

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



Alessandro Bertarelli, CERN (EN/MME)

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 ...

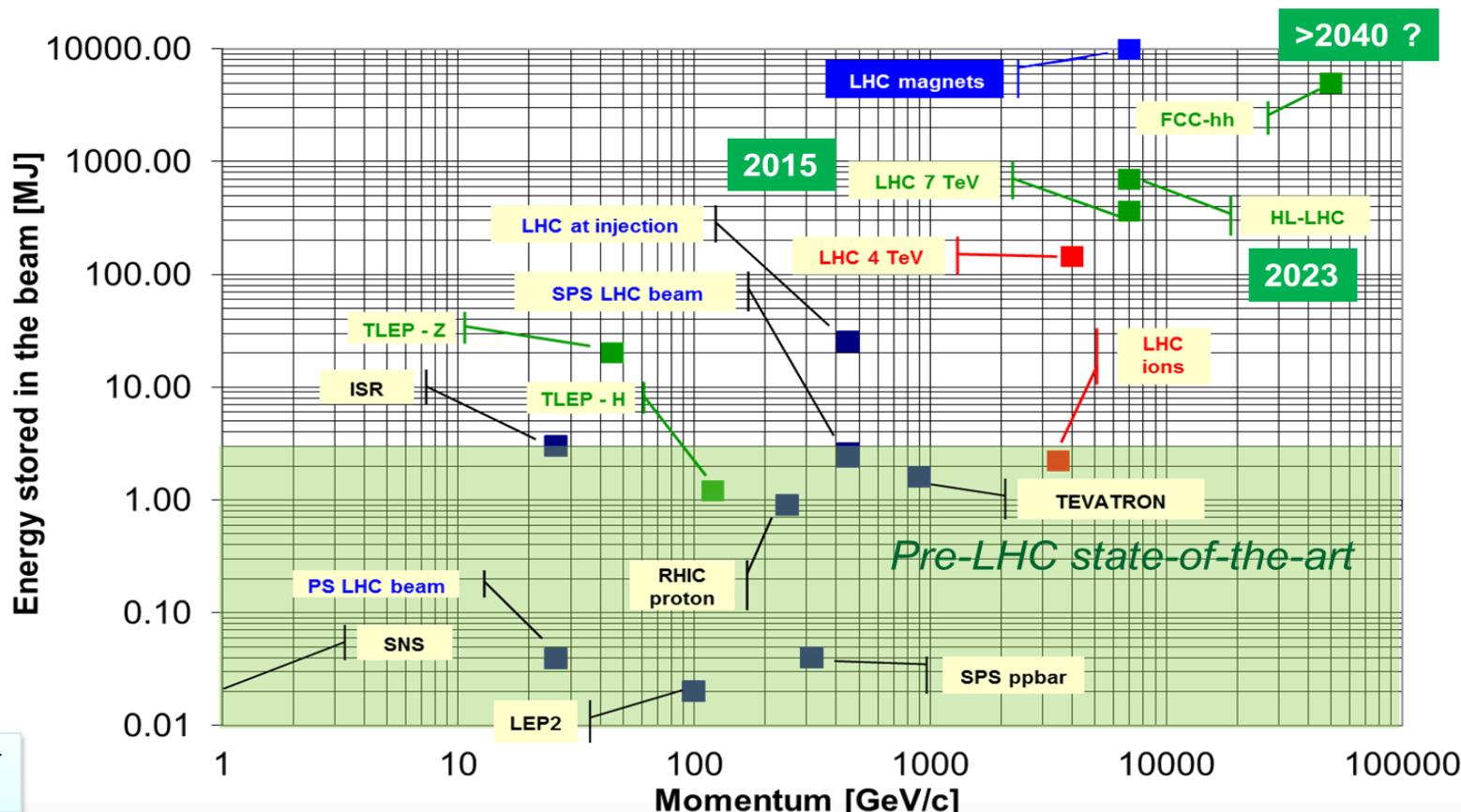


HB2014 Workshop
East Lansing, MI, USA – November 13, 2014

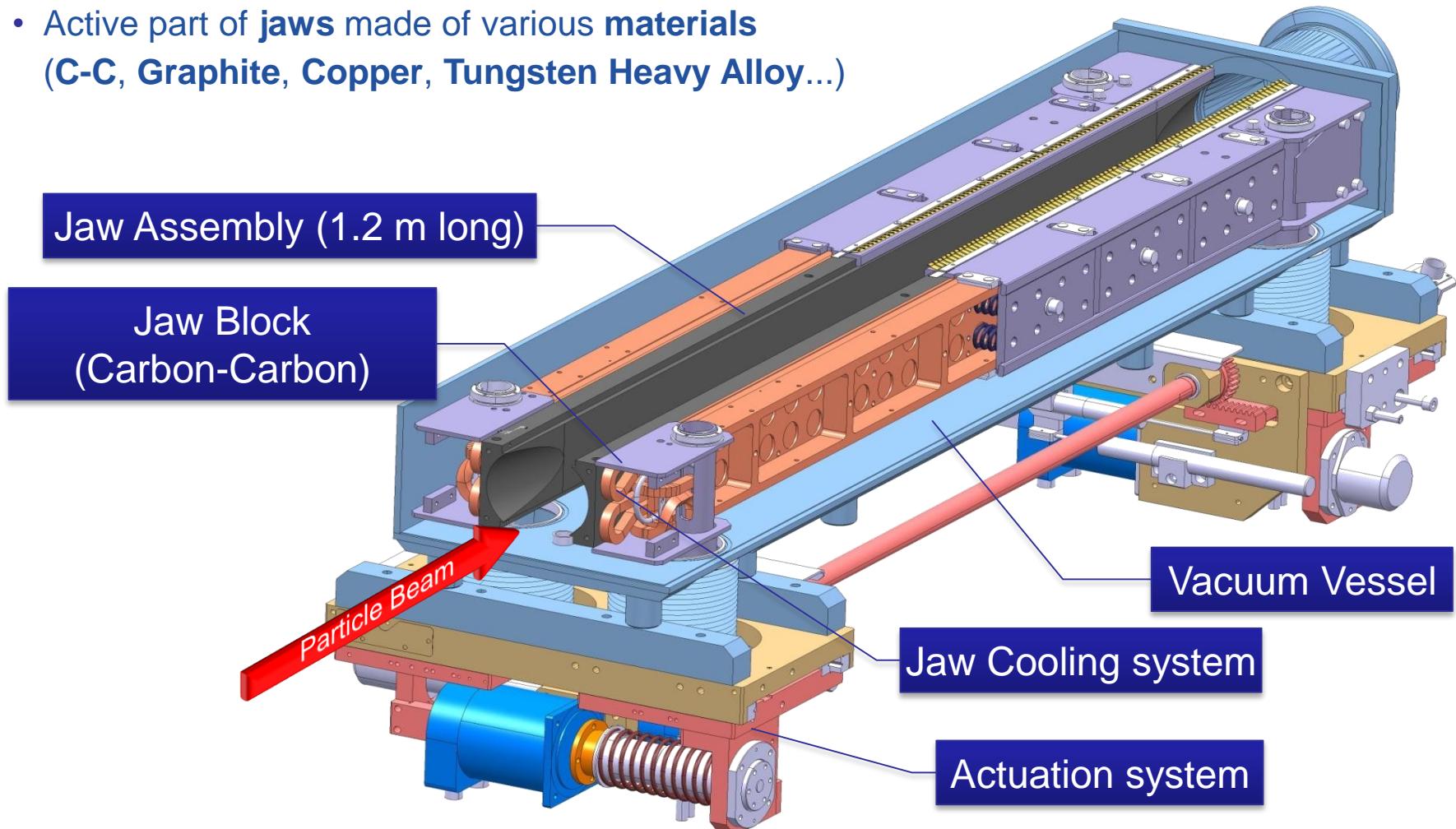
- Introduction and Motivations
 - High Energy Particle Accelerator Challenges
 - LHC Collimation System
 - LHC Collimators Requirements
- Novel Materials for Collimators
- HL-LHC Collimator Design and Testing
- Summary

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



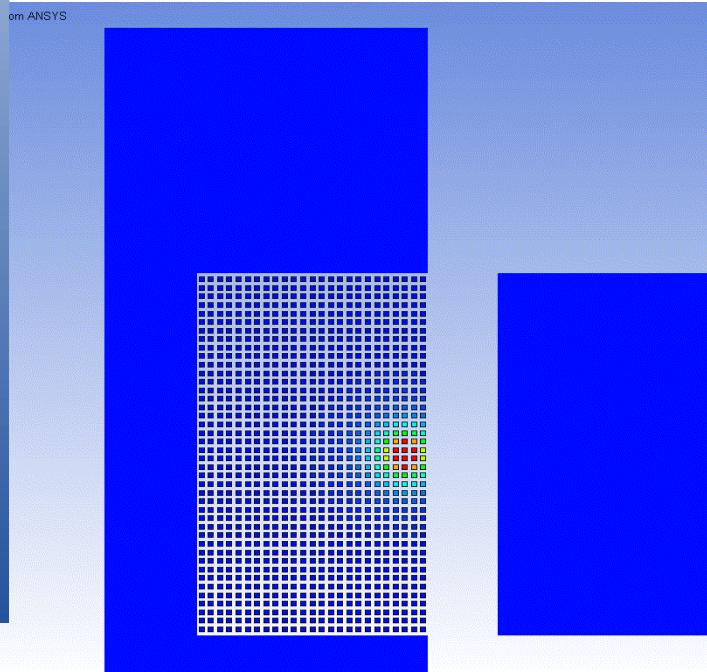
- Several types of collimators for multi-stage cleaning (primary, secondary, tertiary units) at multiple LHC locations (**100+ Collimators**).
- Active part of **jaws** made of various materials (**C-C, Graphite, Copper, Tungsten Heavy Alloy...**)



LHC Secondary Collimator (TCSG) Cutaway

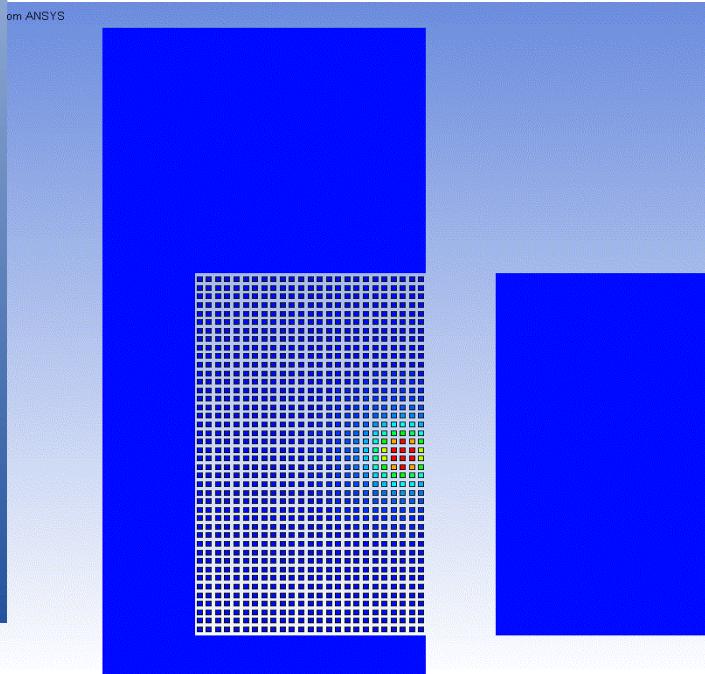
- Collimators are required to **survive** the **beam-induced accidents** to which they are inherently exposed given their vicinity to the beam

Introduction and Motivation



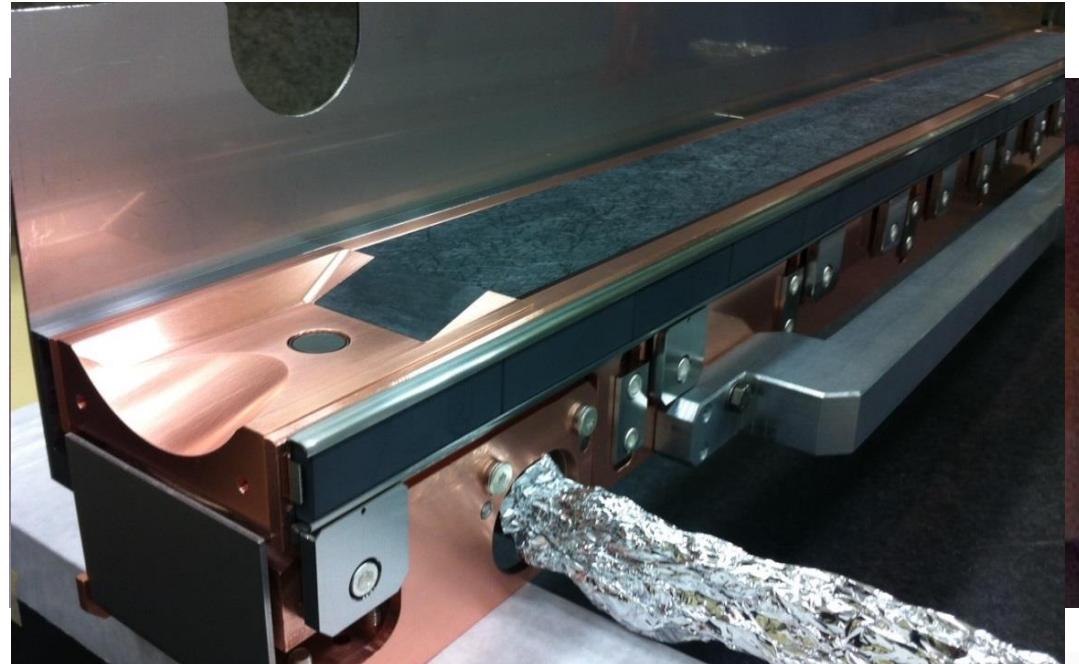
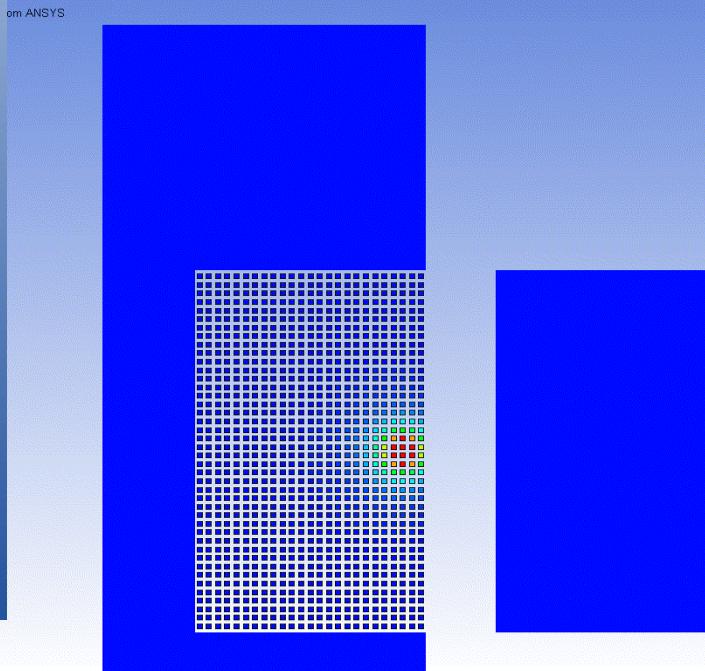
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Introduction and Motivation



Introduction and Motivation

- 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 **beam cleaning efficiency**

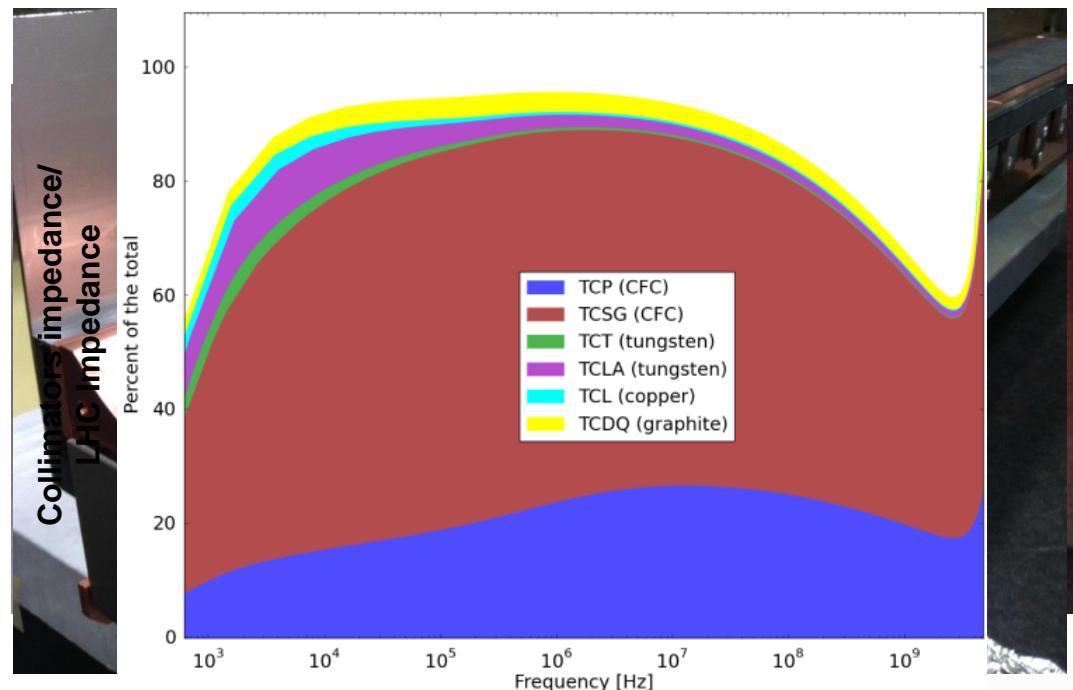
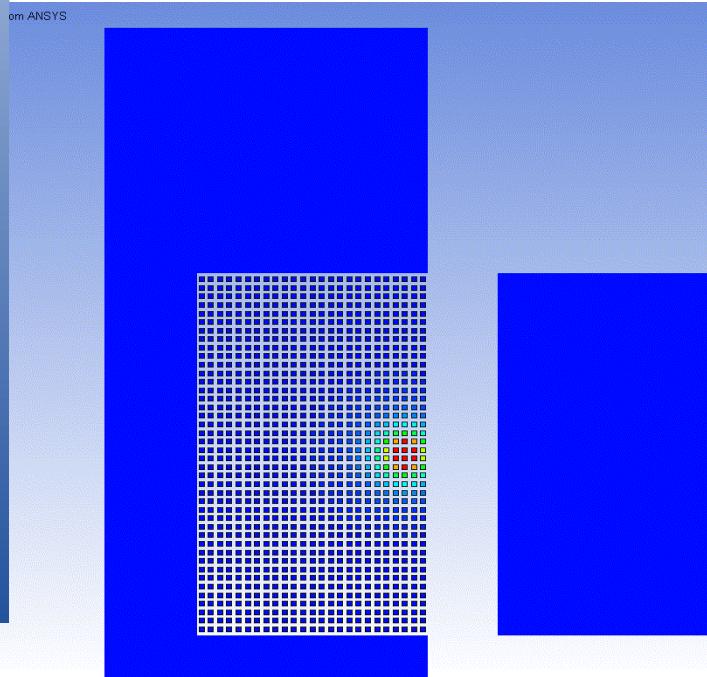


LHC Collimator Requirements

LHC Collimator Requirements

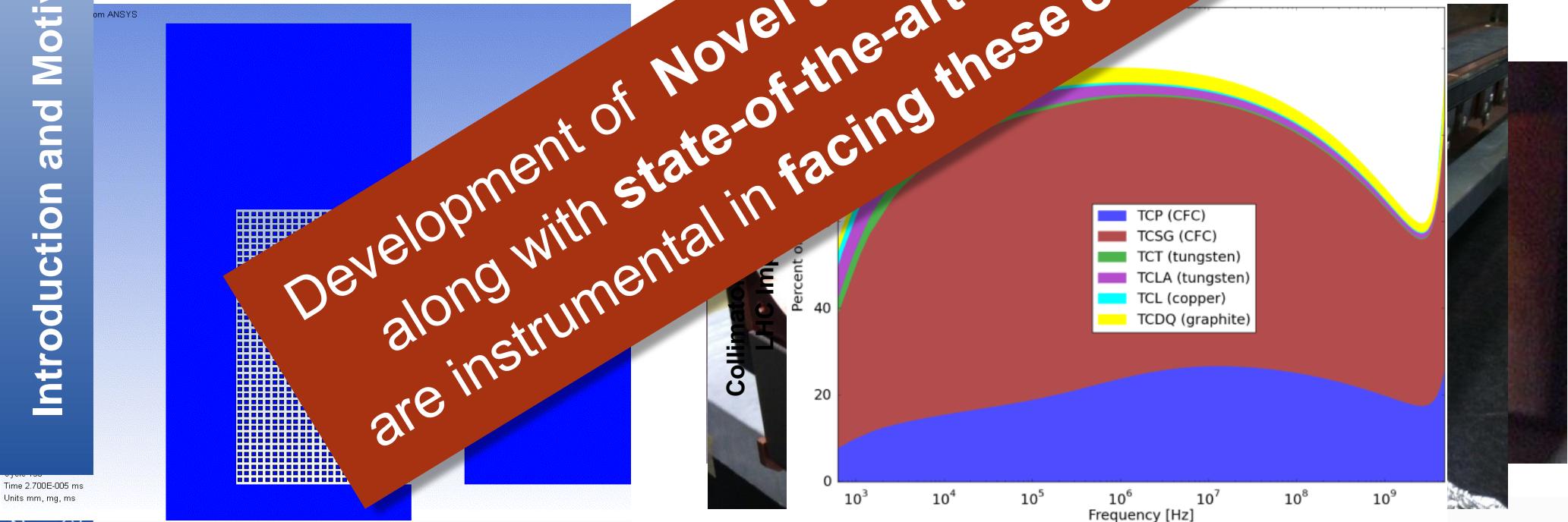
- Collimators are required to **survive** the **beam-induced accidents** to which they are inherently exposed given their vicinity to the beam
- They must possess extremely **accurate jaw flatness** to maintain their **beam cleaning efficiency**
- The collimation system is, by far, the highest contributor to **accelerator impedance** which may significantly limit machine performances: they must have **lowest possible electrical resistivity**
- Their lifetime and efficiency should be conserved under **long-term particle irradiation**
- **No existing material** can simultaneously **meet all requirements** for LHC Future Upgrades!

Introduction and Motivation



- 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 beam steering efficiency
- The collimation system is, by far, the highest contributor to **accelerator inefficiencies**, which may significantly limit machine performances: they must have low **losses** and high **resistivity**
- Their lifetime and efficiency should be conserved under **radiation damage**
- **No existing material** can simultaneously meet all these requirements!

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



- 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

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

- **Electrical Conductivity (γ)** Maximize to limit Resistive-wall Impedance
- **Thermal Conductivity (λ)** Maximize to maintain geometrical stability under steady-state losses
- **Coefficient of Thermal Expansion (α)** Minimize to increase resistance to thermal shock induced by accidental beam impact.
- **Melting/Degradation Temperature (T_M)** Maximize to withstand high temperatures reached in case of accidents.
- **Specific Heat (c_p)** Maximize to improve thermal shock resistance (lowers temperature increase)
- **Ultimate Strength (R_M)** Maximize to improve thermal shock resistance (particularly strain to rupture)
- **Density (ρ)** Balance to limit peak energy deposition while maintaining adequate cleaning efficiency
- **Radiation-induced Damage.** Minimize to improve component lifetime under long term particle irradiation

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

- **Electrical Conductivity (γ)** Maximize to limit Resistive-wall Impedance
 - **Thermal Conductivity (λ)** Maximize to maintain geometric stability under heat fluxes
 - **Coefficient of Thermal Expansion (α)** Minimize to reduce thermal stresses induced by accidental beam impact.
 - **Melting/Degradation Temperature (T_m)** Maximize to withstand temperatures reached in case of accidents.
 - **Specific Heat (c_p)** Maximize (to reduce temperature increase)
 - **Ultimate Strength** (to withstand forces due to beam impact or rupture)
 - **Ductility** (to withstand energy deposition while maintaining adequate cleaning efficiency)
 - **Radiation Resistance** (to withstand particle damage. Minimize to improve component lifetime under long term particle irradiation)
- Most requirements shared with a broad range of applications requiring highly efficient Thermal Management!

- 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 (especially) **MoGr**



CuCD



RHP
TECHNOLOGY

MoCuCD



BREVETTI BIZZ

AgCD



EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

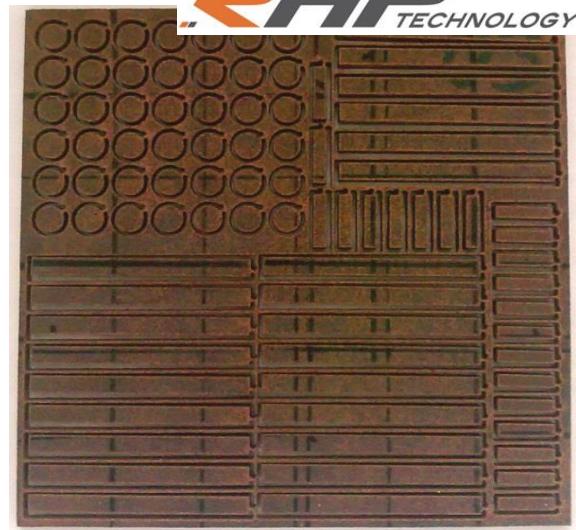


- Developed by **RHP-Technology** (Austria)

Composition :

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

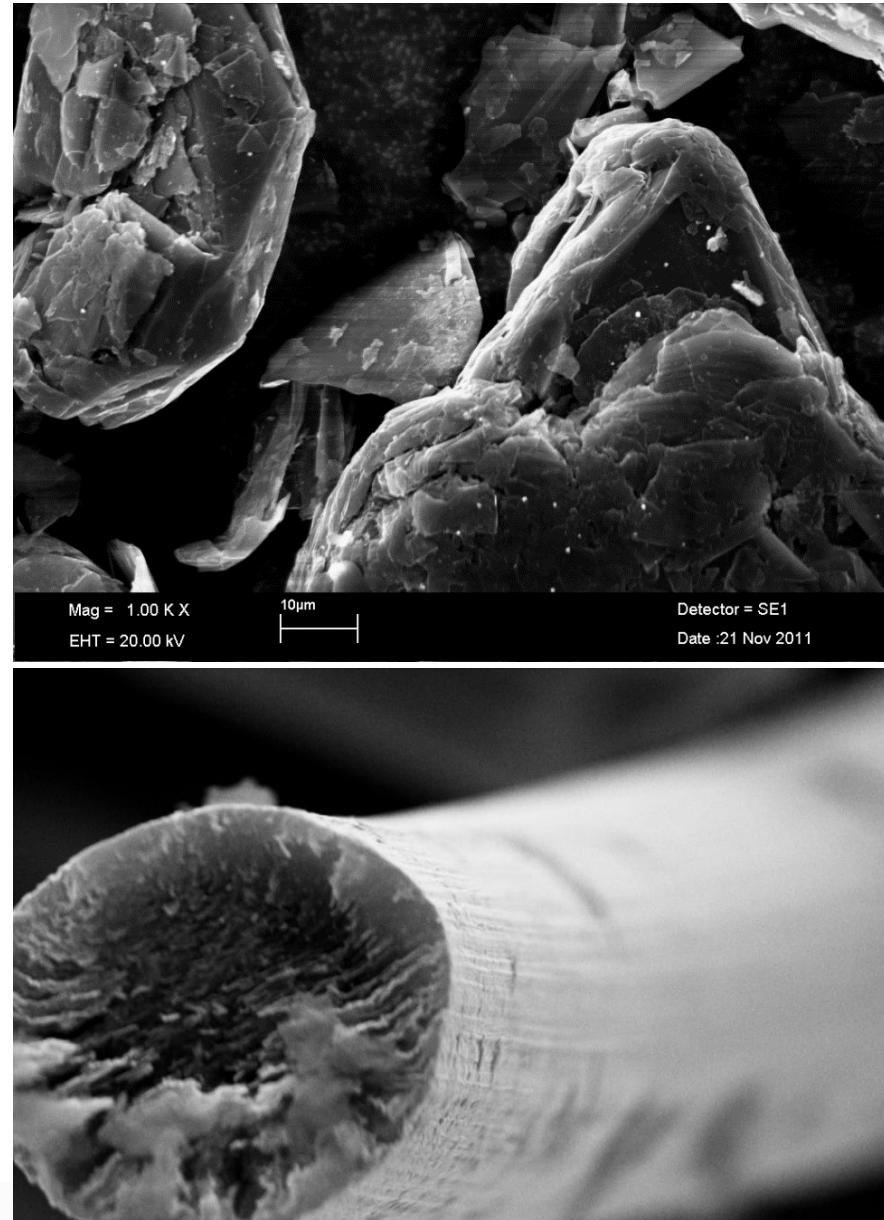
- ↑ No diamond degradation
- ↑ Thermal ($\sim 490 \text{ Wm}^{-1}\text{K}^{-1}$) and electrical conductivity ($\sim 12.6 \text{ MSm}^{-1}$)
- ↔ No direct interface between Cu and CD (lack of affinity) impairs mechanical strength. Issue partly offset by limited bonding assured by Boron Carbides ($\sim 120 \text{ MPa}$).
- ↓ Cu low melting point (1083°C)
- ↓ CTE increases significantly with T due to high Cu content (from $\sim 6 \times 10^{-6} \text{ K}^{-1}$ at RT up to $\sim 12 \times 10^{-6} \text{ K}^{-1}$ at 900°C)



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

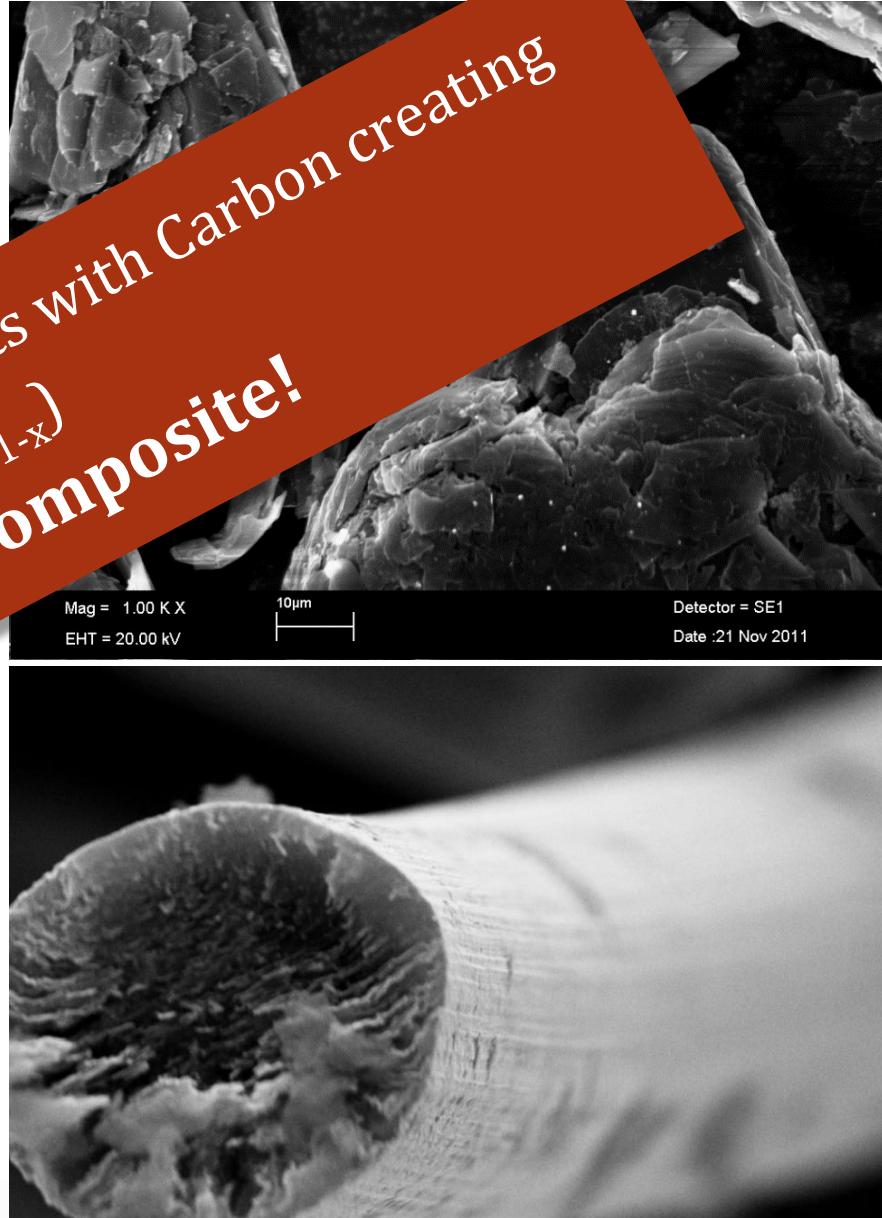


- Co-developed by **CERN** and **Brevetti Bizz** (Italy)
- Broad range of processes and compositions investigated (**Molybdenum**, **Natural Graphite**, **Mesophase Pitch-based Carbon Fibers**).
 - **Why Molybdenum?**
 - Refractory metal
 - Density lower than Tungsten
 - **Why Natural Graphite?**
 - Low CTE (along basal plane)
 - High Thermal Conductivity (along basal plane)
 - Low Density
 - Very High Service Temperatures
 - High Shockwave Damping
 - Low cost
 - **Why Mesophase Pitch-based Carbon Fibres?**
 - Increase mechanical strength
 - Contribute to Thermal Conductivity (highly ordered structure)



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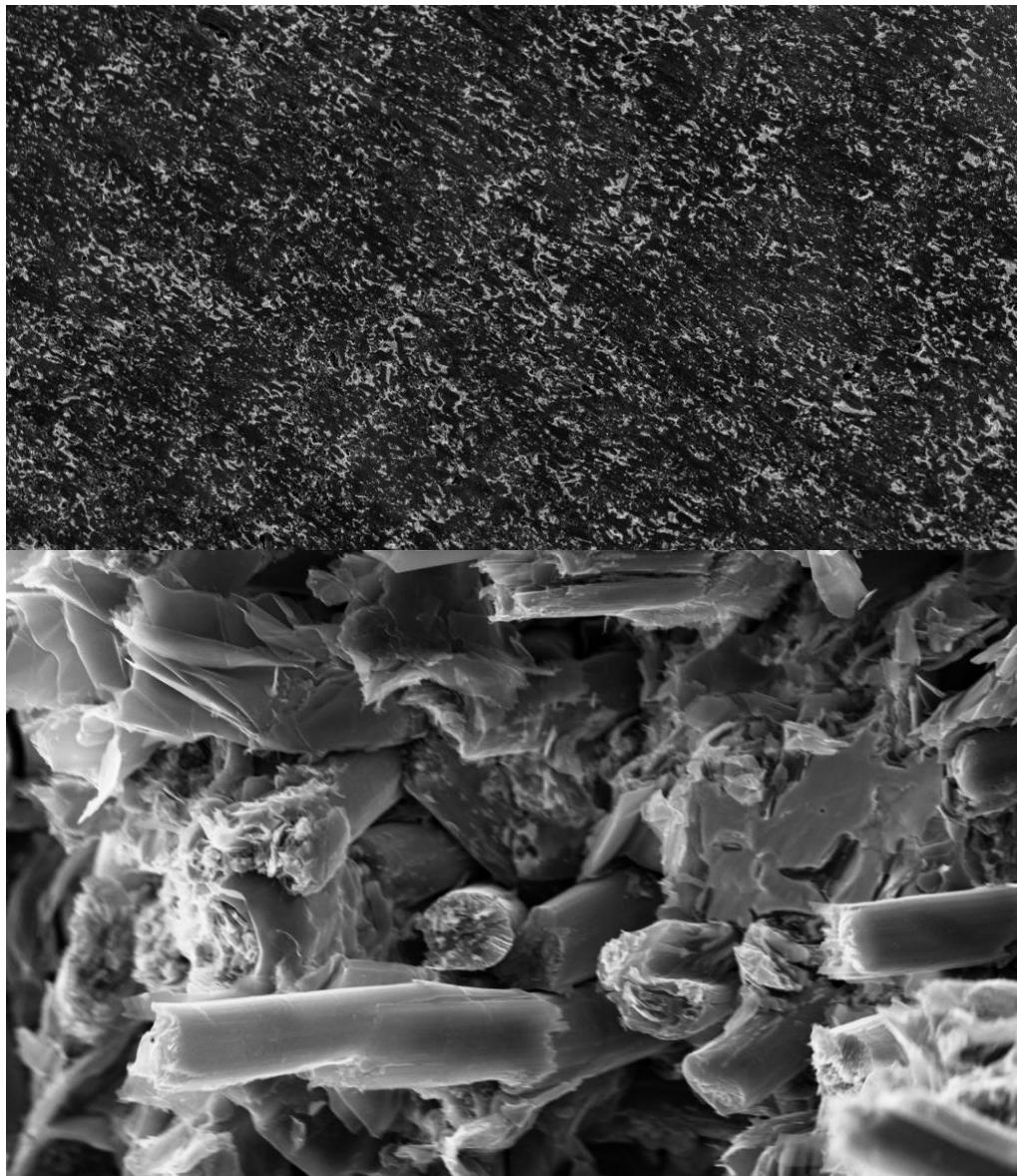
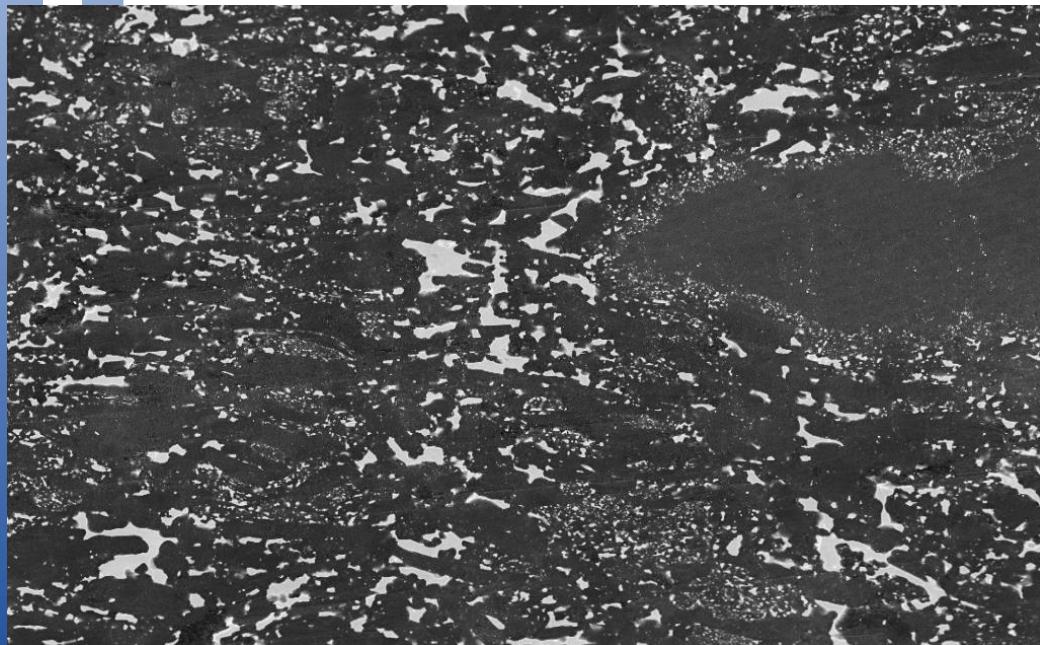
During sintering all Molybdenum reacts with Carbon creating Carbides (MoC_{1-x}) Ceramic Matrix Composite!



Molybdenum Carbide – Graphite

Limiters

- 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



Molybdenum Carbide – Graphite

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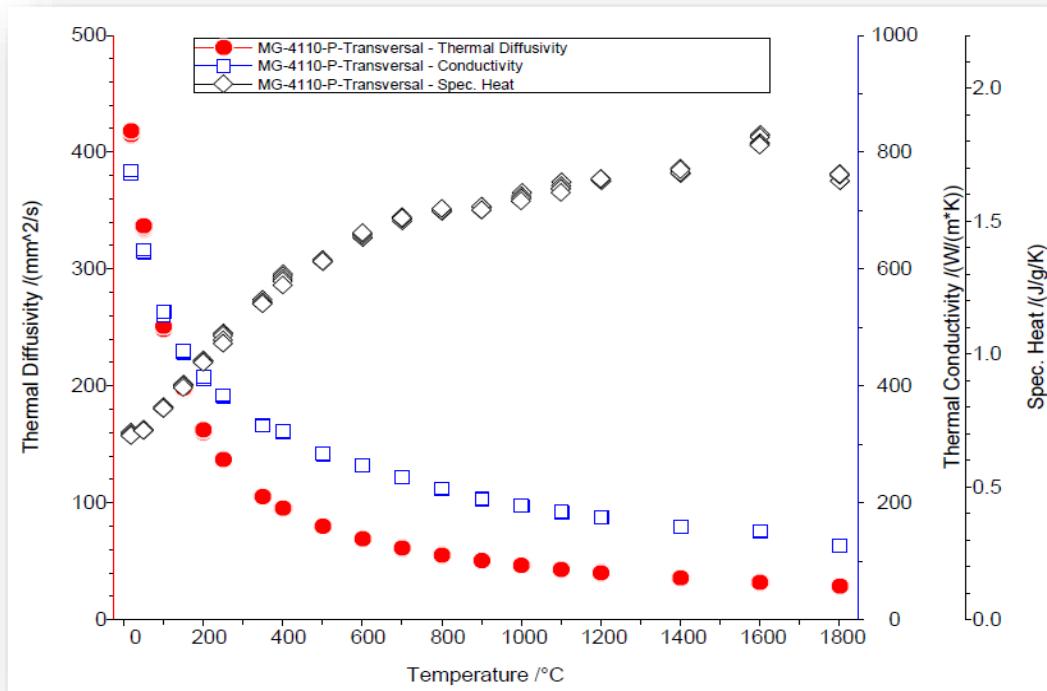
High degree of graphitization obtained by the catalyzing effect of molten carbides!
(They favor atom transport through liquid phase and graphite crystallite ordering!)



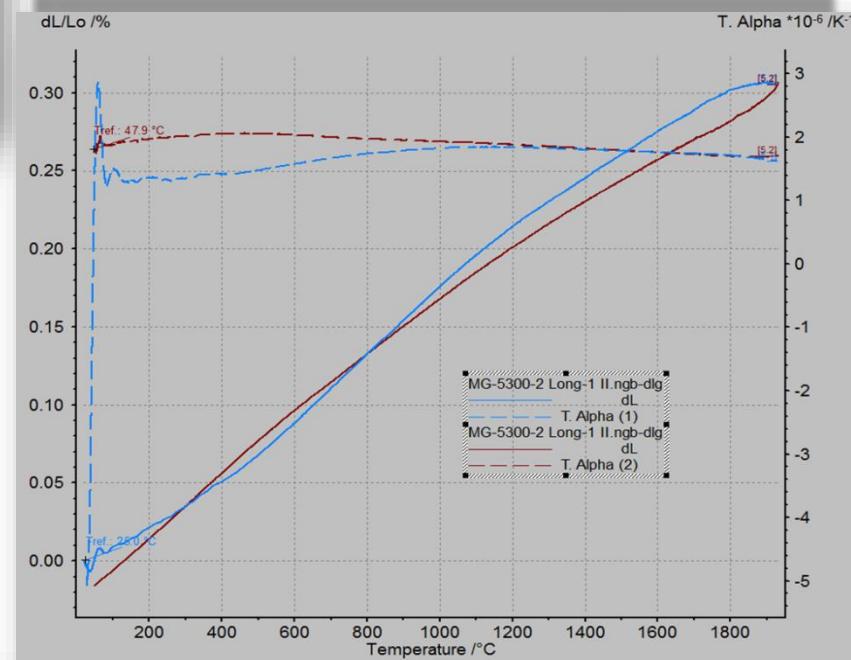
Novel Materials for Collimators



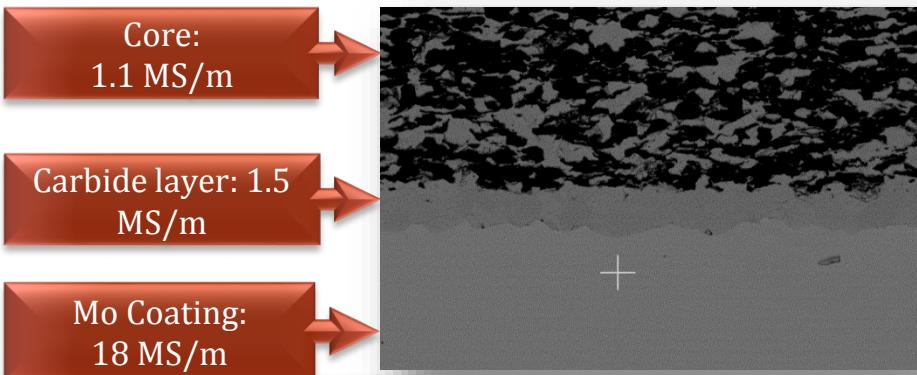
Molybdenum Carbide – Graphite



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



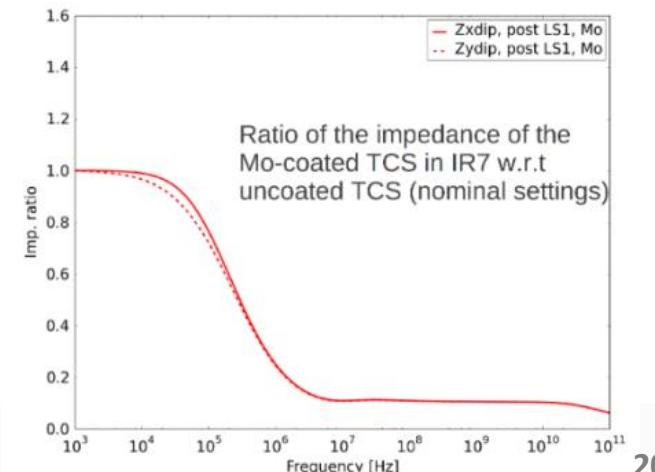
MoGr can be Mo-coated to increase surface conductivity



- Several **Figures of Merit** 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
- ***Thermal Stability Index (TSI)*** provides an indication of the ability of the material to **maintain the geometrical stability** of the component (e.g. Collimator jaw)
 - It 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**).
- ***Electrical conductivity (γ)*** Resistive-wall impedance is inversely proportional to electrical conductivity \Rightarrow **highest electrical conductivity** is sought for materials sitting closest to circulating beams!

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

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



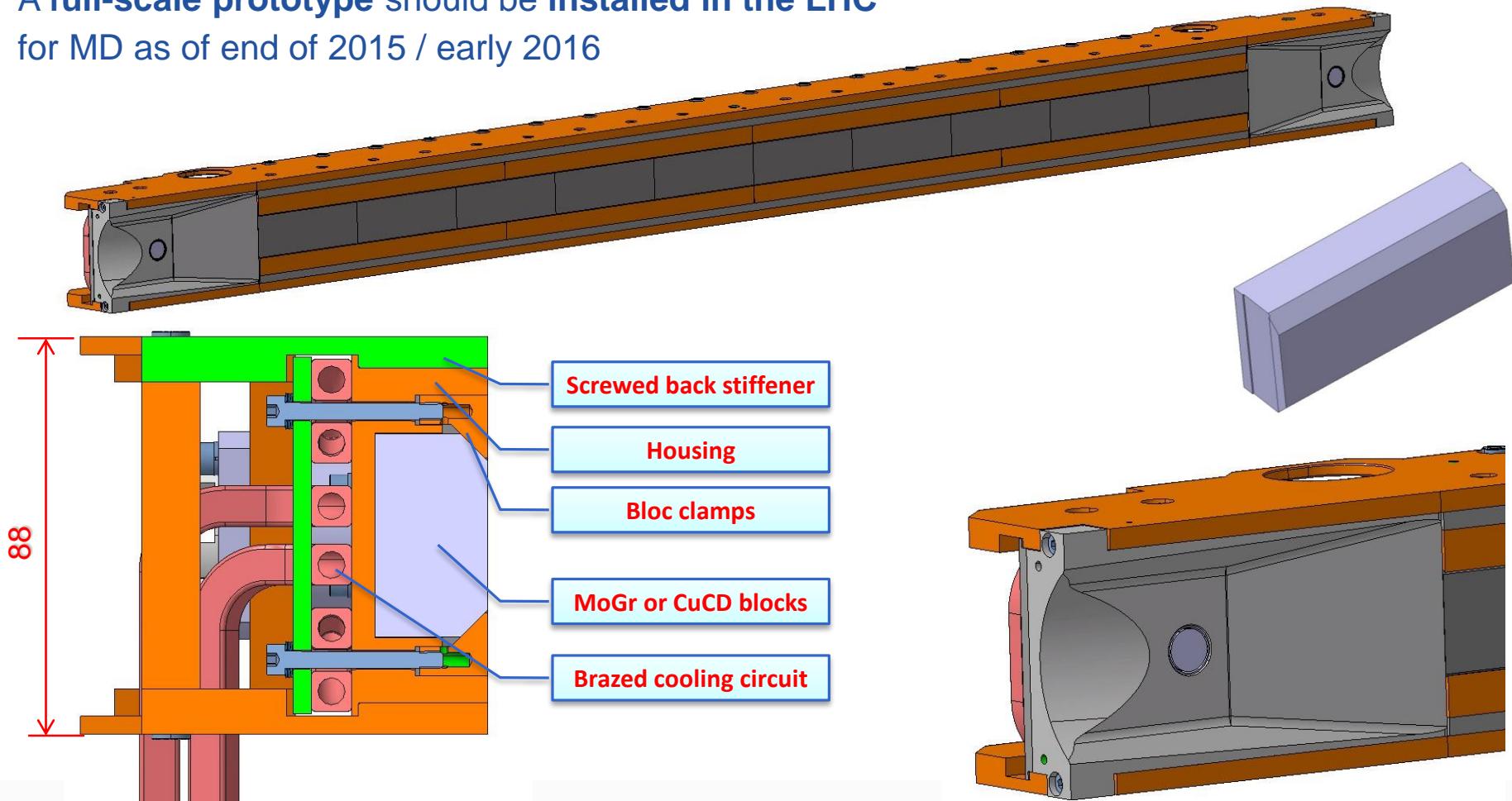
- The higher the FoM, the better the material ... No one-fits-it-all material!
- **Carbon-based materials** feature excellent **TRI** and **TSI** thanks to low-Z, low CTE, low density, high degradation temperature, high conductivity
- **Beryllium** is outstanding under practically all points of view ... 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

- 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

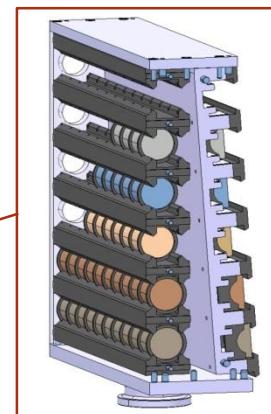
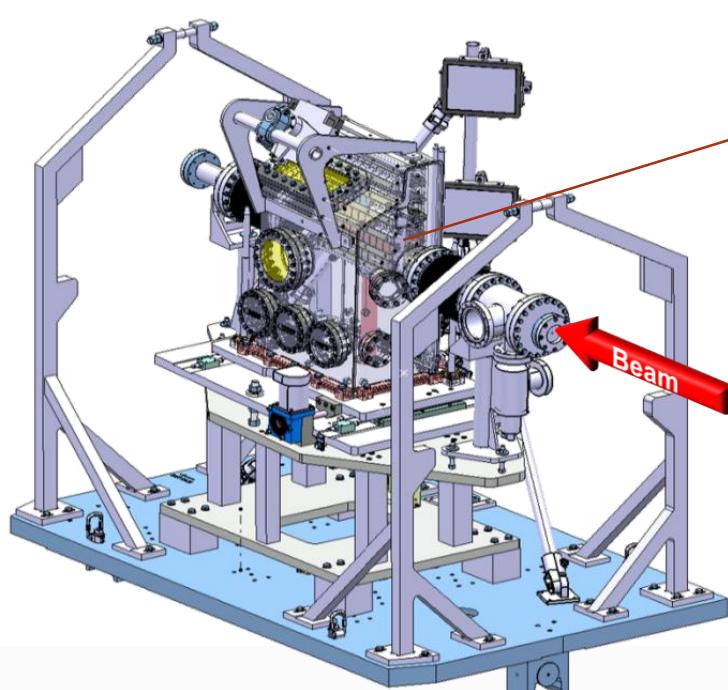


Why Beam Impact Tests at CERN HiRadMat Facility?

- 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
- Material constitutive models at **extreme conditions** are **scarce** 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

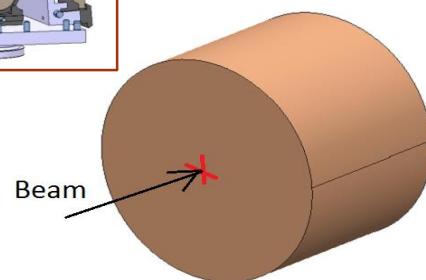
- HRMT14 (2012) Experiment Goals

- 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, primarily in **real time**, experimental data from different acquisition systems (**Strain Gauges, Laser Doppler Vibrometer, High Speed video Camera, Temperature and Vacuum probes**)

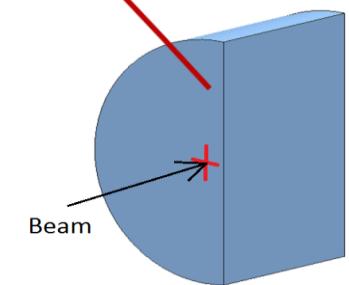


Beam Parameters	
Beam energy	440 GeV
Number of protons per bunch	1.1e11
Bunch Spacing	25 ns

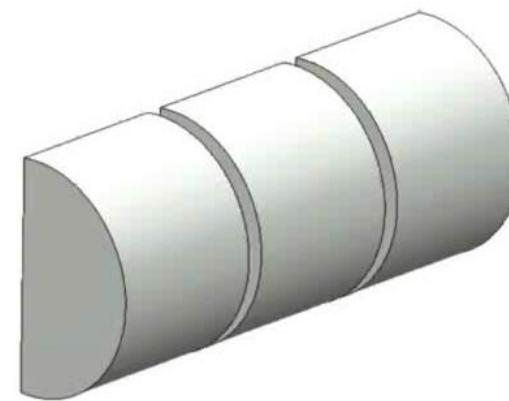
High Intensity Tests:
Sample: half-moon;
Beam Offset 2 mm



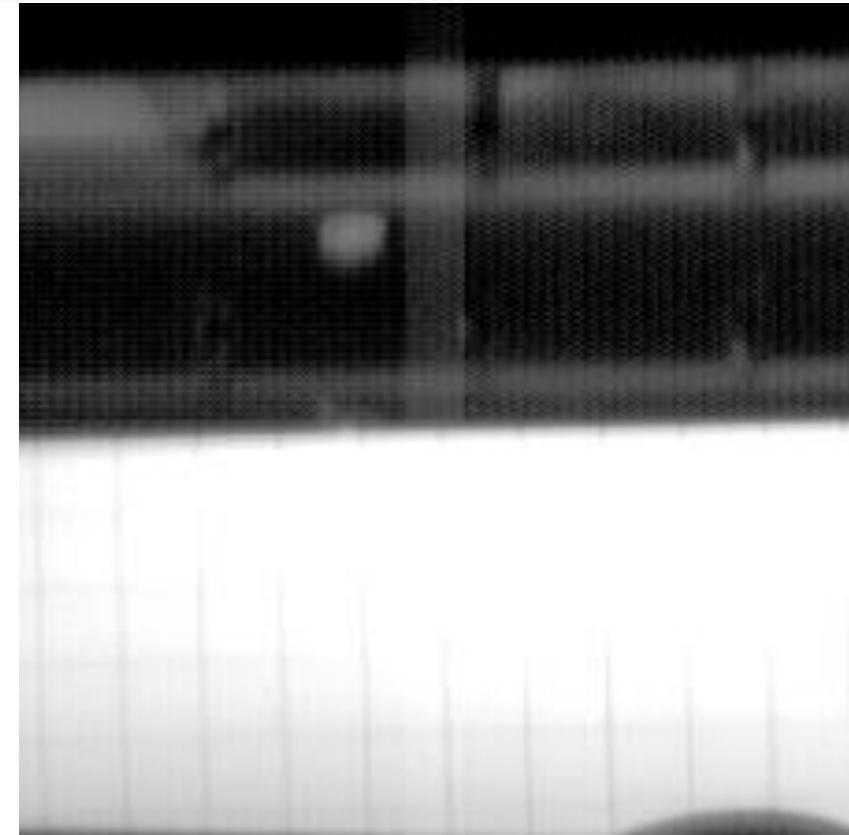
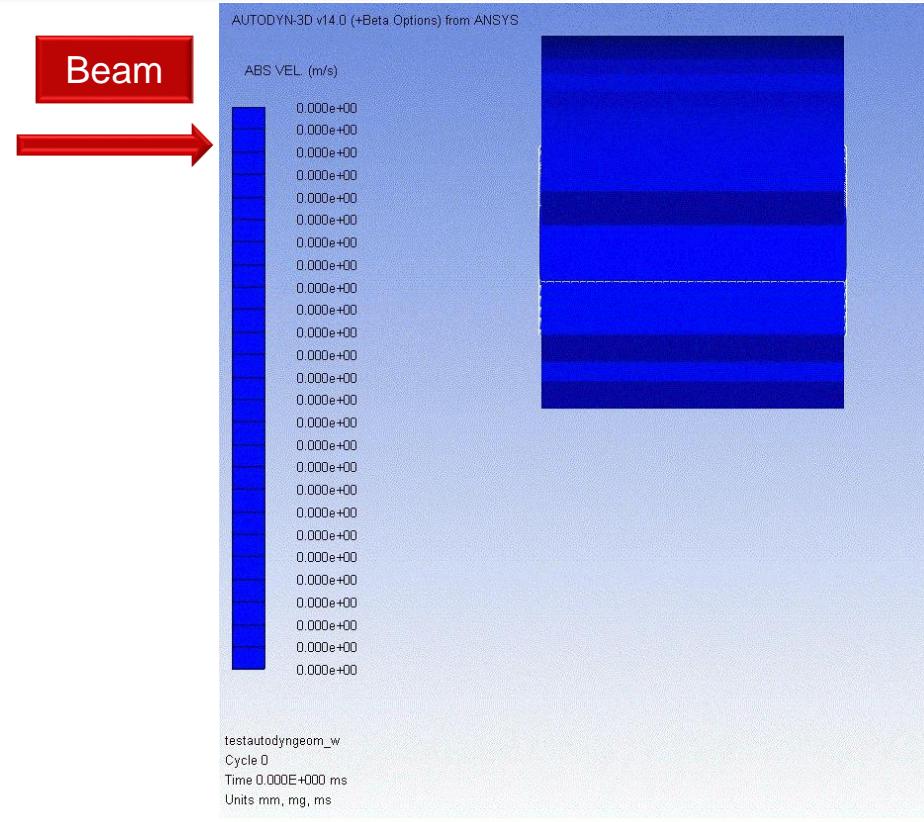
Medium Intensity Tests:
Sample: Ø 40 mm , L30 mm



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



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

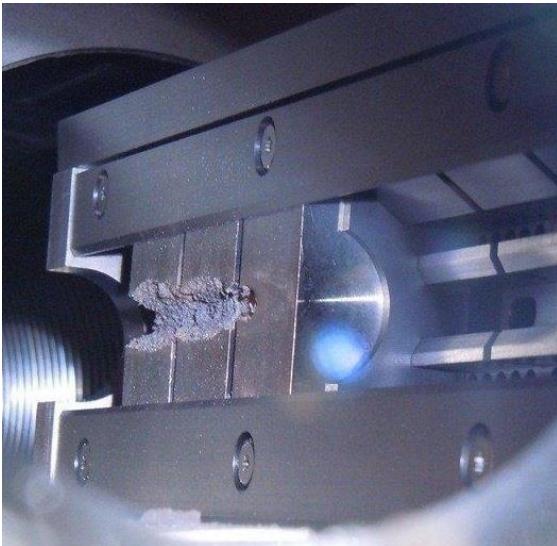


Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	316 m/s
Experiment	72	1.26e11	9.0e12 p	1.9 mm	8 (partly 9)	~275 m/s

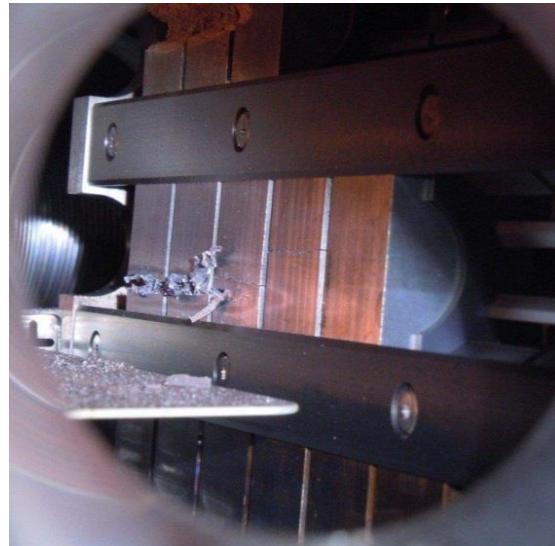
Design and Testing for HL-LHC Collimators



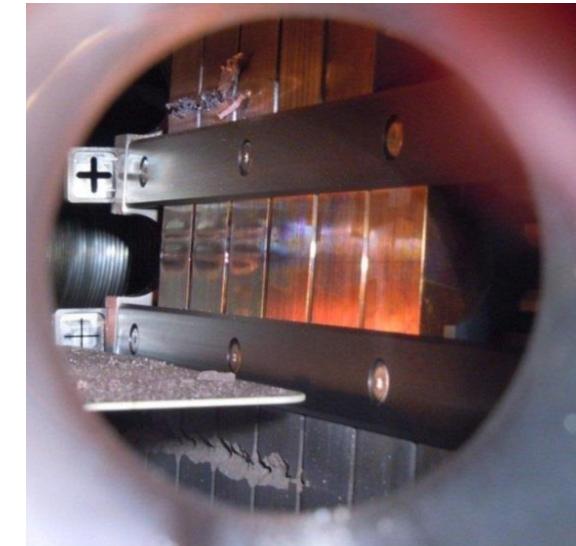
HRMT14 Experiment



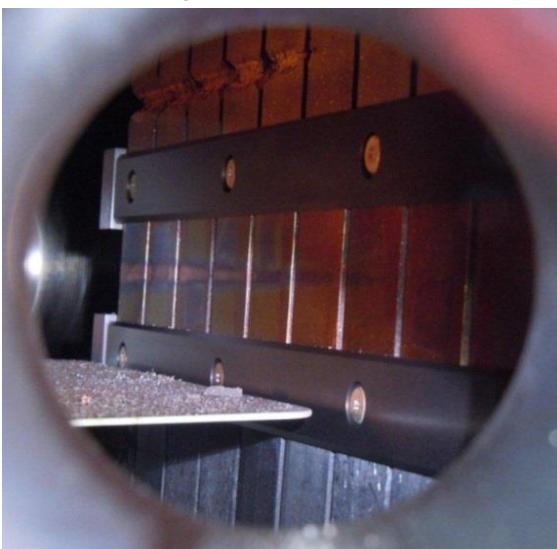
Tungsten Alloy, 72 b



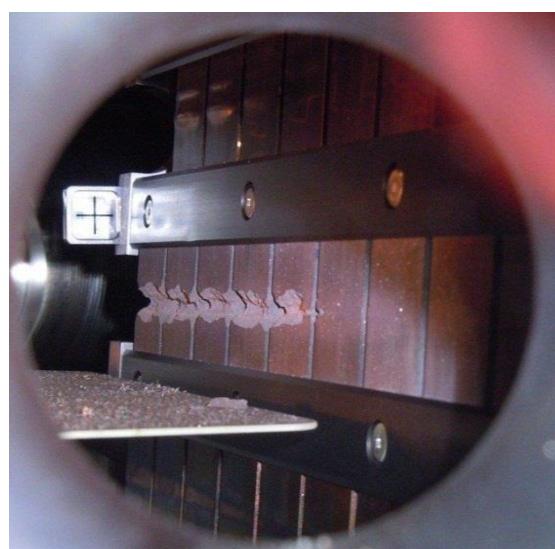
Molybdenum, 72 & 144 b



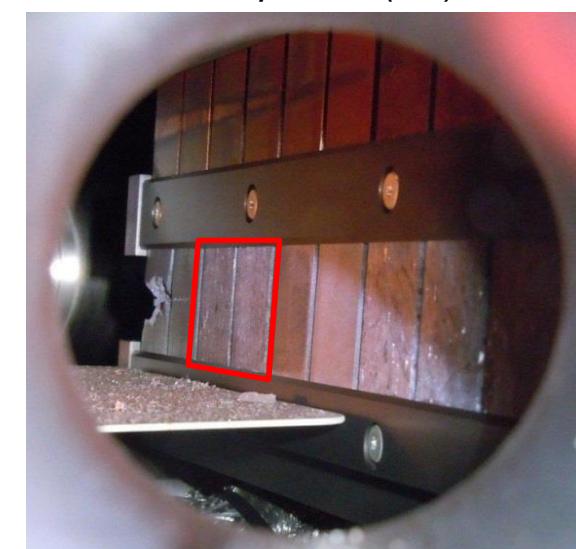
Glidcop, 72 b (2 x)



Copper-Diamond
144 b

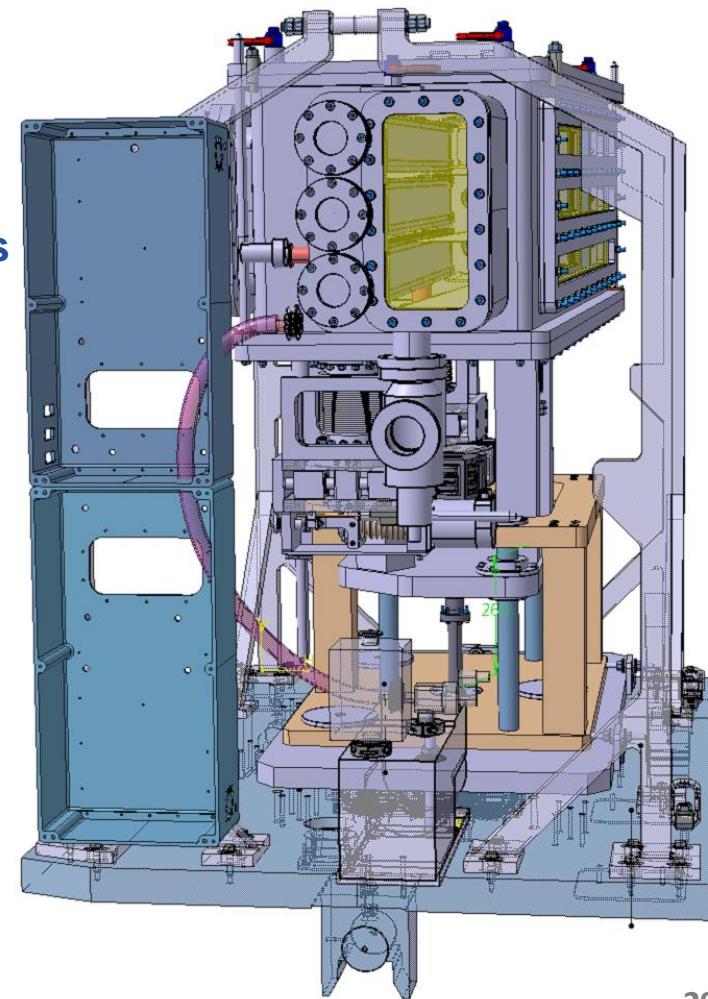
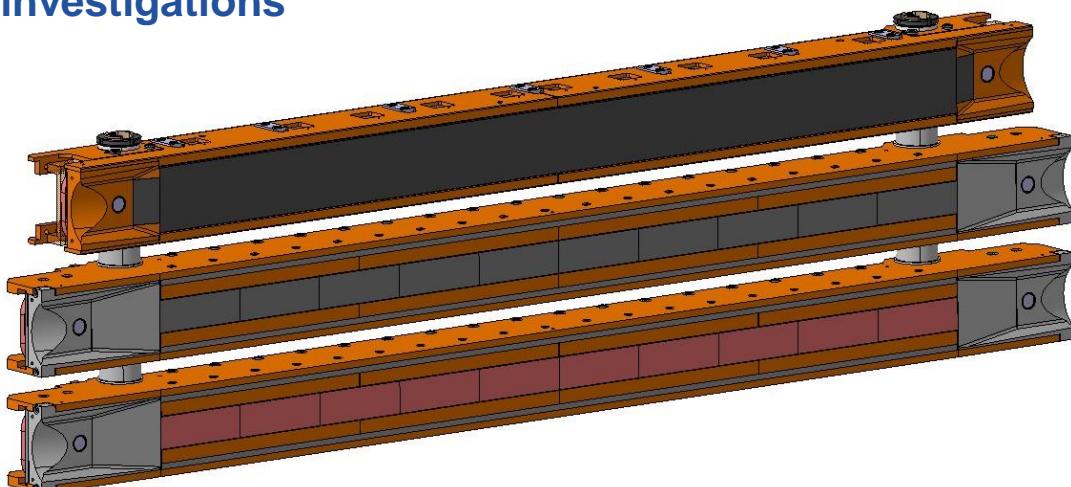


Molybdenum-Copper-Diamond
144 b



Molybdenum-Graphite (3 grades)
144 b

- 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 \times ~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 **online sensors** (strains, displacement, structural damage, temperature ...) viewports for **optical acquisition** (LDV, high-speed camera) and fast dismounting system for glove box **post-irradiation investigations**





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 ...

February-March 2014:

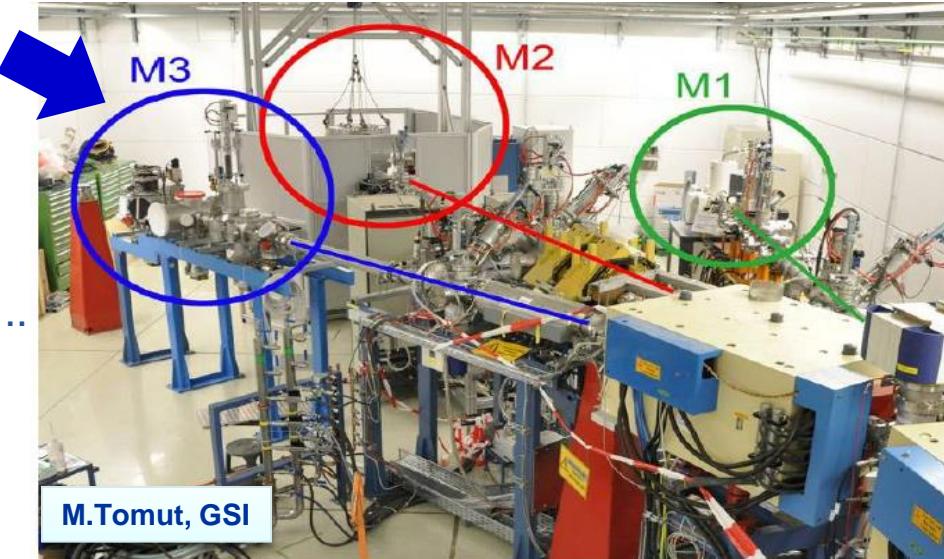
- ^{238}U irradiation: 1.14 GeV, 4×10^9 ions $\text{cm}^{-2}\text{s}^{-1}$
- ^{208}Bi irradiation: 1 GeV, 1.2×10^9 ions $\text{cm}^{-2}\text{s}^{-1}$,
- **Materials tested:** CuCD, C-C, MoGr (non-annealed),
- Fluence: up to 1×10^{14} ions cm^{-2}

July 2014:

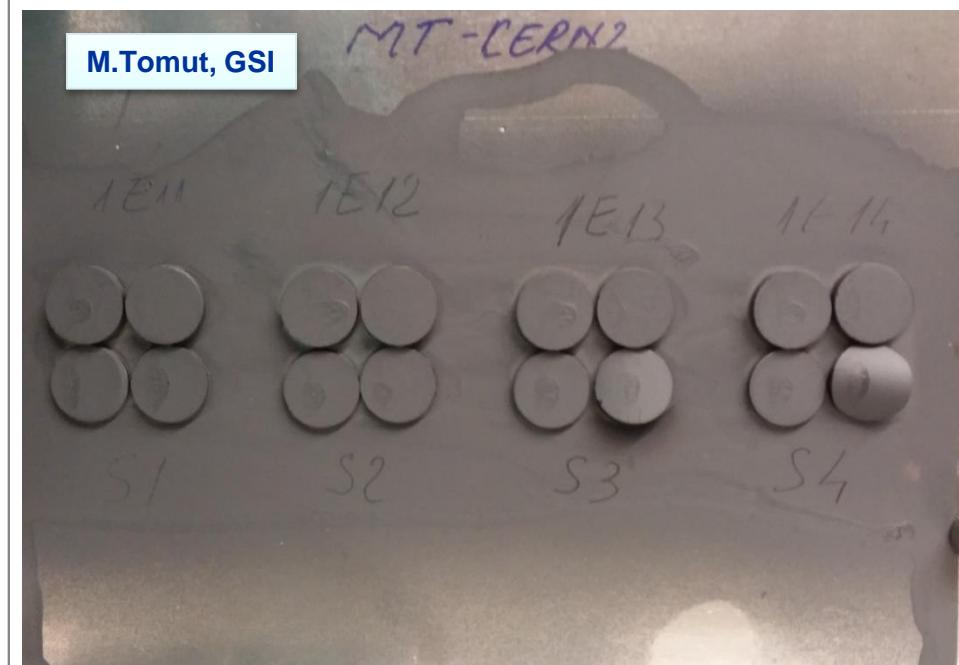
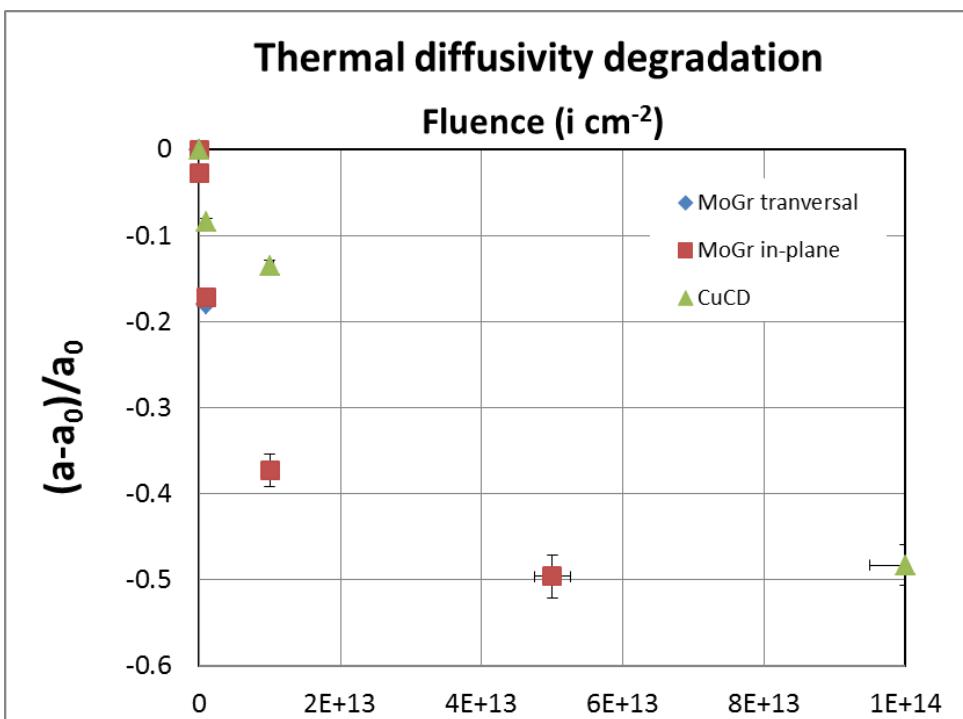
- ^{197}Au irradiation: 945 MeV, $\sim 1-2 \times 10^9$ ions $\text{cm}^{-2}\text{s}^{-1}$
- C irradiation: 11.4 MeV/u, 5×10^9 ions $\text{cm}^{-2}\text{s}^{-1}$
- CuCD, C-C (2x orient.), MoGr (low-temperature annealed), C fibres
- Fluence: up to 1×10^{14} ions $\text{cm}^{-2}\text{s}^{-1}$

October 2014

- Sm irradiation: 360 MeV/u
- Fluence: up to 2×10^{12} ions $\text{cm}^{-2}\text{s}^{-1}$

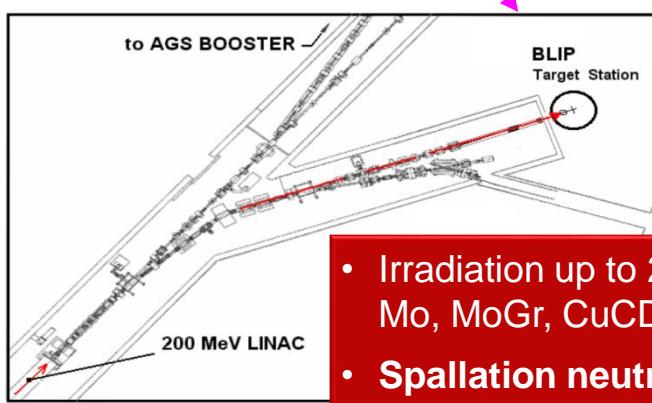
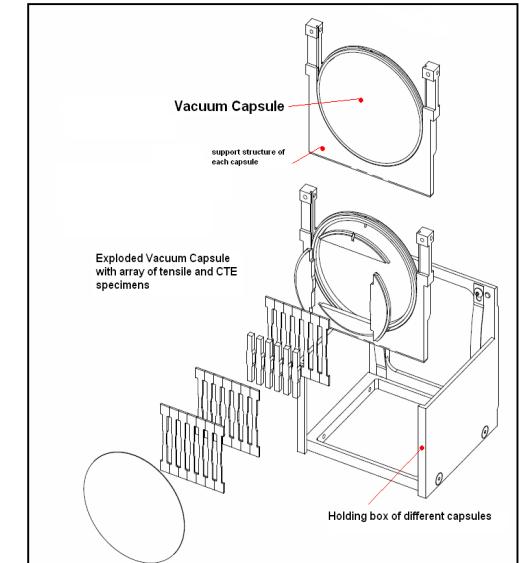
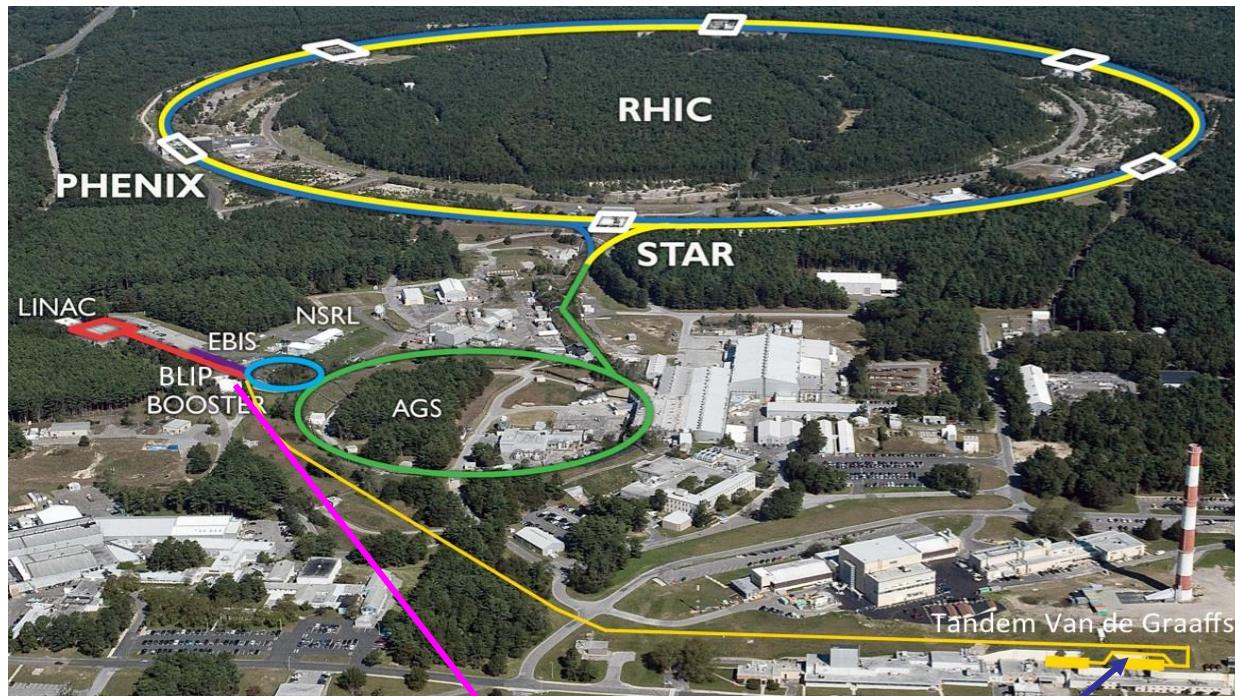


- Analysis of experimental data is just starting
- Preliminary results indicate a degradation of thermal diffusivity for both CuCD and MoGr (larger for MoGr)
- Deformation under irradiation was also observed on MoGr transversal samples: this is likely due to release of internal residual strains. Annealing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



Irradiation Tests at BNL

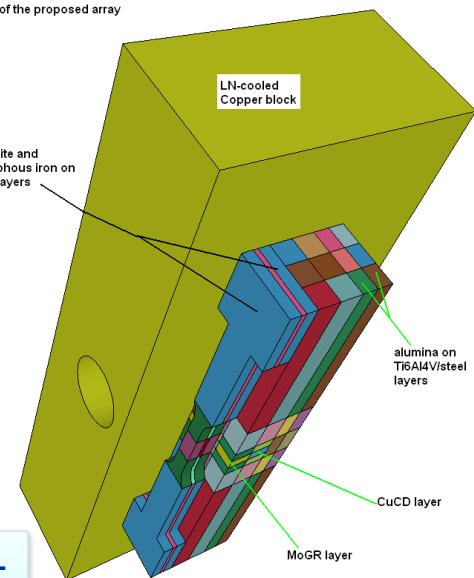
Design and Testing for HL-LHC Collimators



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)

N. Simos, BNL



- 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 particularly **Molybdenum Carbide – Graphite** (MoGr)
- **Outstanding properties** were reached for MoGr produced by High Temperature Liquid Phase Sintering (RT Thermal Conductivity $770+ \text{ Wm}^{-1}\text{K}^{-1}$, CTE $\sim 1\div 2 \times 10^{-6} \text{ K}^{-1}$)
- 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 simulation methods and materials constitutive models calls for ad-hoc **comprehensive tests** to be carried out in dedicated facilities such as CERN **HiRadMat**
- An **extensive campaign** to study **materials behavior under irradiation** is underway at **GSI**, **BNL** and **Kurchatov Institute**. Data being analyzed: preliminary results helped in optimizing new material production process

Thank you for your attention!



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Novel Materials for Collimators

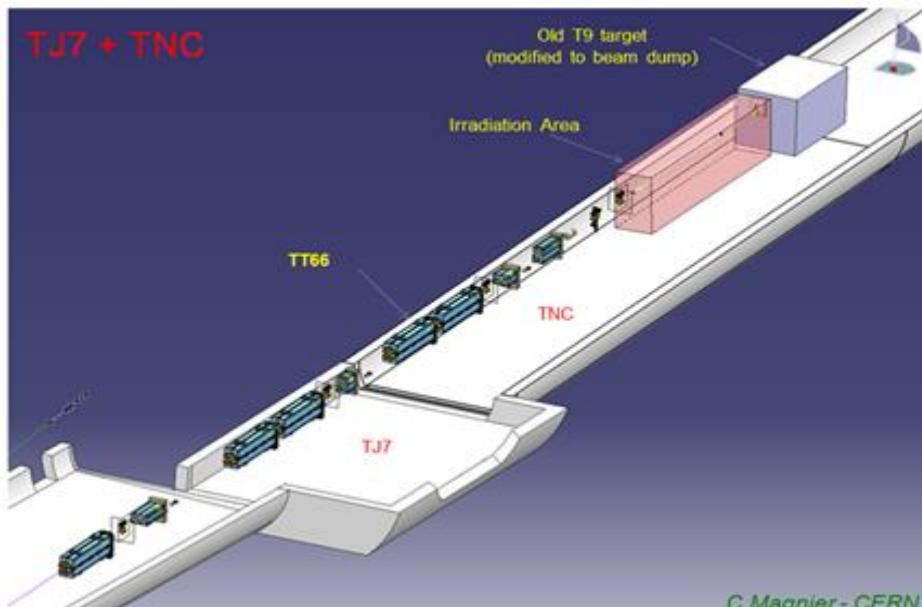
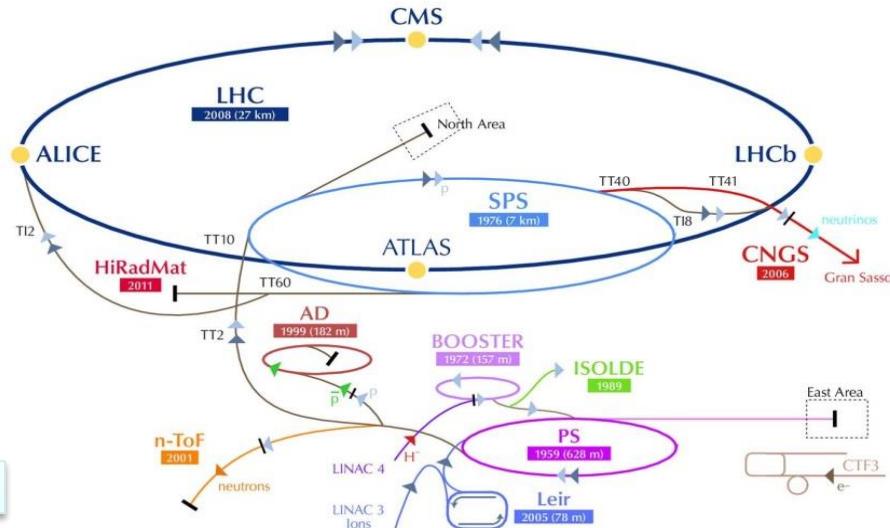
Material	Beryllium	Carbon-Carbon	Graphite	Molybdenum Graphite	Copper-Diamond	Glidcop ®	Molybdenum	Tungsten Alloy (IT180)
ρ [g/cm ³]	1.84	1.65	1.9	2.50	5.4	8.90	10.22	18
Z	4	6	6	~6.5	~11.4	~29	42	~70.8
X _g [cm]	35	26	19	17	4.8	1.4	0.96	0.35
c _p [Jkg ⁻¹ K ⁻¹]	1925	780	760	750	420	391	251	150
$\bar{\alpha}$ [10 ⁻⁶ K ¹]	18.4	4.1	5.5	5.0	7.8	20.5	5.3	6.8
$\bar{\lambda}$ [Wm ⁻¹ K ⁻¹]	216	167	70	547	490	365	138	90.5
T _m [°C]	1273	3650	3650	2589	~1083	1083	2623	~1400
\bar{E} [GPa]	303	62.5	12	44	220	130	330	360
R _M [MPa]	370	87	30	80	70	365	660	660
ΔT_q [K]	0.36	1.2	1.7	2.1	15.1	60.1	144	745
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

Experimental Testing and Validation

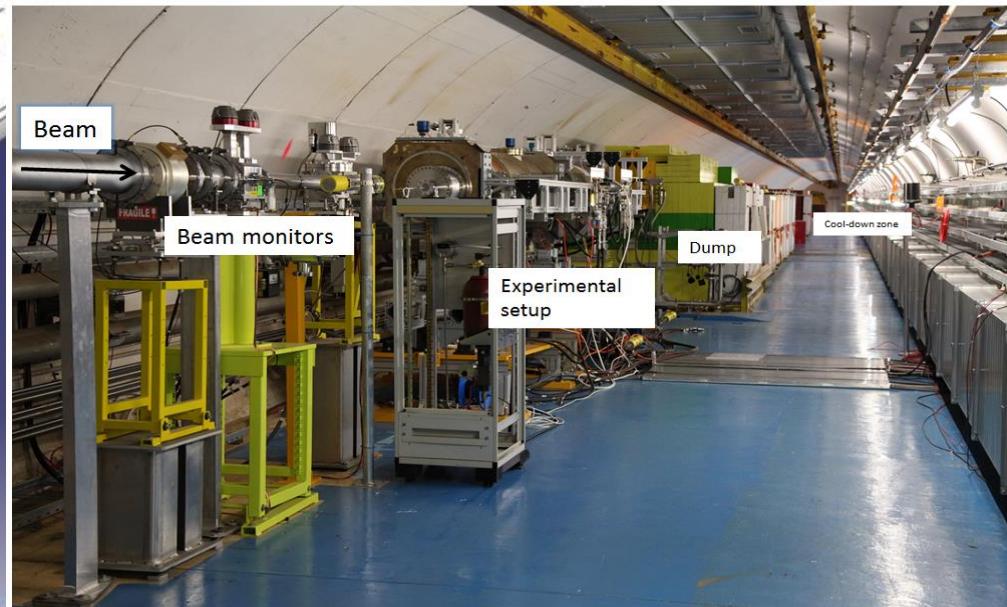
HiRadMat (High Radiation to Materials) Facility

- Dedicated facility for studying the impact of intense pulsed beams on materials
 - Material damage
 - Material vaporization
 - Thermal management
 - Radiation damage to materials
 - Beam-induced pressure waves
 - 9 experiments in 2012

A. Fabich, I. Efthymiopoulos (CERN)

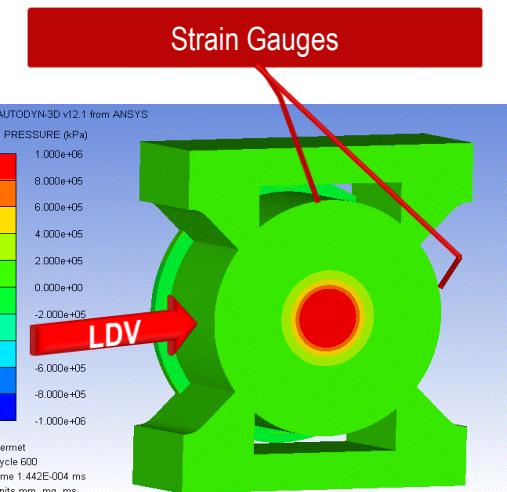


A. Bertarelli – Joint International Accelerator School – Newport Beach – November 2014



- Medium Intensity Tests

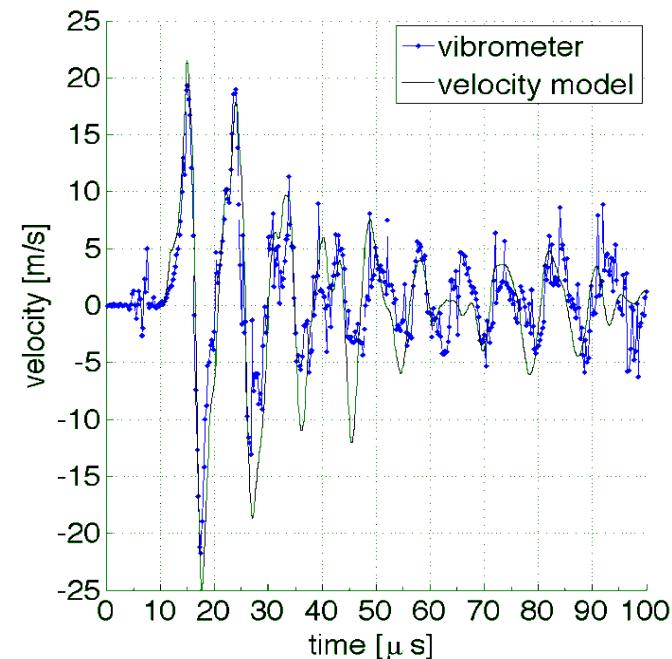
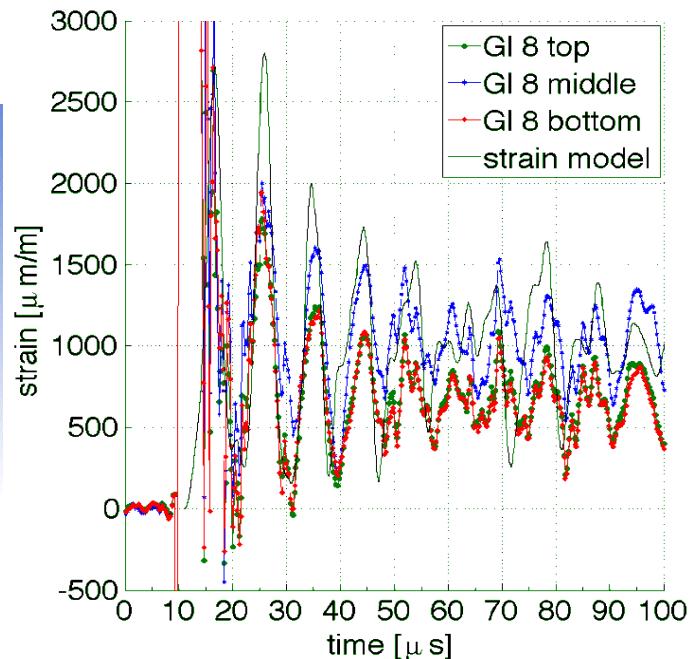
- Extensive hydrocode numerical analysis (Autodyn).
- Comparison of simulated **circumferential strains** and **radial velocity** with measured values on sample outer surface.



Inermet180
24 b (scraped)

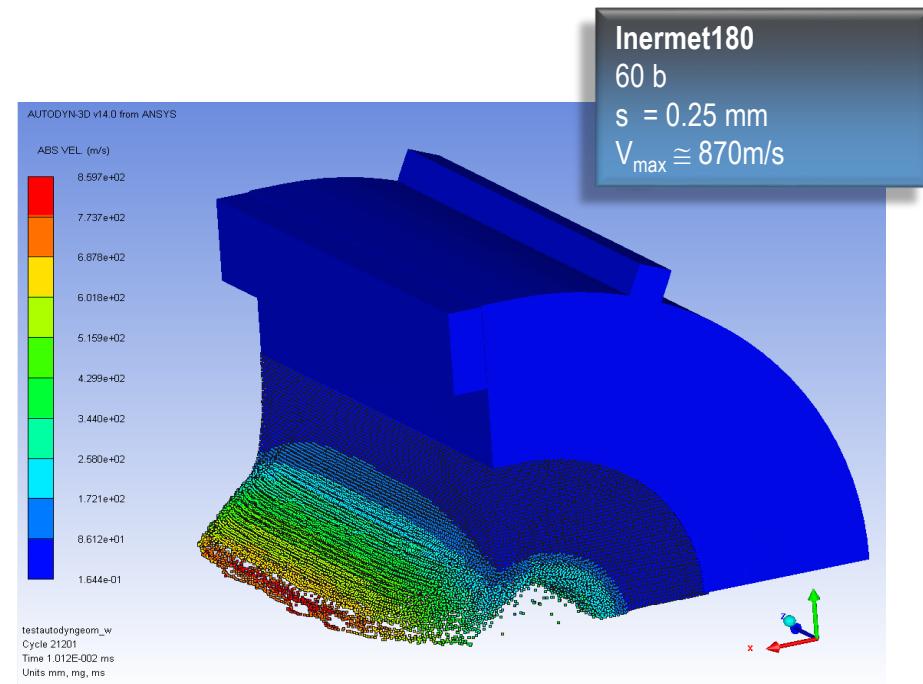
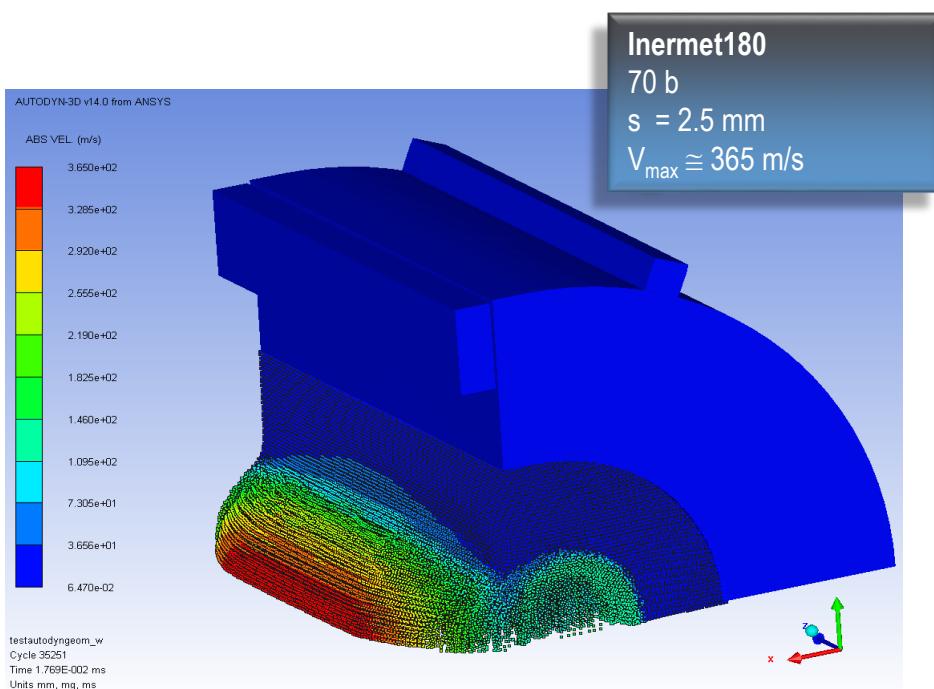
Total intensity: 2.7×10^{12}

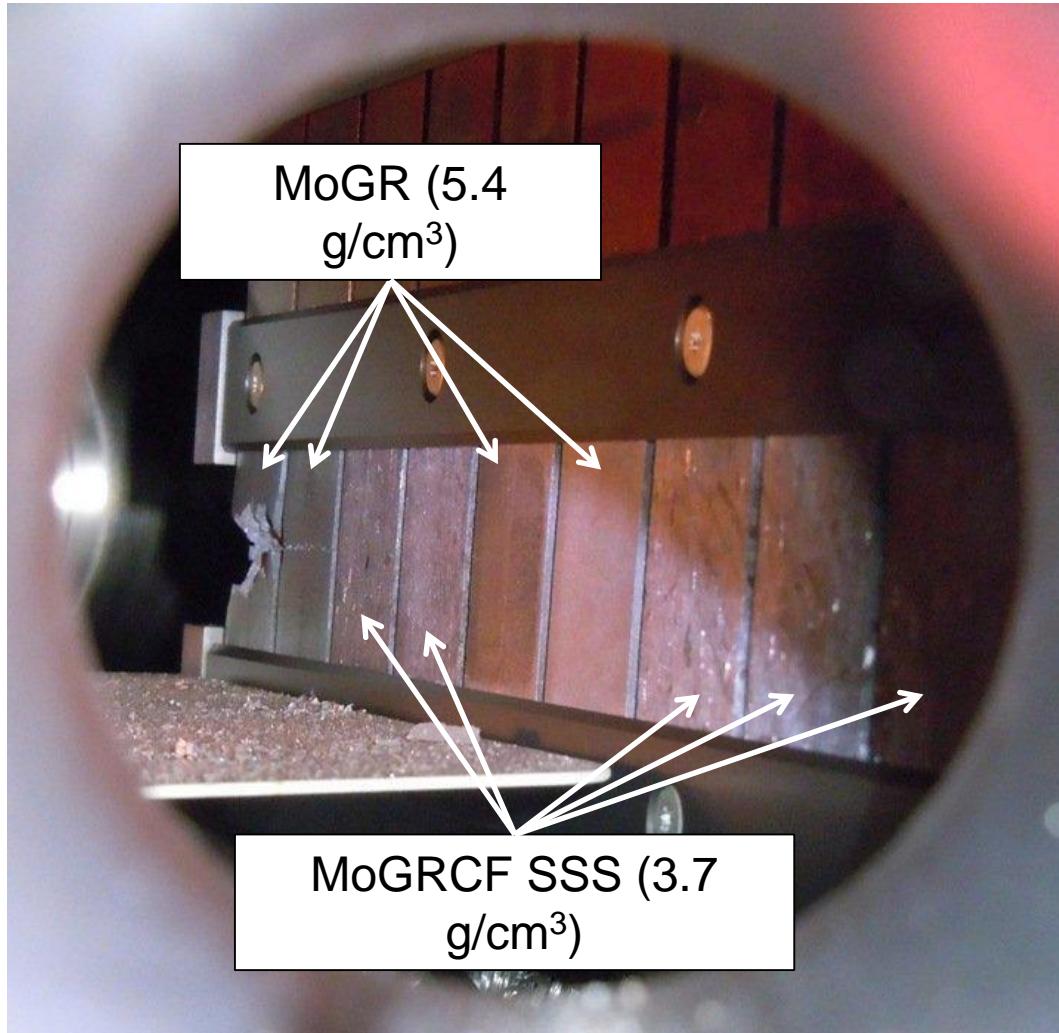
$$p \\ \sigma \approx 1.4 \text{ mm}$$



- High Intensity Tests

- Smooth-Particle-Hydrodynamics (SPH) calculations allowed determining damage extension, particle fragment velocity and trajectories.
- Assessment of potential damages to tank, windows and viewports.
- Material density changes.





MoGR H1_CENTER:

144 bunches at 450 GeV,

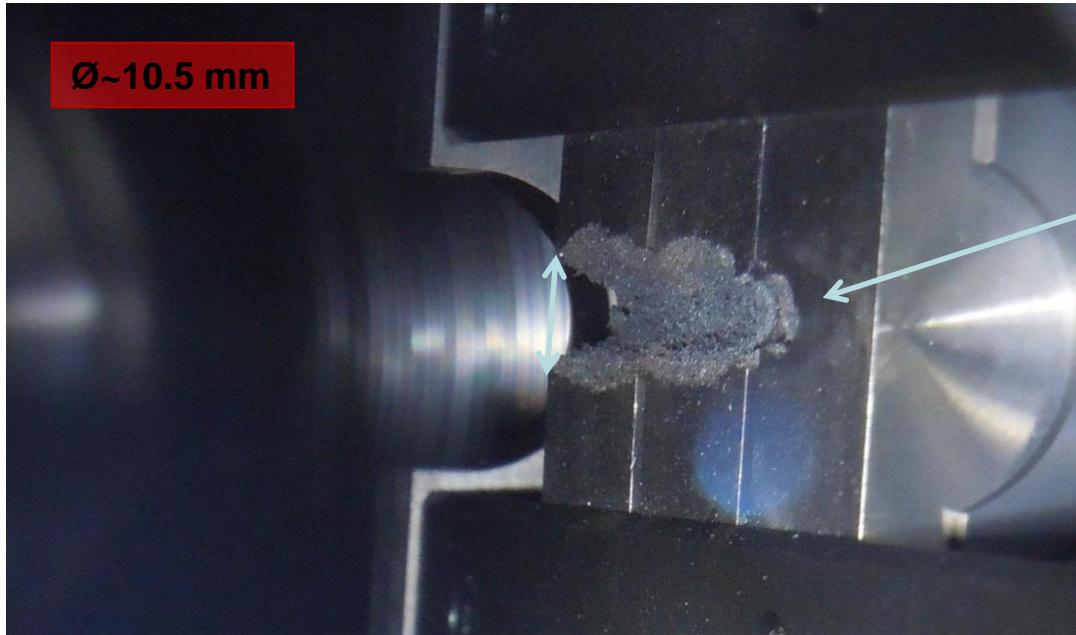
(1.95E13 protons),

impact at 2 mm from the free surface.

Results:

- Damage on denser MoGr (last samples),
- No damage on MoGRCF samples,
- No color variation!
- **LPS MoGR (2.5 g/cm³) expected better!**

W95-NiCu: Post-irradiation

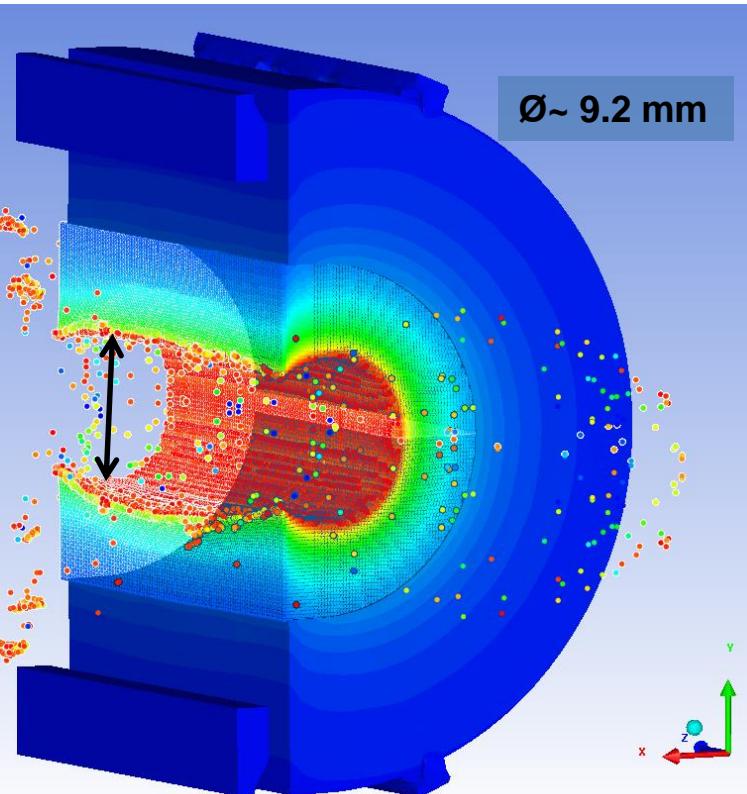
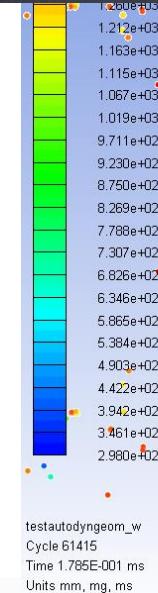
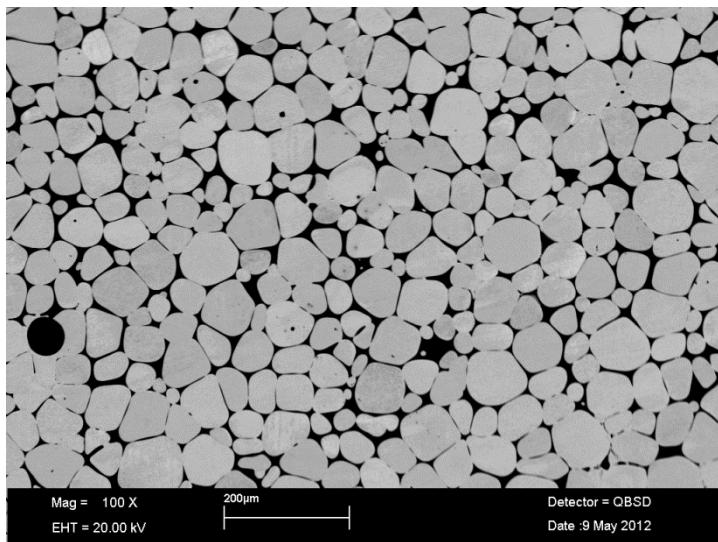


Inermet180 H6_CENTER:

72b, 1.9 mm σ,

9.05E12 Total Intensity

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



- 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

