The RaDIATE collaboration - Goals, status, and future plans

Patrick Hurh (Fermilab, on behalf of the RaDIATE collaboration)

IWSMT 2016

31 October 2016

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

Broad aims are threefold: radiate.fnal.gov

- to generate new and useful materials data for application within the **accelerator** and **fission/fusion** communities
- to recruit and develop new scientific and engineering experts who can **cross the boundaries** between these communities
- to initiate and coordinate a **continuing synergy** between research in these communities, benefitting both **proton accelerator applications** in science and industry and **carbon-free energy technologies**

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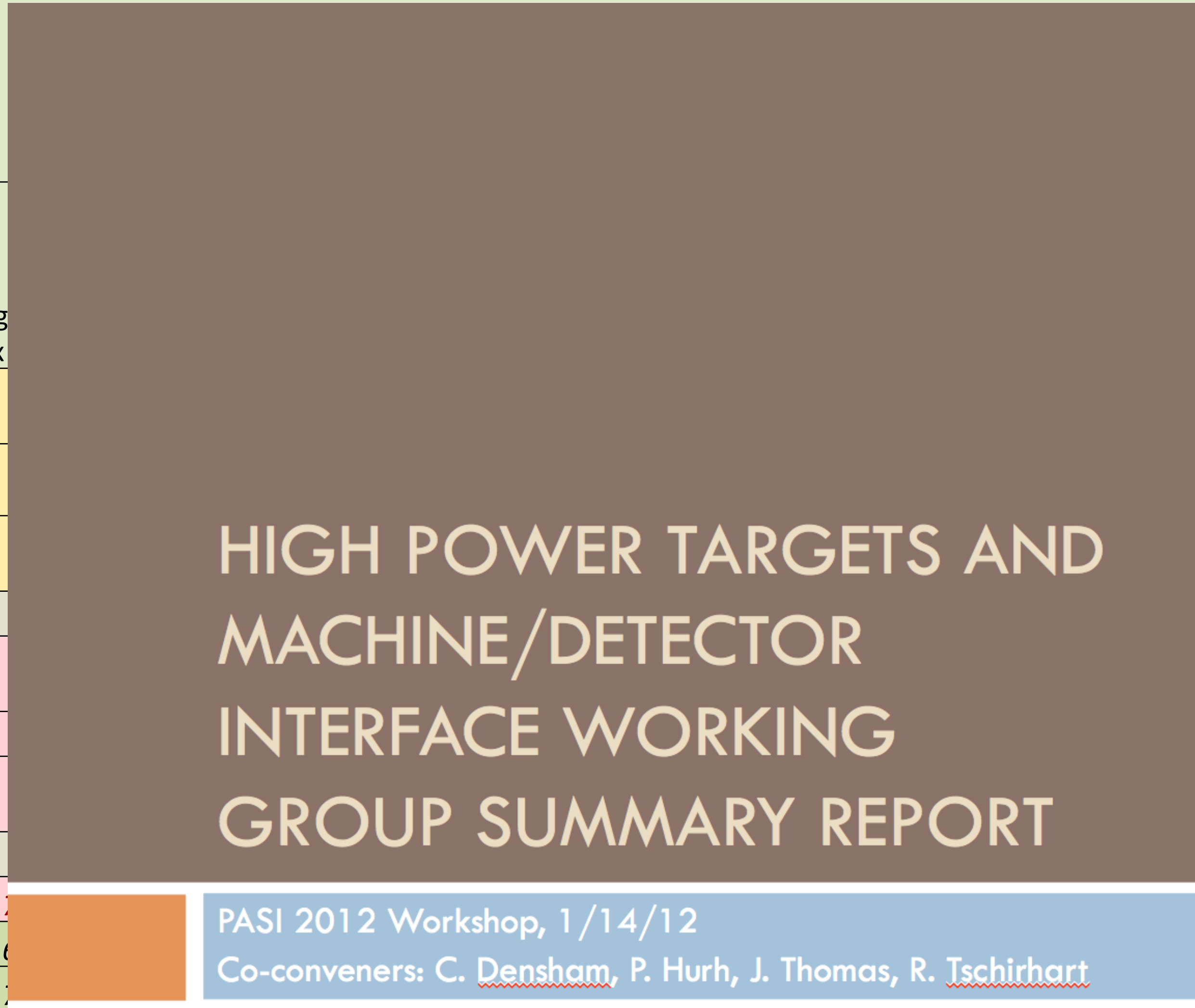
Currently adding CERN and J-PARC to the MOU

PASI 2012 Workshop

The Matrix

Potential Facility	Hig Flux	Monitoring and Instrumentation	"Score" (Avg)
Neutrino (conv, SBL & LBL)		5	6.86
Kaon (LE stopping)		7	5.80
Muon (LE stopping)		7	6.00
Spallation (ISOL)			0.00
Spallation (M&LS, UCN)		8	6.63
ADS Demo		8	7.67
NuFact/Muon Collider			9.38
"Score" (Avg)		7.00	
Count		5.00	
Score X Count/6		5.83	



PASI 2012 Workshop

The Matrix	Target Technology Issue/Challenge									
Potential Facility	High Heat Flux Cooling	Thermal "shock" (solid)	Thermal "shock" (liquid, incl. cooling medium)	High Magnetic Field (rad damage to sc cond)	Novel Target/ Window Design	Liquid Metals	Radiation Damage and Corrosion	Radiation Protection & Facility Design	Monitoring and Instrumentation	*"Score" (Avg)*
Neutrino (conv, SBL & LBL)	5	8	8		8		8	6	5	*6.86*
Kaon (LE stopping)	6				3		7	6	7	*5.80*
Muon (LE stopping)	6			7	3		7	6	7	*6.00*
Spallation (ISOL)										*0.00*
Spallation (M&LS, UCN)	8	9	10		4	3	7	4	8	*6.63*
ADS Demo	8				8	7	7	8	8	*7.67*
NuFact/Muon Collider	10	10	10	10	5	10	10	10		*9.38*
"Score" (Avg)	*7.17*	*9.00*	*9.33*	*8.50*	*5.17*	*6.67*	*7.67*	*6.67*	*7.00*	
Count	*6.00*	*3.00*	*3.00*	*2.00*	*6.00*	*3.00*	*6.00*	*6.00*	*5.00*	
Score X Count/6	*7.17*	*4.50*	*4.67*	*2.83*	*5.17*	*3.33*	*7.67*	*6.67*	*5.83*	

PASI 2012 Workshop

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Largest "Cross-cutting" Challenge to Future HPT Facilities

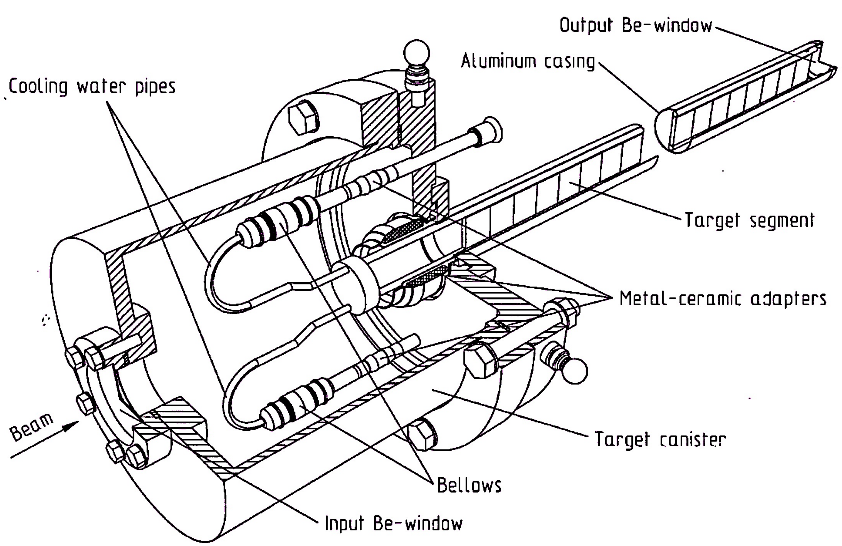
High Energy Physics HPT Future Needs

Exp/Facility	Laboratory	Time frame (yrs)	"On the books"?	Beam Power (kW)	Comments
ANU/NOvA	FNAL	0.1	Y	700	Full power soon
T2K	J-PARC	2	Y	750	Ramping Up!
LBNF-1.2 MW	FNAL	10	Y	1,200	PIP-II enabled
HyperK	J-PARC	10?	?	1,660+	~4 MW long-term?
ILC	Japan?	15?	?	220	photons on Ti
Next-Gen Nu Facility –2.5 MW	FNAL	20?	N	2,500?	Mid-Term
Next-Gen Nu Facility - 5 MW	FNAL	30?	N	5,000?	Longer-term

Other low power (but high intensity) target facilities will also be needed. Notably follow-on experiments to Mu2e/COMET, CERN anti-proton, etc… These are still challenging targets due to high-Z targets and small beam spots, but are not listed here.

Recently Operating Nu-beams

Facility	p Beam Energy (GeV)	Target Material	Cooling	Op/Design Beam Power (kW)	Total Protons on Target (10^{20})	Protons per pulse (10^{12})	Beam Spot Size, RMS (mm)
NuMI/ MINOS	120	Graphite	Water	375 / 400	16	44	1.0 - 1.1
NuMI/ NOvA	120	Graphite	Water	580 / 700	11	49	1.3 – 1.4
BNB	8	Beryllium	Air	30 / 30	22	5	1.5
T2K	30	Graphite	Helium	400 / 750	13	200	4.2
CNGS	400	Graphite	Passive Helium	500 / 750	2	48	0.5



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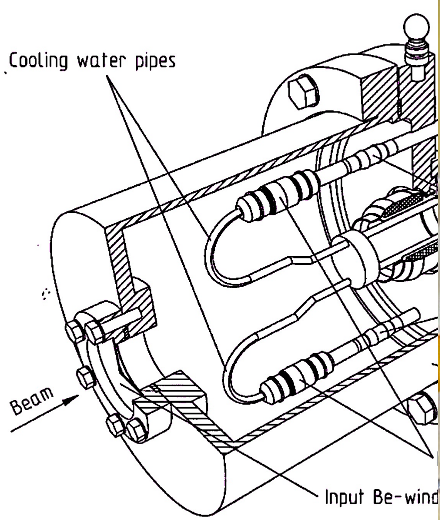

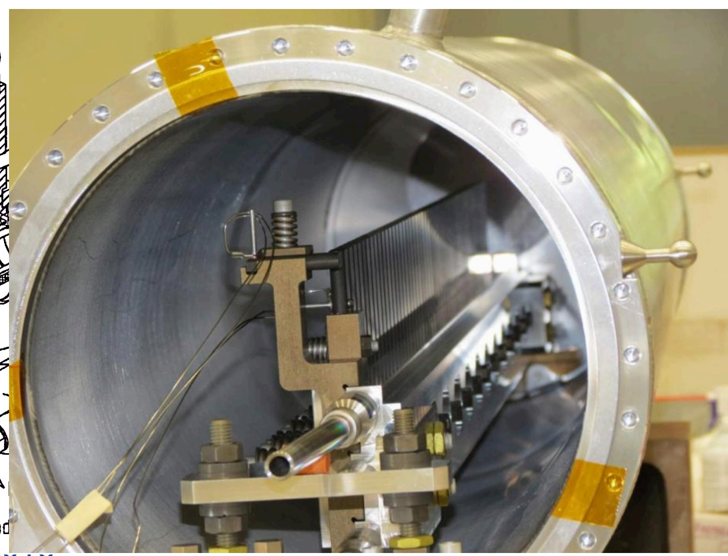

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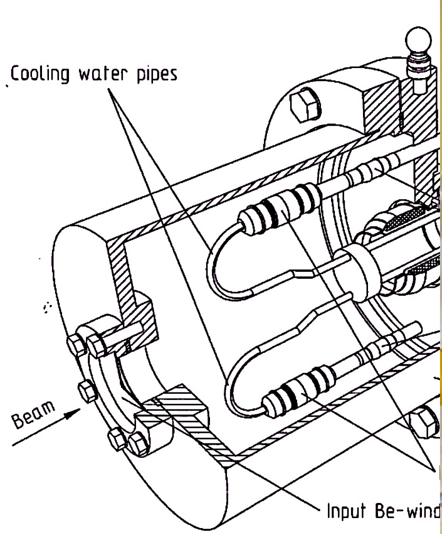

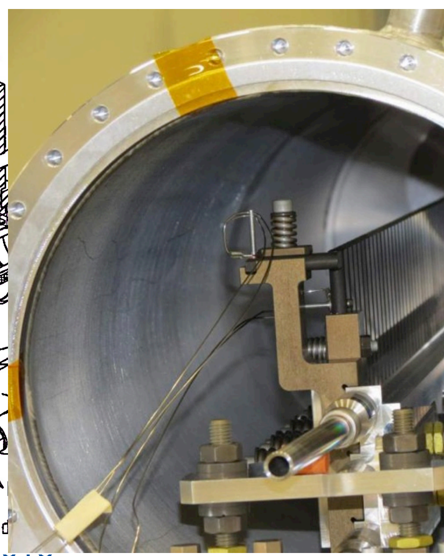
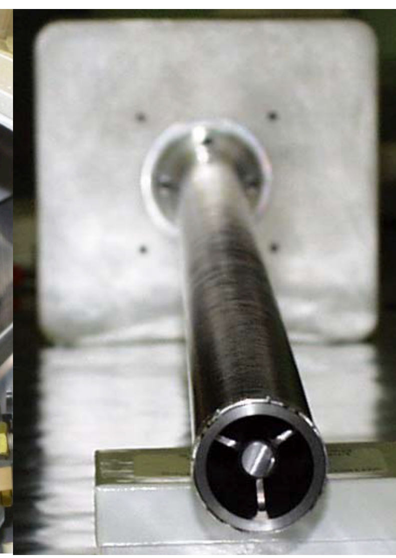

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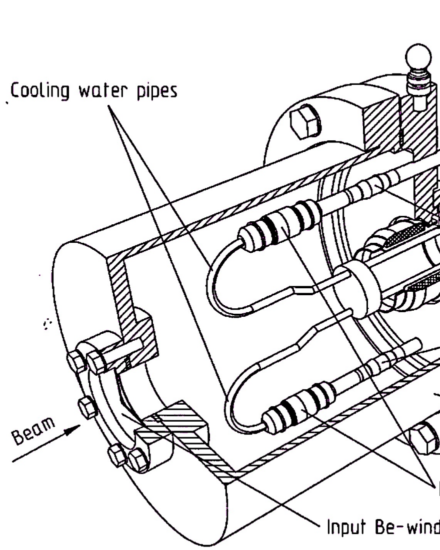

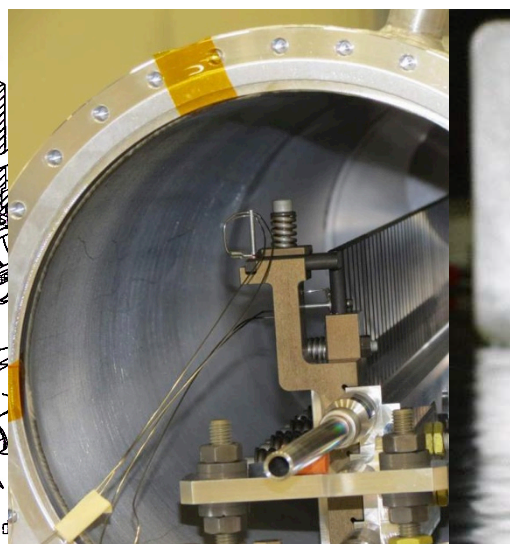
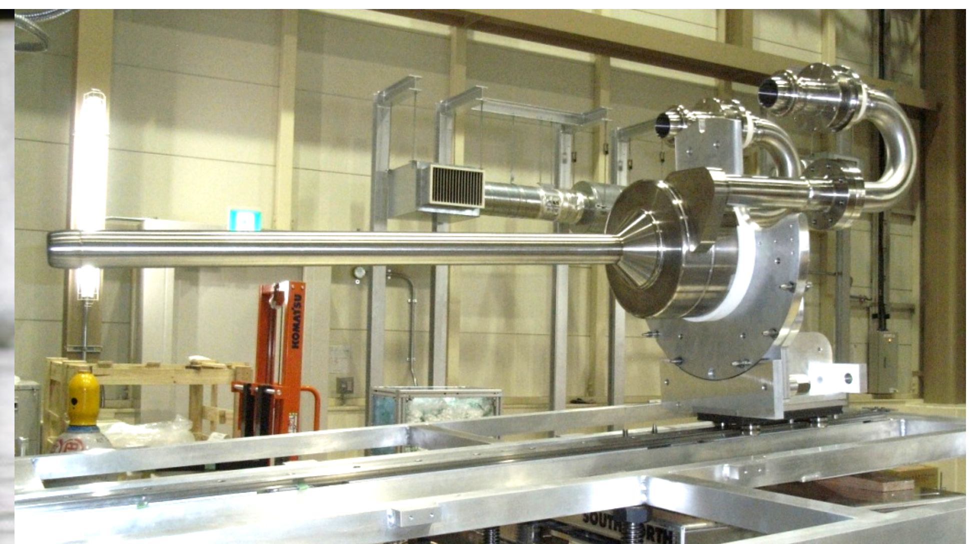

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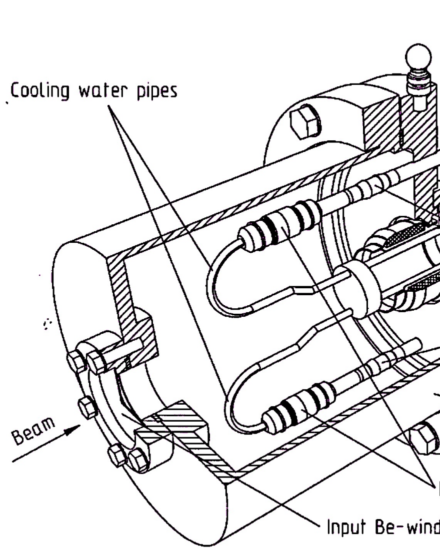
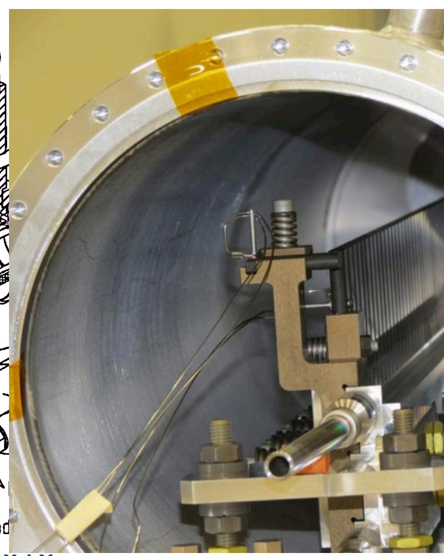
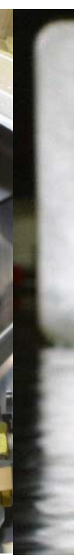
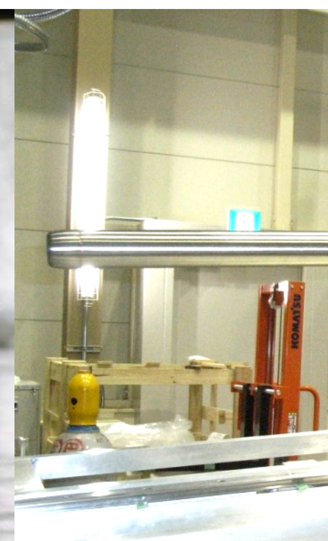


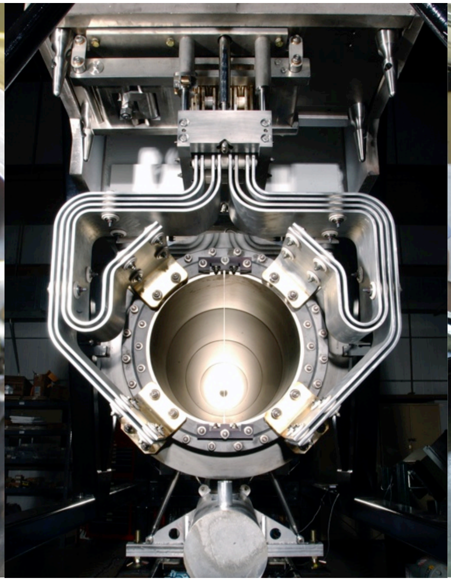




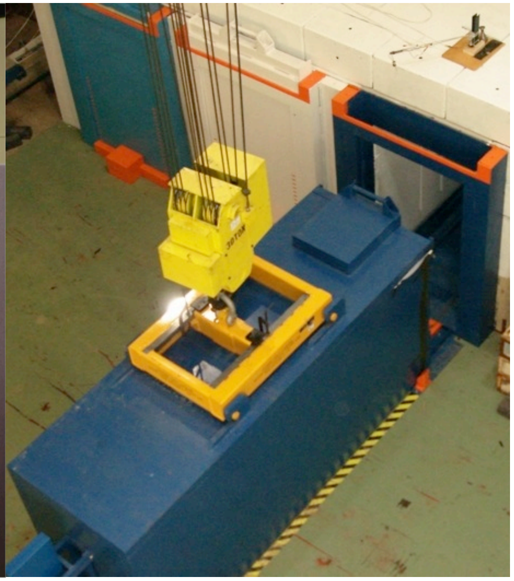
Upgrades and Future Nu-beams

Facility	p Beam Energy (GeV)	Target Material	Cooling	Design Beam Power (kW)	Cycle Frequency (Hz)	Protons per pulse (10^{12})	Beam Spot Size, RMS (mm)
BNB	8	Beryllium	Air	60	10	5	1.5
T2K Upgrade	30	Graphite	Helium	750	0.77	200	4.2
Hyper-K	30	Graphite	Helium	1,300	0.86	320	4.2
LBNF-DUNE (PIP-II)	60 – 120	Graphite	Water	~1,200	0.8 – 1.4	~75	1.7
LBNF-DUNE (Upgrade)	60 – 120	?	?	~2,400	0.8 – 1.4	200	2 – 4?

Future beam power and intensities present major challenges to reliable and efficient high power target facilities

High Power Targetry Scope



R&D Needed to Support:

- Target
  - Solid, Liquid, Rotating, Rastered
- Other production devices:
  - Collection optics (horns, solenoids)
  - Monitors & Instrumentation
  - Beam windows
  - Absorbers

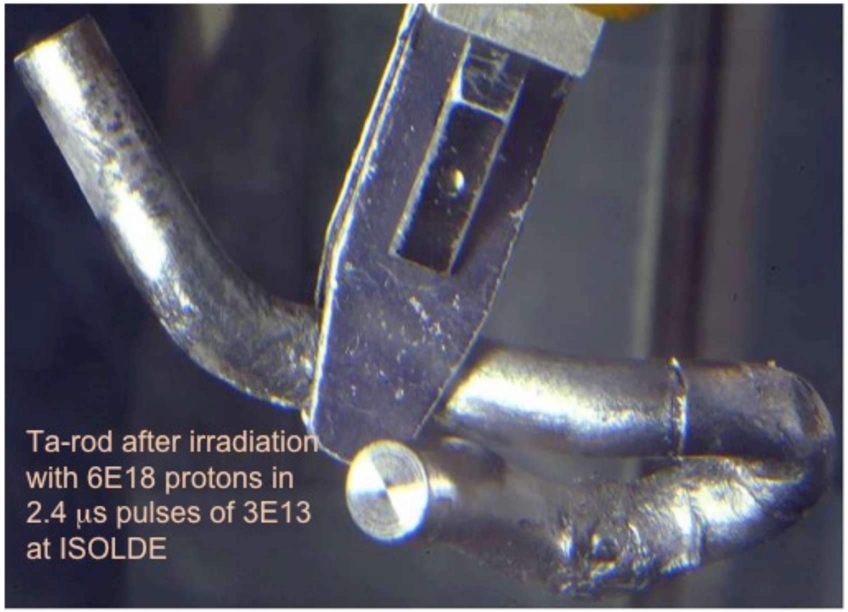
- Facility Requirements:
  - Remote Handling
  - Shielding & Radiation Transport
  - Air Handling
  - Cooling Systems

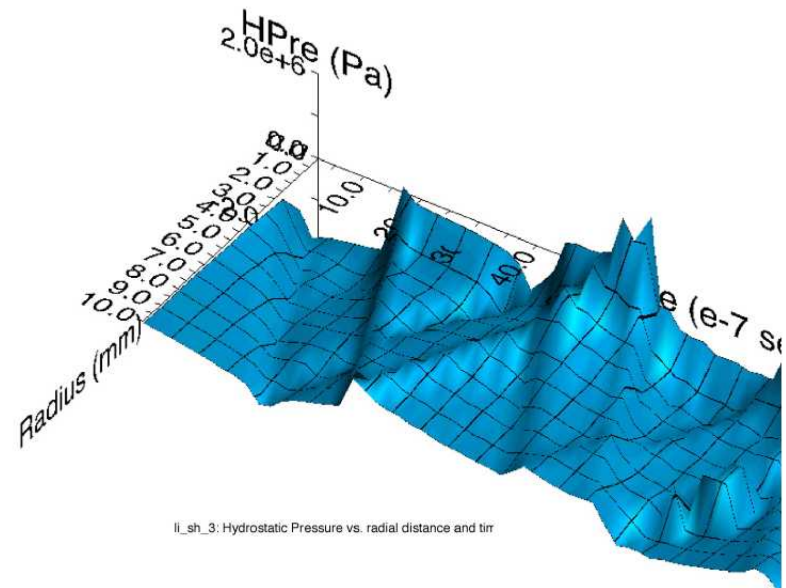
High Power/Intensity Targetry Challenges

- Material Behavior
  - ***Thermal "shock" response***
  - ***Radiation damage***
  - Highly non-linear thermo-mechanical simulation
- Targetry Technologies (System Behavior)
  - Target system simulation (optimize for physics & longevity)
  - Rapid heat removal
  - Radiation protection
  - Remote handling
  - Radiation accelerated corrosion
  - Manufacturing technologies

Focus of the remainder of this talk

Thermal Shock (stress waves)



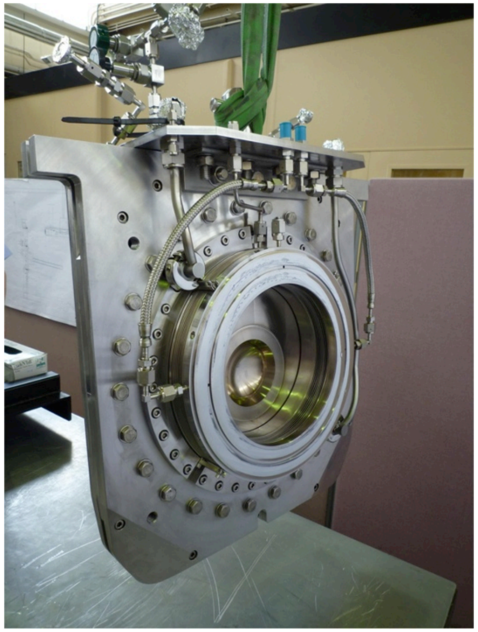


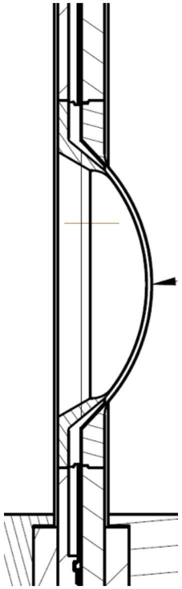
Ta-rod after irradiation with 6E18 protons in 2.4 μs pulses of 3E13 at ISOLDE (photo courtesy of J. Lettry)

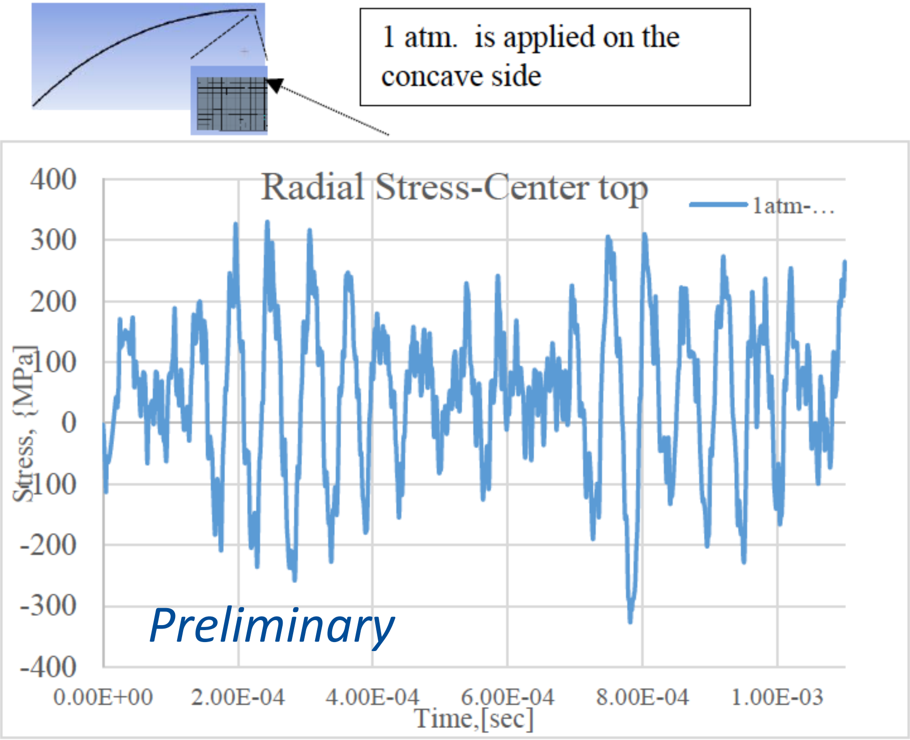
Simulation of stress wave propagation in Li lens (pbar source, Fermilab)

- Fast expansion of material surrounded by cooler material creates a sudden local area of compressive stress
- Stress waves (not shock waves) move through the target
- Plastic deformation, cracking, and fatigue can occur

Stress wave example: T2K window







S. Bidhar, FNAL

- Material response dependent upon:
  - Specific heat (temperature jump)
  - Coefficient of thermal expansion (induced strain)
  - Modulus of elasticity (associated stress)
  - Flow stress behavior (plastic deformation)
  - Strength limits (yield, fatigue, fracture toughness)

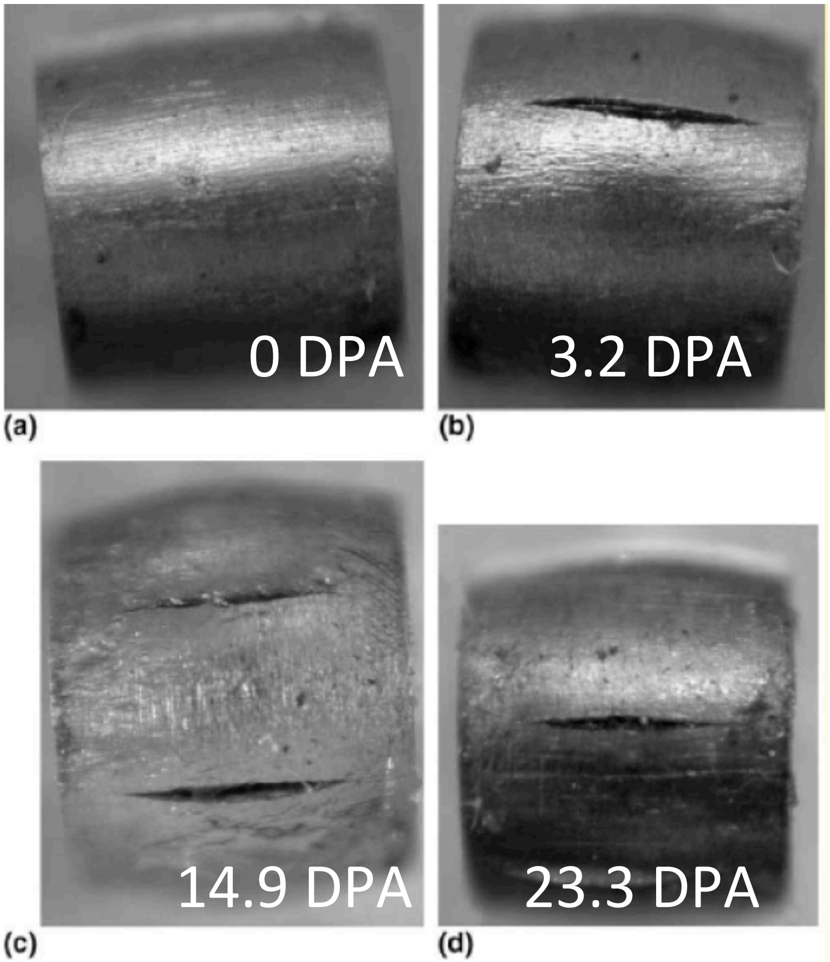
For more on the T2K window, see Ref. [1] at end of slides

Heavy dependence upon material properties, but:
Material properties dependent upon Radiation Damage…

Radiation Damage

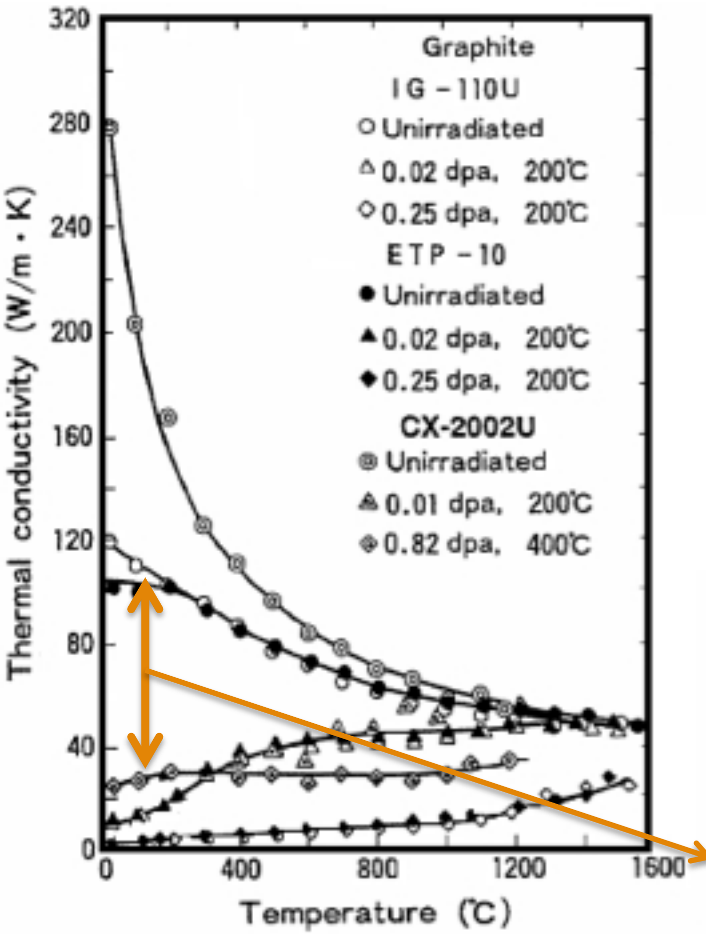
- Displacements in crystal lattice
  (expressed as Displacements Per Atom, DPA)
  - Embrittlement
  - Creep
  - Swelling
  - Transmutation products
    - H, He gas production can cause void formation and embrittlement (expressed as atomic parts per million per DPA, appm/DPA)
  - Fracture toughness reduction
  - Thermal/electrical conductivity reduction
  - Coefficient of thermal expansion
  - Modulus of Elasticity
  - Fatigue response
- Dependent upon material condition and irradiation conditions (e.g. temp, dose rate)

For an in-depth treatment of radiation damage effects, see Ref. [2] at end of slides



S. A. Malloy, et al., Journal of Nuclear Material, 2005. (LANSCE irradiations)

Examples of radiation damage



N. Maruyama and M. Harayama, "Neutron irradiation effect on … graphite materials," Journal of Nuclear Materials, 195, 44-50 (1992)

Factor of 10 reduction in conductivity at 0.02 DPA

D.L. Porter and F. A. Garner, J. Nuclear Materials, **159**, p. 114 (1988)

Void swelling in 316 Stainless steel tube (on right) exposed to reactor dose of 1.5E23 n/cm^2

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Radiation Damage

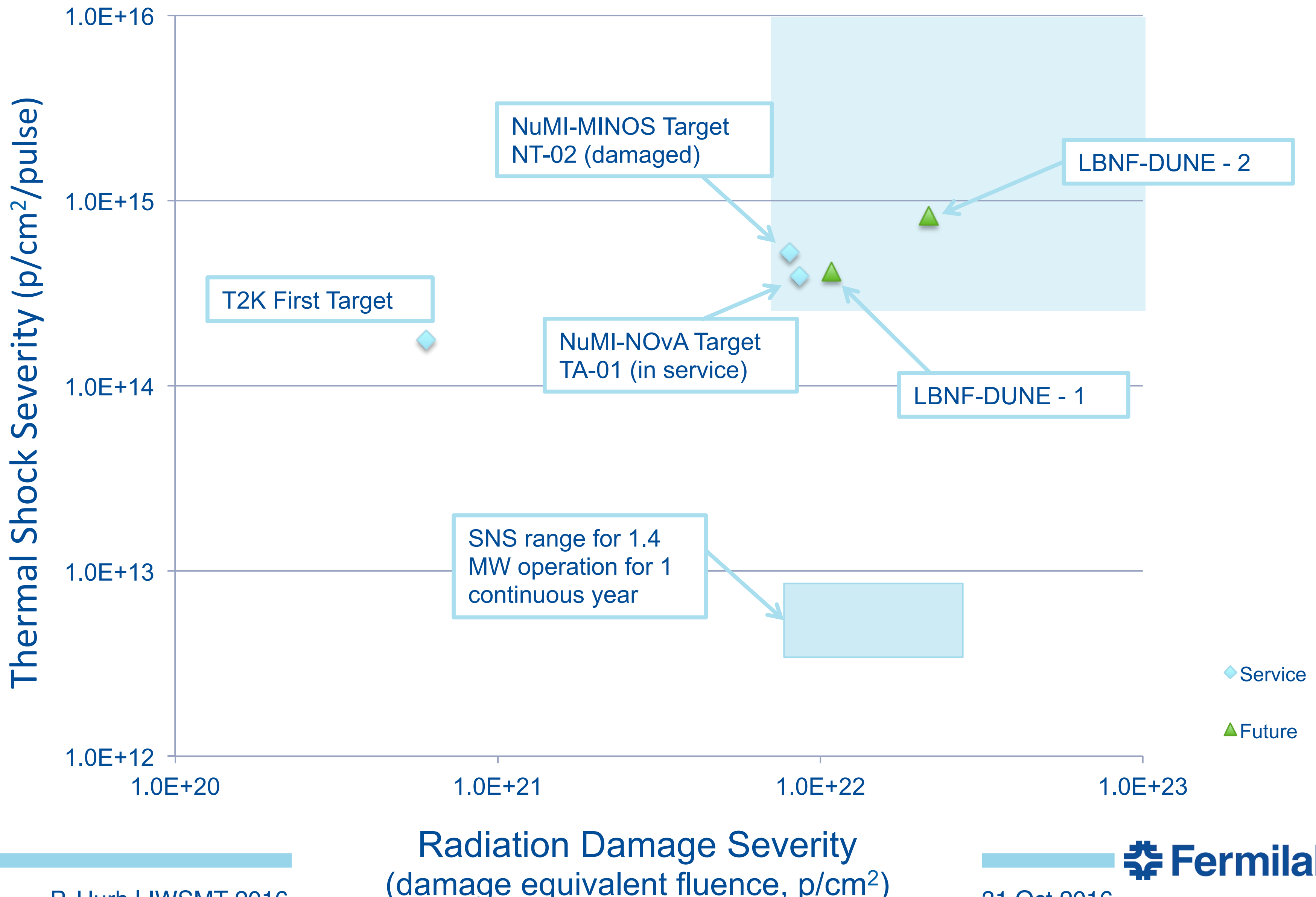
n ≠ p
1-14 MeV 100+ MeV

Irradiation Source	DPA rate (DPA/s)	He gas production (appm/DPA)	Irradiation Temp (°C)
Mixed spectrum fission reactor	3×10^{-7}	1×10^{-1}	200-600
Fusion reactor	1×10^{-6}	1×10^{1}	400-1000
High energy proton beam	6×10^{-3}	1×10^{3}	100-800

Effects from low energy neutron irradiations do not equal effects from high energy proton irradiations. Table compares typical irradiation parameters.

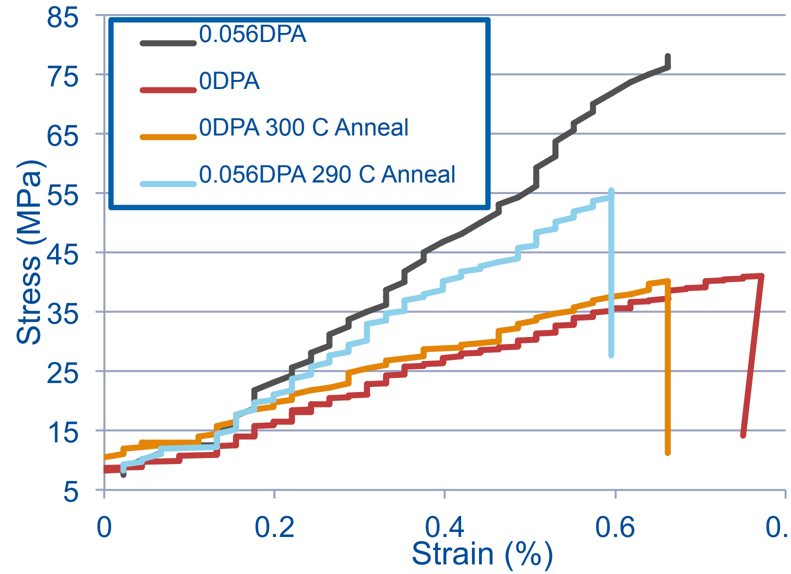
Cannot directly utilize data from nuclear materials studies!

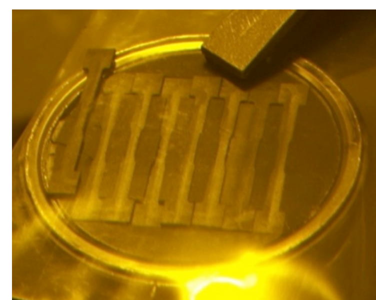
Nu HPT R&D Materials Exploratory Map

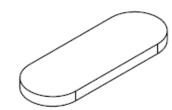


RaDIATE R&D Progress

- 181 MeV p irradiation @ BNL's BLIP facility [3]
  - 4 graphites & h-BN exposed to 6.7E20 p/cm^2
  - h-BN structurally degraded beyond recovery
  - Changes in material properties (30-50%)
  - Annealing (>150 ˚C) achieves partial recovery
  - Confirmed choice of POCO-ZXF-5Q (least change in critical properties)
  - Irradiating at higher temp may be beneficial, however:
    - Diffusion assisted effects are increased (e.g. swelling from He bubble formation, creep) [4]
    - Oxidation must be avoided
    - Elev. temp properties affecting thermal shock resistance are generally degraded
- Future work includes 2017 BLIP irradiation
  - Organized by RaDIATE collaboration
  - Includes graphite at various temp (up to ~1,000 ˚C)
  - Also Beryllium, Ti alloys, Si, TZM, Al, & Ir
  - Post-Irradiation Examination (2018) includes mechanical, thermal, micro-structural, and fatigue evaluation
  - Participants: BNL, PNNL, FRIB, ESS, CERN, J-PARC, STFC, Oxford, LANL

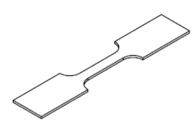




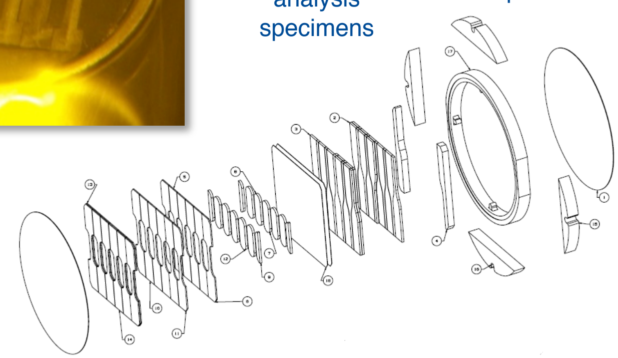


Microstructural analysis specimens

Fatigue specimens



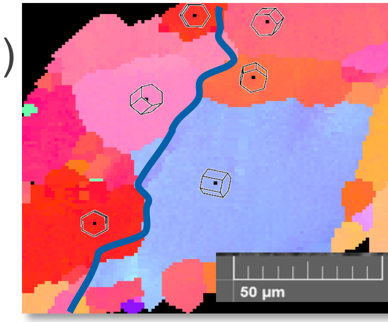
Tensile specimens

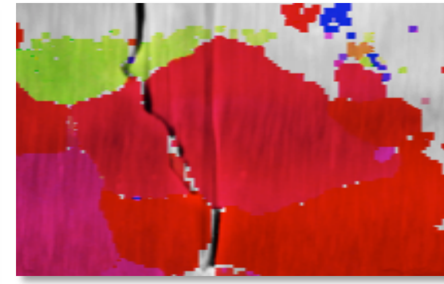


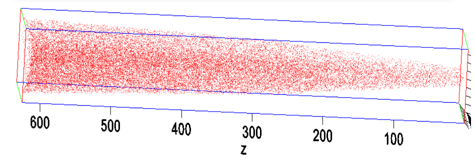
Fermilab

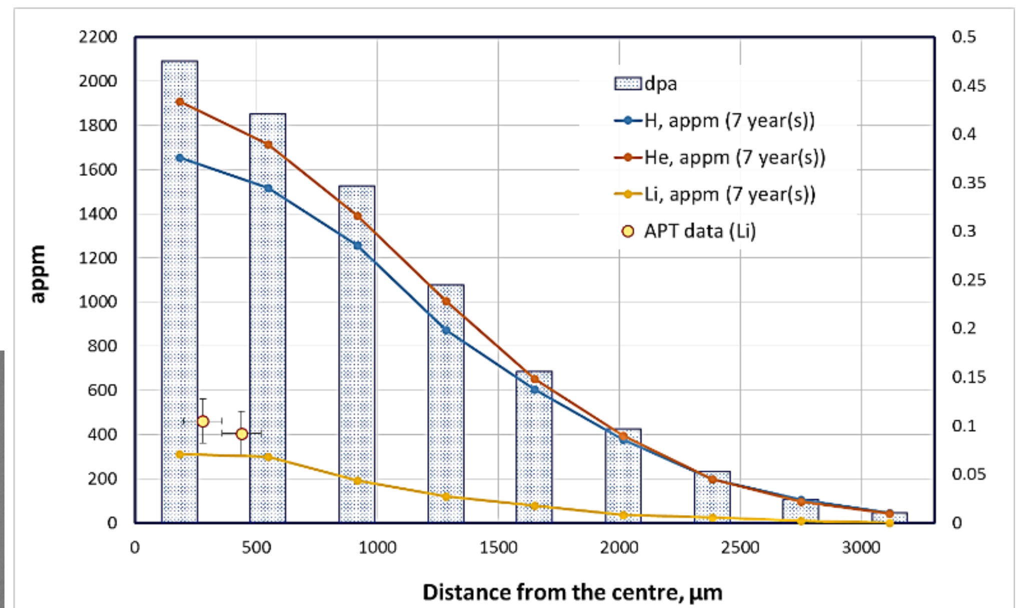
RaDIATE R&D Progress

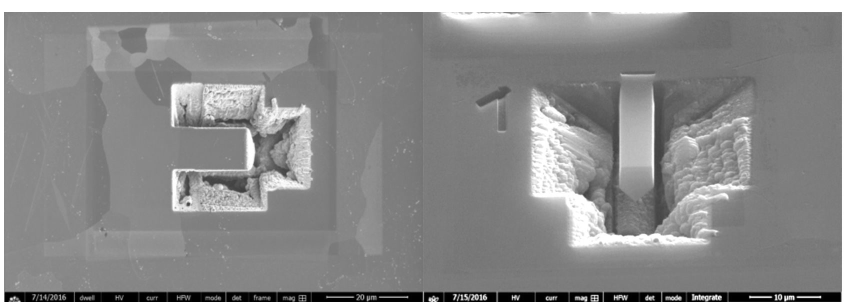
- NuMI Be window PIE (FNAL, Kuksenko,Oxford)
  - Be window to 1.57E21 POT analyzed [5]
  - Advanced microscopy techniques ongoing
  - Li matches predictions and remains homogeneously distributed at ~50 ˚C
  - Crack morphology changes at higher doses (transgranular to grain boundary fracture)
- Future Work with Be window (2016-17)
  - Micro-mechanics testing
    - micro-cantilever
    - nano-indentation
  - Annealing
    - He bubble coalescence and growth?
    - recovery of properties?





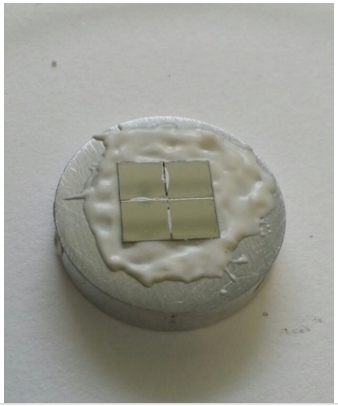


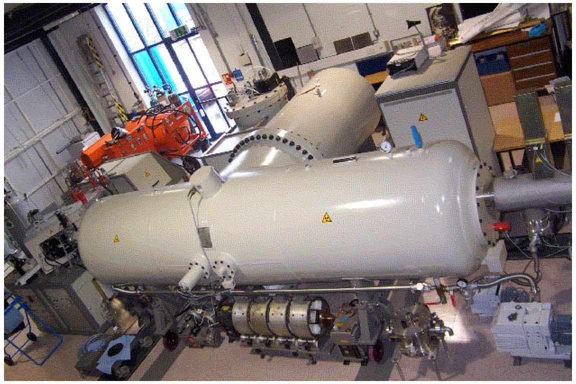


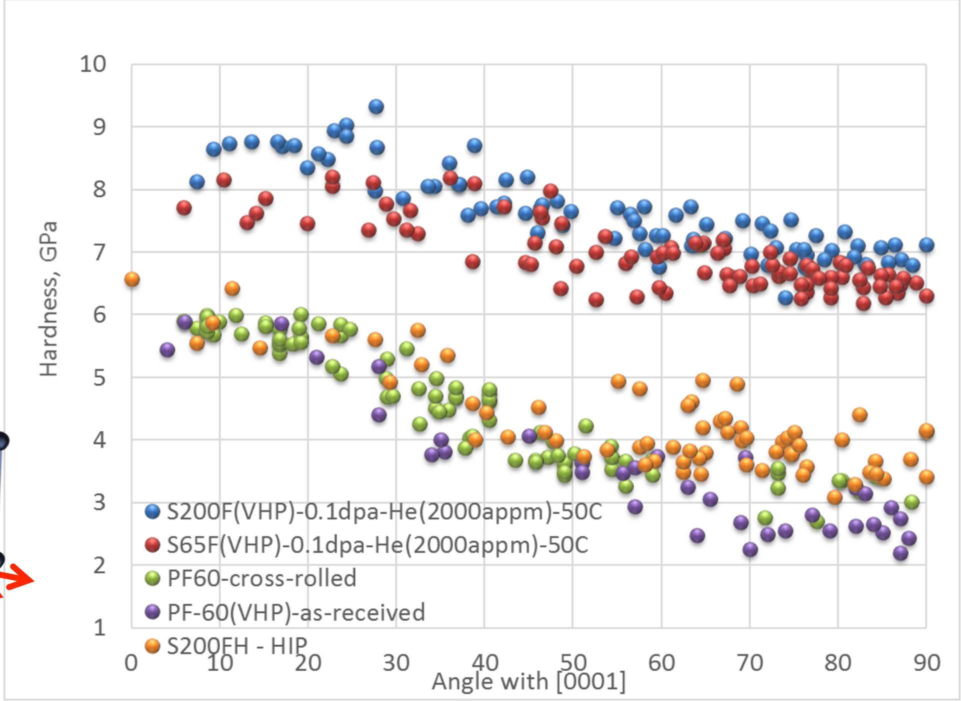


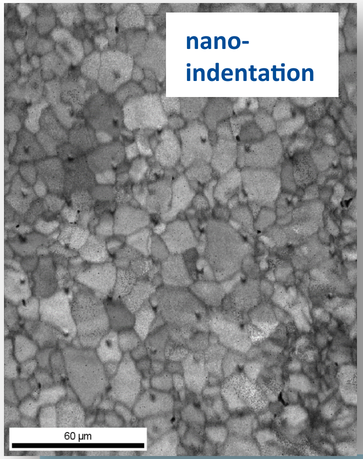
RaDIATE R&D Progress

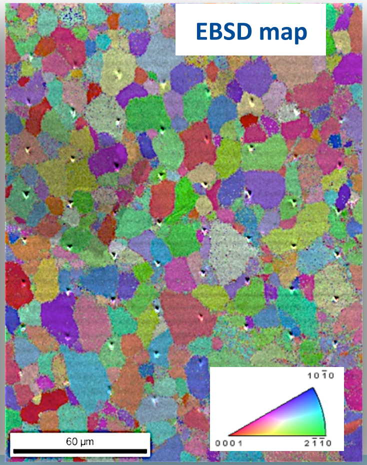
- Helium implantation study at Surrey/Oxford
  - Ions: He+
  - Maximum beam energy: 2 MeV => 7.5μm implantation depth (SRIM)
  - Dose: up to 0.1 dpa currently
  - Temperature: 50°C and 200°C
  - Nano-indentation indicates significant hardening at 0.1 DPA and 50 °C
  - Work of V. Kuksenko (Oxford)
- Future Work with He in Be (2016-17)
  - Micro-mechanics testing
    - micro-cantilever
  - Higher dose and temperature irradiations

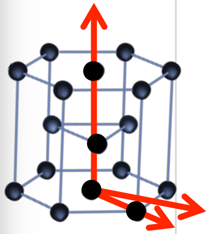






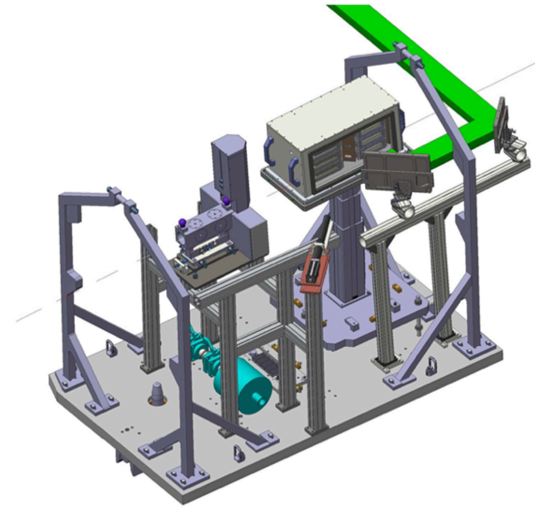


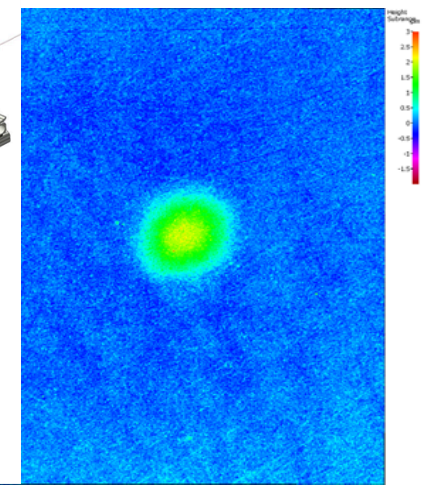


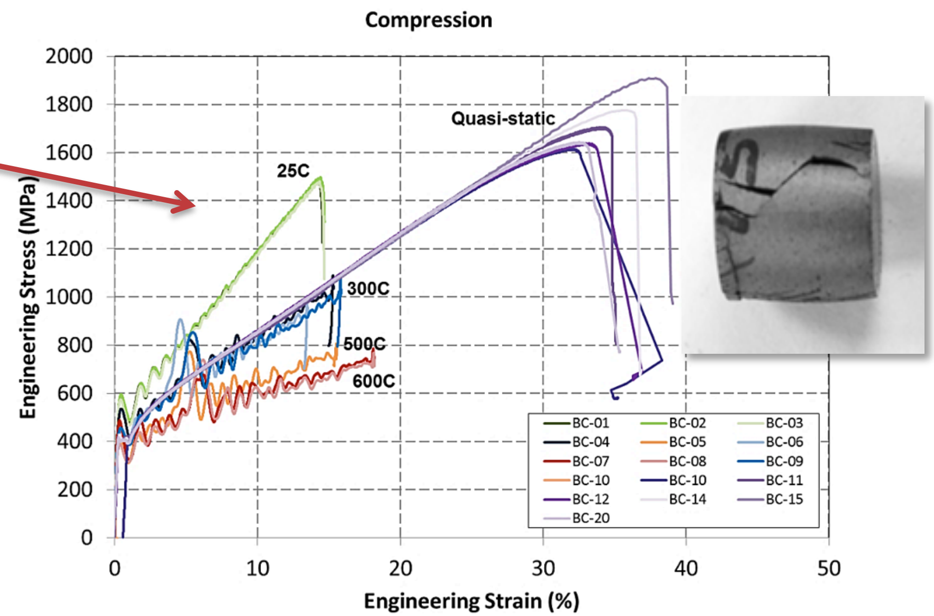


RaDIATE R&D Progress

- In-beam thermal shock test of Be at CERN's HiRadMat [6] (FNAL, RAL, Oxford, CERN)
  - All 4 Be grades showed less plastic deformation than predicted by generic strength models
  - S200FH showed least plastic deformation
  - Glassy Carbon windows survived without signs of degradation
  - Multiple pulses showed diminishing ratcheting in plastic deformation
  - Work continues on advanced strength model and data analysis
    - Johnson-Cook strength model developed at SwRI through SHB high strain-rate testing (elevated temp) [7, 8]
- Future work (2018) at HiRadMat includes:
  - Testing of irradiated materials (BLIP)
    - Beryllium grades
    - Graphite grades
    - Glassy Carbon
  - Higher p beam intensities
  - Development of J-C damage model for Be

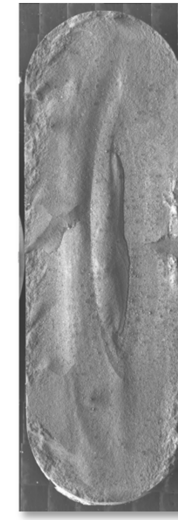


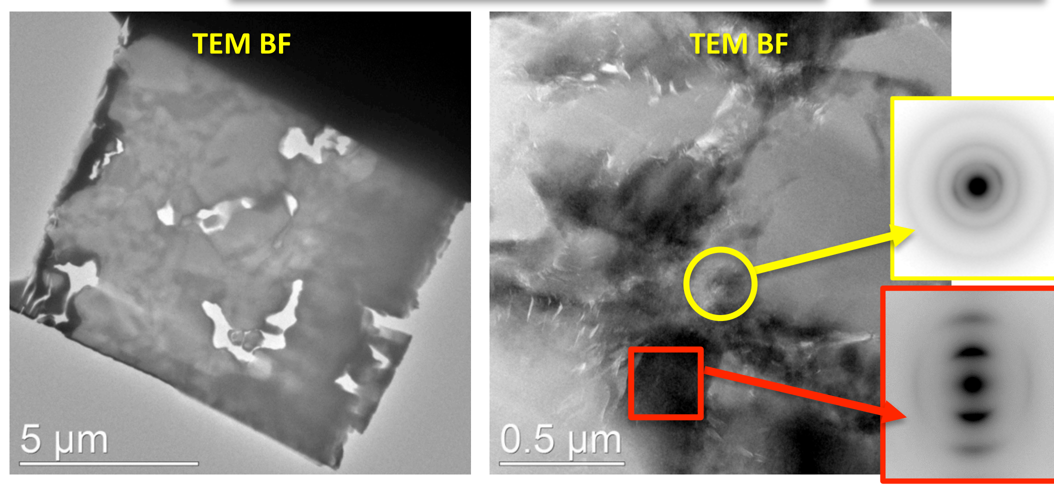




RaDIATE R&D Progress

- NuMI target (NT-02) autopsy and graphite PIE [9] (FNAL, PNNL)
  - Graphite fins saw 8E21 p/cm^2 fluence
- Evidence of Bulk Swelling
  - The micrometer measurements indicate swelling did occur
    - More swelling is associated with US fin locations
    - More swelling is associated with the fractured fins
  - Absence or low occurrence rate of Mrozowski cracks
- Evidence of fracture during operation
  - Symmetric fracture structure
  - Limited impurity transport into whole fins relative to fractured fins
- Evidence of limited radiation damage and material evolution
  - Surface discoloration appears to be mostly solder and flux material
  - Crystal structure & porosity consistent with as-fabricated conditions





- Taken from fracture surface at the center where the beam was targeted
- Lamella has mixed regions of what appear to be amorphous (yellow insert diffraction pattern) and nanocrystalline microstructure (red circle)
- Mrozowski cracks at the interfaces between these two regions

RaDIATE R&D Progress

New directions and techniques

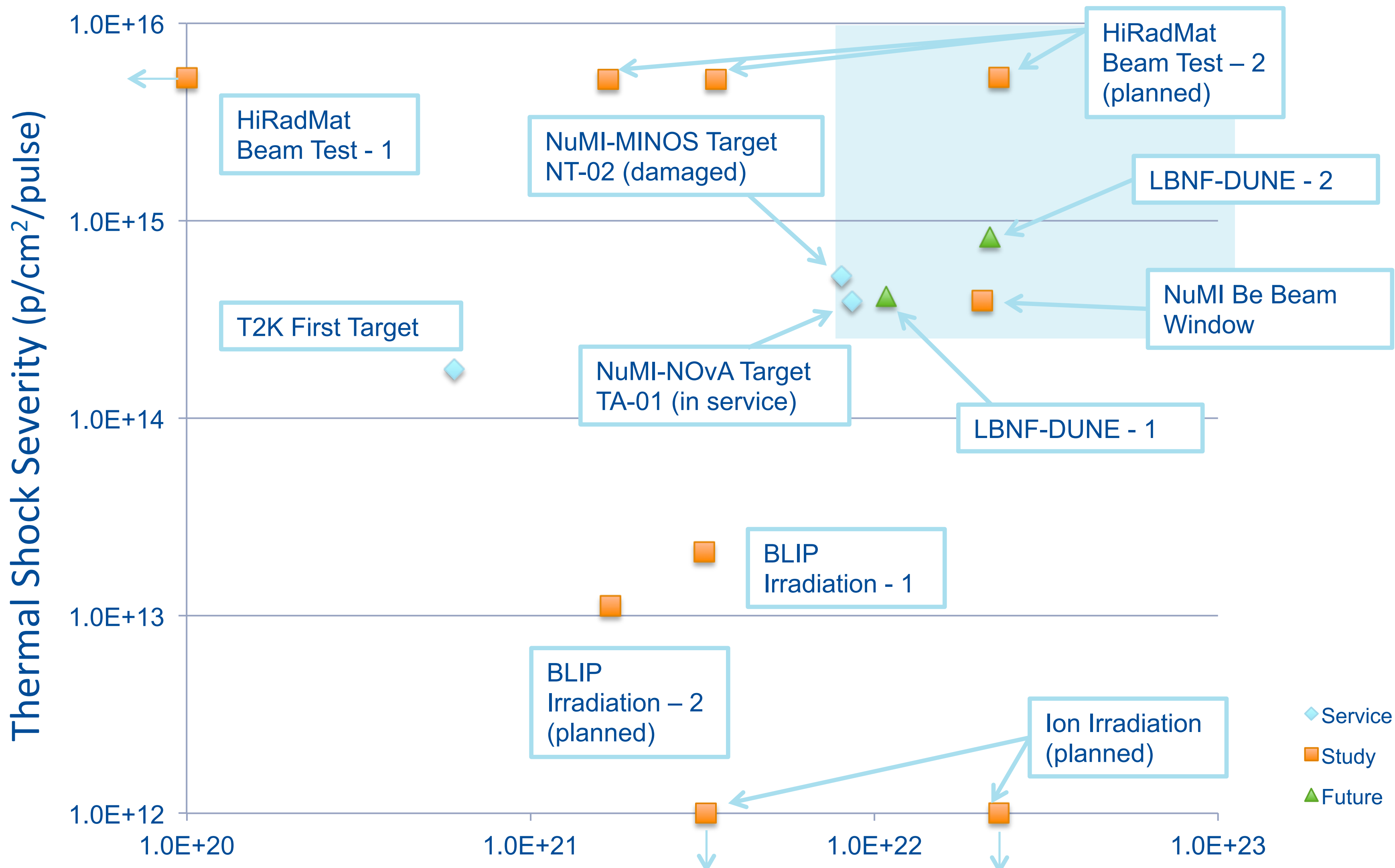
- High frequency meso-scale fatigue testing (20 kHz, 100 um foil) (Wilkenson/Gong, Oxford)

Unpublished results figures removed

Other planned work

- Graphite
  - 2016 Low E ion irradiation studies (Notre Dame?)
  - 2017 – Micro-mechanics (Liu @ Oxford?)
  - 2017? - NOvA TA-01 target autopsy/PIE (PNNL)
- Beryllium
  - 2016-17 – Recovery of NuMI NT-02 target window & PIE (Kuksenko @ Oxford?)
  - 2016-17 – Irradiation of Be fins in NOvA TA-02 target with PIE in 2018-19?
- Titanium 6Al-4V
  - 2018 - Macro-fatigue testing of BLIP specimens (BNL?)
  - 2018 - Meso-fatigue testing of BLIP specimens (20 kHz) (Oxford, Culham?)

Nu HPT R&D Materials Exploratory Map



Radiation Damage Severity
(damage equivalent fluence, p/cm^2)

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Summary

- ***The RaDIATE Collaboration has been active for ~3 years and is starting to produce results benefitting primarily High Energy Physics targetry global community (KEK, Fermilab, CERN)***
- ***Current and planned activities will also now directly benefit the Nuclear Physics and Spallation Source communities (FRIB, ESS, CERN) and potentially indirectly benefit others (SNS, MLF)***
- ***Radiation damage and thermal shock are highest priority***
  - Fundamental limits of solid materials
  - Mechanisms and conditions unique to accelerator target facilities
  - Sustained effort with multiple approaches
- ***The IWSMT workshop series has already built a solid and active materials science global community to address radiation damage, in the context of spallation sources, for over more than 2 decades***
  - ***The RaDIATE collaboration needs to more fully leverage this existing community for the benefit of all accelerator target facilities in the future***

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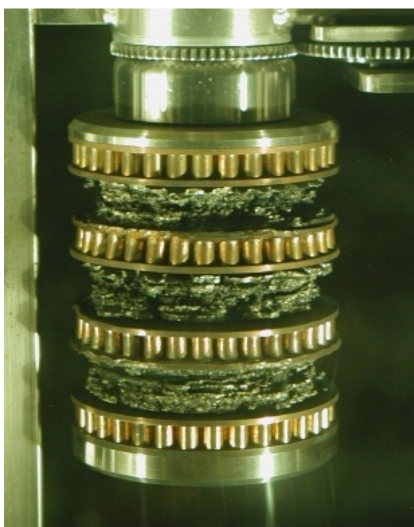
- [7] Dannemann, K. et al., “Johnson-Cook Strength Model Characterization of Beryllium S200FH”, internal FNAL report**, 2016.
- [8] Johnson, G.R and Cook, W.H., “A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures”, International Symposium on Ballistics, 7., p. 541 – 547, 1983.
- [9] Senor, D. et al., “Preliminary Results from Post-Irradiation Examination of Graphite from the NuMI NT-02 Target”, presentation of the 6th High Power Targetry Workshop*, Oxford, 2016.

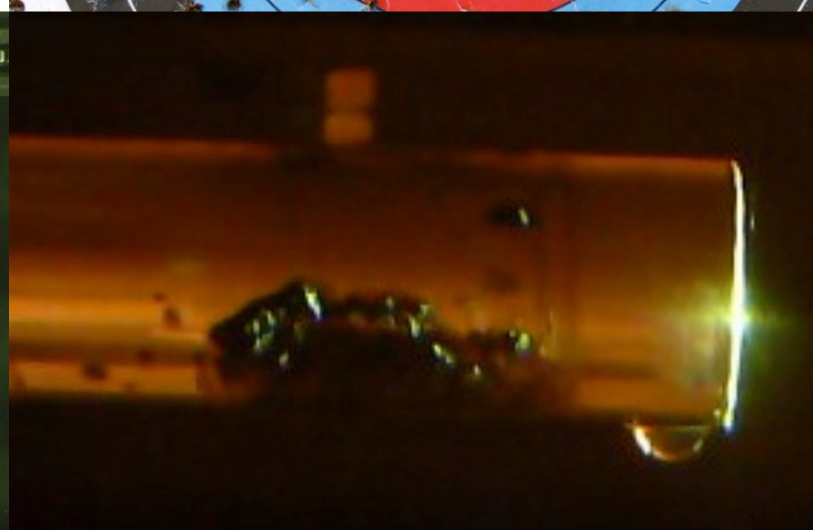
*Presentations from the 6th High Power Targetry Workshop can be found at:
https://eventbooking.stfc.ac.uk/news-events/6th-high-power-targetry-workshop-309?agenda=1

**Contact hurh@fnal.gov for access to internal reports

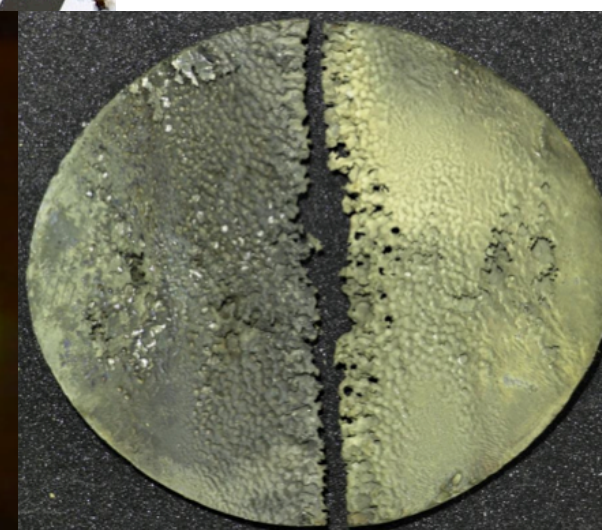
High Power Targetry Extra Motivation!



P-bar source, FNAL



NuMI-MINOS LE Target, FNAL



SNS Hg Target Vessel, ORNL

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