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Updates in Material R&D for multi-MW Accelerator Components under US-Japan and RaDIATE Collaboration in High Energy Physics

Sujit Bidhar

Target Systems

June 26, 2023

8th RaDIATE Collaboration Meeting

June 26 ~ 30, 2023

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

Brookhaven National Laboratory

Outline

- Funding proposal US- Japan collaboration in high energy physics
- US-JP symposium-Hawaii 2023
- HighRadMat 60
- Ti Fatigue validation
- DPA cross section measurements

US- Japan collaboration in high energy physics

- Started in 1979 to support current experiment and technology in high energy physics between US and Japanese institute
  - Advanced detector and accelerator technology R&D
- Participating institutes :
  - US labs : Fermilab, BNL, PNNL
  - Japanese institutes: JAEA, KEK, University of Tokyo, NIQST
- Past proposal on advanced materials research for high intensity proton production windows and targets
- Renewal proposal was submitted in December 2022 (LAB 23-2858)
  - PIE on Beryllim, Ti-alloy
  - Development of radiation damage model in Ti-alloys
  - Quantification of thermal shock resistance
  - TGS as candidate PIE technique
  - Development of HEA

US- Japan Proposal FY23

- Total of 19 proposal submitted spanning 1 to 3 years of funding→ 90% new research
- Total requested funding US$ 8.8million
- Total awarded US$ 2.2 million

DOE Lab	Proposal
BNL	3
FNAL	7
LLNL	0
ANL	3
LANL	1
LBNL	3
SLAC	2

Total Proposals	19	
Renewal	2	10%
New	17	90%

	submitted	accepted
Accelerator	10	7
Intensity	2	1
Theory	0	0
Detector	4	2
Energy	1	0
AIML	2	1
Total proposals	**19**	**11**

US- Japan Proposal FY23

Our renewal proposal was accepted for funding

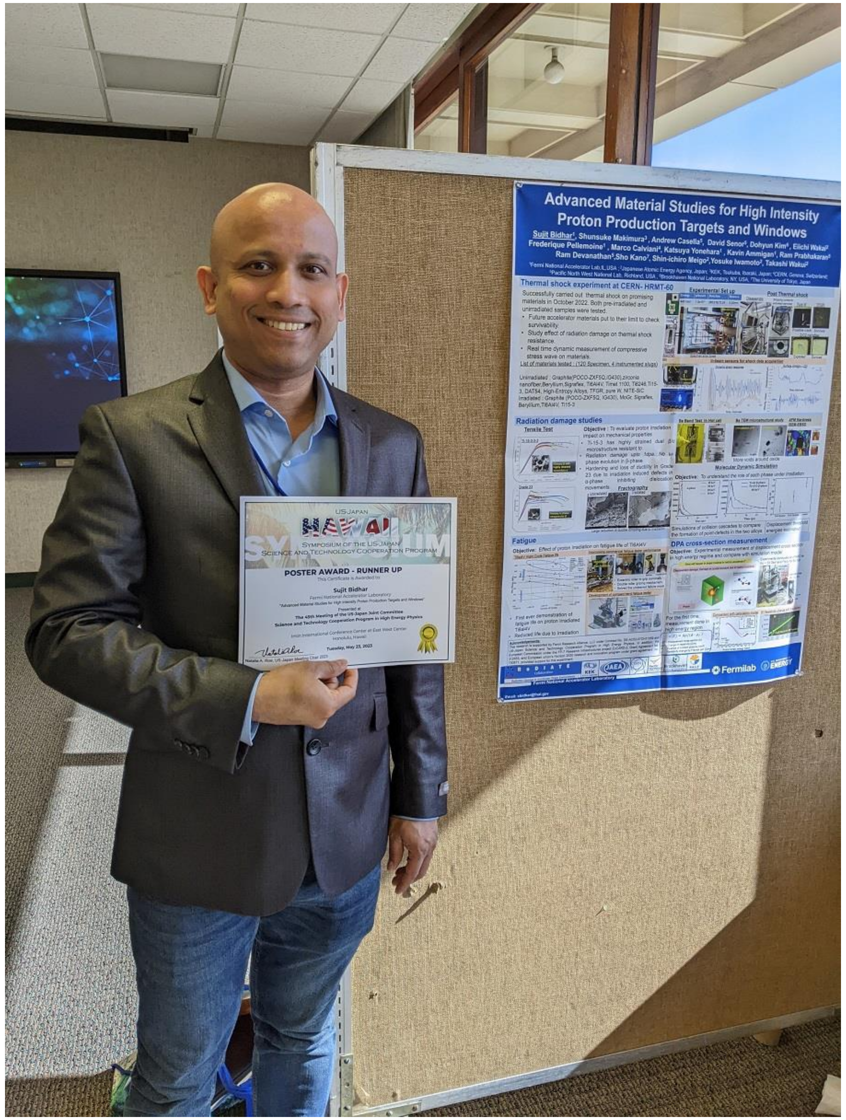
- Funding requested : US$ 1.4 million for 3 years
- Received : US$ 343,000
- Funding period : for 2 years July 2023 – June 2025

	FY 23	FY 24
Fermilab	90,000	90,000
BNL	9,000	9,000
PNNL	75,000	70,000

Recommendations

- Complete the work initiated from previous award
- Focus on BLIP 2018 irradiated Be and Ti
- Thermal shock modeling
- Exploration of alternate proton irradiation facilities

45th US- Japan cooperation in HEP mini-symposium- Hawaii 2023



- Held May 22-23
- Poster highlighting progress on Ti and Be work funded under US-JP
- Interests from committee members about our experiment methodologies
- Runner-up award

Thermal Shock experiment : HighRadMat-60 @ CERN

Successfully carried out thermal shock on promising materials in October 2022. Both pre-irradiated and unirradiated samples were tested.

- Future accelerator materials put to their limit to check survivability.
- Study effect of radiation damage on thermal shock resistance.
- Real time dynamic measurement of compressive stress wave on materials.

List of materials tested : (120 Specimen, 4 instrumented slugs)

Unirradiated : Graphite(POCO-ZXF5Q,IG430),zirconia nanofiber,Beryllium,Sigraflex, Ti6Al4V, Timet 1100, Ti6246,Ti15-3, DAT54, High-Entropy Alloys, TFGR, pure W, NITE-SiC

Irradiated : Graphite (POCO-ZXF5Q, IG430), MoGr, Sigraflex, Beryllium,Ti6Al4V, Ti15-3

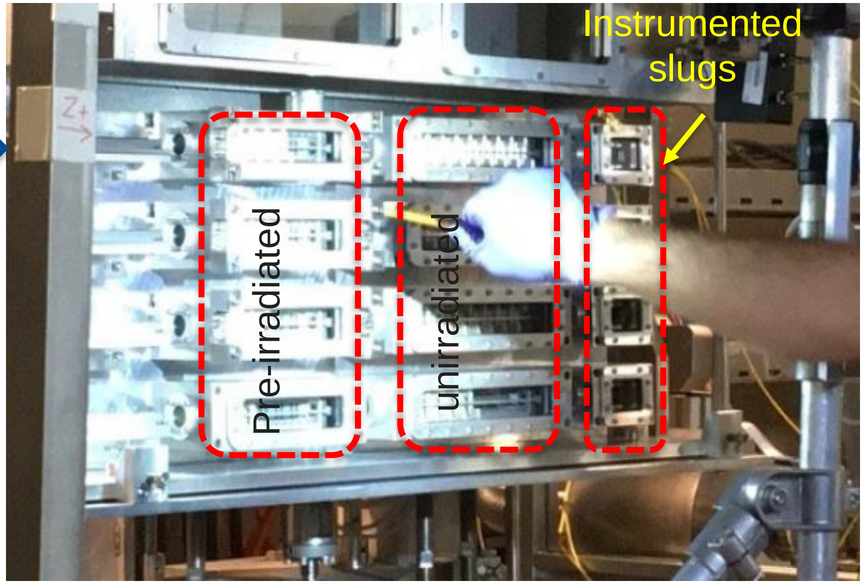
HighRadMat 60

Energy	p/bunch	Bunches	Beam-σ
440 GeV	1.3×10^{11}	288,216,72,24	0.25mm

Experimental Set up

Specimen holder

Specimen box



Specimen array boxes

Post- thermal shock

Disassembly

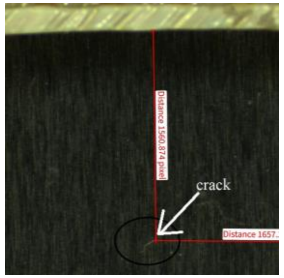
Shipping container for activated samples

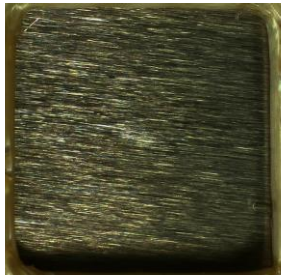
Will be shipped to MRF and PNNL for further PIE

Materials packed in 4 different arrays and bunches selected appropriately

HighRadMat 60

Pure W | TFGR





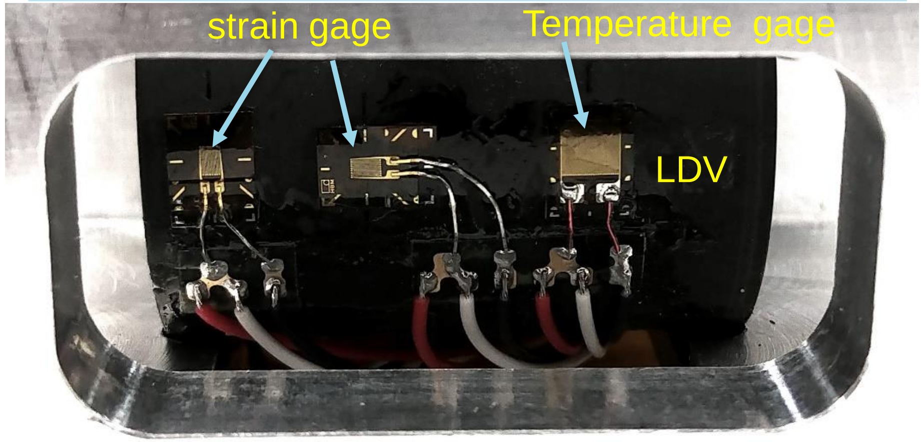
Possible crack | Survived

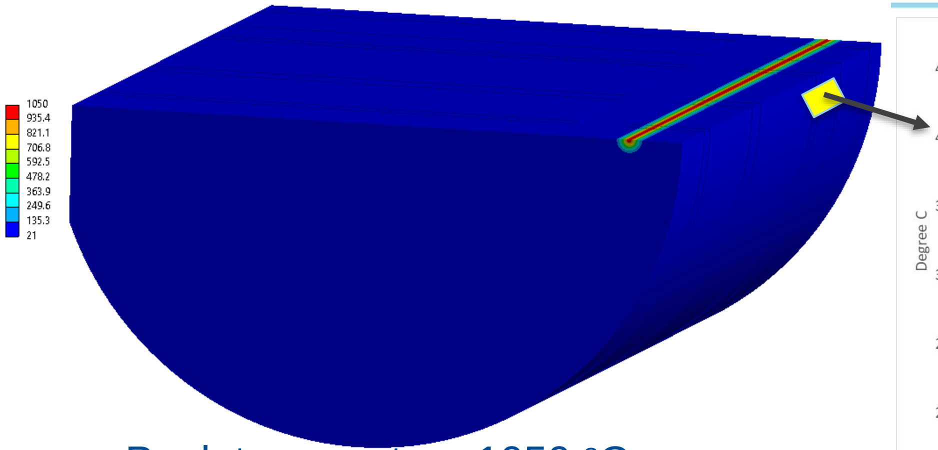
ZrO2 nanofiber

Exploded | Survived

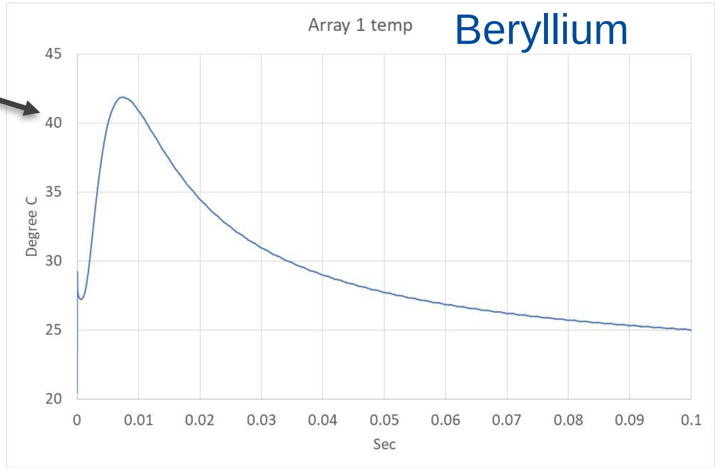
- Preliminary visual inspection
  - TFGR sustained the shock
  - Some of the nanofiber samples survived while others exploded.
  - Strong dependence on packing densities and thickness of the sample
  - Heat and mass transport in nanofiber media : Will’s PhD work (6/29 talk)
- Further PIE work
  - Profilometry for out of plane plastic deformation @ MRF
  - SEM for finding micro cracks
  - Nano-indentation
  - XRD → extent of residual plastic strain
  - Quantify thermal shock resistance → strain rate dependent fracture toughness, hardening, energy dissipation etc.

HiRadMaT-60 in-situ measurements



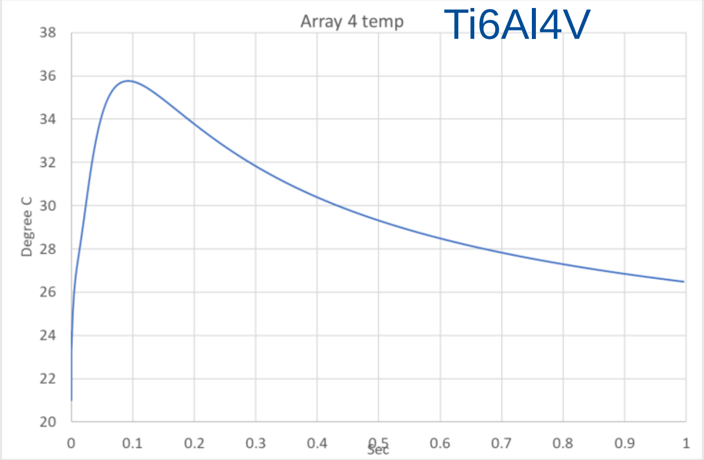


Peak temperature 1050 ^{o}C



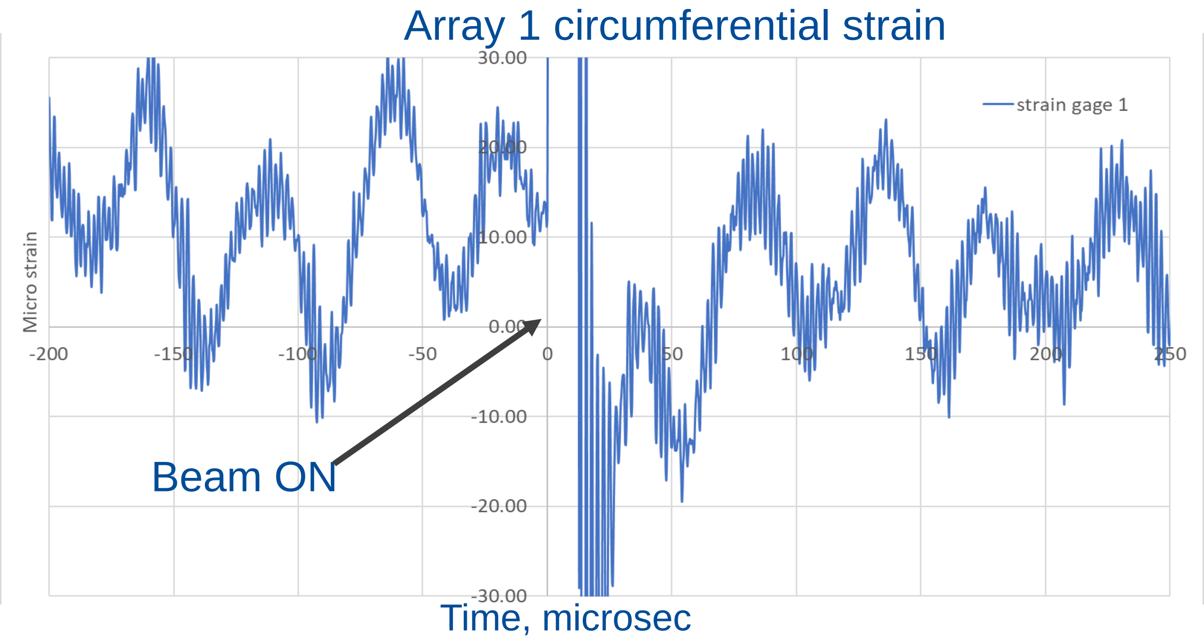
- Strain gages→ for axial and circumferential dynamic strain
- LDV→ for out of plane velocity and displacement measurement
- Temperature sensor
- Slugs : Be, NITE SiC/SiC, Ti6Al4V

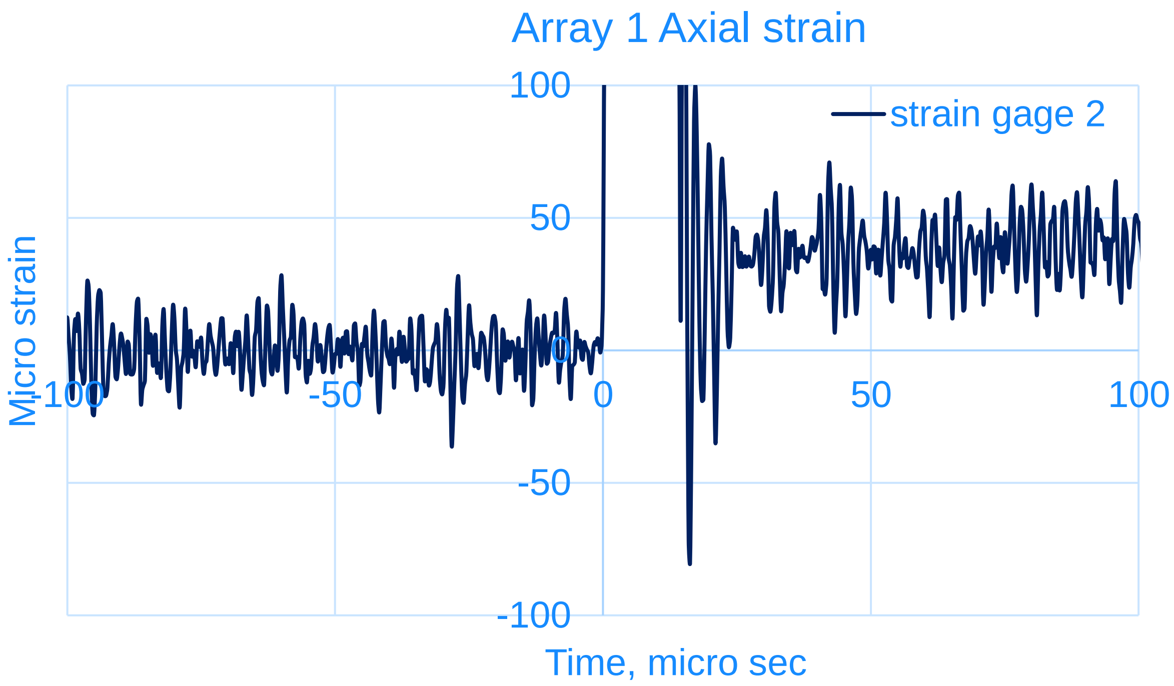
@4MHz



Help in validating strength modeling in simulation

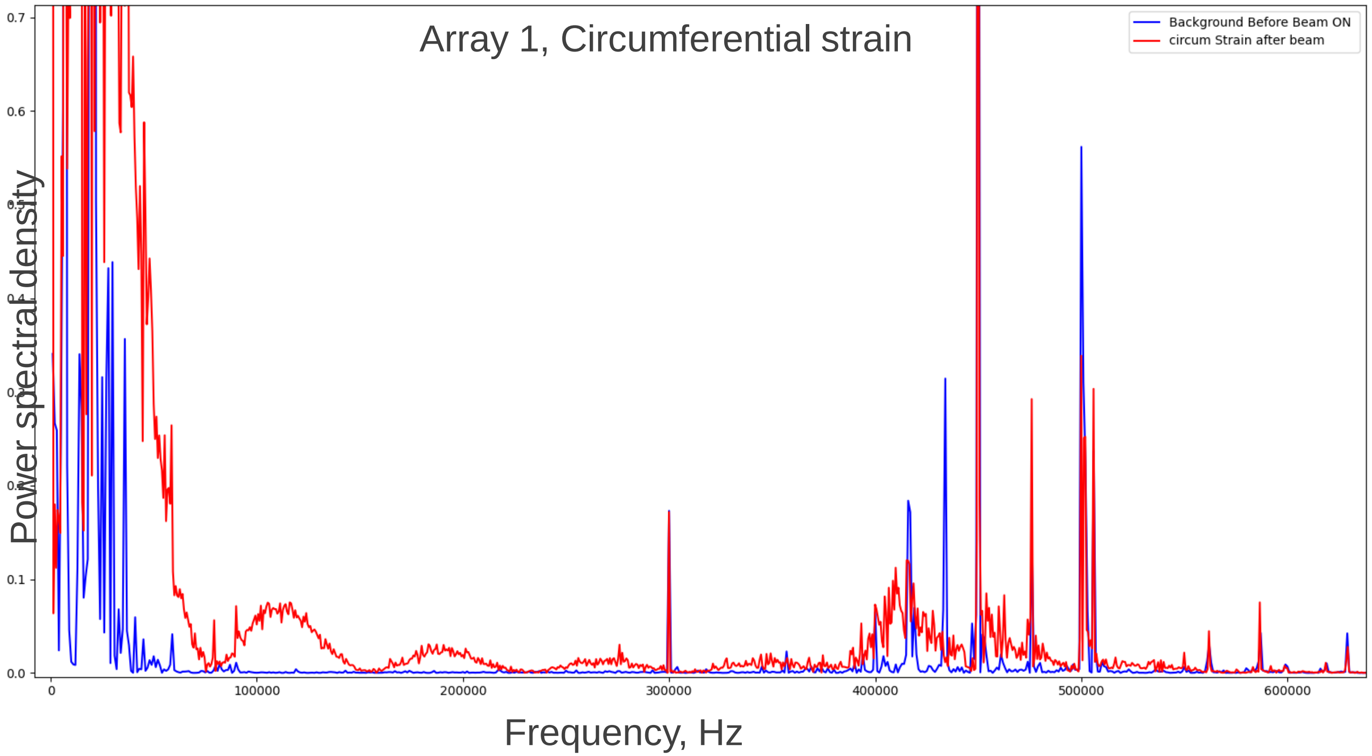
HiRadMaT-60 in-situ measurements

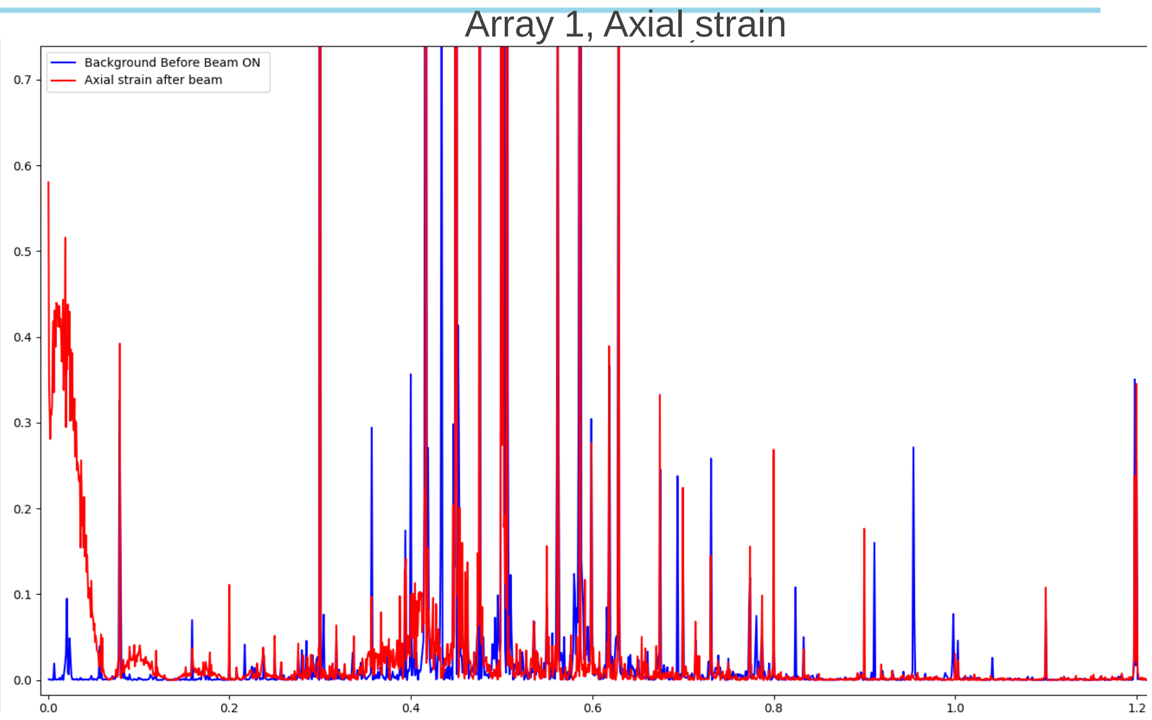




- Considerable background noise
- Very large spike in strain value during beam interaction→ due to induced voltage in strain sensors
- Further signal analysis is going on to reduce these effects

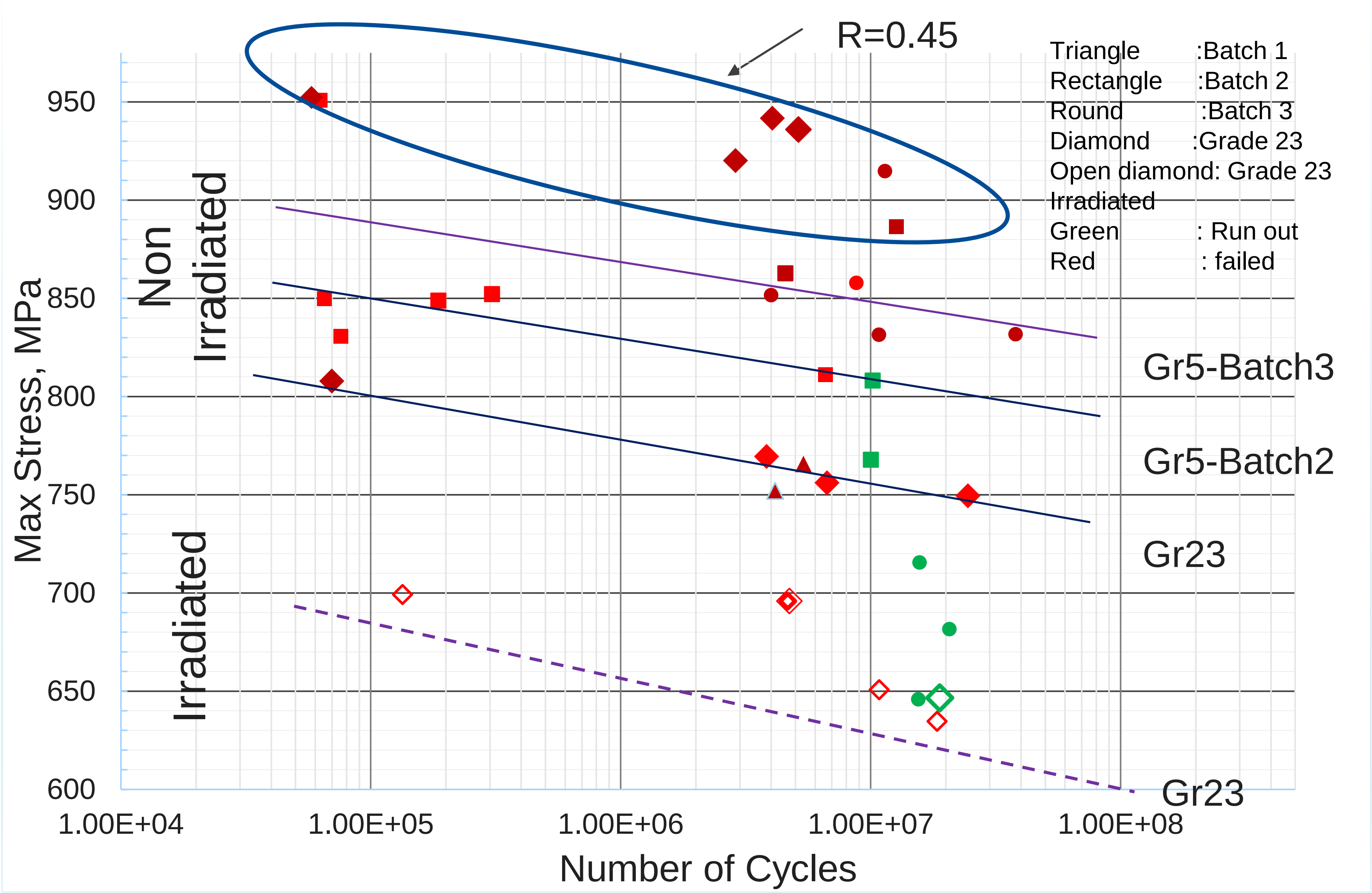
HiRadMaT-60 in-situ measurements





Analysis of frequency spectrum can identify background
Estimate of signal frequency →from FEA result
Use appropriate filter : Band pass, notch, Kaiser-window

Titanium Fatigue- SN Curve- all specimen



Irradiation reduced fatigue life.
Spread is too much in unirradiated samples.
No. of sample tested are few.

Need to benchmark the results of custom-fatigue tester.

Steps for validation

- Utilize VSS-40H(loaner fatigue tester) to carry out fatigue test
  - Modify it for miniature sample testing.
- Two sets of unirradiated sample → one based on ASTM B592 (Krouse type), other same as Fermilab sample.
- Surface finish → same as published data
- Number of samples→ 21 each
- Fatigue test with Ra=0.2
- Test atleast 3 samples at same stress level

Sample 1 Constant stress area

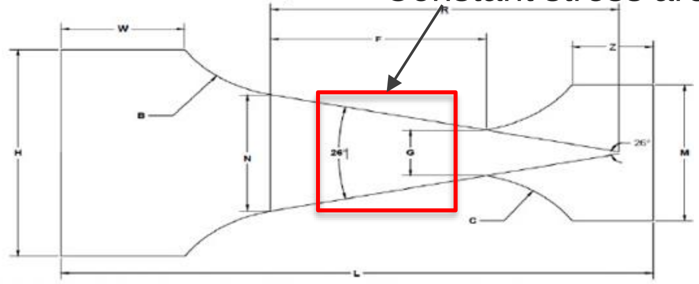
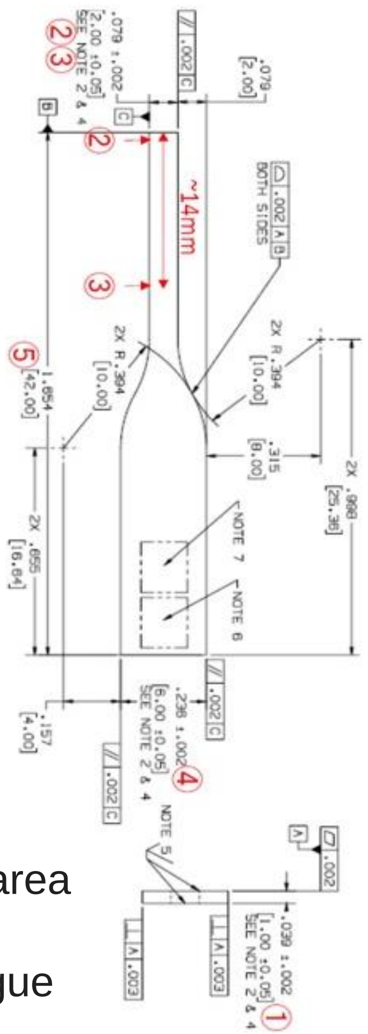


Figure 1: Sketch of the mini fatigue test specimen (all dimensions are in millimetres) [3]

Table 1: Mini Fatigue Test Specimen dimensions comparing with ASTM B593 Standard

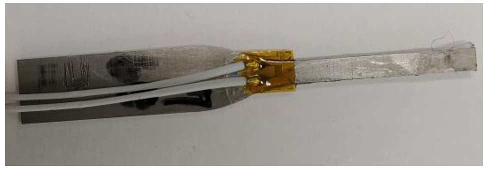
Letter #	Description	ASTM B593 Standard specimen dimension, in [mm]
F	Gage length	-
H	Width of grip section	1.38 in
M	Width of grip section	0.75 in
	Thickness	0.008 to 0.031 in (0.203 to 0.787 mm)
L	Overall length	2.31 in
G	width of reduced section	
W	Length of grip section	0.75 in
Z	Length of grip section	0.5 in
C	Radius of fillet, min	3/8 in
B	Radius of fillet, min	3/8 in
R	Distance between the connecting pin (apex of triangle) and the width of the specimen at a distance L from the point of load application	-
N	Width of the specimen at a distance R from the point of load	-

Sample 2



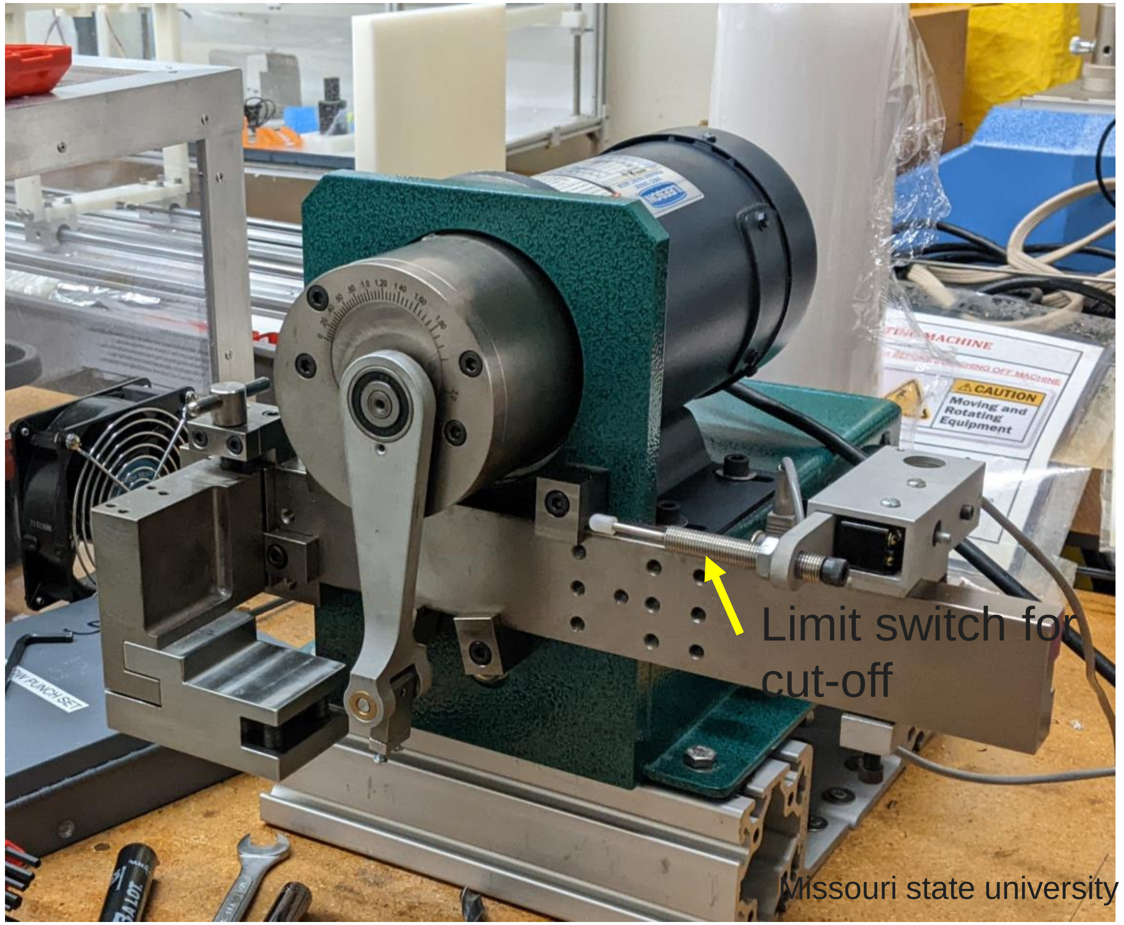
ASTM B592

Fermilab



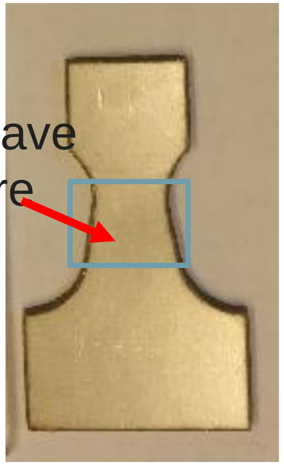
B592→Maxm. stress spread over a larger area
Fermilab sample→maxm. stress limited to single point, causing large variability of fatigue life

Upgrading a commercial bend fatigue tester

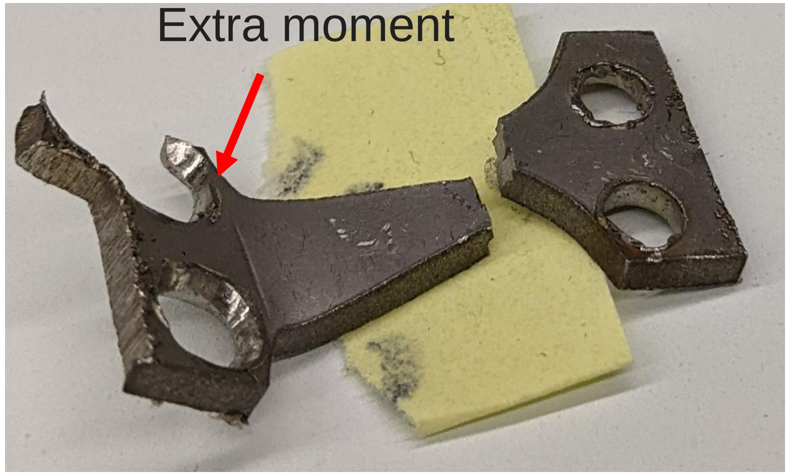


ASTM B592

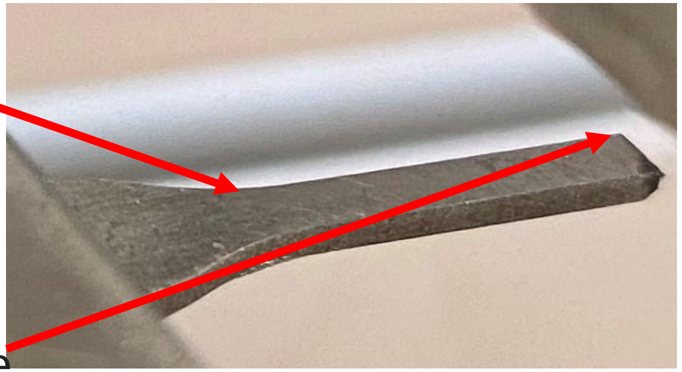
Should have failed here



Extra moment



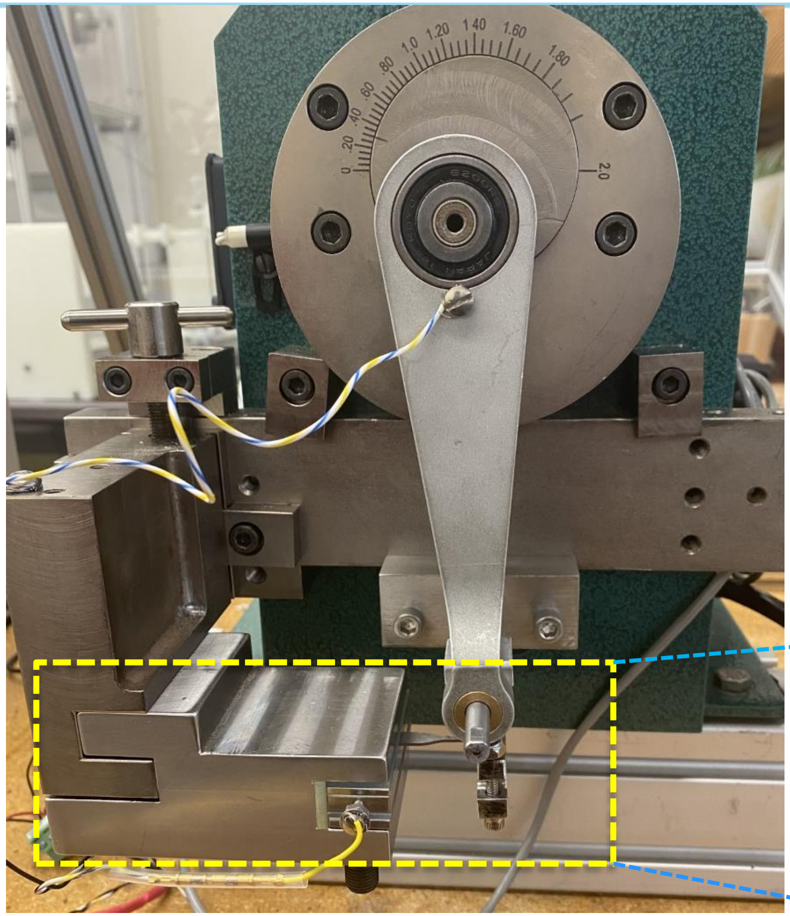
Should have failed here



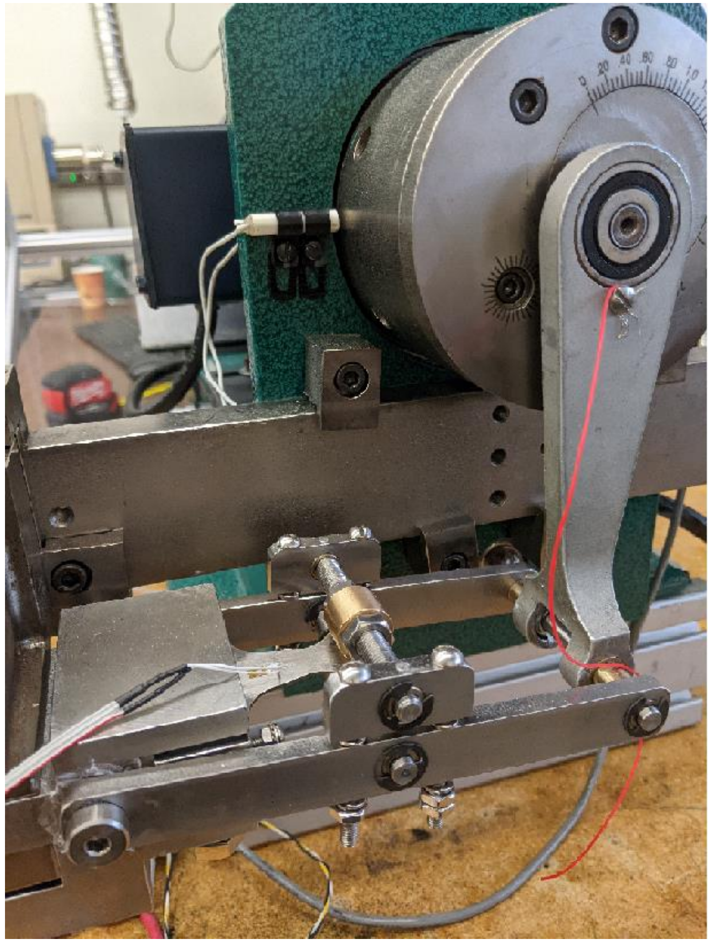
Instead, failed here

- ASTM standard sample failure in unexpected mode
- Mechanical cut-off switch which only activated when failed catastrophically (safety issues)
- Fatigue machine needed some modification

Upgrading a commercial bend fatigue tester

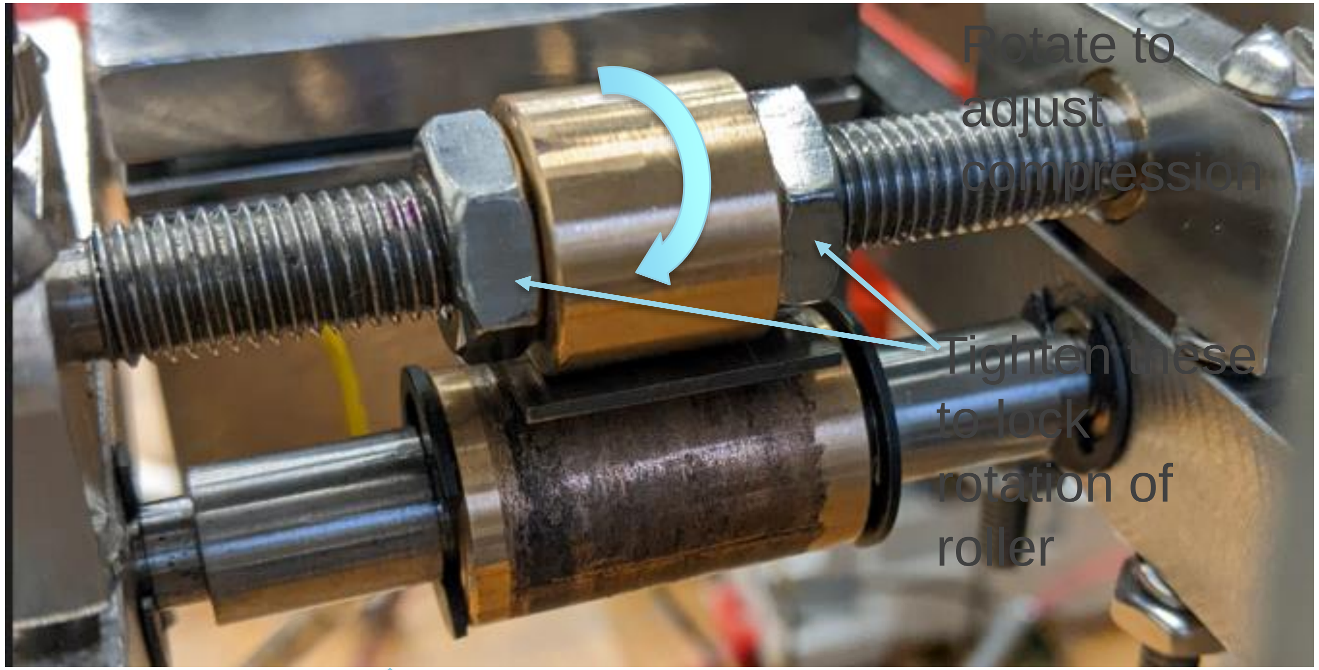


Electronic cut-off switch for
automatic crack detection

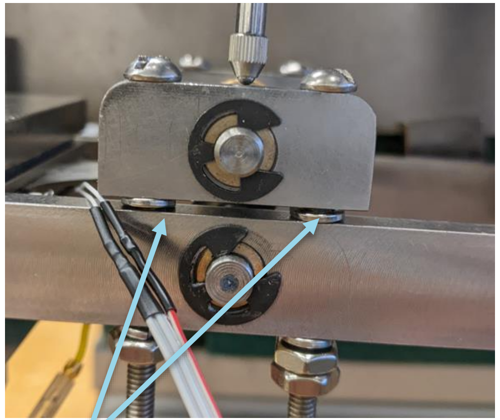


Double bearing grip for sample tip
Grip location detached from connecting rod pin

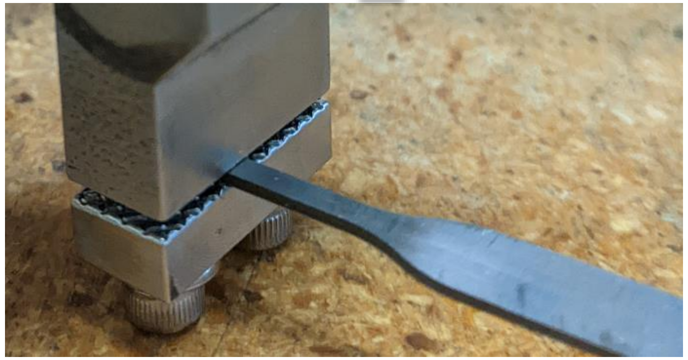
Upgrading a commercial bend fatigue tester



Eccentric top roller accommodate variation in thickness



Split ring for pre-tension



Flat plate grip

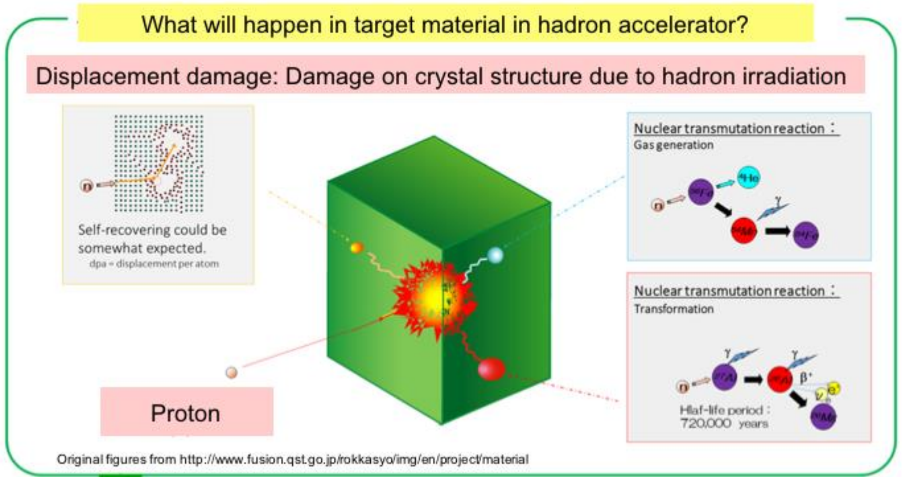
Flat plate grip replaced by double roller grip for sample tip
Minimized tip grip moment while maintaining nominal compression

<u>Failure at expected location</u>

2.8million cycles, R=-1, 30Hz

Displacement (dpa) cross section measurement

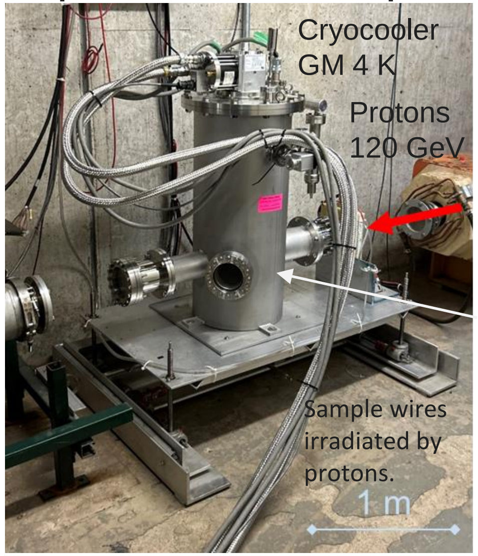
- Displacement per atom (dpa):
  - Damage index of irradiated materials
    dpa = ∫Fluence(E) x σ(E) dE
    σ : Displacement cross section
  - Although dpa is essential, displacement cross section has not been measured in the high energy region.
  - Experiments were conducted at J-PARC for Ep < 30 GeV and FNAL for Ep 120 GeV.



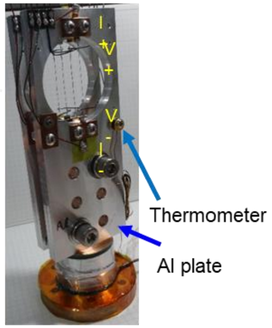
Displacement cross section：

- Following Matthiessen's law, it can be obtained by the change of resistivity.
- To sustain the damage in sample, cryocooling is required for Temp < 20 K.

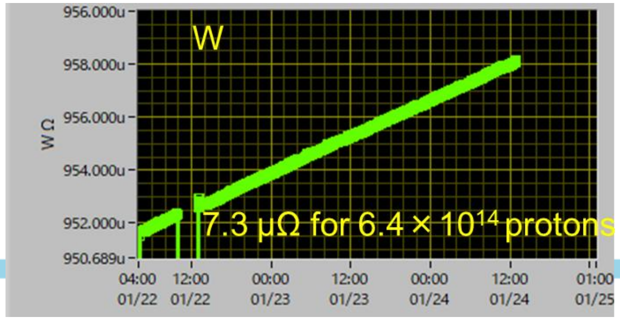
Experimental setup at FNAL (FTBF)



Sample wires (Al, Cu, W)



Electrical resistivity change of Tungsten(W) wire for beam irradiation

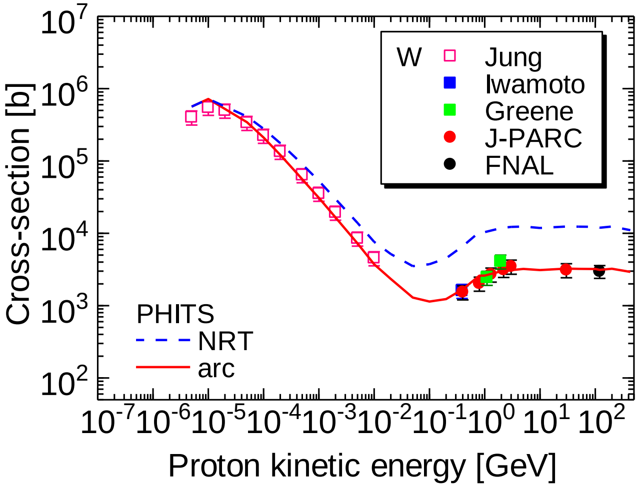


Experimental displacement X-sec

$$\sigma(E) = \Delta\rho/(\phi \cdot \rho_f)$$

σ(E): Displacement cross section [b]
Δρ : Change of resistivity [Ω/m]
Φ: Fluence of incident protons [/cm^2]
ρ_f: Resistivity change by Frenkel pair [Ω/m]

Comparison with calculation model



(Widely used but over est.)
(Showing good agreement)

Shinichiro Meigo (JAEA), Katsuya Yonehara (FNAL)

Fermilab

Collaboration activities with other institutes

- BLIP irradiated Beryllium PIE → Dave/Andy at PNNL
  - Bend test, tensile test (completed)
  - Microstructural analysis : TEM, EBSD, AFM (to be done)
- Molecular Dynamic (MD) simulation of various Ti-alloys to understand radiation damage → R. Devanathan, PNNL
- Profilometry, microhardness of BLIP/HRMT Beryllium → Slava at MRF
- High energy XRD → Kim Dohyun, BNL

Summary

- Secured funding under US-Japan HEP
  - Committee members shown interest in our work however funding is limited. Need to explore other sources
  - Funding would help in completing PIE on Be and Ti
- HiRadMat 60 data analysis is challenging due to high background noise.
- Validation of irradiated Ti6Al4V is undergoing. Success in modifying commercial bend fatigue tester for miniature sample.
- There is a need to find alternate proton irradiation facility: 10~30MeV

Thanks for your attention!