Updates on BLIP irradiation tests and RaDIATE activities

N. Solieri
Under the supervision of M. Calviani
On behalf of the RaDIATE collaboration

Outline

1. Radiation damage in Beam Impacted Devices (BIDs)
   - Material R&D approaches for BIDs at different time-scales
   - The RaDIATE collaboration

2. BLIP Irradiations
   - BNL's BLIP facility
   - Organization of an irradiation at BLIP and subsequent PIE
   - An overview of the irradiations that we have launched
   - The CERN2 capsule

3. An overview of some of the other RaDIATE activities
   - BeGrid2 (HRMT43) organization and subsequent PIE (K. Ammigan, FNAL)
   - Fatigue testing of Ti alloys for FNAL beam windows (S. Bidhar, FNAL)
   - Ti-base alloy tensile testing and microscopy (D. Senor, PNNL)
   - Radiation damage effects in Be (S. Kuksenko, UKAEA)
   - Development of ANSYS scripts for the implementation of radiation damage data (N. Solieri, CERN)

Material R&D studies for BIDs

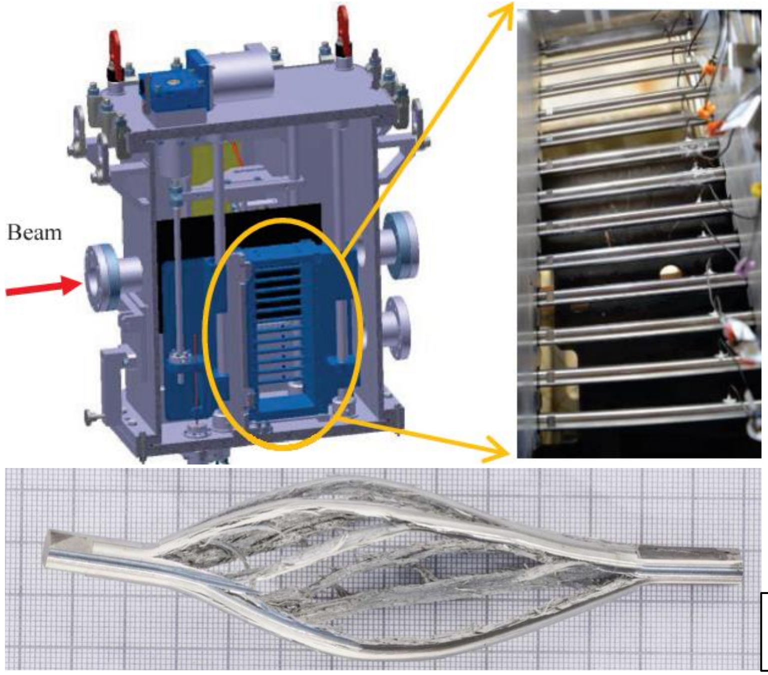
- Data from material studies for nuclear reactors poorly translate to BID scenarios → **<u>Need own material R&D</u>**

TIMESCALE

ns / µs ⟷ **months / years**

<u>HiRadMat</u>

Characterization of the dynamic response of the materials/prototypes under proton beam impact. No relevant radiation damage produced



1

[1]Courtesy C. Torregrosa

[2] Courtesy E. Fornasiere, in collaboration with Framatome GmbH

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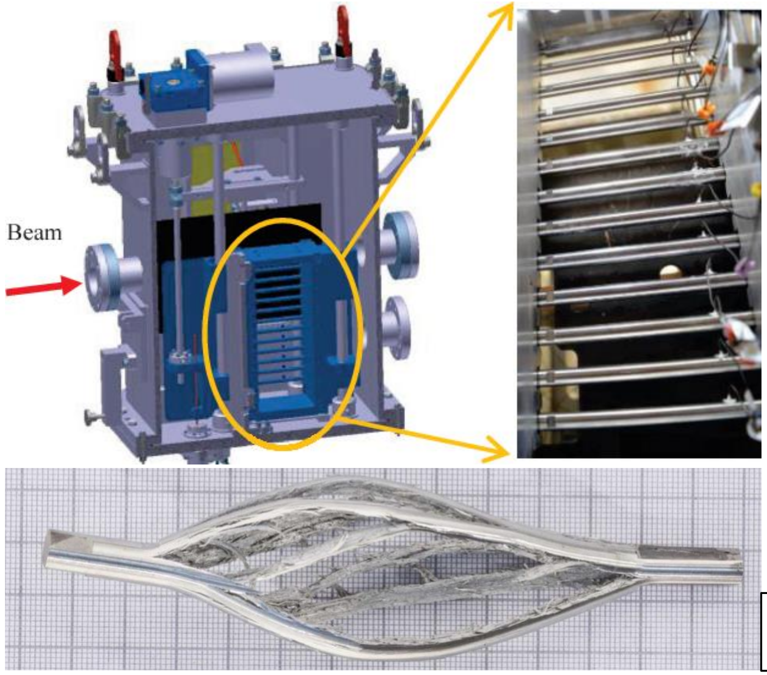

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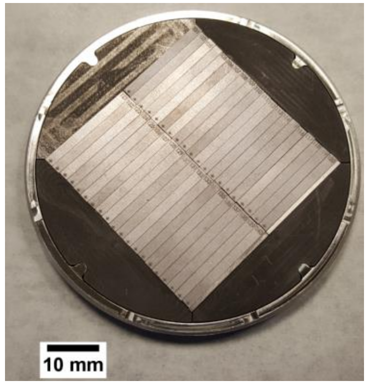
Post-mortem irradiation examination

Opening of a spent AD-Target after 7 years of irradiation

2

BLIP Irradiations



Several small samples for material testing enclosed in welded stainless steel capsules (Ø70 mm, 5 mm thick)

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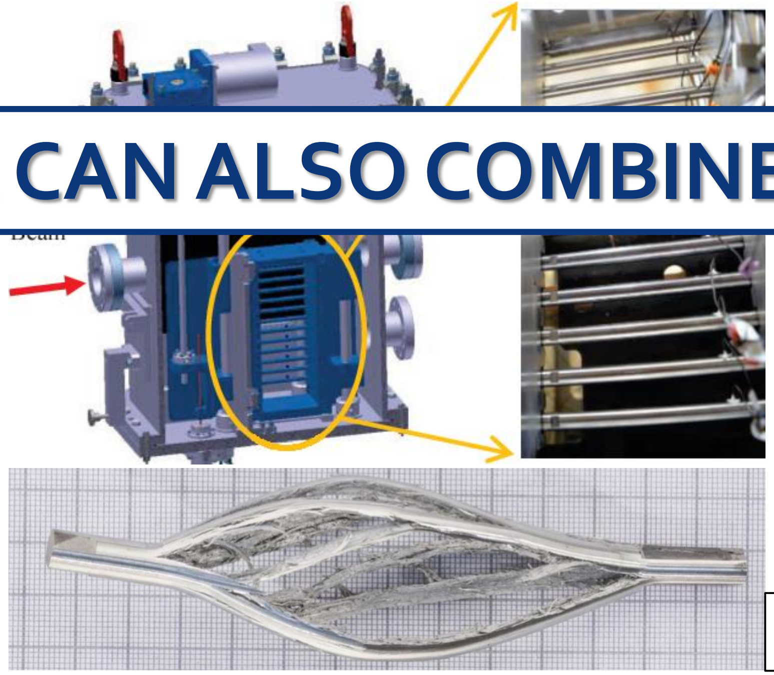

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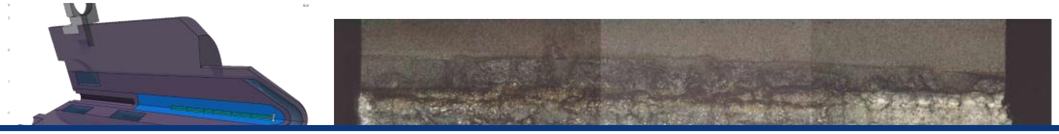
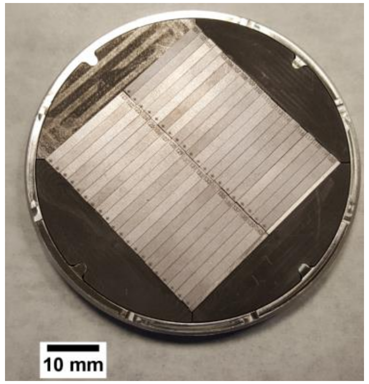


WE CAN ALSO COMBINE THE TWO APPROACHES (BeGrid2)

BLIP Irradiations



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RaDIATE Collaboration

Radiation **D**amage **I**n **A**ccelerator **T**arget **E**nvironments

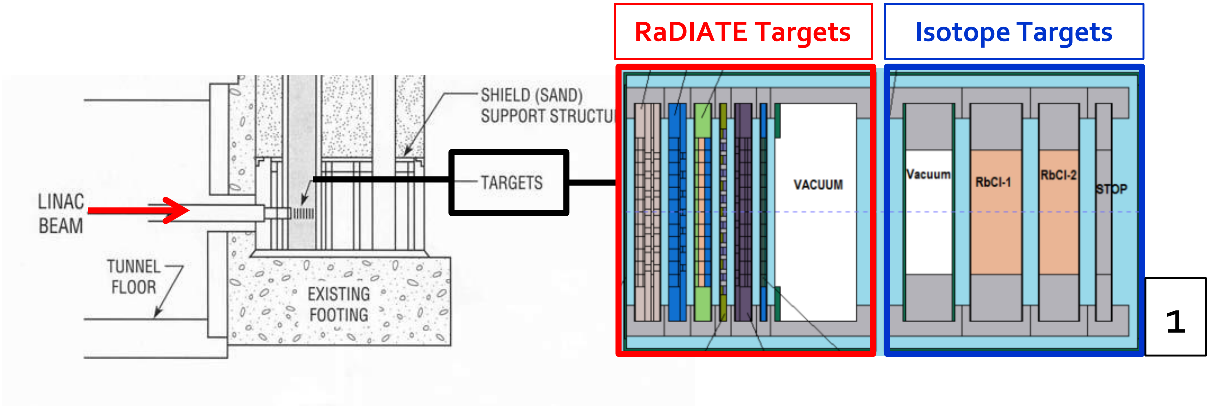
Broad aims are threefold:

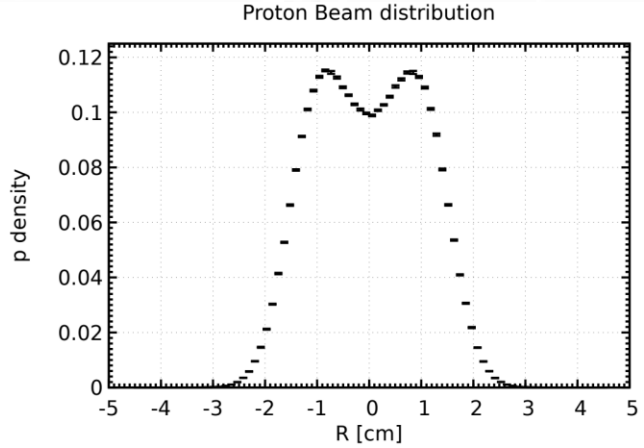
- to generate materials data for **accelerator** and **fission/fusion** communities
- Bring together HEP and nuclear fusion/fission materials research communities
- to initiate a **continuing synergy** between research in these communities, benefitting both **proton accelerator applications** in science and industry and **carbon-free energy technologies**

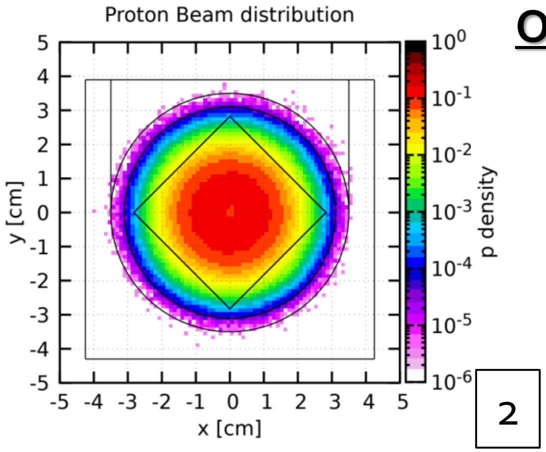
5th in-person collaboration meeting held at CERN in Dec. 2018

Irradiations at BLIP

BLIP – Brookhaven Linear Isotope Producer at BNL







Material irradiation in tandem and upstream of isotope targets:

- Primary proton energy: up to 200 MeV
- RaDIATE Target array needs to be optimized for each run to deliver a beam that is appropriate for isotope production
- POT ~ 1E21
- Peak DPA: 0.88 (Ta2.5W, CERN2 capsule), 1.2 (Ir, HighZ capsule)
- Rastered beam profile to achieve more constant irradiation profile
- Irradiation length O(months)

Objectives:

- Evaluate radiation damage effects from high-energy protons in various accelerator materials:
  - Beam windows, Secondary particle production targets, Beam dumps
- Perform PIE activities to characterize property changes due to proton irradiation damage
  - Strength (tensile, bend, fatigue)
  - Thermal (CTE,conductivity)
  - Annealing effects and microstructure (SEM, TEM, EBSD)

[1]Courtesy K. Ammigan
[2]Courtesy J. Canhoto

Organization of an irradiation at BLIP and subsequent PIE

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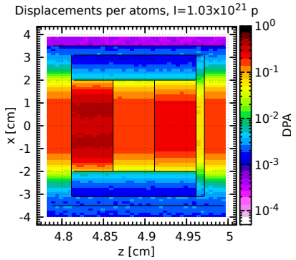
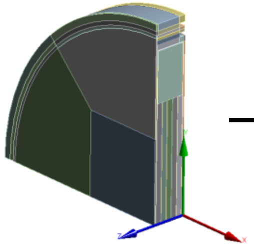


FLUKA Studies



ANSYS Studies

Comparison with the conditions achieved in the BID and BNL proton energy budget

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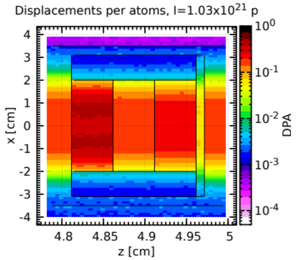

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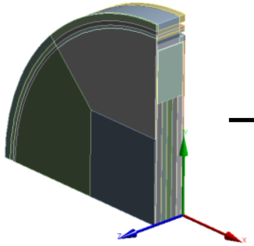

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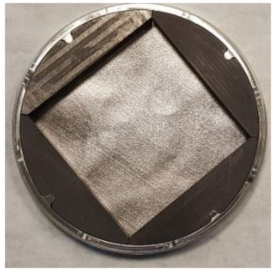
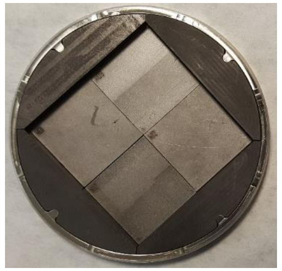
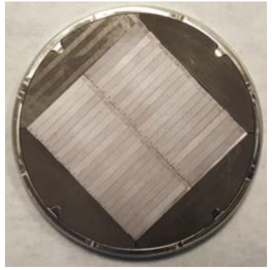
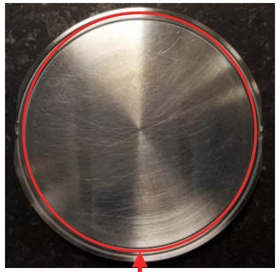


Capsule Cover





Filling with specimens



EBW

[1]Courtesy K. Ammigan

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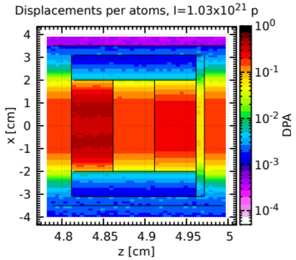

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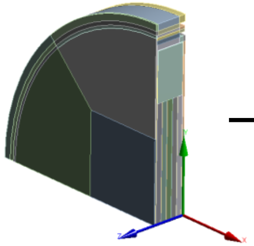

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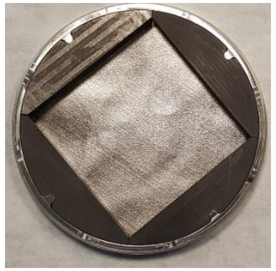

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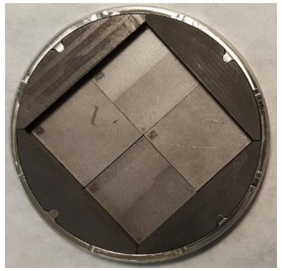

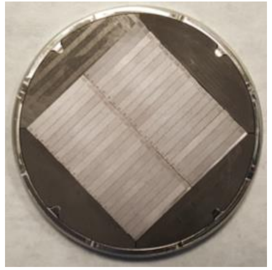

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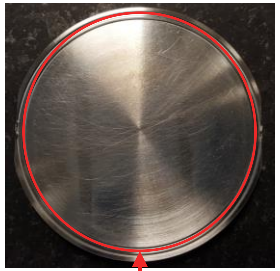

EBW

3. Shipment of capsule to BNL and installation in the beamline

Capsule fitted in capsule holder

Basket assembly (2.5 mm water gap)

Target box assembly [1]

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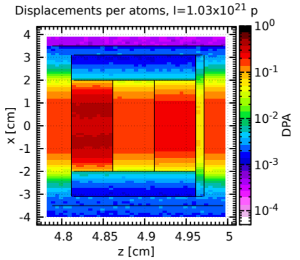

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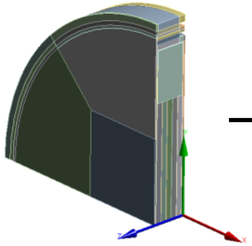

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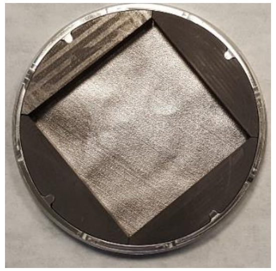

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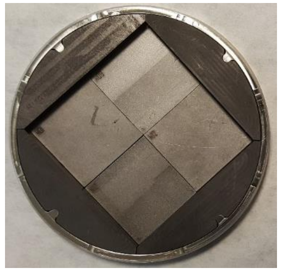

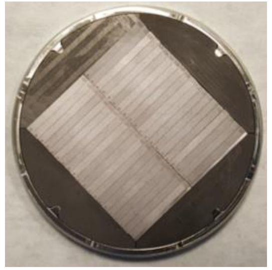

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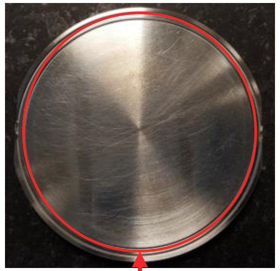

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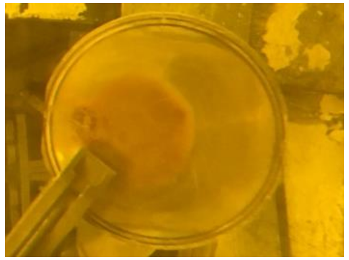

CERN2 Capsule: Computed dose sum @ 1m after 18 months cooldown ~4 mSv/h

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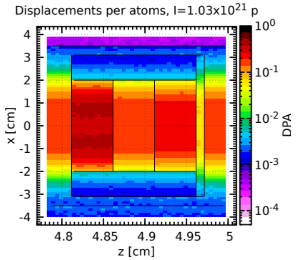

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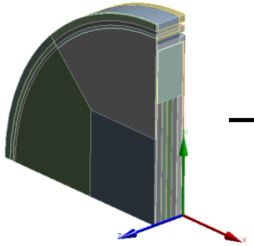

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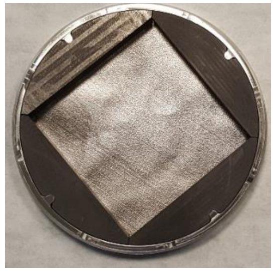

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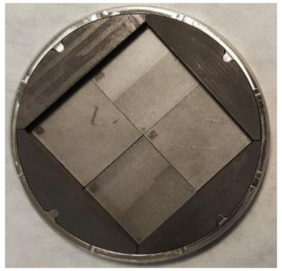

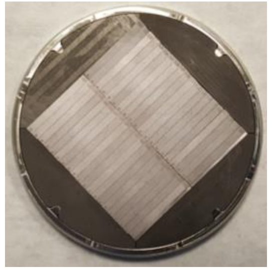

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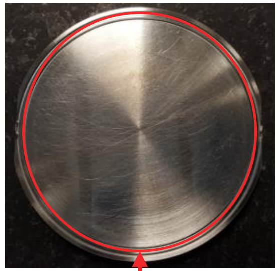

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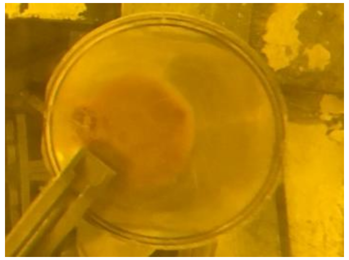

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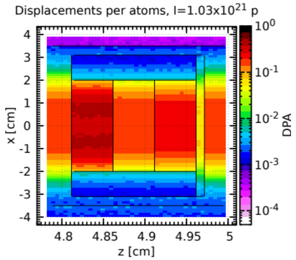

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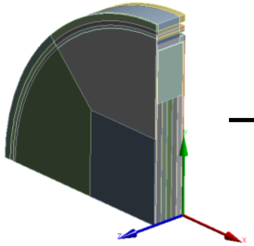

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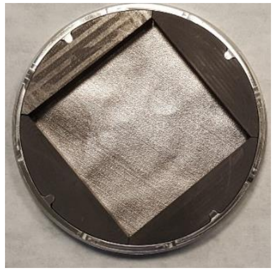
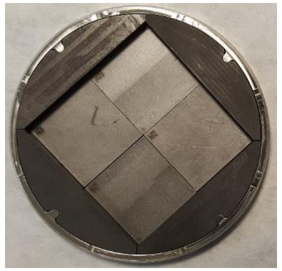
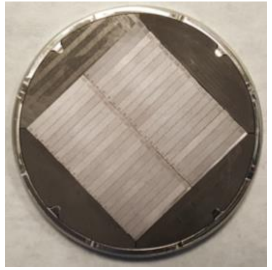
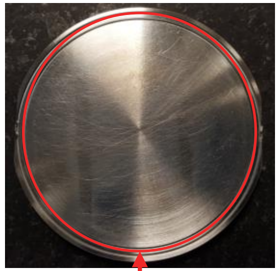

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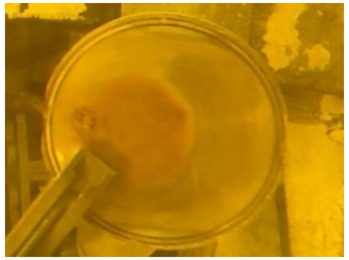


CERN2 Capsule: Computed dose sum @ 1m after 18 months cooldown ~4 mSv/h

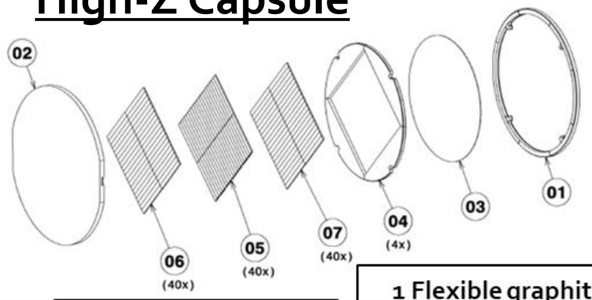
6. PIE ACTIVITIES

CERN2 Capsule → Design started in second half of 2017
PIE on some of the specimens will take place during 2020

[1]Courtesy K. Ammigan

An overview of the BLIP irradiation runs we launched

1. **<u>High-Z Capsule</u>**



40 bend bars each for CuCrZr, Ir, TZM

1 Flexible graphite sheet

- POT: 1.03E21
- Peak DPA: 2.75 (Ir)
- Max T_{irr}: ~850 °C

- CuCrZr, TZM → SPS Int. Dump
- Ir → AD-Target

- Capsule currently at PNNL
- Opening will take place in the coming weeks
- PIE → 4-point bending test

- A previous capsule suffered catastrophic damage and all the specimens were destroyed

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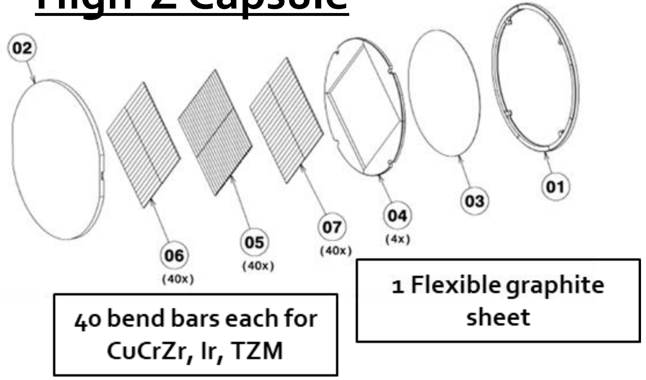

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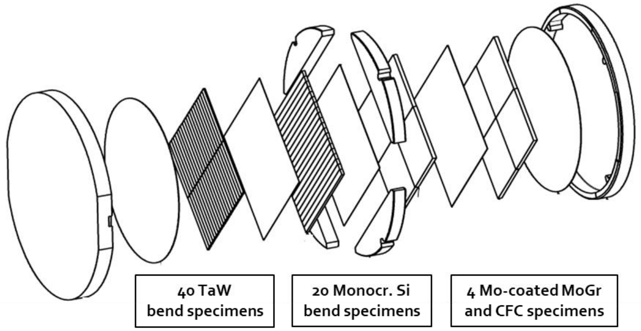

- POT: 2.8E21
- Peak DPA: 4.77 (Ta)
- Max T_{irr}: ~230 °C
- Mo-Coated MoGr and CFC → HiLumi Collimators
- Monocr. Si → SPS Dump

- Capsule currently at BNL
- Opening was scheduled for end of Mar-Apr. 2020 @ Framatome
- Restart of activities being planned in collaboration with BNL
- PIE → Coating visual inspection, adhesion test, 4-point bend test

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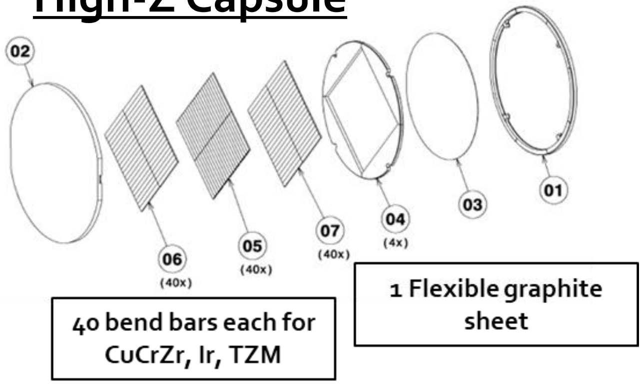

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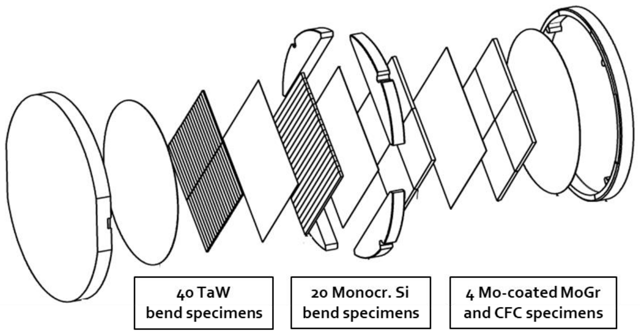

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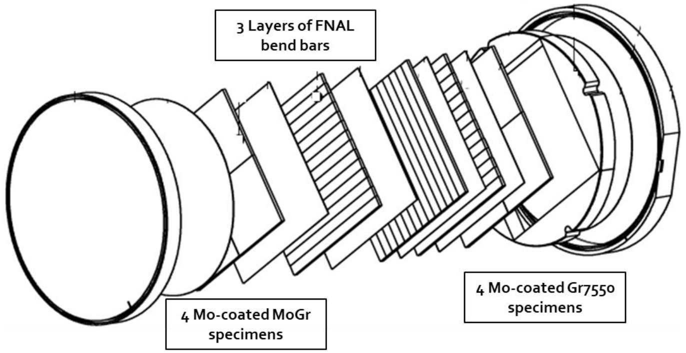
3. CERN3 Capsule (CERN/FNAL)



- POT: 7.5E21 (expected)
- Max T_{irr}: ~170 °C (CERN specimens)

- Mo-coated MoGr and Gr7550 → HiLumi Collimators
- Capsule construction under way at CERN
- Irradiation was scheduled to take place in May 2020, now scheduled for second half of 2020

An overview of some of the other RaDIATE activities

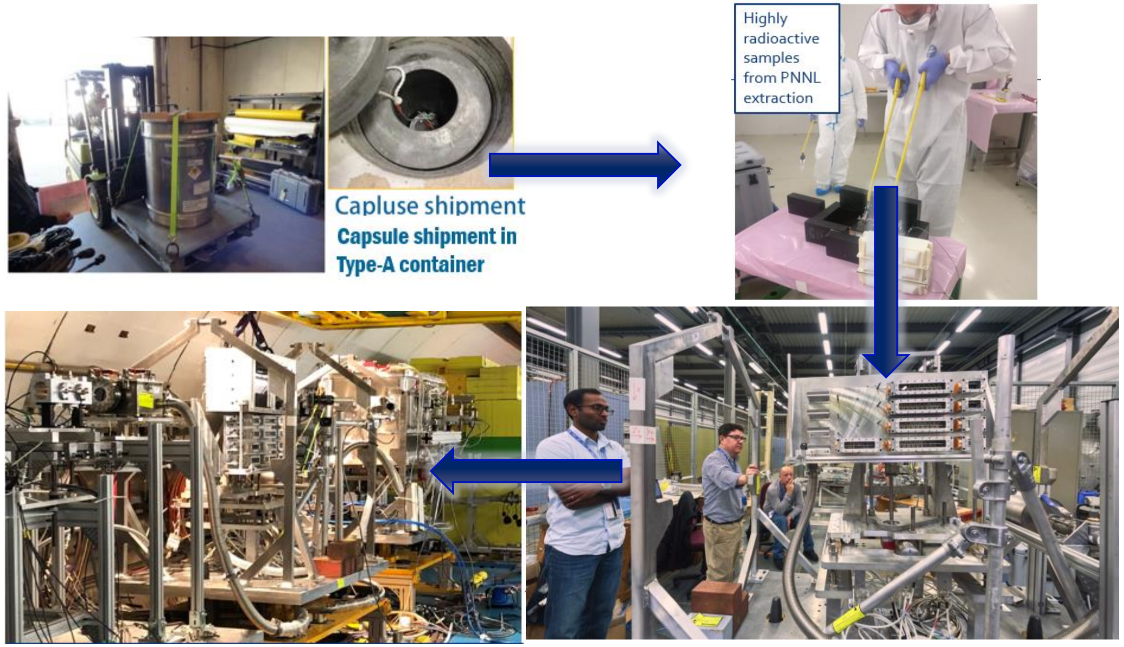
K. Ammigan (FNAL)

BeGrid2 (HRMt43) - Organization

Objectives →
- Identify **thermal shock response differences between non-irradiated and previously proton-irradiated specimens** from BNL BLIP:
  (Be, C, Ti-alloys, Si, SiC-coated C)

First and unique tests with pre-activated materials at HiRadMat

- Explore novel materials such as:
  - Metal foams (C, SiC)
  - Electrospun fiber mats (Al_2O_3, ZrO_2)



- Very complex coordination between BNL, FNAL, PNNL and CERN for handling of highly radioactive samples
- Real-time measurement of dynamic thermo-mechanical response of graphite specimens in an effort to benchmark numerical simulations
- Completed in Oct. 2018

K. Ammigan (FNAL)

BeGrid2 (HRMt43) - Organization

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(Be, C, Ti-alloys, Si, SiC-coated C)

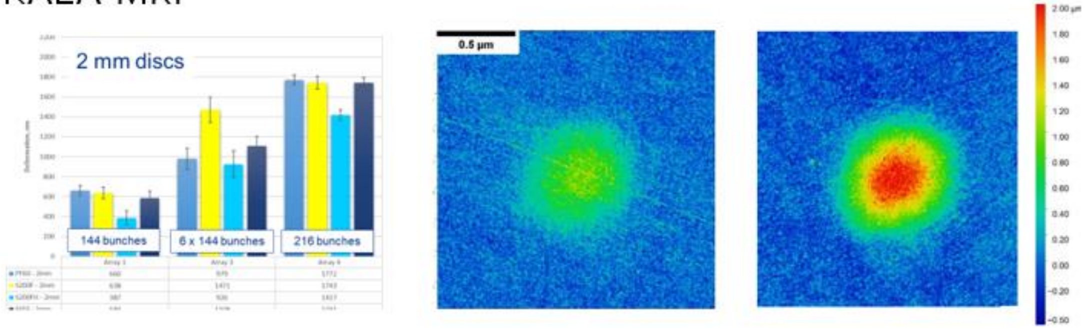
First and unique tests with pre-activated materials at HiRadMat

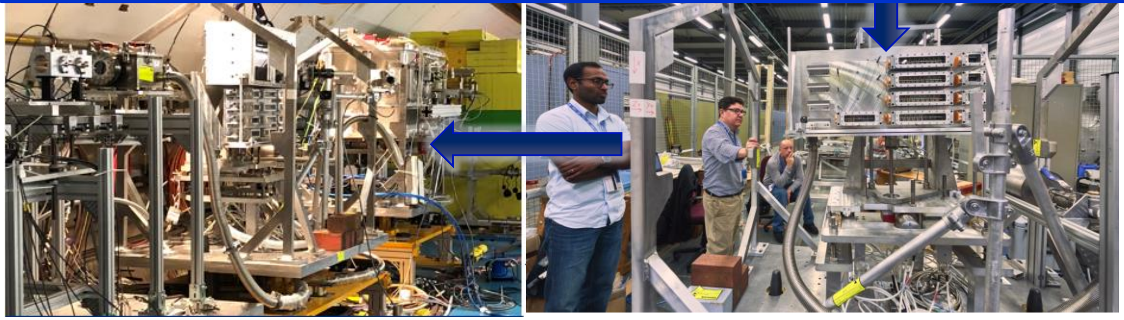
▪ Explore novel materials such as:

BeGrid2 (HRMt43) – Upcoming PIE at UKAEA-MRF

PIE of the HRMT high-dose-irradiated specimens carried out a UKAEA-MRF

- Topographic Raman Imaging
- Confocal microscopy in reflected light
- Fluorescent and Raman spectroscopy
- 3D layer mapping
- Profilometry
- SEM





- Real-time measurement of dynamic thermo-mechanical response of graphite specimens in an effort to benchmark numerical simulations
- Completed in Oct. 2018

S. Bidhar (FNAL)

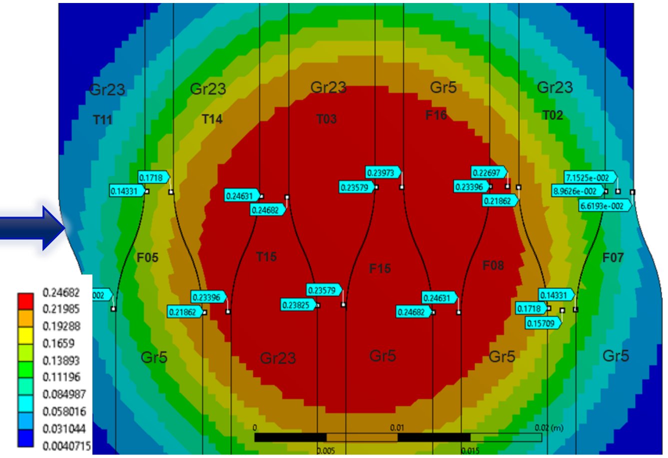
Fatigue testing of Ti alloys for FNAL T2K beam window (1/2)

- T2K's Ti beam window subjected to thermal shock-induced load cycles **AND** long-term proton beam irradiation damage

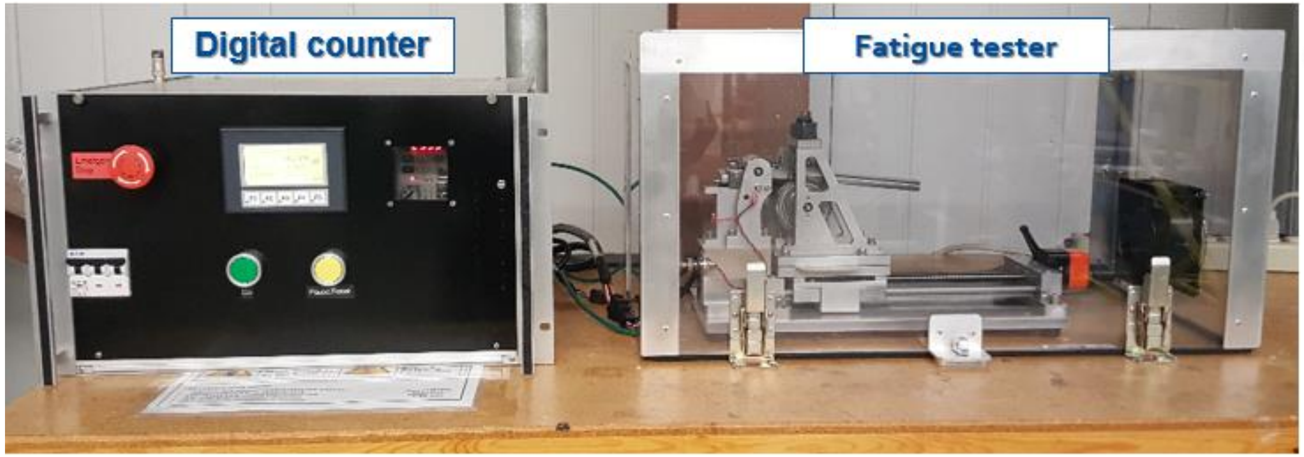
Ti bend specimens for fatigue testing

Ti specimens in BLIP capsule

BLIP capsule in capsule holder



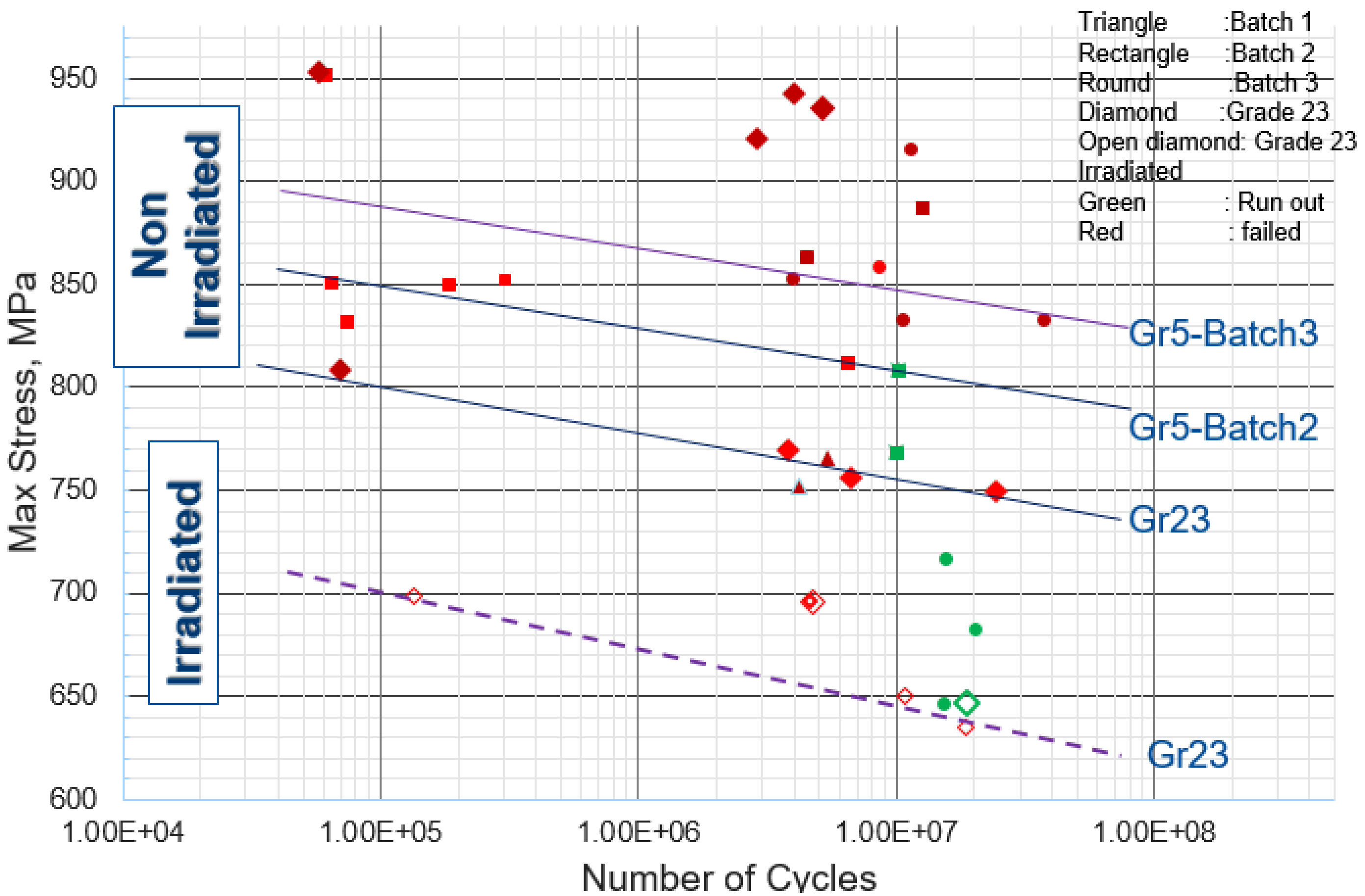
BLIP irradiation – dose map (DPA) on Ti specimens



FNAL custom-made Bending Fatigue tester

- Cyclic load frequency of 15 Hz
- Stress range of 375MPa - 1250 Mpa
- Automatically stops when sample cracks
- Ti Grade 5 and 23 tested
- Testing completed in Feb 2020

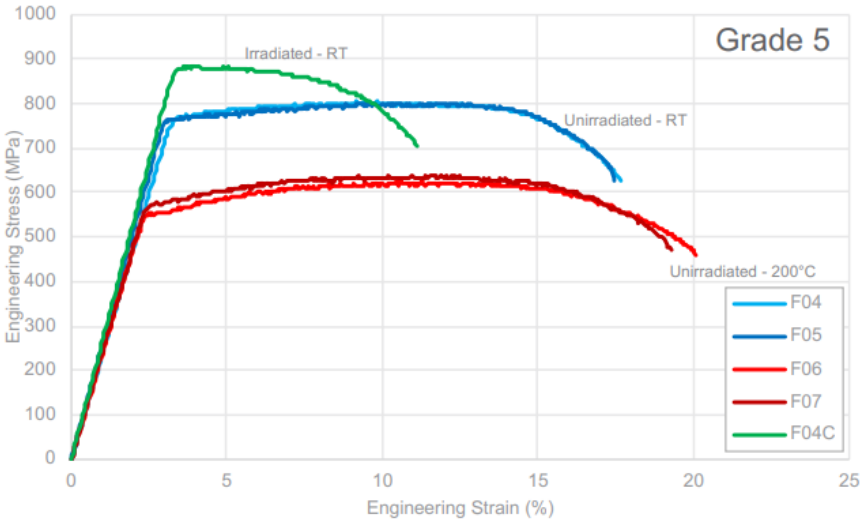
Fatigue testing of Ti alloys for FNAL T2K beam window (2/2)

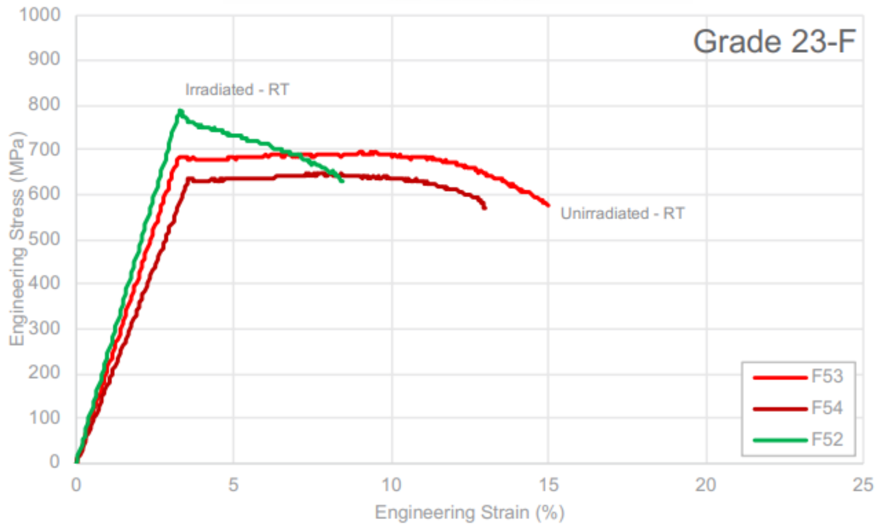


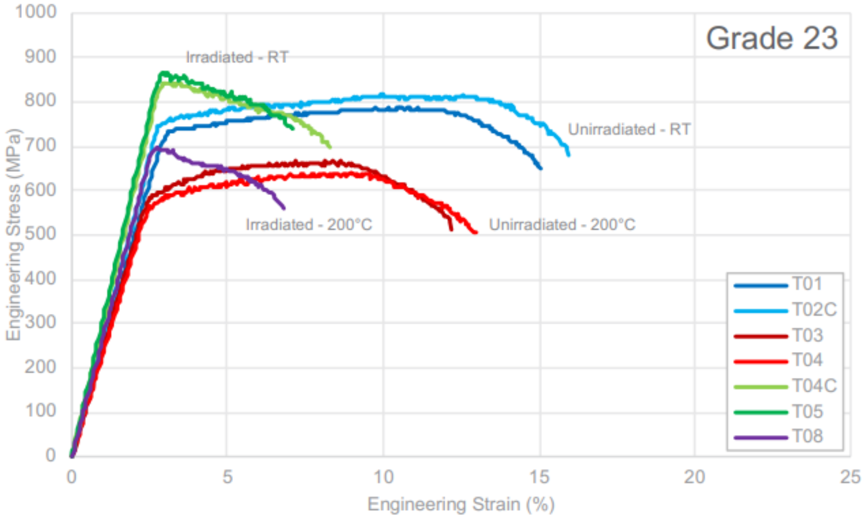
Similar slope between irradiated and un-irradiated specimens but decrease in the fatigue life for a given stress amplitude

D. Senor (PNNL)

Ti-base alloys tensile testing and microscopy







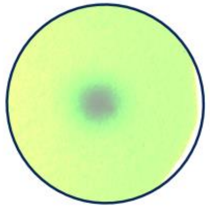
Distinct radiation hardening observed for each of the analyzed Ti grades

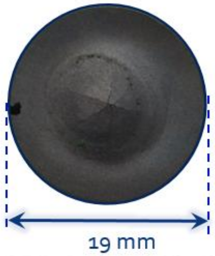
Radiation damage effects in Be

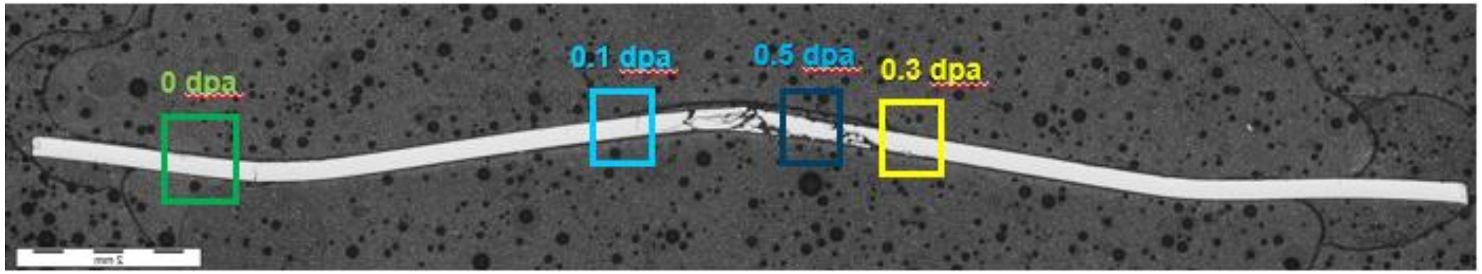
S. Kuksenko (UKAEA)

NuMI beam window:

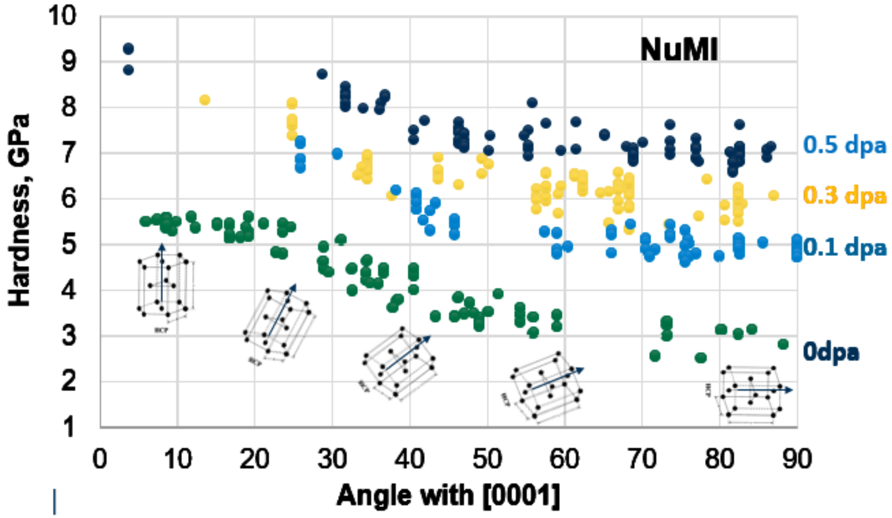
- 120 GeV proton beam
- 1.57×10^{21} protons during its lifetime
- Up to 0.5 dpa
- T ≈ 50°C







- **Significant hardening** is observed in the p-irradiated beryllium even at 0.1 dpa
- Hardening increases with irradiation to higher doses (at least up to 0.5 dpa)
- Hardness of the irradiated beryllium is less anisotropic



N. Solieri (CERN)

Development of ANSYS scripts for the implementation of radiation damage data

We need a way to easily implement the radiation damage to material properties data accumulated through the BLIP irradiations into ANSYS Workbench for the assessment of our devices

1. Importation of FLUKA-generated DPA map into ANSYS and its scaling to integrated intensity
2. Discretization into N DPA levels and generation of N corresponding materials
3. Implementation of law of degradation of material property with respect to DPA:
   - Thermal conductivity/expansion
   - Hardening
   - …
4. Assignment of material to element depending on DPA value at element centroid coordinates

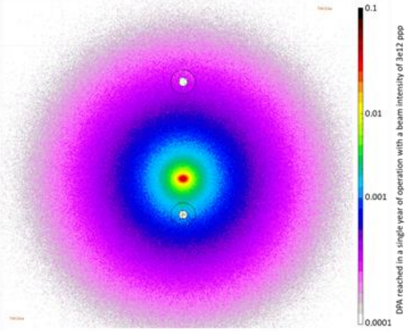
- Only adds a couple of minutes of computation time for typical size-models
- Already available for XYZ and RPZ binning

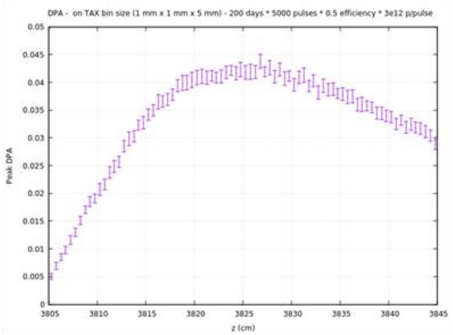
```
/PREP7

!****************************
!----- INPUT PARAMETERS ------
!****************************

FILENAME = 'E:\FLUKAf\TAXBDDPA.dat'  !FLUKA DPA FILE DIRECTORY

COMPNAME='TAX1'       !NAMED SELECTION IN ANSYS TO WHICH THE COMMAND WILL BE APPLIED


INTEGR_INTENSITY=2.4e19  !Integrated intensity for DPA scaling
DPAMINCUTOFF=0.001  !Minimum DPA, below which the script will not be applied
DPAMAXCUTOFF=0.72    !MAXIMUM DPA, TO WHICH THE DPA VALUES WILL BE CAPPED
NDISCR=100        !NUMBER OF DISCRETIZATION POINTS FOR EVALUATION OF MATERIAL
PROPERTIES


!READ THE FLUKA OUTPUT COORDINATE SYSTEM ---------------------------------------
*SET,SCALE LENGTH,1E-2  !Convert units of length from FLUKA to ANSYS (cm to m)
ALLSEL
*DIM,BINS,ARRAY,3,4


        *SET,NSKIP,8
        *SREAD,HEADER,FILENAME,,,,,NSKIP


        BINS(1,1)=VALCHR(STRSUB(HEADER(1,3),25,12))
        BINS(2,1)=VALCHR(STRSUB(HEADER(1,4),25,12))
        BINS(3,1)=VALCHR(STRSUB(HEADER(1,5),25,12))
        BINS(1,3)=VALCHR(STRSUB(HEADER(1,3),56,6))
        BINS(2,3)=VALCHR(STRSUB(HEADER(1,4),56,6))
        BINS(3,3)=VALCHR(STRSUB(HEADER(1,5),56,6))
        BINS(1,4)=VALCHR(STRSUB(HEADER(1,3),69,11))
        BINS(2,4)=VALCHR(STRSUB(HEADER(1,4),69,11))
        BINS(3,4)=VALCHR(STRSUB(HEADER(1,5),69,11))


! SET THE NUMBERS OF BINS IN EACH DIRECTION -----------

*SET,NX,BINS(1,3)
*SET,NY,BINS(2,3)
*SET,NZ,BINS(3,3)

! SET AND SCALE POSITION OF FIRST BIN IN EACH DIRECTION ------------------------

*SET,X1,BINS(1,1)*SCALE_LENGTH
*SET,Y1,BINS(2,1)*SCALE_LENGTH
```

Example – Th. Conductivity Degradation in first block of K12 TAX

- ❑ What would happen to the thermal conductivity of the C10300 in the first TAX block after 4 years of 4x intensity BD mode (integrated intensity 2.4E19)?

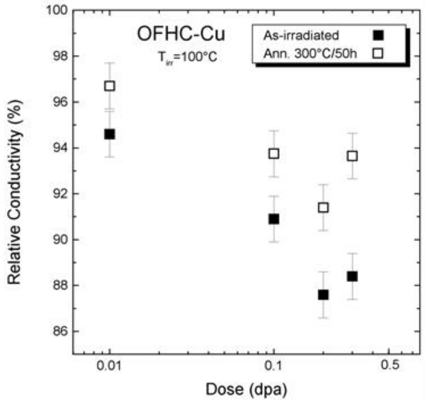
Evaluation of the DPA with FLUKA (scaled max DPA 0.4)





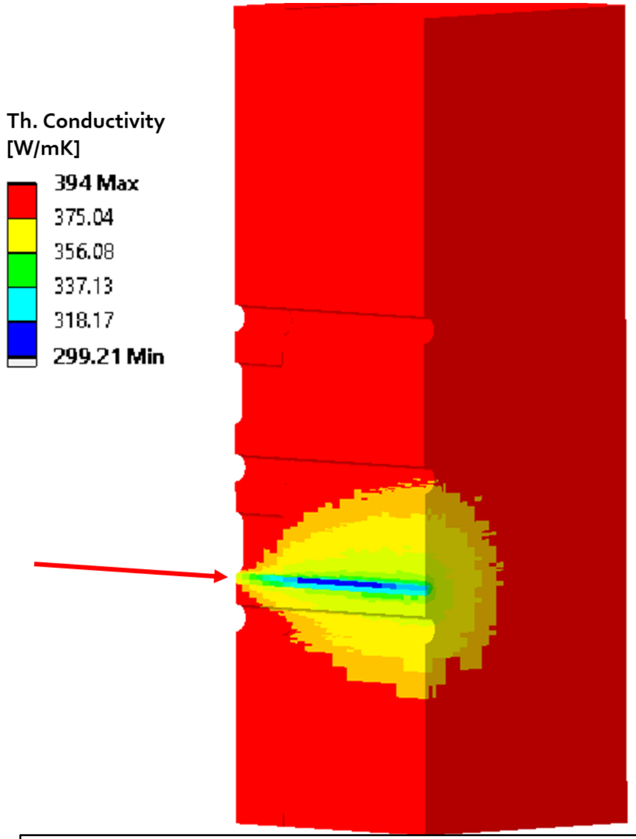
1

Derivation of law of variation of property with DPA from exp. data (neutrons)



2

APDL Script



24% peak reduction in Th. Cond!

[1]Courtesy A. Ciccotelli

[2]M. Eldrup, N. Singh, Influence of composition, heat treatment and neutron irradiation on the electrical conductivity of copper alloys

Conclusions & future outlook

- Proton-beam-induced radiation damage to materials is one of the main challenges in the design, operation of current and future BIDs

- BLIP Irradiations: assessing long-term radiation damage on materials that we employ in BIDs

- Two capsules will be opened during 2020:
  - High-Z Capsule → CuCrZr, TZM (SPS Internal Dump), Ir (AD-Target)
  - CERN2 Capsule → Mo-coated MoGr and CFC (HiLumi collimators)

- A new irradiation is scheduled for 2020:
  - CERN3 Capsule → Mo-coated MoGr and Gr7550 (HiLumi collimators)

- Plenty of results coming from RaDIATE work packages in the coming months

BACKUP SLIDES

Microscopic radiation damage effects

Three main effects of irradiation on the microstructure of structural materials:

1) **Structural changes from displacement and rearrangement of atoms**
    - Creation of vacancies and self-interstitials (and their recombination or clustering)
    - Growth of cavities (swelling), climb of dislocations (creep), microvoids
    - …
2) **Kinetic effects** → Radiation Enhanced Diffusion, Segregation and Precipitation (RED, RIS, REP)
3) **Transmutation** → Production of new atomic species. Production cross sections are highest for light transmutants (H, He)
    - *Displacement cross section σ_{dpa}* → Above 20 MeV (for Fe) only very slightly increases with energy
    - ***H and Helium production cross section σ_{α}*** → **Continuously increasing with energy**

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
[1] High energy proton beam	6×10^{-3}	1×10^{3}	100-800

[1] P. Hurh

Microscopic radiation damage effects

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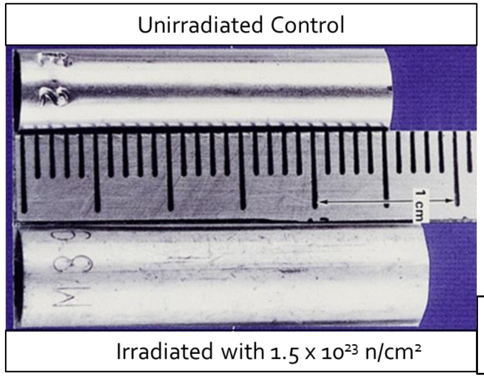
	Mixed spectrum			
1	High energy proton beam	6 x 10^{-3}	1 x 10^{3}	100-800

Effects from low energy neutron irradiations do not equal effects from high energy proton irradiations (transmutation)

[1] P. Hurh

Radiation damage effects on macroscopic material properties

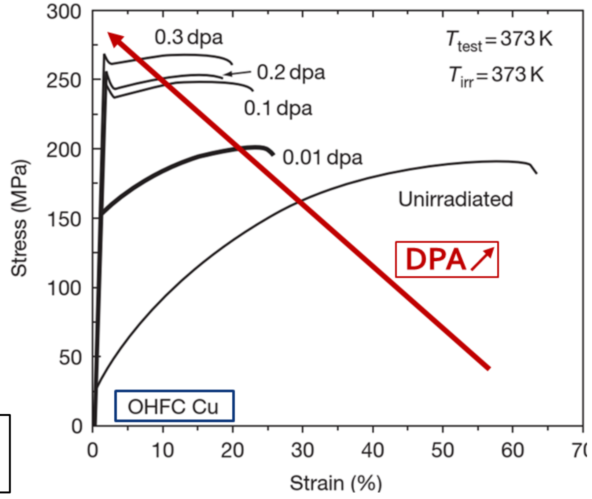
- **Dimensional Change and associated reduction of density**



1

E.g. SS316

- **Reduction of thermal/electrical conductivity and thermal expansion**
- **Hardening and embrittlement**



2

- Loss of ductility
- Hardening
- Reduction of fracture toughness, change of fracture mode from ductile to brittle

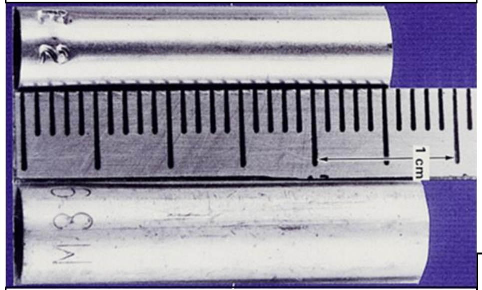
- Irradiation embrittlement → Mostly due to pinning of dislocations by irradiation induced dislocation loops, precipitates, cavities or bubbles
- H and He embrittlement
- Accelerated corrosion

[1]K. Whittle, Radiation Damage, Ch.2
[2]M. Li, S. J. Zinkle, Physical and Mechanical Properties of Copper and Copper Alloys, Comprehensive Nuclear Materials, vol.4 (2012)

Radiation damage effects on macroscopic material properties

- ❑ **Dimensional Change and associated reduction of density**

Unirradiated Control

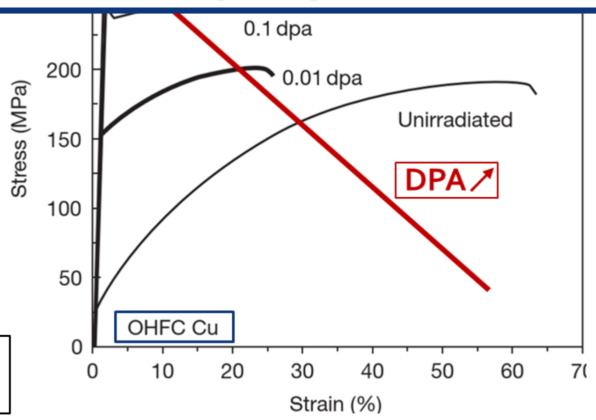


Irradiated with 1.5 x 10^{23} n/cm^2

1

- ❑ **Reduction of thermal/electrical conductivity and thermal expansion**

Thermo-mechanical response of BIDs heavily depend on material properties, but material properties heavily dependent upon Radiation Damage



2

- ❑ Hardening
- ❑ Reduction of fracture toughness, change of fracture mode from ductile to brittle

- ❑ Irradiation embrittlement → Mostly due to pinning of dislocations by irradiation induced dislocation loops, precipitates, cavities or bubbles
- ❑ H and He embrittlement
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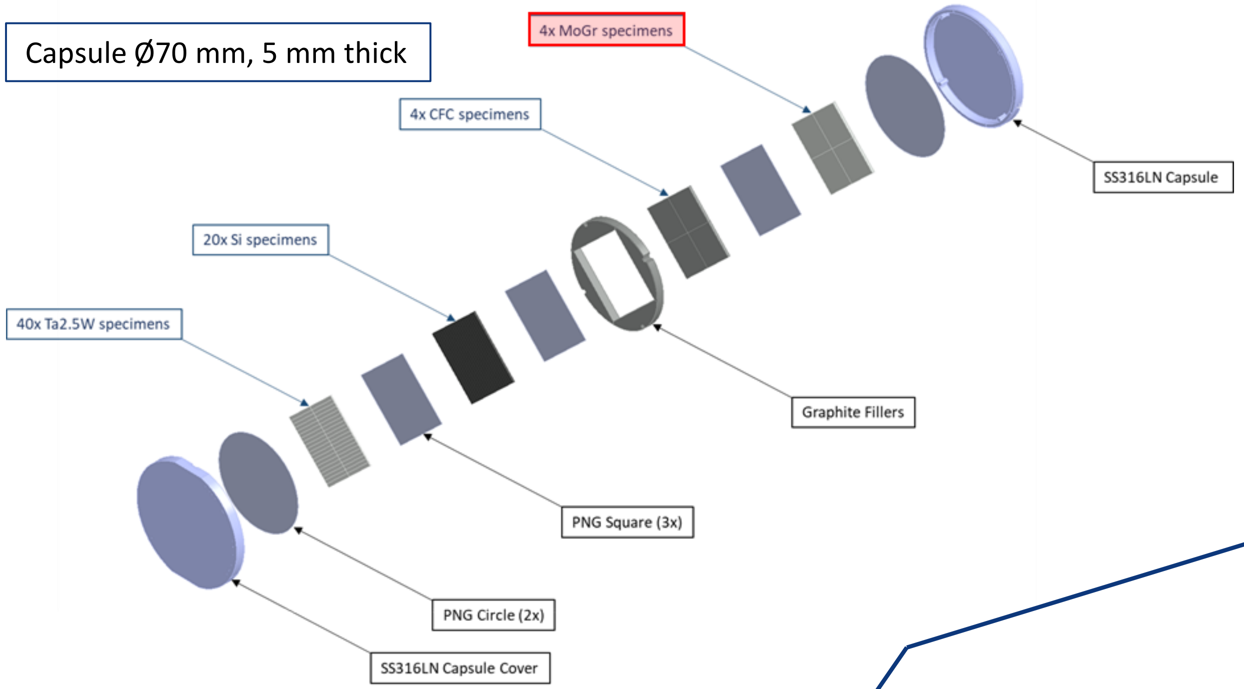
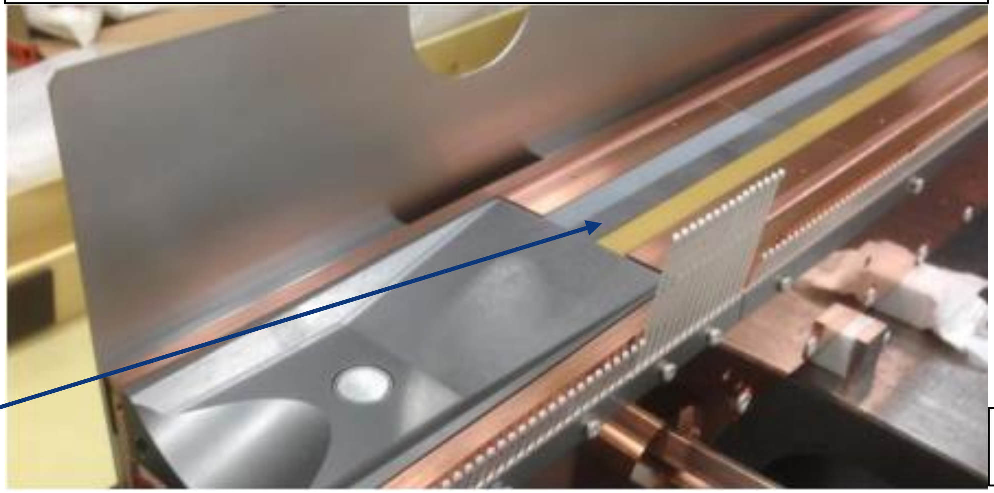
The CERN2 capsule



TCSPM Prototype



1

- ❑ <u>Stainless steel welded capsule containing</u>:
  - 40x Ta2.5W specimens (BDF Target)
  - 20x Monocrystalline Si specimens (SPS Int. Dump)
  - 4x Mo-coated CFC specimens (HiLumi Collimators)
  - **4x Mo-coated MoGr specimens**
  - Panasonic graphite foils
  - Graphite fillers

	Primary MoGr collimators		CERN2 MoGr
	Left	Right	
POT	~ 1E17		2.8E21
DPA (peak)	0.15	0.18	0.154
He appm	110	130	101
He appm/DPA	600-1000	600-1000	1759

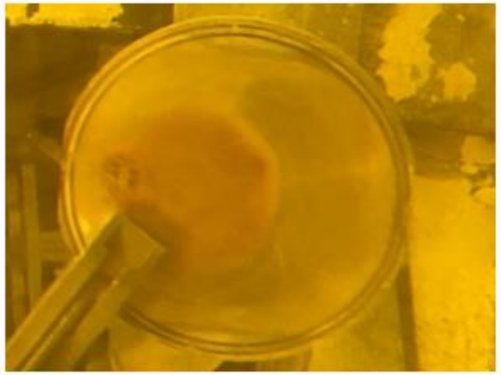
2

[1]Courtesy I. Lamas

[2]A. Waets, FLUKA simulations on residual gas production in IR7 collimators, ColUSM 20/09/2019

Scope of the Contract – Baseline activities

CERN rules →
- ❑ Technical specification for the activities
  - ❑ Tendering procedure for companies who have experience in the field
    - ❑ Awarding of contract: **Framatome GmbH (DE)**


Current status of the capsule at BNL

1. Shipment of the capsule to the contractor's facility (Capsule currently at BNL, USA)
2. Opening of the capsule:
   a) Preparation of opening procedure. Evaluation of applicability of opening procedure when the CERN2 irradiated capsule is unloaded in the hot cell
   b) Validation of opening procedure on spare CERN2 capsule supplied by CERN
   c) Extraction of the specimens by means of vacuum tweezers
   d) Sorting and storage of the specimens
3. PIE activities:
   a) Visual inspection on **4 Mo-coated MoGr and 4 Mo-coated CFC specimens**
   b) Test adhesion of the coating on **2 Mo-coated MoGr specimens**
4. Transport of all the specimens from contractor's facilities to CERN

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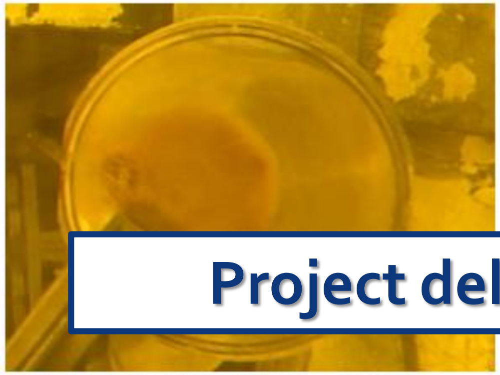

Current status of the capsule at BNL

1. Shipment of the capsule to the contractor's facility (Capsule currently at BNL, USA)
2. Opening of the capsule:

hen

Project delayed due to COVID but now on track to completion during 2020

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