Towards the Construction & Operation of a New Generation p-bar Targets:

Beam-induced Spalling in Ta and learnings from Prototypes Testing towards Final Assembly

Claudio Torregrosa on behalf of the AD-Target Consolidation project

CERN | EN ENGINEERING DEPARTMENT | STI

Technical RaDIATE meeting
07/12/2020

RaDIATE Collaboration
Radiation Damage In Accelerator Target Environments

Outline

1) Introduction to the **CERN's AD-Target Area Consolidation Project**.

2) **Mechanical Response** of the **Core** of the **Antiproton Target**

3) **Prototyping** and **in-Beam tests of the** New Generation Design

4) **Manufacturing** New Generation Targets and **Commissioning Plans**

Introduction: The AD-Target Consolidation Project

Renovation and upgrade activities to guarantee $\bar{p}$ physics for the next decades. Executed from 2019 to mid 2021. Involves:

b. 232

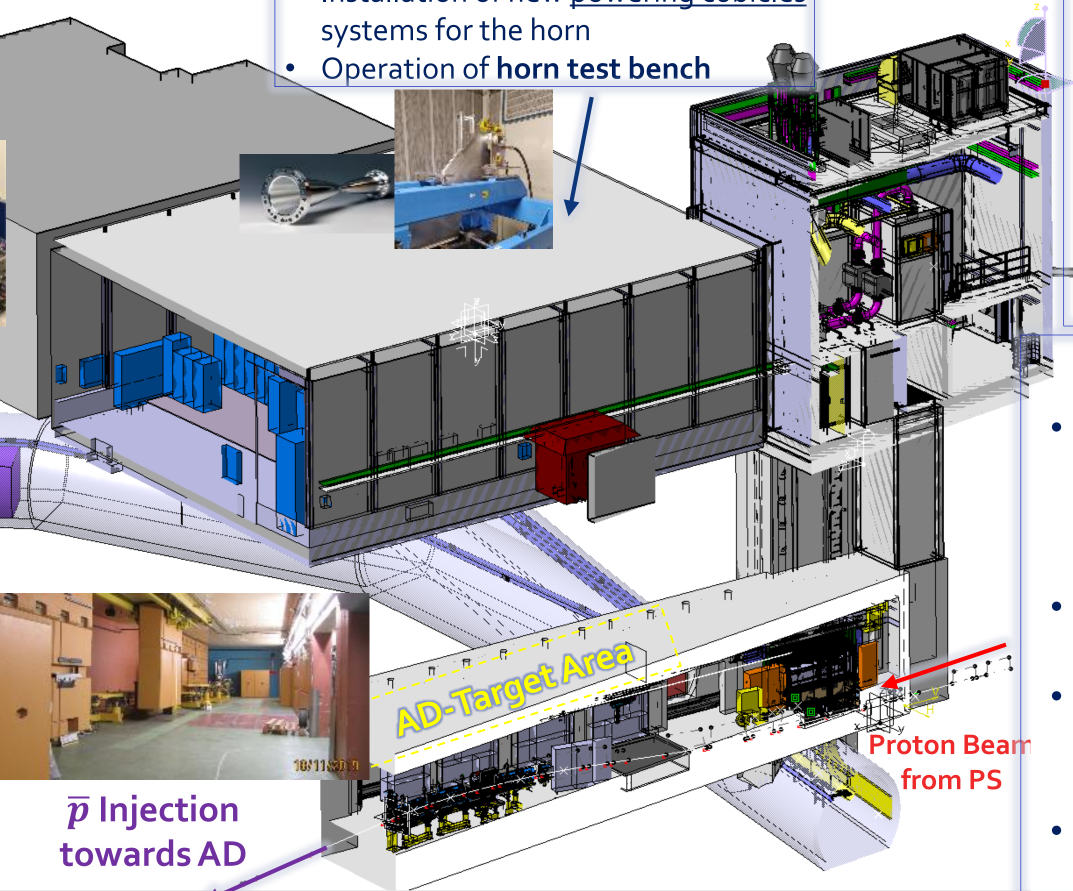
Surface mock-up of target & horn trolleys

b. 195

- Installation of new powering cubicles systems for the horn
- Operation of **horn test bench**

b. 196

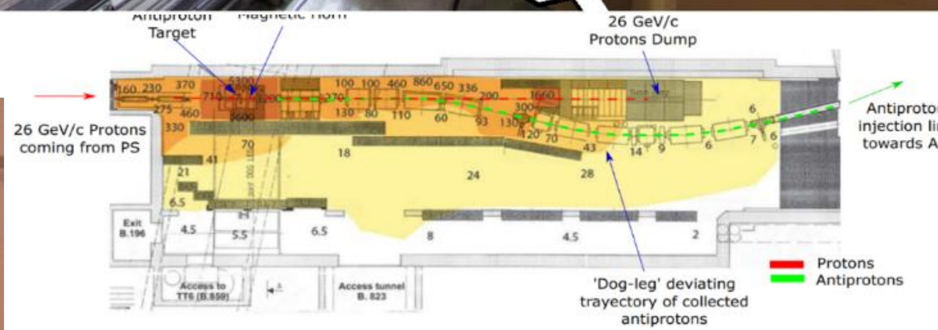
Demolition and construction of a new building to house a renovated ventilation system

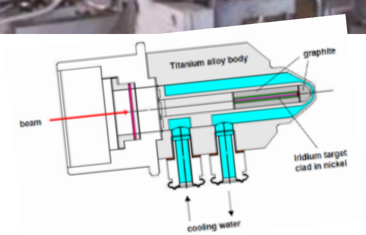


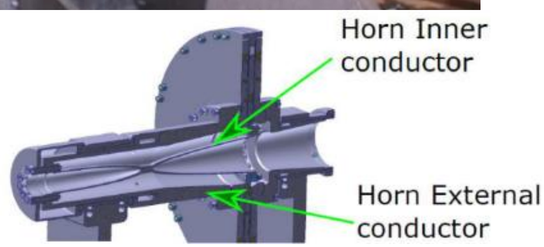
AD-T Area

- New **positioning system** of the target & horn + new target design
- Clean-up and **Decontamination.**
- New permanent magnet focusing quadrupoles.
- Consolidation of movable shielding curtain

Elements for Antiproton Production





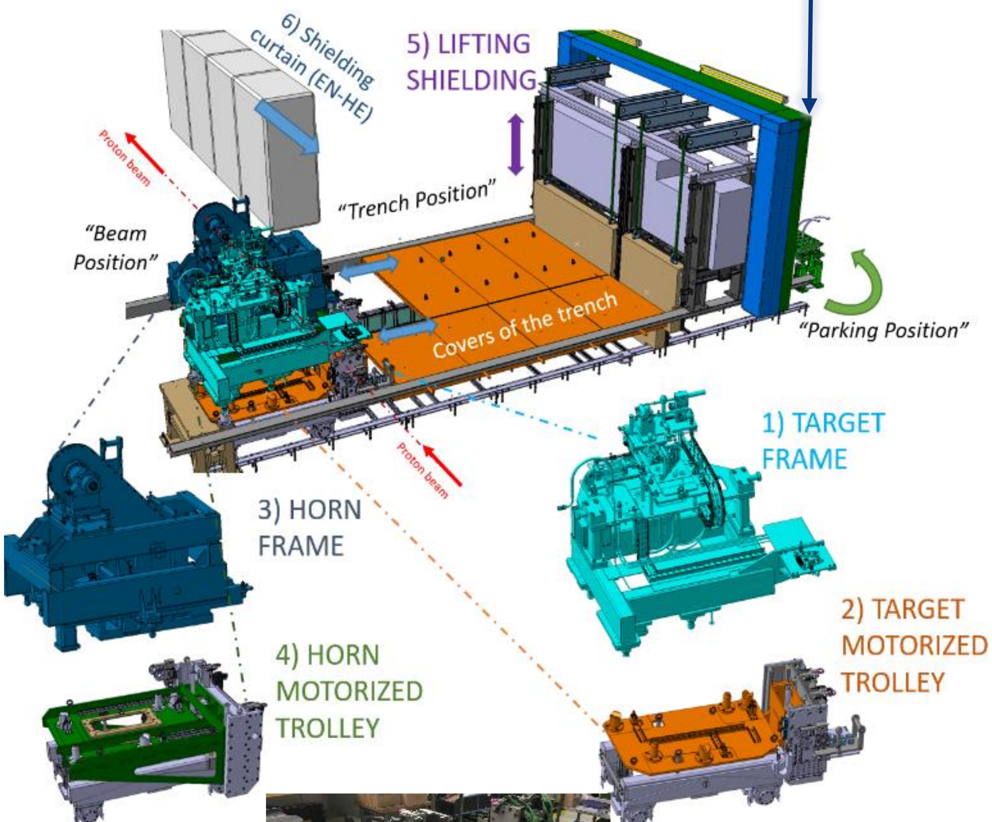


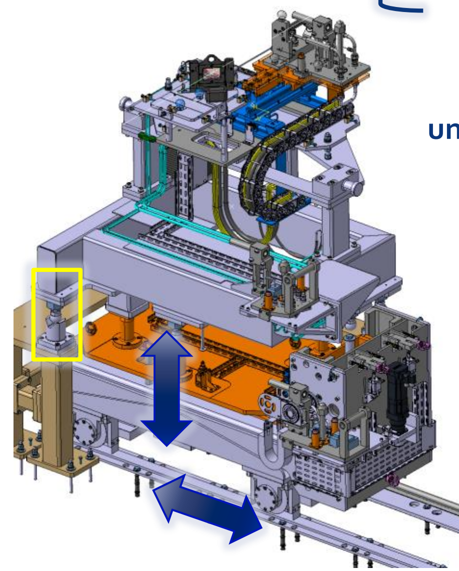
- Elements required for antiproton production
  - Target
  - Horn
  - Magnetic Spectrometer

New AD-Target Trolleys System

New Rationale: Horn/Target trolley divided in two systems:

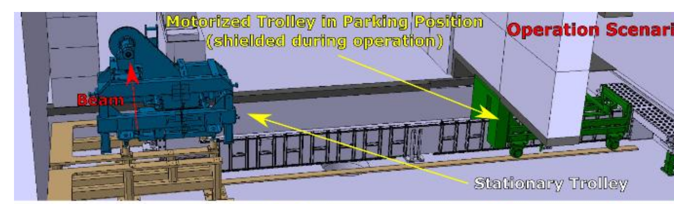
- **1) "Passive" chassis**
- **2) Motorized Trolley**

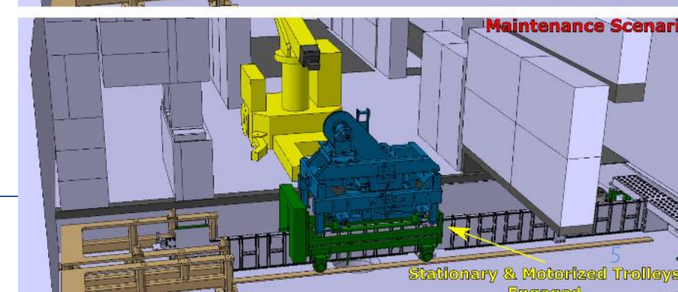




To pick up the Chassis, **the motorized trolley goes underneath and lift it above its 3x fixed supporting points**

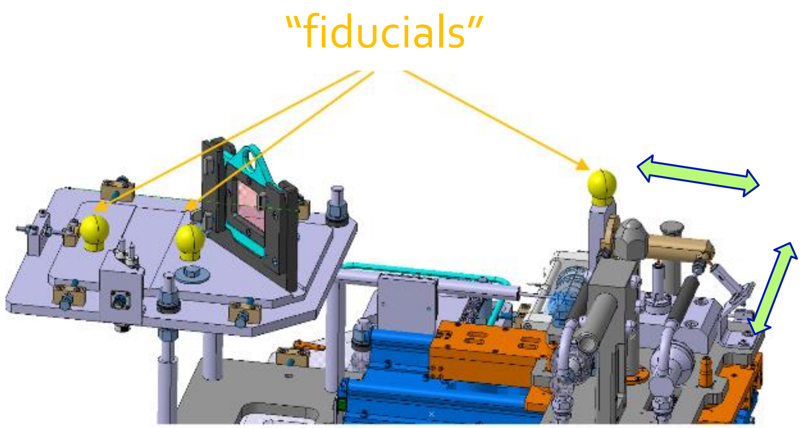
Coupled horizontal/vertical movements.
Bound to this configuration given the geometry of the area





New Features and System for fast Target Exchange

New Beam TV system and "fiducials" for improving accuracy on the impact position

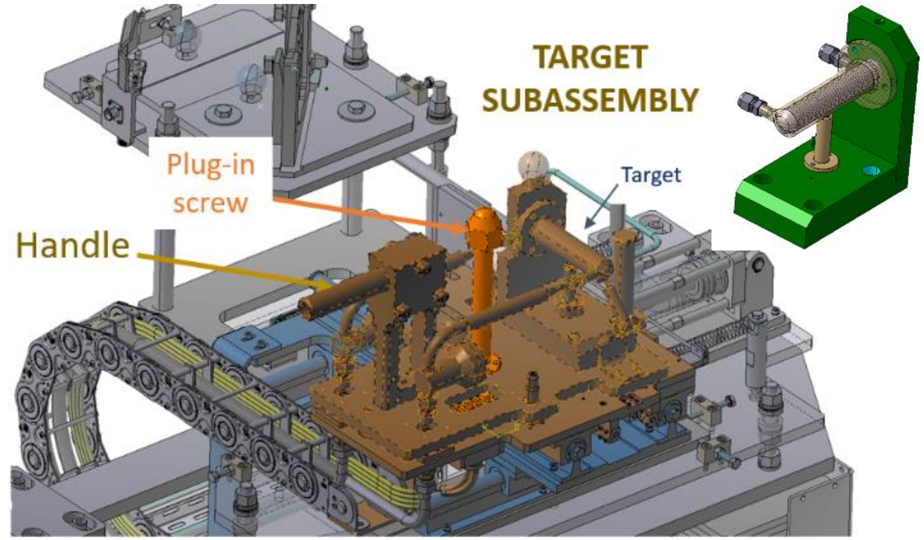


The Chassis keeps the functional Target movements:

1) Transversal (target IN/OUT)
2) Longitudinal (for Target-Horn distance optimization)

Previous mechanical mechanisms in the old design are **replaced by radhard pneumatic actuators** (metal seals and hard-Cr or bronze surfaces)

For a target exchange, the whole "Target Sub-assembly" is replaced (Plug-in system with a single screw)



Several Targets exchanges rehearsal are foreseen at the mock-up area and during commissioning

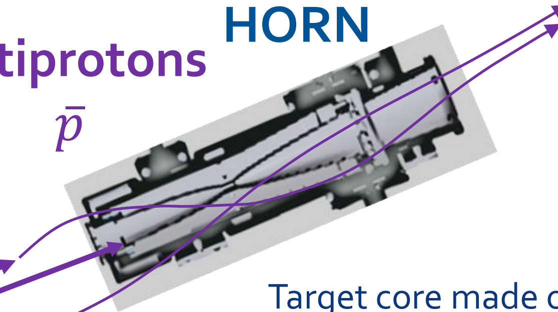
R&D Studies related to the Thermo-mechanical Response of the Target Core

$\bar{p}$ Production in the Target Core and Thermomechanical Response

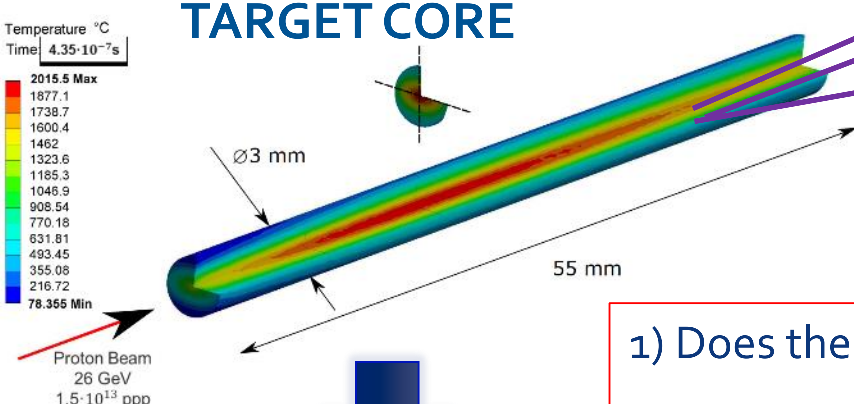
$\bar{p}$ production requires **maximizing p-target interaction in short distance**

Antiprotons $\bar{p}$

HORN



TARGET CORE



Target core made of ⌀ 3 mm x 55 mm length rod of **Iridium**

$\rho = 22.5\ g/cm^3$

Rise of Temperature ~ 2000 °C in 0.43 µs

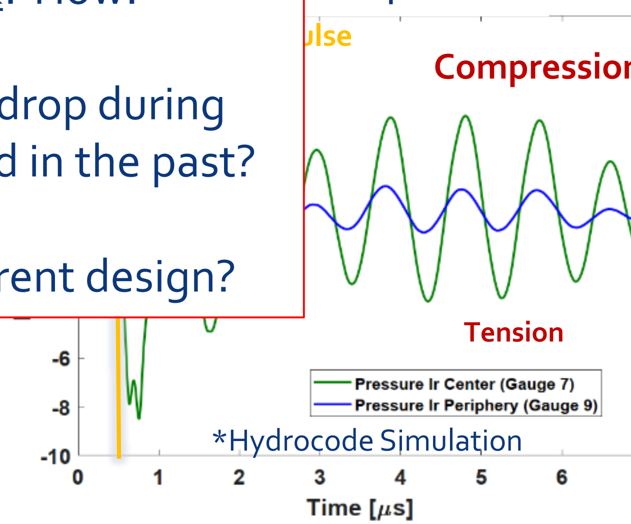
- Highest Possible density
- Very focused primary bear
  (< 1x1 mm)
- Thin target core

1) Does the material break? How?

2) Is this the reason of a $\bar{p}$ drop during early operation as reported in the past?

3) Can we improve the current design?

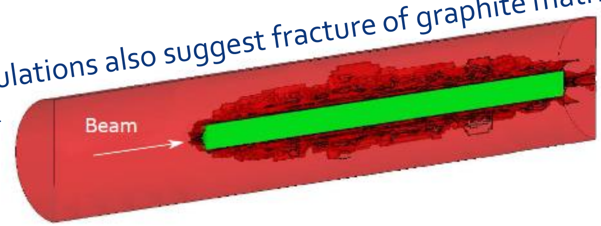
response!



*Hydrocode Simulation

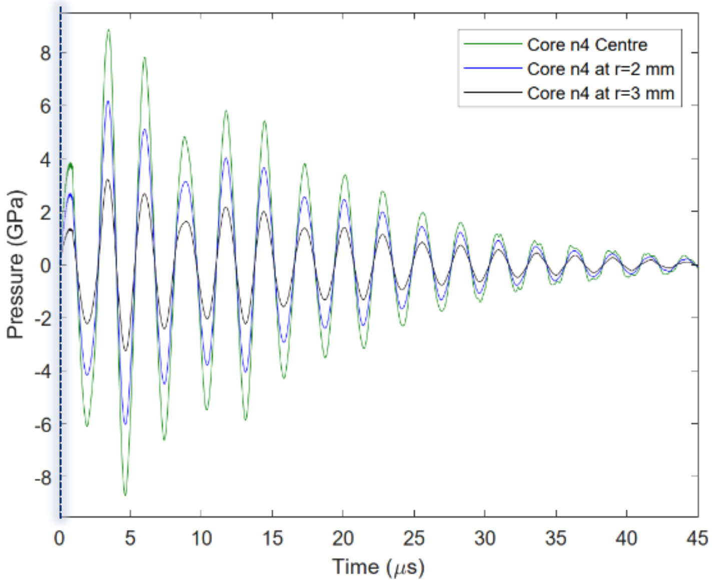
$\dot{\varepsilon}_{max} \sim 5 \cdot 10^4\ s^{-1}$

Simulations also suggest fracture of graphite matrix



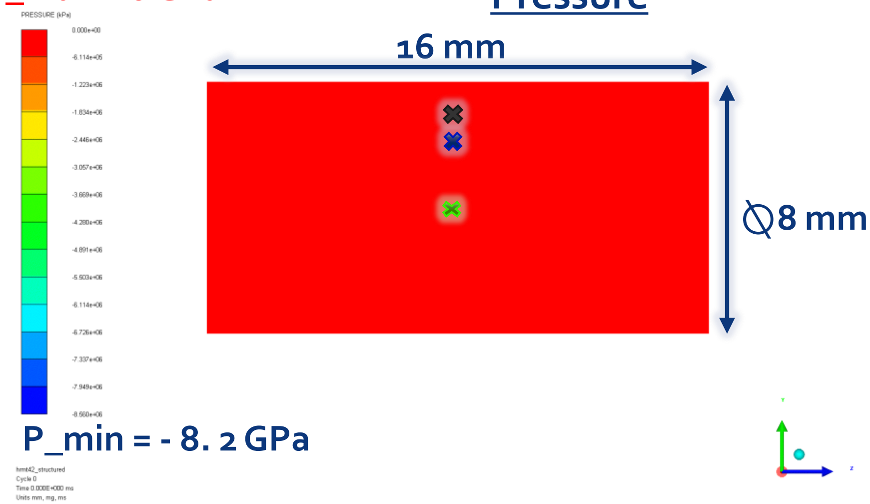
*C. Torregrosa et al. "CERN antiproton target: Hydrocode analysis of its core material dynamic response under proton beam impact" Phys. Rev. Accel. Beams **19**, 073402 July 2016*

Example of Dynamic Response of a cylindrical Core



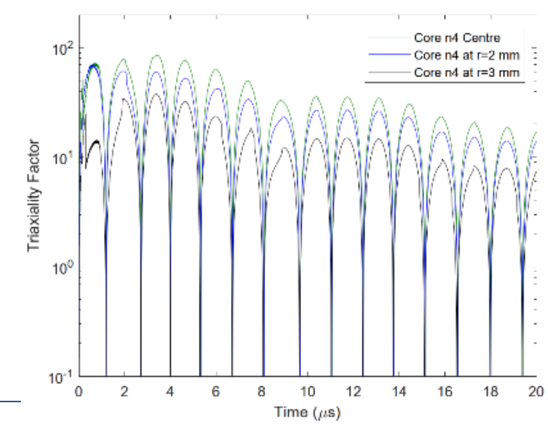
Velocity Field and Tensile Pressure

P_max = 0 GPa



Plastic yielding is reached in every oscillation (limiting deviatoric stress)

Tri-axiality factor above 15 for most of the time



The load is mostly hydrostatic

Fracture mode depending on the type of refractory metal:

- **Brittle:** Cracks appear -> The mode is distorted
- **Ductile:** material flow, no cracks -> Damping of the vibration

Studied in HRMT-27 experiment

C. Torregrosa et al. "First observation of spalling in tantalum at high temperatures induced by high energy proton beam impacts" E. Journ. Mechs-A/Solids, 85, 2021, 104149

Findings from HiRadMat Experiments and Spent Target Opening

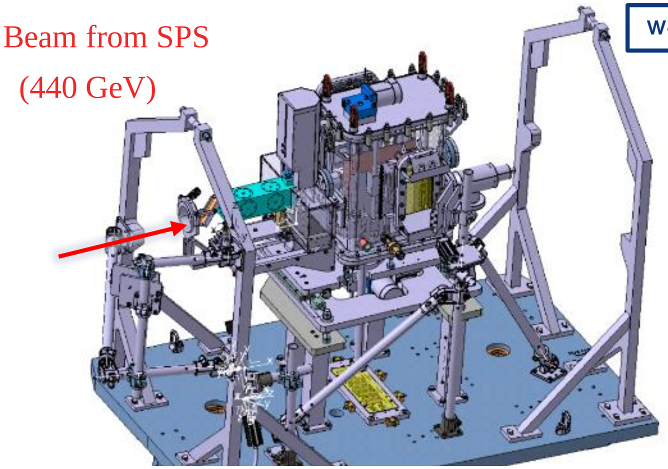
1) **HRMT-27 (2015)**

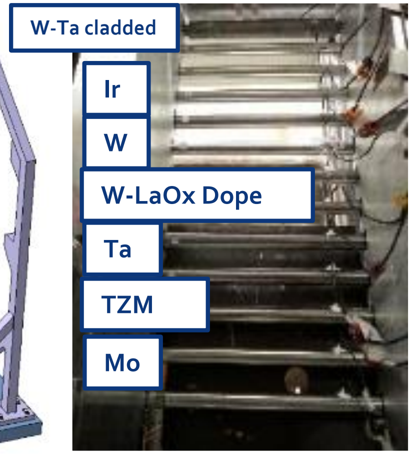
2) **Spent AD-Target Opening**

3) **HRMT-42 (2017)**

PhysRevAccelBeams.22.013401

The HiRadMaT-27 Experiment (2015)





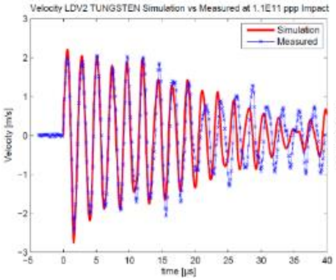
- 13 rods of high-Z materials impacted by 440 GeV/c beam
- Irradiation performed in a **ramped** way to obtain material response at intermediate state before reaching AD-Target conditions

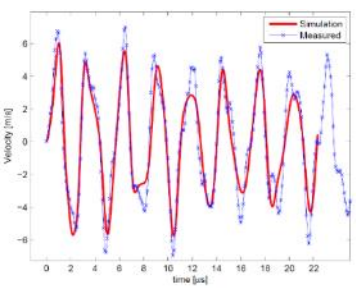
Results:

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

C. Torregrosa *et al.* <u>"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"</u> Phys. Rev. Accel. Beams 22, 013401, January 2019

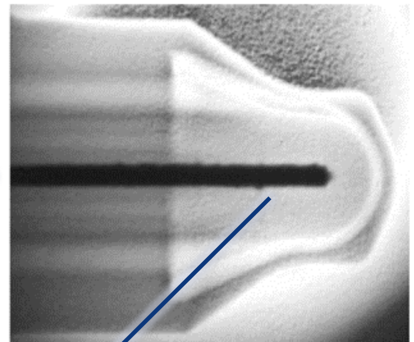
Spent Target Opening (2018)

Spent AD-Target (in operation between 2000 and 2008) opened in FRAMATOME. **POT 1.6·10^{19}**

ESTIMATED DPA

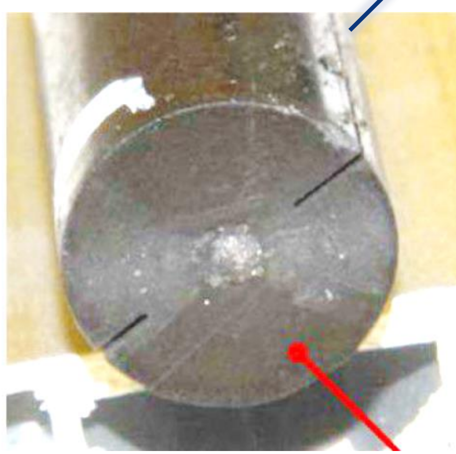
Material	dpa (average)	H appm	He appm
Ir	5.7	4300	3180
Graphite	0.05	83	114
Ti6Al4V	0.28	406	438
Al.	1.53	1516	1163

Neutron imaging of the target in CERN's nTOF

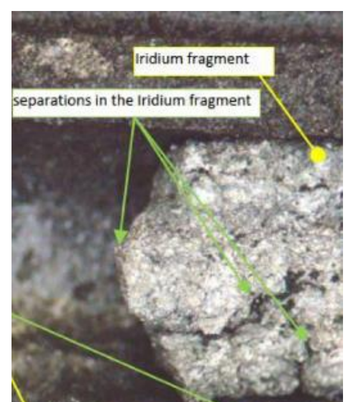


Upstream face

Mid face



Iridium Fragment



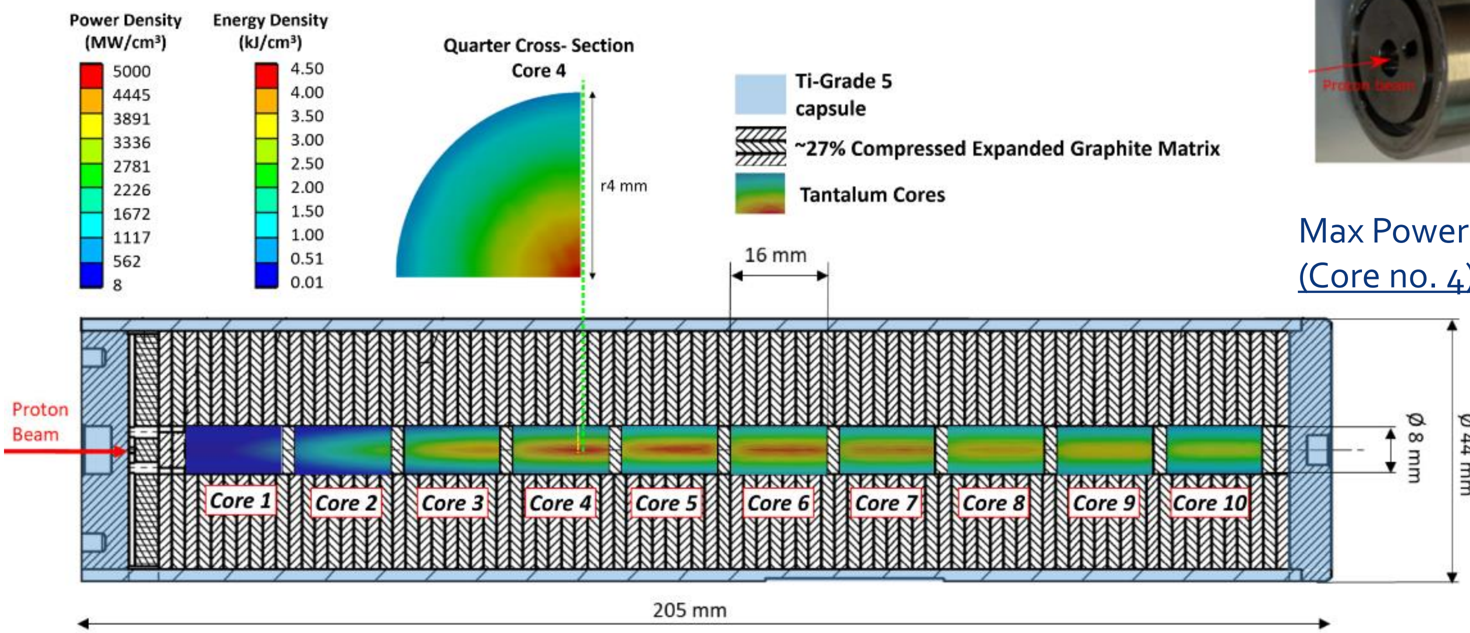
-Iridium core is an **amalgam of broken, melted & re-solidified** fragments

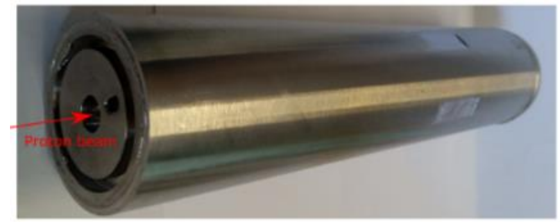
-Cracks in the graphite matrix also observed

PhD Thesis. E. Fornasiere "Post-irradiation examination of refractory metal candidates for antiproton targets at the European Laboratory for Particle Physics (CERN)", 2020

The HRMT-42 Experiment (2017)

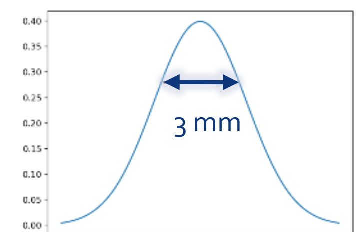
- Target Core made of <u>10x **Ta rods**</u> (un-annealed) 8 mm diameter by 16 mm in length
- Embedded in a matrix made of <u>**compressed layers of Expanded Graphite (EG).**</u>
- Encapsulated in Ti-6V-4Al e-beam welded container





Max Power Density = 5000 MW/cm³
<u>(Core no. 4)</u>

Pulse duration = 0.9 μs
Pulse size σ = 1.5 mm



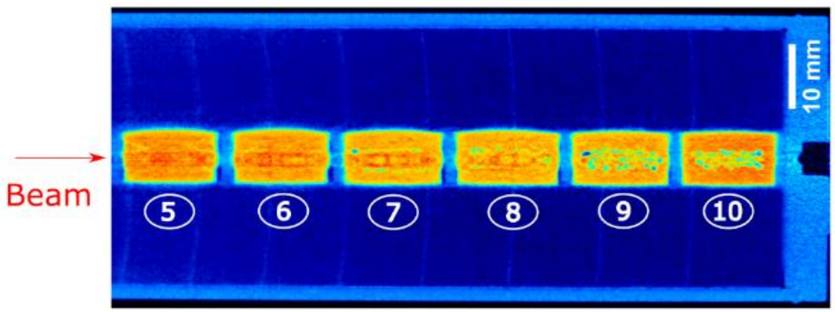
- <u>**x49 Pulses impacted**</u> (ΔT_{max}/pulse = 1800 °C) (40 s between each pulse, with 12 mins waiting after 8 pulses)
- No significant instrumentation this time. <u>**Rely on post-experiment examinations**</u>

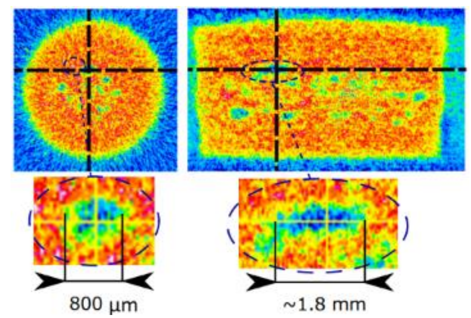
C. Torregrosa et al. <u>" Scaled Prototype of a Tantalum Embedded in Expanded Graphite Target for Antiproton Production: Design, Manufacturing and Testing under Proton Beam Impacts at HiRadMat"</u> Phys. Rev. Accel. Beams 21, 073001, 24 July 2018

Findings of PIEs of HRMT-42 targets

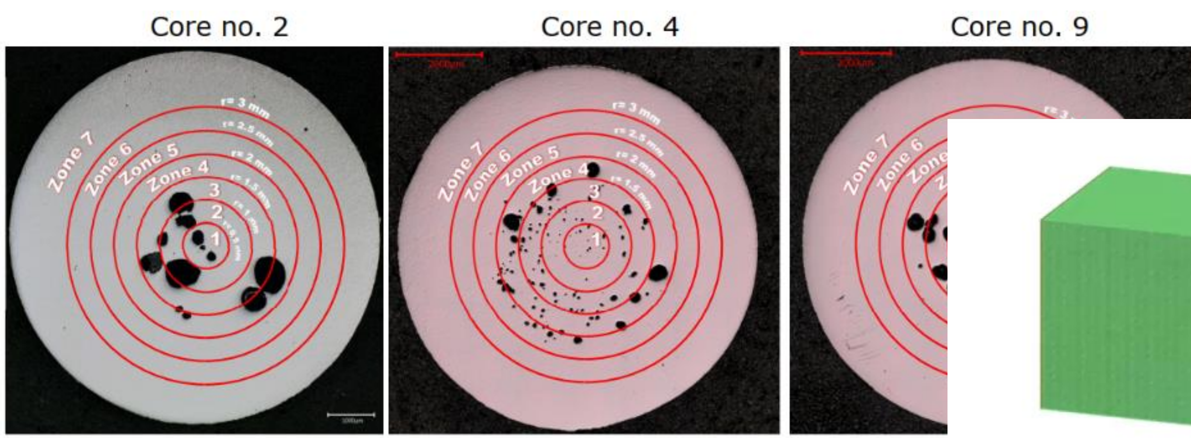
1) Neutron tomography at PSI (Switzerland)

Neutrons can penetrate the dense Ta core and reveal its interior

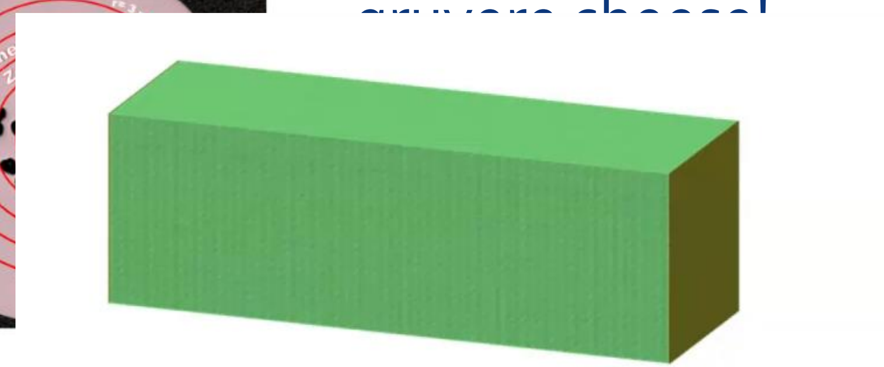




2) Target opening and slicing cores at CERN

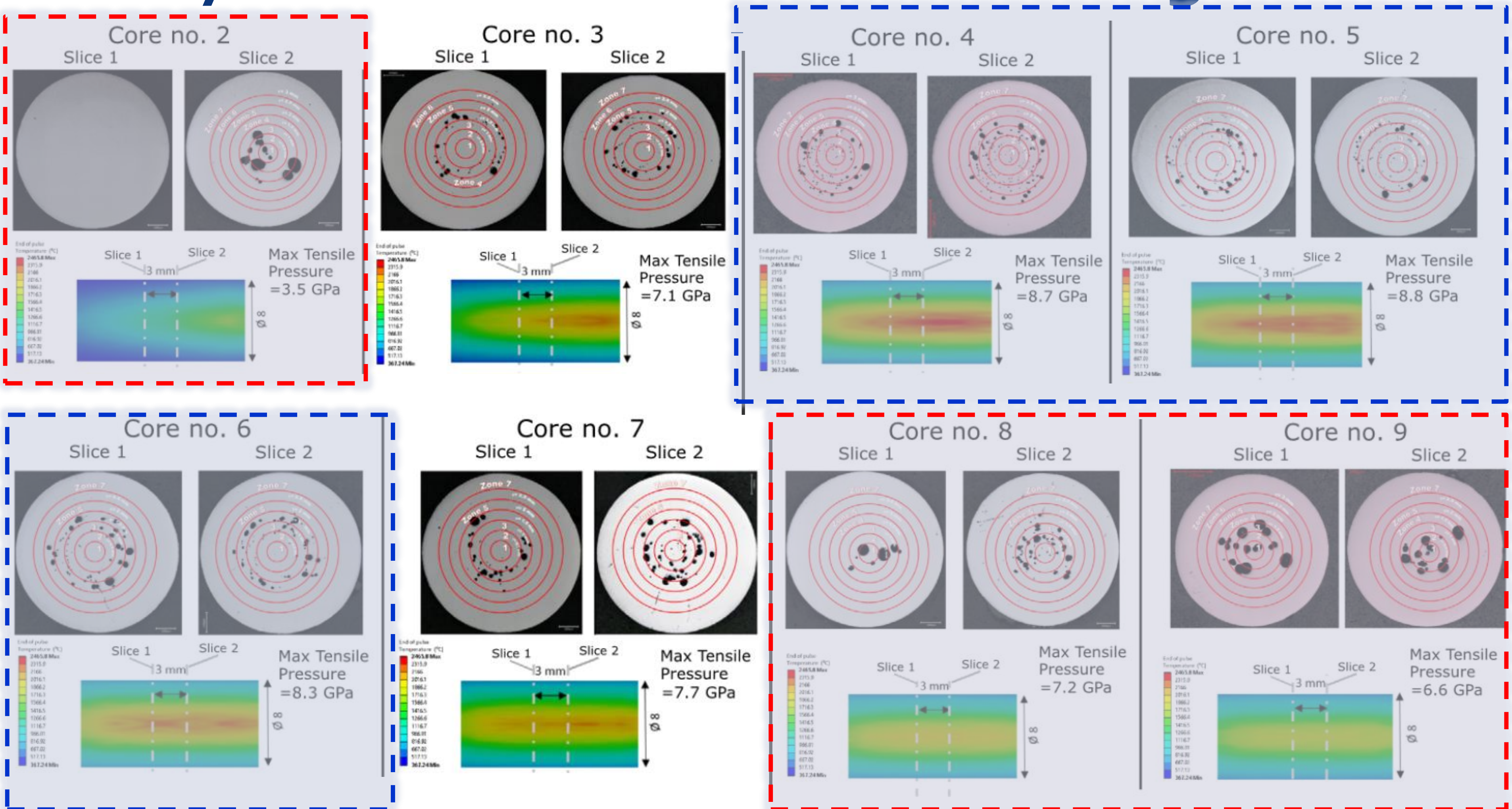


Spalling voids:
Tantalum becomes a



Video of Piston Impact Test on Ta using Molecular Dynamics *from: E. N. Hahn et al. "On the ultimate tensile strength of tantalum" Acta Materialia Volume 126, March 2017, Pages 313-328*

Why these voids are so interesting?

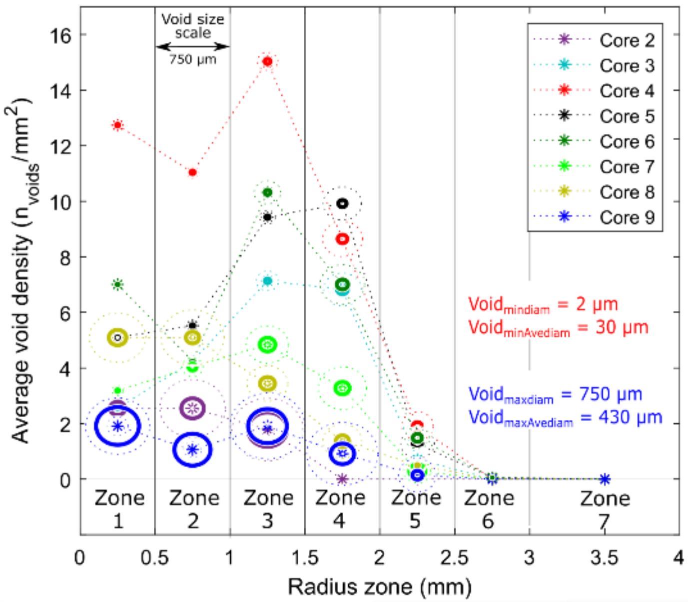


Response A: Large, isolated voids

Response B: Many small voids, “crown” distribution

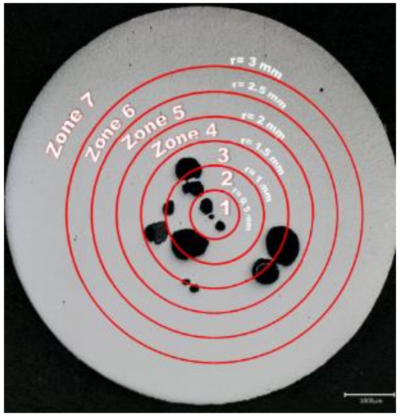
Quantitative Analysis of the voids

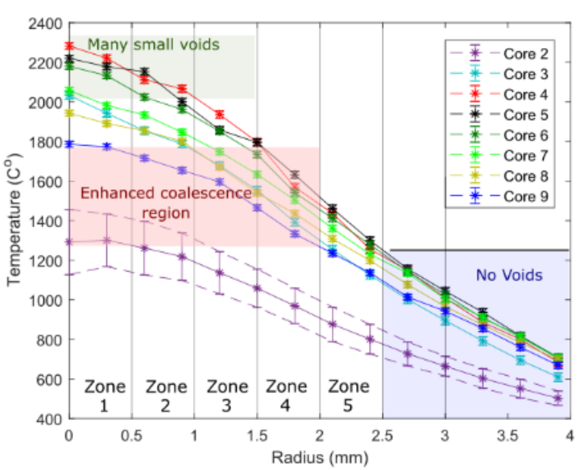
Map of **voids size** and **distribution** for all the cores

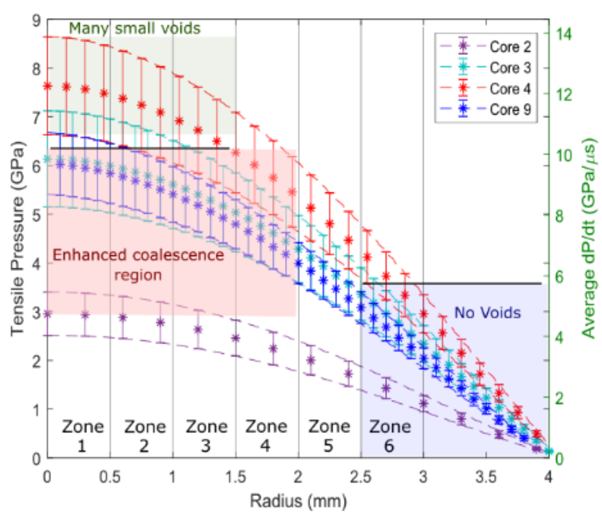


Voids growth and coalescence are really influenced by **temperature, tensile pressure, pressure rate, microstructure.**.

The relation is <u>not</u> monotonic i.e: *higher temperatures/pressure* ***<u>do not</u>*** *mean larger voids*







<u>Three clearly differentiated regions:</u>

1) Region <u>without voids</u>

T < 1250 °C, P< 3 GPa

2) Region with <u>enhanced coalescence</u>

1300 °C > T < 1800 °C

3 GPa > P < 6.5 Gpa

3.5 GPa/μs > dP/dt < 10 Gpa/μs

3) Region with <u>limited void</u>

T > 2000 °C, P> 6.5 GPa , dP/dt > 11 Gpa/μs

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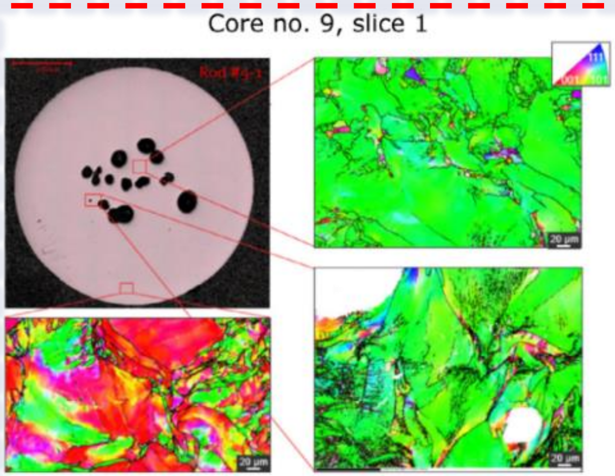
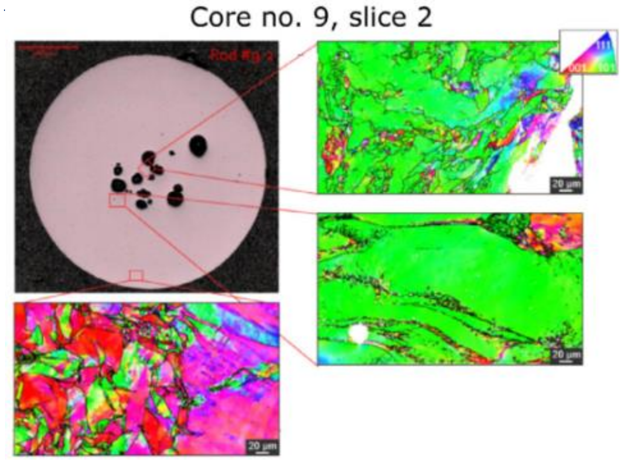
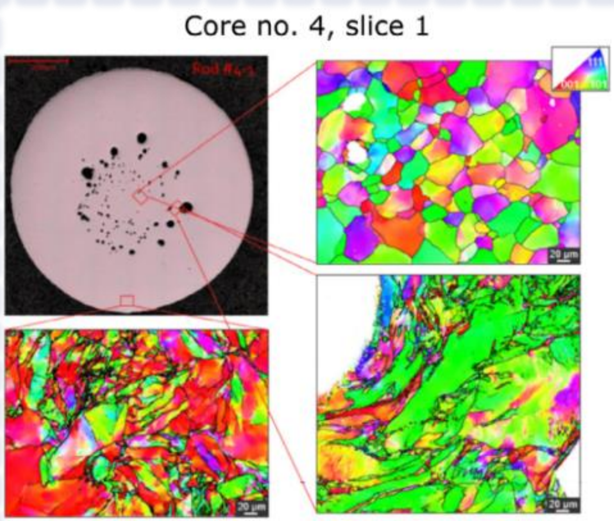
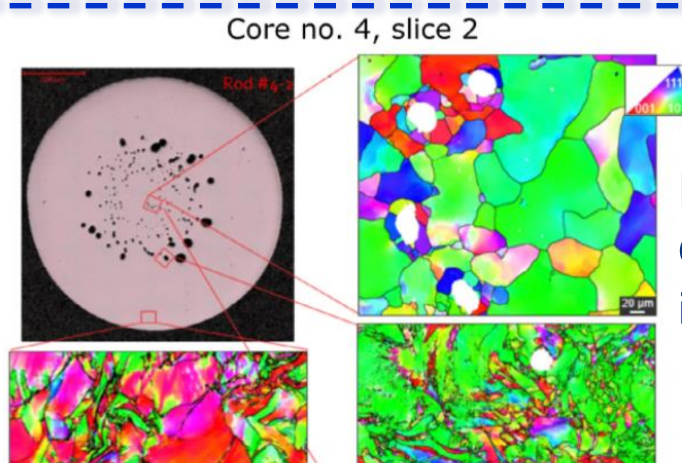
Additional Process: **Recrystallization**





Response A:
Absence of recrystallization in areas with **large voids**





Response B:
Complete recrystallization in areas with **small voids**

Extra lesson: recrystallization is fast!

complete recrystallization when exposed above 2000°C for nearly 1 s and above 1600 °C for 3–4 s

Possible hypotheses

1) **Temperature:** literature reports slower void growth at 420 °C for Cu in comparison to RT, BUT no data about Ta and higher regimes.
2) **Strain and pressure rates:** literature reports lower void nucleation void growth at high strain rates BUT, the orders of magnitude of influence at which this sensitivity is reported are much higher.
3) **Loading Path and Tension/Compression asymmetry of the Ta:** Higher compressive pressure in central and hot areas may limit void growth or even close nucleated voids. It is reported in literature that asymmetries in the compression–tension behaviour of porous metals greatly influences the mechanisms of void growth.
4) **Microstructure and recrystallization:** Literature reports higher void growth rates of inter-granular voids (at GBs). Re-crystallization implies new, and large, grains, with less GBs for fast growing voids.

C. Torregrosa et al. " First observation of spalling in tantalum at high temperatures induced by high energy proton beam impacts, European Journal of Mechanics / A Solids 85 (2021) 104149

Implications of spalling in Ta for the AD-Target

1) Appearance of large voids in the Ta core material may be more detrimental for pbar production than the appearance of cracks in a material as Iridium
2) Tensile Pressures in Ta shall be kept below 2-3 GPa to avoid voids nucleation.
3) The role of the microstructure (annealing vs forged deformed) as well as grades with higher yield strength (Ta2.5W) could be further studied.

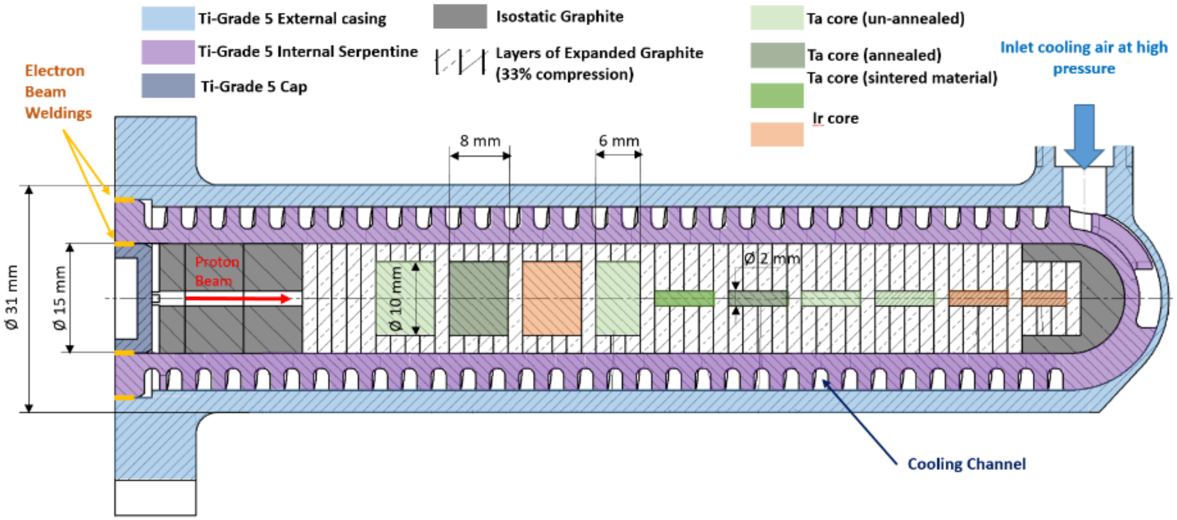
These ideas were taken into account in the prototyping activities

Manufacturing of new Targets Prototypes and Testing in HiRadMat

1) **HRMT-48 -> PROTAD (2018)**

New Target Design

x6 target prototypes tested in HiRadMat in Sept 2018



Components:

1) External Ti-5 Assemblies
2) Expanded Graphite / Isostatic Graphite Matrixes
3) High density cores (Iridium and/or Tantalum)

New Features

AIR-COOLED

Baseline Parameters:
-5 bars
- 3 Nm³/h

(for 40 W operation corresponding to 90 s repetition rate)
EDMS2102227

Sliced Cores

Variable core diameters and lengths

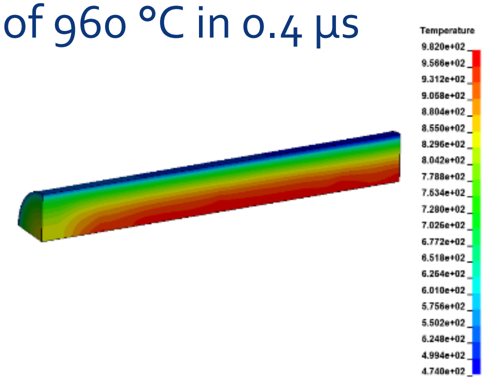
New Matrix material

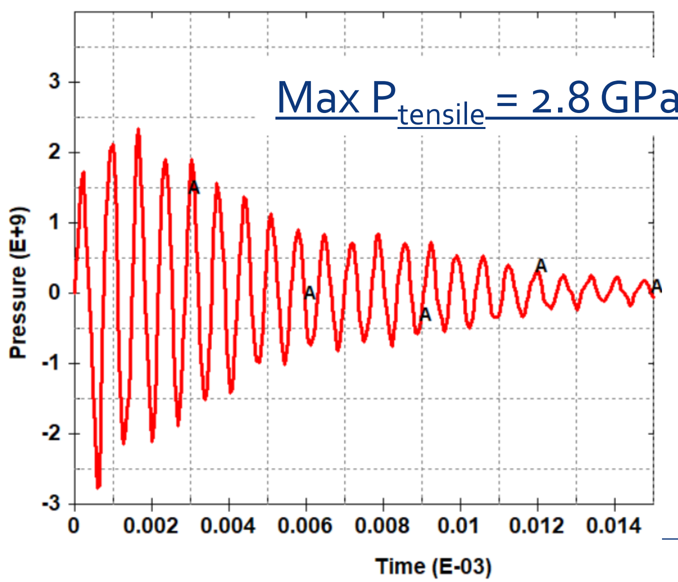
1) **Layers of compressed EG**
   or
2) **Isostatic graphite**
   or
3) **CfC composites**

Why larger core diameters?

Improvement of thermo-mechanical response!

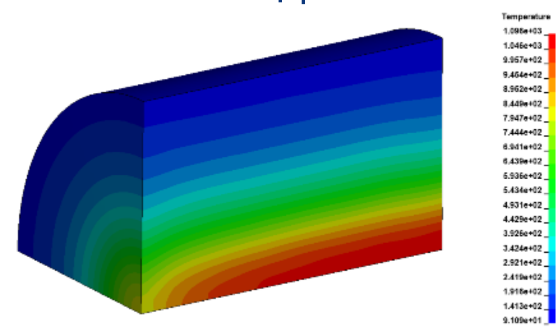
<u>Ø 2 mm rod</u>
exposed to ΔT of 960 °C in 0.4 µs

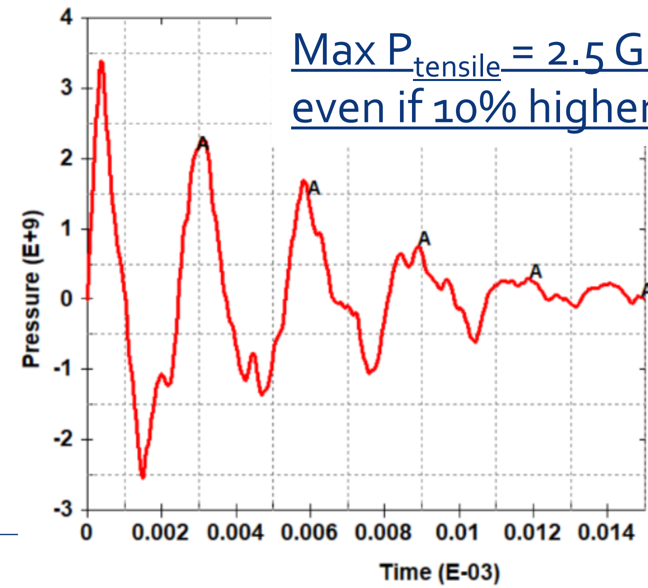




Max $P_{tensile}$ = 2.8 GPa

<u>Ø 10 mm rod</u>
exposed to ΔT of 1060 °C in 0.4 µs



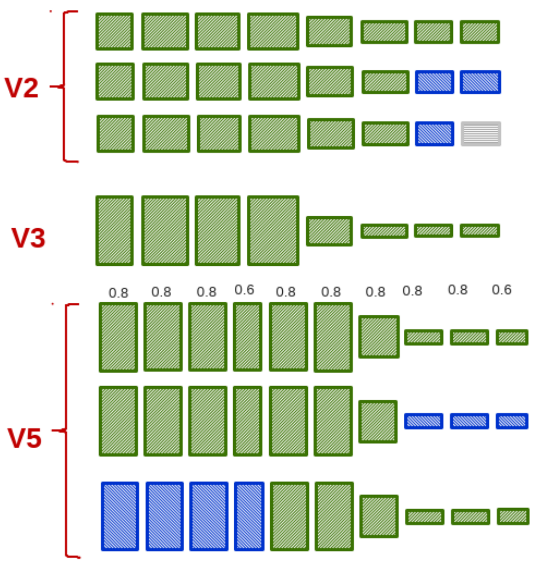


Max $P_{tensile}$ = 2.5 GPa even if 10% higher ΔT

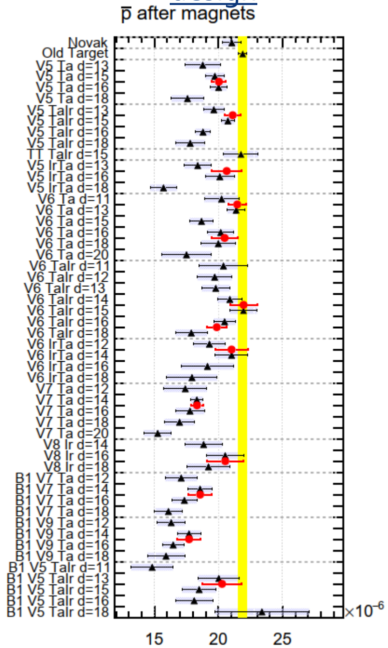
Why variable core diameters?

Fluka pbar Optimization Studies

Different core configurations simulated

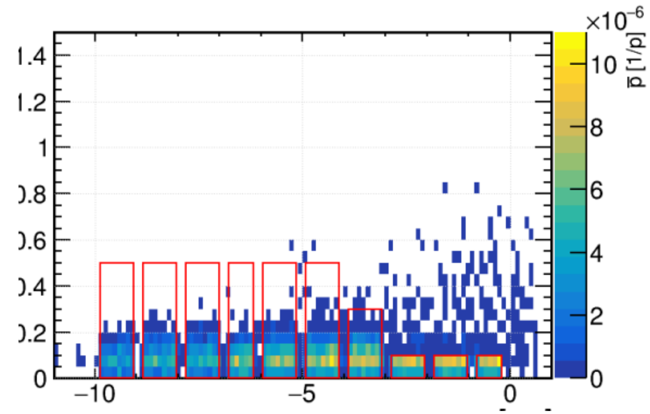


Comparison with pbar yield of current design

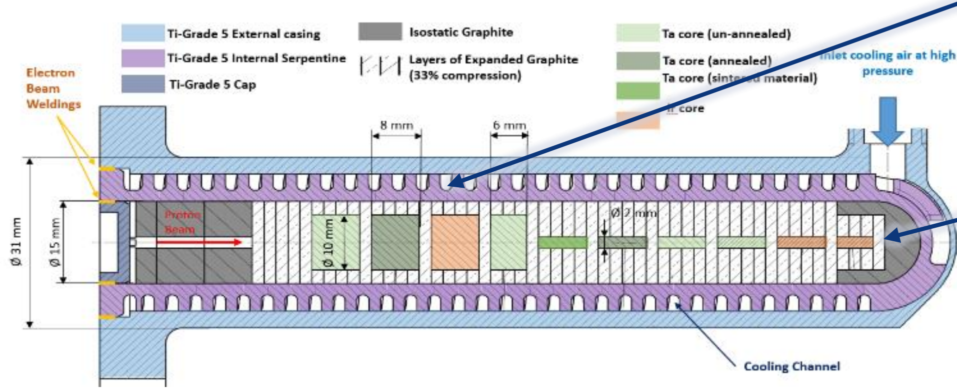


Courtesy of J. Canhoto

Detailed studies of from *where* 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



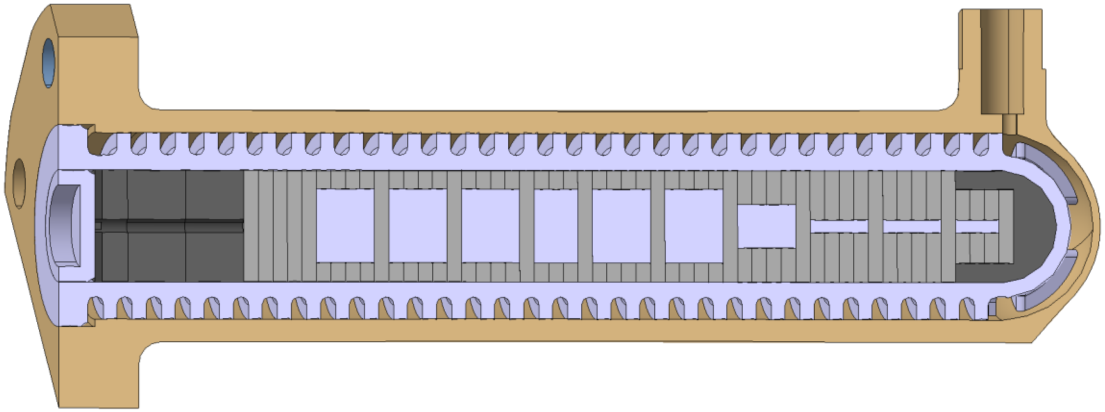
Upstream cores of Ø 10 mm

(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)

New Core Concept Explored



-10 mm diameter Ta rods
-2 mm diameter Ir rods at the downstream.

Pros:

~ 7 % Pbar improvement vs old design
Max Tensile Pressure Ta= -2GPa

Cons:

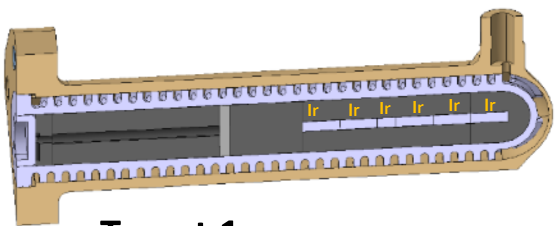
- Max Tensile Pressure Ir ~ 6 GPa
Ir will break most probably

Uncertainties

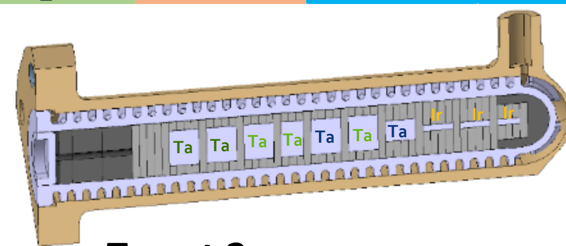
- Survival of the Ir 2 mm at downstream
- Spalling in the 10 mm diameter Tantalum?
- Influence on Material grades?
- Influence of dowstreams core fracture in pbar production?

Targets Prototypes tested in HiRadMat 2018

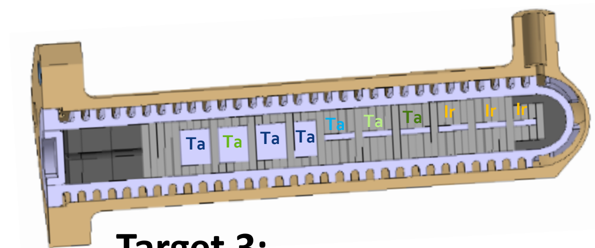
	1	2	3	4	5	6	7	8	9	10
T1										
T2	Ta WHS_non_ann	Ta WHS_non_ann	Ta WHS_ann	Ta WHS_ann (6 lo	Ta_Plansee_non-	10 mm Ta WHS_ar	6 mm Ta Plansee_	2 mm Ir	2 mm Ir	2 mm Ir
T3	Ta_Plansee_non-	Ta WHS_ann	Ta_Plansee_non-	Ta_Plansee_non-	2mm diam TaS	2mm diam WHS_	2mm diam WHS_	2 mm Ir	2 mm Ir	2 mm Ir
T4	TaW non_ann	TaW ann	TaW non_ann	TaW ann (6 lower	2mm diam TaW n	2mm diam TaW a	2mm diam TaW n	2mm diam TaW a	Tube Ir	Tube Ir
T5	Ta WHS_ann	W-TiC (S1,S3,S5)	W-TiC (S2,S7,S6)	Ta_Plansee_ann	10 mm Ir	10 mm Ir	6 mm Ta Plansee_	2 mm Ir	Tube Ir	Tube Ir
T6	10 mm Ir	Ta_Plansee_ann	Ta_Plansee_ann	Ta WHS_non-ann	10 mm Ir	2mm diam TaS	2mm diam TaS	Tube TaM	Tube TaM	Tube Ir



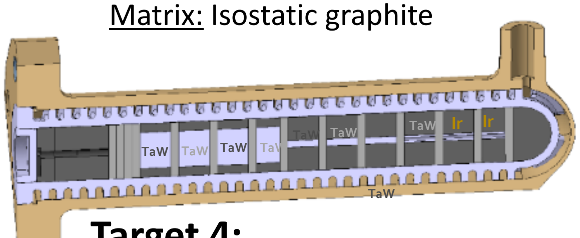
Target 1:
Core: Ø 3 mm Ir
Matrix: Isostatic graphite



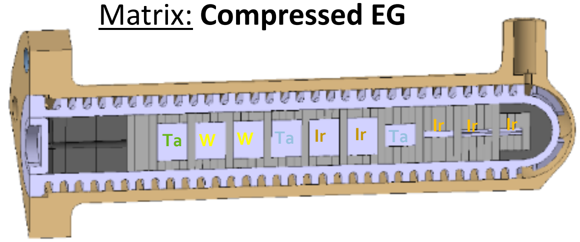
Target 2:
Core: Ø 10 mm Ta + Ø 2 mm Ir
Matrix: **Compressed EG**



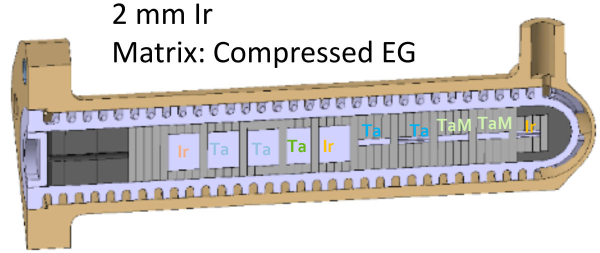
Target 3:
Core: Ø 10 mm Ta + Ø 2 mm Ta + Ø 2 mm Ir
Matrix: Compressed EG



Target 4:
Core: Ø 10 mm Ta2.5W + Ø 2 mm Ta2.5W + Ø 2 mm Ir tube
Matrix: Isostatic graph



Target 5:
Core: Ø 10 mm Ta +
Ø 10 mm W + W-1.1TiC + Ø 10 mm Ir
+Ø 2 mm Ta tube
Matrix: Compressed EG



Target 6:
Core: Ø 10 mm Ir Ø 10 mm Ta +
Ø 2 mm Ta tube
Matrix: Compressed EG

WHS	Ta WHS_non_ann	Ta WHS_ann		
TaW	TaW non_ann	TaW ann		
Plansee	Ta_Plansee_non-ann	Ta_Plansee_ann	Ta_Plansee_ann 1400 C, 1h	TS

Prototypes Manufacturing

C. Torregrosa et al. *"First prototypes of the new design of the CERN's antiproton production target", MDPC 2019*

External Ti-6Al-4V Assembly

Two Strategies

- Two independent assemblies (EBW in the upstream part)

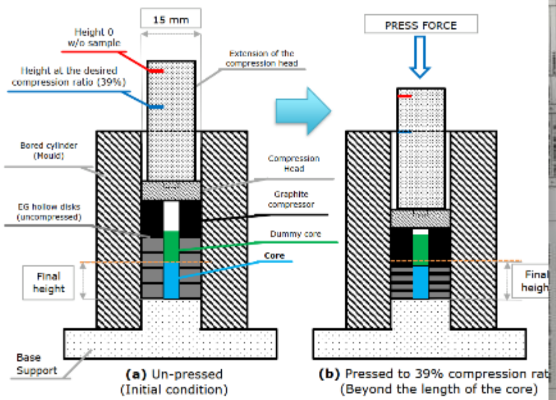
- Single part 3D-Printed at CERN

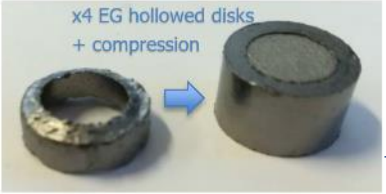
To our knowledge, First 3D-Printed TiGr5 component tested in high energy intensity proton beams

EG Matrix and Cores

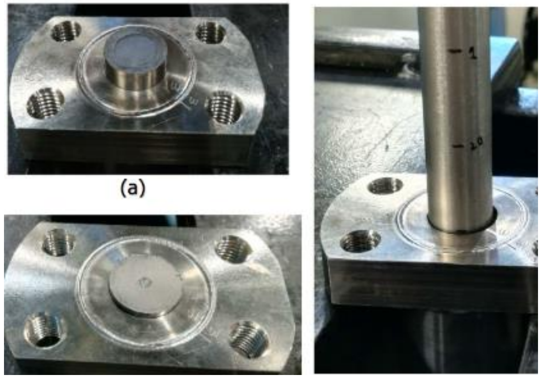
Different procedure from HRMT-42: **2-stage compression to ensure a constant compression ratio**

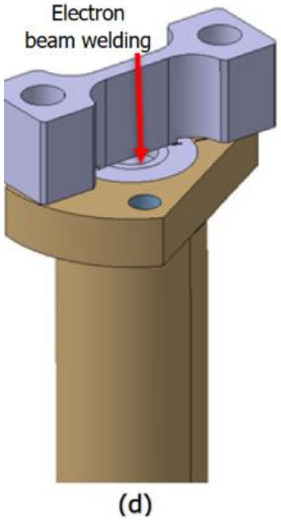
Stage (1): Pre-Compression around the cores





Stage (2): Insertion in the target cavity with un-compressed EG disks and progressive compression

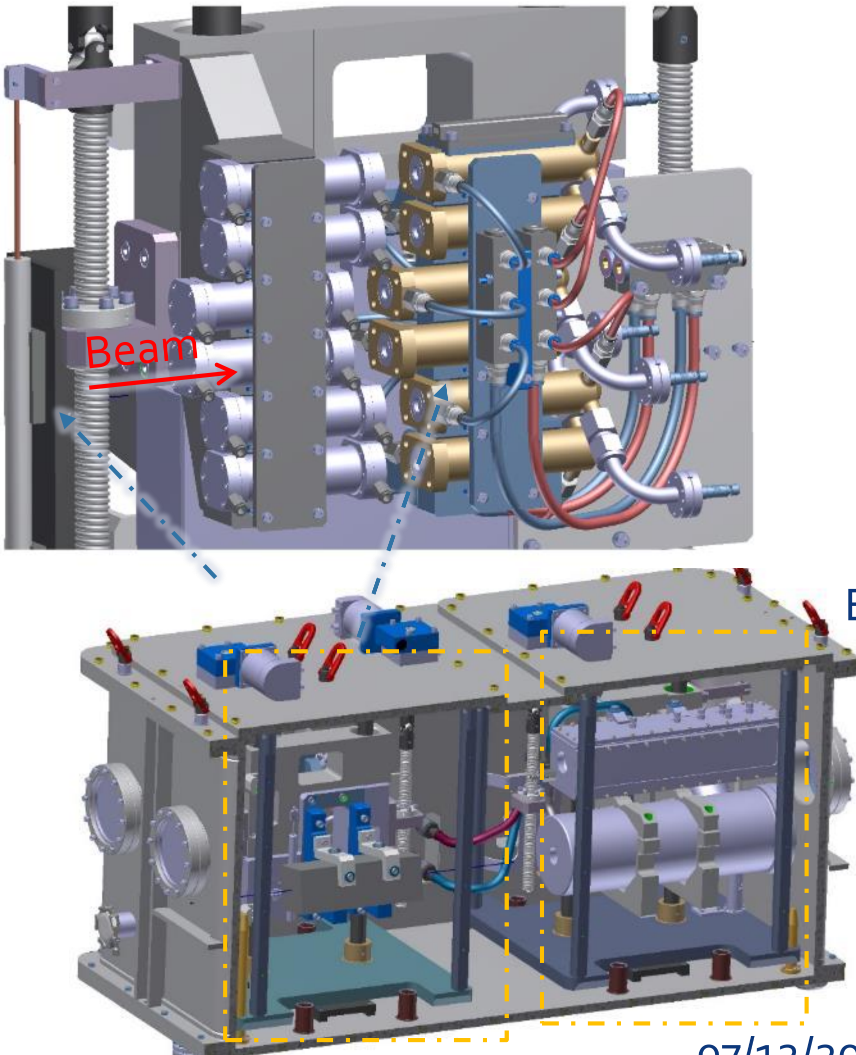


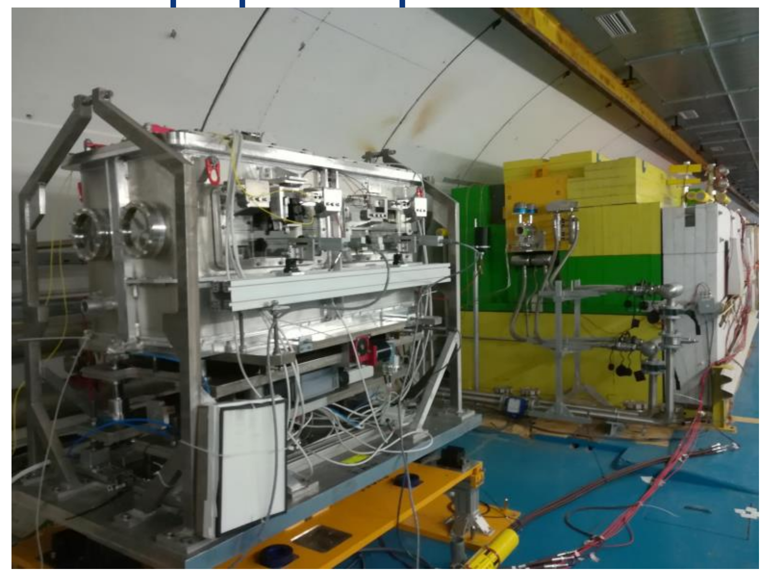


Inclusion of novel materials (W-TiC) manufactured by out colleagues from KEK and JPARC (Japan)

Installation of Prototypes in the HiRadMat Multipurpose Experiment

PROTAD targets tested within a HiRadMat Multipurpose Experiment





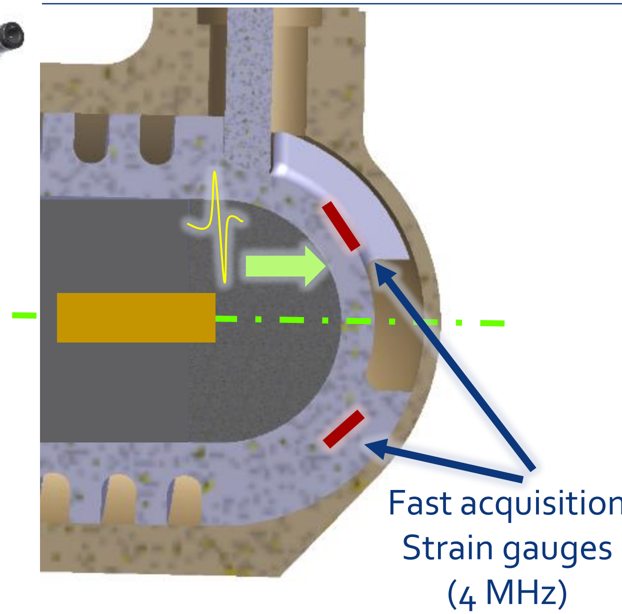
Experiment executed on **28th/29th September 2018**

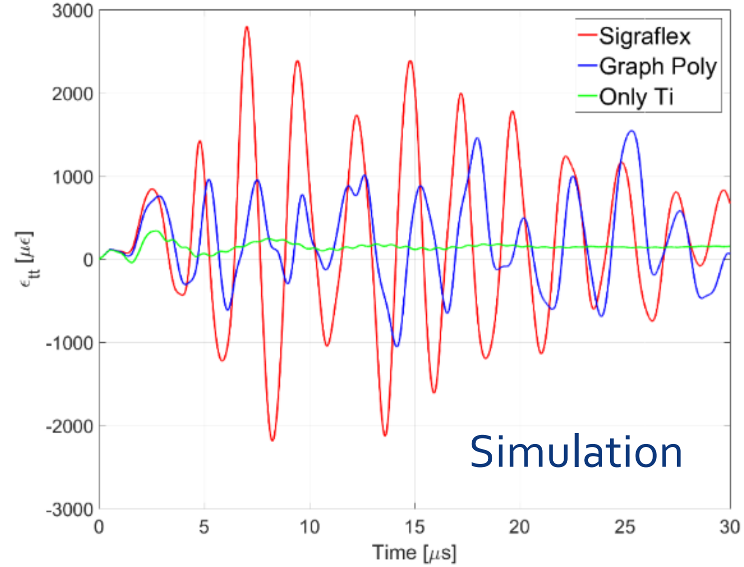
50 pulses/per target impacted in 5 targets

Target no. 6 received **140 pulses**

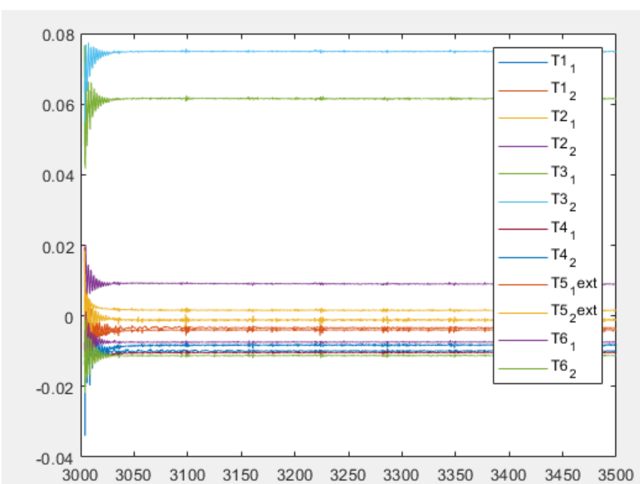
$3.2\cdot10^{13}$ -$1.12\cdot10^{14}$ POT per target

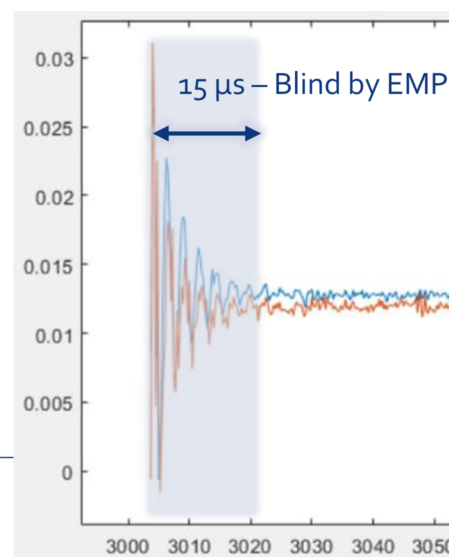
Online Instrumentation: Monitoring downstream windows





Measurements



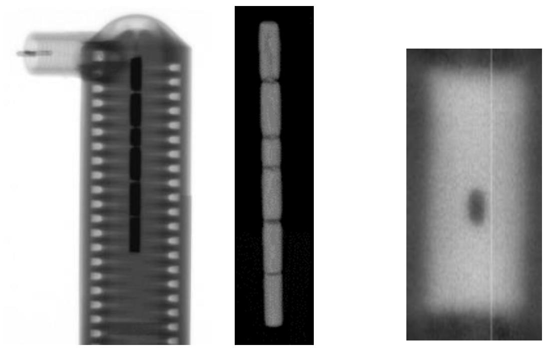


No Signal was recorded beyond the non-physical window ☹

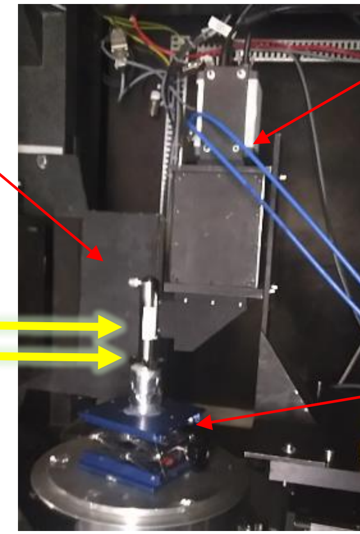
No relevant wave front reaches the window ☺

PIEs on the Target Prototypes

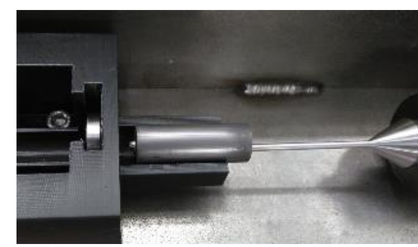
1) Neutron Tomography in ILL (Grenoble) -2019



Achieved resolution within 90-60 μm and 30 μm (depending of FOV)

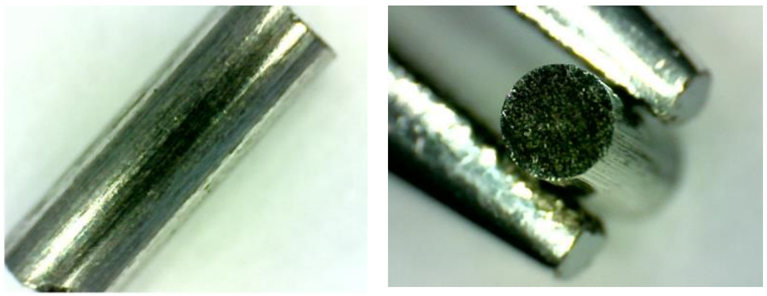


2) Targets Opening and Core Extractions at CERN -2020



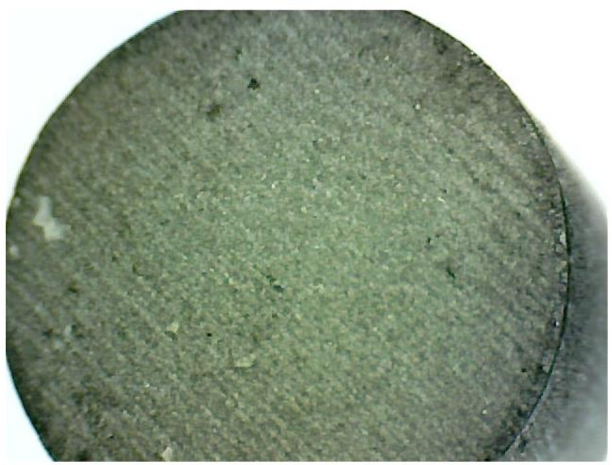
Core Materials at Pristine Conditions

Iridium rods of **Ø2 mm**



Iridium rod of **Ø3 mm**

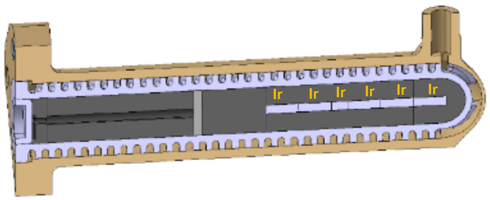
Iridium rods of **Ø10 mm**

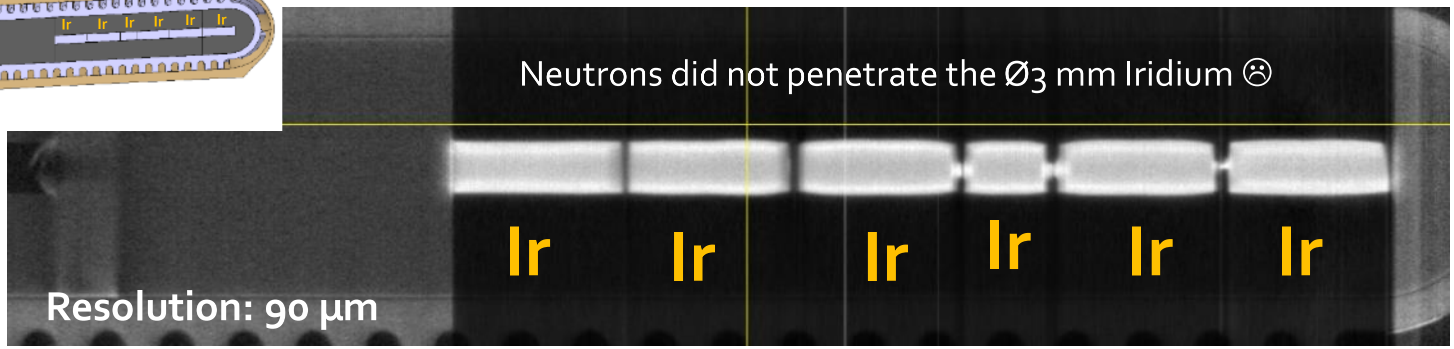


Iridium material is produced from Vacuum arc re-melted ingots
-hot swage
-Cut and ground to the desired dimensions
-Delivered in non-annealed condition

Results Target 1:

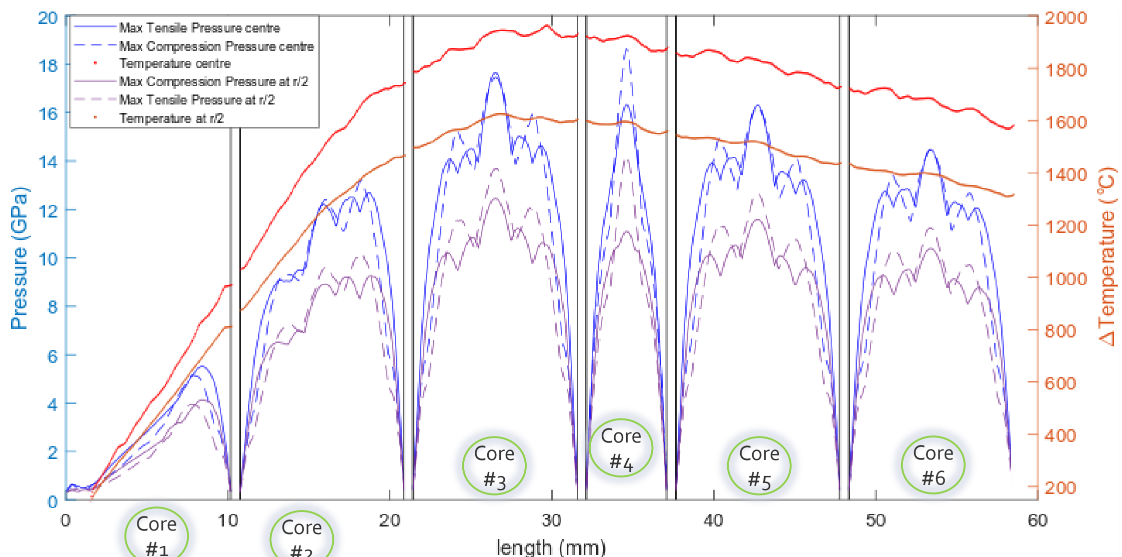
-Equivalent configuration as old design
-Exposed to 50 pulses with 0.7x0.7 mm beam size (at 1 σ)





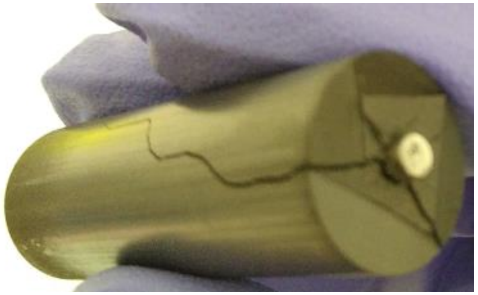
- Tensile Pressure well above 10 GPa
- ΔT close to 2000 °C. (potential melting due to temperature build-up)

  - Peak of compressive pressure reached in the rod of 5 mm length

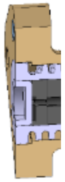


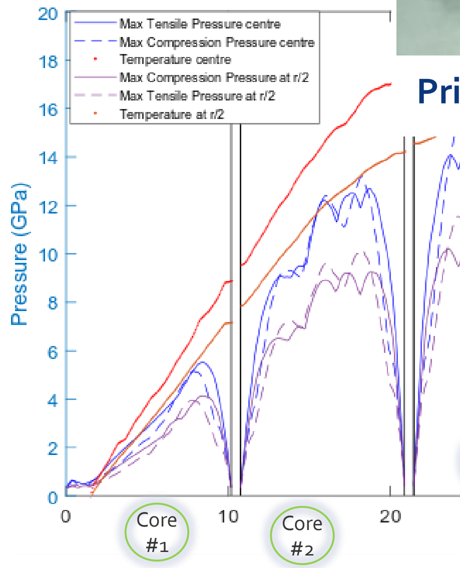
Results Target 1:

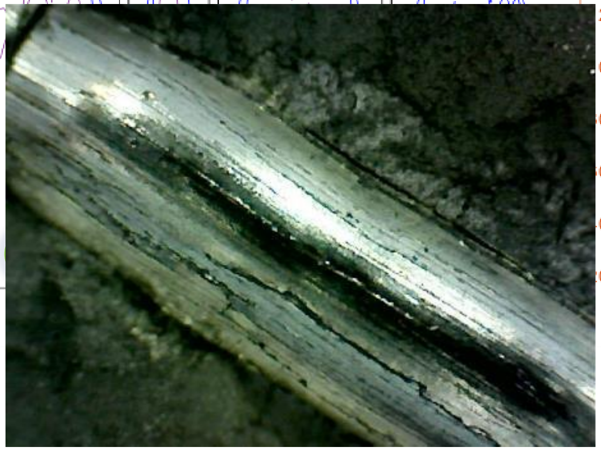
Longitudinal cracks in the isostatic-graphite matrix!



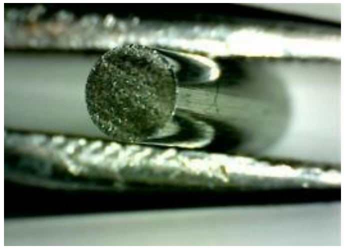
Proton beam

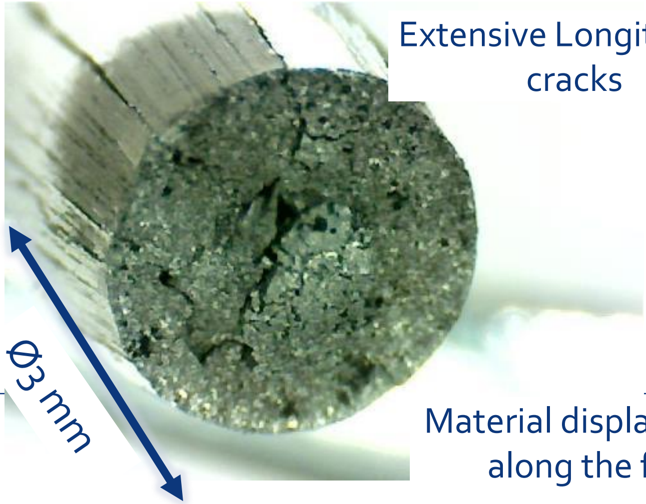






Pristine Material



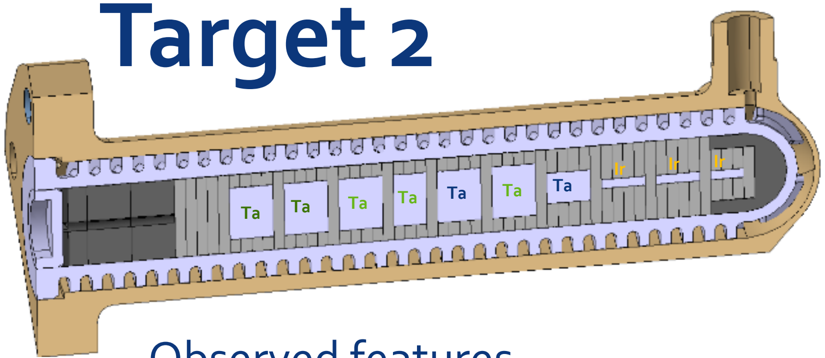


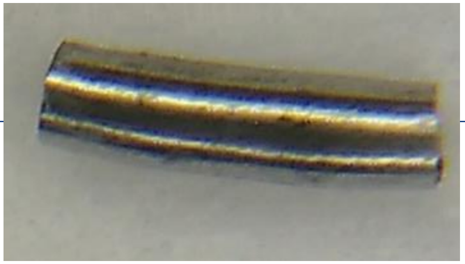
Extensive Longitudinal cracks

Material displacement along the face

Exposed to 50 pulses with 1x1 mm beam size

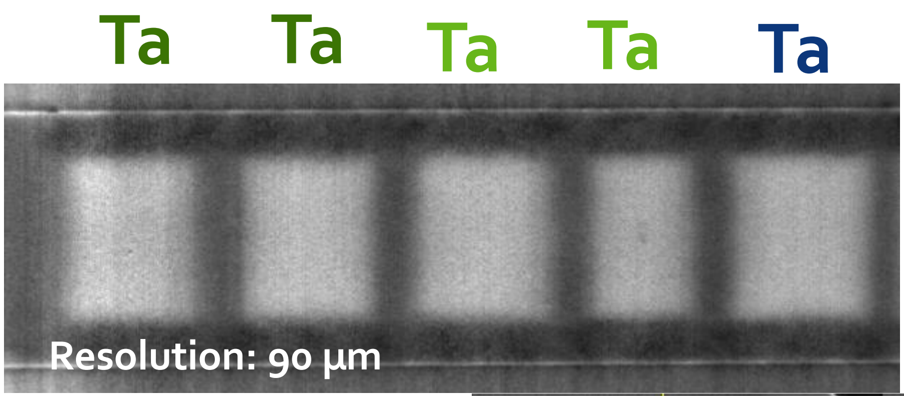
Target 2

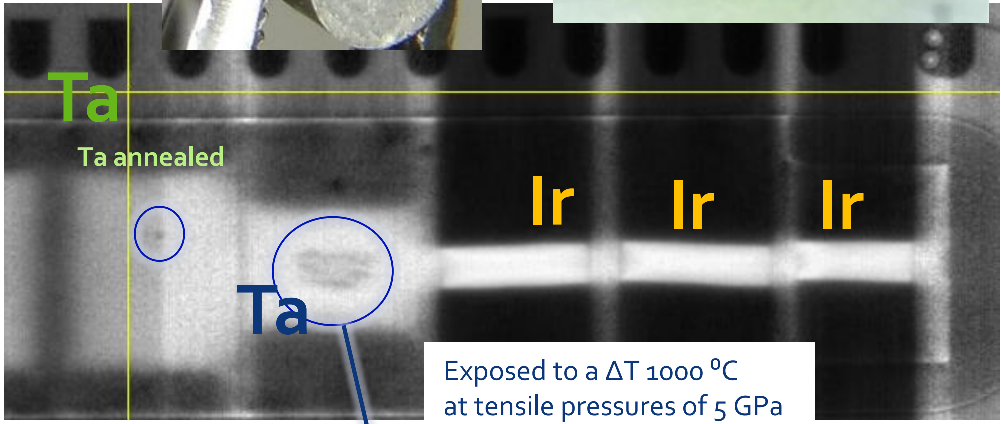


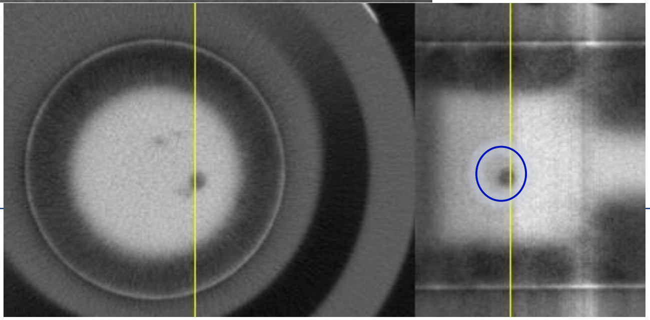


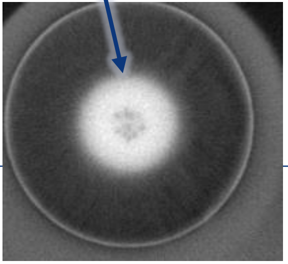
Observed features

- 6 mm diameter Ta full of voids
- Some large voids also present in 10 mm diam Ta annealed
- 1 void in the 10 mm diam Ta annealed x 6 mm length
- No observed voids in the rest of un-annealed 10 mm Ta rods







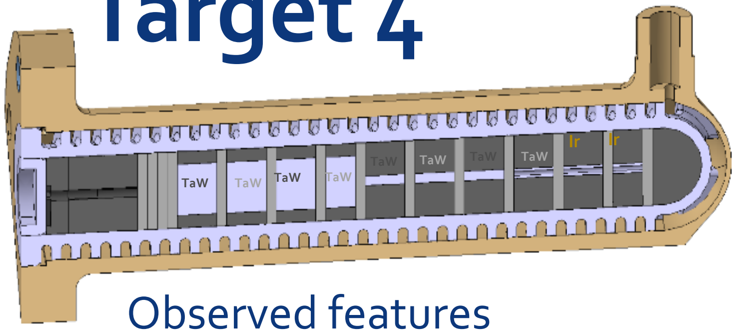


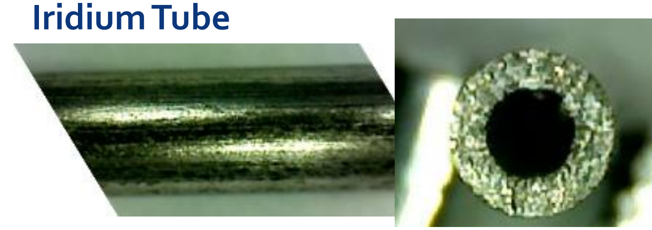
- Misalignments of the downstream Ir rods

Target 4

-Exposed to 50 pulses with 1x1 mm beam size

-Target **equipped isostatic graphite matrixes**

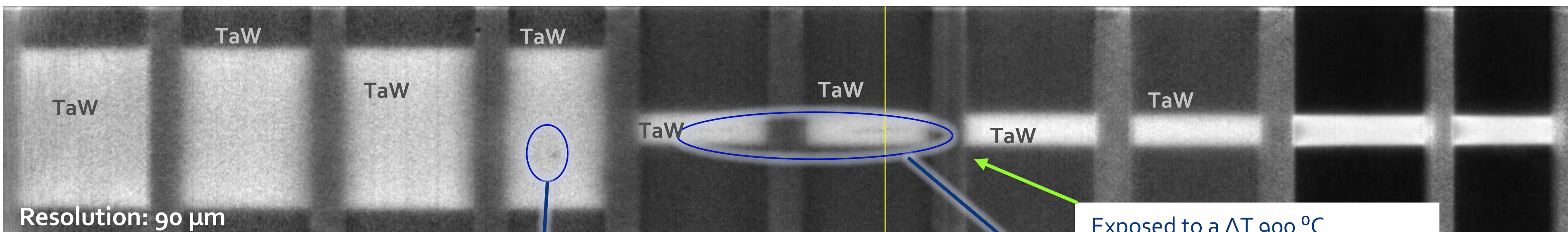




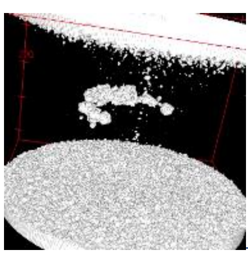
Observed features

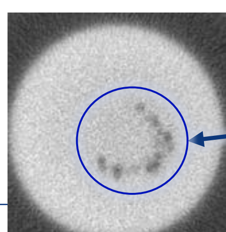
- Large amount of voids in the 10 mm diam x 6 mm length TaW rod annealed
- Axis of 2 mm diam TaW rods full of voids. Un-annealed TaW may have a better response.
- No observed voids in the rest of upstream 10 mm Ta rods

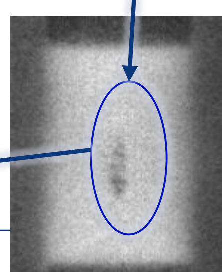
Bending of 2 mm rods does not occur with the isostatic graphite!



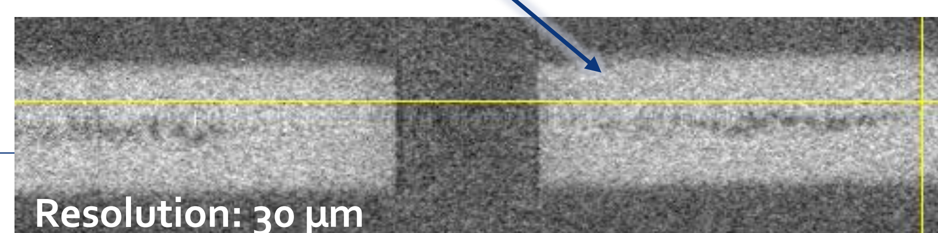
Exposed to a ΔT 900 °C
at tensile pressures of 2.5 GPa



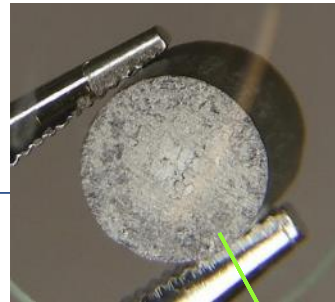




*zoom of the high resolution tomography



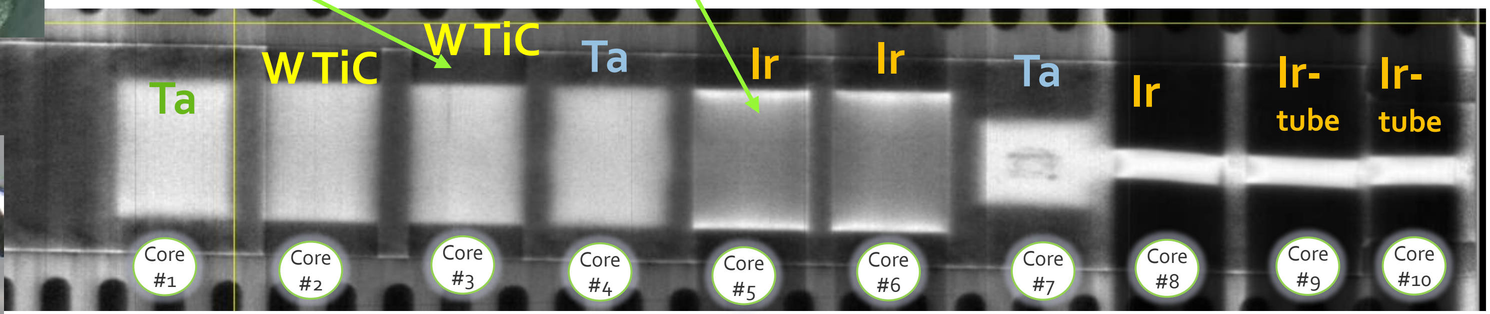
Target 5



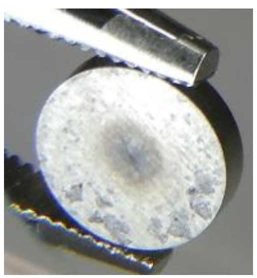
Maximum tensile pressure reached in the W = 1.5 GPa

Just many minor-cracks observed in the core Ir-5

hot rolled W- recrystallized

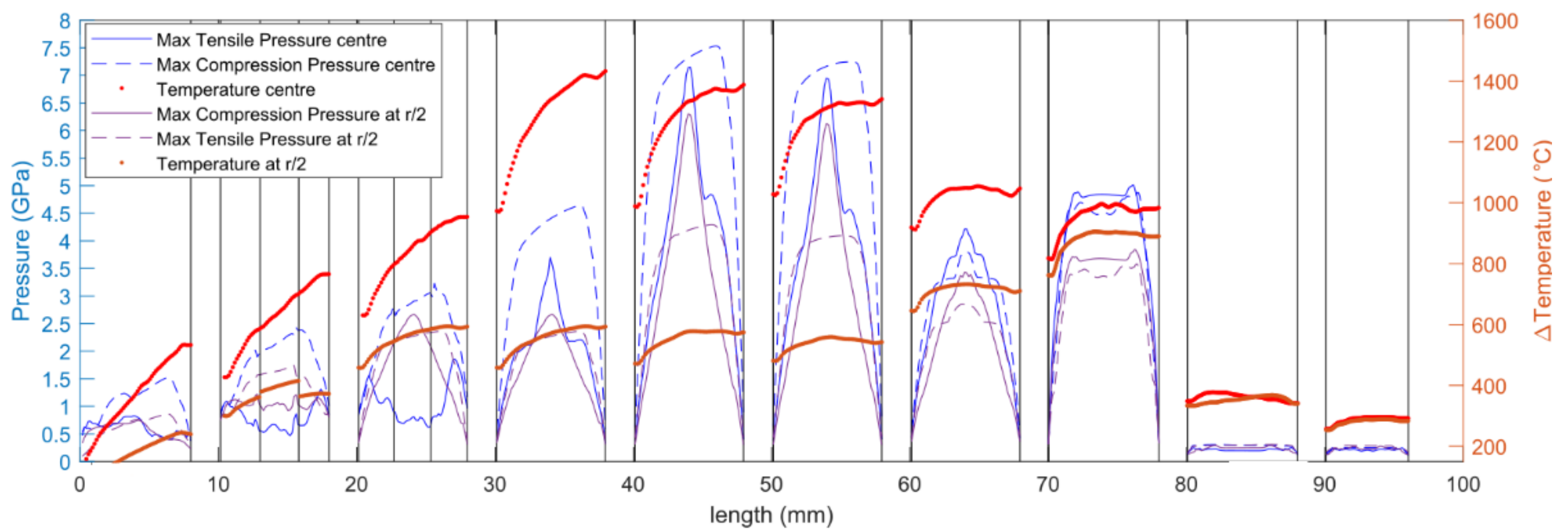


W-TiC- with GSMM



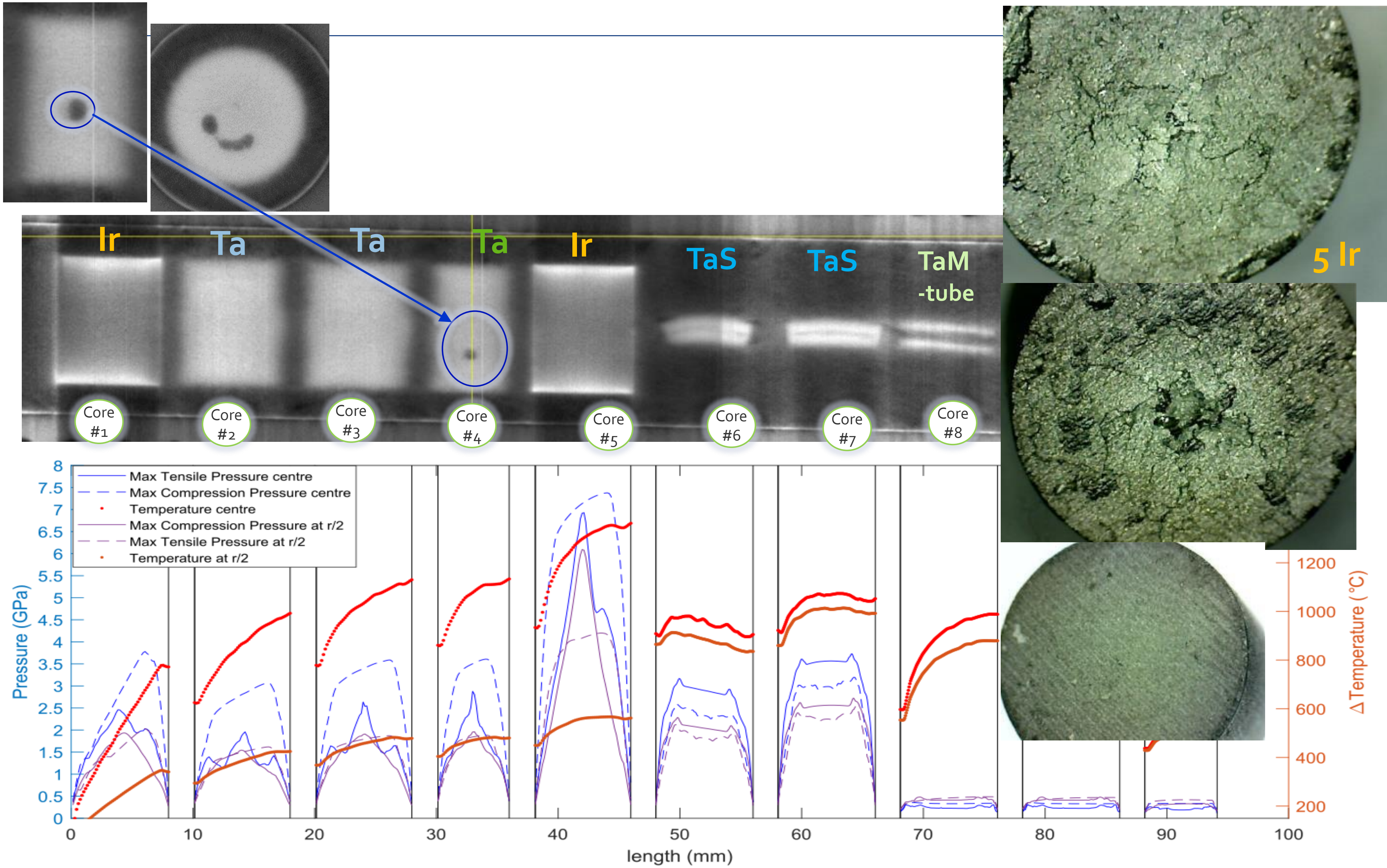
W-TiC- without GSMM

Hot rolled W



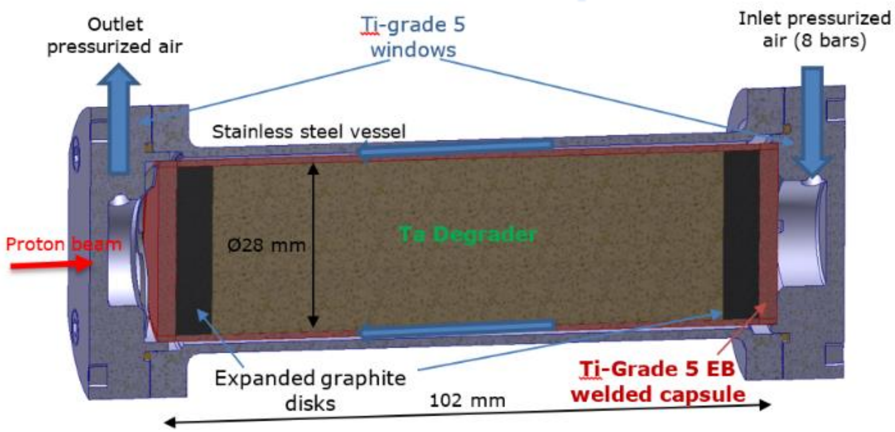
Target 6

- saw x3 times more pulse impacts than the others

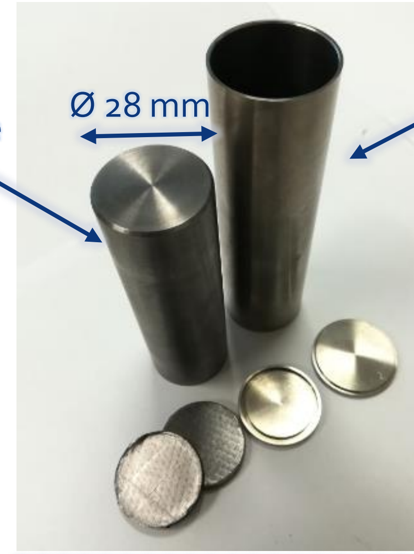


Bonus: Response of the Upstream Ta degraders

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



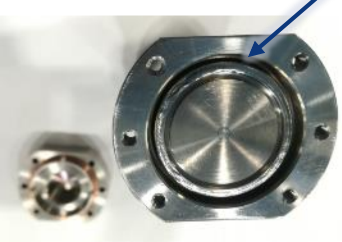
Ta Core



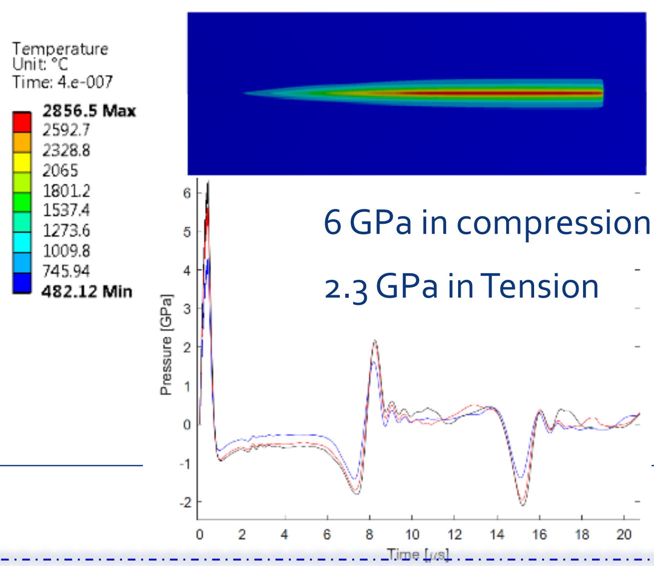
Ti6Al4V Cladding (1 mm thickness)

Ta Press Fitted in the cladding, and lids EBWelded

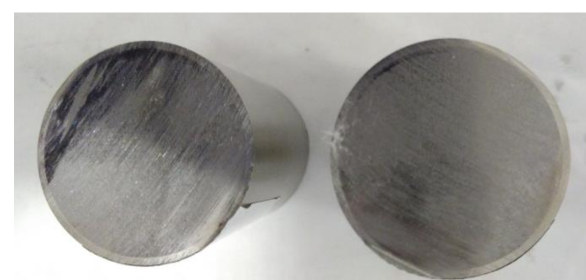
Cooling channel



Response in the Ta Core



Recent slicing of the Ta Degrader did not show any void



Main Conclusions of the Prototyping

Regarding Iridium response

1) The Ø3 mm Ir cores of T1 (equivalent to old target configuration, impacted by 0.7x0.7σ mm beam) are the ones which are more extensively cracked. It confirms all the previous studies.
2) Ø2 mm Ir rods seem to behave better than Ø3 mm, certainly less cracked as shown by cores T2_8_Ir, T3_8_Ir or T5_8 Ir. *Although impacted by a more relaxed beam (1x1 σ mm)
3) Only minor cracks are observed in Ø10 mm Ir rods – Very good candidate for its use in the upstream parts of the target

Regarding Ta response

1) No cracks but spalling voids are definitely present. Progressive growing > 1 mm. Even present in rods with Ø10 mm. Rods with Ø6 mm present many voids
2) Annealed Ta seem to present larger voids, but not enough info to withdraw conclusions. Sintered Ta seems to behave a bit better too.

Regarding Graphitic response

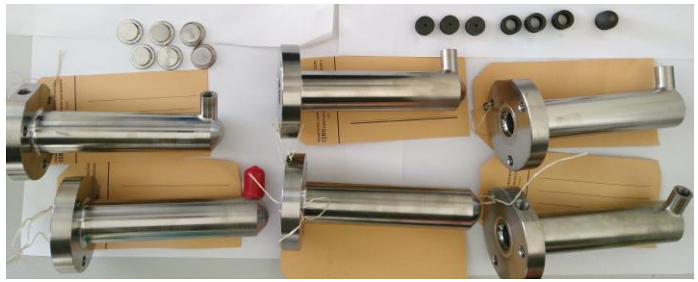
1) Low stiffness of EG induces core bending and misalignment
2) Isostatic graphite ensures core positioning, but it may crack. CfC could be an alternative

Regarding ultrafine samples of W TiC

Promising response, no noticeable damage even if exposed to ΔT of 500-700 and tensile pressures of 1 GPa

Manufactured Targets during 2020

x6 Ti6Al4V External assemblies have been manufactured during 2020



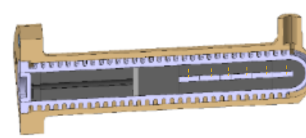
Most of the Ir and Ta material to equip such assemblies already delivered

Similarly as Isostatic Graphite for the matrixes

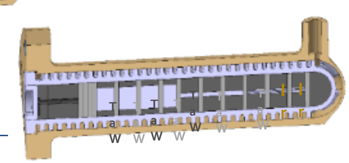
Matrixes in CfC are also purchased

<u>x4 Targets will be closed in early 2021</u>

- x3 Targets with Ø3 mm Ir cores



- x1 Target with Ø10 mm and Ø2 Ir cores



the x2 additional assemblies will be equipped and closed based on operational feedback

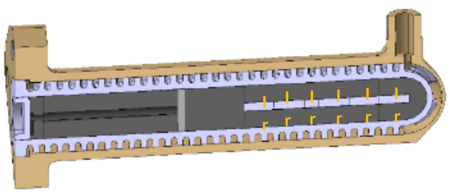
Commissioning and Further Target testing

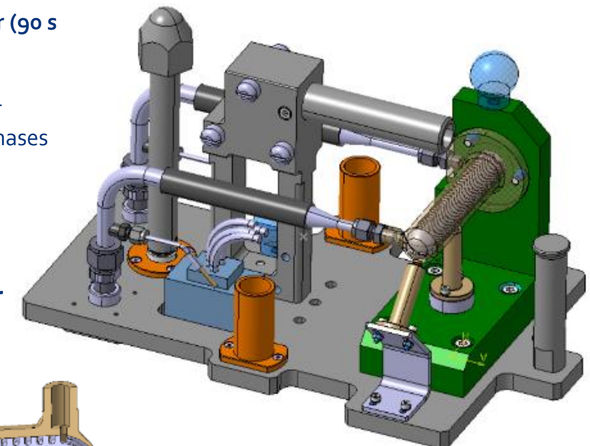
Target beam commissioning Jun-July 2021:

1- Alignment and beam optics verification
2- Progressive ramp-up of intensity on target
3-Target-horn distance and beam tuning optimization

Baseline Operational Power (90 s rep. rate) = 40 W

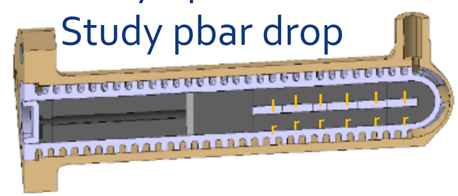
Potential short duty cycle for Validation & Optimization phases **(20 s rep. rate)** = 180 W

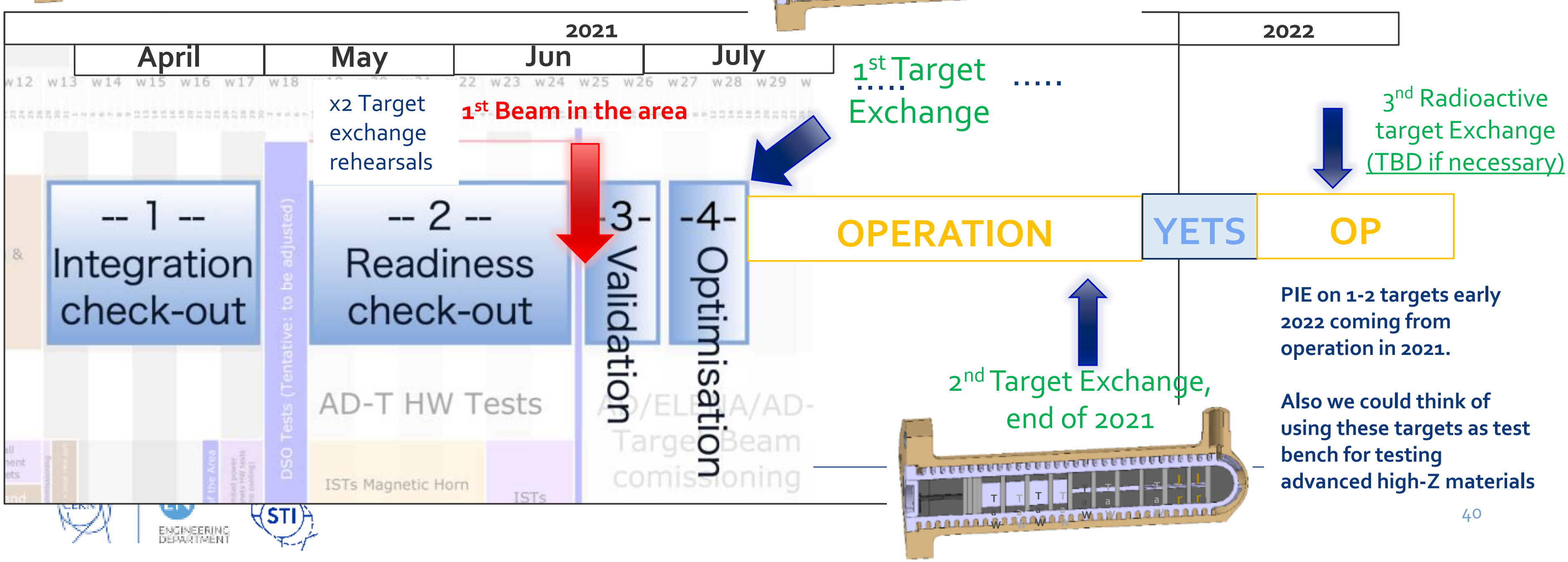




For repeatability:
Same core configuration of as pre LS-2 design

"Fresh" target for early operation
Study pbar drop





PIE on 1-2 targets early 2022 coming from operation in 2021.

Also we could think of using these targets as test bench for testing advanced high-Z materials

Conclusions

1) The design of **new Generation of antiproton production targets triggered many R&D activities** over the last 6-7 years.

2) Such Research **has broaden our understanding of the dynamic response of materials exposed beam impacts**, beyond their mechanical limits, as well as **experience within in-beam prototype testing and PIEs techniques**

3) Such experience is already being **transversally applied to other BIDs dynamically** loaded (LHC beam dump).

4) We look forward to learning more during **commissioning phases** and coming AD-Target operation.

5) We hope that this experience could be **useful to other projects within the RaDIATE collaboration**

Big Thanks for the dedication to all the Contributors in this Project!

CERN EN-STI

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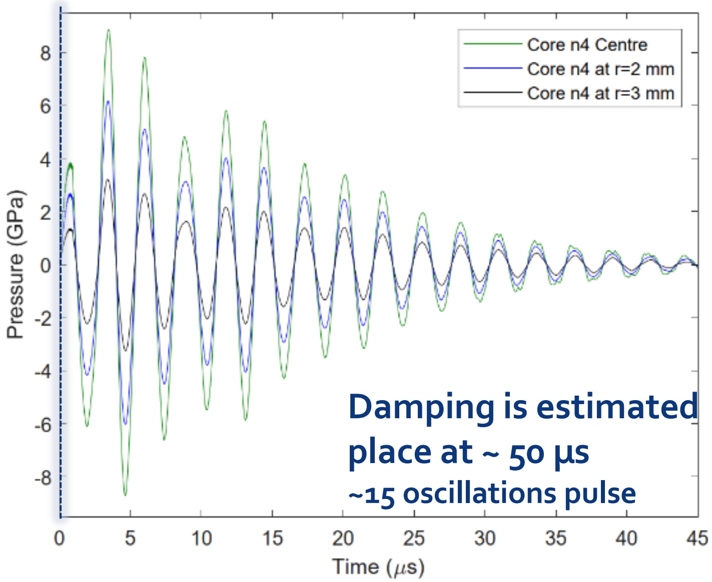
Back-Up Slides

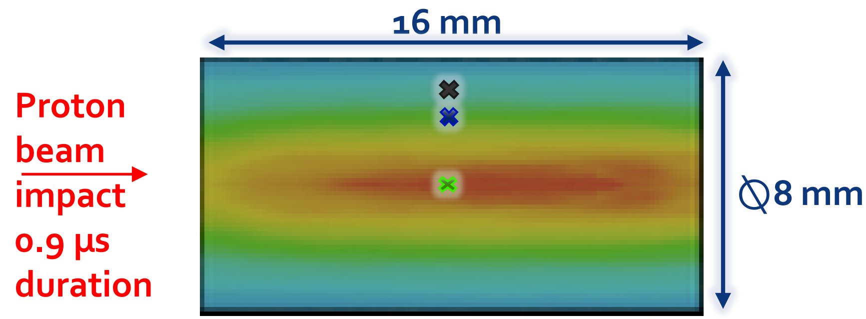
Dynamic Response of a Core in the HRMT-42



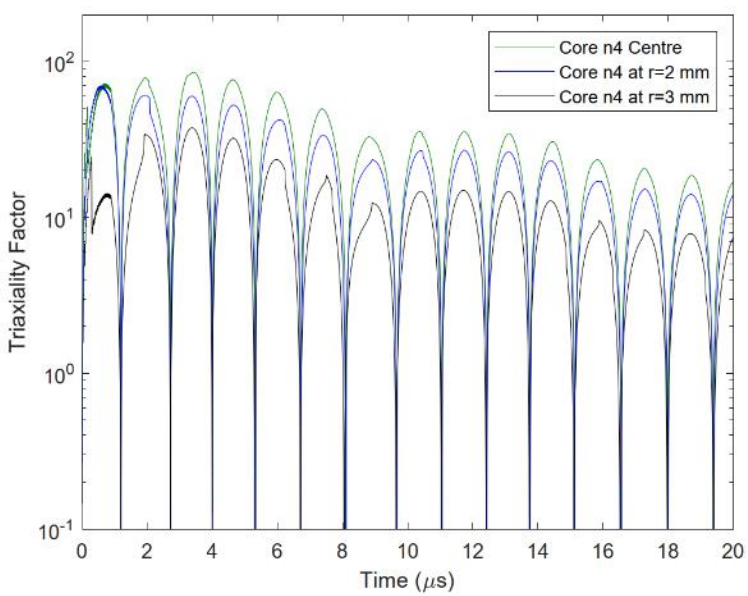
Damping is estimated place at ~ 50 µs

~15 oscillations pulse

Velocity Field and Tensile Pressure

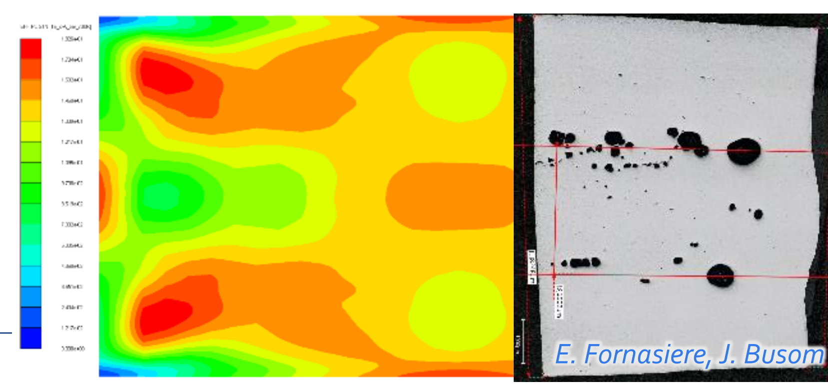


Tri-axiality factor above 15 for most of the time



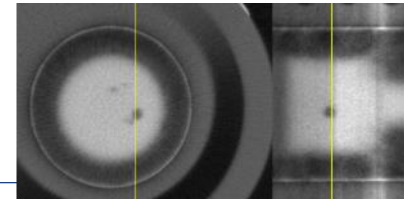
Plastic deformation and tensile load takes place in every oscillation

Plastic Strain distribution is consistent with the observations

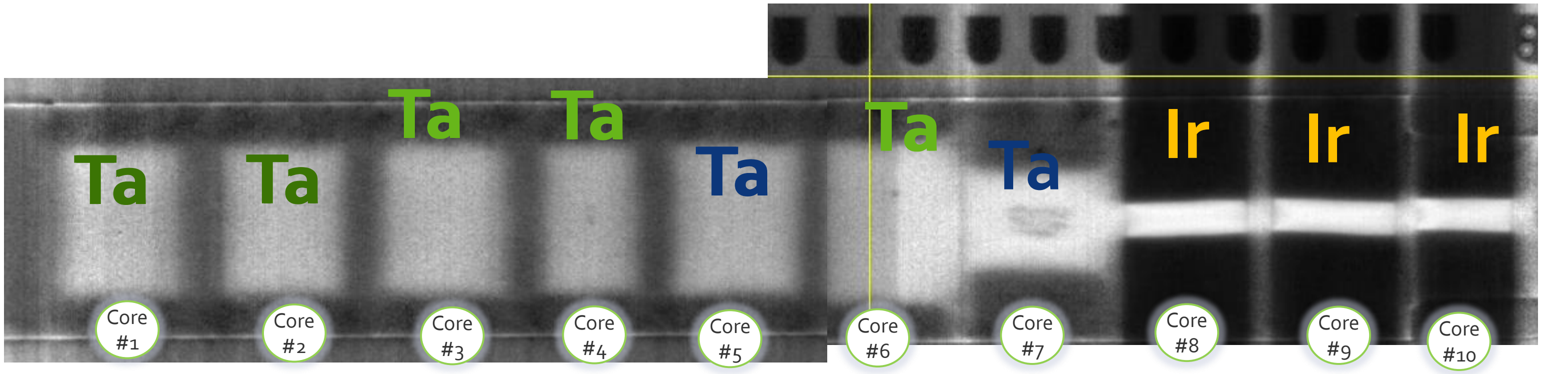


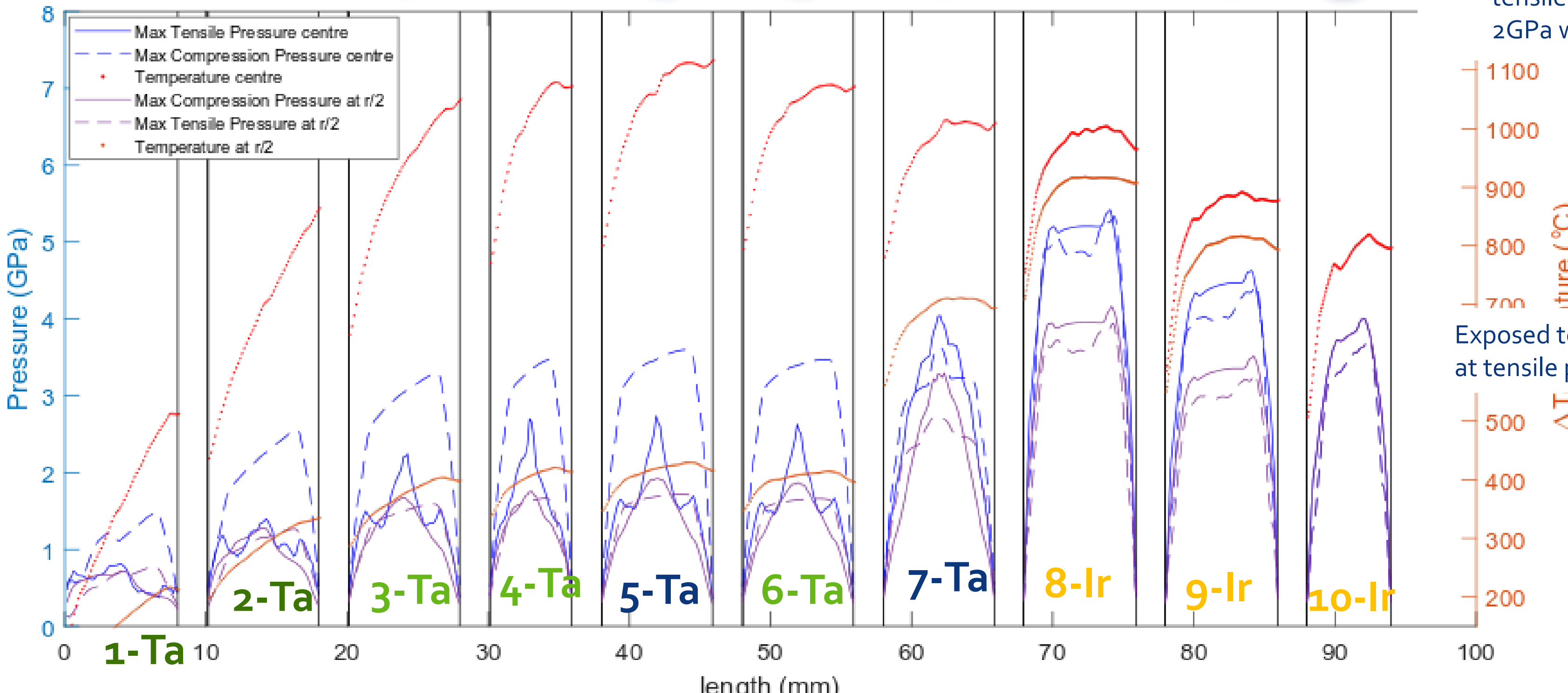
*Max estimated plastic strain up to 18 %/per pulse

Target 2: Results



- Lower ΔT and P in downstream iridium cores in comparison with the 3 mm diam of Target 1
- Tensile Pressure well above 3 GPa in the centre and r/2 of core 7
- Annealed seems to be worse (cores 5 and 6 have similar conditions, but only voids in core 6
- Voids observed in r/2 of Ta-6 where estimated tensile pressure is just 2GPa with

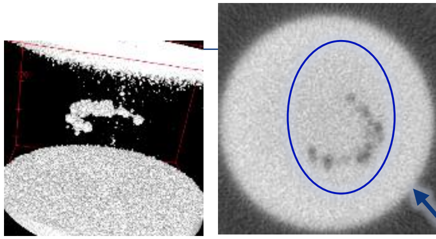


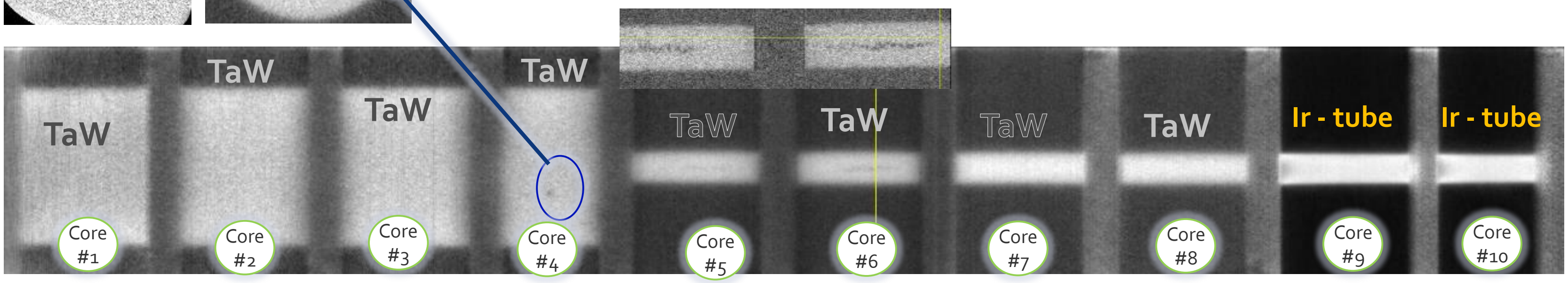


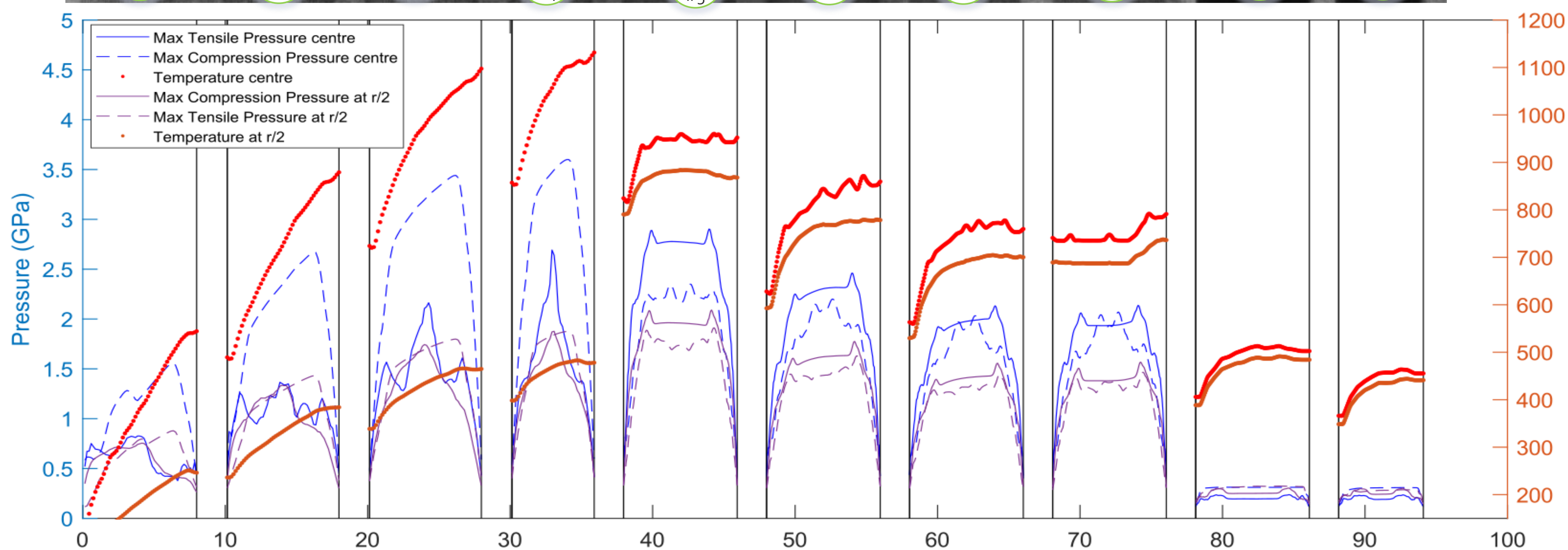
Exposed to a ΔT 1000 °C at tensile pressures of 5 GPa

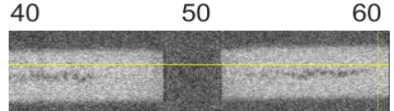
Estimated Conditions Target 4

- Very large voids following crone distribution in core 4 (even if max tensile pressure there is only 1. 7 GPa
- Similar conditions as in core 3, but no voids (i.e. annealed may be worse)
- Comparison of Core 5 vs the one of TaS of Target 3 suggests that TaS may be better than TaW
- Tensile Pressure in downstream Ir tubes in reduced by x10 times in comparison to solid rods.

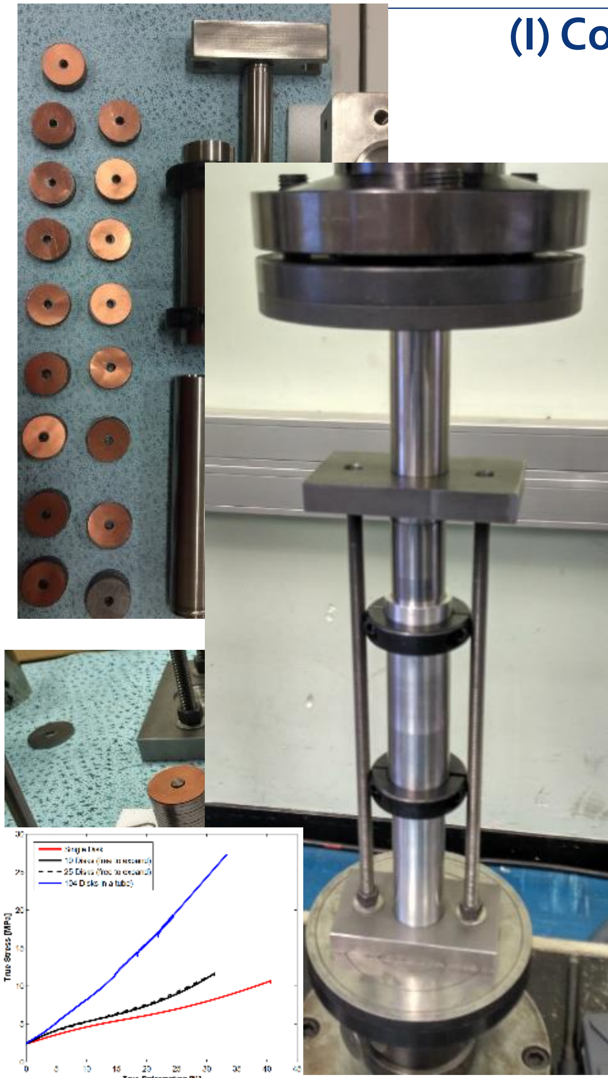




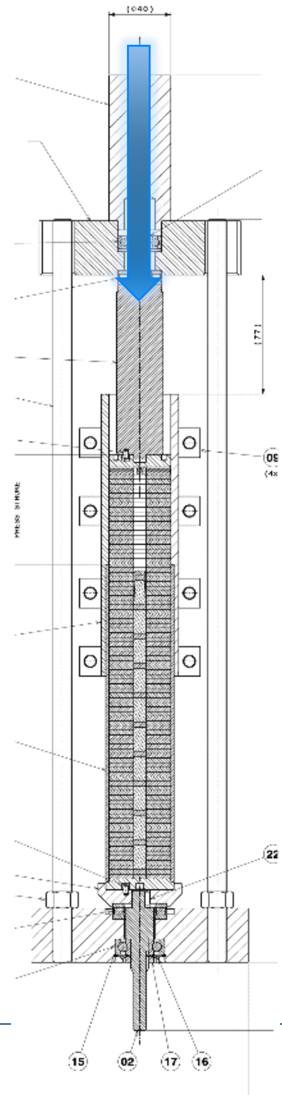




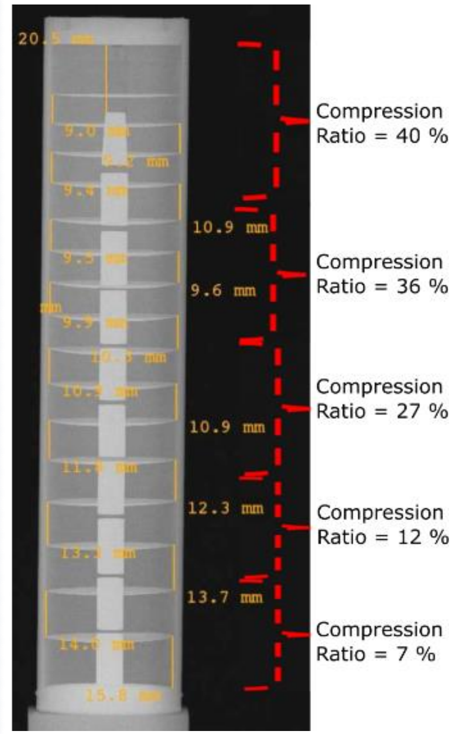
The HRMT-42 Target: Assembly and Welding Procedure



(I) Compression Phase



(II) Welding Phase



Non-Uniform over Compression Ratio over the length ☹

HRMT-42 Destructive PIEs

Target Opening carried out at CERN

- Opening of the target took place the STI bunker of b. 867.
    - The two Ti windows were sliced out.
- Extraction of the EG matrix and Ta rods took place at the **ISOLDE fume hood.**

PIEs of Ta Core