Engineering Department

EN

Research and Development of Novel Advanced Materials for Next-generation Collimators

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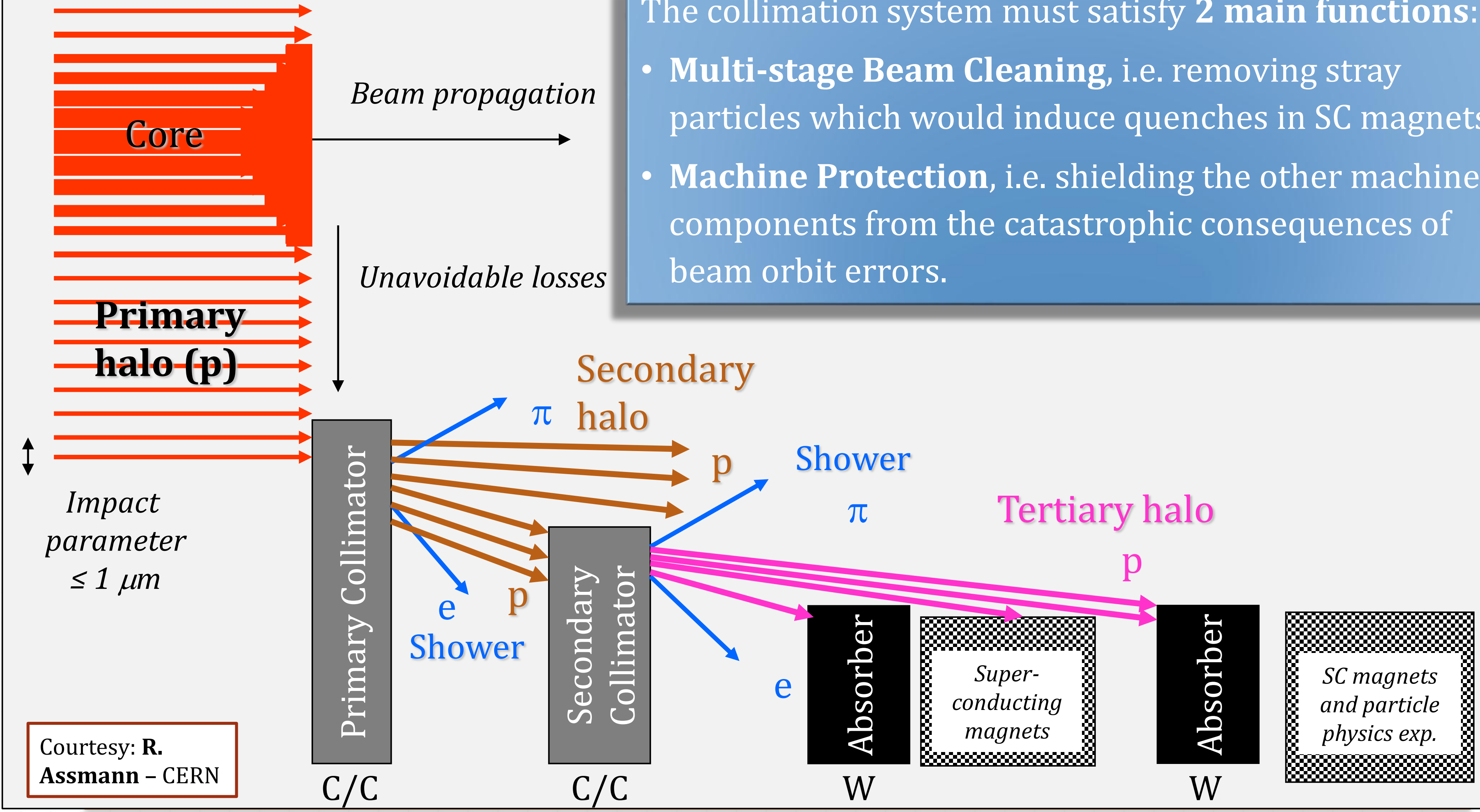
What is a (Phase I) LHC collimator

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.

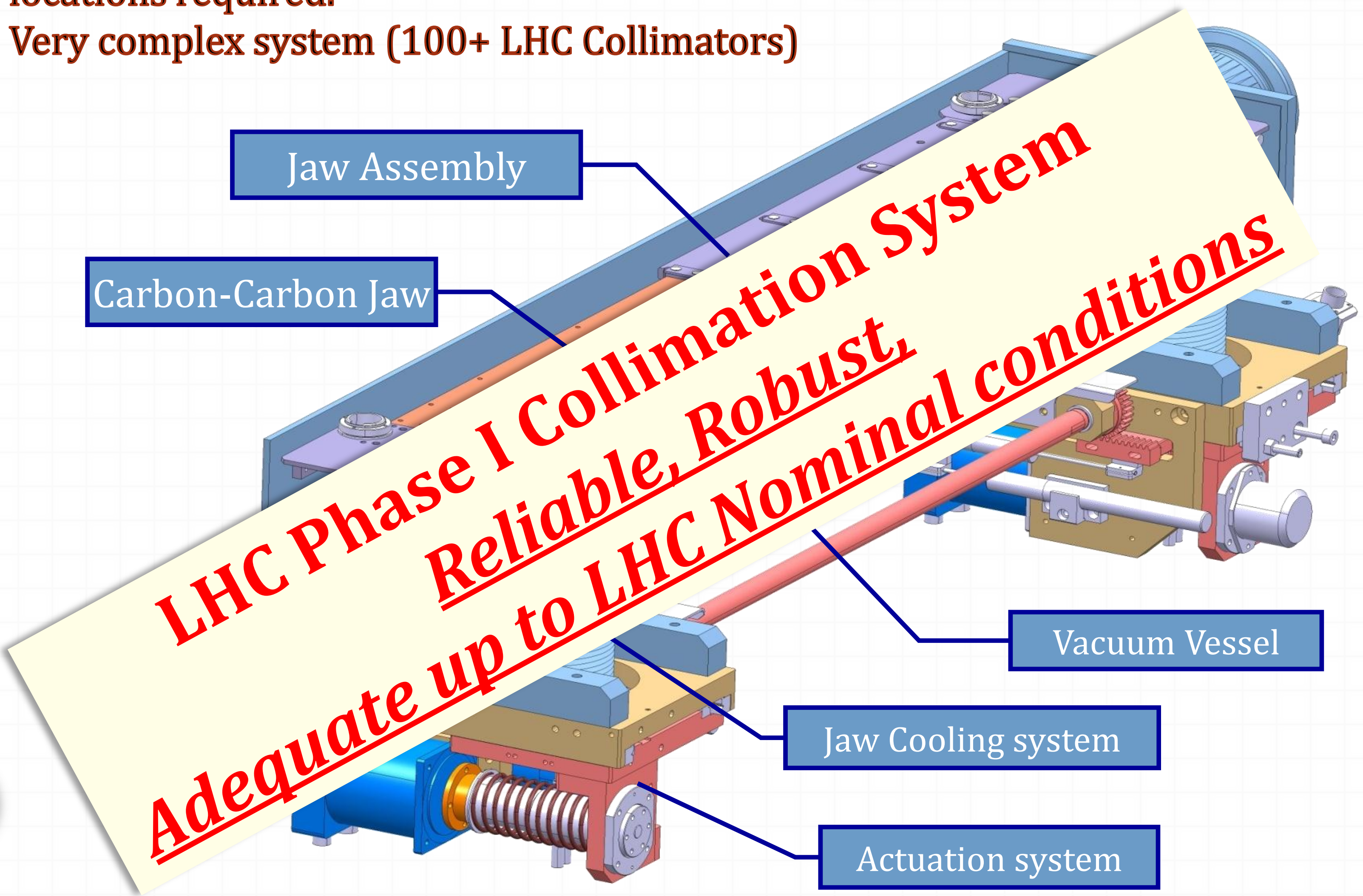


Courtesy: **R. Assmann** – CERN

What is a (Phase I) LHC Collimator

- Several types of collimators at multiple locations required.
- Very complex system (100+ LHC Collimators)

Secondary Collimator (TCSG) Cutaway



LHC Phase I Collimation System

<u>Reliable, Robust,</u>

<u>Adequate up to LHC Nominal conditions</u>

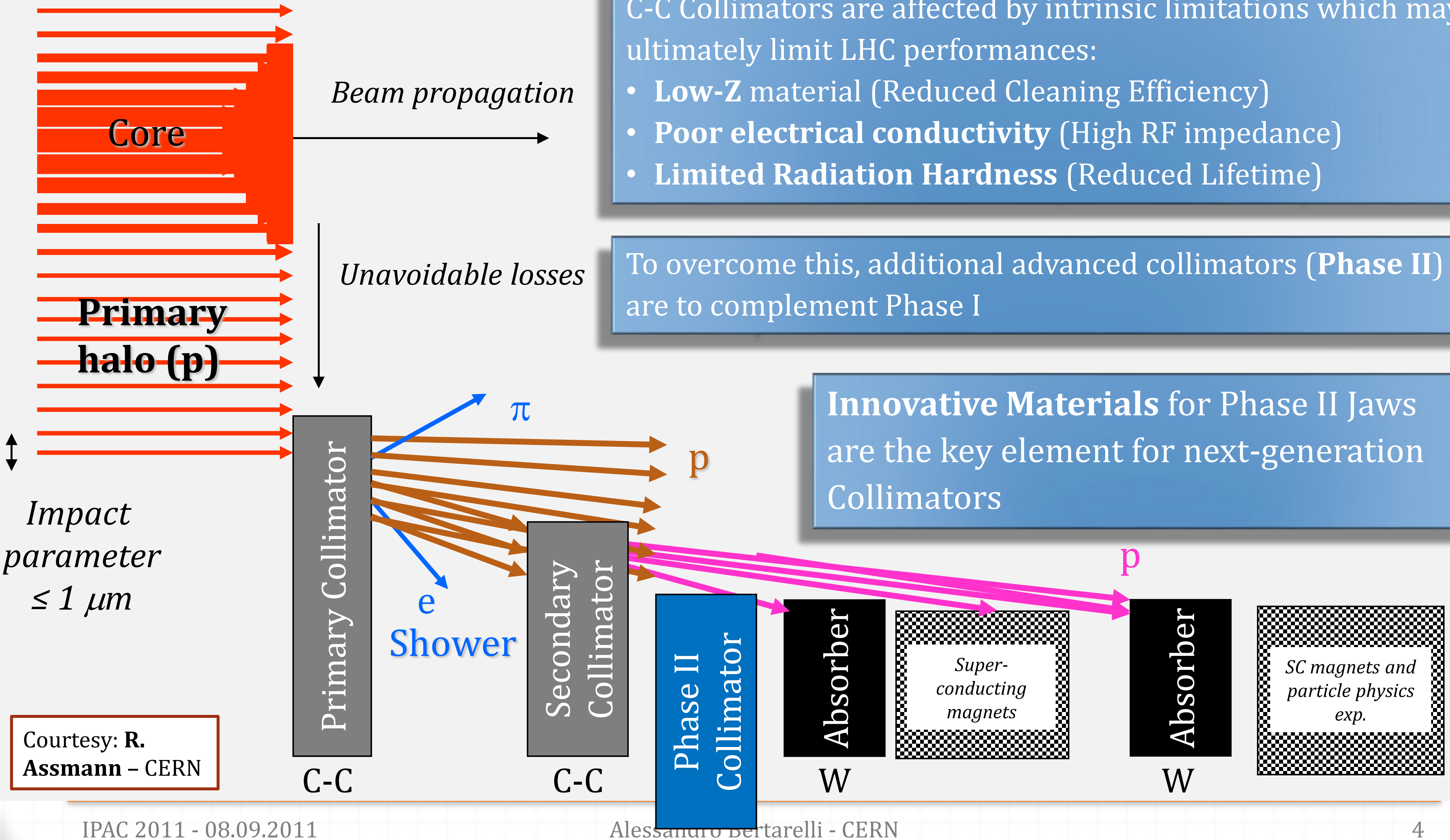
Limits of Phase I Collimators

C-C Collimators are affected by intrinsic limitations which may ultimately limit LHC performances:

- **Low-Z** material (Reduced Cleaning Efficiency)
- **Poor electrical conductivity** (High RF impedance)
- **Limited Radiation Hardness** (Reduced Lifetime)

To overcome this, additional advanced collimators (**Phase II**) are to complement Phase I

Innovative Materials for Phase II Jaws are the key element for next-generation Collimators



Courtesy: **R. Assmann** – CERN

Figures of Merit

Five Figures of Merit have been identified to classify and rank candidate materials

- **Electrical Conductivity**
  Must be maximized to limit RF impedance

ν

- **Steady-state Stability Normalized Index (SSNI)**
  Indicates the ability to maintain jaw geometrical stability

- **Transient Thermal Shock Normali**
  Related to highest particle absorpt
  indicator)

$$\frac{(1-\nu)c_{pv}}{E\alpha\rho}$$

- **Atomic Nu**
  Relat ficiency (Radiation and

Z

- temperature a material can reach before melting.

T_m

Add al "standard" requirements include ...

- Radiation Hardness, UHV Compatibility, Industrial producibility of large components (up to 400x80x25 mm^3), Possibility to machine, braze, join, coat ..., Limited brittleness

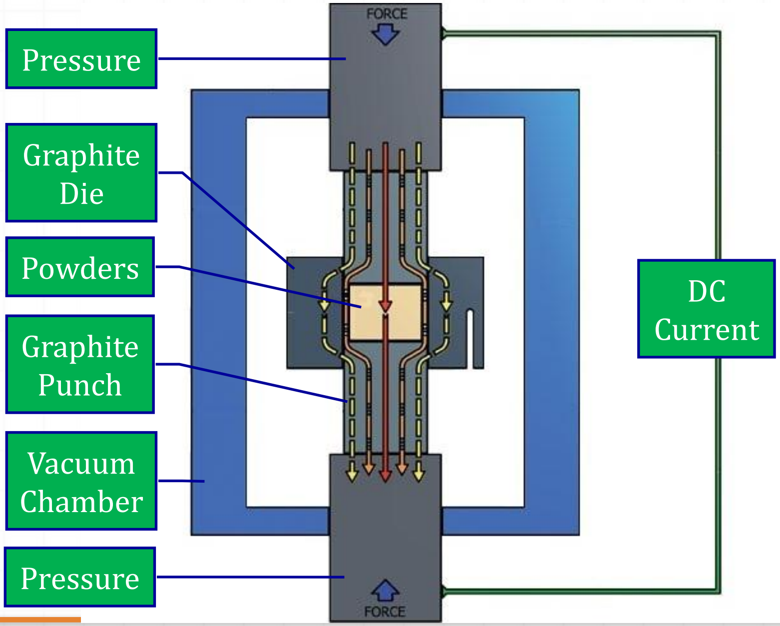
These indicators are partly self-conflicting.

A fit-all material does not exist!

Can metal-diamond composites be the answer?

Metal-diamond Composites

- **Metal-diamond composites** are advanced thermal management materials combining properties of Diamond (namely high ***k*** and low ***CTE***) with those of Metals (**strength**, γ, etc.**).**
- Sintering techniques include **Rapid Hot Pressing** (**RHP**), aka Spark Plasma Sintering (**SPS**), and **Liquid Infiltration**.
- Candidate materials include **Copper-diamond** (**Cu-CD**), **Molybdenum-diamond** (**Mo-CD**) and **Silver-diamond** (**Ag-CD**)



Pressure

Graphite Die

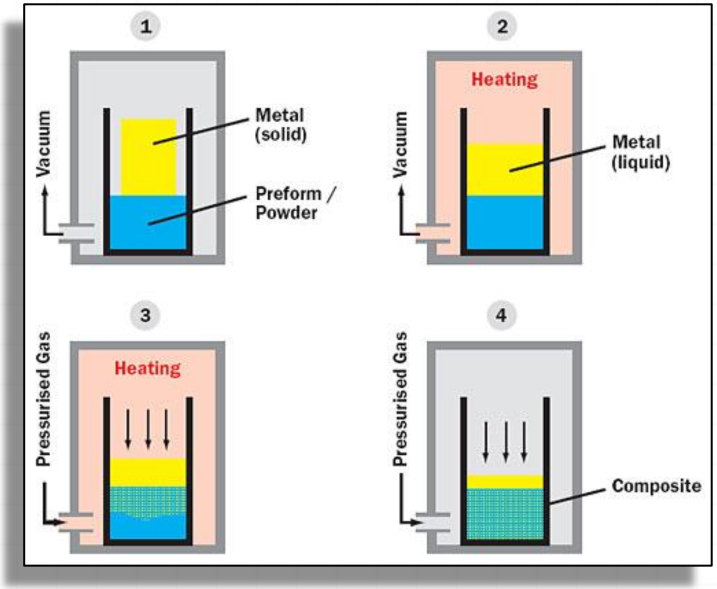
Powders

Graphite Punch

Vacuum Chamber

Pressure

DC Current



Material Ranking

Material	C-C	Mo	Glidcop ®	Cu-CD	Mo-CD	Ag-CD
Density [kg/m^3]	1650	10220	8900	~5400	~6900	~6100
Atomic Number (Z)	6	42	29	~11.4	~17.3	~22.4
T_m [°C]	3650	2623	1083	~1083	~2623	~840
SSNI [kWm^2/kg]	24	2.6	2.5	13.1 ÷ 15.3	6.9 ÷ 10.9	11.4 ÷ 15.4
TSNI [kJ/kg]	793	55	35	44 ÷ 51	72 ÷ 96	60 ÷ 92
Electrical Conductivity [MS/m]	0.14	19.2	53.8	~12.6	~9.9	~11.8

worse 🟥 🟩 **better**

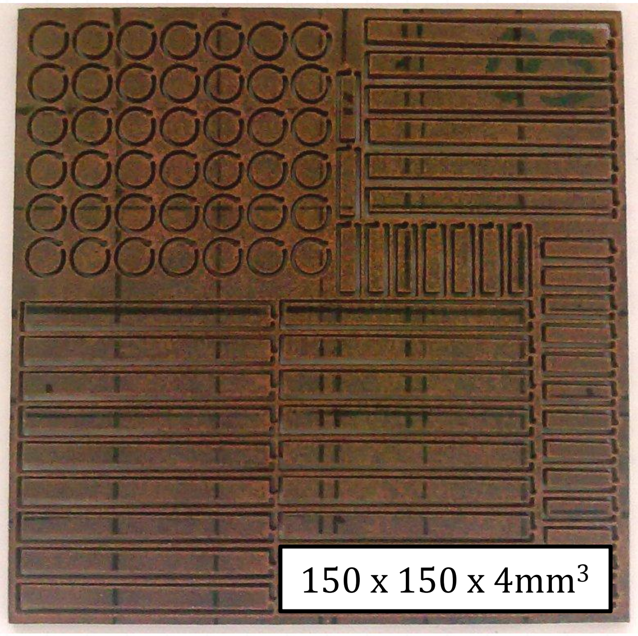
- **C-C** stands out as to thermo-mechanical performances. Adversely outweighed by poor electrical conductivity, low Z, expected degradation under irradiation.
- **High-Z metals** (**Cu**, **Mo**) possess very good electrical properties. High density adversely affects their thermal stability and accident robustness.
- **Metal-diamond composites** exhibit a balanced compromise between TSNI, SSNI, electrical conductivity , density, atomic number.
- **Mo-CD** limits the consequences of high temperatures induced by very intense beam impacts

Cu-CD Composites

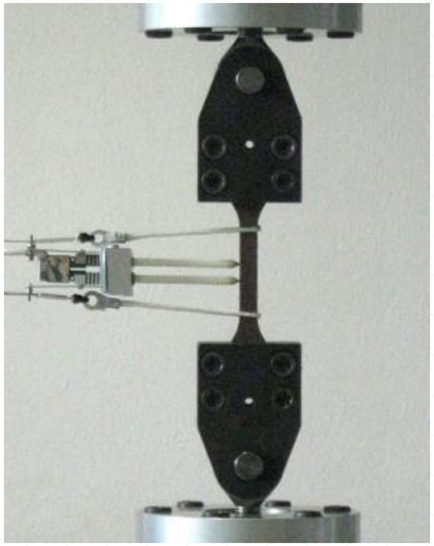
- **Cu-CD** developed by **RHP-Technology** (spin-off of Austrian Institute of Technology), Austria
- Characterized in the frame of **EuCARD** / ColMat collaboration

- **R&D objectives**:
    - **Geometrical stability**
    - **Electrical conductivity**
    - **Intermediate density**

- Produced by RHP under $N_2 + H_2$ Atmosphere
- 60% Diamond, 40% Cu
- Small addition of Boron
- Sintering T ~1000º C
- Good homogeneity and compaction rate (~95%)



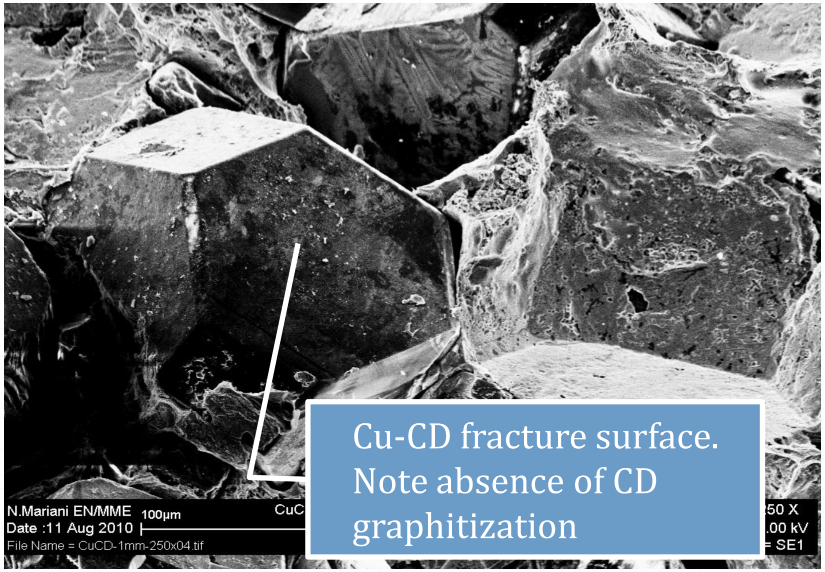
150 x 150 x 4mm³



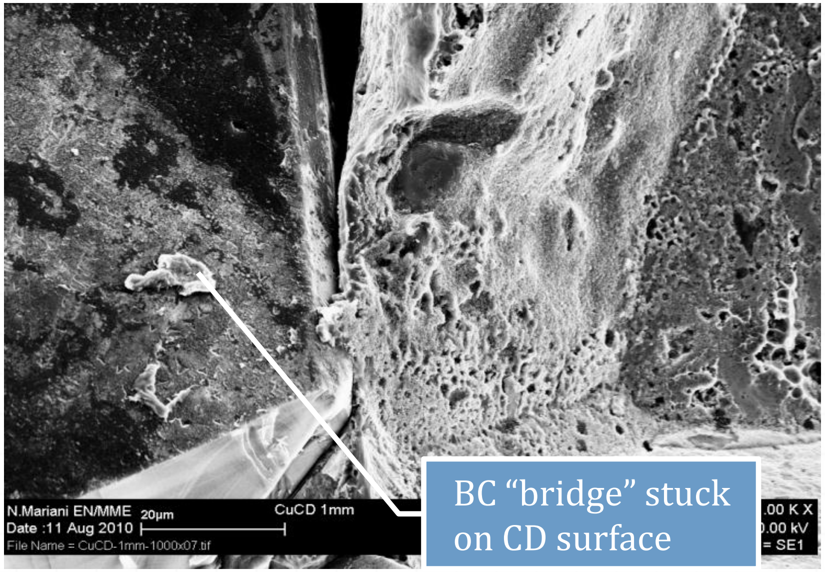
Courtesy: **E. Neubauer, M. Kitzmantel** – RHP-Tech

Cu-CD Composites

- ↑ No diamond degradation (in reducing atmosphere graphitisation starts at **~ 1300 °C**)
- ↑ Good thermal (**~490 W/mK**) and electrical conductivity (**~12.6 MS/m**).
- ↓ No direct interface between Cu and CD (lack of affinity). Limited bonding surface assured by Boron Carbides hampers mechanical strength (**~120 MPa**).
- ↓ BC brittleness adversely affects material toughness.
- ↓ Cu low melting point (**1083 °C**) limits Cu-CD applications for highly energetic accidents.
- ↓ CTE increases significantly with T due to high Cu content (from ~**6 ppmK^{-1} at RT** up to **~12 ppmK^{-1} at 900 °C**)



Cu-CD fracture surface. Note absence of CD graphitization

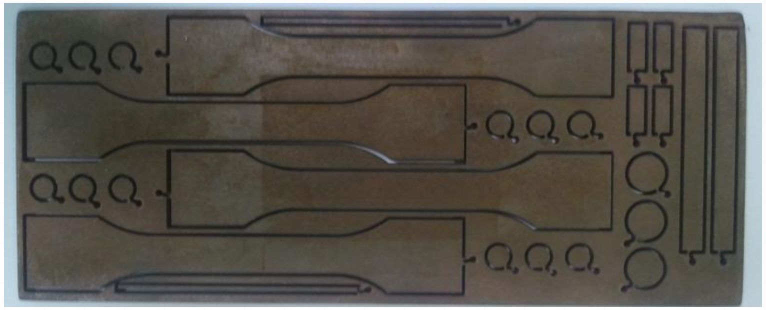


BC “bridge” stuck on CD surface

Mo-CD Composites

- Co-developed by **CERN** and a SME, **Brevetti Bizz**, Verona, Italy

- **R&D objectives** :
    - **Decrease** pure Mo **density** to optimize deposited energy distribution
    - Increase **mechanical properties** w.r.t. other Metal-CD
    - Increase **thermal stability** and **robustness** at **high temperatures**
- Manufactured through RHP
- Mo and CD create a good interface by forming Mo Carbides.
- Large components can be produced.
- High sintering T of Mo (**~1700 °C**) leads to diamond graphitisation. 2 alternative processes:
    - **Assisted Solid-state Sintering** (**ASS**)
    - **Liquid Phase Sintering** (**LPS**)

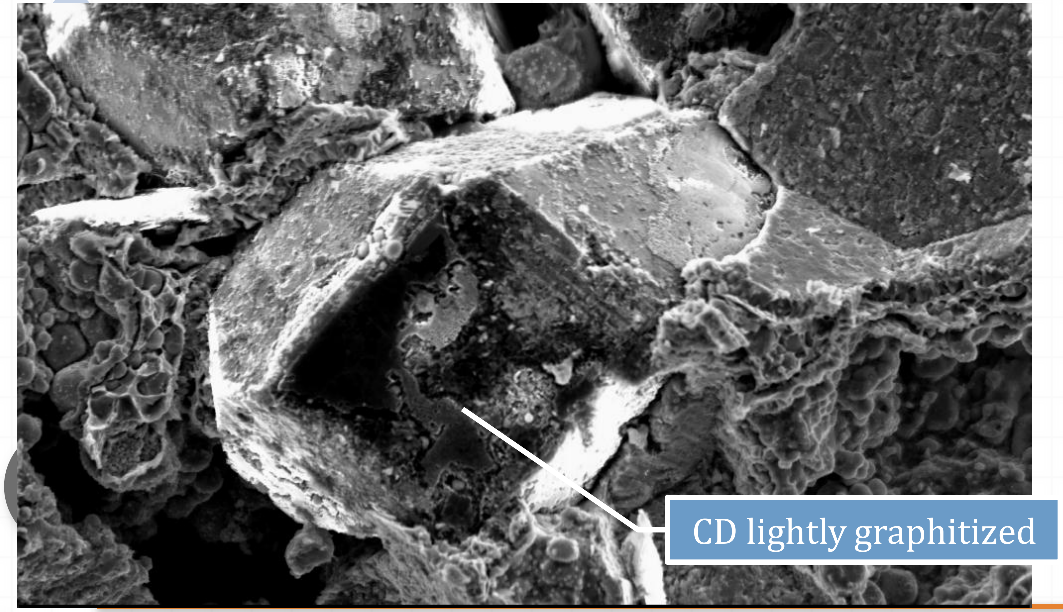


200 x 80 x 20 mm^3

Mo-CD Composites

Liquid Phase Sintering (LPS)

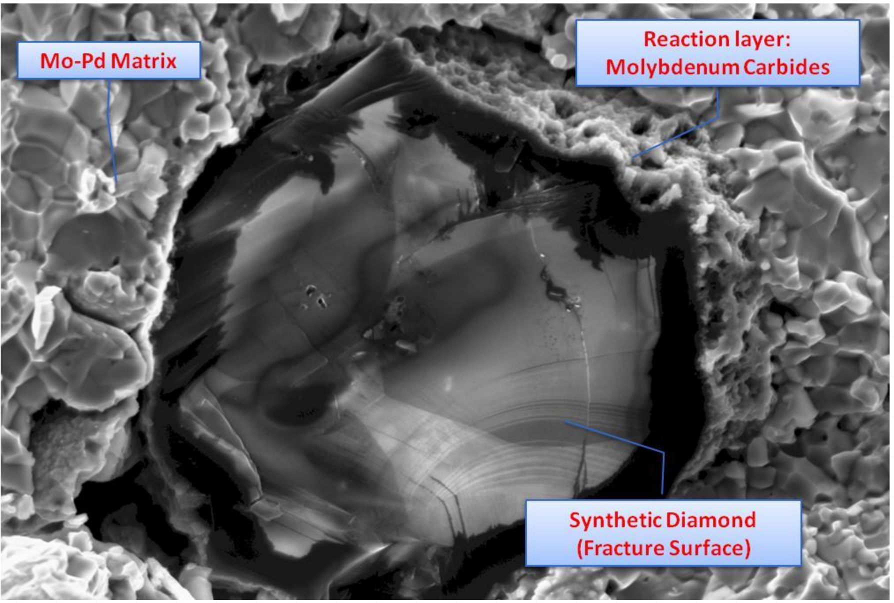
- ⬆ Addition of low-melting phase (Cu or Cu-Ag) to fill in the pores between Mo and CD
- ⬆ Good mechanical strength (400+ MPa) and Thermal Conductivity (185 W/mK)
- ⬇ Max $T_{Service}$ limited by low-melting phase (Cu)



CD lightly graphitized

Assisted Solid-state Sintering (ASS)

- ⬆ Addition of small amounts of activating elements (Ni, Pd) enhances Mo sintering at low T (~1300 °C)
- ⬆ Absence of low-melting phase increases service T up to ~2600 °C
- ⬇ Large diamond particles interfere with Mo compaction.
- ⬇ Diamond graphitization not fully avoided.



Ag-CD Composites

- Developed by **EPFL**, Switzerland.
- Characterized at EPFL and CERN (**EuCARD**).
- Manufactured by Liquid Infiltration of cylindrical samples (Ø100 mm, H 100 mm)
- ~60% Diamond**,** **~**40% Ag-Si alloy

↑ Excellent bonding between Ag and CD assured by Silicon Carbides formation on diamond.

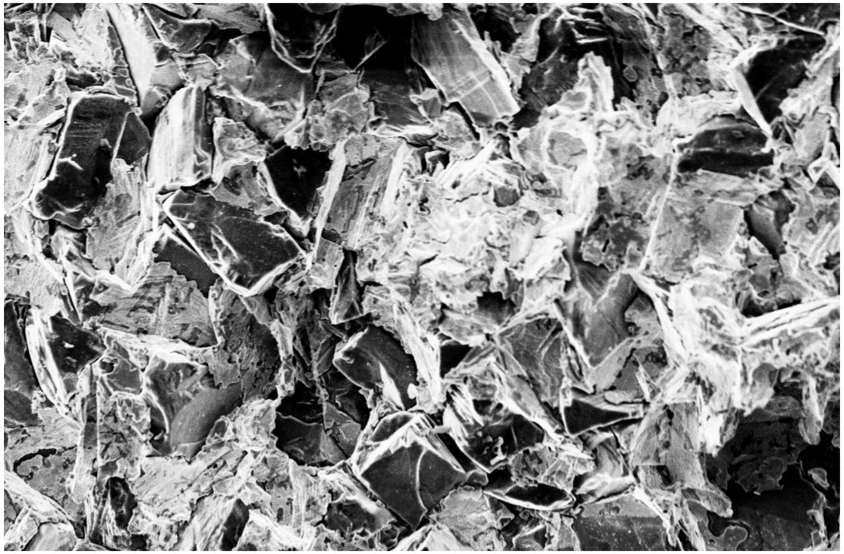
↑ High Flexural Strength (**~500 MPa**) and toughness.

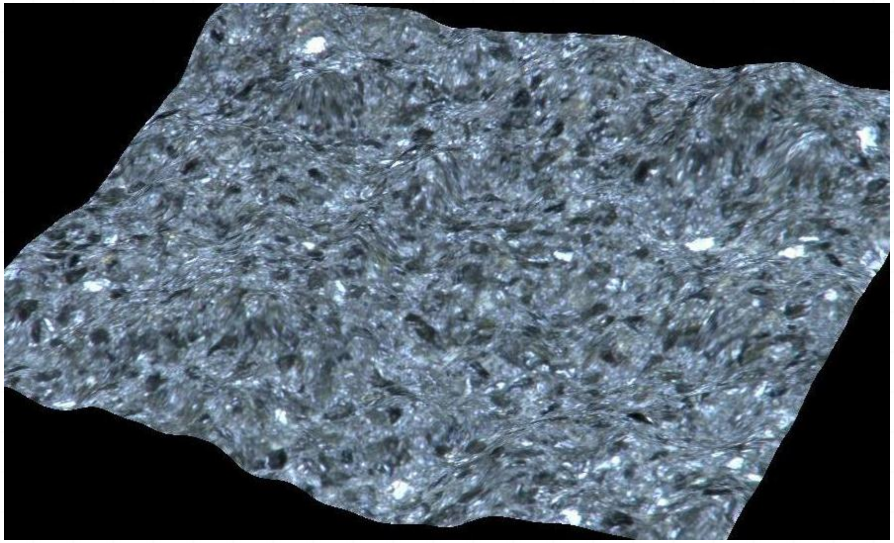
↑ High Electrical Conductivity.

↓ Max $T_{Service}$ limited by low-melting eutectic phase Ag-Si (**840 °C**).

↓ Hard to manufacture large components (>100 mm)

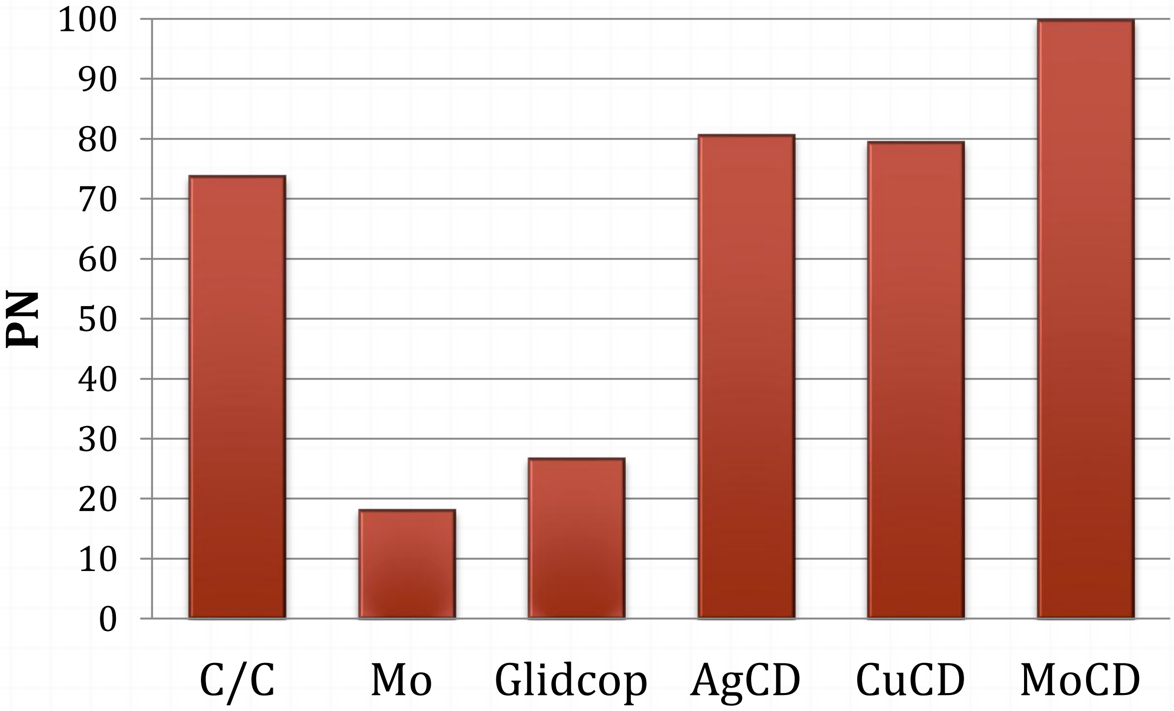
↓ Material non homogeneities due to liquid metal infiltration intrinsic limitations.





Studied material comparison

- A single, comprehensive comparison of characterized materials is proposed on the basis of normalized Figures of Merit.
- Needless to say, any choice of Figures of Merit, of their combination and target values is arbitrary …
- This said, this comparison confirms that Mo-CD is, so far, the best candidate.



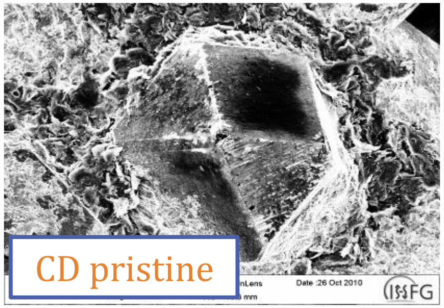
$$Pn_i = [P_i / Max(P)]$$

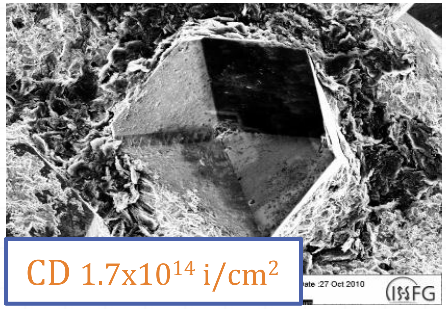
$$Pn_Z = 1 - \left(\frac{|Z - 12|}{42}\right)$$

$$PN = \frac{\prod Pn_i}{Max(\prod Pn_i)}$$

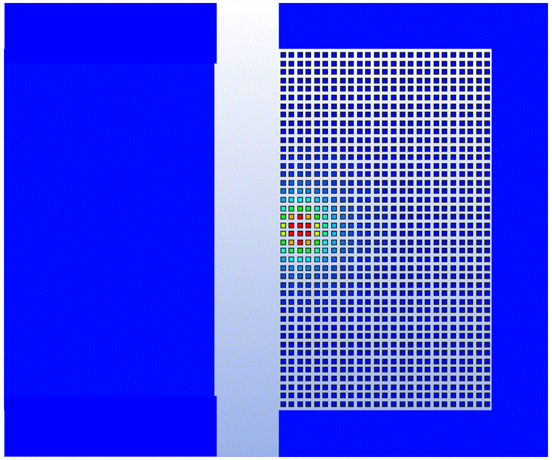
Simulations and Testing

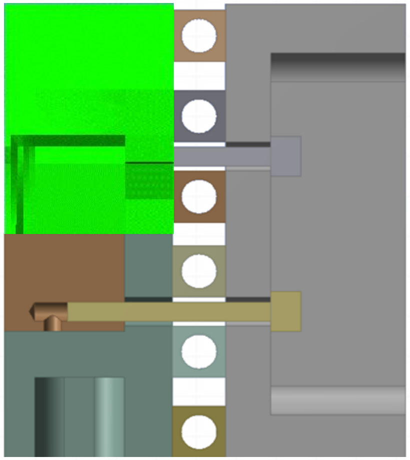
- **Irradiation damage tests** at **RRC-KI** and **GSI**.
- Preliminary results from GSI on Cu-CD show no degradation of Cu/CD interface. Defects in CD lattice seem to occur.
- **Advanced simulations** being performed at **CERN** and **Polito** on materials under extreme conditions.
- Beam tests in CERN’s **HiRadMat** to experimentally assess material models.

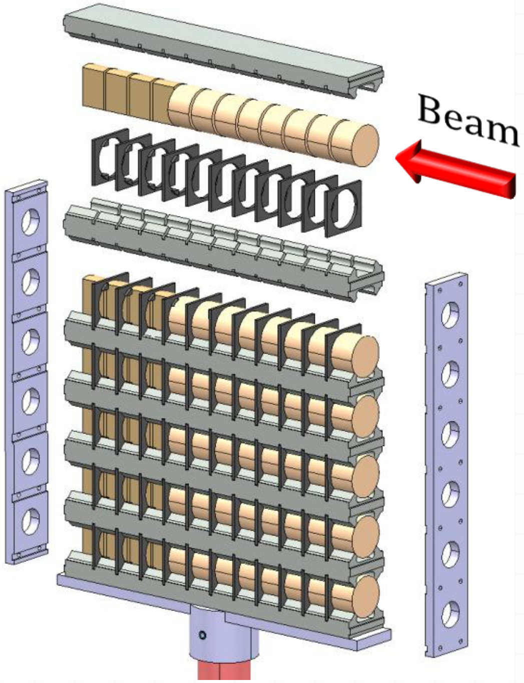

CD pristine


CD 1.7x10^{14} i/cm^2

Courtesy: **M. Tomut** – GSI







Conclusions

- Bringing LHC beyond nominal performances might require new generation collimators embarking novel advanced materials.
- Metal-diamond composites are particularly appealing as they promise to combine diamond and metal properties.
- Figures of Merit were defined, allowing to pinpoint “best” candidates and to set ambitious goals.
- An intense R&D program has been launched at CERN with partners partly within the EuCARD collaboration
- Cu-CD, Mo-CD and Ag-CD were studied and successfully produced. Size challenge has been met for Cu-CD and Mo-CD.
- A large characterization effort has been carried out: a magic material does not exist, but Mo-CD seems to stand out as a balanced compromise between key parameters.
- Radiation hardness assessment is ongoing for selected materials. Beam tests under extreme conditions are foreseen at CERN’s HiRadMat facility.
- The R&D program is still in full progress.

Acknowledgements

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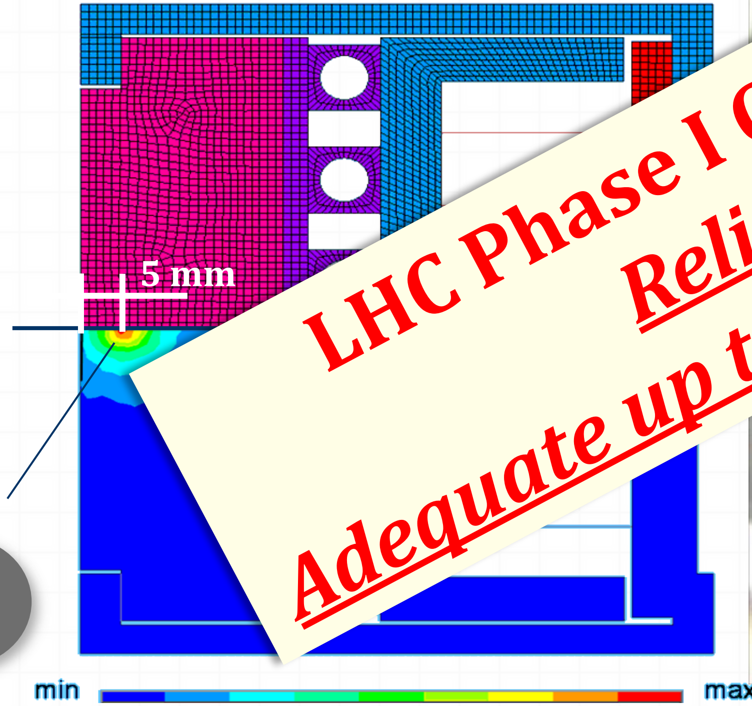
M. Kitzmantel, E. Neubauer, *RHP-Technology*

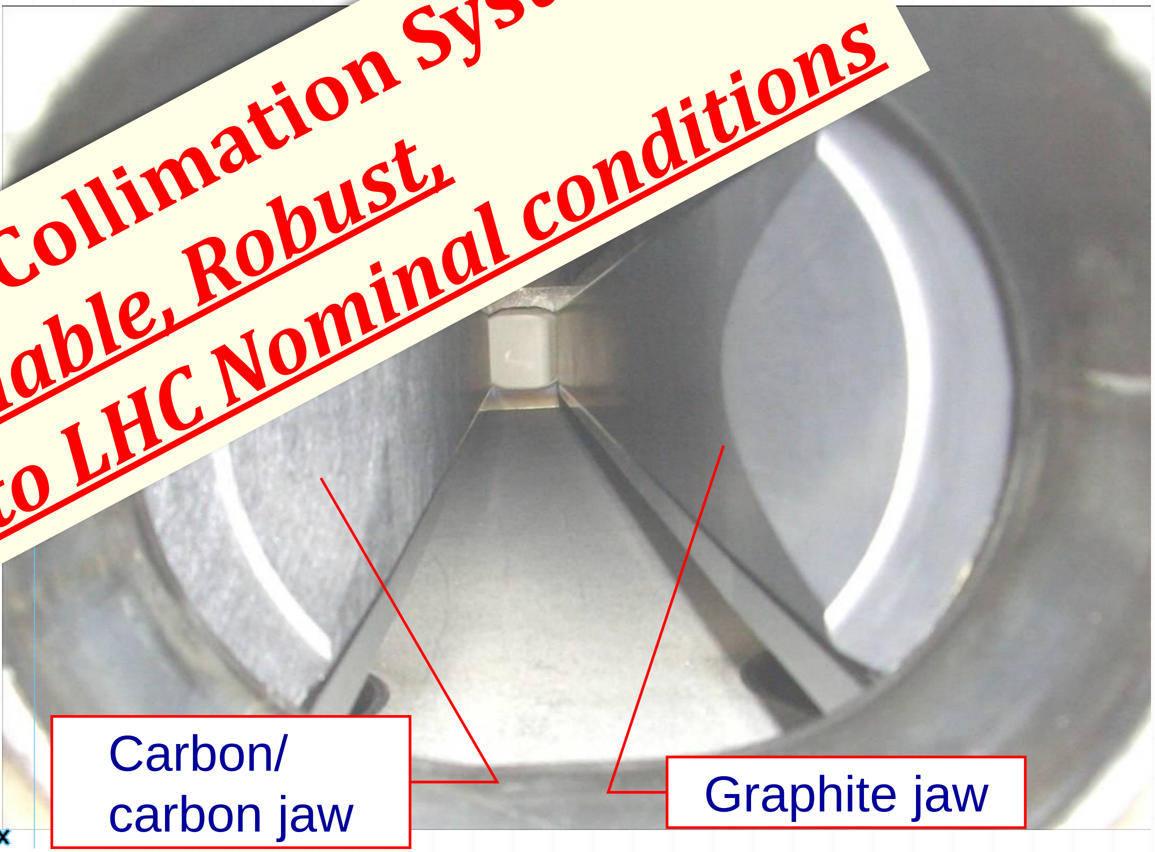
A. Ryazonov, *RRC-Kurchatov Institute*

What is a (Phase I) LHC Collimator

Robustness Test at 450 GeV 3.2x10^{13} protons
Collimator jaws after impact … no signs of mechanical damage

- 5 full intensity shots ranging from 1 to 5 mm, 7.2ms …
- Each impact energy equivalent to more than ½ kg of TNT





LHC Phase I Collimation System
Reliable, Robust,
Adequate up to LHC Nominal conditions

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