HiRadMat and Beam Tests Experiments for High Power Targetry at CERN


NUFACT 2019
21ST INTERNATIONAL WORKSHOP ON NEUTRINOS FROM ACCELERATORS
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Outline

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

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

   1) HRMT-27 Experiment
   2) HRMT-42 Experiment
   3) HRMT-48 PROTAD Experiment
   4) HRMT-46 nTOF Experiment
   5) BDF prototype tested in CERN’s North Area

3) Conclusions

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STI Group at CERN’s Engineering Department

1. Sources, Targets and Interactions 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) 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**
- 440 GeV/c Proton Beam
- Dump
- Experimental Tank and Setup *(specific to the experiment)*
- Experimental Tables *(standard)*
- Experimental Stand *(standard)*
- Cool-Down Area

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Ad-hoc Testing Area for BDF in TCC2

Fully dedicated experimental setup in TCC2 (North Area)

- Representative beam tests → SPS high intensity
- Slow extraction required (1 second spill)
- Remote Installation
- Dedicated Beam instrumentation and water cooling system
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) Integral testing of prototyping equipment
   1) Validating the global response of a mechanical assembly to impacts
   2) Important to validate system-wide mechanical assembly 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
   • 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.)
   - HRMT 46 for n_TOF spallation target (pure Pb)
   - HRMT 49 for TIDVG5 (polycrystalline Si block)

2) Experiments applied to Collimators (response to project requirements for uncharted beam intensities (LIU & HL-LHC requirements)
   - HRMT 28/44 for LIU SPS-to-LHC transfer line collimators (3D CC)
   - HRMT 18 for crystal collimation

3) Experiments applied to Absorbers
   - HRMT 35 for coated collimators materials (operational-driven)
   - HRMT 45 for HL-LHC injection dump (TDIS)

4) General material R&D
   - HRMT 24/43 supporting Fermilab team

11 experiments in total executed in 3 years

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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

Beam coming from the PS
- 26 GeV/c
- Primary beam
  - 0.5 mm x 1 mm
- 1.45e13 ppp
- 430 ns pulse length

S Adiabatic $\Delta T$ at target core > 2000 °C

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

Target core made of
- Ø 3 mm x 55 mm length
- Rod of Iridium
  - $\rho = 22.5 \text{ g/cm}^3$

Oscillatory nature of the response

Also predicted damage in the graphite matrix

Courtesy of N. Solieri


*Modal analysis

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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 $3 \cdot 10^4 \text{ TW/m}^3$

Max $\Delta T$ 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. In addition, damage of graphite matrix

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

1) Numerical Simulations: Use of hydrocodes

Validate simulations & investigate new candidate material

2) HRMT-27 Experiment (2015)

3) HRMT-42 & HRMT-48 PROTAD Experiments -> Prototyping
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 excitation of radial, longitudinal and bending modes in rods impacted by proton beam impacts
3) Different response of refractory metals
   - Ta -> ductile deformation (no cracks)
   - Ir -> Massive fragmentation

Beam from SPS (440 GeV)

**PhysRevAccelBeams.22.013401**

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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

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?

\[ \Delta T = 1820 \, ^\circ\text{C/pulse} \]

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

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

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HRMT48-PROTAD Experiment

**Goal:** Testing New AD-Target Design (PROTAD)

- Cooled by Air
- Different core materials/geometry configurations

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### 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

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### 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

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

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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

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Extraction of the targets took place in summer 2019

Further Plans for PIEs:

 Similarly as HRMT-42:
- Non-destructive
- Destructive

  Neutron tomography at ILL (Grenoble)

  Targets opening and core retrieval tentatively at CERN

  Microscope examination SEM/EBSD

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

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CERN’s n_TOF Target

Different target generations since 2001

n_TOF #1 (2001-2004)
n_TOF #2 (2008-2018)

All designs use Pb as Target material

New Design

New Design shifted from water to nitrogen cooling

R. Esposito et. al.
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.

$\Delta T/$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
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.
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

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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: Search for Hidden Particles (SHiP)
- Current status: Design Phase → Aiming for approval mid/end 2020

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

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

High Temperatures and stresses induced in the Ta cladding during operation

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BDF Target Prototyping and Testing

Scaled Prototype manufactured and tested in a fully dedicated experimental facility:

- 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

Extensive instrumentation for online monitoring of temperature and deformation
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
- High raise of temperature during beam impact: temperature limitations in the Ta cladding $\rightarrow$ 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 $\rightarrow$ chosen cladding material: tantalum-tungsten alloy, Ta$_{2.5}$W
<table>
<thead>
<tr>
<th>Baseline characteristics</th>
<th>Final BDF target</th>
<th>Target prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton momentum [GeV/c]</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td><strong>Beam intensity [p+/cycle]</strong></td>
<td>$4.0 \cdot 10^{13}$</td>
<td>$3.0 - 4.0 \cdot 10^{12}$</td>
</tr>
<tr>
<td><strong>Beam dilution</strong></td>
<td>4 circular sweeps / s</td>
<td>No</td>
</tr>
<tr>
<td>Cycle length [s]</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Spill duration [s] (slow extraction)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Average beam power [kW]</td>
<td>350</td>
<td>35</td>
</tr>
<tr>
<td>Average beam power/spill [MW]</td>
<td>2.56</td>
<td>0.26</td>
</tr>
<tr>
<td>Beam size (H/V) [mm]</td>
<td>8/8</td>
<td>3/3</td>
</tr>
</tbody>
</table>
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

Electron beam welding

Target Rotation allowed by the tooling