Brief Recall of HRMT Tests: Preliminary Considerations on Jaw Robustness for HL Beams

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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 – *26 October, 2015*

Engineering Department

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Outlook

- Introduction and motivations of beam impact tests on collimators
- Overview of past beam impact experiments
- HRMT-23 "Jaws"
  - Experiment description
  - First results
  - Preliminary experimental/numerical benchmarking
- Conclusions and next steps

Why Do We Need Beam-Impact Tests?

- **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

Overview of Past Beam-Impact Tests

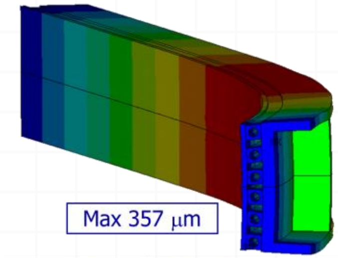
2004: **full TCSG** collimator in TT40 (CFC + Graphite blocks)

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

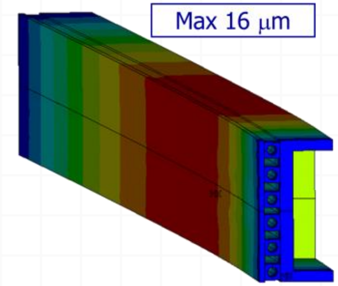
2006: **full TCSG** collimator in TT40 (CFC)

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

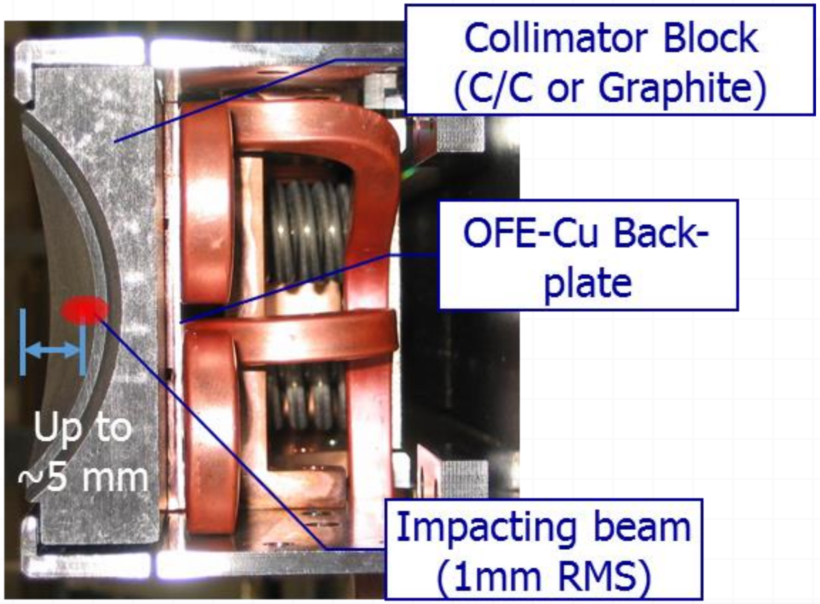
Full intensity shots from 1 to 5 mm, 3.2x10^{13} p, 7.2 μs, σ =1 mm

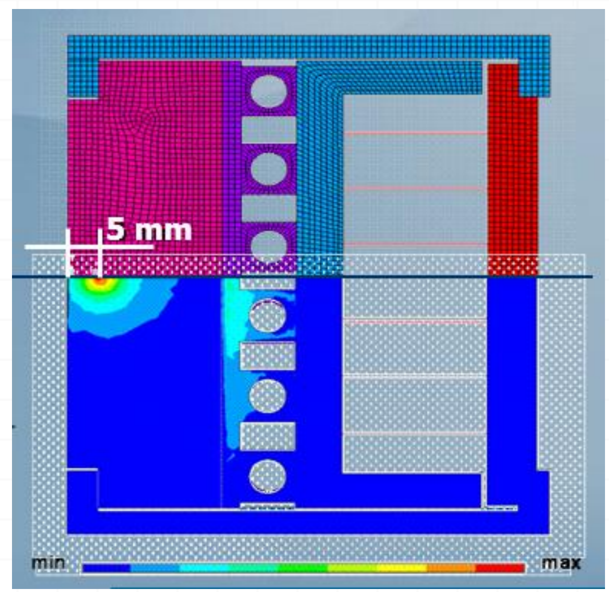


2004: Cu deformation



2006: Glidcop deformation

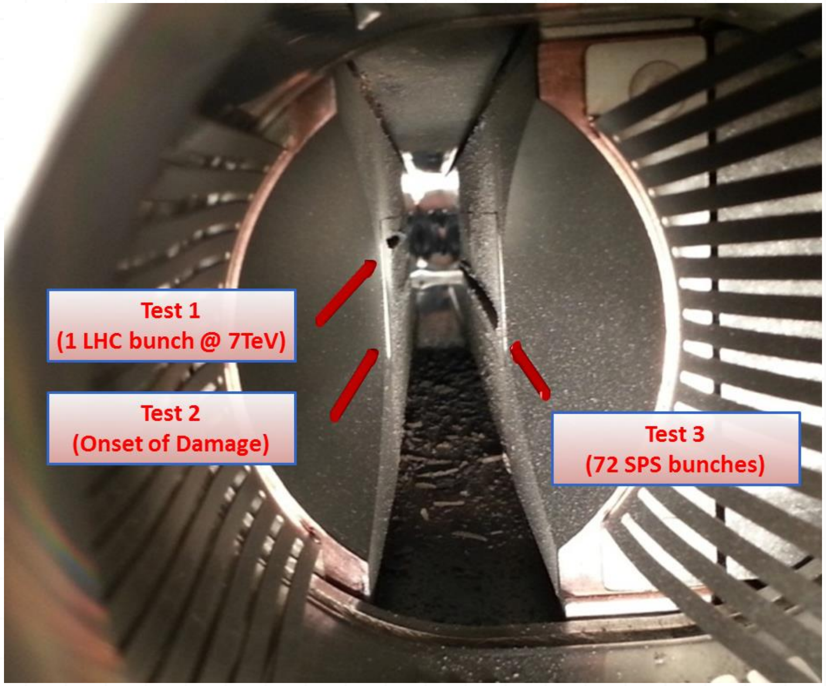


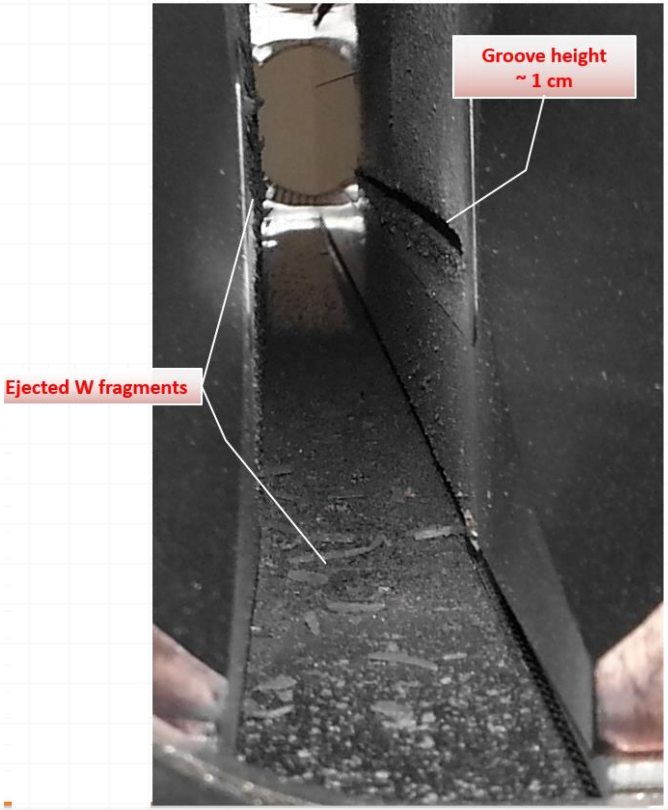


Overview of Past Beam-Impact Tests

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

- 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)

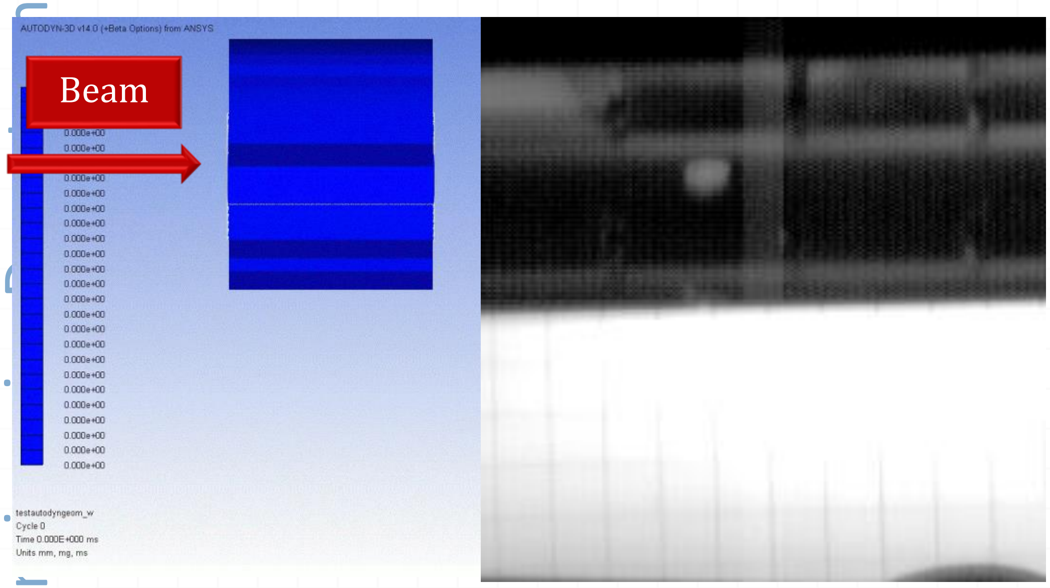


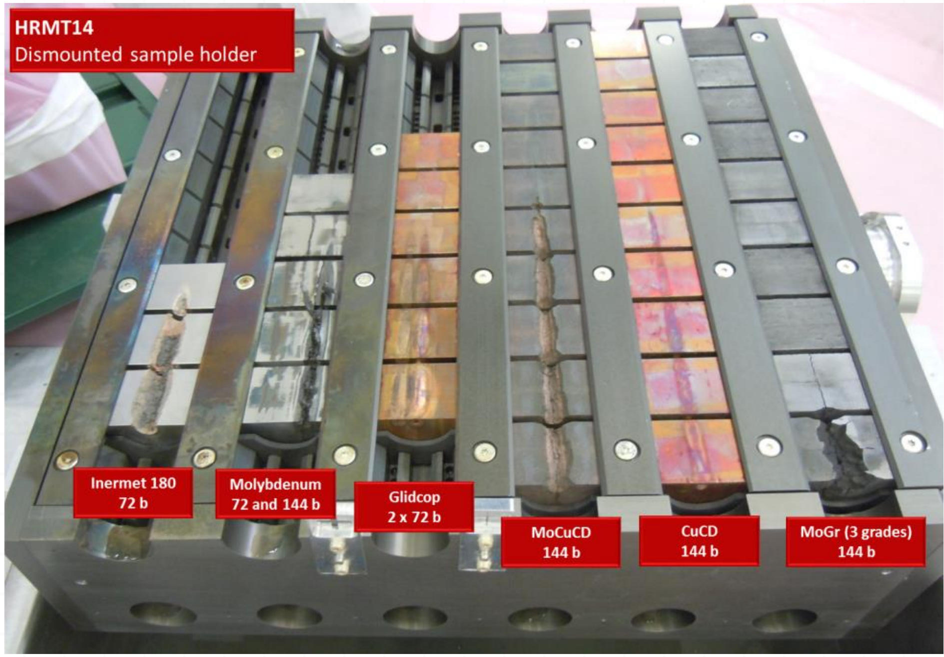


Overview of Past Beam-Impact Tests

2012 HRMT-14: 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

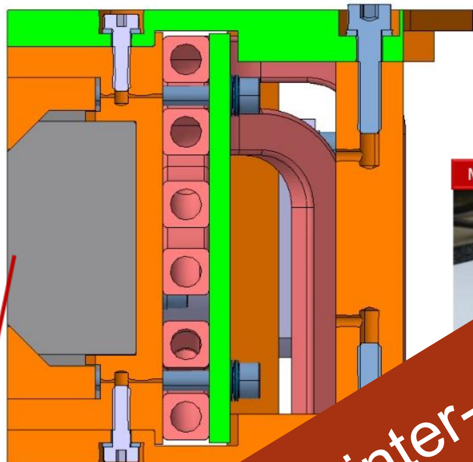




Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	316 m/s
Experiment	72	1.26e11	9.0e12 p	1.9 mm	8 (partly 9)	~275 m/s

HL-LHC Collimator Design

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



Rich and inter-disciplinary R&D program on novel collimator materials with collaboration between Laboratories, Industries and Academia (supported by EuCARD2 and HiLumi)

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

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

M…

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

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High Luminosity LHC

HRMT-23 Experiment

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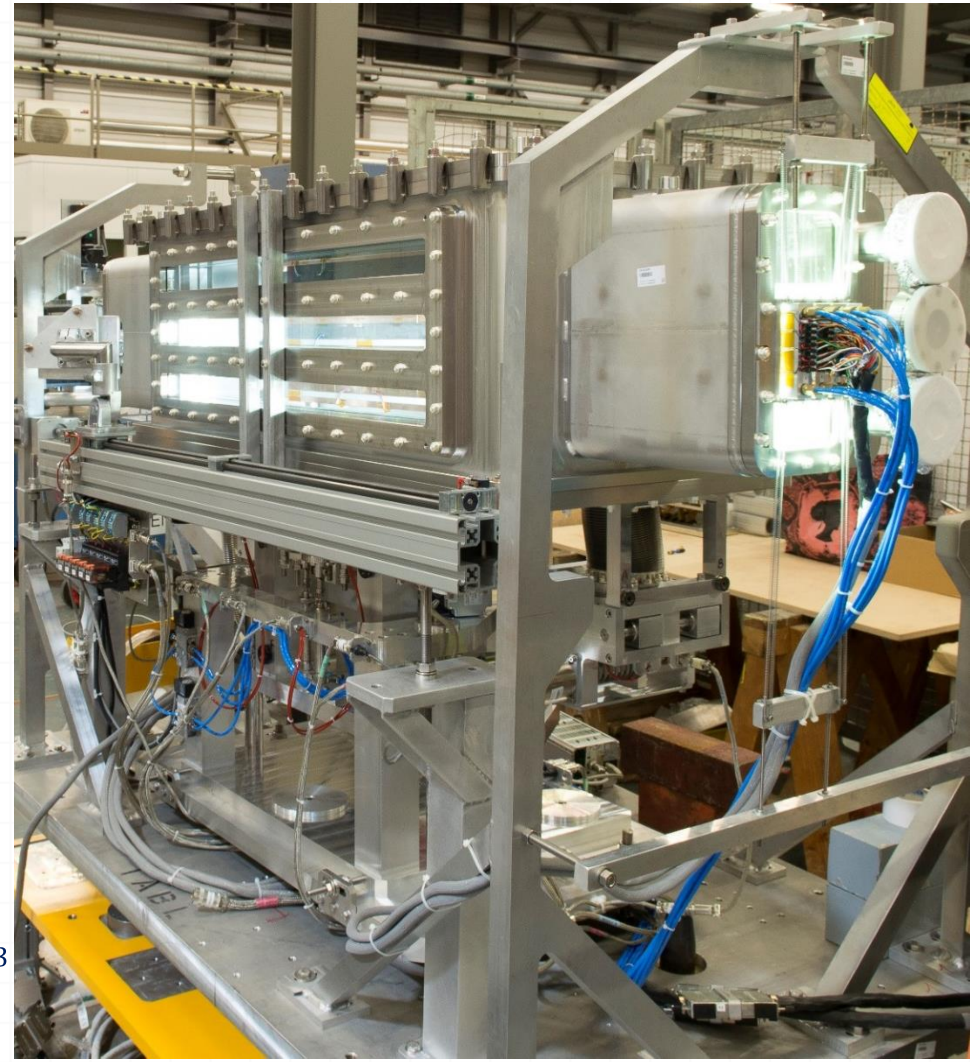
- **3** separate **complete jaws** extensively instrumented.
- **Stainless steel vacuum vessel** (p > 10^{-3} mbar). Quick dismounting system to access and manipulate jaws in a glove box.
- **Be/CFC vacuum windows**: design to withstand higher energy density and intensity
- **Horizontal actuation** inspired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

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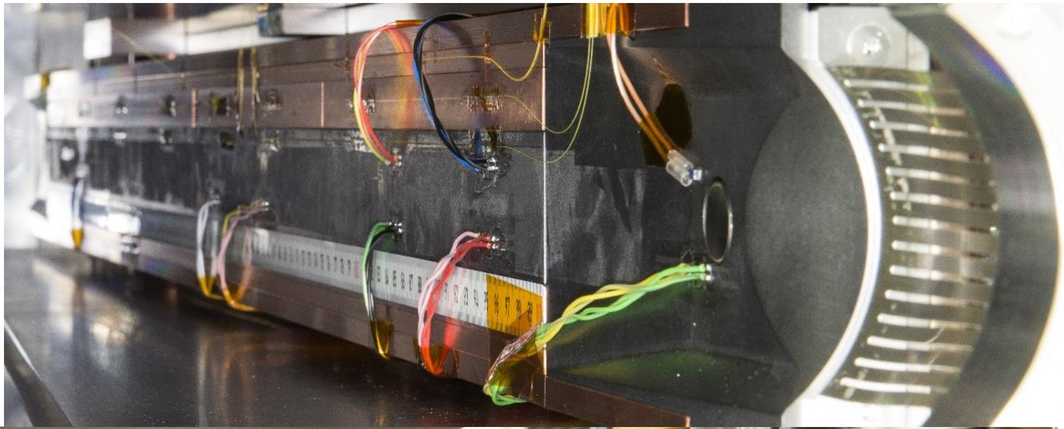
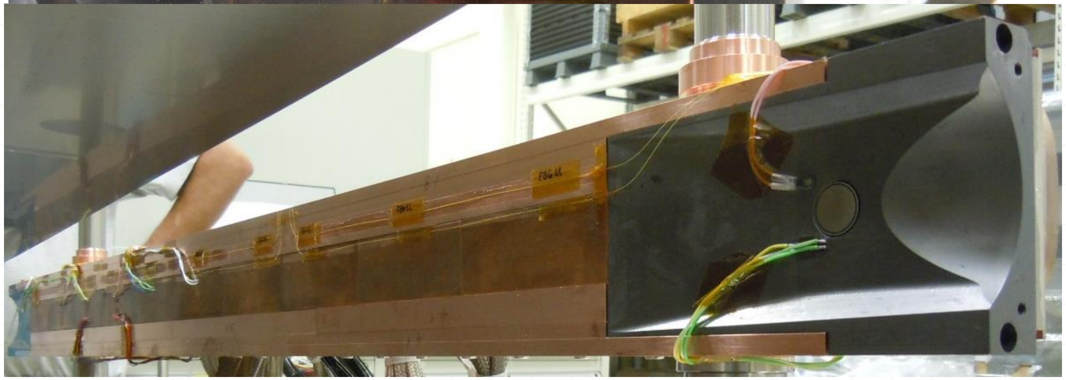
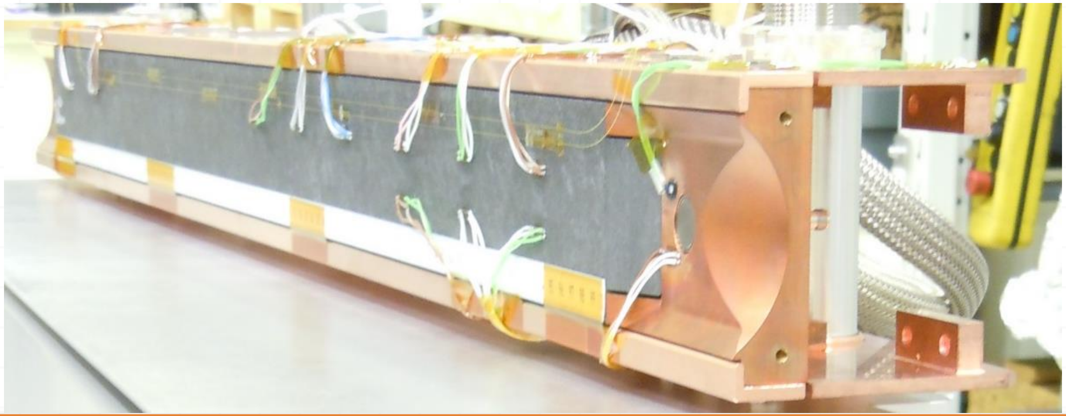
1. **HL-LHC Secondary Collimator Jaw** (TCSPM) with 8 **MoGr** inserts and taperings



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**

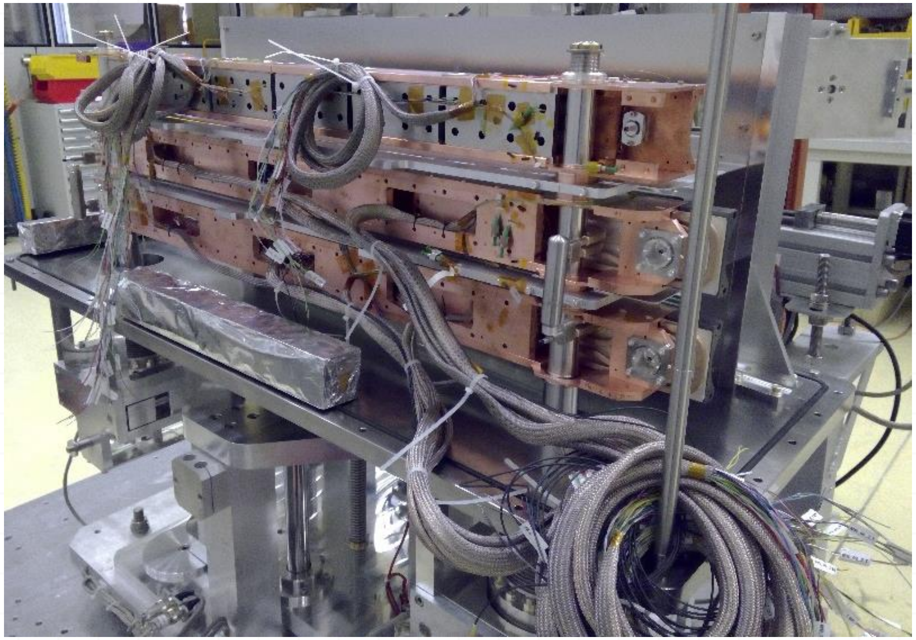
Jaw		# Bunches	Total Intensity	Nominal σx [mm]	Nominal σy [mm]	Nominal Target X [mm]
CuCD	1	6	7.47E+11	0.61	0.61	3.05
CuCD	2	12	1.51E+12	0.61	0.61	3.05
CuCD	3	18	2.56E+12	0.61	0.61	3.05
CuCD	4	24	3.13E+12	0.61	0.61	3.05
CuCD	5	24	2.95E+12	0.35	0.35	0.18
CuCD	6	24	2.86E+12	0.35	0.35	0.7
CuCD	7	24	2.88E+12	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

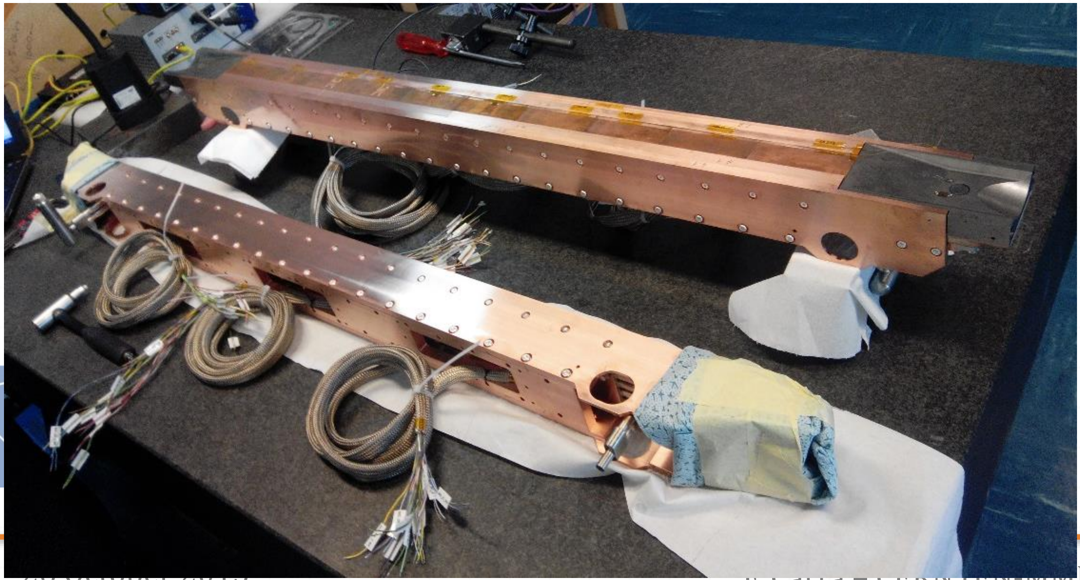
Jaw		# Bunches	Total Intensity	Nominal σx [mm]	Nominal Target X [mm]
TCSP	1	12	7.12E+11	0.35	3.05
TCSP	2	12	7.12E+11	0.35	1.83
TCSP	3	12	7.13E+11	0.35	0.61
TCSP	4	12	7.12E+11	0.61	3.05
TCSP	5	12	1.47E+12	0.61	1.83
TCSP	6	12	1.48E+12	0.61	0.61
TCSP	7	12	1.39E+12	1.00	3.05
TCSP	8	12	1.49E+12	1.00	1.83
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

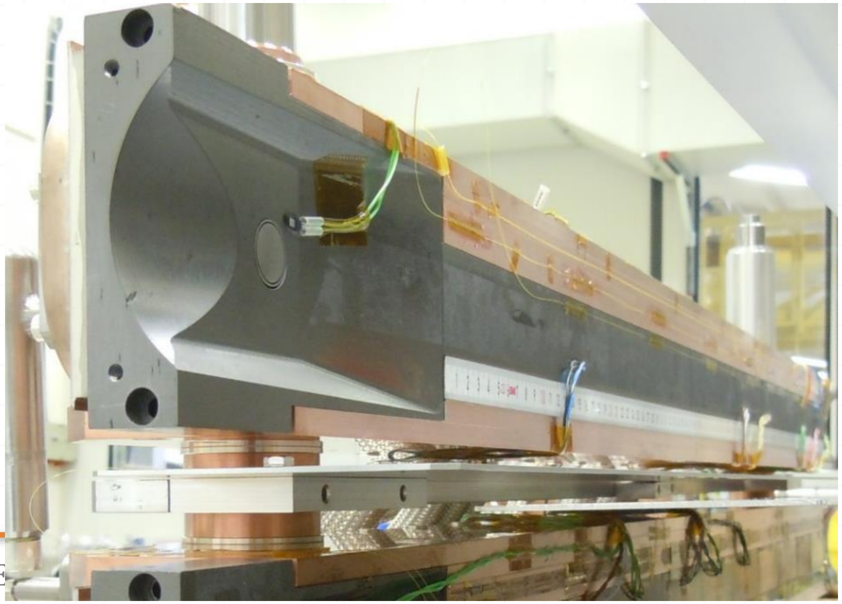
Jaw		# Bunches	Total Intensity	Nominal σx [mm]	Nominal Target X [mm]
MoGr	1	12	7.13E+11	0.35	3.05
MoGr	2	12	7.12E+11	0.35	1.83
MoGr	3	12	7.12E+11	0.35	0.61
MoGr	4	12	7.12E+11	0.61	3.05
MoGr	5	12	7.12E+11	0.61	1.83
MoGr	6	12	7.12E+11	0.61	0.61
MoGr	7	12	1.51E+12	1.00	3.05
MoGr	8	12	1.46E+12	1.00	1.83
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

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)	-



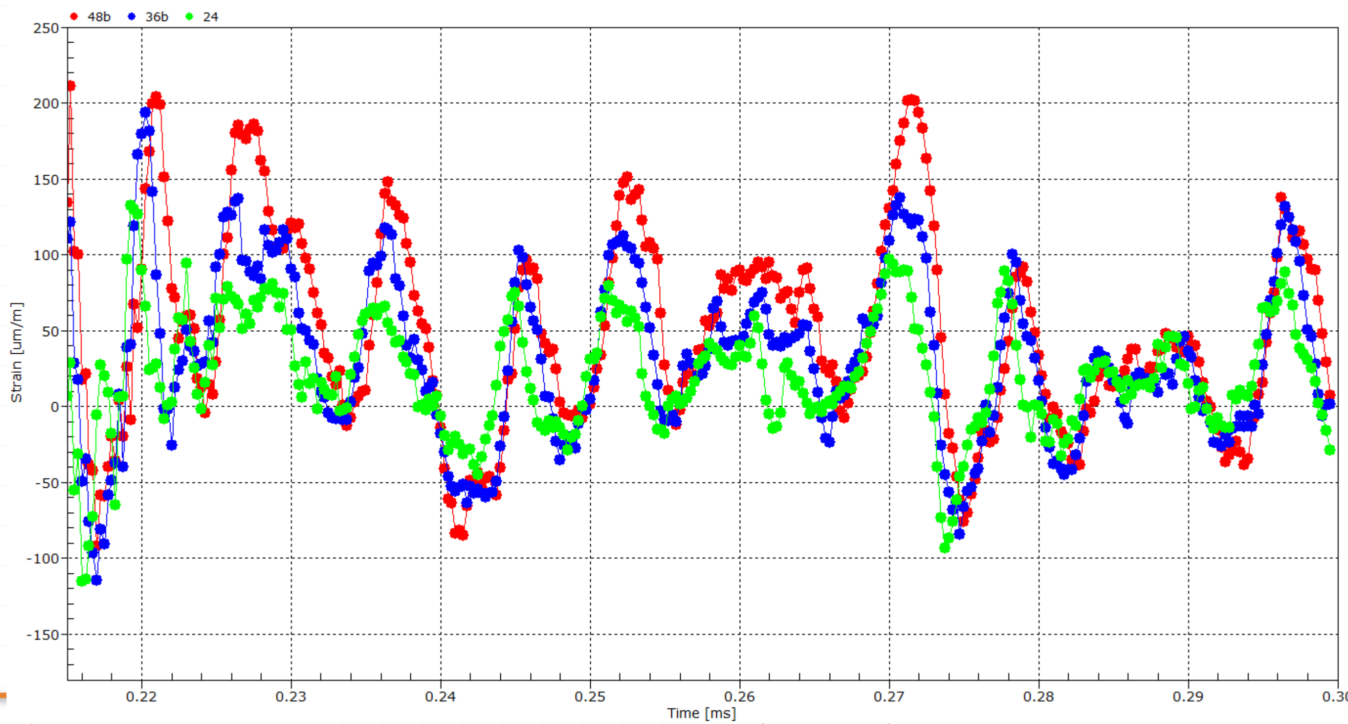




HRMT-23 First Results Overview

- **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 First Results Overview

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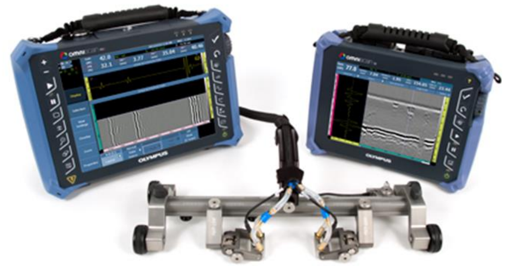
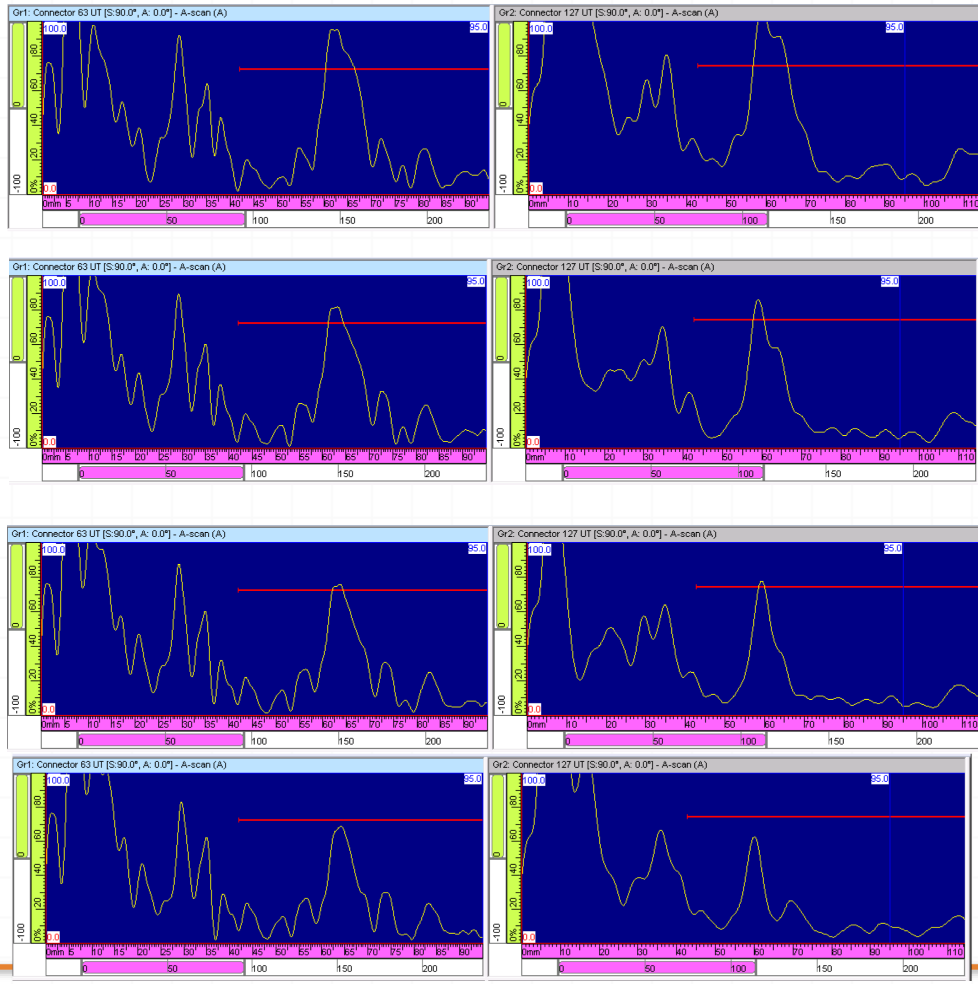
Ultrasound signals readout from CuCD Jaw



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

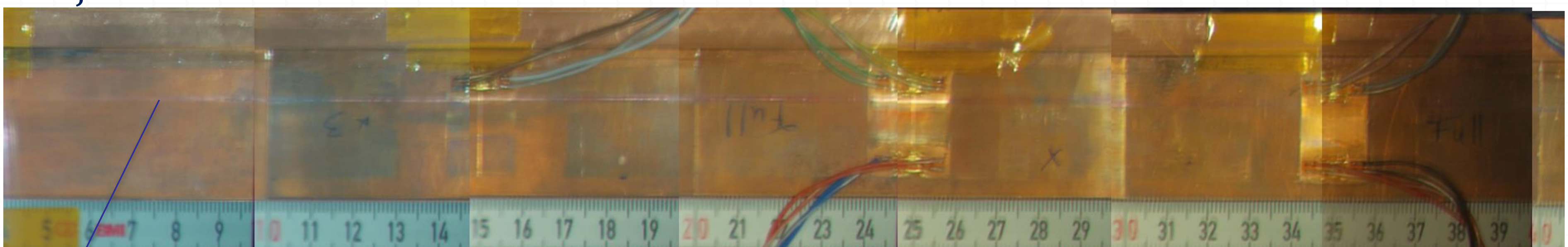
27 July 2015, 23:51:55

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

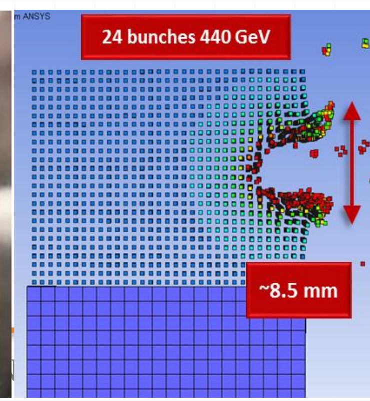
28 July 2015, 01:05:27

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 5th 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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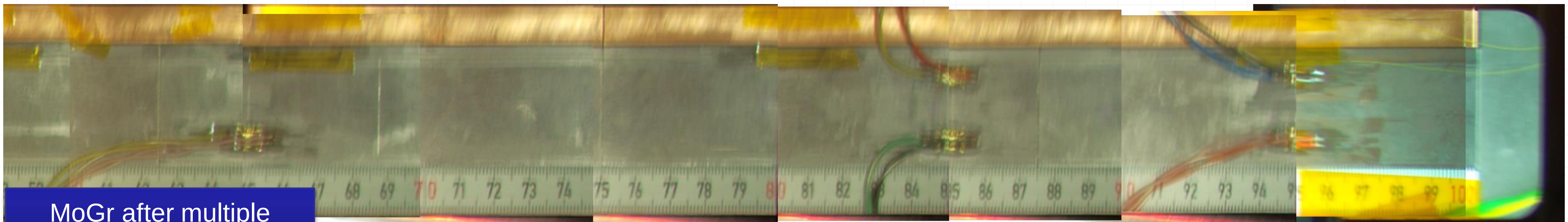
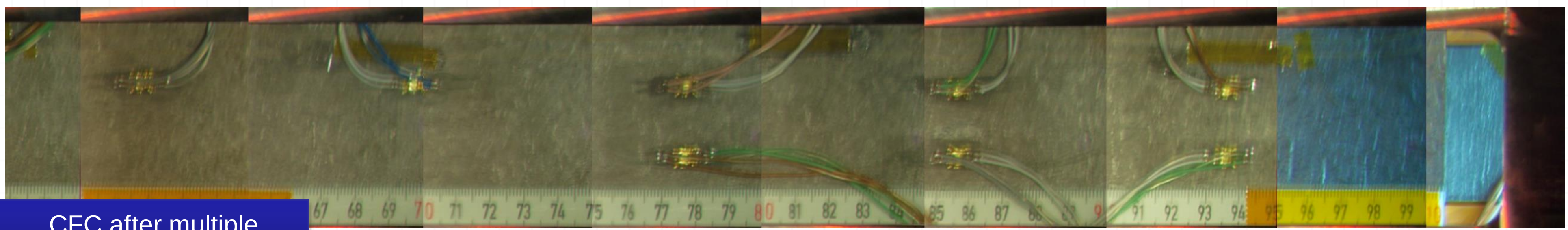
HRMT-23 First Results, CuCD

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

HRMT-23 First Results, MoGr&CFC

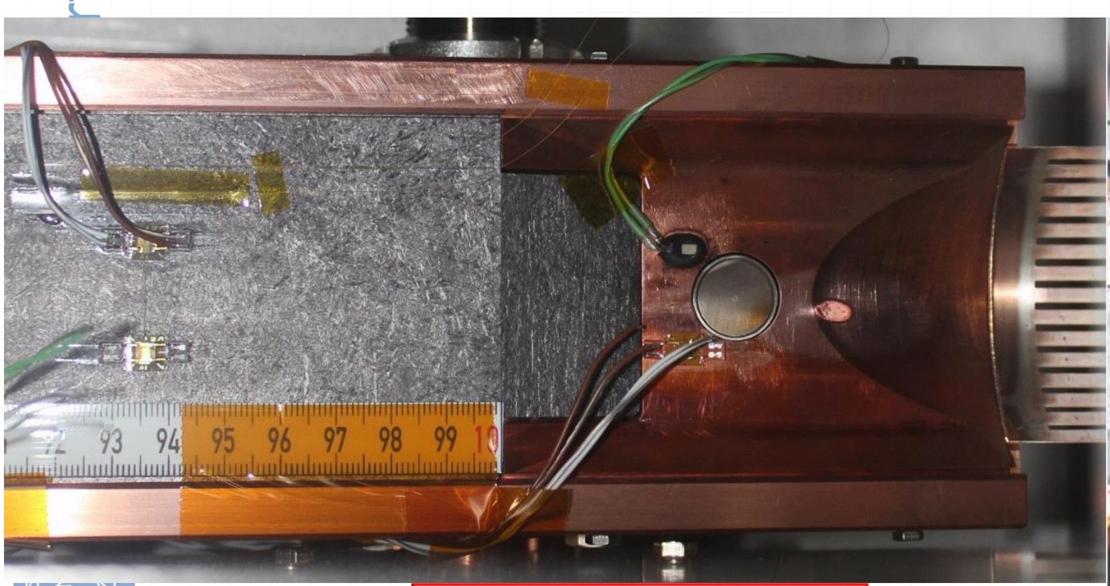
- **MoGr** on HL-LHC jaw survived the impact of several **288 b pulses** with σ down to 0.35 mm (**peak energy density slighly higher than HL-LHC and BCMS LIU injection error)**
- **CFC** on LHC jaw **survived the same impacts**
- Preliminary results would qualify MoGr (from robustness point of view)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


MoGr after multiple impacts

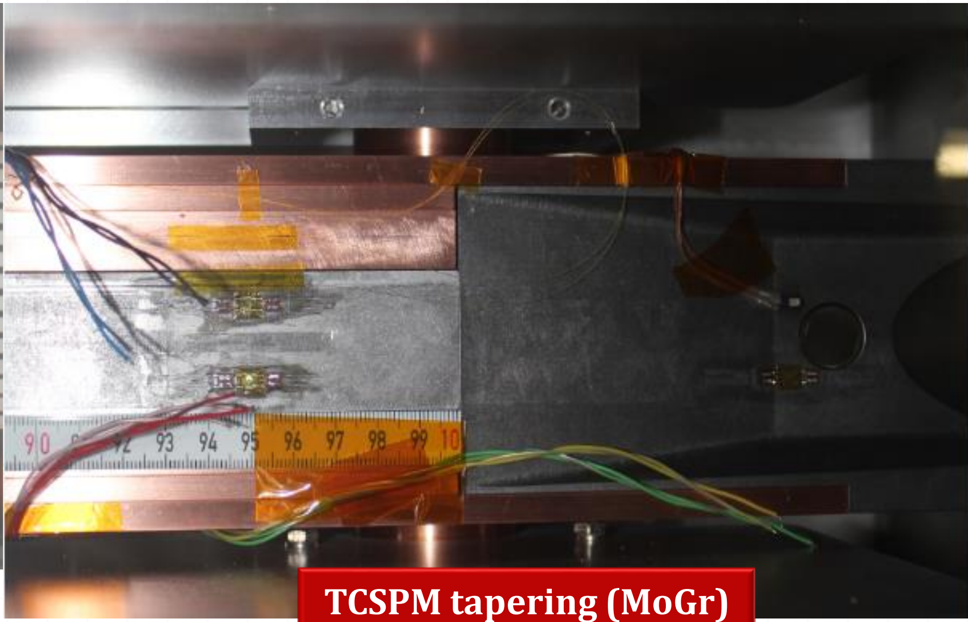

CFC after multiple impacts

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



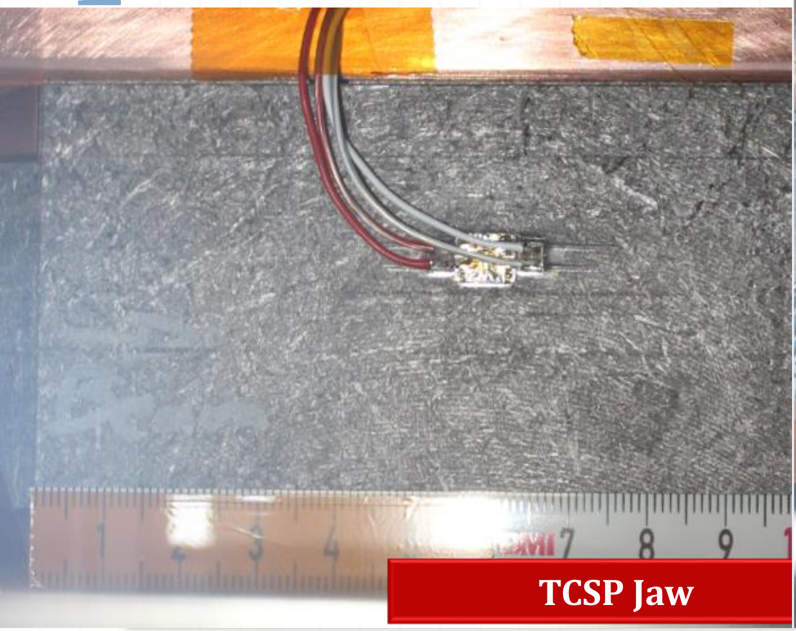
TCSP tapering (Glidcop)



TCSPM tapering (MoGr)

HRMT-23 First Results, MoGr&CFC

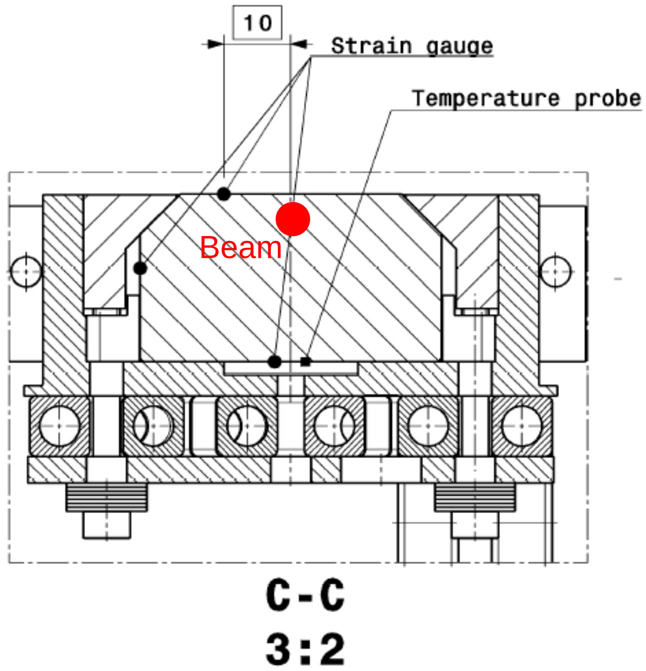
- Post-experiment observations also allowed to observe some marks on the CFC and MoGr surfaces
- The visibility of the marks changes with the light orientation
- Probably generated during the 0.5 sigma impacts by **detachment of the surface powders** (pencil-like surface typical of graphitic materials,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



Preliminary Experimental/Numerical Benchmarking

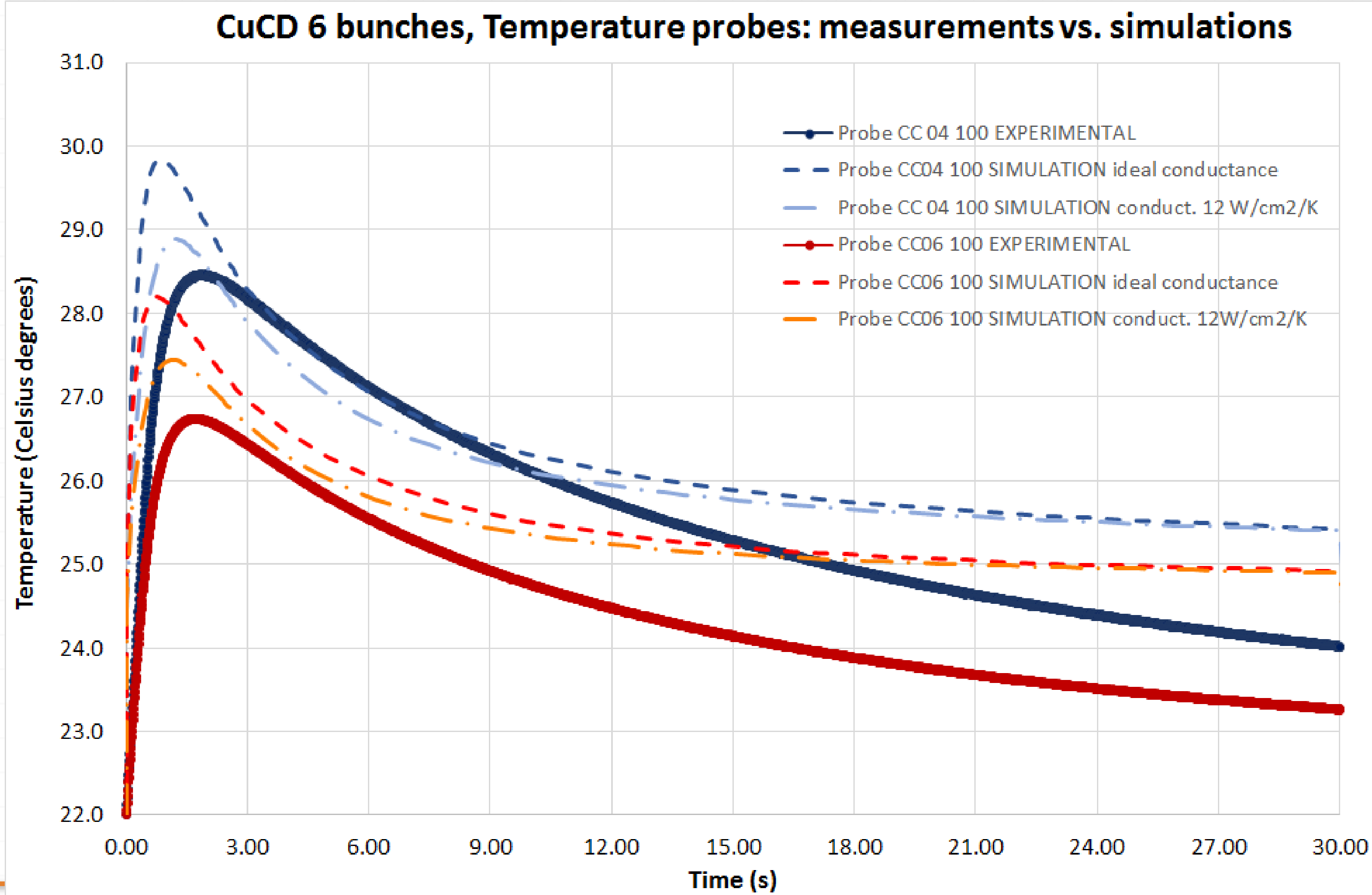
- Benchmarking started using the available FLUKA maps (courtesy of **E. Skordis, A. Lechner**)
- Existing FLUKA analyses possibly to be complemented in the future, including the impact scenarios not simulated yet (in particular, only one impact depth is present for the σ 0.35 mm)
- We are focusing on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

Section view of instrumented TCSPM jaw



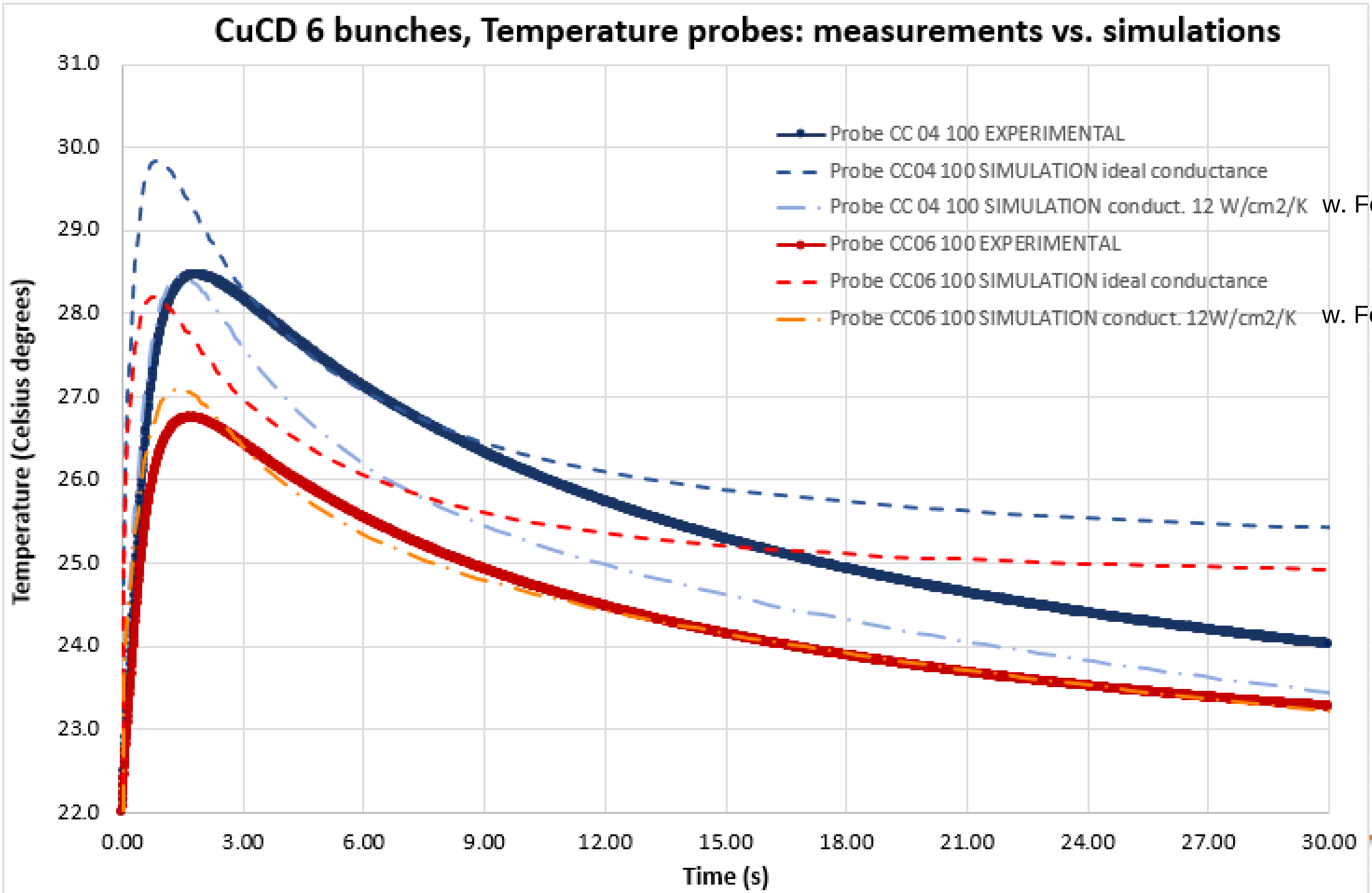
Preliminary Experimental/Numerical Benchmarking

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



Preliminary Experimental/Numerical 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?**



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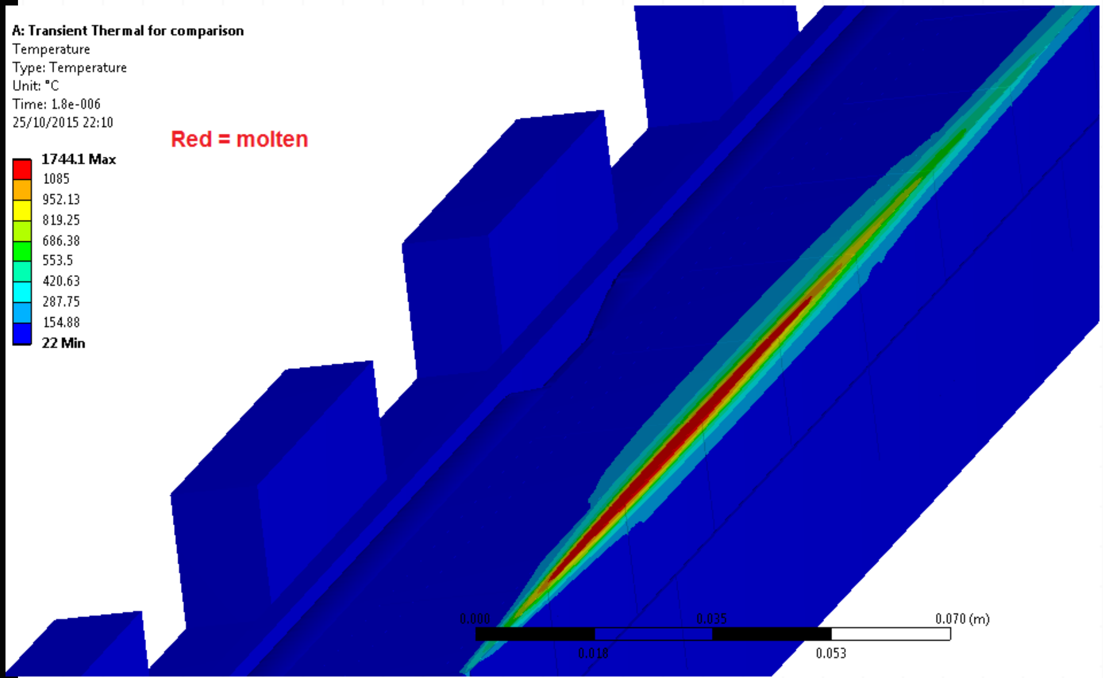
Preliminary Experimental/Numerical Benchmarking

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

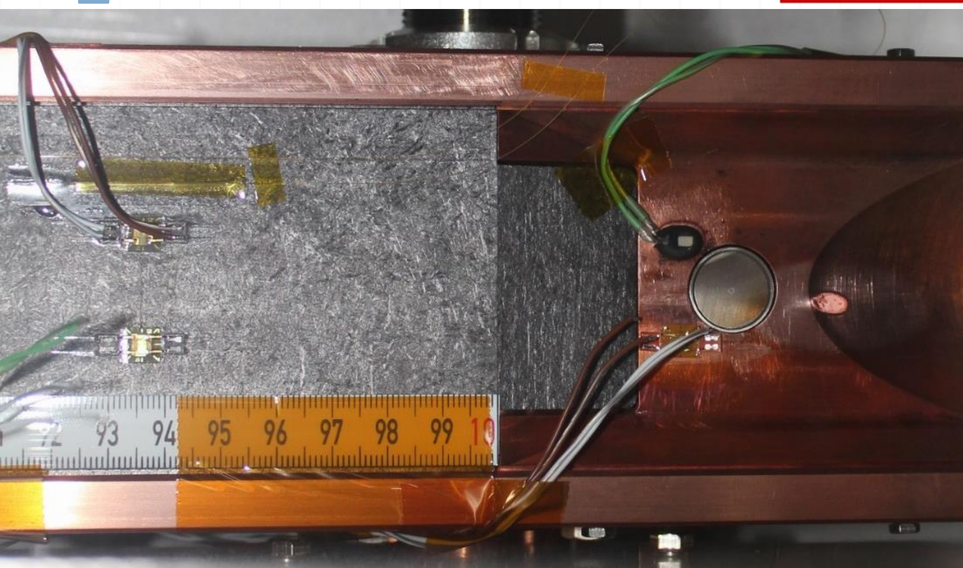
TCSPM CuCD 72 bunches

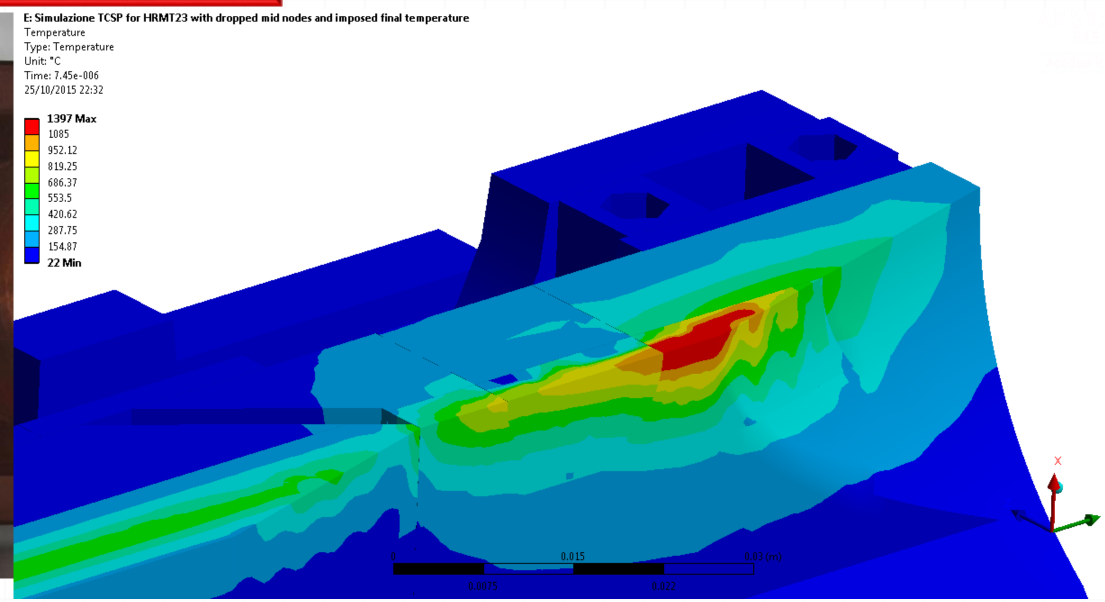


Preliminary Experimental/Numerical Benchmarking

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

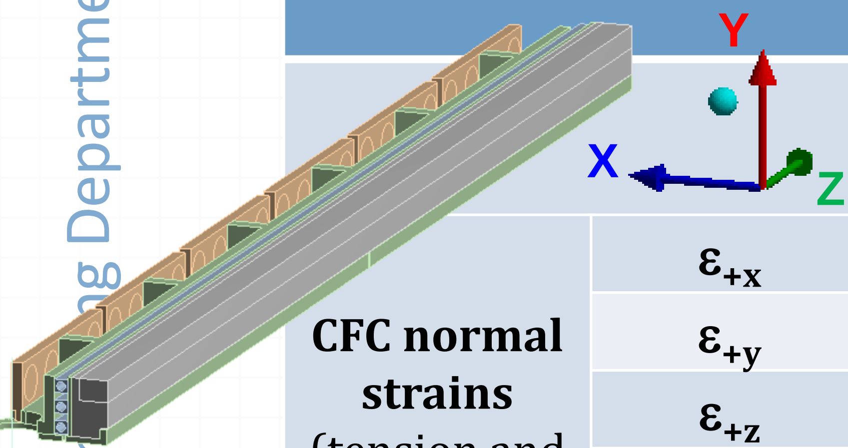
TCSP CFC 288 bunches





Preliminary Experimental/Numerical Benchmarking

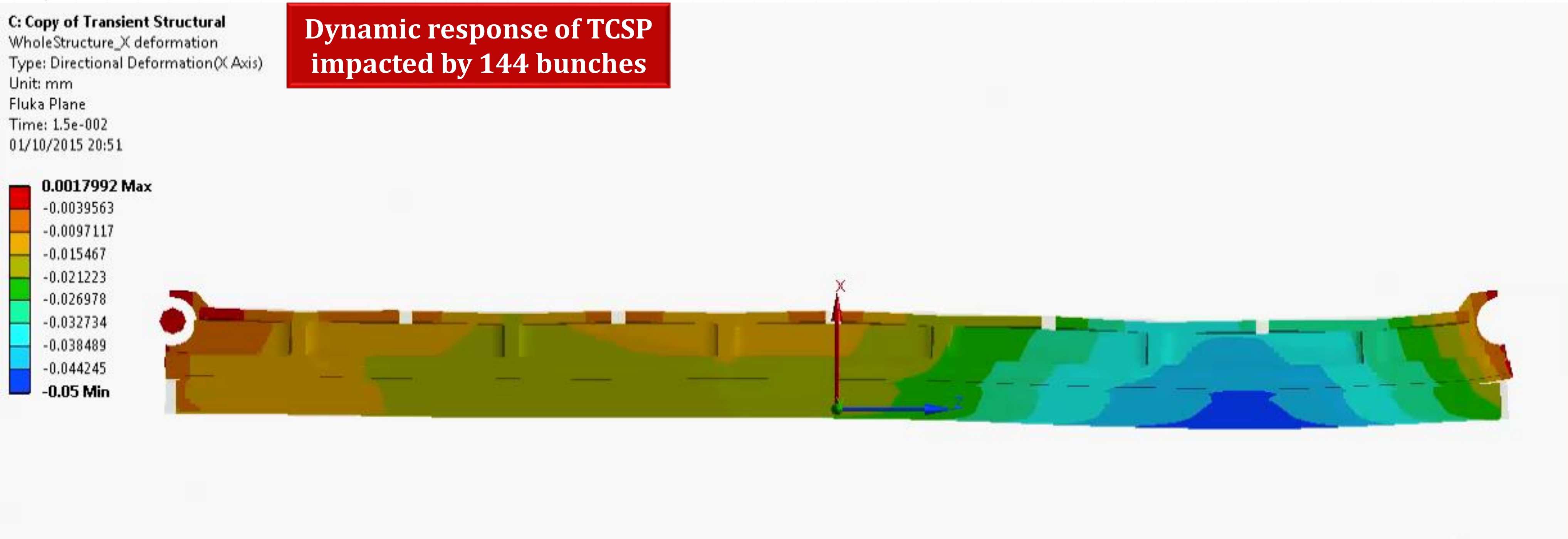
- While thermal simulations on MoGr are ongoing, and structural on the three materials are next, **a structural simulation performed on BCMS beam features parameters very close to a HRMT-23 case**
- BCMS cases simulated: 144 & **288** bunches, σ **0.61** & 1 mm, impact 1σ



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)



Dynamic response of TCSP impacted by 144 bunches

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)**
- Most promising materials of HRMT14: **MoGr and CuCD**
- 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

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Summary (2/2)

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- Detailed non destructive and destructive tests will be possible only after opening the tank, but the embarked instrumentation and post-irradiation visual inspection lead to the following (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)
  - While 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 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!

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What's next?

- The thermal analyses, necessary to compare the temperature probe response and serving as a first step for the structural simulations, are fully ongoing
- Structural simulations are next. Similar cases on TCSP jaw already simulated in the frame study of BCMS beam safety
- Some FLUKA analyses are needed in order to complete the full picture of impact scenarios
- The **construction of a TCSPM prototype** with MoGr jaw has started, with the goal of installing it in the LHC for testing in 2016/17
- HRMT-23 will be followed by a **dedicated HiRadMat experiment** to test a broad range of materials (including coatings), joining forces / creating synergies with other equipment and teams → **MultiMat**

LHC Collimation Project

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We warmly thank all the people who made the experiment possible through their support (EN/MEF, EN/STI, EN/ICE, EN/HE, BE/OP, BE/ABP, BE/BI, DGS/RP …)!

And thank you all for your attention!

From HRMT14 (2012)...

... to HRMT23 (2015)!!!

Backup slides