Performance of New HL Collimators Design

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on behalf of the HL-LHC Collimator Design Team with many contributions from BE-ABP, BE-BI, EN/SMM, EN-STI, TE-VSC

12.02.2019 – International Review of the HL-LHC Collimation System, CERN

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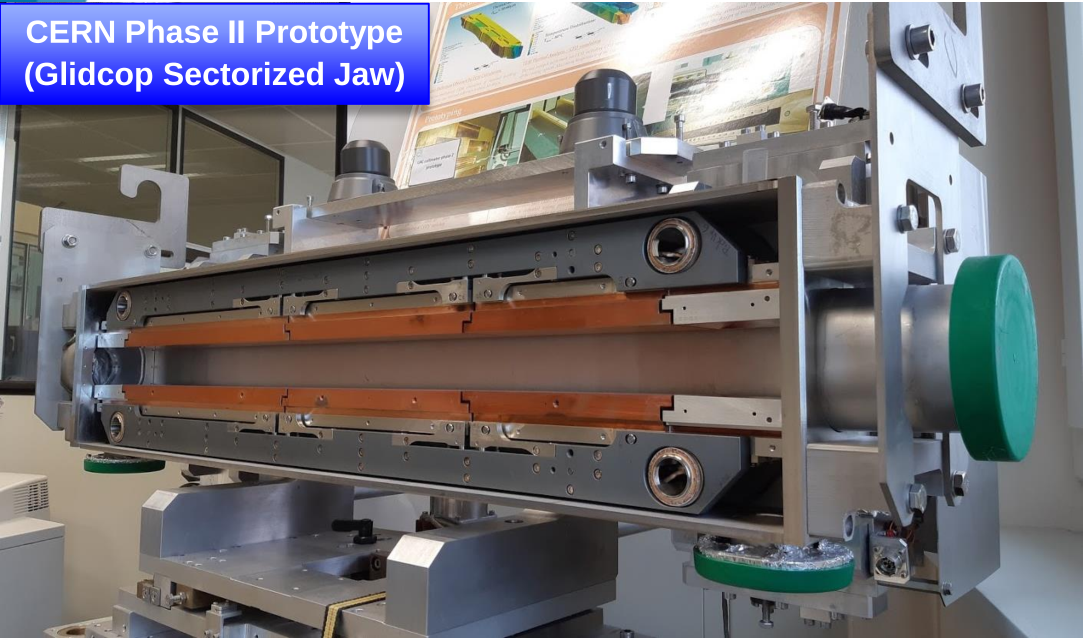
- Designs of HL-LHC Collimators
- Normal and Accidental Scenarios
- Experimental Validation
- Outlook and Possible Future Developments

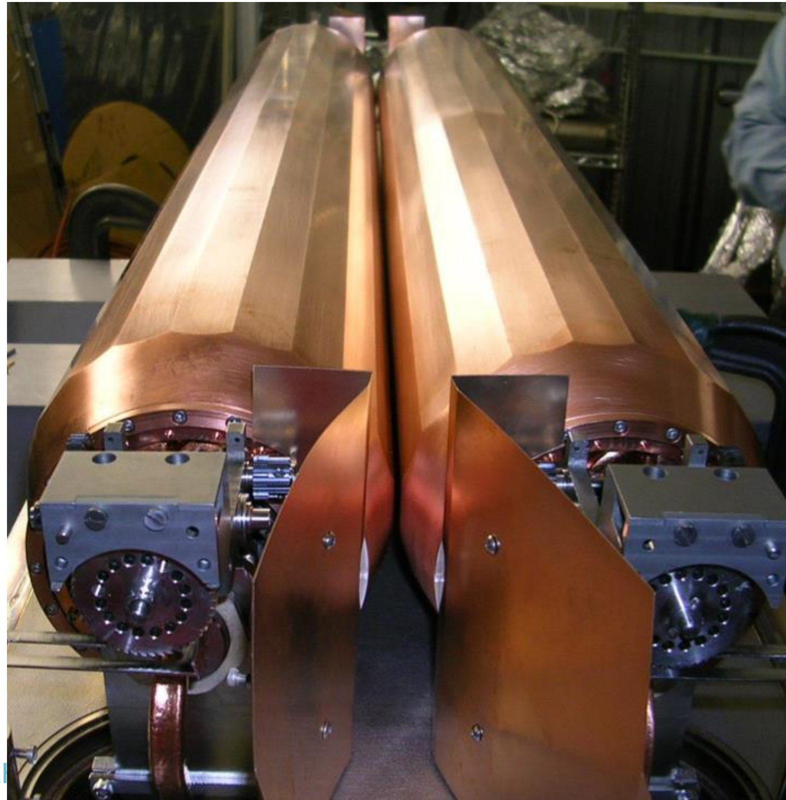
Historic Overview

- LHC collimation was conceived from inception as a phased-deployment system
- After first robust carbon collimators (Phase I), a new generation was foreseen for LHC (Phase II) aiming at:
  - Reducing impedance → lower electric resistivity
  - Increasing cleaning efficiency → higher density
  - Keeping Phase I geometrical stability
  - Trade-off on mechanical robustness → metallic jaws (able to operate with stable beams only)
- New designs and materials required
  - 2 alternative designs
    - CERN Phase II (Glidcop sectorized jaw)
    - SLAC (US-LARP) Rotatable Collimator
  - Novel materials R&D campaigns (also through EuCARD, EuCARD2, US-LARP, ARIES …)
  - Coating initially not an option because of low robustness

Historic Overview



CERN Phase II Prototype (Glidcop Sectorized Jaw)



US-LARP SLAC Phase II Prototype (Glidcop Rotatable Jaws) Recently tested successfully in HiRadMat

Design Criteria for HL-LHC: Materials

- Design of HL-LHC Collimators is inspired by LHC-Phase I experienc … maintains LHC-Phase II requirements
- In particular, for HL-LHC **Halo Cleaning,** materials are si … ception of **Robustness,** which must be comparable to Phase I (
  - **Balanced Density** to limit peak energy depositi … efficiency
  - **High Electrical Conductivity** to limit Re
  - **High Thermal Conductivity** to eff … ghtness
  - **Low Coefficient of Therma** … ons and stresses
  - **High Melting/Sublim** … temperatures reached n case of accidents
  - **High Specific**
  - **High Ultimat** … ock resistance
  - **Good Radiatio** … maintain lifetime under long term particle irradiation
  - **UHV compatibilit** … sing and contaminants
- Ensure industrial feas … at acceptable costs

Intense Material R&D Campaign.
Most promising materials identified are **Molybdenum Carbide – Graphite** and **Copper – Diamond**
(see F. Carra's talk)

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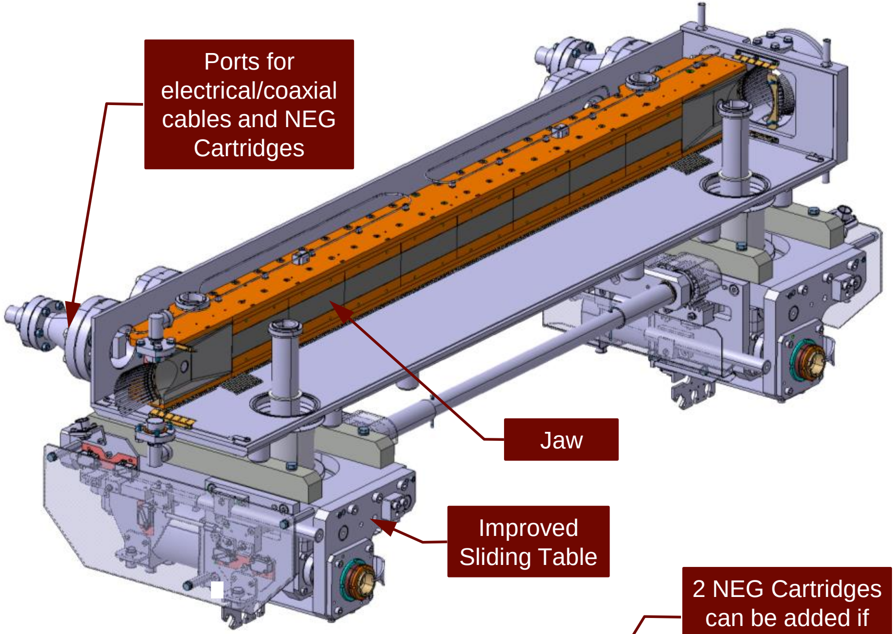
  - Halo Cleaning Collimators (Pri rtiary)
  - DS Cleaning Collimators
  - IR Cleaning Colli , TCTPXH)
- Normal an s (Halo Cleaning)
- Experime
- Outlook an ble Future Developments

Other designs (e.g. Passive Absorbers, Masks, ...) not explicitly covered in this talk

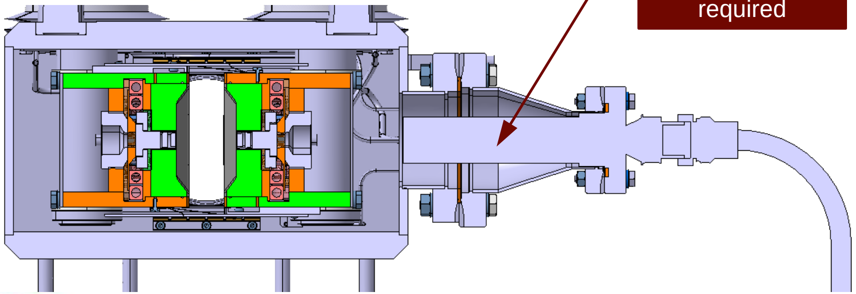
HL-LHC Collimators for Halo Cleaning



Ports for electrical/coaxial cables and NEG Cartridges

Jaw

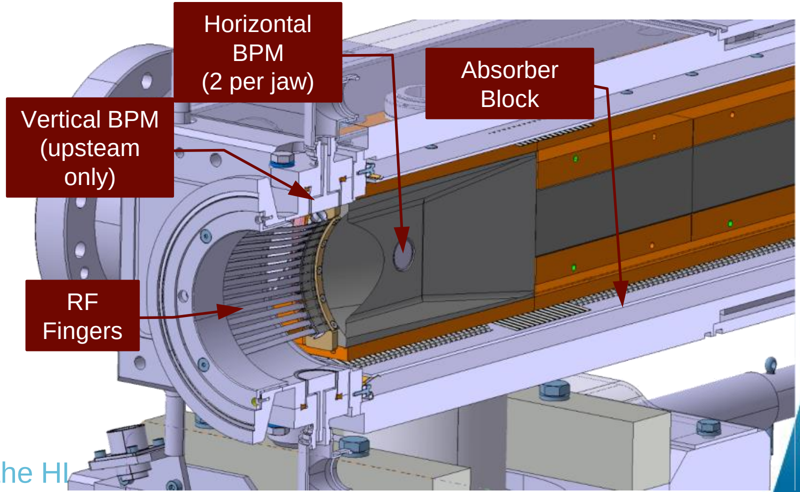
Improved Sliding Table



2 NEG Cartridges can be added if required

Comparison with LHC Collimator

- **Common design** for Primary, Secondary and Tertiary collimators
- **Longer taperings (125 mm)** to reduce geometric impedance, hosting in-jaw BPMs, **made of MoGr** ensuring bulk electrical conductivity for pickups
- Longer vessel, shorter transitions and RF fingers
- **Same flange-to-flange length**
- **Vertical BPM pickups** upstream only



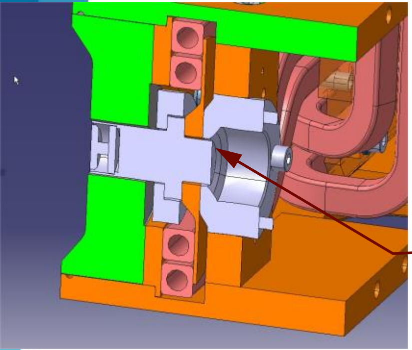
Horizontal BPM (2 per jaw)

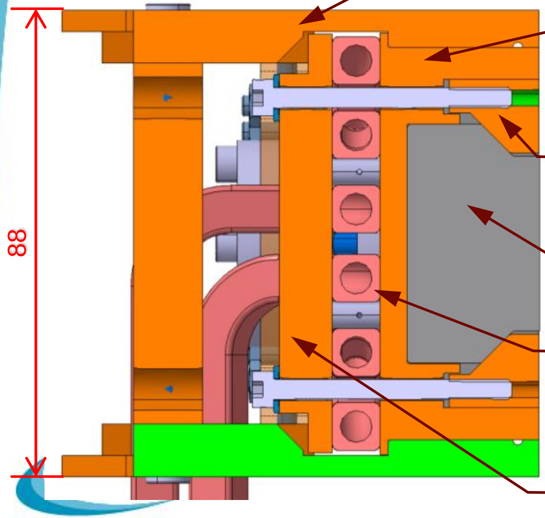
Absorber Block

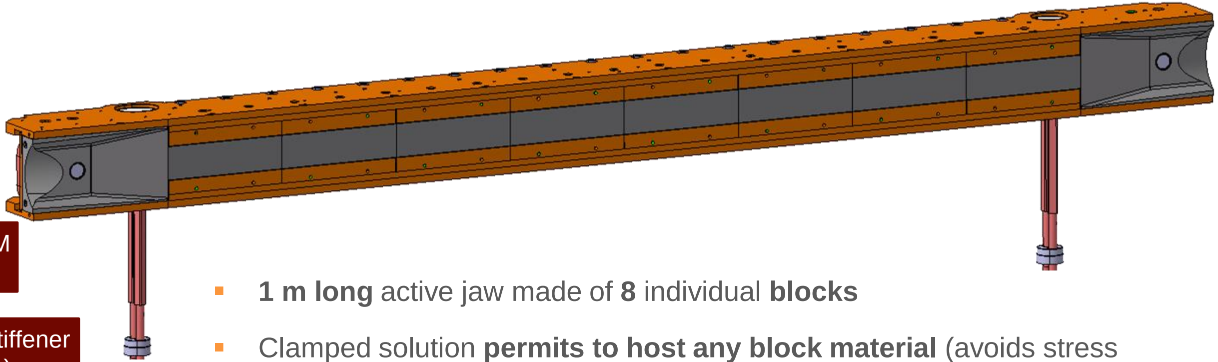
Vertical BPM (upsteam only)

RF Fingers

HL-LHC Collimators for Halo Cleaning

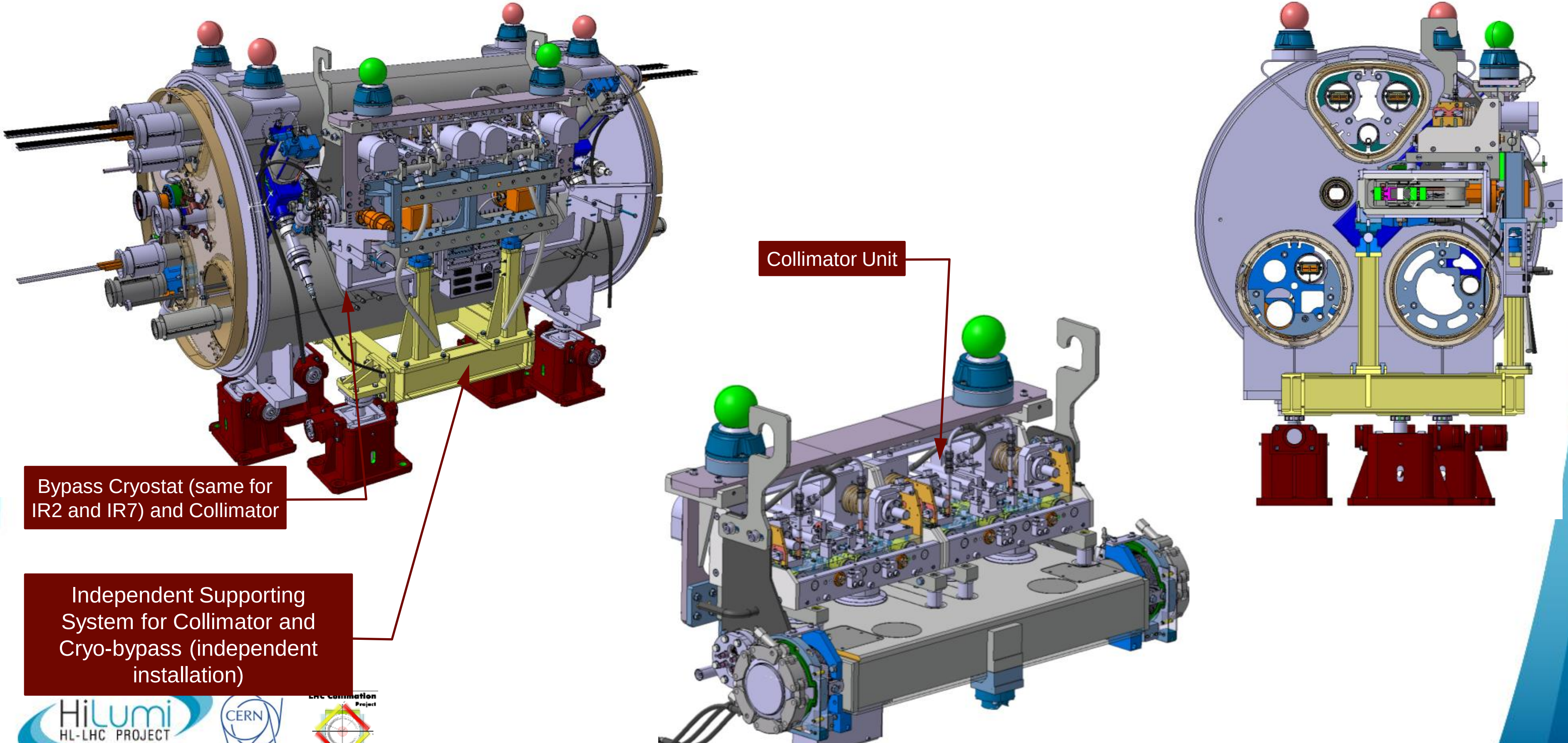






- **1 m long** active jaw made of **8** individual **blocks**
- Clamped solution **permits to host any block material** (avoids stress concentrations and allows sliding between materials with different CTE)
- **Primary (TCPPM)** baseline is **bulk MoGr** (no coating), since these are the most exposed to concentrated slow losses and grazing impacts; **higher cleaning** compared to CFC
- **Secondary (TCSPM)** baseline is **Mo-coated MoGr**, to further **reduce impedance.** MoGr substrate ensures good adhesion and fair conductivity in case of coating loss as well as improved cleaning
- **Tertiary (TCTPM)** baseline is **CuCD**: ensures adequate cleaning, while having **higher robustness** than Tungsten Heavy Alloy (Inermet180)
- **5th axis** jaw shift by ±10 mm allows **compensation** in case of block (limited) damage

DS Cleaning Collimator (TCLD)



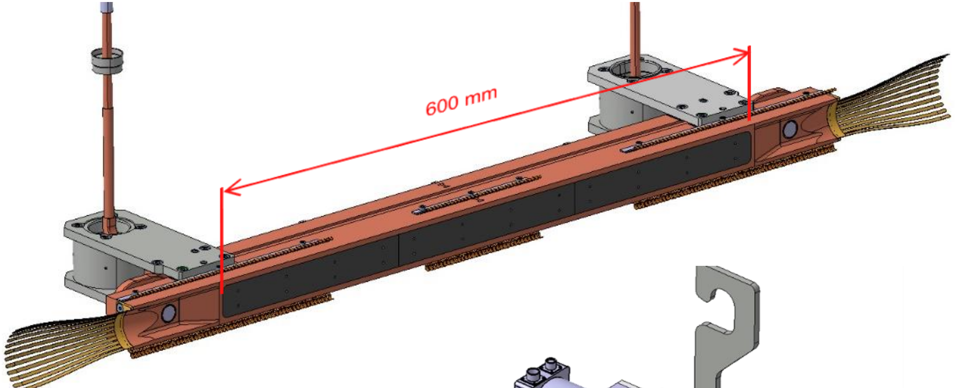
Collimator Unit

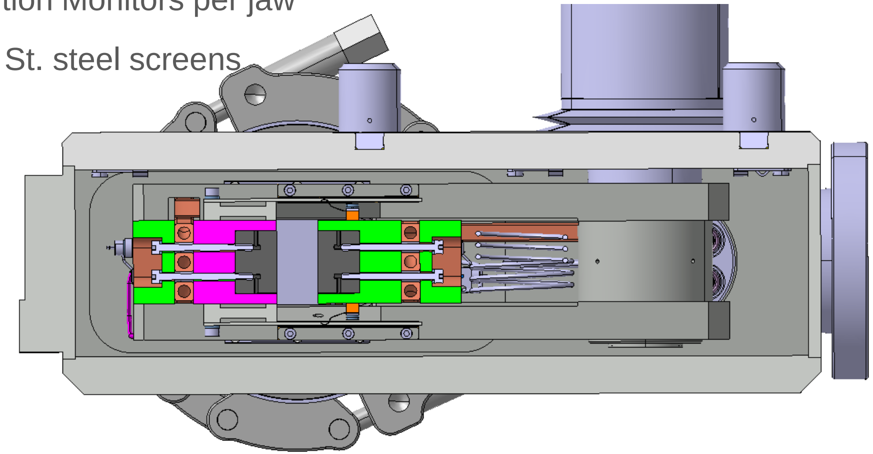
Bypass Cryostat (same for IR2 and IR7) and Collimator

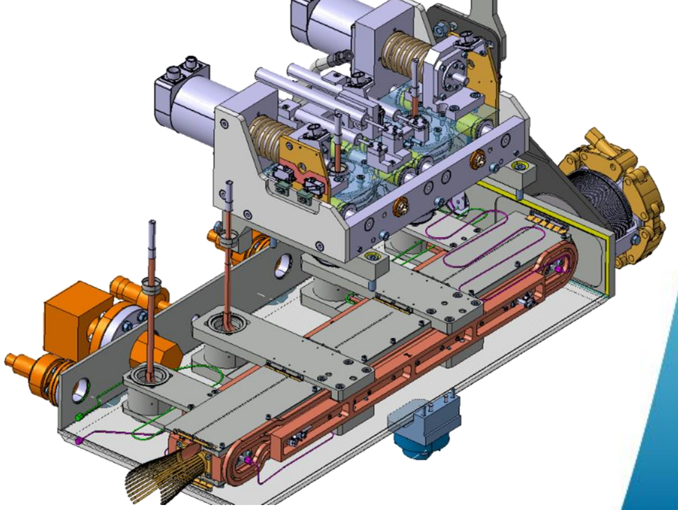
Independent Supporting System for Collimator and Cryo-bypass (independent installation)

DS Cleaning Collimator (TCLD)

- Active length 600 mm
- 3 W alloy (Inermet180) blocks, screwed, 30 mm high
- Brazed cooling circuit between housing and back-stiffener
- Cantilevered jaws (all shafts on one side)
- 1 cooling pipe per jaw (CuNi90-10) with 3 cooling channels
- All Vacuum Equipment on tank
- 2 temperature probes (PT100) per jaw
- 2 Beam Position Monitors per jaw
- RF fingers + St. steel screens

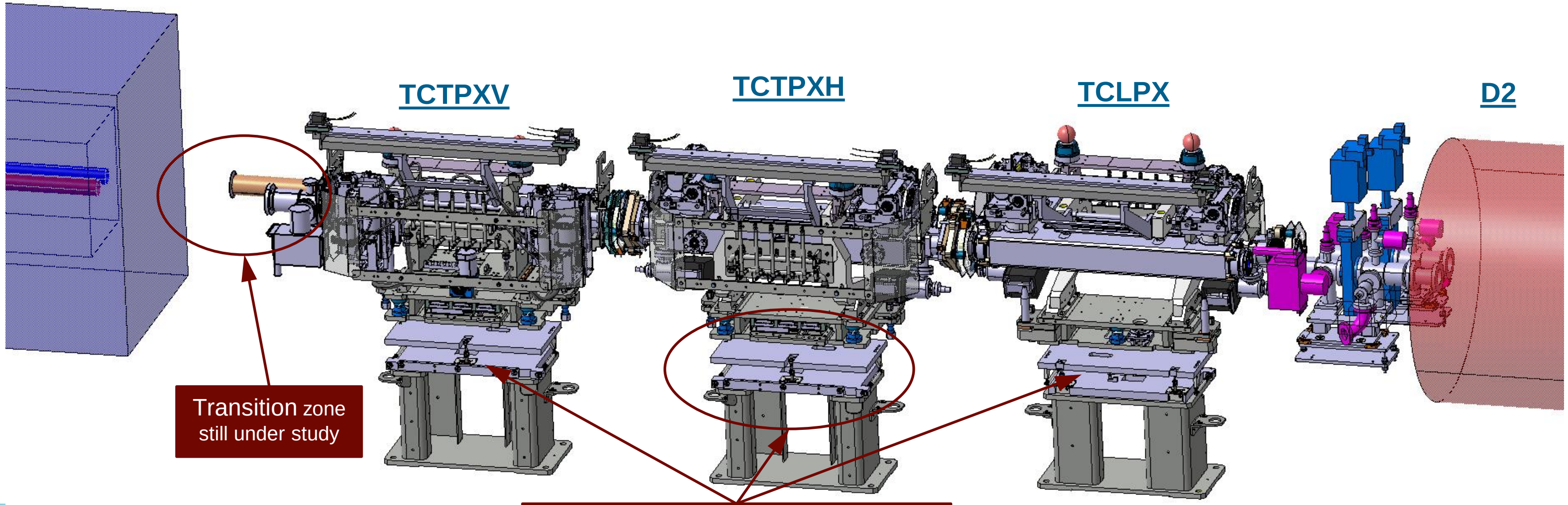






IR Cleaning Collimators

	TCTPXH	TCTPXV	TCLPX
Orientation	Horizontal	Vertical	Horizontal
Absorber Material	CuCD	W Alloy	W Alloy
Absorber Cross-section	34 x 20 mm^2	34 x 20 mm^2	70 x 40 mm^2
Jaw Stroke	35 (+5) mm	40 (+5) mm	40 (+5) mm
Beam Lines Layout	2 in 1	1 in 1	2 in 1

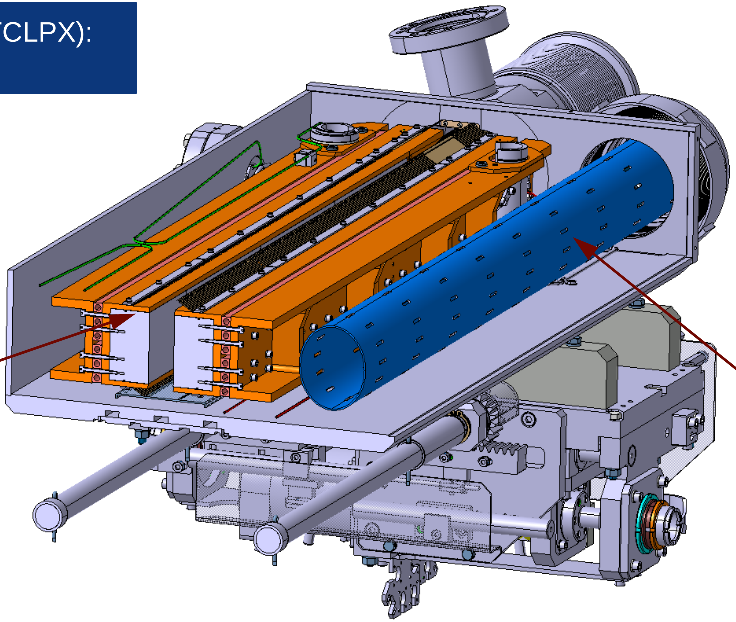


Transition zone still under study

Remote alignment system under study, based on EN/SMM concept (see also P. Fessia's talk)

IR Cleaning Collimators

- Design of IR Cleaning Collimators is currently well advanced
- Design of remote alignment system, based on EN/SMM concept is starting
- Prototypes to be built at CERN after LS2 to validate design before launching production



Physics Debris Collimator (TCLPX):
2 in 1 Design

Thicker and higher absorbers (40x70)

Elliptic beam pipe (to optimize aperture)

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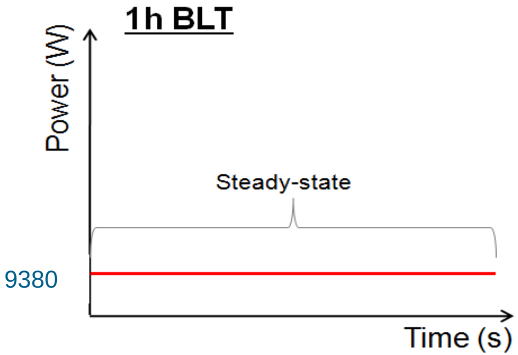
Normal Operation and Accident Scenarios

- **Design cases** derived from LHC
  - **Slow losses** (Normal Operation)
    - **Continuous: 1 h Beam Life Time (BLT)**
    - **Peak: 0.2 h BLT during 10 s**
  - **Direct beam impact** (Accident Scenarios)
    - **Beam Injection Error**: impact of **288 bunches** at 450 GeV, impact parameter up to 5 σ (σ = 0.7 mm)
    - **Asynchronous beam dump**: impact of **8 bunches** at 7 TeV on TCSPM, TCPPM, impact parameter up to 5 σ
    - **Asynchronous beam dump**: impact of **1 bunch** at 7 TeV on TCTPM, impact parameter up to 5 σ
- **We assume all other operational scenarios are embraced by these design cases**

Slow Losses: 1h BLT Design Case

- HL-LHC 7 TeV 25ns (standard)
- N_{tot} = 6.1E+14 → losses on full collimation system **1.68E+11 p/s**
- Energy deposition maps: *Primary in CFC (conservative assumption for power loads)*
- Main requirement: Maintain **geometrical stability** → Maximum jaw **flatness** error **100 µm**
- **Steady-state** assumed for thermomechanical calculations



	Energy deposition on most loaded TCSPM (TCSGA6L7)	
	GeV/p	kW
Tank	86.35	2.03
Left Jaw	395	9.30
Right Jaw	398.4	9.38
Total		**20.71**

factor 4.5 higher than LHC Secondary Collimator

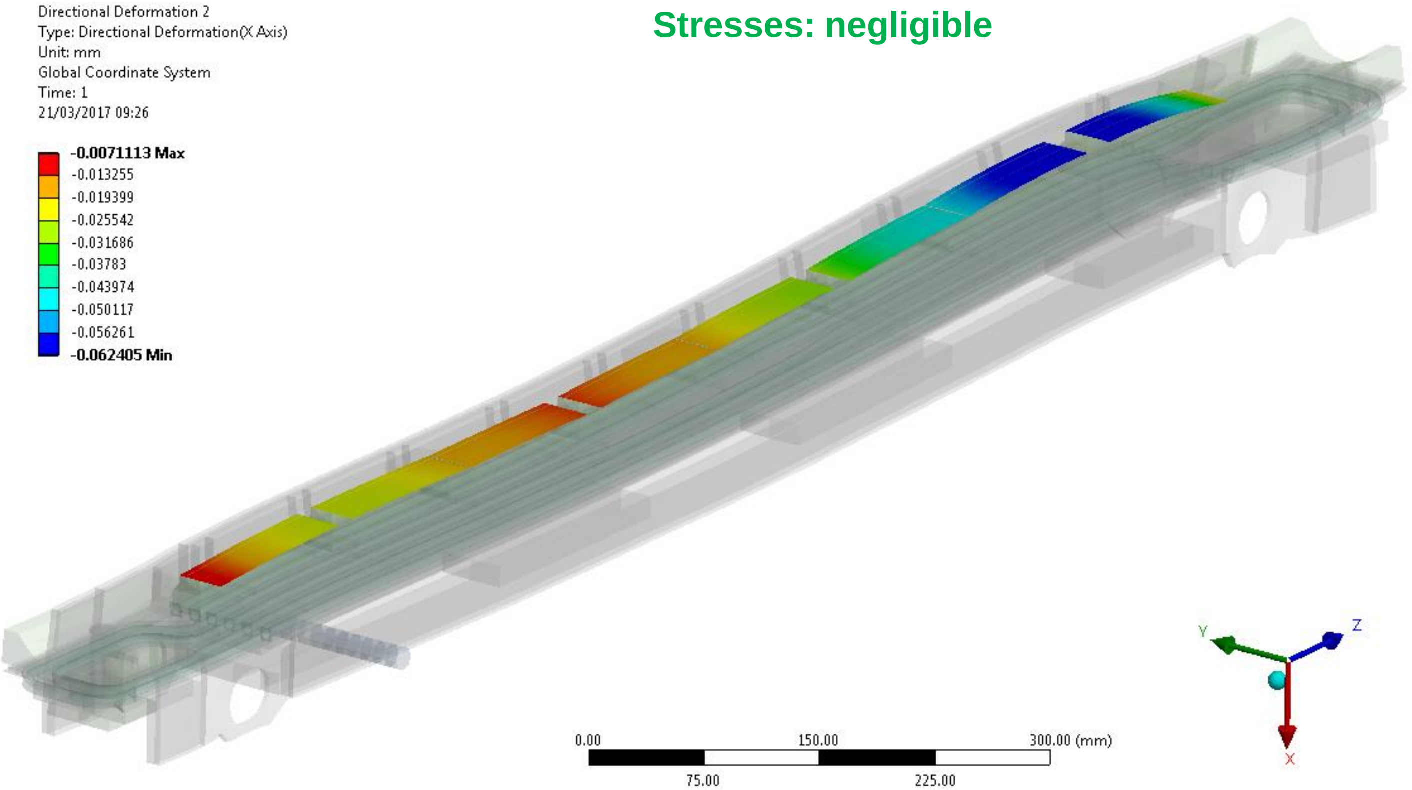
1h BLT Design Case: Structural Results

Effect of Thermal Load

Transverse Deformation (X dir.)

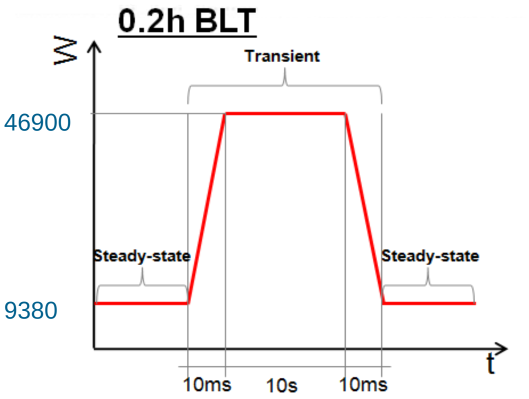
Thermally induced flatness error = 55 µm

Stresses: negligible



Peak Losses: 0.2h BLT Design Case

- HL-LHC 7 TeV 25ns (standard)
- $N_{tot} = 6.0E+14 \rightarrow$ **losses 8.34E+11 p/s**
- **~1 MW** on the collimation system!

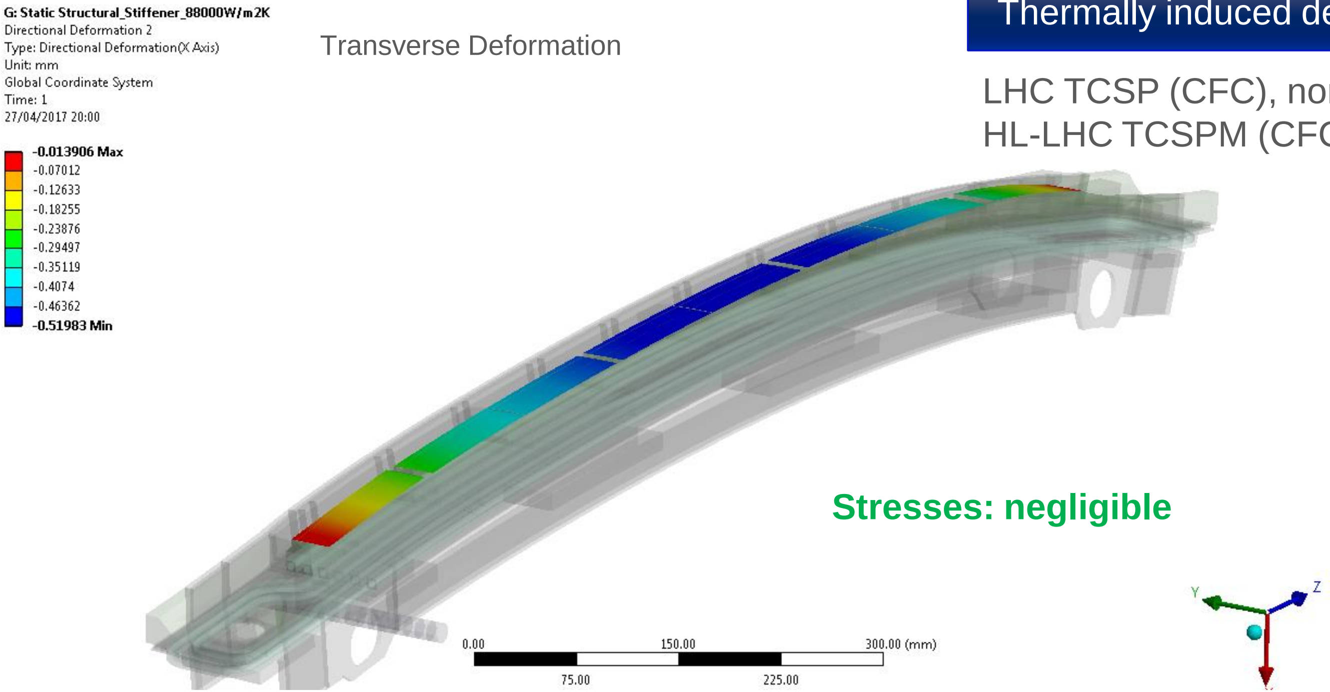


	Energy deposition on most loaded TCSPM (TCSGA6L7)	
	GeV/p	kW
Tank	86.35	10.15
Left Jaw	395	46.5
Right Jaw	398.4	46.9

factor 1.7 higher than TCSPM in CFC

0.2h BLT Design Case: Structural results

Transverse Deformation



Thermally induced deflection = 505 μm

LHC TCSP (CFC), nominal LHC = 130 μm[1,2]
HL-LHC TCSPM (CFC) = 300 μm[3]

Stresses: negligible

[1] TCSG → A. Dallocchio, *Study of thermomechanical effects induced in solids by high-energy particle beams: analytical and numerical methods.* CERN-THESIS-2008-140

[2] TCSP → G. Maitrejean, *TCSP collimator jaw: influence of the thermal conductance on the thermally induced transverse* , https://edms.cern.ch/document/1297290/1.0

[3] TCSP → F. Carra, *96th ColUSM*, https://indico.cern.ch/event/676105

Summary of Thermomechanical Results

- In spite of a much higher thermal load due to HL-LHC intensity and higher MoGr density, the **thermal-induced deflection at 1h BLT of a MoGr TCSPM is comparable to the LHC Secondary Collimators** (at half intensity)
- In the **0.2h BLT scenario, the sagitta is above** the specification for most loaded collimators. This does not concern HL **collimators installed in LS2** which **undergo much smaller thermal loads** (**loads 10+ times lower**)
- **Design optimization** necessary for more exposed **collimators to be installed in LS3**

Values obtained with a CFC Primary Collimator: expect 10-15% less with a MoGr Primary

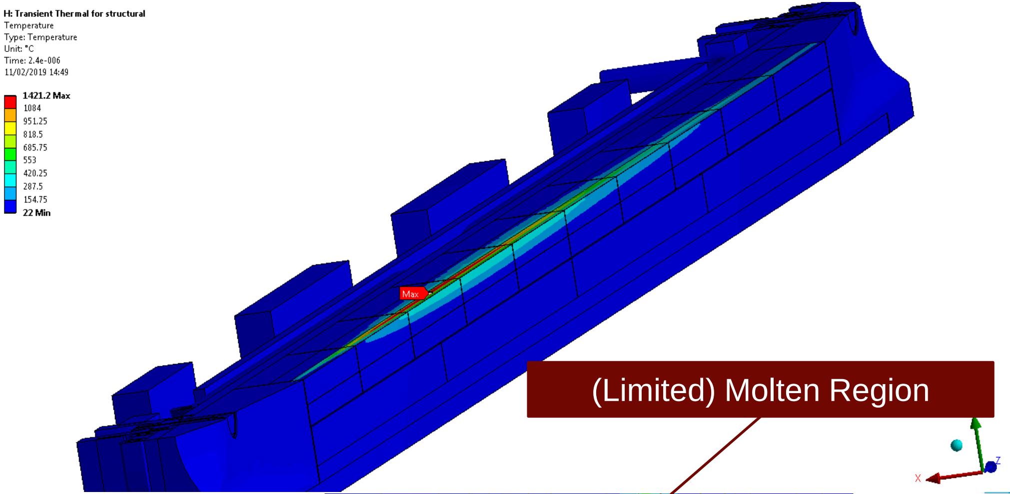
	1h BLT			***0.2h BLT***		
	TCSP$_{CFC}$ (LHC)	*TCSPM$_{CFC}$ (HL-LHC)*	*TCSPM$_{MoGr}$ (HL-LHC)*	*TCSP$_{CFC}$ (LHC)*	*TCSPM$_{CFC}$ (HL-LHC)*	*TCSPM$_{MoGr}$ (HL-LHC)*
Deposited Power on jaw [kW]	2	5.5	9.4	10	27.5	46.9
Stresses	OK	OK	OK	OK	OK	OK
Total Sagitta [μm]	+83	-110	+76	+96	+300	+505

+ : jaw moving towards the beam
– : jaw moving outwards the beam

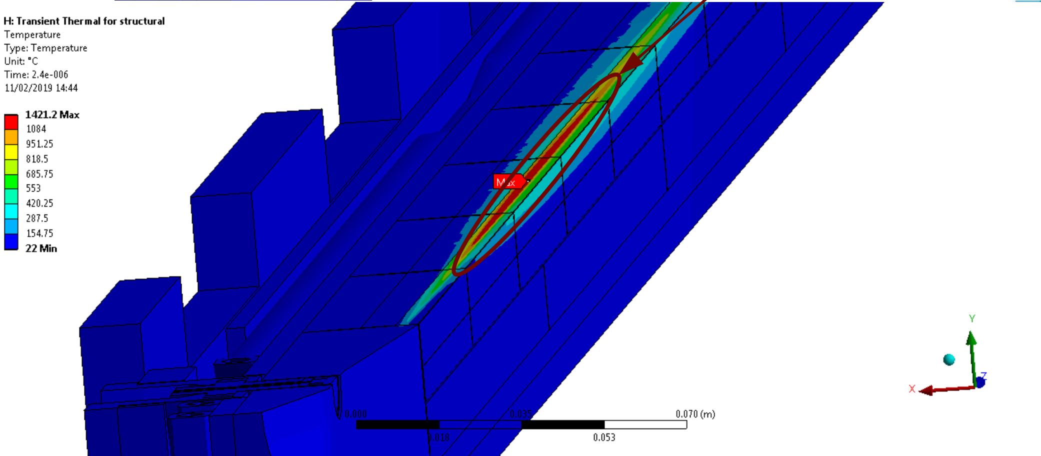
Includes effect of gravity and mechanical tolerances

HL-LHC Asynchronous Beam Dump on CuCD jaw

- Simulations based on a SPS pulse at Run2 intensity, equivalent to **1 HL-LHC bunch** at 7 TeV:
  - 48 bunches
  - $6.2 \cdot 10^{12}$ p
  - 440 GeV
  - 1.2 µs impact duration
  - Beam sigma 0.61 mm
  - Impact parameter 3.05 mm
- Linear Elastic and plastic material model
- Isotropic behaviour
- Melting temperature and yield strength failure model



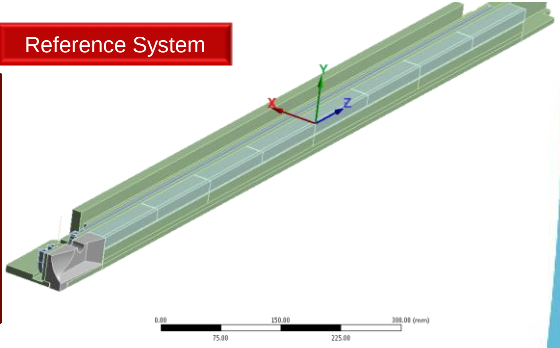
(Limited) Molten Region

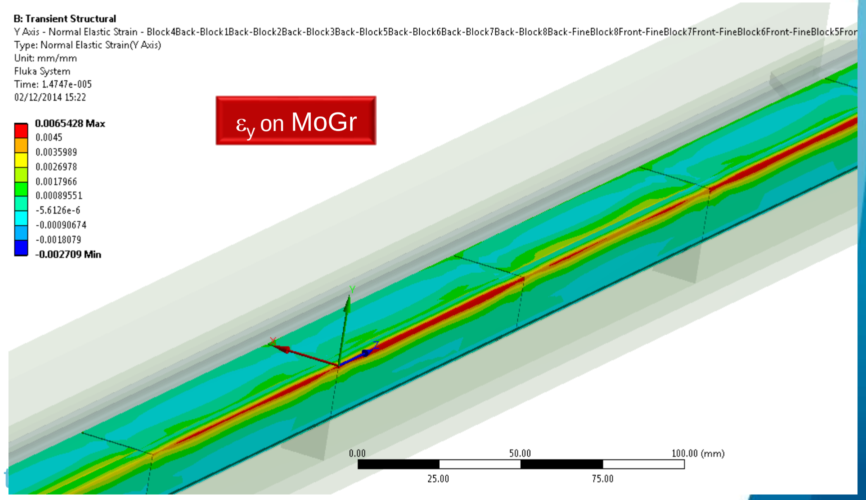


HL-LHC Beam Injection Error on MoGr Jaw

- Beam parameters for simulations:
  - 288 bunches
  - $6.6 \cdot 10^{13}$ p
  - 440 GeV
  - Beam sigma 1 mm (old value)
  - Impact parameter 5 mm
- Linear Elastic Material Model
- Transversely isotropic behaviour
- Maximum strain-to-failure approach

- Calculated strain in y-direction higher than admissible imply a thin crack may appear.
- Similar results are predicted for CFC …
- Should we worry?


Reference System


ε_y on MoGr

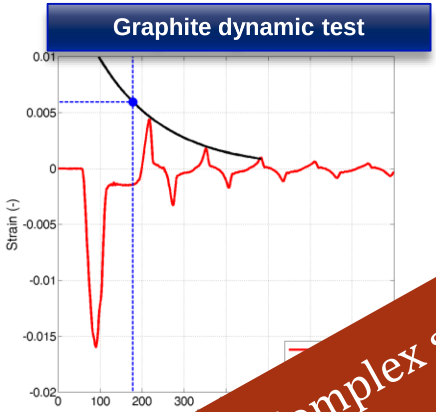
B: Transient Structural
Y Axis - Normal Elastic Strain - Block4Back-Block1Back-Block2Back-Block3Back-Block5Back-Block6Back-Block7Back-Block8Back-FineBlock8Front-FineBlock7Front-FineBlock6Front-FineBlock5Fro
Type: Normal Elastic Strain(Y Axis)
Unit: mm/mm
Fluka System
Time: 1.4747e-005
02/12/2014 15:22

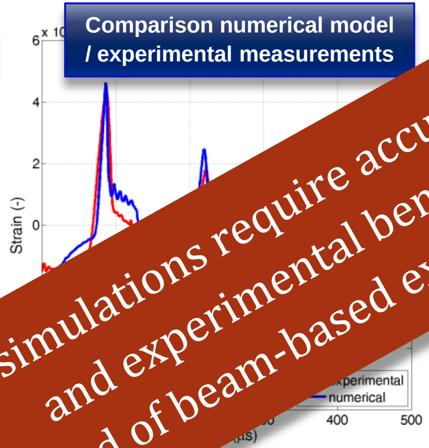
Normal strains on MoGr jaw

	Maximum in time Simulation [µstrain]	Reference value Ultimate strain [µstrain]
ε_x	4500	5200
ε_y	6500	2000
ε_z	1800	2000

Numerical Simulations Assessment

- Numerical Models can be (very) conservative. Why?
  - CFC, graphite and MoGr are not linear in σ/ε.
  - Strong energy dissipation occurs because of internal friction → They shoul terials

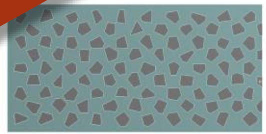

Graphite dynamic test

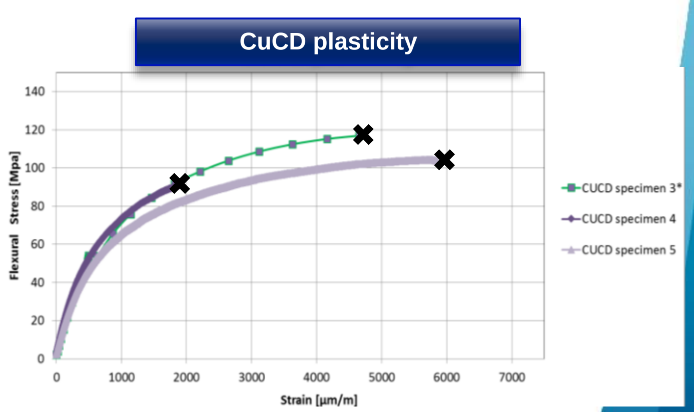

Comparison numerical model / experimental measurements

$$G_\infty + G_0 e^{-\frac{t}{\tau}}$$

built for R4550 graphite[1], ore complex for anisotropic materials as CFC and MoGr…

- CuC plasticity of Cu matrix, inter ection at Cu-CD interfaces!




CuCD plasticity

Complex simulations require accurate materials models and experimental benchmarking →
Strong need of beam-based experiments as HiRadMat

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[1] *L. Peroni, M. Scapin, F. Carra and N. Mariani (2013). Investigation of dynamic fracture behavior of graphite. In B. Basu, Damage assessment of structures X, Trans Tech Publications Inc, pp. 103-110.*

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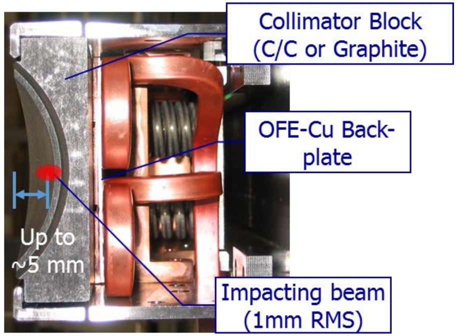
Survey of LHC Collimation Impact Tests

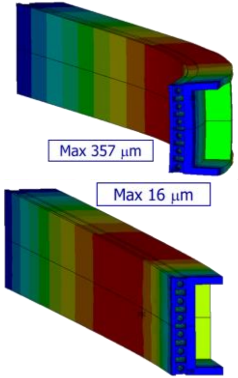
2004: **full LHC Secondary** collimator in TT40 (CFC + Graphite blocks)

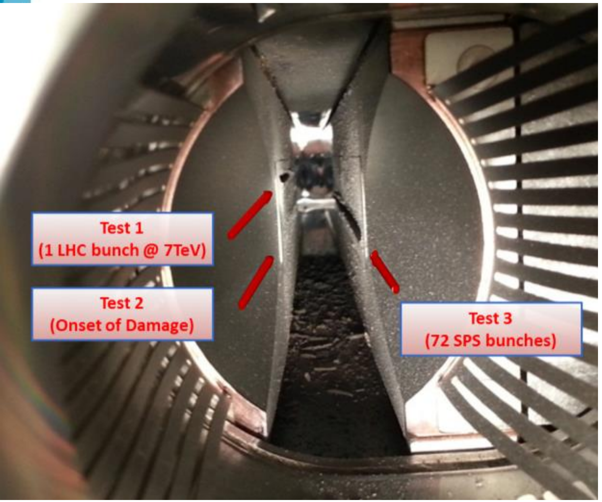
Block material ok, but unacceptable deformation found on Cu jaw support! Cu back-plate was then changed to Glidcop.

2006: **full LHC Secondary** collimator in TT40 (CFC)

Validated final LHC Collimator design!

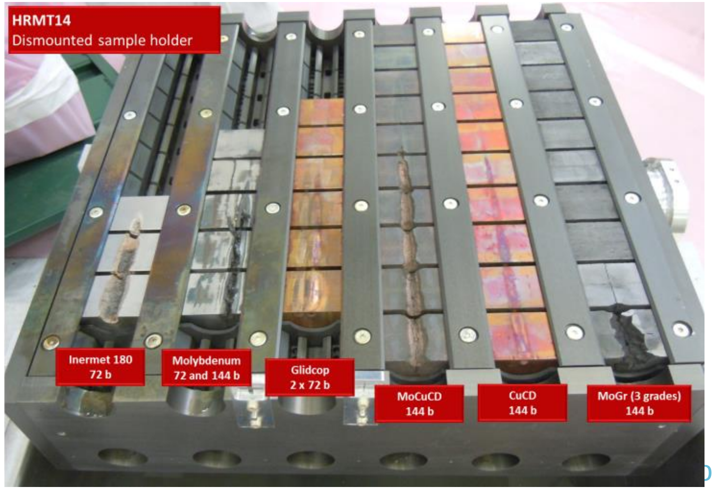






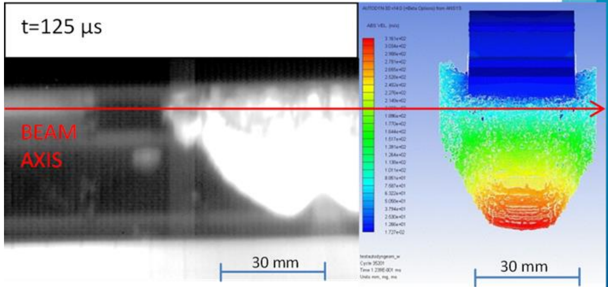
2012 HRMT-09: full Tertiary collimator (Tungsten alloy) in HiRadMat

Allowed deriving damage limits for Tertiary Collimator jaw



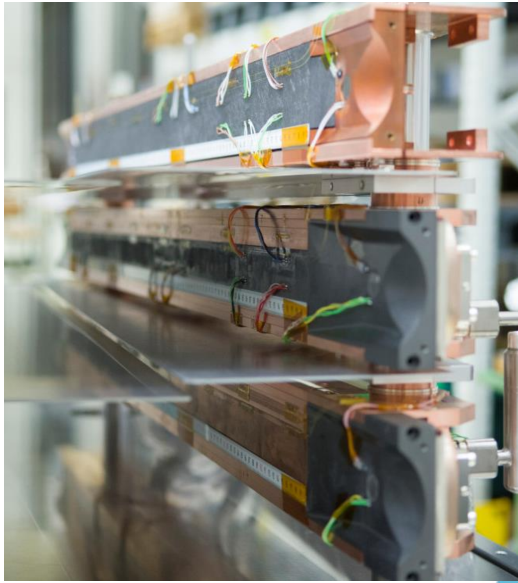
2012 HRMT-14: test of specimens from 6 different materials, including novel composites

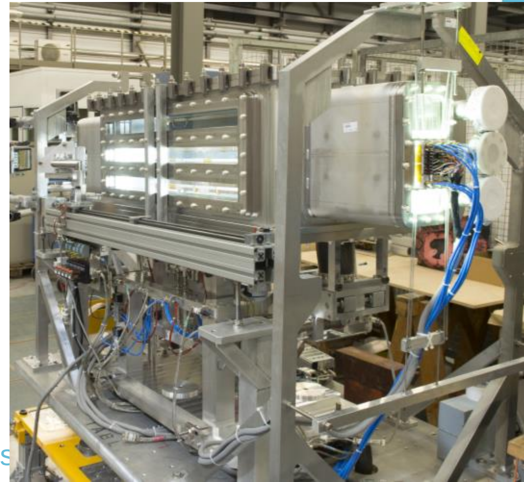
Materials characterization, constitutive models and simulation benchmarking



HiRadMat-23 Experiment

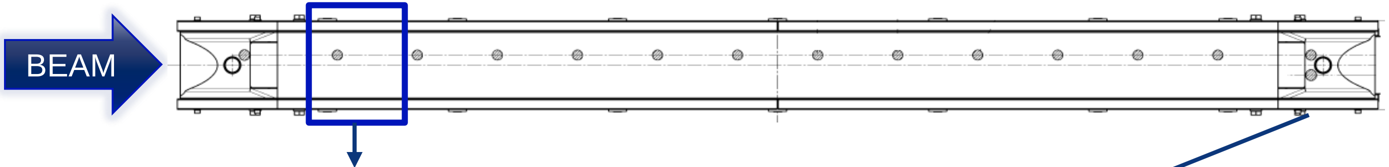
- HRMT 23 experiment carried out in **2015** testing **3 full collimator jaws**, with extensive on-board and remote instrumentation:
  - **LHC Secondary Collimator in CFC**
  - **HL-LCH Secondary Collimator in MoGr**
  - **HL-LHC Tertiary Collimator in CuCD**
- Main objectives:
  - **Mimic HL-LHC Beam Injection Error on Secondary** with LHC injection train (~ 55% of HL-LHC intensity) by **squeezing beam** to half beam size (0.35 mm vs 0.70 mm) to reach **comparable energy density**
  - **Mimic Asynchronous Beam Dump** at 7 TeV with equivalent energy pulse at 440 GeV for Tertiary
  - **Validate** the **new collimator design** and **assess** behaviour of jaw **materials**
  - Gather, online and offline, information on the **thermomechanical response** of jaw materials, for **simulation benchmarking**

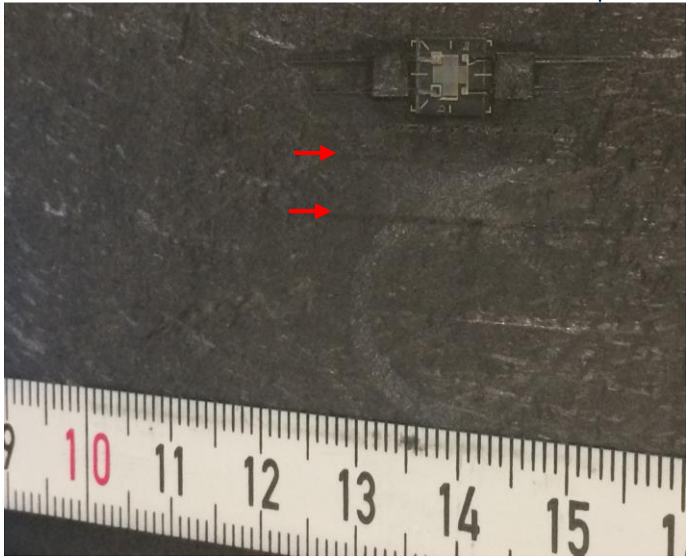




HRMT-23: LHC Secondary Collimator – CFC Jaw

- **8 pulses** at **288 b**, **σ 0.35** and **0.61 mm**, **impact parameter 0.18 to 5 mm**
- Max Energy Density: **3.16 kJ/cm3 (+ 29% vs. HL-LHC Beam Injection Error**)
- Some scratches on the surface, but overall undamaged. Downstream Glidcop tapering locally melted, BPM button lost functionality → For HL-LHC, change to **MoGr tapering** and **Ti BPM**

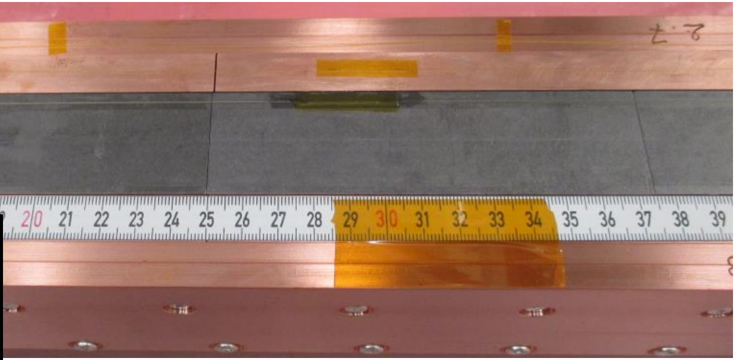


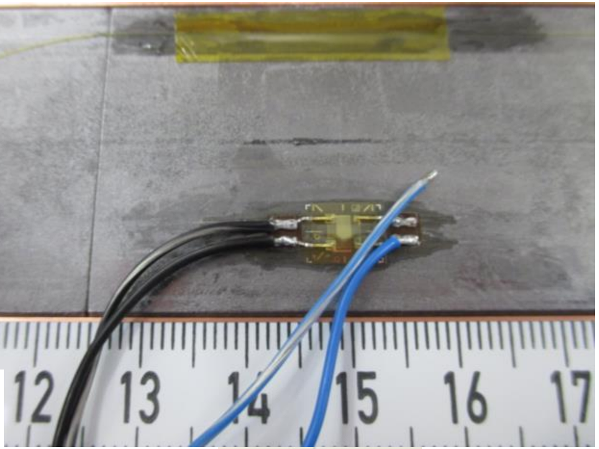


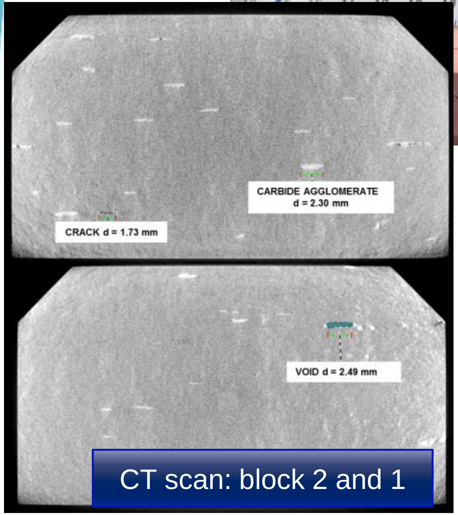
E_{tot} 2.67 MJ, σ 0.35 mm, η_x -5.00mm

HRMT-23: HL-LHC Secondary Collimator – MoGr Jaw

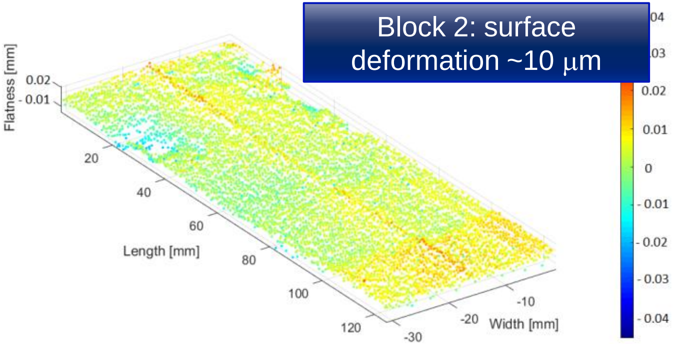
- **6 pulses** at **288 b**, **σ 0.35** and **0.61 mm**, **impact parameter 0.18 to 3 mm**
- **Max Energy Density**: 5.66 kJ/cm3 **(+ 5% vs. HL-LHC Beam Injection Error**)
- Scratches on the surfaces of the first three blocks (upstream). Both MoGr taperings unaffected
- No internal damage in MoGr; no change to electrical conductivity; no damage to jaw components



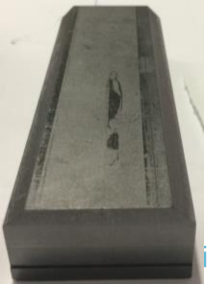




CT scan: block 2 and 1



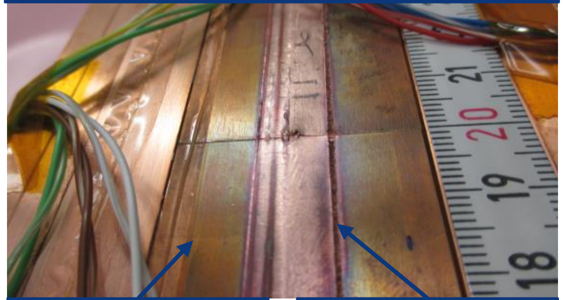
Block 2: surface deformation ~10 μm



HRMT-23: HL-LHC Tertiary Collimator – CuCD Jaw

- Several pulses at **24** (≅ **1 LHC b** at 7 TeV**), 48** (≅ **1 HL-LHC b** at 7 TeV**), 72 and 144 b**, **σ 0.35** and **0.61 mm**, **impact parameter 0.18 to 3 mm**
- 0.2 – 0.5 mm grooves on the surface of the blocks due to the high-intensity grazing beam impacts
- Fracture of bulk material and craters (energy dependent) at block edges for deep impacts and energy density 2-3 times higher than the design scenario
- Both MoGr taperings unaffected
- In spite of damage, tertiary collimator jaw can maintain its functionality thanks to 5th axis compensation

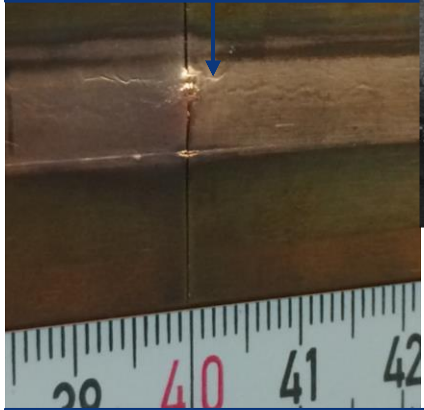
Grazing impacts: spallation, micro-spallation and micro-jetting

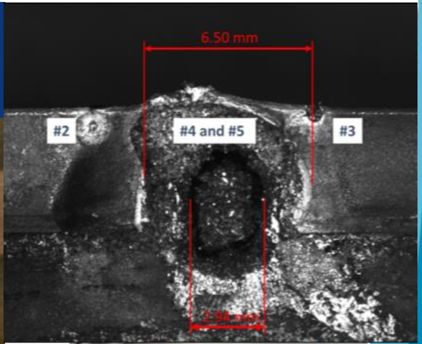


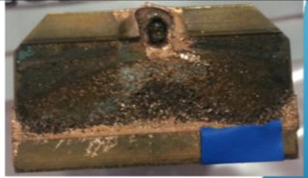
24 b, σ=0.35mm, impact 0.5 σ

48 b, σ=0.35mm, impact 0.5 σ

144 b (factor 3 higher than HL-LHC ABDσ=0.61mm, impact 3.05mm







Deep impacts (beyond HL-LHC): global plastic deformation and fractures on the free surface

HiRadMat-36 Experiment (Multimat)

- Experiment performed in **October 2017**
- Al vessel hosting under inert gas a rotatable barrel equipped with **16 target stations**, each one embarking up to 8 **slender specimens**, with rectangular cross-section
- **18** different **materials** tested, ranging from ultra light C foams to W heavy alloys
- **MoGr** (4 grades), **CFC** and **graphite coated** with **Mo**, **Cu**, **TiN**
- **Platform reusable** in future HRMT tests

Main objectives:

- Acquire material dynamic responses and derive / extend constitutive models to **benchmark complex numerical simulations** (see back-up slide for details)
- Test materials and coatings with **beam brightness** equivalent or exceeding **HL-LHC Beam Injection Error**
- In spite of lower available intensity, exploit sample shape to **reach or exceed some stress components** induced by **HL-LHC high intensity accidents**

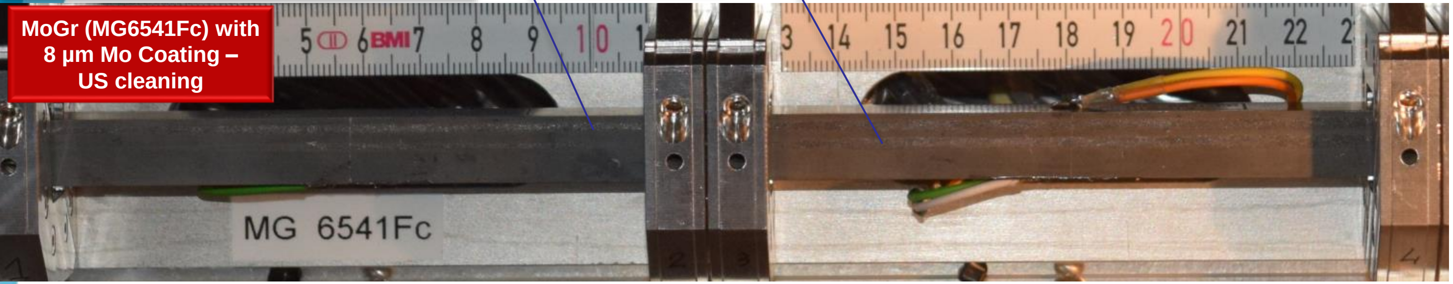
HRMT-36: Grazing Impacts on Mo coatings

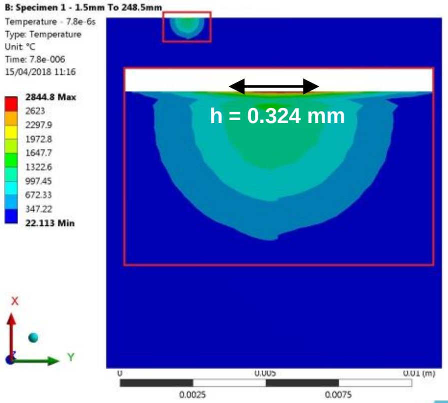
E_{max} = 6.11 kJ/cm3 (bulk)
E_{max} = 13.9 kJ/cm3 (coat.) T_{max} = 2844°C

MoGr (MG6541Fc) with 8 µm Mo Coating – US cleaning

288 b, σ 0.25 mm, impact 150 µm

288 b, σ 0.25 mm, impact 500 µm





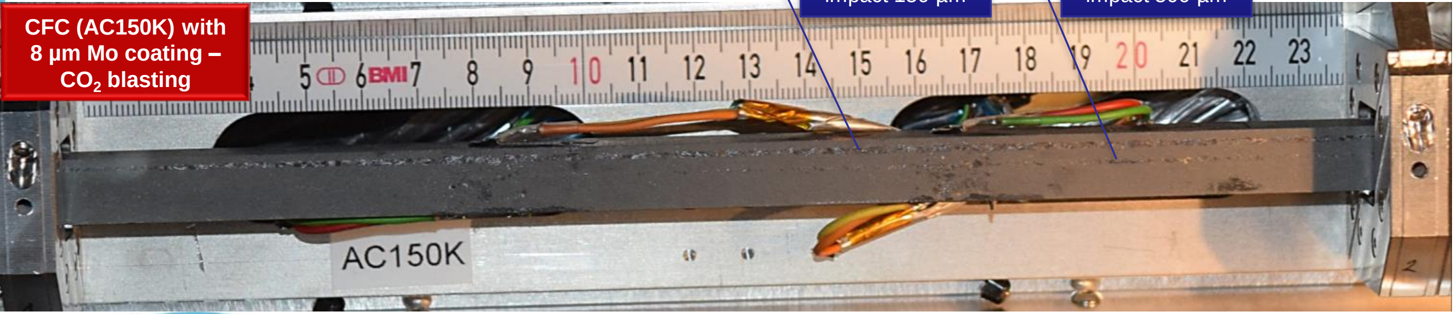
h = 0.324 mm

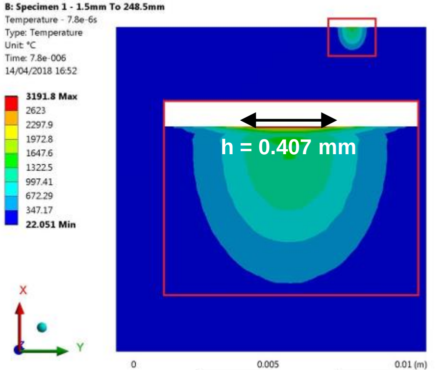
E_{max}= 3.72 kJ/cm3 (bulk)
E_{max} =14.3 kJ/cm3 (coat.) T_{max} = 3192°C

CFC (AC150K) with 8 µm Mo coating – CO_2 blasting

288 b, σ 0.25 mm, impact 150 µm

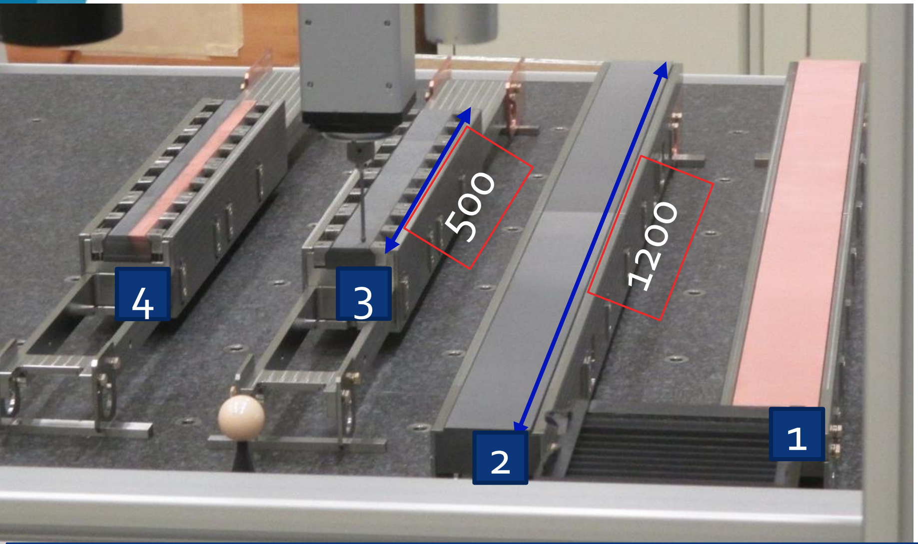
288 b, σ 0.25 mm, impact 500 µm





h = 0.407 mm

HiRadMat-35 Experiment

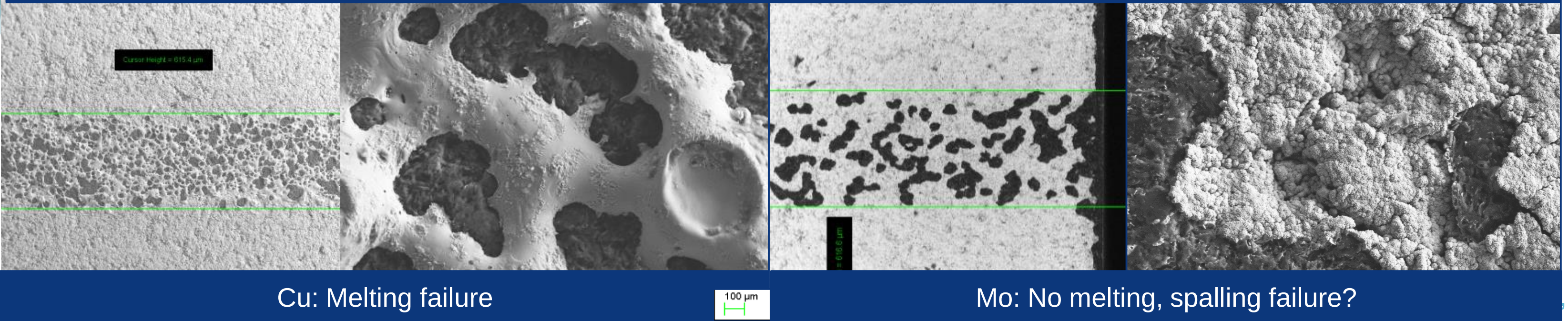


- Experiment by **EN/STI** carried out in 2017 mainly to test **TDI** absorber and validate its Cu-coated Graphite jaw in impact conditions similar to Collimators Beam Injection Error
- Simultaneously test behaviour of low impedance coatings on low-Z carbon materials when grazed by a high intensity proton beam

Tested materials:

1. TDI Jaw with Cu-coated Graphite (length 120 cm)
2. TDI Jaw with Mo-coated Graphite (length 120 cm)
3. Mo- coated CFC (AC150K) block (length 50cm)
4. Mo- and Cu-coated MoGr (old grade, tested in HRMT-23) (length 50 cm)

Grazing impacts on coated graphite blocks: microscopy



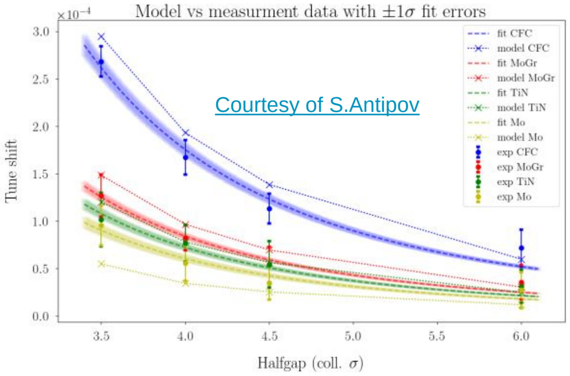
Cu: Melting failure

Mo: No melting, spalling failure?

Courtesy
I. Lamas
EN/STI

Design Validation through Prototypes

- Mechanical Design was also validated through **2 full collimator prototypes** built at CERN (EN/MME Workshop)
  - 1 HL-LHC Secondary Collimator with multiple coatings on jaw, **installed in LHC** ring to benchmark collimation impedance
  - 1 HL-LHC DS Collimator, now available as **spare**
- **Additional prototypes and demonstrators to be built** after LS2 to validate designs of IR Cleaning Collimators and evolutions of Halo Cleaning collimators



Courtesy of S.Antipov

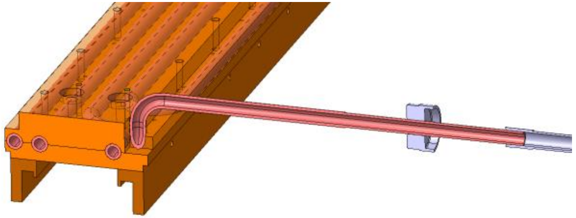
Table of contents

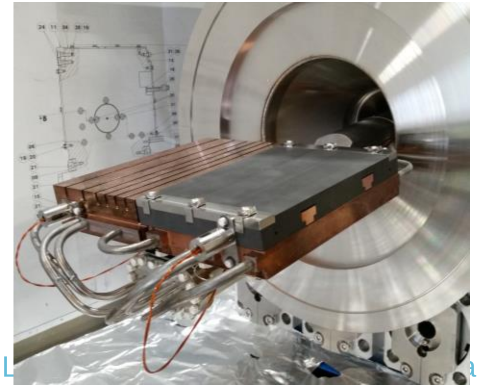
Outlook

- A **new collimation system** is being mechanically engineered for HL-LHC (installation in LS2 and LS3), largely relying on the successful LHC experience
- **DS Cleaning Collimators** were validated by one prototype and are currently being received ahead of installation in LS2
- New **IR Cleaning Collimators** are being designed; they will rely on a new remote alignment system. Prototypes to be built at the end of LS2 in view of design validation
- **Halo Cleaning Collimators** (Primary, Secondary, Tertiary) share the same design. Baseline jaw materials are uncoated **MoGr for Primary**, **Mo-coated MoGr for Secondary**, **CuCD for Tertiary**
  - Their **design is robust**, both for accidental and normal operating conditions in spite of much higher thermal loads due to the HL-LHC increased intensity and MoGr higher density
  - Accidental scenarios were extensively assessed through HiRadMat experiments aiming at mimicking HL-LHC accidental conditions benchmarking complex simulations
  - The extent of **damage** by grazing accident to **Mo coating** is limited to **less than 2mm**
  - However, it must be stressed that these tests did not entirely reproduce HL-LHC conditions: **HiRadMat experiments with full LIU beams are hence essential after LS2!**
  - The main specification parameter which is not met by the new design is the **jaw deformation in the 0.2 hr Beam Lifetime** scenario. This only affects two most loaded collimators to be installed in LS3 … optimizations to be studied.
- Other design optimizations could also be considered after LS2 (e.g sliding tables …), particularly in view of simplifying manufacturing, installation and alignment: all modifications should be validated by prototypes

HIPped jaws for HL-LHC Secondary Collimators

- Hot Isostatic Pressing (HIP) is a process allowing, inter alia, diffusion bonding between dissimilar materials by the simultaneous application of heat and pressure
- Realization of a HIPed LHC collimator jaw – compatible with the current design
- Based on experience with other designs by EN/STI currently under manufacturing
- Advantages:
  - No more brazing required
  - Increased cooling efficiency
  - Production of the jaw could open the market to other firms (which are not equipped with brazing) – and reduce collimator production costs

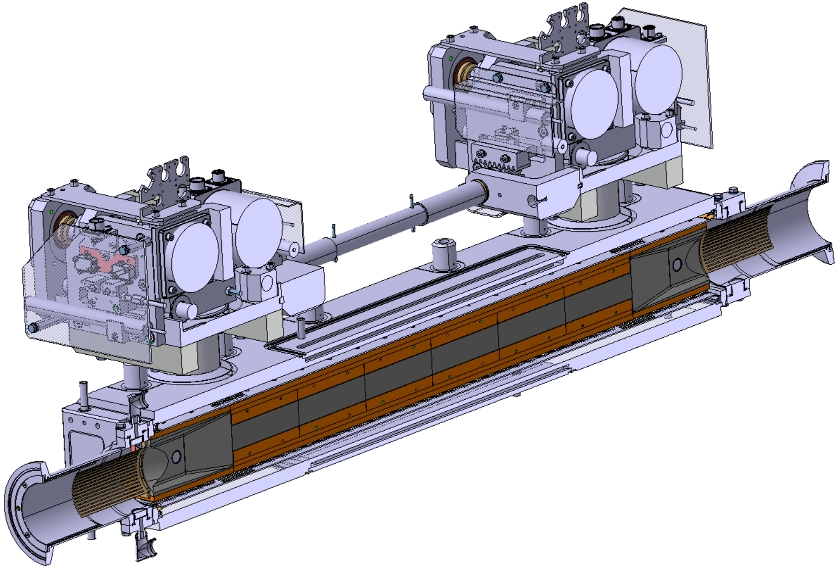




M. Calviani; I. Lamas;
A. Perillo
EN/STI

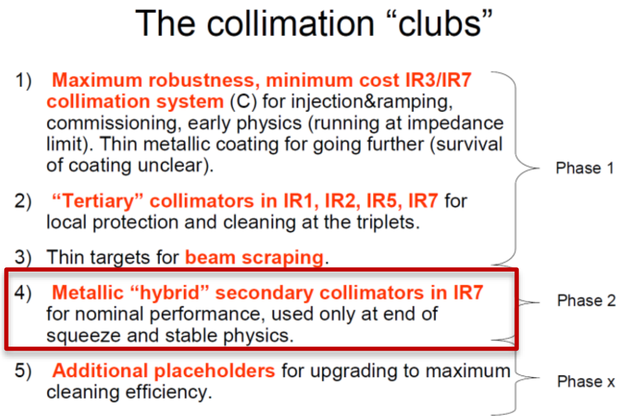
Shorter Collimator Jaw

- **MoGr**, through density and Z, has a **cleaning efficiency significantly superior** to standard carbon materials (CFC and graphite) …
- (Crazy?) Idea: can we reduce the active length of (some) MoGr Secondary Collimators for LS3 to **0.5 ÷ 0.75 m**, maintaining the same overall protection?
- Advantages:
  - Jaw deflection significantly reduced (thermal sagitta scales with the square of the length)
  - Lower resistive wall impedance (linearly scales with length); geometric impedance unaffected
  - Simpler manufacturing; easier to fulfill mechanical tolerances
  - Lower thermal loads, less activation
  - Not for a technical review but … lower cost for material (MoGr) procurement!



Thank you!

Historic Overview



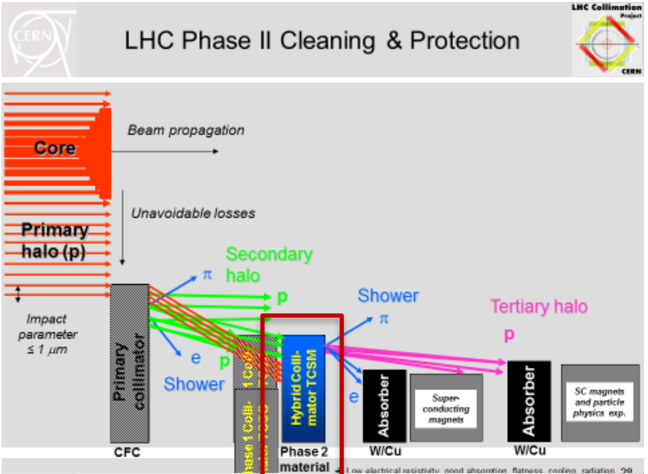
The collimation "clubs"

1) **Maximum robustness, minimum cost IR3/IR7 collimation system** (C) for injection&ramping, commissioning, early physics (running at impedance limit). Thin metallic coating for going further (survival of coating unclear).
2) **"Tertiary" collimators in IR1, IR2, IR5, IR7** for local protection and cleaning at the triplets.
3) Thin targets for **beam scraping**.
4) **Metallic "hybrid" secondary collimators in IR7** for nominal performance, used only at end of squeeze and stable physics.
5) **Additional placeholders** for upgrading to maximum cleaning efficiency.

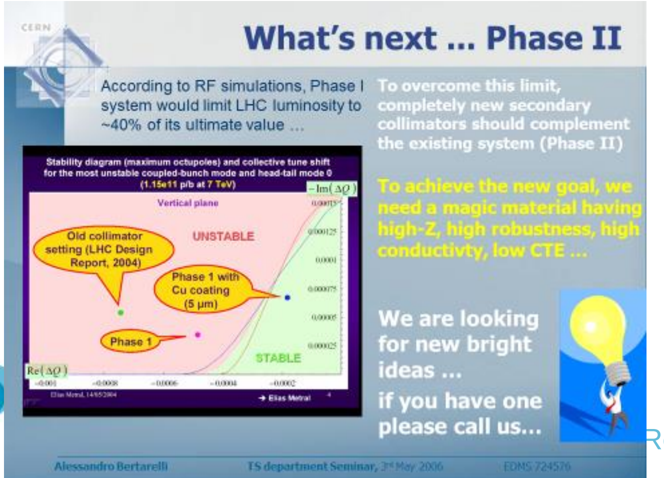
Phase 1 (items 1–3)

Phase 2 (item 4)

Phase x (item 5)



LHC Phase II Cleaning & Protection



What's next … Phase II

According to RF simulations, Phase I system would limit LHC luminosity to ~40% of its ultimate value …

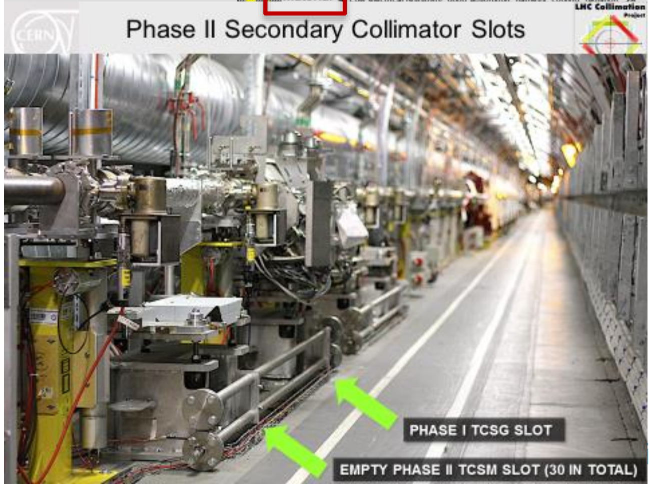
To overcome this limit, completely new secondary collimators should complement the existing system (Phase II)

To achieve the new goal, we need a magic material having high-Z, high robustness, high conductivty, low CTE …

We are looking for new bright ideas …

if you have one please call us…

Alessandro Bertarelli TS department Seminar, 3rd May 2006 EDMS 724576



Phase II Secondary Collimator Slots

Design Criteria for HL-LHC: General Concept

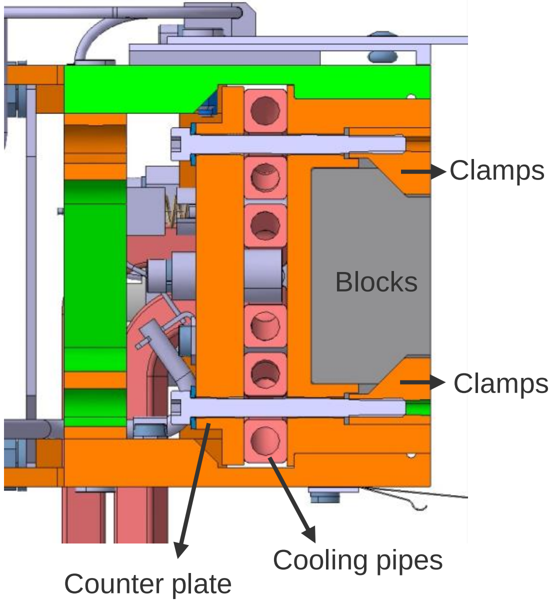
- Design of HL-LHC Collimators is inspired by LHC-Phase I experience and largely maintains LHC-Phase II requirements
- Key Features of all collimator designs:
  - 2 long movable jaws in a Vacuum Vessel
  - 2 degrees of freedom each (lateral and tilt), 2 motors per jaw
  - On-jaw BPM pick-ups
  - Sliding tables with improved design
  - Halo Cleaning Collimators (Betatron and off-momentum cleaning):
    - Modular jaw design allowing to host any active material (MoGr, CuCD, Graphite, …)
    - 5th axis movement parallel to jaw surface allows compensation of jaw damage
    - Addition of 2 BPM to detect beam orbit drift parallel to jaw surface
    - Interchangeability with Phase I (same interfaces)
  - New designs for IR Cleaning and DS Collimators (special space constraints)

Case study 1 h BLT

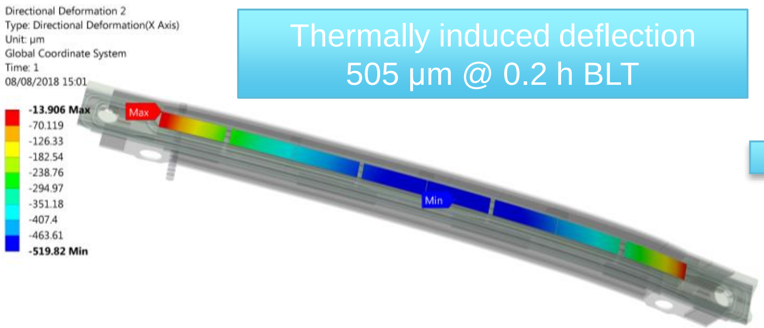
	Energy deposition on TCSPM	
	GeV/p	kW
Tank	86.35	2.03
Left Jaw	395	9.30
Right Jaw	398.4	9.38
Total		**20.71**

Power deposition breakdown

Components	Materials	Energy deposition kW
Blocks	MoGr 6403 Fc	4
Taperings	MoGr 6403 Fc	0.6
BPMs	Stainless Steel	0.07
Clamps	Glidcop Al-15	1.37
Cooling Pipes	CuNi 90-10	0.35
Housing	Glidcop Al-15	1.8
Counter plate	Glidcop Al-15	0.43
Stiffener	Glidcop Al-15	0.76



TSCPM design optimization



Thermally induced deflection
505 µm @ 0.2 h BLT

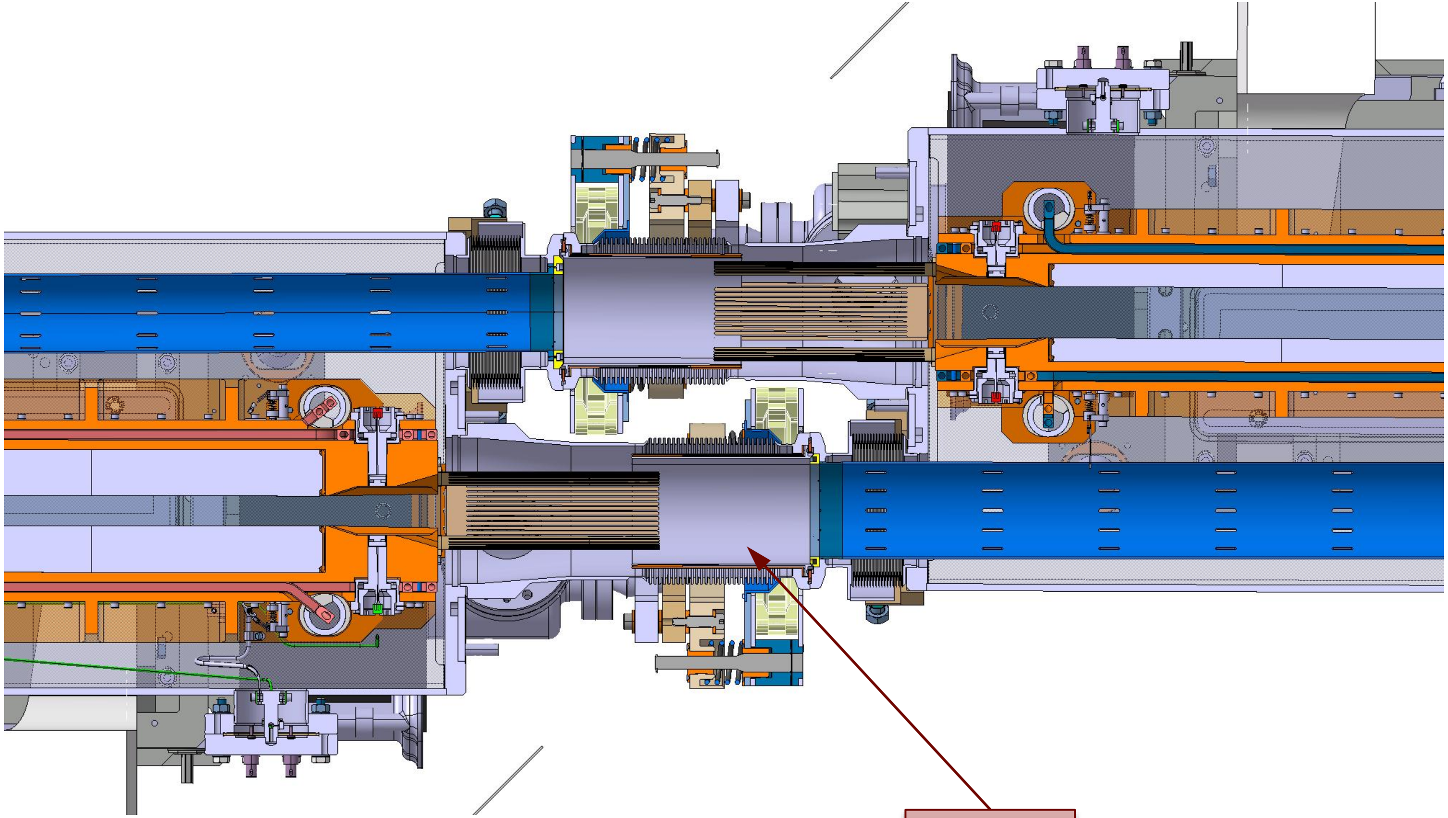
Reduce deflection @0.2 h BLT → **Housing**:
- Material
- Geometry

A wide range of **materials** was explored, among them the most promising one are:

Housing	**Material Proprieties**				**0.2h BLT**		**1h BLT**	
	Density [g/cm^3]	E [GPa]	CTE [K^{-1}]	Thermal conductivity [W·m^{-1}·K^{-1}]	Max Temp [ºC]	Flatness [µm]	Max Temp [ºC]	Flatness [µm]
Glidcop	8.9	120	16	365	241	505	127	76
Nb	8.5	104	7.1	52	268	85	155	320
Ti Grade 2	4.5	110	7.6	17	325	117	217	338

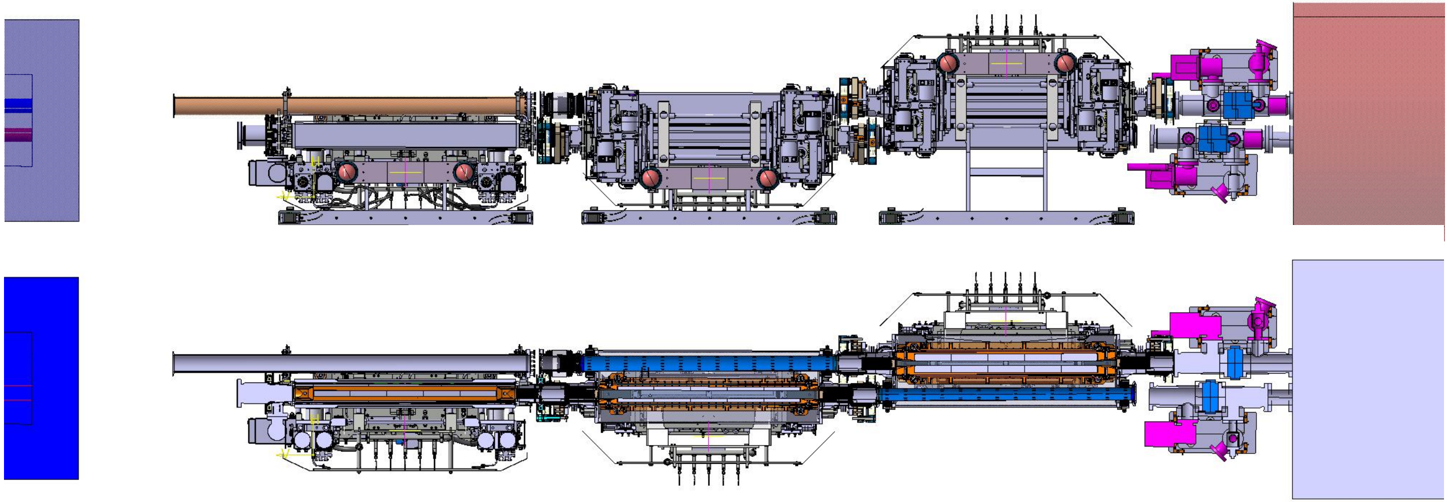
* Simulations done with same Fluka maps as Glidcop case

Interface between TCLPX and TCTPXH



Complex Layout, still under development

TctpXH / TCTPXV / TCLPX



TAXN

TCTPXV

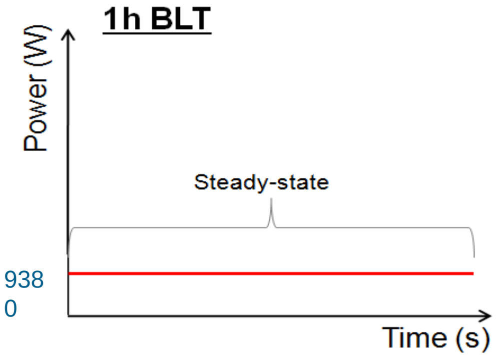
TCTPXH

TCLPX

D2

Slow Losses: 1h BLT Design Case

- HL-LHC 7 TeV 25ns (standard)
- N_{tot} = 6.1E+14 → losses on full collimation system **1.68E+11 p/s**
- Configuration: *TCPs@5.7 σ in CFC (conservative assumption for power loads) and TCSPMs@ 7.7σ*
- Main requirement: Maintain **geometrical stability** → Maximum jaw **flatness** error **100 µm**
- **Steady-state** assumed for thermomechanical calculations



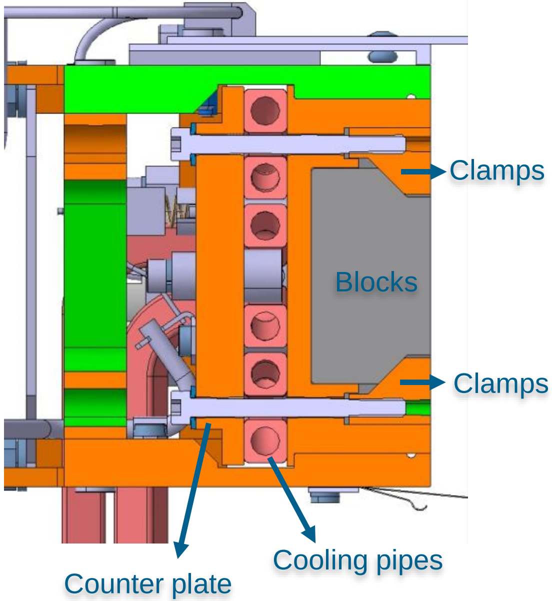
	Energy deposition on most loaded TCSPM (TCSGA6L7)	
	GeV/p	kW
Tank	86.35	2.03
Left Jaw	395	9.30
Right Jaw	398.4	9.38
Total		**20.71**

factor 4.5 higher than LHC Secondary Collimator

Continuous Losses: 1h BLT Design Case

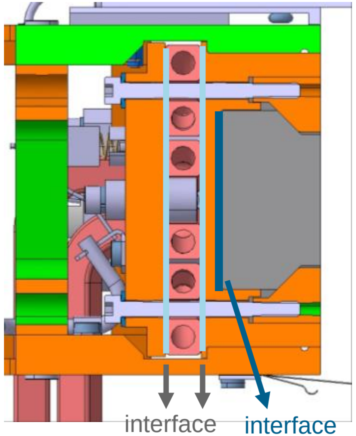
Energy deposition breakdown

Components	Materials	Power Deposition [kW]
Blocks	MoGr 6403 Fc	4.0
Taperings	MoGr 6403 Fc	0.6
BPMs	Stainless Steel	0.07
Clamps	Glidcop Al-15	1.37
Cooling Pipes	CuNi 90-10	0.35
Housing	Glidcop Al-15	1.8
Counter plate	Glidcop Al-15	0.43
Stiffener	Glidcop Al-15	0.76

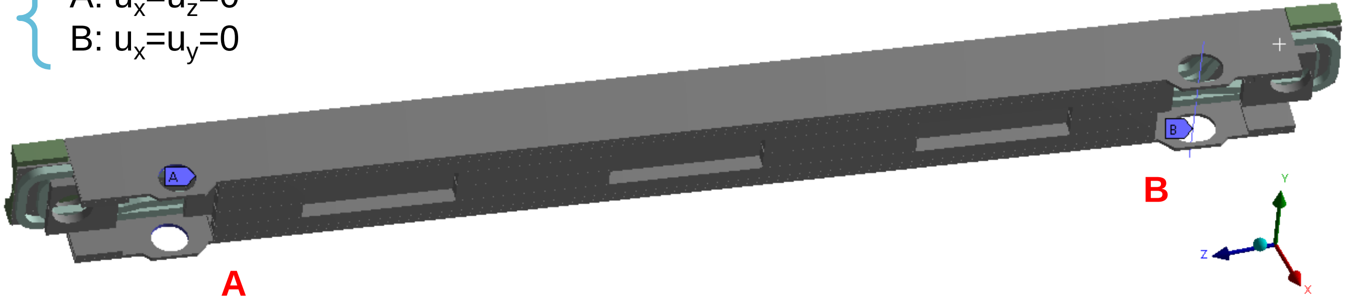


1h BLT Design Case: Boundary Conditions

Parameters	Values
Convective coefficient (v=3 m/s)	13800 W/(m^{2}K)
T initial of water	22°C
ΔT out-in cooling pipes	14°C
Conductance interface 1	83000 W/(m^{2}K)
Conductance interfaces 2,3	25000 W/(m^{2}K)



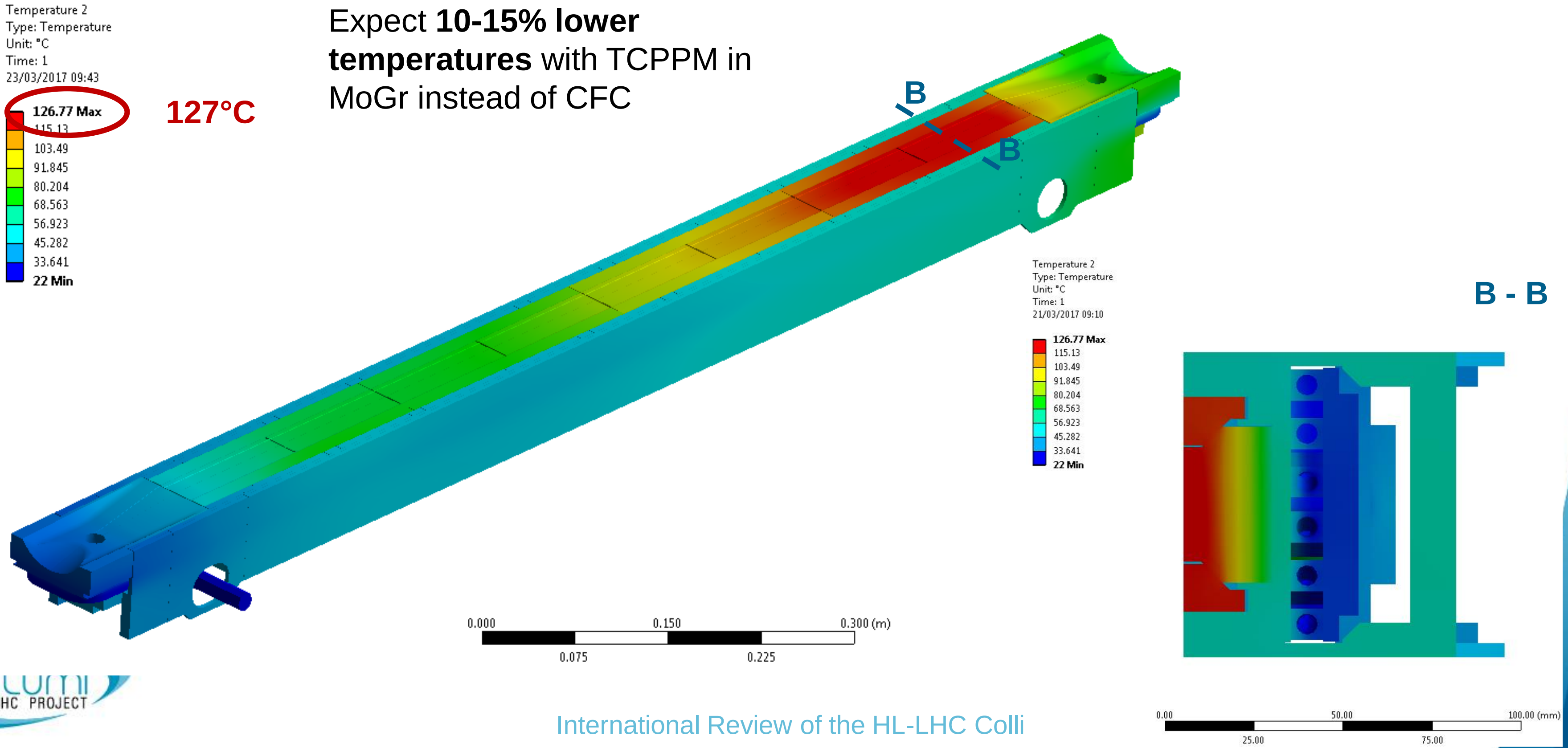
A: $u_x=u_z=0$
B: $u_x=u_y=0$



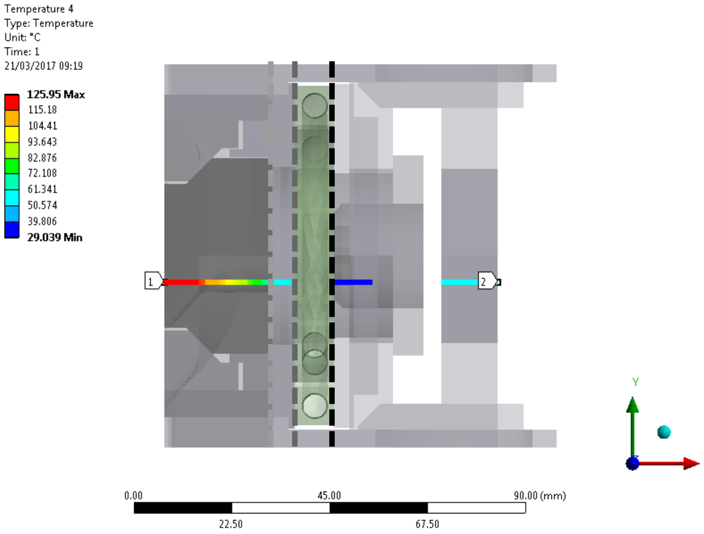
1h BLT Design Case: Thermal Results

Expect **10-15% lower temperatures** with TCPPM in MoGr instead of CFC

127°C



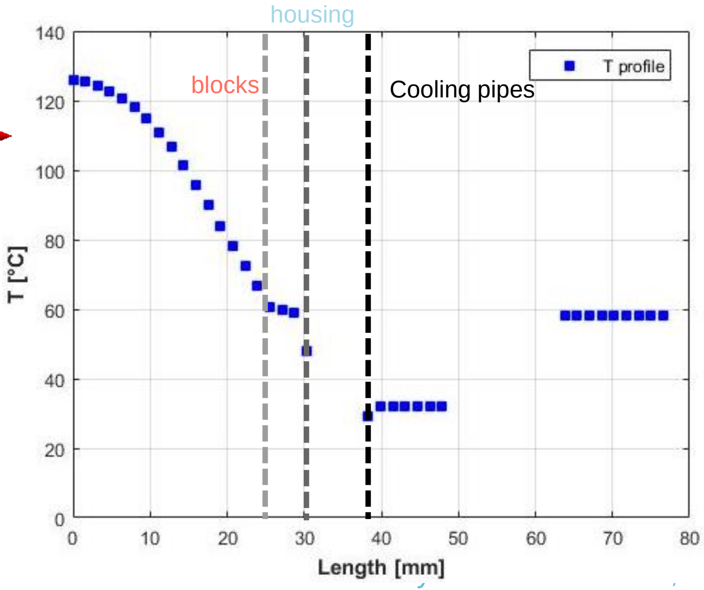
1h BLT Design Case: Thermal results



Temperature gradient at most loaded cross-section

- Interface MoGr block – Glidcop ~ 2 °C
- Interface Glidcop – Cooling Pipe ~ 11 °C

  *conductance value = 25000 W/(m^2 K)
- T internal tube ~ 24 °C

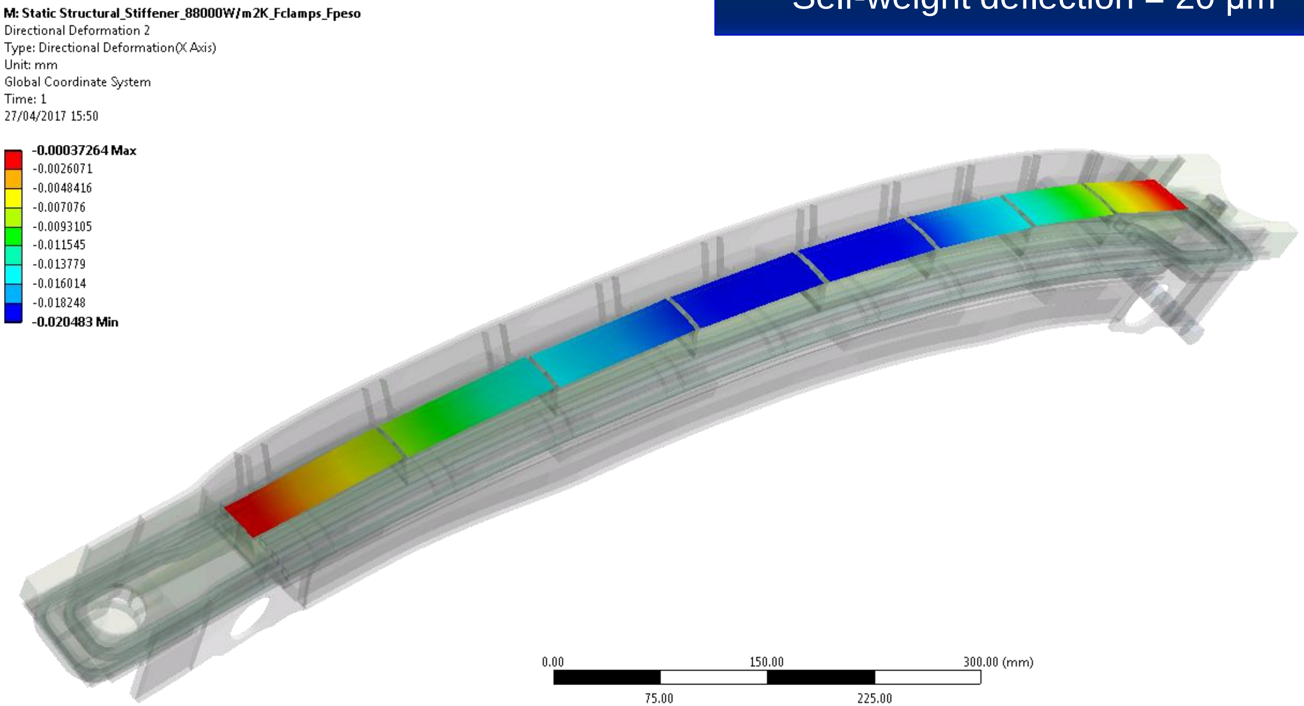


1h BLT Design Case: Structural Results

Effect of Standard Earth Gravity (skew collimator)

X-Deformation

Self-weight deflection = 20 µm



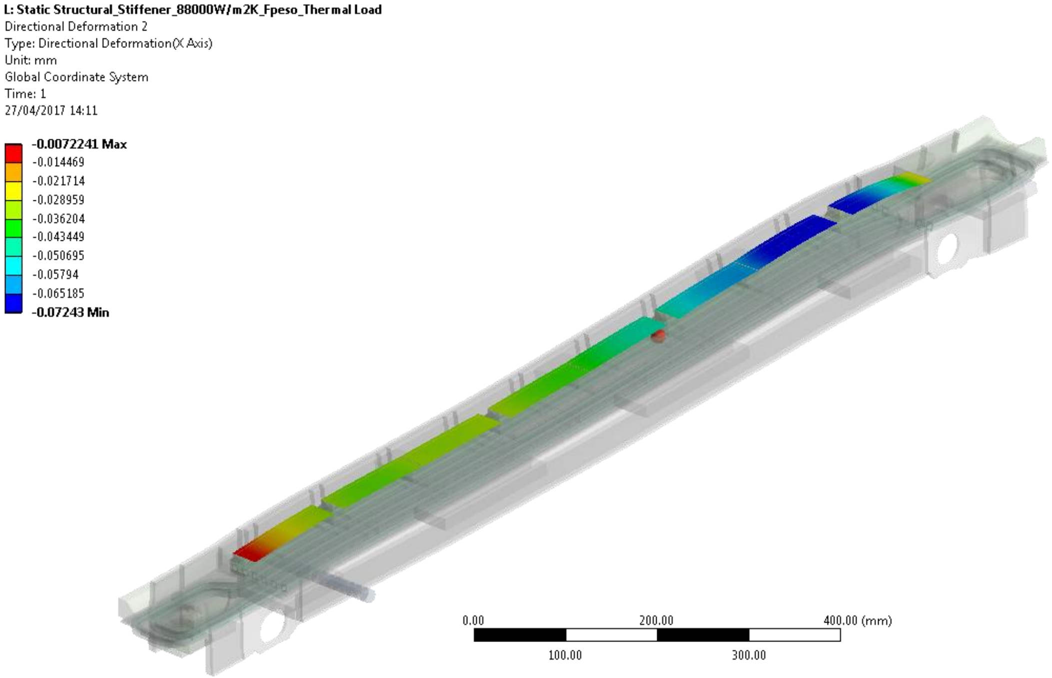
M: Static Structural_Stiffener_88000W/m2K_Fclamps_Fpeso
Directional Deformation 2
Type: Directional Deformation(X Axis)
Unit: mm
Global Coordinate System
Time: 1
27/04/2017 15:50

1h BLT Design Case: Structural Results

Combined Effect of Standard Earth Gravity and Thermal Load

X-Deformation

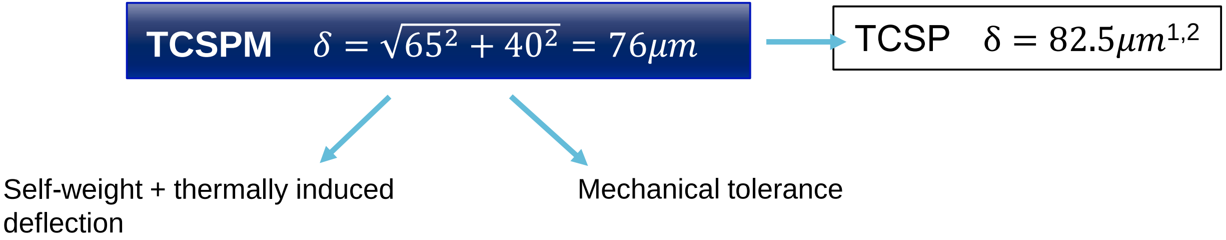
Self-weight + thermal induced deflection = 65 µm



L: Static Structural_Stiffener_88000W/m2K_Fpeso_Thermal Load
Directional Deformation 2
Type: Directional Deformation(X Axis)
Unit: mm
Global Coordinate System
Time: 1
27/04/2017 14:11

1h BLT Design Case: Structural Results

- Total estimated deflection δ is:



TCSPM $\delta = \sqrt{65^2 + 40^2} = 76\mu m$ → TCSP $\delta = 82.5\mu m^{1,2}$

Self-weight + thermally induced deflection

Mechanical tolerance

Specification: the maximum admissible deflection is **100µm**
No problems from the structural point of view

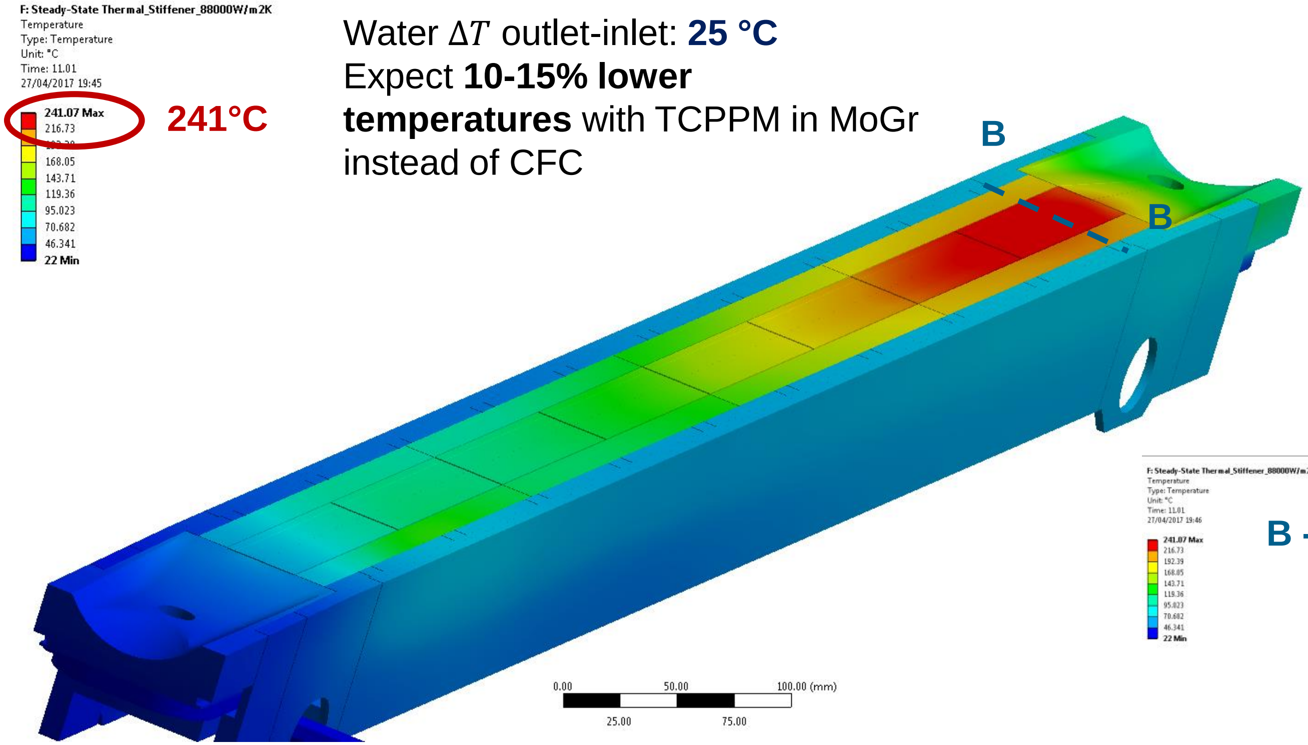
---

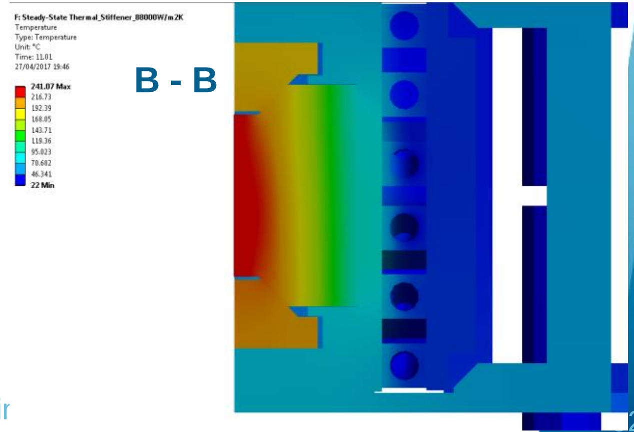
[1] TCSG → A. Dallocchio, *Study of thermomechanical effects induced in solids by high-energy particle beams: analytical and numerical methods.* [CERN-THESIS-2008-140]

[2] TCSP → G. Maitrejean, *TCSP collimator jaw: influence of the thermal conductance on the thermally induced transverse* , [https://edms.cern.ch/document/1297290/1.0]

0.2h BLT Design Case: Thermal results

Water ΔT outlet-inlet: **25 °C**
Expect **10-15% lower temperatures** with TCPPM in MoGr instead of CFC

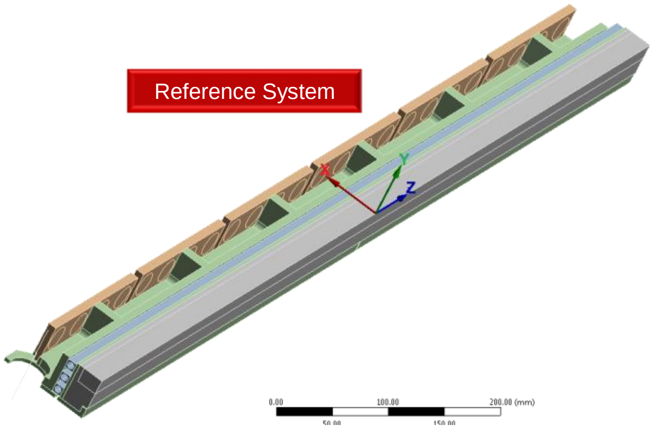




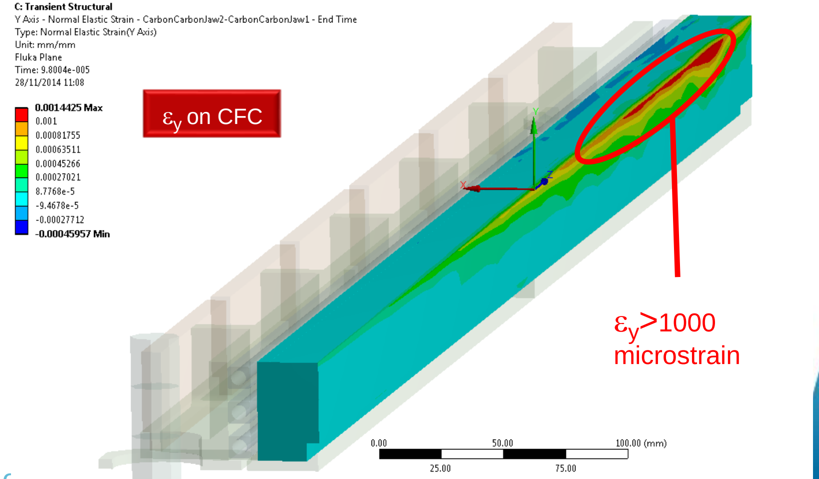
HL-LHC Beam Injection Error on CFC Jaw

- Beam parameters:
  - 288 bunches
  - $6.4 \cdot 10^{13}$ p
  - 440 GeV
  - Beam sigma 1 mm
  - Impact parameter 5 mm
- Linear Elastic Material Model
- Orthotropic behaviour
- Maximum strain-to-failure approach

Normal strains on CFC jaw		
	Maximum over time Simulation [microstrain]	Reference value Ultimate strain [microstrain]
ε_x	**2000**	**2600**
ε_y	**1400**	**850**
ε_z	**740**	**1800**



Reference System



C: Transient Structural
Y Axis - Normal Elastic Strain - CarbonCarbonJaw2-CarbonCarbonJaw1 - End Time
Type: Normal Elastic Strain(Y Axis)
Unit: mm/mm
Fluka Plane
Time: 9.8004e-005
28/11/2014 11:08

ε_y on CFC

ε_y>1000 microstrain

Motivations and Objectives for Impact Tests

- 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

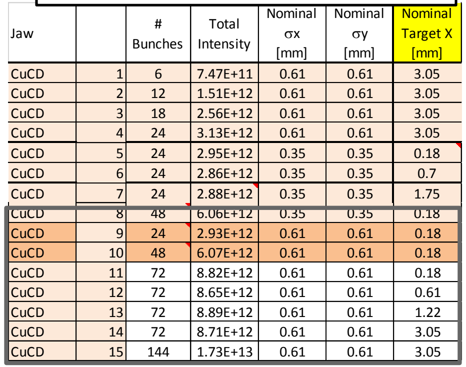
- Requirements for the Collimation System to be addressed (from Run1 to HL-LHC):
  - Demonstrate the viability of a low-impedance collimator solution (long-standing limitation on intensity reach, amplified by HL-LHC settings)
  - Mitigate/remove TCT robustness limit that affected operational choices of beta* and optics of present machine
  - Re-assess robustness of present carbon-based design (TCS and TCP) against injection failures with smaller emittances (see A. Lechner at LMC n. 226)

Pulse list

Accidental case scenarios for HL-LHC:

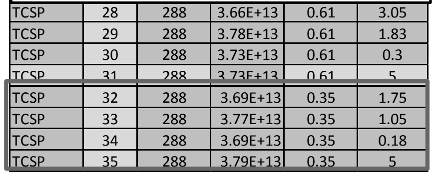
- Primaries and secondaries → 288 bunches SPS (2443 J/cm^3, σ = 0.61 mm, intensity 6.6E13 p)
- Tertiaries → 1 bunch HL-LHC equivalent to 48 bunches SPS

Equivalence SPS/LHC in terms of damage for Asy. Dump (Inermet) → 24 bunches
HL-LHC → 48 bunches



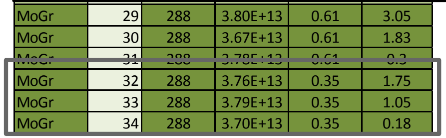
Jaw		# Bunches	Total Intensity	Nominal σx [mm]	Nominal σy [mm]	Nominal Target X [mm]
CuCD	1	6	7.47E+11	0.61	0.61	3.05
CuCD	2	12	1.51E+12	0.61	0.61	3.05
CuCD	3	18	2.56E+12	0.61	0.61	3.05
CuCD	4	24	3.13E+12	0.61	0.61	3.05
CuCD	5	24	2.95E+12	0.35	0.35	0.18
CuCD	6	24	2.86E+12	0.35	0.35	0.7
CuCD	7	24	2.88E+12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

HL-LHC injection error on CFC:
2443 J/cm^3
HRMT-23 max energy on CFC:
3158 J/cm^3 (+29%)



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

HL-LHC injection error on MoGr:
5413 J/cm^3
HRMT-23 max energy on MoGr:
5659 J/cm^3 (+5%)



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-36 (MultiMat) – Materials

#	Material	Density $[g/cm^3]$	Coated	Coating Material
1	IT180	18.8	✗	
2	Ta10W	16.9	✗	
3	Ta2.5W	16.7	✗	
4	TZM	10.0	✗	
5	CuCD IFAM	5.40	✗	
6	CuCD RHP	5.40	✗	
7	SiC	3.21	✗	
8	MG-6403Fc	2.54	✓	TiN
9	ND-7401-Sr	2.52	✗	
10	MG-6530Aa	2.50	✓	Cu
11	MG-6541Fc	2.49	✓	Mo
12	HOPG	2.26	✗	
13	TG-1100	2.19	✗	
14	R4550	1.90	✓	Cu
15	CFC AC150K	1.88	✓	Mo
16	Ti6Al4V (AM)	1.62	✗	
17	CFOAM	0.40	✗	
18	Al 6082-T651 (HU)	2.70	✗	

high density

medium density

low density

actuation

The experiment will see the adoption of 18 different materials/grades to be tested. They include:

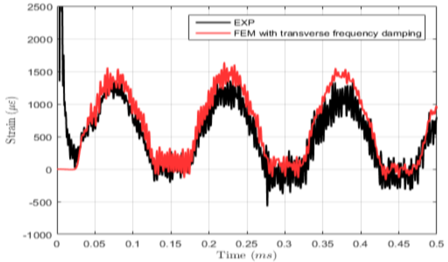
- 4 grades of MG from two different manufacturers;
- 3 different coatings, done both internally at Cern (Cu, Mo) and externally (TiN);
- Different combination of surface and thermal treatments (48h firing, CO2 blasting, US cleaning);
- 2 grades of CuCD from different suppliers;
- New carbon-based materials as HOPG (high in-plane conductivity) and TG-1100 (low density);
- Additively manufactured samples (Ti6Al4V);
- Active control of flexural vibration via piezoelectric

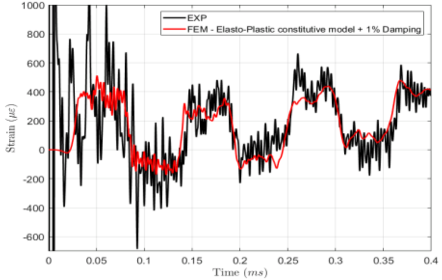
HRMT-36 Signals and Material Modelling

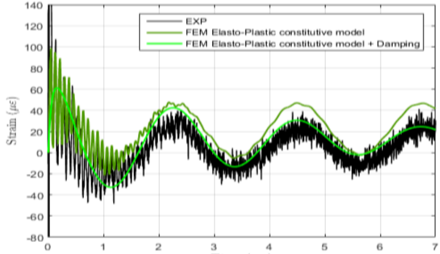
- Specimen geometry chosen to generate easily detectable, separable, mostly uniaxial signals which can be associated to quasi-independent phenomena with different timescales:
  - **Pulse duration (τ) < 1 ÷ 10 µs**. Associated to signal rise time. Highest strain rate effects ($\dot{\varepsilon} \cong 10^1 \div 10^4 s^{-1}$). Specimen design induces highest stresses in cross-section. Transverse strength.
  - **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 impacting targets with **variable offsets** at various intensities and brightnesses:
  - **Zero offset**. Excites longitudinal vibration. High frequency (5÷50 kHz). **Intensity**: **1 to 288 b** at 440 GeV. **Beam size**: **0.25, 0.5, 2 mm**
  - **Intermediate offset**. Additionally excites lateral oscillations. Lower frequencies (100÷2000 Hz). **Intensity**: **1 to 288 b** at 440 GeV. **Beam size**: **0.25, 0.5, 2 mm**
  - **Grazing impact**. Probe coating strength. Surface damage. **Intensity**: **144 and 288 b** at 440 GeV. **Beam size**: **0.25 mm**

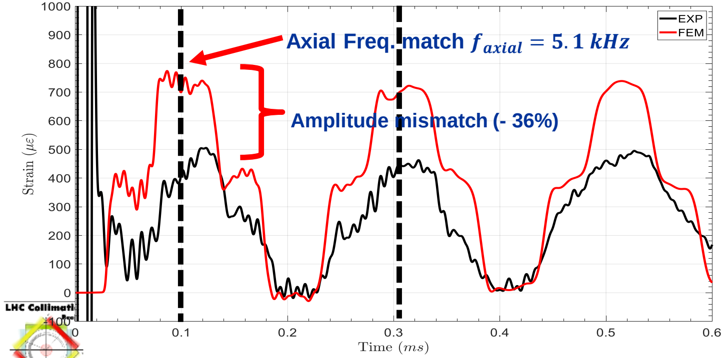
HRMT-36: Results for Bulk Impacts

- Post-processing of wealth of data and comparison to simulation is ongoing:
  - In general good agreement, particularly for isotropic materials
  - Elastic constants of several materials updated (e.g. CFC, CuCD)
  - Role and extent of internal damping assessed
  - In some cases (e.g. Graphite), energy mismatch to be interpreted
  - For anistropic materials,





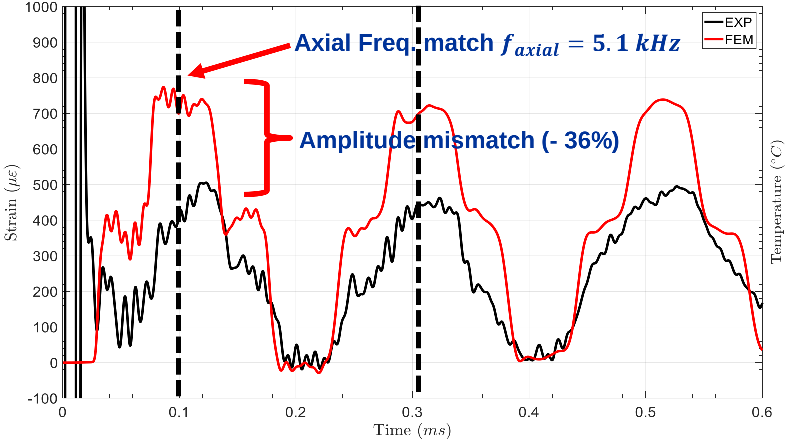



Axial Freq. match $f_{axial} = 5.1\ kHz$

Amplitude mismatch (- 36%)

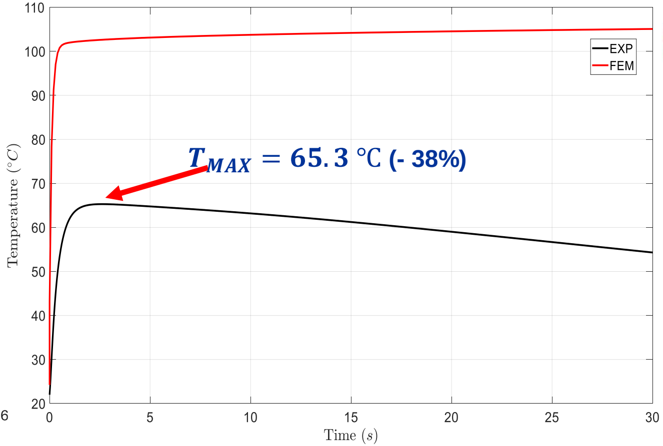
Shots on bulk: R4550

- The longitudinal strain at z = 5/7 L with linear elastic constitutive law and damping ratio ζ = 2.5%
  - Pulse intensity: **144 bunches, 1.25E11 p/b**
  - Sigma: **0.5 mm** Offset: **0 mm**
  - E_{max} : **0.91 kJ/cm^3 (4.15 kJ/cm^3)**



Axial Freq. match $f_{axial} = 5.1\ kHz$

Amplitude mismatch (- 36%)



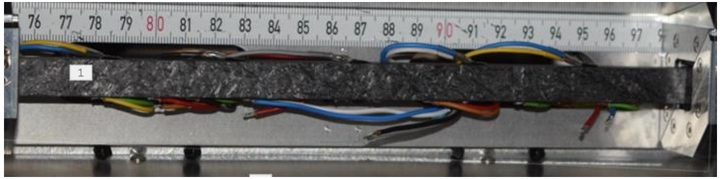
$T_{MAX} = 65.3$ ℃ (- 38%)

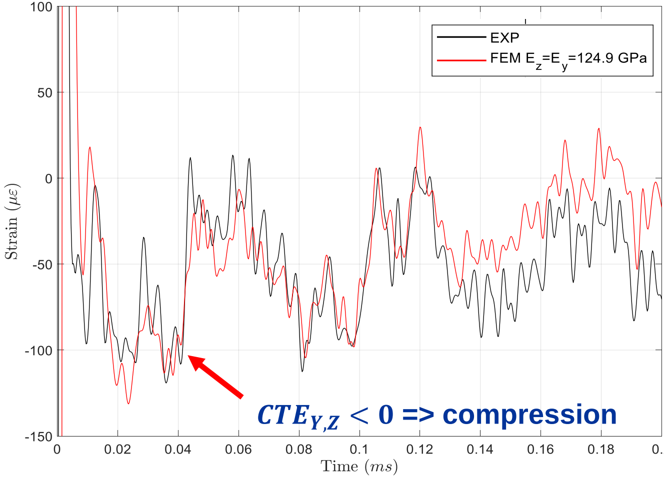
- Correct density curve $\rho(T)$
- Correct expansion curve $CTE(T)$
- Correct **E = 11.5 GPa**

- **Higher spec. heat $c_p(T)$ / lower dep. energy** E_{TOT} **than expected**
- Derived **ζ = 2.5%**
- Constitutive behavior = **Linear-elastic**

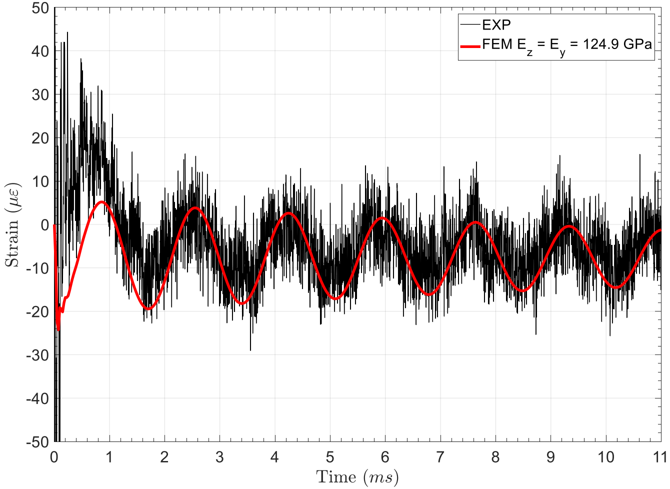
Shots on bulk: CFC AC150k

- The longitudinal strain at z = l/2 with linear elastic constitutive law and damping ratio ζ = 2.0%
  - Pulse intensity: **36 bunches, 1.24E11 p/b**
  - Sigma: **0.5 mm** Offset: **2.7 mm**
  - E_{max} : **0.21 kJ/cm³ (3.72 kJ/cm³)**





$CTE_{Y,Z} < 0$ => compression

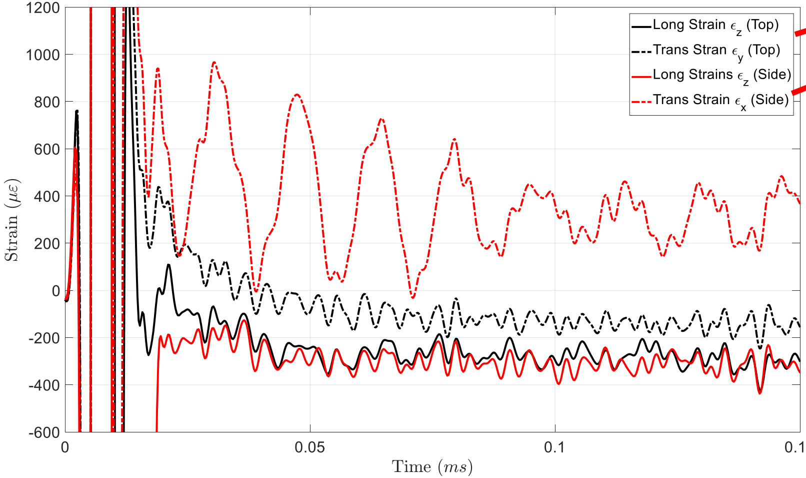


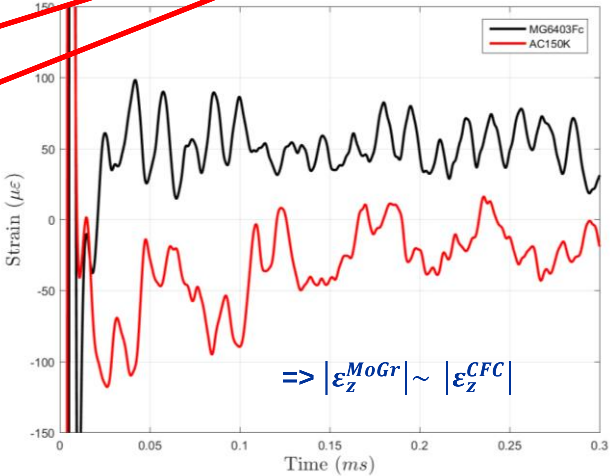
- Correct density curve $\rho(T)$
- Correct specific heat curve $c_p(T)$
- Correct $CTE(T)$

- **Higher $E_{Z,Y}$ than expected (124.9 GPa vs. 98 GPa)**
- Derived **ζ = 2.0%**
- Constitutive behavior = **Linear-elastic**

Shots on bulk: MG6403Fc

- The longitudinal strain at z = l/2 of the last (8th) sample (Experimental data only)
  - Pulse intensity: **36 bunches, 1.25E11 p/b**
  - Sigma: **0.5 mm** Offset: **1 mm**
  - E_{max} : **$0.21\ kJ/cm^3$**

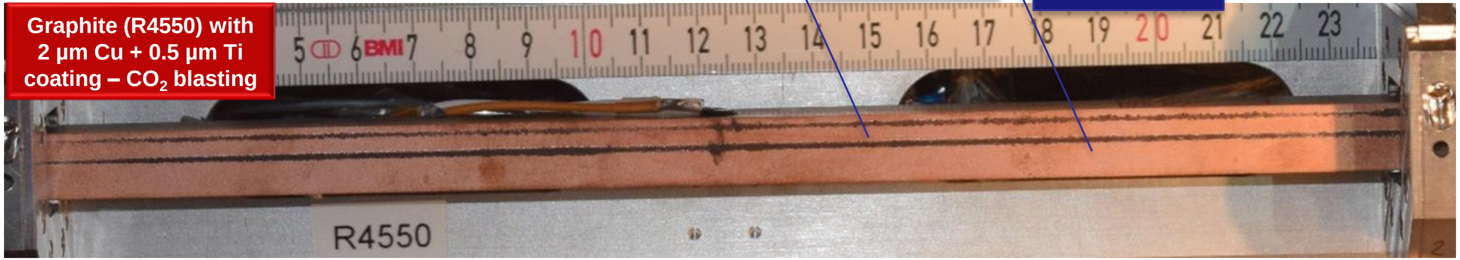




=> $\left|\varepsilon_z^{MoGr}\right| \sim \left|\varepsilon_z^{CFC}\right|$

- Much more complex experimental responses (anisotropy)
- Transverse strains much larger than longitudinal
- Longitudinal MG6403Fc strains ~ Longitudinal CFC AC150k strains

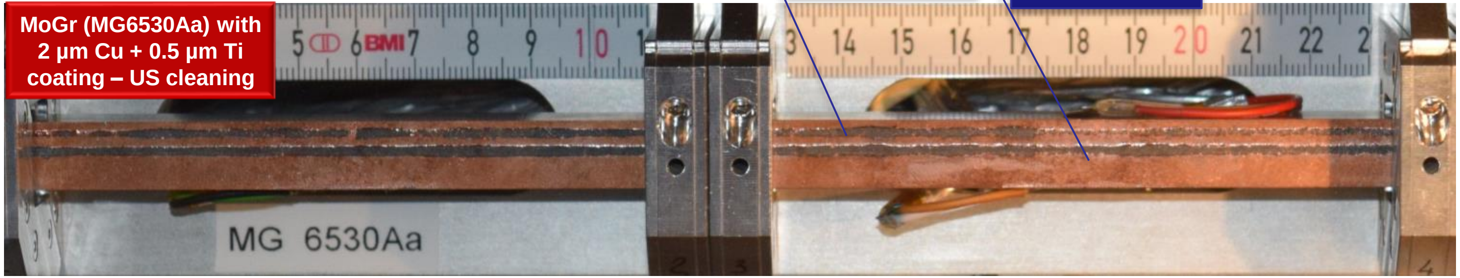
HRMT-36: Grazing Impacts on Cu coatings



Graphite (R4550) with 2 µm Cu + 0.5 µm Ti coating – CO_2 blasting

144 b, σ 0.25 mm, impact 150 µm

288 b, σ 0.25 mm, impact 150 µm

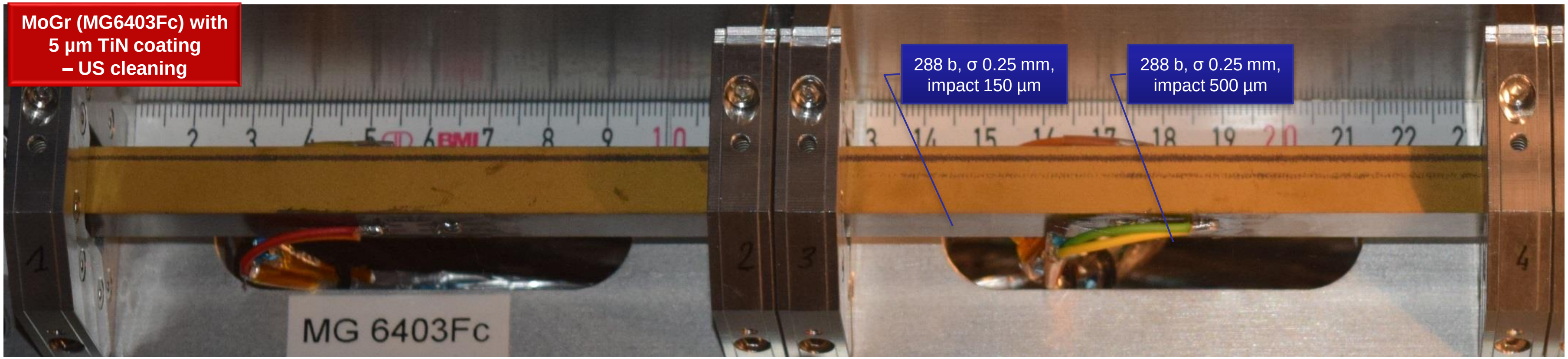


MoGr (MG6530Aa) with 2 µm Cu + 0.5 µm Ti coating – US cleaning

144 b, σ 0.25 mm, impact 150 µm

288 b, σ 0.25 mm, impact 150 µm

HRMT-36: Grazing Impacts on TiN coatings



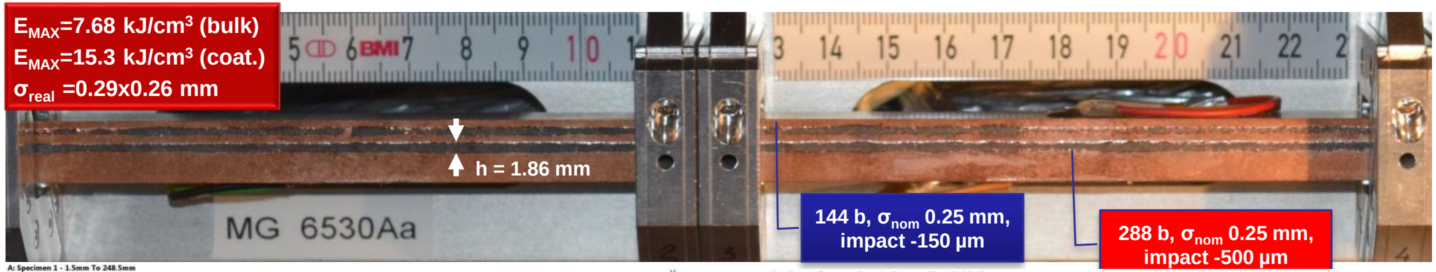
MoGr (MG6403Fc) with 5 µm TiN coating – US cleaning

288 b, σ 0.25 mm, impact 150 µm

288 b, σ 0.25 mm, impact 500 µm

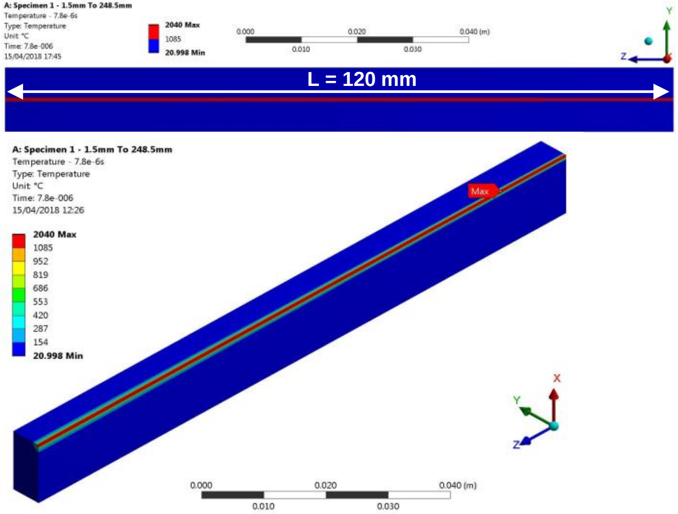
HRMT-36 Grazing Impact on MoGr + Cu

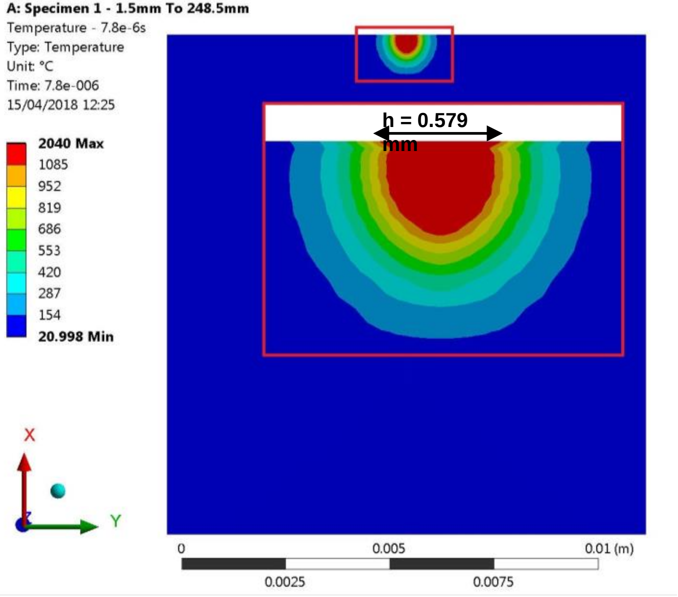
E_{MAX}=7.68 kJ/cm^3 (bulk)
E_{MAX}=15.3 kJ/cm^3 (coat.)
σ_{real} =0.29x0.26 mm



144 b, σ_{nom} 0.25 mm, impact -150 μm

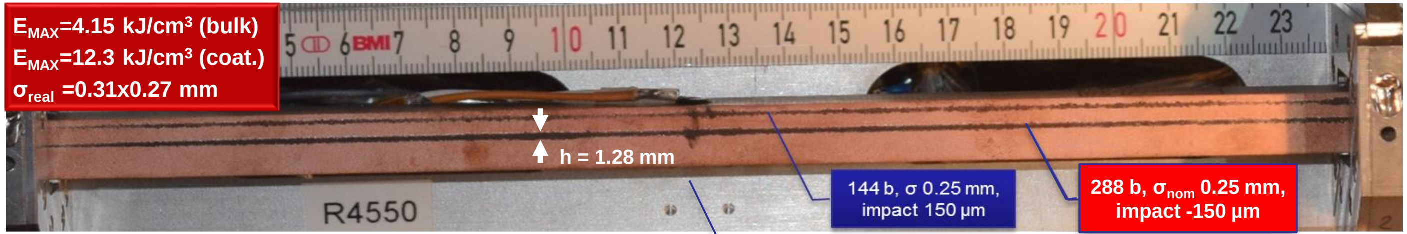
288 b, σ_{nom} 0.25 mm, impact -500 μm





- T_{max} = 2040ºC (3432ºC) T_f^{Cu} = 1085ºC
- L = 120 mm, h = 0.579 mm (120 mm, 0.581 mm)

HRMT-36: Grazing Impact on Graphite + Cu

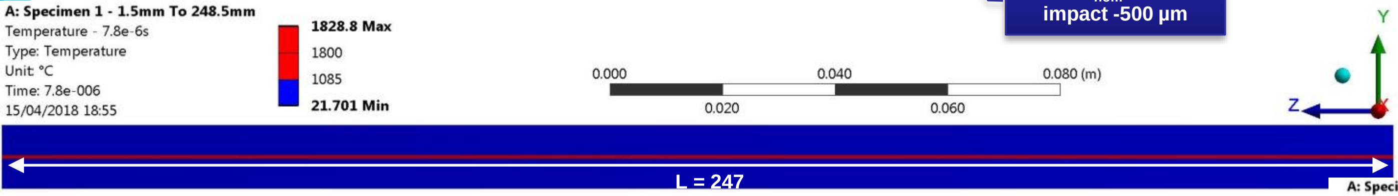


E_{MAX}=4.15 kJ/cm^3 (bulk)
E_{MAX}=12.3 kJ/cm^3 (coat.)
σ_{real} =0.31x0.27 mm

144 b, σ 0.25 mm, impact 150 µm

288 b, σ_{nom} 0.25 mm, impact -150 µm

288 b, σ_{nom} 0.25 mm, impact -500 µm



- T_{max} = 1828ºC (3326ºC) T_f^{Cu} = 108
- L = 247 mm, h = 0.717 mm (247 mm,