EuCARD² WP11 Topical Meeting
University of Malta, Valletta, Malta
28th April 2016

# HiRadMat Tests on HL-LHC Collimators and Collimator Materials

**F. Carra[1,2]**, A. Bertarelli[1], E. Berthome[1], L. Gentini[1], P. Gradassi[1], J. Guardia[1], M. Guinchard[1], L. Mettler[1], S. Redaelli[1], A. Rossi[1], O. Sacristan[1]

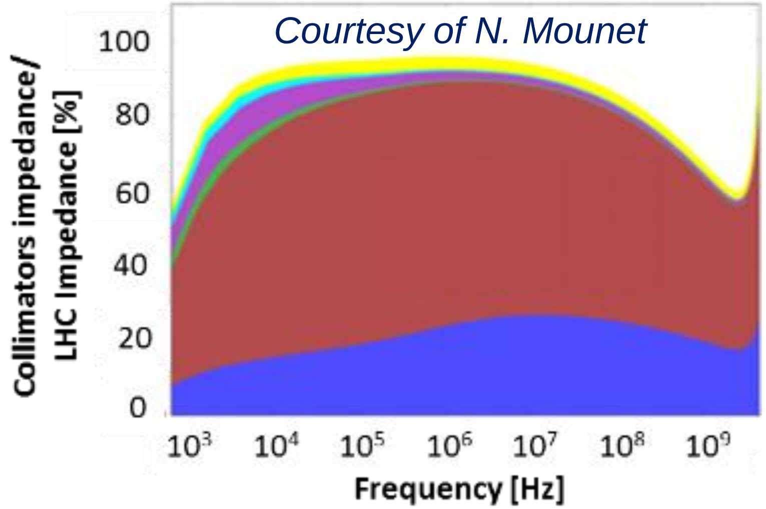
[1]CERN – European Organization for Nuclear Research
[2]Politecnico di Torino

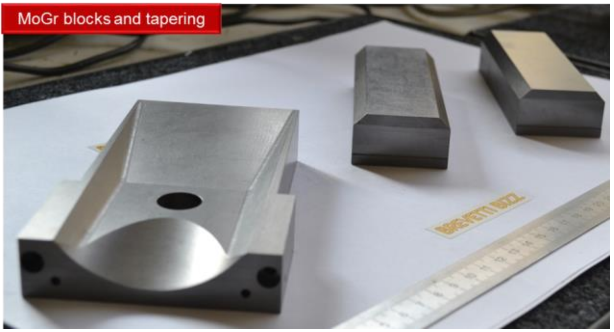
# Outlook

- Context
- HL-LHC Collimator Design
- HRMT-23 “Jaws” Experiment
  - Experiment description
  - First results
  - Preliminary experimental/numerical benchmarking
- HRMT-14 Experiment: post-irradiation analyses
- Summary and next steps

# Context

- LHC collimation system: **robust, reliable, efficient!**
- However: HL-LHC beam stability can be guaranteed only **decreasing the RF impedance** of the system
- **New collimator design** studied in 2014/15, featuring **high-electrical conductivity** jaw materials
- Novel composites developed in the frame of **Eucard², WP11**, with **RHP (Copper-Diamond – CuCD)** and **BrevettiBizz (Molybdenum-Graphite – MoGr)**
- The new collimator should maintain or improve the performances in terms of **robustness, geometrical stability, radiation hardness, UHV compatibility**



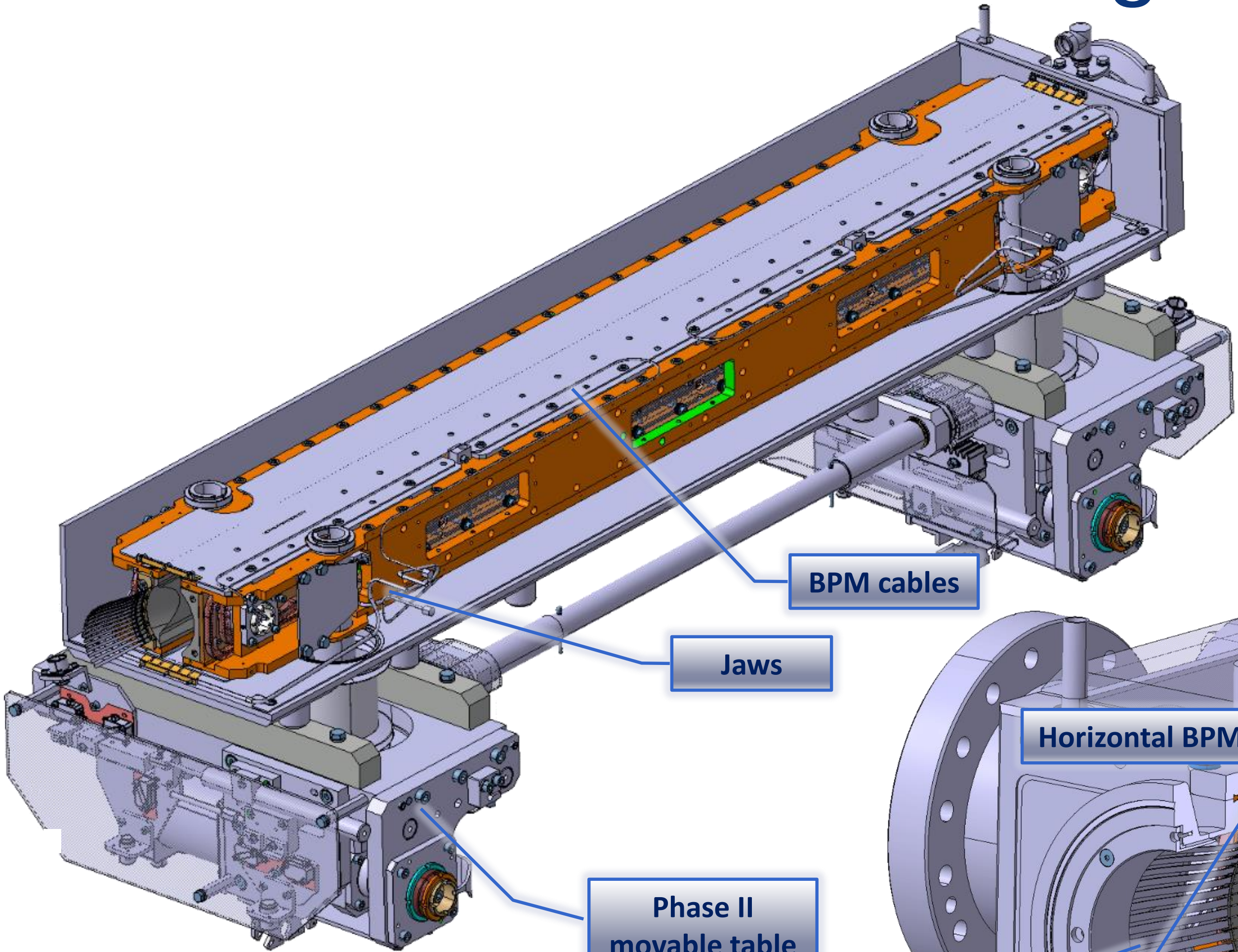



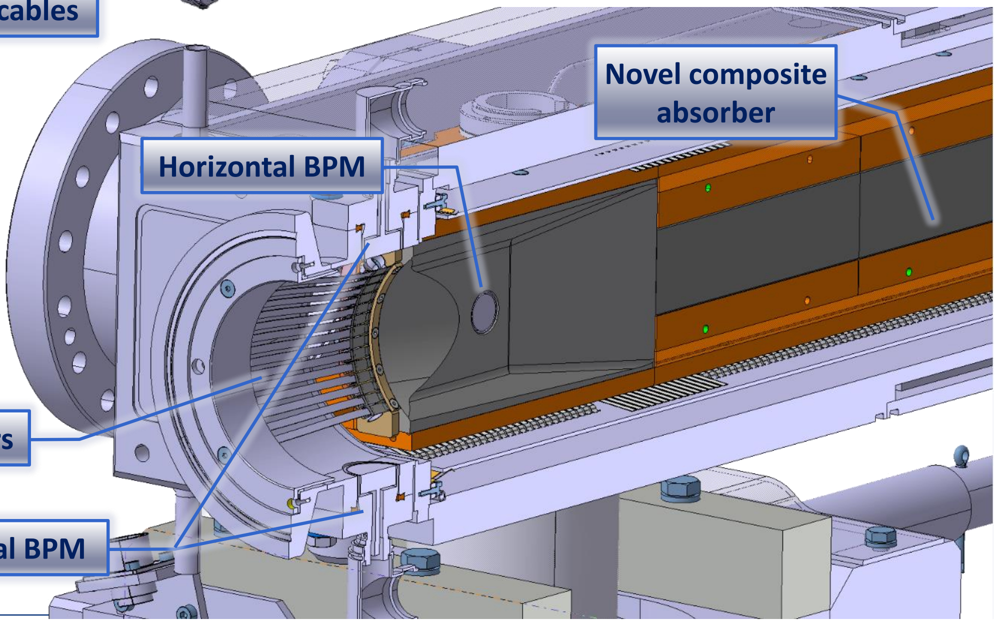

***Molybdenum Carbide – Graphite (MoGr)**, co-developed by CERN and Brevetti Bizz (IT): high thermo-mechanical properties and low electrical resistivity (factor 5 to 10 better than carbon).*


***Copper-Diamond (CuCD)**, produced by RHP-Technology (AT): composite keeping most of Cu thermo-electrical properties, while reducing density and improving structural behavior.*

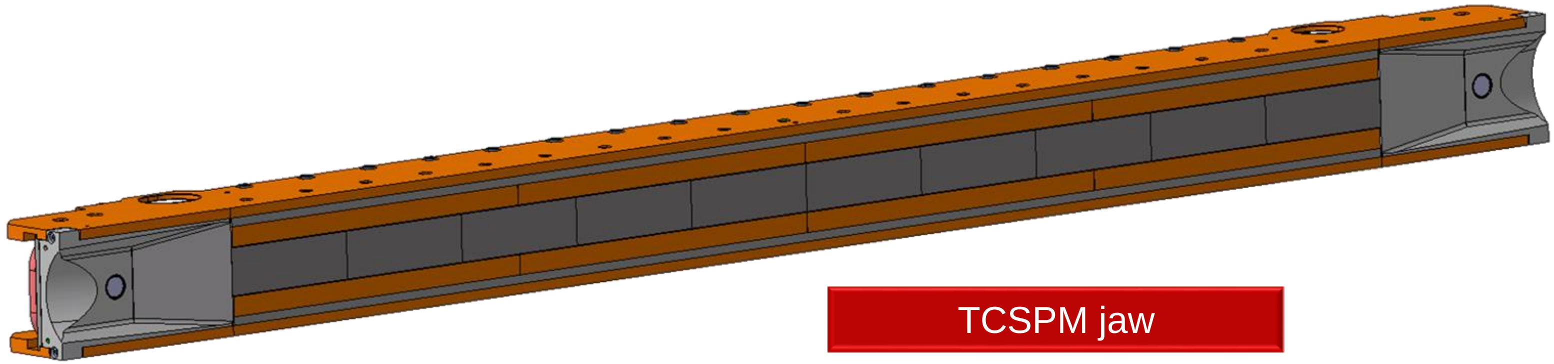
# HL-LHC Collimator Design

- **Longer** jaws, tapering and vacuum tank
- **Shorter** RF fingers, upstream and downstream flange collars
- **Same flange-to-flange length**
- **BPM vertical buttons** upstream, on top of the **horizontal BPMs** for jaw positioning

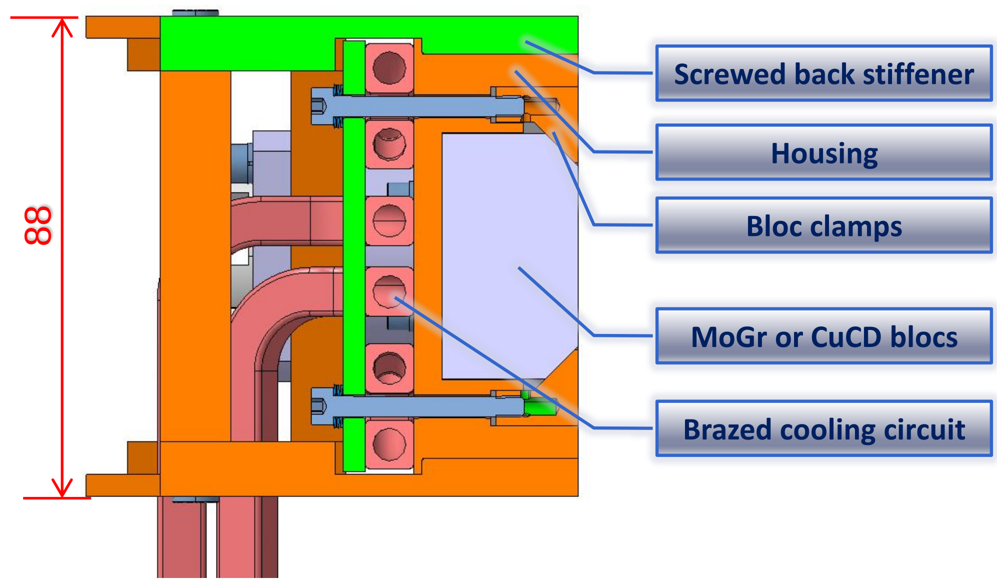


# HL-LHC Collimator Design

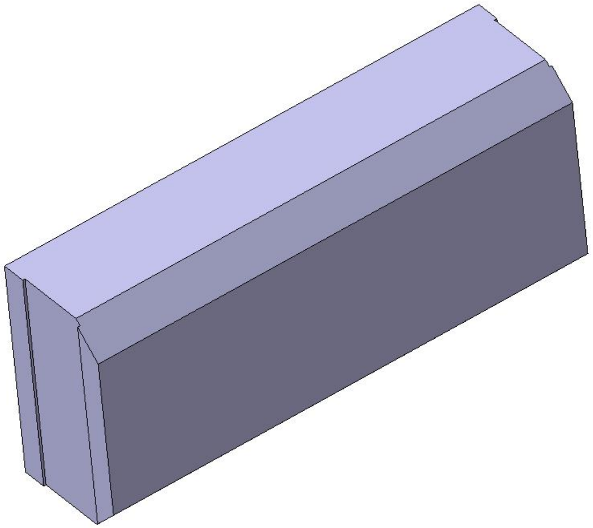


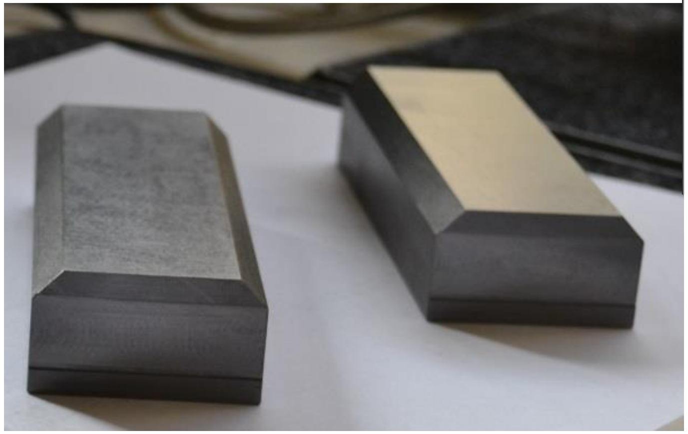

- 1m active jaw made of **8 composite blocs**
- **Clamped solution** to host any block material (avoids stress concentrations and allows sliding between components with different CTE)
- **One-side brazed cooling circuit** (CuNi90-10)
- **Screwed stiffener** to increase the geometrical stability of the jaw
- Housing, stiffeners and clamps in **Glidcop Al-15 LOX**
- Outgassing holes for trapped volumes

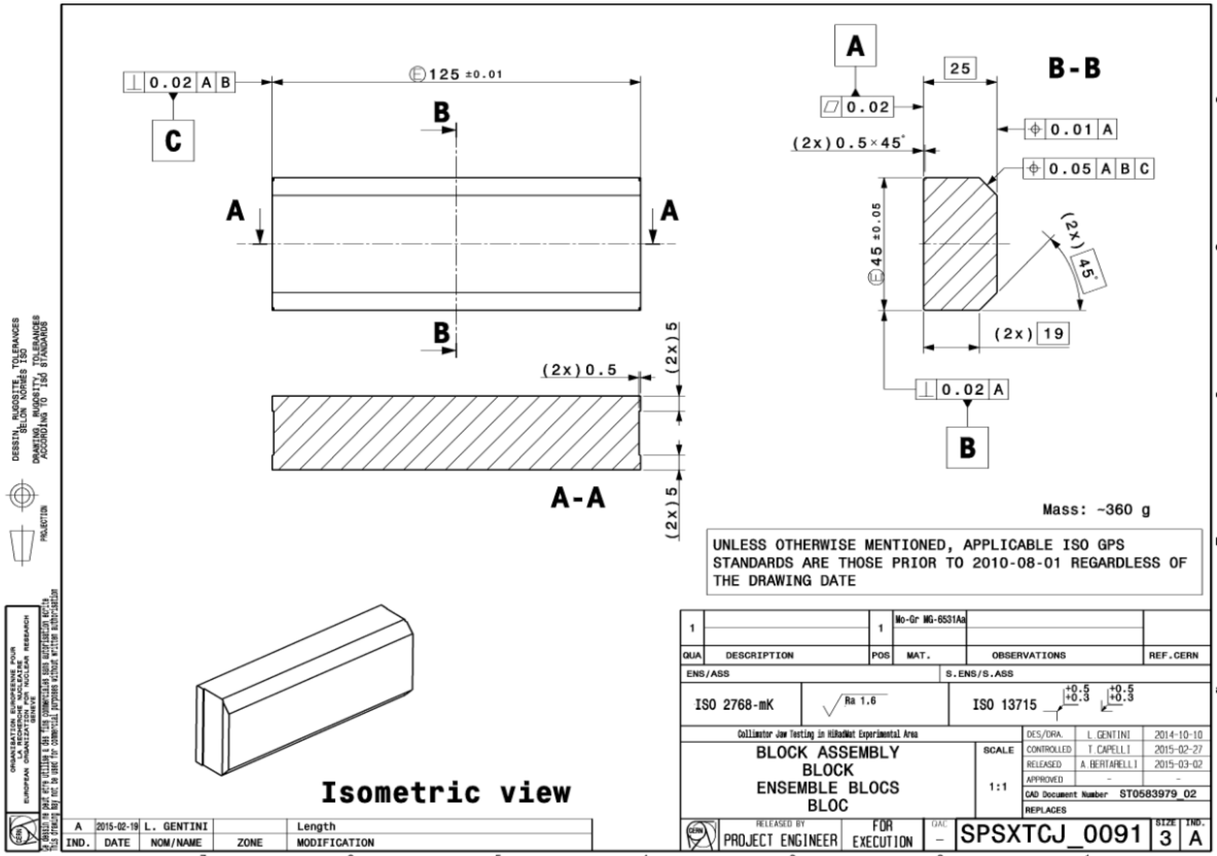


# HL-LHC Collimator Design

**MoGr blocs**



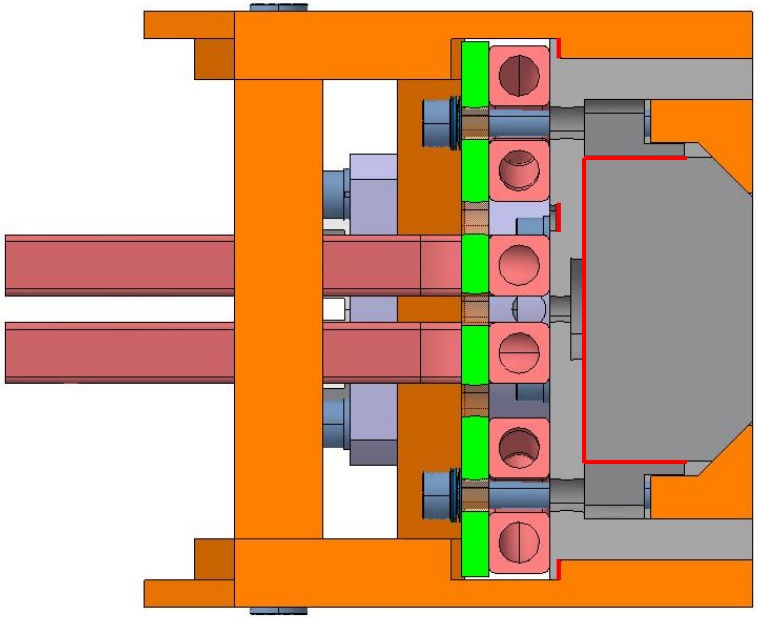





*In case of **copper-diamond**, for manufacturing reasons the bloc length is 100 mm (10 blocs)*

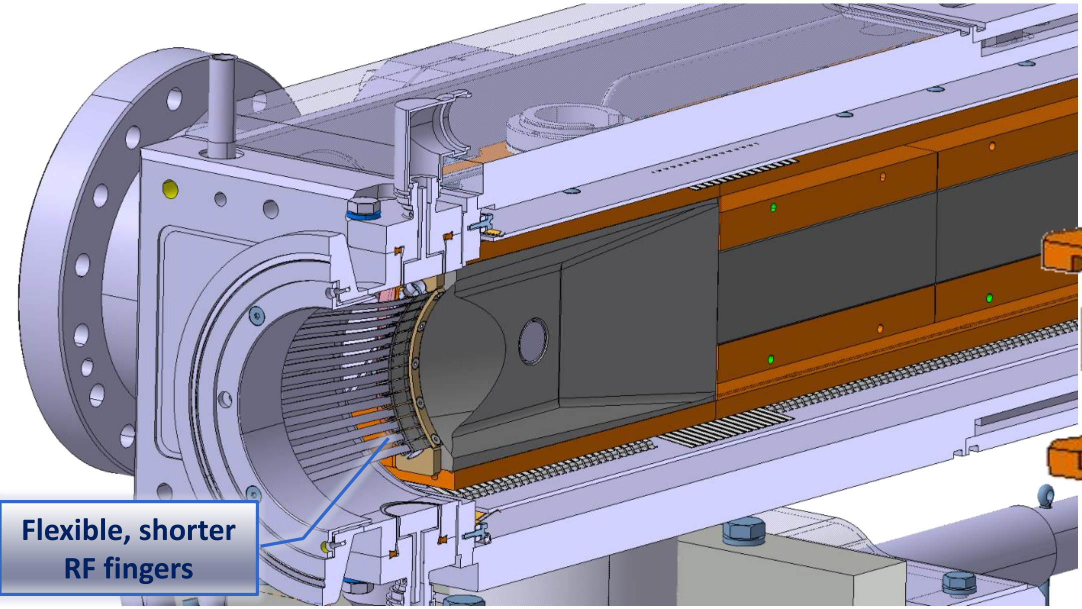
# HL-LHC Collimator Design

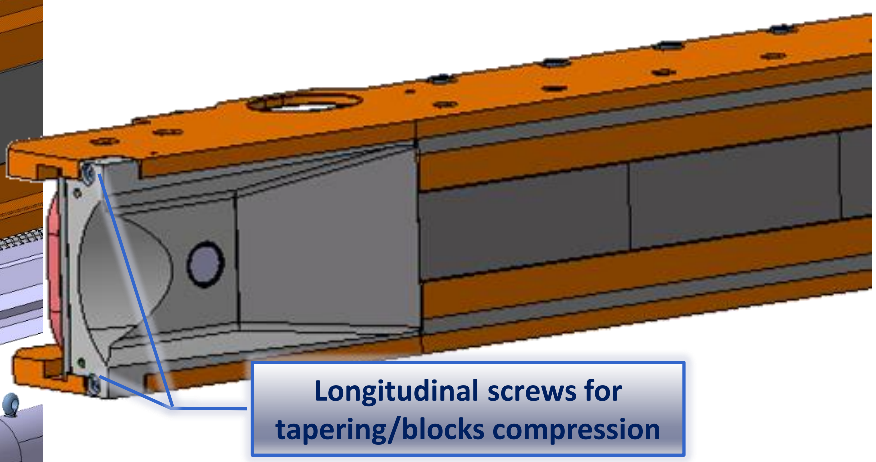
**Assembling procedure**



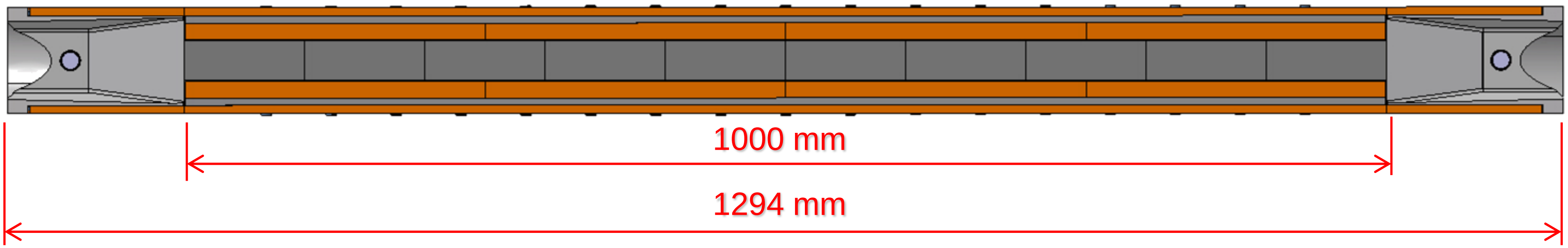
# HL-LHC Collimator Design

- **Longitudinal RF fingers (C17410 CuBe) instead without ferrite**
- Extremity fingers (C17410 CuBe) **re-designed and under cycling**
- **Electrical conductance** between blocs and tapering assured by a pressure imposed by screws during the assembling

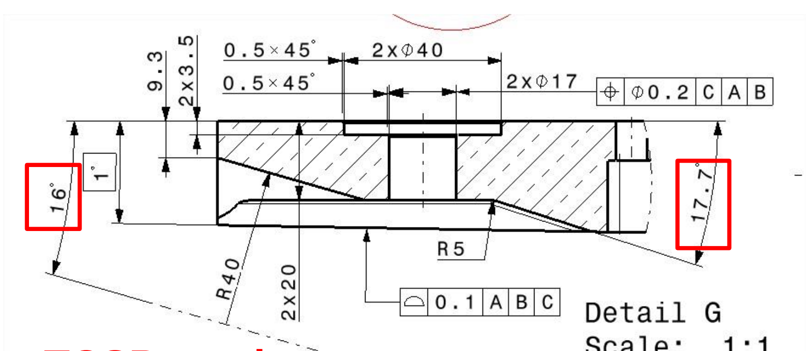


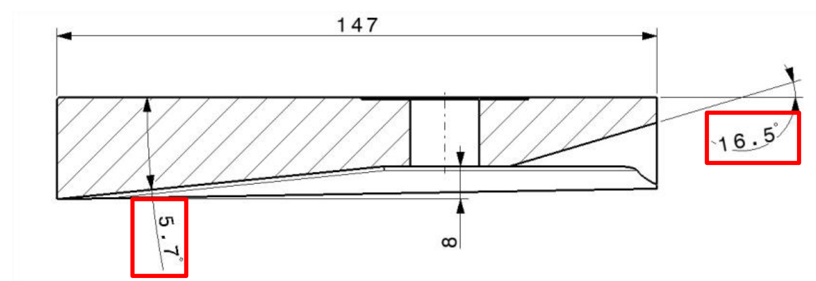
# HL-LHC Collimator Design




- **Jaw 100 mm longer than TCSP**, allowing a reduction of the tapering angle to **further decrease the collimator impedance**
- The tapering will also be made of a novel composite, to **increase its robustness to particle beam impact** (more on this later)



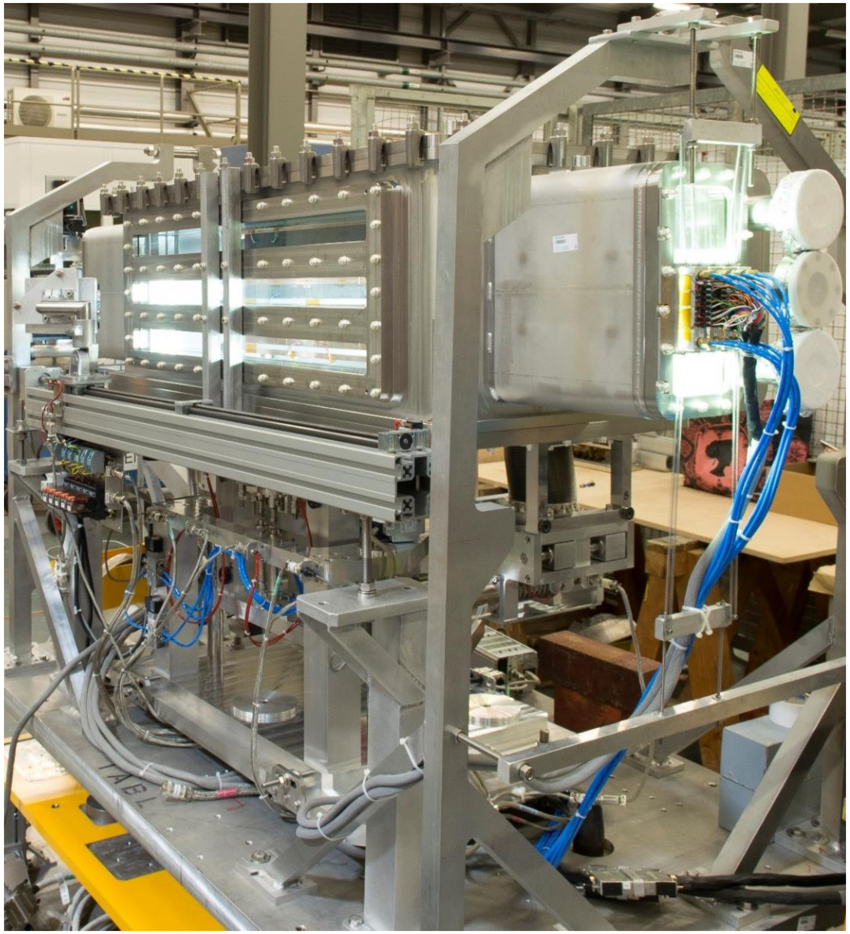

TCSP section




TCSPM section

# HRMT-23 "Jaws" Experiment

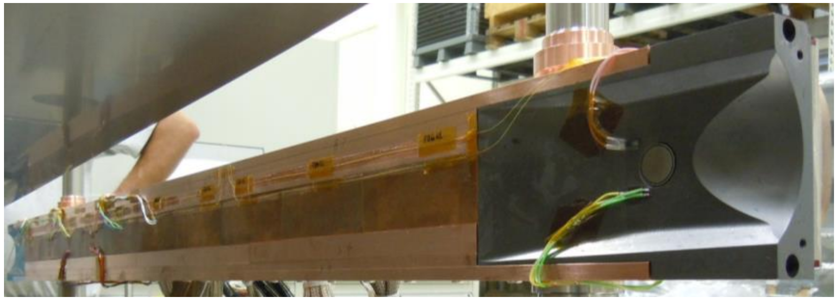
- **3** separate **complete jaws** extensively instrumented.
- **Stainless steel vacuum vessel** (p > $10^{-3}$ mbar). Quick dismounting system to access and manipulate jaws in a glove box.
- **Be/CFC vacuum windows**: designed to withstand higher energy density and intensity
- **Horizontal actuation** inspired by collimator movable tables; Stroke (H): 35 mm
- **Vertical movement of the whole tank**; stroke (V) +/-140 mm. 3 separate windows sets for each jaw
- **Control system** derived from previous HRMT tests (2012)
- **Standard HiRadMat support table**:
  - Total envelope: 1.2(H) x 0.4(W)x 2.1(L) $m^3$
  - Total mass ~ 1600 kg



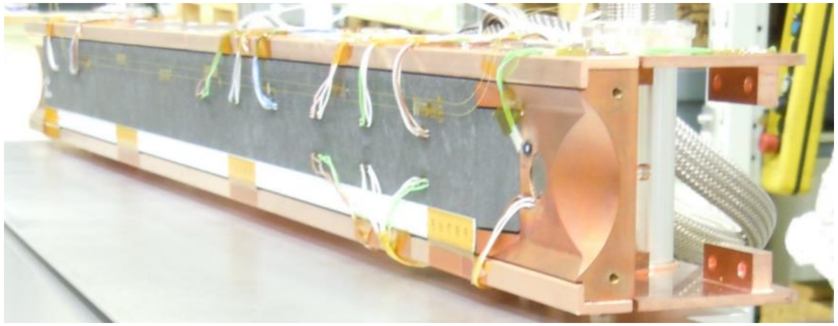
# HRMT-23 “Jaws” Experiment

1. **HL-LHC Secondary Collimator Jaw** (TCSPM) with 8 **MoGr** inserts and taperings

2. **HL-LHC Secondary Collimator Jaw** (TCSPM) with 10 **CuCD** inserts (MoGr taperings)

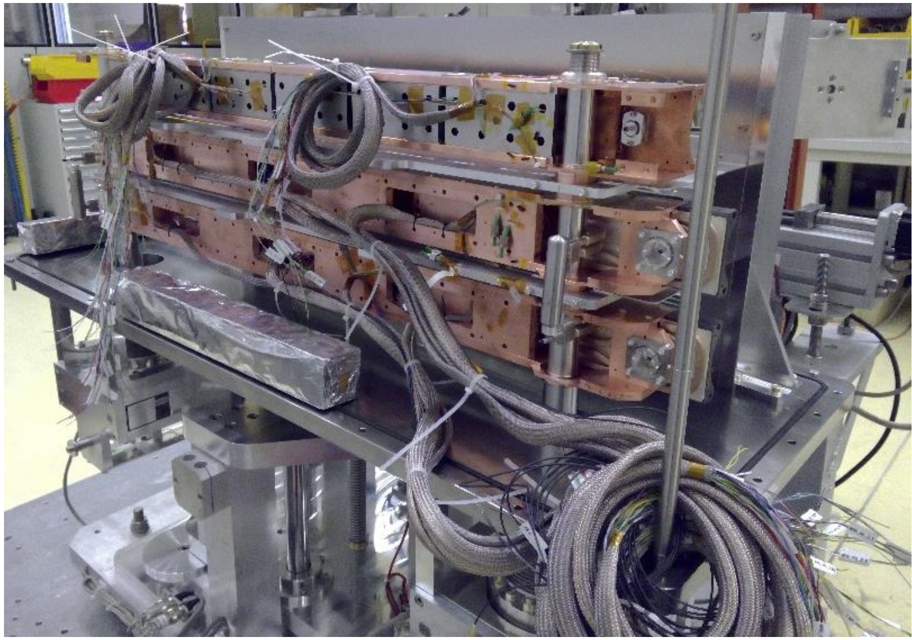


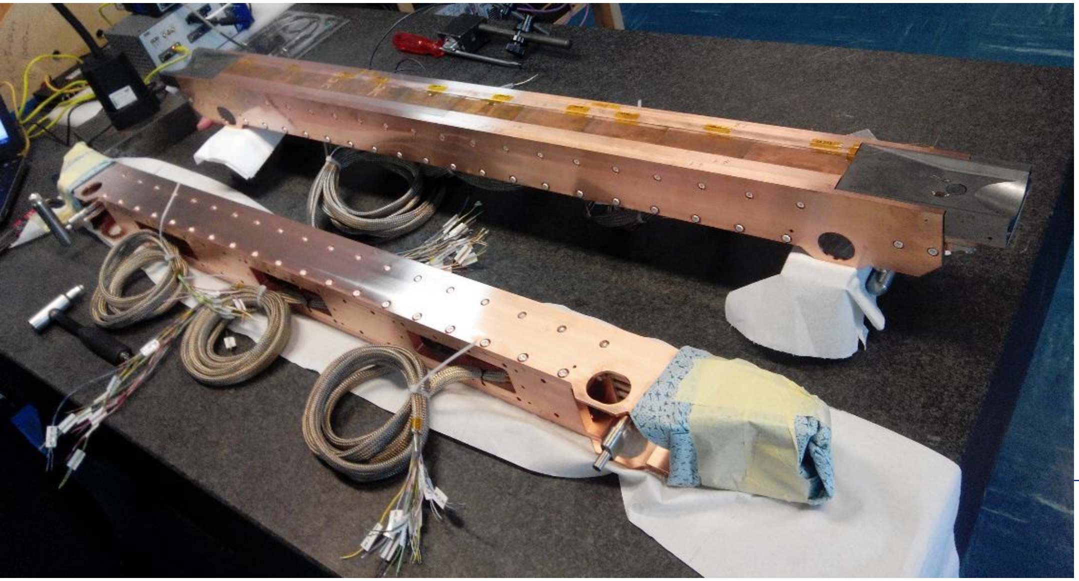
3. **LHC Secondary Collimator Jaw** (TCSP): to verify the resistance of Phase I CFC jaw to beam injection accident with HL-LHC parameters

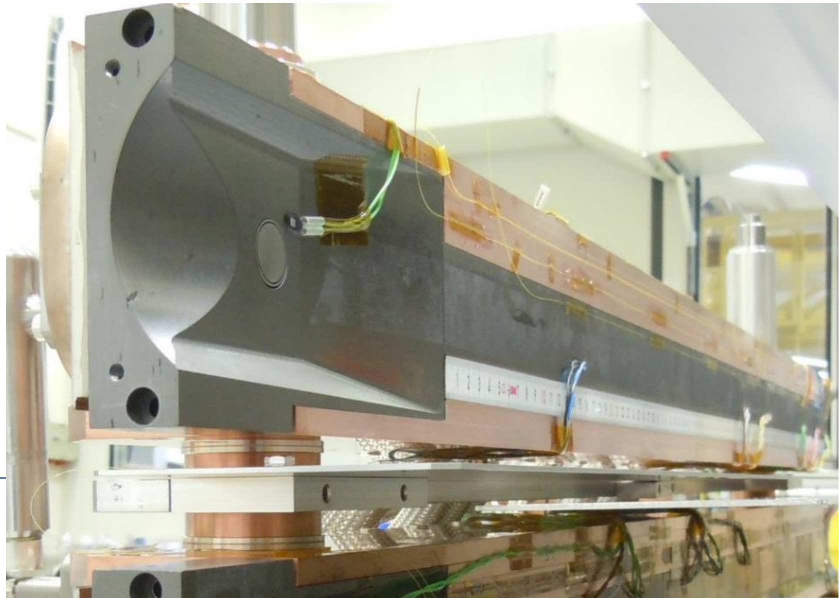


# HRMT-23 “Jaws” Experiment

| Experiment Instrumentation | Sampling frequency |
|---|---|
| 126 electrical strain gauges | 4 MHz |
| 42 temperature probes | 200 Hz |
| Laser Doppler Vibrometer | 4 MHz |
| Water pressure sensor | 100 kHz |
| 60 strain Optical Fibre Bragg Gratings | 500 Hz |
| Inspection HD Camera (4K) | - |
| High Speed Camera + LED lighting system | 20 000 fps |
| In-jaw US probes (Omniscan) | - |







# HRMT-23 Beam Parameters

- Test Runs: **24-31 July 2015**
- Beam energy: **440 GeV**
- Bunch spacing: **25 ns**
- Protons/bunch: up to **1.32e11**
- 1 to **288 bunches** per pulse
- Beam size (σ): **0.35** to **1 mm**
- Different **impact positions**
- Total Pulses: **100** (excluding alignment)
- Total Bunches: **8110** (excluding alignment)
- Total Protons: **~ 1e15**

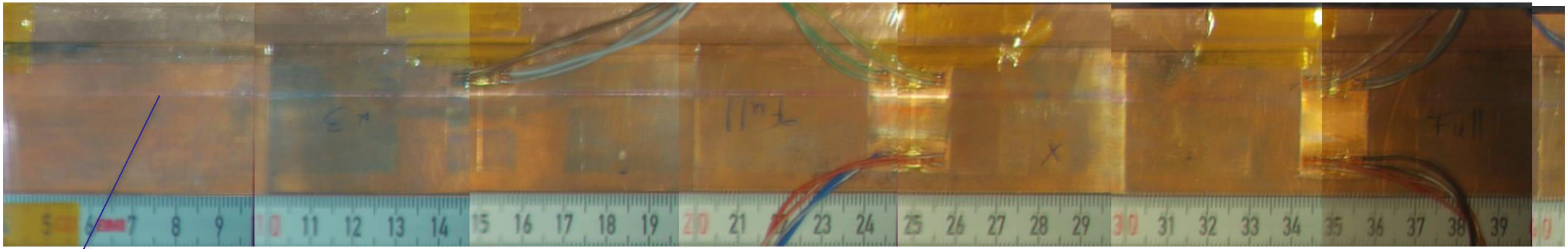
| Jaw | | # Bunches | Total Intensity | Nominal σx [mm] | Nominal σy [mm] | Nominal Target X [mm] |
|---|---|---|---|---|---|---|
| CuCD | 1 | 6 | 7.47E+11 | 0.61 | 0.61 | 3.05 |
| CuCD | 2 | 12 | 1.51E+12 | 0.61 | 0.61 | 3.05 |
| CuCD | 3 | 18 | 2.56E+12 | 0.61 | 0.61 | 3.05 |
| CuCD | 4 | 24 | 3.13E+12 | 0.61 | 0.61 | 3.05 |
| CuCD | 5 | 24 | 2.95E+12 | 0.35 | 0.35 | 0.18 |
| CuCD | 6 | 24 | 2.86E+12 | 0.35 | 0.35 | 0.7 |
| CuCD | 7 | 24 | 2.88E+12 | 0.35 | 0.35 | 1.75 |
| CuCD | 8 | 48 | 6.06E+12 | 0.35 | 0.35 | 0.18 |
| CuCD | 9 | 24 | 2.93E+12 | 0.61 | 0.61 | 0.18 |
| CuCD | 10 | 48 | 6.07E+12 | 0.61 | 0.61 | 0.18 |
| CuCD | 11 | 72 | 8.82E+12 | 0.61 | 0.61 | 0.18 |
| CuCD | 12 | 72 | 8.65E+12 | 0.61 | 0.61 | 0.61 |
| CuCD | 13 | 72 | 8.89E+12 | 0.61 | 0.61 | 1.22 |
| CuCD | 14 | 72 | 8.71E+12 | 0.61 | 0.61 | 3.05 |
| CuCD | 15 | 144 | 1.73E+13 | 0.61 | 0.61 | 3.05 |

| Jaw | | # Bunches | Total Intensity | Nominal σx [mm] | Nominal Target X [mm] |
|---|---|---|---|---|---|
| TCSP | 1 | 12 | 7.12E+11 | 0.35 | 3.05 |
| TCSP | 2 | 12 | 7.12E+11 | 0.35 | 1.83 |
| TCSP | 3 | 12 | 7.13E+11 | 0.35 | 0.61 |
| TCSP | 4 | 12 | 7.12E+11 | 0.61 | 3.05 |
| TCSP | 5 | 12 | 1.47E+12 | 0.61 | 1.83 |
| TCSP | 6 | 12 | 1.48E+12 | 0.61 | 0.61 |
| TCSP | 7 | 12 | 1.39E+12 | 1.00 | 3.05 |
| TCSP | 8 | 12 | 1.49E+12 | 1.00 | 1.83 |
| TCSP | 9 | 12 | 1.47E+12 | 1.00 | 0.61 |
| TCSP | 10 | 6 | 7.47E+11 | 0.61 | 3.05 |
| TCSP | 11 | 18 | 2.26E+12 | 0.61 | 3.05 |
| TCSP | 12 | 24 | 3.07E+12 | 0.61 | 3.05 |
| TCSP | 13 | 24 | 2.89E+12 | 0.60 | 3.05 |
| TCSP | 14 | 24 | 2.89E+12 | 0.60 | 1.83 |
| TCSP | 15 | 24 | 2.93E+12 | 0.60 | 0.61 |
| TCSP | 16 | 24 | 2.96E+12 | 0.60 | 0 |
| TCSP | 17 | 48 | 5.88E+12 | 0.35 | 0.18 |
| TCSP | 18 | 48 | 6.07E+12 | 0.35 | 1.05 |
| TCSP | 19 | 48 | 5.84E+12 | 0.35 | 1.75 |
| TCSP | 20 | 72 | 7.49E+12 | 0.35 | 0.18 |
| TCSP | 21 | 72 | 7.36E+12 | 0.35 | 1.75 |
| TCSP | 22 | 144 | 1.48E+13 | 0.35 | 1.75 |
| TCSP | 23 | 144 | 1.49E+13 | 0.35 | 1.05 |
| TCSP | 24 | 144 | 1.49E+13 | 0.35 | 0.18 |
| TCSP | 25 | 144 | 1.86E+13 | 0.35 | 1.75 |
| TCSP | 26 | 144 | 1.88E+13 | 0.35 | 1.05 |
| TCSP | 27 | 144 | 1.84E+13 | 0.35 | 0.18 |
| TCSP | 28 | 288 | 3.66E+13 | 0.61 | 3.05 |
| TCSP | 29 | 288 | 3.78E+13 | 0.61 | 1.83 |
| TCSP | 30 | 288 | 3.73E+13 | 0.61 | 0.3 |
| TCSP | 31 | 288 | 3.73E+13 | 0.61 | 5 |
| TCSP | 32 | 288 | 3.69E+13 | 0.35 | 1.75 |
| TCSP | 33 | 288 | 3.77E+13 | 0.35 | 1.05 |
| TCSP | 34 | 288 | 3.69E+13 | 0.35 | 0.18 |
| TCSP | 35 | 288 | 3.79E+13 | 0.35 | 5 |

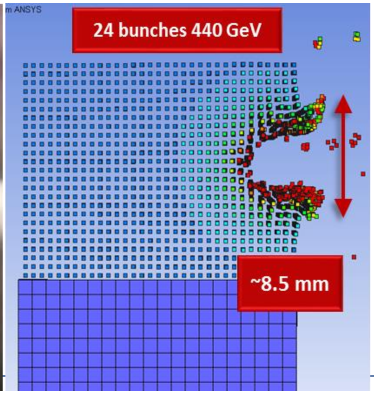
| Jaw | | # Bunches | Total Intensity | Nominal σx [mm] | Nominal Target X [mm] |
|---|---|---|---|---|---|
| MoGr | 1 | 12 | 7.13E+11 | 0.35 | 3.05 |
| MoGr | 2 | 12 | 7.12E+11 | 0.35 | 1.83 |
| MoGr | 3 | 12 | 7.12E+11 | 0.35 | 0.61 |
| MoGr | 4 | 12 | 7.12E+11 | 0.61 | 3.05 |
| MoGr | 5 | 12 | 7.12E+11 | 0.61 | 1.83 |
| MoGr | 6 | 12 | 7.12E+11 | 0.61 | 0.61 |
| MoGr | 7 | 12 | 1.51E+12 | 1.00 | 3.05 |
| MoGr | 8 | 12 | 1.46E+12 | 1.00 | 1.83 |
| MoGr | 9 | 12 | 1.51E+12 | 1.00 | 0.61 |
| MoGr | 10 | 6 | 7.47E+11 | 0.61 | 3.05 |
| MoGr | 11 | 18 | 2.25E+12 | 0.61 | 3.05 |
| MoGr | 12 | 24 | 3.07E+12 | 0.61 | 3.05 |
| MoGr | 13 | 24 | 2.95E+12 | 0.60 | 3.05 |
| MoGr | 14 | 24 | 2.88E+12 | 0.60 | 1.83 |
| MoGr | 15 | 24 | 2.88E+12 | 0.60 | 0.61 |
| MoGr | 16 | 24 | 2.88E+12 | 0.60 | 0 |
| MoGr | 17 | 24 | 2.86E+12 | 0.60 | 0 |
| MoGR | 18 | 24 | 2.88E+12 | 0.35 | 0.18 |
| MoGR | 19 | 48 | 5.93E+12 | 0.35 | 0.18 |
| MoGr | 20 | 72 | 7.47E+12 | 0.60 | 3.05 |
| MoGr | 21 | 72 | 7.39E+12 | 0.60 | 1.83 |
| MoGr | 22 | 72 | 7.39E+12 | 0.60 | 0.3 |
| MoGr | 23 | 144 | 1.45E+13 | 0.60 | 3.05 |
| MoGr | 24 | 144 | 1.48E+13 | 0.60 | 1.83 |
| MoGr | 25 | 144 | 1.44E+13 | 0.60 | 0.3 |
| MoGr | 26 | 144 | 1.87E+13 | 0.61 | 3.05 |
| MoGr | 27 | 144 | 1.79E+13 | 0.61 | 1.83 |
| MoGr | 28 | 144 | 1.80E+13 | 0.61 | 0.3 |
| MoGr | 29 | 288 | 3.80E+13 | 0.61 | 3.05 |
| MoGr | 30 | 288 | 3.67E+13 | 0.61 | 1.83 |
| MoGr | 31 | 288 | 3.78E+13 | 0.61 | 0.3 |
| MoGr | 32 | 288 | 3.76E+13 | 0.35 | 1.75 |
| MoGr | 33 | 288 | 3.79E+13 | 0.35 | 1.05 |
| MoGr | 34 | 288 | 3.70E+13 | 0.35 | 0.18 |

# HRMT-23 first results CuCD

- **CuCD** on HL-LHC jaw survived (with a limited surface scratch on the Cu coating) the impact of **24 b, σ 0.35 mm** at 440 GeV, roughly **equivalent to 1 LHC bunch** at 7 TeV
- At **48 b** (~2 LHC 7 TeV bunches) the scratch is more severe, but the jaw appears globally undeformed
- This would qualify CuCD as an superior material for TCT jaws (presently in Tungsten alloy). Local damage induced by Asynchronous Beam Dump could be compensated by jaw shift with 5$^{th}$ axis



CuCD jaw after 24 b, σ 0.35 mm. Note thin, long groove

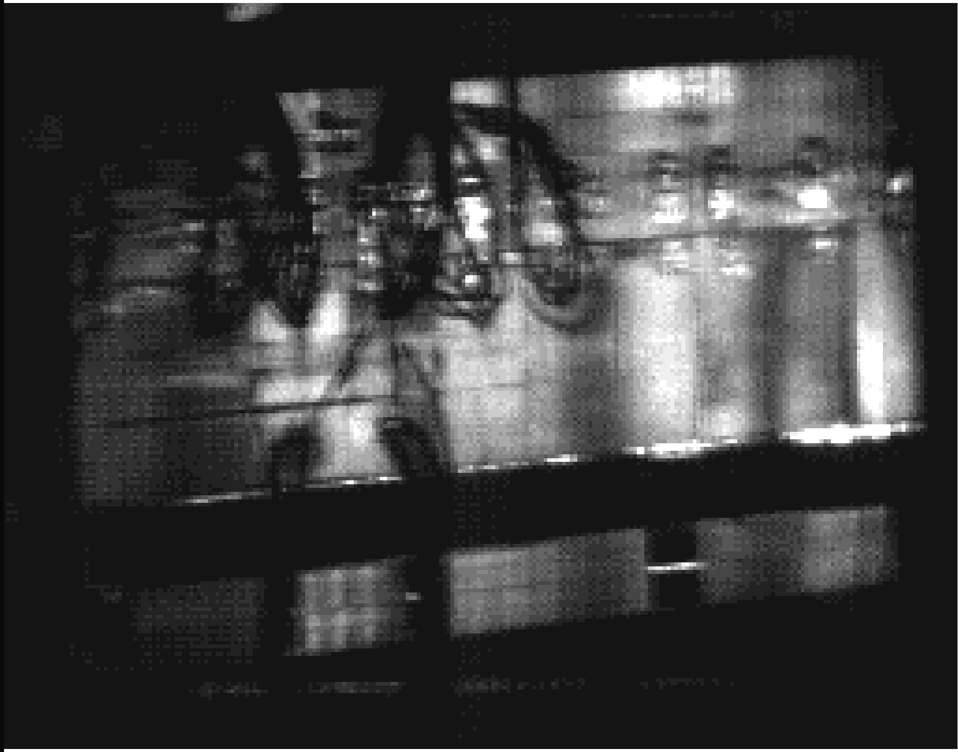

Groove caused on TCT by an SPS 24 b pulse (HRMT-09, 2012)

# HRMT-23 first results CuCD

- CuCD 48 bunches, σ 0.35 mm, impact 0.5σ
- CuCD 144 bunches σ 0.61 mm, impact 5 σ

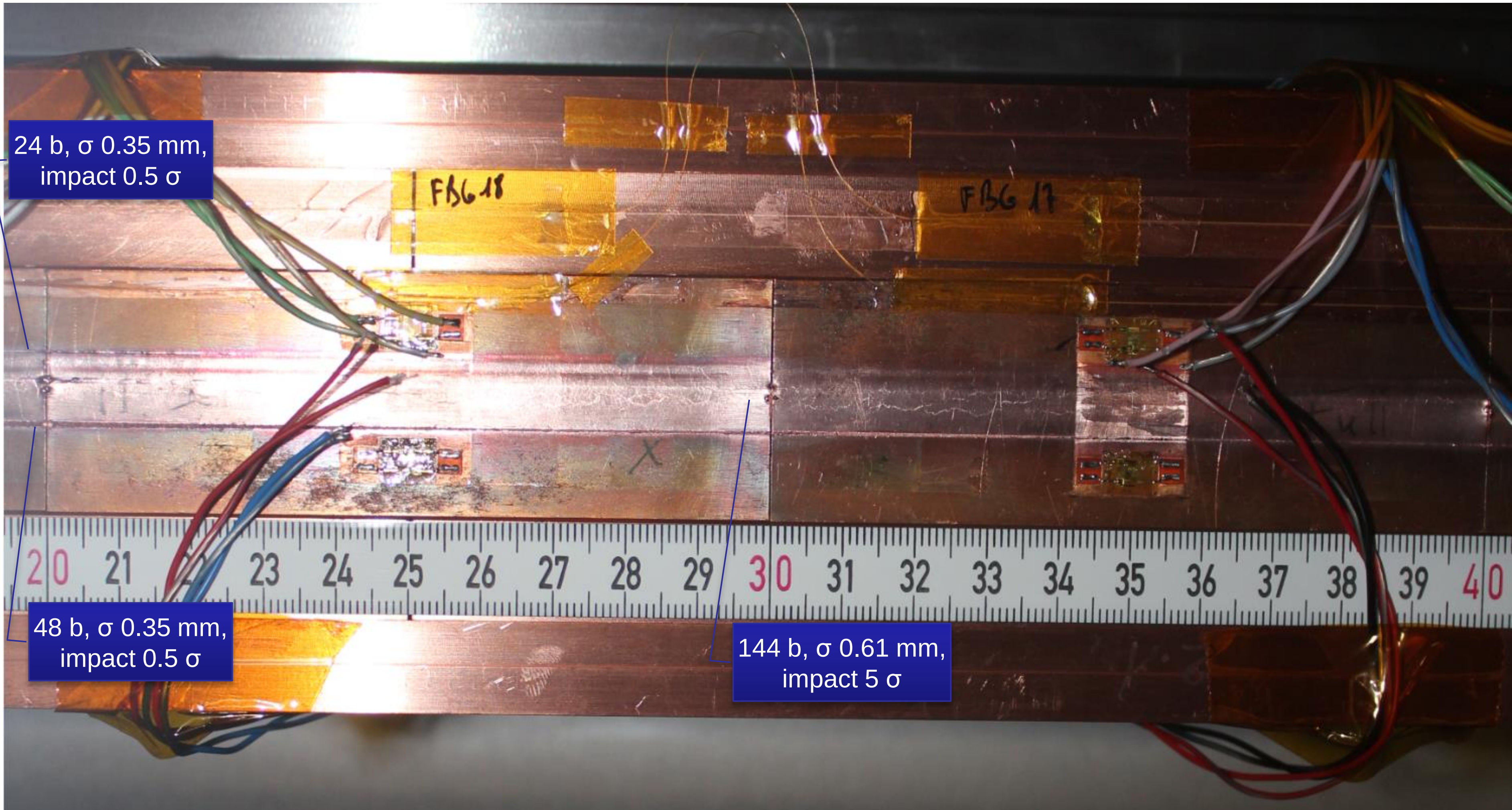
**TCSPM CuCD 48 bunches**

**TCSPM CuCD 144 bunches**



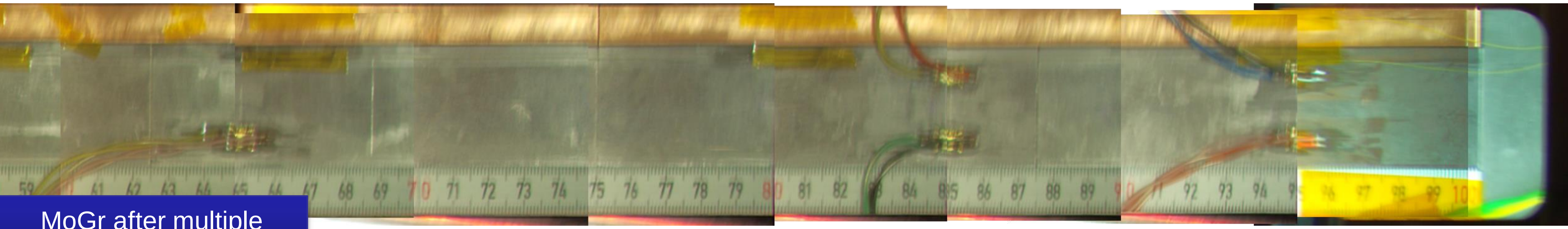
# HRMT-23 first results CuCD

- **Post-irradiation visual inspection**

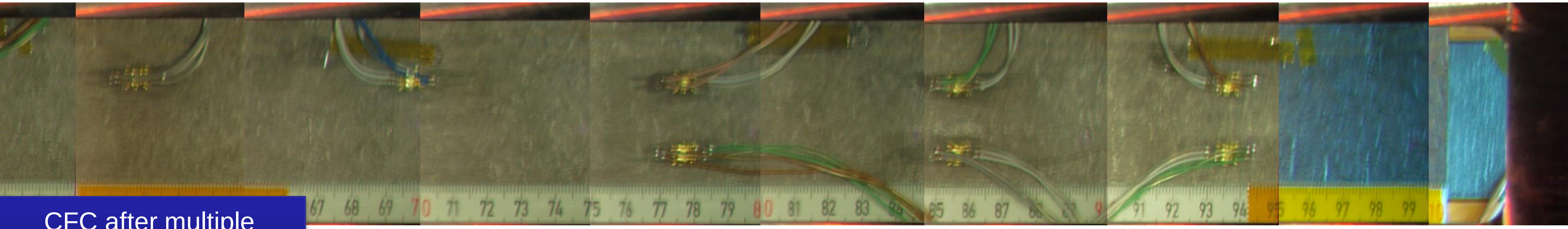


# HRMT-23 first results MoGr & CFC

- **MoGr** on HL-LHC jaw survived the impact of several **288 b pulses** with $\sigma$ down to 0.35 mm (**peak energy density slightly higher than HL-LHC injection error)**
- **CFC** on LHC jaw **survived the same impacts**
- Preliminary results would qualify MoGr (from robustness point of view) as an alternative to CFC with a factor 5 to 10 **gain in electrical conductivity**



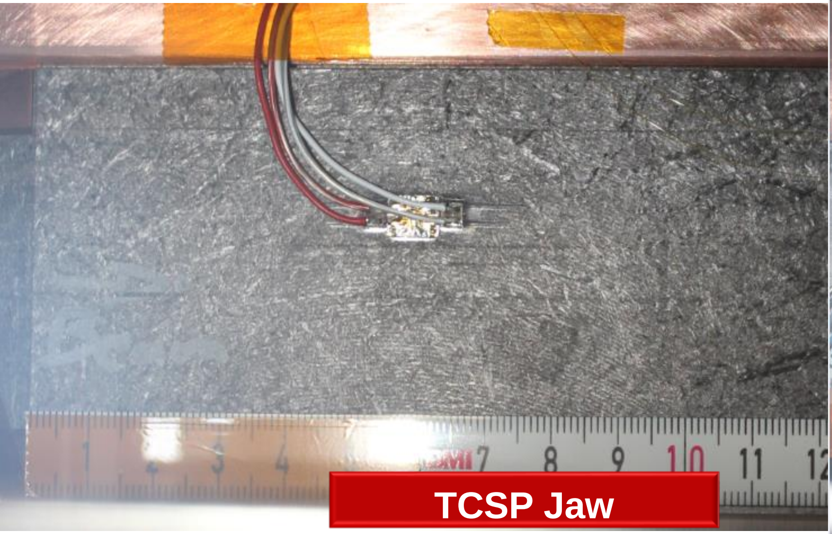
MoGr after multiple impacts



CFC after multiple impacts

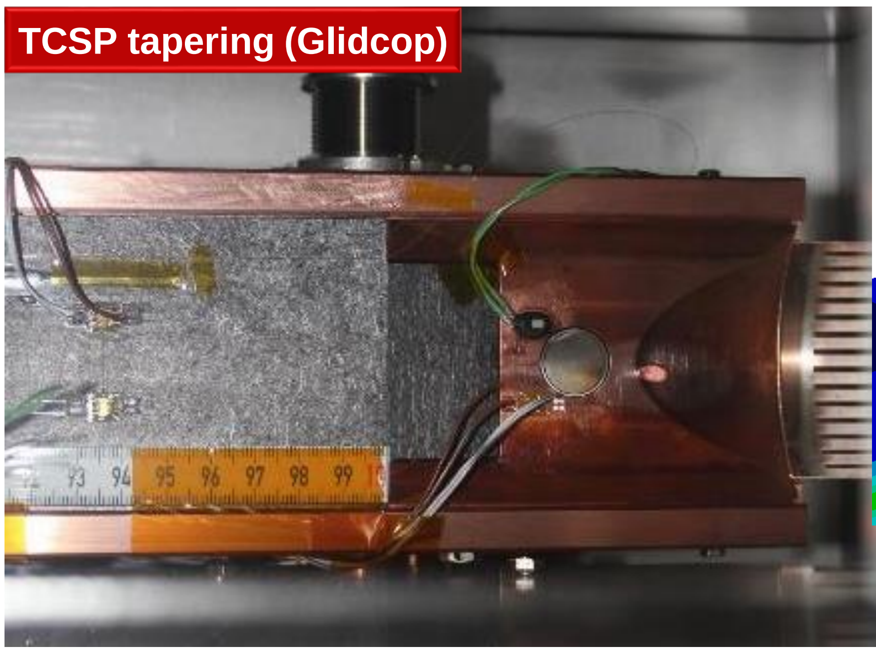
# HRMT-23 first results MoGr & CFC

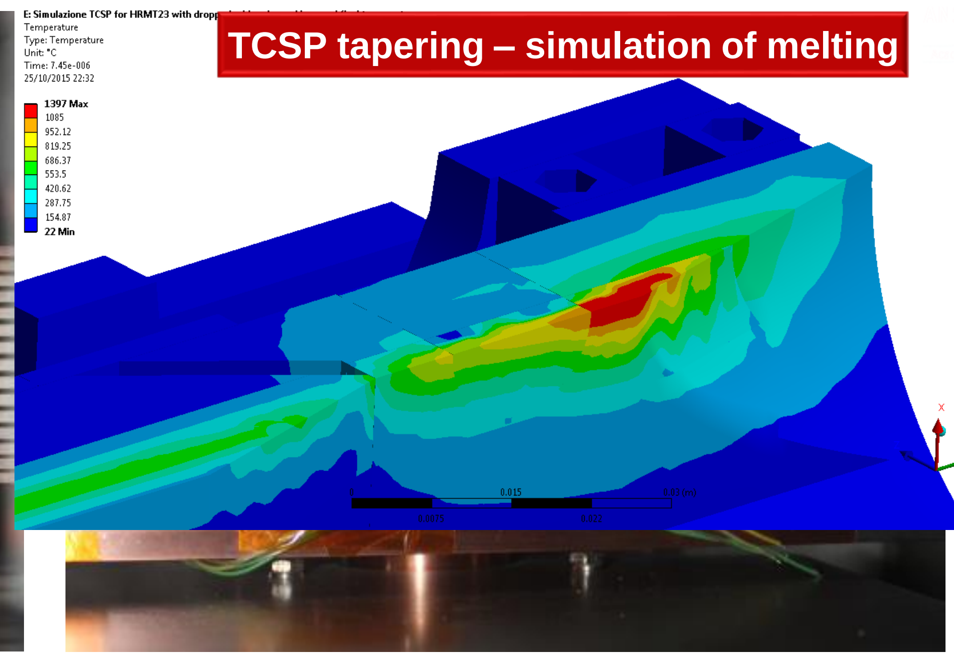
- Post-experiment observations also allowed to observe some marks on the CFC and MoGr surfaces
- The visibility of the marks changes with the light orientation
- Probably generated during the 0.5 sigma impacts by **detachment of the surface powders** (pencil-like surface typical of graphitic materials, no etching done before the experiment)
- **No cracks are visible**




# HRMT-23 first results MoGr & CFC

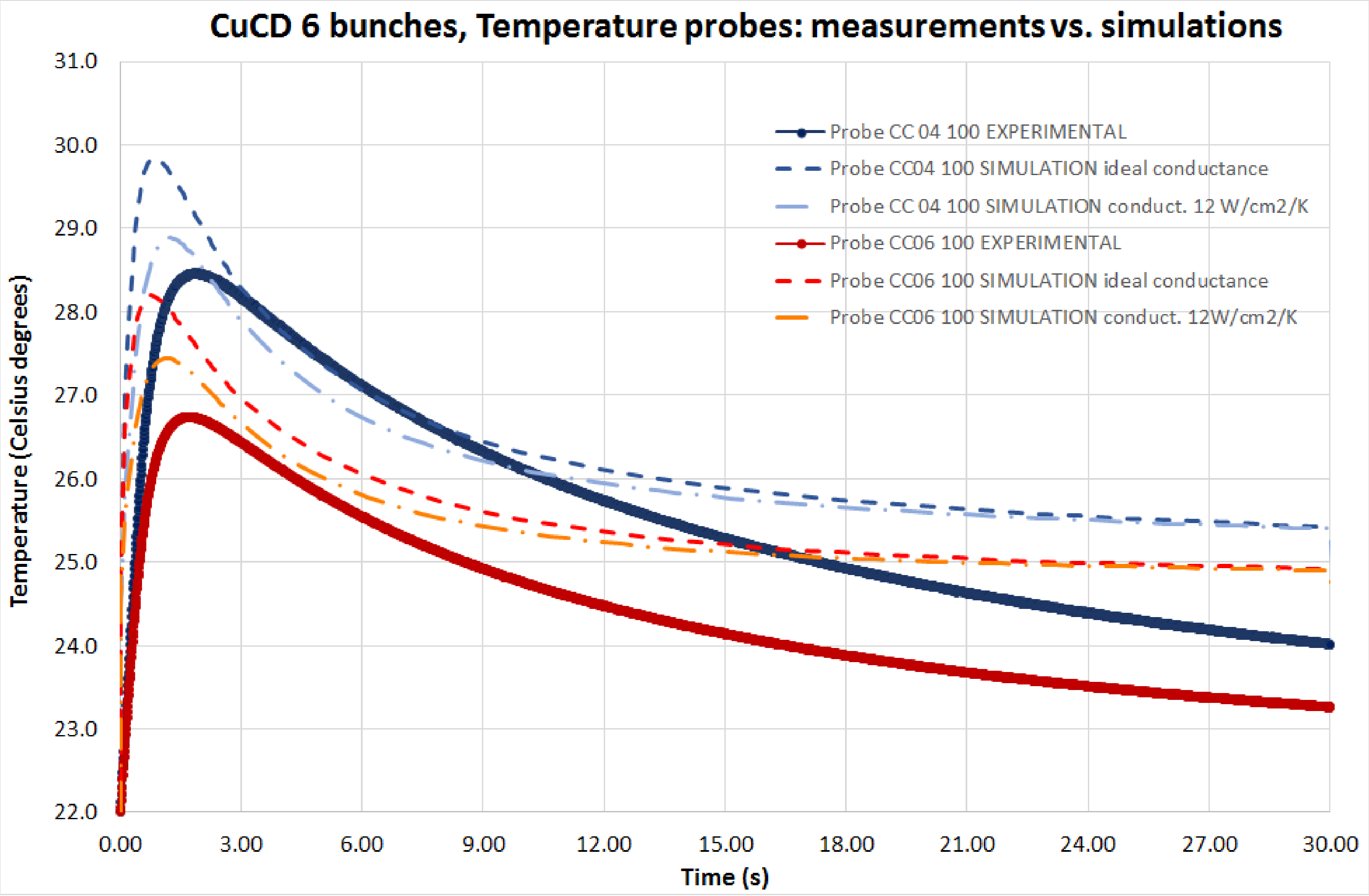
- Hole in the TCSP Glidcop tapering observed, two TCSPM jaw taperings, in MoGr, visually unscathed → **MoGr is a more robust option as a tapering material also for TCSP**
- The **electrical functionality of the BPM** embarked in the three jaws will be verified during the post-irradiation experiments, once opening the tank



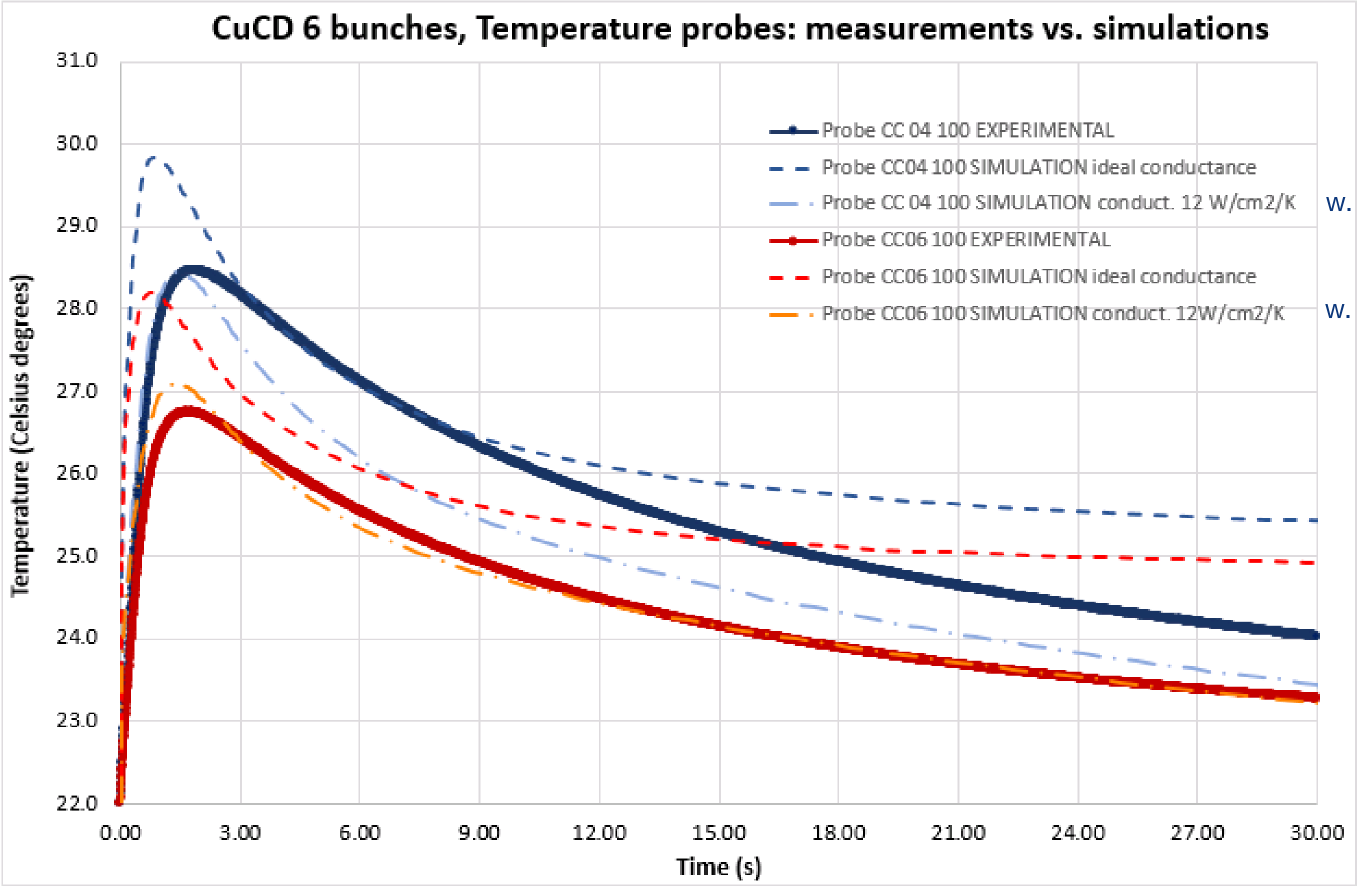
# Numerical benchmarking – Thermal

- **THERMAL: CuCD 6 bunches, σ 0.61 mm, impact 5σ**



# Numerical benchmarking – Thermal

- Cool-down simulated is much slower, **typical of forced convection** (nominal film coefficient of LHC collimators with circulating water!)
- **Shock-enhanced water forced convection?**

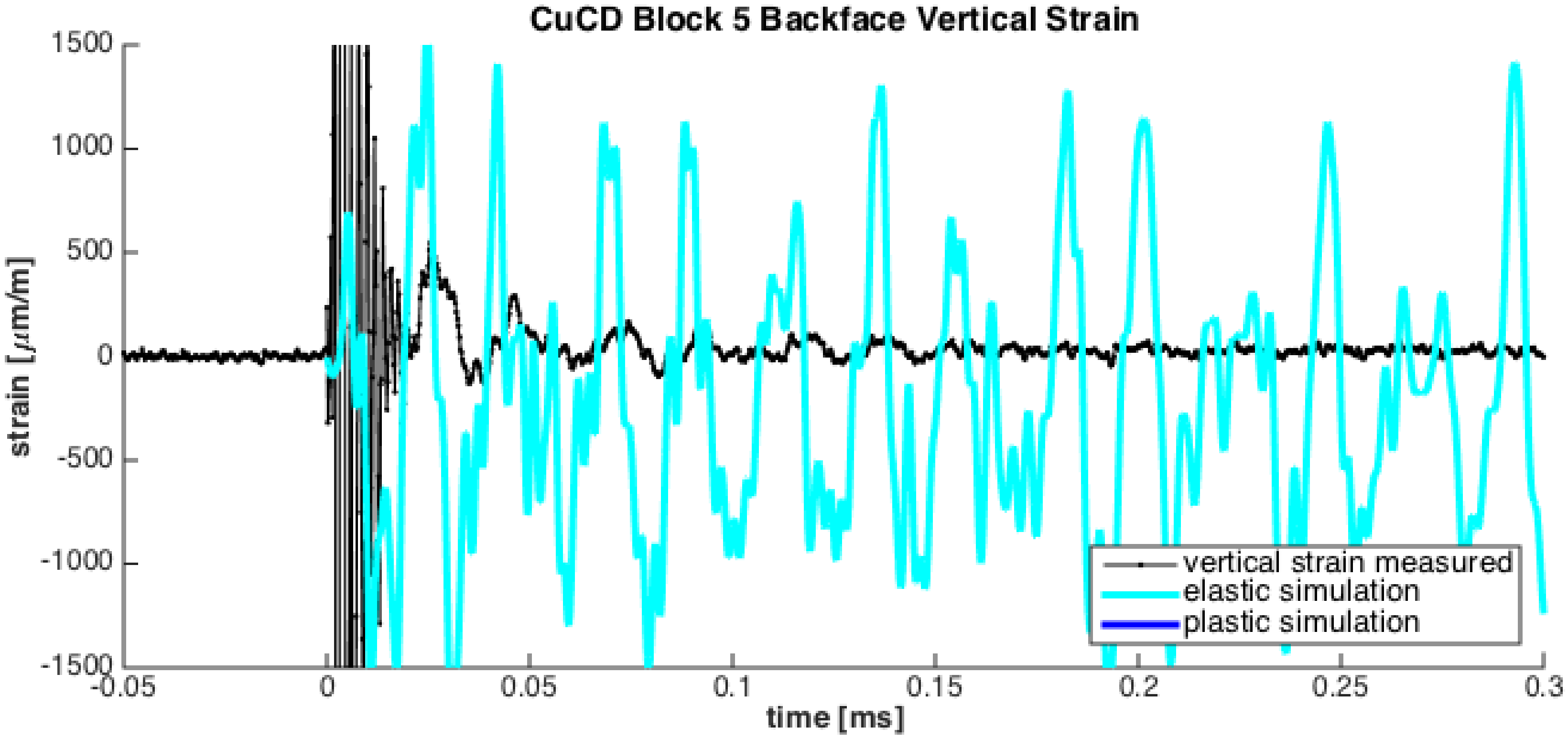



w. Forced convection

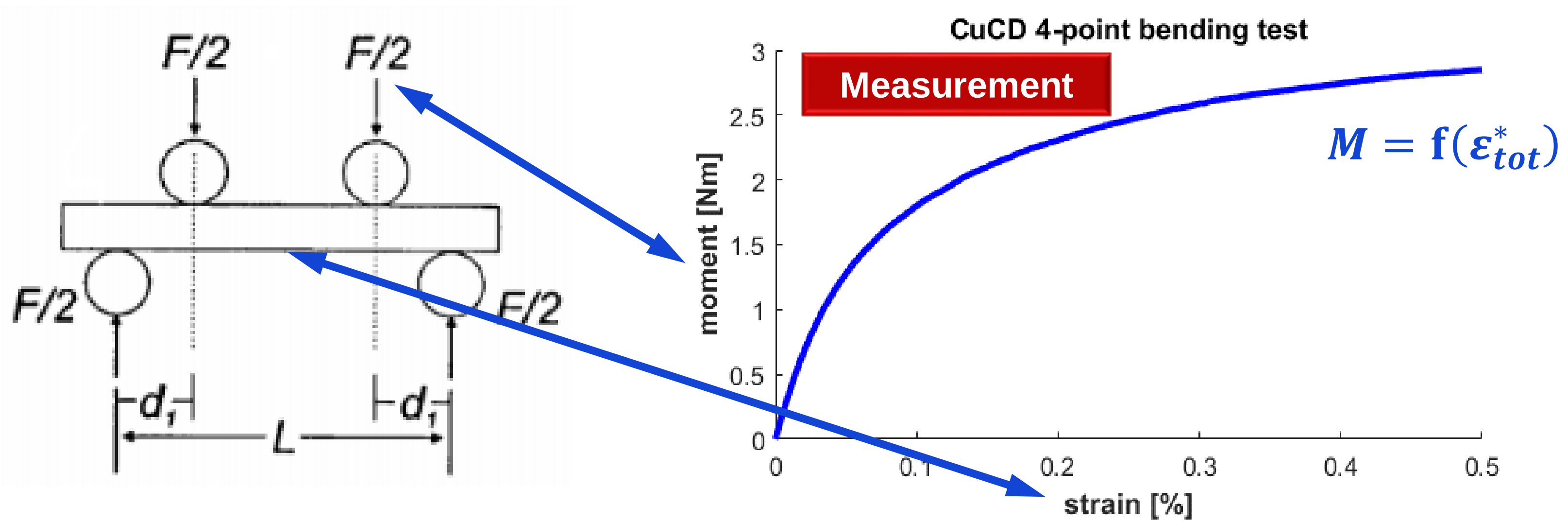
w. Forced convection

# Numerical benchmarking – Structural, CuCD

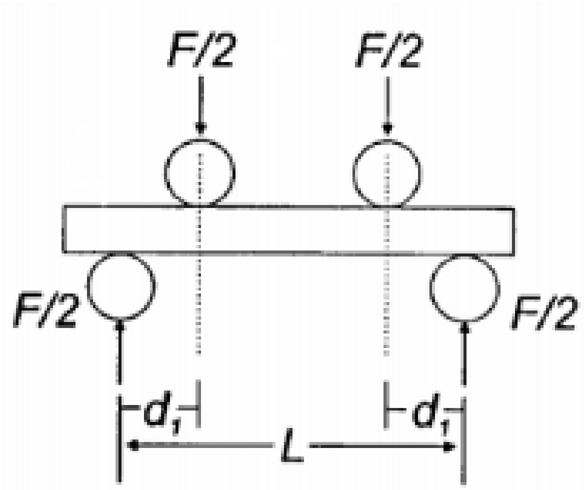
- Structural: **CuCD 24 bunches**, σ 0.61 mm, impact 5σ
- Reasonably **low noise levels**
- **Electromagnetic coupling beam/strain gauges** for the first microseconds after the impact

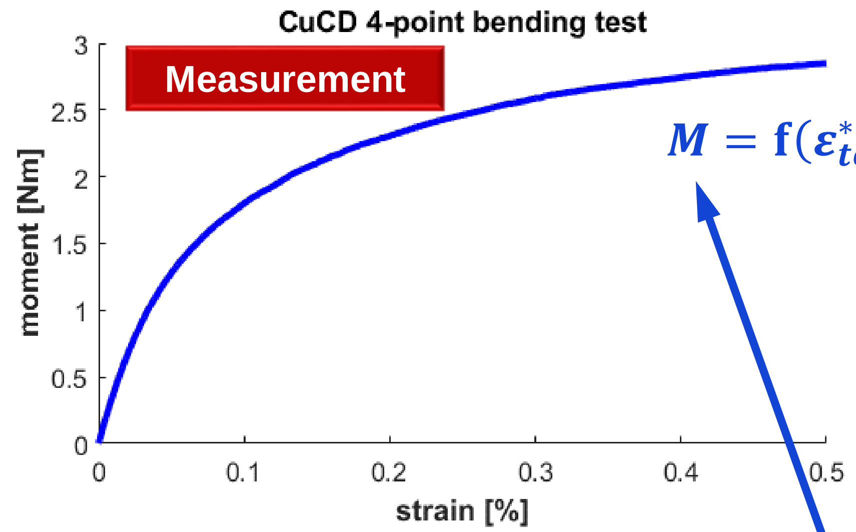


# Elasto-Plastic Material Modelling

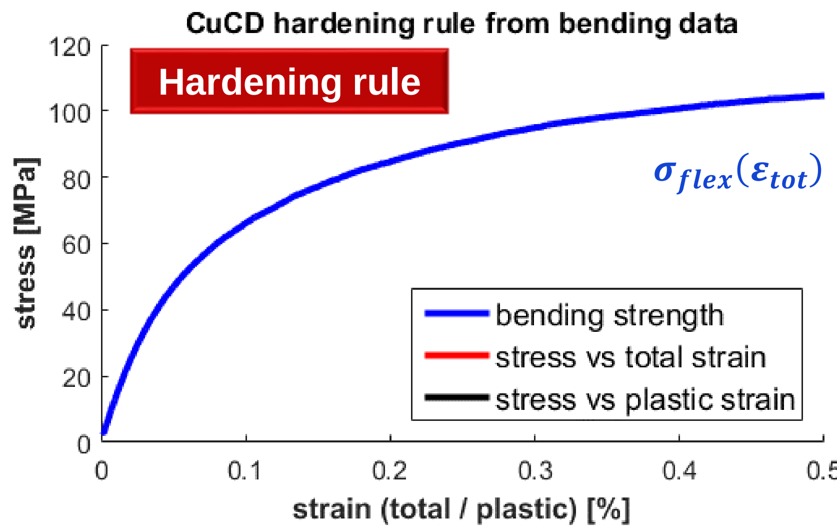


# Elasto-Plastic Material Modelling



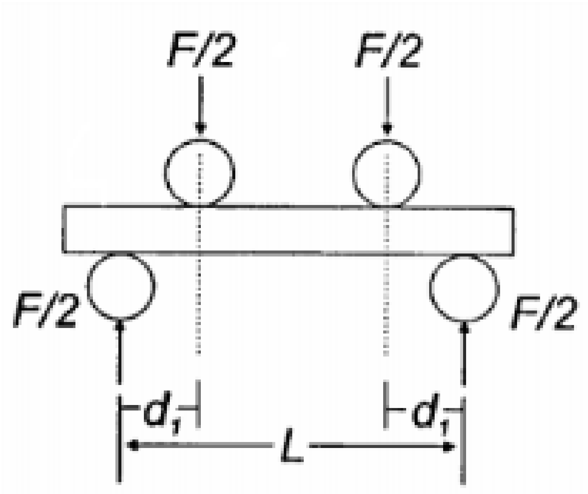



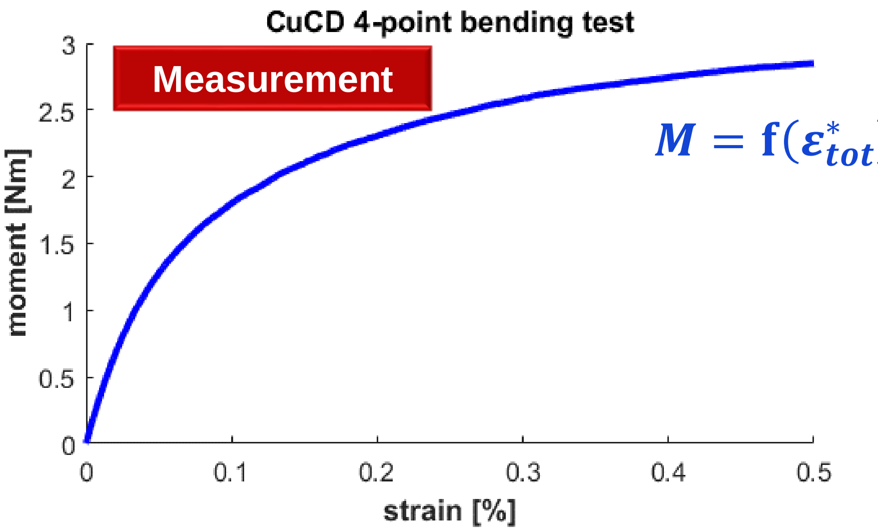

$$M = \mathrm{f}(\varepsilon_{tot}^{*})$$

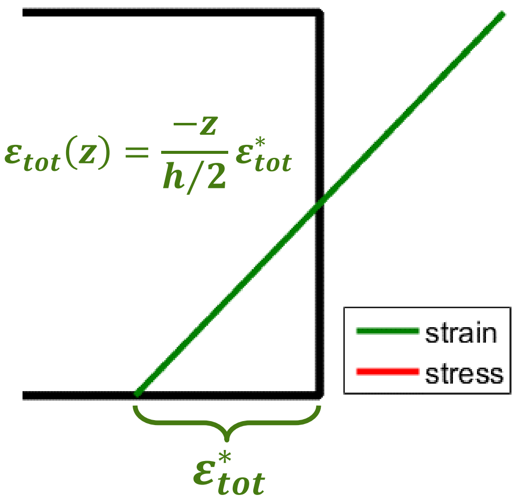


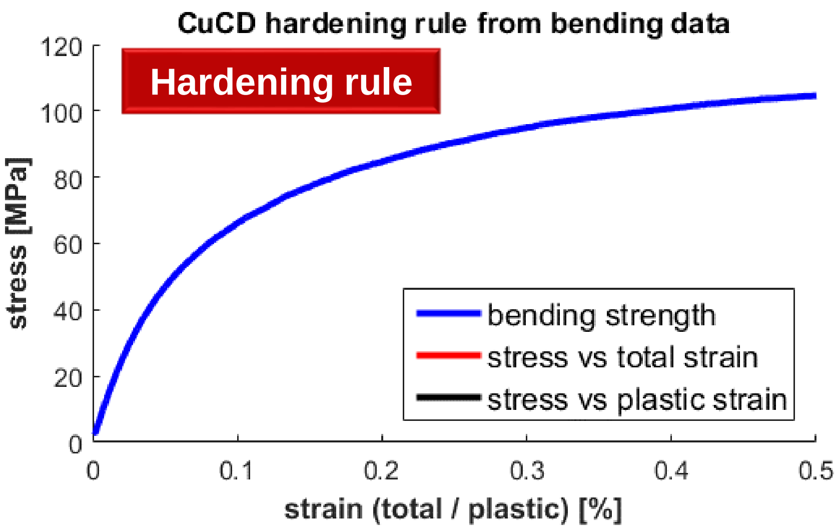

$$\sigma_{flex}(\varepsilon_{tot}) = \frac{M}{I_x} \cdot h/2$$

# Elasto-Plastic Material Modelling

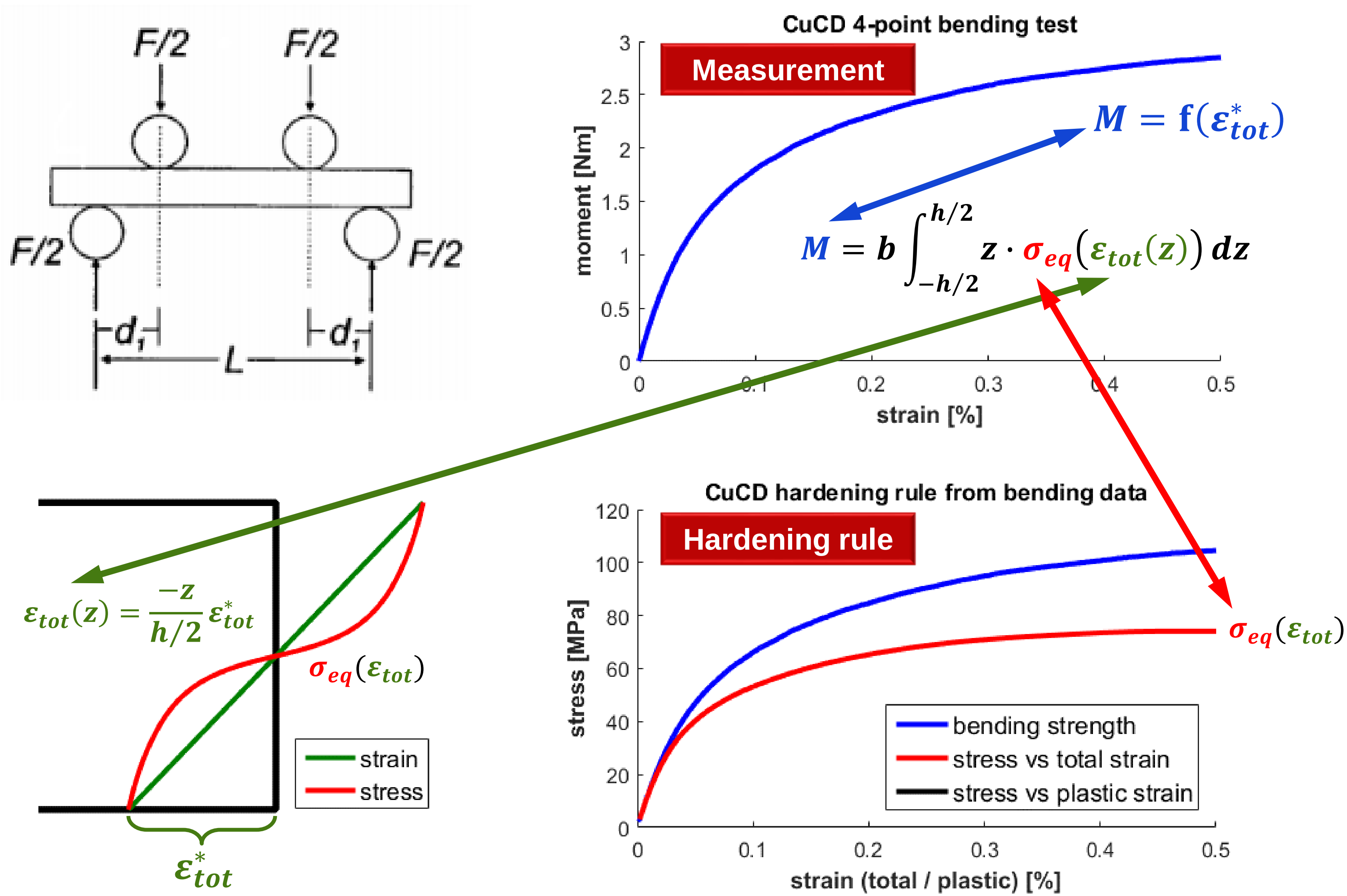


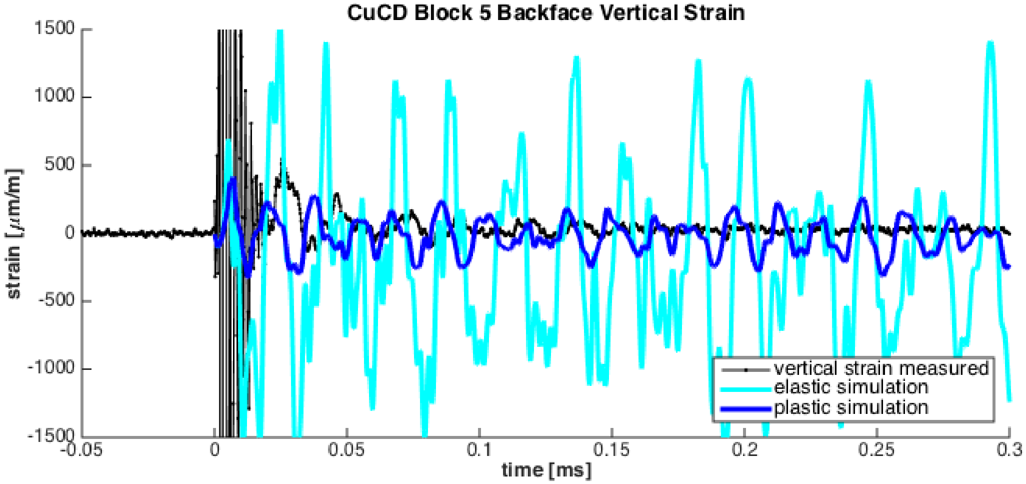



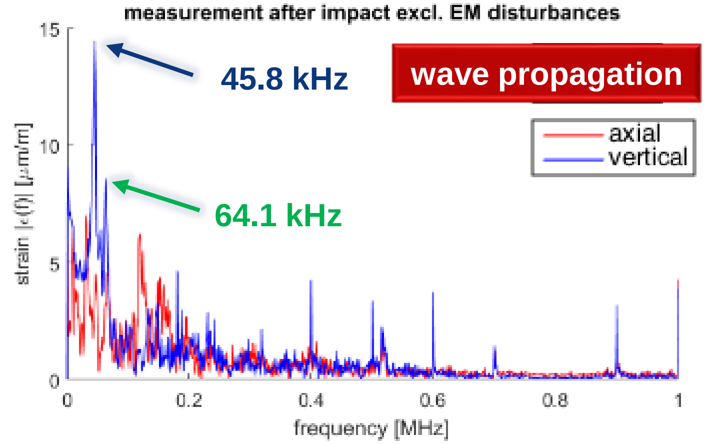
# Elasto-Plastic Material Modelling

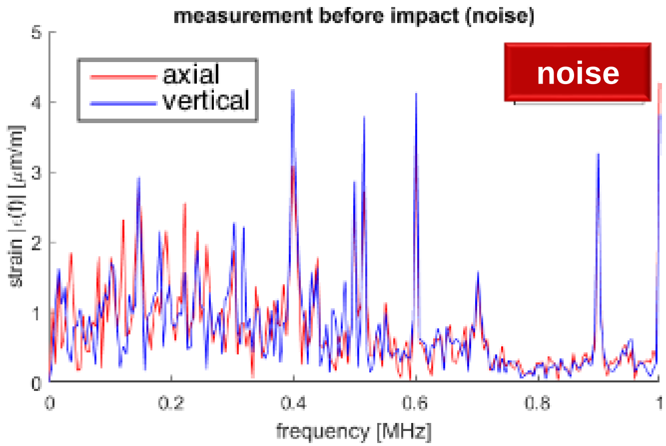


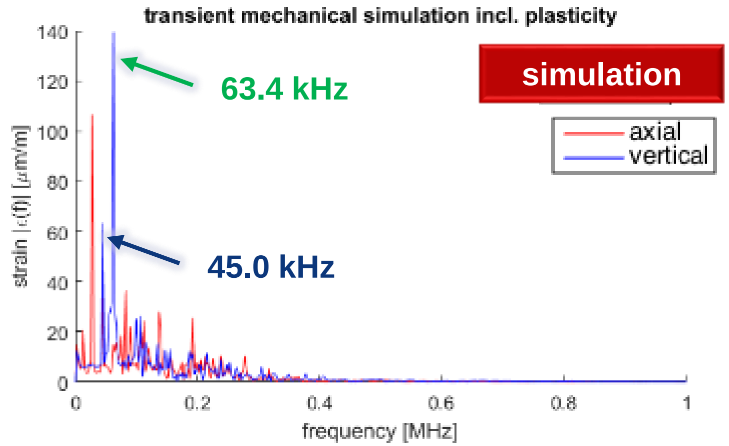
# Numerical benchmarking – Structural, CuCD

- Structural: **CuCD 24 bunches**, σ 0.61 mm, impact 5σ
- Pseudo-plasticity of the material taken into account!



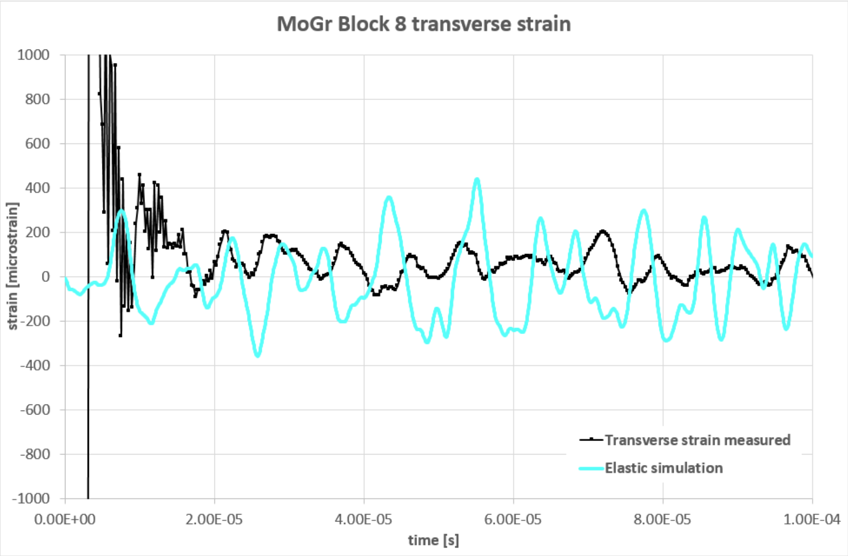



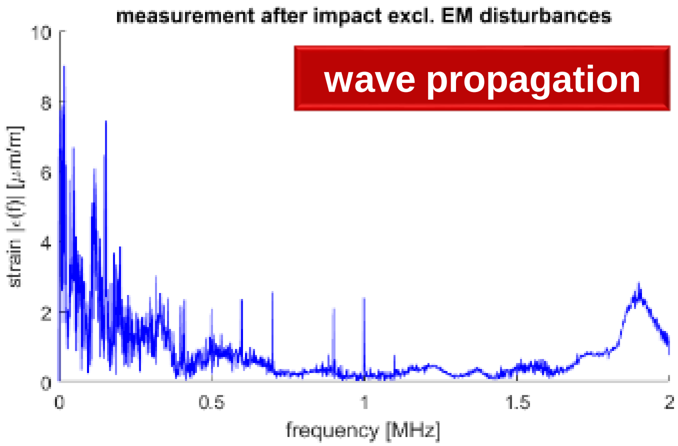



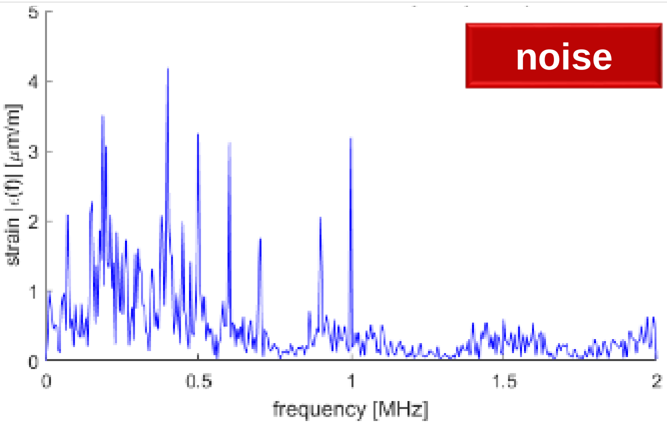

- Ongoing: **wave damping, phase, increased simulation duration** (to catch lower frequencies)

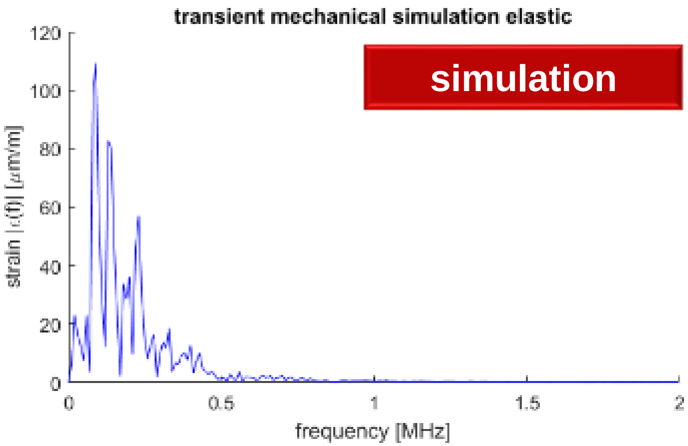
# Numerical benchmarking – Structural, MoGr

- Structural: **MoGr 24 bunches**, σ 0.6 mm, impact 5σ
- **Elastic models for MoGr** so far: important to include plasticity! Difficult, because **anisotropic material**



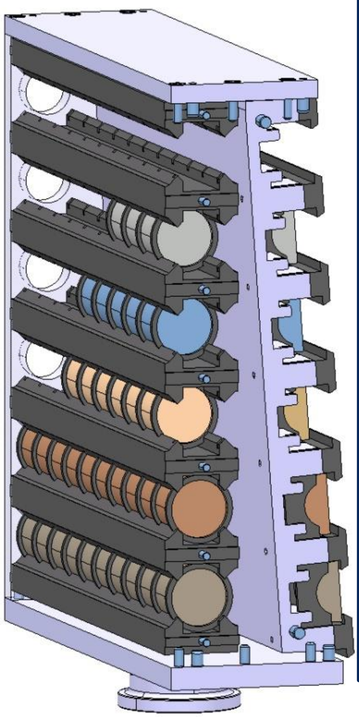
# HRMT-14: Material Sample Holder

**2012: test of specimens from 6 different materials, including novel composites**

- Allowed characterization of materials of interest for collimators
- Tuning of numerical models, with very good benchmarking between measurements and simulations

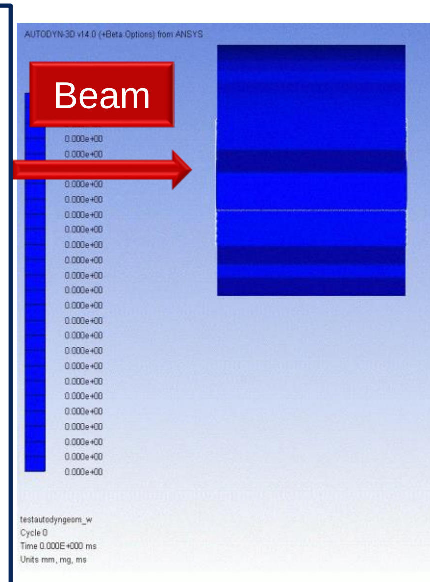
**Medium Intensity Samples (Type 1)**

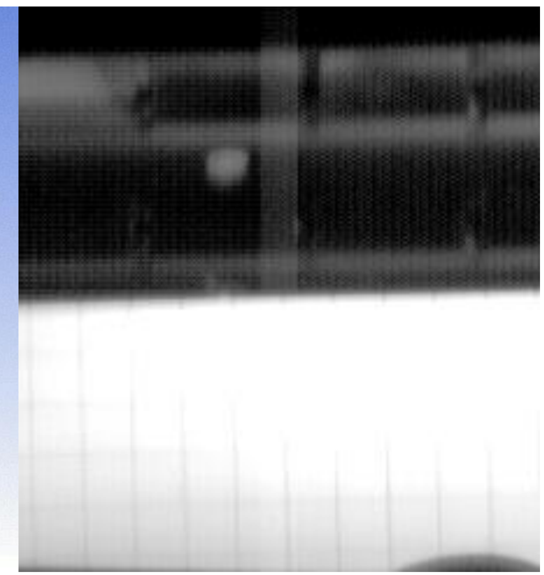
- Strain measurements on sample outer surface;
- Radial velocity measurements (LDV);
- Temperature measurements;
- Sound measurements.



**High Intensity Samples (Type 2)**

- Strain measurements on sample outer surface;
- Fast speed camera to capture fragment front formation and propagation;
- Temperature measurements;
- Sound measurements.



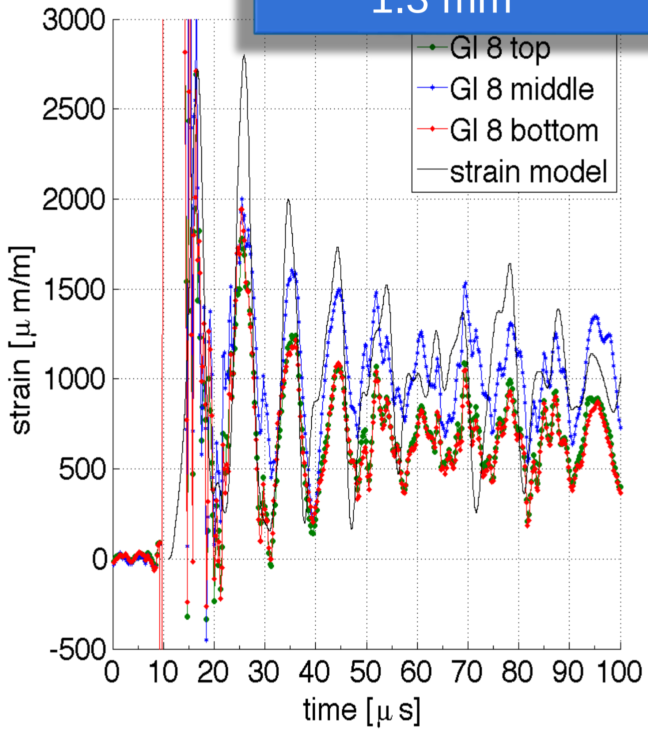



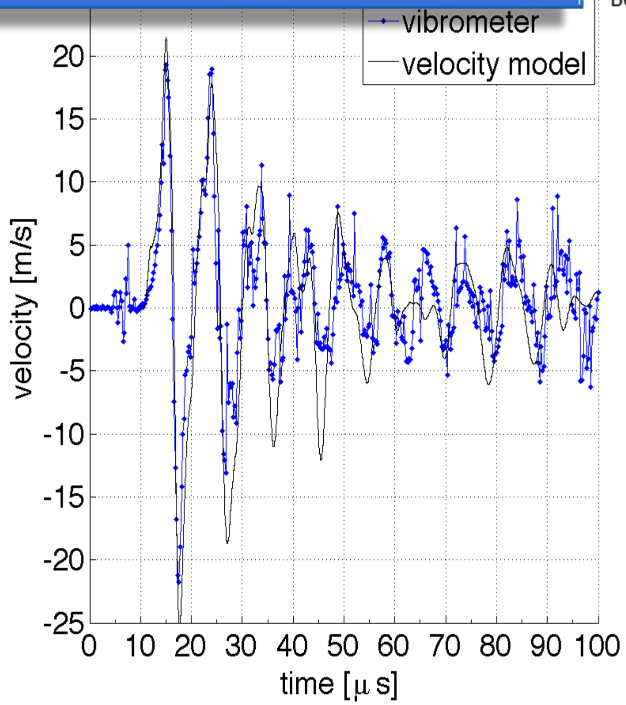
| Case | Bunches | p/bunch | Total Intensity | Beam Sigma | Specimen Slot | Velocity |
|---|---|---|---|---|---|---|
| Simulation | 60 | 1.5e11 | 9.0e12 p | 2.5 mm | 9 | **316 m/s** |
| Experiment | 72 | 1.26e11 | 9.0e12 p | 1.9 mm | 8 (partly 9) | **~275 m/s** |

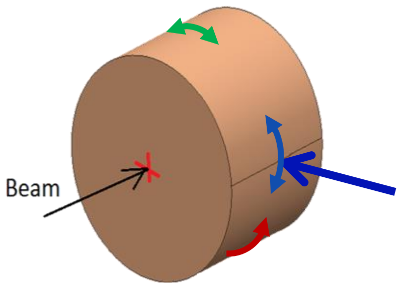
**2012: test of specimens from 6 different materials, including novel composites**

- Allowed characterization of materials of interest for collimators
- Tuning of numerical models, with very good benchmarking between measurements and simulations

Glidcop Sample – Slot#08
72 b (scraped), Total intensity: 4.66e12 p, σ ≅ 1.3 mm



# HRMT-14: Post Irradiation Tests

- Tank opened in **May 2015** in b. 109 (CERN), after **2 ½ years of cool-down**
- Activation was low, but **risk of contamination** due to radioactive fragments and powders (mostly Cu and W)
- Non-destructive and destructive tests planned

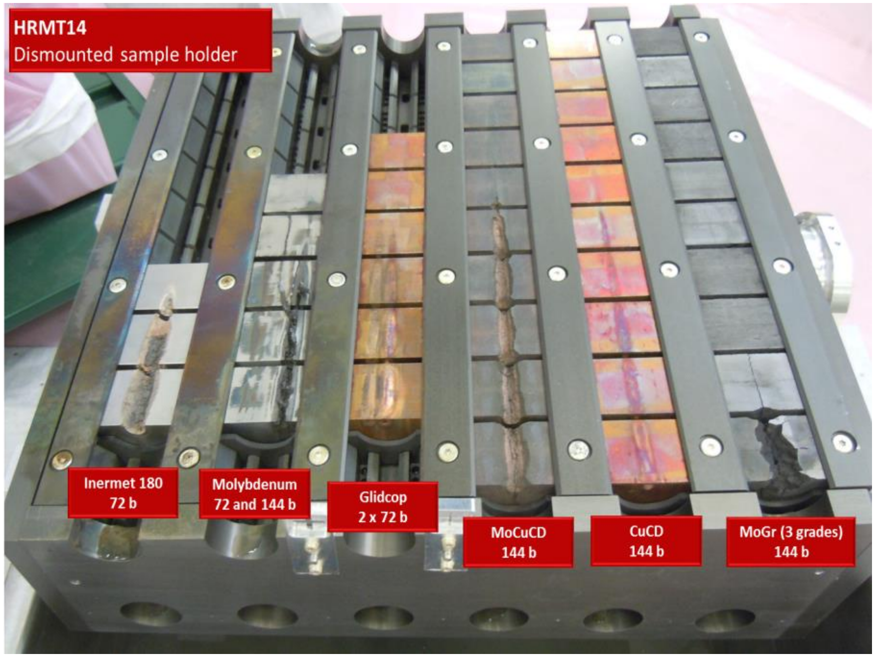
| | Order | TEST |
|---|---|---|
| NON-DESTRUCTIVE TESTING | | |
| | 1 | Visual Observation |
| | 2 | Radiography |
| | 3 | Optical microscopy |
| | 4 | SEM microscopy |
| | 5 | XRD |
| | 6 | Sigmatest |
| | 7 | Microhardness |
| | 8 | Degassing test |
| | 9 | Metrology |
| | 10 | Weight/Density meassurement |

+

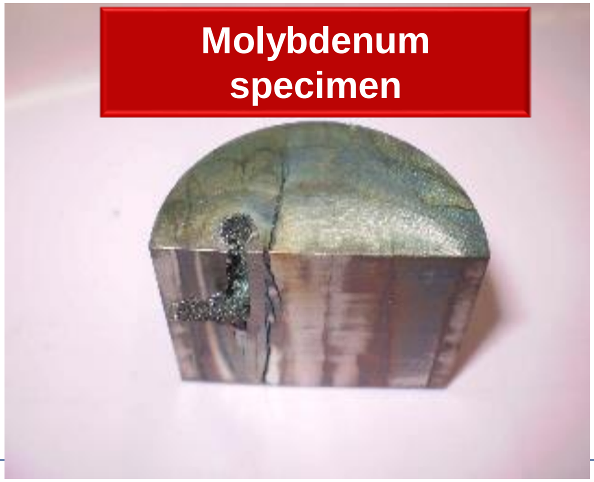
**Destructive**: inner section observations, machining of specimens for thermo-mechanical characterization, electrical conductivity measurements, etc.

# HRMT-14: Post Irradiation Tests

- Tank opened in **May 2015** in b. 109 (CERN), after **2 ½ years of cool-down**
- Activation was low, but **risk of contamination** due to radioactive fragments and powders (mostly Cu and W)
- Non-destructive and destructive tests planned

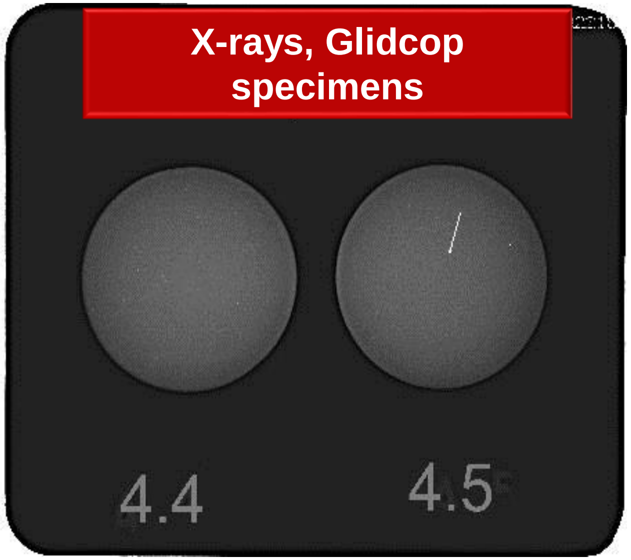




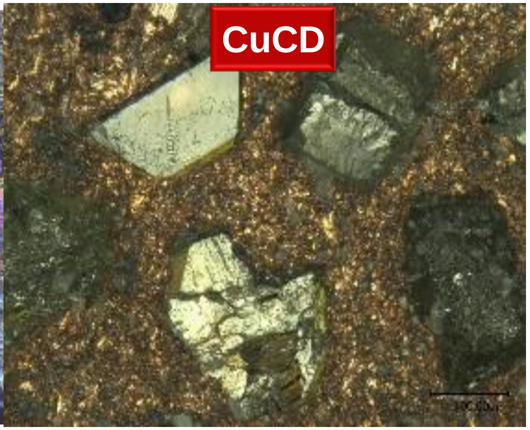


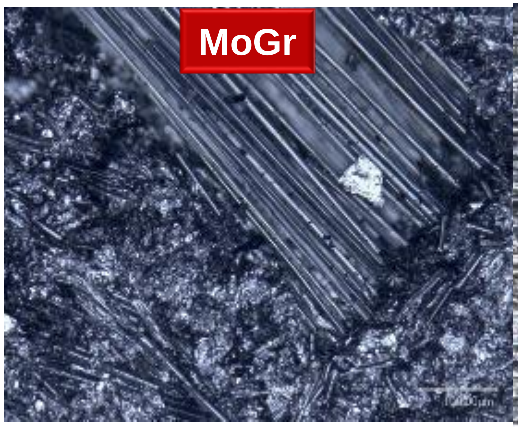
# HRMT-14: Post Irradiation Tests

- Radiography campaign did not reveal any major damage on top of what visible
- Optical microscopy highlighted shrinkage of copper-based materials








# Summary

- New materials developed in EuCARD[2], WP11: **MoGr** and **CuCD**
- Proposed as solutions for **HL-LHC collimators** (low-impedance primary and secondary, high-robustness tertiary)
- HiRadMat test (**HRMT-23**) in August 2015 to demonstrate the validity of the two HL-LHC collimators, and to test a TCSP at the energy density of HL-LHC injection error
- **CFC** and **MoGr survived** all impacts up to 288 b, σ 0.35 mm, grazing and deep impacts, **slightly in excess of peak energy density of HL-LHC and LIU BCMS Beam Injection Error**
- **CuCD survived** (with surface scratch) by 24 b, σ 0.35 mm roughly **equivalent to 1 full LHC bunch (asynchronous beam dump failure)**
- **TCSP Glidcop tapering locally melted**, **MoGr taperings** of TCSPM jaws **survived** unscathed the beam impacts → MoGr taperings to be considered also for all the other future collimators
- After HRMT-23, **green light for the construction of a prototype of secondary HL-LHC collimator (TCSPM) to be tested in the LHC in 2017** → production well ongoing

# Next steps

- **Numerical/experimental benchmarking:**
  - **The plastic model proposed for CuCD seems to work well**, still few points to be addressed (material damping, signal phase, full-scale model)
  - Plastic model to be extended also to **CFC** and **MoGr** (so far, anisotropic elasticity considered) → wrt CuCD, further difficulty is due to the **material orthotropy**
  - More sophisticated signal analysis ongoing (e.g. **wavelet analysis**)
- **HRMT-23 Post-irradiation campaign**:
  - **Tank opening** to be coordinated with RP, once activated dose will be low enough
  - With respect to past HiRadMat tests (HRMT-09 and HRMT-14) **lower level of contamination**
  - **Non-destructive** and **destructive tests** once opened
- **HRMT-14 Post-irradiation campaign**:
  - Non-destructive campaign almost finished, then global review of the results
  - Destructive characterization, with sample cutting for verifying the material properties after the impact, to start soon

Thank you.