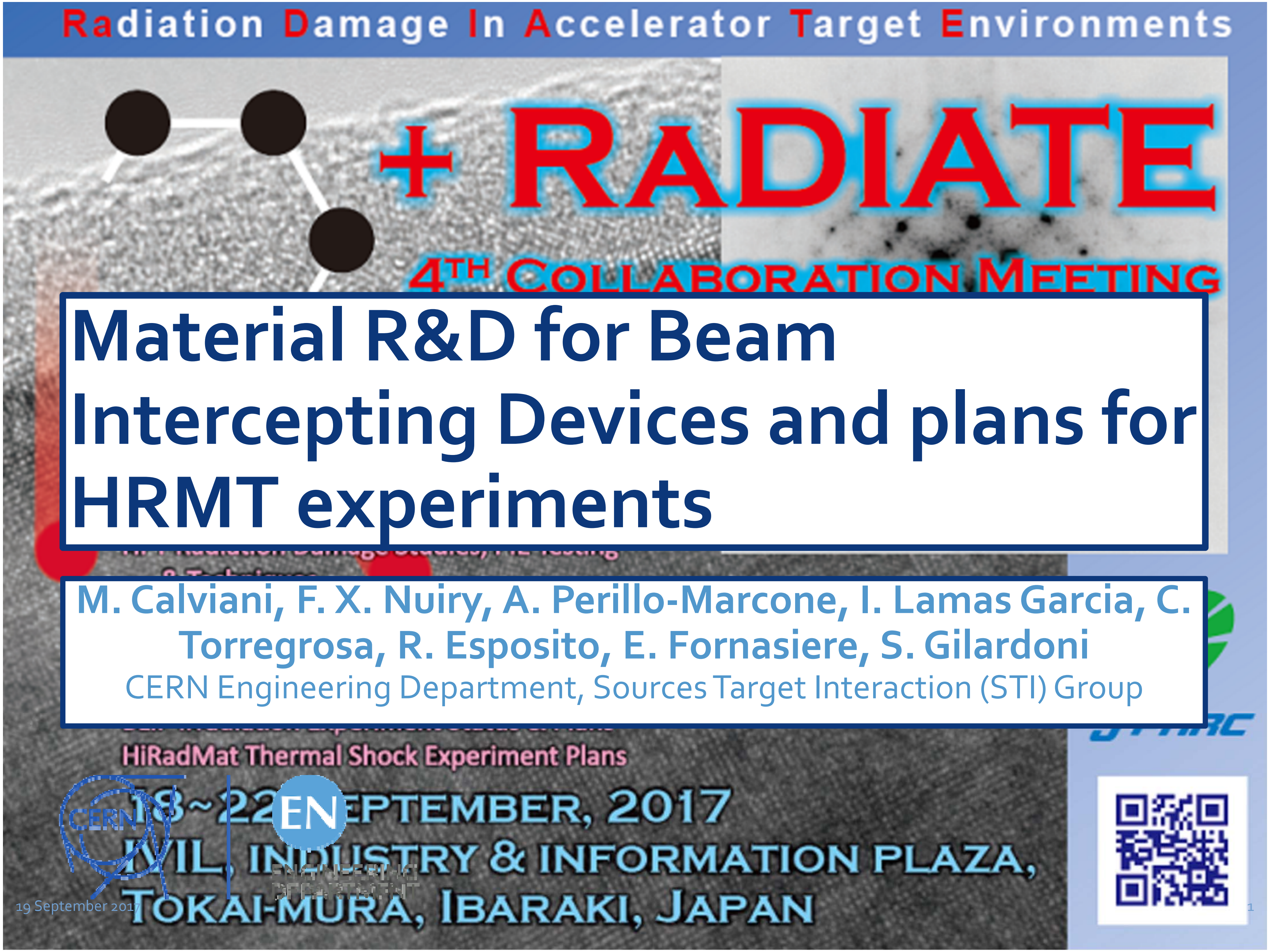
Material R&D for Beam Intercepting Devices and plans for HRMT experiments

M. Calviani, F. X. Nuiry, A. Perillo-Marcone, I. Lamas Garcia, C. Torregrosa, R. Esposito, E. Fornasiere, S. Gilardoni
CERN Engineering Department, Sources Target Interaction (STI) Group



R&D steps of "new" materials

- Identification of **needs** (from low-Z (e.g. flexible graphite at 1.0 g/cm^3) to high Z (e.g. iridium 22 g/cm^3)
- Execution of **mechanical testing** (in-house or outside labs) – eventual **dynamical characterizations**
- Beam shock tests at the **HiRadMat facility**
- Long-term **radiation damage** tests

Low-Z material characterization

Graphite-based materials

- Graphite is highly employed in CERN's accelerator as beam intercepting device due to low density & high operational temperature
- Historically, two carbon-based materials are employed:
  - Isostatic graphite (e.g. SGL 7550)
  - 2D reinforced CfC (due to higher electrical conductivity)
- Recently, the use of more thermo-mechanical resistant graphite was suggested (3D CC)

R&D on 3D CC for collimation applications

- The LIU **TCDI project (SPS to LHC transfer line collimators)** as an opportunity to explore new materials for collimators jaws
- More intense and more focus beams create huge thermal shocks within the collimator jaws

Beam Parameter	*Ultimate LHC*	*Standard LIU*	*BCMS*
Proton energy [GeV]		450	
Emittance (rms, norm.) [mm mrad]	3.5	**2.1**	**1.3**
Emittance [nm rad]	7.3	**4.4**	**2.7**
Number of bunches	288	**288**	**288**
Number of protons per bunch	1.7×10^{11}	$\mathbf{2.3 \times 10^{11}}$	$\mathbf{2.0 \times 10^{11}}$
Length of bunch train [μs]	7.8	7.8	8.2
Beam Size [horz,x] (σ used in ANSYS and FLUKA studies) [mm]	-	0.405	0.320
Beam Size [vert,y] (σ used in ANSYS and FLUKA studies) [mm]	-	0.647	0.511

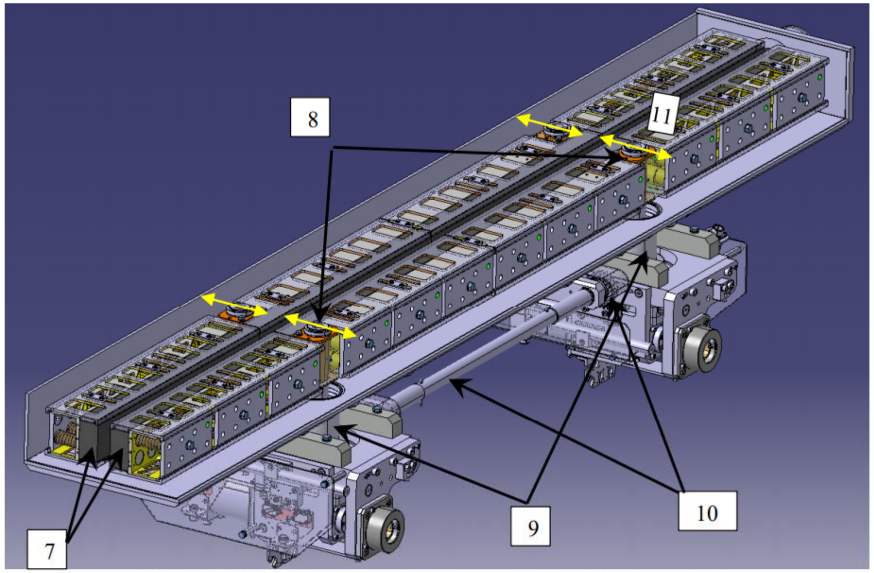


Figure 5: TCDI collimator with jaws and mechanical table units

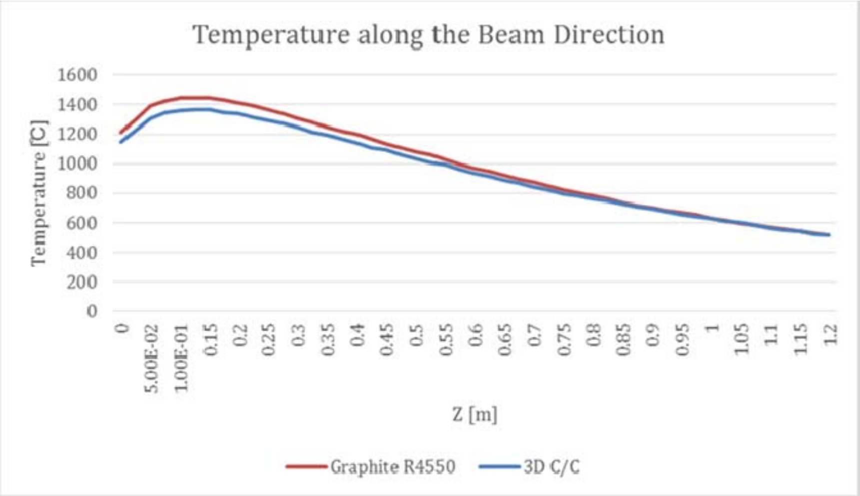
Item (7): Collimator absorber material (graphite and 3D CC blocks, clamped inside the jaw);
Item (8): Two stainless steel shafts per jaw, linking jaws to mechanical table units;
Item (9): Stainless steel bellows, linking the vacuum vessel to the mechanical table units;
Item (10): Rack-pinion system to prevent excessive jaw misalignment;
Item (11): Jaw advancement per motor step: 5 μm. Jaw stroke: 35 mm (switch 'in' to switch 'out')

R&D on 3D CC for collimation applications

- Requirements:
  - Light materials (density <2 g/cm^3)
  - Highest thermal shock resistance (R_T)
  - UHV compatibility (max outgassing 2 mbar*l*s^{-1})
  - Machinability
  - Procurement possibilities

$$R_T = \frac{K\sigma_T(1-\upsilon)}{\alpha E}$$

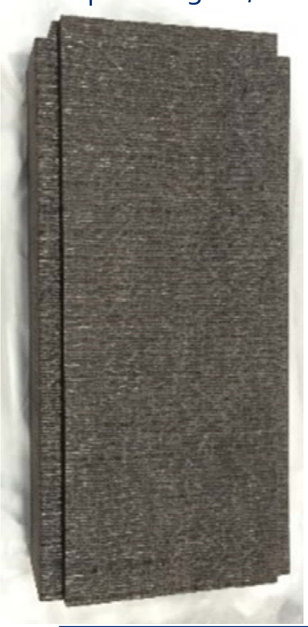
K is the thermal conductivity [W.m-1. ℃-1];
σ_T is the tensile limit [MPa];
α is the coefficient of thermal expansion [℃-1];
υ is the Poisson's ratio;
E is the Young's modulus [MPa].



R&D on 3D CC for collimation applications

- 3D Carbon/Carbon composites good alternatives to graphite, due to their ability to stop an eventual crack propagation due to their architecture. High strain to failure
- Very high service temperature (characterized up to 2750 C)
- Materials at least 2 to 3 times higher tensile strength and CTE inferior or equal to the graphite one

Sepcarb® 3D C/C

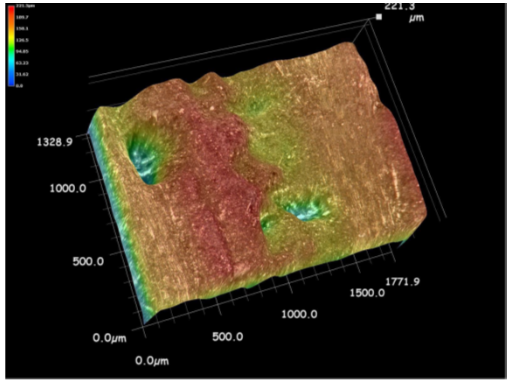


	Sigrafine® R7550	Graphite 2123 PT	Sepcarb® 3D C/C	C/C A412
Density [g/cm³]	1.83	1.84	>1.81	1.7
Thermal Conductivity W.°C⁻¹.m⁻¹	100	112	Non-Disclosure Agreement	-
Coefficient of Thermal Expansion 10^{-6} [C-1]	4	5.6	2	-
Young's modulus [GPa]	11.5	11.4	Non-Disclosure Agreement	15
Tensile Strength [MPa]	30	35	100	60

3D C/C A412

R&D on 3D CC for collimation applications

- Available characterization:
  - **Tensile** strength, stain at failure, Young's modulus from room T to 2750 C, tested according to EN-658-1
  - **Compression** strength, from room T to 2750 C, tested according to EN-658-2
  - + **shear** measurements, **diffusivity** and **dilatation** measurements over a wide range of temperature, as well as UHV characterisation…
  - Microscopy & micro tomography



Material	Outgassing rate bakeout [mbarl/s]	RGA Baked	Outgassing rate Unbaked [mbarl/s]	RGA Unbaked	
				< 50 amu	> 50 amu
3d CC Heracles	$2.5\cdot10^{-8}$ ✓	✓	$1.35\cdot10^{-5}$ ✗	✗	✓
Graphite Mersen	$2.0\cdot10^{-8}$ ✓	✓	$6.0\cdot10^{-6}$ ✓	✓	✓
3d CC Mersen	$8.0\cdot10^{-8}$ ✗	✓	$2.0\cdot10^{-5}$ ✗	✓	✓
Graphite SGL	$3.8\cdot10^{-9}$ ✓	✗	$1.7\cdot10^{-6}$ ✓	✓	✗

Results for RT working condition. Any deviation must be analysed and accepted

- **Next steps are high-strain rate characterization**

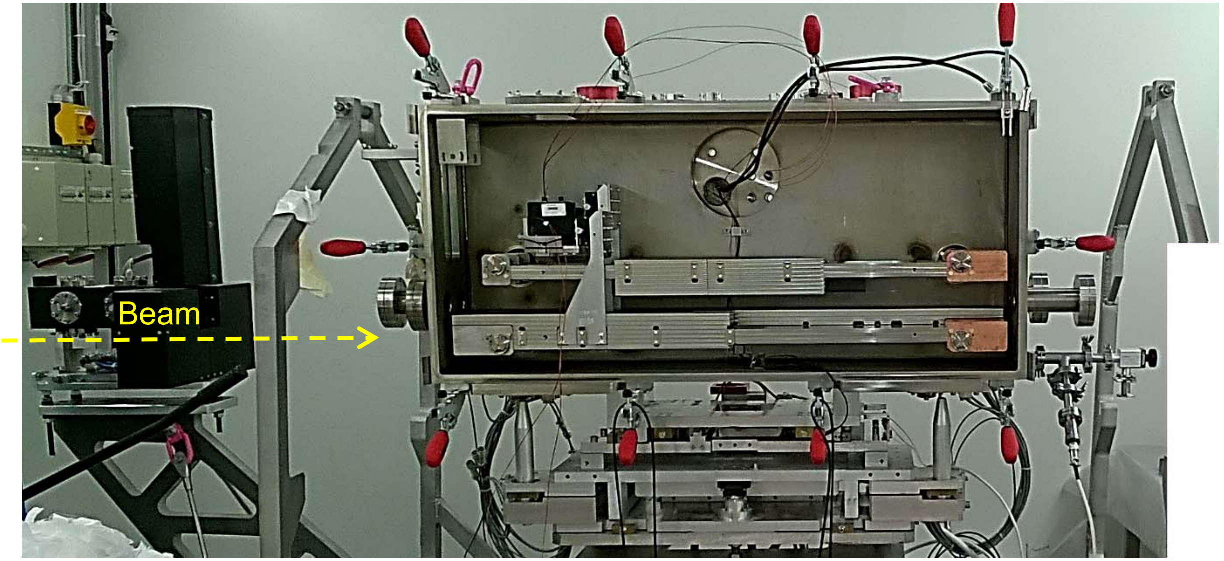
HRMT28
Dynamic tests on graphite and 3D CC

HRMT28

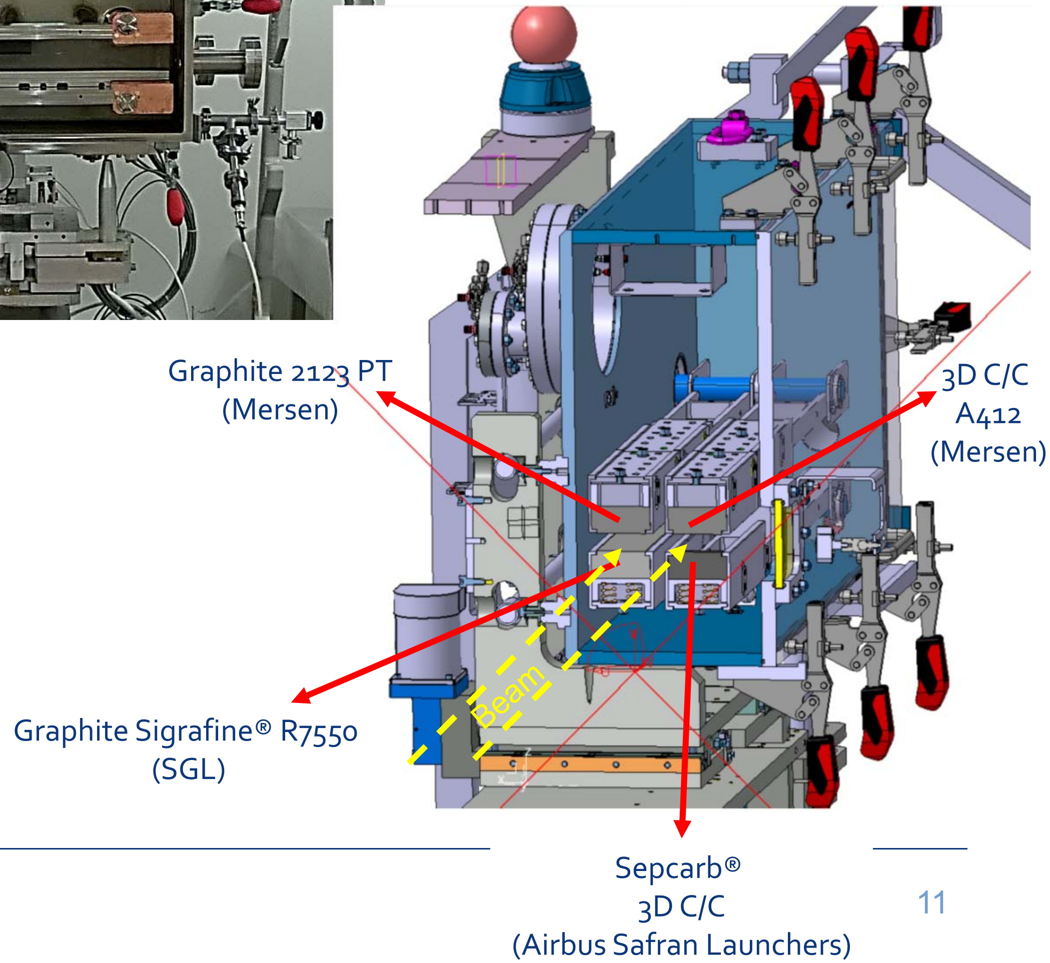
1. Assess the Integrity of Graphite for TCDIs and TDIs during Run 3 and test 3D CC. The goal is to reproduce the worst accidental scenario that the TCDI and the TDI can see during their life time
2. Cross-check simulations

Beam	Intensity	Sig X[mm] × Sig Y[mm]	Peak per Primary [GeV/cm³]	Max Temperature [°C]	M-C Safety Factor*
Run 3 BCMS	5.76 E13	0.320×0.511	0.436	1450	0.8 [~1]
HiRadMat requested beam	3.46 E13 (originally requested 1.3 E11 ppb)	0.313×0.313	0.663 (3.98 kJ/cm³)	1342	0.75 [0.96]
HiRadMat alternative beam (phase II)	2.6 E13	0.25×0.25	0.974 (4 kJ/cm³)	1371	[0.97]

HRMT28 Dynamic tests on graphite and 3D CC

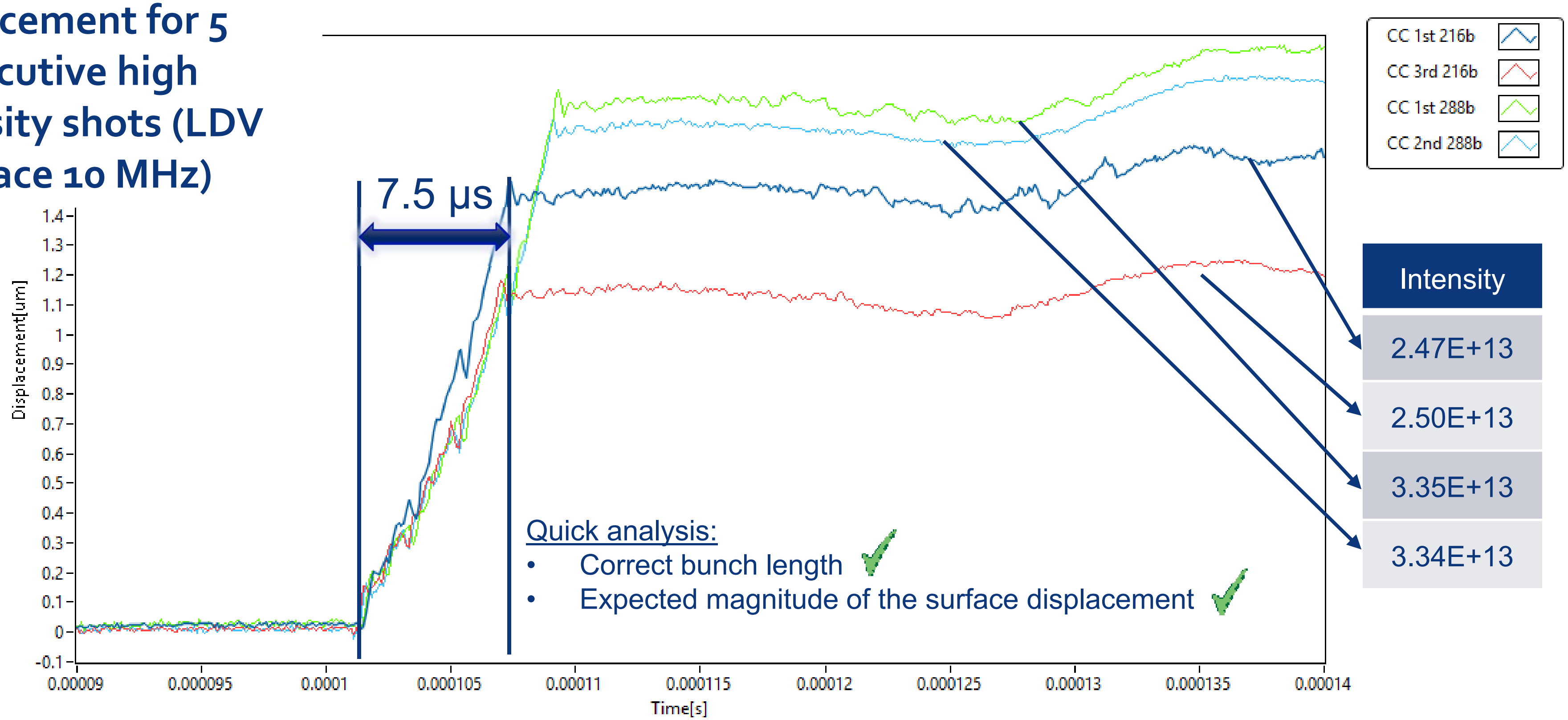


- **4 low density materials** impacted for BID applications;
- About **1.12E15** total POT spread over **3 runs**;



HRMT28 Dynamic tests on graphite and 3D CC

3D CC (ASL) surface displacement for 5 consecutive high intensity shots (LDV interface 10 MHz)



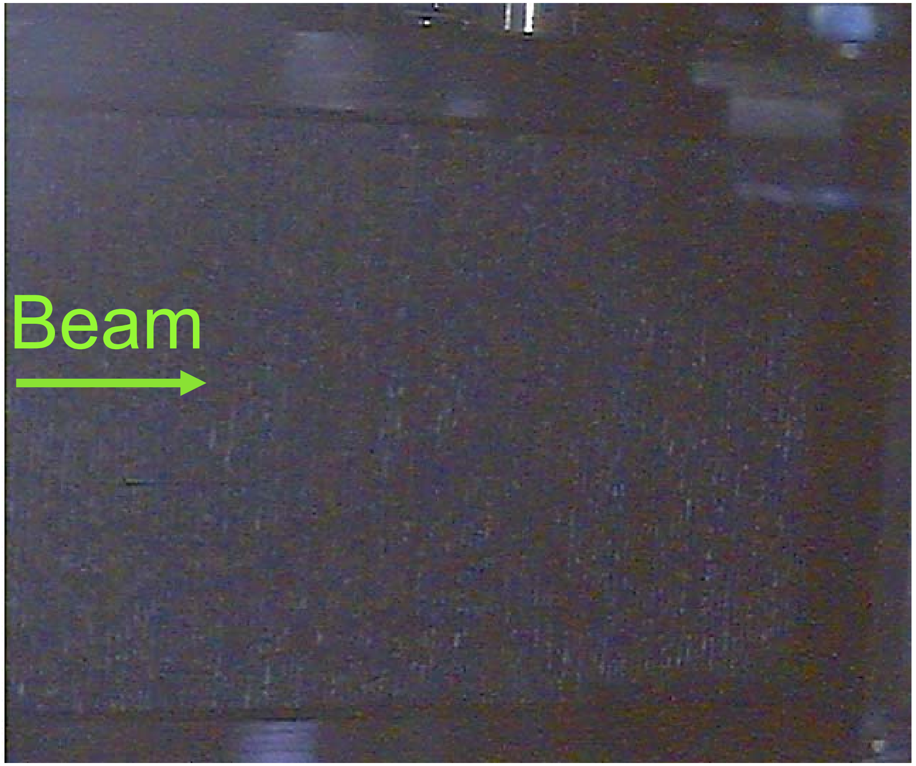
Very similar surface displacement curves → expected no beam induced damage

The amplitude difference for the 1st and 3rd shots at 216b can be due to a spot offset in X

HRMT28 Dynamic tests on graphite and 3D CC

Online pictures

Before impact on 3D CC



After 5x216 and 4x288 bunches shots

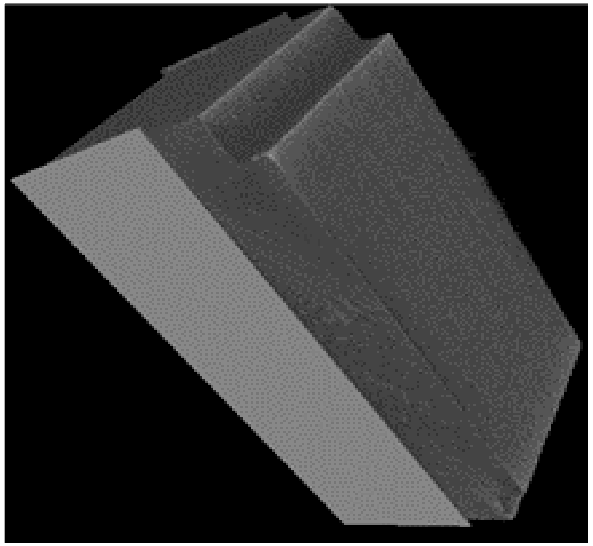
No apparent damage by the beam

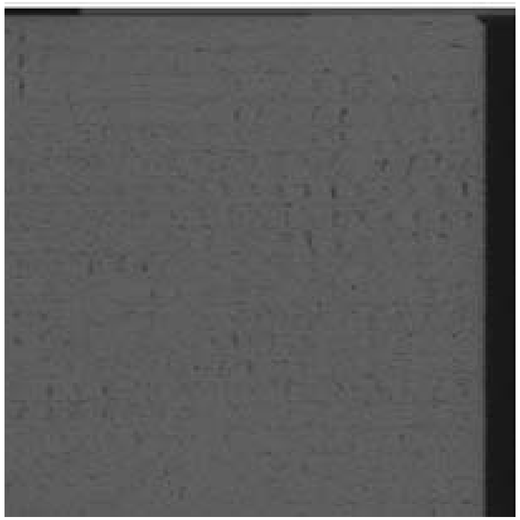
HRMT28 Dynamic tests on graphite and 3D CC

PIE is ongoing:

- ➢ HD pictures of the jaw surface,
- ➢ Detailed metrology control of the flatness,
- ➢ Ultrasound tests of the graphite,
- ➢ Micro-tomography of the 3D CC.

- Micro-tomography of 3D CC done at ESRF in November 2015
- Complete 3D Scan of the irradiated 3D CC blocks with a of 22.5 microns resolution to be scheduled.





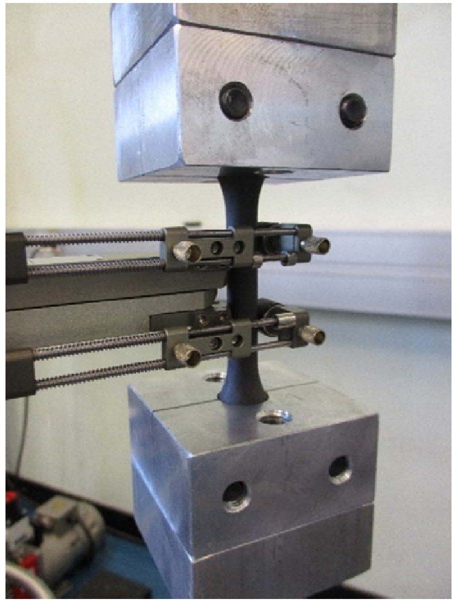
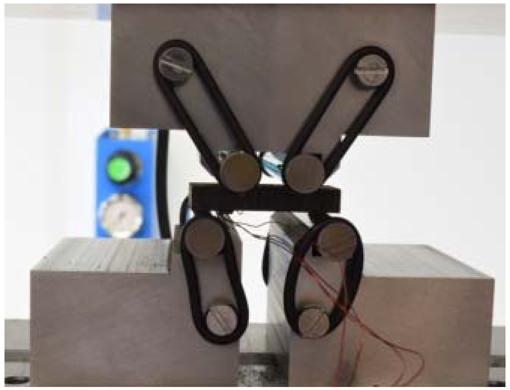
CfC R&D
HRMT35 for validation of coating robustness

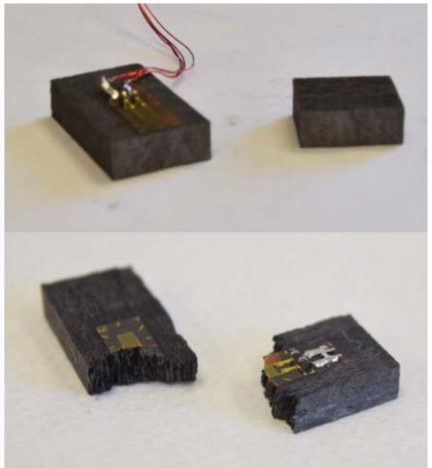
CfC R&D (Motivation, strategy and facilities)

- CFC AC150 (**baked up to 2800C**) is the material currently used in the primary and secondary collimators.
- The CFC AC150 is no longer produced. The CFC FS140 is the alternative material produced by the same supplier.
- A characterization campaign was launched with the aim of:
  - Validating the new CFC grade in view of possible LHC spare collimators needs;
  - Finding an alternative candidate for the production of the new HL-LHC collimators which are dominated by low impedance requirements.
- The CFC FS140 (**baked up to 2500C**) has been supplied by Tatsuno and samples have been mechanized (by external company) for the mechanical and electrical characterization (done at CERN)

CfC R&D (Results and publications)

- The properties characterized in both longitudinal and transversal fibers directions are (EDMS 1750582):
  - Specific heat, Cp;
  - Coefficient of thermal expansion, CTE;
  - Thermal diffusivity, λ and thermal conductivity, α;
  - Flexural strength in terms of stress and strain to rupture;
  - Compression strength;
  - Electrical conductivity.



Focus on coating

- Movable jaws in beam intercepting devices are often placed very close to the beam axis (6-10 sigma)
- **Impedance** is a critical factor both for the beam instabilities as well as for the joule heating on the BID
- Use of **high electrical conductivity** material is critical
  - In some cases graphite-based materials or ceramics are coated with a thin layer of Cu, Ti or pure molybdenum

HRMT35 (Motivation, strategy and facilities)

- After dismounting the TDI (injection stopper for the LHC) in 2016, severe damage on the Ti coated surface on the hBN absorbing blocks was found
- The absorbing blocks of the currently installed TDI are made out of Cu sputtered on SGL Graphite R4550.
- Given the past issues and the general uncertainties on coatings behavior when grazed by a high intensity proton beam, there is a high priority recommendation to test and **validate the sputtered Cu performance under the worst impact conditions that the TDI could face**

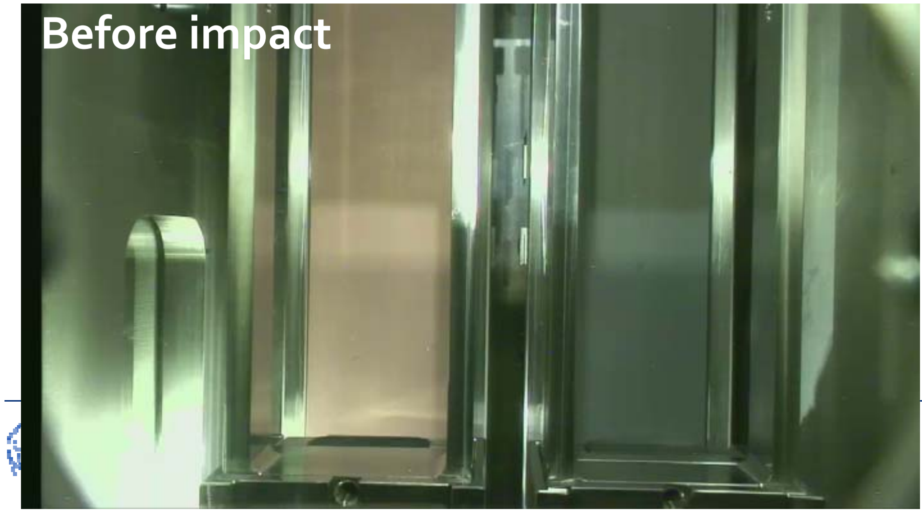
→ HRMT35 experiment (in the same tank as of HRMT28)

HRMT35 (Motivation, strategy and facilities)

- HRMT35 configuration houses up 4 different absorbing materials and coating configurations:
  - SGL Graphite R4550 TDI coating configuration with Cu coating;
  - SGL Graphite R4550 TDI coating configuration with Mo coating;
  - Tatsuno CfC FS140 in a TCPPM/TCSPM configuration with Mo coating + SiC-SiC;
  - Molybdenum Graphite (MoGr) in a TCPPM/TCSPM configuration with:
    - Half of its surface coated with Mo and half with Cu.

HRMT35 (Status and next steps)

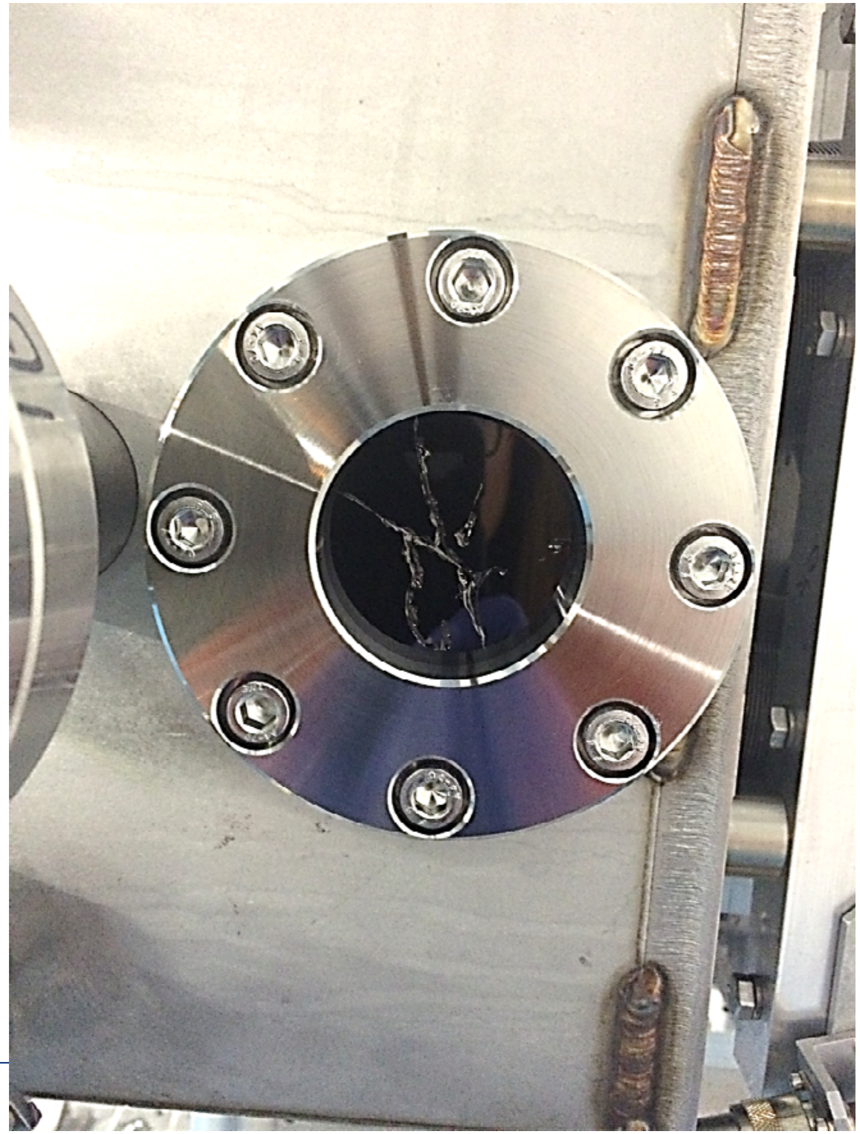
- HRMT35 completed on 23rd August 2017
- PIE to be performed:
  - HD pictures of the coated surface;
  - Metallographic analysis of the coated surface;
  - Coating adhesion tests;
  - Electrical conductivity tests;
  - Ultrasound tests;
  - Detailed metrology control of the flatness



Stripes of molten Cu

HRMT35 opening (and a surprise)

- Still quite hot (~5 mSv/h as of today)
- Anticipated removal from target area for HD inspection
- But… window is broken – consequences?
- PIE will follow



“medium-Z” R&D and production techniques

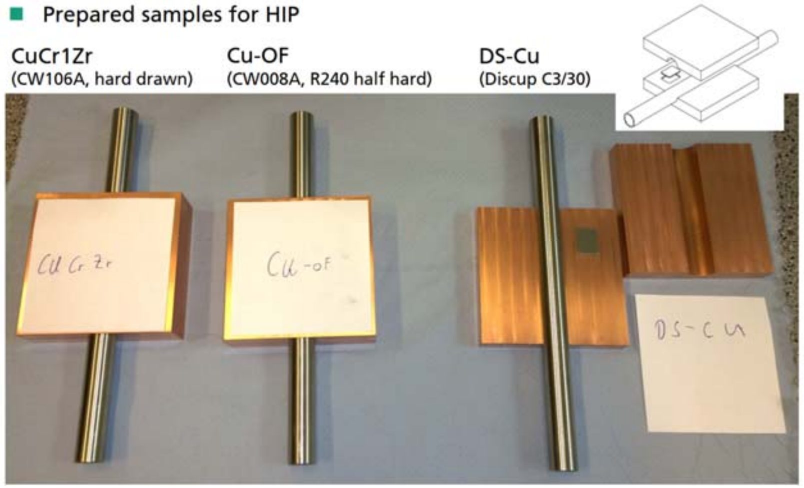
e.g. diffusion bonding between SS and cuprous materials

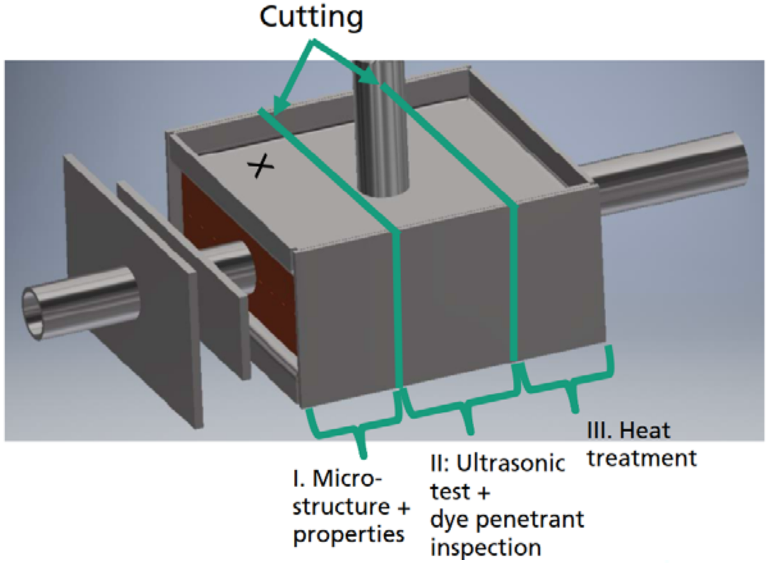
Objectives and scope

- To obtain the best possible contact conductance between cooling pipes and bulk materials (e.g. efficient heat removal)
- Diffusion bonding provides “perfect” thermal conductivity at interface
- Produce robust, UHV compatible water-cooled devices
- Bonding between SS (or CuNi) pipes and cuprous materials (Cu-OF, CuCrZr, Glidcop/Discup)
  - R&D useful for a variety of devices: TIDVG, PS Internal dump, LHC collimator back-stiffener, D3 external dump, future dumps (e.g. Isolde)

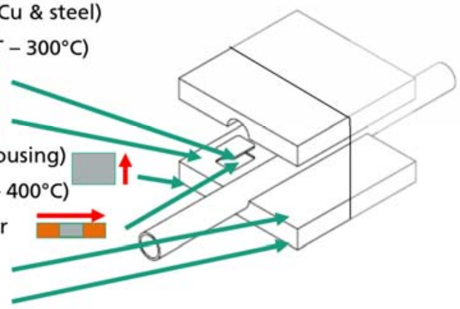
Characterisation and prototypes

- Prepared samples for HIP

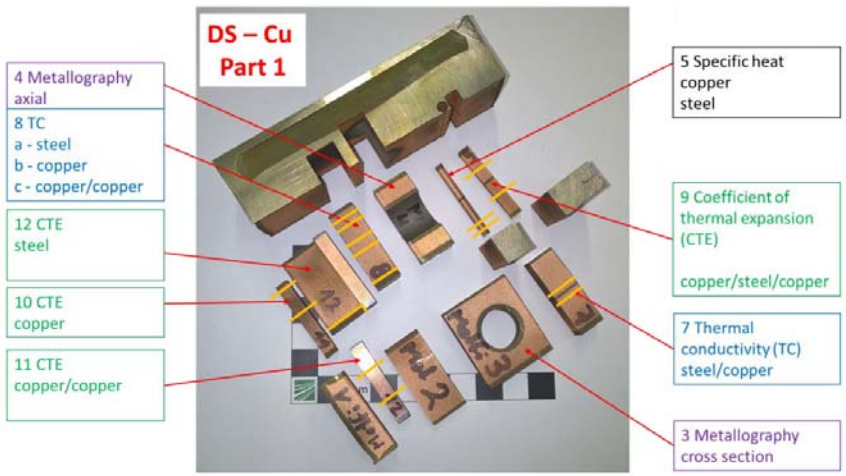




- Sample preparation
  - I. Properties (as HIP)
    - Density
    - Specific heat (RT-300°C, Cu & steel)
    - Thermal conductivity (RT – 300°C)
      - Copper/ steel
      - Copper bulk
      - Steel material (HIP housing)
    - Thermal expansion (RT – 400°C)
      - Copper/ Steel/ Copper
      - Copper
      - Steel

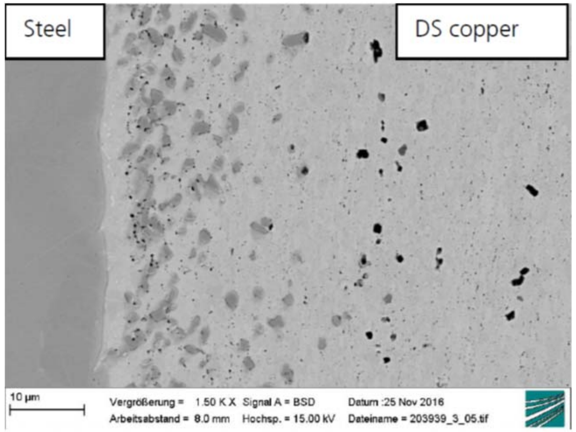


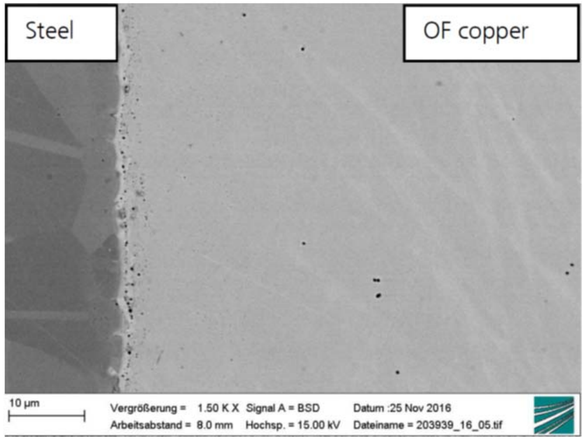
Measuring direction

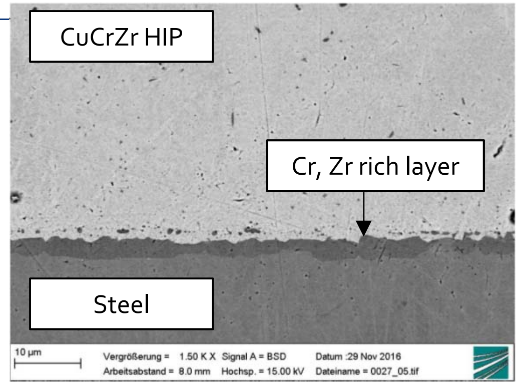


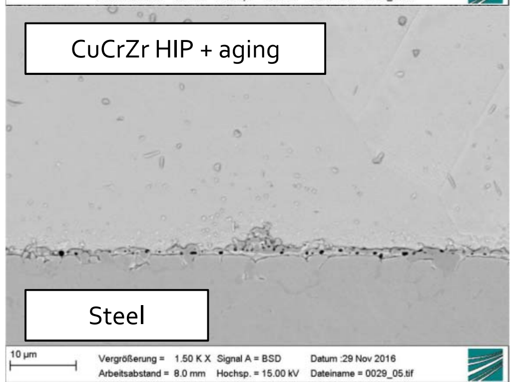
Microstructural examinations

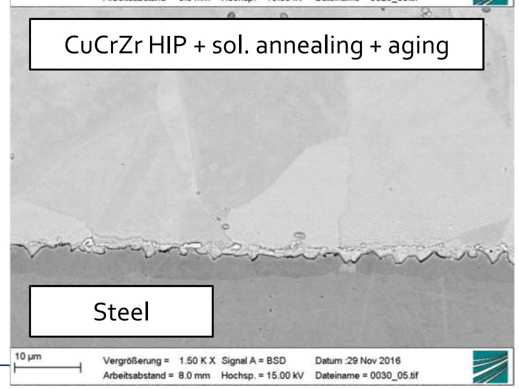
Excellent bonding observed in all samples, even after thermal treatments





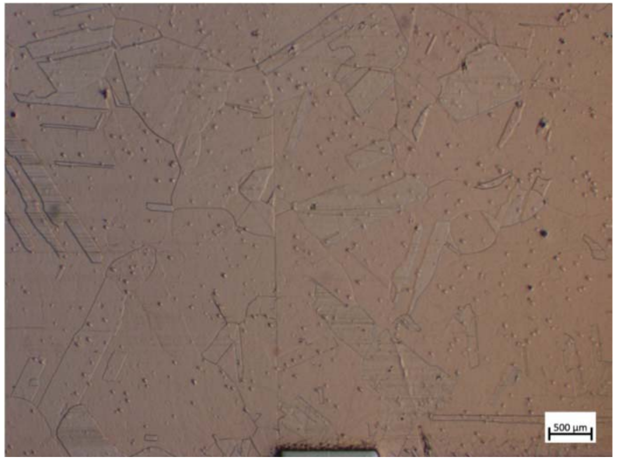




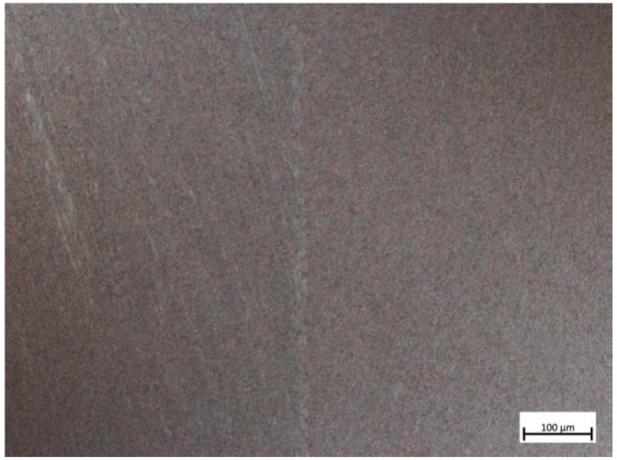


Inspections at CERN

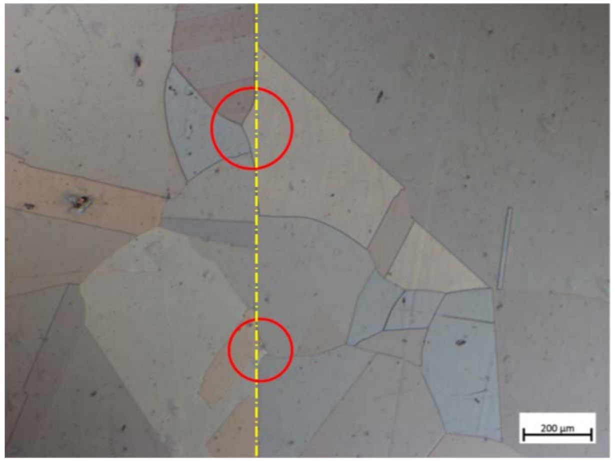
OF Cu



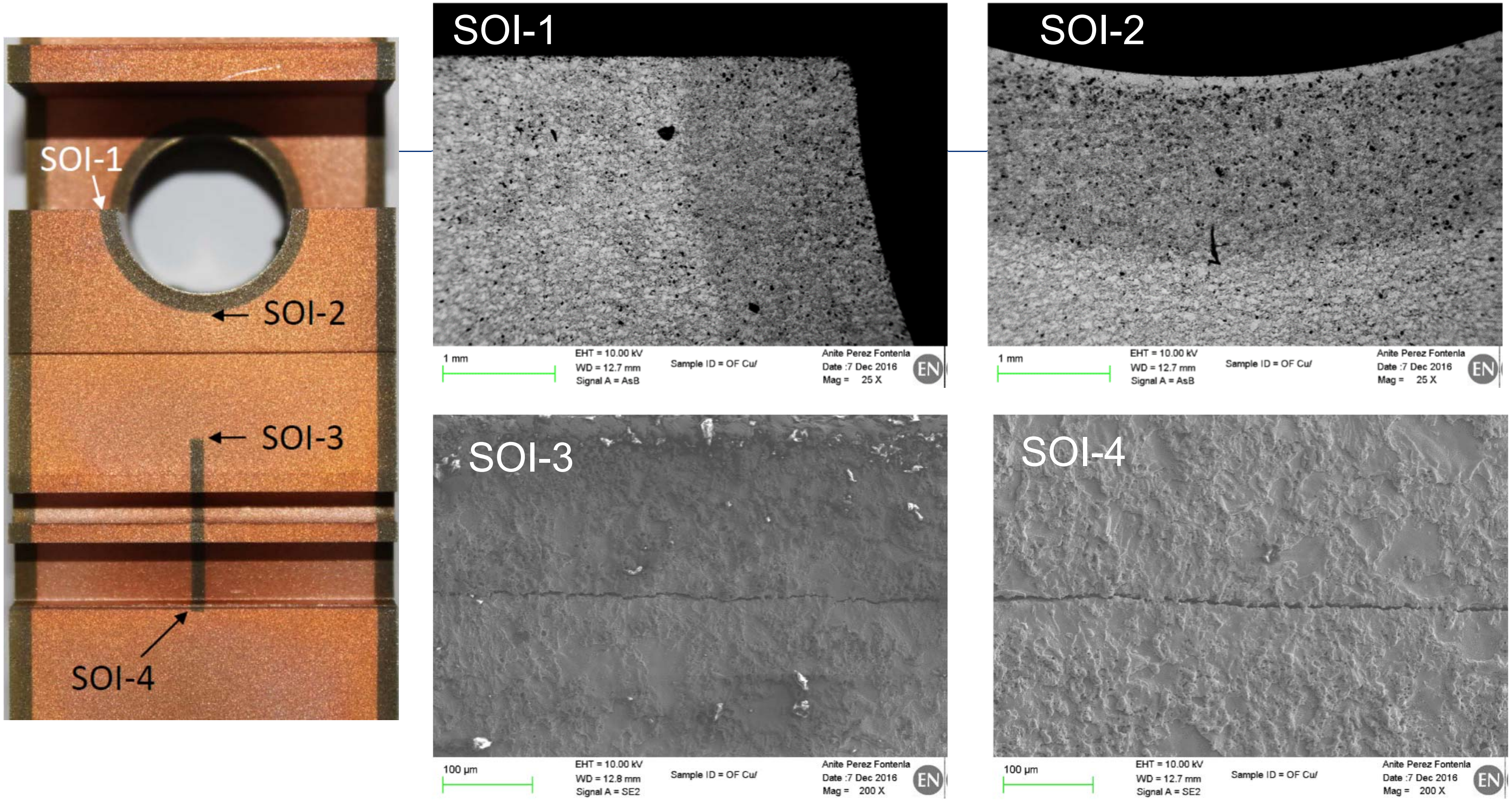
DS Cu



CuCrZr

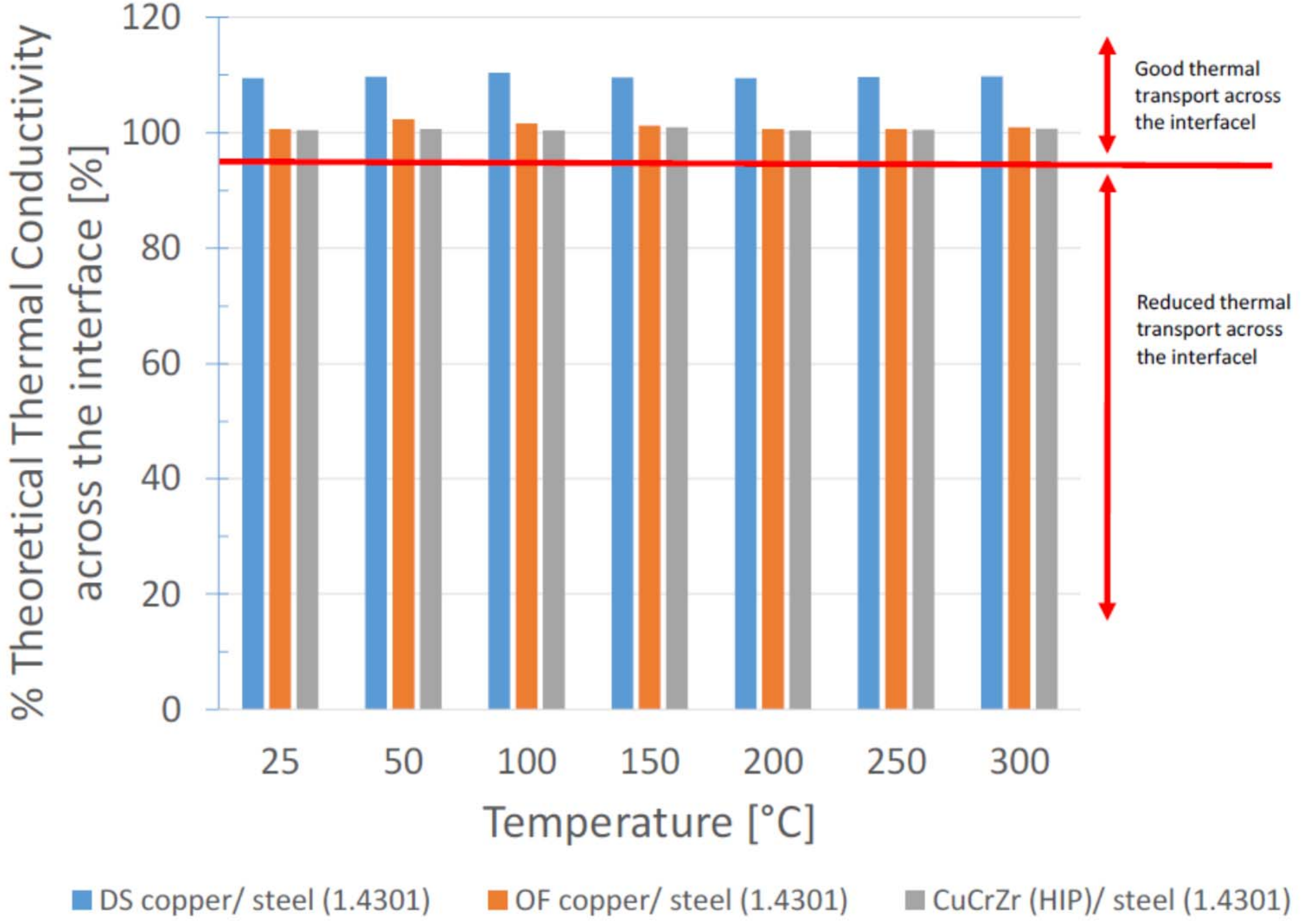


- In all samples the diffusion bonding line was appreciable
- OF Cu sample showed various sites were crossing grains were visible. Clear symptom of a good bonding joint



- Surface is very rough for small discontinuities detection by OM and SEM
- Nevertheless, no major defects were found at the tube-Cu interface
- Some discontinuities were observed at the witness-Cu interface (SOI-3 and SOI-4)

Thermal conductivity at interface

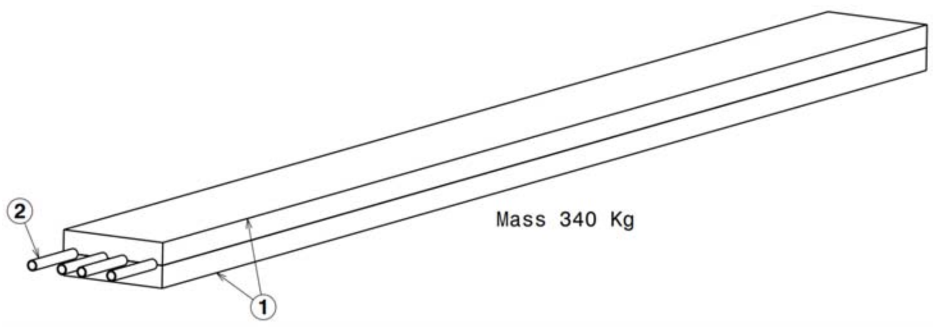


Thermal conductivity at interface equivalent to theoretical value of perfect bonding

Results from first study

- Analyses performed in partnership with Fraunhofer institute in Germany
- Excellent bonding achieved for all 3 materials
- In-depth thermal analysis shows perfect performance
- No defects found on microstructural inspections
- Properties of CuCrZr recovered after HIP by making heat treatments
- Mechanical tests needed to quantify bonding strength

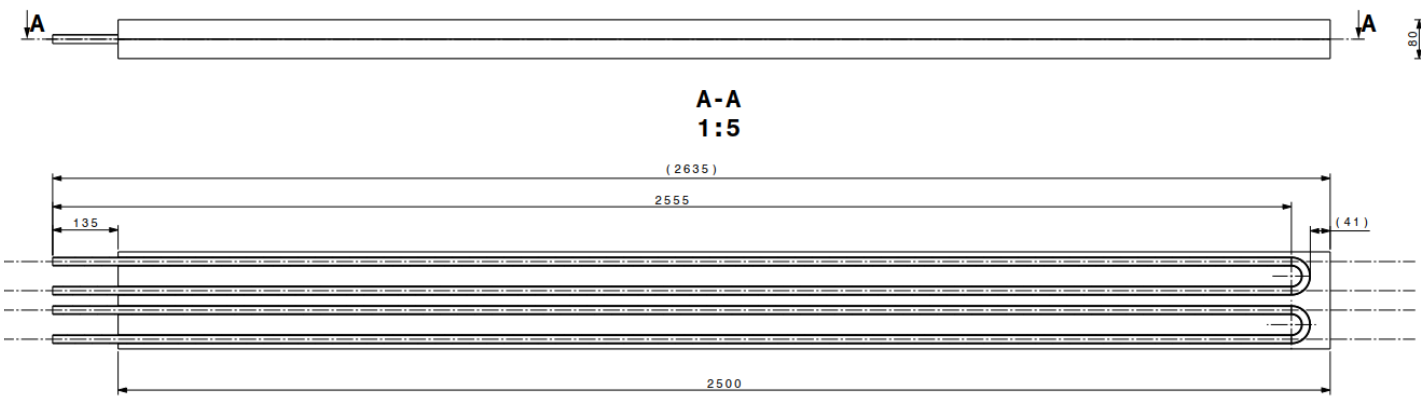
Next steps

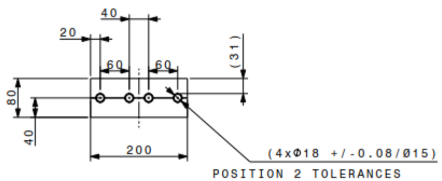


Possible validation at HiRadMat being foreseen

<u>Full scale prototype for TIDVG#5 being produced.</u>

- Seamless SS tubes embedded in a CuCrZr plate
- Overall thermal efficiency to be tested (special test-bench to be produced)
- US inspection from inside pipes (new development)
- Thermal/mechanical characterisation of samples extracted from prototype
- Study to be completed by Autumn 2018.



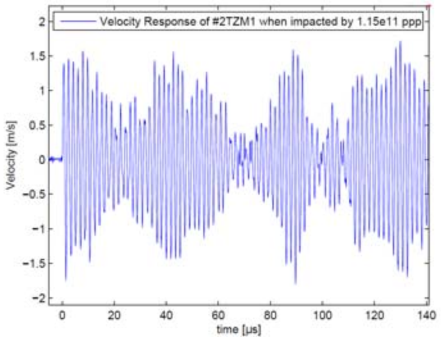


Topics that I will not cover

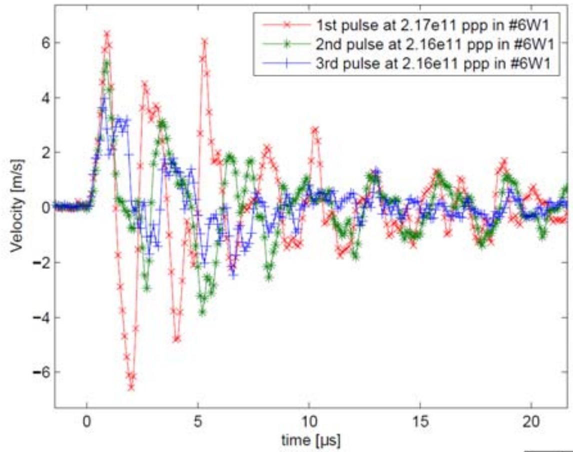
- High-Z R&D for refractory metals at high T & strain rates ++ HRMT27/42
- Expanded Graphite (EG) Testing and Characterization
  e.g. low-density graphite (1-1.1 g/cm^3)
- Cladding of W and TZM with Ta or TaW by Hot Isostatic Pressing (HIPing)
- Material and production R&D for a Ti-contained Pb target

Results of the HRMT27 experiment

Extensive measurements of the predicted waves were recorded.

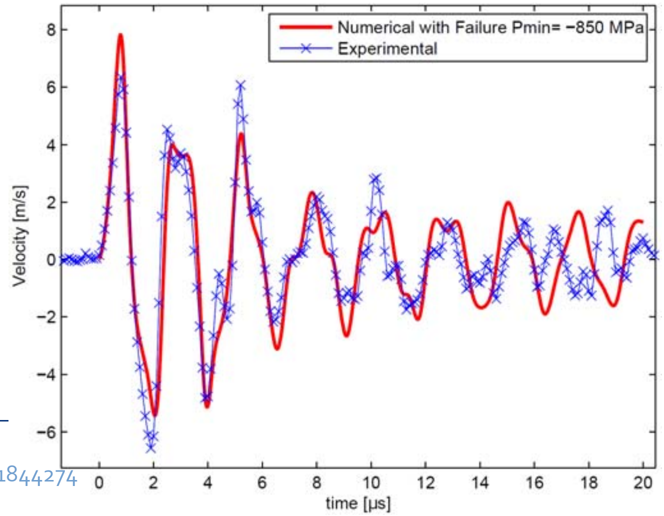


All the materials except tantalum fractured from conditions 5-7 times less demanding than the ones taking place in the AD-Target



Apparently **Tantalum** survived AD-Target conditions → Baseline core material for the future design.

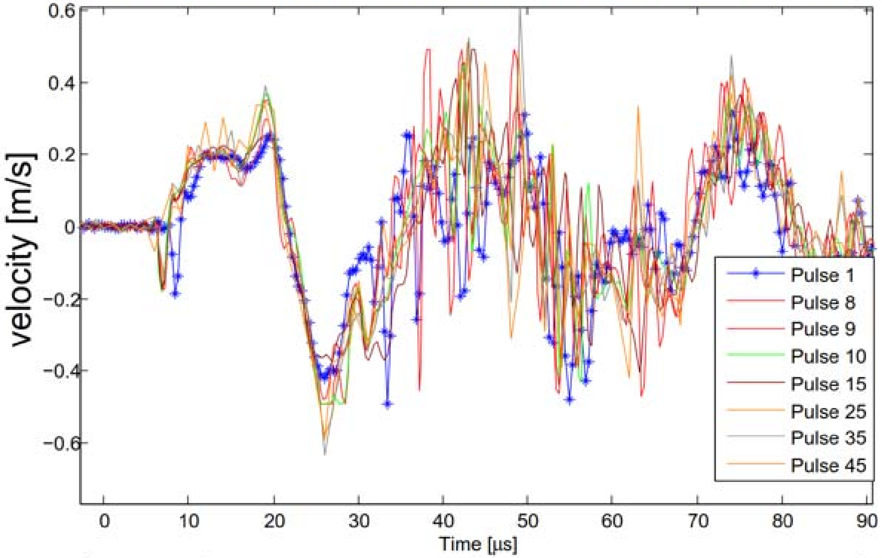
Simulations & Experiment show very good agreement. Failure models have been benchmarked.

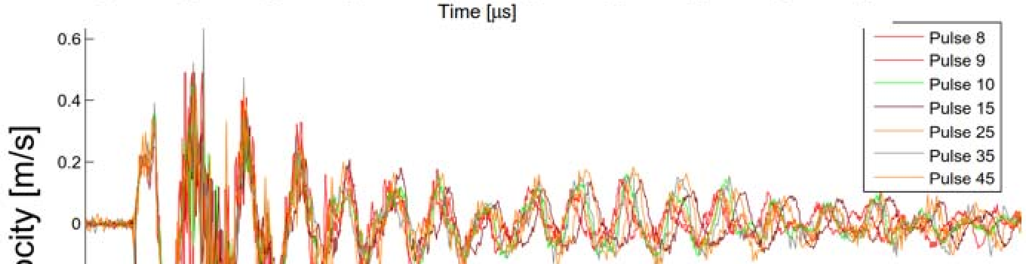


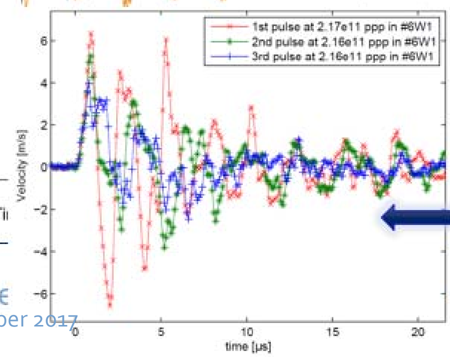
LDV Online Results (2)

HRMT42

Comparisons between the velocity response of different pulses







- High level of repeatability in the amplitude of the recorded wave is observed even after 45 pulses.
- No significant change in the damping time and frequencies of the recorded waves.
- Good indications of the EG matrix performance and state of the Ta-Matrix interface.

To be confirmed by the PIEs..

***Recorded velocity successive pulses HRMT27, change of the wave indicated fracture.**

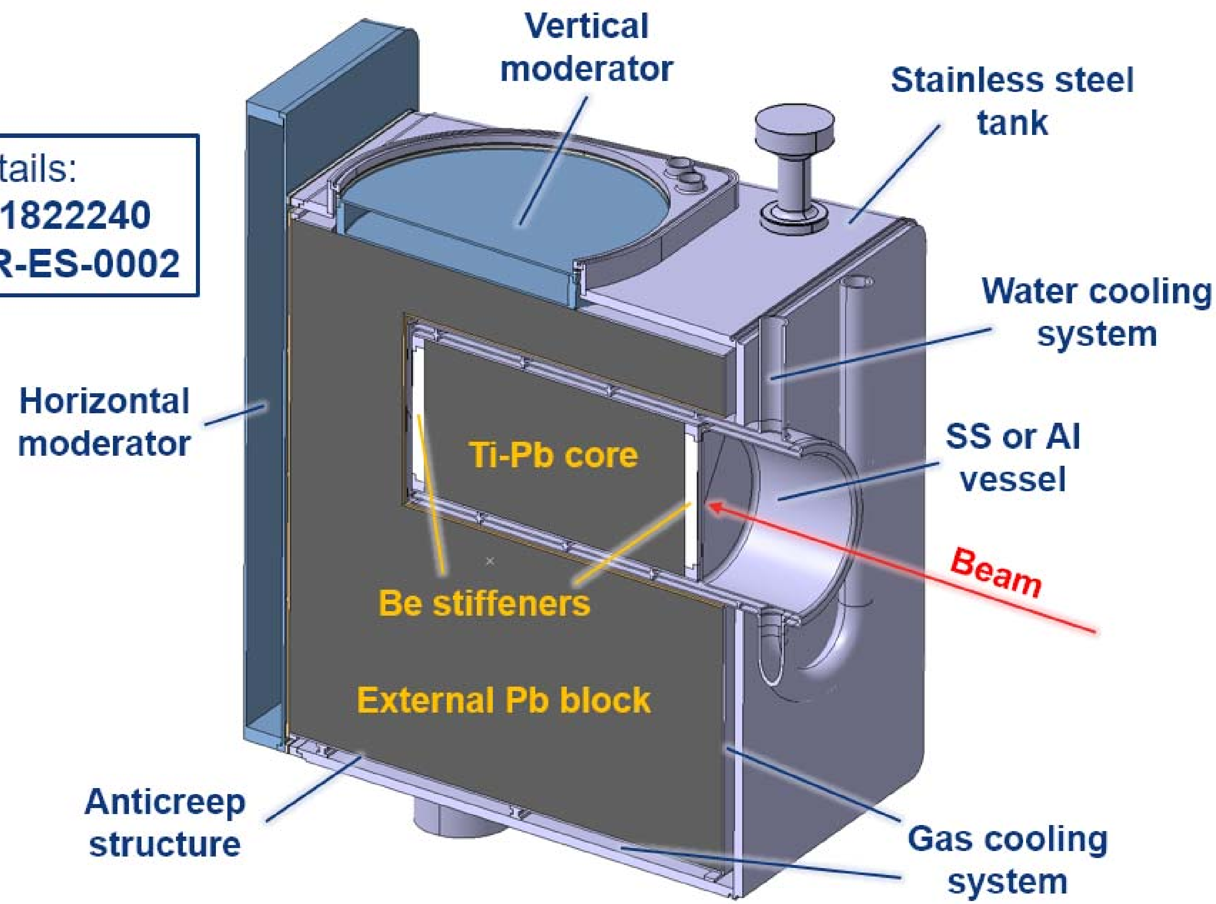
Perspective on new thermal shock experiments at HRMT in 2018

3 out of 5 planned experiments

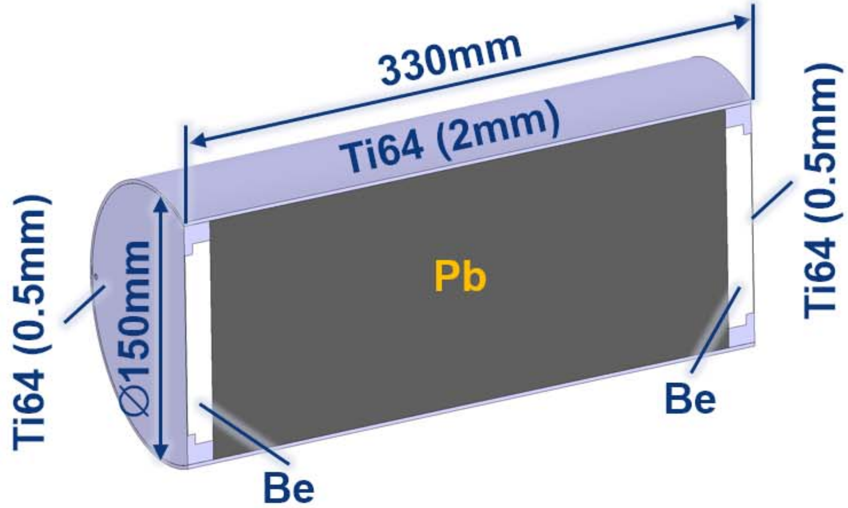
n_TOF spallation target

New target (Target #3)

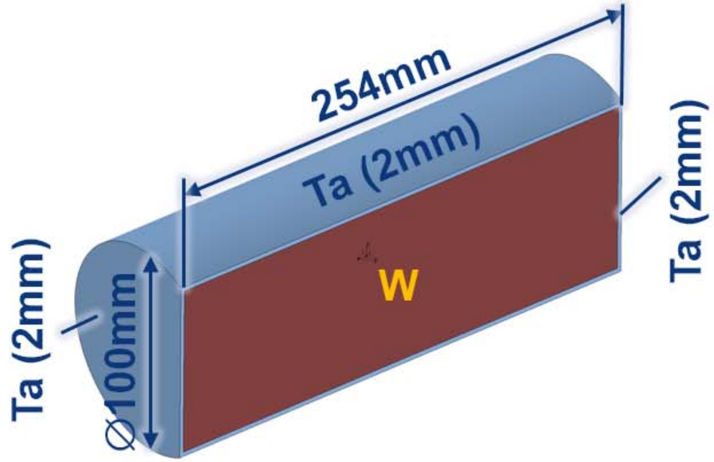
Details:
EDMS 1822240
TOF-TAR-ES-0002



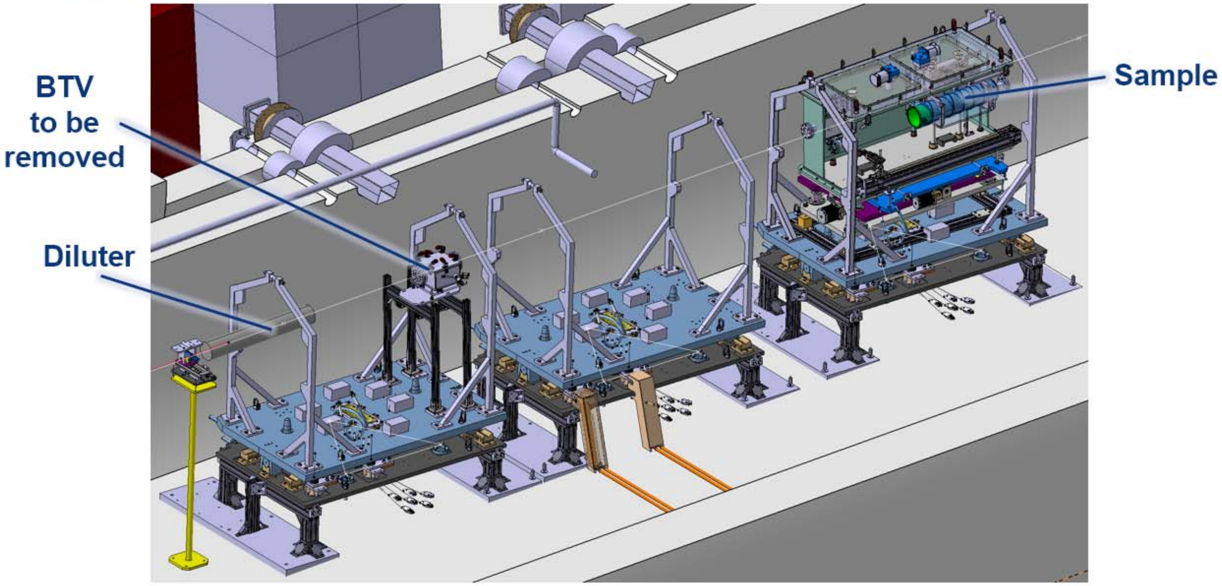
1) Ti-contained Pb sample with Be inserts



2) Ta-cladded W sample by HIP process



σ_{n_TOF}: 15 mm
σ_{HRMT}: 2 mm → **Diluter needed to obtain similar temperature distribution!**

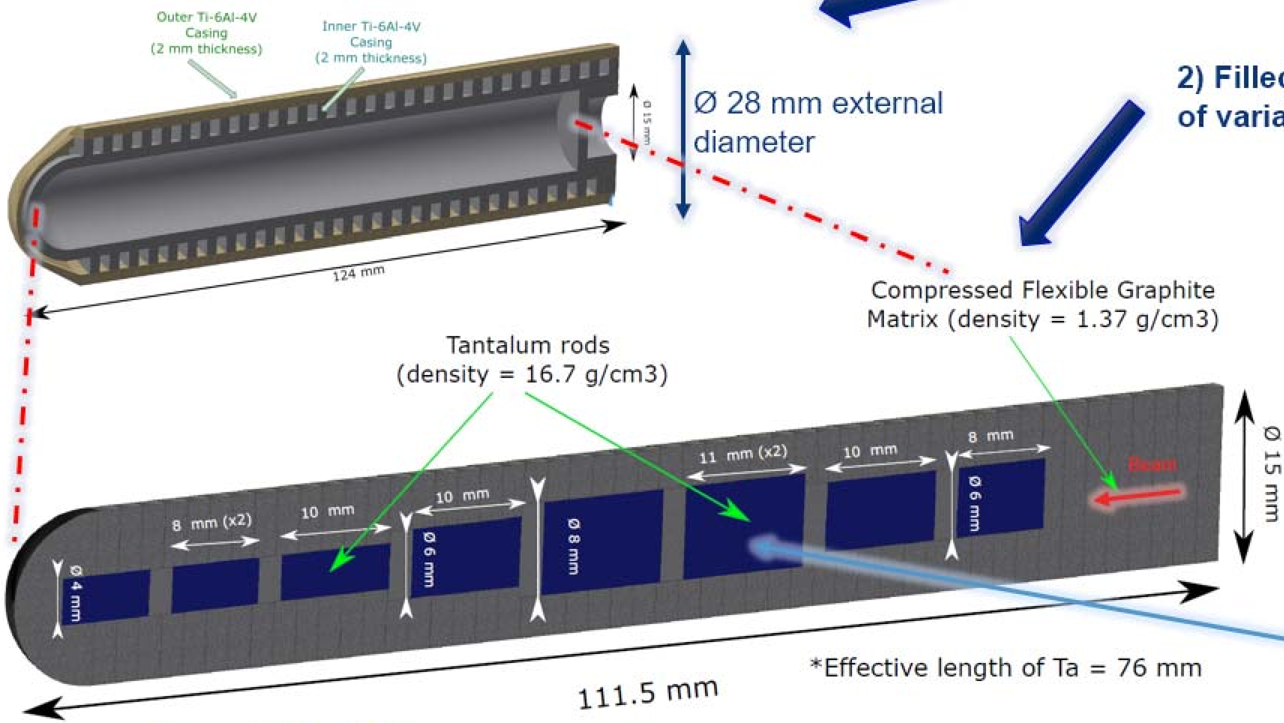


Baseline Configuration of the New AD-Target Design

***Geometry to be recreated in HiRadMat**

1) External Ti-6V-4Al housing, cooled by pressurized air

2) Filled by an EG matrix and Ta core of variable diameter

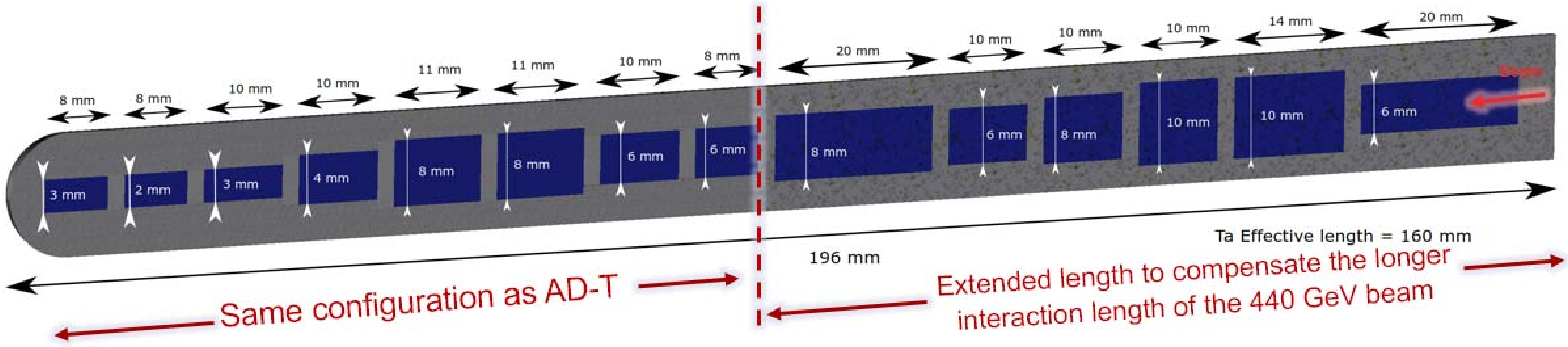


Simulations show that larger core diameters reduce significantly the reached tensile pressures

The concept is to use larger diameters in the rods where higher energy is deposited to enhance their chances of survival

Impacted by PS beam
- 26 GeV, 1.5e13 ppp
- 0.5x1 mm at 1σ

Proposed Geometry for the PROTAD Targets



*Target will be encapsulated in a Ti-6Al-4V body (potentially cooled)

- **Same diameters as real AD-Target.**
- **Target length is increased from 124 mm (AD-T) to 210 mm (PROTAD)**
- **5-6 different targets will be irradiated:**
  1. Ta core with EG matrix
  2. Ta-2.5%W core with EG matrix
  3. Ir core with EG matrix
  4. Ta core with graphite matrix
  5. Ir core with graphite matrix
  6. Composed Ta + Ir core

Preliminary

→ **Ductile tungsten test?**

HiRadMat beam shall be:

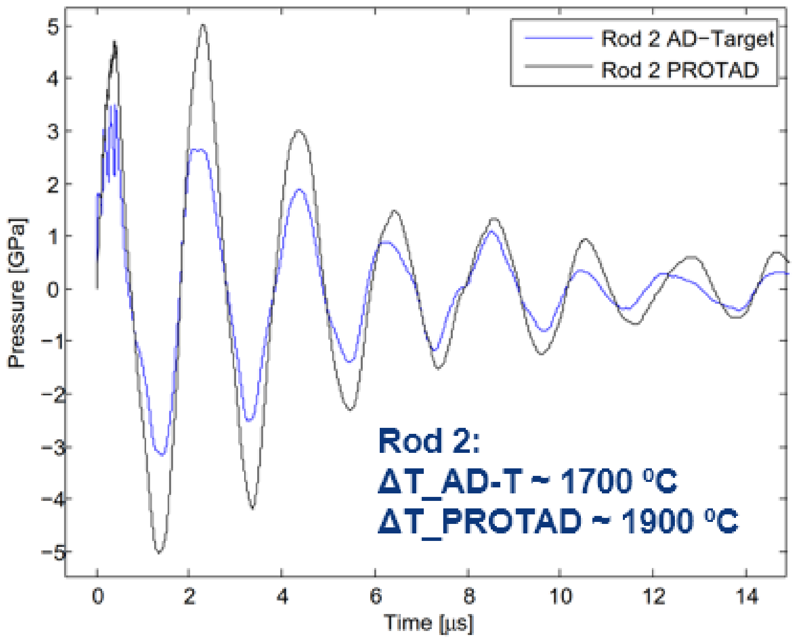
- As focused as the AD-Target beam
- Have a similar duration (~0.45μs)

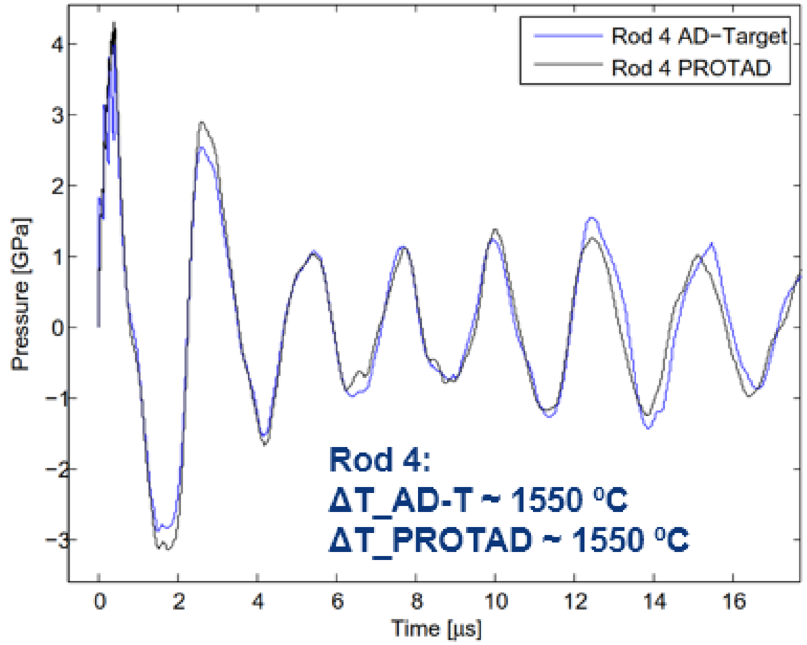
(excite radial wave as in the AD-Target)

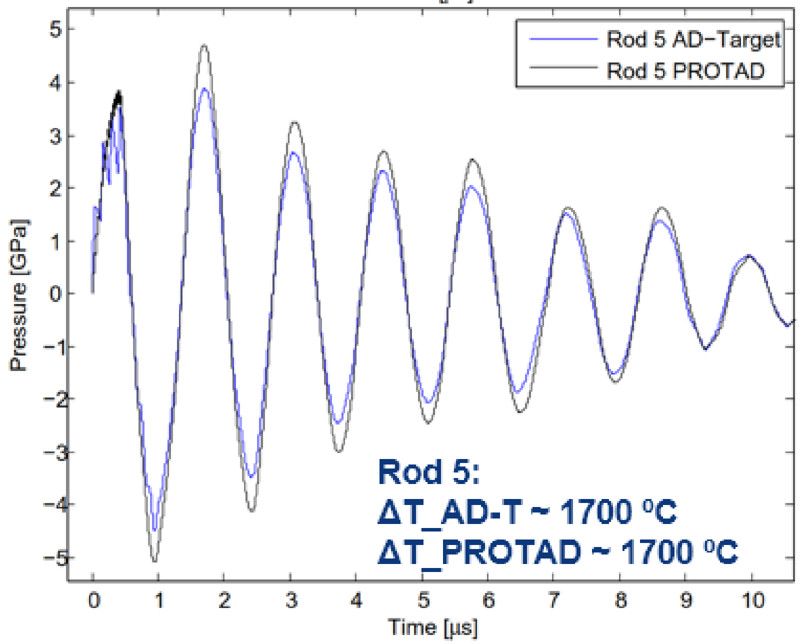
Intensity: **$8.4 \cdot 10^{11}$ ppp**

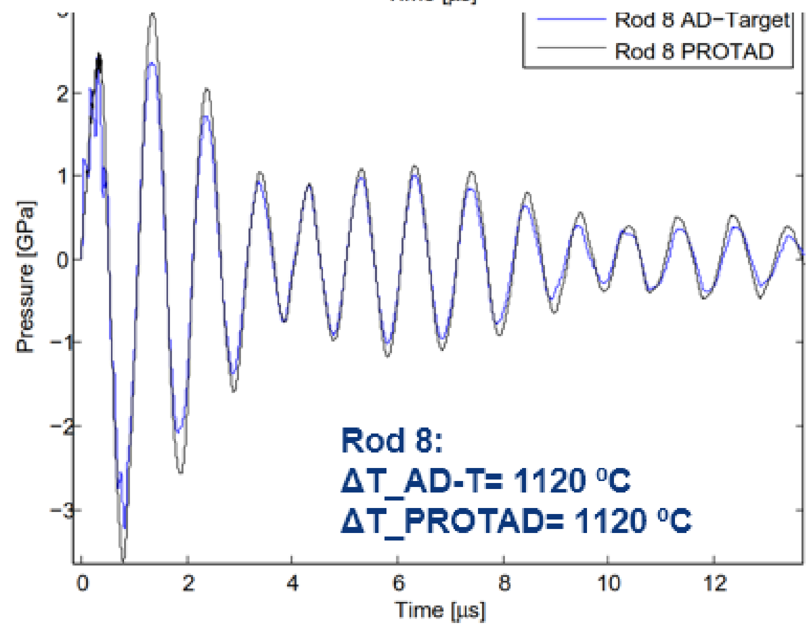
Made by: **18 bunches spaced by 25 ns**

Beam size **0.7x0.7 mm at 1σ**


Rod 2 AD−Target
Rod 2 PROTAD
Pressure [GPa]
Time [µs]
Rod 2:
ΔT_AD-T ~ 1700 °C
ΔT_PROTAD ~ 1900 °C


Rod 4 AD−Target
Rod 4 PROTAD
Pressure [GPa]
Time [µs]
Rod 4:
ΔT_AD-T ~ 1550 °C
ΔT_PROTAD ~ 1550 °C

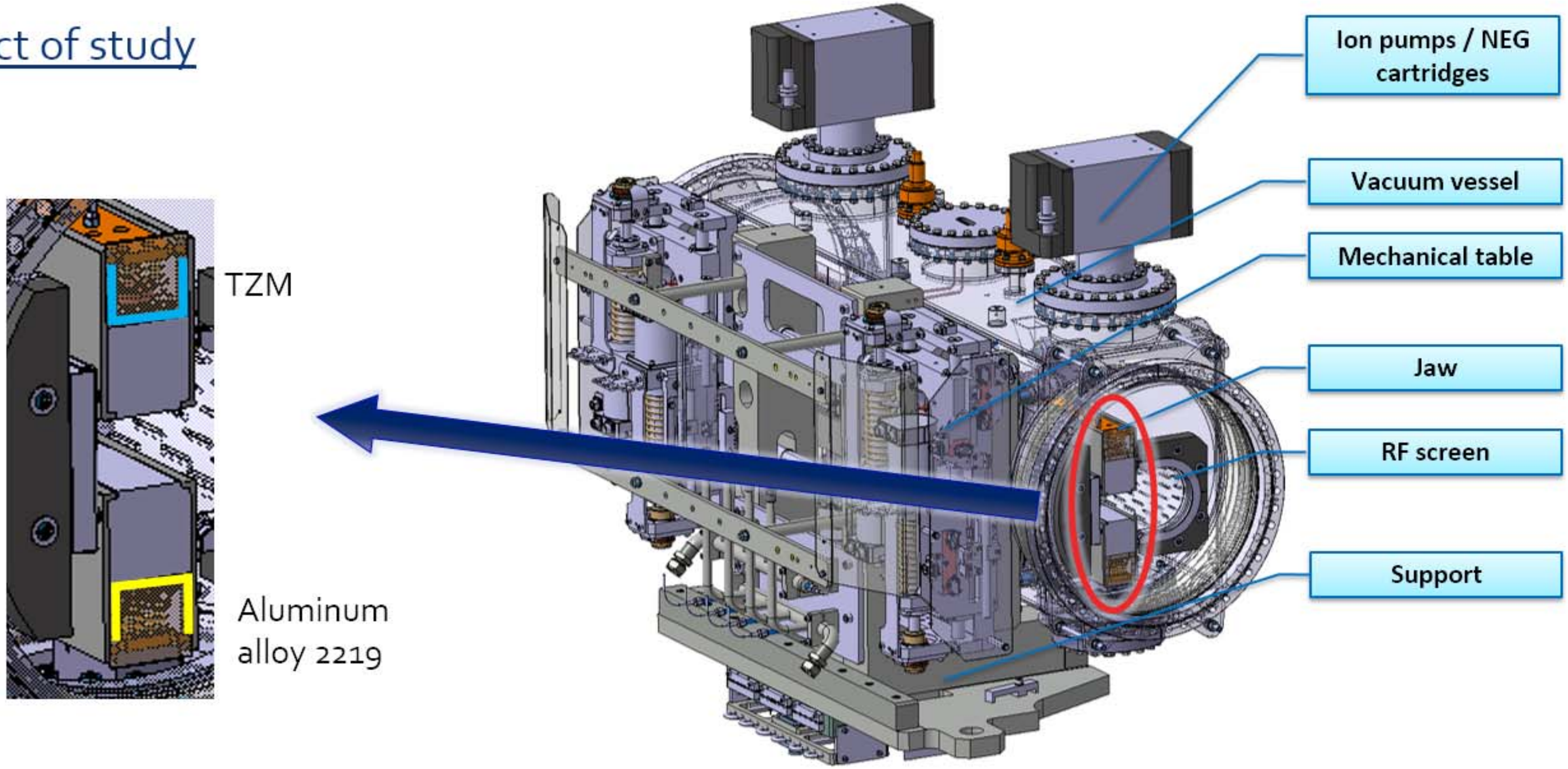

Rod 5 AD−Target
Rod 5 PROTAD
Pressure [GPa]
Time [µs]
Rod 5:
ΔT_AD-T ~ 1700 °C
ΔT_PROTAD ~ 1700 °C


Rod 8 AD−Target
Rod 8 PROTAD
Pressure [GPa]
Time [µs]
Rod 8:
ΔT_AD-T= 1120 °C
ΔT_PROTAD= 1120 °C

WP14 TDIS jaw validation testing

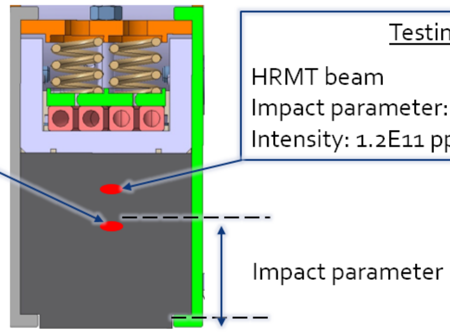
HiRadMat 2018

Object of study



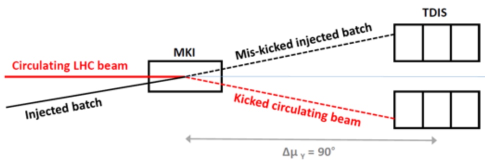
Real failure scenario (worst-case)

HL-LHC beam
Impact parameter: 38 mm
Intensity: 2.3E11 ppb (320 bunches)



Testing scenario

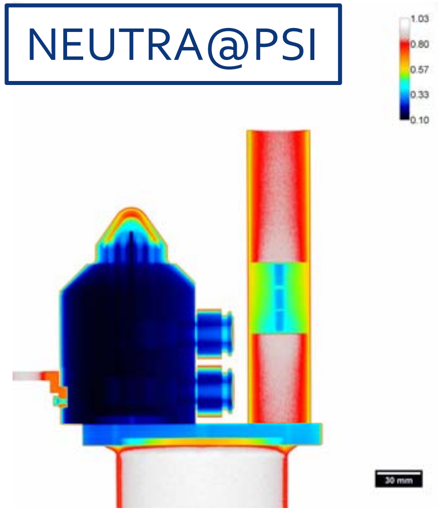
HRMT beam
Impact parameter: 52 mm
Intensity: 1.2E11 ppb (288 bunches)



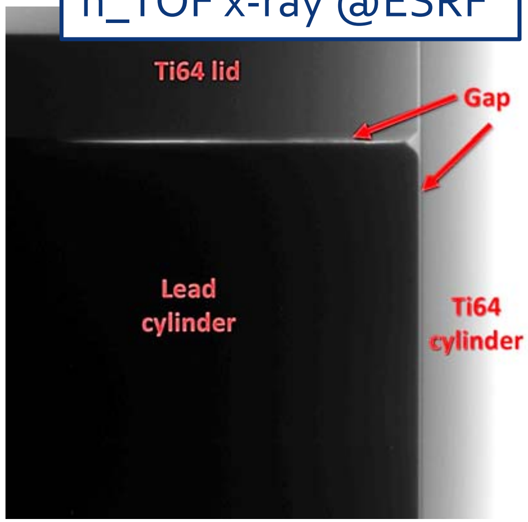
Bonus – NDT PIE

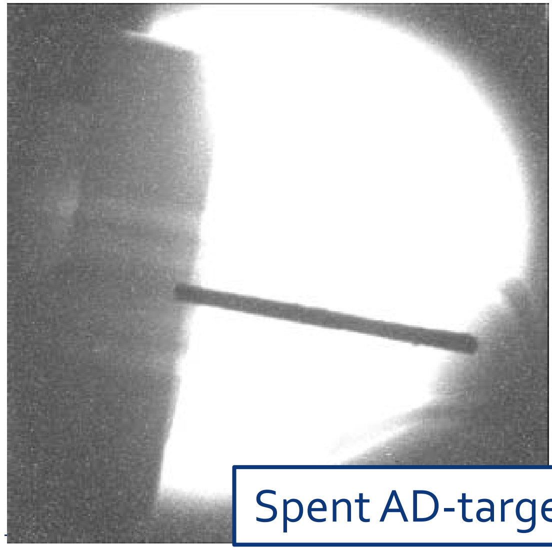
- Developing the use of "alternative" ND PIE activities including neutron radiography & x-ray tomography

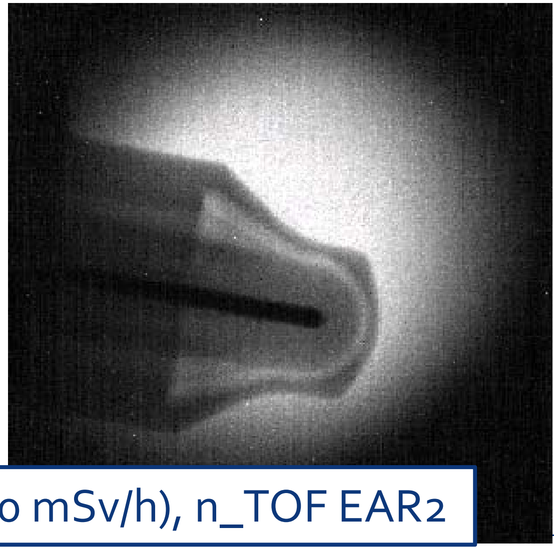
NEUTRA@PSI



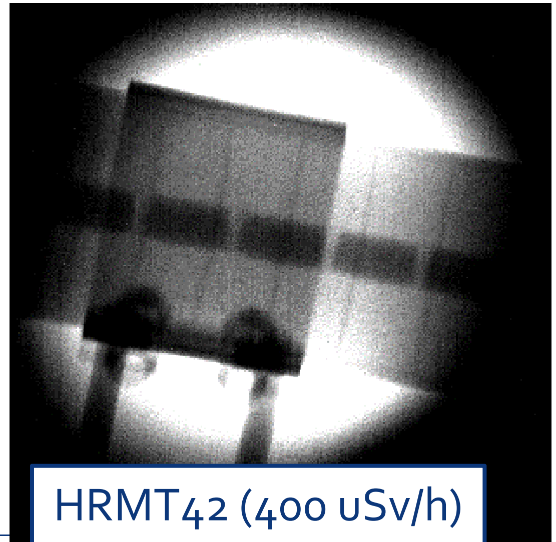
n_TOF x-ray @ESRF







Spent AD-target (10 mSv/h), n_TOF EAR2



HRMT42 (400 uSv/h) n_TOF EAR2