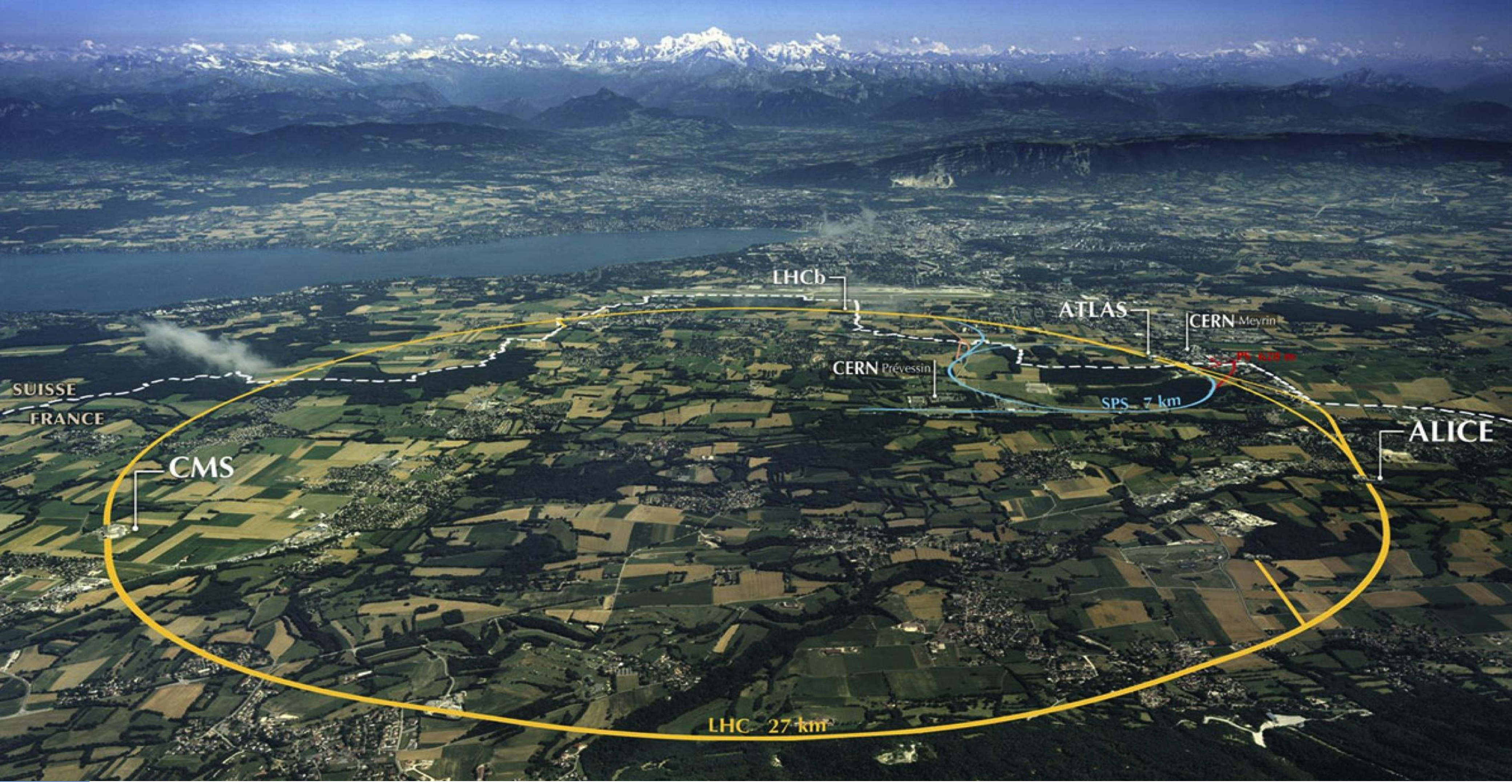
The HRMT-36 Experiment (MultiMat)

Michele Pasquali, CERN (EN/MME)

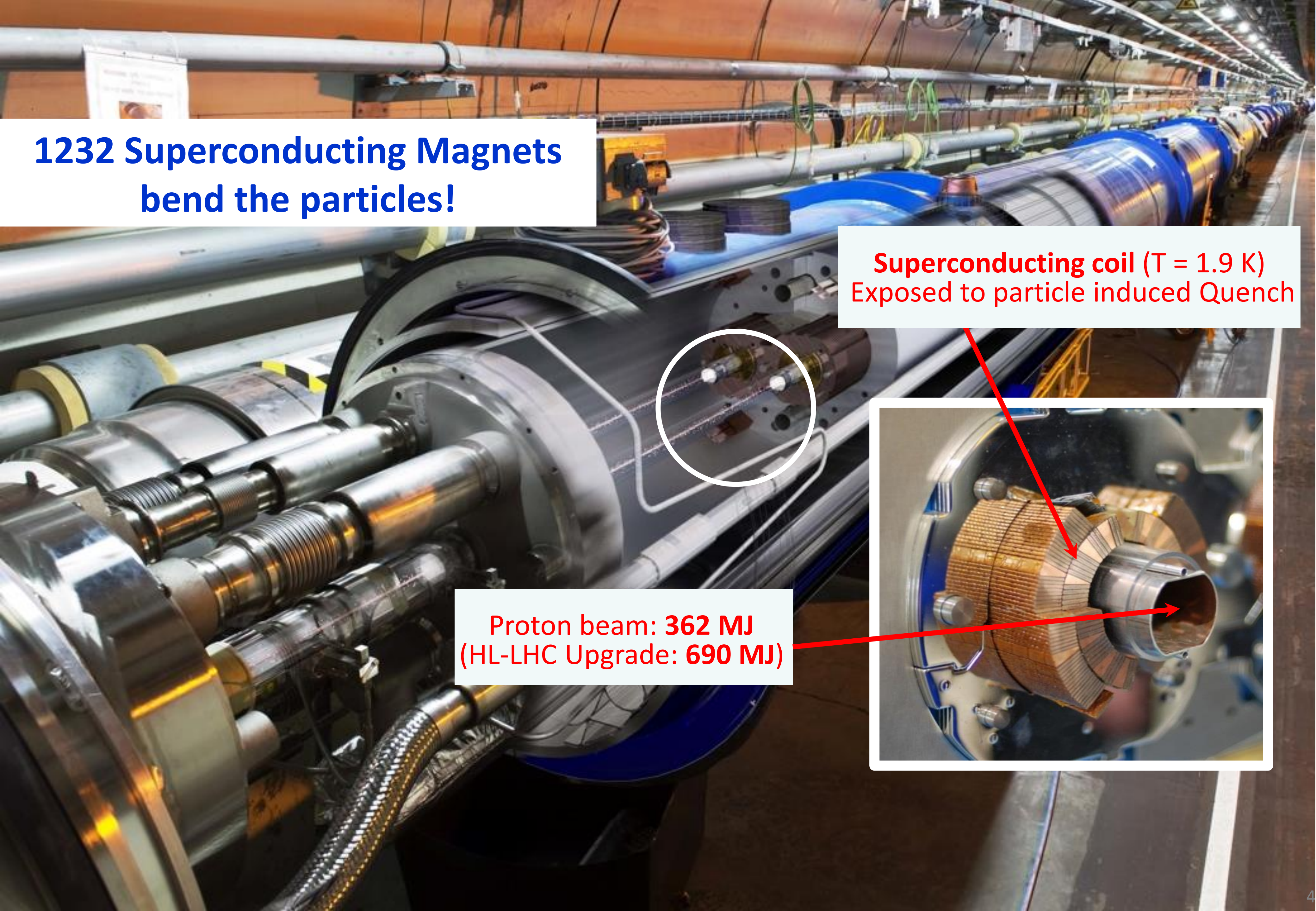
with contributions from A. Bertarelli, A. Dallocchio, E. Berthome, F. Carra, T. Furness, G. Gobbi, J. Guardia, M. Guinchard.

1st Workshop of ARIES WP17 PowerMat
Politecnico di Torino, Turin – November 27-28, *2017*

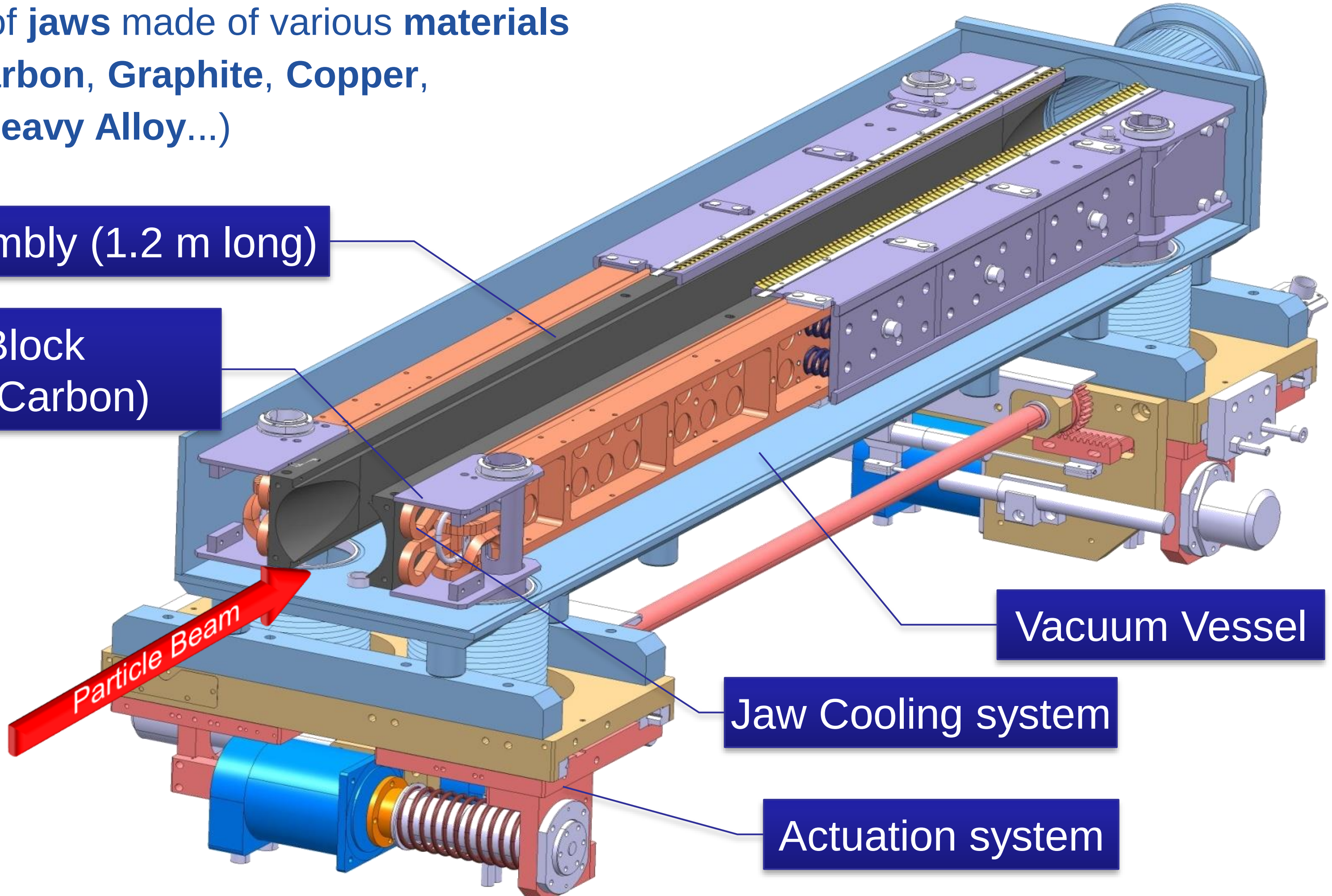
- Introduction and Motivations
- Context of the Experiment
- Goals of the HRMT-36 Experiment
- Overview of the Experiment Design
- Controls and Actuation
- Data Acquisition and Instrumentation
- Test Run Description
- Materials Tested
- Theoretical Analysis and Expected Signals
- Post-irradiation



- CERN flagship. **World's largest scientific experiment**
- **27 km** underground tunnel
- **2** counter-rotating **7 TeV proton beams** (**bunched**) in **Ultra-High Vacuum** at **1.9 K**
- **8 Sections** (Arcs and Straight Sections)
- **1 Radio Frequency System** (Acceleration)
- **1 Beam Dump Point**
- **2 Collimation Regions** (Beam Cleaning and Machine Protection)


1232 Superconducting Magnets
bend the particles!
Superconducting coil (T = 1.9 K)
Exposed to particle induced Quench
Proton beam: 362 MJ
(HL-LHC Upgrade: 690 MJ)

- **Several types of collimators** for **multi-stage cleaning** (primary, secondary, tertiary units) at multiple LHC locations (**100+ Collimators**).
- Active part of **jaws** made of various **materials** (**Carbon-Carbon**, **Graphite**, **Copper**, **Tungsten Heavy Alloy**...)



LHC Secondary Collimator (TCSG) Cutaway

LHC Collimator Requirements

- Collimators are required to **survive** the **beam-induced accidents** to which they are inherently exposed given their vicinity to the beam
- They must possess extremely **accurate jaw flatness** to maintain their **beam cleaning efficiency**
- The collimation system is, by far, the highest contributor to **accelerator impedance** which may significantly limit machine performances: they must have **lowest possible electrical resistivity**
- Their lifetime and efficiency should be conserved under **long-term particle irradiation**
- **No existing material** can simultaneously **meet all requirements** for LHC Future Upgrades!

Bunched charged particles passing near a non-perfect conductor generate EM wake-fields, which perturb following bunches (as ship wakes in the sea …)

→ Development of **Novel advanced materials,** along with **state-of-the-art simulations** to face these challenges.

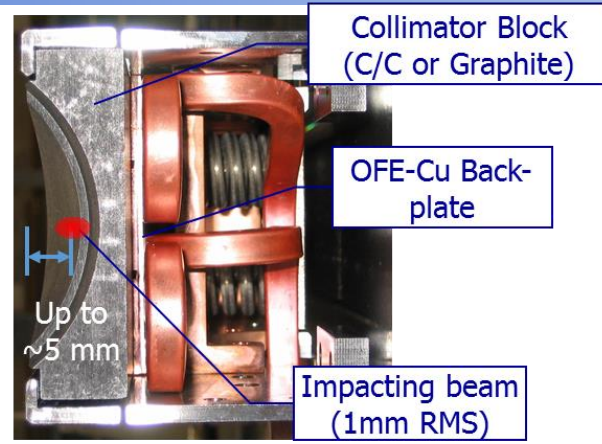
Context of the Experiment

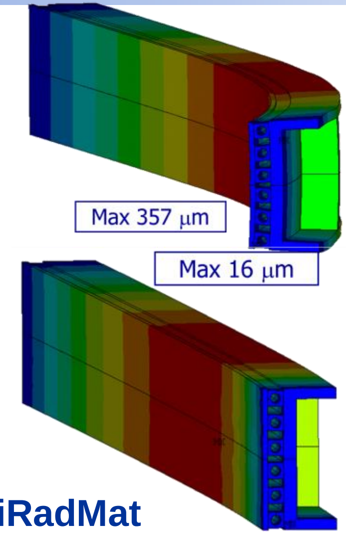
2004: **full TCSG** collimator in TT40 (CFC + Graphite blocks)

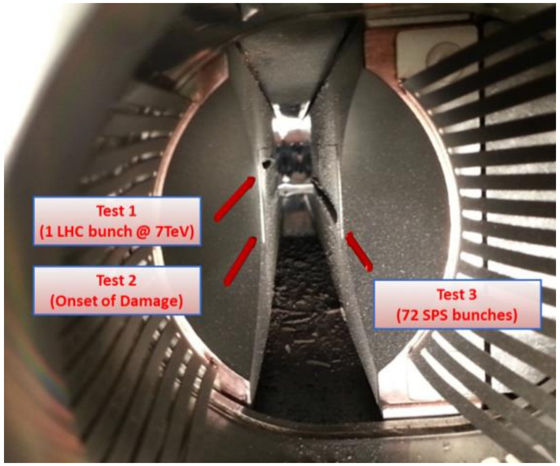
Block material ok, but unacceptable deformation found on Cu jaw support! Cu back-plate was then changed to Glidcop.

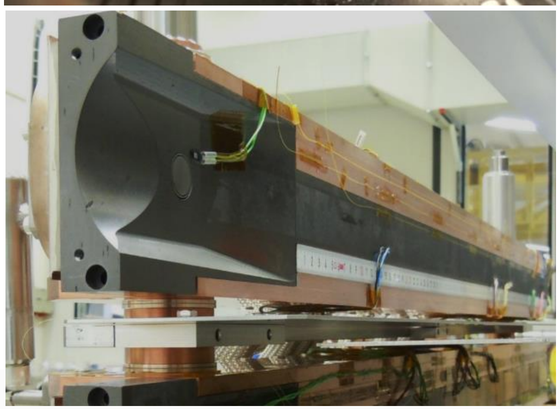
2006: **full TCSG** collimator in TT40 (CFC)

Validated final TCP/TCS design!



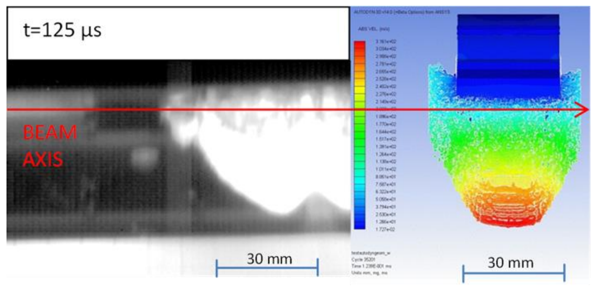






2012 HRMT-09: full TCT collimator (Tungsten alloy) in HiRadMat

Allowed deriving damage limits for Tertiary Collimator jaw



2012 HRMT-14: test of specimens from 6 different materials, including novel composites

Materials characterization, constitutive models and simulation benchmarking

2015 HRMT-23: 3 full jaws (1 TCSG C/C + 2 new TCSPM MoGr and CuCD)

Validated TCSPM with MoGr against HL-LHC density; confirmed C/C robustness with HL-LHC; validated CuCD robustness as TCT alternative; confirmed Glidcop tapering limits in deep accident.

Objectives and Rationale of HRMT-36 Experiment

Goals of the HRMT-36 Experiment

- Request by the **LHC Collimation** project mainly to **assess/validate materials** for the HiLumi upgrade.
- Offer a single, flexible platform to test **specimens** of a large p**alette of materials (**including **coatings, anisotropic materials, foams etc.)** used in **Collimators** (and other **Beam Intercepting Devices**) under high brightness beams (as close as possible to HL-LHC and LIU/BCMS).
- Dedicate target stations to **assess behaviour of components** (sensors, electronic devices, beam diagnostics, etc.) in close vicinity of high intensity beams.
- Acquire **online material dynamic responses** and **derive / extend constitutive models** (to be reused in simulating full scale devices) **without** reaching **extensive material degradation** (with the **possible exception of coatings**)
- **Benchmark** complex numerical **simulations** with little known constitutive equations
- **Design the experiment to be cost effective and reusable**
- Reuse **existing equipment and instrumentation** as much as possible
- Allow **rapid** specimens **disassembling** in view of **Post Irradiation Examination** completing material characterization.

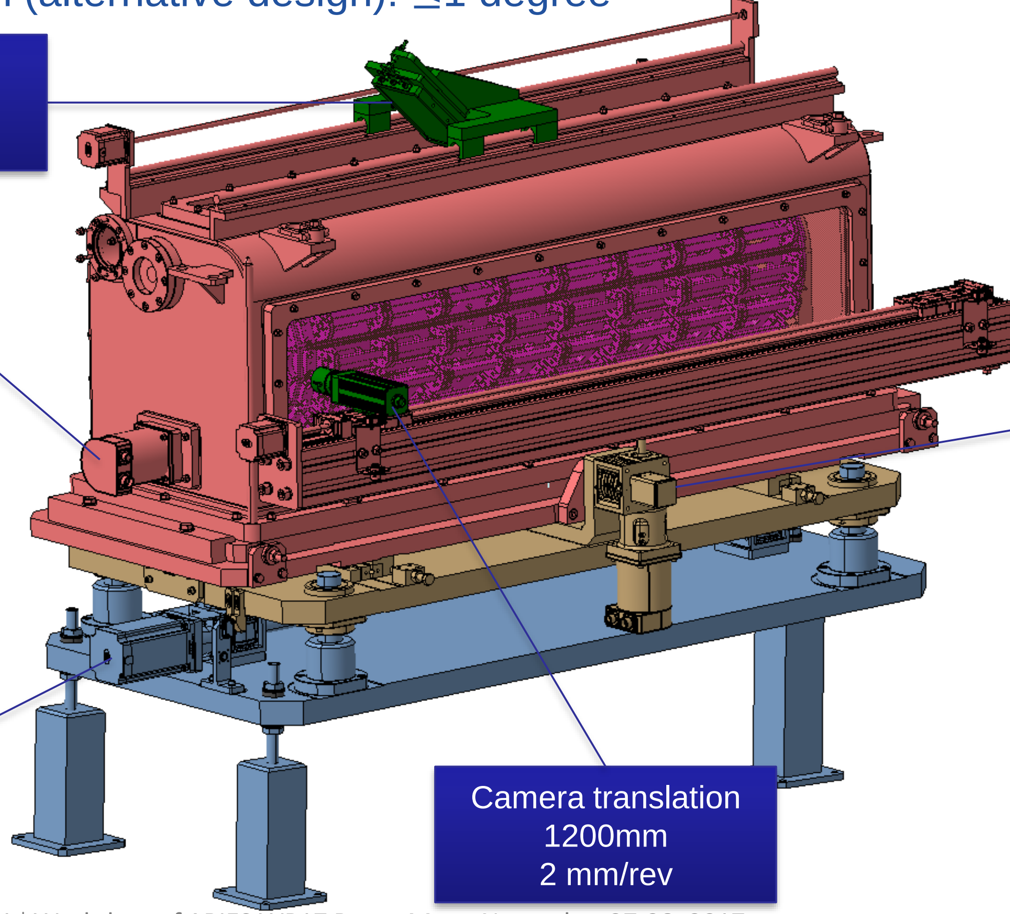
MultiMat Experiment Overview

- **Al** vessel hosting **16 target stations** on a **rotatable barrel**. Each target station equipped with several **specimens** of **18 materials**
- Vessel cooled by forced **Ar inert gas** (rapid cooling ⇒ faster pulse repetition; ΔP ≈ 0 bar ⇒ lighter structure/larger optical windows/lower costs)
- **Comprehensive Acquisition system** based on Strain Gauges, Temperature probes, LDV, Rad-hard Camera

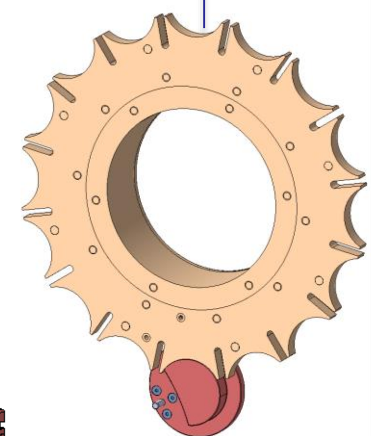
- Dedicated station for **Adaptive Collimation System demonstrator** (**University of Huddersfield**)
- Beam monitoring always-on Glassy C OTR **BTV on Table A** and embarked **BPKG** and **BTV**.
- LDV and non rad-hard controls located in TT61 and TJ7

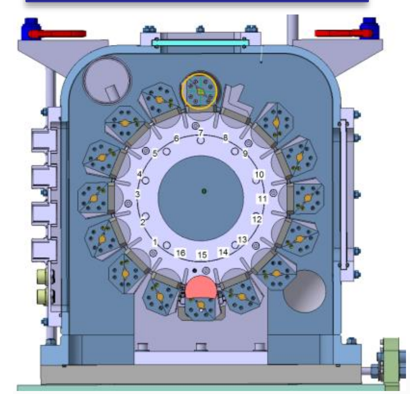
HRMT-36 Actuation Controls

- Control system derived from HRMT-14 and HRMT-23 experiments (**EN/STI**)
- Main requirements:
  - Barrel with 3 D.o.F (rotation, vertical and lateral adjustment)
  - Adjustment Resolution: ~5 µm
  - Rotation precision (alternative design): ≤1 degree



Maltese cross for 16 lines (Geneva mechanism)

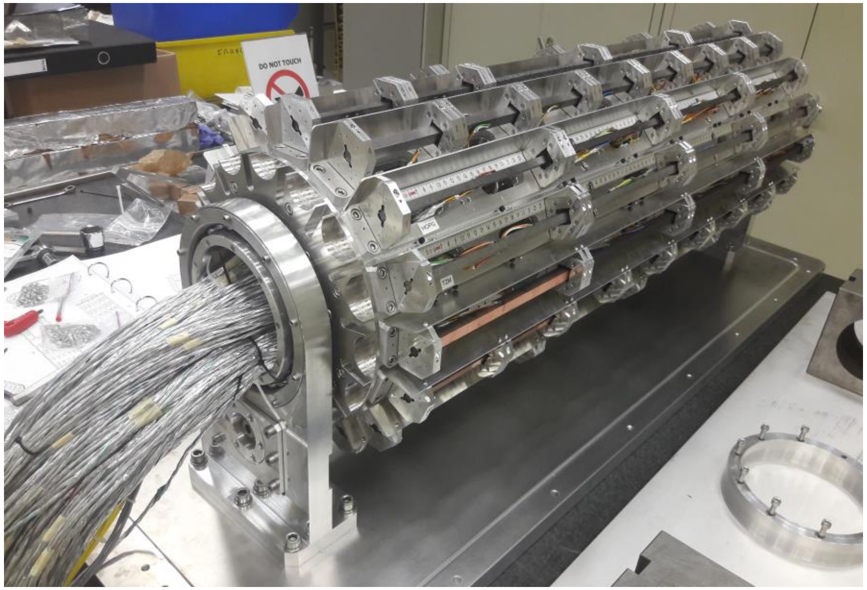


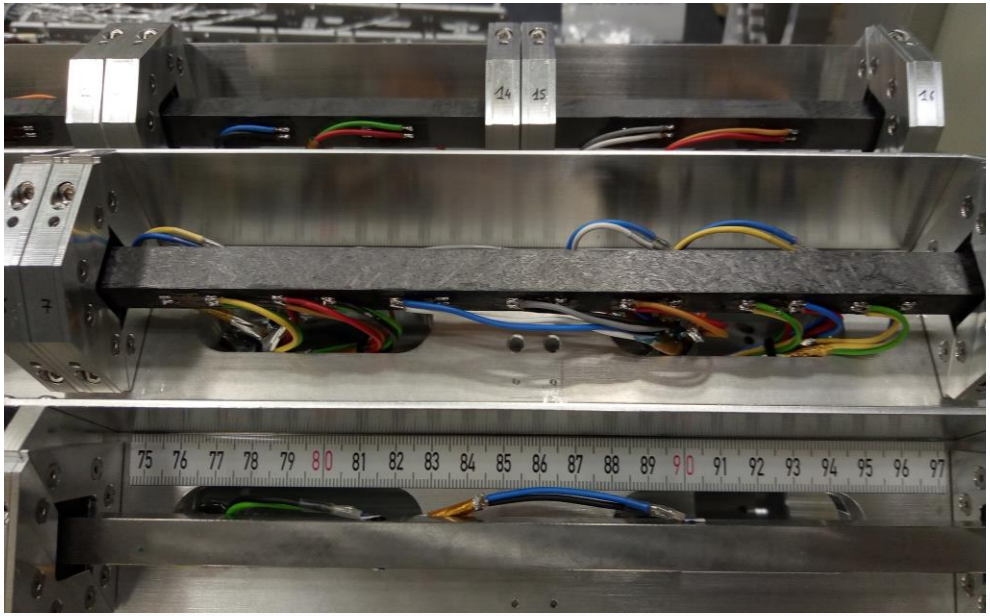


The Acquisition System

The acquisition system featured:

- 335 electrical strain gauges placed depending on the material and on the deposited energy distribution (longitudinal/transverse strain);
- 112 electrical temperature probes (total of 894 wires);
- 1 laser-doppler vibrometer (speed of spec. top faces);
- 1 Rad-hard camera (side-mounted);
- 4 optic fibers integrated on the **Adaptive Collimation System demonstrator** (**University of Huddersfield**)

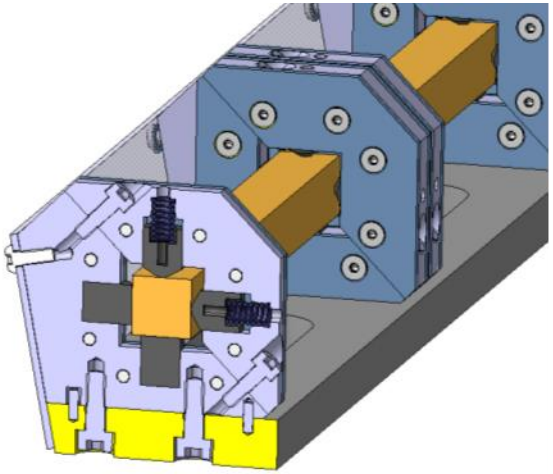




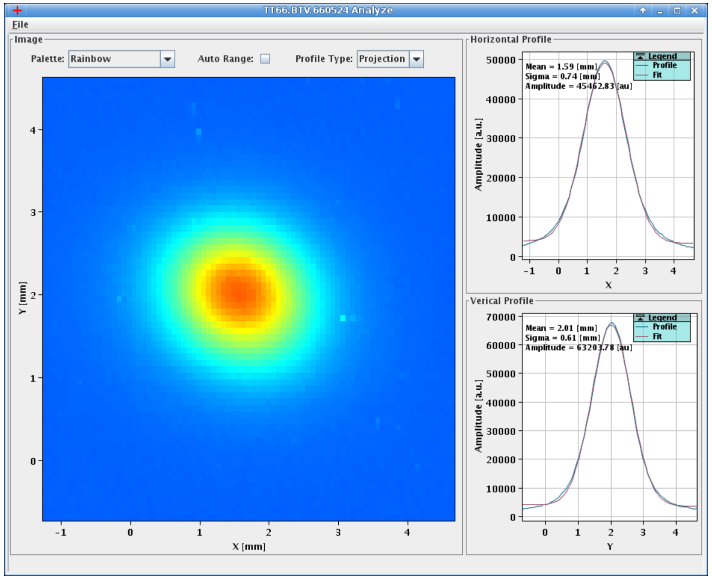
Physical effects	Amplitude threshold	Freq. range	Samp. Freq.	Sensors selected
Longitudinal waves	20 µm/m	≈ 50kHz + pulse	1MHz	Electrical strain gauges
Bending waves	20 µm/m	≈ 2000Hz	1MHz	Electrical strain gauges
Temperature	20°C	≈ 1Hz	100Hz	Pt100
Radial oscillation	0,05 m/s	≈ 2000Hz	1MHz	Laser Doppler Vibrometer
Surface damage	-	-	-	Rad-hard camera or 4K Camera

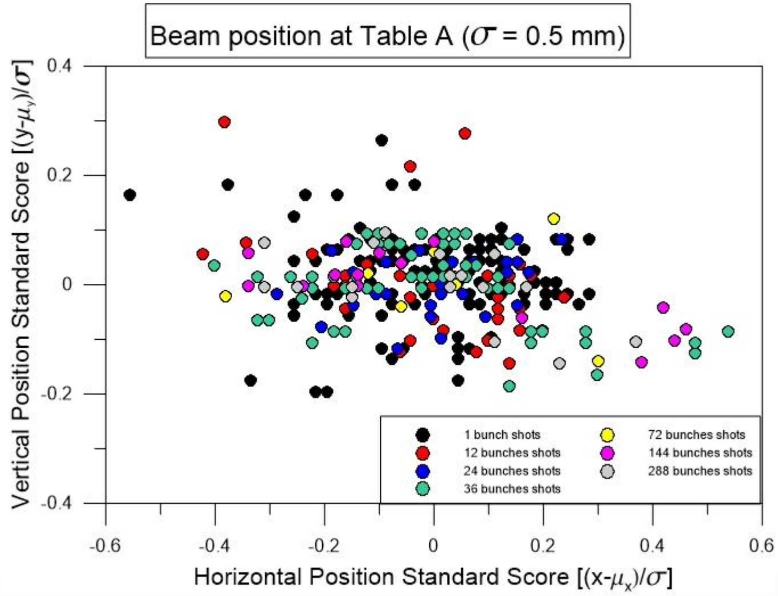
Specimens description

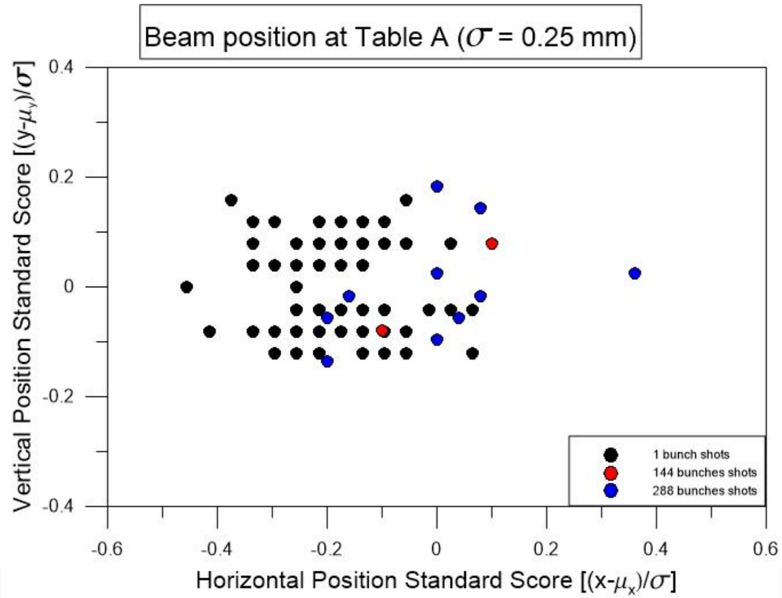
- Specimens of simple geometry (**slender bars,** length **120** or **247 mm**) to generate simple wave signals, relatively easy to acquire and benchmark. **Some low-Z samples coated** (Mo, Cu, TiN)
- **Simply supported** bars, axially **free** to expand.
- Mainly **square cross section** (8×8 to 12×11.5 mm^2) to disentangle anisotropy and simplify PIE



- Installed **2 October at HiRadMat facilities**
- Experimental runs from **3 October** to **17 October**
- 478 pulses (including BBA and parking position)
  2.25x10^{15} POT
- Intensity ranging from **1** to **288 b**, typically **1.3x10^{11} p/b**
- Beam rms size (nom.): **0.25×0.25**, **0.5×0.5**, **2×2 mm^2**
- Good beam stability and repeatability, particularly important for grazing impacts;

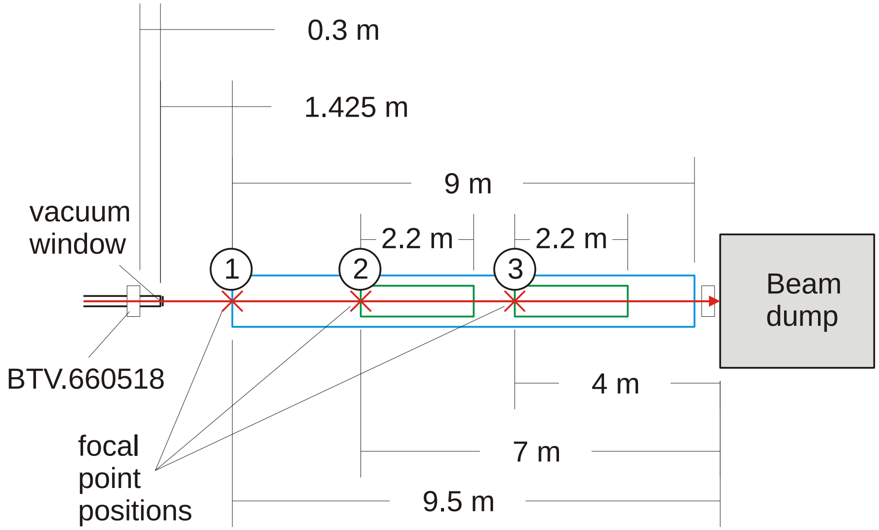


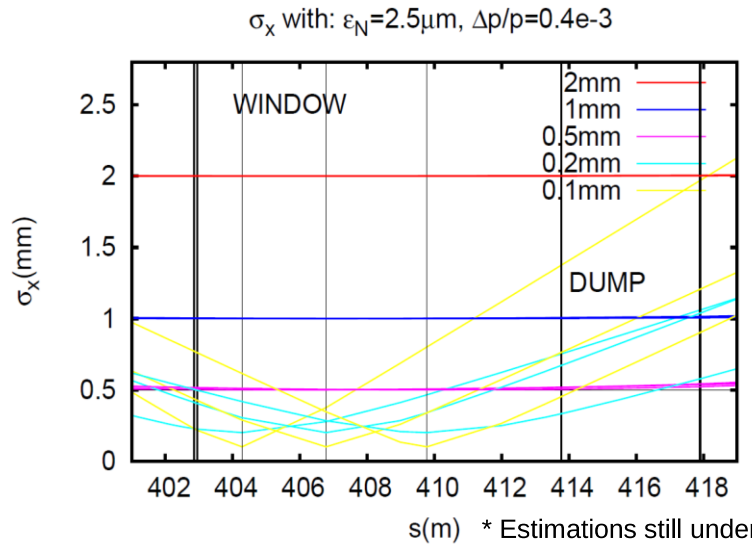




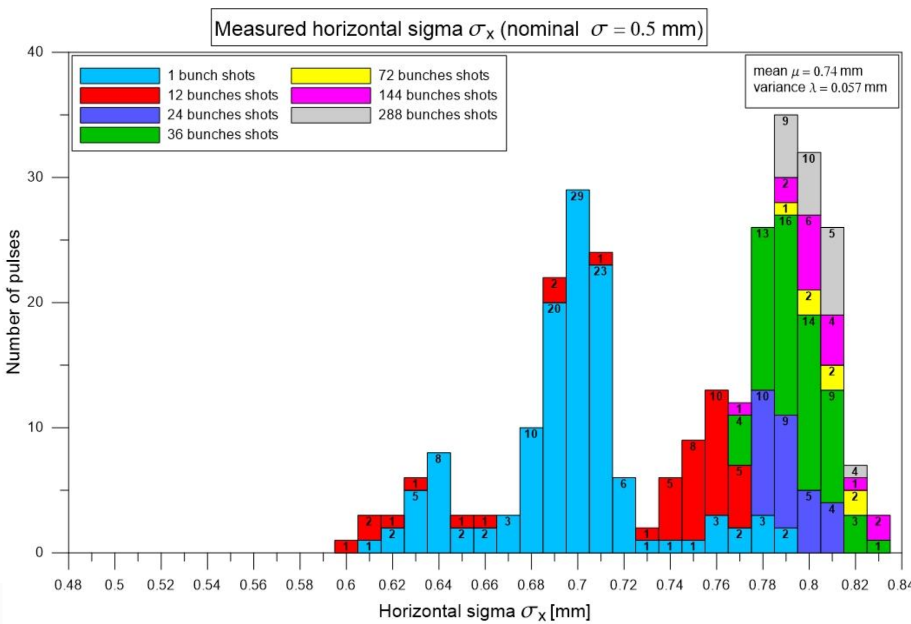
Test Run Description

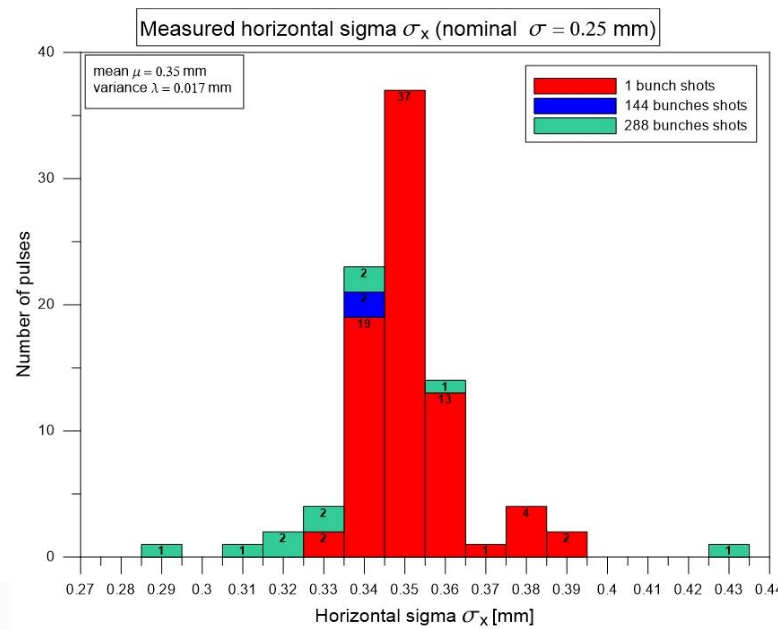
Beam position and sigma (BTV/BPKG)





* Estimations still under evaluation



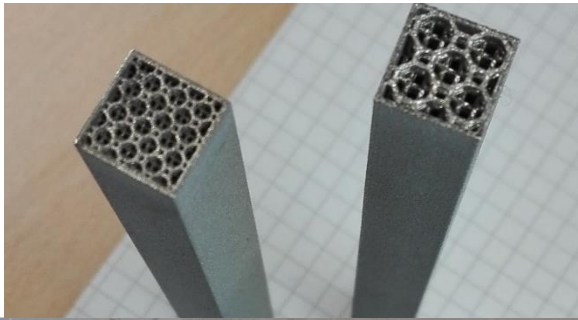


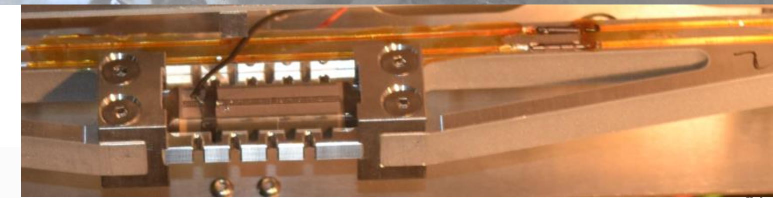
Materials Tested in the HRMT-36 Experiment

Tested Materials

#	Material	Density [g/cm³]	Coated	Coating Material	
1	IT180	18.0	✗		high density
2	Ta10W	16.9	✗		
3	Ta2.5W	16.7	✗		
4	TZM	10.0	✗		
5	CuCD IFAM	5.40	✗		medium density
6	CuCD RHP	5.40	✗		
7	SiC	3.21	✗		
8	MG-6403Fc	2.54	✓	5µm TiN	low density
9	ND-7401-Sr	2.52	✗		
10	MG-6530Aa	2.50	✓	2µm Cu	
11	MG-6541Fc	2.49	✓	8µm Mo	
12	HOPG	2.26	✗		
13	TG-1100	2.19	✗		
14	R4550	1.90	✓	2µm Cu	
15	CFC AC150K	1.88	✓	8µm Mo	
16	Ti6Al4V (AM)	1.62	✗		
17	CFOAM	0.40	✗		
18	Al 6082-T651 (UoHud)	2.70	✗		Dedicated setup

- **18 materials/grades** tested.
- **4 grades** of **MoGr** from 2 manufacturers (BB and Nanoker)
- **3 coatings**, **Cu**, **Mo** (CERN) and **TiN** (DTI)
- Different combination of surface and thermal treatments (48h firing, CO2 blasting, US cleaning);
- **2 grades** of **CuCD** from 2 suppliers (RHP and IFAM)
- Novel **carbon-based materials** as **HOPG** (Highly-Ordered Pyrolitic Graphite) and **Titanium-Graphite (TG-1100)**
- Additively Manufactured Titanium samples (**Ti6Al4V**);
- Actively controlled (via piezoelectric transducers) **Al** samples (UoH)





Materials Requirements for BIDs

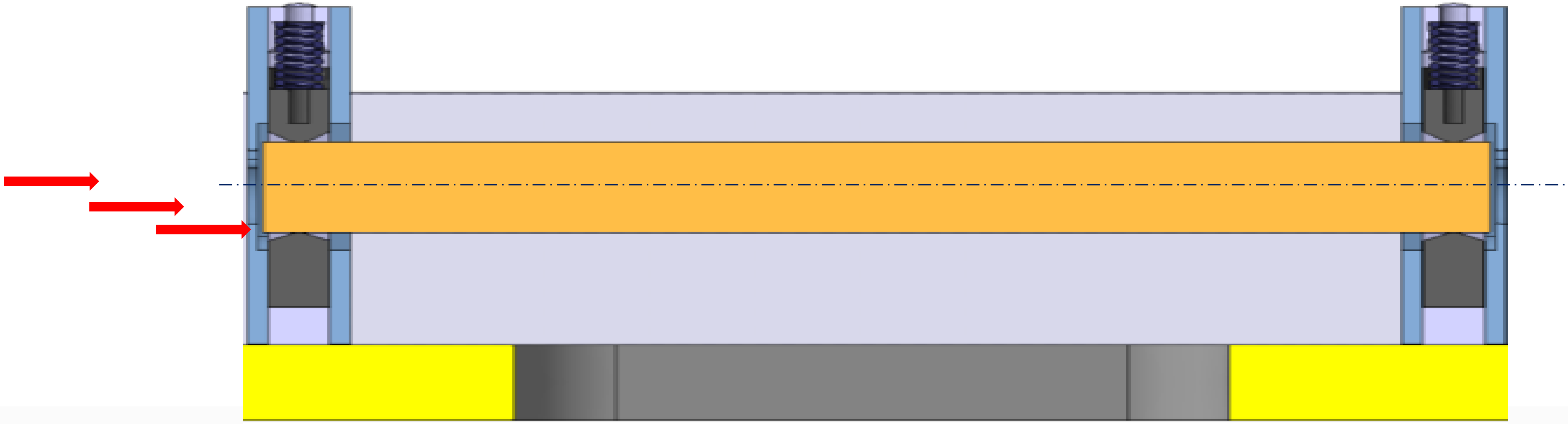
Key properties must be optimized to meet requirements for Beam Intercepting Devices in High Energy Particle Accelerators …

- **Electrical Conductivity.** Maximize to limit Resistive-wall impedance
- **Thermal Conductivity.** Maximize to maintain geometrical stability under steady-state losses
- **Coefficient of Thermal Expansion.** Minimize to increase resistance to thermal shock induced by accidental beam impact
- **Melting/Degradation Temperature.** Maximize to withstand high temperatures reached in case of accidents
- **Specific Heat.** Maximize to improve thermal shock resistance (lowers temperature increase)
- **Ultimate Strength.** Maximize to improve thermal shock resistance
- **Density.** Balance to limit peak energy deposition while maintaining adequate cleaning efficiency
- **Radiation-induced Degradation.** Minimize to improve component lifetime under long term particle irradiation
- **Outgassing Rate**. Minimize to ensure compatibility with UHV environment.

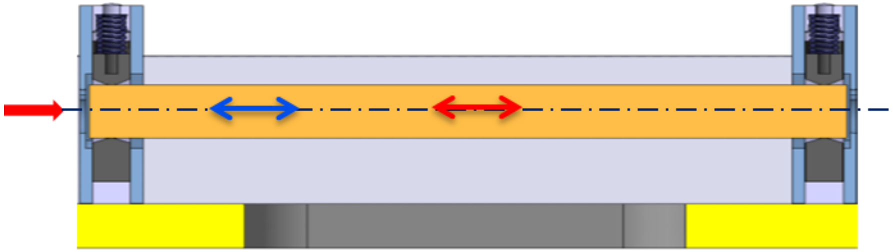
→ **Most requirements shared with applications requiring highly efficient Thermal Management and Thermal Shock Resistance! Possibility of spin-offs**

Expected Signals and Material Modelling

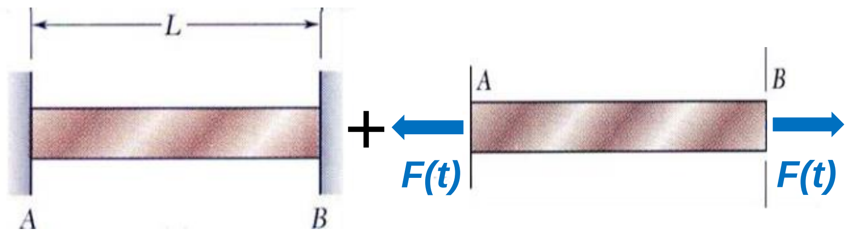
- Specimen geometry chosen to generate easily detectable, separable, mostly uniaxial signals which can be associated to quasi-independent phenomena with different timescales:
  - **Pulse duration** (τ) **<** 1 ÷ 10 µs. Associated to signal rise time. Highest strain rate effects. $\dot{\varepsilon} \cong 10^1 \div 10^4 s^{-1}$
  - **Longitudinal Period** (T_L) ~100 µs. Frequency of longitudinal waves (adiabatic). Dynamic elastic constants and damping ratio. Axial strength.
  - **Flexural Period** (T_F) ~1 ms. Frequency of lateral oscillations. Plasticity. Flexural strength. Permanent deformations.
  - **Thermal diffusion time** (t_d) 0.1 ÷ 1 s. Temperature measurement. Drift in lateral oscillations.
- Beam impacts targets with **variable offsets**.
  - **Zero offset**. Excites longitudinal vibration. High frequency (5÷50 kHz).
  - **Intermediate offset**. Additionally excites lateral oscillations. Lower frequencies (100÷2000 Hz).
  - **Grazing impact**. Probe coating strength. Surface damage.

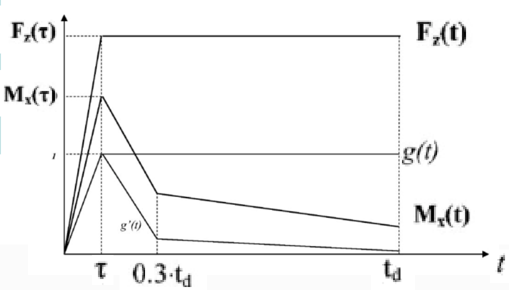


No Offset Impact



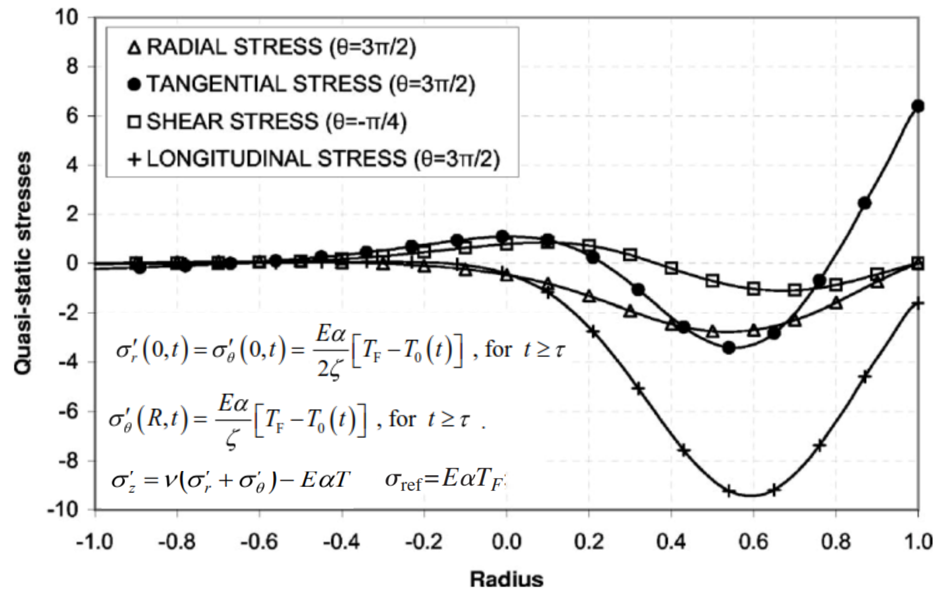
- Excites longitudinal vibration.
- High frequency (5÷50 kHz).
- Shock. Strain rate effects. Internal damping.
- Main Hypotheses:
  - Linear elastic model - No cost. dep. on T
  - Weak thermo-mechanical coupling
  - Negligible radial inertia effects

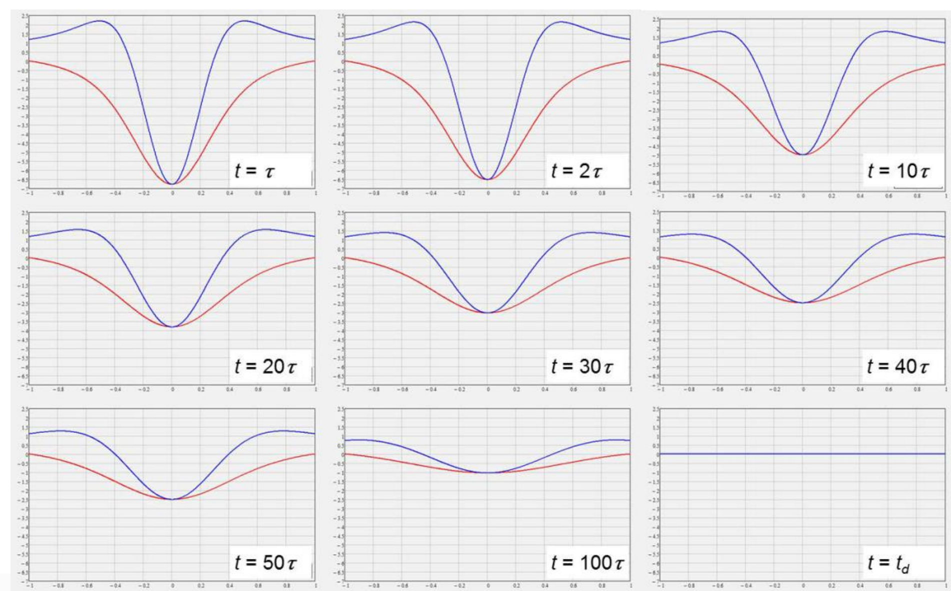




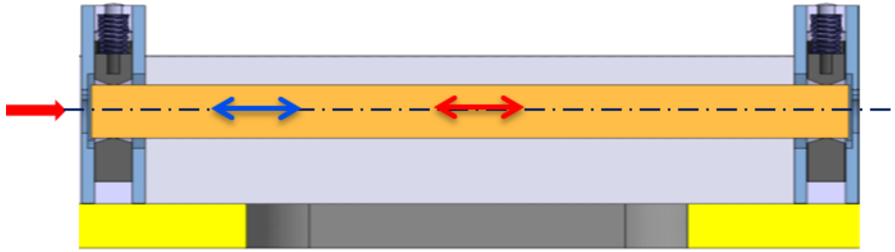
Deposition time
$\tau \sim 10^{-8} \div 10^{-6}$ s

Diffusion time (section)
$t_d \sim 1$ s

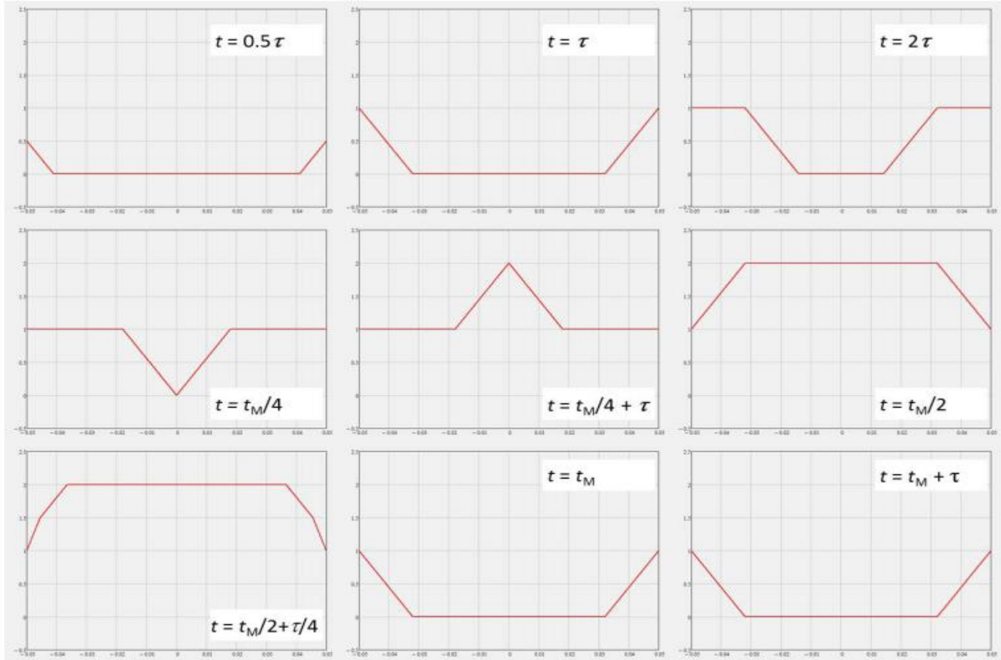


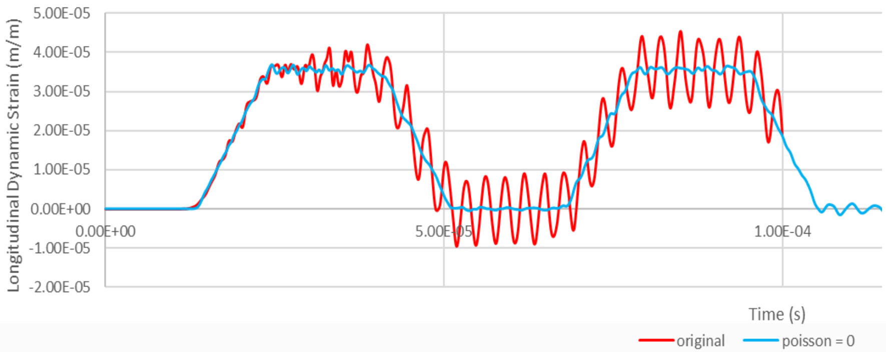


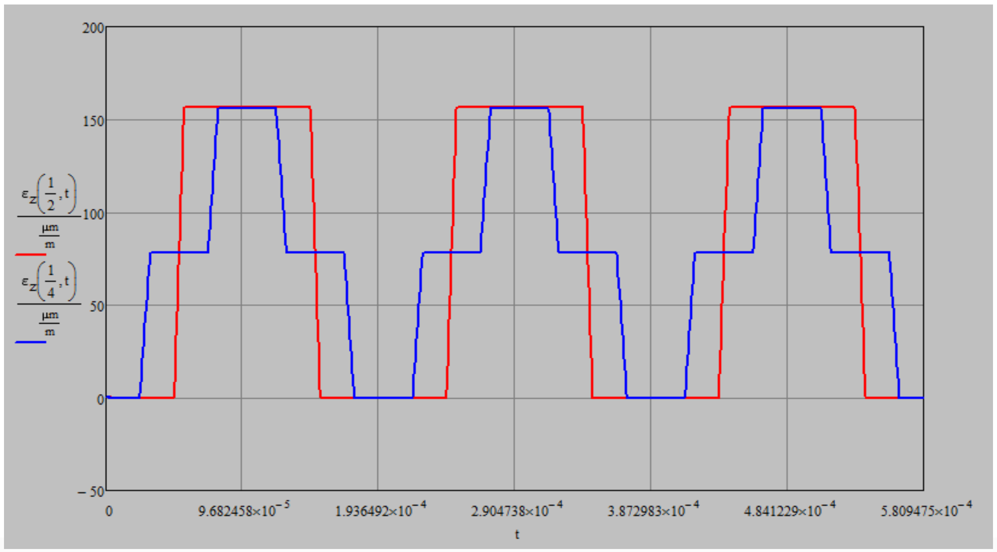
No Offset Impact



- Excites longitudinal vibration.
- High frequency (5÷50 kHz).
- Shock. Strain rate effects. Internal damping.
- Weaker signals for low-Z materials → Small cross-section
- Larger beam size (2 mm) to prevent excessive radial and azimuthal stresses in high-Z materials
- Radial waves (ignored in analytical approximation) depending on Poisson's ratio and target geometry

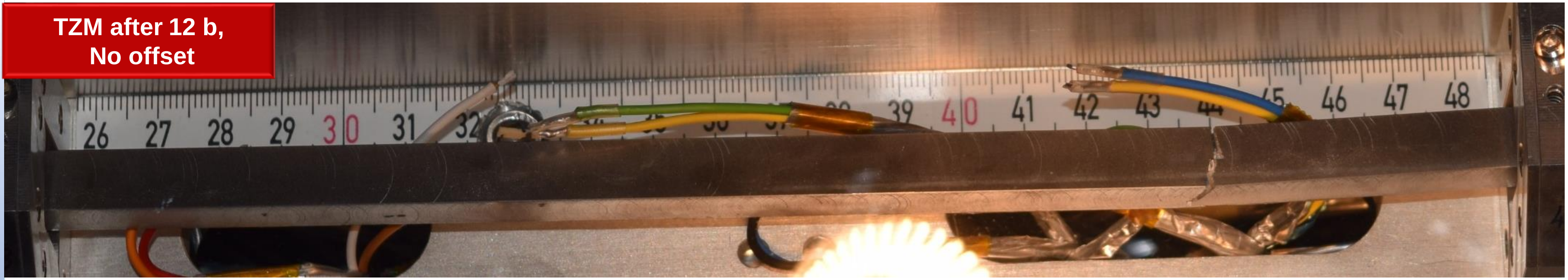




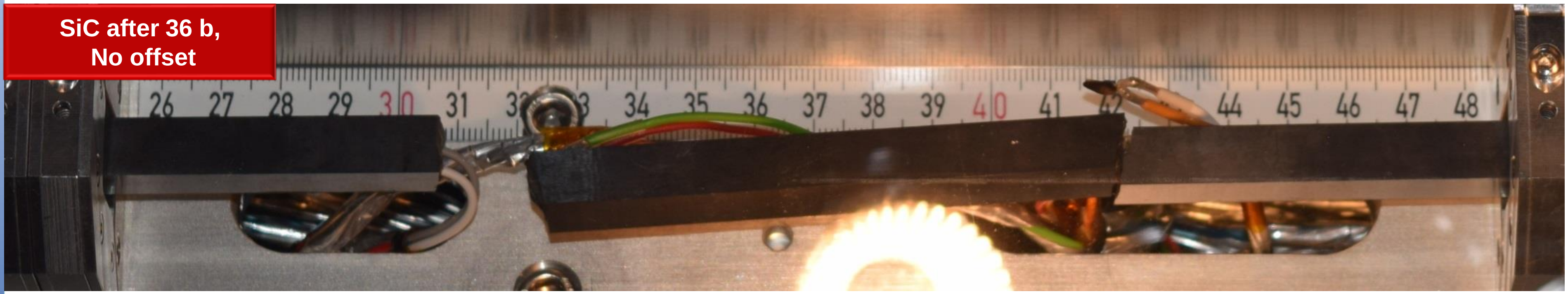


No Offset Impact: TZM and SiC

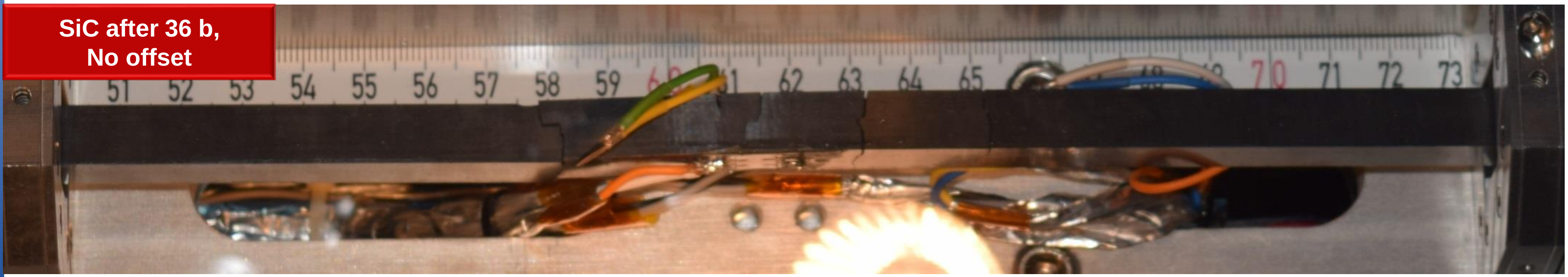
TZM after 12 b,
No offset



SiC after 36 b,
No offset

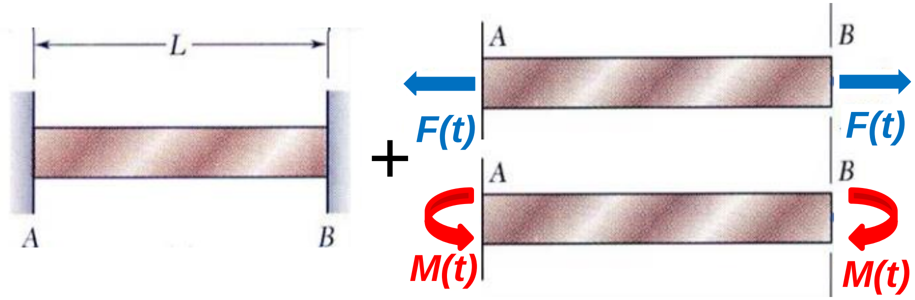


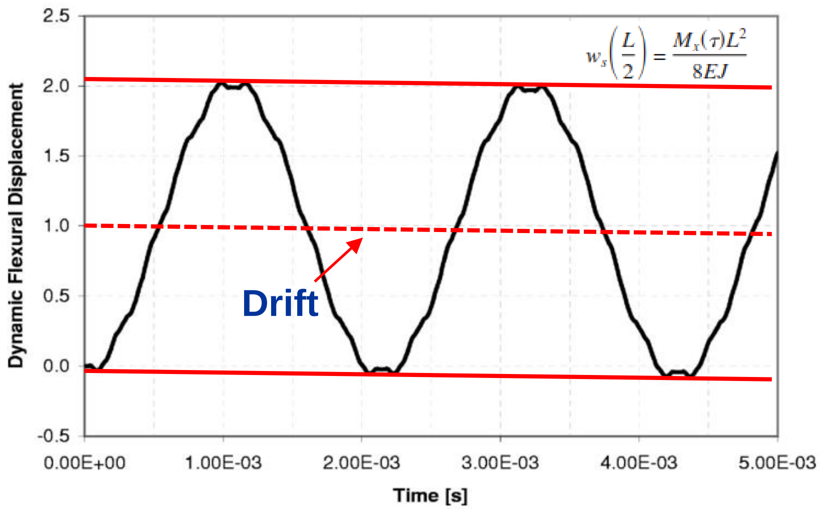
SiC after 36 b,
No offset

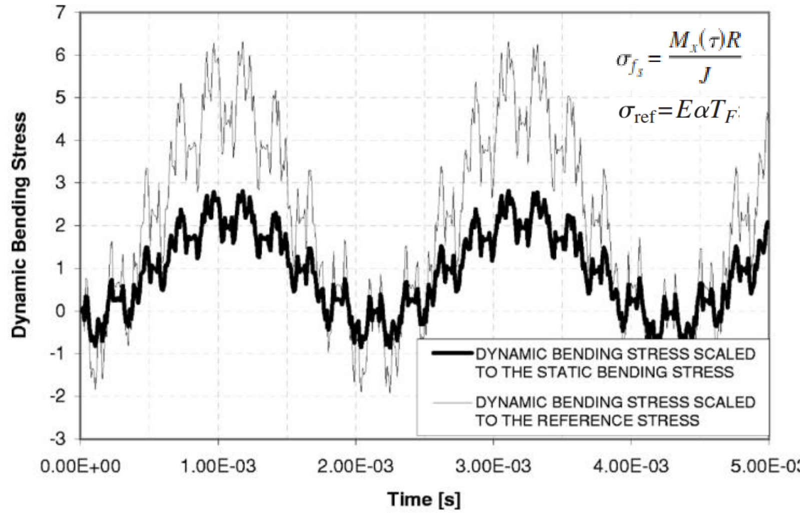


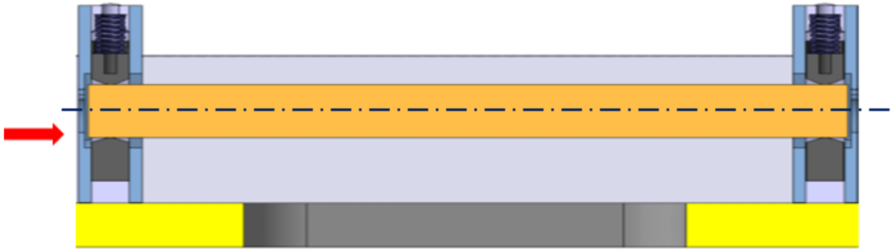
Offset Impact

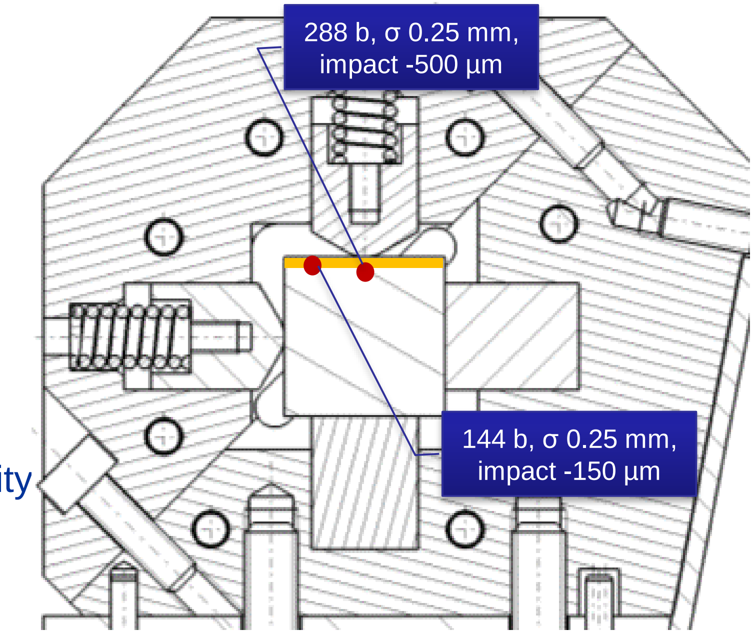
- **Intermediate offset**.
- Lower frequencies (100÷2000 Hz).
- Material strength. Delamination. Internal damping.
- Larger signal intensity



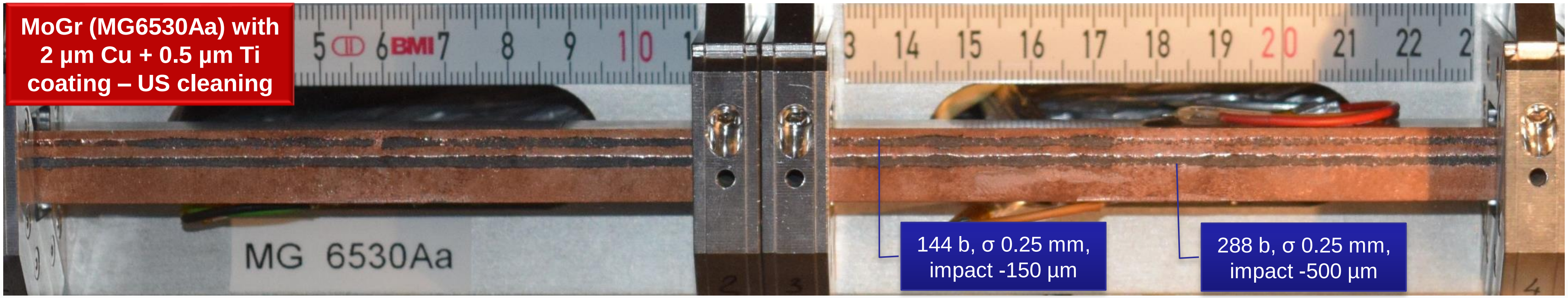




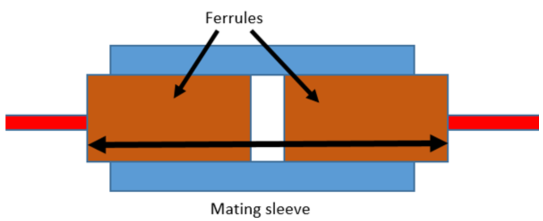


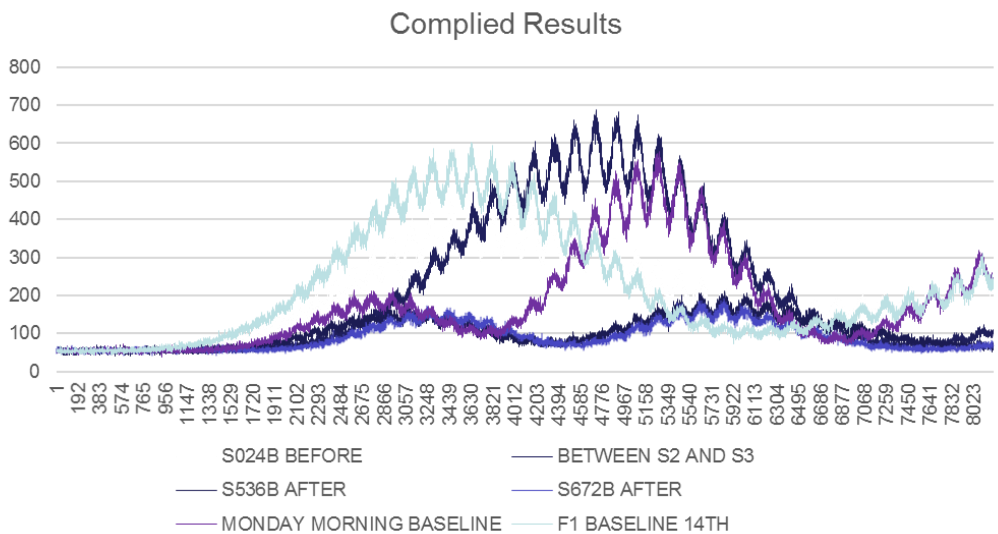


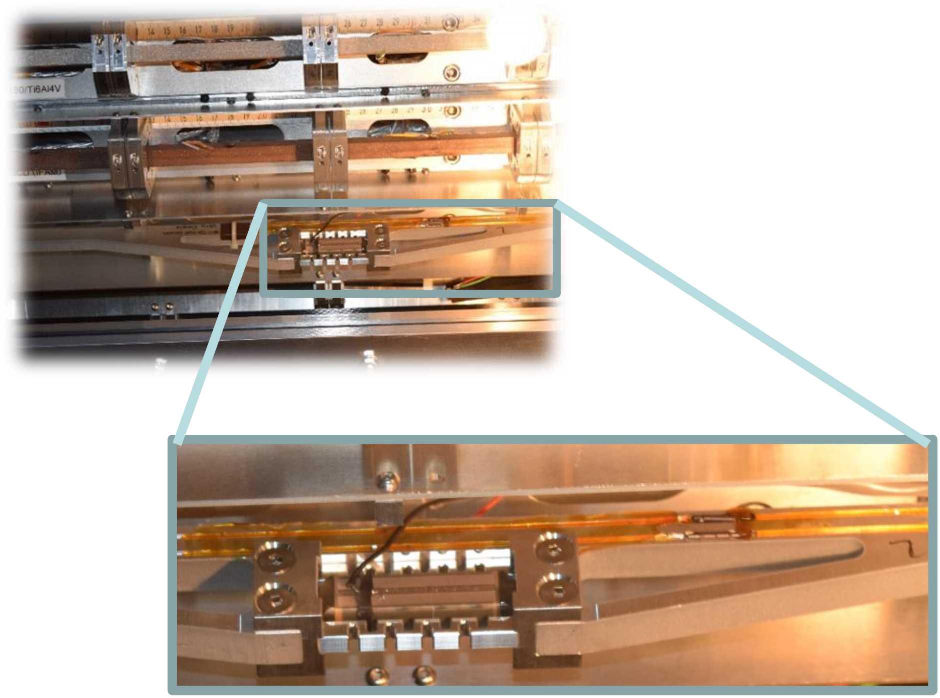
- **Grazing impact**. Probe coating strength (Cu, Mo, TiN) and surface damage.
- Coating on 0 – 250 mm (first specimens)
- Smallest available beam size (**0.25×0.25 mm^2**) at max bunch intensity (**1.4e11 p/b**) to mimic or exceed HL-LHC energy density
- Impacts at **144** (on Cu) and **288 b** (all) at different spots
- 2 impact parameters: -**150 µm** and -**500 µm from the surface**
- Target alignment by BTV combined with Beam-based alignment



- **Multimat Adaptive Collimator System (MACS)**
- Fibres survived with same returned light intensity as started
- Piezo actuators still operational – observed by increased noise in signal response
- Noisy results on flexural response: UoH working on new algorithm to cope with low intensity data.
- Termination cavity issue solved as future fibres will be fusion spliced.







Post Irradiation Examination

- HRTM-36 currently transferred to cooldown area.
- After irradiation, additional analyses are foreseen. These include:
- Remote observation of impacted specimens through cameras.
- Close-by observation through viewports at the sides of experiment.
- After appropriate cool-down time, rapid opening of the tank, dismounting of target stations and removal of single specimens.
- After RP approval Metrology, NDT and analysis of specimens. If appropriate, cutting and destructive testing of specimens

Summary

- MultiMat experiment was successfully concluded in October 2017 totalling ~2.3e15 POT
- Good stability and repeatability of delivered pulses
- All carbon-based materials (Cu Foam, CFC, Isotropic Graphite, HOPG, MoGr, TiGr) survived impacts at maximum available intensities, in all conditions
- Unexpected failure was only achieved in SiC. A TZM sample failed possibly because of fabrication defect.
- Plastic permanent deflections induced in high-Z materials (IT180, Ta10W, TZM).
- Surface damage was induced on coatings: larger in Cu coatings (lower melting point), smaller in Mo and TiN. Damaged stripes ~ 1÷3 mm wide
- Online instrumentation worked very well: a wealth of data available for post-processing. Preliminary analyses indicate good matching with numerical and analytical predictions
- A number of unknown materials properties can be derived: dynamic constants, damping, viscoelastic parameters, dynamic strength.
- MACS still operational after high intensity impact: low signal to noise ratio makes assessment of flexural response difficult. System to be improved in next demonstrator
- Post Irradiation analysis will be performed at CERN with standard equipment (existing experience with HRMT-14), including NDT and (if required) DT.

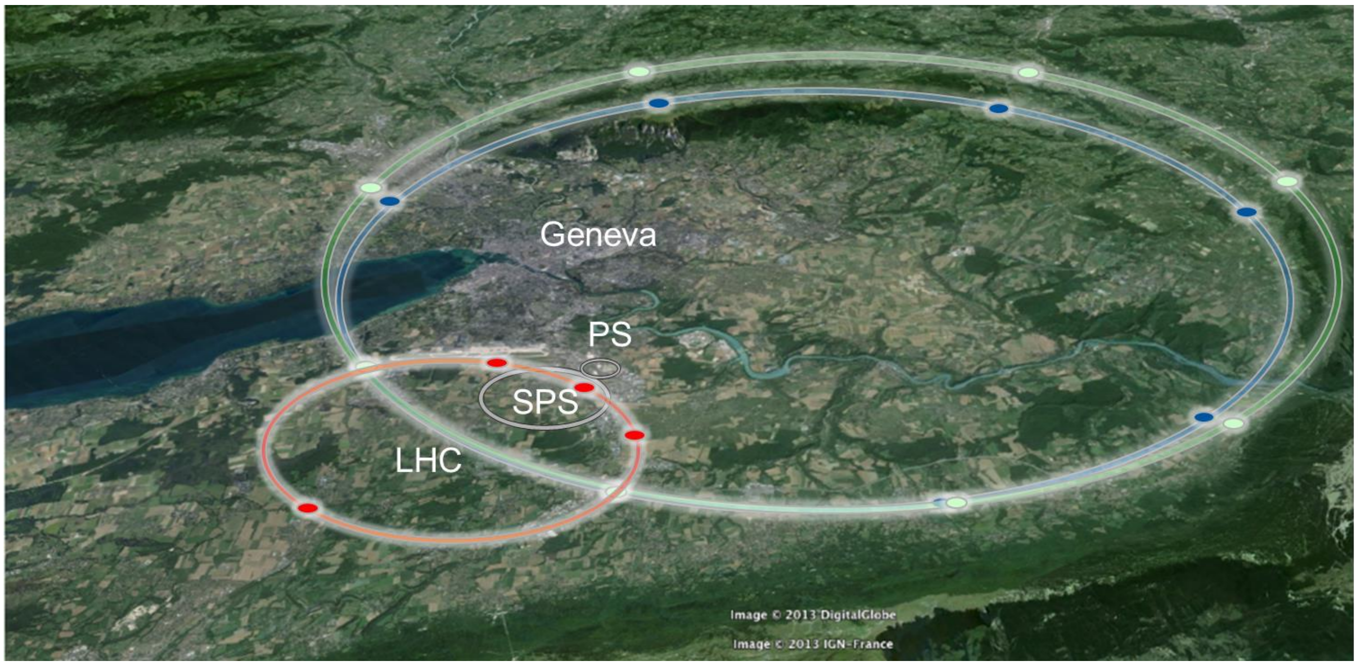
Thank you for your attention!

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project EuCARD-2, Grant Agreement 312453 and HiLumi LHD Design Study, Grant Agreement 284404

michele.pasquali@cern.ch

High Energy Particle Accelerators Challenges

- Particle beams have reached **unprecedented energy** and **energy density.** This trend is set to continue for future accelerators (**690 MJ** for **HL-LHC,** **8500 MJ** for **future 100 km FCC-hh** proposal)
- **Beam-induced accidents**, **beam losses** and **beam stability** are among the **most relevant issues** for high power particle accelerators!
- **Beam Intercepting Devices** (such as **collimators**) are inherently exposed to such events!

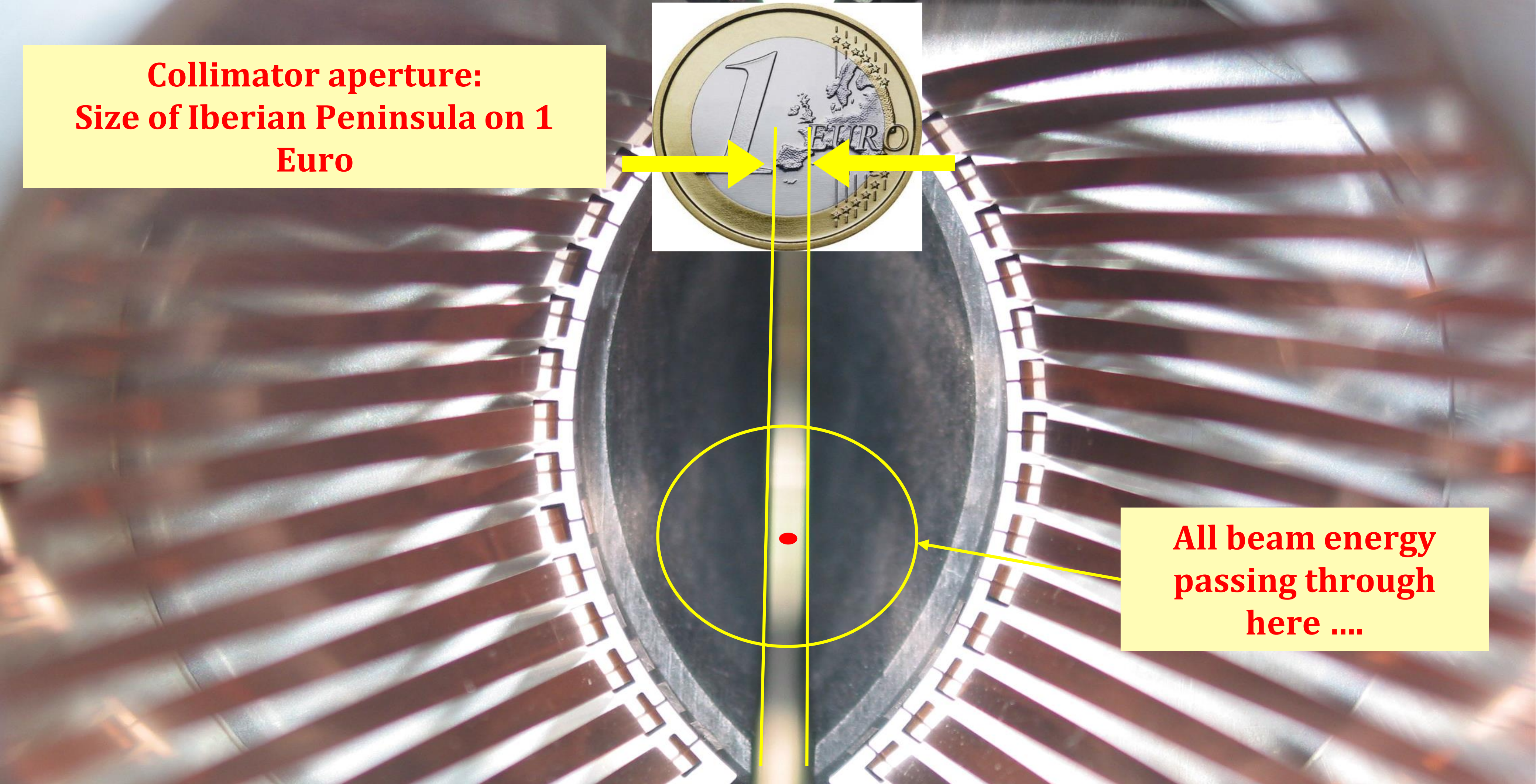


What is HL-LHC Energy equivalent to?

USS Harry S. Truman

TGV

160 kg TNT



The collimation system must satisfy **2 main functions**:

- **Multi-stage Beam Cleaning**, i.e. removing stray particles which would induce quenches in SC magnets.
- **Machine Protection**, i.e. shielding the other machine components from the catastrophic consequences of beam orbit errors.

Tested Materials

Material properties are combined and evaluated through FOMs

Parameter	AC150k	R4550	MoGr (6403Fc)	CuCD	TZM	Ta10W	IT180	Cu	Mo	W
Density [g/cm³]	1.88	1.9	2.5	5.4	10.0	16.9	18.0	8.93	10.22	19.26
Radiation length	22.8	25.8	15.8	4.8	1.0	0.4	0.42	1.44	0.96	0.35
Melting Temp [°C]	3650	3650	2589	1083	2620	3044	1350	1083	2623	3422
Thermal cond. [W/mK]	197	142	508	319	126	65	109	398	142	163
Specific heat [J/kgK]	712	600	624	340	250	139	140	385	251	130
Volumetric CTE [µm/K]	3.9	5.1	5.5	10.6	6.1	7.0	5.5	17.3	5.5	4.3
Electrical cond. [MS/m]		18.7	0.9	12.6			8.4	58.0	18.7	17.7
Young's modulus [GPa]	62	12	61	146	320	205	360	82	330	410
Ultimate strength [MPa]	122	60	58	100	800	500	690	210	560	980

Thermomechanical Robustness Index (TRI)

- TRI is related to the ability of a material to withstand the impact of a rapid particle pulse

$$TRI = \frac{R_M c_p X_g}{\bar{E}(1-\nu)\bar{\alpha} C_R \rho^n}$$

Thermal Stability Index (TSI)

- TSI provides an index of the ability of the material to maintain geometrical stability of the component during steady-state

$$TSI = \frac{\bar{\lambda} X_g}{\bar{\alpha} C_S \rho^n}$$

RFI Impedance Index (RI)

- RF-impedance is inversely proportional to electrical conductivity

Material properties are combined and evaluated through FOMs

Required FOM for LHC Collimators			FOM for Existing Materials						FOM for some Novel Materials			
LHC (nominal)	HL-LHC		AC150k	R4550	IT180	Cu	Mo	W	MoGr (6403Fc)	CuCD	TZM	Ta10W
300÷500	600÷1000	TRI	1372.02	2152.8	0.5	5.8	6.2	1.06	231	8.5	6.79	0.88
~20	~40	TSI	47.34	18.1	0.14	0.96	0.74	0.34	55.9	5.0	0.60	0.10
~0.4	~1	RFI	0.38	0.22	2.9	7.6	4.3	4.2	1	3.5		

No current material fits all the requirement!

- **Carbon-based materials** feature the **best TRI** and **TSI** thanks to low-Z, low CTE, low density, high degradation temperature, high conductivity ….
- However low electrical conductivity penalizes C-C **if RF-impedance is an issue**.
- **CuCD** possesses very good **RFI.** With its **limited robustness but higher density** could be a good candidate for **HL-LHC tertiary collimators**
- **MoGr** presents very similar properties to those of CFC but with much better impedance → **HL-LHC primary and secondary collimators**

Description of the materials tested in HRMT-36

Tested Materials

High density materials:

- **Inermet180:** Tungsten alloy used in LHC collimators. Cu-Ni binder phase melts at around 1350°C.
- **Ta10W/Ta2.5W**: Tantalum alloys with W. Alternative to IT180, very high strain to rupture compared with Inermet (X10).
- **TZM:** Molybdenum alloy with Zr and Ti additions to improve high temperature mechanical behaviour. Very high strength to rupture.

Medium density materials:

- **SiC:** Candidate material for BID, with irradiation studies at Kurchatov institute.
- **CuCD:** Option for HL-LHC tertiary collimators. Good electrical cond (Cu), low CTE (diamond). CuCD already tested in HRMT23.

MoGr - Main option for HL-LHC (primary and secondary) collimators

- **MG-6530Aa:** grade tested in HRMT23. Contains no Ti doping.
- **MG-6403Fc:** grade with Ti doping and sintering+post-sintering cycles modified for improved outgassing behaviour.
- **MG-6541Fc:** grade with Ti dopping, carbon fibres and sintering+post-sintering cycles modified for improved outgassing behaviour.
- **ND-7401-Sr:** grade with good outgassing behaviour.

Graphitic materials:

- **CFC AC150K:** used in LHC collimators. Graphite + 2D carbon fibres composite material.
- **Graphite R4550**: Isotropic nuclear grade, used in dumps and components.
- **HOPG**: Good electrical conductor (2-3 times MoGr), refractory, low density, high thermal conductivity. Poor transverse properties.
- **TG-1100:** Titanium + graphite. Lower density and potential to have better robustness. Needs higher production temperatures.
- **Cfoam/AM Ti:** ultra-low density C/Ti-based materials for extreme-intensity beams (possibly FCC)