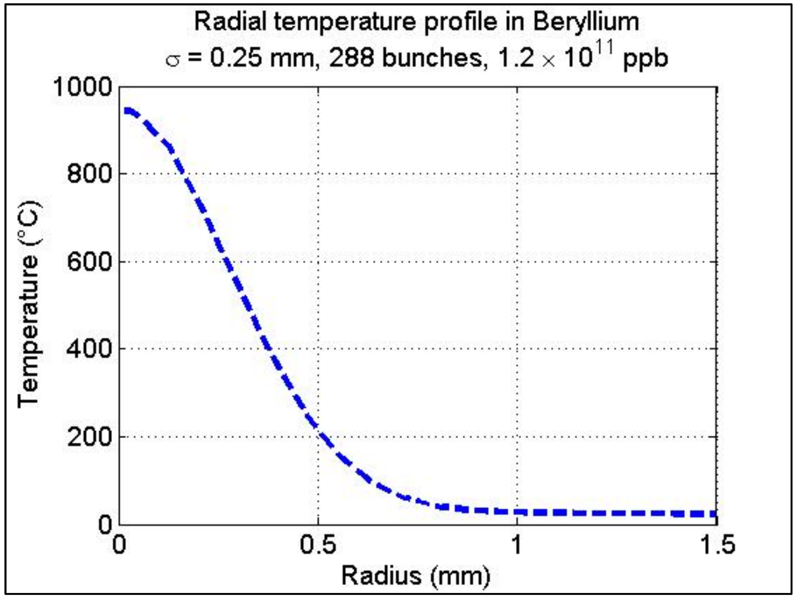
- Real-time measurements of temperature, strain and vibration of graphite cylinders and the associated data acquisition systems

- Extensive post-irradiation analyses

BeGrid2 beam parameters

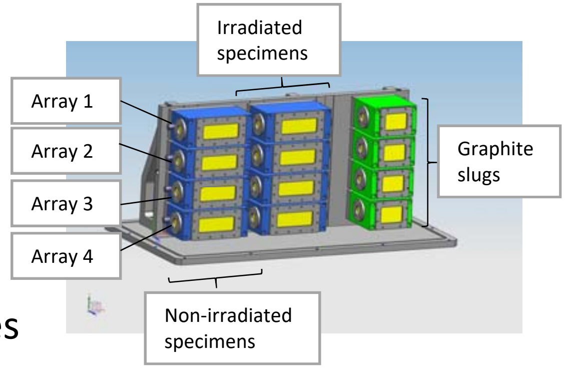
- Beam sigma of 0.25 mm is requested at experimental table 2
- Peak bunch intensity: 1.2e11 protons
- Bunch spacing: 25 ns

- No. of bunches per pulse will be varied to control beam intensity on target



- Max. pulse intensity to induce ΔT of close to 1000 °C in Be
- Pushes Be close to its melting point (1280 °C)

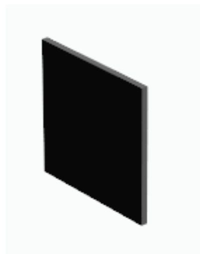
BeGrid2 preliminary test matrix



ARRAY 1 – High Intensity Pulse

- σ = 0.25 mm, 288 bunches x 1.2e11 ppb, 3.5e13 protons
- Irradiated and non-irradiated specimens in separate containment boxes
  - Beryllium, Graphite, Glassy Carbon
- Glassy Carbon foam
- One instrumented graphite cylindrical slug downstream of thin discs
  - Strain gages, temperature gages, LDV

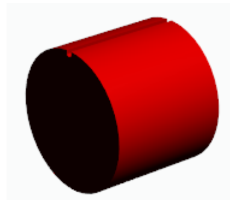
Thin specimens
10 mm x 10 mm x 0.75 mm



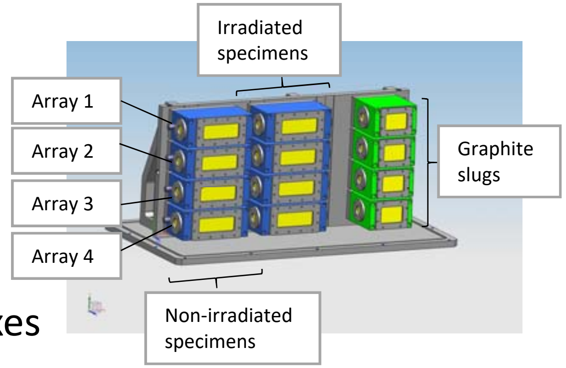
ARRAY 2 – Medium High Intensity Pulse

- σ = 0.25 mm, 216 bunches x 1.2e11 ppb, 2.6e13 protons
- Irradiated and non-irradiated specimens in separate containment boxes
  - Beryllium, Graphite, Silicon
- SiC (solid & foam), Al_2O_3 (solid & electro-spun), CfC
- One instrumented graphite cylindrical slug downstream of thin discs
  - Strain gages, temperature gages, LDV

Cylindrical specimens
D: 35 mm, L: 30 mm



BeGrid2 preliminary test matrix



ARRAY 3 – Medium Intensity Pulse

- σ = 0.25 mm, 144 bunches x 1.2e11 ppb, 1.7e13 protons
- Irradiated and non-irradiated specimens in separate containment boxes
  - Titanium alloys, Silicon
- Tungsten (solid & foam), electro-spun ZrO_2, CfC, WGr
- One instrumented graphite cylindrical slug downstream of thin discs
  - Strain gages, temperature gages, LDV

ARRAY 4

- σ = 0.25 mm, pulse intensity to be finalized
- Irradiated and non-irradiated specimens in separate containment boxes
  - Titanium alloys
- Tungsten (solid & foam), electro-spun ZrO_2, CfC, WGr
- Ti window resonance set-up (design and implementation under consideration)

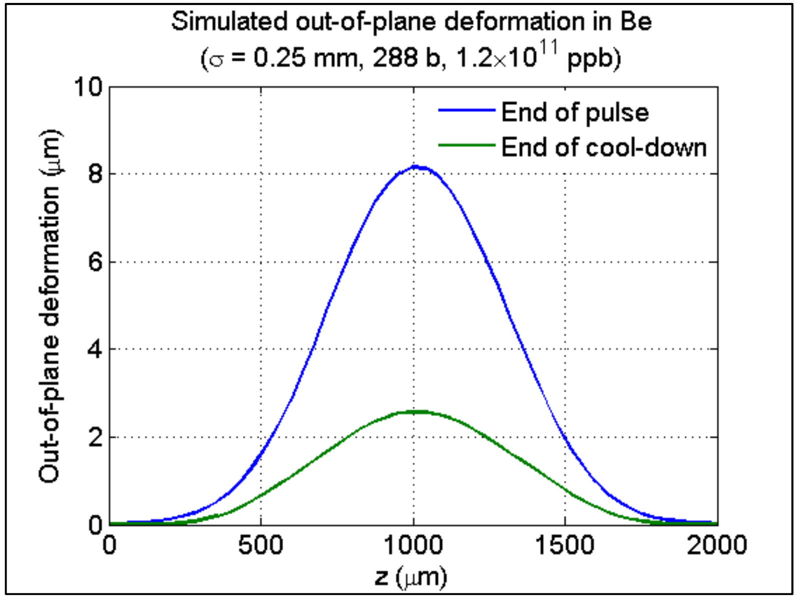
Total proton on target for all 4 arrays < 1.5e14

Numerical simulations

Beam Induced Stress and Strain

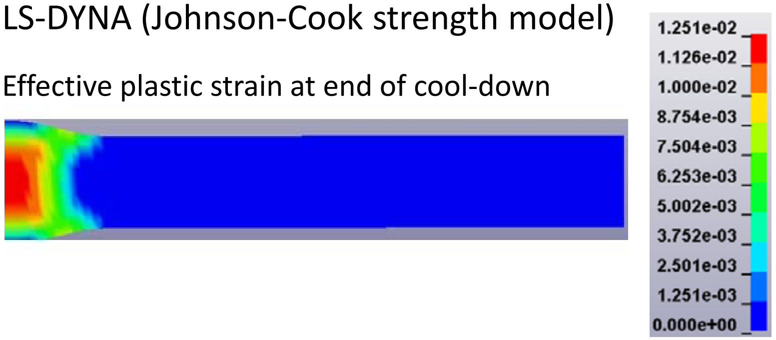
<u>Beryllium</u>

- Peak temperature jump ~1000 °C



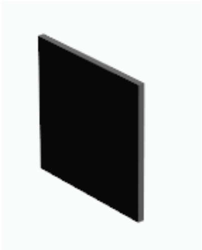
LS-DYNA (Johnson-Cook strength model)

Effective plastic strain at end of cool-down



Irradiated Be specimens: 0.03 DPA

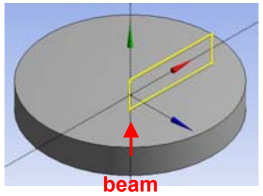
- Explore effect of radiation damage on thermal shock response
- Reduced ductility expected (~100 appm He)



- Peak effective plastic strain at end of cool-down: 1.25 %
    - Failure plastic strain from literature: 1-2 %
- Out-of-plane deformation will be measured with profilometer during PIE

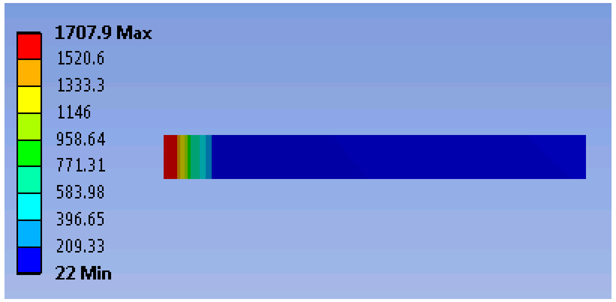
Numerical simulations

Graphite



- Peak beam intensity: σ = 0.25 mm, 288 x 1.2e11 ppb (3.5e13 ppp)
- Temperature dependent thermal/strength properties
- UTS: 79 MPa, UCS: 175 MPa

2D axisymmetric ANSYS model

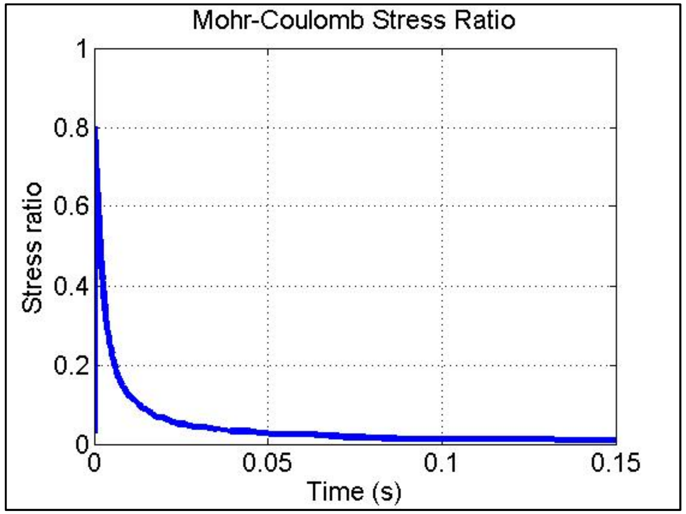


Peak temperature: ~1700 °C

- Stress ratio (0.8) highest at end of beam pulse, then drops back to zero as disc cools down to RT
  - close to graphite's failure limit
- Compare response of irradiated **(0.05 DPA)** to non-irradiated graphite specimens during PIE

Mohr-Coulomb failure criterion

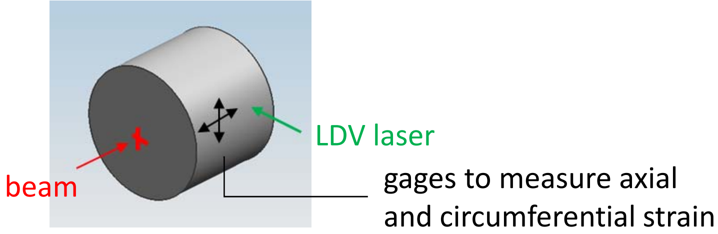
$$\frac{\sigma_1}{S_{tensile}} + \frac{\sigma_3}{S_{compressive}} < 1$$

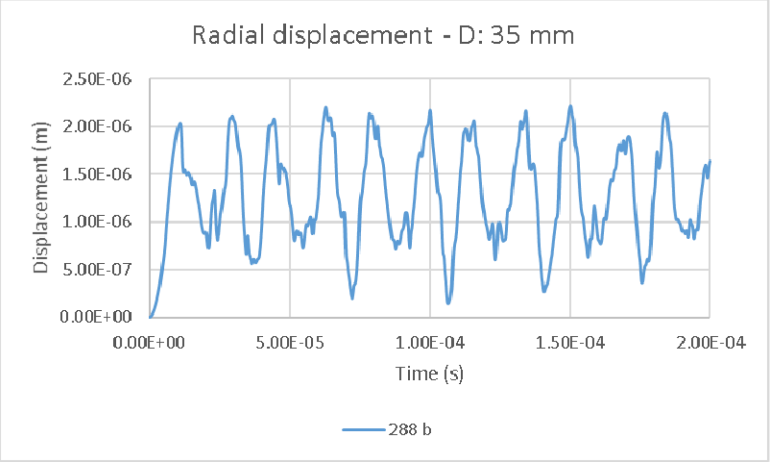


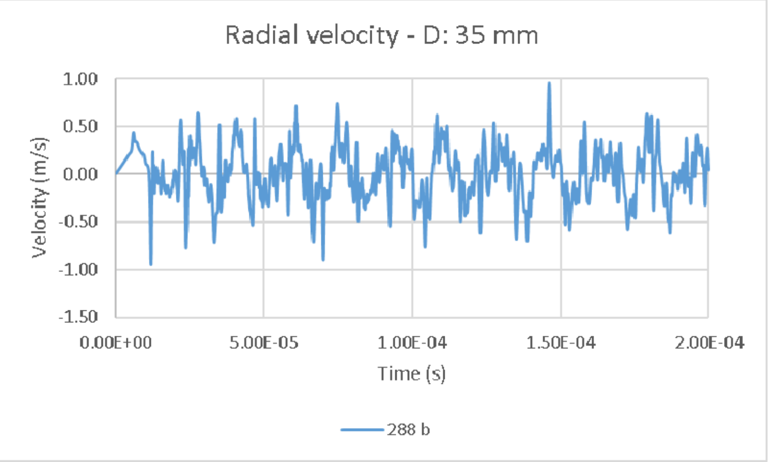
Numerical simulations

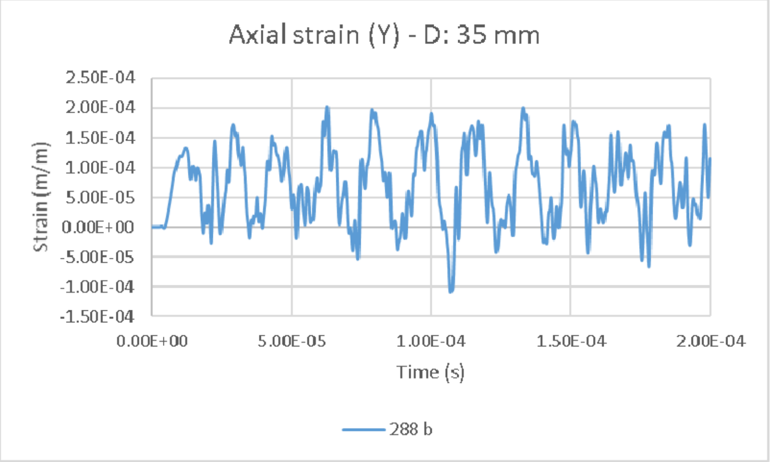
Dynamic response of graphite cylinders

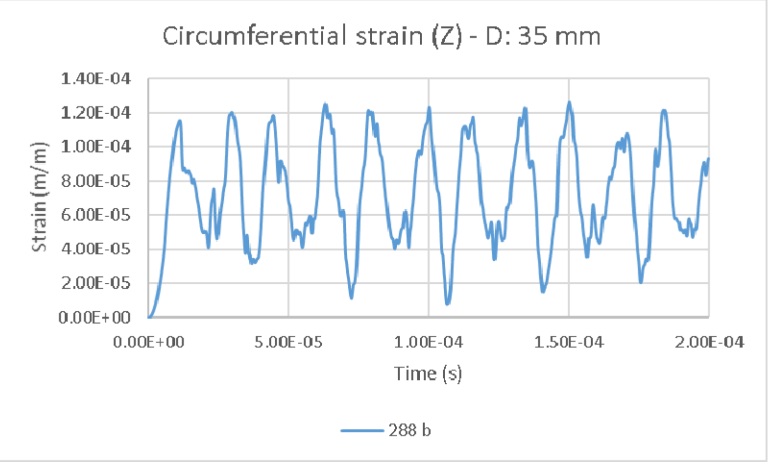
- Beam pulse: 288 x 1.2e11 ppb, 7.2 µs pulse
- Slug diameter: 35 mm, length: 30 mm









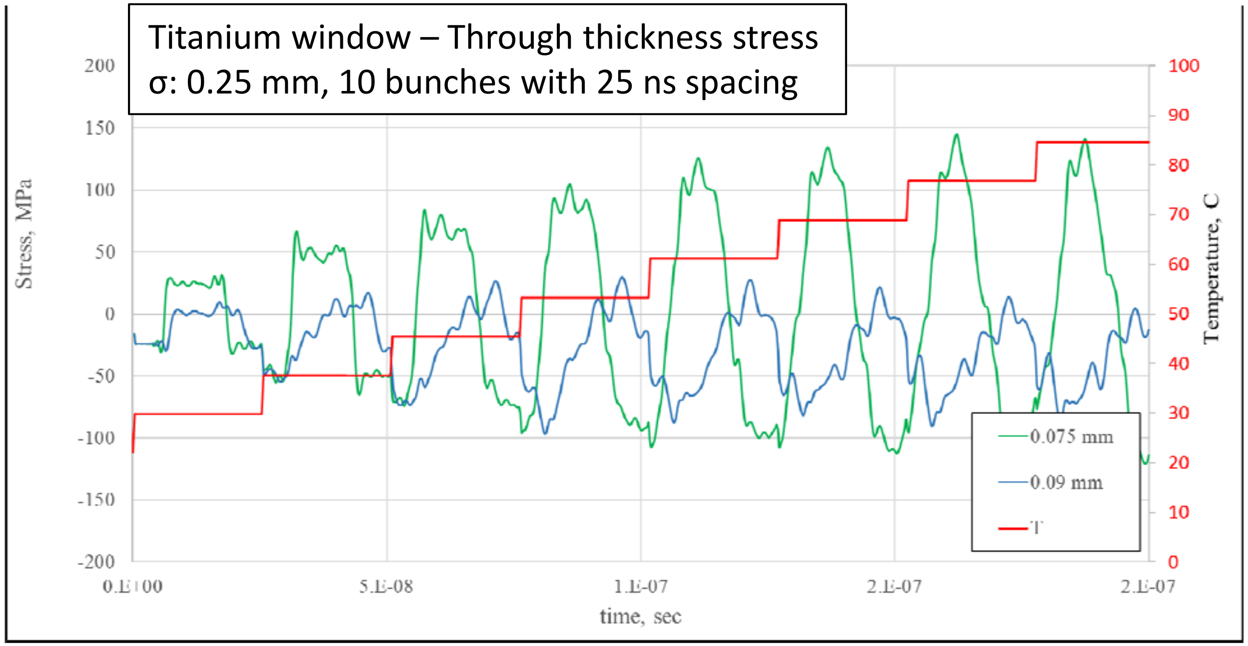


Numerical simulations

Window resonance effects

- Constructive stress wave interference when beam bunches are in phase with acoustic transit time across window thickness can lead to stress resonance

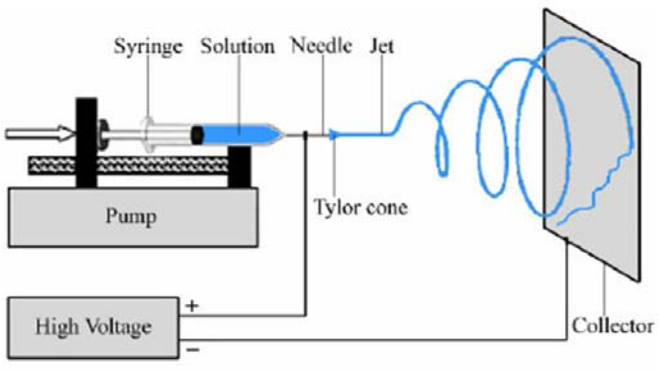
$$Oscillation\ period = \frac{2\ \times window\ thickness}{sonic\ velocity}$$



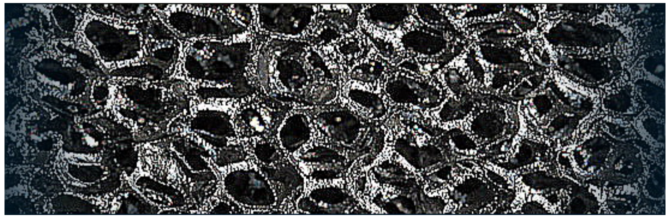
- Investigating ways to impose static pressure on window to push it closer to its failure limit to generate measurable effect during experiment

Novel materials

- Electro-spun and foam materials
  - Local damage of fibers do not affect structural integrity as a whole
  - Reduced temperature gradient limited to fibers
  - High surface area and gaps: improved cooling by flowing gas
- In-beam test to evaluate thermal shock response of foam/fiber mats compared to solid material



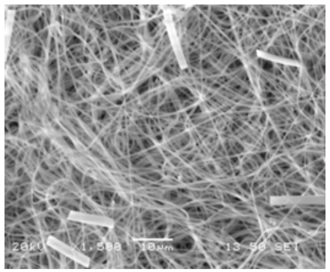
Reticulated vitreous carbon foam



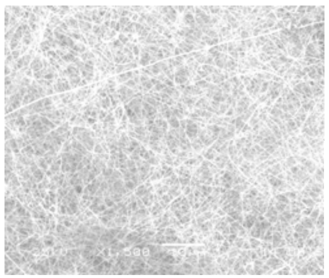
SiC foam

As-spun alumina-pvp mat

SEM: as-spun Al_2O_3



Al_2O_3 SEM after heat treatment

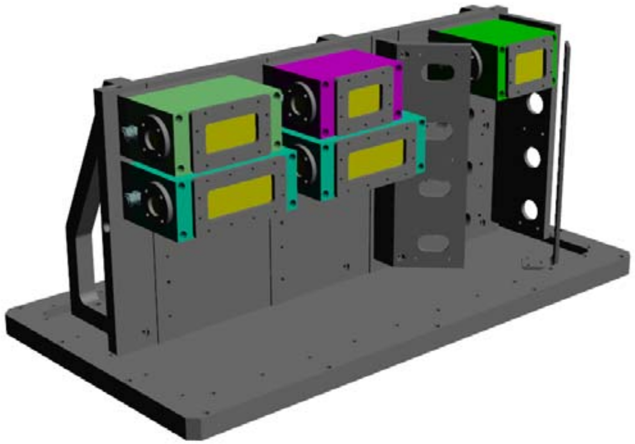


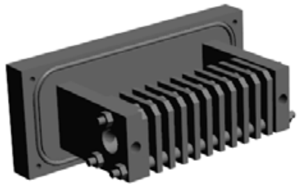
BeGrid2 design overview

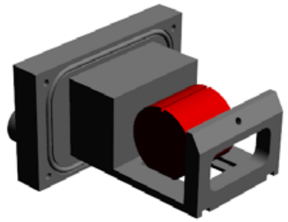
- Plan to re-use outer containment box from HRMT24
- Inner containment boxes will be re-designed/fabricated according to new layout
- Total of four specimen arrays (similar to HRMT24)

BeGrid (HRMT24) outer containment box
currently at Fermilab (not contaminated)
Dose rate was 0.4 μSv/hr at 10 cm in Jan, 2016

Inner containment box and array
configurations will be re-designed

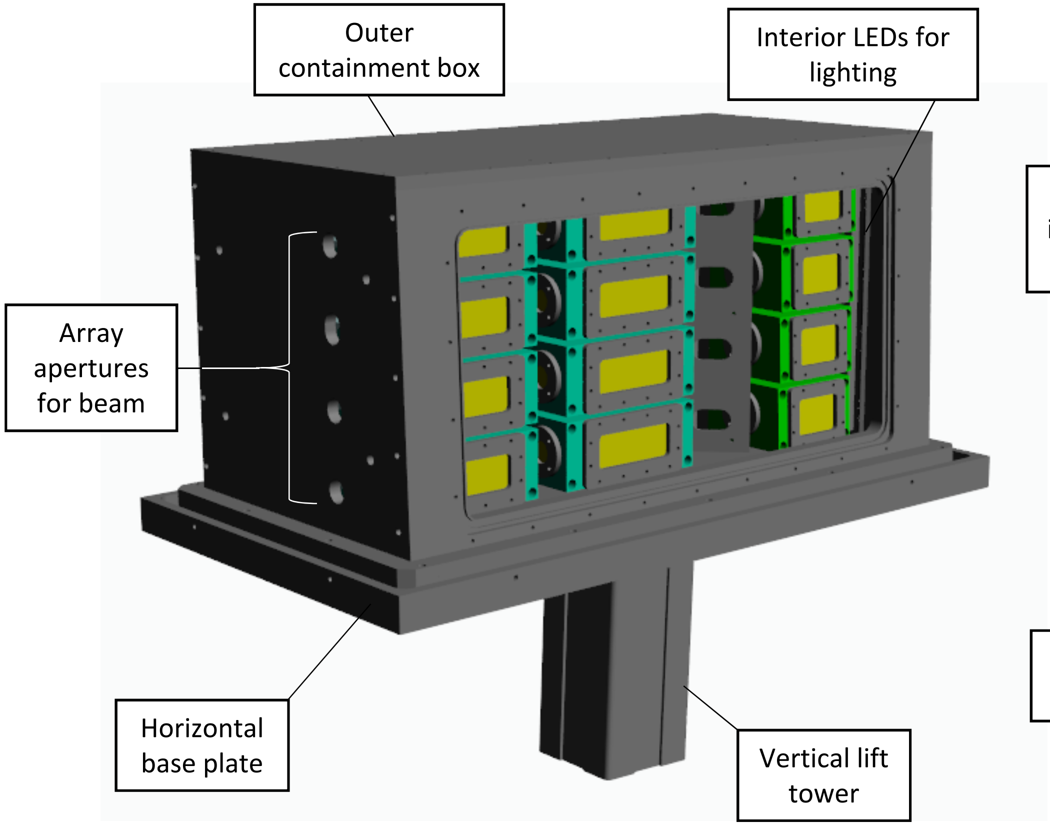




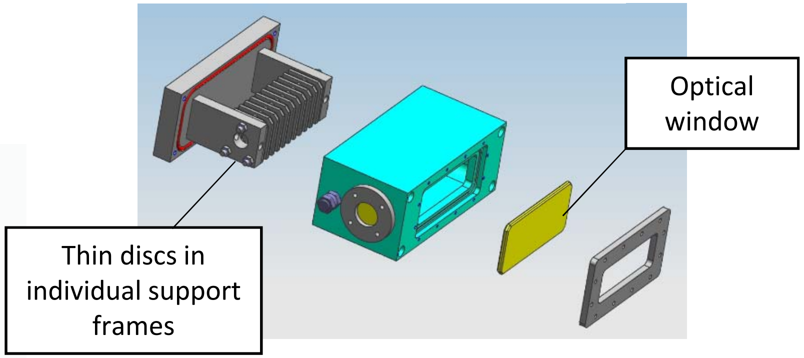


BeGrid2 design overview

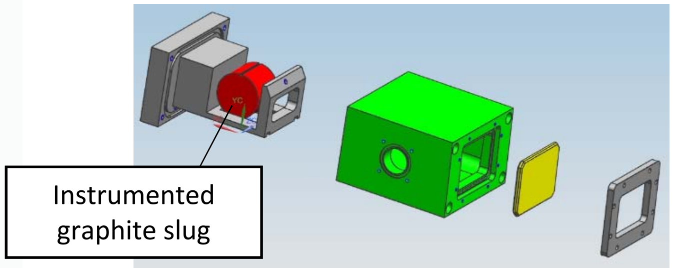
- Double containment design
  - Inner boxes hermetically sealed
  - Negative pressure in outer containment box
- Outer box dimension: 0.60 m x 0.35 m x 0.30 m



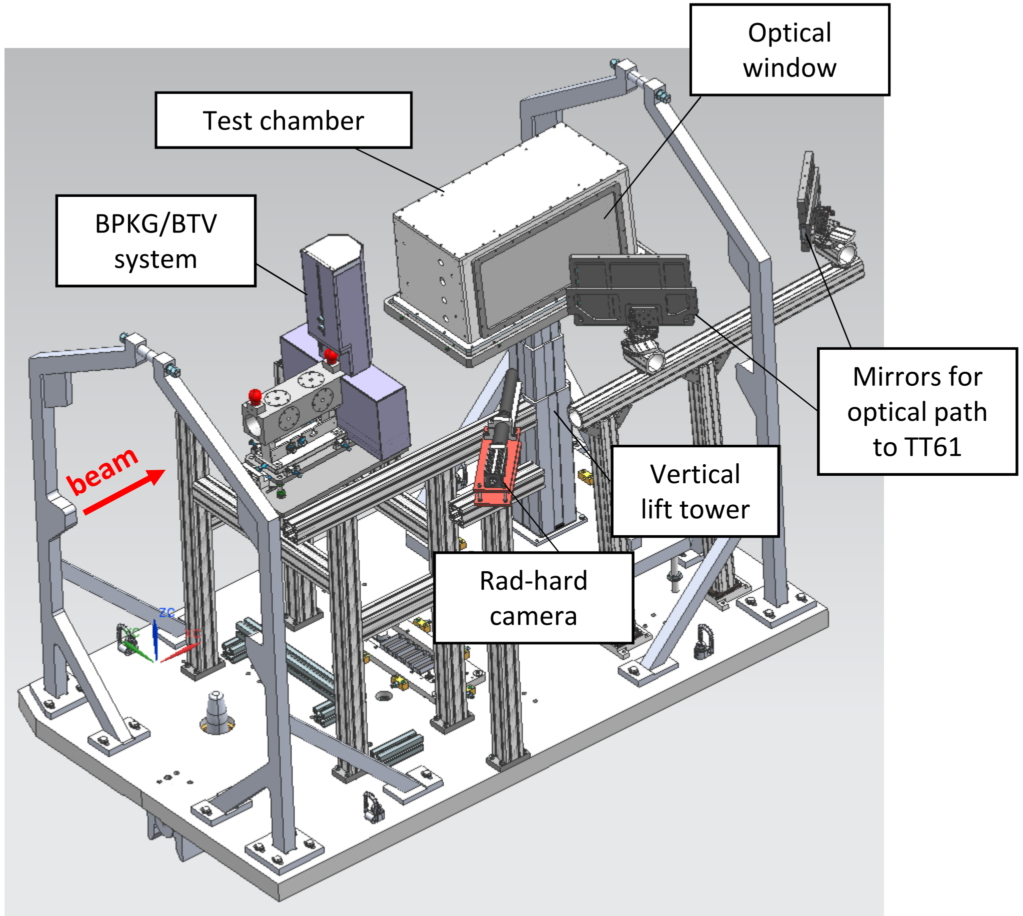
Thin specimen inner containment box



Graphite slug inner containment box



BeGrid2 design overview



Main features

- Double containment
- Vertical alignment to beam
- Optical viewports
- Quick-disassembly system

Irradiated specimens will be encased in separate containment boxes. Estimated dose rate per specimen at time of installation:

- Be: ~5 µSv/hr @ 1 ft, Qty: 8
- C: ~6 µSv/hr @ 1 ft, Qty: 4
- Ti: ~90 µSv/hr @ 1 ft, Qty: 4

Discussions on specimen handling and installation ongoing with CERN's RP group

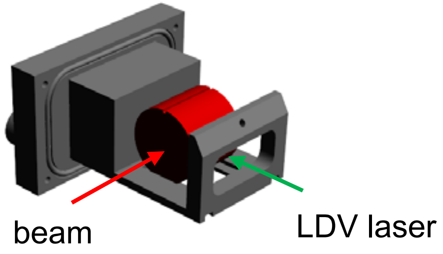
BeGrid2 instrumentation list

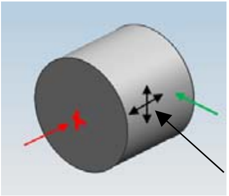
- ***Beam profile/size/position measurements***
  - Standard BPKG/BTV system upstream of test rig on mobile table
  - Dosimetry foil inside outer containment box and rad-hard camera
  - BPKG/BTV with optical line for OTR measurements installed upstream o Table 1
  - Synchrotron light monitor (BSRT) in SPS, prior to beam extraction to HiRadMat

Dosimetry foils (HRMT24)

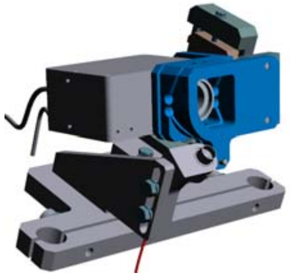
- ***Slug dynamic response measurements***
  - LDV for radial surface velocity/displacement measurements of graphite slugs
  - Strain (axial and circumferential) and temperature gages
  - Associated DAQ systems

Strain/temperature gages attached to cylindrical edge of slugs





LDV head positioned on mobile table next to outer containment box optical window



BeGrid2 instrumentation list

- ***High resolution camera***
  - Visual monitoring of specimens and set-up during experiment
  - Internal lighting
  - Mirrors to provide optical path to adjacent tunnel (TT61)

- ***Air pump***
  - Draw out air of outer containment box to maintain negative pressure
  - Used shop vacuum cleaner in HRMT24 (maybe still available to re-use)

- ***Vertical lift tower and associated control system***
  - To vertically align array boxes to beam

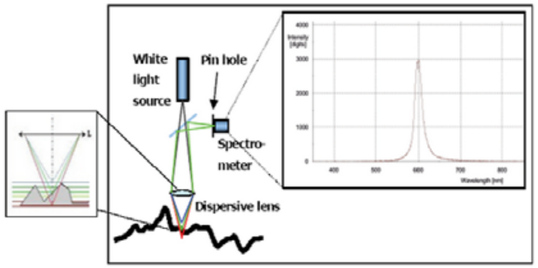
Post-Irradiation-Examination (PIE) activities

Thin specimens

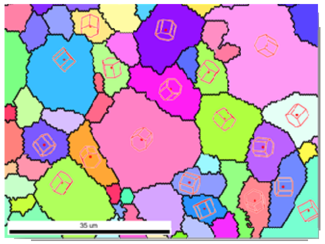
- Profilometer or Atomic Force Microscopy (AFM) to measure permanent out-of-plane deformation
- Scanning Electron Microscopy (SEM) for identifying any local deformations/cracks
- Electron Backscatter Diffraction (EBSD) to map grain structure and localized deformation/crack analysis
- 3D FIB-SEM: 3D analysis of crack morphology

Currently planned to be performed at Culham Center for Fusion Energy (CCFE) laboratory in the UK. Specimens will be shipped after sufficient cool-down time.

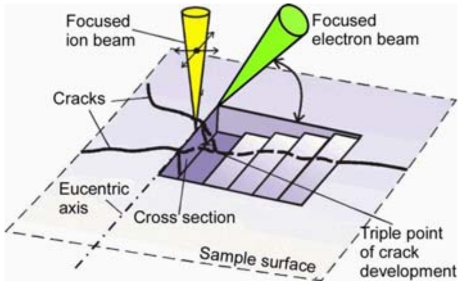
Profilometry



EBSD



FIB



Slug specimens

- Analysis of real time recorded data
- Update numerical simulations with actual beam parameters to compare with measurements

Experiment implementation

Fermilab

- Coordinate activities leading up to beam time
- Design, fabrication and assembly of inner boxes and containment chamber
- Numerical simulations and finalization of test matrix
- MARS activity calculation of test rig
- Strain and temperature gages installation and testing

CERN

- Assembly of irradiated specimens in inner containment box
  - Discussions with RP ongoing
- Instrumentation and DAQ systems
  - LDV, high-res. camera, rad-hard camera, strain/temperature
- Coordination of test rig installation at HiRadMat

RAL

- Design and fabrication of resonance test set-up and diagnostic system (still under consideration)

Expecting to be ready for beam time in September 2018

Summary and conclusion

- Build upon BeGrid experiment to expose specimens to even higher beam intensities and thermal shock conditions
- Test and compare thermal shock resistance of proton-irradiated specimens to non-irradiated specimens
- Evaluate potential novel materials for secondary particle-production targets
- Benchmarking of numerical simulation and material strength models through dynamic strain measurements

- In-beam test necessary to concurrently impose very highly localized strain rates and temperatures in material specimens under controlled conditions
- Last opportunity for an in-beam test at HiRadMat prior to LHC shutdown

Thank you for your attention