Possibilities for HPT ✓ Target Material ✓ Testing at AP0

F. Pellemoine

Potential Fermilab Muon Campus & Storage Ring Experiments

May 27 2021

Background

- High-Power Target System is a key element to complete future High Energy Physics (HEP) experiments
- In the recent past, major accelerator facilities limited in beam power due to beam intercepting device survivability
  - Current target technology tolerates ~ 1MW but future projects aim to deliver up to 2-5 MW
- Thermal Shock and Radiation Damage most cross-cutting challenges facing high power target facilities and can lead to premature failure of the components
- Today all the irradiation tests for thermal shock or radiation damage are performed outside FNAL

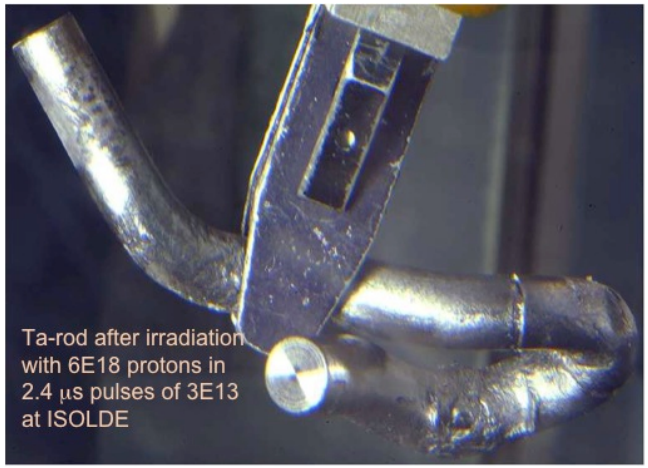

Photo courtesy of J. Lettry

Iridium rod in HRMT27 exploded with single shot 1.27×10^{12} protons

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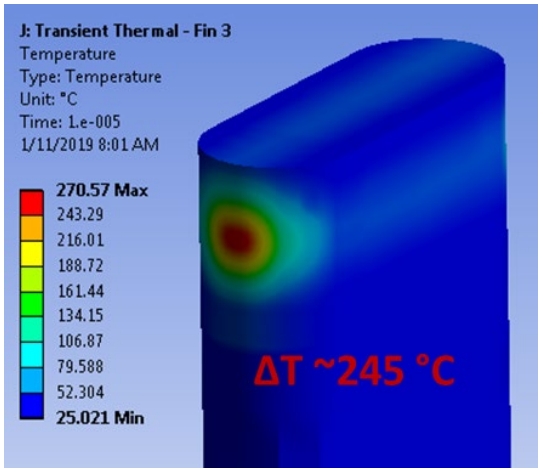
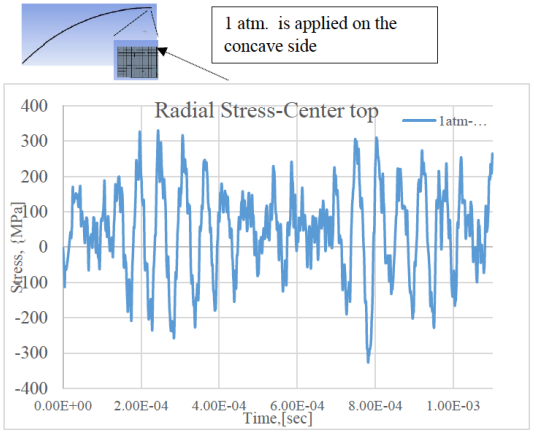
Beam-induced thermal shock

- Rapid thermal expansion of material surrounded by cooler material creates a sudden localized area of high compressive stress
  - Stress waves are generated and propagate through the material
- Dynamic stresses may induce plastic deformation, cracking and fatigue failure of the material
- Thermal shock response dependent on:
  - Beam energy deposition rate
  - Specific heat capacity
  - Coefficient of thermal expansion
  - Modulus of elasticity
- It is critical to understand the behavior of irradiated and non-irradiated material for future High Power Targetry development



K. Ammigan, ΔT from 10 μs beam pulse, 1 MW graphite target fin



S. Bidhar, Dynamic stresses in T2K Ti beam window

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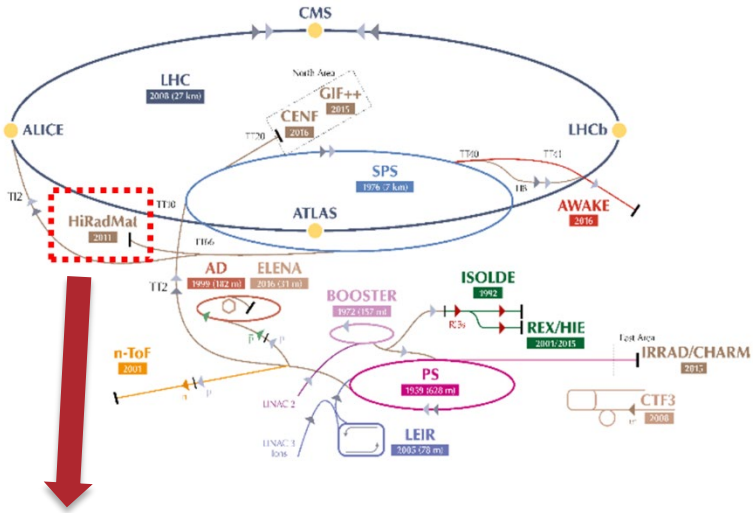
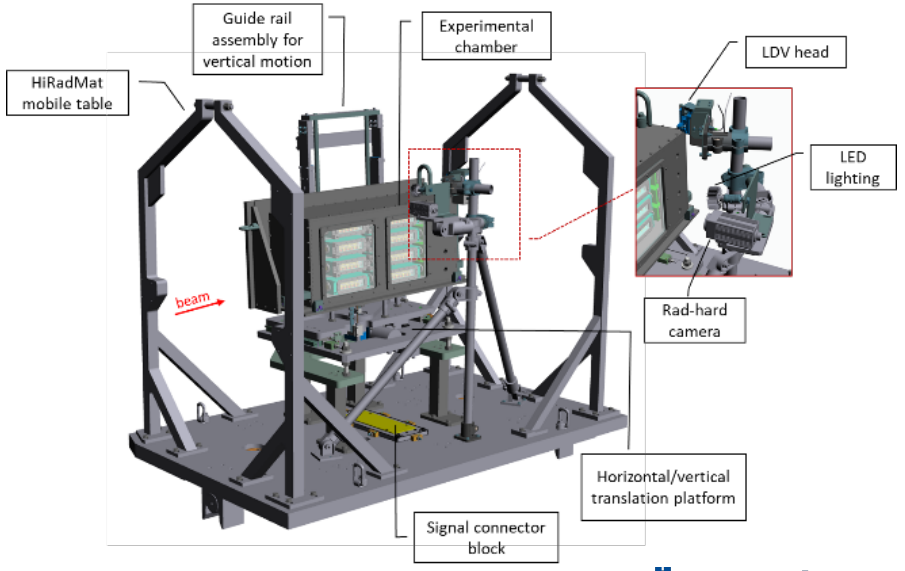
Thermal Shock Study at HiRadMat Facility - CERN

- High Radiation to Materials (HiRadMat) at CERN is a unique facility for material testing with single shots experiments
  - Total allocated protons/year: 1.0 e16 (~10 experiments/yr)

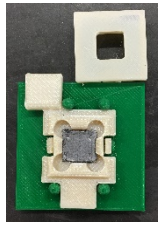


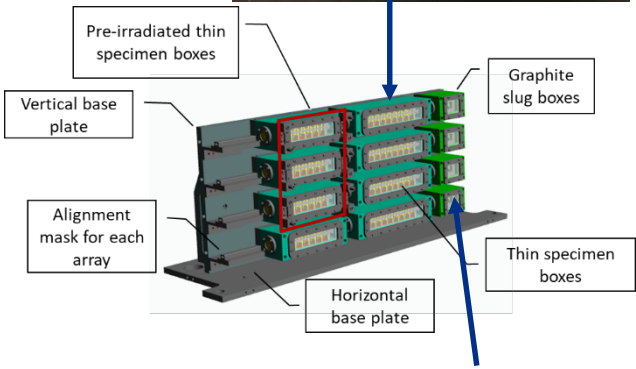
Beam Parameters	
Beam energy	440 GeV
Max. pulse energy	2.4 MJ
Max. bunch intensity	1.2 x 10^{11}
No. of bunches	1 – 288
Max. pulse intensity	3.5 x 10^{13} ppp
Max. pulse length	7.95 μs
Gaussian beam size	1σ rms: 0.25 – 4 mm

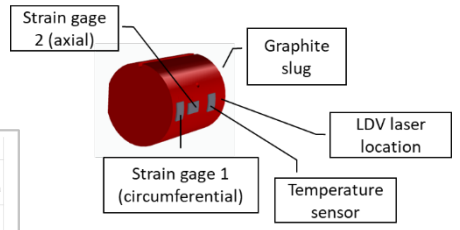


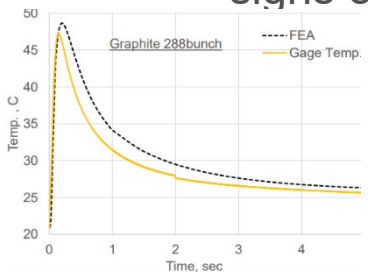
Previous experiments and what we learned

- 2 experiments - HRMT 24 (BeGrid1, 2015) and HRMT43 (BeGrid2, 2018)
  - numerous target and window materials (Be, C, Si-coated C, Si, Ti, novel material) including irradiated and non-irradiated samples
    - Real time dynamic measurements of temperature, strain and displacement
    - Dynamic response measurements to help benchmark and validate highly non-linear numerical simulations
    - PIE of thin disc specimens performed
    - Plastic strain ratcheting observed with multiple pulses
    - Survivability test with several pulses with no signs of degradation

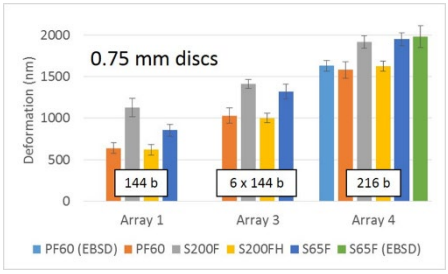




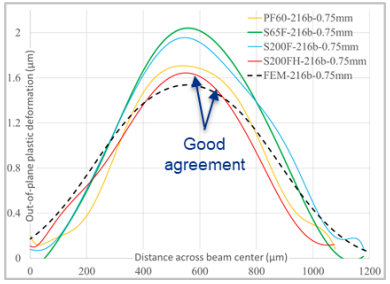




Transient temperature – experimental data vs. simulation



Out-of-plane deformation vs. Beam intensity



Out-of-plane deformation – experimental data vs. simulation

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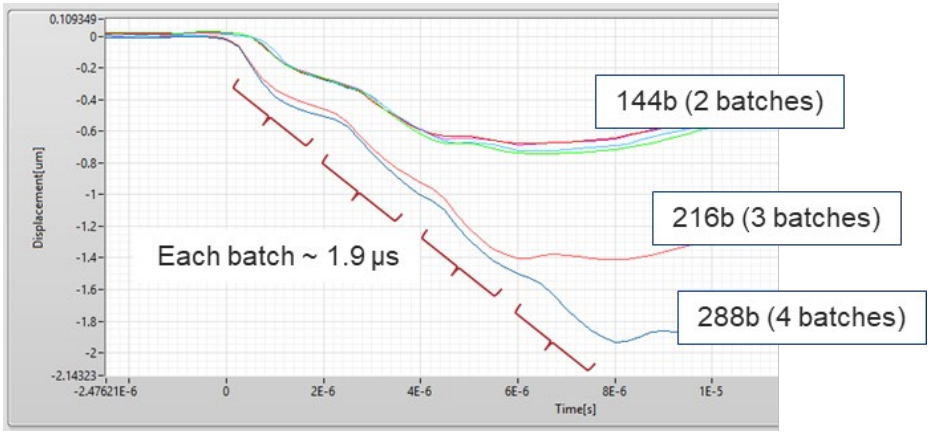
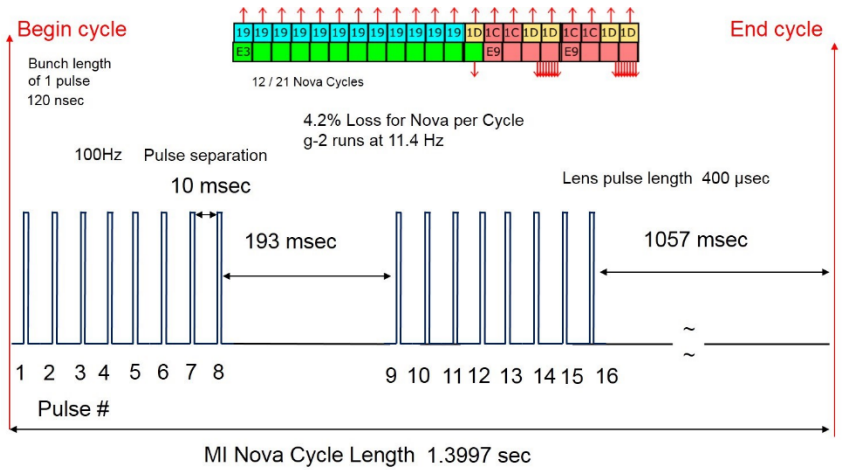
Can we perform similar test at FNAL?

- **HiRadMat beam**
  - Pulse consists of batches of 72 bunches, separated by 250 ns
    - Avg. bunch length ~16 ns, bunch spacing ~25 ns
    - Each bunch = 1.2e11 protons
  - Pulses close each other
    - Let's consider 4 batches (3.5e13 ppp)
- **AP0 pulsed beam**
  - Pulse separation maybe too large (10 ms) to be considered as a batch
    - Let's just focus on one pulse
      - Pulse length ~120 ns
      - Each pulse – 1e12 ppp

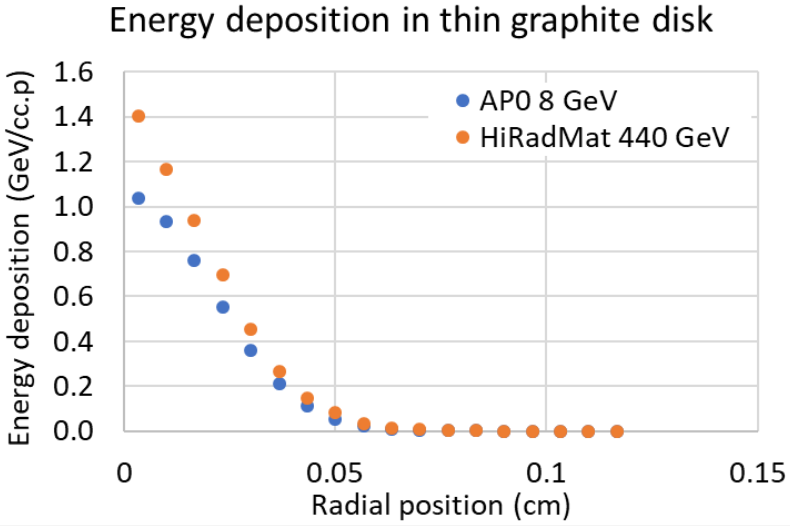




Can we perform similar test at FNAL?

- Some beam parameters are similar while the beam energy is quite different
- The typical peak temperature increase in a 1 MW neutrino target at Fermilab is ~ 250 K in 10 μs (2.5×10^7 K/s)
  - 1 batch at HiRadMat ~ 1.9 μs
  - 1 pulse at AP0 ~ 120 ns
- For similar temperature variation, shorter pulse will give higher compressive stress in the material

	HiRadMat	AP0
Beam sigma [mm]	0.25-4	0.25
Beam Energy [GeV]	440	8
Proton per pulse	3.5e13	1e12



K. Ammigan, MARS simulation

$$\sigma = \sqrt{\rho E} \cdot \alpha \cdot L \cdot \frac{\Delta T}{\Delta t}$$

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Can we perform similar test at FNAL? Probably YES

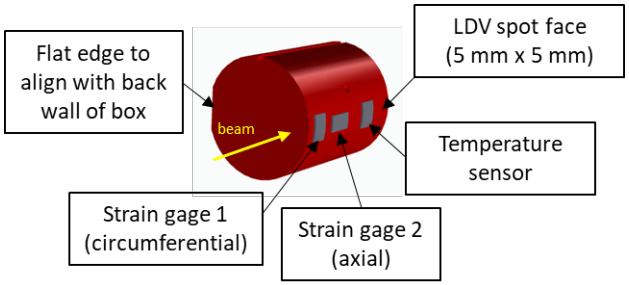
- First estimate give us some promise to reproduce reasonable stress in Targetry material
- ONE-pulse (4 pulses) test looks adequate to understand material behavior and observe potential plastic deformation
- Several-pulses test will help to study the cumulative effects of pulsed beam in material
- Real time dynamic measurements of temperature, strain and displacement will allow to carry out similar studies than the one performed at HiRadMat
- More simulations need to be performed to verify if the temperature and the stress level is achievable with AP0 beam
- More investigations need to be done to verify the feasibility of using real time instrumentations in the vault (space requirement, residual dose, control, etc…)

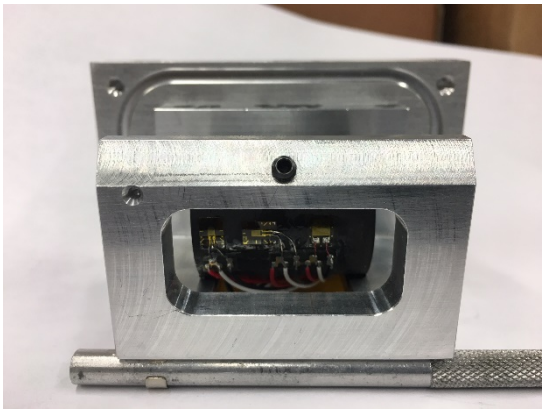
Backup Slides

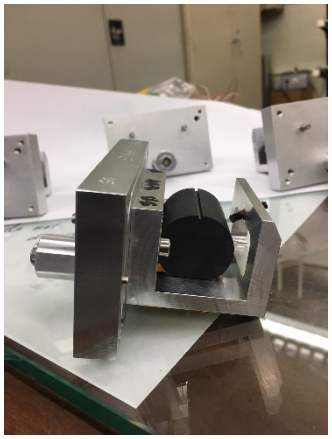
Online real-time measurements

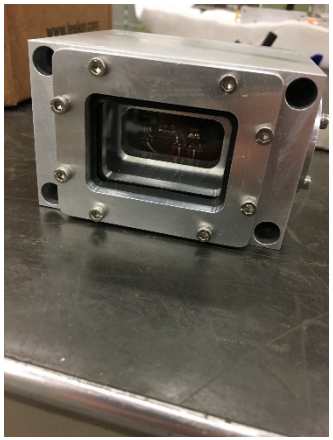
- Dynamic response measurements to help benchmark and validate highly non-linear numerical simulations

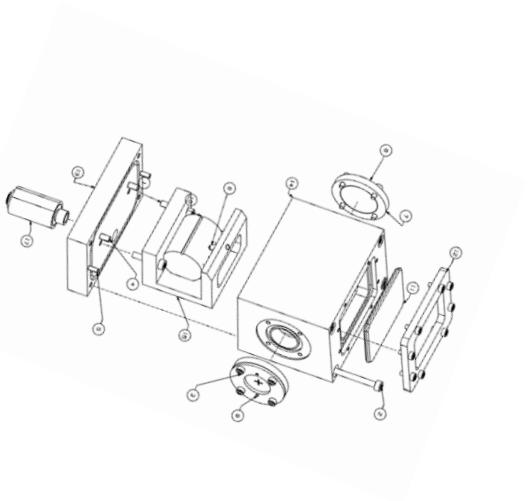
- POCO ZXF-5Q cylinder: 35 mm long, 30 mm OD
- Beam impact 5 mm from cylindrical edge











A. Miller, FNAL

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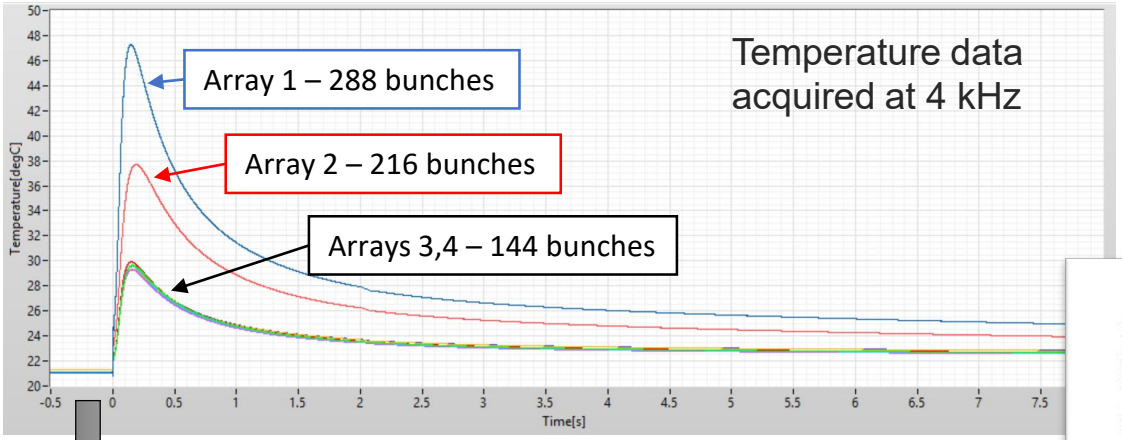
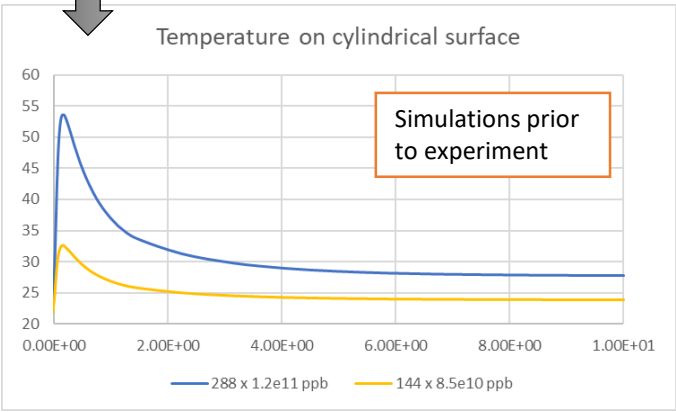
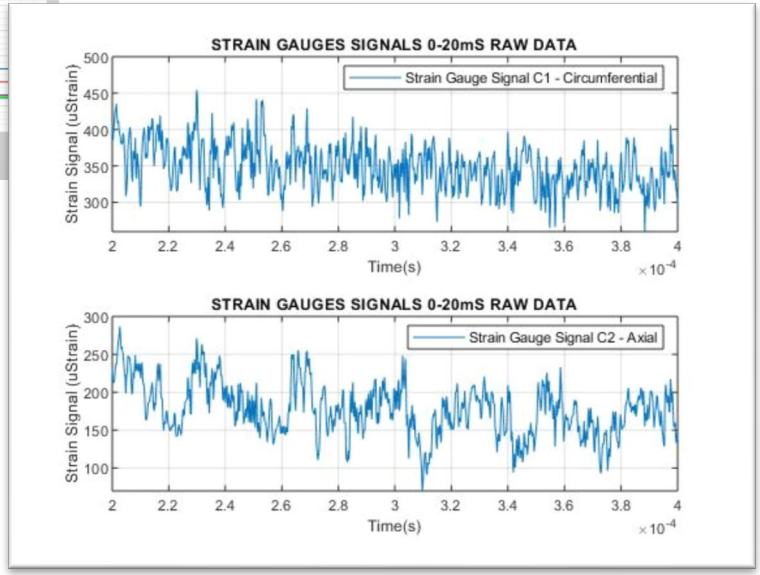
Temperature and strain measurements



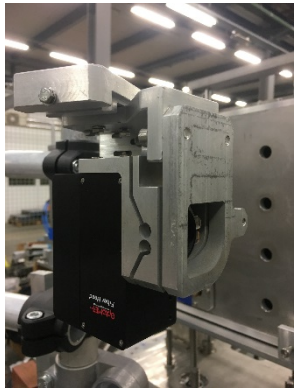


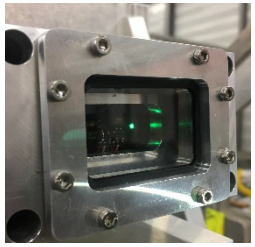
Circumferential and axial strains acquired at 4 MHz to capture dynamic effects

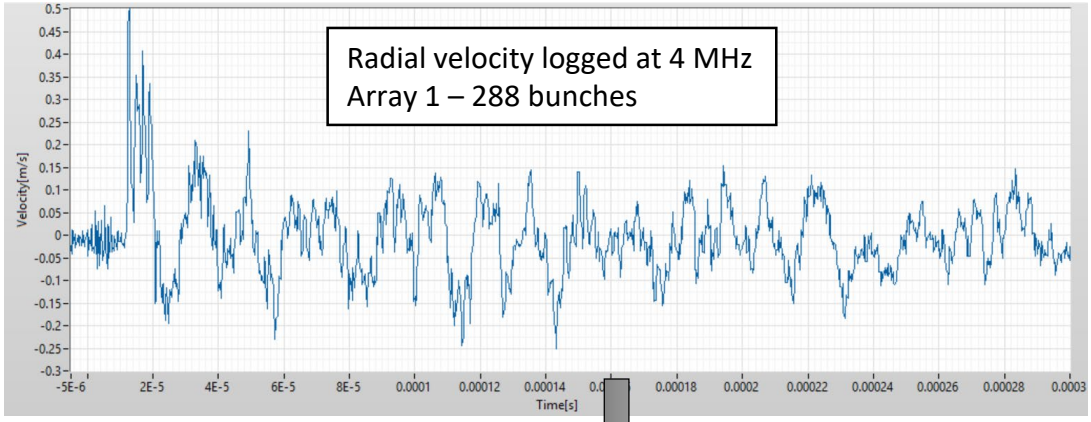


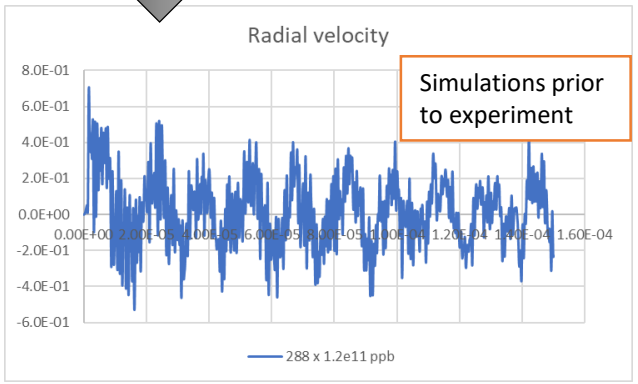
Laser Doppler Vibrometer: velocity

Optomet fiber head located ~100 mm from surface of graphite









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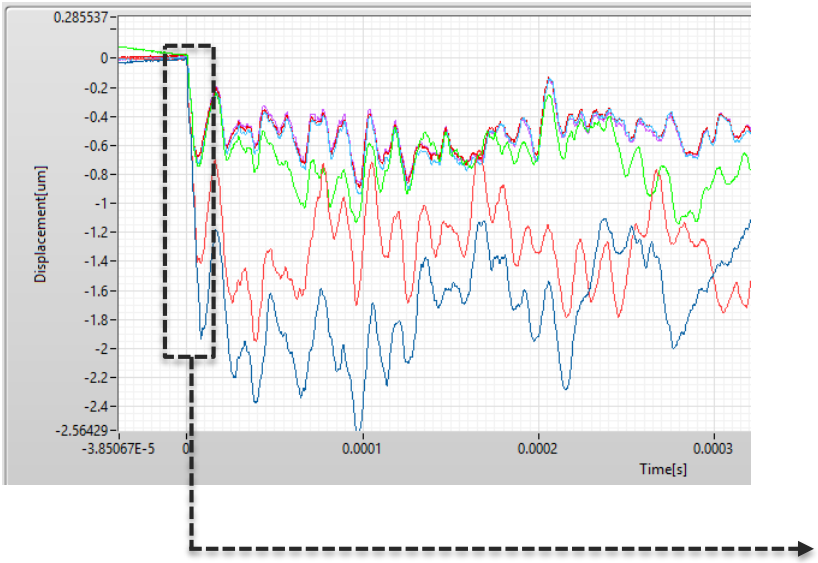
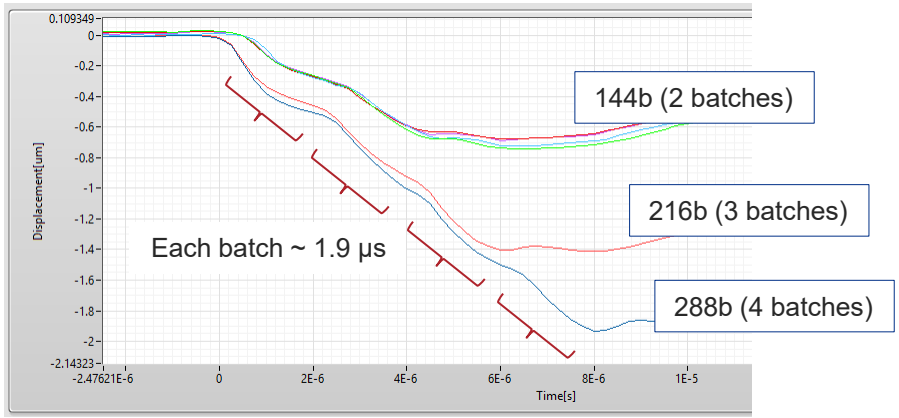
Laser Doppler Vibrometer: displacement

- 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

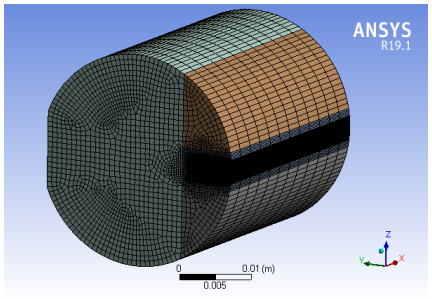




Numerical simulation validation

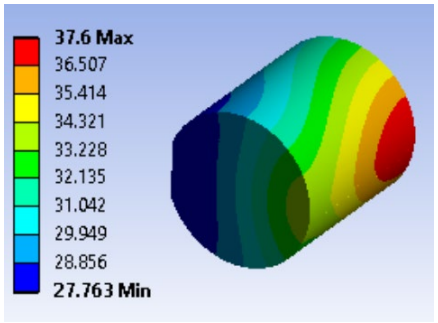
- Goal is to compare numerical simulation results with experimental results to validate graphite strength model
  - Temperature, dynamic axial/circumferential strain and radial velocity/displacement

- Data analysis ongoing - FEA model is being updated with experimental beam parameters
  - MARS heat generation data with actual beam spot size and intensity
  - Beam spot location from BTV and BA-7 alignment info

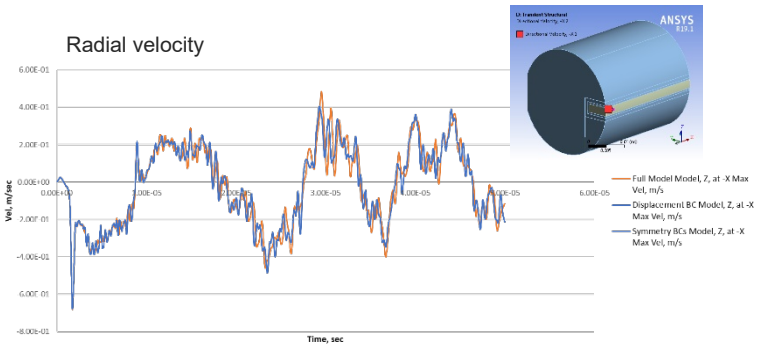


R. Campos & S. Bidhar, FNAL

Array 1: Temperature distribution after 1s



Radial velocity



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