FERMILAB-SLIDES-20-116-AD

Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Behind the High Power Targetry R&D at Fermilab

Frederique Pellemoine

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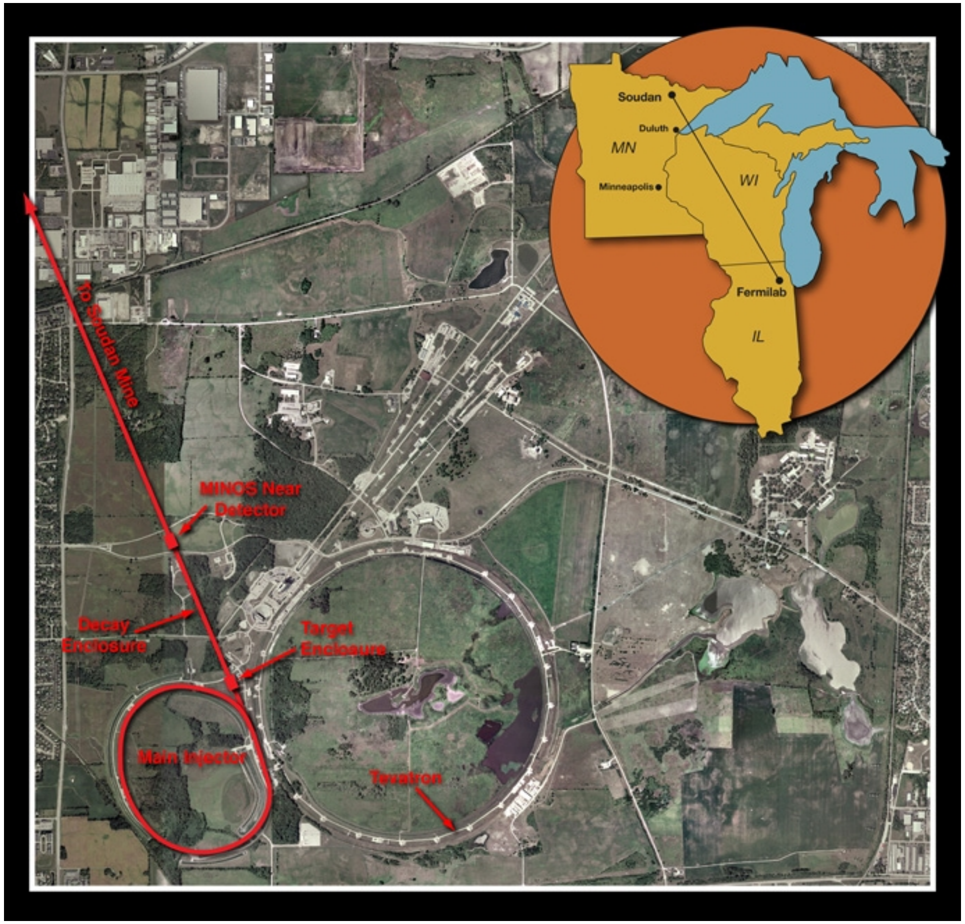
Outline

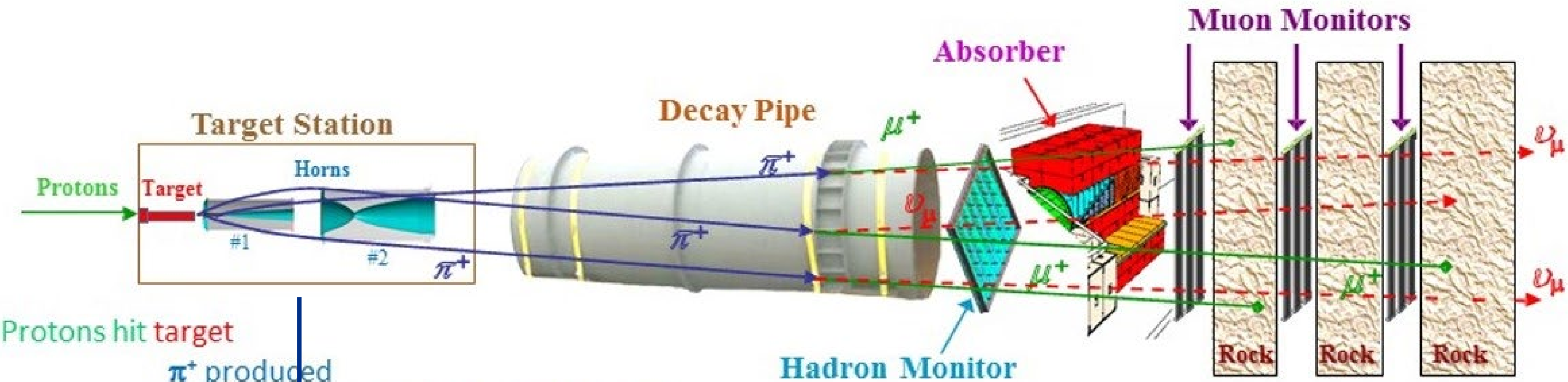
- Neutrino production at Fermilab
- Recently major accelerator facilities have been limited in beam power not by their accelerators, but by their target facilities
  - Current high power, high intensity targets in use at Fermilab
  - Plans for future high power, high intensity target facilities
- High Power Targetry Challenges
- How we must address these challenges
- Examples of current studies
- Investigate some alternatives

NuMI Facility - Making Neutrino Beam at Fermilab

- Scientists at Fermilab create a muon neutrino beam by slamming protons from the main injector accelerator into a graphite target. Several experiments (MINOS, NOvA, MINERvA) at the laboratory count on the high-intensity beam of neutrinos to unravel the mysterious properties of these ghost-like particles and their role in the evolution of the Universe



The NuMI Beam “Neutrinos at the Main Injector”



Protons hit target

π^+ produced

magnetic horn to focus π^+

π^+ decay to $\mu^+ \nu$ in long evacuated pipe

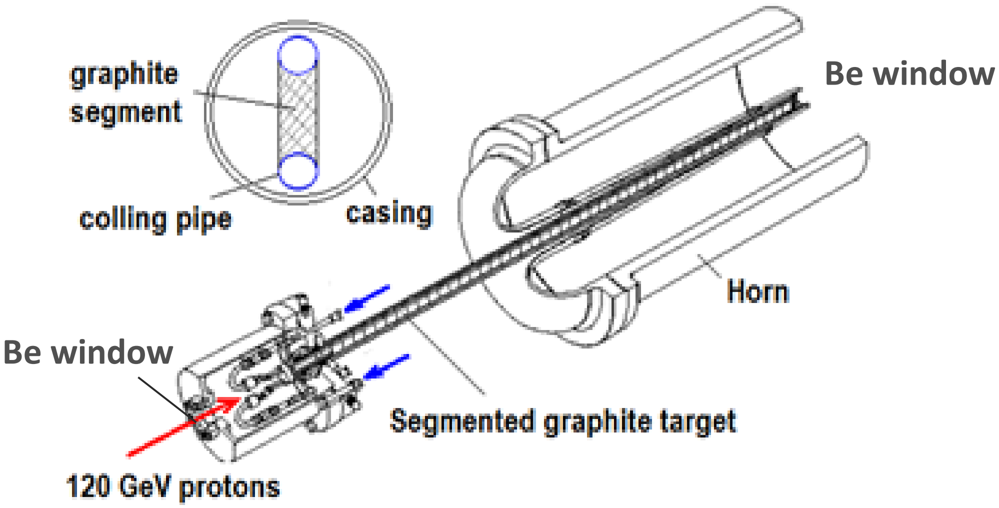
left-over hadrons shower in hadron absorber

rock shield ranges out μ^+

ν beam travels through earth to experiment

- Current high power, high intensity targetry in use at Fermilab
  - NuMI-MINOS target
  - NuMI-NOvA target
  - Beryllium Beam Window

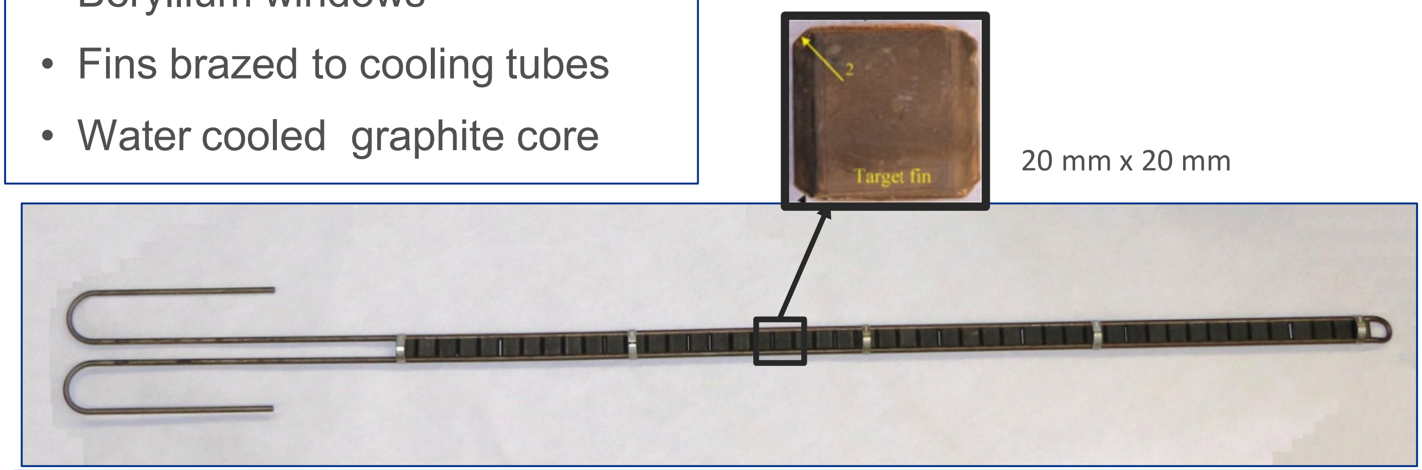
The MINOS Target



	MINOS
Graphite fins	47 x 20 mm x 6.6 mm
Beam energy [GeV]	120
p/pulse	3.37E+13
Power [kW]	340
σ [mm]	1.1
Peak Temp. [°C]	330
QS Temp [°C]	60
POT	6.55E+20
Peak dpa	0.63
Peak He [appm]	2270

- Helium atmosphere
- Beryllium windows
- Fins brazed to cooling tubes
- Water cooled graphite core

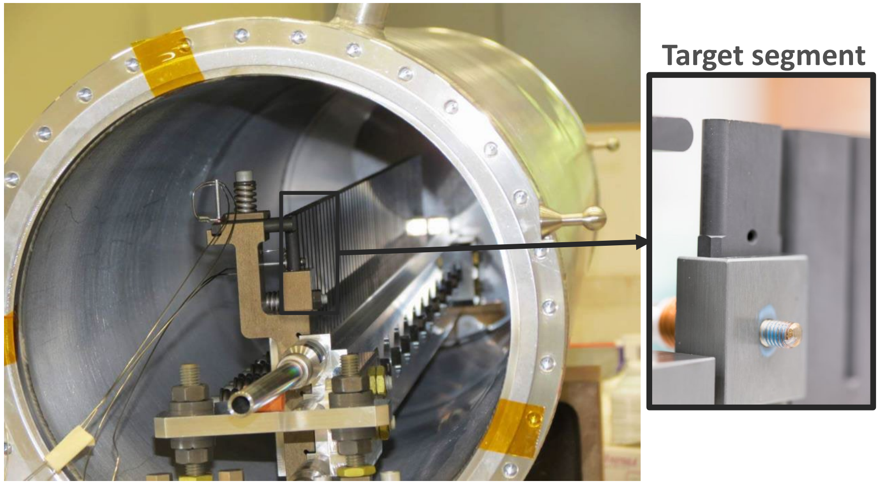
Target segment



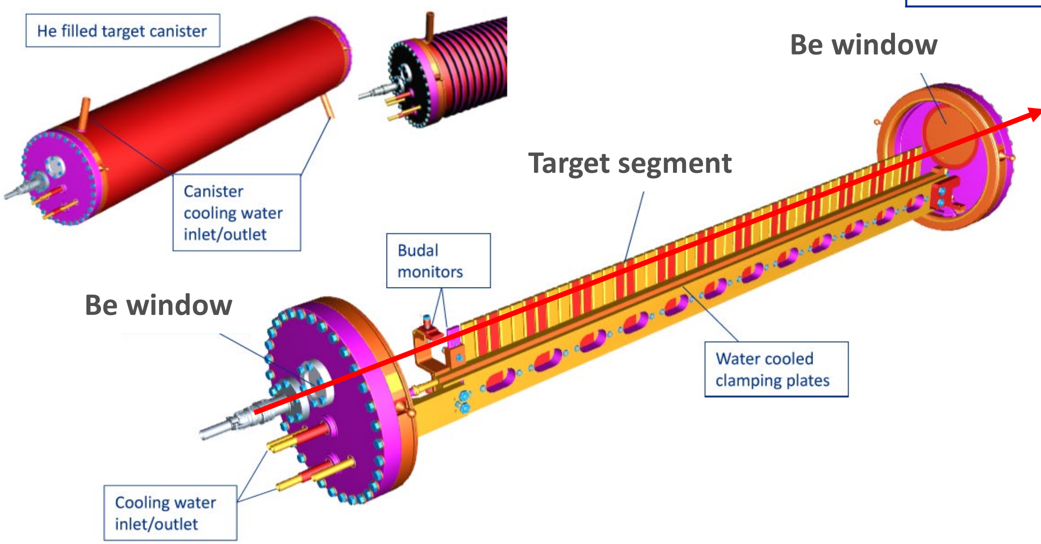
20 mm x 20 mm

Fermilab

The NOvA Target



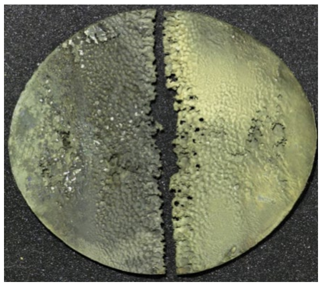
	NoVA	AIP
Graphite fins	50 x 24 mm x 7.4 mm	50 x 24 mm x 9 mm
Beam energy [GeV]	120	120
p/pulse	4.90E+13	6.50E+13
Power [kW]	700	1000
σ [mm]	1.3	1.5
Peak Temp. [°C]	670	1000
QS Temp [°C]	390	890
POT	1.10E+21	1.28E+21
Peak dpa	1.10	0.96
Peak He [appm]	5580	3600



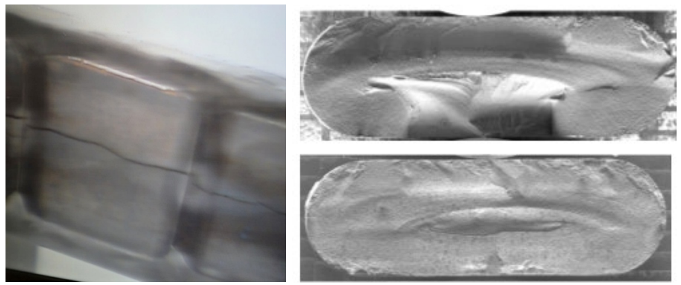
- Helium atmosphere
- Beryllium windows
- Water cooled aluminum pressing plates
- Fins not brazed to cooling tubes
- Water cooled outer vessel

High Power Targetry Challenges

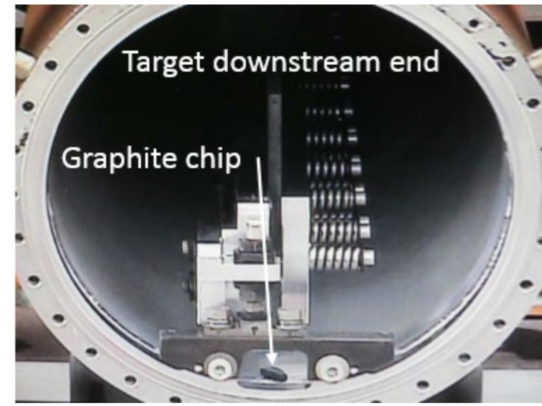
Recently major accelerator facilities have been limited in beam power not by their accelerators, but by their target facilities (SNS, CERN, MINOS-NOvA)



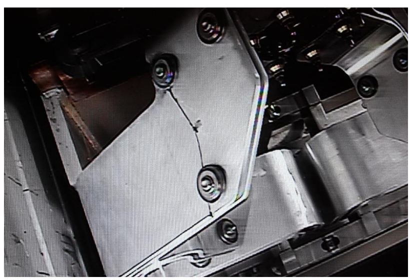
SNS-cavitation



Fermilab-bulk swelling suggested crack initiated

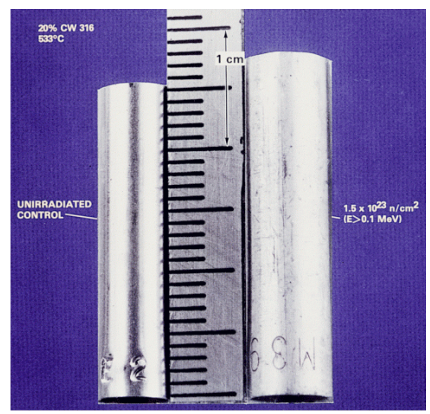


Fermilab-NOvA target autopsy

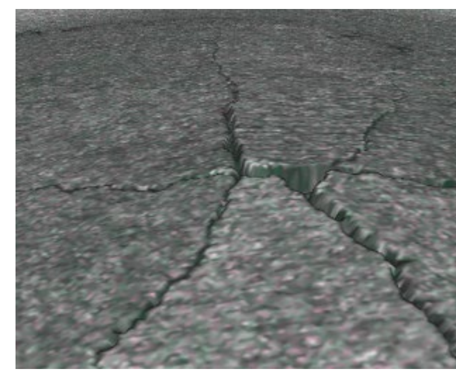


Fermilab-fatigue

Fermilab-water leak



Swelling – JNM 159 (1988) p.114



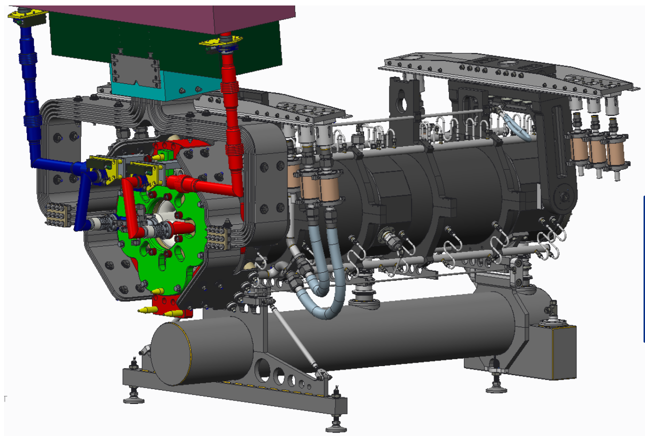
Fermilab- H embrittlement

CERN-HiRadMat – thermal shock

Challenges for the future – LBNF-DUNE

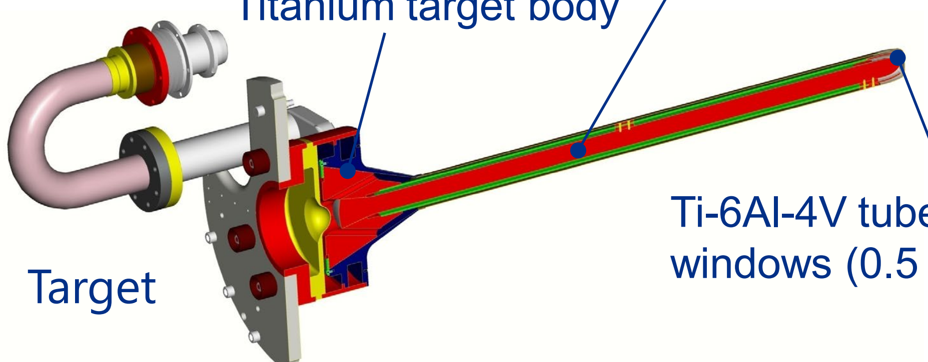
- Plans for future high power, high intensity target facilities will present even greater challenges

	DUNE
Graphite fins	TBD
Beam energy [GeV]	60-120
p/pulse	7.50E+13
Power [kW]	1200-2400
σ [mm]	2.67
Peak Temp. [°C]	TBD
QS Temp [°C]	TBD
POT	2.54E+21
Peak dpa	0.73
Peak He [appm]	400



Horn

- Helium atmosphere
- Ti-6AL-4V windows



Fermilab

Challenge: Targets / beam intercepting devices

- Optimal target:
  - Low-Z to optimize pion production (minimize energy deposition in devices)
  - High density to stay within depth of focus
  - Roughly two nuclear interaction lengths long
  - The optimized width to allow a certain amount of reinteraction, but limit absorption
- But, the target must survive for a non-negligible duration
  - Material must withstand thermomechanical shock
  - Material must withstand radiation damage
  - Heat must be removed
    - Supporting materials (e.g. water & pipes) must be far enough from the beam to avoid boiling
- Above contradictions drive us to graphite, beryllium and Ti-alloys
  - Water cooling is the baseline, but air is not out of the question
  - **R&D** has a substantial capability to improve the efficiency of neutrino and muon production

Challenge: Targets / be

- Optimal target:
  - Low-Z to optimize pion pro
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RaDIATE

Subjects of the RaDIATE Collaboration

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

- Fermilab is the collaboration program coordinator since its inception in 2012
- 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**
- **14 international institutions**
- **More than 70 members**

http://radiate.fnal.gov

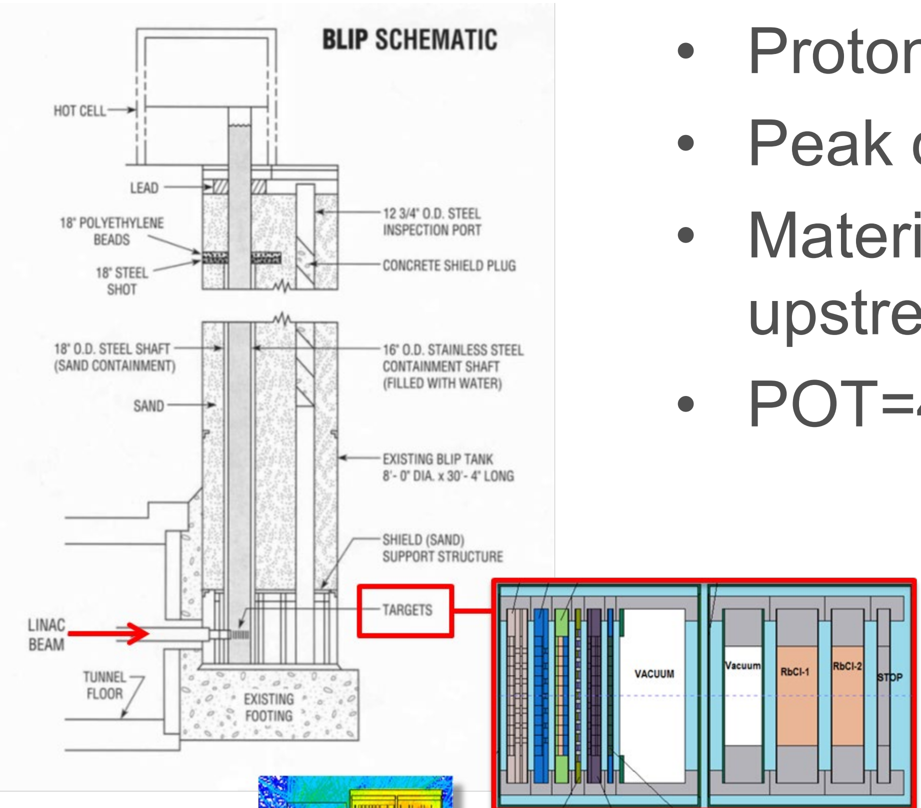
Fermilab
University of Oxford
Argonne National Laboratory
Science & Technology Facilities Council
Brookhaven National Laboratory
CERN
Pacific Northwest National Laboratory
Los Alamos National Laboratory EST. 1943
FRIB
European Spallation Source
Oak Ridge National Laboratory
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

High Power Targetry: Materials R&D – Radiation damage and thermal shock

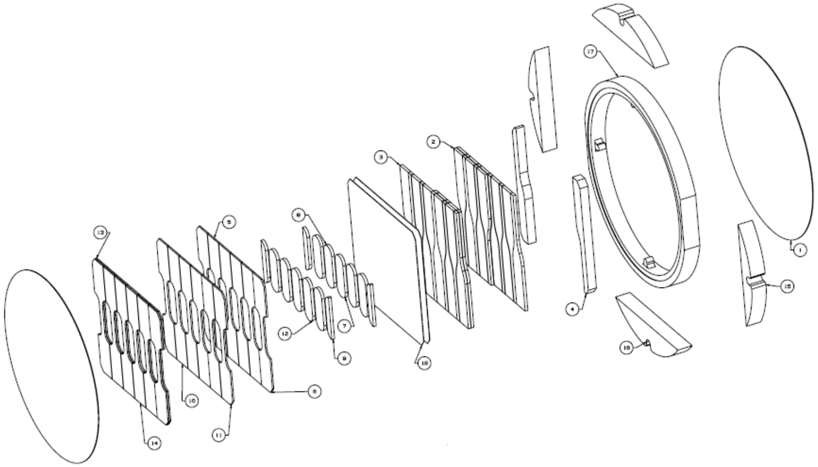
Multi-MW Neutrino Targets & Beam Windows Materials:

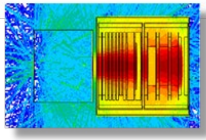
- Graphite (target core material) studies:
  - Swelling/fracture studies
  - Preparing for HE proton irradiation at BNL-BLIP Facility to confirm elevated temperature annealing
- Beryllium (beam window material) studies:
  - Examination of BNL-BLIP irradiated Be specimens underway
  - Helium implantation studies show bubble formation at irradiation temperatures above 360 ˚C
- Titanium Alloys (beam window material) studies:
  - Examination of BLIP irradiated specimens underway
  - World first high cycle fatigue testing of irradiated titanium underway at FNAL

Radiation Damage - High Energy Proton Irradiation @ BNL's BLIP facility



- Proton energy up to 200 MeV
- Peak current 165 µA
- Materials irradiation in tandem and upstream of isotope targets
- POT=4.5E21, 1.52 dpa on Ti-alloy

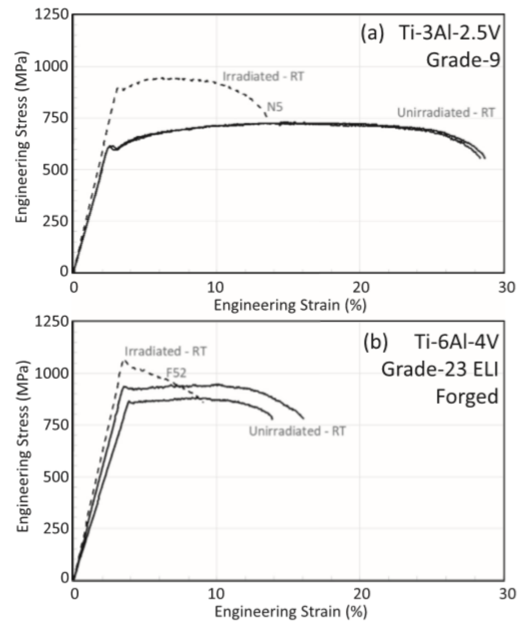




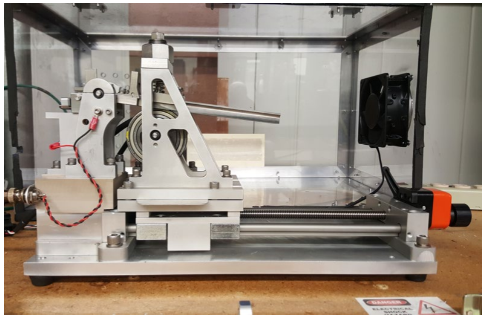
BROOKHAVEN NATIONAL LABORATORY

Radiation Damage - High Energy Proton Irradiation @ BNL's BLIP facility completed on March 2018

- Over 200 specimens including graphite, Be, Ti-alloys, Si, TZM, Al, Ir
- Post Irradiation Examination (PIE) on going
  - Significant hardening at low dose in Be and Ti
  - First ever fatigue study on irradiated Ti alloys (test complete, analysis ongoing)
    - Indicates about 10% reduction in fatigue strength
  - Microstructural examinations underway



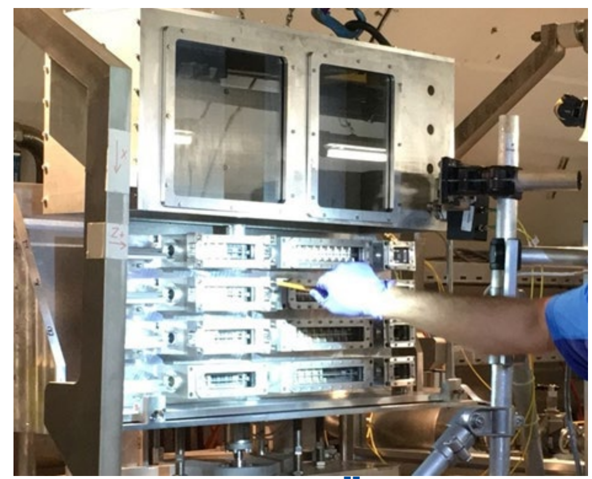
T. Ishida, E. Wakai and S. Makimura et al., JNM 541 (2020) 152413



Thermal Shock Response – HiRadMat facility (CERN)

- Rapid 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
- Heavy dependence upon material properties, but: Material properties dependent upon Radiation Damage…
- 2 campaigns at HiRadMat Facility (CERN)
  - High Radiation to Materials (HiRadMat) facility at CERN for material testing
  - Testing facility for single shots experiments

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



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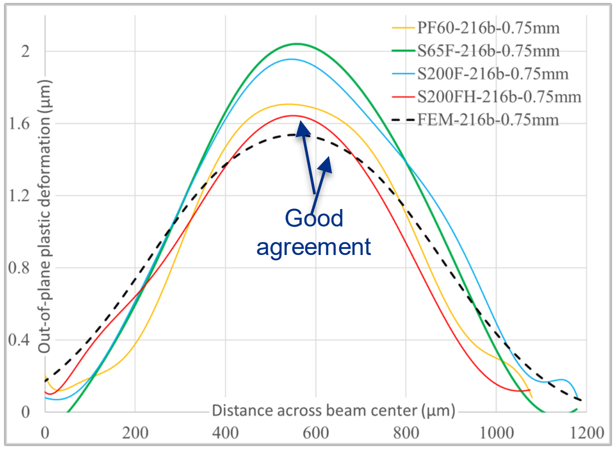
Thermal Shock Response – HiRadMat facility (CERN) – 2015 and 2018, next planned in 2022

- 100 specimens Including graphite, Be, Si-coated graphite, Ti-alloys, Si, novel materials
- Analysis ongoing
  - thermal shock response of various grades of beryllium, as well as the successful validation of S200FH Johnson-Cook strength model
  - Direct comparison of thermal shock response between irradiated and non-irradiated materials
  - Evaluate novel materials and their suitability as target materials
  - Beryllium response to even higher pulse intensities
- Next experiment will include graphite (irradiated and un-irradiated), Ti-alloys (irradiated and un-irradiated), novel materials

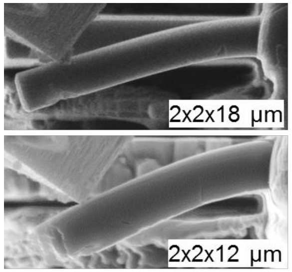


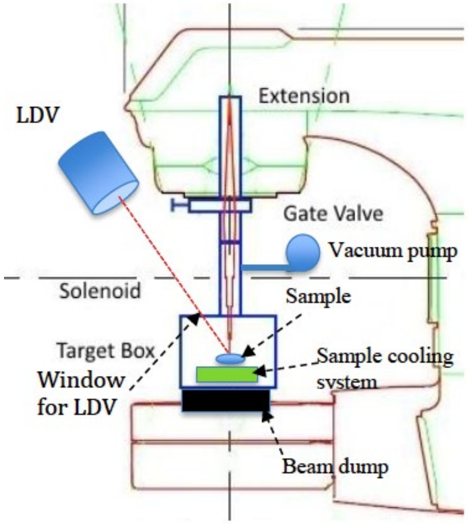
S. Bidhar, FNAL

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

Alternative to High Energy Proton Beam

- High energy proton irradiation
  - Highly activated material
  - Low dpa rate
  - Expensive
- Alternative radiation damage method
  - Low-energy ion irradiation
    - Lower cost, high dose rate without activating the specimen
    - Narrow penetration depth
      - Micro-mechanics and meso-scale testing
    - Doesn’t reproduce the gas (H and He) production
      - He implantation in Graphite at Michigan Ion Beam Lab
- Alternative thermal shock method
  - Use of electron beams, lasers, or other techniques could reduce the cost and length of R&D cycles compared to proton beam-line tests
- Ab initio and MD modeling could help guide the development of alternative techniques
  - e.g. understanding the differences between radiation damage effects from HE protons vs. LE ions

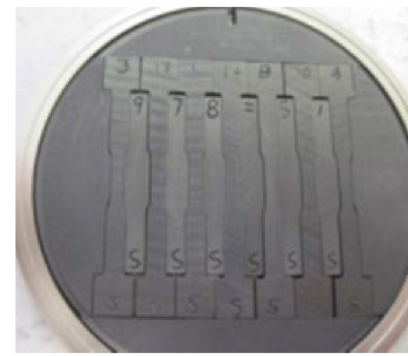




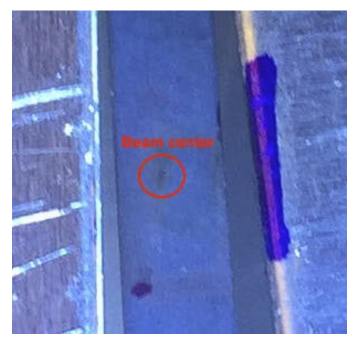
Significant University Involvement in HPT R&D

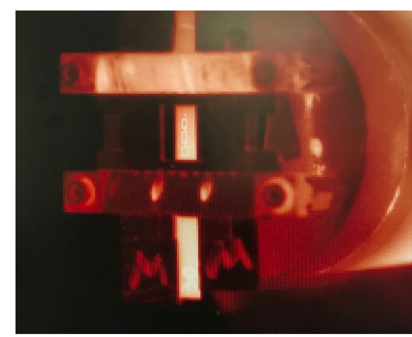
- High Dose Ion Irradiation of Graphite
  - Abraham Burleigh (PhD student, **IIT**) under Prof. J. Terry
- Characterization of Graphite by Raman Spectroscopy and Nano-tomography
  - Ming (Eric) Jiang (PhD student, **Bristol**) under Dr. D. Liu
- Modeling of He bubble Nucleation and Growth in irradiated Beryllium
  - Jianqi Xi (Post-Doc, **UW**) under Prof. I. Szlufarska
- Replicating proton beam interaction damage with little or no residual activity. Use of electron beam
  - Gurkan Karaman (PhD student, **University of Iowa**) under Prof. Y. Onel

High Dose Ion Irradiation of Graphite – A. Burleigh - IIT

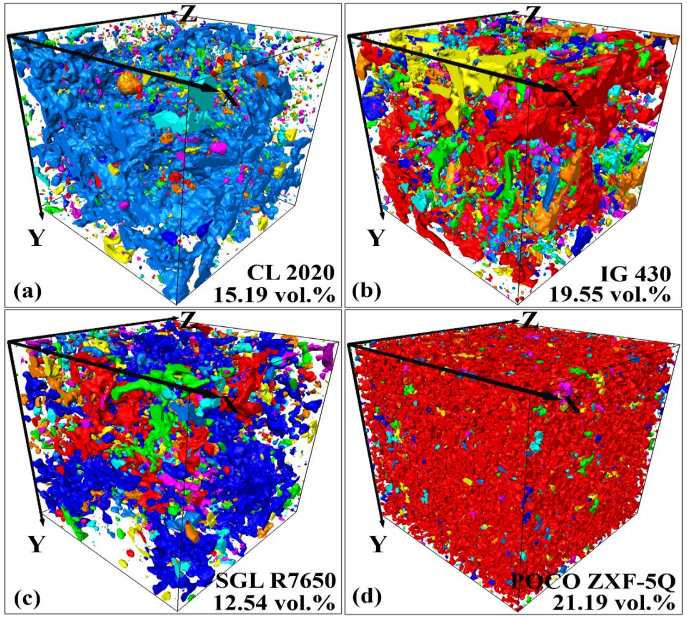


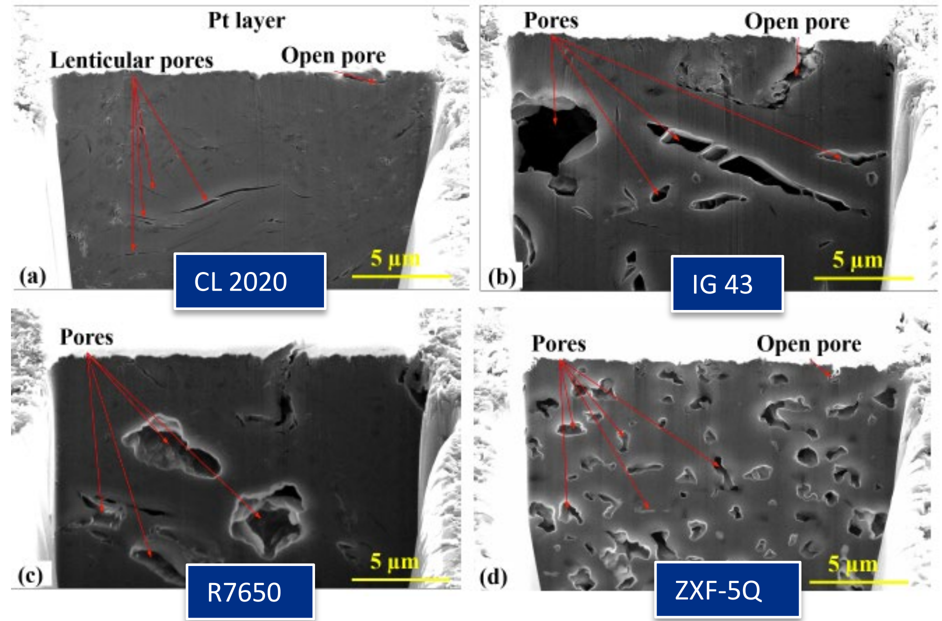
- High energy proton irradiation presents many difficulties: sample activation, high costs, long irradiation times, rigorous planning and sample preparation
- Low-energy ion irradiations suggest a method of testing new beam designs without the costly and time-consuming high-energy irradiations commonly undertaken while also allowing for faster experiment iteration without sample activation
- Comparison between graphite targets irradiated during
  - NUMI/NoVA and MINOS operation (high energy proton)
  - High energy proton irradiation at BLIP
  - Low energy heavy ion irradiation at Michigan Ion Beam Lab (UoM)





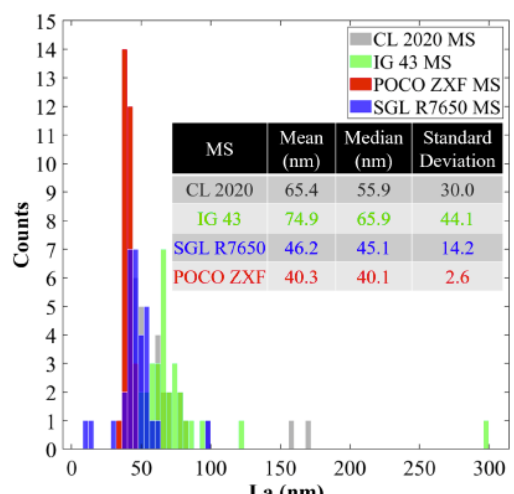
Graphite Characterization - Eric Jiang – Bristol-UK



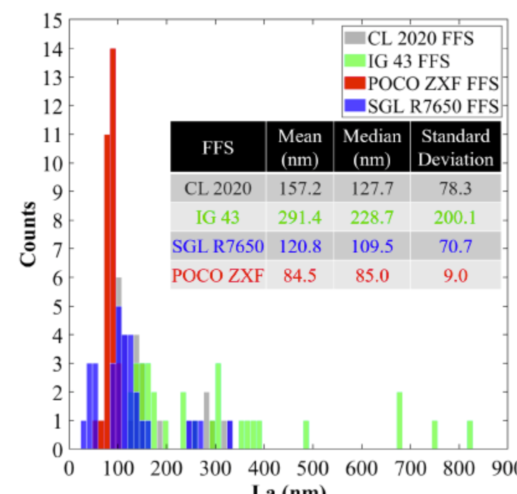


CT scans, FIB Nano-tomography, and Raman Analysis show:

- Highest degree of porosity (open): POCO ZXF-5Q
- Smallest and most uniform crystallite size: POCO ZXF-5Q
- Largest and most non-uniform crystallite size: Toyo-Tanso IG 43



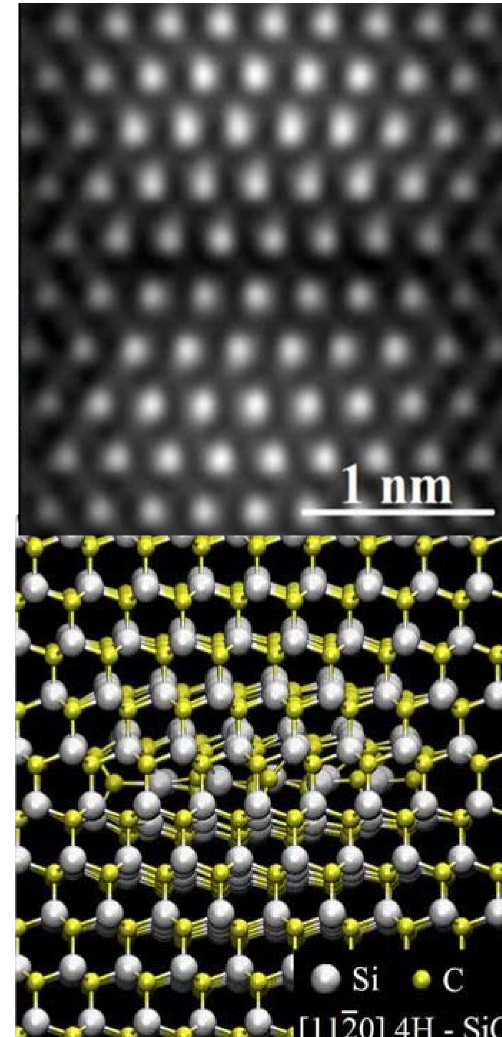
MS	Mean (nm)	Median (nm)	Standard Deviation
CL 2020	65.4	55.9	30.0
IG 43	74.9	65.9	44.1
SGL R7650	46.2	45.1	14.2
POCO ZXF	40.3	40.1	2.6



FFS	Mean (nm)	Median (nm)	Standard Deviation
CL 2020	157.2	127.7	78.3
IG 43	291.4	228.7	200.1
SGL R7650	120.8	109.5	70.7
POCO ZXF	84.5	85.0	9.0

Ab Initio and Molecular Dynamics Material Modeling - Jianqi Xi – U of Wisconsin

- Ab initio and molecular dynamics (MD) modeling are still not yet mature enough to model atomistic changes to micro-structural evolution to macro-properties of real-world materials. However:
- Prediction of fundamental response of various material classes to irradiation helps steer material choices and experiment design for future irradiation studies
- Collaboration with Computation Materials Group at University of Wisconsin
  - Modeling of He gas bubbles in Beryllium with University of Wisconsin
  - (research associate), Prof. Izabela Szlufarska and Prof. Dane Morgan
  - Specializes in atomic scale modeling to understand and design new materials
  - Experience in radiation damage

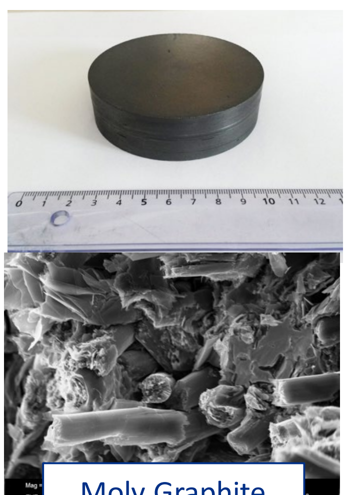


Computational Materials Group
Department of Materials Science and Engineering

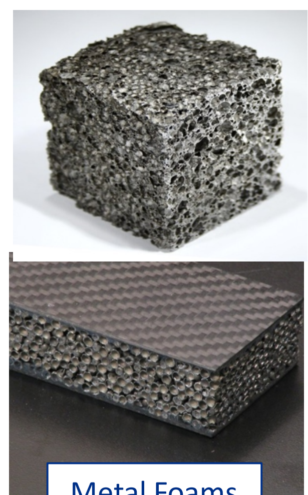
Development of New Targetry Materials

- An ultimate objective is to develop new materials specifically addressing the requirements of future target facilities. Some progress is being made in exploring some of the newer materials and forms of material that have been developed.
  - Glassy carbon (BeGrid2 material, CERN/FNAL)
  - Molybdenum graphite (RaDIATE BLIP run material, CERN)
  - Metal foams (BeGrid2 material, FNAL)
  - 3-D Printed Ti alloy (RaDIATE BLIP run material, FRIB)
  - Nano-fiber mats (BeGrid2 material, FNAL LDRD)
  - High Entropy Alloys (collaboration with University of Wisconsin-Madison)

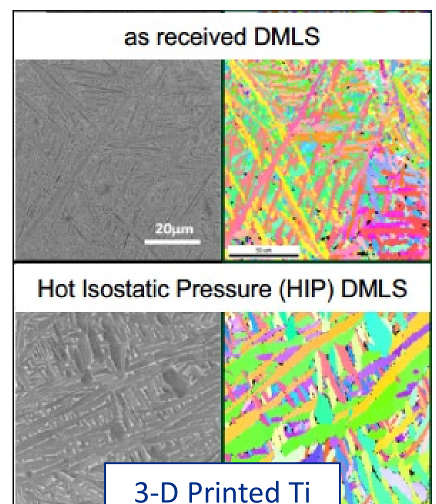
Glassy Carbon



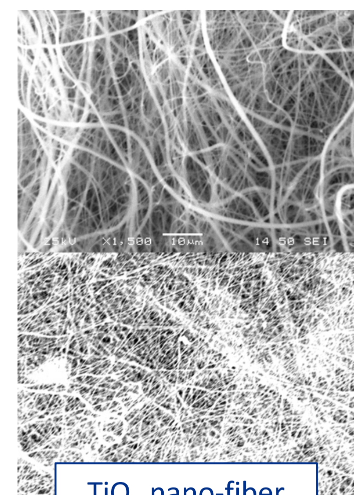
Moly Graphite



Metal Foams



3-D Printed Ti



TiO_2 nano-fiber

RaDIATE / HPT R&D Future Plans

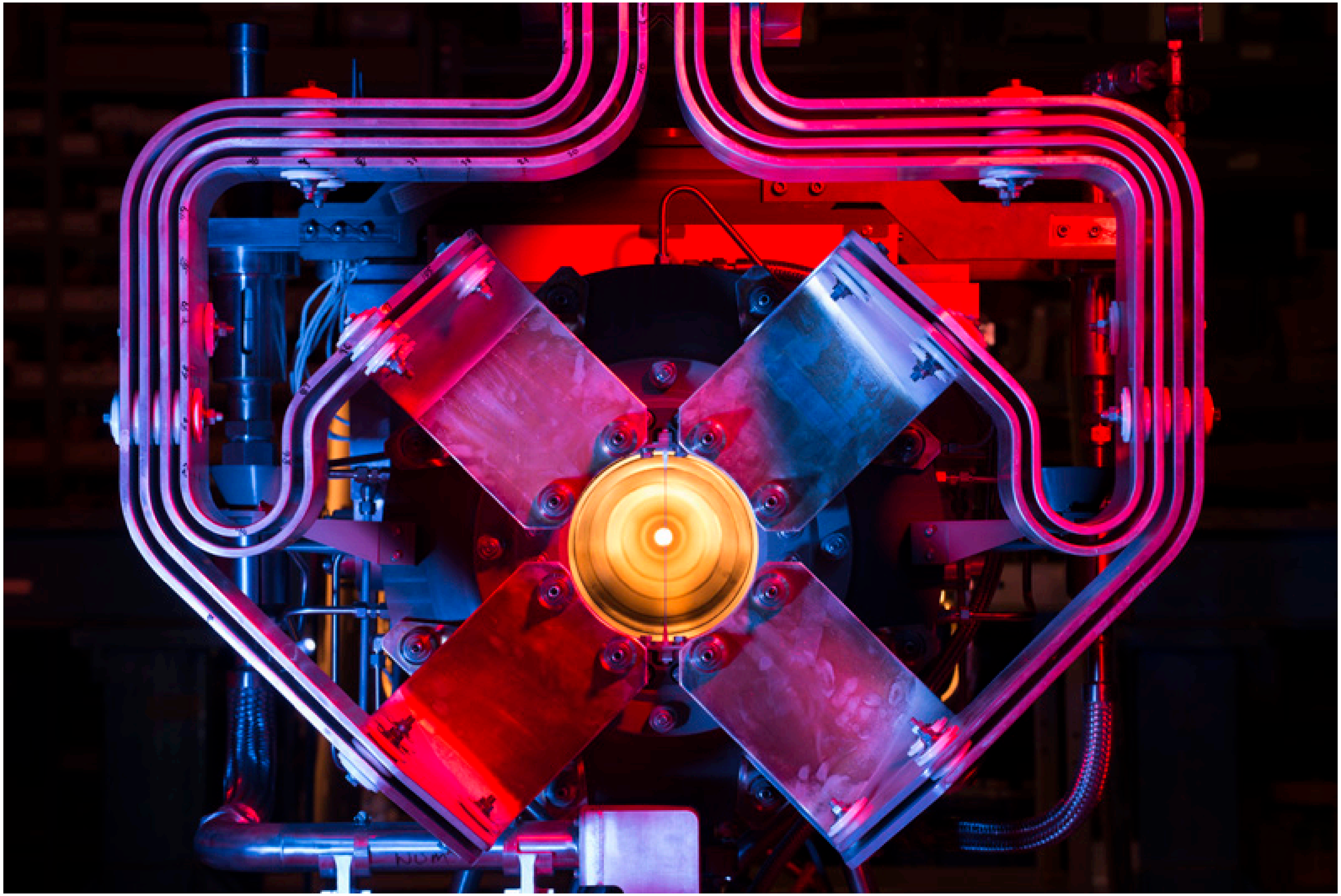
- Continue with PIE of BLIP and HiRadMat irradiated materials
  - Micro-structural evaluation , Mechanical testing , Synch light studies, Micro-mechanics, Fatigue testing of Ti alloys
- Continue to develop alternative methods
  - Heavy ion irradiation, electron beam, modeling
- Plan new HE-proton irradiations
  - BLIP or alternative proton facility
- Continue to investigate new material to support high power Targetry
- Continue collaborate with University Materials groups
  - Illinois Institute of Technology (J. Terry, nuclear materials)
  - UW-Madison (I. Szlufarska, nano-scale modeling, HEA)
  - University of Iowa (Prof. Y. Onel, electron beam)
  - Bristol University (D. Liu, graphite characterization)

Acknowledgements

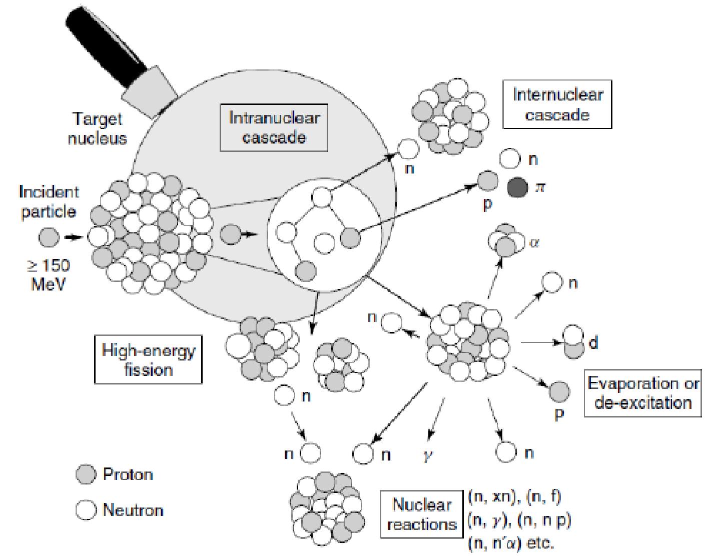
K. Ammigan[1], K. Anderson[1], S. Bidhar[1], R. Campos[1], M. Geelhoed[1], P. Hurh[1], G. Lolov[1], A. Miller[1], N. Mokhov[1], T. Spina[1], G. Waver[1], K. Yonehara[1], R. Zwaska[1], M. Calviani[2], R. Losito[2], C. Torregrosa[2], R. Seidenbinder[2], K. Kershaw[2], F. Harden[2], Y. Kadi[2], A. Bouvard[2], C. Saury[2], M. Butcher[2], V. Kuksenko[3], D. Senor[4], A. Casella[4], C. Densham[5], A. Atherton[5], G. Burton[5], O. Caretta[5], T. Davenne[5], P. Loveridge[5], J. O'Dell[5], M. Fitton[5], T. Ishida[6], S. Makimura[6], E. Wakai[6], S. Roberts[7], E. Jiang[8], D. Liu[8], A. Couet[9], D. Morgan[9], I. Szlufarska[9], J. Xi[9], G. Kamaran[10], Y. Onel[10], A. Burleigh[11], J. Terry[11],D. Kim[12], N. Simos[12]

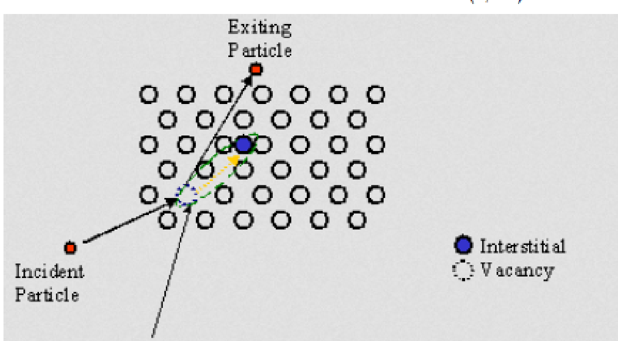
[1]Fermi National Accelerator Laboratory (FNAL), [2]European Organization for Nuclear Research (CERN), [3]Culham Center for Fusion Energy (CCFE), [4]Pacific Northwest National Laboratory (PNNL), [5]STFC Rutherford Appleton Laboratory (RAL), [6]High Energy Accelerator Research Organization (KEK), [7]University of Oxford , [8] Bristol University, [9] University of Wisconsin-Madison, [10] University of Iowa, [11] Illinois Institute of Technology, [12] Brookhaven National Laboratory (BNL)

Thank you for your attention



Radiation Damage Disorders Microstructure





A Frenkel pair consists of a vacancy and an interstitial atom.

Microstructural response:

- *creation of transmutation products;*
- *atomic displacements (cascades)*
  - *average number of stable interstitial/vacancy pairs created = DPA (Displacements Per Atom)*
- *Gas production (hydrogen / helium)*