Material Testing for Collimators

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on behalf of "Jaws" HRMT-23 experiment team and LHC Collimation Project

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5th Joint HiLumi LHC-LARP Annual Meeting
CERN – *28 October, 2015*

Engineering Department

Outlook

- Material tests in specialized laboratories
- Beam-impact experiments
  - TT40 tests (2004 & 2006)
  - HRMT09
  - HRMT14
  - HRMT23
- Future tests: MultiMat
- Conclusions

Engineering Department

LHC Collimation Project CERN

High Luminosity LHC

Why Do We Need Material Tests?

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- **Goal**: explore and determine consequences of Failure Scenarios affecting machine performance for LHC Run 2, Run 3 and HL-LHC

Failure Scenario	Beam Type	Beam Energy [TeV]	Intensity Deposit. [p+]	Beam Emittance [µm]	RMS beam size [mm]
Injection Error	LHC Ultimate	0.45	4.9e13	3.5	1
Injection Error	Run 2 BCMS	0.45	3.7e13	1.3	0.61
Injection Error	HL-LHC	0.45	6.6e13	2.1	0.77
Injection Error	LIU BCMS	0.45	5.8e13	1.3	0.61
Asynchronous Beam Dump	BCMS Run 2	7	1.3e11	1.3	~0.5
Asynchronous Beam Dump	HL-LHC	7	2.3e11	2.1	~0.6

- Demonstrate the viability of a **low-impedance collimator solution**
- Address the issue of **TCT robustness limit**
- Demonstrate the **robustness of present carbon-based collimators (TCS, TCP)** against injection failures with smaller emittances

Why Do We Need Material Tests?

- **Two main categories of tests for collimator materials:**
  - Characterization of **material specimens** in a specialized laboratory (CERN EN/MME Laboratory, Politecnico di Torino)
    - Allows to evaluate the main mechanical and thermo-physical properties at different levels of strain, strain rate and temperature
    - Main contribution to material models
  - Proton/Ion beam or laser impacts on **material specimens or full devices**
    - Facilities such as **HiRadMat** (CERN), **Eli-NP** (Bucharest, Romania)
    - Reproduction of conditions as close as possible to those of HL-LHC
    - Benchmarking of simulations
    - Validation of the design of full devices
    - Highlights of possible additional issues (vacuum, RP activation, contamination, etc.)

Laboratory Tests

Courtesy of O. Sacristan and L. Peroni

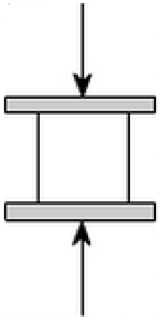
THERMAL DIFFUSIVITY

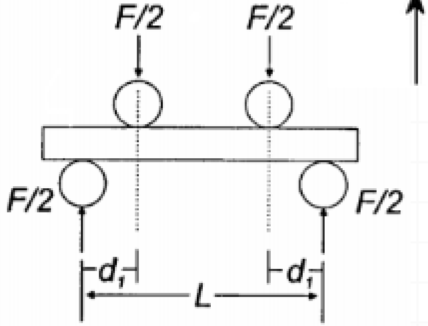
THERMAL EXPANSION

SPECIFIC HEAT

ELASTIC CONSTANTS

MECHANICAL PROPERTIES (STATIC)





MECHANICAL PROPERTIES (DYNAMIC)

Hopkinson bar –Politecnico di Torino (Vercelli)

HiRadMat: TT40 Tests (2004 & 2006)

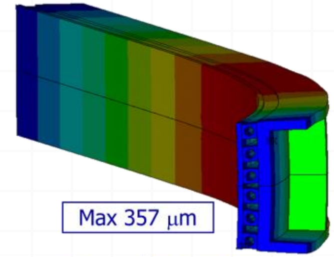
2004: **full TCSG** collimator in TT40 (CFC + Graphite blocks)

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

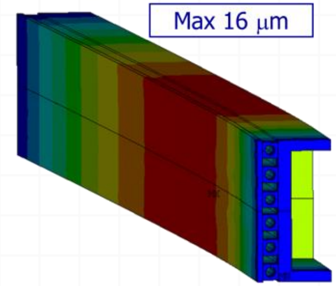
2006: **full TCSG** collimator in TT40 (CFC)

Glidcop housing: minimized deflection. This validated the final TCP/TCS design

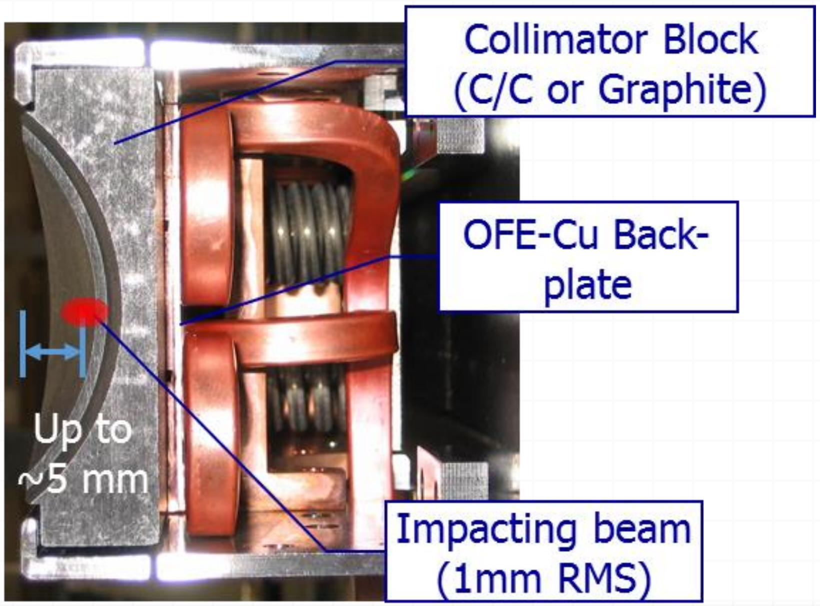
Full intensity shots from 1 to 5 mm, 3.2x10^{13} p, 7.2μs, σ=1 mm

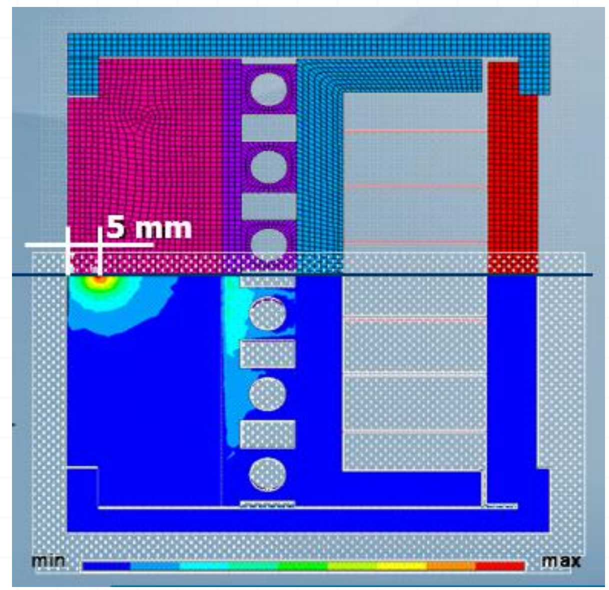


2004: Cu deformation



2006: Glidcop deformation





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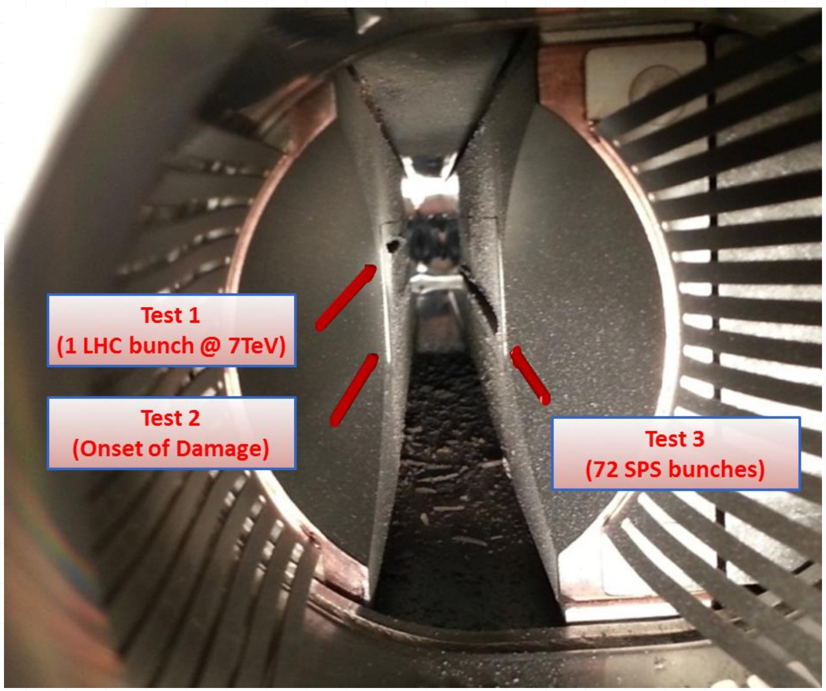
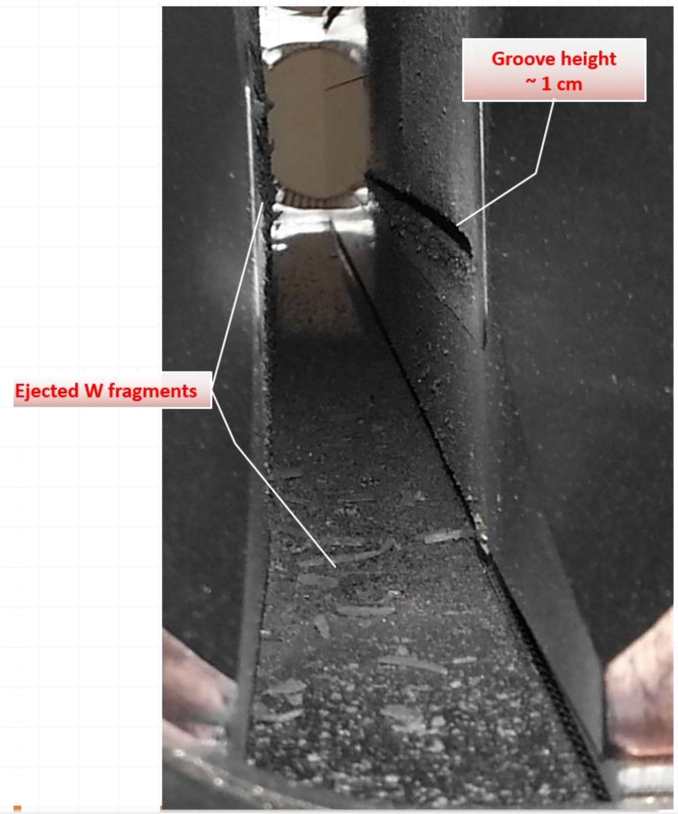
HiRadMat: HRMT-09

2012: full TCT collimator (Tungsten alloy)

- Allowed to derive **damage limits for tertiary collimator jaws**
- Highlighted **additional potential machine protection issues on top of mechanical damage**, due to projection of fragments and dust (UHV degradation, contamination of vacuum chambers, complication of dismounting procedure)





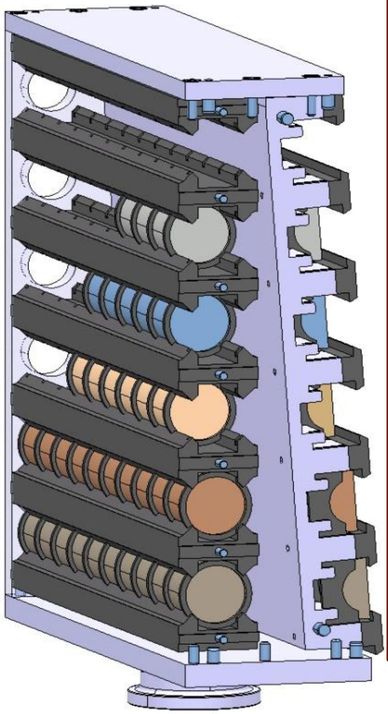
HiRadMat: HRMT-14

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

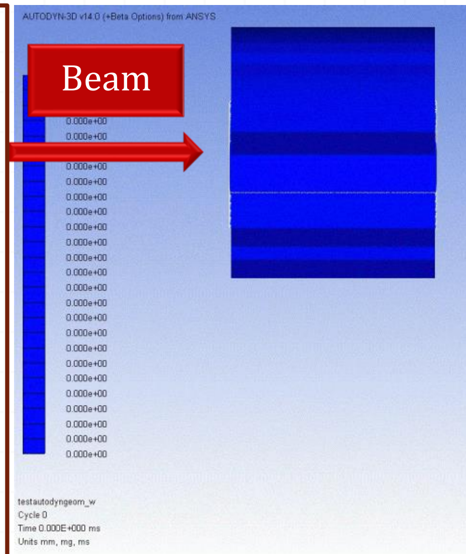
Medium Intensity Samples (Type 1)

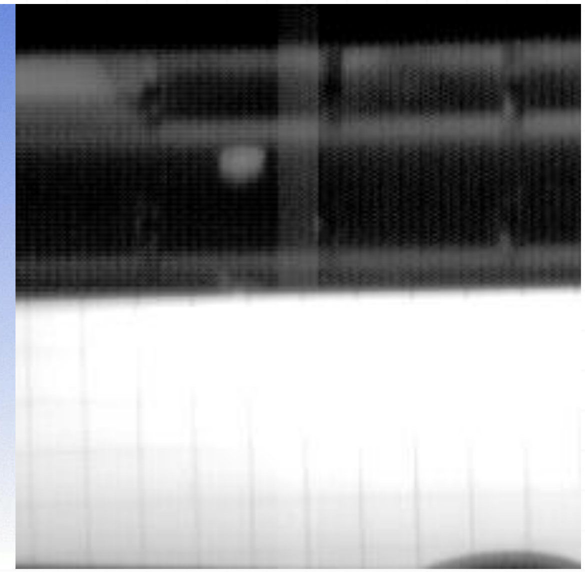
- Strain measurements on sample outer surface;
- Radial velocity measurements (LDV);
- Temperature measurements;
- Sound measurements.



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.





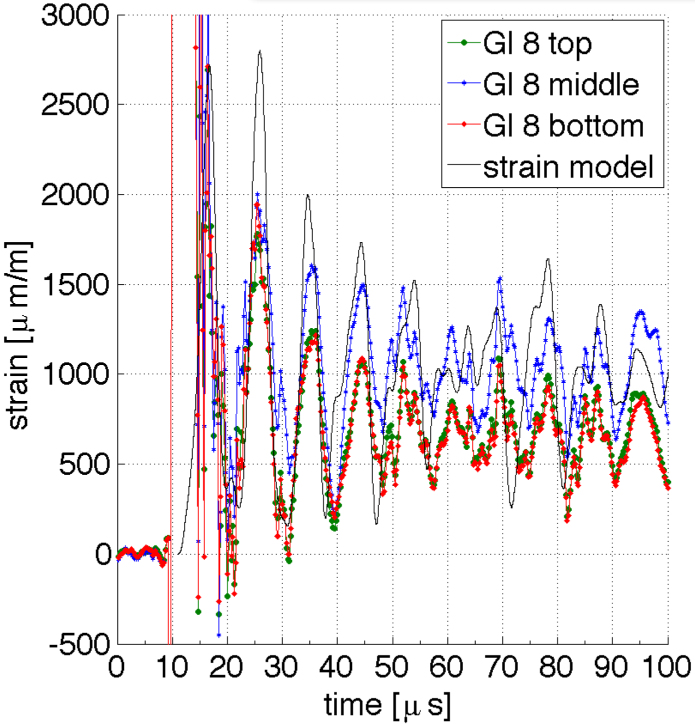
Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	316 m/s
Experiment	72	1.26e11	9.0e12 p	1.9 mm	8 (partly 9)	~275 m/s

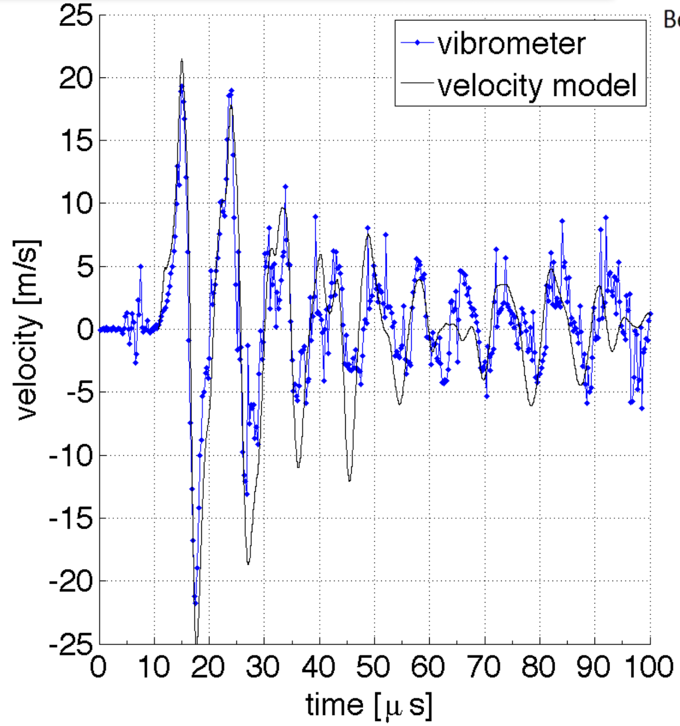
HiRadMat: HRMT-14

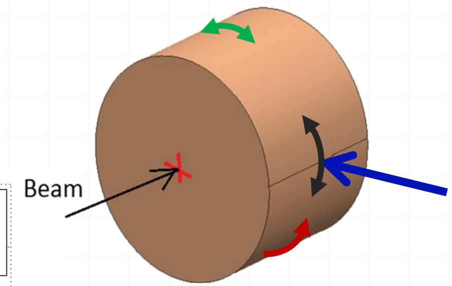
2012: test of specimens from 6 different materials, including novel composites

- 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.

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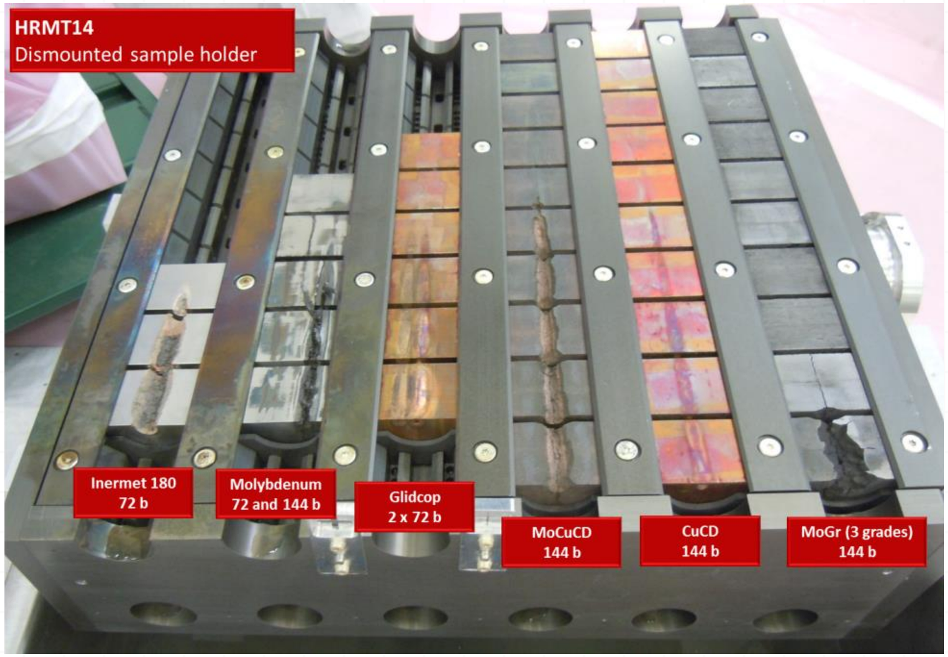
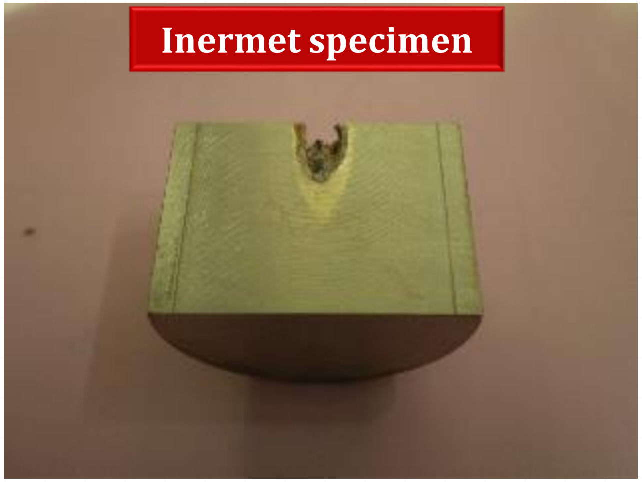
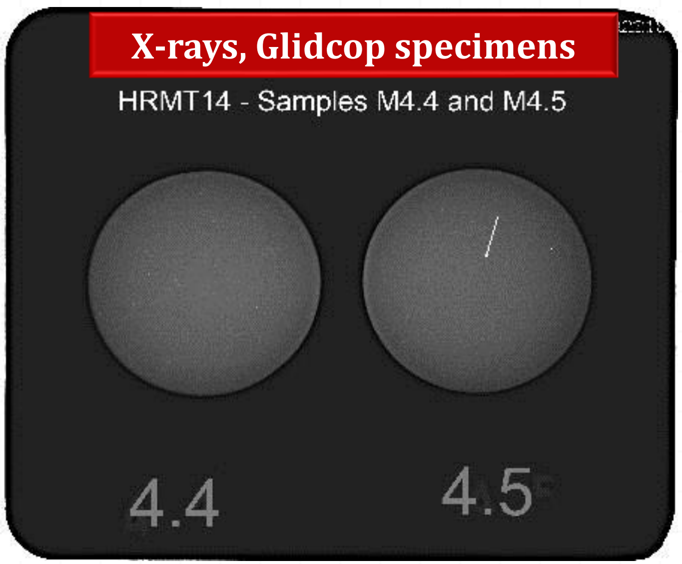
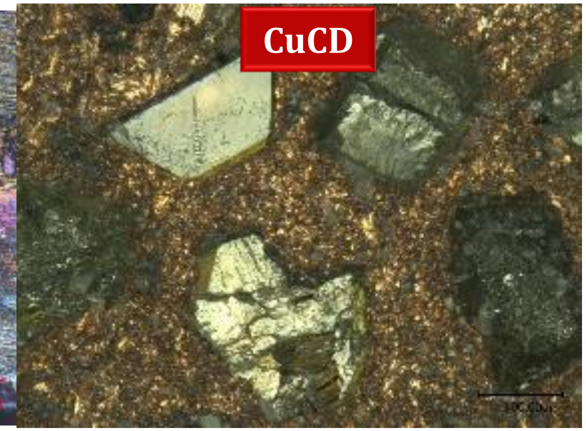


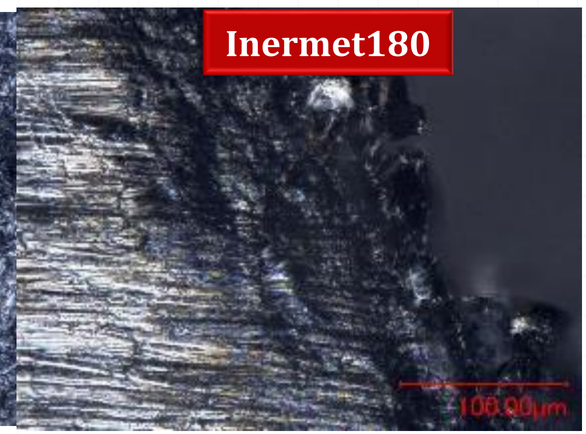


HRMT-14: Post Irradiation Tests

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







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HRMT-23 Experiment

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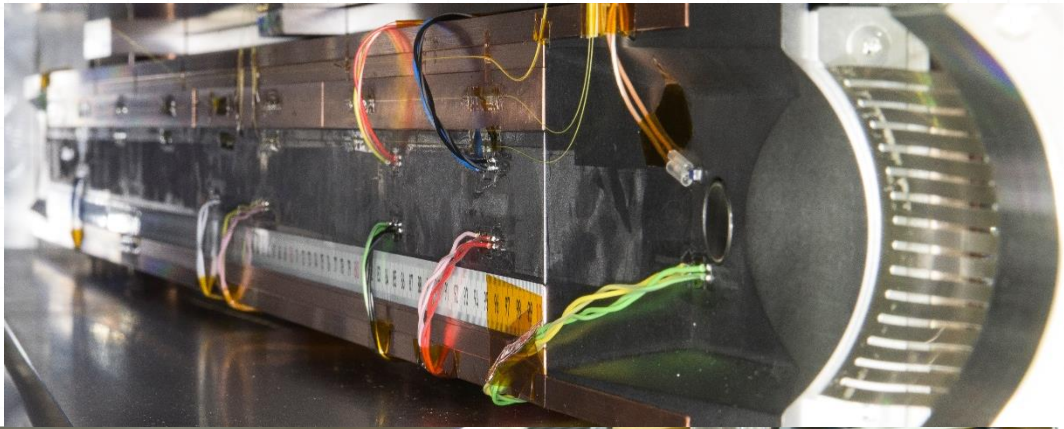
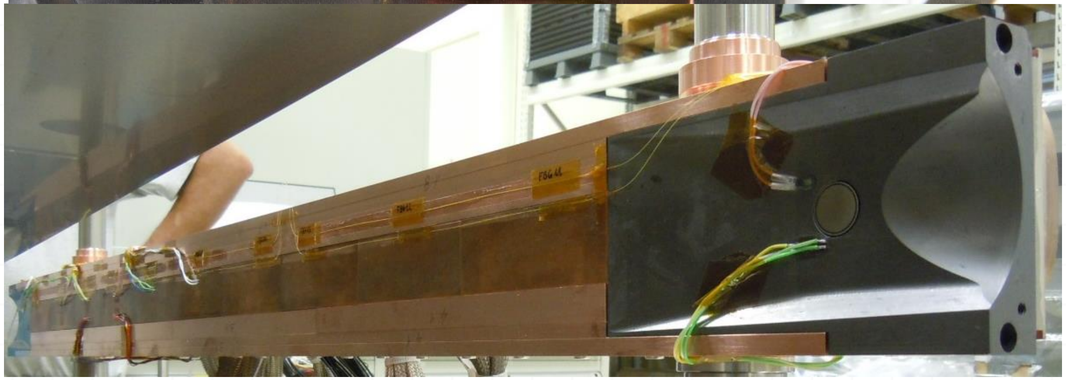
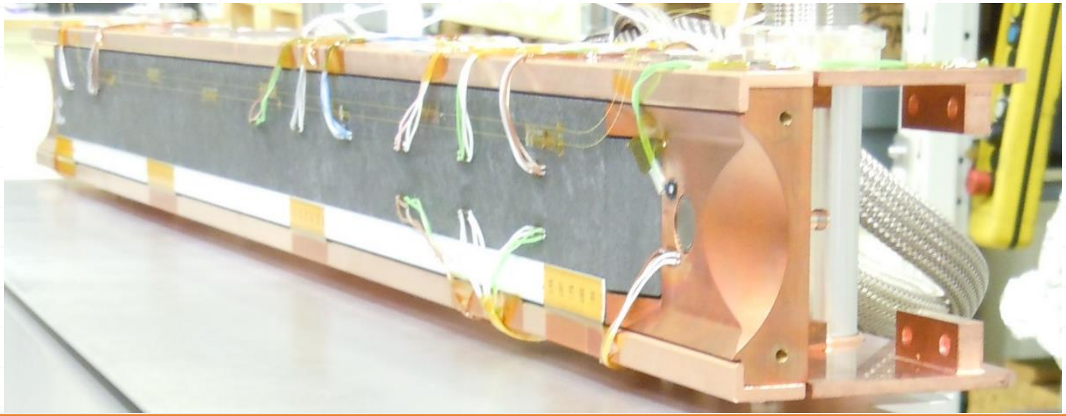
1. **HL-LHC Secondary Collimator Jaw** (TCSPM) with 8 **MoGr** inserts and taperings



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



3. **TCSP jaw**: to verify the resistance of Phase I C/C jaw to beam injection accident with HL-LHC parameters



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**
- 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 Instrumentation

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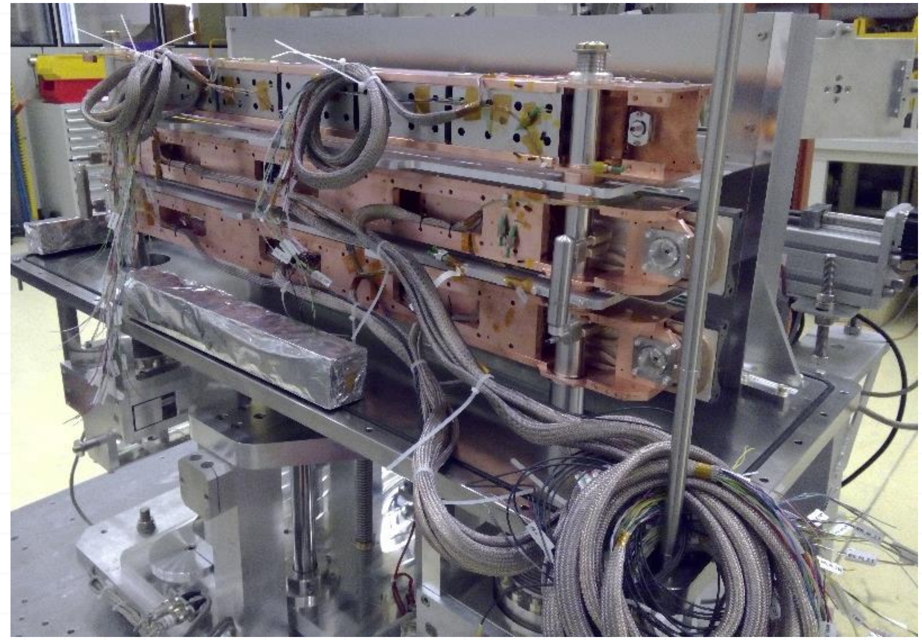
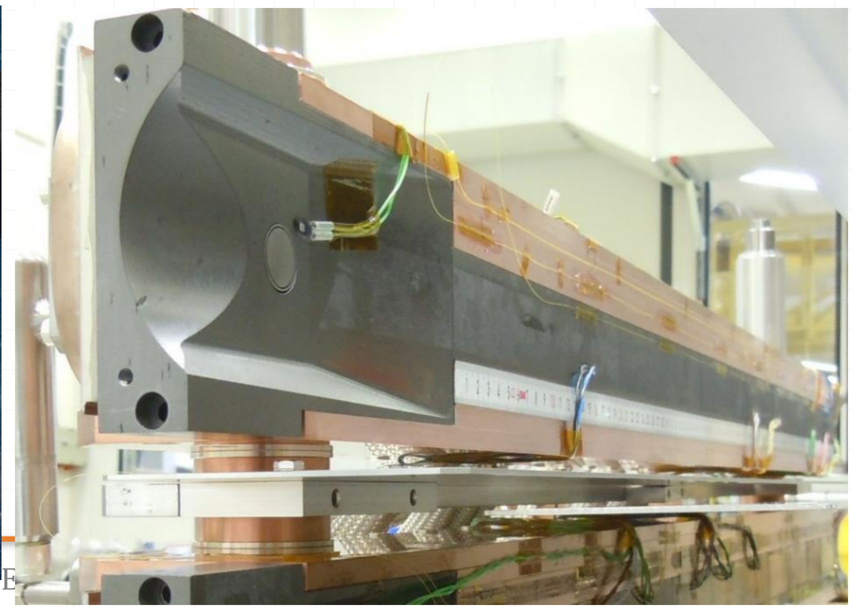
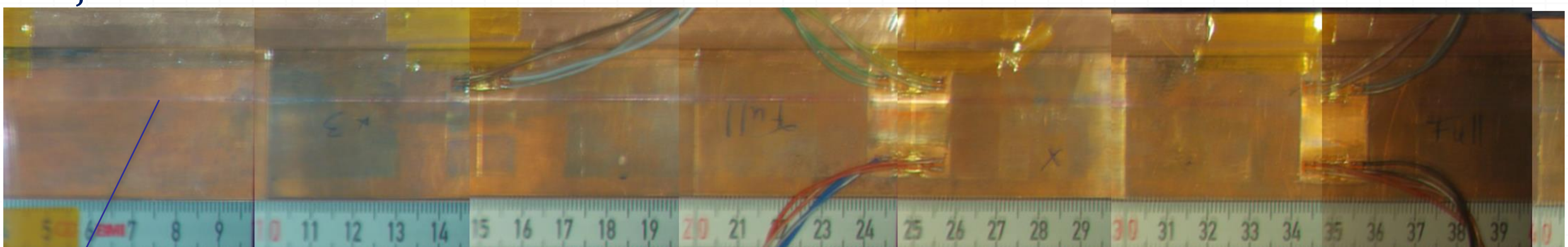
Experiment Instrumentation	Sampling frequency
126 electrical strain gauges	4 MHz
42 temperature probes	200 Hz
Laser Doppler Vibrometer	4 MHz
Water pressure sensor	100 kHz
60 strain Optical Fibre Bragg Gratings	500 Hz
Inspection HD Camera (4K)	-
High Speed Camera + LED lighting system	20 000 fps
In-jaw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



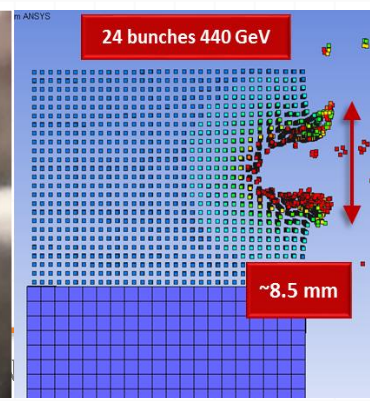


HRMT-23 First Results, CuCD

- **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, with peak energy density 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 alternative 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)

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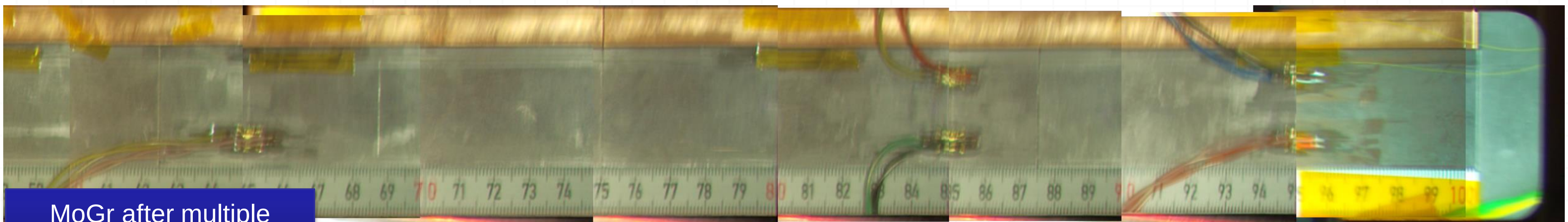
HRMT-23 First Results, CuCD

Impacts on CuCD jaw
48 bunches, σ 0.35 mm, Impact depth 0.5 σ

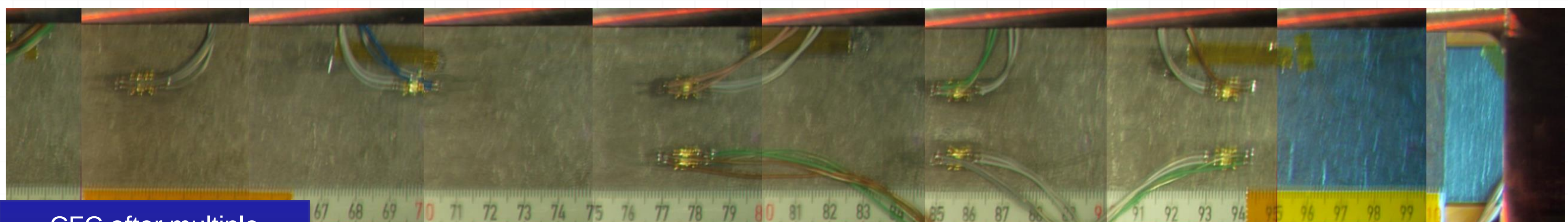
Impacts on CuCD jaw
72 bunches, σ 0.61 mm, Impact depth 1 σ

HRMT-23 First Results, MoGr&CFC

- **MoGr** on HL-LHC jaw survived the impact of several **288 b pulses** with σ down to 0.35 mm (**peak energy density slighly higher than HL-LHC and BCMS LIU 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**



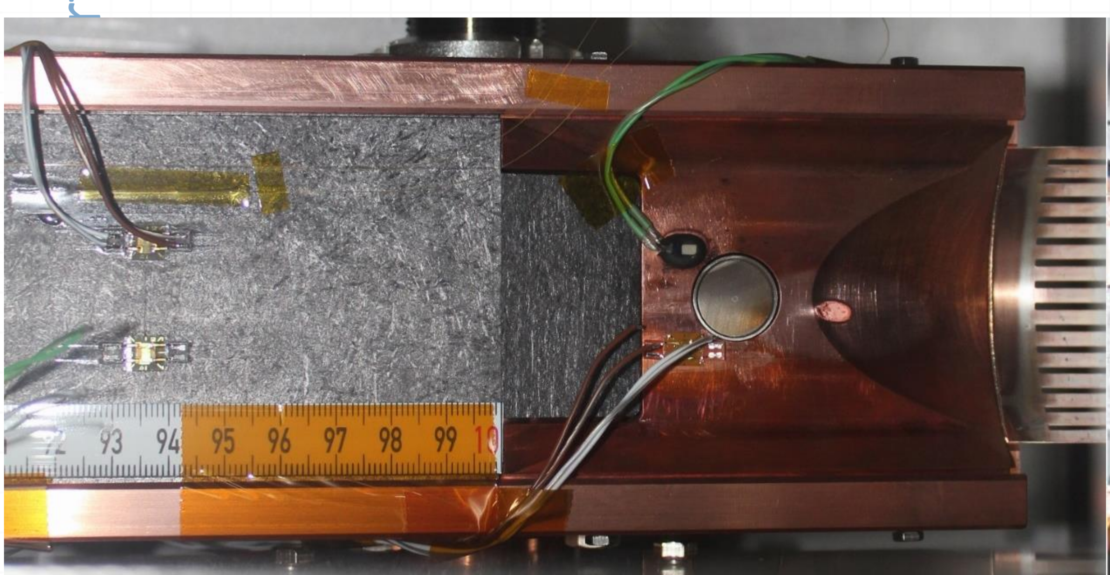
MoGr after multiple impacts



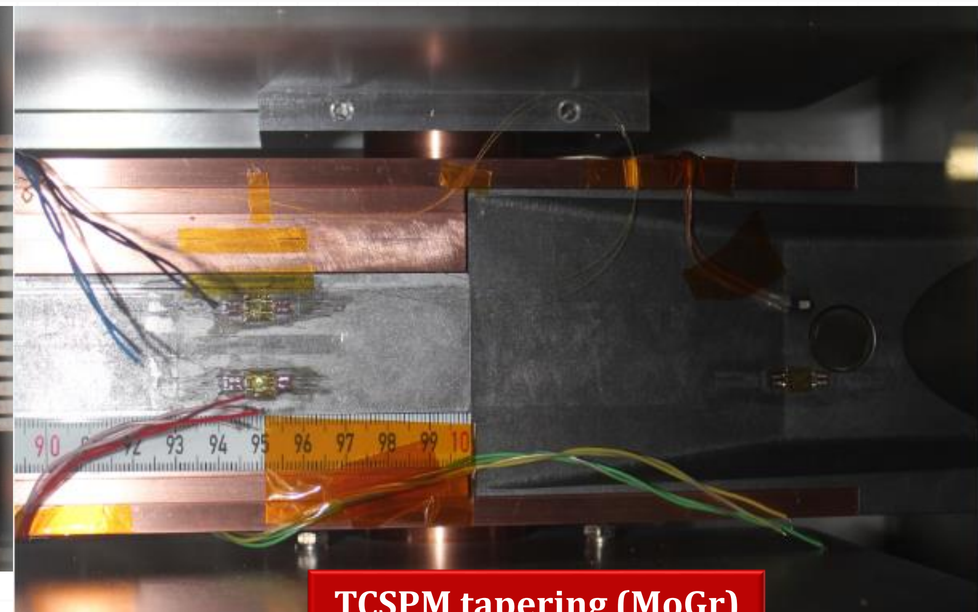
CFC after multiple impacts

HRMT-23 First Results, MoGr&CFC

- Post-irradiation HD pictures were taken one month after the experiment
- A hole in the TCSP Glidcop tapering was observed, while the two TCSPM jaw taperings, in MoGr, are 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



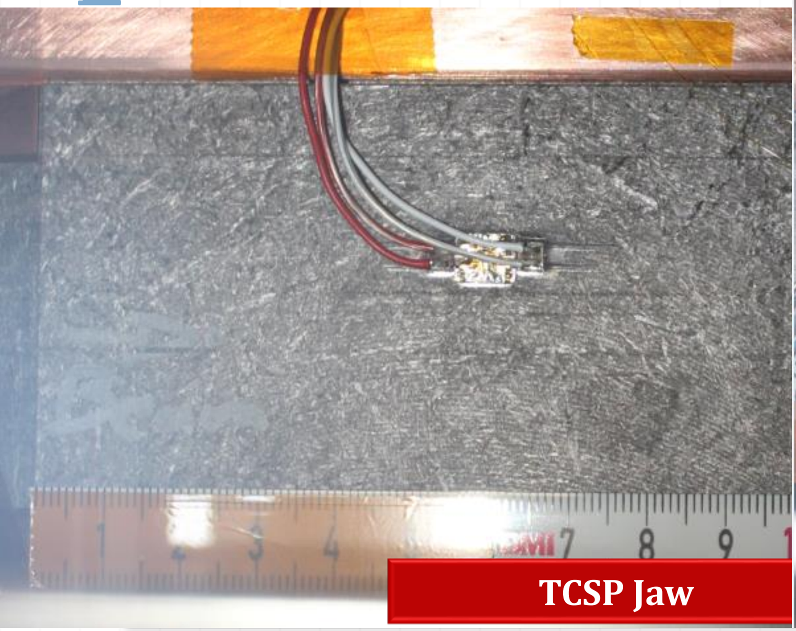
TCSP tapering (Glidcop)



TCSPM tapering (MoGr)

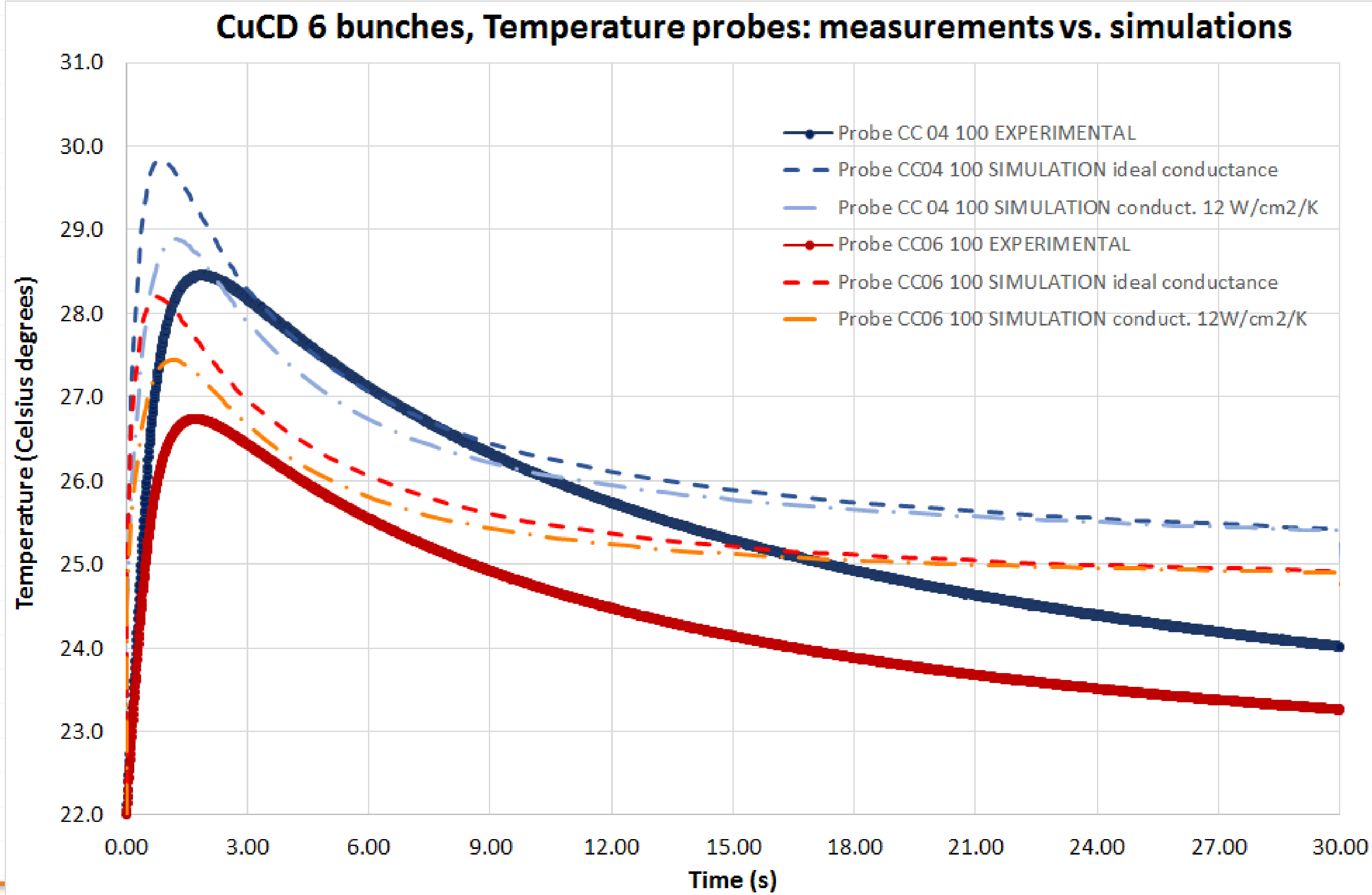
HRMT-23 First Results, MoGr&CFC

- 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**



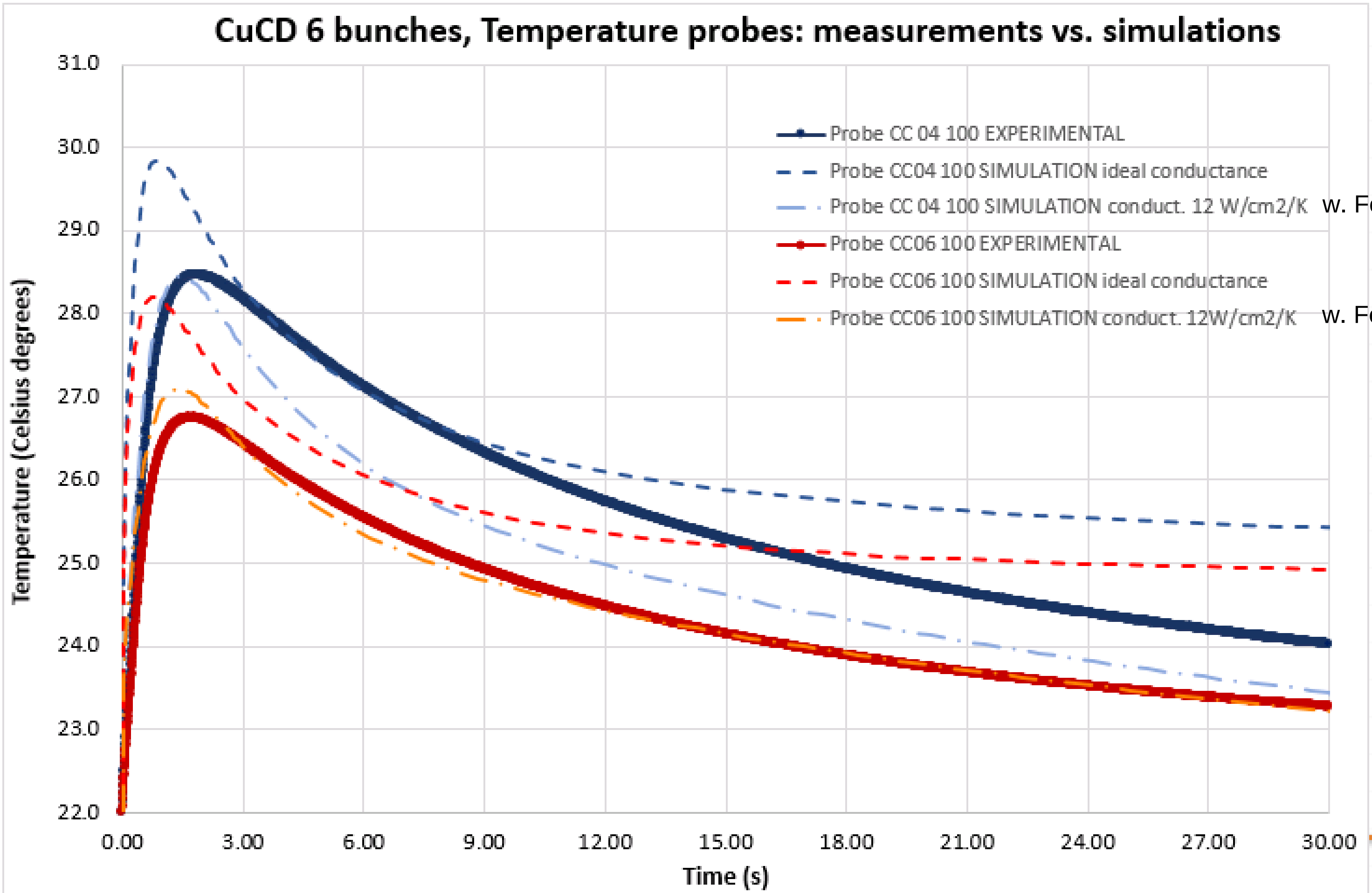
HRMT-23 Numerical/Experimental Benchmarking

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



HRMT-23 Numerical/Experimental Benchmarking

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



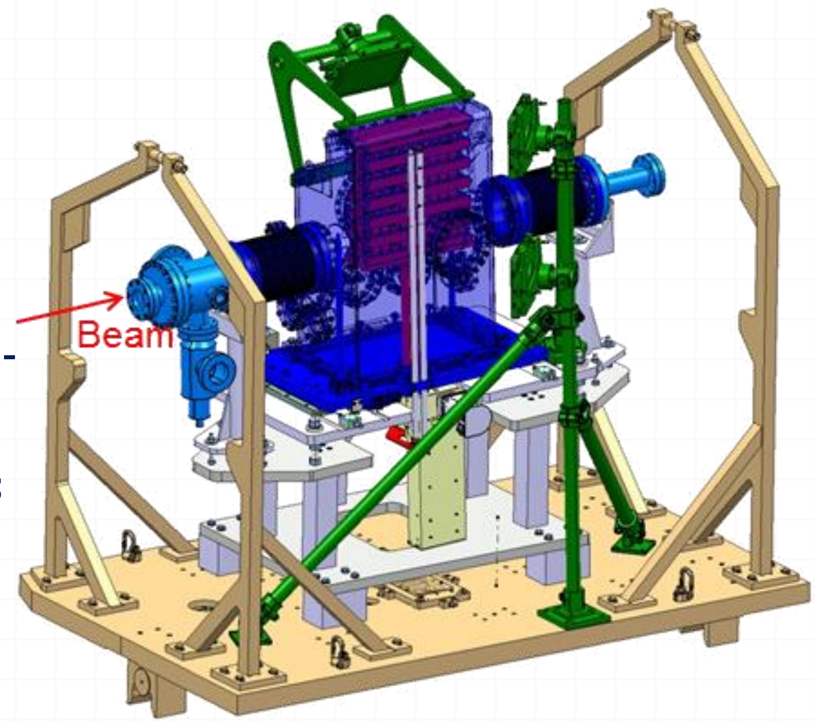
What's Next: MultiMat

- **TT40/HRMT-09 → HRMT-23**
  - Improved instrumentation for **monitoring of temperature**
  - Addition of **strain gauges, LDV, HD and high-speed camera, US probes**
  - Shock-wave propagation into **water**

- **HRMT-14 → MultiMat**
  - Sample holder including materials of interest for injection and dump absorbers, protection devices (in addition to collimators)
  - Improved geometry and instrumentation to be able to acquire clear signals from **low-Z materials** (problematic in HRMT-14)
  - **Synergy** with other projects such as **TDI, TCDI, etc.**
  - Join forces, optimize resources and share costs between **BE/ABP, BE/OP, EN/MME, EN/STI, TE/ABT**
  - Scientific board of HiRadMat already approved the proposal! Scheduled for **2017**

What's Next: MultiMat

- **MultiMat goals**:
  - Test samples of novel/advanced materials under very bright beams
  - Acquire online exploitable data particularly for low-Z materials
  - Confirm/extend constitutive model for high-Z materials
  - Benchmark not-yet-explored effects such as code coupling
- Beam intensity up to 288 bunches, 2.3e11 p/b, beam size down to 0.3x0.3 mm^2 → **target is HL-LHC equivalent energy density**
- Design and instrumentation inspired by HRMT14 experiment
- **12 target stations** each hosting several specimens



- **Estimated size: 2100x1200x400 mm^3**
- **Estimated weight ~ 1.5 tons**

Engineering Department

What's Next: MultiMat

- Materials to be tested will likely include:
  - Molybdenum Carbide – Graphite
  - Copper - Diamond
  - Other Ceramic-Graphite composites (under development)
  - Carbon/Carbon (both 2D and 3D grades)
  - Graphite
  - Boron Nitride
  - Glidcop
  - Molybdenum
  - Tungsten heavy alloys (Inermet, W-Re etc.)
- Coatings also to be tested:
  - High-conductivity (electrical)
  - Vacuum-relevant coatings? (NEG, carbon, ...)

HiRadMat High-Radiation to Materials

HiRadMat - Experiment Proposal
EDMS No: 1213282
Version 2.0

HiRadMat Beam Time Request Form

Designation	
Experiment Name	to be assigned
Acronym	to be assigned

Date	08.09.2014

General		
Responsible/primary contact		Person completing this beam request
Name	Alessandro Bertarelli	
Home institute	CERN	
E-mail	alessandro.bertarelli@cern.ch	
Phone	+41-22-7672337	
Participating institutes	Politecnico di Torino, Italy Participations from other EuCARD2 partners are also possible.	List of participating institutes, relevant information for EuCARD2 Transnational Access.
Number of team members	At least 2	Estimated number of persons participating to the preparation and/or the experiment with travel/stay at CERN.
Interested in Transnational Access	Yes	More information at http://cern.ch/hiradmat

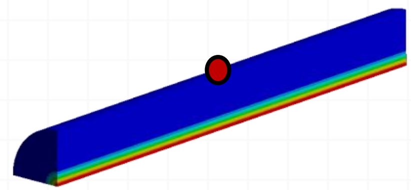
Scientific description		
Executive summary	Impact tests with beam pulses up to HL-LHC nominal injection parameters (440 GeV, 288 bunches, 2.3e11 p/b) on a several target stations each hosting specimens made of one relevant materials. The experiment includes a comprehensive acquisition system monitoring on- and off-line the response of material specimens to beam impacts.	A very short (couple of phrases) description of the scientific purpose and the experimental setup.
Scientific motivation	During the post-LS1 runs and, even more, in the HL-LHC era, machine components located close to the beam orbit must meet extremely demanding requirements against the consequences of accidental beam impacts, considering the expected increase in beam intensity and brightness.	Extended description of the scientific purpose (couple of paragraphs) including the expected scientific results.

MultiMat Specimens

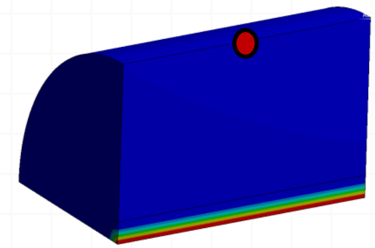
Specimen shapes and dimensions are being optimized (disks, cylinders, bars …), varying according to material to improve measurements sensitivity.

Dynamic behaviour after impact

Material Graphite (R4550 grade)
Energy: *Radial* gaussian axialsymmetric
Axial Constant
Regime: Elastic

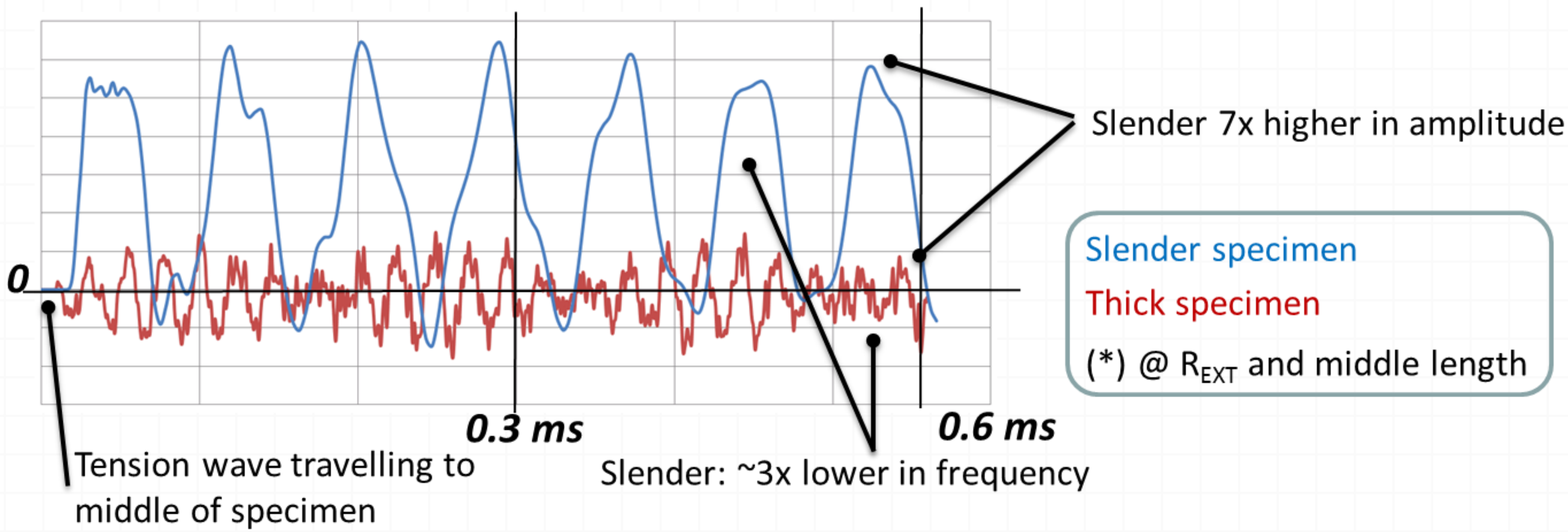


Ø=12 mm, L=100 mm



Ø=30 mm, L=40 mm

Axial Strain [-] VS. time [ms] (*)

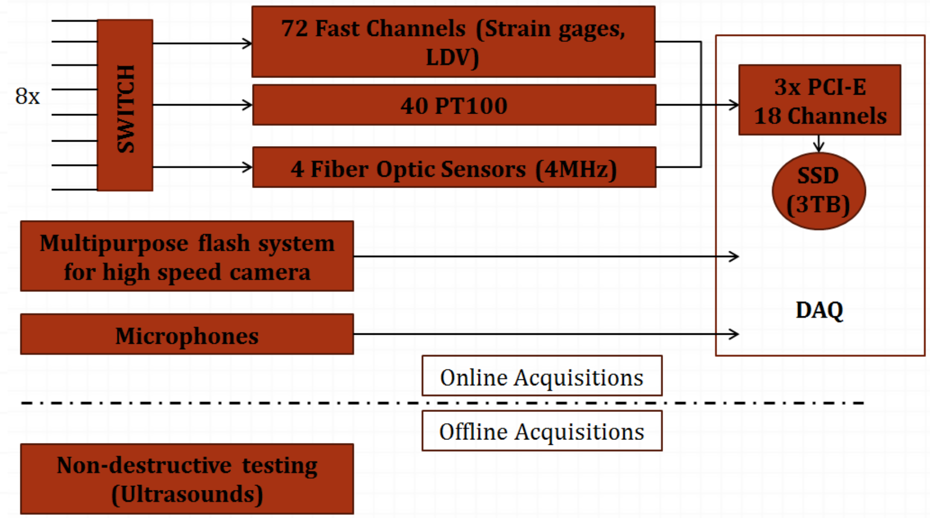


MultiMat Instrumentation

- Instrumentation (MME Mechanical Lab). Main objectives:
  - Acquire online pressure waves at relevant locations.
  - Acquire online temperatures on relevant locations.
  - Detect online high speed vibrations (pressure wave – induced)
  - Detect online low speed oscillations (typically induced on slender structure by off-center beams)
  - Visually Record (possible) specimen explosion / fragmentation
  - Detect offline (possible) internal material damage (e.g. delamination, cracks, tunneling …)
- Motorization: controls and hardware compatible with HRMT-14. Updated software interface required. Help by EN/STI/ECE …
- Acquisition System: the DAQ hardware and infrastructure should be designed and implemented with a comprehensive view on a larger spectrum of HiRadMat Experiments ⇨ ***Modular DAQ with synergy with and contribution from other experiments and projects.***

MultiMat Instrumentation

- A modular acquisition system is being developed to allow online and offline monitoring of several HiRadMat experiments:
  - 8:1 switch for online acquisition
    - 72 fast channels (strain gages, LDV)
    - 40 PT100
    - 4 Fibre Optic Sensors (FOS)
  - Flash or LED system for wider range of applications, to be used together with high speed cameras
  - Non-destructive testing (Ultrasounds)



Engineering Department EN

MultiMat Post-Irradiation

- After successful experience with HRMT-14 PI: exploiting existing facilities in **building 109** equipped to work on contaminated materials
- Design to be studied keeping in mind **space constraints** given by b. 109 machines!
- In particular for opening system

Summary (1/2)

- In the last ~10 years, several **beam-impact tests** on collimator and collimator materials have been performed

- Tests in **2004** and **2006** validated the CFC-based collimator design (TCP, TCS)

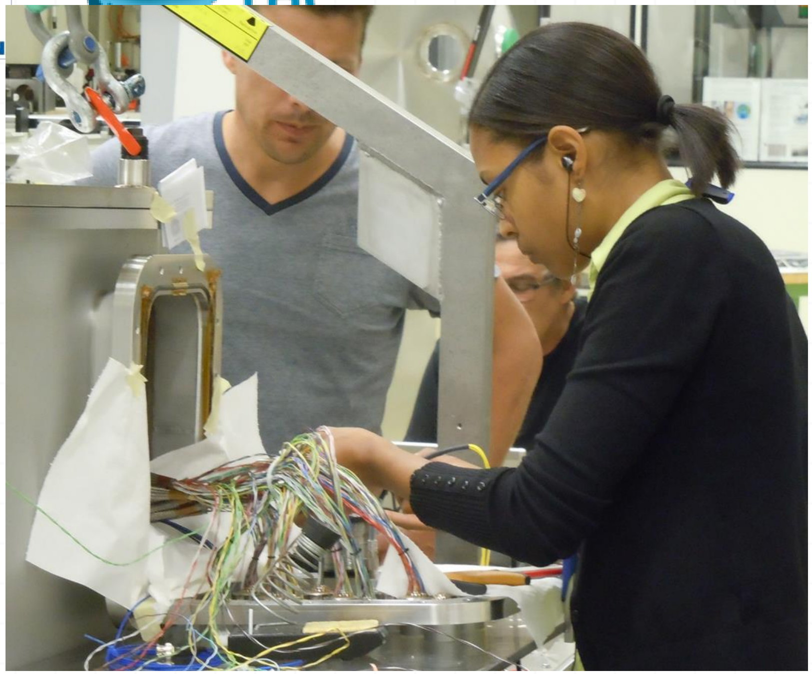
- Tests in **2012** in the HiRadMat facility showed the **low robustness of tungsten tertiary collimators (HRMT09)** and characterized **novel materials for HL-LHC challenges (HRMT14)**

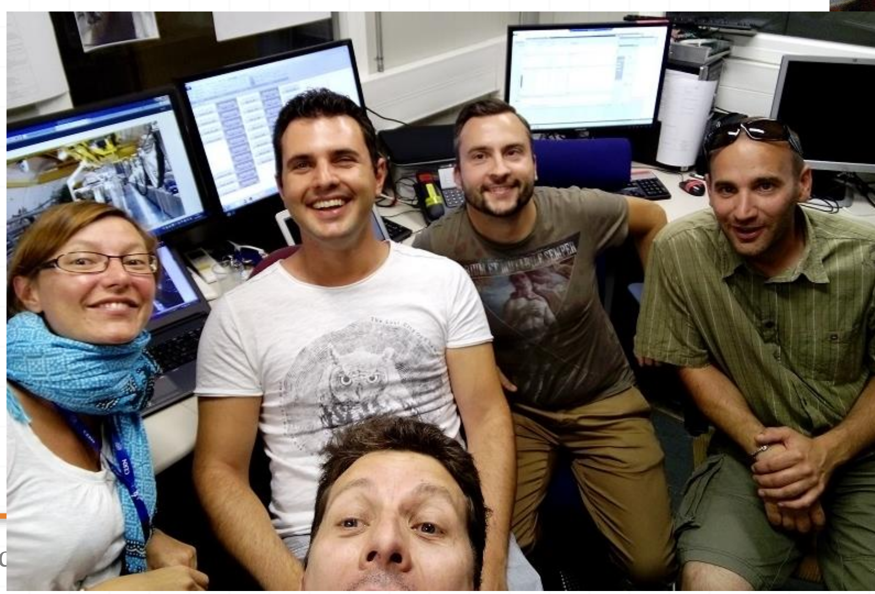
- A **new secondary collimator design** has been proposed in 2014 around CuCD and MoGr, to cope with the demanding HL-LHC requirements (in particular **impedance, robustness and geometrical stability**)

- A **new HiRadMat test (HRMT-23) was run 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

Summary (2/2)

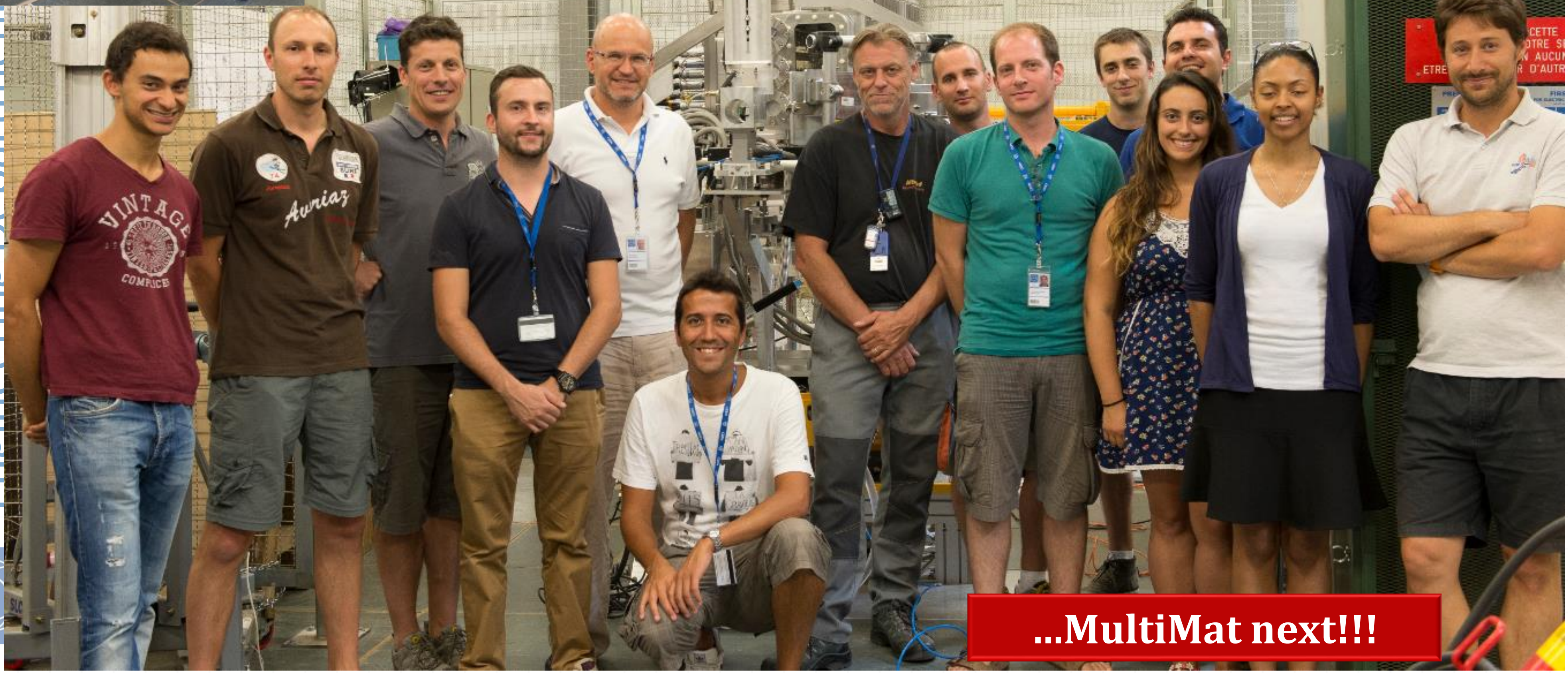
- HRMT-23 preliminary considerations:
  - **CFC** and **MoGr** seemingly **survived** all impacts up to **288 b, σ 0.35 mm**, grazing and deep impacts, slightly **in excess of peak energy density of HL-LHC and LIU BCMS Beam Injection Error**
  - **CuCD survived** (with surface scratch) by **24 b, σ 0.35 mm roughly equivalent to 1 full LHC bunch** (asynchronous beam dump failure)
  - Contrarily to Glidcop, **MoGr taperings of TCSPM jaws survived unscathed the beam impacts** → MoGr taperings to be considered also for all the other collimators with embedded BPMs!
  - Instrumentation and controls, which worked very well in spite of R2E in the service tunnel, can possibly reused in series production!
- **MultiMat** experiment will **complement and improve HRMT-14 test**, including materials for **collimators, injection and dump absorbers**, **protection devices**, and exploring further **mechanisms of shock-wave propagation**
- Collaboration with other departments and groups (BE/ABP, BE/OP, EN/MME, EN/STI, TE/ABT, ...)
- **Experiment scheduled in 2017 → Engineering design to start soon!**





Thank you all for your attention!

From HRMT14 (2012)...



... to HRMT23 (2015)...

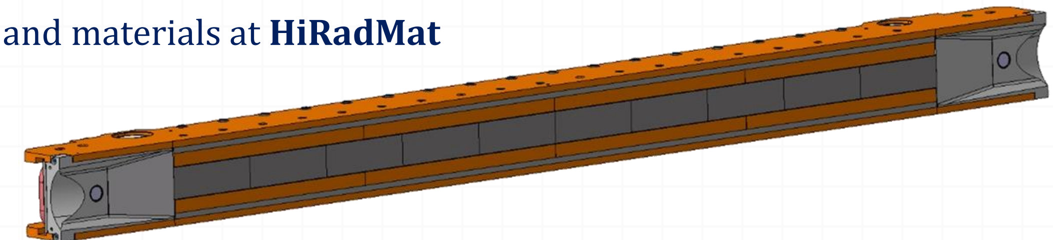
...MultiMat next!!!

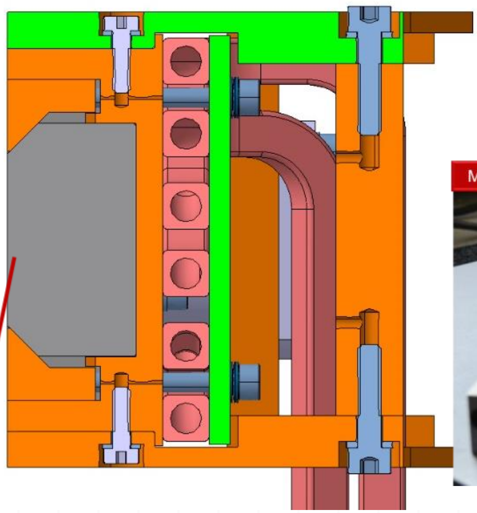
Backup slides

Engineering Department

HRMT-23: HL-LHC Collimator Design

- **Modular design** allowing to install 8 or 10 jaw inserts made of **advanced materials** (**MoGr** or **CuCD**), with optimized RF features
- (Ambitious) timeline (defined by the ATS directorate after the 2013 review) aiming to produce a **full collimator prototype** for beam tests in LHC in 2016/17
- Pre-requisite: **full validation** of new design and materials at **HiRadMat**





MoGr (high robustness)
CuCD (higher density)

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).*

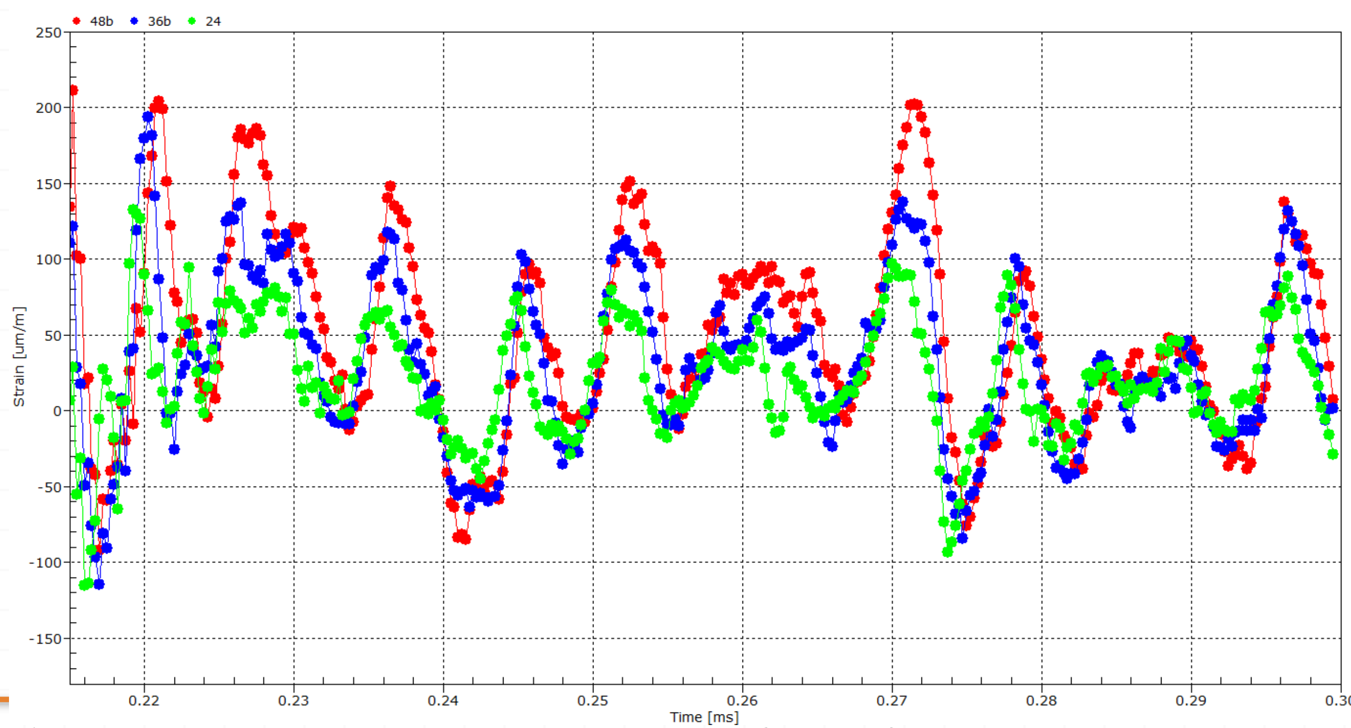
Favorite option for low-impedance, high-robustness Secondary Collimators

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

HRMT-23 First Results Overview

- **HRMT-23 successfully installed and operational** in line with HiRadMat planning.
- **All instrumentation, control and acquisition systems worked remarkably well** including newly operated systems such as fibre optics sensors and ultrasound sensors.
- High R2E in particular at the end of the experiment, at high intensity shots: this triggered an **upgrade of the shielding system in the parallel tunnel**

24, 36, and 48 bunches in MoGr. Signals recorded by high-frequency resistive strain-gauges



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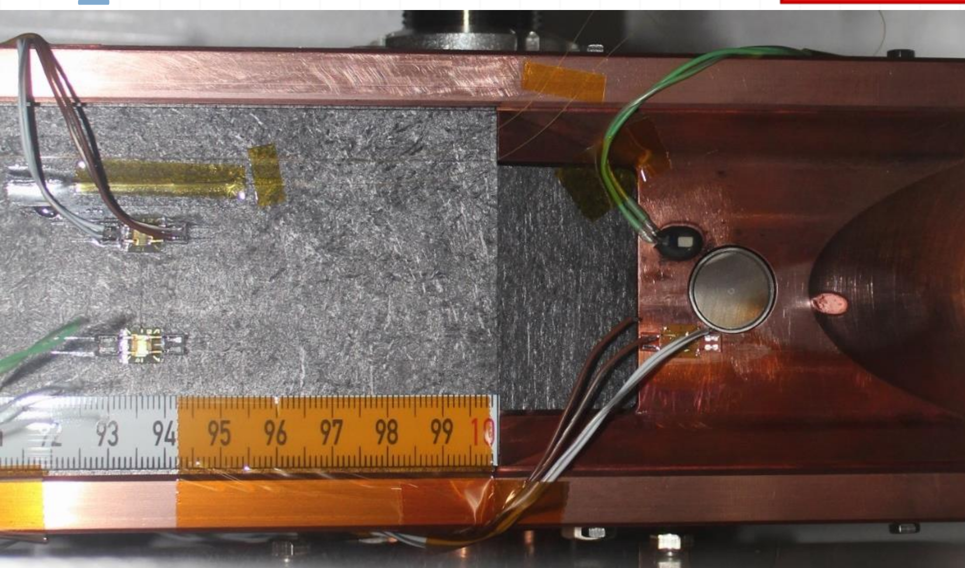
HRMT-23 Experiment

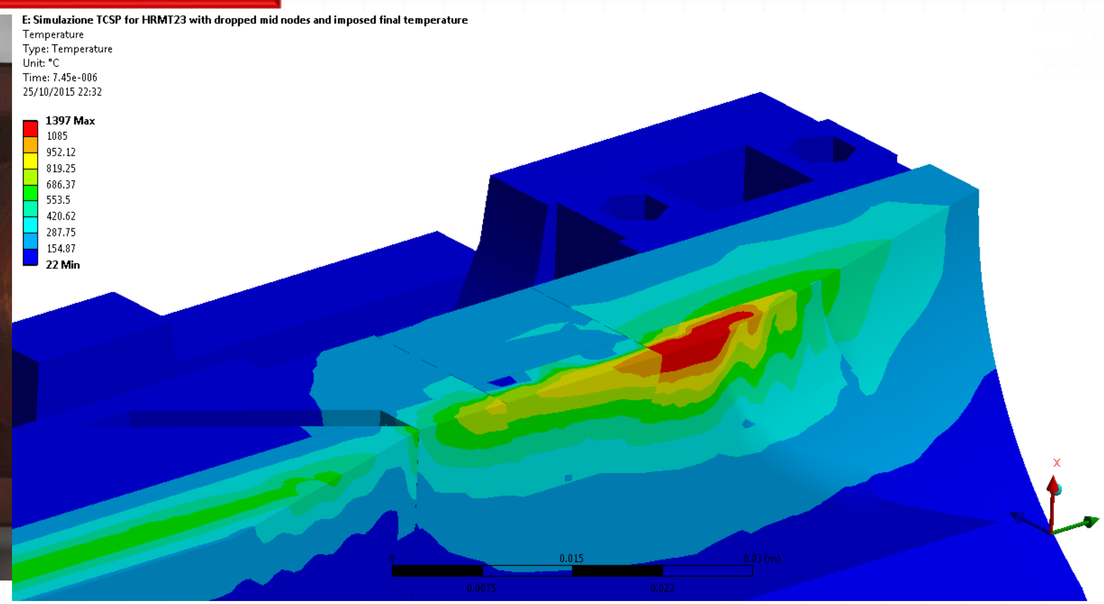
- **3** separate **complete jaws** extensively instrumented.
- **Stainless steel vacuum vessel** (p > 10^{-3} mbar). Quick dismounting system to access and manipulate jaws in a glove box.
- **Be/CFC vacuum windows**: design to withstand higher energy density and intensity
- **Horizontal actuation** inspired 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 HRMT-14
- **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 Numerical/Experimental Benchmarking

- **THERMAL: TCSP 288bunches, σ 0.35 mm, impact 5 mm**
- **Simulation: σ 1 mm, impact 5 mm**
- Hole dug in the Glidcop tapering

TCSP CFC 288 bunches

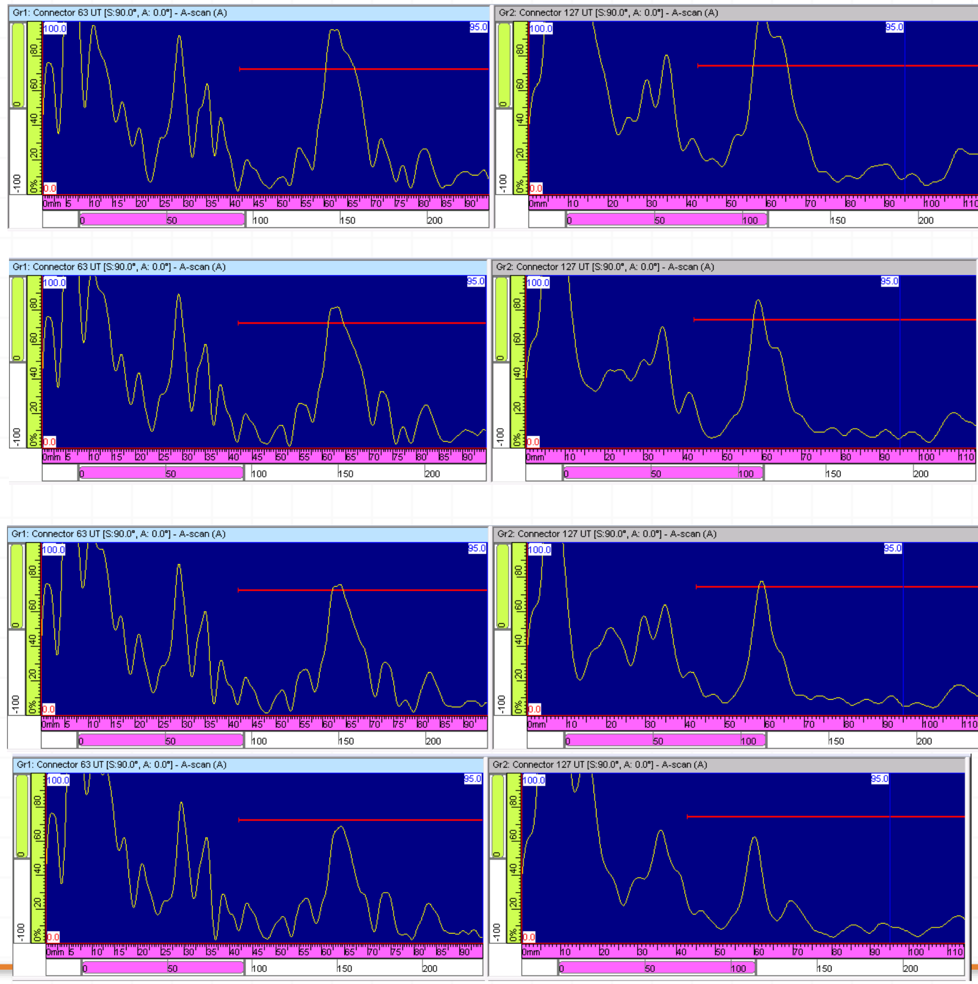




HRMT-23 First Results Overview

Ultrasound signals readout from CuCD Jaw

UT probe glued | UT probe + grease



27 July 2015, 22:32:19
Before shot 233

Shot 233 (24 b)
Grease: amplitude drop of backwall echo + change in intermediate echoes
Glue: small amplitude drop of backwall echo

27 July 2015, 23:42:51

Shot 234 (24 b)
Grease: amplitude drop of backwall echo + change in intermediate echoes
Glue: small amplitude drop of backwall echo

27 July 2015, 23:51:55

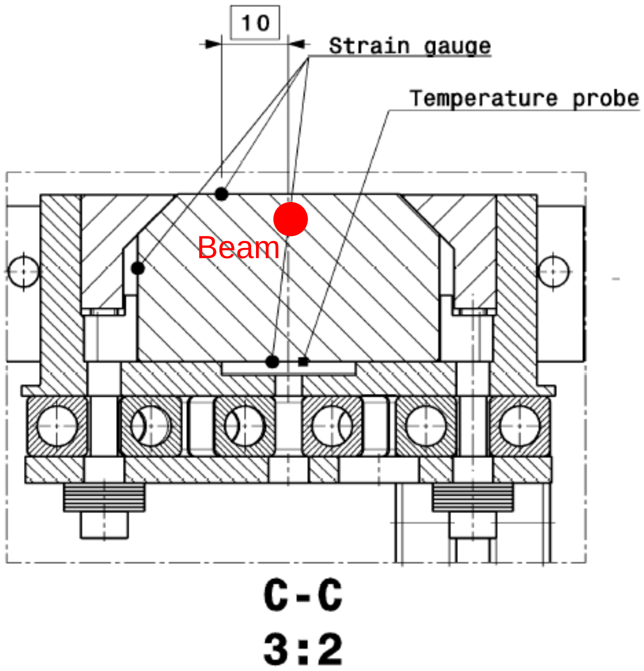
Shot 259 (24 b)
Grease: amplitude drop of backwall echo + change in intermediate echoes
Glue: small amplitude drop of backwall echo

28 July 2015, 01:05:27

Preliminary Experimental/Numerical Benchmarking

- Benchmarking started using the available FLUKA maps (courtesy of **E. Skordis, A. Lechner**)
- Existing FLUKA analyses possibly to be complemented in the future, including the impact scenarios not simulated yet (in particular, only one impact depth is present for the σ 0.35 mm)
- We are focusing on **the thermal simulations/measurements** at first
- Example: temperature probes on CuCD jaw

Section view of instrumented TCSPM jaw

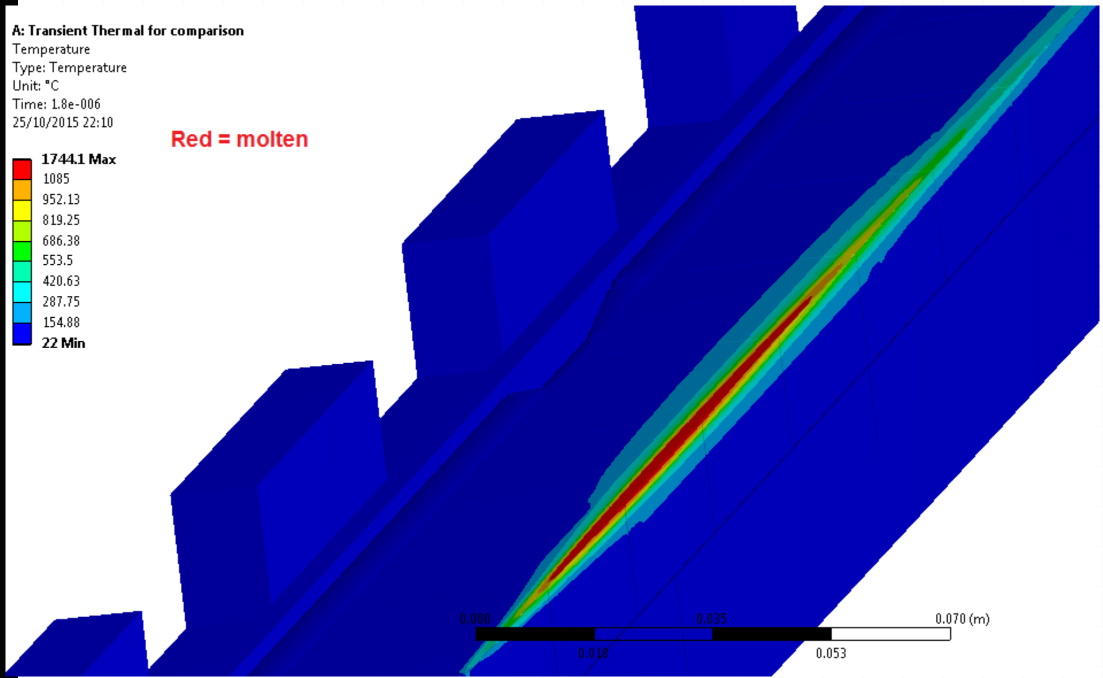


Engineering Department

Preliminary Experimental/Numerical Benchmarking

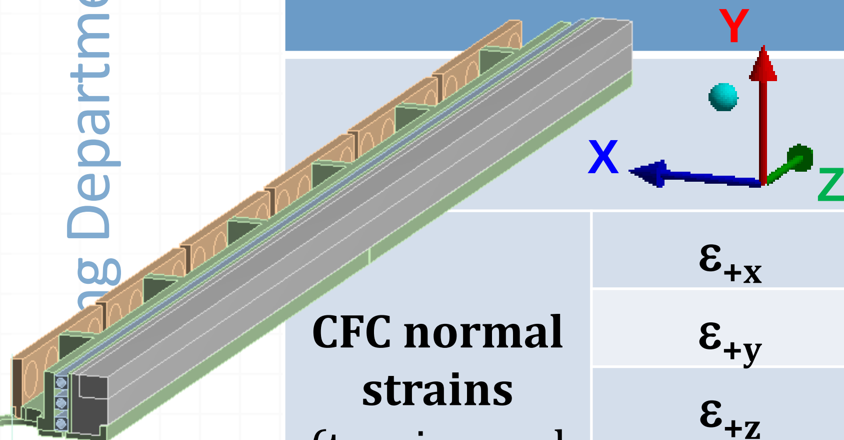
- **THERMAL: CuCD 72 bunches, σ 0.61 mm, impact 1σ**
- Both CuCD bulk and Cu coating melted and were ejected

TCSPM CuCD 72 bunches



Preliminary Experimental/Numerical Benchmarking

- While thermal simulations on MoGr are ongoing, and structural on the three materials are next, **a structural simulation performed on BCMS beam features parameters very close to a HRMT-23 case**
- BCMS cases simulated: 144 & **288** bunches, σ **0.61** & 1 mm, impact 1σ



Simulated scenarios: summary of results

		144 bunches		288 bunches		Reference
		0.61	**1**	**0.61**	**1**	
CFC normal strains (tension and compression) [μm/m]	ε_{+x}	650	700	2000	2100	2600
	ε_{+y}	400	320	800	730	850
	ε_{+z}	400	320	470	440	1800
	ε_{-x}	-2500	-2800	-7600	-7700	-150000
	ε_{-y}	-180	-170	-410	-470	-8000
	ε_{-z}	-80	-80	-160	-170	-7500
Plastic strain on jaw components		0	0	0	0	

Preliminary Experimental/Numerical Benchmarking

- Damage of the jaw not expected, although very close to the limits in case of 288 b → **likely numerical simulations conservative wrt reality?** (material damping, strain hardening, improvement of graphite materials with temperature all not considered)