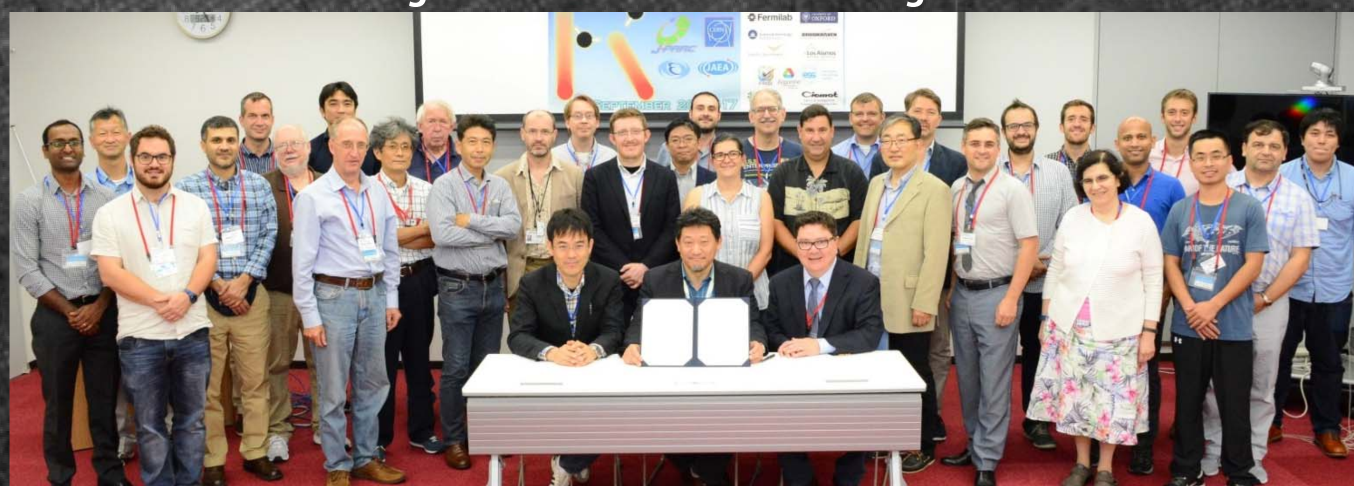
Recent Progress on Radiation Damage Studies at RaDIATE

Taku Ishida (J-PARC / KEK)
Patrick G.Hurh, Kavin Ammigan (FNAL)
on behalf of
RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments



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3. Thermal Shock Study at HiRadMat Facility
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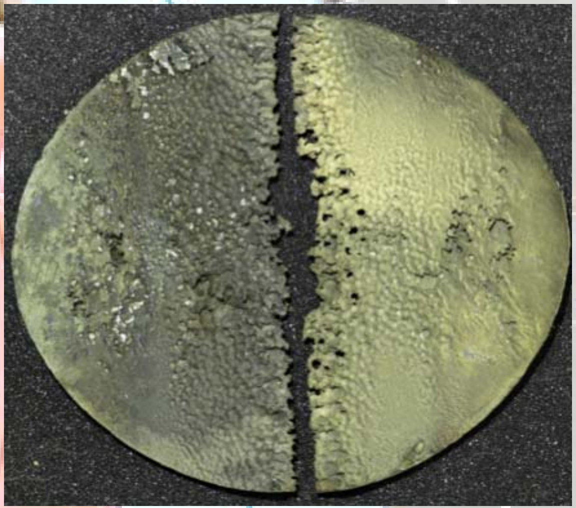
1. Introduction to RaDIATE collaboration

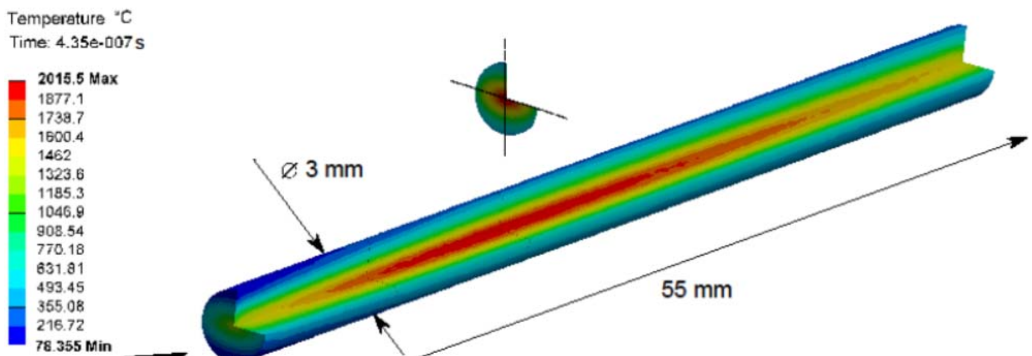
- Recent major accelerator facilities have been limited in beam power & operation time by target and window survivability



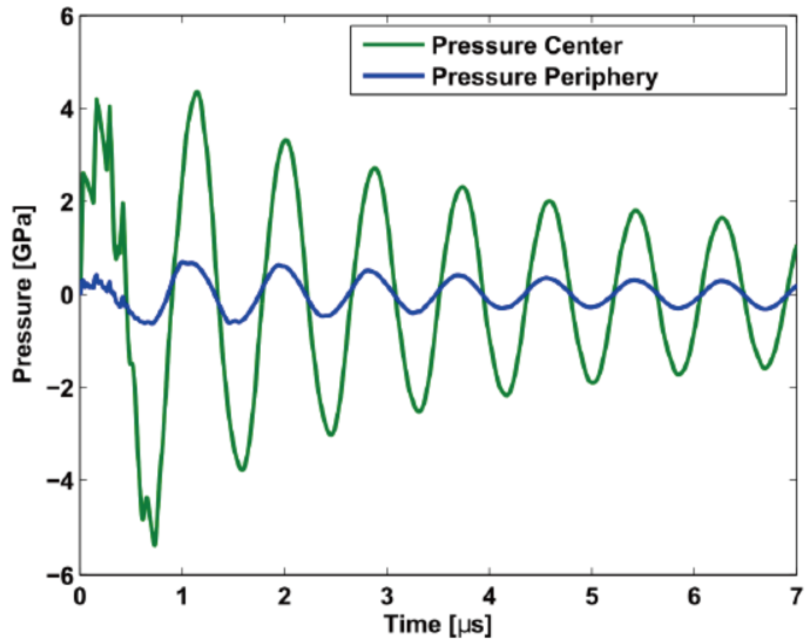


- Plans for future high power, high intensity target facilities will present even greater challenges
- To maximize the benefit of high power accelerators, these challenges must be addressed in time to provide critical input to multi-MW target facility design, construction and operation (LBNF/DUNE, J-PARC/Hyper-Kamiokande, ESS, MLF-2nd TS…)

Thermal Shock / Stress Waves



Simulation assumed tungsten as CERN-AD target material



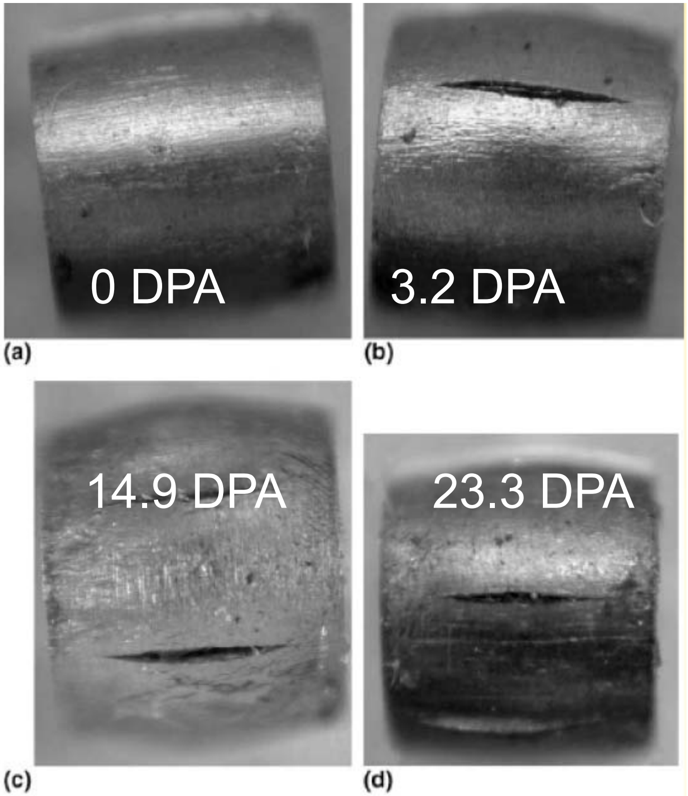
Iridium rod in HRMT27 exploded with single shot 1.27 x10^{12} ppp

C. Torregrosa et al. CERN-EN-2016-004

- **Fast expansion of material surrounded by cooler material creates a sudden local area of compressive stress**
- **Stress waves move through the target**
- **Plastic deformation, cracking, and fatigue can occur**

Radiation Damage Effects

- **Displacements in crystal lattice, expressed as Displacements Per Atom (DPA)**
  - Embrittlement / Creep / Swelling
  - Fracture toughness reduction
  - Thermal/electrical conductivity reduction
  - Change of thermal expansion coefficient / modulus of elasticity
  - Fatigue response
  - Accelerated corrosion
  - Void formation/ embrittlement caused by Hydrogen/Helium gas production (expressed as atomic parts per million per DPA, appm/DPA)
- **Recent high-intensity proton target facilities meet irradiation with a few to several DPA**
  - Effects from low energy neutron irradiations (as fusion/fission reactor materials) do not equal effects from high energy proton irradiations

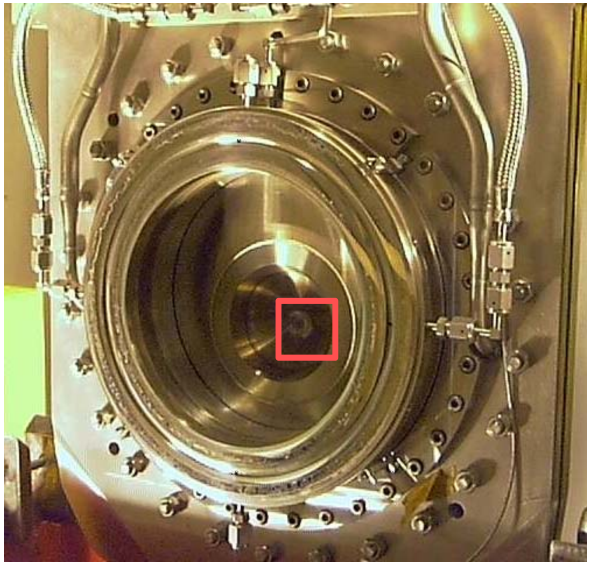


Tungsten, 800MeV proton irradiation at LANSE

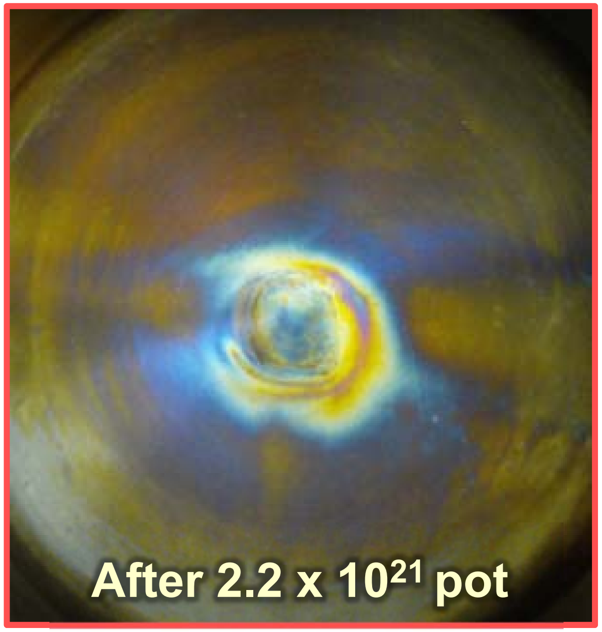
after compression to ~20% strain at room temperature

S. A. Maloy, et al., Journal of Nuclear Materials 343 (2005) 219-226.

Example: J-PARC Ti-6Al-4V Beam Window



- Periodic thermal stress wave caused by the intense proton beam energy deposition → C.J.Densham's talk
- 750kW operation will cause radiation damage of ~1DPA/ops-year, whereas significant irradiation hardening and loss of ductility has been reported with 0.1~0.3DPA (*no higher DPA data exists*)
- No known data exists on high cycle fatigue (>10^3 cycles) of irradiated titanium alloys



Beam Power	PPP	Rep. cycle	POT / 100 days
485kW (achieved)	2.5 x 10^{14}	2.48 sec	0.9 x 10^{21}
750kW (proposed)	2.0 x 10^{14}	1.3 sec	$\boxed{1.3 \times 10^{21}}$
750kW [original plan]	$\boxed{3.3 \times 10^{14}}$	2.1 sec	1.3 x 10^{21}
1.3 MW (proposed)	3.2 x 10^{14}	$\boxed{1.16 \text{ sec}}$	2.4 x 10^{21}

designed

～8M pulses/yr

～1DPA/yr

Motivation

- To replicate the High-Energy Physics target environment and provide bulk samples for analysis, high energy, high fluence and large volume proton irradiations are needed
- These runs, including Post-Irradiation Examination (PIE), are expensive and can take a very long time

To promote these studies, international and inter-facility cooperation are necessary

- ✓ Accurate targetry component lifetime prediction
- ✓ Design robust multi-MW targetry components
- ✓ Develop new materials to extend lifetimes

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

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

- Founded in 2012 by 5 institutions led by FNAL and STFC to bring together the HEP/BES accelerator target and nuclear fusion/fission materials communities

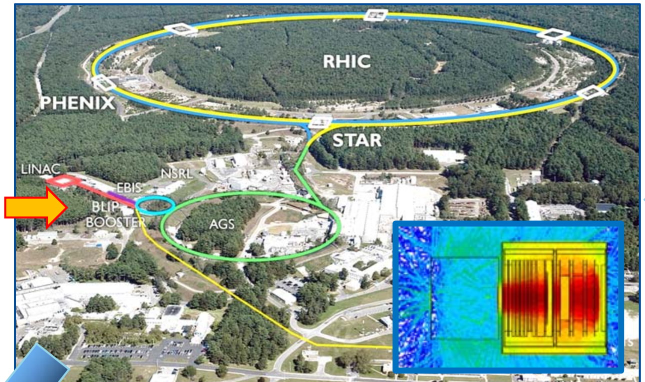
http://radiate.fnal.gov

In 2017, 2nd MoU revision has counted J-PARC (KEK+JAEA) & CERN as official participants
Collaboration has now grown to
13(14) Institutions, 70 members
Program manager: Patrick G.Hurh(FNAL)

RaDIATE Program Overview

High Power Proton Beam Irradiation at BLIP

Brookhaven
Linac
Isotope
Producer



Specimen Preparation

Fermilab

EUROPEAN SPALLATION SOURCE

CERN

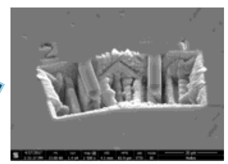
FRIB

Science & Technology Facilities Council

UNIVERSITY OF OXFORD

BROOKHAVEN NATIONAL LABORATORY

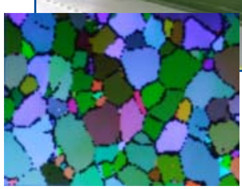
PIE



UNIVERSITY OF OXFORD

(CCFE)

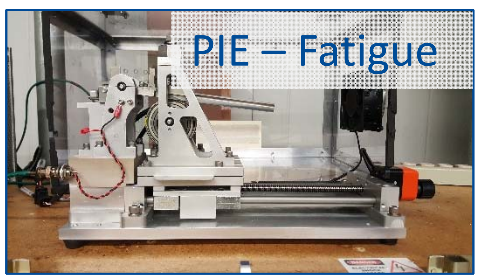
Unloading / PIE



Pacific Northwest NATIONAL LABORATORY

Fermilab

PIE – Fatigue



In-beam Thermal Shock

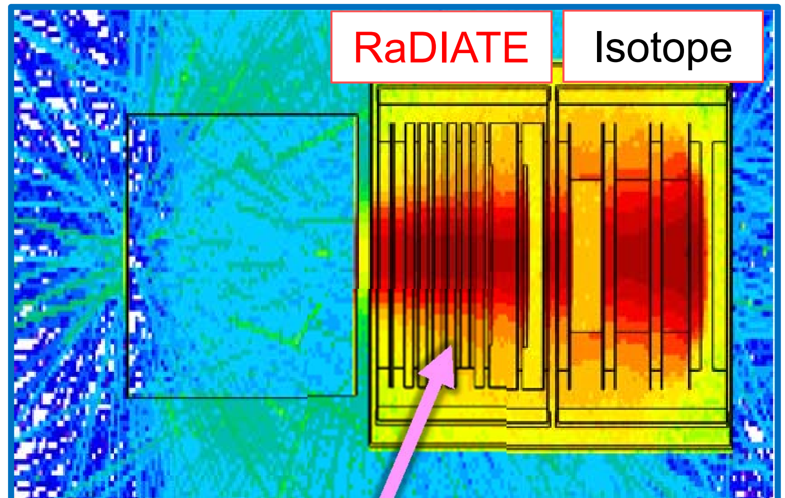
HiRadMat High-Radiation to Materials

CERN

2. High Power Proton Irradiation at BLIP and Post-Irradiation Examination (PIE)

- Brookhaven Linac Isotope Producer (BLIP) facility to produce medical isotope w 116 MeV primary proton beams
- Linac capable to deliver protons up to 200 MeV → operate at higher energies in tandem with RaDIATE material targets upstream
- 1st phase irradiation (2017)
  - 1.76 x 10^{21} POT in 22d@146μA average
- 2nd phase irradiation(Jan-Mar 2018)
  - 2.81 x 10^{21} POT in 33d@158uA average

181MeV rastered beam with
165uA peak current
7×10^{13} p/cm^2·s
(3 cm dia. footprint) 8weeks



Example: Accumulated Damage on Titanium:
1.5 DPA at peak (MARS-NRT)
Much more than existing data (~0.3DPA)
Close to that for future MW facility op.yr.

Water-

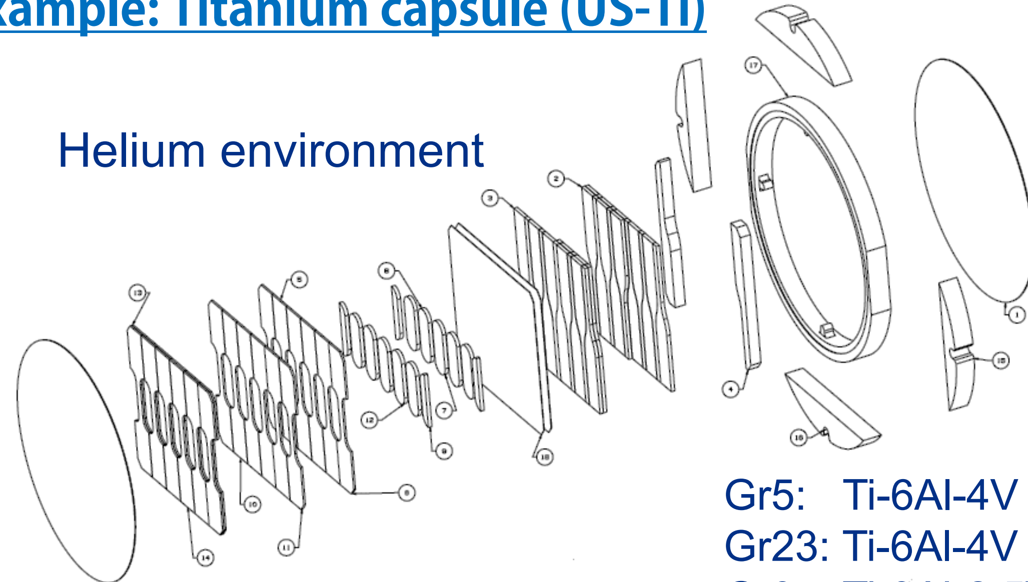
Specimens and Capsules Assembly

Over 200 specimens from 6 RaDIATE institutions

1. Beryllium in Ar [FNAL]
2. Graphite in vacuum
   IG-430 /ZXF-5Q/GC20 [FNAL]
3/8. Silicon in vac.
   Si / Expanded graphite [CERN]
   SiC-Coated Graphite [J-PARC]
4. Aluminum in He [ESS]
5/7/9. Titanium in He
   Several Grades [J-PARC]
   3 microstructures [FRIB]
   Meso-scale fatigue foil [Oxford]
6. Heavy materials in vac.
   TZM, Iridium, CuCrZr [CERN]

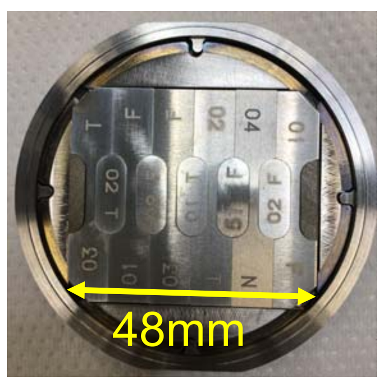
Example: Titanium capsule (US-Ti)

Helium environment

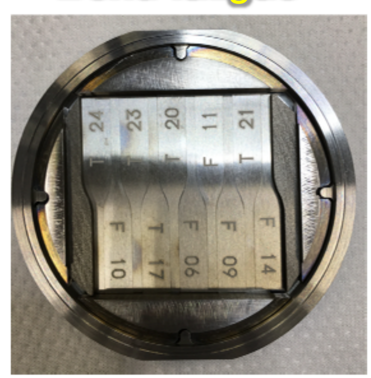


Gr5: Ti-6Al-4V
Gr23: Ti-6Al-4V ELI
Gr9: Ti-3Al-2.5V

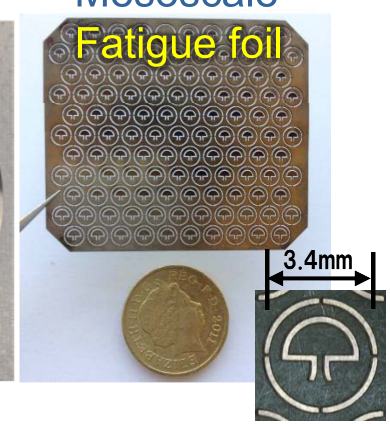
Tensile+Micro



Bend-fatigue



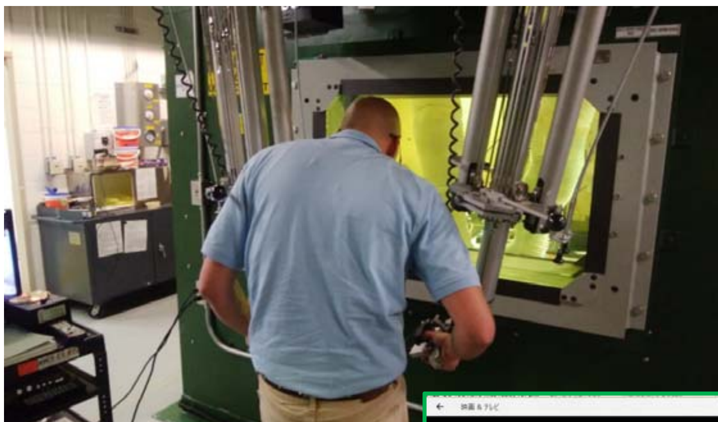
Mesoscale

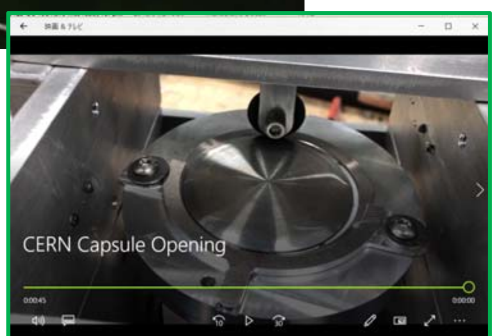


Handling at PNNL PRL Laboratory

Radiochemical Processing Lab.(RPL)

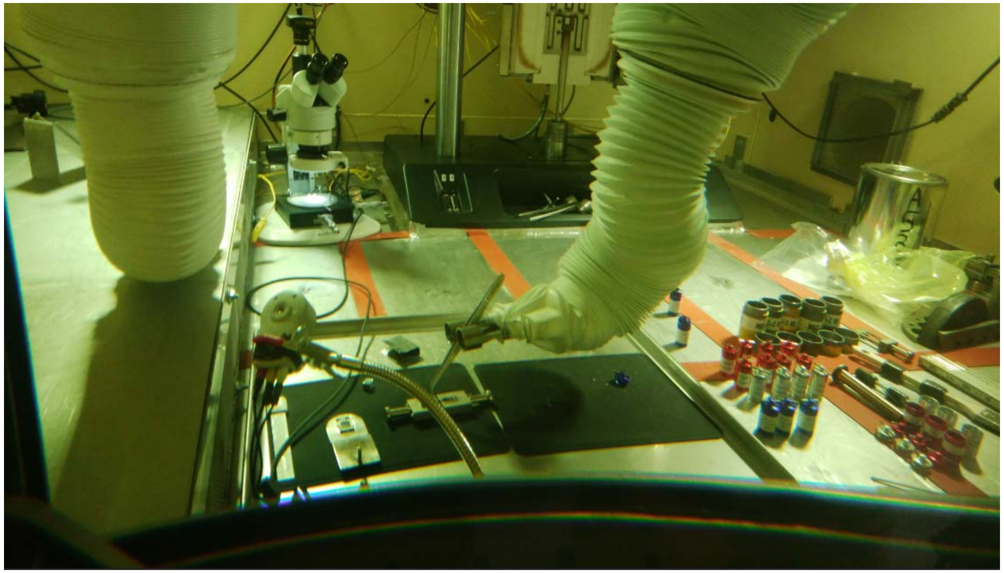
Capluse shipment in Type-A container

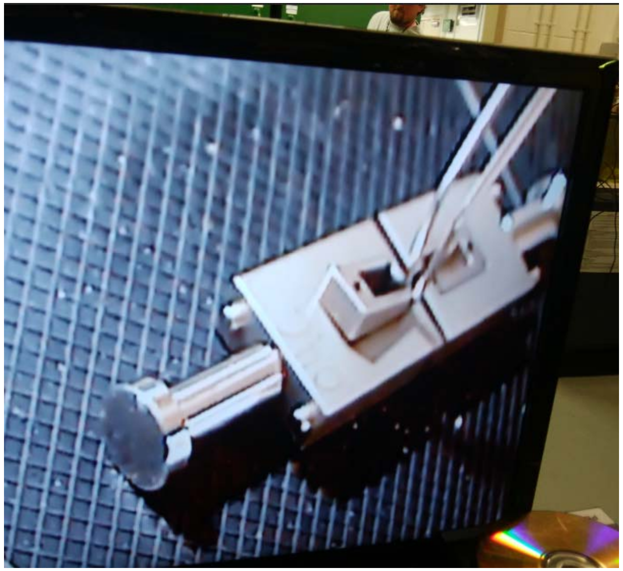


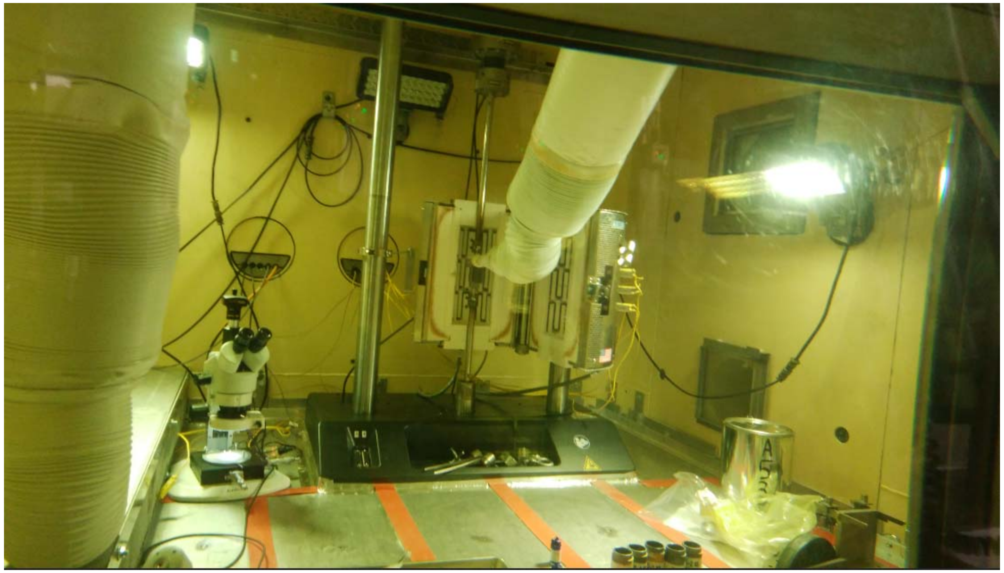


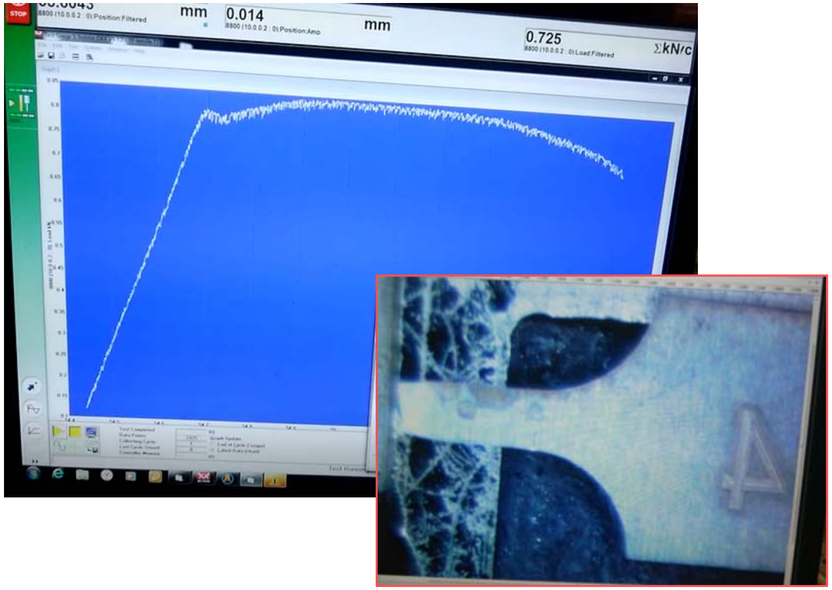
Remote-handling capsule opener

Tensile Test on Ti Specimens (Low dose capsule)

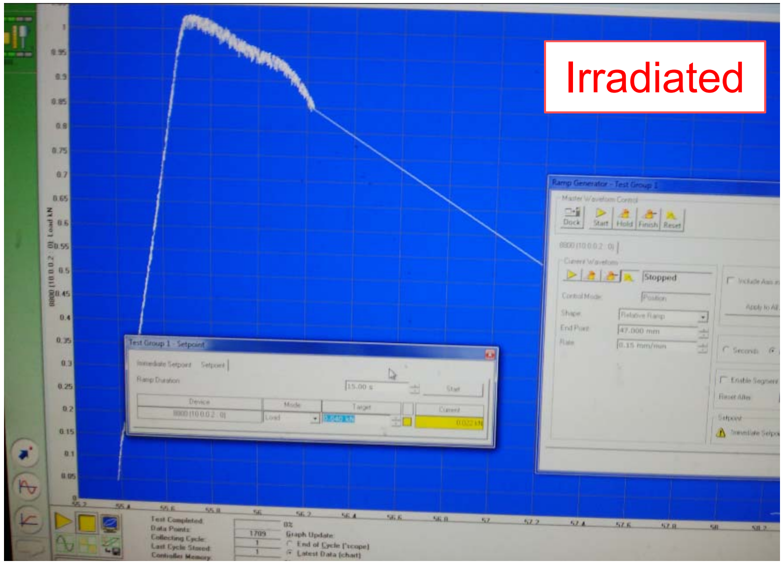


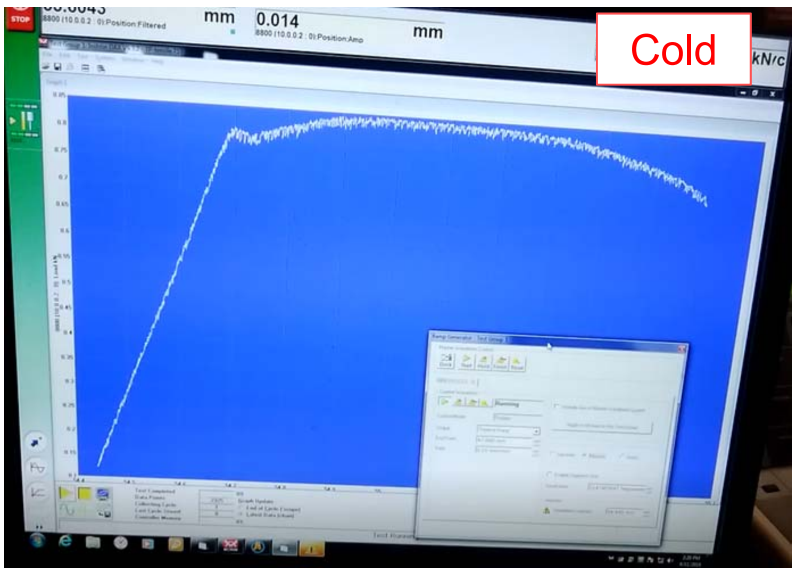






On-line Observations





- **Irradiation hardening effect clearly identified**

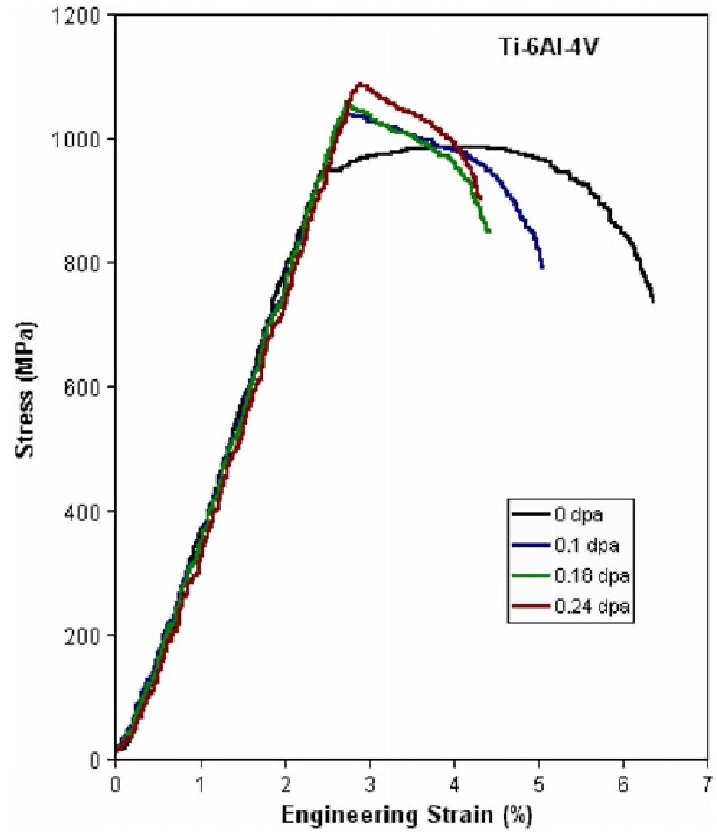


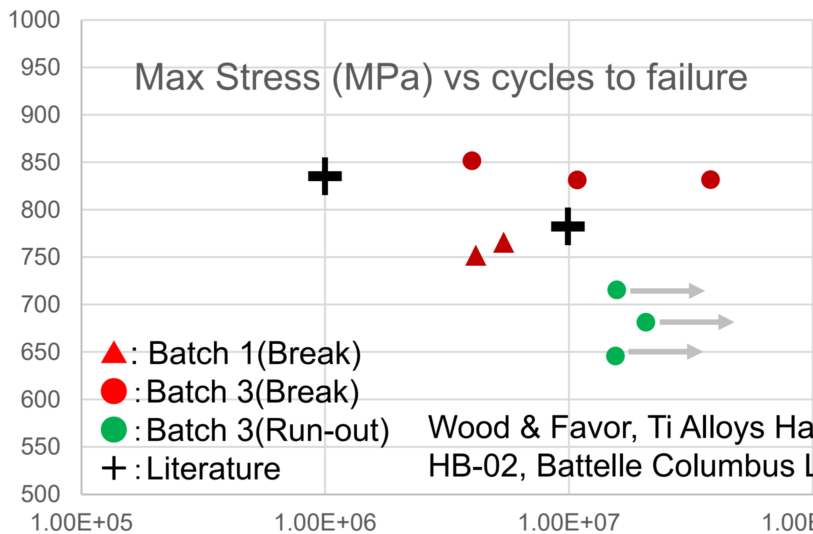
Fig. 13. Irradiation effects on the stress–strain relation of Ti–6Al–4V.

N.Simos et al., J.Nucl. Mat. 377 (2008) 41–51

Fatigue Testing at Fermilab & at UK

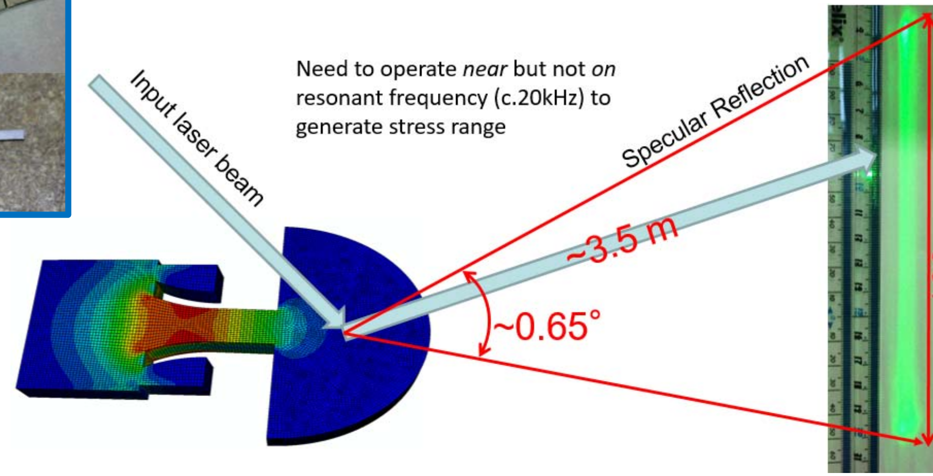
Macro-scale Fatigue Testing

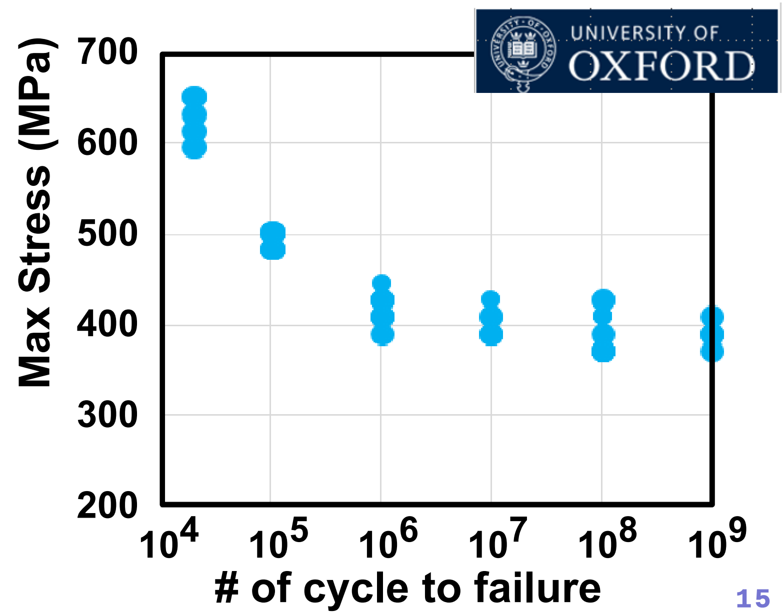
- Gr5/23



Meso-scale Fatigue Testing

- Gr23 A&STA, Gr2, 15-3Ti



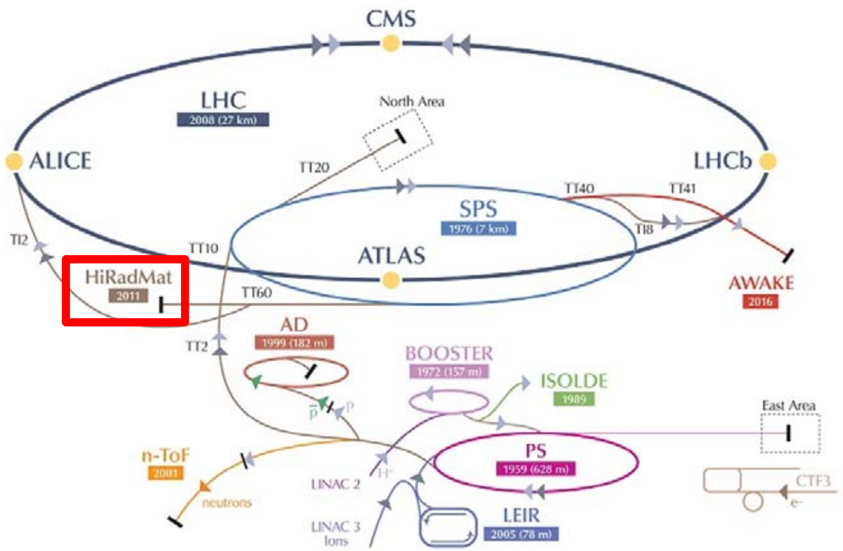


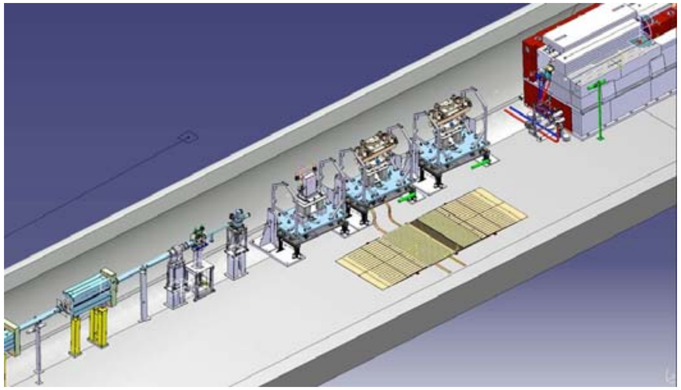
3. Thermal Shock Study at HiRadMat Facility

RaDIATE collaboration is now promoting HRMT43-BeGrid2:

- Expose non-irradiated and irradiated material specimens at BLIP to single high intensity beam pulses to compare thermal shock response
  - Irradiated specimens will include Beryllium, Graphite, Silicon, Titanium, SiC-coated Graphite, Glassy Carbon specimens from BLIP: First /unique test with rad. damaged materials
- Follow-up of a past experiment (HRMT24-BeGrid1) to expose Beryllium to even higher beam intensities than what was achieved
- Explore novel materials
  - Electrospun nano-fiber mats & foam materials
- Measurement of dynamic thermomechanical response of graphite slugs in an effort to benchmark numerical simulations

HiRadMat Facility at CERN

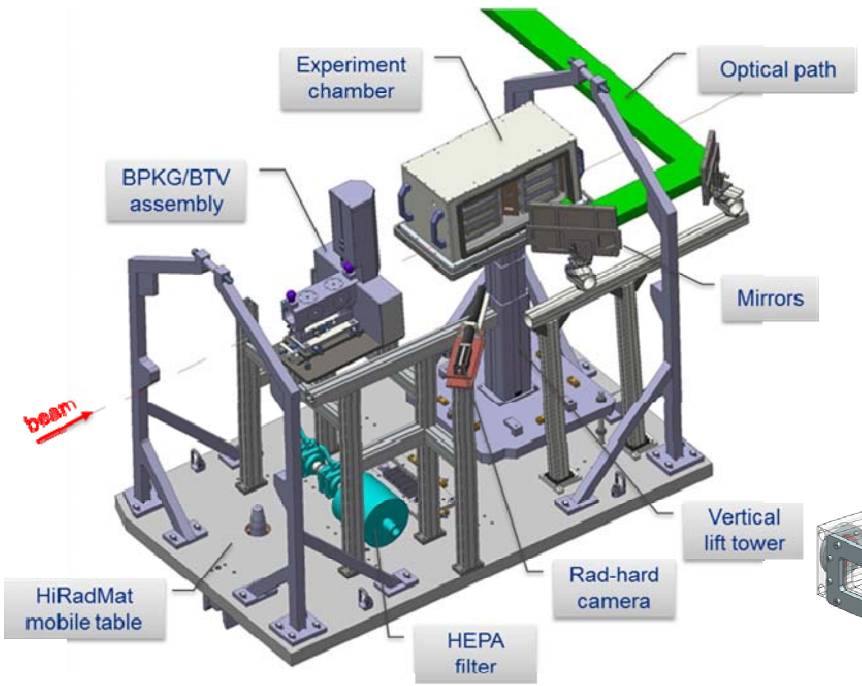


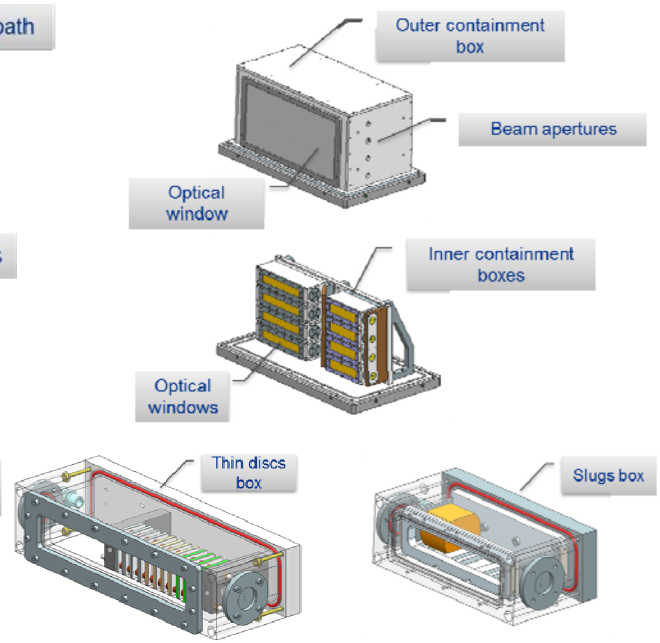


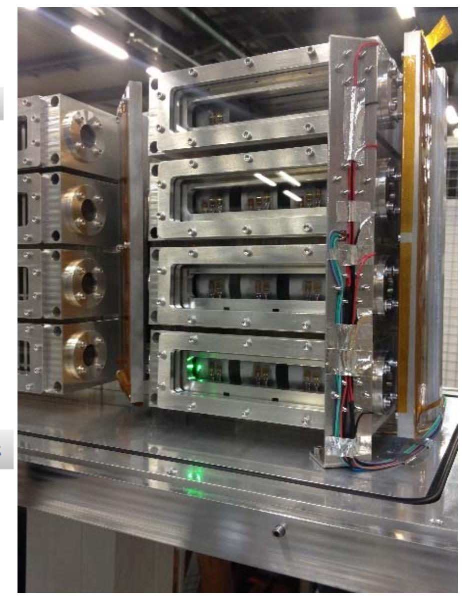
Beam Parameters	
Beam energy	440 GeV
Max. bunch intensity	1.2×10^{11}
No. of bunches	1 – 288
Max. pulse intensity	3.5×10^{13} ppp
Max. pulse length	7.2 μs
Gaussian beam size	1σ: 0.1 – 2 mm

BeGrid1 (HRMT24) completed in Sep. 2015

- Consisted of four specimen arrays of thin Beryllium discs and slugs
  - Various commercial grades (S200F, S200FH, PF60, S65F) and thicknesses
  - Real time measurements of temperature, strain and displacement
- PIE of thin disc specimen at the University of Oxford (2016-2017)





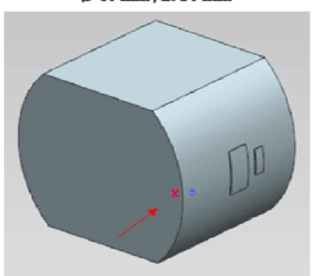


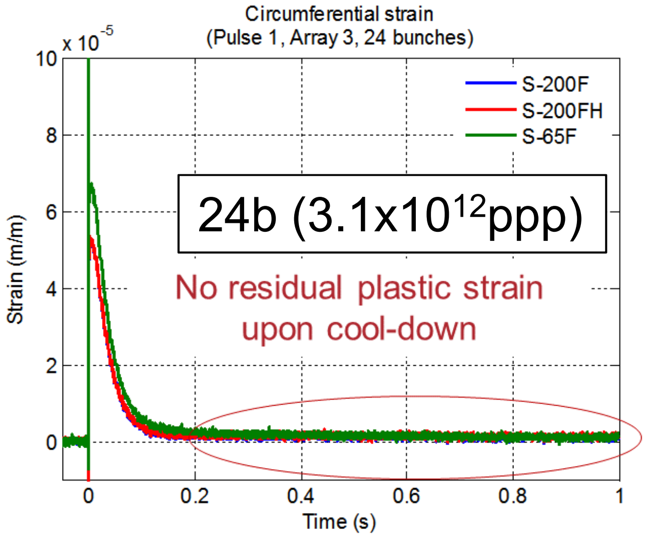
BeGrid-1 Achievements

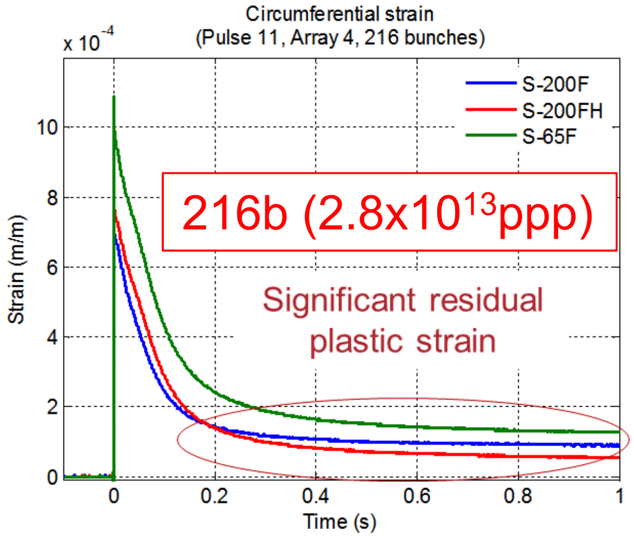
- Real-time thermomechanical measurements
  - Instrumented Be slugs in downstream containment boxes
  - LDV for radial displacement measurements
  - Strain and temperature gages

average bunch intensity: 1.3x10^{11}
beam σx: 0.3 mm, σy: 0.25 mm

Ø 40 mm , L: 30 mm





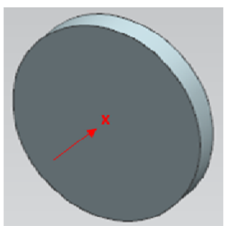


- Distinctive strain response for the three different Be grades
- Residual plastic strain observed upon cool-down

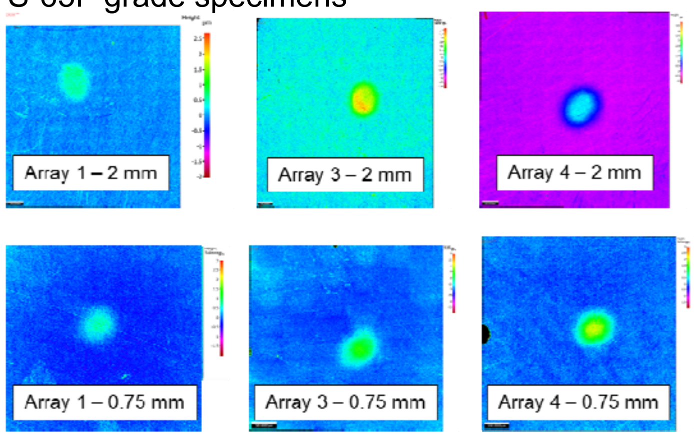
Post Irradiation Examination Results

- Thin disc specimen PIE performed at University of Oxford
- Optical microscopy and profilometry to measure out-of-plane plastic deformations

Ø 15 mm, t: 0.25, 0.75, 2 mm



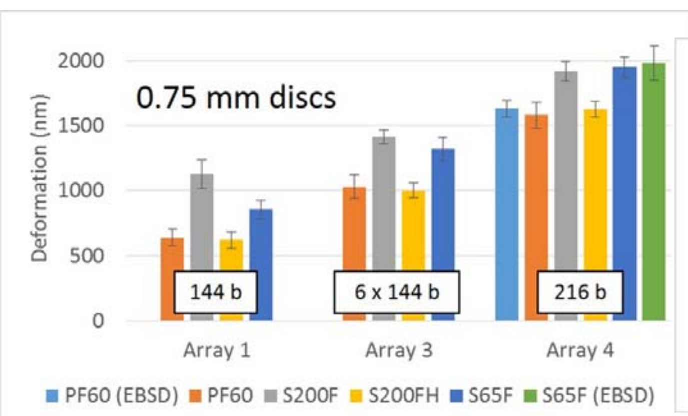
S-65F grade specimens

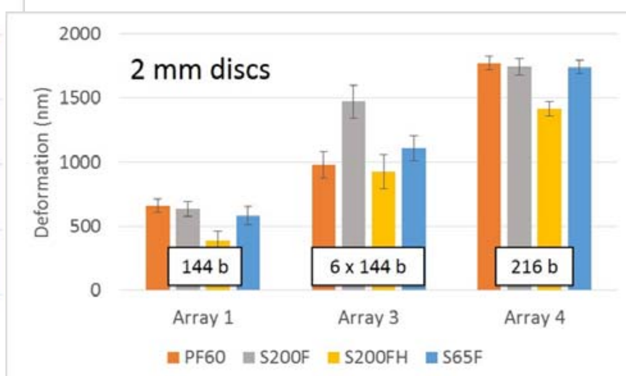


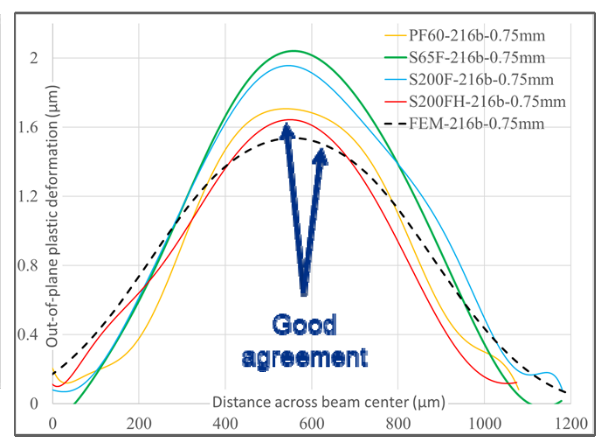
V. Kuksenko (University of Oxford)

- ➢ All Be grades showed less plastic deformation than predicted by available literature strength models
- ➢ S200FH showed least plastic deformation, in agreement with advanced empirical strength model
- ➢ Observed plastic strain ratcheting in Array 3

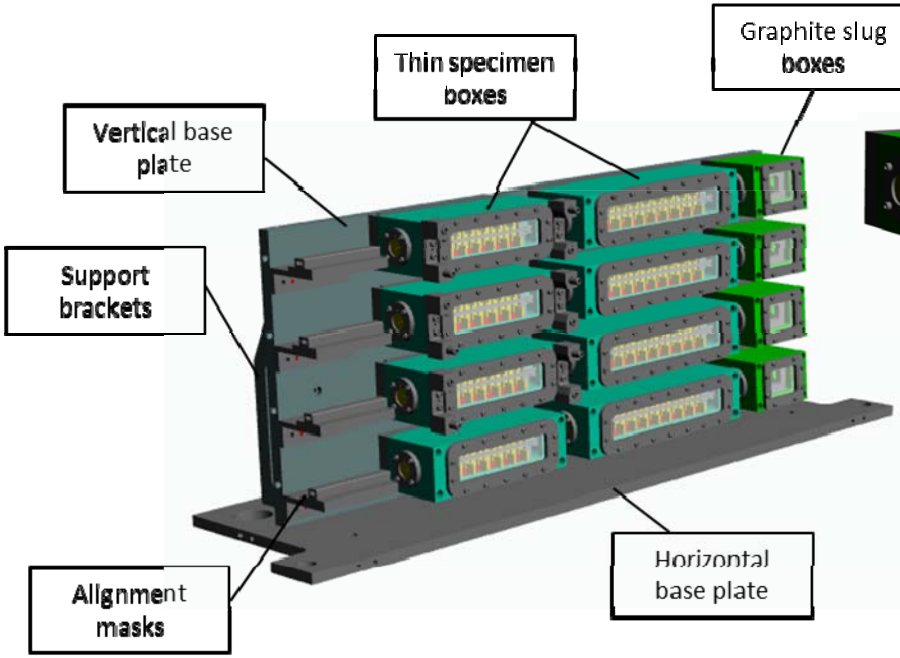
validation of Johnson-Cook strength model

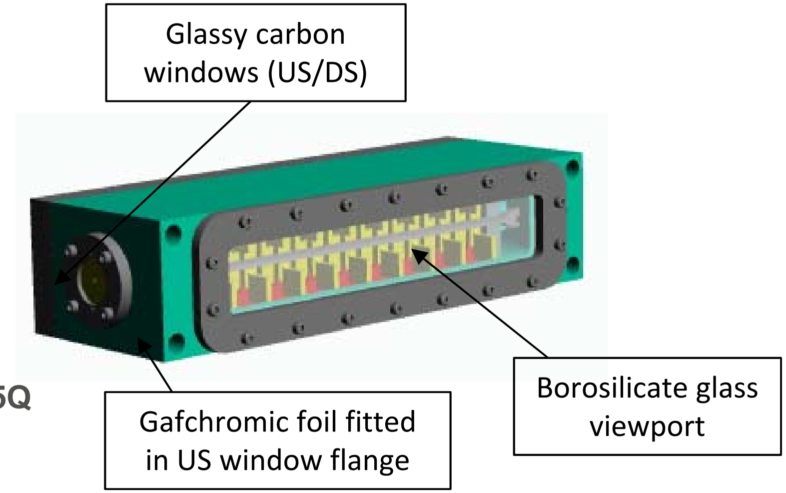


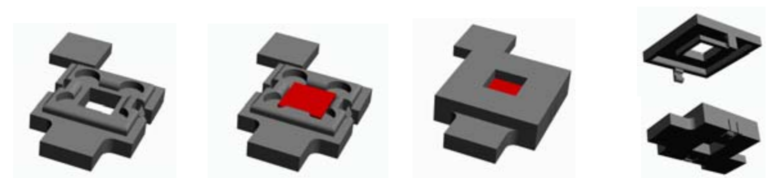


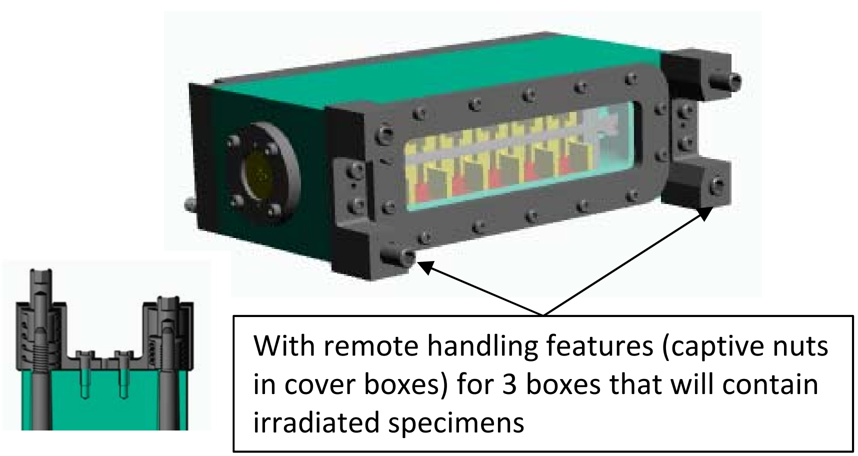


BeGrid2 (HRMT43) scheduled on Oct.1st week 2018



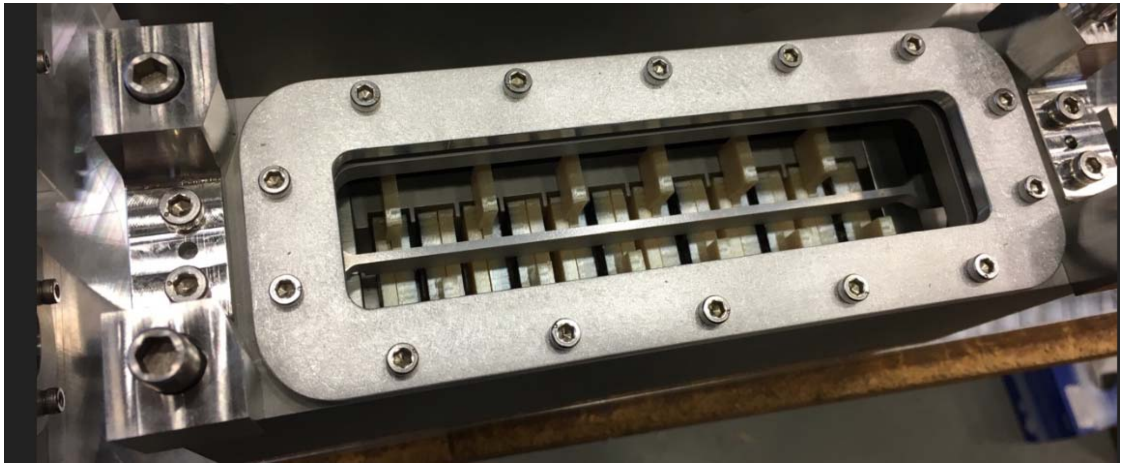






- Hermetically-sealed in air to fully contain specimens and avoid contamination release
- Irradiated specimens have been shipped from BNL to PNNL
  - Assemble specimens in holders and inner containment boxes
- Irradiated boxes to be shipped from PNNL to CERN for final assembly to vertical base plate

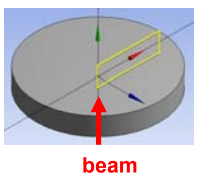
Assembling BeGrid2 setup on-going at FNAL

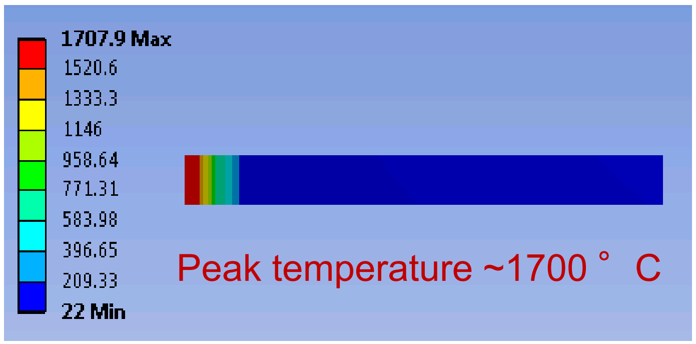
Beam-Induced Strain&Stress at BeGrid2

- Increasing beam intensities on different arrays
- Peak beam intensity: σ=0.25mm, 288 x 1.2e11ppb (3.5e13ppp)
  - Peak proton pulse fluence: 9.5×10^{15} p/cm^2

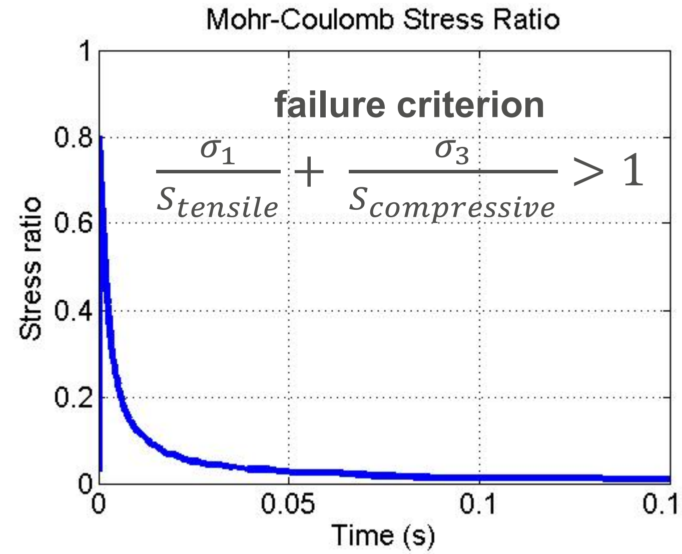
Graphite



2D axisymmetric ANSYS model



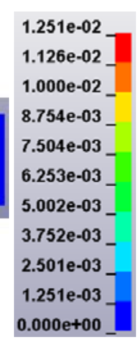
Irradiated BLIP graphite specimens
4.5e21 POT (~0.05 DPA)



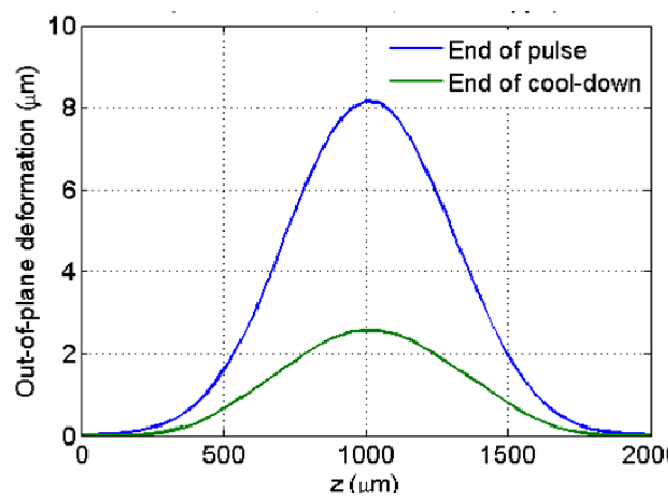
Beryllium LS-DYNA (Johnson-Cook strength model)

Effective plastic strain at end of cool-down

1.25 %



Irradiated BLIP Be specimens
4.5e21 POT (~0.03 DPA)



Reduced ductility expected (~100 appm He)

4. Summary and Prospect

BNL-BLIP proton irradiation runs have been completed March 2018

- The POT / accumulated peak DPA reached to unprecedented values, which are comparable to MW facility operation

PIE campaign starts now. First outcomes expected within current FY

- Capsules receiving, opening, specimen extraction and cataloguing
- Mechanical testing PIE on Ti alloys, beryllium, iridium, etc.
- Fatigue testing PIE of Ti alloy specimens
  - Radiation damage on high-cycle fatigue in Ti alloys has never been done before
  - Novel meso-scale fatigue testing technique also to be applied at UK

In-beam thermal shock experiment at CERN HiRadMat facility

- Incorporating various specimens irradiated at BLIP
  - Testing highly irradiated samples with thermal shock from high intensity beam has also never happened before
- Assembly of irradiated specimens in holders and inner containment

HPT is very challenging to materials. The RaDIATE collaboration is to address these challenges even to be successful with 1-2 MW primary beam power, let alone 4 MW

Recent / Coming Workshops

- The 10th International Workshop on Neutrino Beams and Instrumentation (NBI2017) + 4th RaDIATE Open Collaboration Meeting
  - Tokai-mura, Ibaraki, Japan, Sep.18~22, 2017
  - https://conference-indico.kek.jp/indico/event/16/
- RaDIATE 2018 Collaboration Meeting
  - At CERN between 17th and 21st December 2018
  - https://indico.cern.ch/event/718767/

address topical issues associated with radiation damage in accelerator targets environment, as well as providing a forum for discussing between experts in this specialized domain. Contribution to this challenging mission is always welcome !