CERN's activities within the RaDIATE Collaboration

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On behalf of:

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CERN | EN ENGINEERING DEPARTMENT

1st Workshop of ARIES WP17 PowerMat
Torino, 27-28 November 2017

Outline

1) Introduction to RaDIATE collaboration

2) Effects and challenges of radiation damage in BIDs

3) Outlook to RaDIATE R&D activities

4) 2017 and 2018 BLIP-BNL proton irradiation campaigns and CERN participation

5) Conclusions

R a D I A T E

Collaboration

Radiation Damage In Accelerator Target Environments

- Stablished from 2012

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**

Currently adding CERN and J-PARC to the MOU

Argonne NATIONAL LABORATORY

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Science & Techn
Facilities Council

FRIB

P. Hurh, FNAL

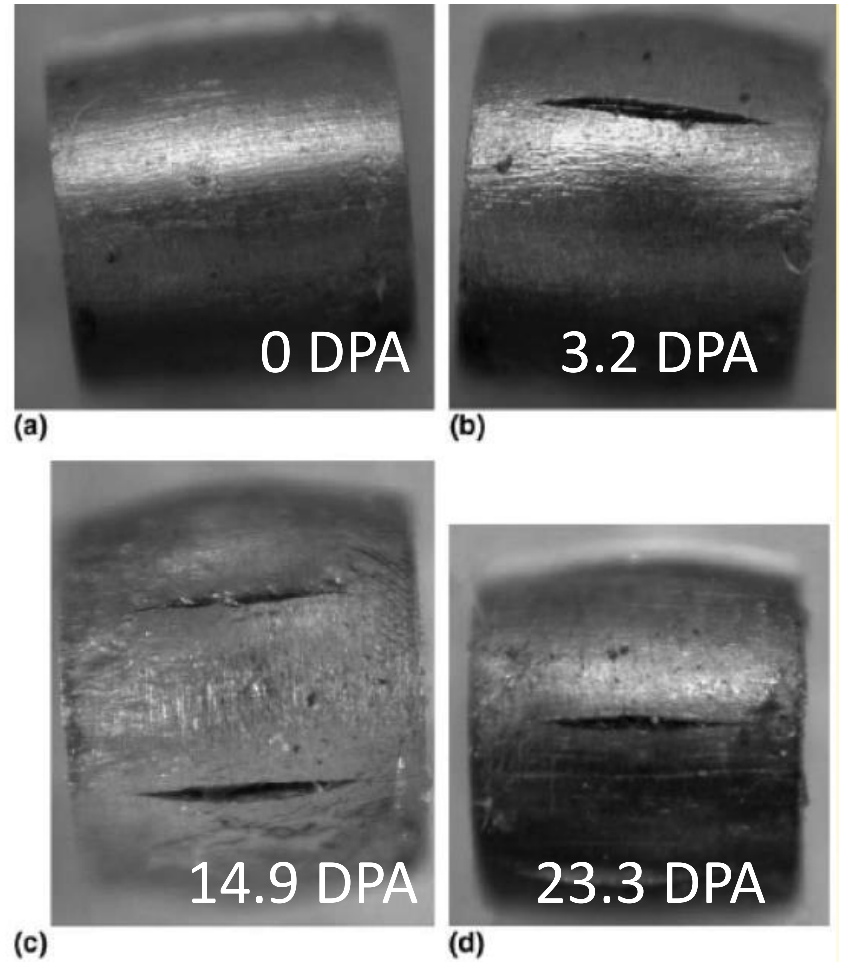
Research Focus of RaDIATE

- Challenges in Targetry technologies
  - Target system simulations (physics & reliability)
  - Rapid heat removal
  - Radiation protection
  - Remote handling
  - Radiation accelerated corrosion
  - Manufacturing technologies
- Challenges in predicting Target material behavior
  - **Thermal “shock” response**
  - **Radiation damage**
  - Highly non-linear thermo-mechanical simulation

Main focus within RaDIATE

Effects of 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)**



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

Challenges of Radiation Damage

1) Challenge to estimate DPA by MC codes and benchmark against experimental data.

2) Challenge to link **microscopic effects (DPA)** to **changes in macroscopic properties.**

- Historically, this has been done by irradiation in nuclear reactors and subsequent PIEs.
- However, when applied to accelerator technology or fusion reactors:

Effects from low energy neutron irradiations do not equal effects from high energy proton irradiations.

$n \neq p$

1-14 MeV 100+ MeV

- Table comparing typical irradiation parameters

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

P. Hurh, FNAL

Cannot directly utilize data from nuclear materials studies!

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
T2K Upgrade	J-PARC	10?	?	1,300	~4 MW long-term?
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
BDF	CERN	10 ?	Y/N	500	High-Z target

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

P. Hurh, FNAL + Marco

Radiation Damage at CERN's BIDs and Related Devices

Type of device	Device	Materials subjected to radiation damage	DPA
Targets	AD-Target	Ir, Ta, Ti-6Al-4V container	~1 DPA/year in the core
	nTOF	Pb, Ti-6Al-4V container	~1 DPA/year in the core 0.2-0.5 DPA/year container
	BDF	TZM, W, Ta, Ta2.5W	~4 DPA over operation
Absorbers and Collimators	TIDVG	Graphite, CuCrZr, Inermet180	0.5 DPA over operation (on a large surface, tens of cm2)
	PS Internal Dump	Graphite, CuCrZr	0.04 DPA/year (on a large surface, tens of cm2)
	LHCTDE (external dump)	Graphite, Expanded Graphite	-
	FCCTDE (external dump)	Graphite, Expanded Graphite	-
	TCSPM Collimators TCTPM Collimators	-MoGr / CfC coated in Mo -CuCD	~0.1 DPA over operation (over small surface 50x100 um2)
Other Devices related to BIDs	Beam windows	Be, Ti-6Al-4V, GlassyC	-
	Collection Optics (horns, solenoids)	Aluminum Alloys	-
	Monitors and Instrumentation		-

The High Costs of High-Energy Radiation Damage Studies

- **High energy, high fluence, large volume proton irradiations are needed to entirely replicate the HEP target environment and provide “bulk” samples for analysis**
  - High cost of irradiation “station” (4+ M$)
    - Beam line and building not included in cost estimate
  - High cost of irradiation beam time (0.5 M$ per 12 weeks)
  - High cost of Post-Irradiation Examination (PIE) of activated samples (20+ k$ per sample)

High-Energy irradiations including PIE are expensive and can take a very long time

Low Energy Ion Irradiations Instead?

Fission and Fusion materials R&D community (e.g. University of Michigan Ion Beam Laboratory, MIBL ++ Europe as well)

- **Positives:**
  - Low to zero activation (PIE in “normal” lab areas)
  - Greatly accelerated damage rates (several DPA in a day)
  - Significantly lower cost irradiations
- **Negatives:**
  - Very shallow penetration (0-10 microns)
  - Little gas production in samples
- **Promising Solutions:**
  - **Micro-mechanics** may enable evaluation of critical properties
  - Simultaneous implantation of He and H ions (**triple-beam irradiation**)

But still need HE proton irradiations to correlate and validate techniques

P. Hurh, FNAL

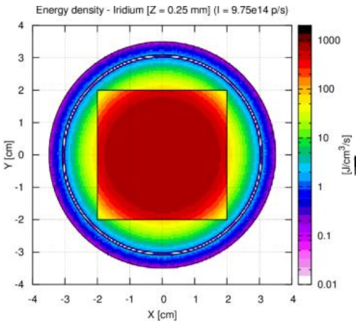
Fermilab

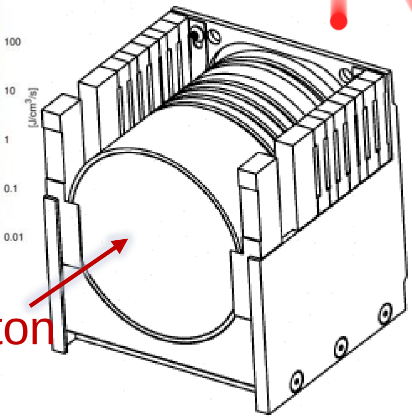
Brief Outlook on RaDIATE R&D Activities

- **181 MeV p irradiation @ BNL's BLIP facility**
  - 2010 BLIP Irradiation
  - 2017 BLIP Irradiation (part of international collaboration)
  - 2018 BLIP Irradiation (part of international collaboration)

  and subsequent PIEs (see later)
- **NuMI Be window PIE & future work (FNAL, Oxford)**
- **He implantation studies at Surrey/Oxford**
- **In-beam thermal shock test on Be and GlassyC at CERN's HiRadMat (FNAL, RAL, CERN, Oxford)**
  - HRMT-24 BeGrid (2015)
  - BeGrid-2 (2018) will test materials already irradiated in BLIP-2017 run
- **NuMI target (NT-02) autopsy and graphite PIE ++ potential CNGS?**
- **Meso-scale fatigue testing (Oxford)**

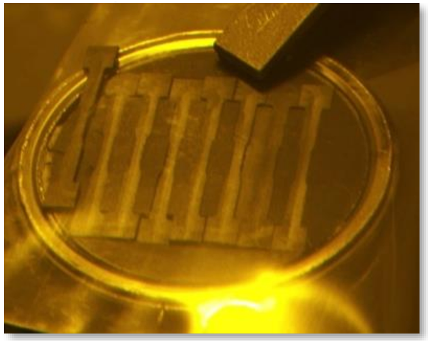
2017 BLIP run

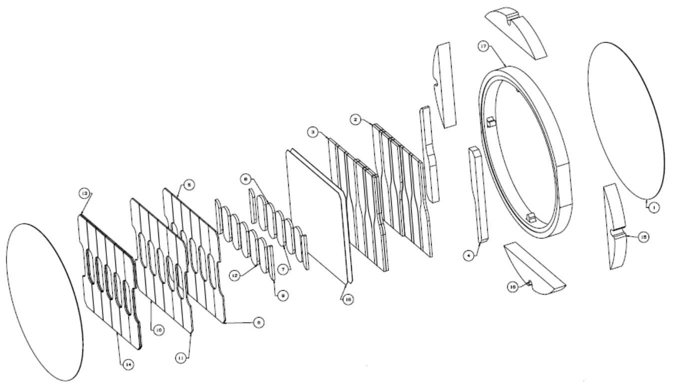




181 MeV proton beam

- Organized by the RaDIATE Collaboration
- Included graphite at various temperature (up to 1000 C)
- Also Be, Ti alloys, Si, TZM, Al, CuCrZr, Ir, SiC-coated C
- Post-irradiation examination (2018) includes mechanical, thermal, microstructural and fatigue evaluation
- Participants: **BNL, PNNL, FRIB, ESS, CERN, JPARC, STFC, Oxford, LANL**



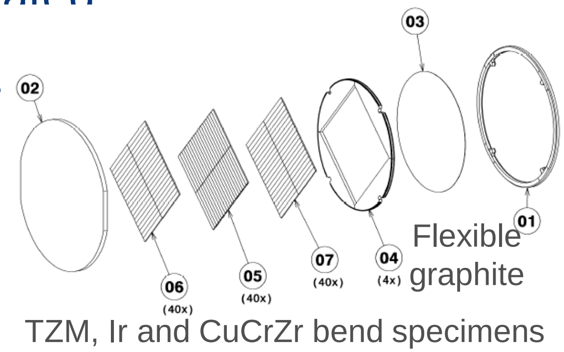


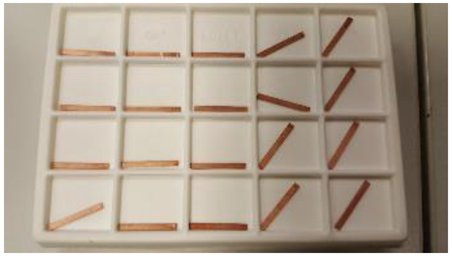
CERN's Materials Irradiated in 2017 BLIP run

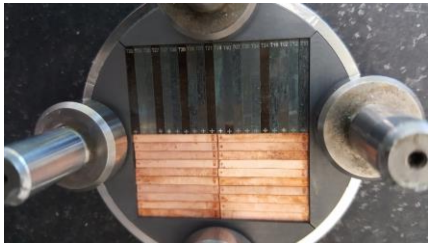
- Two CERN's capsules were irradiated:
  - High-Z Capsule -> Max irr. T

samples of 20x2x0.5 mm

    - **Iridium** up to 0.35 DPA
    - **TZM** up to 0.15 DPA
    - **CuCrZr** up to 0.19 DPA



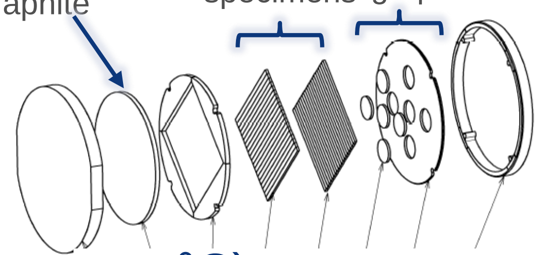




  - Low-Z Capsule -> Max irr. T = 240°C

samples of 40x1x2 mm

    - **Polycrystaline Si** up to 0.18 DPA
    - **SiC-coated graphite** (KEK) up to 0.03 DPA
    - **Expanded graphite** up to 0.04 DPA



- PIEs will take place in 2018 in PNNL (US)
  - 4 point bending tests at different temperatures (up to 800 °C)
  - Thermal & Physical characterization (diffusivity, thermal expansion, density and density)

PIE @ PNNL – Mechanical Properties I

- Bulk tensile properties of high-activity materials obtained using a load frame installed in one of the modular hot cells
  - Instron 8800 →
  - 9800 N and 98,000 N load cells
  - Intended for miniature sample testing
    - Demonstrated for SS-3 tensile and 3-point bend tests with specialized fixtures
    - Other sample types possible with appropriate fixtures

With the courtesy of D. Senor (PNNL) – ATS Seminar @CERN

Photos courtesy of TS Byun

PIE @ PNNL – Mechanical Properties II

- Tensile properties of low-activity materials obtained using a load frame in a walk-in fume hood →
  - Centorr 2500°C W-mesh furnace
  - Can use same fixture types as RPL hot cell load frame
- Fracture toughness of low-activity materials
  - Benchtop Instron 8801 servo-hydraulic load frame with 800°C tube furnace →

With the courtesy of D. Senor (PNNL)
– ATS Seminar @CERN

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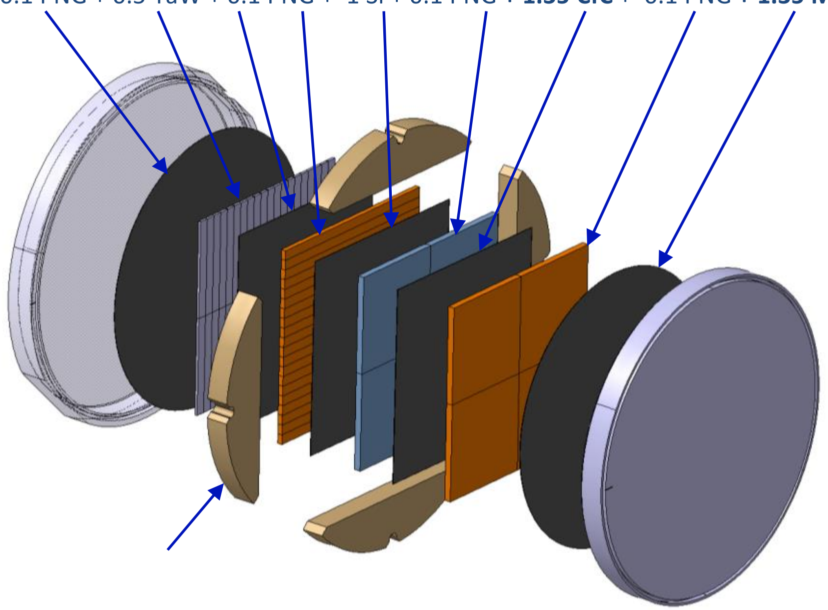
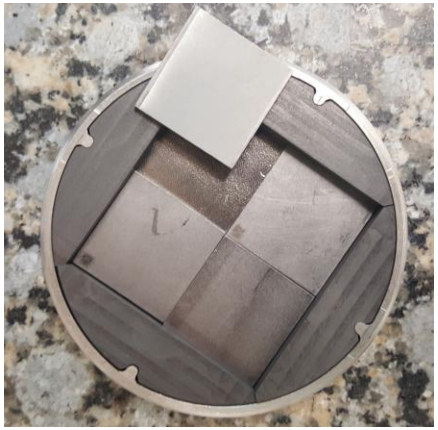
CERN’s Materials Irradiation in 2018 BLIP run

- Materials:
  - **TaW(2.5%)**: Used as cladding material for BDF target
  - **Mo-coated CFC & Mo-coated MoGr:**
    - For TCSPM Collimators
    - Test Mo adherence under radiation
  - **Monocrystalline Si:** For crystal collimation





Currently being assembled, will be sent to Brookhaven by the end of December 2017

Similar PIEs as the ones foreseen for BLIP run 2017 irradiated materials

Conclusions

- The RaDIATE Collaboration has been active for the past ~4 years and is starting to produce results benefitting primarily HEP targetry global community (KEK, FNAL, CERN)
- **Radiation damage** and **thermal shock** are highest priority
  - Mechanisms and conditions unique to accelerator target facilities
  - Sustained efforts with multiple approaches.
- CERN has an active participation in 2017 & 2018 proton irradiation campaigns using the BLIP line in BNL.
- Foreseen PIEs at PNNL aim at extracting mechanical and thermal macroscopic properties of the irradiated materials, directly applicable to the design of BIDs.