PROTAD Target and HRMT-48 Experiment, Relevance for BIDs

RaDIATE Collaboration Meeting

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Outline

1) Introduction: The current *(old)* AD-Target vs New Design (PROTAD)

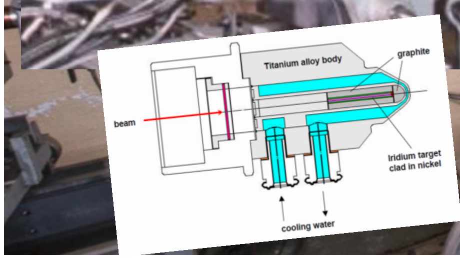
2) Numerical Simulations, understanding the dynamic response of the AD-Target core

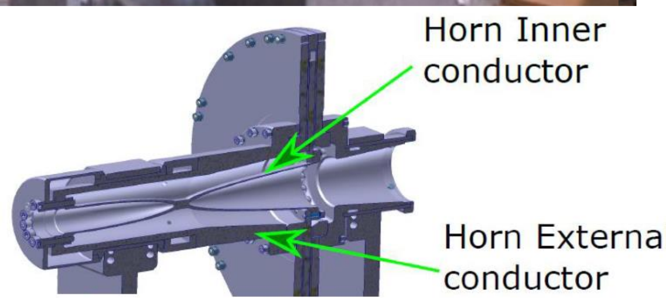
3) Previous HRMT Experiments (HRMT-27 & HRMT-42)

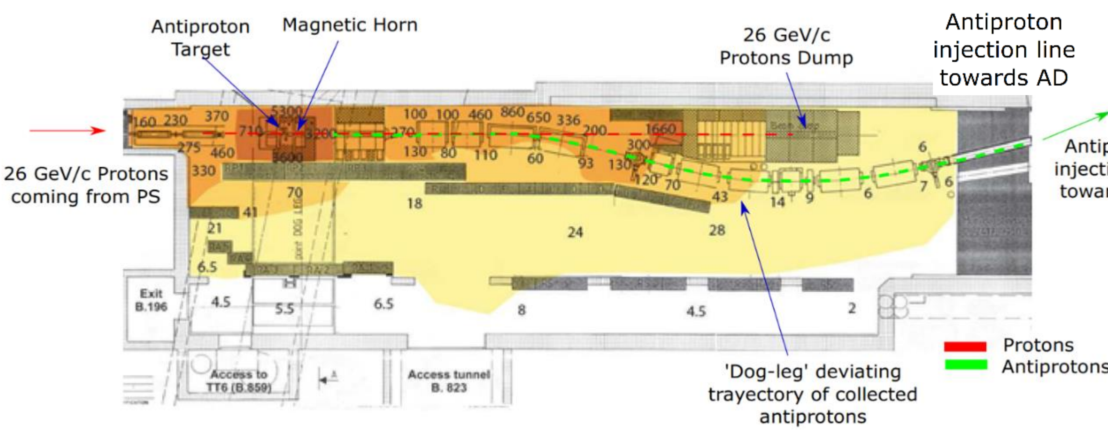
4) HiRadMat-48 PROTAD Experiment: **Testing Real Scale Prototypes**

5) Conclusions and Relevance for BIDs and Future Perspectives

The AD-Target Area



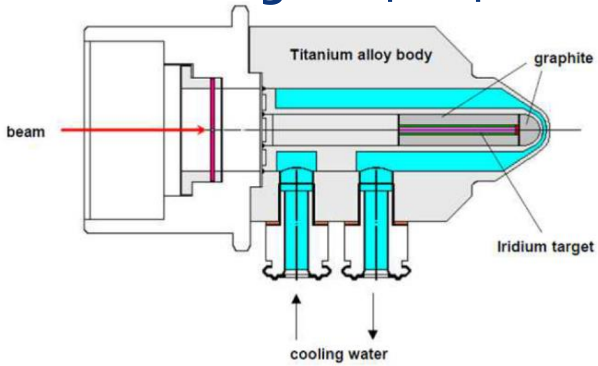




- Renovation of the Area during CERN's Long Shut Down 2 (2019-2021)

Current AD-Target Design vs New Design

Current Design (stoped operation a few weeks ago)

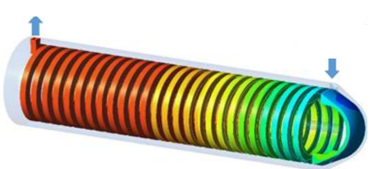


- Design from 1989 maintained until nowadays
- **Water-cooled** double wall Ti-6Al-4V assembly
- **Iridium core,** Ø 3 mm by 55 mm length
- Graphite matrix Ø 15 mm

New Proposed Design

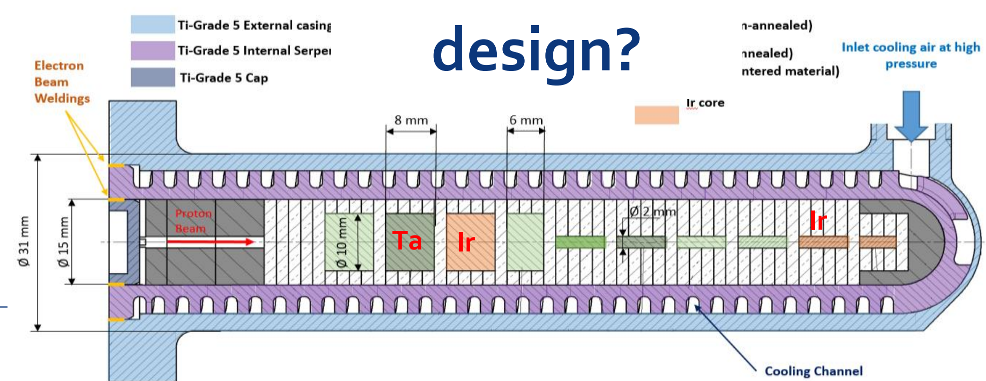
Named PROTAD Target
from (**PROT**otype **AD** Target

- Substantially more compact (Ø30 mm external diam vs old. Ø 100 mm)
- **Pressurized-Air-cooled** (**5-6 bars**) double wall Ti-6Al-4V assembly, with an internal serpentine.
- New core & matrix configuration



1) Larger cores diameter (up to 10 mm)
2) Multi-material core configuration (Ta, Ir)
3) Expanded graphite **(EG)** as matrix material

How did we arrive to this design?



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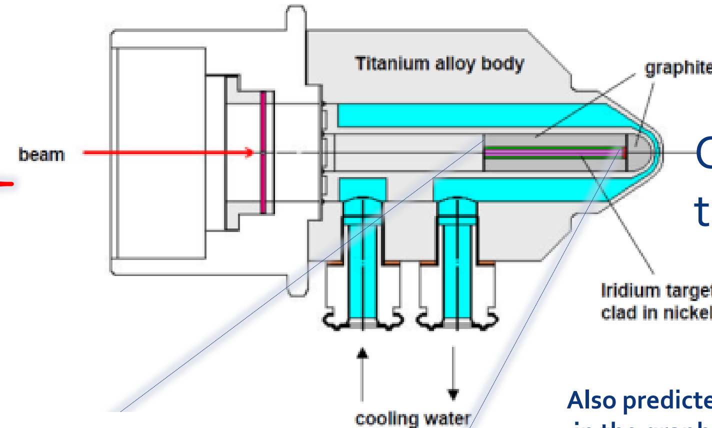
Conditions reached in the AD-Target

(Current/old Design)

Beam coming from the PS

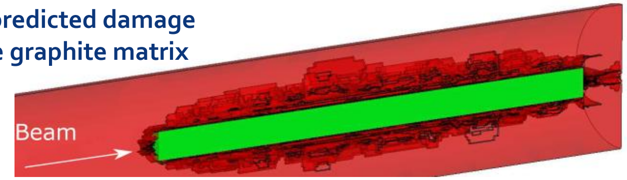
- 26 GeV/c
- Primary beam
  0.5 mm x1mm
- 1.45e13 ppp
- **430 ns pulse length**



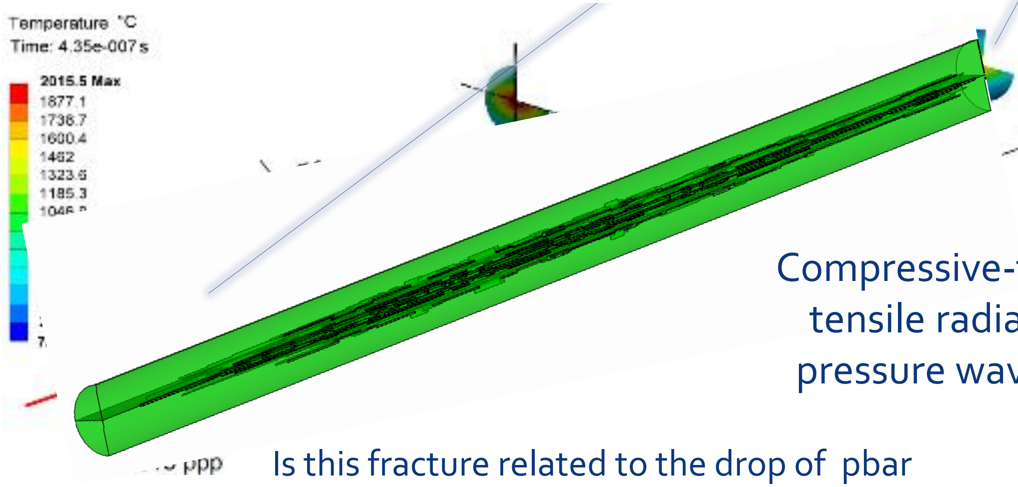
Target core made of
ø 3 mm x 55 mm length
rod of **Iridium**
$\rho = 22.5\ g/cm^3$

Oscillatory nature of the response

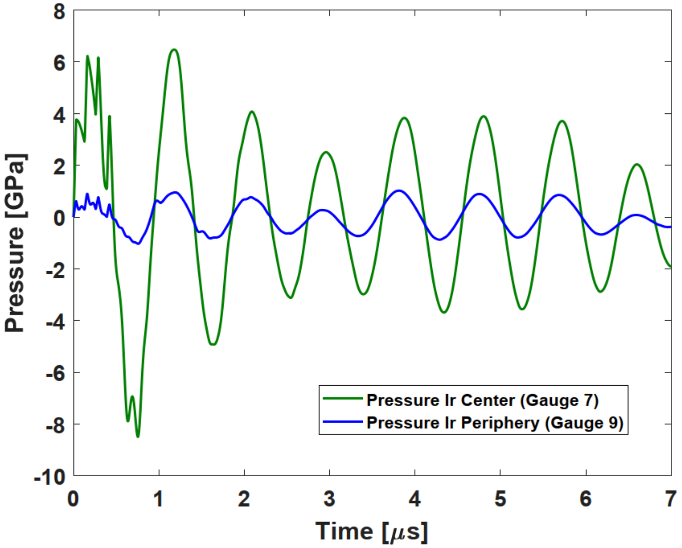
Also predicted damage in the graphite matrix



Adiabatic ΔT at target core > 2000 °C



Compressive-to-tensile radial pressure wave



Is this fracture related to the drop of pbar production historically observed at the beginning of operation?

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

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

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

3) Very short pulse
4) Small core diameter

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>

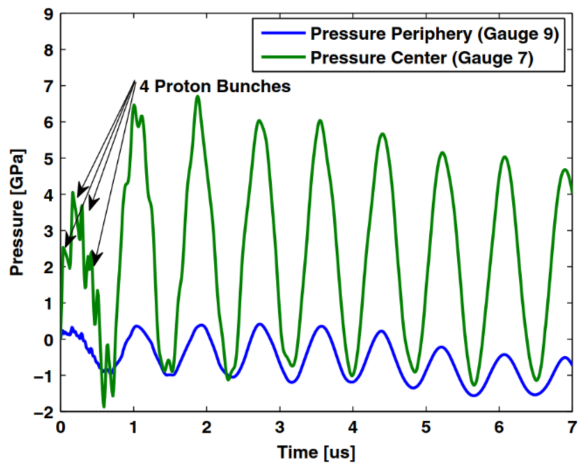
R&D Activities to **study the response of refractory metals at such conditions**

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

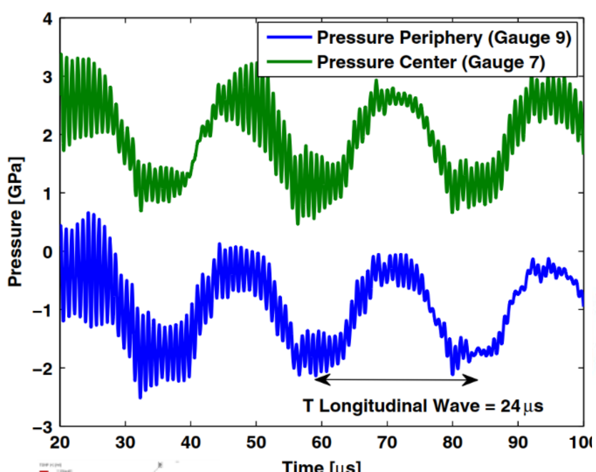
*4) *Opening of a spent AD-Target, see presentation E. Fornasiere*

Hydrocodes applied to the AD-Target Core (1)

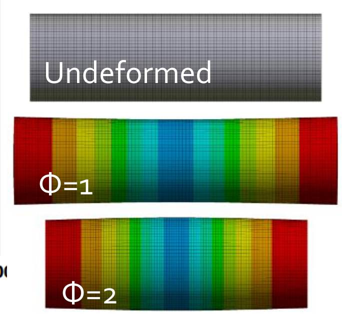
Elastic vs Plastic



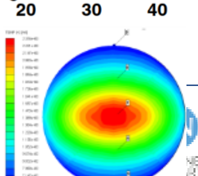
Radial Mode



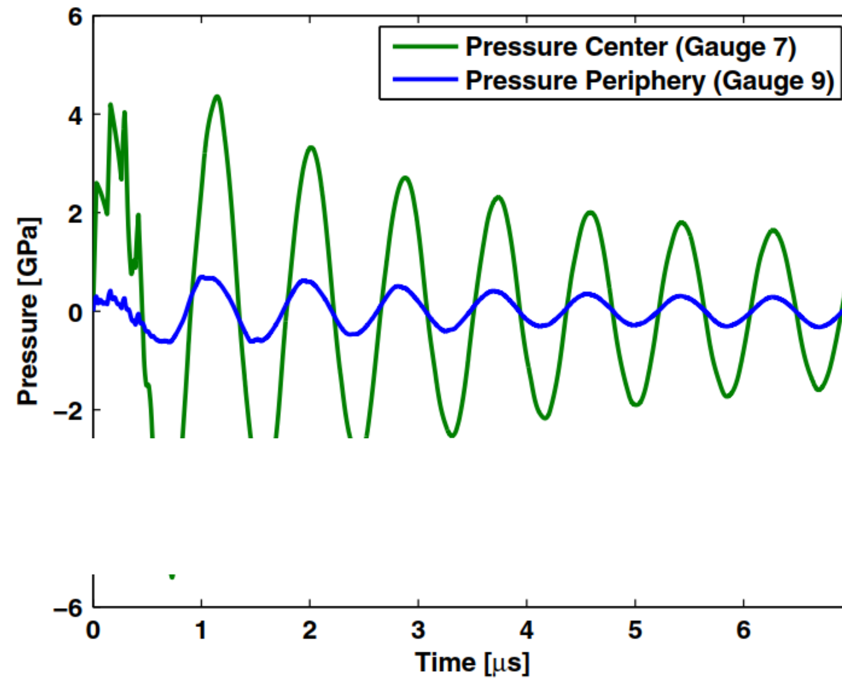
Longitudinal Mode



Courtesy N. Solieri



Considering a J-C strength model



Compressive-to-Tensile response

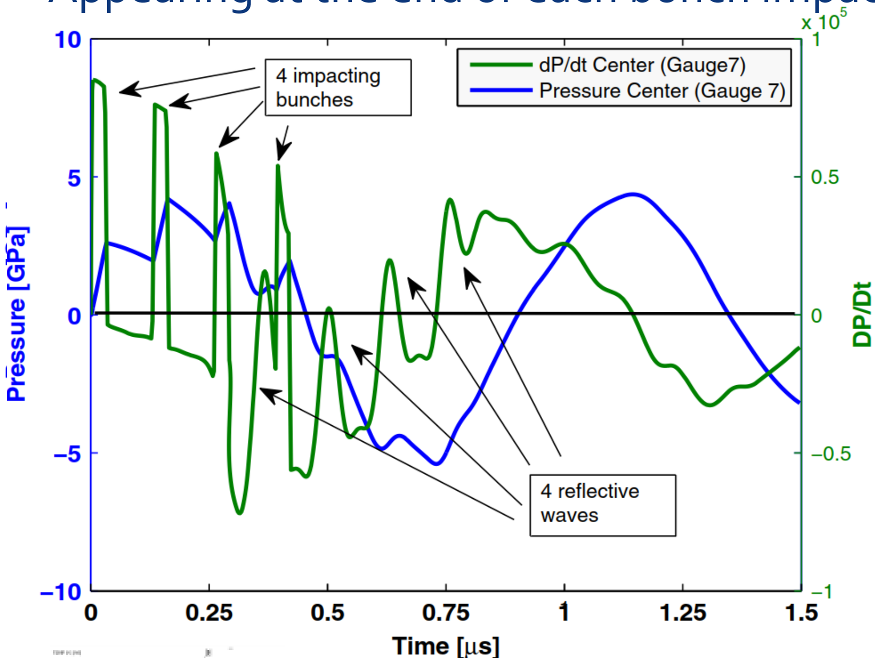
change in the oscillation nature

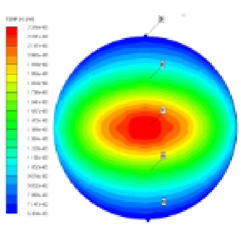
Why this Radial Mode is excited?

It is very important *when* the pulse finishes

End-of-Pulse Tensile Response

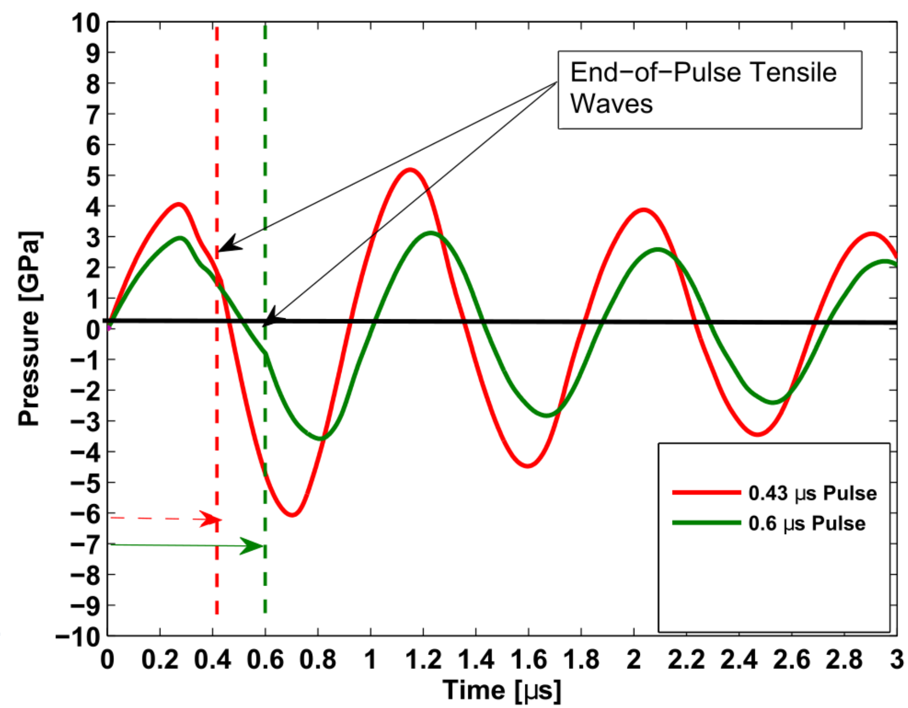
Appearing at the end of each bunch impact





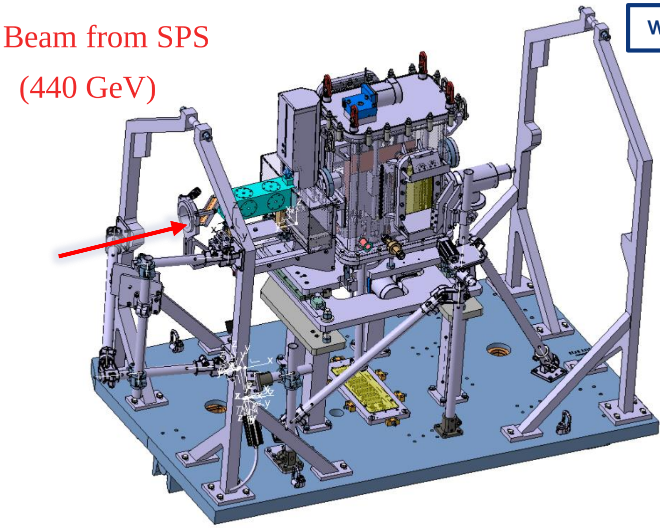
Also it's responsible of reflective waves originated a the surface

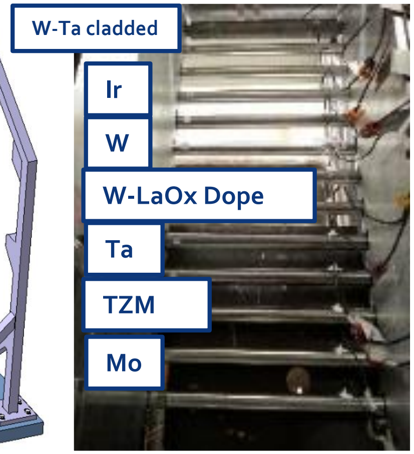
Parametric Analysis Pulse Length



C. Torregrosa *et al.* "CERN antiproton target: Hydrocode analysis of its core material dynamic response under proton beam impact", Phys. Rev. Accel. Beams 19, 073402

The HRMT-27 Experiment (2015)



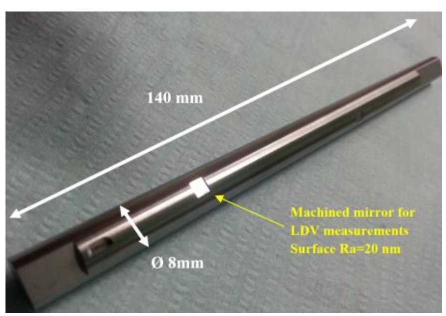


- 13 rods of high-Z materials impacted by 440 GeV/c beam
- Irradiation performed in a **ramped** way to obtain material response at intermediate state before reaching AD-Target conditions

Targets

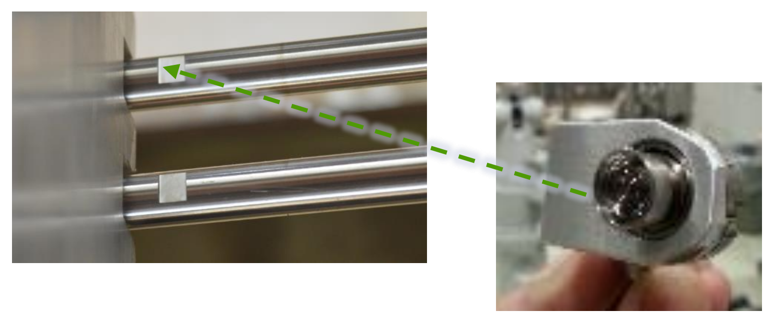
8 mm diameter targets.
Targets geometry and beam parameters adapted to:

- Recreate AD-Target conditions
- Obtain measurable response at their surface



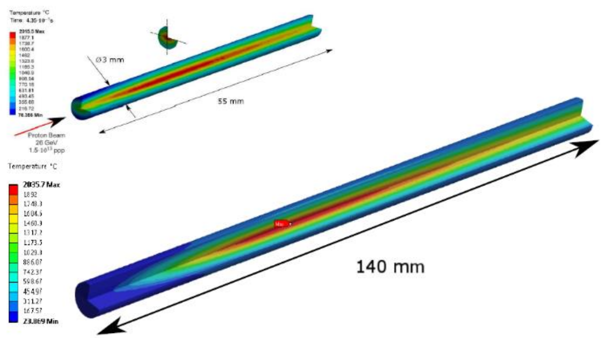
Online Instrumentation

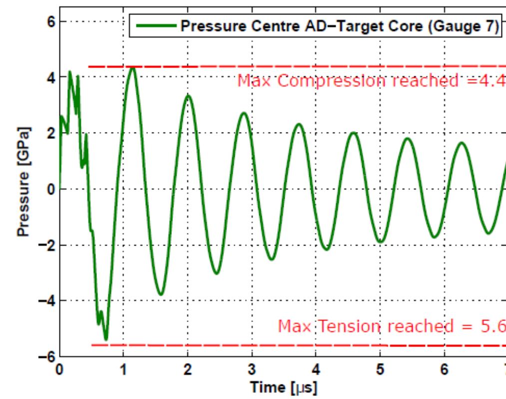
Optical instruments pointing at targets surface to measure their velocity and crosscheck the numerical simulations.

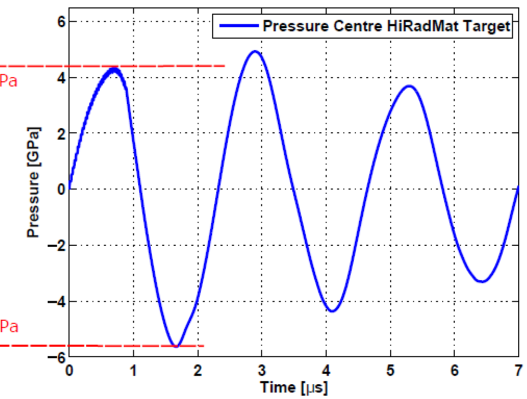


Conditions Reached in the HRMT-27 Targets

At highest intensity: AD-Target conditions





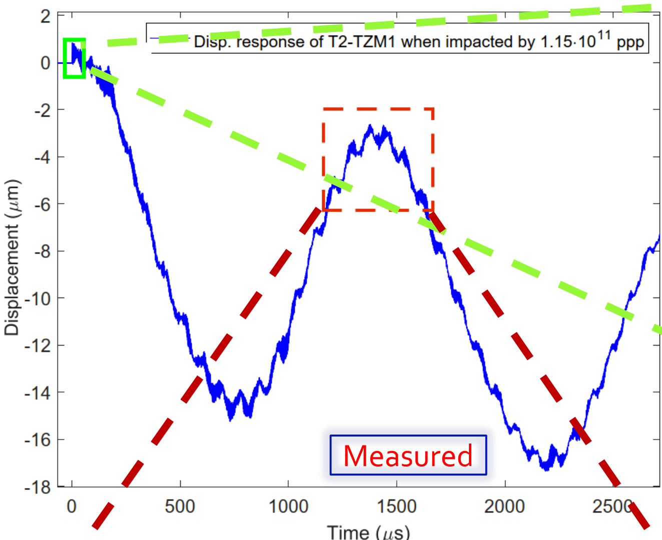


Summary of conditions during the intensity ramp up

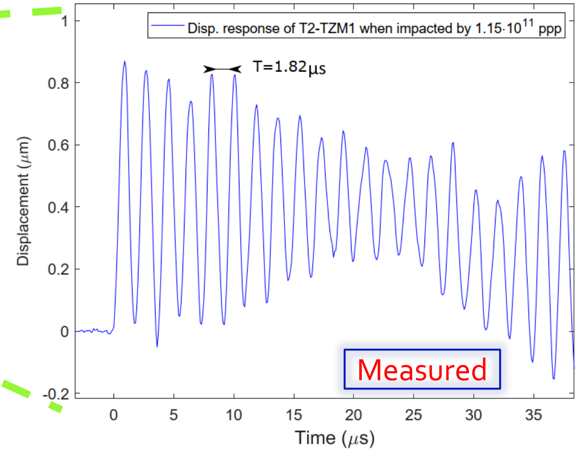
	Lowest Intensity 10^{11} ppp			Medium Intensities $2\cdot10^{11}$ ppp – $5\cdot10^{11}$ ppp – $7.5\cdot10^{11}$ ppp			AD-Target Conditions $1.5\cdot10^{12}$ ppp	
Material	**Max ΔT (°C)**	**Max VM (MPa)**	**Max Tensile Pressure**	**Max ΔT (°C)**	**Max VM (GPa)**	**Max Tensile Pressure GPa**	**Max ΔT (°C)**	**Max Tensile Pressure (GPa)**
Ir	160 °C	500 MPa	250 MPa	450 - 870 - 1300	1.2 – 0.8 - 1 GPa (plastic-work)	0.76 - 2 - 4 GPa	2200 °C	9 GPa
W	130 °C	380 MPa (plastic-work)	200 MPa	430 - 800 -1200	Limited by plastic work	0.5 - 1 -2.1 GPa	2000 °C	5.6 GPa
Mo/ TZM	65 °C	120 MPa	120 MPa	150 - 300 -500	250 MPa < Limited by plastic work	0.2 – 0.24 0.44 GPa	850 °C	1.3 GPa
Ta	115 °C	200 MPa	240 MPa	360-700- 1000	Limited by plastic work	0.78 - 1.6 - 2.6 GPa	1850 °C	4.5 GPa

Dynamic Response at Low Intensity

Recorded Displacement



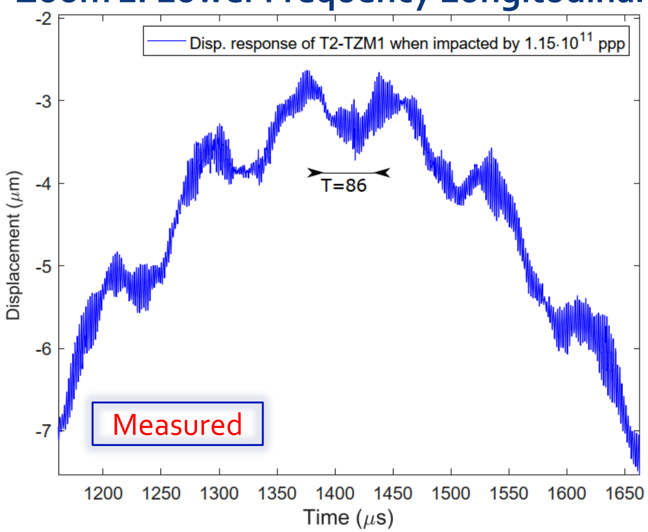
Zoom 1: High Frequency radial mode



Radial Mode

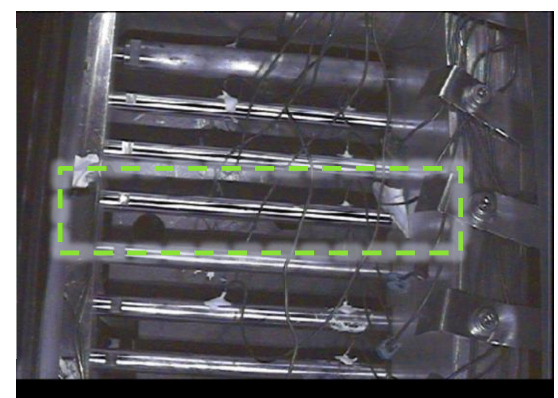
T = 1.82 μs

Zoom 2: Lower Frequency Longitudinal mode



3 Bending mode

T= 1.45 ms

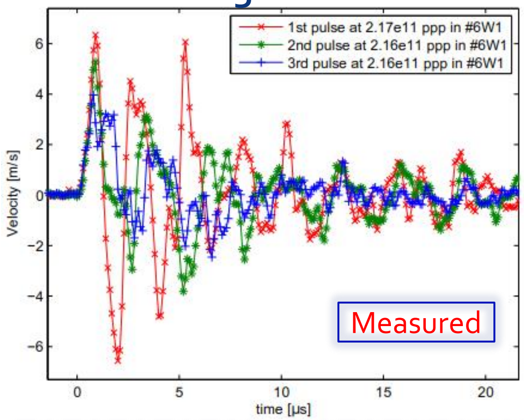


Observation of deformation of the Ir target between pulses at 2.5e11 ppp -1.5e12 ppp

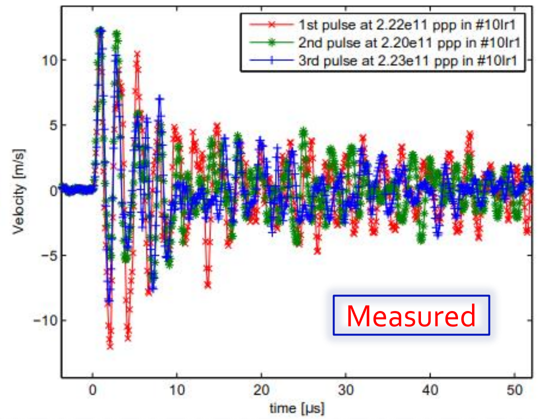
Dynamic Response when Increasing Intensity

Distortion of the radial wave indicated that **internal damage in W, TZM and Ir** already taking place even from the 2nd Irradiation intensity (conditions ~7 times lower as reached in the AD-Target)

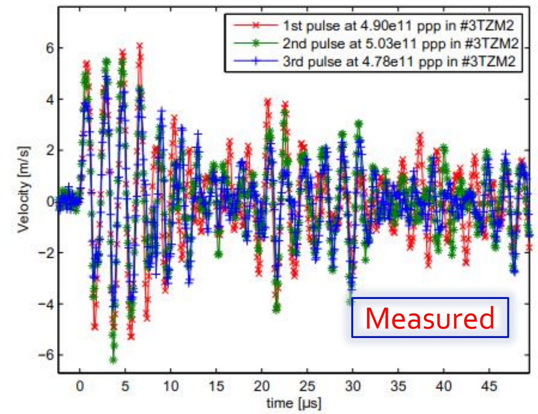
Tungsten



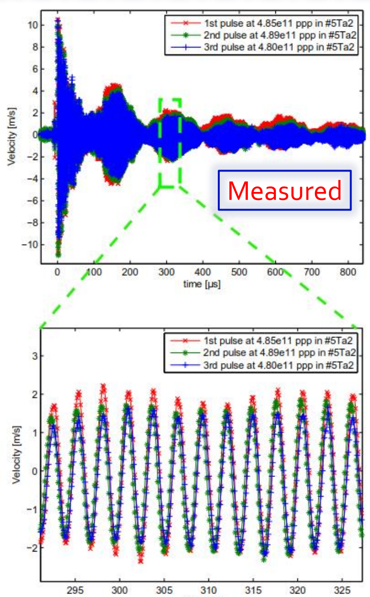
Iridium



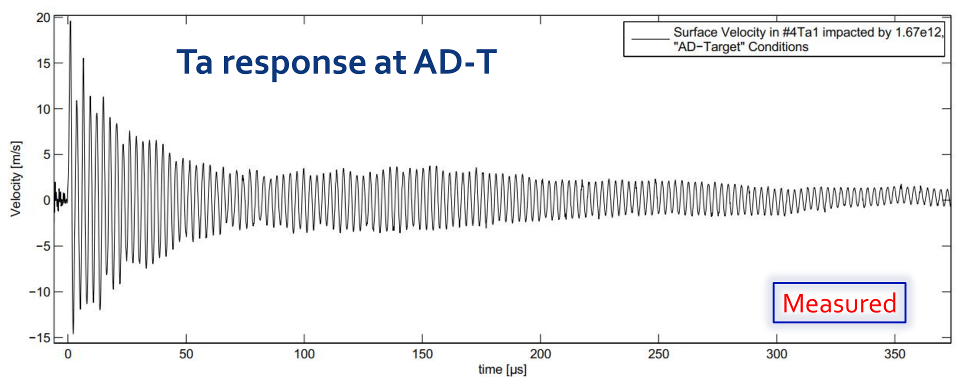
TZM



Estimated Max ΔT of 300 ºC and 0.8 GPa tensile pressure



Ta showed repeatable and "clean radial" response even at AD-Target conditions, suggesting absence of cracks



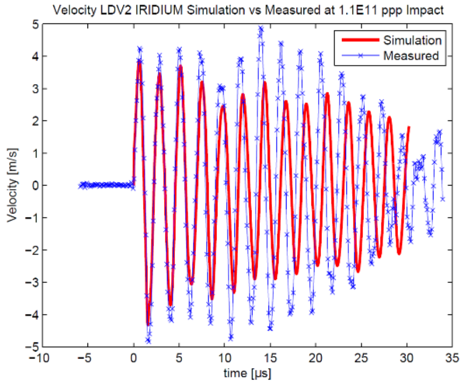
Estimated:
Max ΔT ~ 1700 ºC
Tensile pressure ~ 4GPa

Experimental setup and online results accepted to publication:
C. Torregrosa *et al.* "Experiment exposing refractory metals to impacts of 440 GeV/c proton beams for the future design of the CERN Antiproton Production Target: Experiment design and online results" Phys. Rev. Accel. Beams

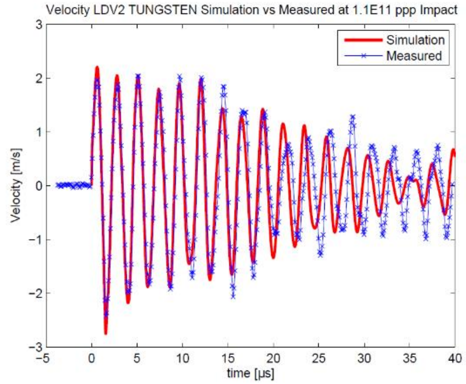
Hydrocodes Simulations vs Experiment (1)

Crosscheck at lowest intensity impacts (ΔT ≈ 160 °C)

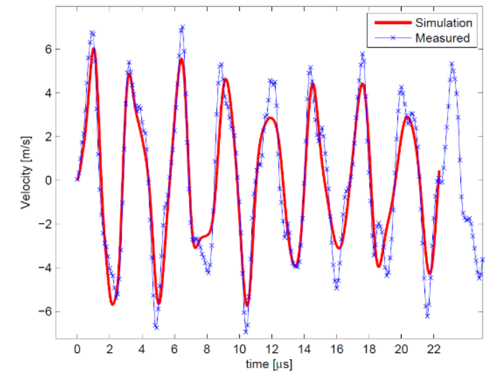
Iridium



Tungsten

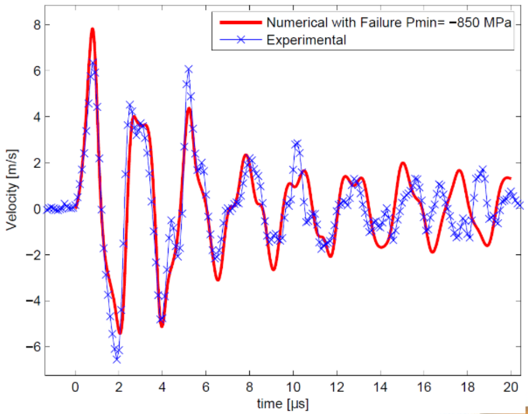


Tantalum



Crosscheck and bench marking of failure models at medium intensity (ΔT ≈ 530 °C)

Tungsten



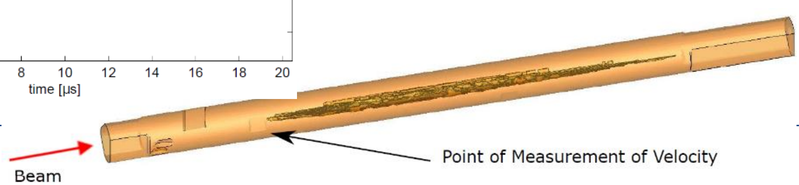
Distortion of the radial wave is emulated with a failure threshold:

for W:

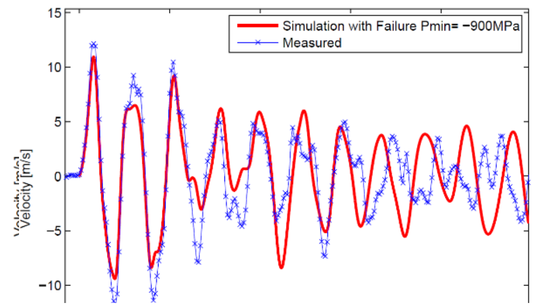
$P_{tensile}$ = 850 MPa

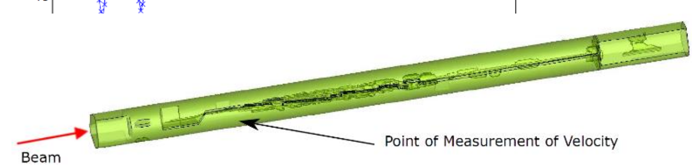
for Ir:

$P_{tensile}$ = 900 MPa



Iridium





HRMT-27 Outcomes + Next Steps

1) Predicted radial and longitudinal modes have been measured.

1) Material damage takes place at conditions ~5-7 times lower than the reached in the AD-Target.

2) **Tantalum** showed the best dynamic response. Strong candidate material for the new design.

Next questions to be answered:

1) Survival of Ta when impacted by high no. of pulses?

2) Avoid target bending when sliced?

3) New Target Prototyping. **What about the core containing matrix?**

2^{nd} Proposed Experiment

HRMT-42

Study the response of a first scaled prototype of the AD-Target

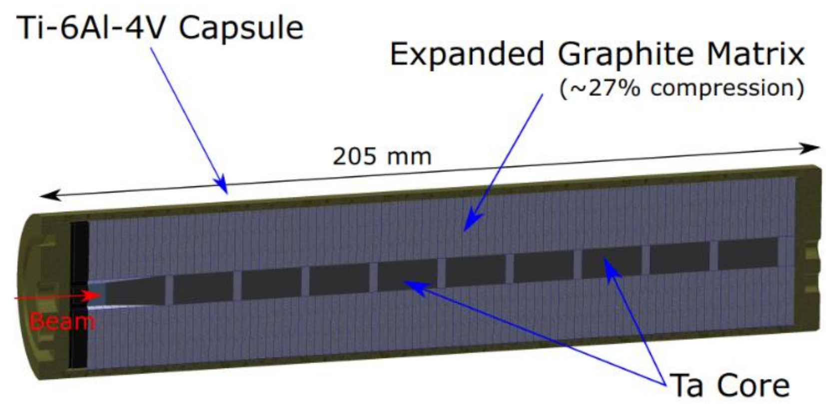
The HRMT-42 Target

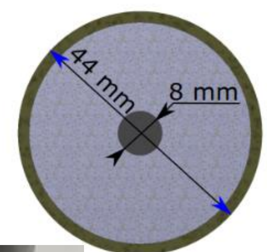
Up-Scaled Prototype of the AD-Target core & Matrix

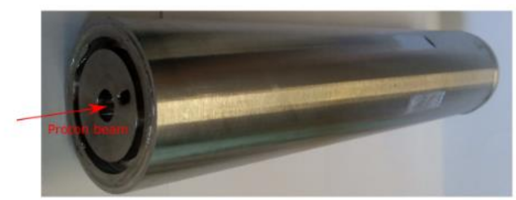
- Core of 8 mm diameter **Ta rods** (un-annealed)

- Core is sliced to avoid excitation of bending modes

- Embedded in a matrix made of **compressed layers of Expanded Graphite (EG).**



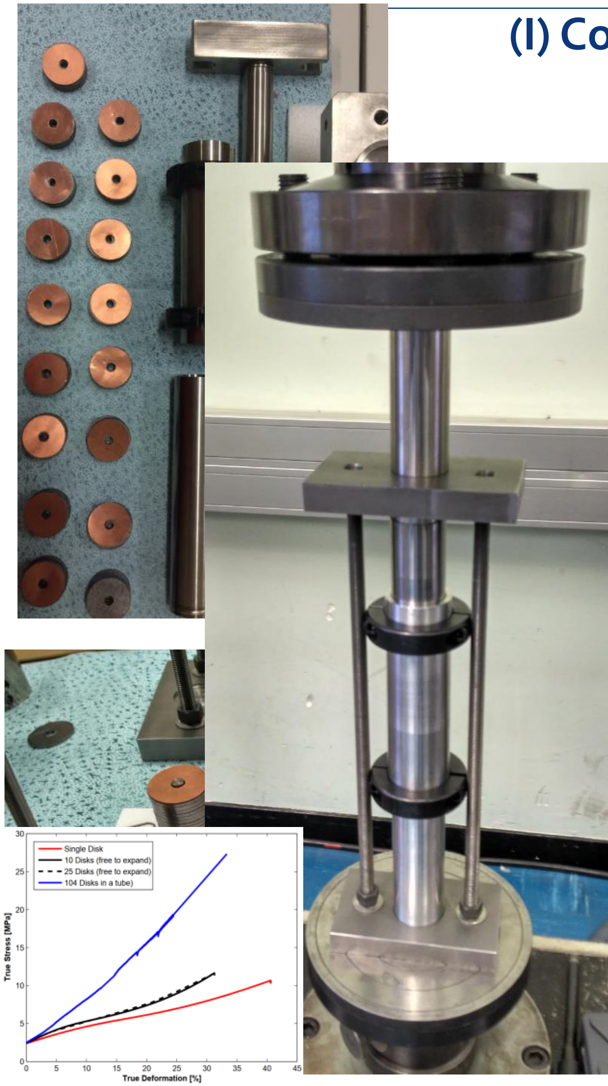




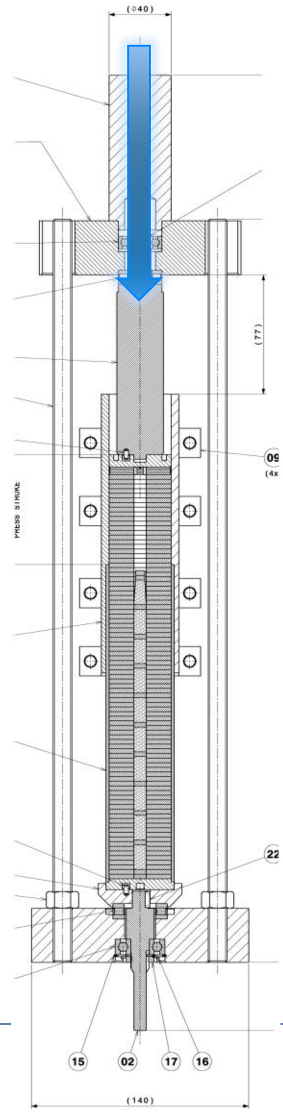
- Provide contact pressure with the core and guarantee a continuous interface (heat transfer) even if the core undergoes plastic deformation.

- Encapsulated in Ti-6V-4Al e-beam welded container

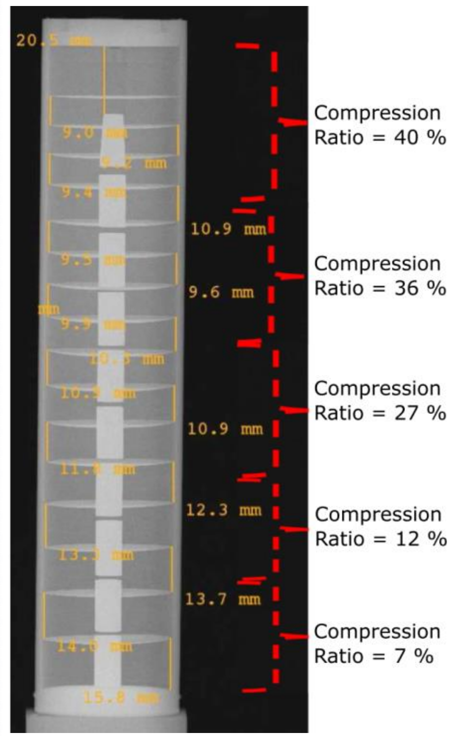
The HRMT-42 Target: Assembly and Welding Procedure



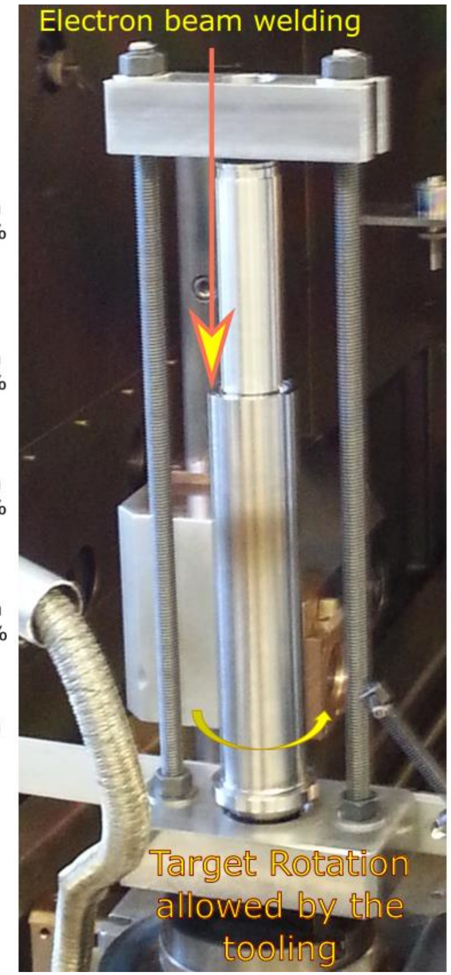
(I) Compression Phase



(II) Welding Phase



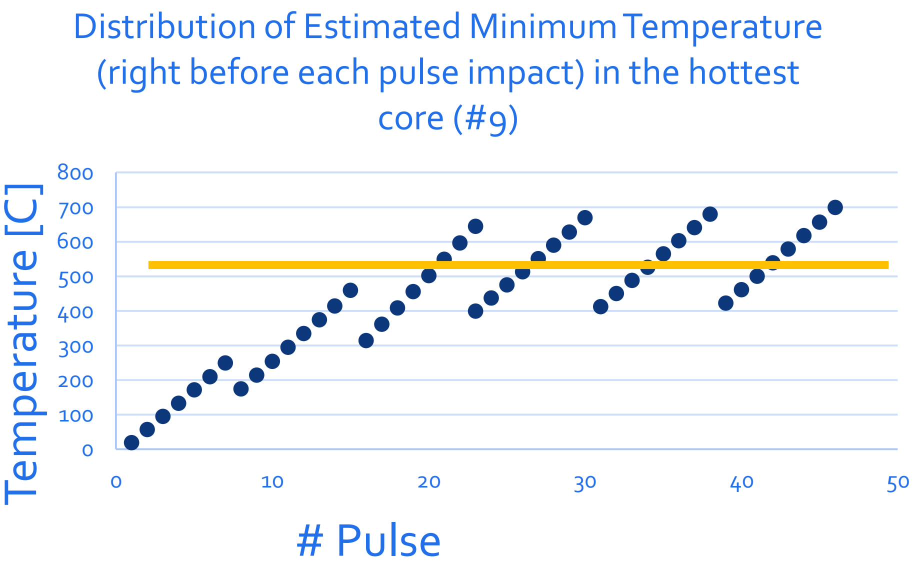
Non-Uniform over Compression Ratio over the length ☹

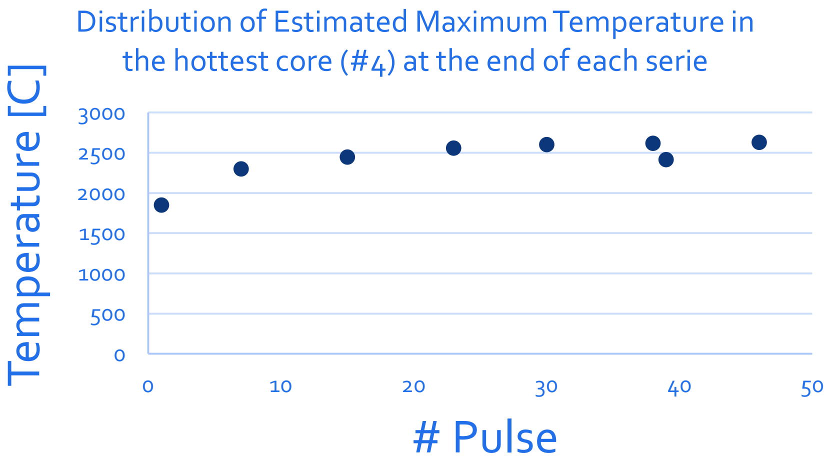


HRMT-42 Target, Testing in HiRadMat

#47 pulses were impacted ($7 \cdot 10^{13}$ POT)

	Pulses	Time Pulses (min)	Time cooling (min)
Serie 1	7	10	20
Serie 2	8	5.333	21
Serie 3	8	5.333	24
Serie 4	8	5.333	27
Serie 5	8	5.333	27
Serie 6	8	8	No relevant



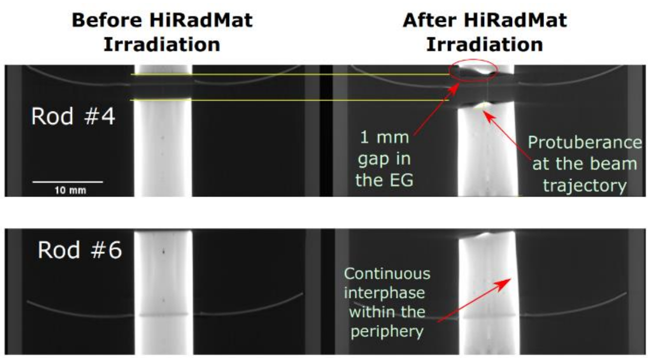


Accumulative heating

- Max temperature reached estimated in **2650 °C**
- Estimated accumulative time above 1600 °C = **14 s**
- Estimated accumulative time above 1000 °C = **5 mins**
- Estimated accumulative time above 800 °C = **15 mins**

Non-Destructive PIEs of HRMT-42 Target

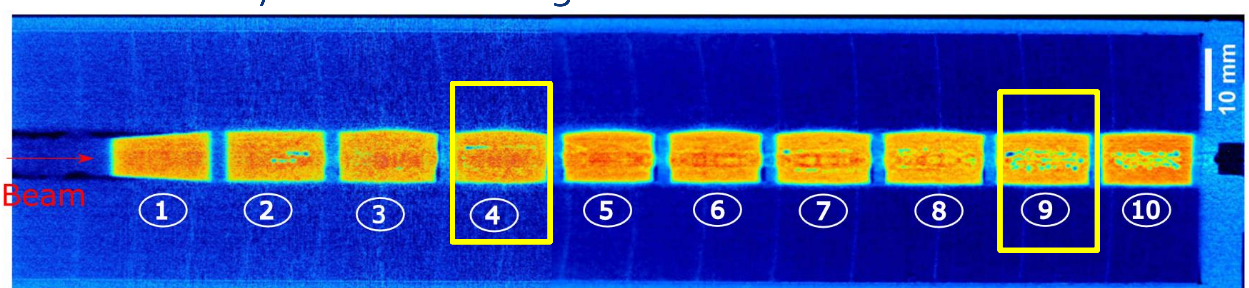
X-ray tomography at the ESRF (Grenoble, France)



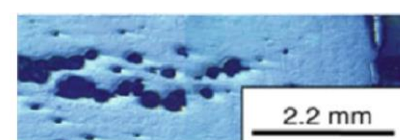
- Extensive plastic in the Ta
- It seems that the EG matrix can adapt to changes in the Ta shape

Neutron Tomography at NEUTRA (PSI, Switzerland)

- Neutron tomography showed the formation of voids in the Ta core, especially in the downstream ones.
- The most loaded rods (T and tensile pressure) are not necessary the most damaged…



- Not observed in HRMT-27
- Similar to «*spalling*» fracture for Ta described in in literature.

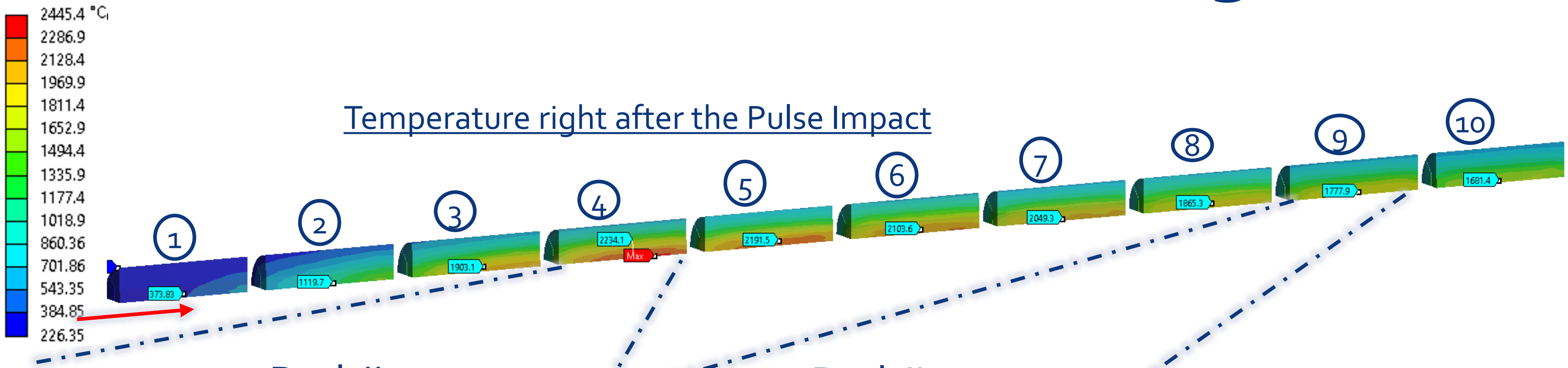


Gray III GT, Bourne NK, Vecchio KS, Millett JCF. Influence of anisotropy (crystallographic and microstructural) on spallation in Zr, Ta, HY-100 steel, and 1080 eutectoid steel. *Int J Fract* 2010; **163**: 243–258.

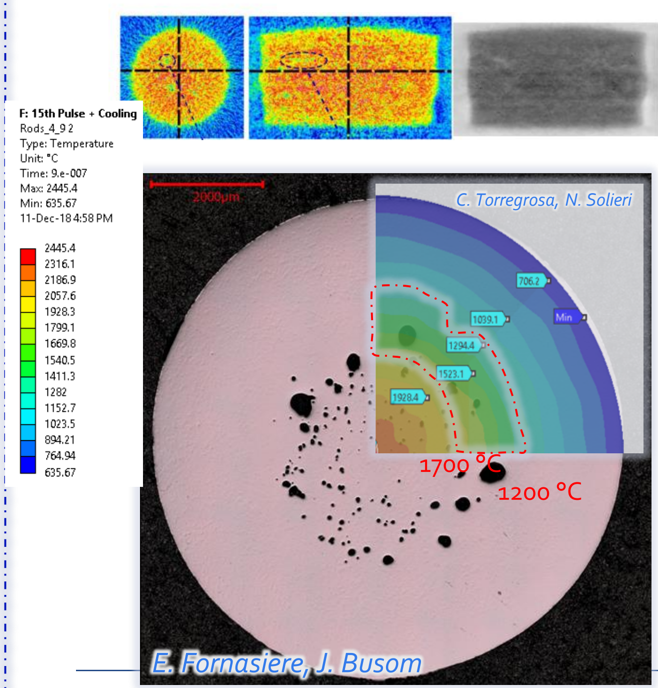
Results published in:
C. Torregrosa *et al.* "Scaled prototype of a tantalum target embedded in expanded graphite for antiproton production: Design, manufacturing, and testing under proton beam impacts" Phys. Rev. Accel. Beams 21, 073001

Observed voids in HRMT-42 Target

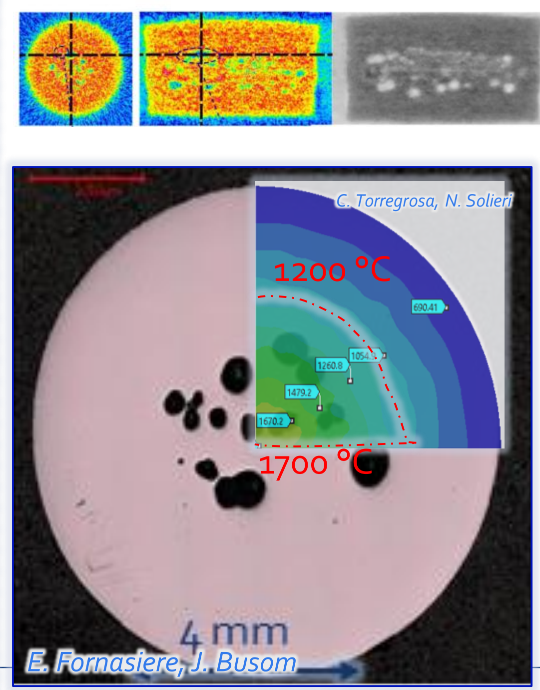
Temperature right after the Pulse Impact



Rod #4



Rod #9



- Large voids seem to appear in a similar temperature range
- It seems to be a progressive damage
  There are hundreds of oscillations of the radial mode with plastic yielding per pulse
- Temperature/recrystallizaton may play an important role in voids grow and its coalescence

See presentation of this morning, **J. Busom - *Update on the post-irradiation examinations on high Z materials from HRMT-27 and HRMT-42 experiments*– 5th RaDIATE Collaboration Meeting**

Outcomes of HRMT-42 + Next Steps

1) **Assembly procedure including EG validated**

   Room for improvement: Non-uniform EG compression ratio…

1) X-ray, neutron tomographies, ongoing PIEs, show **good performance of the EG matrix and revealed a new mode of Ta fracture**.

2) **Conditions** reached in the core of the new design **shall be "relaxed"** (increasing core diameter and/or defocusing the primary beam)

Next Prototyping Steps:

1) **Scaled-down to real dimensions.** Solve non-uniform Compression ratio.

2) Impact of beam parameters "relaxation"?

3) Further understanding of Ta spalling

   Comparison between different Ta grades? (annealing/no annealing, TaW alloys)

4) Direct **comparison between Ta vs Ir, EG vs Isostatic graphite?**

3rd Proposed Experiment

↓

HRMT-48 PROTAD

↓

Test real scale AD-Target prototypes

New AD-Target Design (PROTAD) and Testing in HiRadMat (HRMT-48)

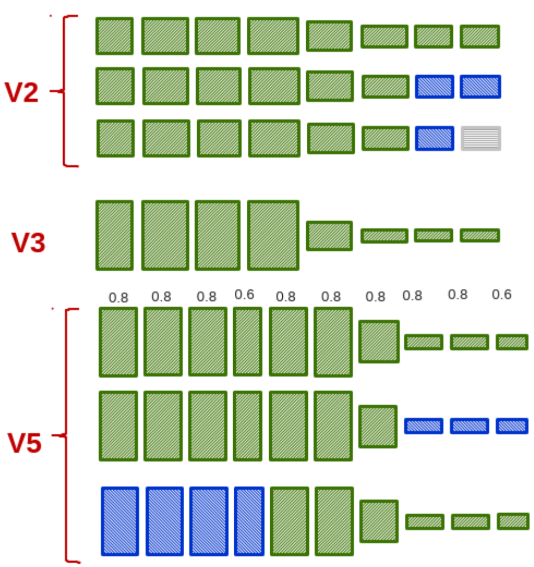
New Core Configuration with variable diameter

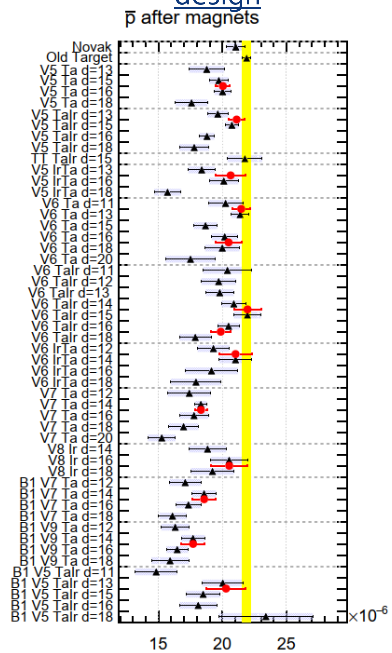
Fluka pbar Optimization Studies

Comparison with pbar yield of current design

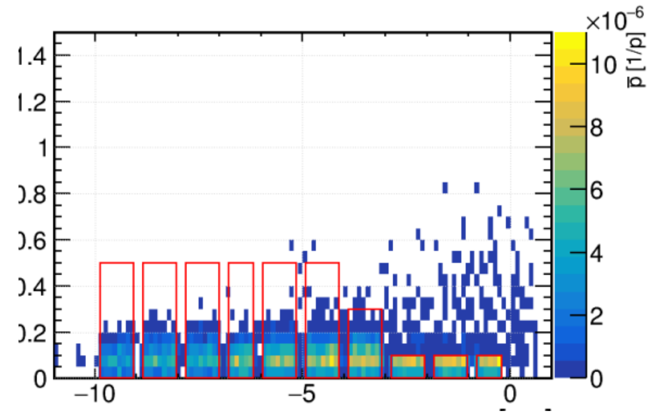
Courtesy of J. Canhoto

Different core configurations simulated

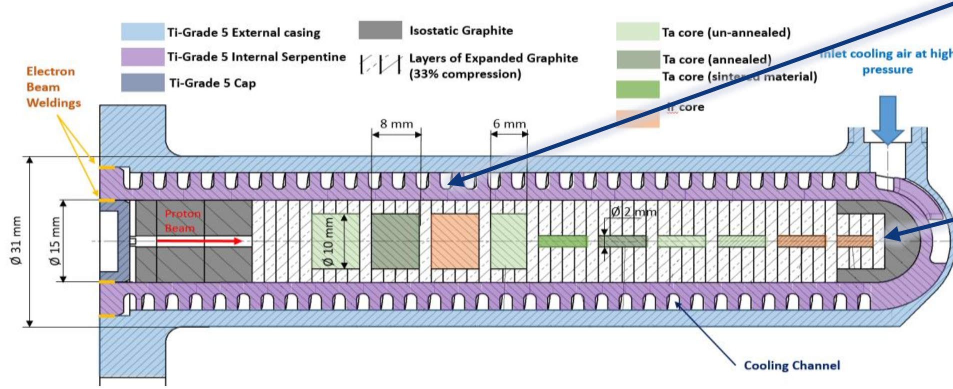




Detailed studies of <u>from *where*</u> in the target core the pbars are coming from



These studies suggest that increasing the diameter in the upstream cores will not affect the pbar production



Upstream cores of Ø 10 mm

(better than the Ø 3 mm of the current design from mechanical point of view)

Downstream cores Ø 2 mm

(better than the Ø 3 mm of the current design from pbar and mechanical point of view)

PROTAD Targets for testing in HiRadMat

Target	Target drawing Number	Core module number									
		1	2	3	4	5	6	7	8	9	10
#1	AD_TARAD0055	Identical to old design: rods of 3 mm diameter by 5-10 mm length									
#2	AD_TARAD0056										
#3	AD_TARAD0062										
#4	AD_TARAD0064										
#5	AD_TARAD0070		S1, S3, S5	S2, S7, S6							
#6	AD_TARAD0075										

Colour legend				
WHS	Ta WHS non-ann	Ta WHS_ann	2 mm diam WHS_non-ann	2 mm diam WHS_ann
TaW	TaW non-ann	TaW ann	2 mm diam TaW non-ann	2 mm diam TaW ann
Plansee	Ta_Plansee non-ann	Ta_Plansee ann	**Ta_Plansee_ann 1400 °C, 1h**	TaS
Ir				
Ir Tube	Tube Ir			
TaM tube	Tube TaM (annealed)			

Colour Legend		
W-(1.2%) TiC	S1	HQ-GSMM
	S2	LQ-GSMM
	S3	HQ-w/o GSMM
	S4	HQ-w/o GSMM
	S5	Hot rolled
W	S6	Hot rolled and recrystallized
	S7	Hot rolled

High Quality – HQ
Low Quality – LQ

PROTAD Targets Manufacturing

<u>External Ti-6Al-4V Assembly</u>

<u>Two Strategies</u>

- Two independent assemblies (EBW in the upstream part)

- Single part 3D-Printed at CERN

Courtesy of R. Gerard

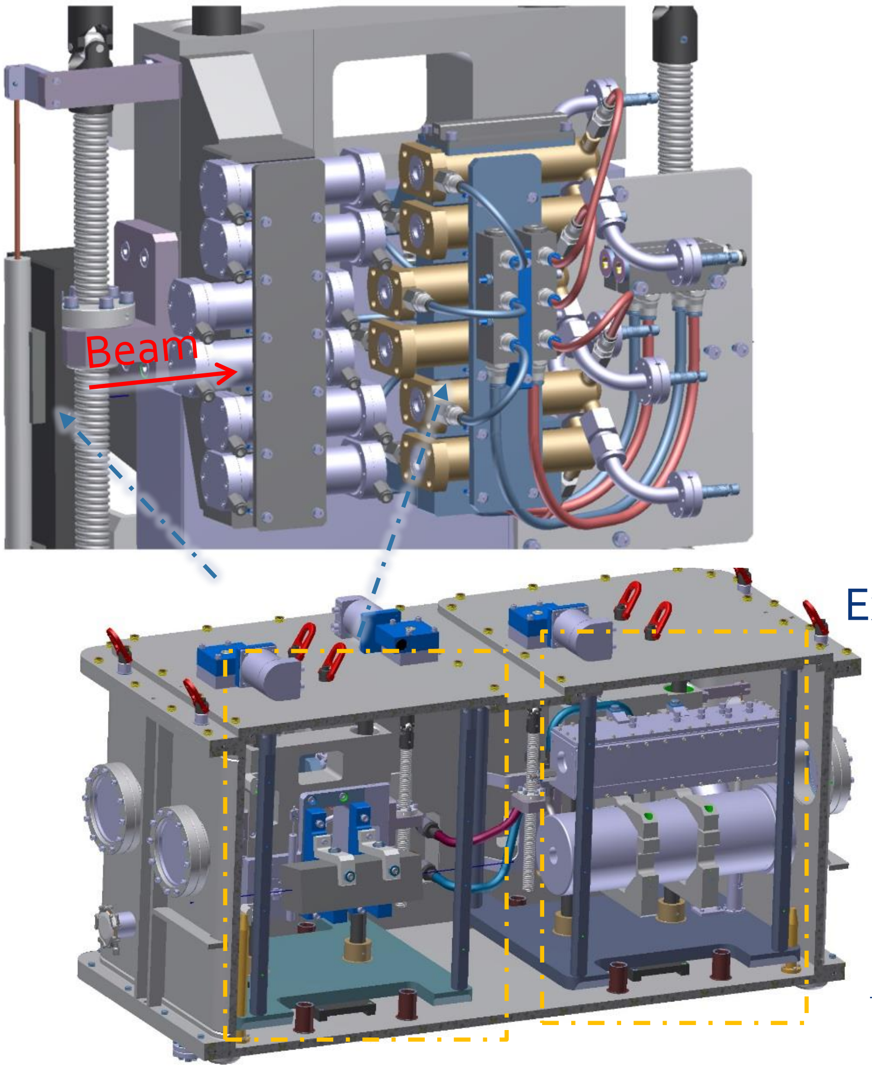
<u>EG Matrix and Cores</u>

Different procedure from HRMT-42: **<u>2-stage</u> compression to ensure a constant compression ratio**

<u>Six targets Manufactured in total</u>

PROTAD HiRadMat Experiment

PROTAD targets tested within a HiRadMat Multipurpose Experiment



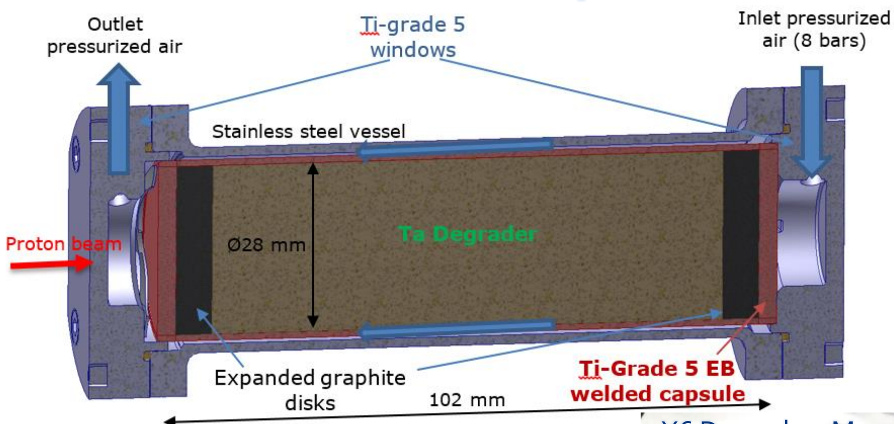
Experiment executed on **28th/29th September 2018**

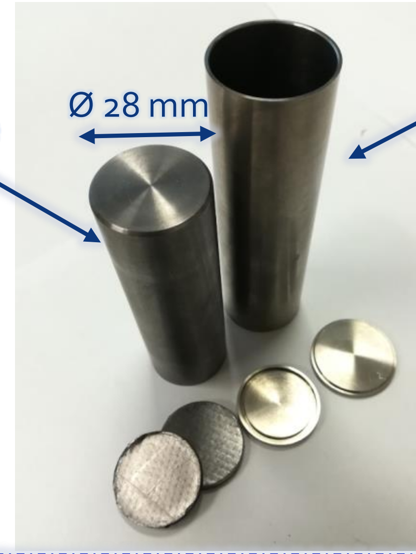
50 pulses/per target impacted in 5 targets
Target no. 6 received **140 pulses**
$4 \cdot 10^{14}$ POTs in **total POTs**

Targets opening and PIEs foreseen during 2019

"The Ta-degrader": An additional development

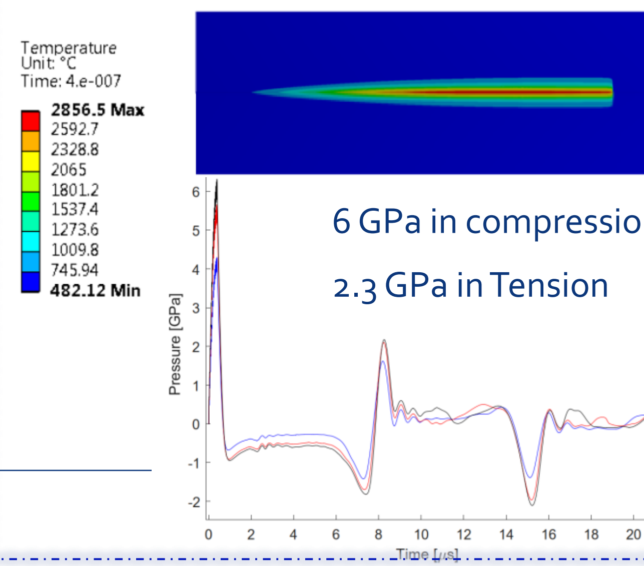
Ta cladded in Ti6Al4V Target, air cooled SS with bolted Ti6Al4V windows





X6 Degraders Manufactured

Response in the Ta Core



Conclusions

Extensive R&D activities in the context of new $\bar{p}$ production target

- **Simulations:** Use of hydrocodes, identification of governing phenomena.

- **HiRadMat experiments:**
  1) **HRMT-27:** Study the fundamental response of thin rods.
     - Simulations validation and benchmarking. Superior response of Ta.
  2) **HRMT-42:** First Target prototyping
     - Spalling fracture in Ta, new interesting type of failure identified.
  3) **HRMT-48 PROTAD Experiment:** Real scale target prototyping

- **Manufacturing:** Use of compressed Expanded Graphite, 3-D printed Ti-Grade 5, Ta cladded in Ti…

General Relevance for other BIDs

- The AD-Target is the most dynamically loaded target currently in operation

1) **Deep understanding of dynamic phenomena** induced by proton beam impacts. Lessons:
   - Importance of pulse length, geometry, excitation of modes
   - Using advanced material models

2) Identification of new modes of failure, using new materials (TaW, WTiC, EG…)

3) **Experience in designing and executing HiRadMat experiments** as well as **PIEs techniques** (i.e. neutron tomography, destructive PIEs at CERN)

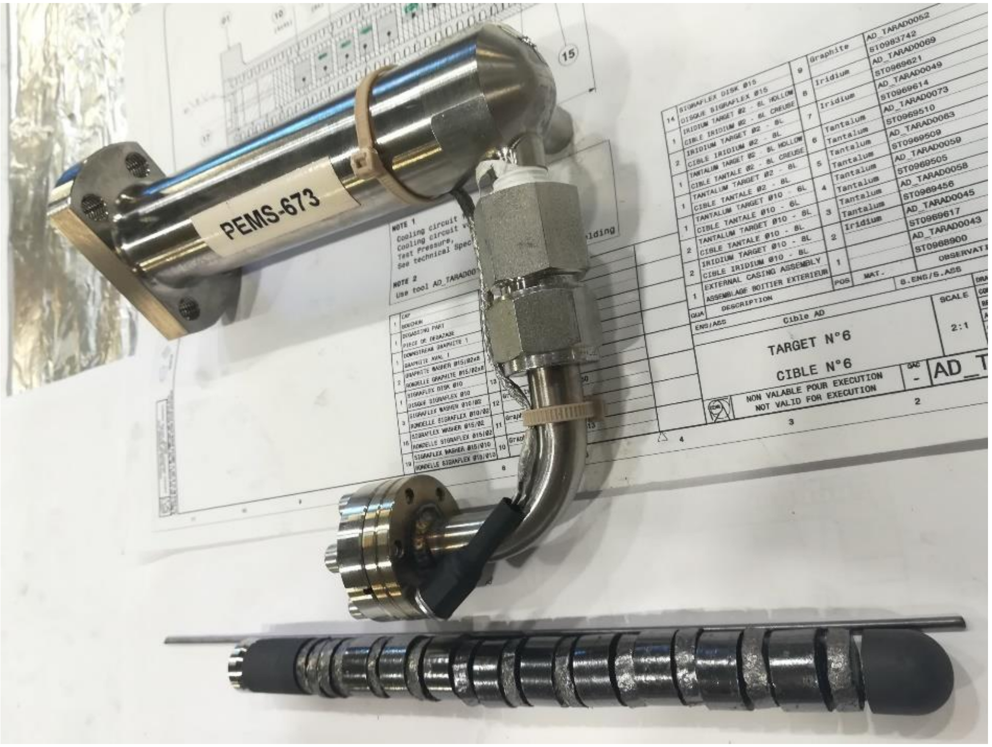
Future Perspectives

- Based on the experience of last prototypes, final batch of targets will be manufactured during 2019.

- PIEs after opening the PROTAD targets will define the final core configuration, EG vs isostatic graphite performance.

- Installation of new target design in the renovated AD-Target area (including new design of target & horn positioning trolleys) by the end of 2020.

New targets operation after CERN's LS2, 2021


PEMS-673
TARGET N°6
CIBLE N°6
NON VALABLE POUR EXECUTION
NOT VALID FOR EXECUTION

Thanks !