Innovative MMC and CMC with very high thermal shock resistance

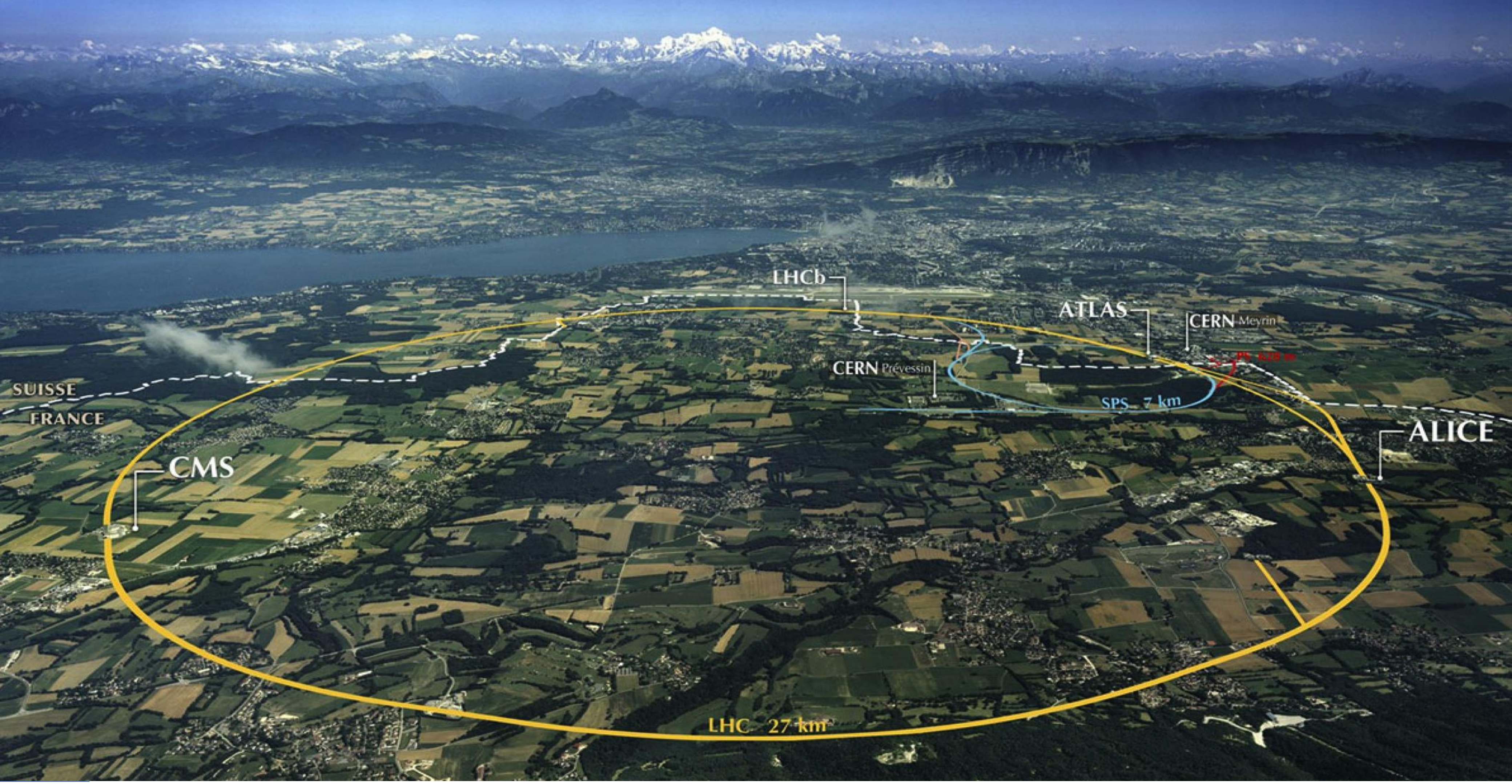
Alessandro Bertarelli, CERN (EN/MME)

with contributions from F. Carra, M. Garlasche, P. Gradassi, A. Lafuente, J. Guardia

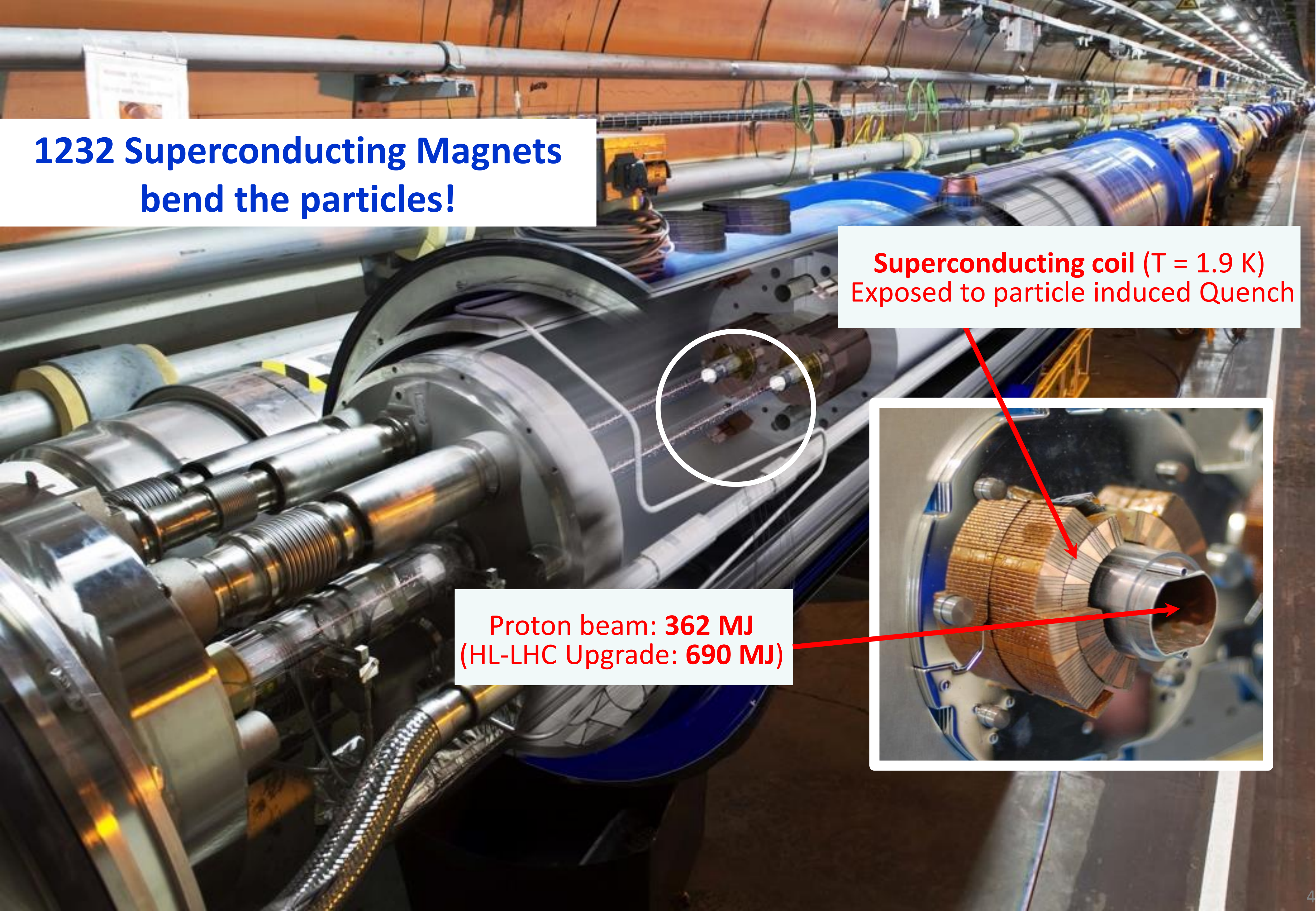
EuCARD-2 Workshop on Applications of Thermal Management Materials

CERN, Geneva – 6 November, *2015*

- Introduction and Motivations
  - High Energy Particle Accelerator Challenges
  - LHC Collimation System and Requirements
- Advanced Materials (MMC and CMC)
- Material and Component Testing
- Perspectives
- Summary

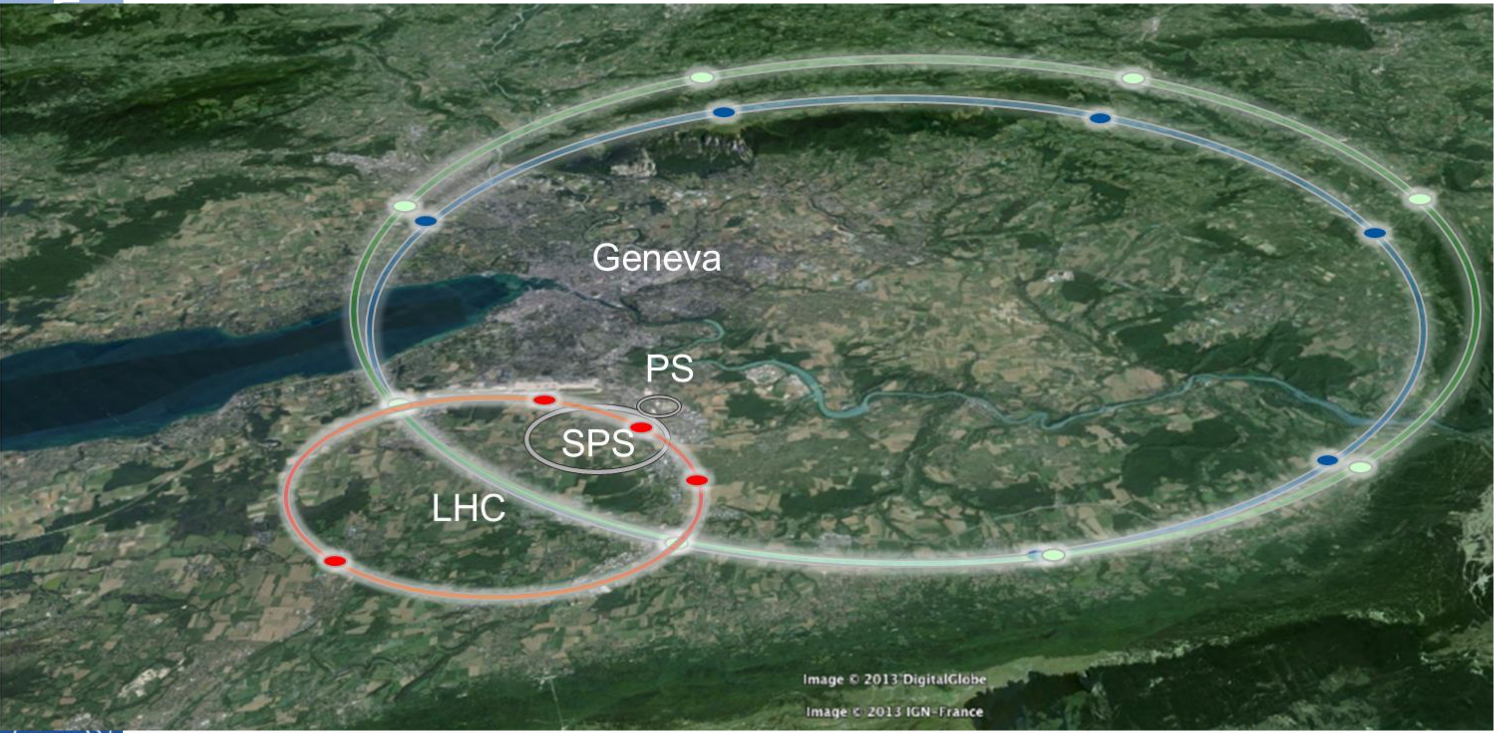


- CERN flagship. **World's largest scientific experiment**
- **27 km** underground tunnel
- **2** counter-rotating **7 TeV proton beams** (**bunched**) in **Ultra-High Vacuum** at **1.9 K**
- **8 Sections** (Arcs and Straight Sections)
- **1 Radio Frequency System** (Acceleration)
- **1 Beam Dump Point**
- **2 Collimation Regions** (Beam Cleaning and Machine Protection)


1232 Superconducting Magnets
bend the particles!
Superconducting coil (T = 1.9 K)
Exposed to particle induced Quench
Proton beam: 362 MJ
(HL-LHC Upgrade: 690 MJ)

High Energy Particle Accelerators Challenges

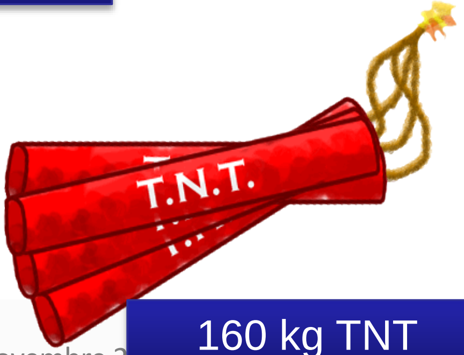
- Particle beams have reached **unprecedented energy** and **energy density.** This trend is set to continue for future accelerators (**690 MJ** for **HL-LHC,** **8500 MJ** for **future 100 km FCC-hh** proposal)
- **Beam-induced accidents**, **beam losses** and **beam stability** are among the **most relevant issues** for high power particle accelerators!
- **Beam Intercepting Devices** (such as **collimators**) are inherently exposed to such events!



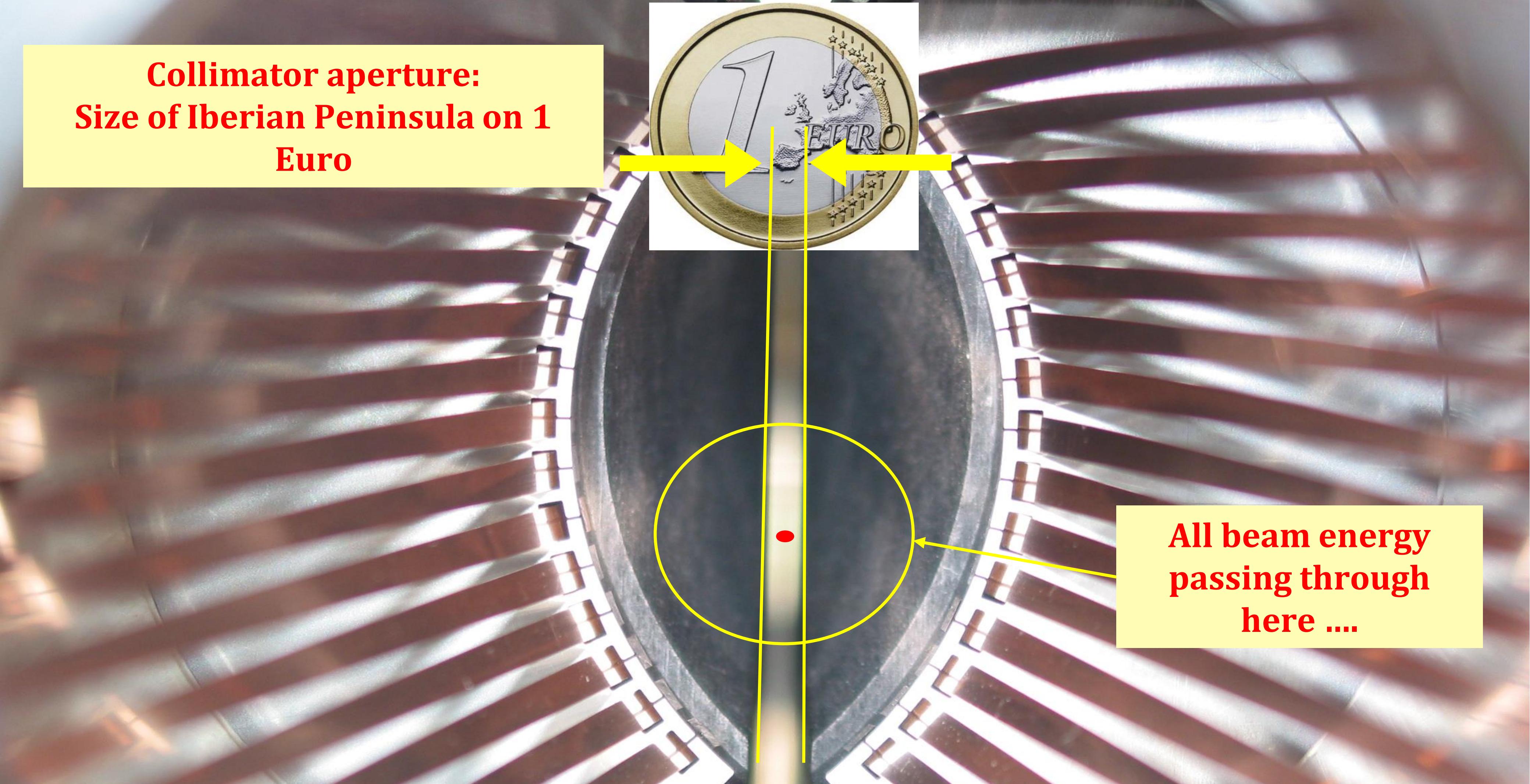
What is HL-LHC Energy equivalent to?

USS Harry S. Truman

TGV



160 kg TNT

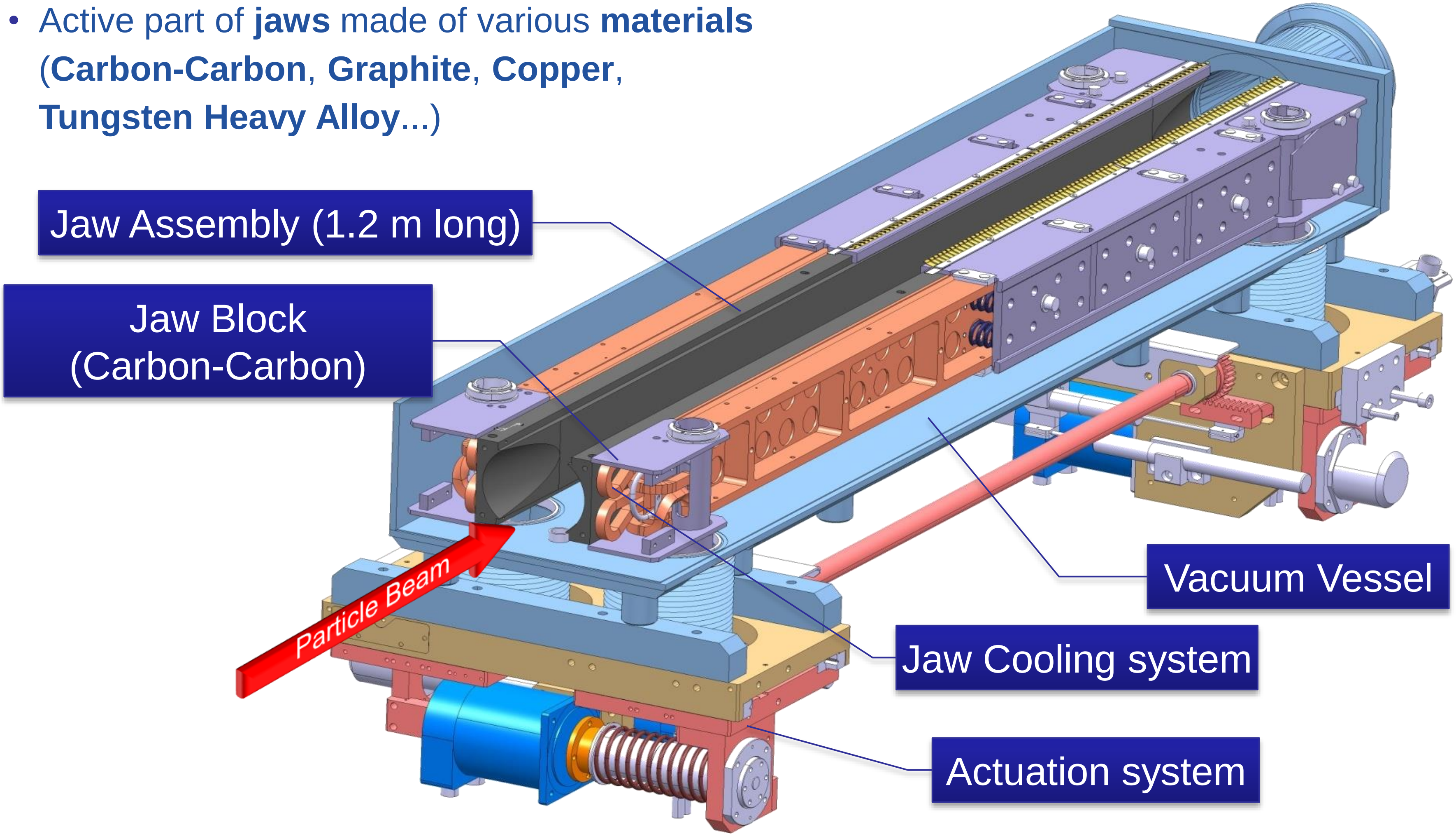


The collimation system must satisfy **2 main functions**:

- **Multi-stage Beam Cleaning**, i.e. removing stray particles which would induce quenches in SC magnets.
- **Machine Protection**, i.e. shielding the other machine components from the catastrophic consequences of beam orbit errors.

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** (**Carbon-Carbon**, **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!**

Bunched charged particles passing near a non-perfect conductor generate EM wake-fields, which perturb following bunches (as ship wakes in the sea …)

- Introduction and Motivations
- Advanced Materials (MMC and CMC)
  - Material Requirements for Beam Intercepting Devices
  - Copper – Diamond (CuCD)
  - Molybdenum Carbide – Graphite (MoGr)
- Material and Component Testing
- Perspectives
- Summary

Materials Requirements for BIDs (Collimators)

- Key properties must be optimized to meet requirements for Collimators (and BIDs) in High Energy Particle Accelerators …

- **Electrical Conductivity.** Maximize to limit Resistive-wall impedance
- **Thermal Conductivity.** Maximize to maintain geometrical stability … te losses
- **Coefficient of Thermal Expansion.** Minimize to increas… induced by accidental beam impact
- **Melting/Degradation Temperature.** Maxim… s reached in case of accidents
- **Specific Heat.** Maximize to i… (lowers temperature increase)
- **Ultimate Strength**… ck resistance
- **Density.** R… sition while maintaining adequate cleaning efficiency
- **Radi**… Minimize to improve component lifetime under long term particle…
- **Outgassi**… minimize to ensure compatibility with UHV environment.

Most requirements shared with applications requiring **highly efficient Thermal Management and Thermal Shock Resistance! Possibility of spin-offs …**

Novel Materials R&D Program

- **Rich materials R&D** and **testing** program on-going in **collaboration** with **international institutes** and **industries** (**EuCARD**, **EuCARD2, HiLumi, US-LARP**), with support from **CERN Knowledge Transfer** group
- **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 include **Silver-Diamond** (**AgCD**), **Copper-Diamond** (**CuCD**), **Molybdenum Carbide-Graphite** (**MoGr**), **Nickel-Graphite** (**NiGr** being developed mostly for ***open market applications*** with KT support)
- Production techniques include **Rapid Hot Pressing**, **Liquid Phase Sintering** and **Liquid Infiltration**
- Most promising for **Beam Intercepting Devices** are **CuCD** and **MoGr**

Copper-Diamond Composite

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

↑ No diamond degradation (in reducing atmosphere graphitisation starts at ~ 1300 °C)

↑ Very good thermal and electrical conductivity

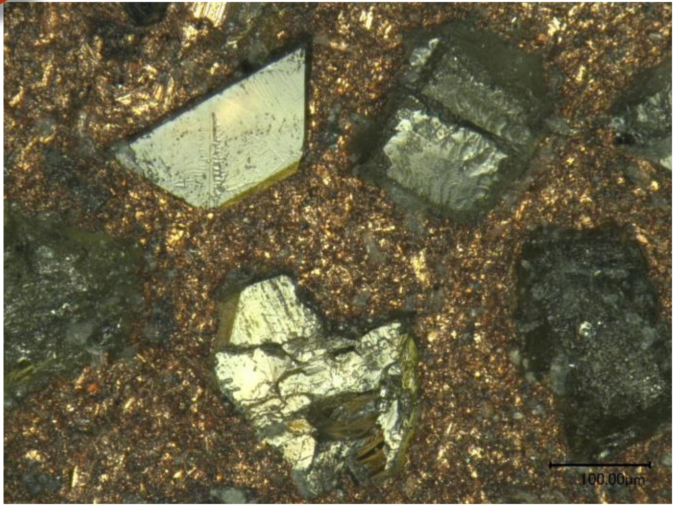
↑ Good radiation hardness

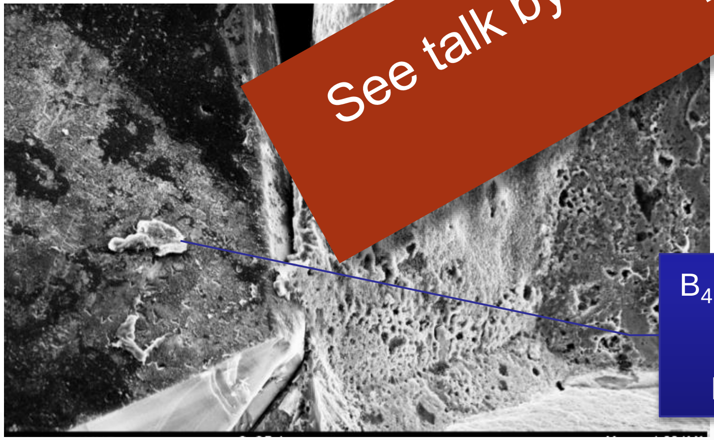
↔ No direct interface between Cu and CD (lack of affinity). Partial bonding bridging assured by Boron Carbides limits mechani… strength.

↓ Cu low melting point (1083 °C) may limit its a… devices exposed to highly energetic acci…

↓ CTE increases significantly wit… …nt

See talk by M. Kitzmantel in the afternoon for more details!





B$_4$C “bridge” stuck on CD surface.

No CD graphitization

Molybdenum Carbide - Graphite Composites

Advanced Materials (MMC and CMC)

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

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 M

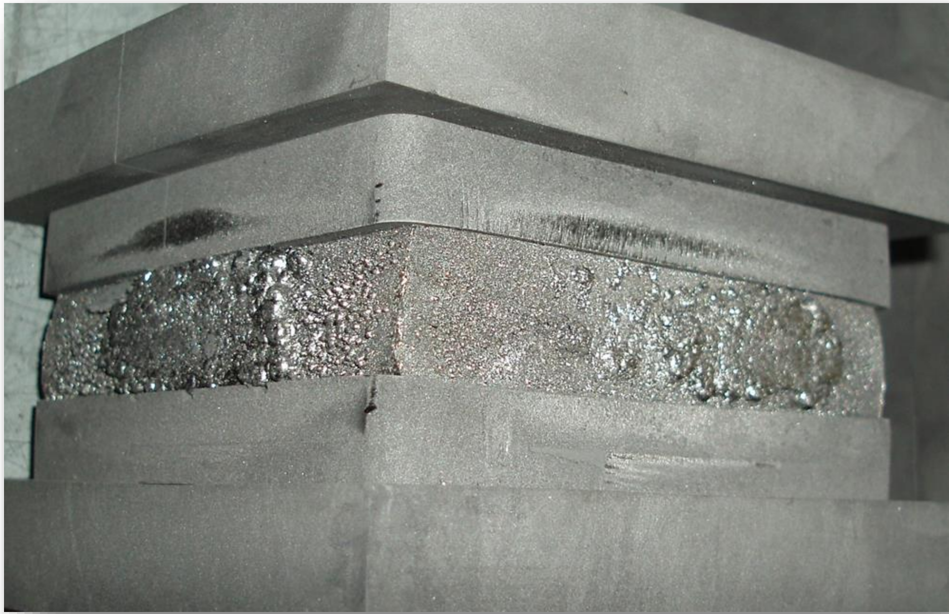
- I
- Co ... ctivity (highly orde

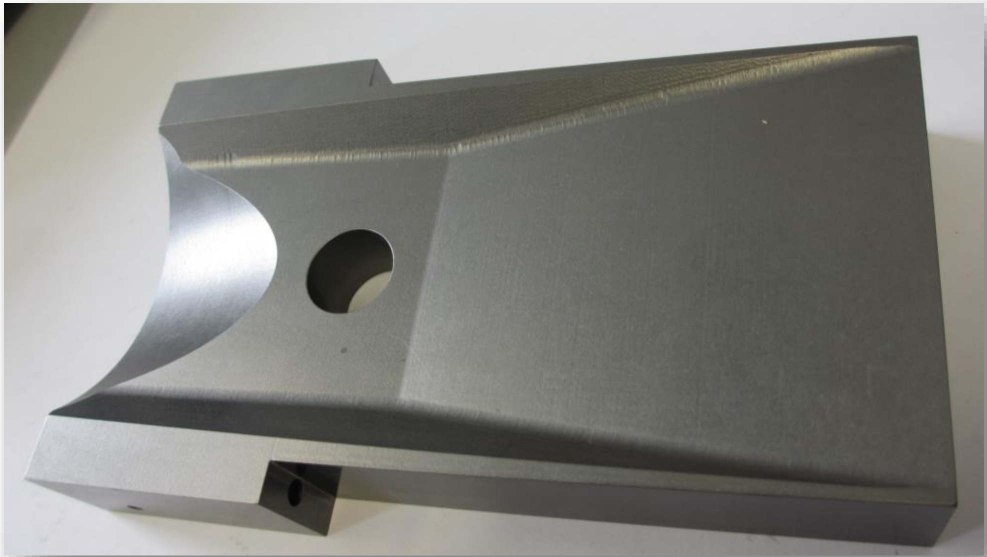
During sintering all Molybdenum reacts with Carbon creating Carbides (MoC_{1-x})

Ceramic Matrix Composite!

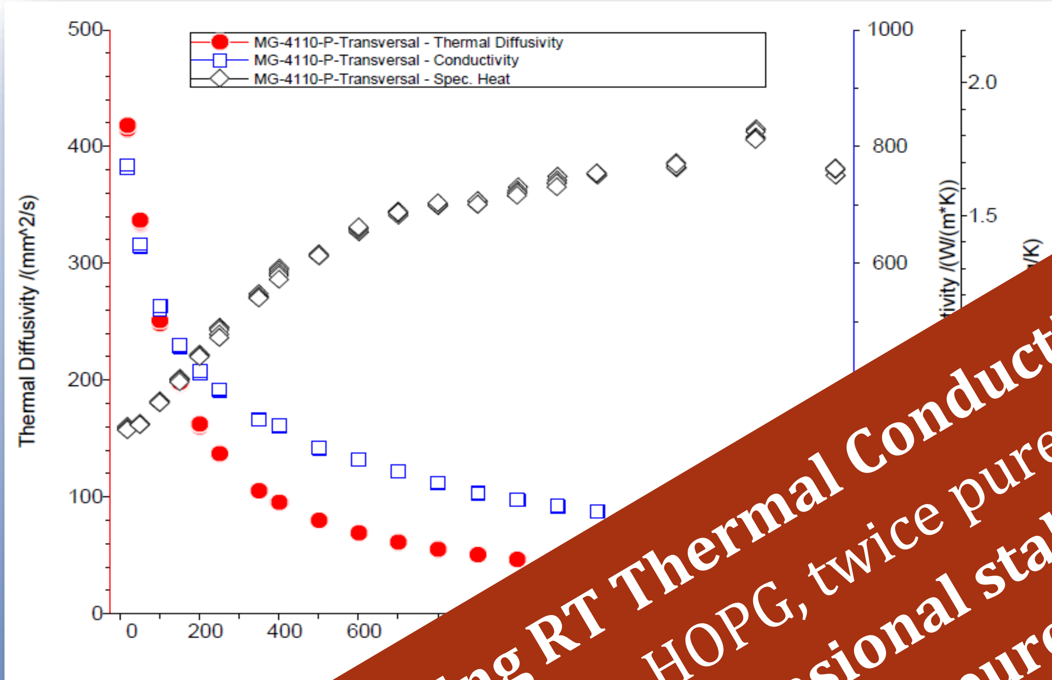
Molybdenum Carbide - Graphite Composites

- Co-developed by **CERN** and **BrevettiBizz** (Italy) and produced by **Pressure-assisted Liquid-phase Sintering (T>2600°C)**
- Excellent crystalline structure of carbonaceous phase with **highly-oriented Graphene planes.** Graphitization favored by the **catalyzing effect** of molten carbides!
- **Excellent thermo-physical properties (twice Cu conductivity)!**
- **Electrical conductivity: factor of 10 higher than graphite!**
- Radiation resistance to be optimized …
- Can be produced in **large components** and easily **machined**





Molybdenum Carbide - Graphite Composites



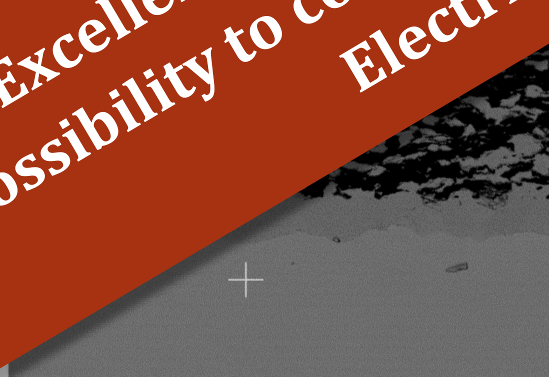
ρ [g/	2.45 – 3.5
$\alpha_{\perp}$ (RT	1 – 2.6
	11 – 15
	– 800
	80
	.1
	0.3
	48 – 64
	60 – 90

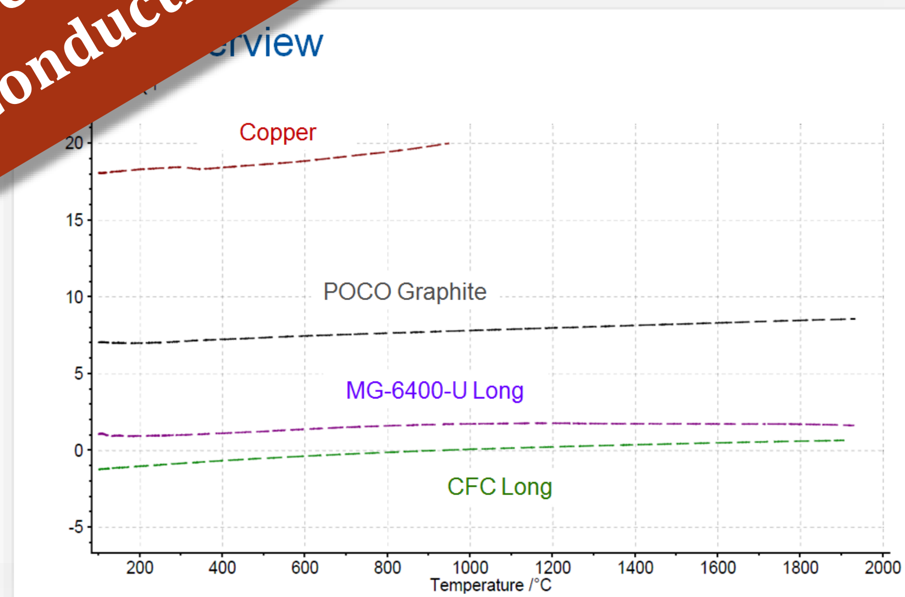
- **Outstanding RT Thermal Conductivity (comparable to HOPG, twice pure Cu)!!**
- **Excellent dimensional stability up to 2000°C**
- **Possibility to coat with pure Mo to further enhance Electrical Conductivity**

MoGr can b

Ca

Mo Co
18 MS

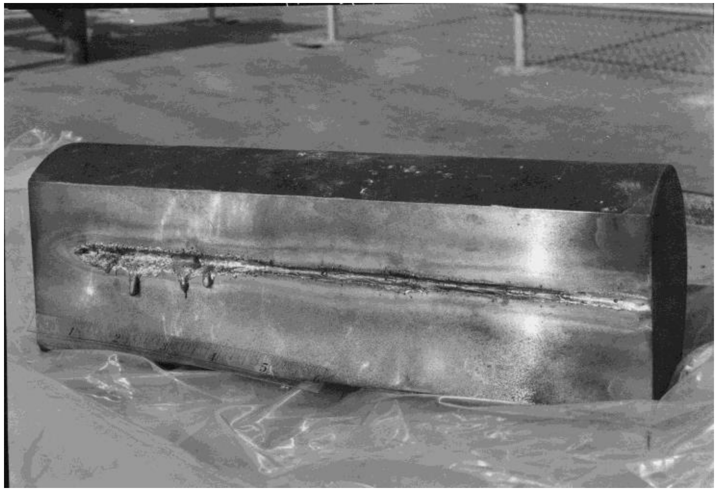




- Introduction and Motivations
- Advanced Materials (MMC and CMC)
- Material and Component Testing
  - Why Experimental Tests?
  - What Kind of Tests?
  - HiRadMat Experiments
- Perspectives
- Summary

Why testing materials and full components?

- Materials and components for Beam Intercepting Devices are exposed to **extreme conditions** (temperature, pressure, strain-rate, radiation), for which it is very hard to find literature data, even in case of standard materials
- **Advanced** and/or **novel materials** are required in high energy accelerators, for which characterization is incomplete or non-existing
- Full components must be tested to verify their response in case of accidental beam impacts, similar to those found in **high power explosions** and **ballistics**

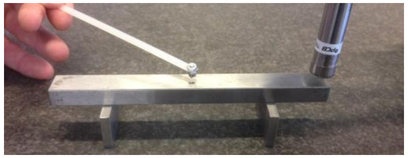
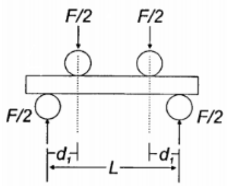


What kind of Tests?

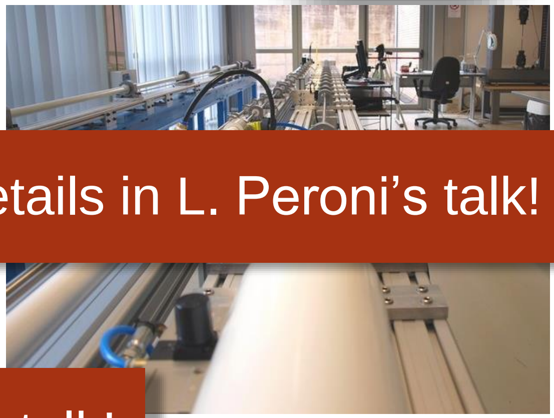
- **Thermo-physical characterization** up to ~2000°C



- **Mechanical characterization** and **static testing** for less known materials

- **High strain-rate mechanical testing** (up to 10^6 s^{-1}) including temperature effects

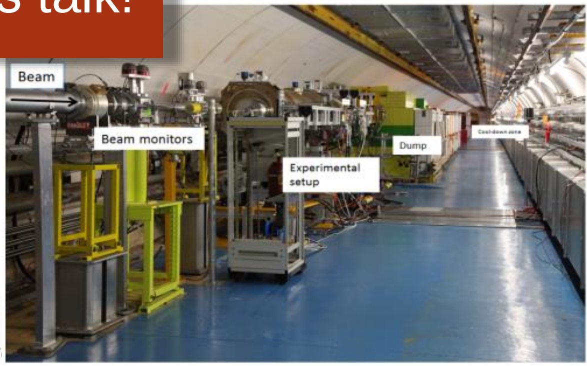


More details in L. Peroni's talk!

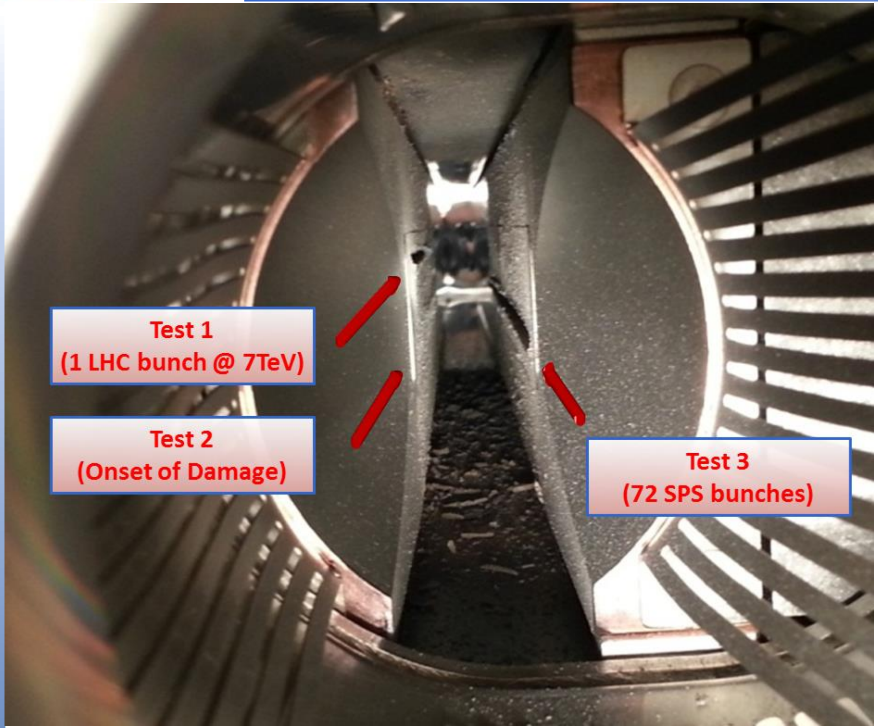
- **Irradiation tests** in **ad-hoc facilities** to ascertain effects of **long-term radiation**

More details in M. Tomut's talk!

- Material and component tests under **direct beam tests** in dedicated facilities (**HiRadMat**)

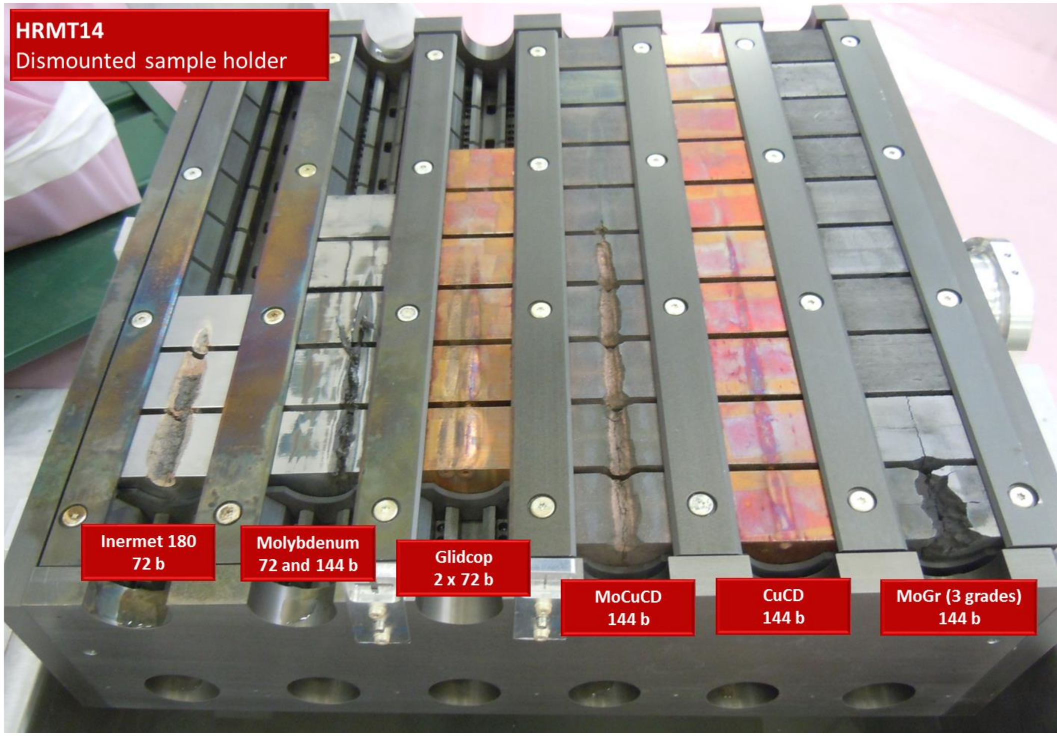


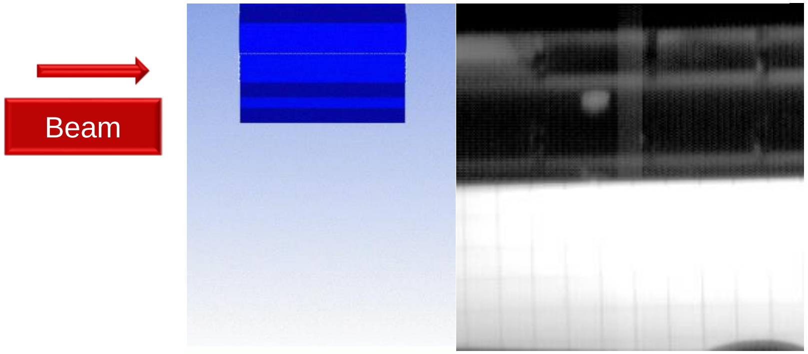
Overview of Collimation Impact Tests



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

Allowed deriving damage limits for Tertiary Collimator jaw



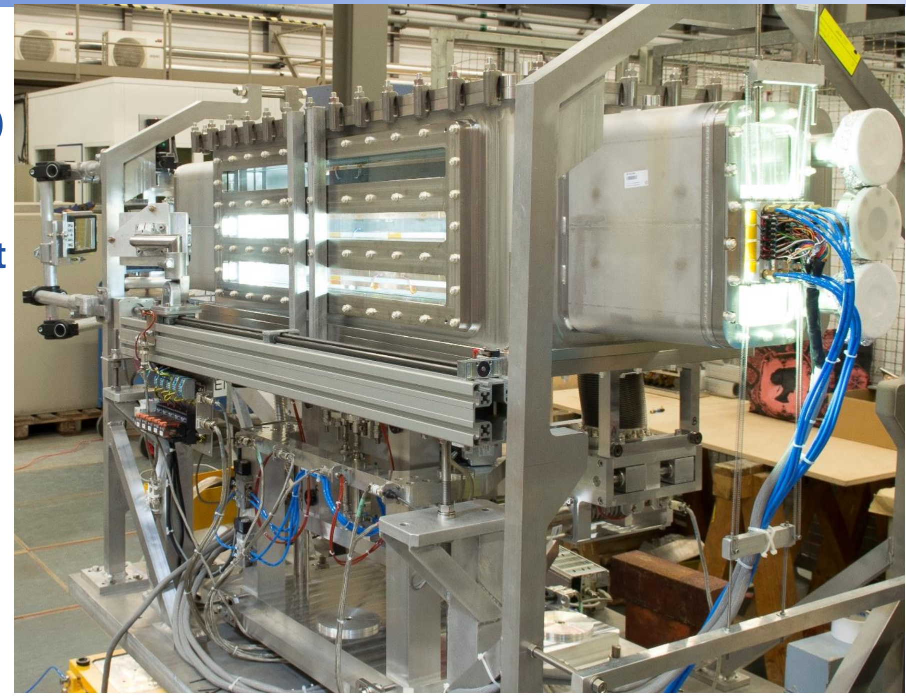


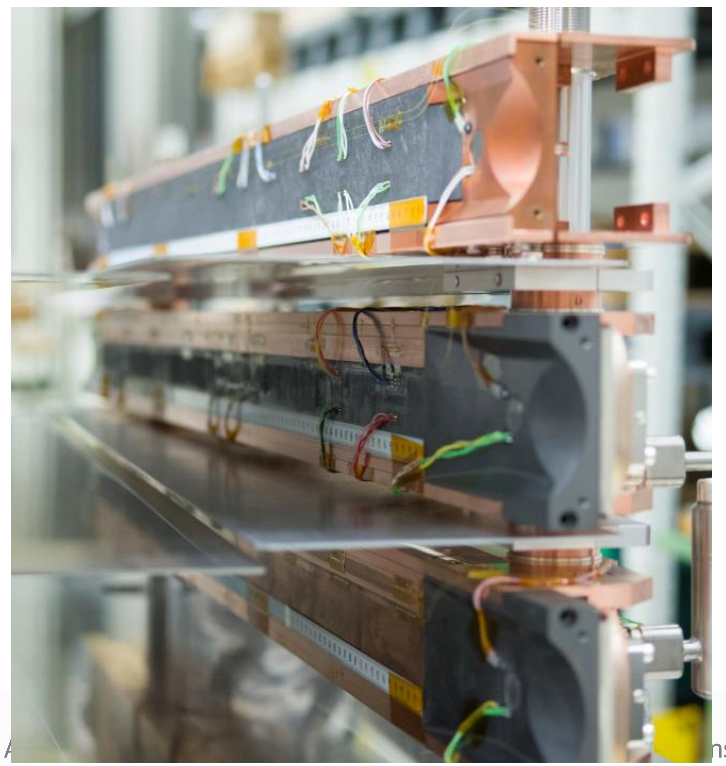
2012 HRMT-14: test of specimens from 6 different materials, including novel composites

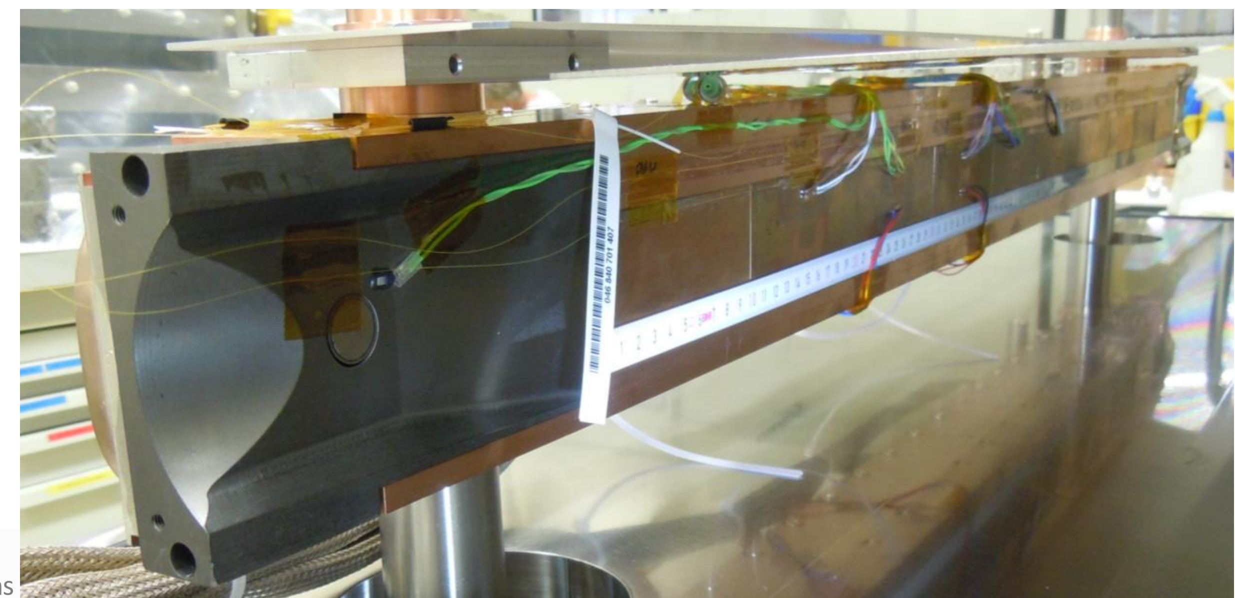
Materials characterization, constitutive models and simulation benchmarking

HiRadMat-23 Experiment

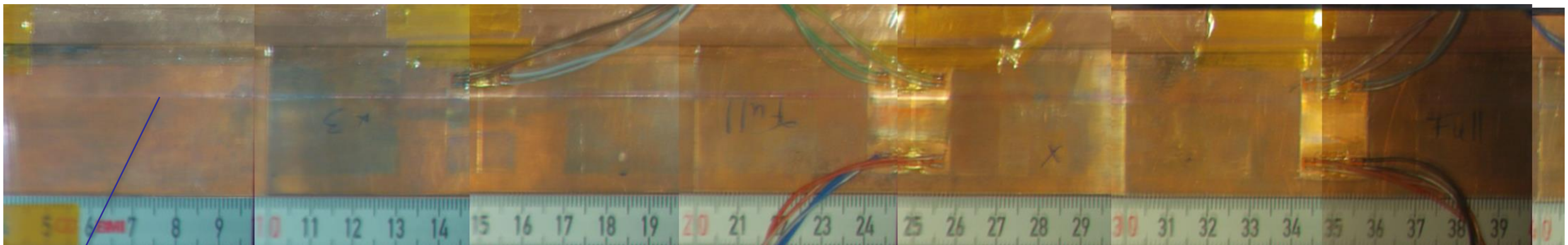
- **HRMT23 experiment** performed in summer 2015 to simultaneously test **3 complete jaws** (in **C/C**, **MoGr**, **CuCD**) of **2 different designs** (LHC and HL-LHC)
- Main goal was to **qualify jaws** under **highest and brightest 450 GeV beam available** (i.e. **288 b** x **~1.3e11 p/b**)
- System equipped with **comprehensive** set of **online sensors**, viewports for **optical acquisition** and fast dismounting system for **post-irradiation investigations**



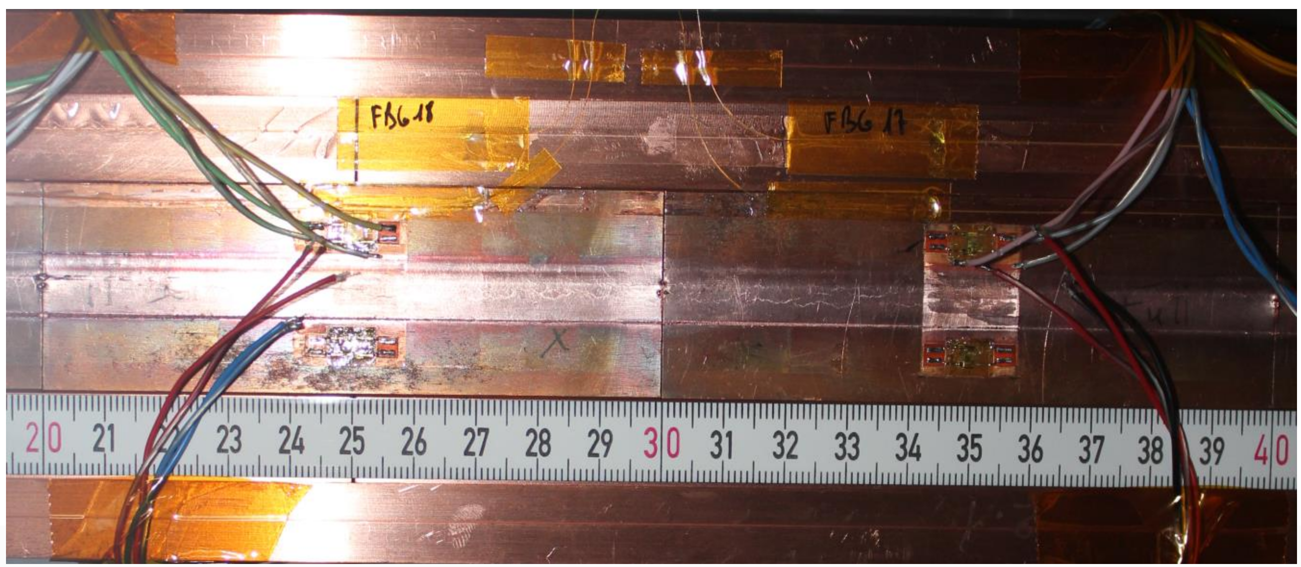




- **CuCD** on HL-LHC jaw survived (with a limited surface scratch on the Cu coating) the impact of **24 b**, **σ 0.35 mm** at 440 GeV, with peak energy density roughly **equivalent to 1 LHC bunch** at 7 TeV
- At **48 b** (~2 LHC 7 TeV bunches) the scratch is more severe, but the jaw appears globally undeformed
- This would qualify CuCD as an alternative material for TCT jaws (presently in Tungsten alloy). Local damage induced by Asynchronous Beam Dump could be compensated by jaw shift with 5th axis.



CuCD jaw after 24 b, σ 0.35 mm. Note thin, long groove



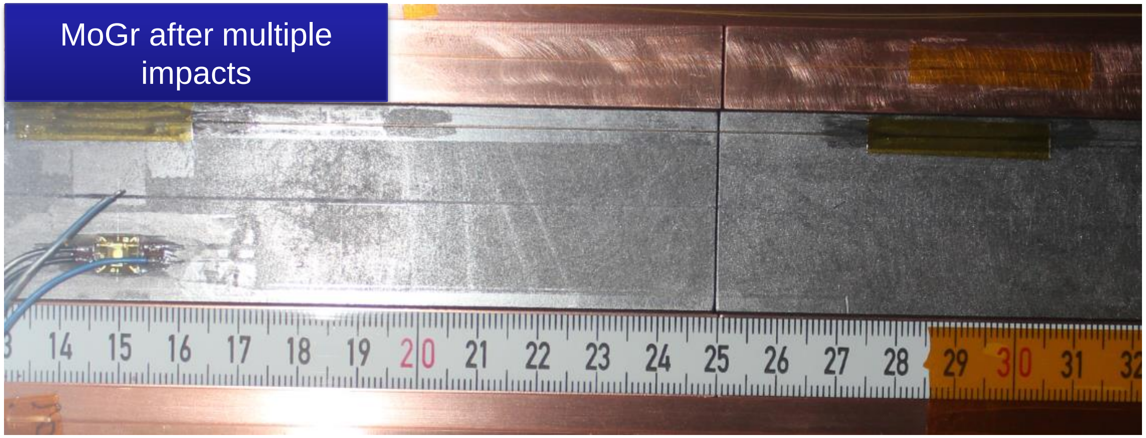
HRMT-23 Results – CuCD

- Impacts on CuCD jaw.
- 48 b. σ 0.35 mm. Impact depth 0.5 σ

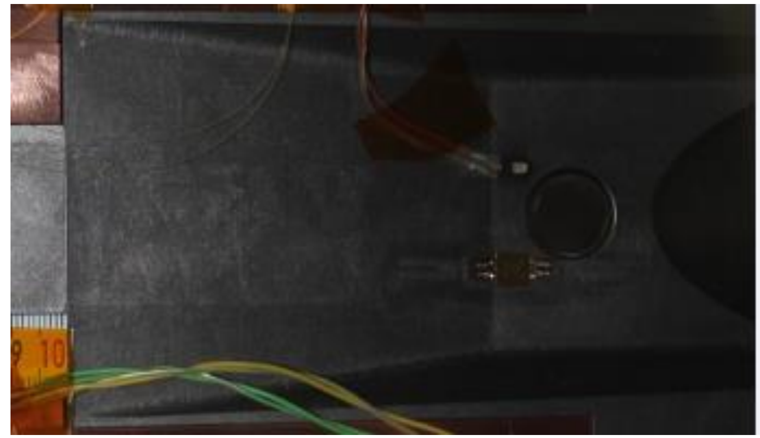
HRMT-23 Results – MoGr and CFC

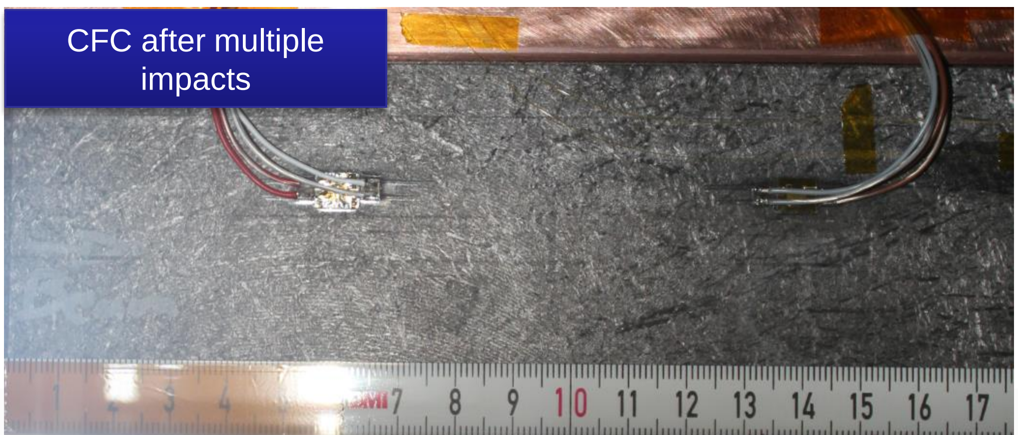
HRTM-23 Experiment (Jaws)

- **MoGr** on HL-LHC jaw survived the impact, without only surface scratches, of several **288 b pulses** with σ down to 0.35 mm (**peak energy density slightly higher than HL-LHC and BCMS LIU injection error)**
- **CFC** on LHC jaw **survived the same impacts** with similar behaviour
- **Glidcop terminal** was damaged by impacts, while MoGr terminal showed no visible effects

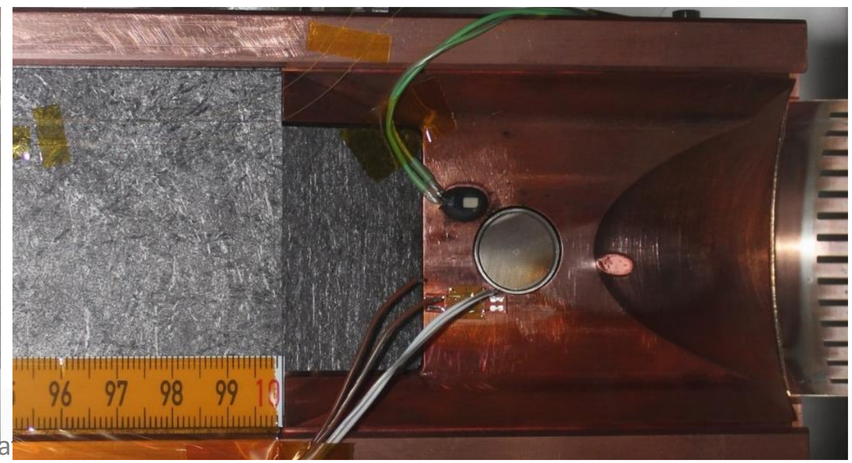


MoGr after multiple impacts





CFC after multiple impacts



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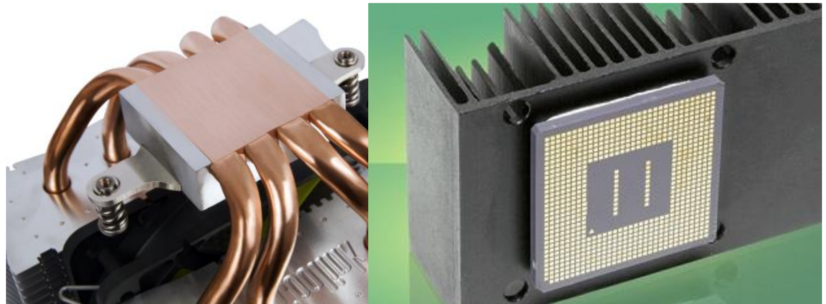
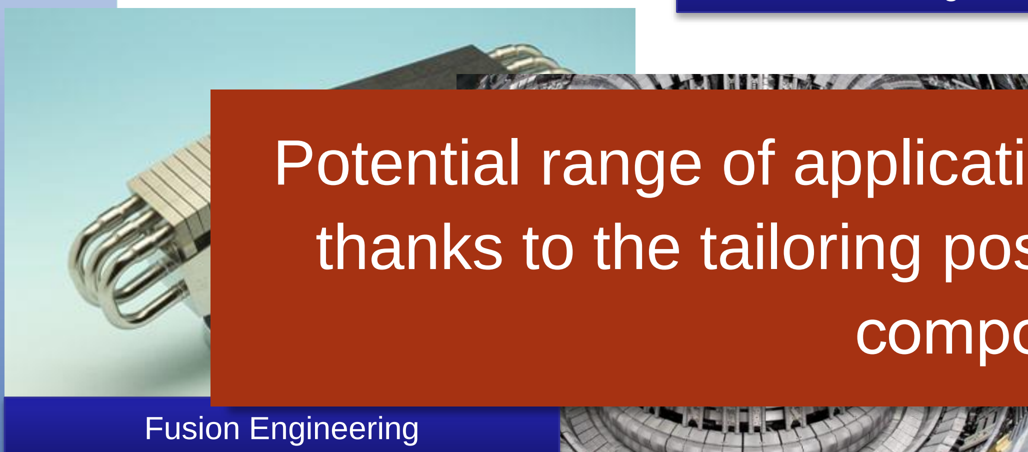
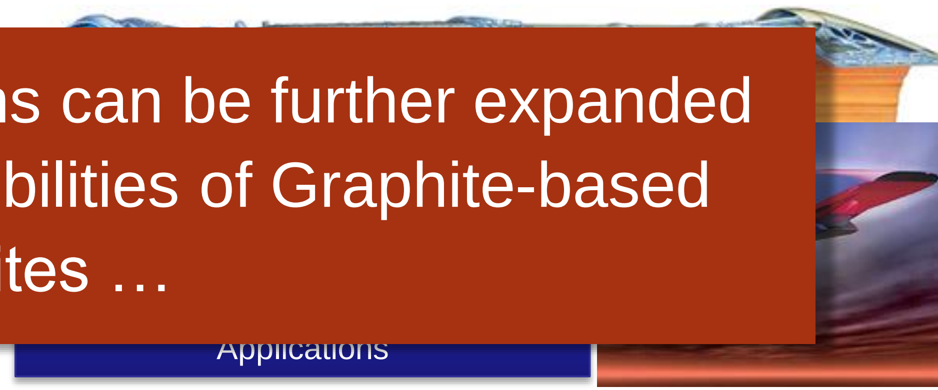
MoGr (and CuCD) Possible Applications …



Thermal Management for High Power Electronics

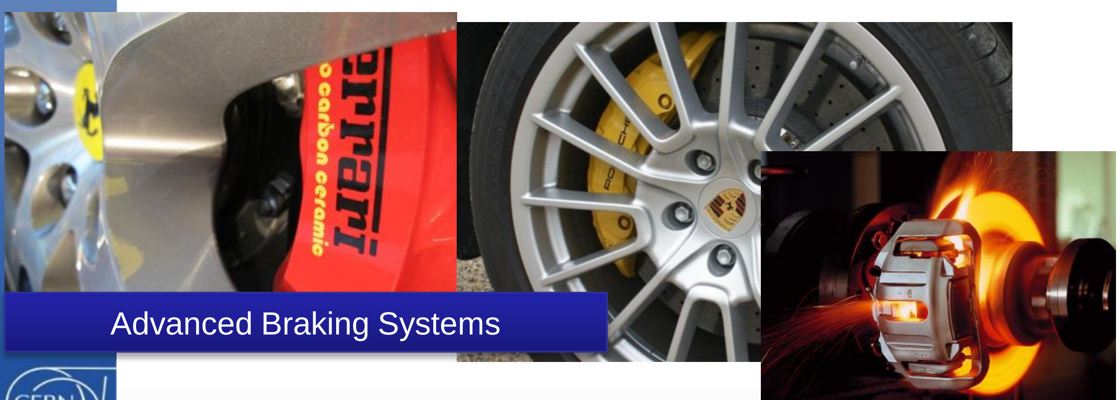


Fusion Engineering



Applications

Potential range of applications can be further expanded thanks to the tailoring possibilities of Graphite-based composites …



Advanced Braking Systems

Solar Energy Applications

Summary

- **Handling** the **extreme energies** stored in **HL-LHC** poses **serious threats** to accelerator components, particularly collimators and BIDs
- No existing material can simultaneously meet all collimator requirements (robustness, stability, low impedance): a **new generation of collimators** is required embarking **advanced materials**, along with advanced design concepts
- A rich **R&D and testing program** is focusing on their development in the frame of EU and international collaborations and industrial partnership, with the potential for spin-offs outside HEP.
- A new generation of **metal- and ceramic- matrix composites** with **diamond** or **carbon** reinforcements is showing promising results, in particular **Copper-Diamond** (for lower temperature applications) and **Molybdenum Carbide – Graphite** (RT Thermal Conductivity 700+ $Wm^{-1}K^{-1}$, CTE ~$1\div2x10^{-6}$ K^{-1})..
- **Material characterization** and **design qualification** call for a **wide spectrum of tests,** including thermo-physical characterization, static and dynamic testing, irradiation campaigns and experiments under direct beam impacts
- In a dedicated experiment in HiRadMat **CFC** and **MoGr survived** multiple impacts roughly equivalent to **worst accident scenarios** for **HL-LHC upgrade,** while **CuCD survived** (with surface scratch) accident **roughly equivalent to 1 full LHC bunch** (sufficient for **HL-LHC Tertiary Collimator**).
- 1 **HL-LHC Secondary Collimator prototype** with MoGr jaws **to be built and tested** in the LHC, early 2017.
- These materials are appealing for a broad range of **industrial applications** where **Thermal Management**, **Thermal Shocks** and **Refractoriness** are an issue …

Thank you for your attention!

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project EuCARD, Grant Agreement 227579 and EuCARD-2 Grant Agreement 312453

alessandro.bertarelli@cern.ch

Why Collimators?

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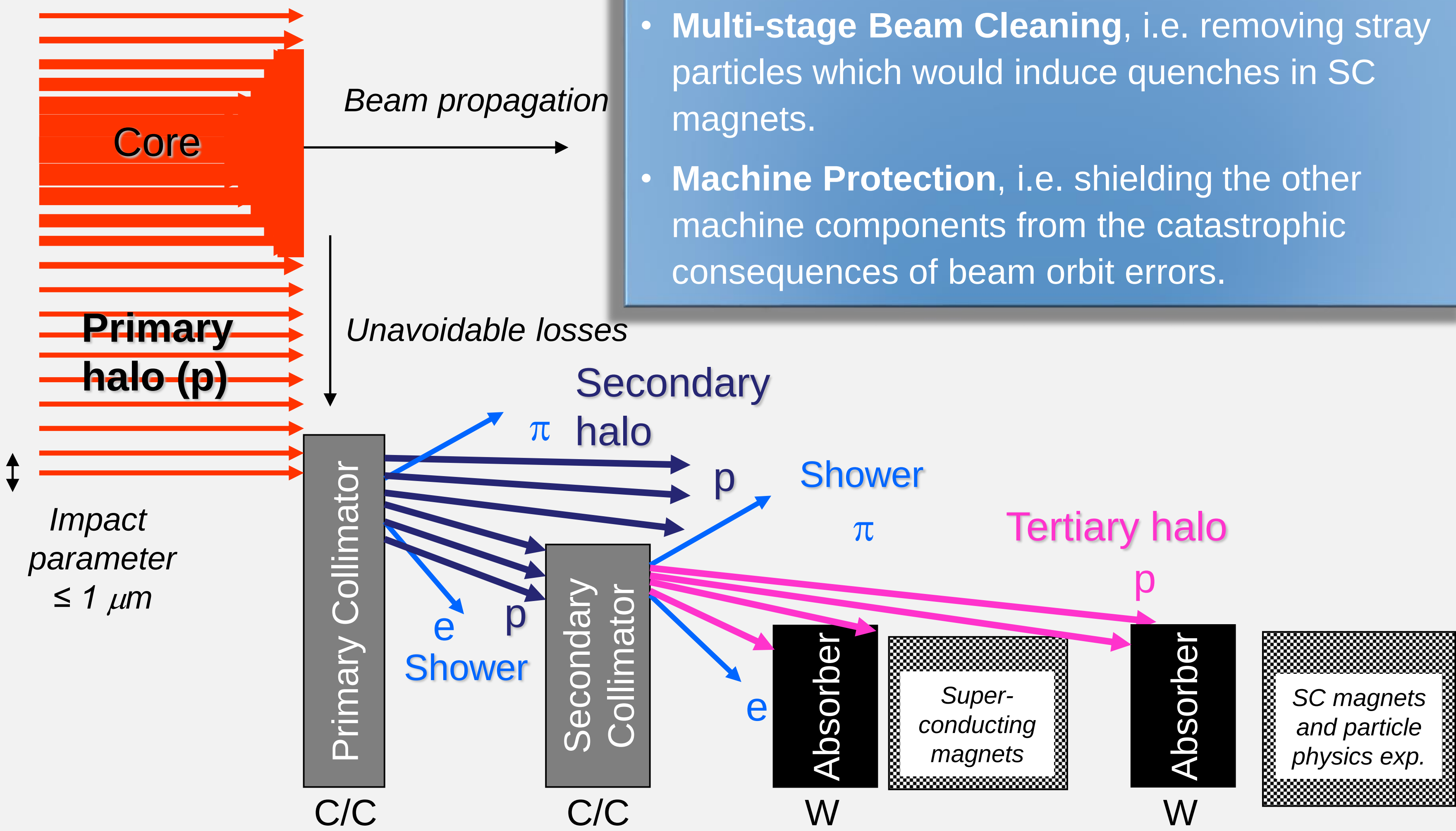
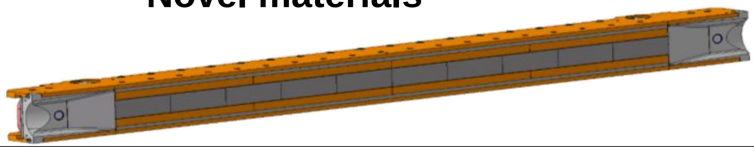
- **Multi-stage Beam Cleaning**, i.e. removing stray particles which would induce quenches in SC magnets.
- **Machine Protection**, i.e. shielding the other machine components from the catastrophic consequences of beam orbit errors.



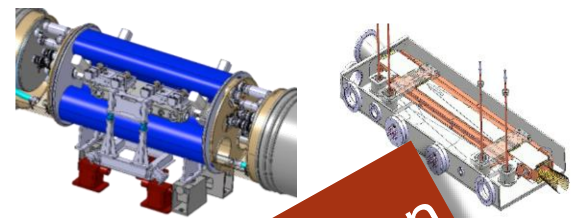
Collimation System for HL-LHC

Where are Collimators?

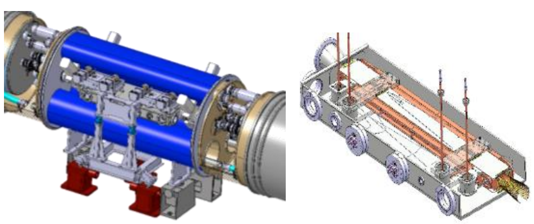
IR1 + IR5:
New **tertiary collimators** and physics debris **absorbers**
Completely **new layouts**
Novel materials

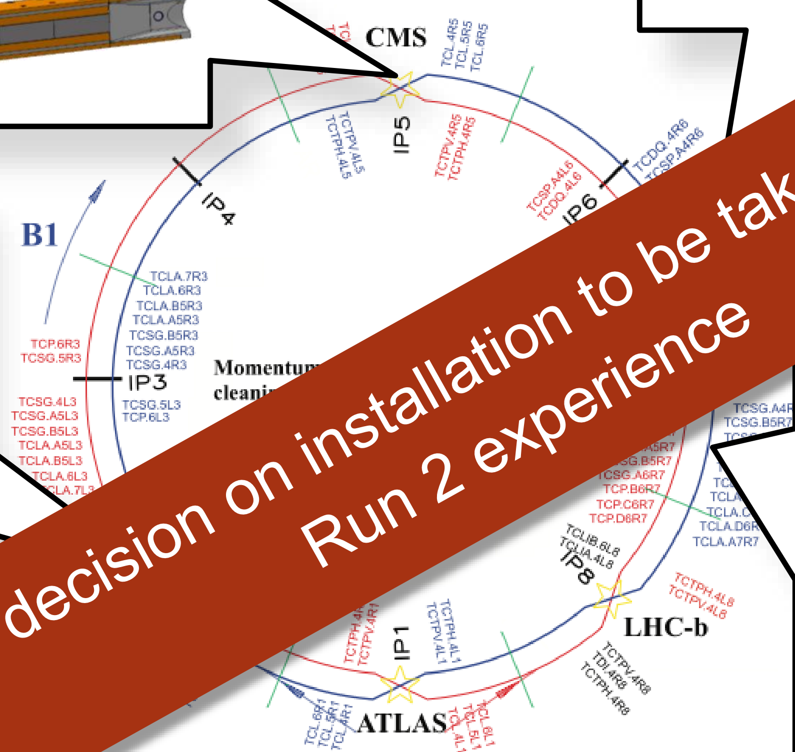


IR7 : **DS collimators** + **11T dipoles**

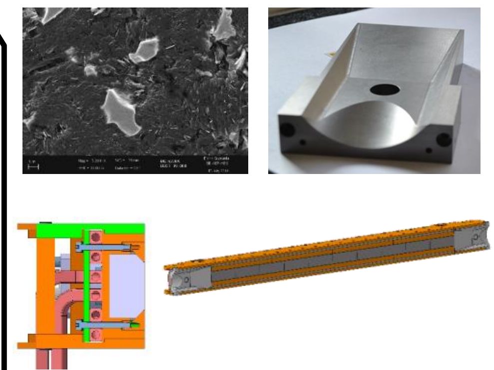


IR2 (Ion physics debris):
DS collimators + **11T dipoles**





IR7: **Low impedance collimators**
New design, novel **advanced materials**



Final decision on installation to be taken based on Run 2 experience

- Total of **118 collimators presently installed**
- ~10 different design!
- 108 Movable units
- Roughly 40 units to be replaced for HL-LHC