HB2014

East Lansing, MI

10-14 November 2014

54th ICFA

Advanced Beam Dynamics

Workshop on High-Intensity,
High Brightness and
High Power Hadron Beams

Novel Materials for Collimators at LHC and its Upgrades

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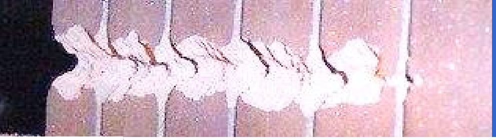
on behalf of F. Carra, A. Dallocchio, M. Garlaschè, L. Gentini, P. Gradassi, M. Guinchard, E. Quaranta, S. Redaelli, A. Rossi, O. Sacristan and many more ...

HB2014 Workshop
East Lansing, MI, USA – November *13, 2014*

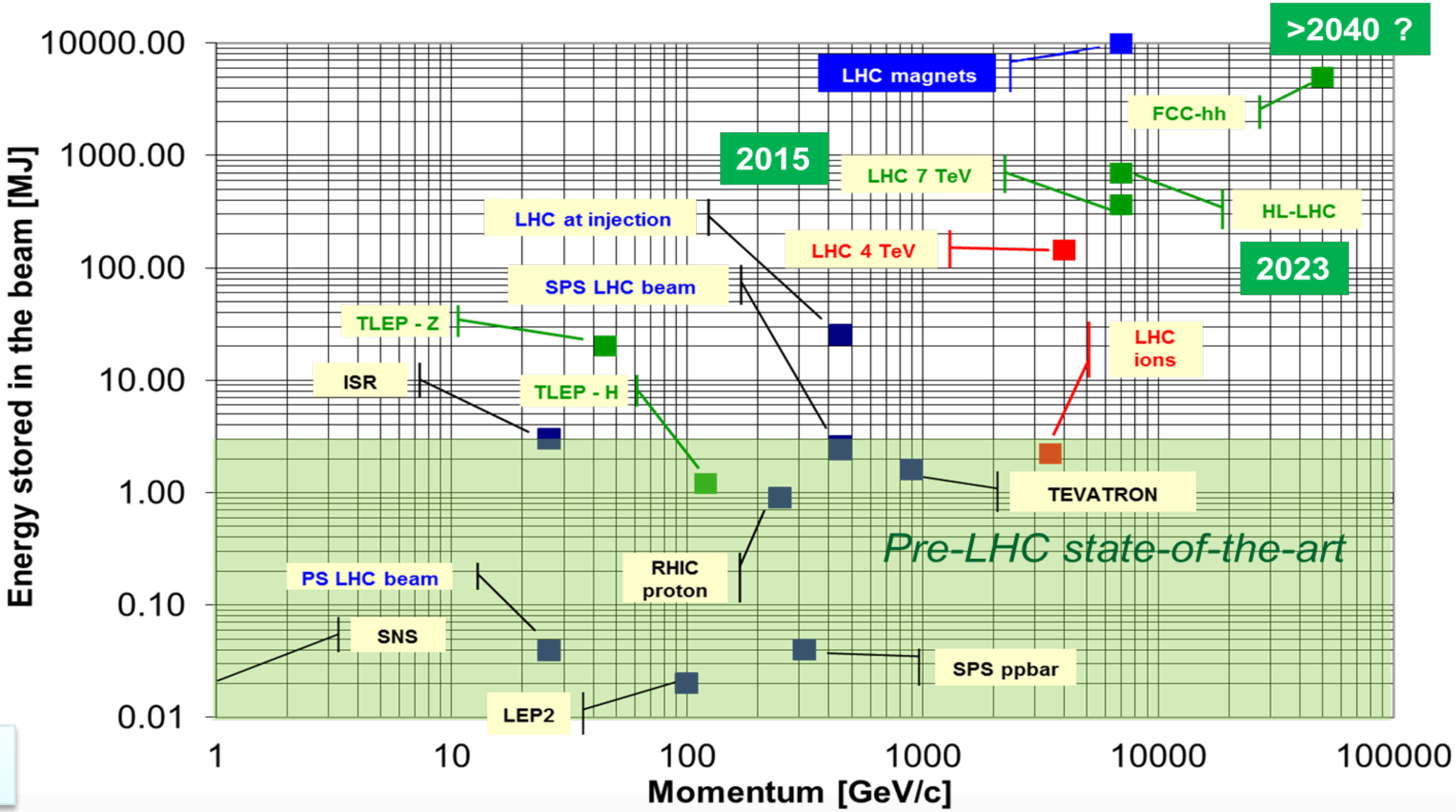


Outline

- Introduction and Motivations
  - High Energy Particle Accelerator Challenges
  - LHC Collimation System
  - LHC Collimators Requirements
- Novel Materials for Collimators
- HL-LHC Collimator Design and Testing
- Summary

High Energy Particle Accelerators Challenges

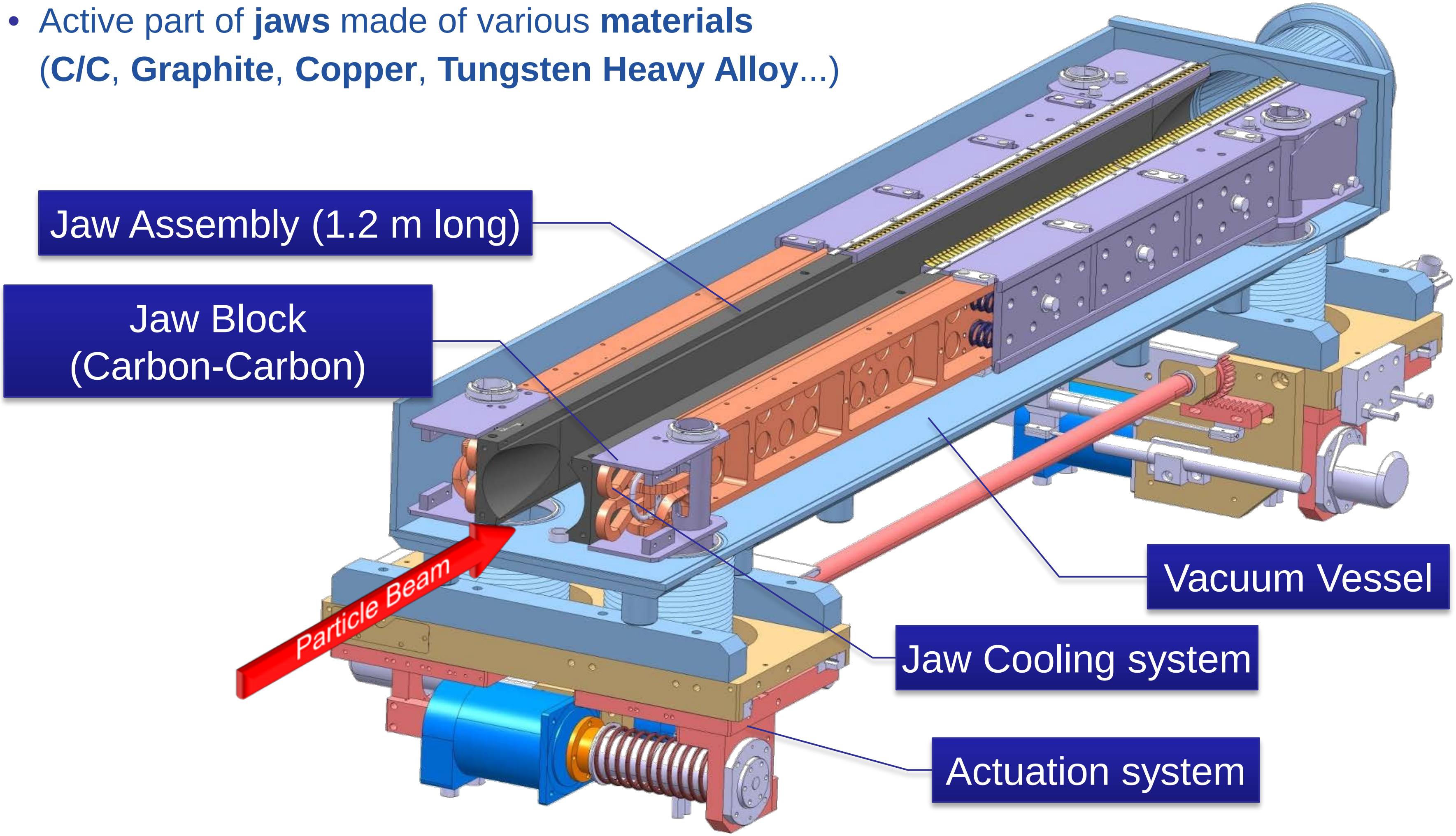
- Beams circulating in last-generation accelerators have reached **unprecedented energy** and **energy density.** This trend is set to continue for future upgrades (e.g. **HL-LHC**)
- **Beam-induced accidents**, **beam losses** and **beam stability** represent one of the **most relevant issues** for high power particle accelerators!
- **Collimators** are one of the most **critical systems** when these issues are of concern



J. Wenninger (CERN)

LHC Collimation System

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

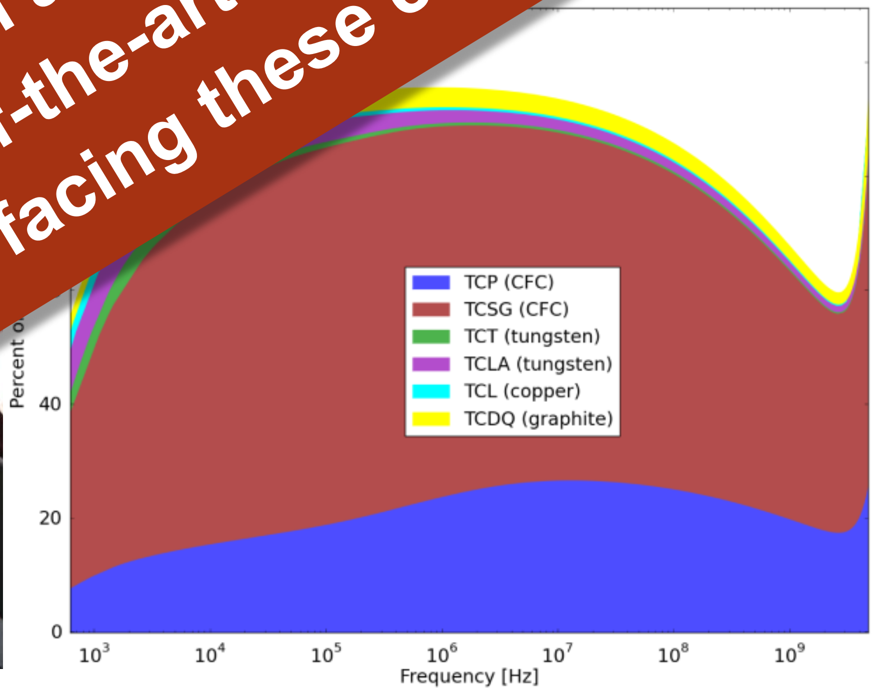


LHC Secondary Collimator (TCSG) Cutaway

LHC Collimator Requirements

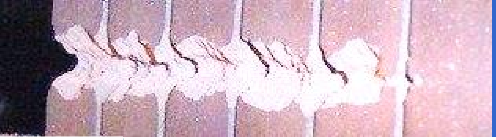
- Collimators are required to **survive** the **beam-induced accidents** to which they are inherently exposed given their vicinity to the beam
- They must possess extremely **accurate jaw flatness** to maintain their **l** **ning efficiency**
- The collimation system is, by far, the highest contributor to **accel** which may significantly limit machine performances: they must have **lo** **esistivity**
- Their lifetime and efficiency should be conserved und
- **No existing material** can simultaneously **mee** Upgrades!

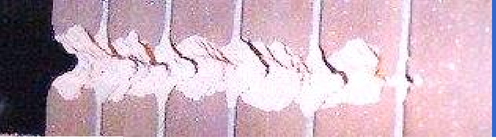
Development of **Novel advanced materials**, along with **state-of-the-art simulations**, are instrumental in **facing these challenges**!



Outline

- Introduction and Motivations
- Novel Materials for Collimators
  - Materials R&D Program
  - Copper – Diamond (CuCD)
  - Molybdenum Carbide – Graphite (MoGr)
  - Figures of Merit and Material Ranking
- HL-LHC Collimators Design and Testing
- Conclusions



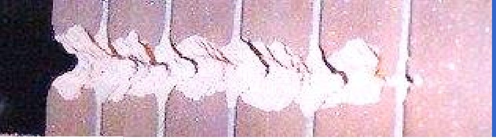


Material Requirements

Key properties must be optimized to meet requirements for Collimators in High Energy Particle Accelerators …

- **Electrical Conductivity (γ)** Maximize to limit Resistive-wall Imped
- **Thermal Conductivity (λ)** Maximize to maintain geometri sses
- **Coefficient of Thermal Expansion (α)** Minimize t shock induced by accidental beam impact.
- **Melting/Degradation Temperature (T** mperatures reached in case of accidents.
- **Specific Heat (c_p)** Maxim istance (lowers temperature increase)
- **Ultimate St** thermal shock resistance (particularly strain to rupture)
- **D** energy deposition while maintaining adequate cleaning ef
- **Radi** **Damage.** Minimize to improve component lifetime under long term particle irradia

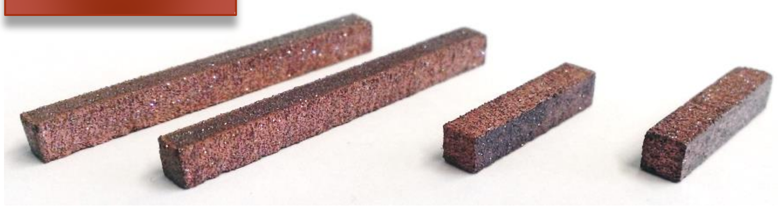
Most requirements shared with a broad range of applications requiring highly efficient Thermal Management!



Novel Materials R&D Program

- Extensive materials R&D program in **collaboration** with **EU institutes** and **industries** (**EuCARD**, **EuCARD2, HiLumi**)
- **Aim**: explore composites combining the properties of **graphite** or **diamond** (**low** ρ, **high** λ, **low** α) with those of **metals** and **transition metal-based ceramics** (**high** R_M, **good** γ)
- Materials investigated are **Copper-Diamond** (**CuCD**), **Silver-Diamond** (**AgCD**), **Molybdenum-Copper-Diamond** (**MoCuCD**), **Molybdenum Carbide-Graphite** (**MoGr**)
- Production techniques include **Rapid Hot Pressing**, **Liquid Phase Sintering** and **Liquid Infiltration**
- Most promising are **CuCD** and (mostly) **MoGr**

CuCD



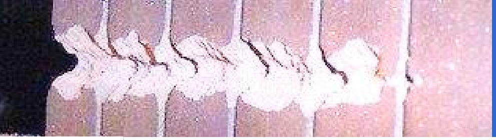
MoCuCD

AgCD

EUCARD²

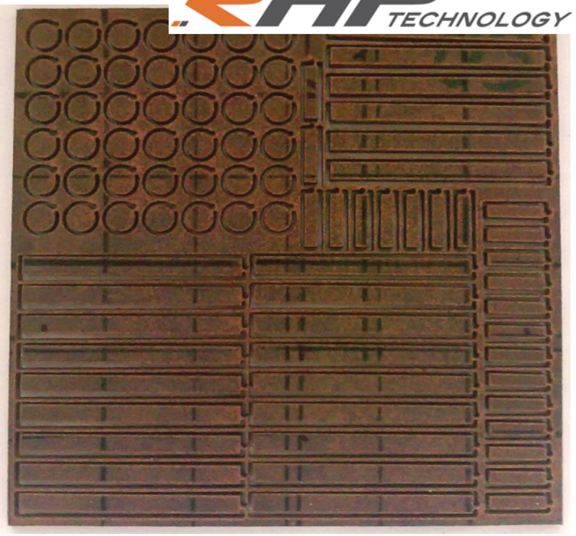
High Luminosity LHC

MoGr



Copper – Diamond

- Developed by **RHP-Technology** (Austria)



Composition :

- 60%$_v$ diamonds (90% 100 µm, 10% 45 µm)
- 39%$_v$ Cu powder (45 µm)
- 1%$_v$ B powder (5 µm)

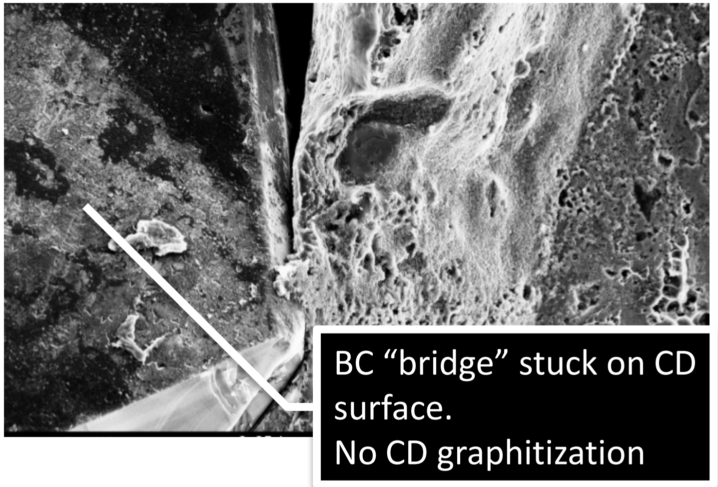
⬆ • No diamond degradation

⬆ • Thermal (**~490 Wm^{-1}K^{-1}**) and electrical conductivity (**~12.6 MSm^{-1}**)

↔ • No direct interface between Cu and CD (lack of affinity). Partial bonding bridging assured by Boron Carbides limits mechanical strength (**~120 MPa**).

⬇ • Cu low melting point (**1083 °C**)

⬇ • CTE increases significantly with T due to high Cu content (from ~**6 ppmK^{-1} at RT** up to **~12 ppmK^{-1} at 900 °C**)



BC “bridge” stuck on CD surface.
No CD graphitization

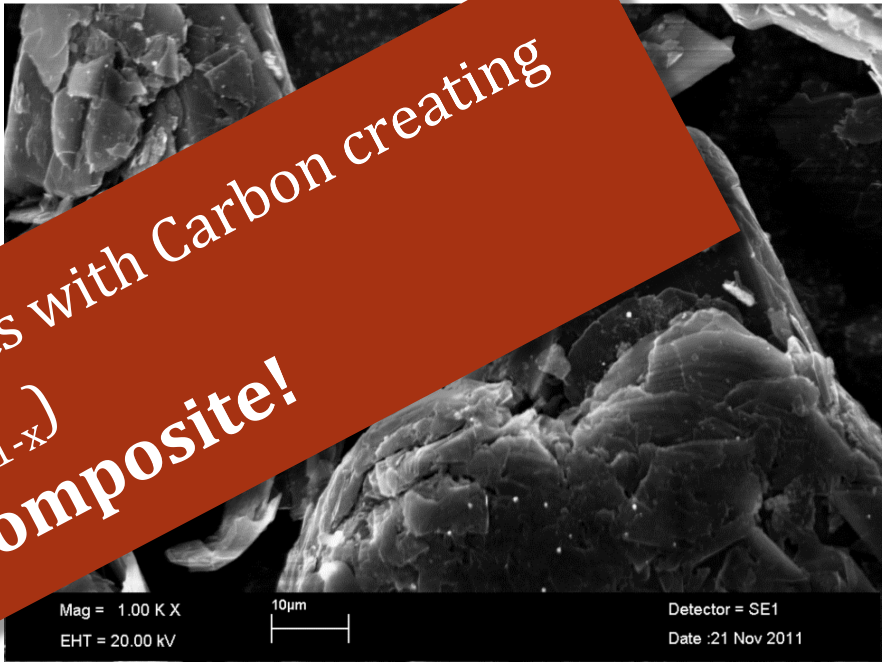
Molybdenum Carbide - Graphite

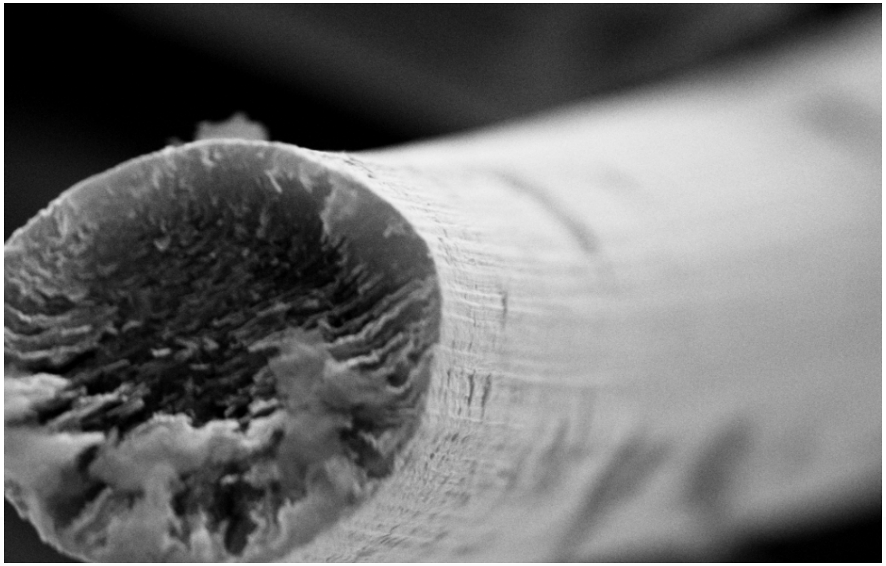
- Co-developed by **CERN** and **Brevetti Bizz** (Italy)
- Broad range of processes and compositions investigated (**Molybdenum**, **Natural Graphite**, **Mesophase Pitch-based Carbon Fibers**).

- **Why Molybdenum?**
  - Refractory metal
  - Density lower than Tungsten
- **Why Natural Graphit**
  - Low CTE (al
  - High Th
  -
- **e Pitch-based Carbon Fibres?**
  - e mechanical strength
  - ontribute to Thermal Conductivity (highly ordered structure)

During sintering all Molybdenum reacts with Carbon creating Carbides (MoC_{1-x})

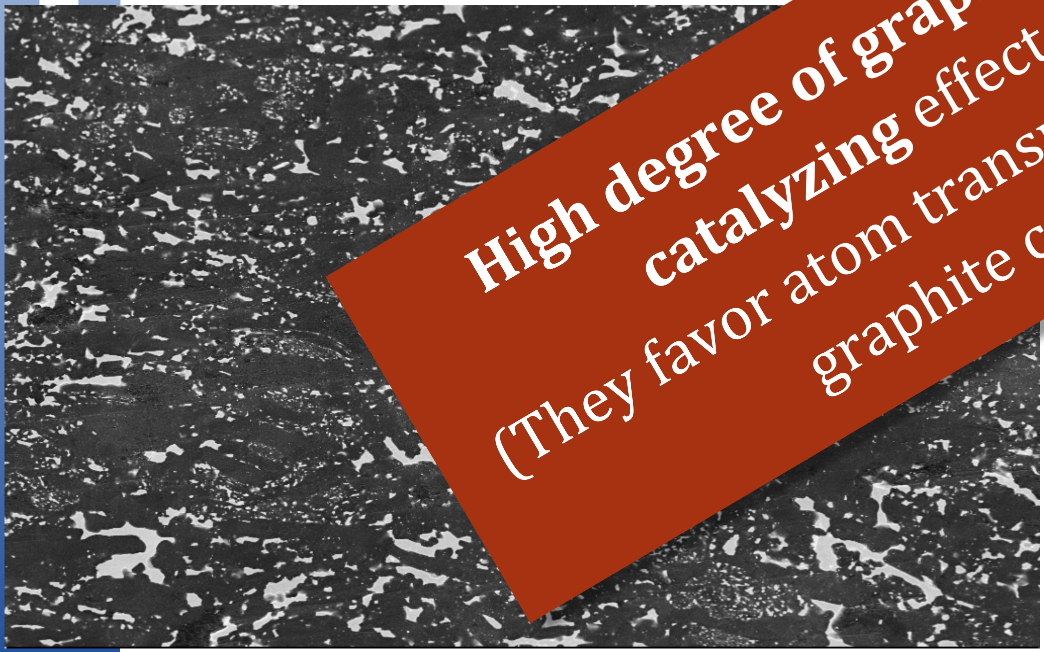
Ceramic Matrix Composite!

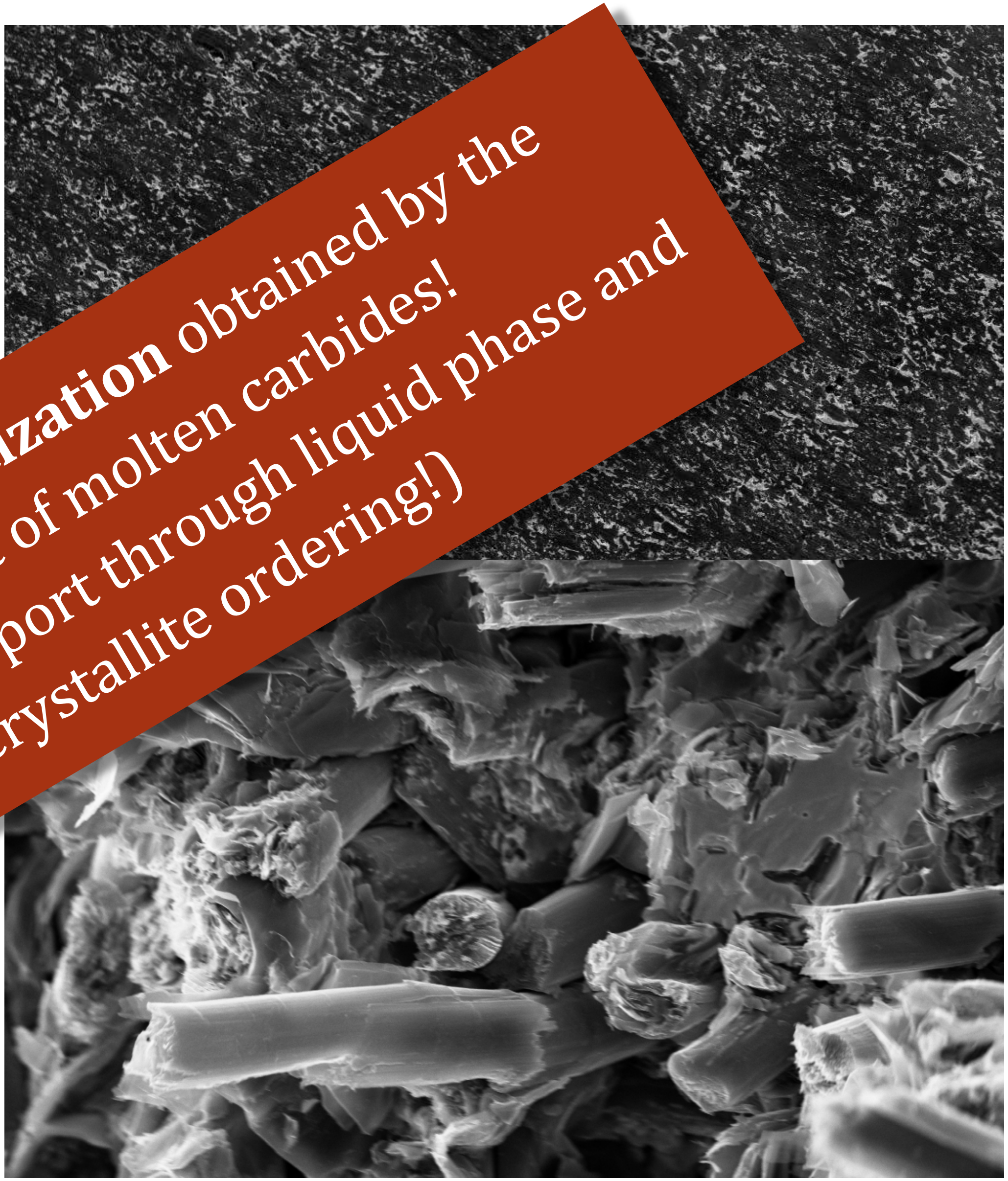




Molybdenum Carbide – Graphite

- Homogeneous distribution of graphite, fibers and fine MoC_{1-x} grains
- Excellent crystalline structure of graphite and Carbon Fibres with highly Oriented Graphene planes
- Strong fiber-matrix bonding

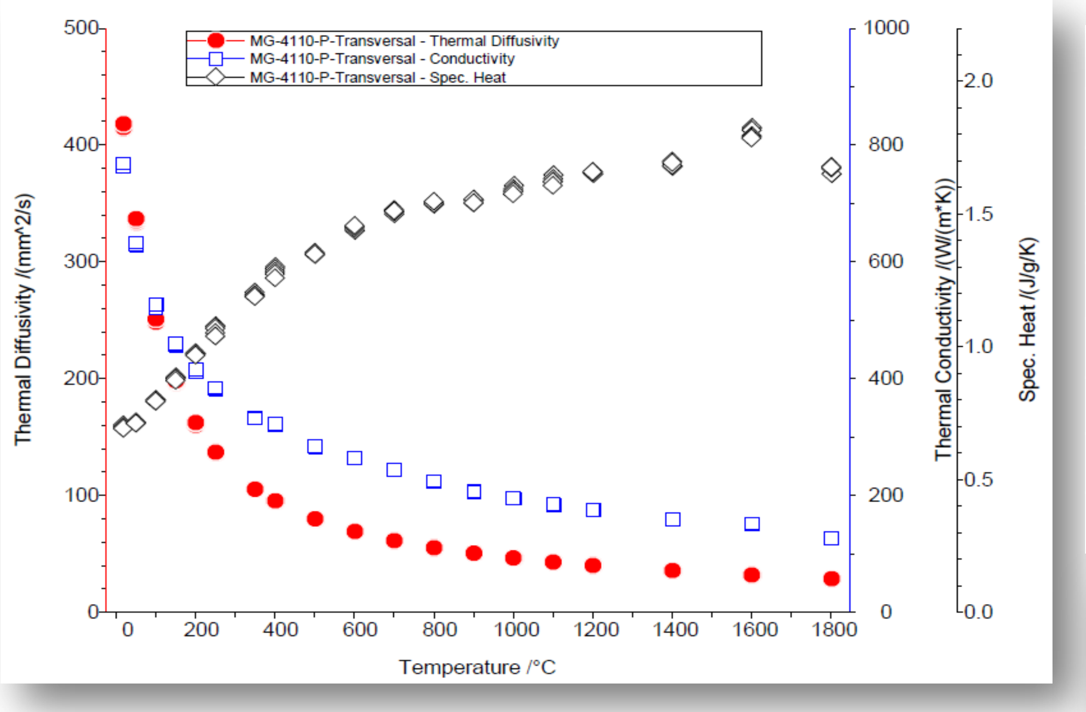




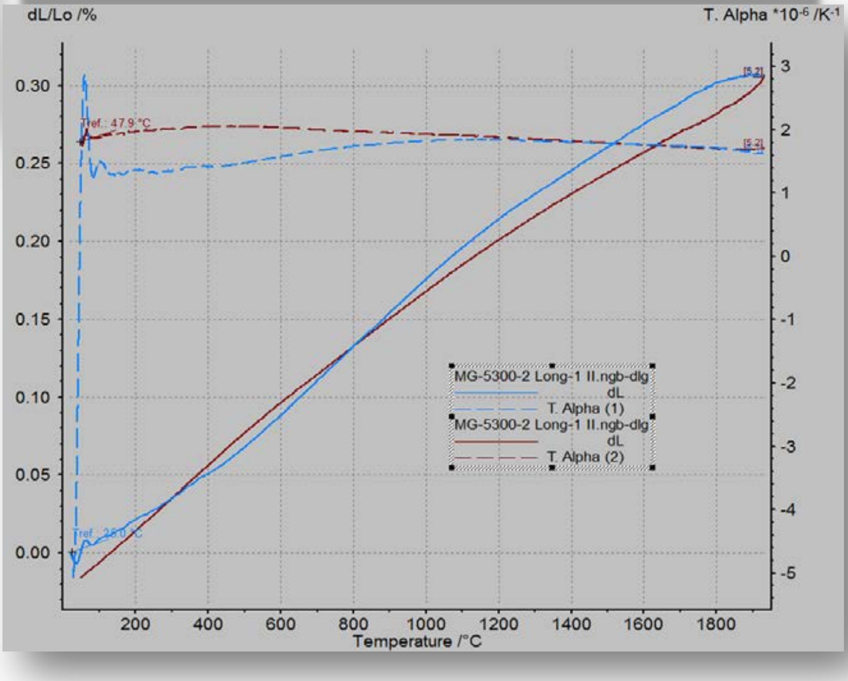
High degree of graphitization obtained by the **catalyzing** effect of molten carbides!

(They favor atom transport through liquid phase and graphite crystallite ordering!)

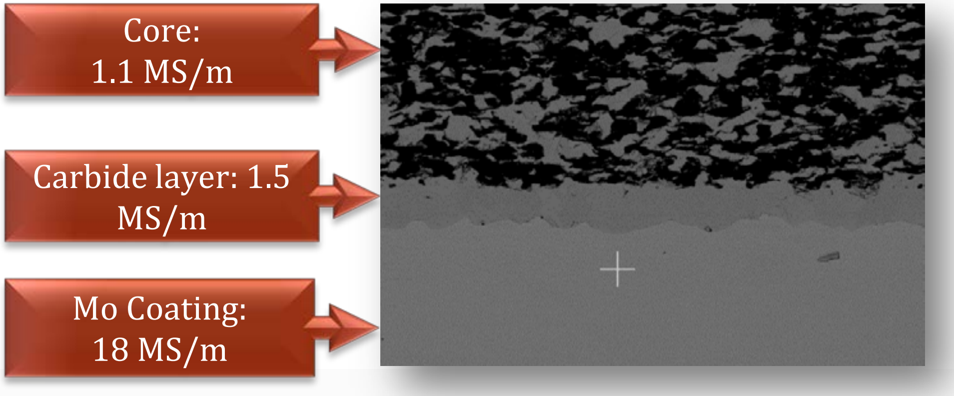
Molybdenum Carbide - Graphite



ρ [g/cm³]	2.5
$\alpha_\perp$ (RT to 1000° C) [$10^{-6}K^{-1}$]	<1.8
$\alpha_{//}$ (RT to 1000° C) [$10^{-6}K^{-1}$]	12
$\lambda_\perp$ (RT) [W/mK]	>770
$\lambda_{//}$ (RT) [W/mK]	85
$\gamma_\perp$ (RT) [MS/m]	1÷18
$\gamma_{//}$ (RT) [MS/m]	0.3
E (Flexural) [GPa]	53
R_{Fl} [MPa]	85



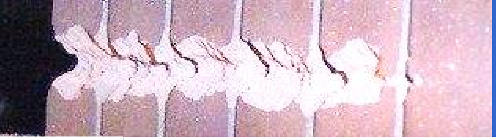
MoGr can be Mo-coated to increase surface conductivity



Core:
1.1 MS/m

Carbide layer: 1.5
MS/m

Mo Coating:
18 MS/m



Figures of Merit

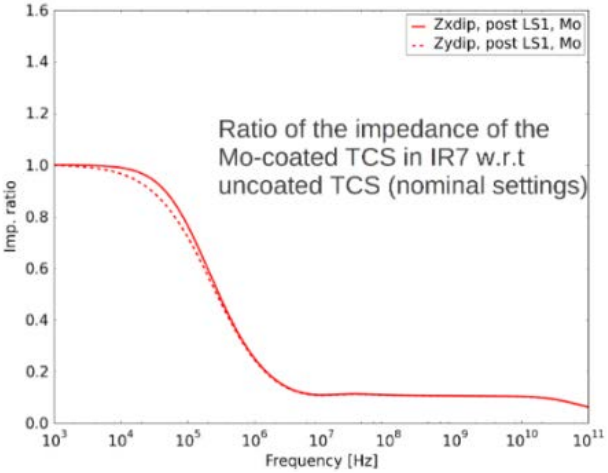
- Several **Figures of Merit** were defined to compare and rank materials against most relevant requirements
- ***Thermomechanical Robustness Index*** (***TRI***) is related to the ability of a material to **withstand the impact** of a short particle pulse.
  - In thermal shock problems, **admissible strain** is the most meaningful quantity
  - The term in T_m (**melting temperature**) provides an indication of the loss of strength at increasing temperature

$$TRI = \frac{\varepsilon_{adm}}{\varepsilon_{ref}} \cdot \left(\frac{T_m}{\Delta T_q} - 1\right)^m$$

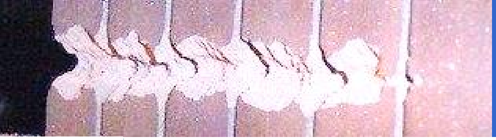
- ***Thermal Stability Index*** provides an indication of the ability of the material **to maintain the geometrical stability** of the component (e.g. Collimator jaw)
  - ***TSI*** is related to the **inverse of the curvature** of a long structure induced by a non uniform temperature distribution (for given **steady-state particle losses**).

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

- ***Electrical conductivity***. Resistive impedance is inversely proportional to electrical conductivity ⇨ **highest electrical conductivity** is sought for materials sitting **closest to circulating beams**!



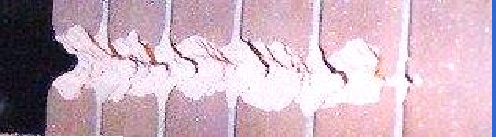
Ratio of the impedance of the Mo-coated TCS in IR7 w.r.t uncoated TCS (nominal settings)



Material Ranking

- **The higher the FOM, the better the material** ... **No one-fits-it-all material**!
- **Carbon-based materials** feature **excellent TRI** and **TSI** thanks to low-Z, low CTE, low density, high degradation temperature, high conductivity ….
- ***Beryllium*** is outstanding under practically all points of view … unfortunately its use is severely limited by its **toxicity**.
- **Low electrical conductivity** penalizes ***C-C*** and ***graphite* if RF-impedance is an issue**. In such a case, ***MoGr*** is the **most promising compromise**, particularly if coated with higher conductivity thin films.
- **Note poor performance of Tungsten Alloy**, also due to the low melting temperature of the **Ni-Cu matrix** required to reduce material brittleness … **it is not pure W**!

Material	Beryllium	Carbon-Carbon	Graphite	Molybdenum Graphite	Copper-Diamond	Glidcop ®	Molybdenum	Tungsten Alloy (IT180)
ρ [g/cm^3]	1.84	1.65	1.9	2.50	5.4	8.90	10.22	18
Z	4	6	6	~6.5	~11.4	~29	42	~70.8
T_m [°C]	1273	3650	3650	2589	~1083	1083	2623	~1400
TRI [–]	790	1237	1101	634	6.8	5.3	6.4	0.5
TSI [-]	17.1	44.6	10.1	69.4	9.9	0.8	0.7	0.1
γ [MSm^{-1}]	23.3	~0.14	~0.07	~1÷18	~12.6	53.8	19.2	8.6

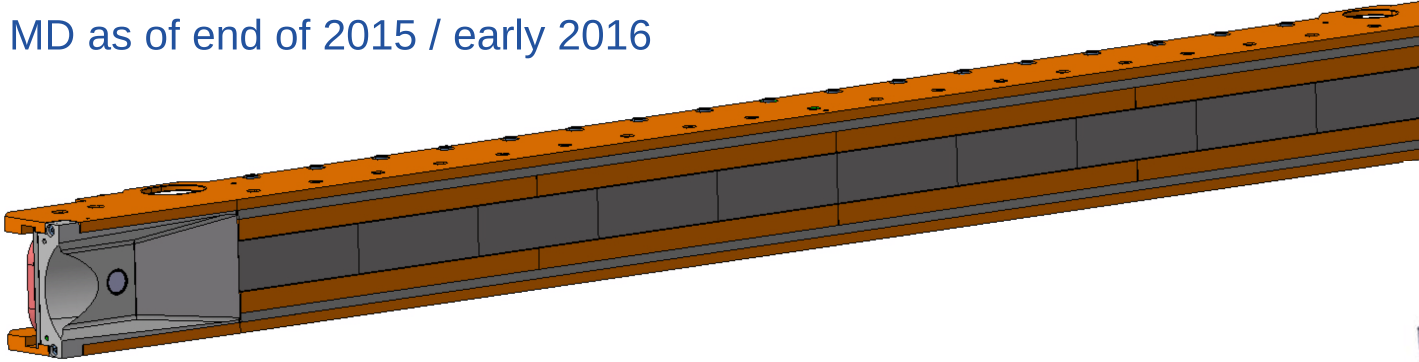


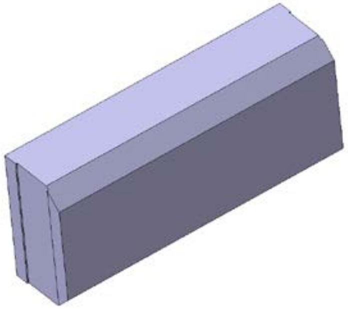
Outline

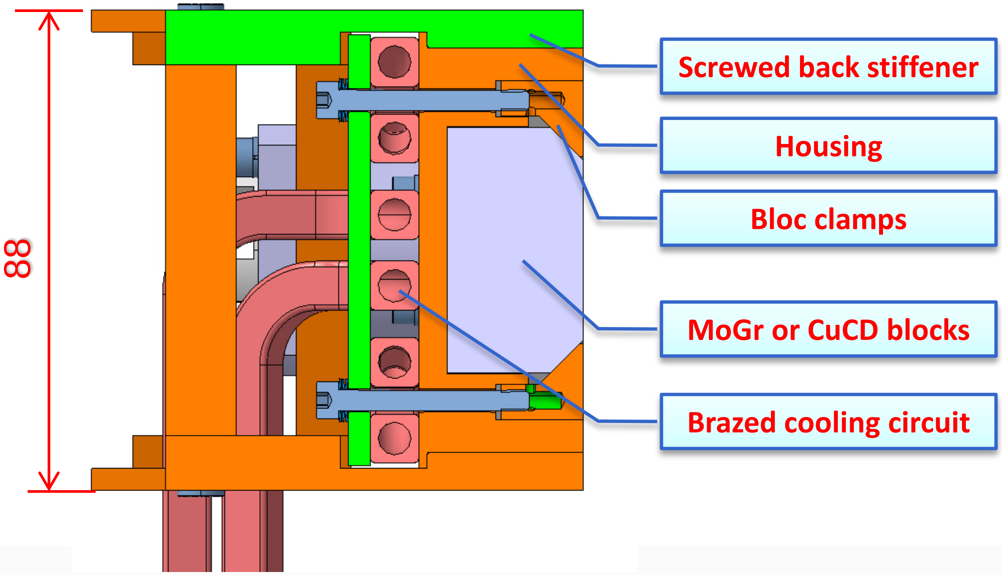
- Introduction and Motivations
- Novel Materials for Collimators
- Design and Testing for HL-LHC Collimators
  - Preliminary Design of HL-LHC Collimator
  - HiRadMat Experimental Tests
  - Irradiation Tests
- Summary

Preliminary Design of HL-LHC Collimator

- A new **modular design** for **HL-LHC Secondary Collimators** is at an advanced stage of design
- The concept allows to install **10 jaw inserts** made of either **CuCD** or **MoGr**
- The **BPM pickup** end seat is lengthened to reduce RF perturbations
- A **full-scale prototype** should be installed in the LHC
  for MD as of end of 2015 / early 2016







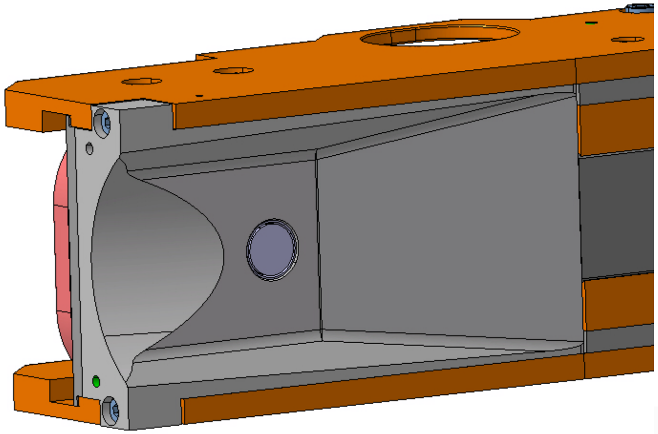
Screwed back stiffener

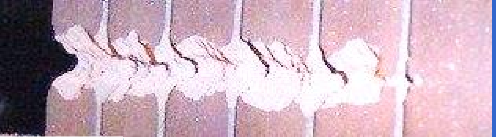
Housing

Bloc clamps

MoGr or CuCD blocks

Brazed cooling circuit





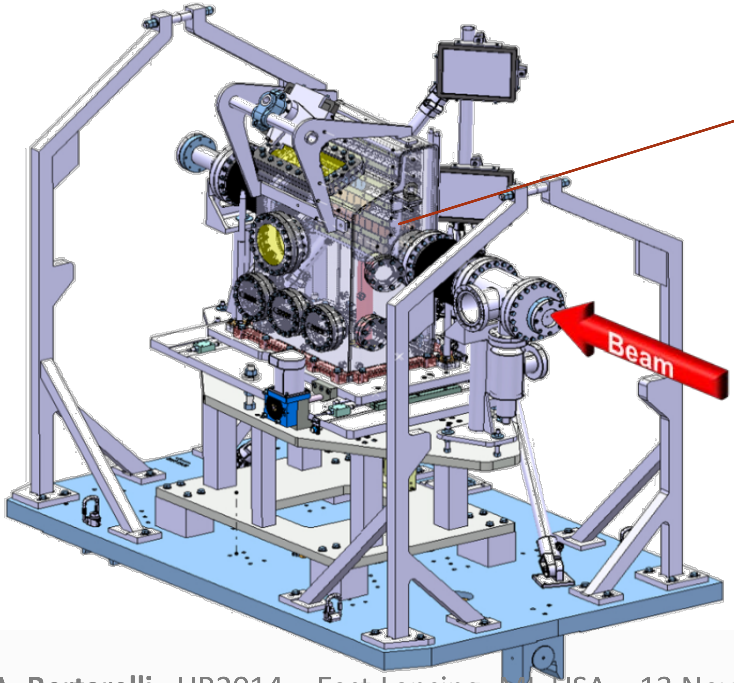
Why Experimental Tests?

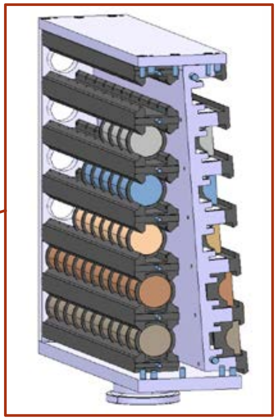
Why Beam Impact Tests at CERN HiRadMat Facility?

- With accidental beam impacts, one enters a relatively **unknown territory**, that of **high power explosions and ballistics**
- The **state-of-the-art wave propagation codes (Hydrocodes)** required to deal with **large density changes, phase transitions, fragmentations** can be very reliable, provided the **complex material models** required are available and precise
- Existing material constitutive models at **extreme conditions** are limited and mostly drawn from military research (**classified**). They are often **unavailable** for specific alloys and composites
- **Additional consequences** on UHV, electronics, bellows, etc. **cannot be easily anticipated** by numerical simulations
- Only **ad-hoc material tests** can provide the correct inputs for numerical analyses and validate/benchmark simulation results on **simple specimens** as well as on **complex structures**.
- A **dedicated facility** has been designed and commissioned at CERN to test materials and systems under high intensity pulsed particle beams: **HiRadMat** (High Radiation to Materials)
- Every new component to be installed in the **LHC** exposed to beam accidental impacts must be first qualified in HiRadMat

HRMT14 Experiment

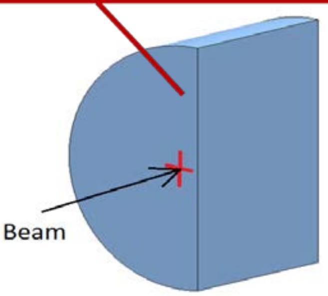
- **HRMT14 (2012) Experiment Goals**
  - **Benchmark** advanced **numerical simulations** and material **constitutive models** through extensive acquisition system
  - Characterize **six existing** and **novel materials** currently under development for future Collimators: **Inermet180**, **Molybdenum**, **Glidcop**, **MoCuCD**, **CuCD**, **MoGr**
  - Collect, mostly in **real time**, experimental data from different acquisition systems (**Strain Gauges**, **Laser Doppler Vibrometer**, **High Speed video Camera**, **Temperature and Vacuum probes**)

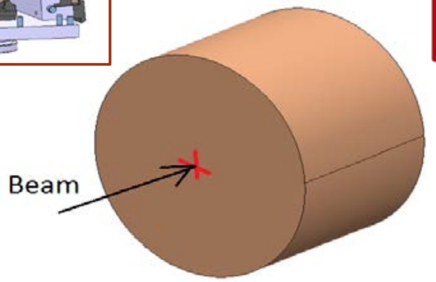




Beam Parameters	
Beam energy	440 GeV
Number of protons per bunch	1.1e11
Bunch Spacing	25 ns

High Intensity Tests:
Sample: half-moon;
Beam Offset 2 mm

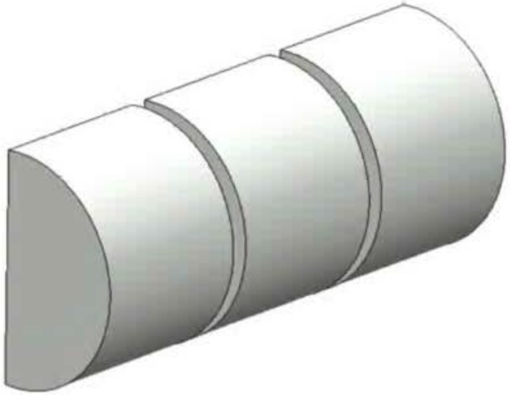


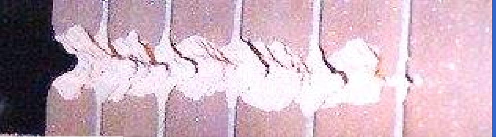


Medium Intensity Tests:
Sample: Ø 40 mm , L30 mm

HRMT14 Experiment

Inermet180 (Tungsten Alloy) samples as seen from viewport and camera

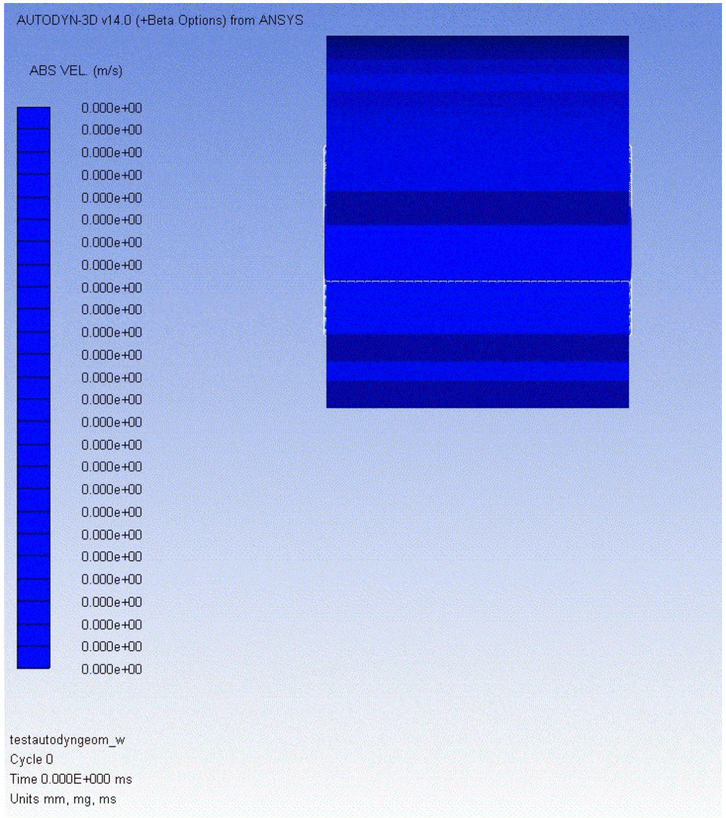




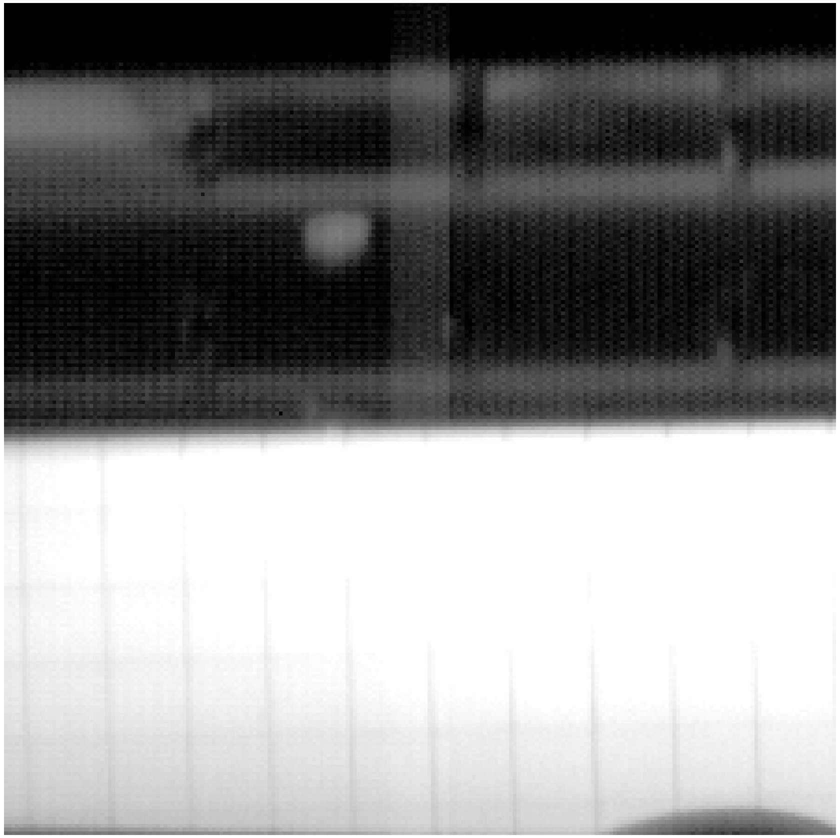
HRMT14 Experiment

High Intensity Tests: Comparison between numerical simulation (SPH) and experiment

Beam

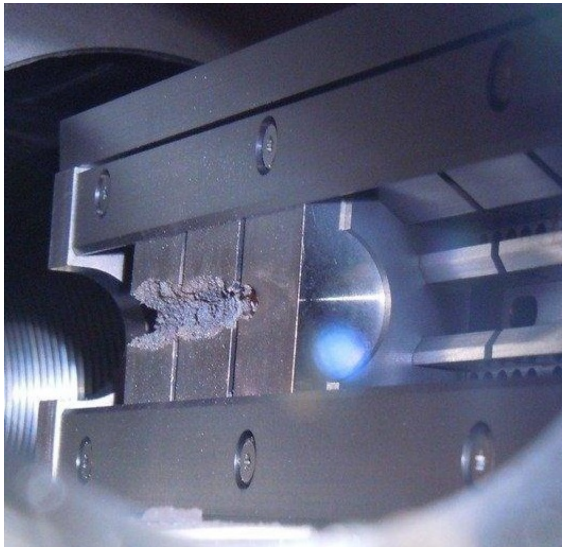


testautodyngeom_w
Cycle 0
Time 0.000E+000 ms
Units mm, mg, ms

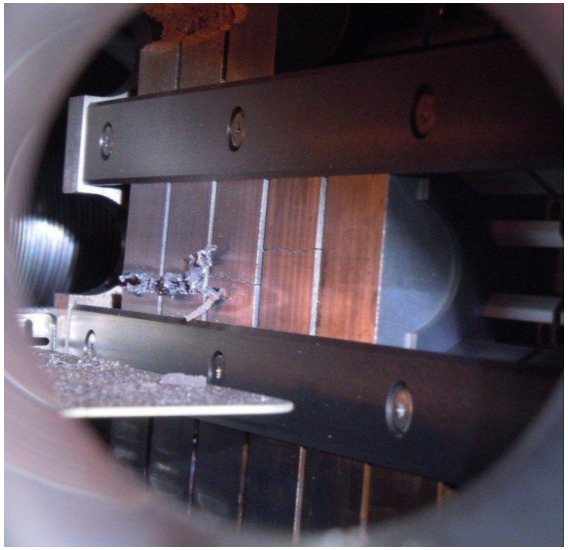


Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	316 m/s
Experiment	72	1.26e11	9.0e12 p	1.9 mm	8 (partly 9)	~275 m/s

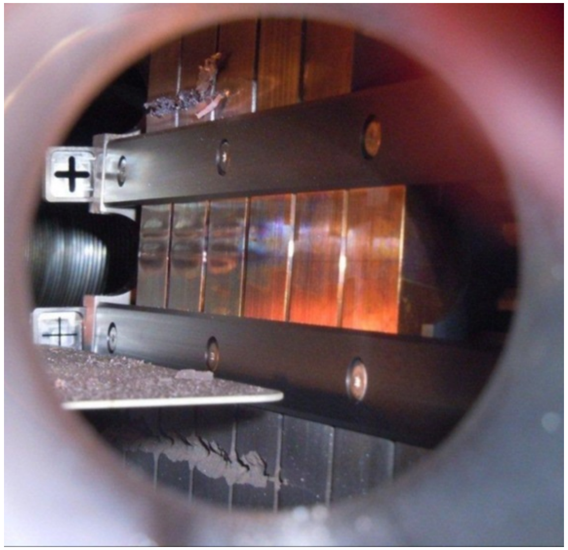
HRMT14 Experiment



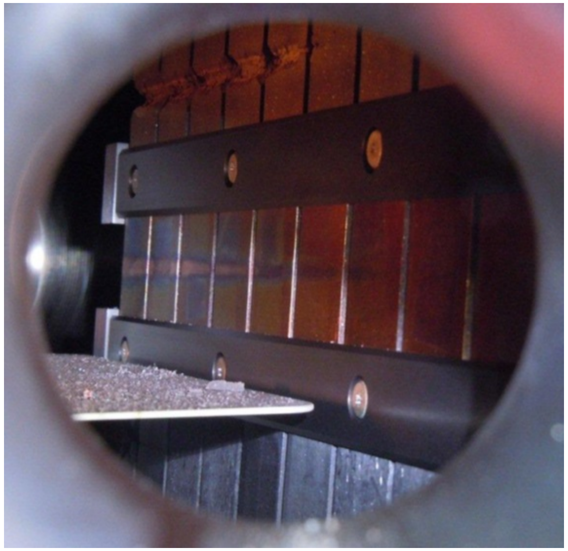
Tungsten Alloy, 72 b



Molybdenum, 72 & 144 b

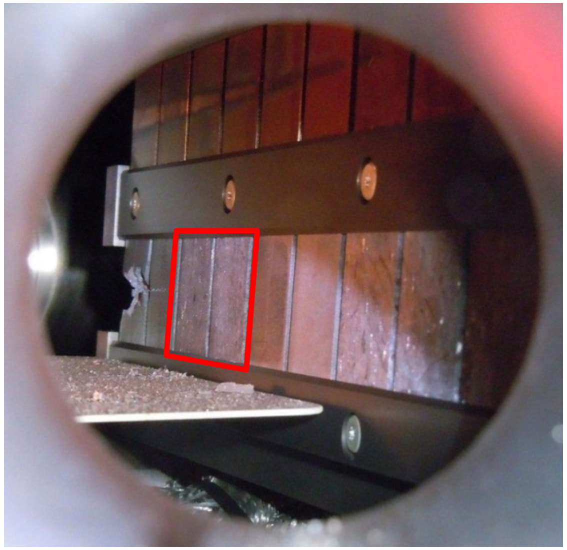


Glidcop, 72 b (2 x)



Copper-Diamond
144 b

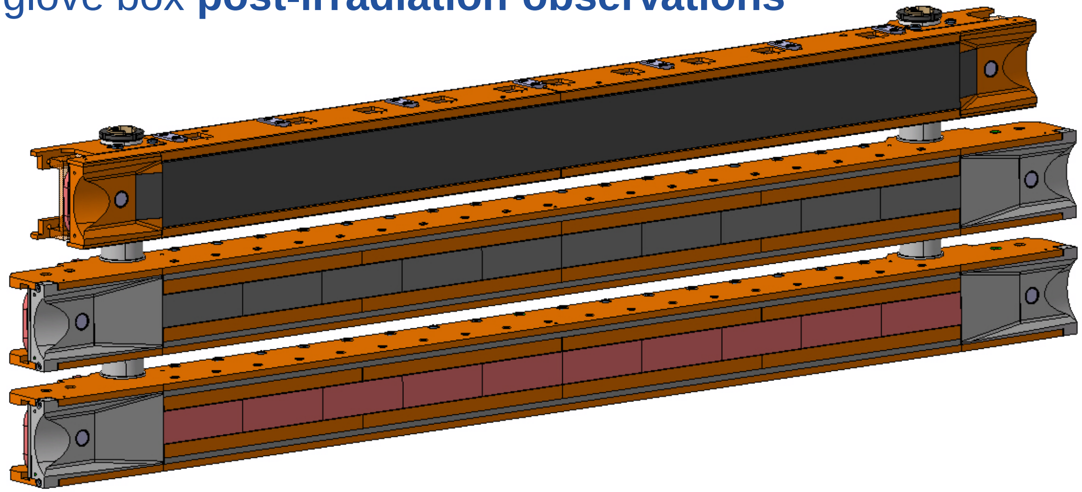
Molybdenum-Copper-Diamond
144 b

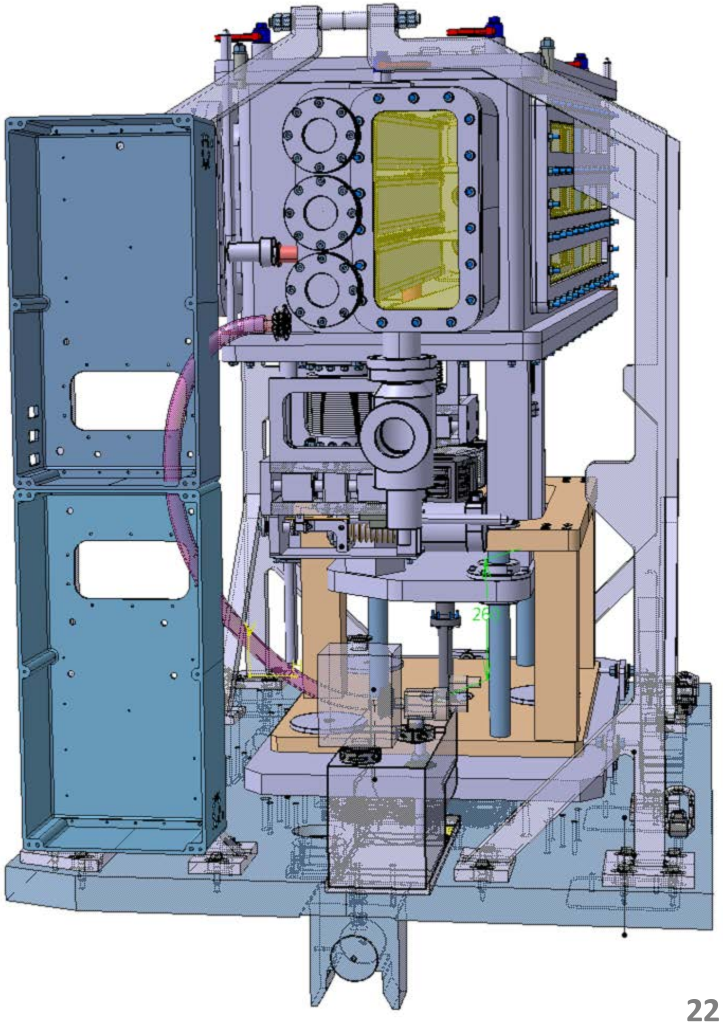


Molybdenum-Graphite (3 grades)
144 b

HRMT23 Experiment

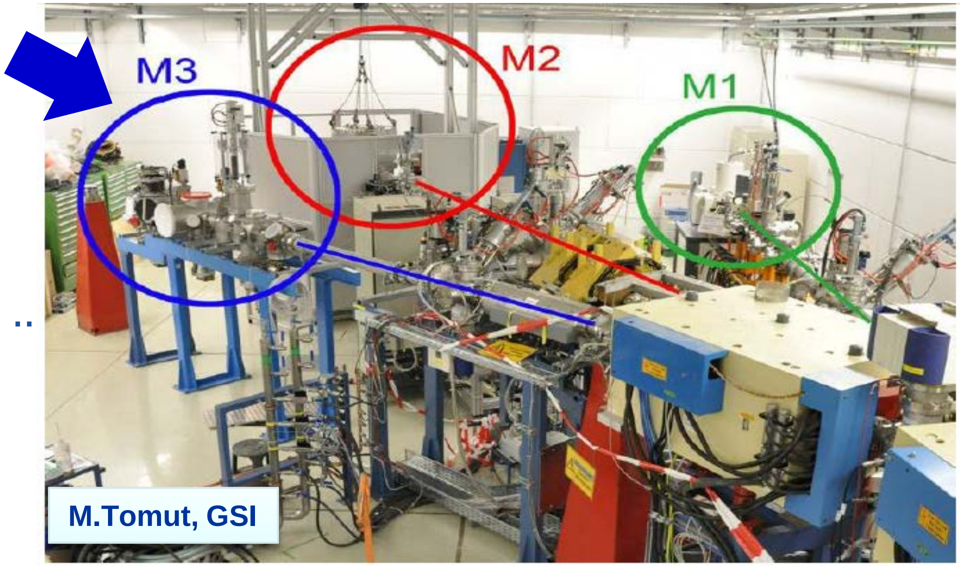
- A **new experiment (HRMT23)** currently **under manufacturing** is planned for mid-2015 to simultaneously test **3 separate complete jaws** extensively instrumented
- Main goal is to **qualify** (or disqualify) **jaws** to be used in a full-scale HL-LHC prototype **under highest and brightest 450 GeV beam available** (e.g. **288 b** x **~1.5e11 p/b**) in view of **LIU** parameters
- **2 HL-LHC jaws** (inserts in CuCD and MoGr)
- **1 LHC secondary collimator jaw** (TCSP) …
- System equipped with comprehensive set of strain gauges, and sensors for **online acquisition**, viewports for optical acquisition, LDV, etc. and fast dismounting system for glove box **post-irradiation observations**





Irradiation Tests at GSI

- M-branch irradiation facility at **GSI UNILAC**
- **In-situ online and offline monitoring**: camera, fast IR camera, SEM, XRD, LFA, nanoindentation and Raman spectroscopy
- 3 irradiation campaigns completed, more to come ..



M.Tomut, GSI

February-March 2014:

- ^{238}**U** irradiation: 1.14 GeV, 4x10^{9} ions cm^{-2}s^{-1}
- ^{208}**Bi** irradiation: 1 GeV, 1.2x10^{9} ions cm^{-2}s^{-1},
- **Materials tested: CuCD**, **C-C, MoGr** (non-annealed),
- Fluence: up to 1x10^{14} ions cm^{-2}

July 2014:

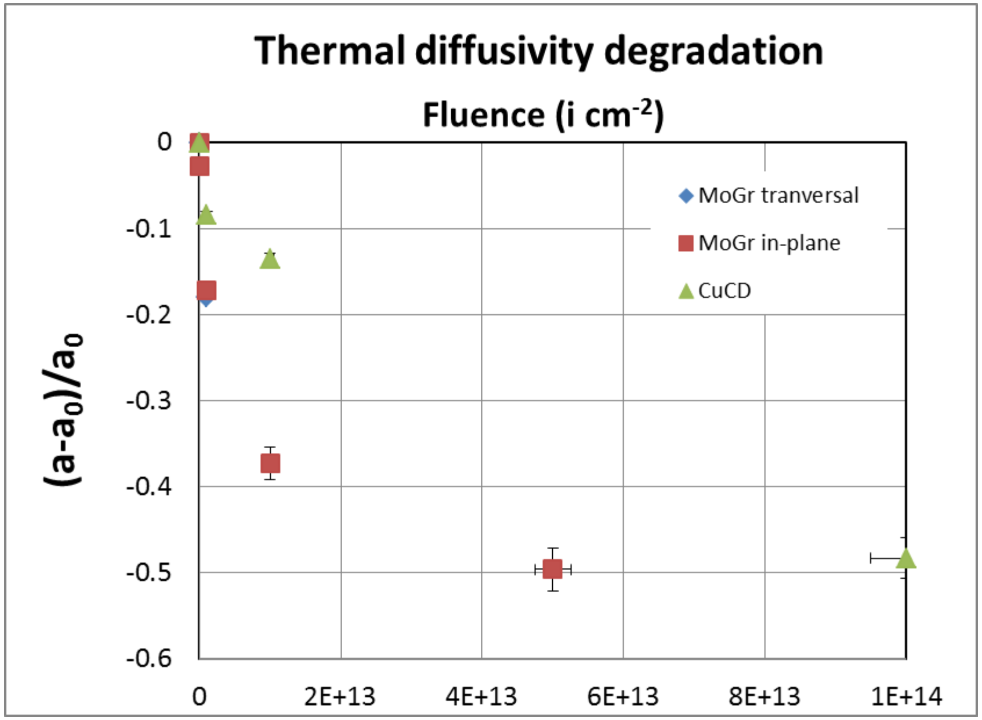
- ^{197}**Au** irradiation: 945 MeV, ~1-2x10^{9} ions cm^{-2}s^{-1}
- **C** irradiation: 11.4 MeV/u, 5x10^{9} ions cm^{-2}s^{-1}
- **CuCD**, **C-C** (2x orient.), **MoGr** (low-temperature annealed), **C fibres**
- Fluence: up to 1x10^{14} ions cm^{-2}s^{-1}

October 2014

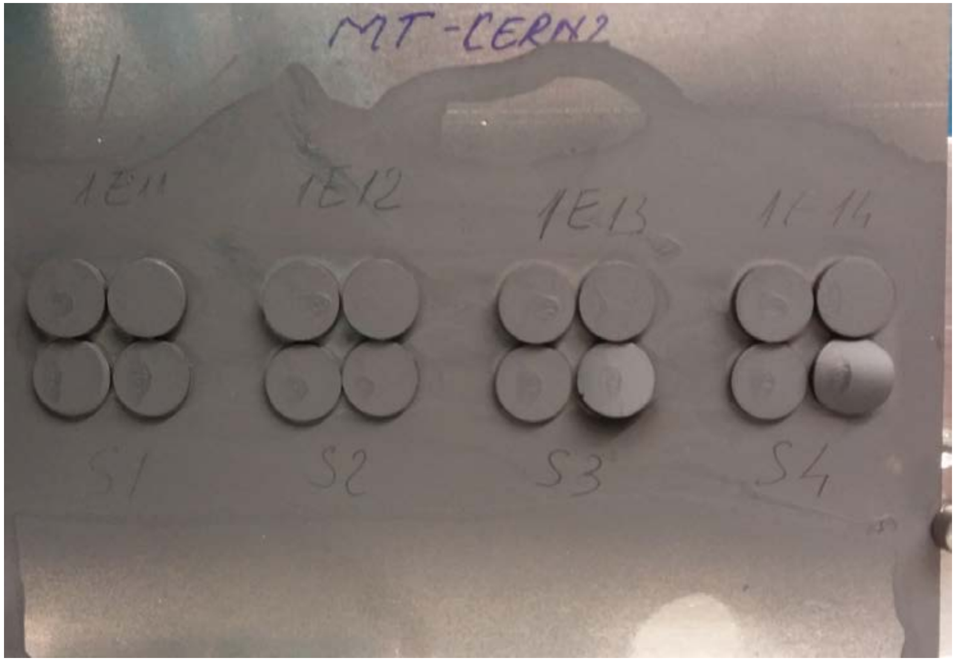
- **Sm** irradiation: 360 MeV/u
- Fluences: 1e11, 5e11, 1e12, 2e12):

Irradiation Tests at GSI

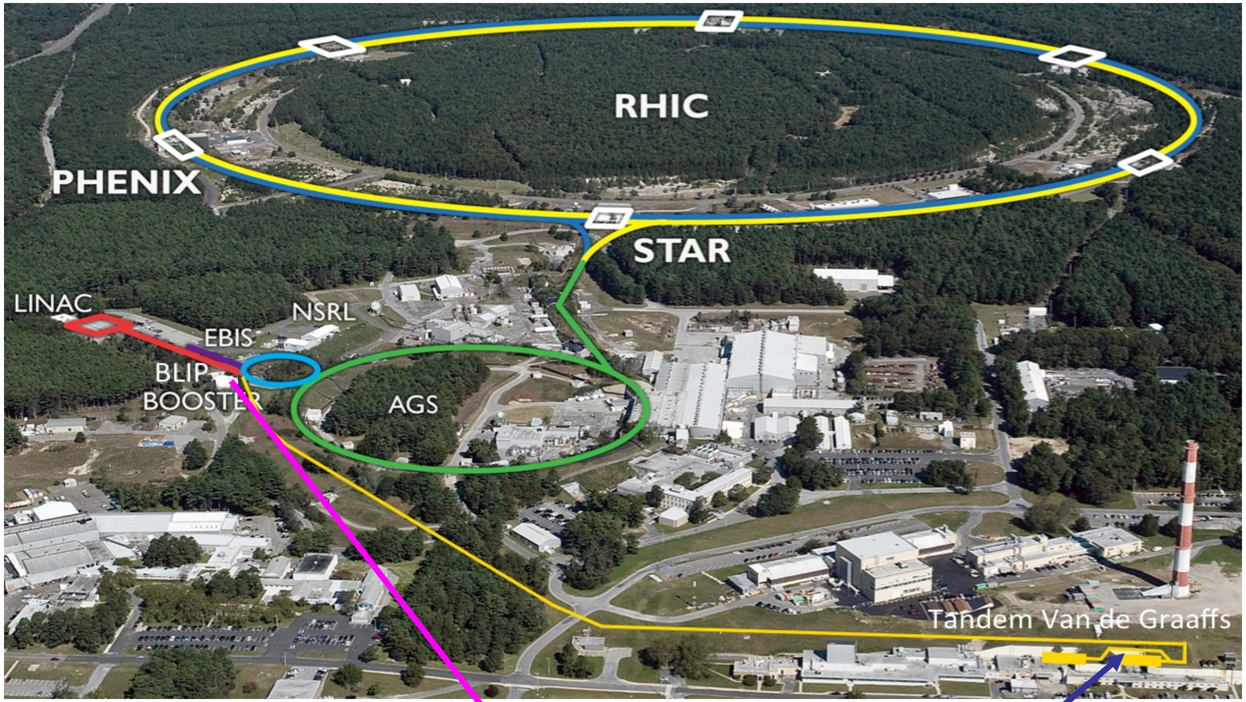
- Analysis of experimental data is just starting
- Preliminary results indicate a degradation of thermal diffusivity for both CuCD and MoGr (larger for MoGr)
- Deformation under irradiation was also observed on MoGr transversal samples: this is likely due to release of internal residual strains. Subsequent annealing was seen to have beneficial effects.

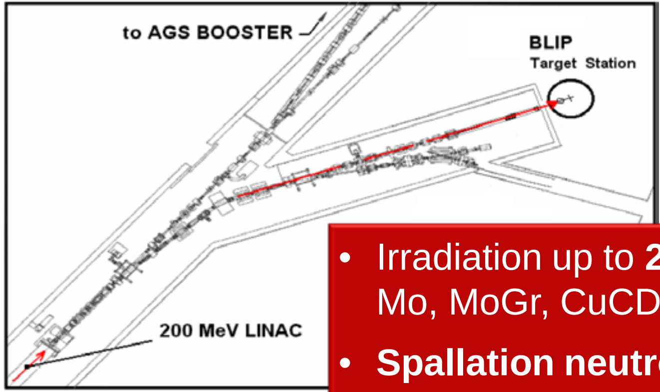


Thermal diffusivity degradation



Irradiation Tests at BNL

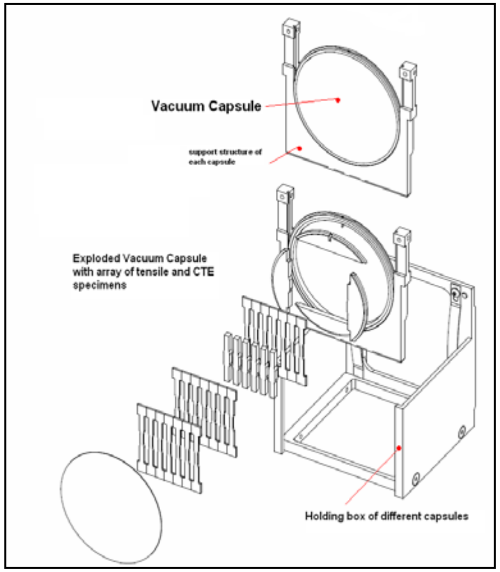




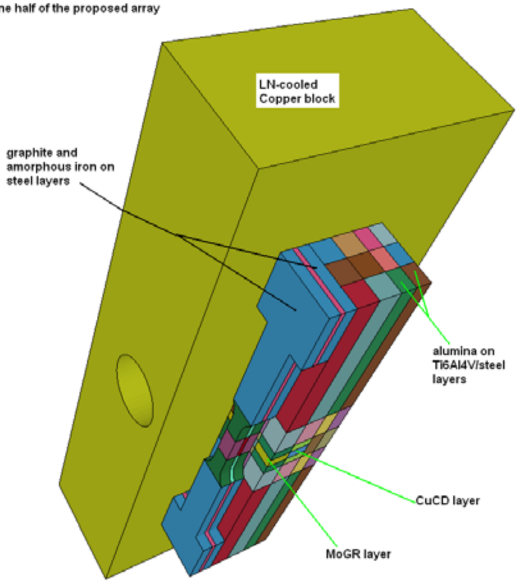
Tandem van de Graaff:

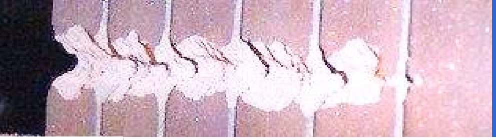
Irradiation with **28 MeV protons** for very localized damage (MoGr, CuCD, Glidcop)

- Irradiation up to **200 MeV protons** (Glidcop , Mo, MoGr, CuCD)
- **Spallation neutrons** from **112 MeV protons** (CuCD, Graphite)



28 MeV Tandem Irradiation
One half of the proposed array





Summary

- Bringing LHC beyond nominal performances will require a **new generation of collimators** embarking **advanced materials**.
- An ambitious **R&D program** at CERN is focusing on their development in the frame of EU-sponsored collaborations and Partnership agreement.
- A new generation of **metal- and ceramic- matrix composites** with **diamond** or **carbon** reinforcements is showing promising results, in particular **Copper – Diamond** (CuCD) and specially **Molybdenum Carbide – Graphite** (MoGr)
- **Outstanding properties** were reached for **MoGr** produced by High Temperature Liquid Phase Sintering (RT Thermal Conductivity 770+ $Wm^{-1}K^{-1}$, CTE ~$1\div2 \times 10^{-6}$ K^{-1}).
- A **full-scale prototype** of a newly designed **HL-LHC Collimator** should be installed in the LHC in the coming months
- Qualification of the design and validation of advanced materials constitutive models calls for ad-hoc **comprehensive tests** to be carried out at CERN **HiRadMat facility**
- An **extensive campaign** to study **materials behavior under irradiation** is underway at **GSI**, **BNL** and **Kurchatov Institute**. First results should become available soon.

Thank you for your attention!

CERN

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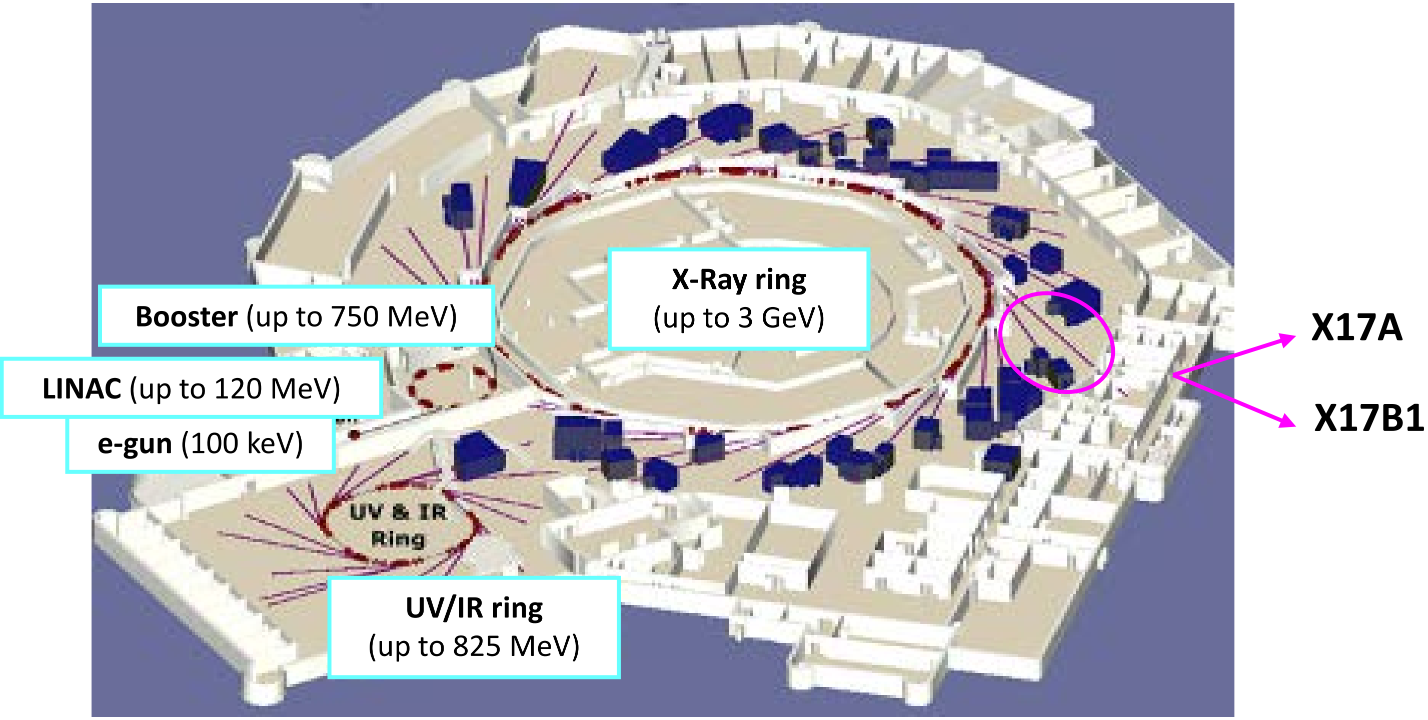
- Irradiation campaign completed. Data analysis to start soon
- X-ray beam from NSLS at Brookhaven National Laboratory has been used for phase and strain mapping of cold and irradiated collimator material samples.
- 2 runs: April and September 2014 (“last light” before NSLS shutdown).
- The new beamlines in NSLS II will start the operations in mid-2015



Booster (up to 750 MeV)

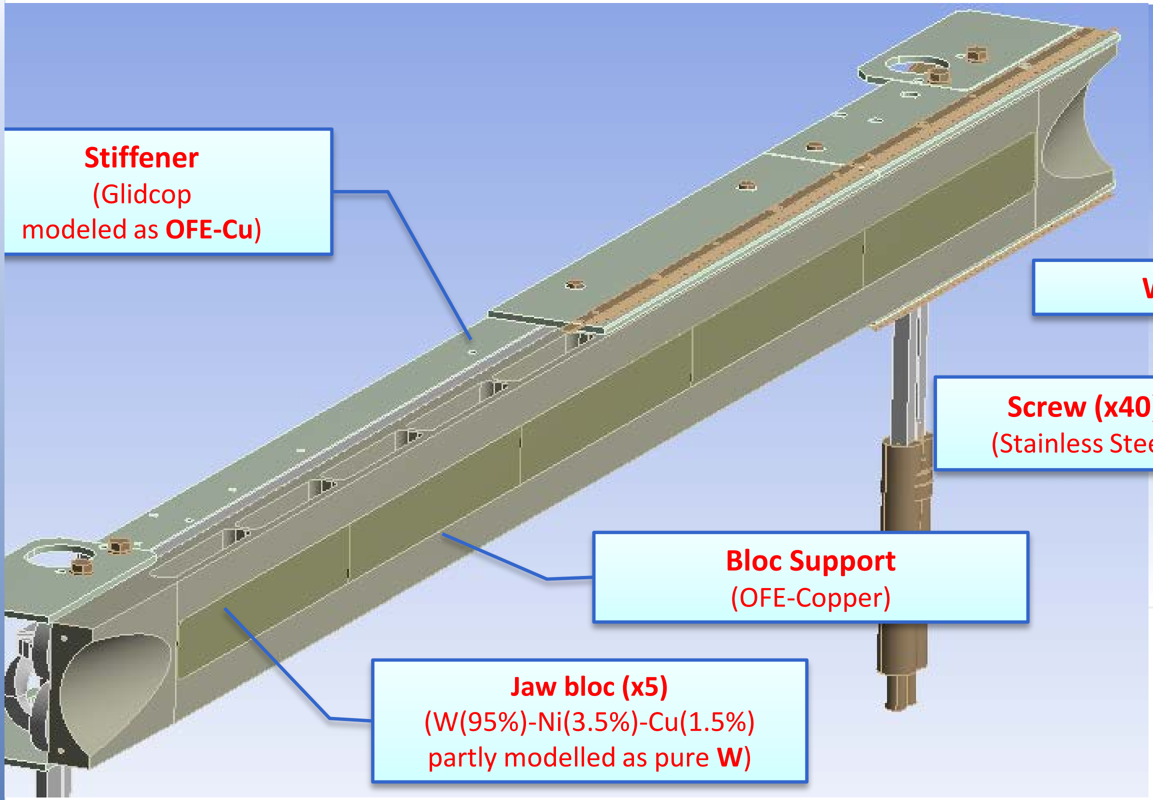
X-Ray ring (up to 3 GeV)

LINAC (up to 120 MeV)

e-gun (100 keV)

UV/IR ring (up to 825 MeV)

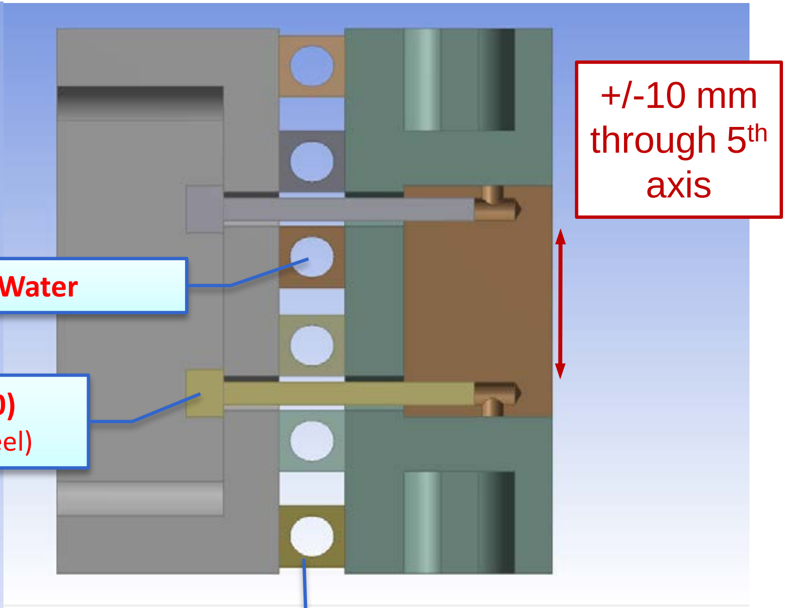
Accident Simulations on TCTA



Stiffener
(Glidcop
modeled as **OFE-Cu**)

Bloc Support
(OFE-Copper)

Jaw bloc (x5)
(W(95%)-Ni(3.5%)-Cu(1.5%)
partly modelled as pure **W**)



Water

Screw (x40)
(Stainless Steel)

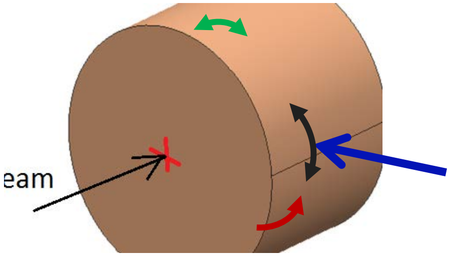
+/-10 mm
through 5th
axis

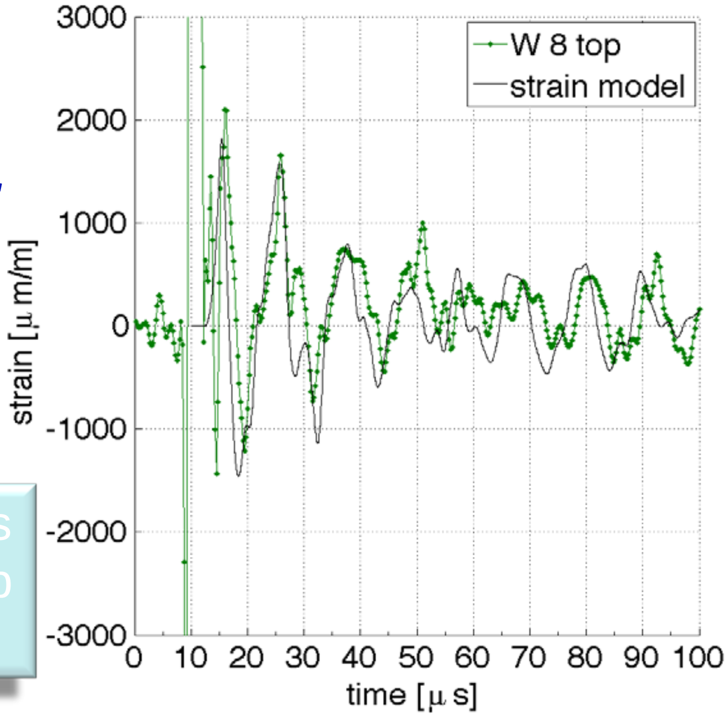
Cooling Pipes
(Cu(89%)-Ni(10%)-Fe(1%) modeled
as **OFE-Cu**)

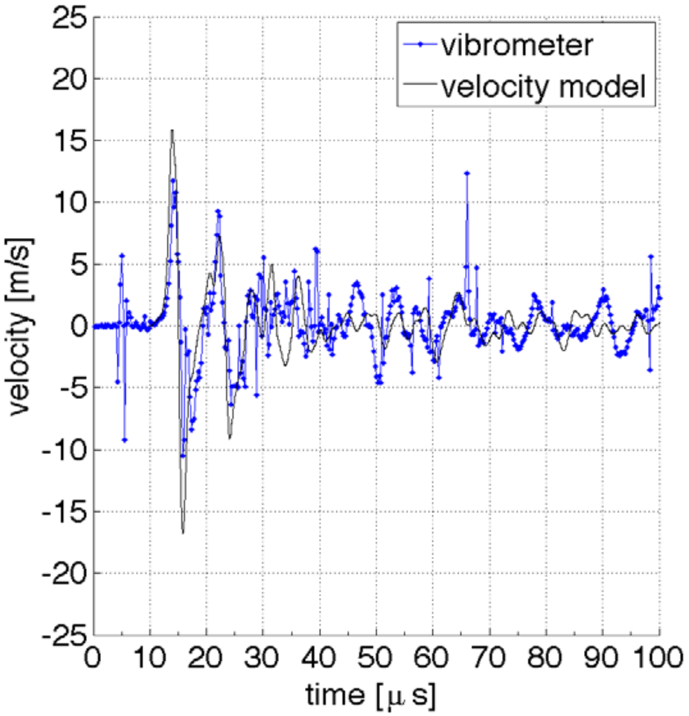
Material	EOS	Strength model	Failure model
Tungsten	Tabular (SESAME)	Johnson-Cook	Plastic strain/ Hydro (Pmin)
Copper OFE	Polynomial	Johnson-Cook	Johnson-Cook
Stainless steel AISI 316	Shock	Johnson-Cook	Plastic strain
Water	Shock	-	Hydro (Pmin)

HRMT14: Medium Intensity Tests

- Extensive numerical analysis (**Autodyn**), based on FLUKA calculations to determine **stress waves**, **strains and displacements**.
- Comparison of simulated **Hoop and Longitudinal Strains and Radial velocity** very well match measured values on sample outer surface.

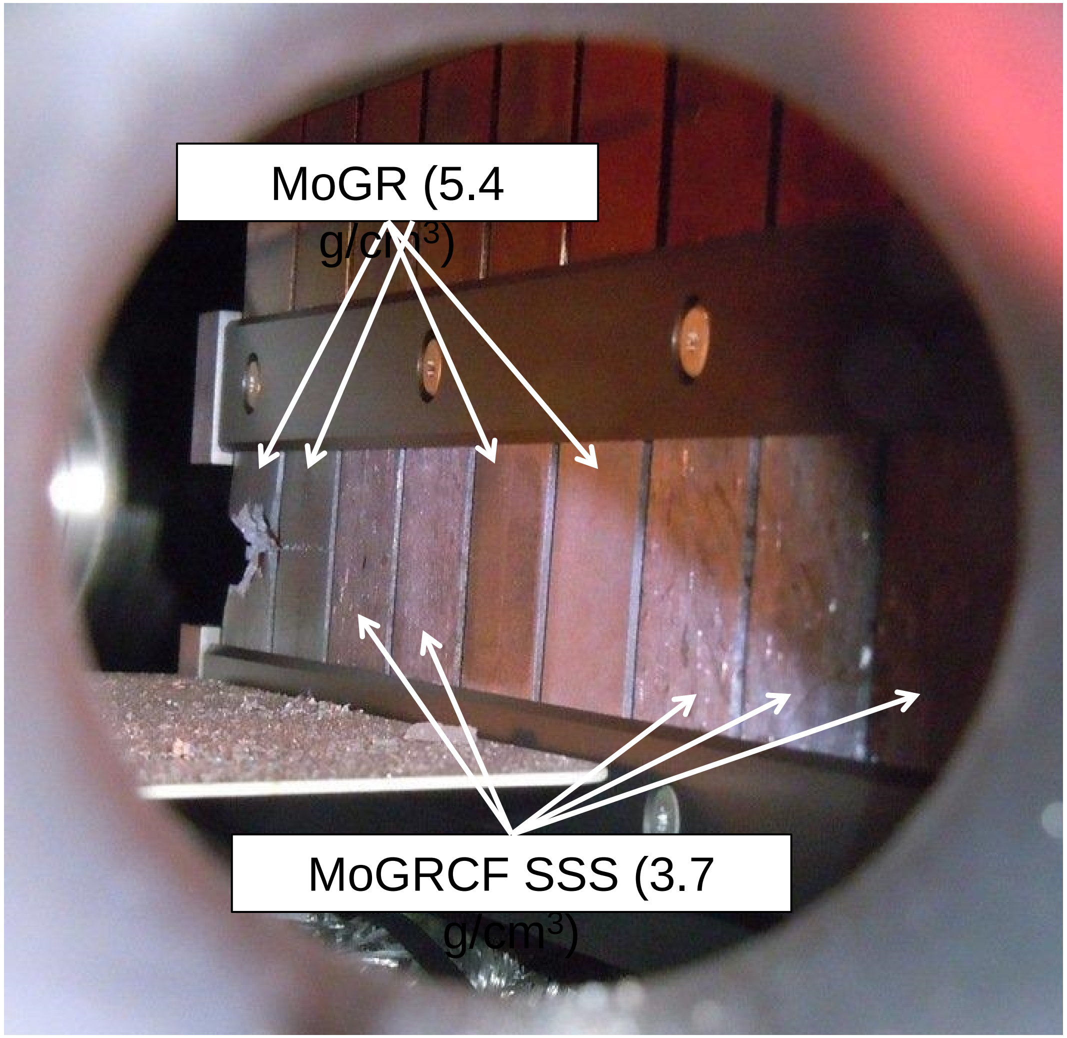






Inermet180 24 bunches
Total intensity: 2.7e12 p
σ ≅ 1.4 mm

MoGr, MoGrCF Post-irradiation



MoGR (5.4 g/cm^3)

MoGRCF SSS (3.7 g/cm^3)

MoGR H1_CENTER:

144 bunches at 450 GeV,

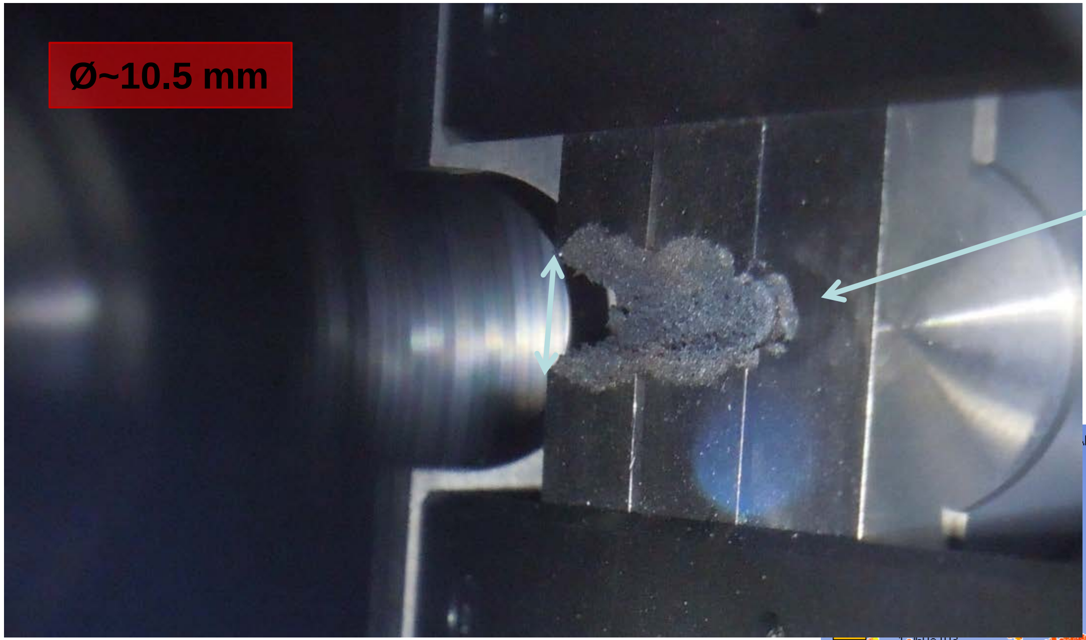
(1.95E13 protons),

impact at 2 mm from the free surface.

Results:

- Extended damage on denser MoGr (last samples),
- No damage on MoGRCF samples,
- No color variation!
- **LPS MoGRCF (2.7 g/cm^3) can only be better!**

W95-NiCu: Post-irradiation



Inermet180 H6_CENTER:
72b, 1.9 mm σ,
9.05E12 Total Intensity

- ➔ Extended damage (~1 cm)
- ➔ No visible plastic deformation
- ➔ Granular aspect of damaged microstructure.