Overview of Past RaDIATE HiRadMat Experiments

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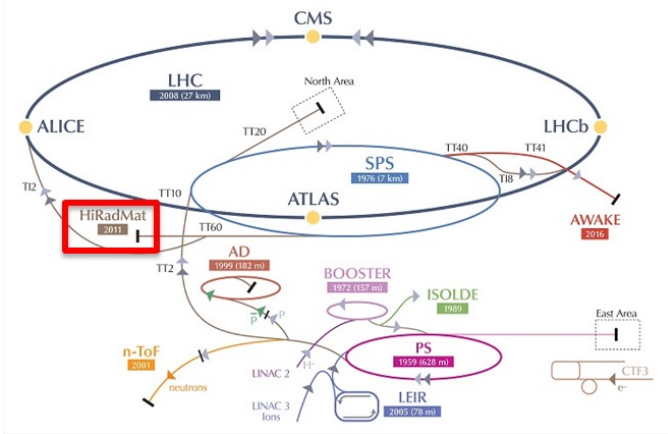
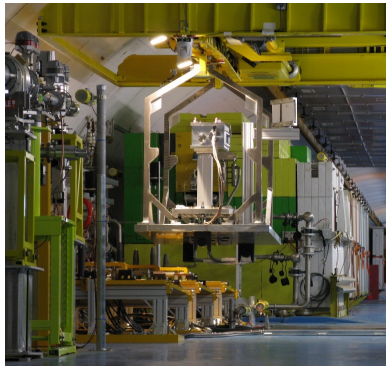
RaDIATE Collaboration Meeting

30 June 2023

RaDIATE HiRadMat Experiments

- → HRMT-24: BeGrid (2015)
- → HRMT-43: BeGrid2 (2018)
- → HRMT-60: RaDIATE2022 (2022)





Beam Parameters	
Beam energy	440 GeV
Max. pulse energy	2.4 MJ
Max. bunch intensity	1.2×10^{11}
No. of bunches	1 – 288
Max. pulse intensity	3.5×10^{13} ppp
Max. pulse length	7.95 μs
Gaussian beam size	1σ rms: 0.25 – 4 mm

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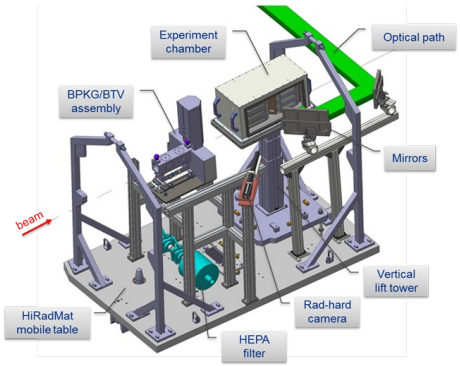
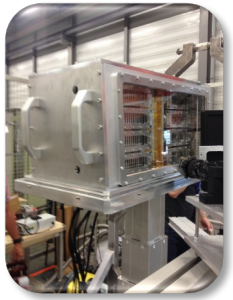
HRMT-24: BeGrid (2015)

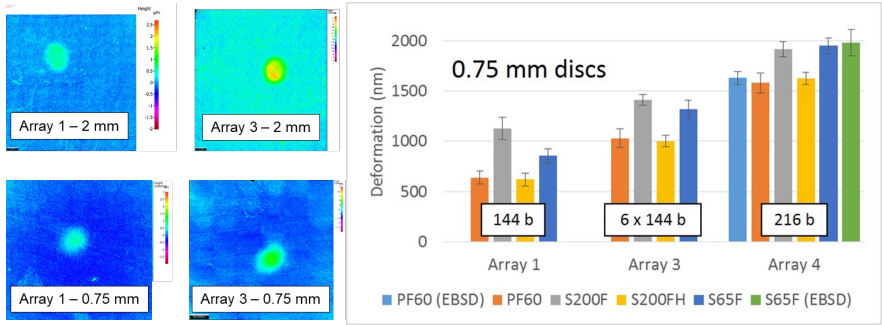
Thermal shock response of various commercially available beryllium grades

- Real time dynamic measurements of temperature, strain and displacement
- PIE of thin disc specimens performed at Oxford University





Profilometry to measure plastic out-of-plane deformations



- Distinctive strain responses for each Be grade (PF60, S65F, S200F, S200FH)
  - S200FH grade showed least amount of plastic deformation
- Plastic strain ratcheting observed with multiple pulses
- Glassy carbon windows survived with no signs of degradation

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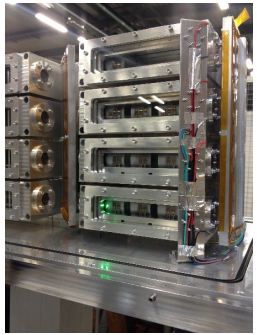
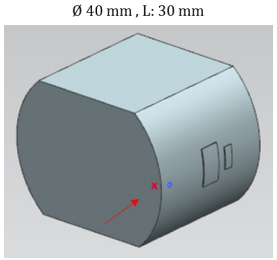
HRMT-24: BeGrid (2015)



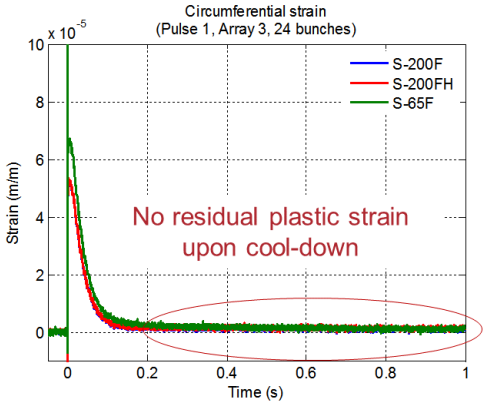
Real-time thermo-mechanical measurements

- Instrumented Be slugs with strain/temperature gages
- LDV for radial velocity/displacement measurements

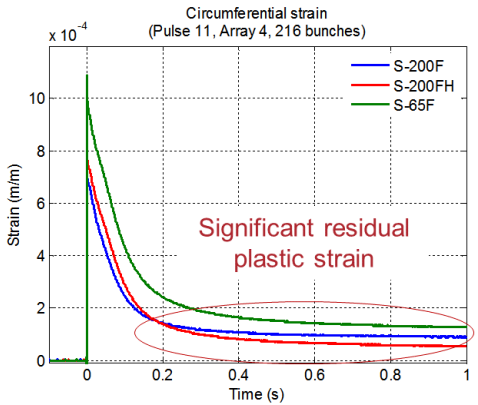


- Distinctive strain response for the three different Be grades
- Residual plastic strain observed upon cool-down
- Results provide indication of threshold at which plastic strain is induced

3.2E12 protons



2.8E13 protons



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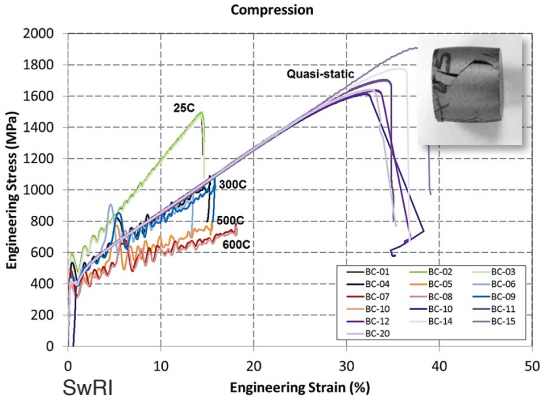
HRMT-24: BeGrid (2015)

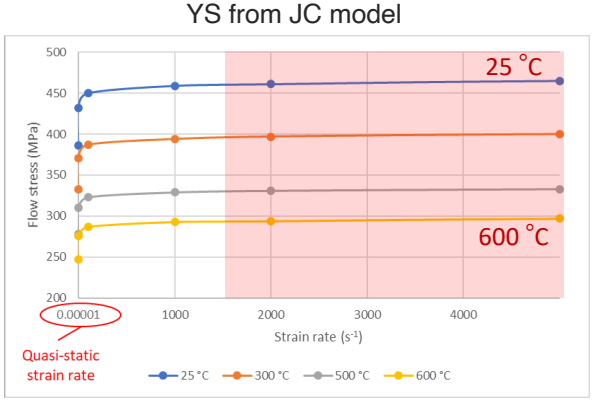
Successful validation of beryllium S200FH Johnson-Cook strength model developed at SwRI

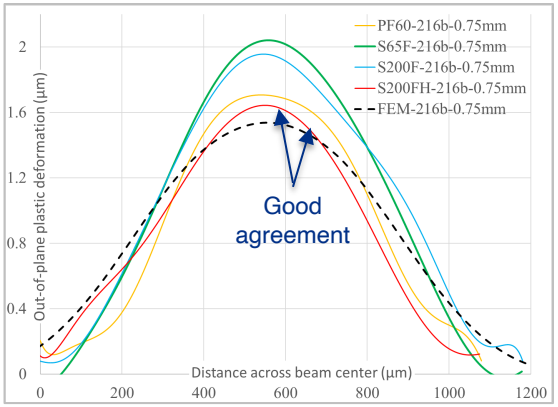
$$\sigma_Y = \left[A + B(\varepsilon_{eff}^{p})^{n}\right][1 + C ln\dot{\varepsilon}^{*}][1 - T_H^{m}]$$

- Flow stress (σ_y) dependency on strain rate and temperature
- Model parameters A, B, C, m, n empirically determined

Ammigan et al., "Thermal shock experiment of beryllium exposed to intense high energy proton beam pulses", Phys. Rev. Accel. Beams 22, 044501.







S. Bidhar, FNAL

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HRMT-43: BeGrid2 (2018)

Experimental objectives

- Identify thermal shock response differences between non-irradiated and previously irradiated specimens from BLIP
  - First and unique test with activated materials at HiRadMat
- Explore novel materials such a metal foams (C, SiC) and electrospun fiber mats (SiO2, ZrO2) to evaluate their resistance to thermal shock and suitability as target materials

HRMT43 BeGrid2 beam time completed on Oct. 2, 2018, 4 am

- Follow-up of HRMT24 (BeGrid) to expose beryllium to even higher beam intensities
- Real-time measurement of dynamic thermomechanical response of graphite slugs to help benchmark numerical simulations

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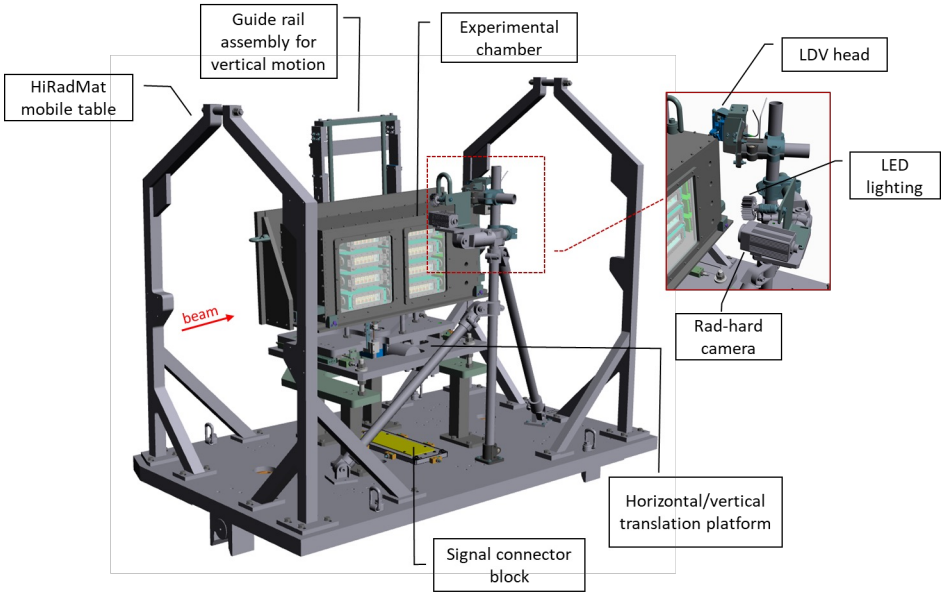
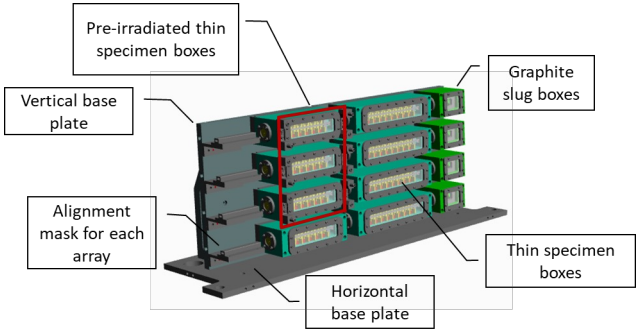
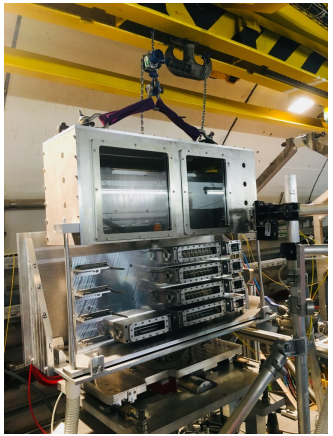
HRMT-43: BeGrid2 (2018)







- Double containment design with outer chamber as a dynamic secondary containment
- Four arrays separated vertically (92 specimens in total)

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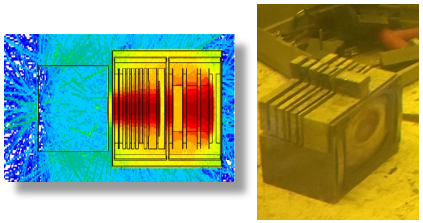
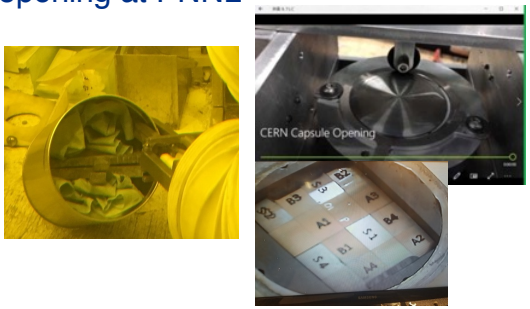
HRMT-43: BeGrid2 (2018)

Complex coordination between BNL, FNAL, PNNL and CERN

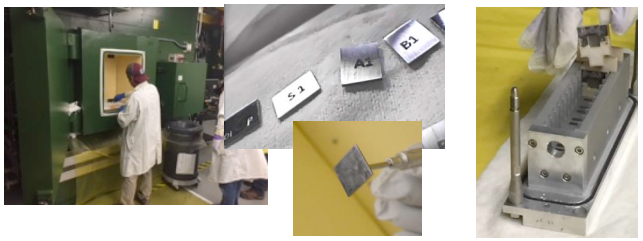
8-week irradiation at BNL BLIP



Capsule shipment from BNL and opening at PNNL

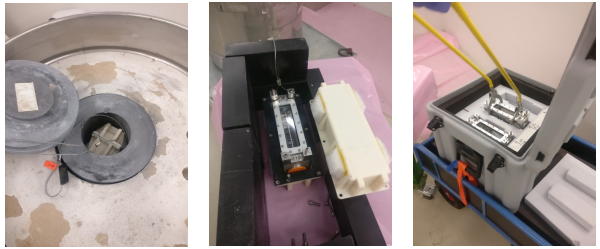


Specimen sorting and assembly in HRMT43 inner box at PNNL

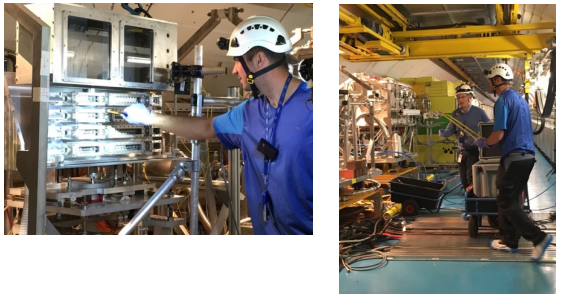


Packaging and shipment of inner boxes to CERN in Type A container

Opening of Type A container at CERN Bldg. 867 (3 boxes: 0.85 mSv/hr at 30 cm)



Inner boxes transported to TNC tunnel for direct installation in test rig



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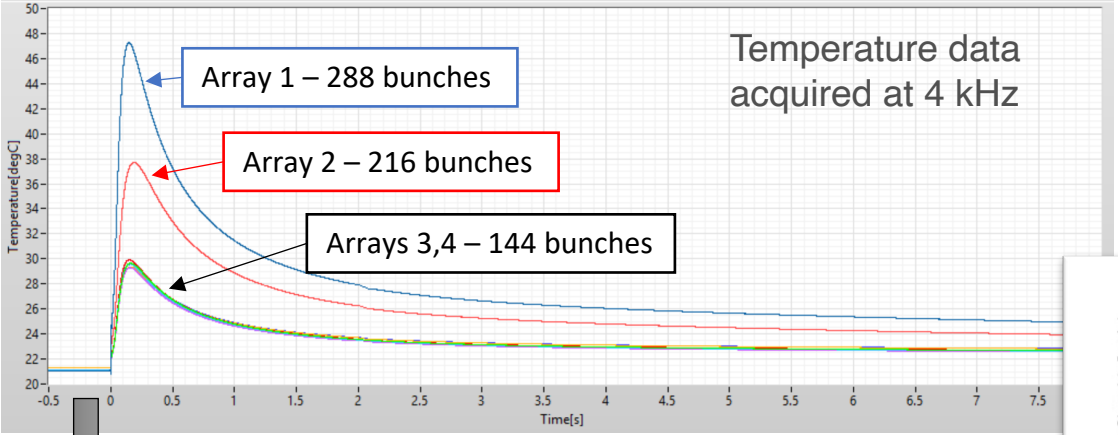
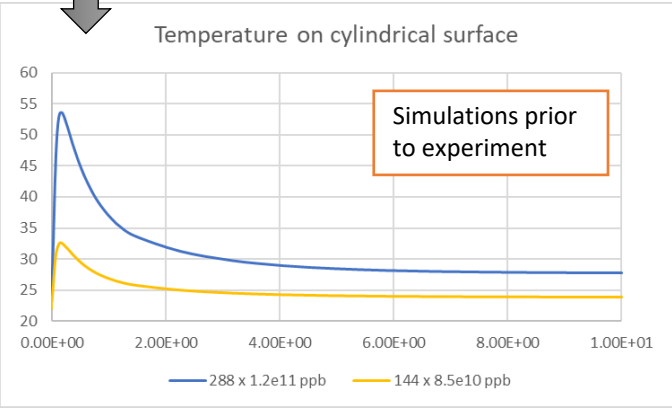
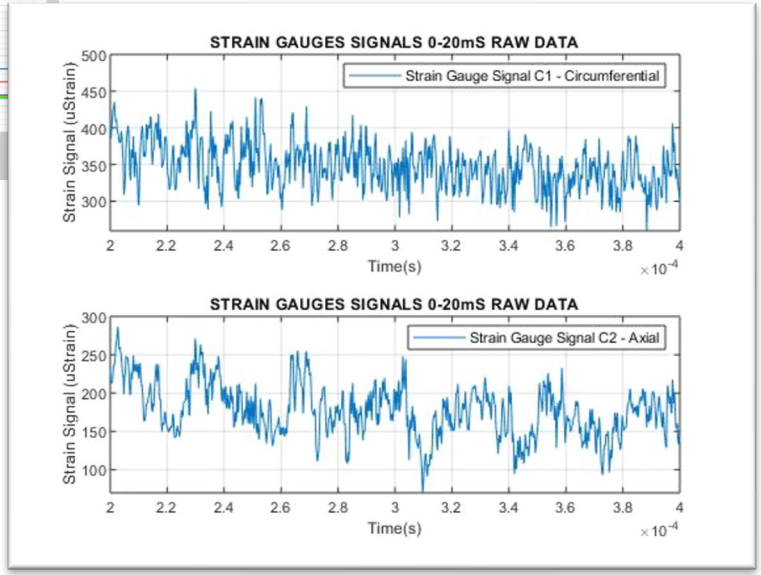
HRMT-43: BeGrid2 (2018)





Circumferential and axial strains acquired at 4 MHz to capture dynamic effects



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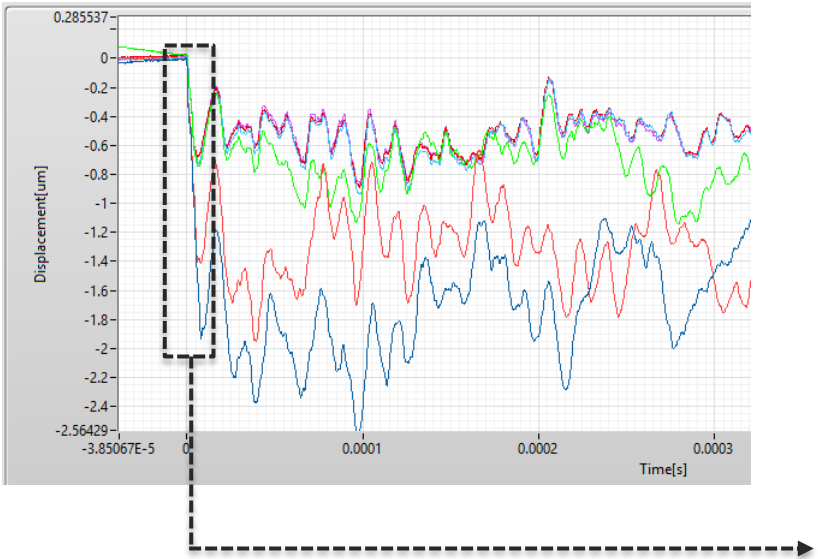
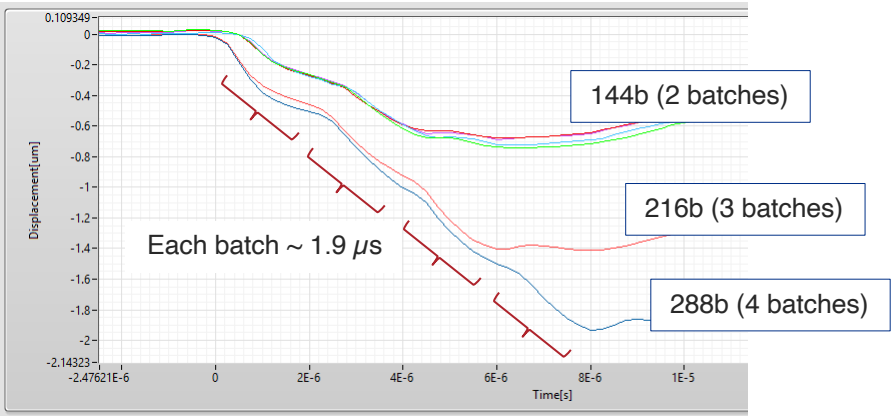
HRMT-43: BeGrid2 (2018)

- Radial displacement data appear to reveal beam pulse structure
- Pulse consists of batches of 72 bunches, separated by 250 ns
  - Avg. bunch length ~16 ns, bunch spacing ~25 ns



- PIE of thin specimens almost complete at MRF
- Manuscript in preparation to report online data measurement



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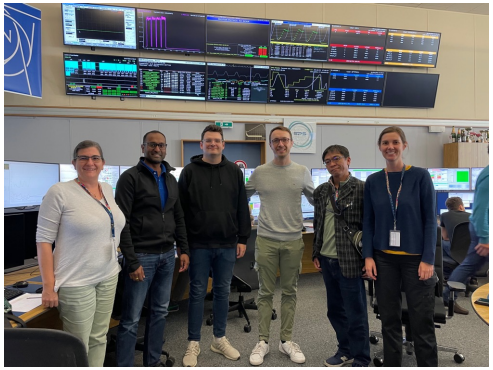
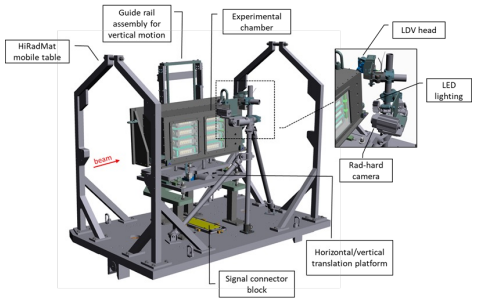
HRMT-60: RaDIATE2022 (2022)

- Understand single-shot thermal shock response and limits
- Explore advanced novel materials
- Assess performance of various grades and processing of conventional materials
- Compare behavior of non-irradiated to pre-irradiated materials
- Directly measure dynamic thermomechanical effects to validate numerical models



HRMT60 RaDIATE2022 beam time completed on Oct. 26, 2022, 5 pm



- Re-used HRMT-43 test chamber with small modifications of inner containment boxes
  - 116 thin specimens
  - 4 instrumented cylinders (SiC/SiC, 2 Be, Ti)

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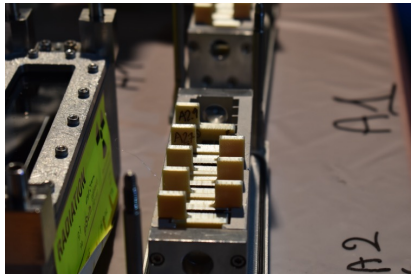
HRMT60: RaDIATE2022 (2022)

- Oct. 20-21st, 2022
- Installation of experimental table in TJ7/TNC
- Receipt of Type A container and assembly of pre-irradiated specimens in TJ7
  - At the very last minute!
- Irradiated box installation to test chamber in TNC
- Final instrumentation/connection checks



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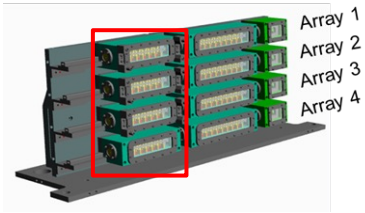
HRMT-60: RaDIATE2022 (2022)



Pre-irradiated specimens

ARRAY 1	Irradiated specimen box													Non-irradiated specimen box																	Slug
	A1.1	A1.2	A1.3	A1.4	A1.5	A1.6	A1.7	A1.8	A1.9	A1.10	A1.11	A1.12		A1.13	A1.14	A1.15	A1.16	A1.17	A1.18	A1.19	A1.20	A1.21	A1.22	A1.23	A1.24	A1.25	A1.26	A1.27	A1.28	A1.29	A1.30		A1s
288b, 1.3e11 ppb, σ: 0.25 mm	POCO ZXF-5Q graphite (NT-02) ID:1	POCO ZXF-5Q graphite (NT-02) ID:3	IG-430 graphite (BLIP) - S4-1	IG-430 graphite (BLIP) - S4-2	BLIP Be S200FH (B4)	Be S200FH (B)	Sigr. Autopsy	Sigr Autopsy	L20012C	L20012C	L10010C	L10010C		POCO ZXF-5Q graphite	POCO ZXF-5Q graphite	IG-430 graphite	IG-430 graphite	Be PF-60 (P03)	L30010C	L30010C	L20010C	L20010C	F05010C	F05010C	F05010Z	F05010Z	ZrO2 (0.14g/cc)	ZrO2 (0.56 g/cc)	ZrO2 (0.14g/cc)	ZrO2 (0.56 g/cc)	ZrO2-SiO2 (0.14g/cc)		Beryllium S-200-FH

ARRAY 2	Irradiated specimen box													Non-irradiated specimen box																	Slug
	A2.1	A2.2	A2.3	A2.4	A2.5	A2.6	A2.7	A2.8	A2.9	A2.10	A2.11	A2.12		A2.13	A2.14	A2.15	A2.16	A2.17	A2.18	A2.19	A2.20	A2.21	A2.22	A2.23	A2.24	A2.25	A2.26	A2.27	A2.28	A2.29	A2.30		A2s
216b, 1.3e11 ppb, σ: 0.25 mm	POCO ZXF-5Q graphite (NT-02) ID:2	POCO ZXF-5Q graphite (NT-02) ID:4	IG-430 graphite (BLIP) - S5-1	IG-430 graphite (BLIP) - S5-2	BLIP Be S200F (A3)	Be S200F (A)	Sigr Autopsy	L20012C	Sigr Autopsy				L20012C	POCO ZXF-5Q graphite	POCO ZXF-5Q graphite	IG-430 graphite	IG-430 graphite	Be PF-60 (P04)	L30010C	L30010C	L20010C	L20010C	F05010C	F05010C	F05010Z	F05010Z	ZrO2 (0.14g/cc)	ZrO2 (0.56 g/cc)	ZrO2 (0.14g/cc)	ZrO2 (0.56 g/cc)	ZrO2-SiO2 (0.14g/cc)		Beryllium S-200-FH

ARRAY 3	Irradiated specimen box													Non-irradiated specimen box																	Slug
	A3.1	A3.2	A3.3	A3.4	A3.5	A3.6	A3.7	A3.8	A3.9	A3.10	A3.11	A3.12		A3.13	A3.14	A3.15	A3.16	A3.17	A3.18	A3.19	A3.20	A3.21	A3.22	A3.23	A3.24	A3.25	A3.26	A3.27	A3.28	A3.29	A3.30		A3s
72b, 1.3e11 ppb, σ: 0.25 mm	Ti 15-3 STA (B01-1)	Ti 15-3 STA (B05-1)	Ti-6Al-4V A (Gr23) (T15-1)	Ti-6Al-4V A (Gr23) (T17-1)	Ti-6Al-4V STA (Gr23) (W01-1)	Ti-6Al-4V STA (Gr23) (W04-1)	Ti-6Al-4V UFG (Gr5) (U01-1)	Ti-6Al-4V UFG (Gr5) (U04-1)	Ti (Gr2) (P3-1)	Ti (Gr2) (P4-1)	Ti-5Al-2.5Sn (Gr6) (S01-1)	Ti-5Al-2.5Sn (Gr6) (S05-1)		Ti-6Al-4V 3D	Ti-6Al-4V FA	Ti-6Al-4V STA	Ti-6Al-4V SQA	Ti Timet 1100	Ti IMI834	Ti-6-2-4-6	Ti 15-3 ST	Ti 15-3 ST2A	Ti DAT54	HEA1 - CrMnV	HEA2 - CrMnTiV	HEA3 - AlCrMnTiV	HEA4 - AlCoCrMnTiV	NITE SiC-SiC	NITE SiC-SiC	ZrO2-TiO2			NITE SiC/SiC

ARRAY 4	Irradiated specimen box													Non-irradiated specimen box																	Slug
	A4.1	A4.2	A4.3	A4.4	A4.5	A4.6	A4.7	A4.8	A4.9	A4.10	A4.11	A4.12		A4.13	A4.14	A4.15	A4.16	A4.17	A4.18	A4.19	A4.20	A4.21	A4.22	A4.23	A4.24	A4.25	A4.26	A4.27	A4.28	A4.29	A4.30		A4s
24b, 1.3e11 ppb, σ: 0.25 mm	Ti 15-3 STA (B01-2)	Ti 15-3 STA (B05-2)	Ti-6Al-4V A (Gr23) (T15-2)	Ti-6Al-4V A (Gr23) (T17-2)	Ti-6Al-4V STA (Gr23) (W01-2)	Ti-6Al-4V STA (Gr23) (W04-2)	Ti-6Al-4V UFG (Gr5) (U01-2)	Ti-6Al-4V UFG (Gr5) (U04-2)	Ti (Gr2) (P3-2)	Ti (Gr2) (P4-2)	Ti-5Al-2.5Sn (Gr6) (S01-2)	Ti-5Al-2.5Sn (Gr6) (S05-2)		Ti-6Al-4V 3D	Ti-6Al-4V FA	Ti-6Al-4V STA	Ti-6Al-4V SQA	Ti Timet 1100	Ti IMI834	Ti-6-2-4-6	Ti 15-3 ST	Ti 15-3 ST2A	Ti DAT54	HEA1 - CrMnV	HEA2 - CrMnTiV	HEA3 - AlCrMnTiV	HEA4 - AlCoCrMnTiV	TFGR W-1.1%TiC	TFGR W-1.1%TiC	TFGR W-3.3%TaC	Pure W		Titanium (Ti6Al4V)

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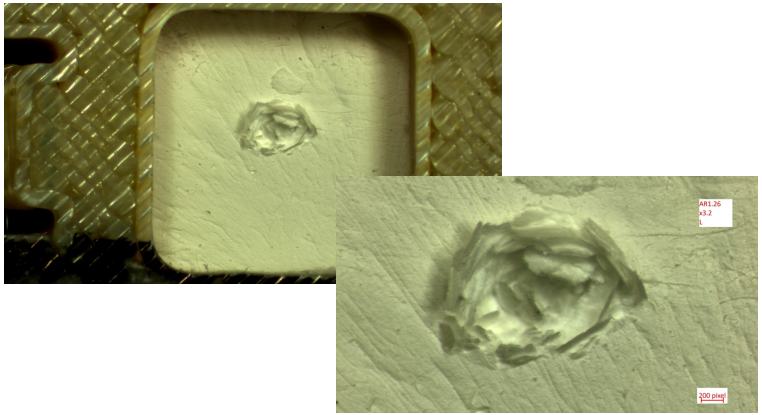
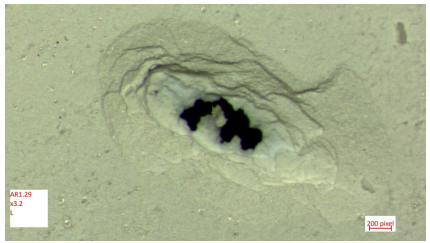
HRMT-60: RaDIATE2022 (2022)

- Disassembly completed in March, 2023
- Visual inspection and high-res pictures of specimens
- All specimens have been packaged for shipment to PNNL and MRF for PIE work
- Online data analysis has started





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RaDIATE Participants

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[4]Pacific Northwest National Laboratory (PNNL)
[5]STFC Rutherford Appleton Laboratory (RAL)
[6]High Energy Accelerator Research Organization (KEK)
[7]University of Oxford
[8]University of Wisconsin-Madison (UW-Madison)
[9]Brookhaven National Laboratory (BNL)

RaDIATE Collaboration
Radiation Damage In Accelerator Target Environments

Fermilab
CERN
Materials Research Facility
UKRI Science and Technology Facilities Council
Pacific Northwest National Laboratory
KEK
College of Engineering, University of Wisconsin-Madison
Brookhaven National Laboratory
University of Oxford

Next RaDIATE HiRadMat Experiment…

- Possibility of another RaDIATE HiRadMat experiment before the CERN long shut-down in 2027
  - 2024 beam time slots almost fully booked
  - 2025 has open slots
    - Beam time request should probably be submitted late 2023 or early 2024

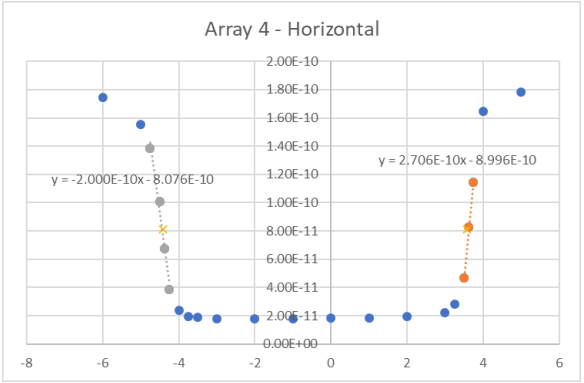
- Ideas for next test?
  - Which materials or components to test?
  - Under what conditions?
    - Elevated temperatures?
    - Pre-stressed specimens/windows?
  - Investigate target geometry for diffusing stress waves
  - Stress wave resonance studies?
  - Multiple beam pulses on targets
  - …

Supplemental Slides

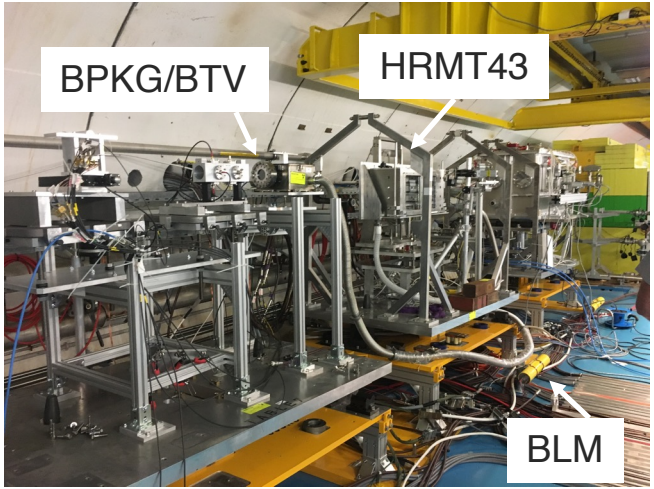
Beam-based alignment (HRMT-43)

Alignment mask positioned upstream of each array

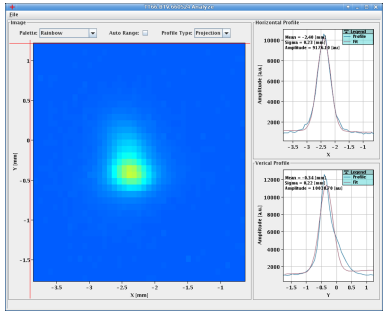
- Beam scan across 4 mm x 8 mm mask aperture



- BLM data normalized by pulse intensity
- Test rig position adjusted accordingly to center beam on mask and downstream targets



Beam location and size info from BTV image



Fermilab

Experimental beam parameters (HRMT-43)

Pulse	Array	No. of bunches	Bunch intensity	Pulse intensity	σ_x (mm)	σ_y (mm)
1	3	144	8.40E+10	1.21E+13	0.26	0.19
2	4.1	144	8.47E+10	1.22E+13	0.25	0.19
3	4.2	144	8.54E+10	1.23E+13	0.26	0.20
4	4.3	144	8.33E+10	1.20E+13	0.26	0.19
5	4.4	144	8.26E+10	1.19E+13	0.25	0.19
6	4.5	144	8.30E+10	1.21E+13	0.25	0.19
7	2	216	1.17E+11	2.53E+13	0.28	0.21
8	1	288	1.22E+11	3.51E+13	0.27	0.22

Total protons on target: 1.33E14

Experimental chamber disassembly (HRMT-43)

- Experimental table was removed from TNC tunnel and transported to Bldg. 867 for disassembly in May 2019
- Inner boxes retrieved and packaged in Type A containers for shipment to CCFE, UK

R. Seidenbinder, CERN

980 μSv/hr on contact

0.5 μSv/hr on contact

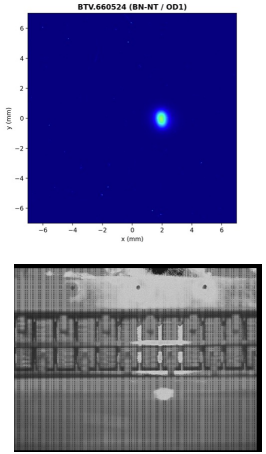
0.8 μSv/hr on contact

Beam Time and Final Beam Pulse (HRMT-60)

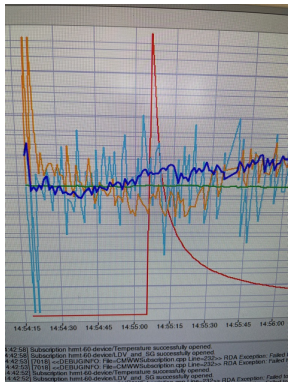
- Beam-based alignment of all four arrays
- Completed experiment on Oct. 26th
- Achieved design beam parameters and conditions in material specimens

Array	No. of bunches	Pos_x (mm)	Pos_y (mm)	Sigma_x (mm)	Sigma_y (mm)	Beam intensity
1	288	-0.191	-0.041	0.223	0.347	3.43E13
2	216	-0.184	-0.052	0.237	0.344	2.53E13
3	60	-0.092	0.013	0.261	0.338	7.00E12
4	24	-0.063	-0.012	0.265	0.347	2.74E12

- Total of 4 pulses (~7E13 protons total)
- Post-experiment visual inspection (16th Nov. in TNC) did not show any obvious signs of damage to test chamber assembly



Visual monitoring during experiment



Strain and temperature gage response

Fermilab