HiRadMat and Beam Tests Experiments for High Power Targetry at CERN

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CERN | EN ENGINEERING DEPARTMENT

Outline

1) Introduction to the **STI Group, CERN's HiRadMat Facility and TCC2 Line**

2) Executed Experiments applied to Targetry R&D at CERN

HiRadMat (fast extracted beam)

1) HRMT-27 Experiment
2) HRMT-42 Experiment
3) HRMT-48 PROTAD Experiment
4) HRMT-46 nTOF Experiment

Applied to the **Antiproton Production** Target

Applied to **Neutron Production** Target

Dedicated Setup in TCC2 line (slow extracted beam)

5) BDF prototype tested in CERN's North Area

Applied to Target-Dump for **Production of weakly interacting particles**

3) Conclusions

STI Group at CERN's Engineering Department

1. **S**ources, **T**argets and **I**nteractions Group has the mandate to study the **interactions of beam with matter**, aiming to apply its know-how to [...] particle interception such as **targets**, **collimators**, **absorbers** and **dumps**

2. Responsible for the design, construction, operation and maintenance of the respective HW equipment in the accelerator complex → focus on **physics**, **reliability** and **performances**

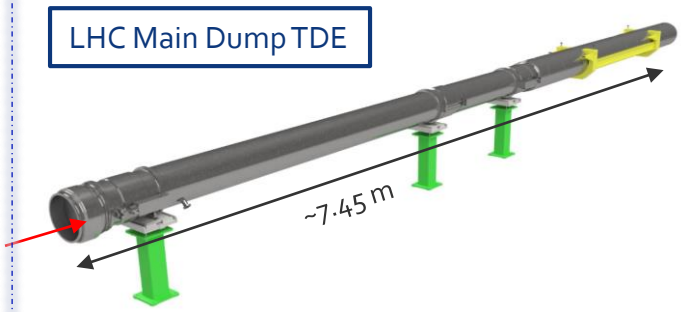
3. Experience and upgrade scenarios in the recent years calls for use of absorbing materials in unprecedented regimes of operation

   Tests in the HiRadMat facility is a fundamental asset to reduce risks whether they are project or operational driven

A few examples of Group Responsibilities

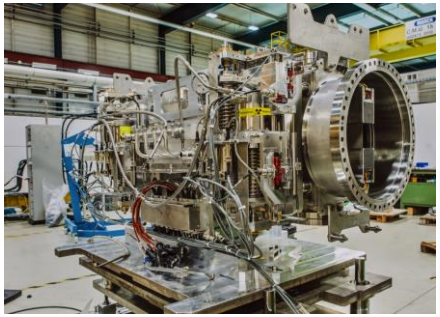
Dumps/Absorbers

LHC Main Dump TDE



SPS internal beam dump TIDVG4

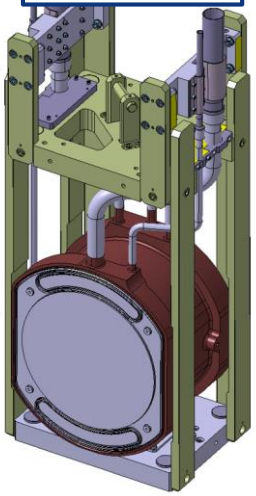
LHC Injector Absorbers TDIS



Targets

AD-Target

n_TOF Target



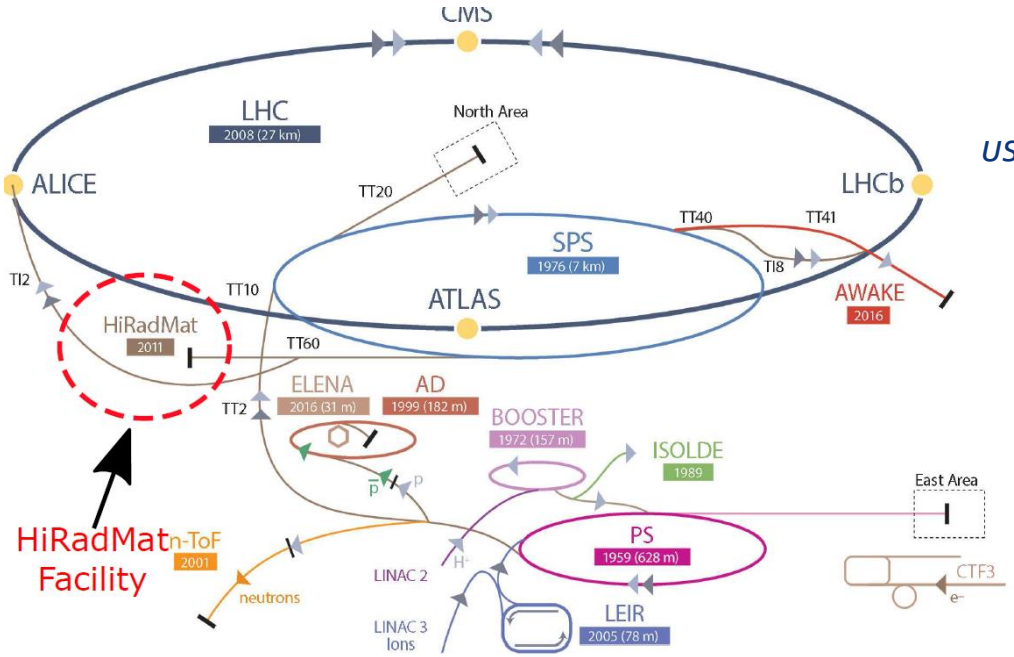
BDF Target Prototype (SHiP)

ISOLDE Targets

Collimators

Injection Line Collimators TCDIL

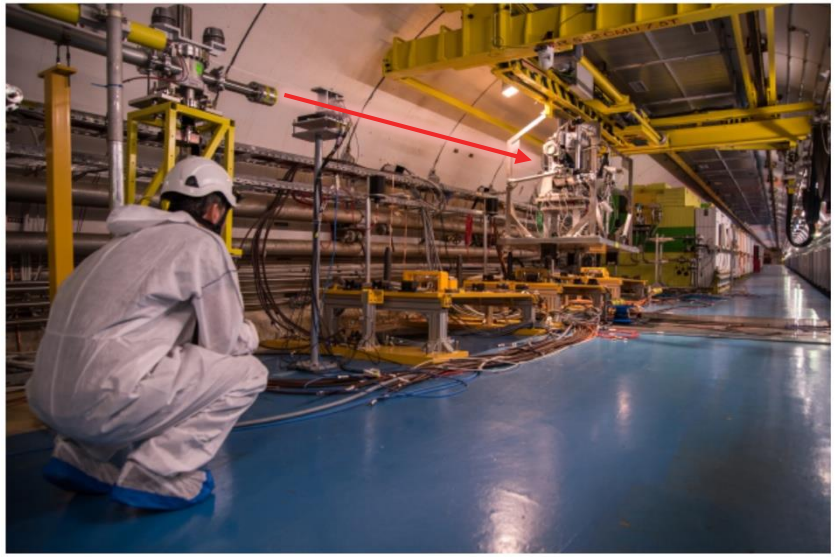
What is the CERN's HiRadMat facility?



HiRadMat
High-Radiation to Materials

*HiRadMat (**Hi**gh-**Rad**iation to **Mat**erials) is a users facility, designed to provide **high-intensity pulsed beams** to an irradiation area where material samples as well as accelerator component assemblies can be tested*

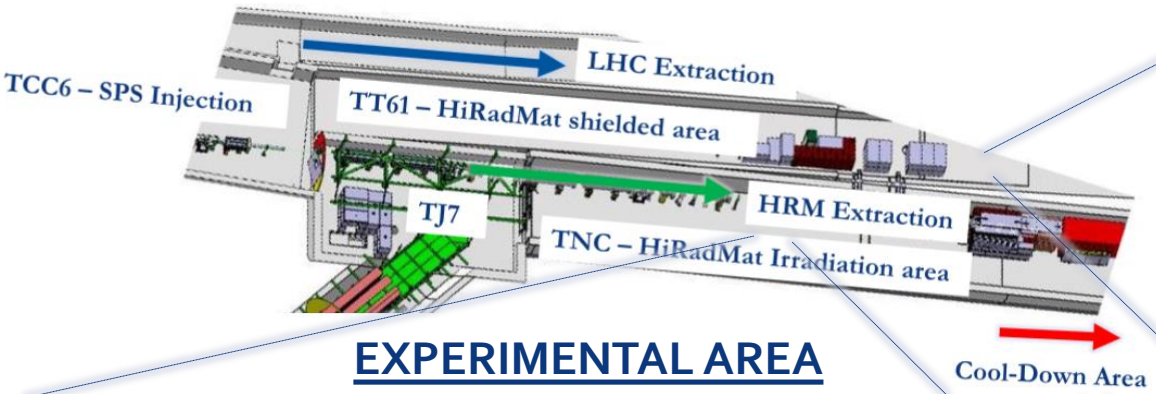
- First beam in 2012.
- Over 40 experiments executed since then.



440 GeV/c Proton Pulses from the SPS, fast extraction, with a wide flexibility in beam parameters:

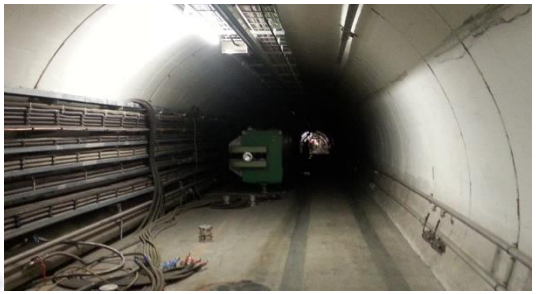
- Intensity: $5.0 \cdot 10^{9}$ - $3.5 \cdot 10^{13}$ protons per pulse
- Pulse Length: 5 ns - 7.75 µs
- Beam Radius (1 σ r.m.s): 0.25 mm - 4 mm

Characteristics of the HiRadMat Experimental Area



TT61- Shielded Area

- Service Systems (vacuum pumps, lights)
- DAQs for Online Instrumentation



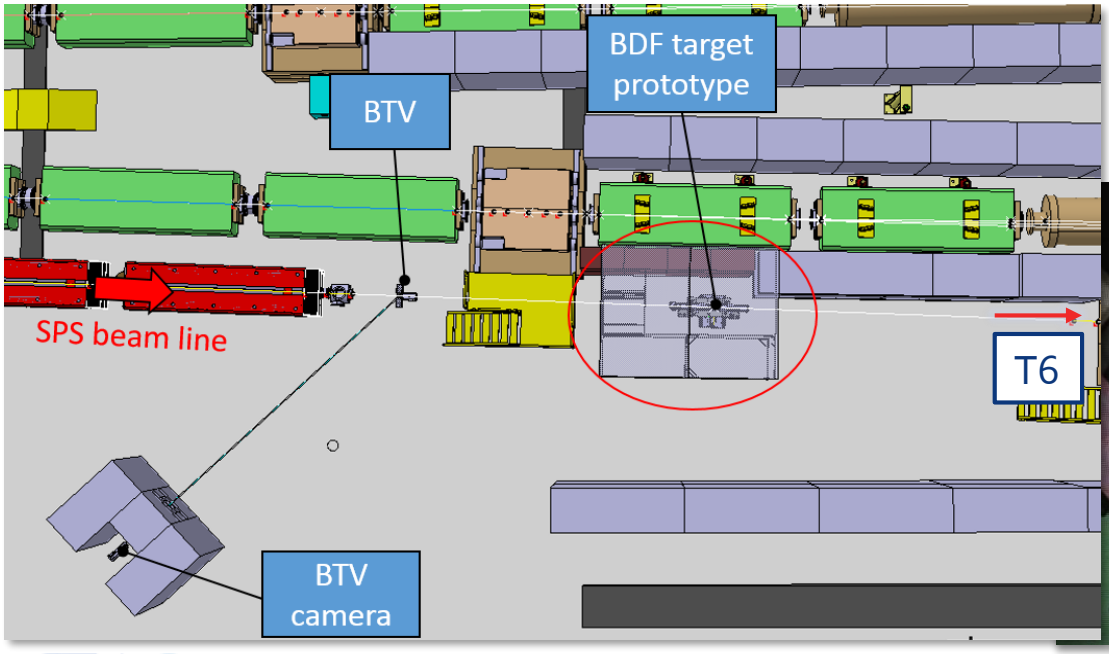
EXPERIMENTAL AREA

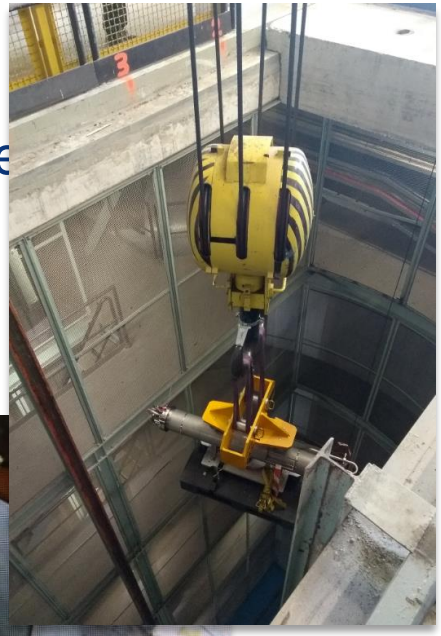
Cool-down Area

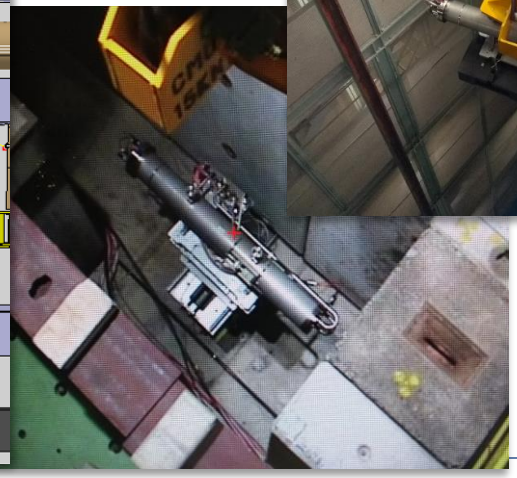
Ad-hoc Testing Area for BDF in TCC2

Fully dedicated experimental setup in TCC2 (North Area)

- Representative beam tests → **SPS high inte**
- Slow extraction required (1 second spill)
- Remote Installation
- Dedicated Beam instrumentation and water cooling syste





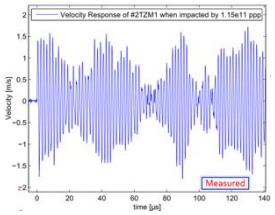


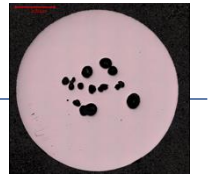
Type of experiments for Targetry R&D

1) **Material and manufacturing processes R&D**
   1) Study in detail the performance of innovative materials or the behavior of well known material against unprecedented beam impacts

2) **<u>Integral testing</u> of prototyping equipment**
   1) **Validating the global response of a mechanical assembly to impacts**
   2) Important to validate <u>system-wide mechanical assembly</u> and potential deformations which might lead to performance reduction in operation

- Crucial importance given both to:
  - **1) Real-time measurements**
  - **2) Post-irradiation Experimentation**





Challenges of the Targetry Experiments

1) Specification of Beam Parameters and Targets Geometry

- The fixed proton beam energy of 440 GeV/c is, quite often, not the one with which the targets in question are operating.
- Intensity, pulse length, beam size and targets geometry have to be carefully selected.
- **Goal:** Recreate analogous conditions (Temperature, stresses..) while obtaining a measurable response.

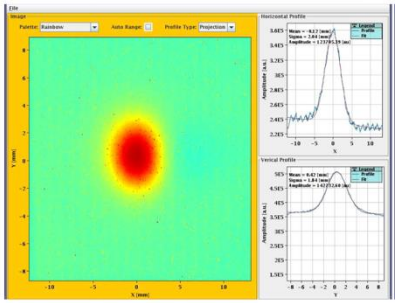
2) Instrumentation

Iterations…

- What to measure? Where?
- How? Instrumentation limitations (acquisition rate, magnitude, temperature)
- Prompt Radiation damaging electronics

3) Mechanical Precision, Alignment and Beam Position Monitoring

- Impact location accuracy (~0.5 mm)
- Knowing impact parameters for simulations crosscheck



About **1-1.5 years** to design, manufacture and execute one experiment

HiRadMat Experiments Executed by STI

1) **Experiments applied Targets and Dumps**
   - **HRMT 27/42/48** for antiproton target materials (Ta, Ir, etc.)
   - **HRMT46** for n_TOF spallation target (pure Pb)
   - **HRMT49** for TIDVG5 (polycrystalline Si block)
2) **Experiments applied to Collimators** **(response to project requirements for uncharted beam intensities (LIU & HL-LHC requirements)**
   - **HRMT28/44** for LIU SPS-to-LHC transfer line collimators (3D CC)
   - **HRMT18** for crystal collimation
3) **Experiments applied to Absorbers**
   - **HRMT35** for coated collimators materials (operational-driven)
   - **HRMT45** for HL-LHC injection dump (TDIS)
4) General material R&D
   - ***HRMT24/43*** *supporting Fermilab team*

11 experiments in total executed in 3 years

Example of HiradMat Experiments applied to Targetry

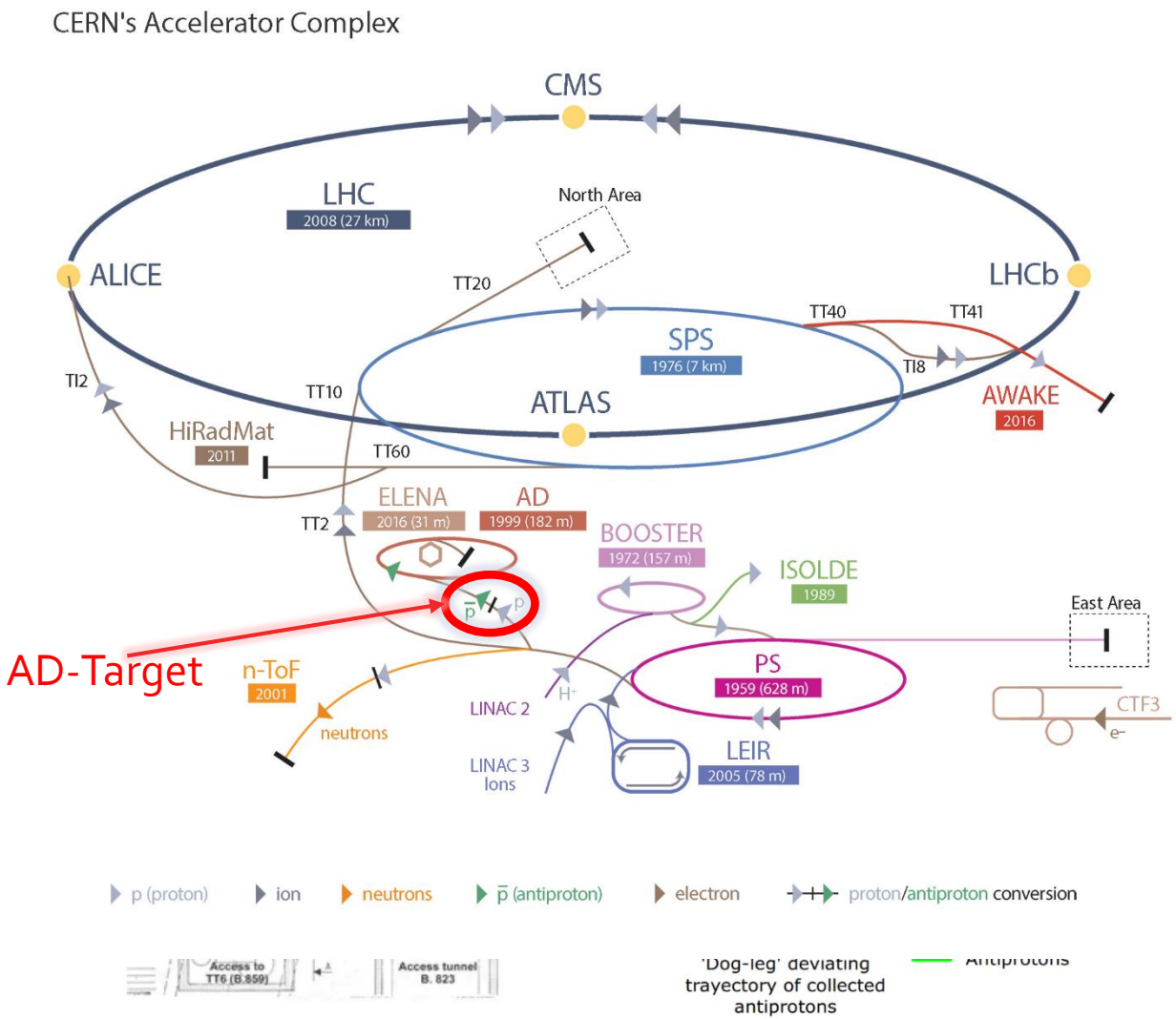
1) **AD-Target (antiprotons production) -> HRMT-27/42/48**

   (Refractory metals; Ta, Ir, W, Mo)

2) **n_TOF Target (neutron production) -> HRMT-46**

   (pure Pb)

The CERN's Antiproton Target (AD-Target)



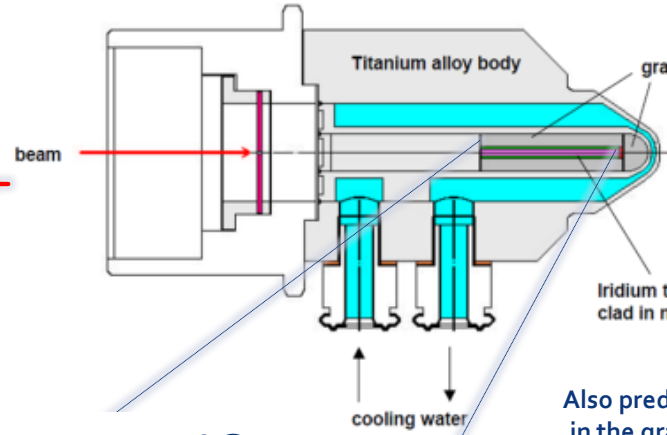
- Renovation of the Area taking place CERN's Long Shut Down 2 (2019-2021)

Conditions reached in the AD-Target

(Current/old Design)

Beam coming from the PS

- 26 GeV/c
- Primary beam
  0.5 mm x1mm
- 1.45e13 ppp
- **430 ns pulse length**

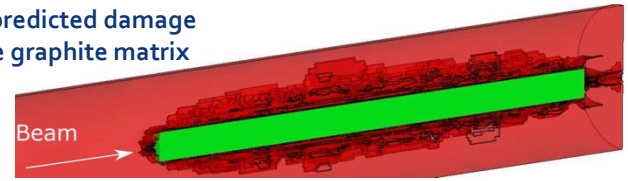


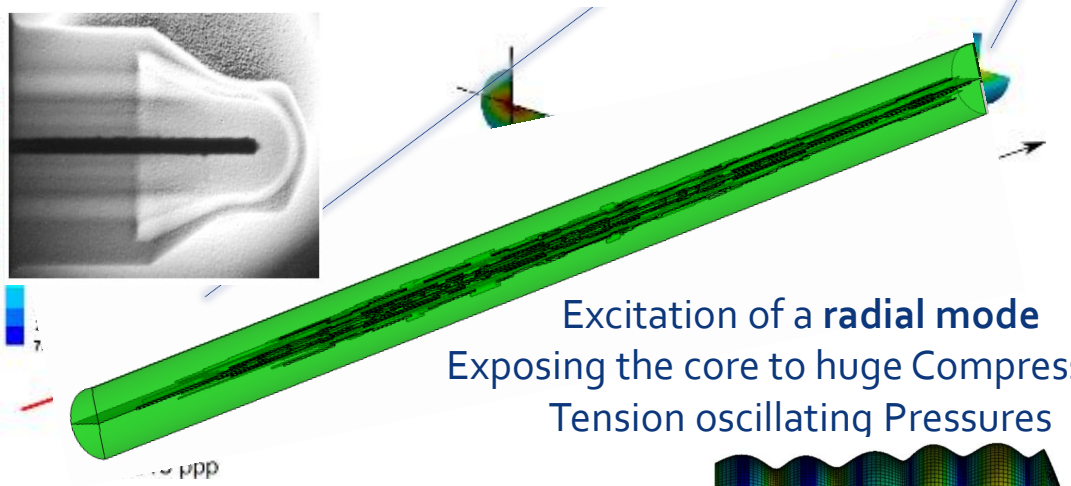
Target core made of
ø 3 mm x 55 mm length
rod of **Iridium**
$\rho = 22.5\ g/cm^3$

Oscillatory nature of the response

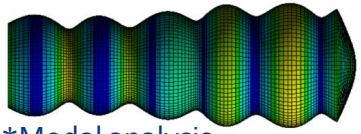
S Adiabatic ΔT at target core > 2000 °C e

Also predicted damage in the graphite matrix

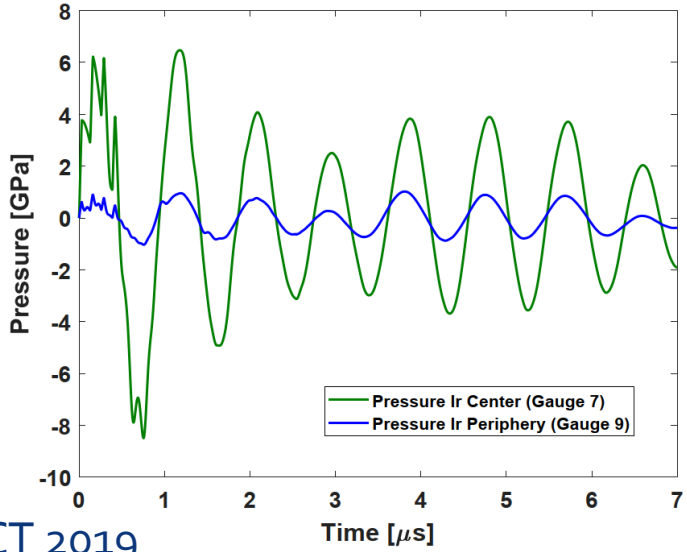




Excitation of a **radial mode**
Exposing the core to huge Compressi
Tension oscillating Pressures



*Modal analysis



Phys.Rev.Accel.Beams19,073402

Particularities of the AD-T Operation

Target core is **subjected** to **extreme dynamic stresses** induced by:

1) high-density core
2) Very focused primary proton beam
3) Very short pulse
4) Small core diameter

Mean "instantaneous" power density of **$3 \cdot 10^4$ TW/m^3**

Max ΔT in the core per pulse = 1800-2000 °C

Excitation of radial mode, **exposing the core to tensile pressures of several GPas**

Fracture of core material may have a **direct influence in pbar production** due to loss of effective core density. <u>In addition, damage of graphite matrix</u>

R&D Activities to **study the response of refractory metals at such conditions**

1) Numerical Simulations: Use of hydrocodes
2) **HRMT-27 Experiment (2015)**
3) **HRMT-42 & HRMT-48 PROTAD Experiments** -> Prototyping

Validate simulations & investigate new candidate material

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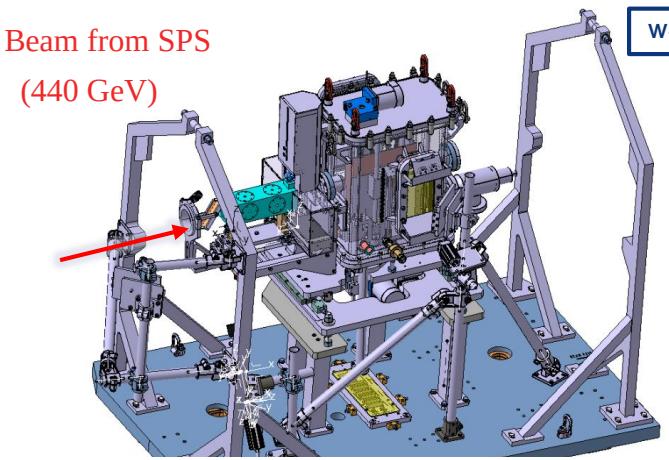
The HRMT-27 Experiment (2015)



- 13 rods of high-Z materials impacted by 440 GeV/c beam
- Irradiation performed in a **ramped** way to obtain material response at intermediate state before reaching AD-Target conditions

Results:

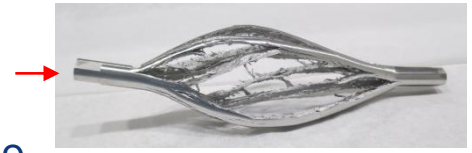
1) Extensive online data recorded and crosschecked with simulations

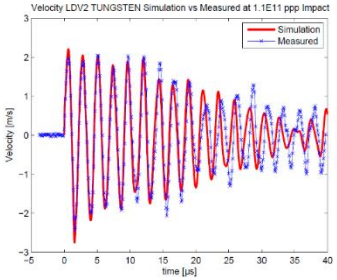
2) Deeper understanding on <u>excitation of radial, longitudinal and bending modes</u> in rods impacted by proton beam impacts

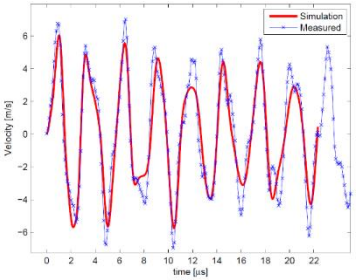
3) Different response of refractory metals

Ta -> ductile deformation (no cracks)

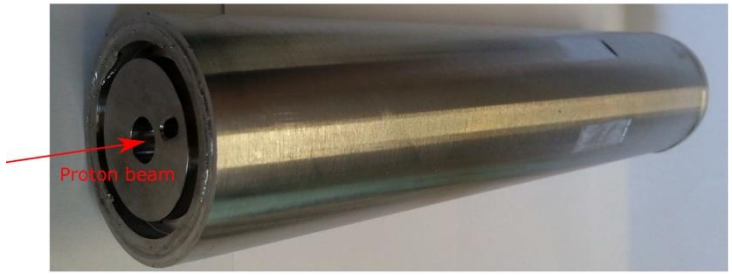
Ir -> Massive fragmentation

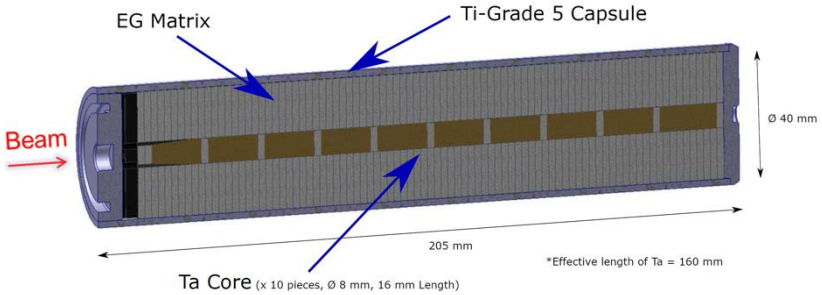


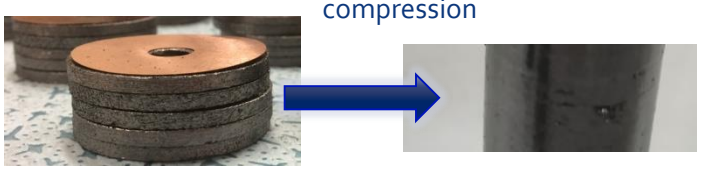




HRMT-42 Experiment (2018)



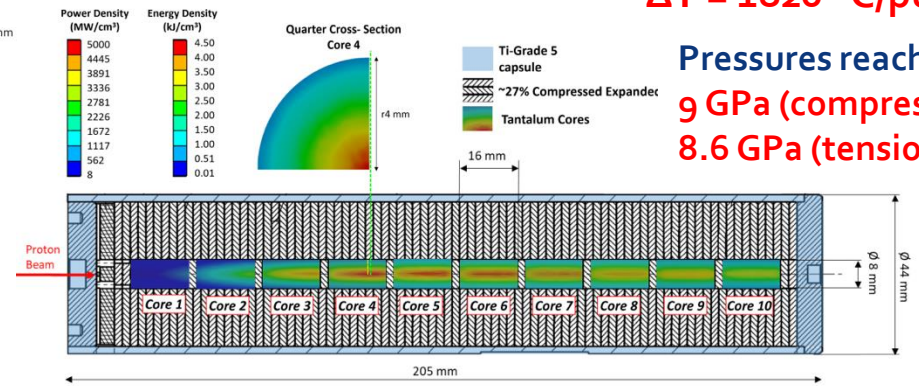




- **Core of 8 mm diameter Ta rods**
- Effective Ta length of 160 mm
- Ta core embedded in a matrix made of compressed layers of **Expanded Graphite (EG).**
- Encapsulated in a 2 mm thickness Ti-6V-4Al e-beam welded container

ΔT = 1820 ºC/pulse

Pressures reached:
9 GPa (compression)
8.6 GPa (tension)

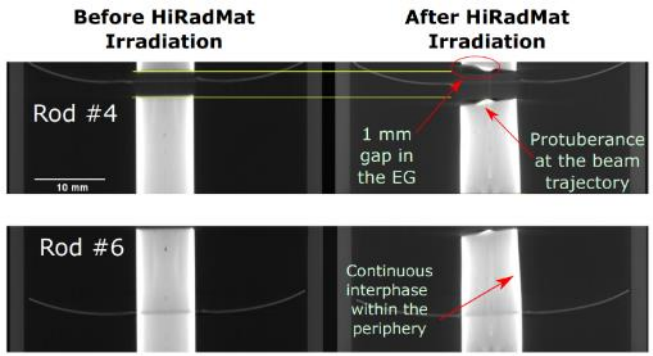


Questions to be answered by the experiment:

1) Survival of Ta when impacted by high no. of pulses?
2) Avoid target bending when sliced?
3) Behavior of Ta-EG interface. Appearance of gaps due to the radial wave?

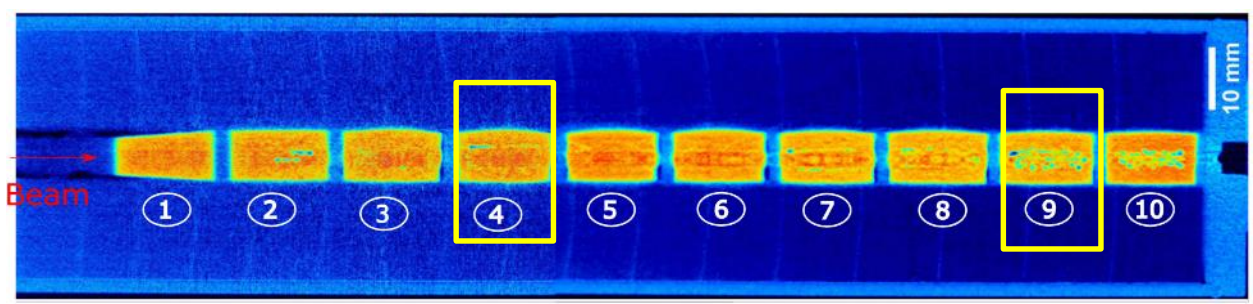
HRMT-42 Non-Destructive Examinations

X-ray tomography at the ESRF (Grenoble, France)



- Extensive plastic in the Ta

Neutron Tomography at NEUTRA (PSI, Switzerland)

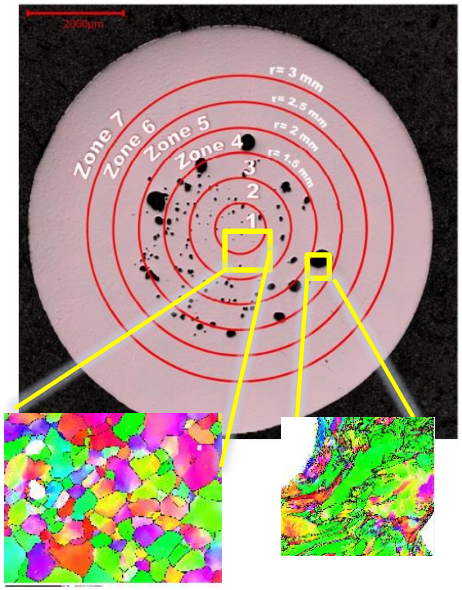


1) **Most of the Ta cores are full of voids, and they are big!**

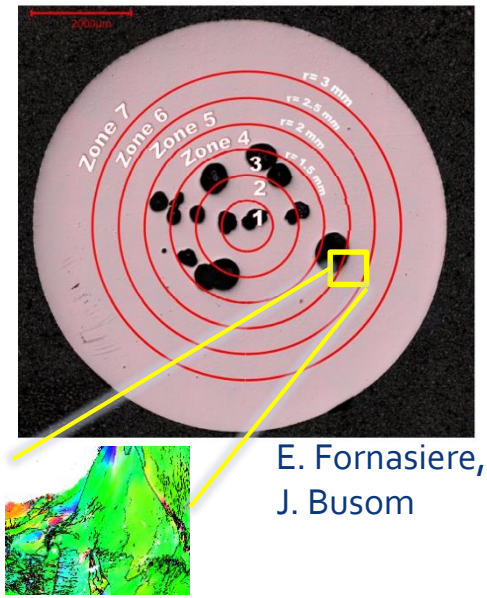
1) **The most loaded rods (T and tensile pressure) are not necessary the most damaged…**

Spalling fracture induced in the Ta Core

Core #4 (Most loaded in terms of T and tensile Pressures)



Core #9



E. Fornasiere, J. Busom

1) Evident change in the voids size and distribution between rods.

2) **Recrystallization** took place in the some areas of some of the rods..

Spalling was induced as a progressive process, consequence of hundreds of oscillations of the radial mode per pulse

The use of proton beams impacts as dynamic loading method revealed unprecedented modes of dynamic fracture

Not monotonic influence of Pressure and Temperature in spall voids growing and coalescence process:

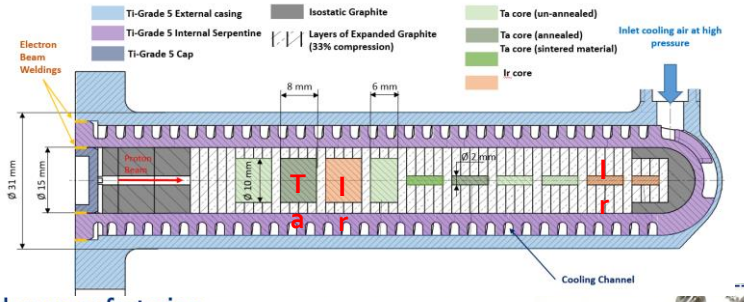
2) Region with enhanced coalescence

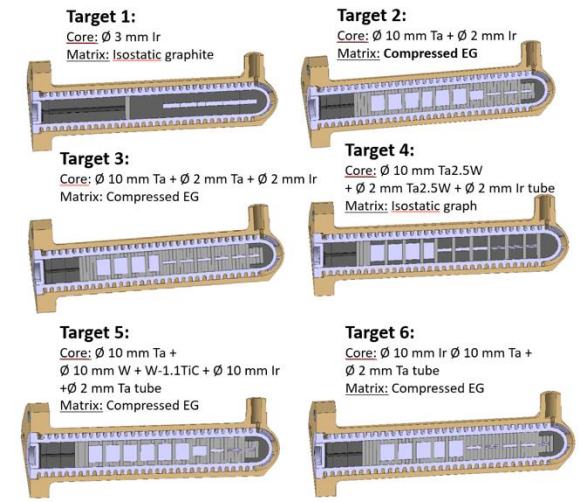
3) Region with limited void growth

HRMT48-PROTAD Experiment

Goal: Testing New AD-Target Design (PROTAD)

- Cooled by Air
- Different core materials/geometry configurations





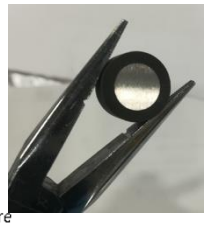
Ta-Degraders manufacturing

- Ø28 mm Ta cylinder press fitted and EBW sealed in Ti-Grade 5 cladding
- Inserted in SS + Ti-Grade 5 windows air cooled capsule

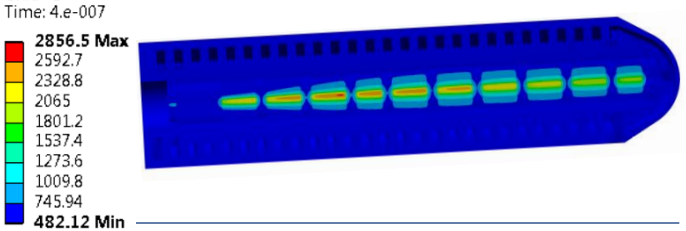
PROTAD Targets manufacturing

1) Ti-grade 5 external envelopes manufactured at CERN
- x6 two/parts machined and EBW
- x2 3D-Printed

2) Filled with the **high-Z cores** and **isostatic graphite or pre-compressed EG matrices** respectively

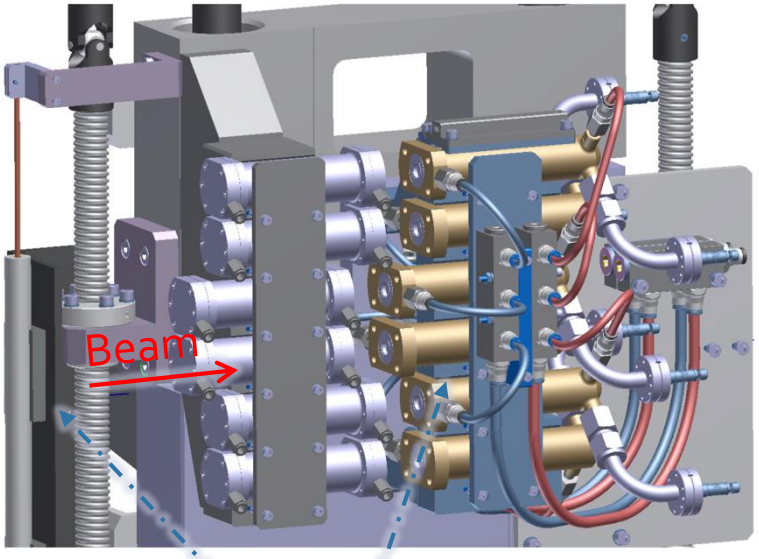


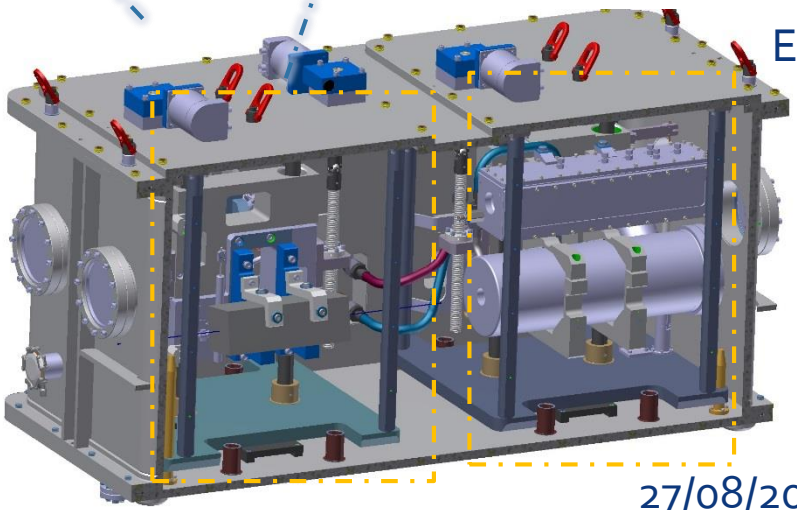
Inclusion of novel materials (W-TiC) manufactured by out colleagues from KEK and JPARC (Japan)



PROTAD Experimental Setup

PROTAD targets tested within a HiRadMat Multipurpose Experiment





Experiment executed on **28th/29th September 2018**

50 pulses/per target impacted in 5 targets
Target no. 6 received **140 pulses**
$4 \cdot 10^{14}$ POTs in **total POTs**

Targets opening and PIEs foreseen during 2019-2020

Perspectives HRMT-48 PROTAD

Extraction of the targets took place in summer 2019

Doses at contact with the targets
~ 200-700 µSv/h

Further Plans for PIEs:

Similarly as HRMT-42: → Neutron tomography at ILL (Grenoble)

- Non-destructive
- Destructive → Targets opening and core retrieval tentatively at CERN → Microscope examination SEM/EBSD

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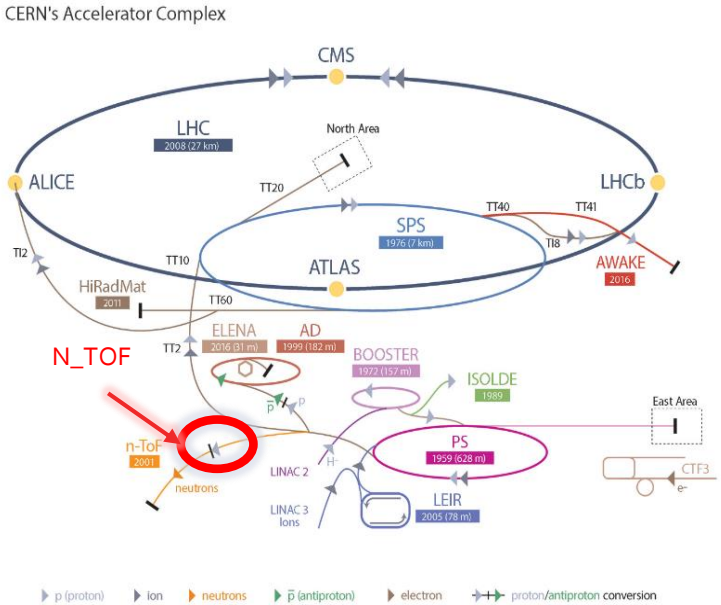
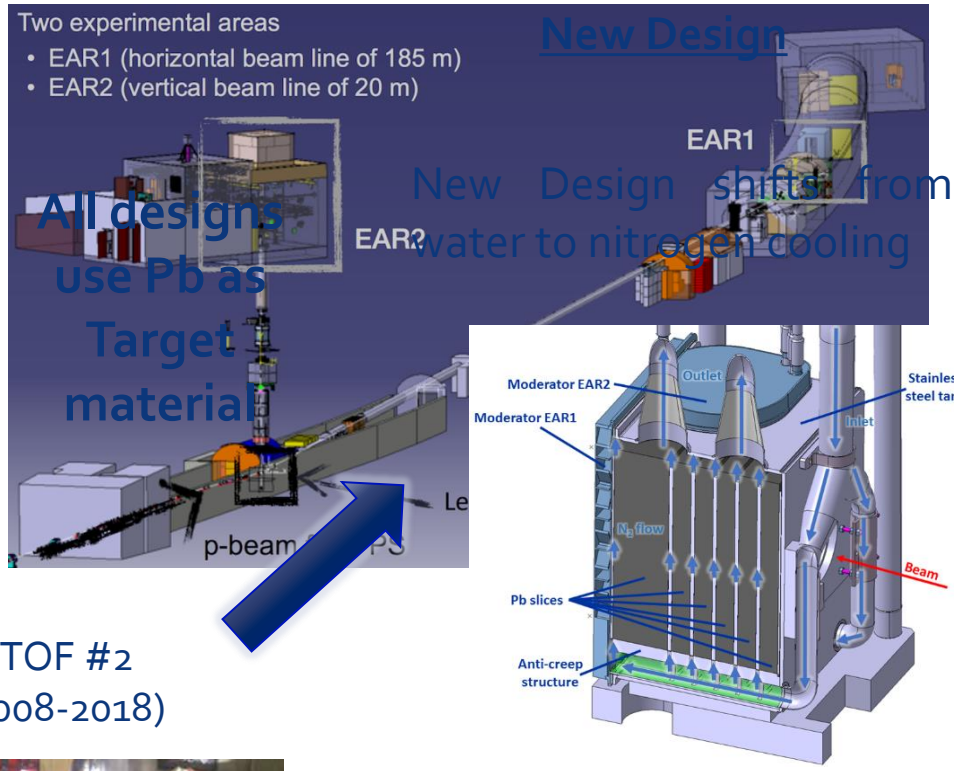
CERN's n_TOF Target



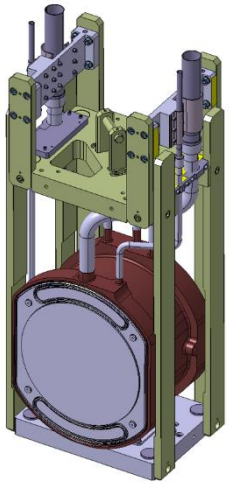


All designs use Pb as Target material

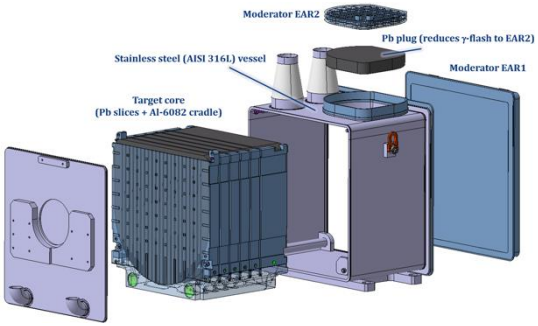
New Design shifts from water to nitrogen cooling

Different target generations since 2001

n_TOF #1 (2001-2004)



n_TOF #2 (2008-2018)



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Operational challenges n_TOF Target

Physics requirements impose Pb as target material and minimize the surrounding ones.

Beam parameters:

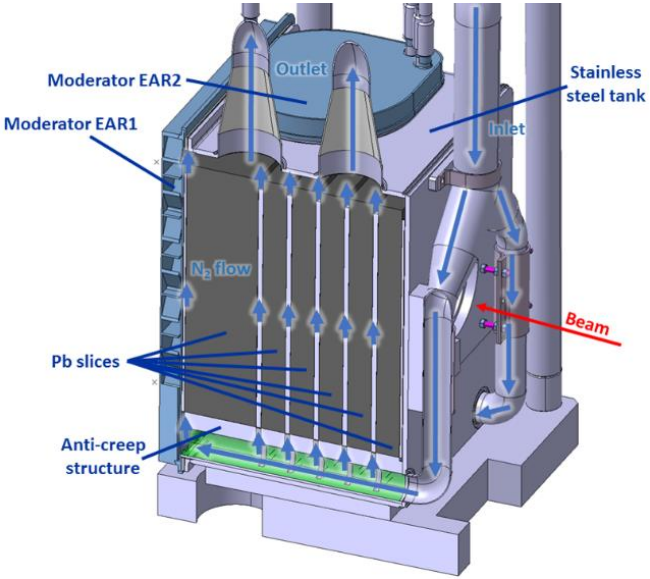
- Beam size: 15 mm (1σ)
- Pulse intensity: 10^{13} p^+ (1x bunch)
- Pulse duration: 7 ns
- Minimum repetition period: 1.2 s
- Average intensity: $1.66 \cdot 10^{12}$ p^+/s

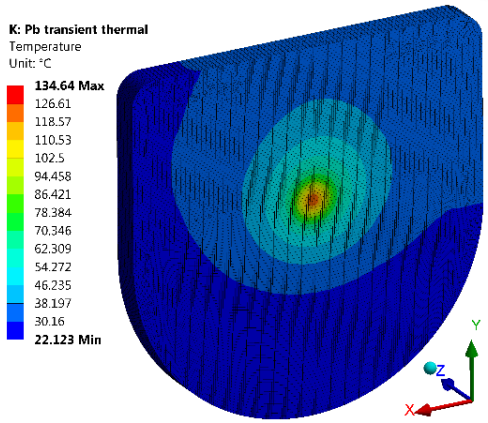
3 kW on target

To be effectively cooled due to low melting T of Pb

(Pb $T_{melting}$ = 327 °C)

- **Water-cooling** in **previous designs** (in direct contact with Pb) led to **erosion-corrosion** and cooling system contamination
- **Plastic deformation** in each beam impact due to the poor Pb mechanical properties.
- Enhanced **creep** due to high temperature operation.





ΔT/pulse = 15 °C

T_{max} = 135 °C

Dynamic Stresses

Fundamental to understand Pb behaviour at these conditions

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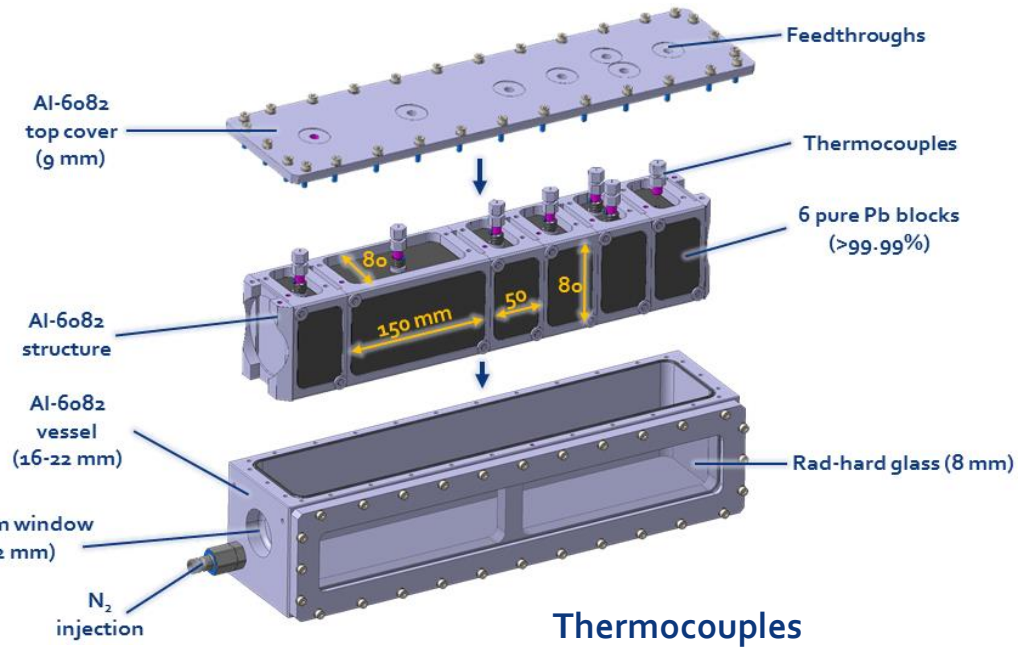
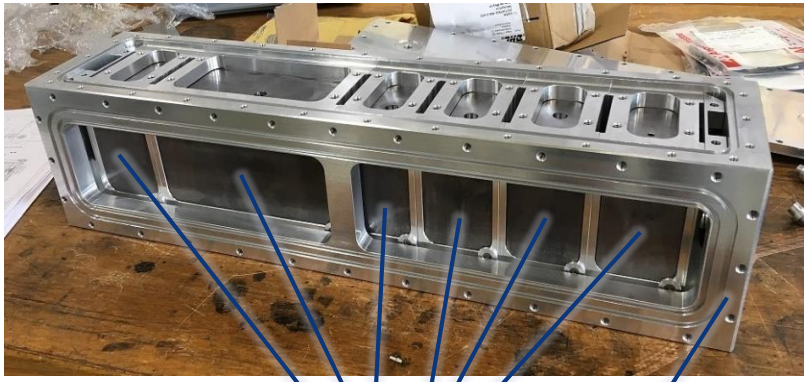
HRMT-46 Experiment: new n_TOF concept

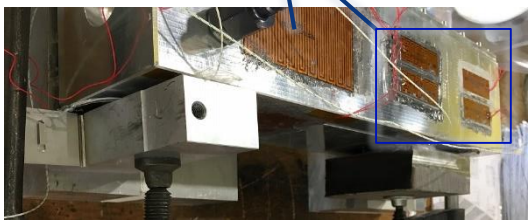
Experiment purpose

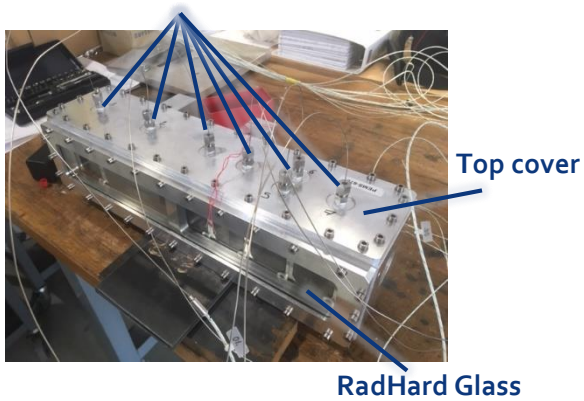
To observe, by PIE, **effects on the Pb blocks due to repeated beam impacts** (creation of voids, defects, etc.) at **temperatures between 100 and 130 °C.**



Testing Prototype for the new design







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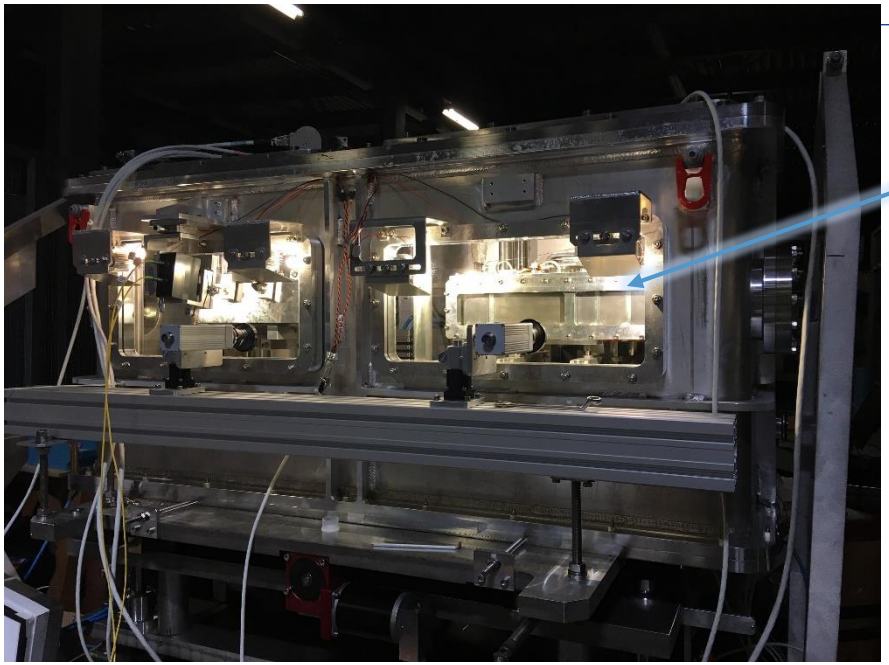
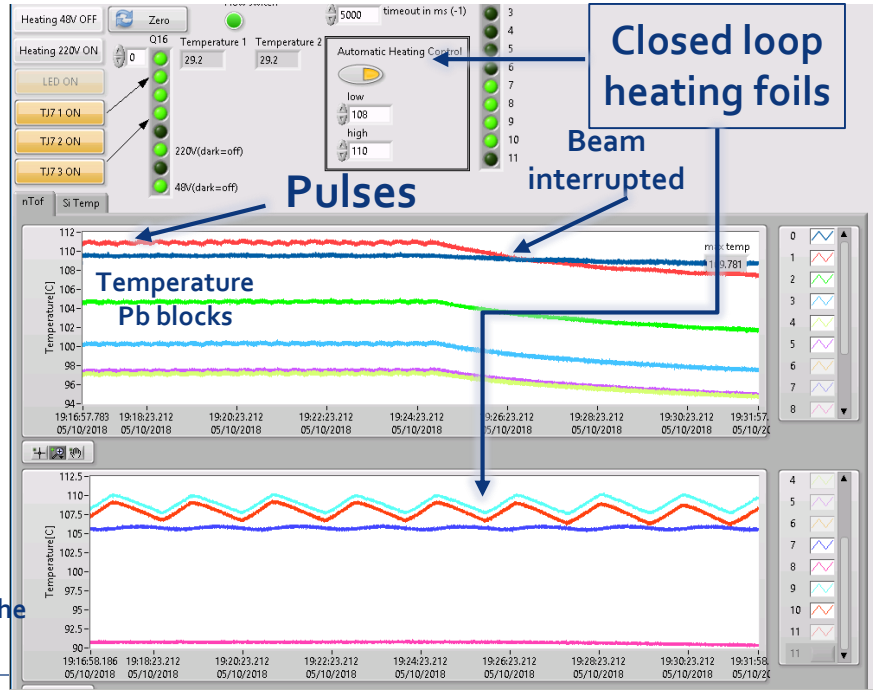
Execution of HRMT-46 n_TOF



nTOF target tested within the HiRadMat Multipurpose Experiment



235 pulses Impacted on the target

Temperature kept between 100 °C and 130 °C during irradiation thanks to a close loop heating system.

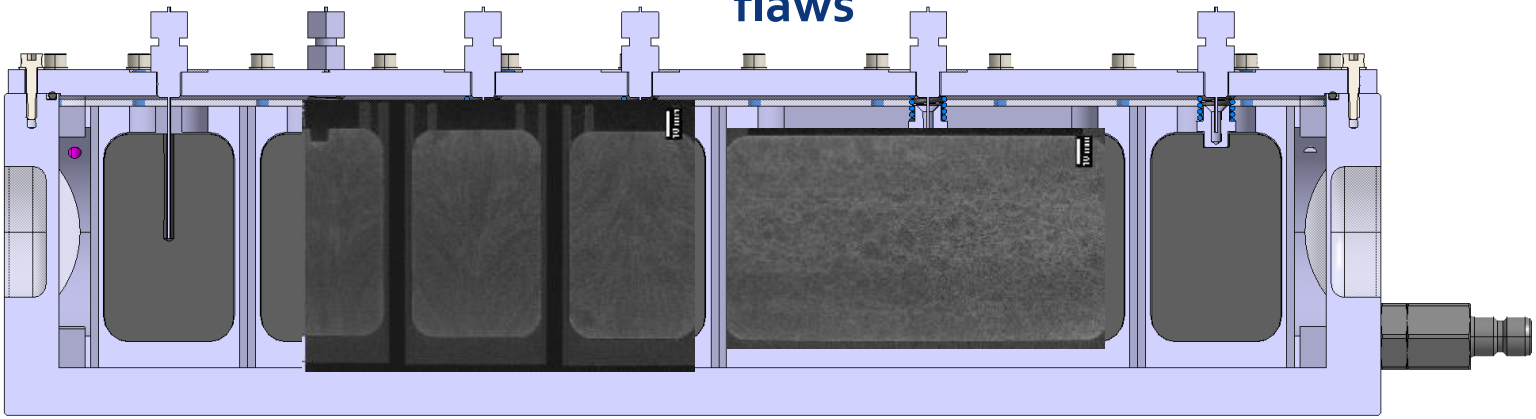
Temperature heating foils (to keep temperature in the desired range)

HRMT-46 Non-Destructive Examination

Extraction of Pb blocks from Target

Tank opening in ISOLDE fume hood

Neutron tomography carried out at PSI (Switzerland) revealed absence of flaws



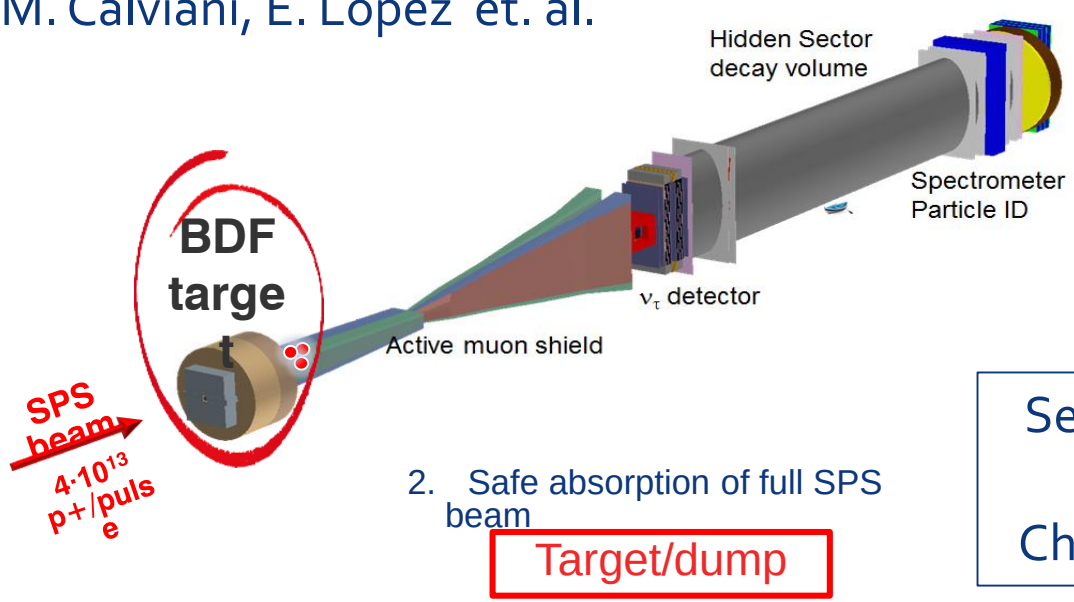
CERN's BDF (Beam-Dump-Facility) Target

New target-dump facility envisaged for construction in CERN's north Area

- Dedicated to high-intensity fixed target experiments
- First user: **S**earch for **Hi**dden **P**articles (SHiP)
- Current status: **Design Phase** → Aiming for approval mid/end 2020

SHiP
Search for Hidden Particles

M. Calviani, E. Lopez et. al.



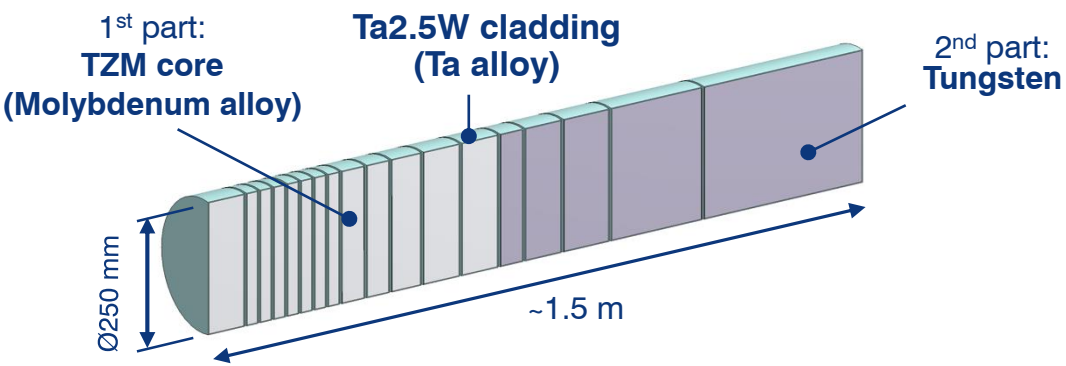
"Search for very weakly interacting long-lived particles capable of accommodating dark matter, neutrino oscillations, …"

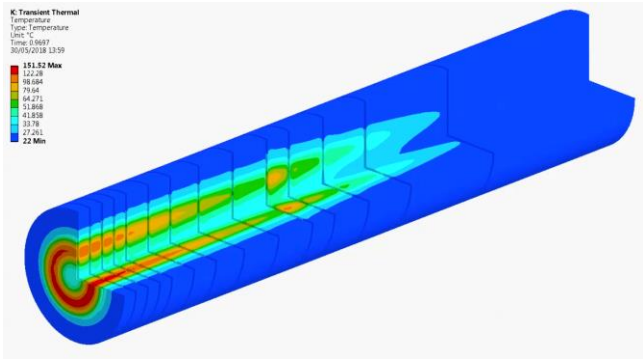
See presentations about SHiP on Thursday by
Chunsil Yoon and Kang Young Lee

E. Lopez et al.

The BDF Target Design and Challenges

- Physics requirement: high-Z materials + short interaction length



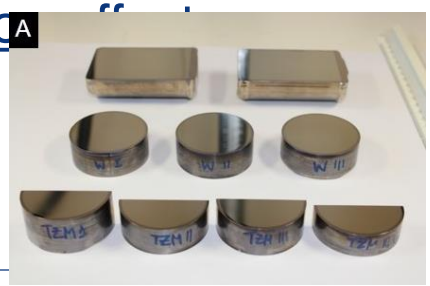


- Slow Extraction (1 s spill duration) beam dilution based on 4 circular sweeps/s
- **320 kW on target** → Optimized segmentation, forced water cooling, high speed
- **Tantalum alloy cladding** to avoid water corrosion/erosion effects

→ achieved by **Hot Isostatic Pressing** (HIP)

High Temperatures and stresses induced in the Ta cladding during operation

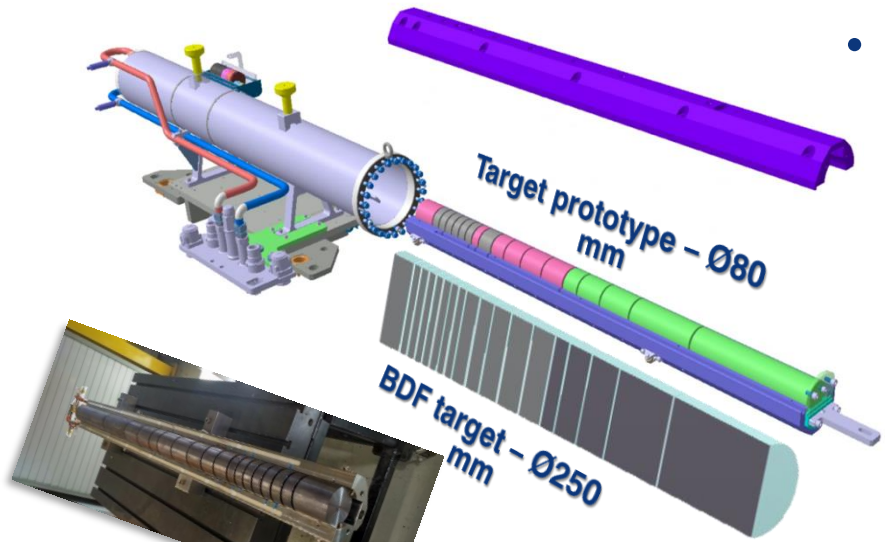
Extensive R&D on W/TZM -Ta2.5 diffusion bonding



E. Lopez et al.

BDF Target Prototyping and Testing

Scaled Prototype manufactured and **tested** in a **fully dedicated experimenta**



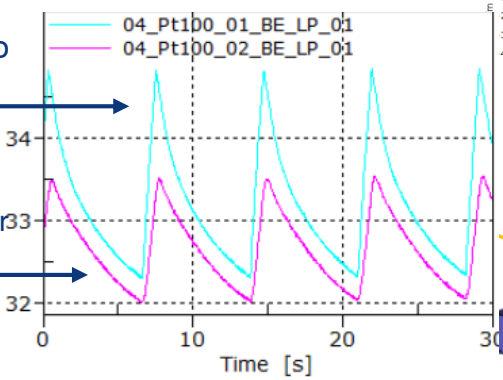
- CERN's North Area;
  - SPS beam (440 GeV/c)
  - 1 s duration, slow extraction, no sweep
  - **35 kW on target**
  - Recreating operation conditions in the Ta alloy cladding

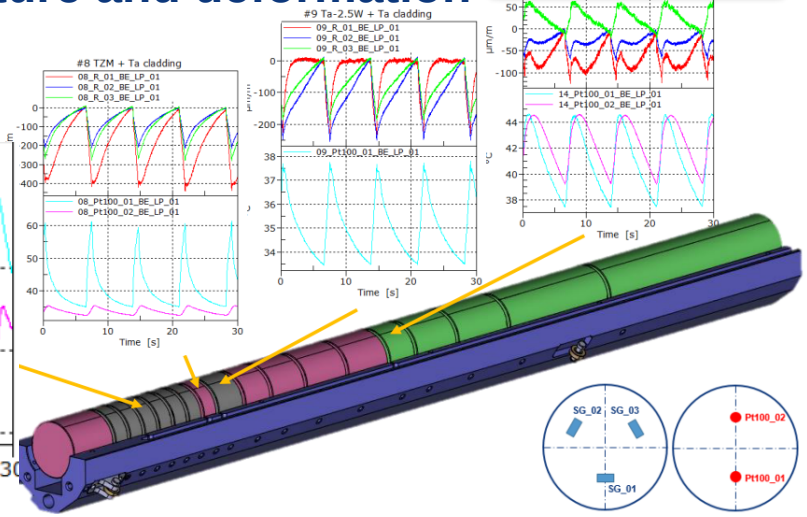
HiRadMat

Extensive instrumentation for **online monitoring of temperature and deformation**

Pt100 close to beam spot

Pt100 further from beam spot





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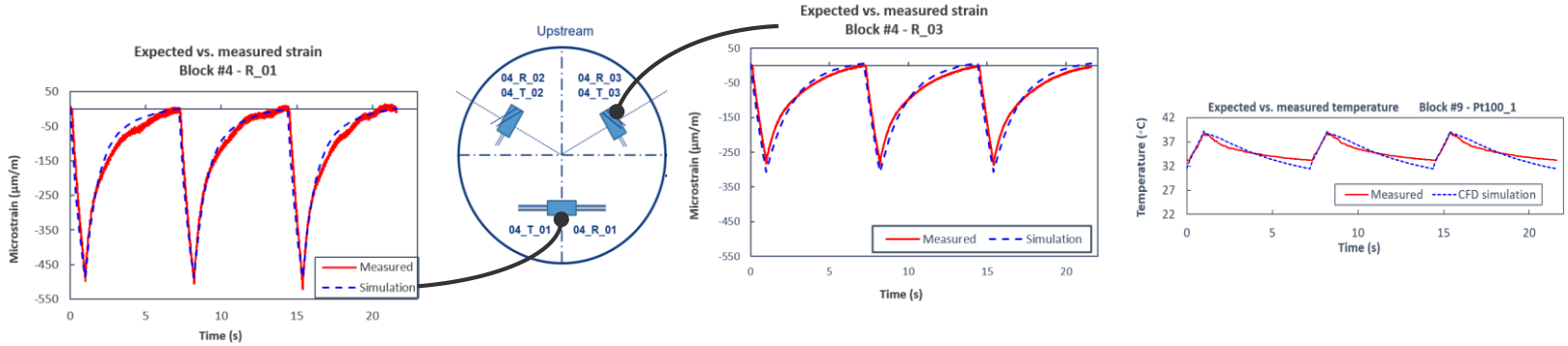
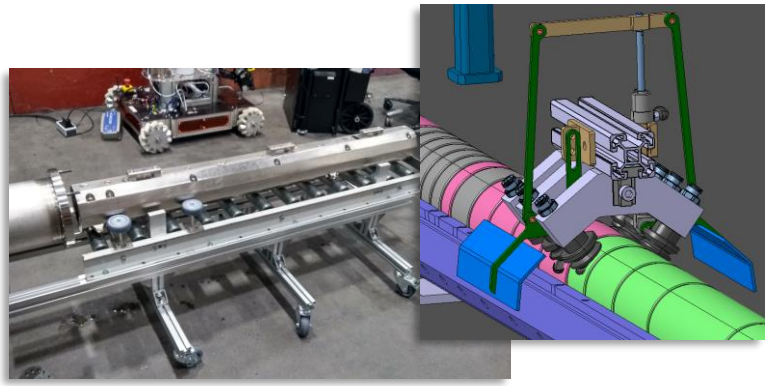
BDF Target Prototype Testing Outcomes

- Preliminary results suggest good agreement between FEM simulations and measurements



- Fully remote target dismantling and shipment to external institute for PIES foreseen in 2020/2021.



Testing in hot-cell

Study influence of stress, thermal cycles, cooling and irradiation in material properties, interface bonding…

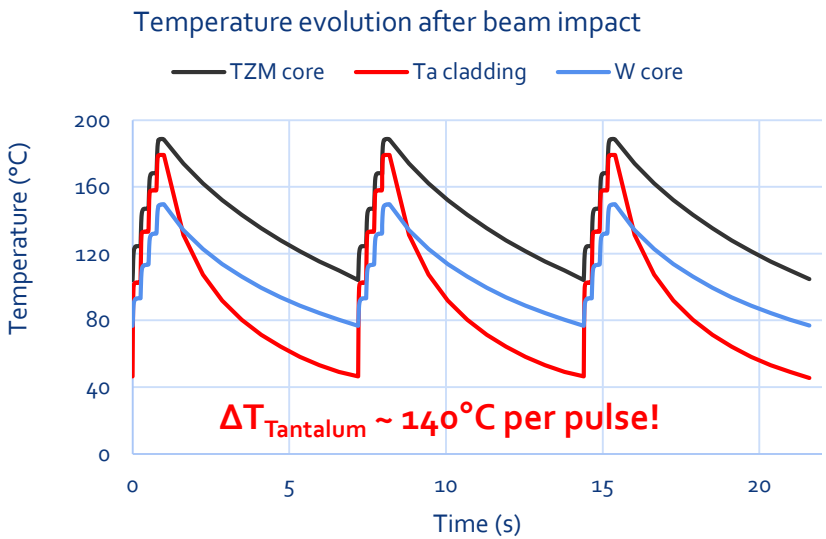
Conclusions

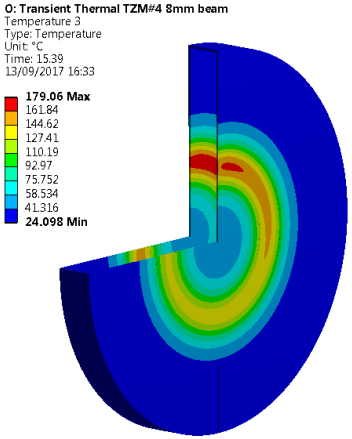
1. The CERN´s HiRadMat facility and dedicated beam tests are a great asset for validating targets designs under impacts of intense, fast/slow extracted, proton pulses.
   1. Validate & benchmark thermomechanical simulations.
   2. Tests materials/assemblies at regimes too complex for being simulated.
2. Five in-beam experiments applied to targetry R&D executed. Applied to:
   1. Antiproton Production target -> Extreme dynamical loading
   2. n_TOF target -> Plastic deformation and creep in Pb at high temperature
   3. Beam Dump Facility: High power, behaviour of HIP-manufactured claddings
3. The HiRadMat facility and experience in targetry R&D could be transversally applicable to neutrino/muons targets.

Thanks!

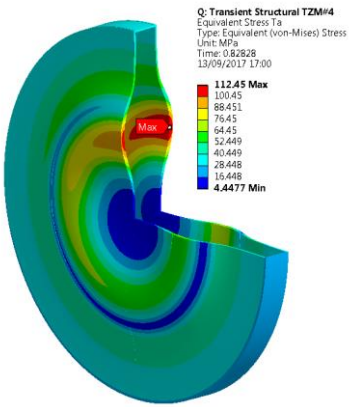
Back-Up Slides

Thermo-mechanical calculations





Max temperature Ta cladding 180°C



Max Von Mises equivalent stress Ta cladding ~110 MPa

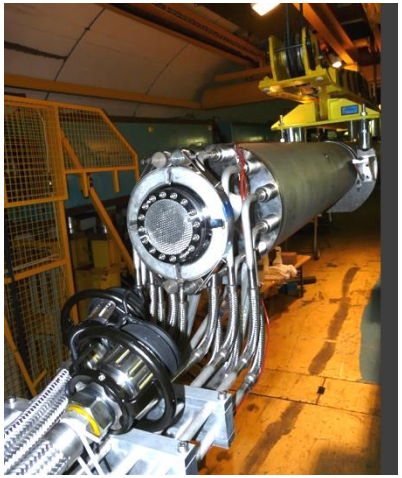
- High raise of temperature during beam impact: **temperature limitations in the Ta cladding** → vapor formation, plastic deformation of the cladding
- The high temperatures reached lead to a high level of stresses
- Properties of **pure Ta** at high temperatures reduced significantly with respect to RT → chosen **cladding material**: tantalum-tungsten alloy, **Ta2.5W**

Baseline characteristics	Final BDF target	Target prototype
Proton momentum [GeV/c]	400	400
Beam intensity [p+/cycle]	**$4.0 \cdot 10^{13}$**	**$3.0 - 4.0 \cdot 10^{12}$**
Beam dilution	**4 circular sweeps / s**	**No**
Cycle length [s]	7.2	7.2
Spill duration [s] (slow extraction)	1.0	1.0
Average beam power [kW]	350	35
Average beam power/spill [MW]	2.56	0.26
Beam size (H/V) [mm]	8/8	3/3

Perspective on future operation

1. New projects would continue to require the use of HiRadMat facility
2. LIU beam intensities would be extremely useful to validate new equipment (HL-LHC beam dump for LS3, FCC, etc.)

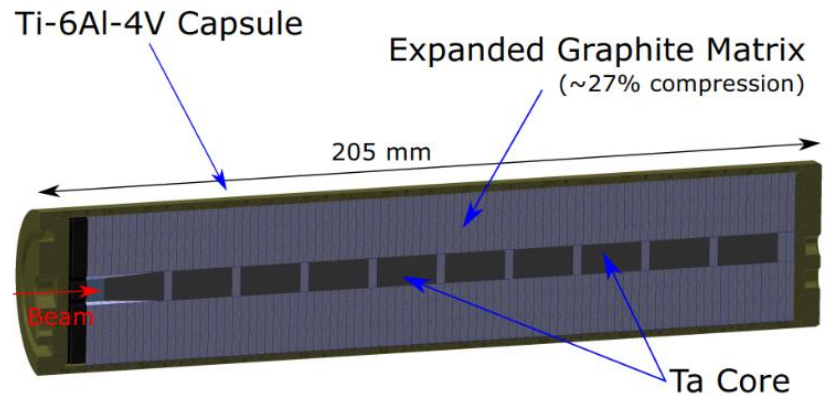
3. Facility-wise the focus shall be put mainly on the HiRadMat dump (so-called TED) as well as – to a lesser extent – to the Be windows

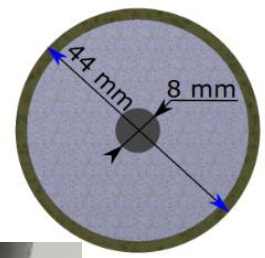


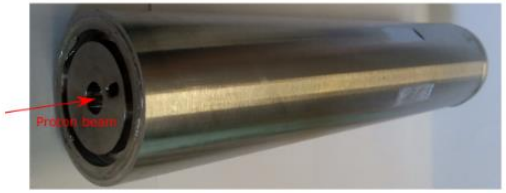
The HRMT-42 Target

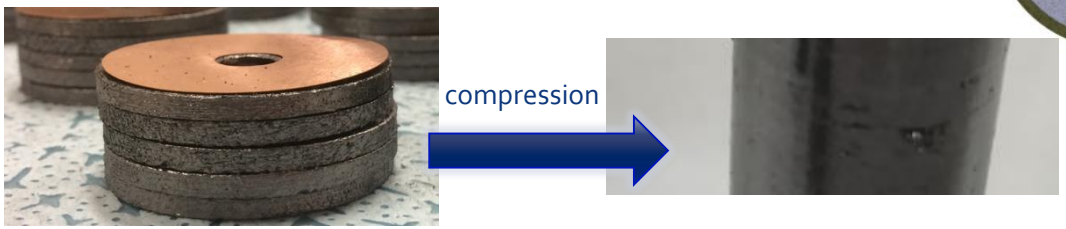
Up-Scaled Prototype of the AD-Target core & Matrix

- Core of 8 mm diameter **Ta rods** (un-annealed)
- Core is sliced to avoid excitation of bending modes
- Embedded in a matrix made of **compressed layers of Expanded Graphite (EG).**



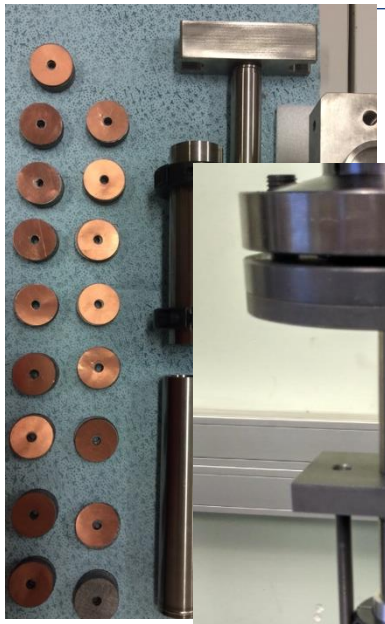


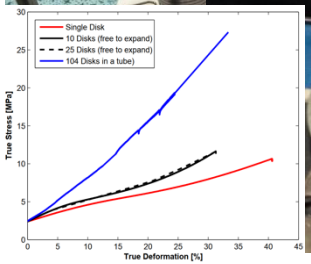




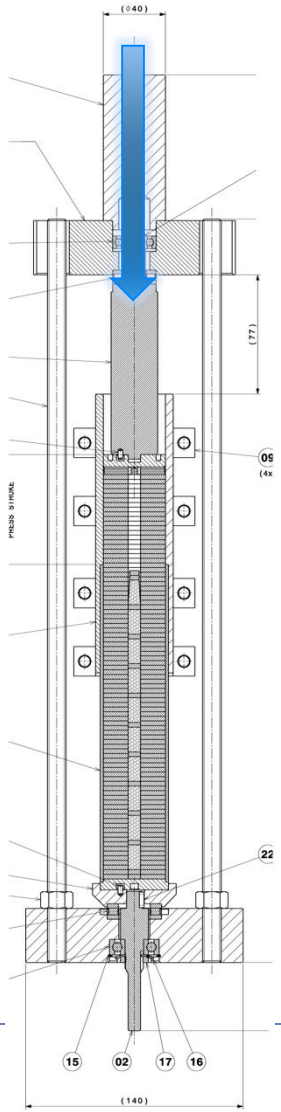
- Provide contact pressure with the core and guarantee a continuous interface (heat transfer) even if the core undergoes plastic deformation.
- Encapsulated in Ti-6V-4Al e-beam welded container

The HRMT-42 Target: Assembly and Welding Procedure

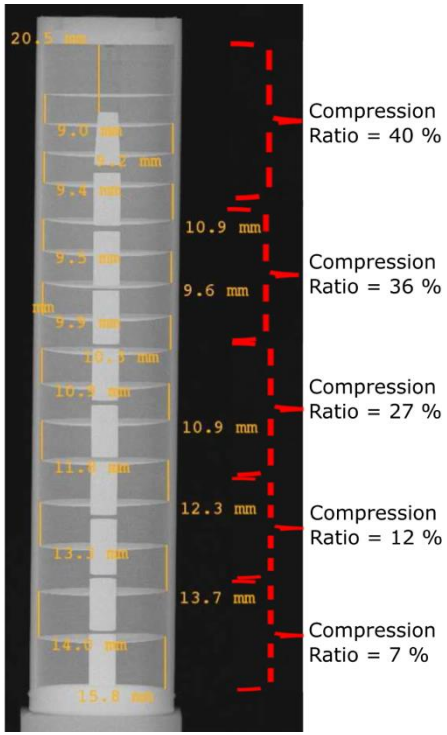




(I) Compression Phase



(II) Welding Phase



Non-Uniform over Compression Ratio over the length ☹