Materials for Phase II Collimators

6th Collimation Upgrade Specification Meeting
20.04.2012

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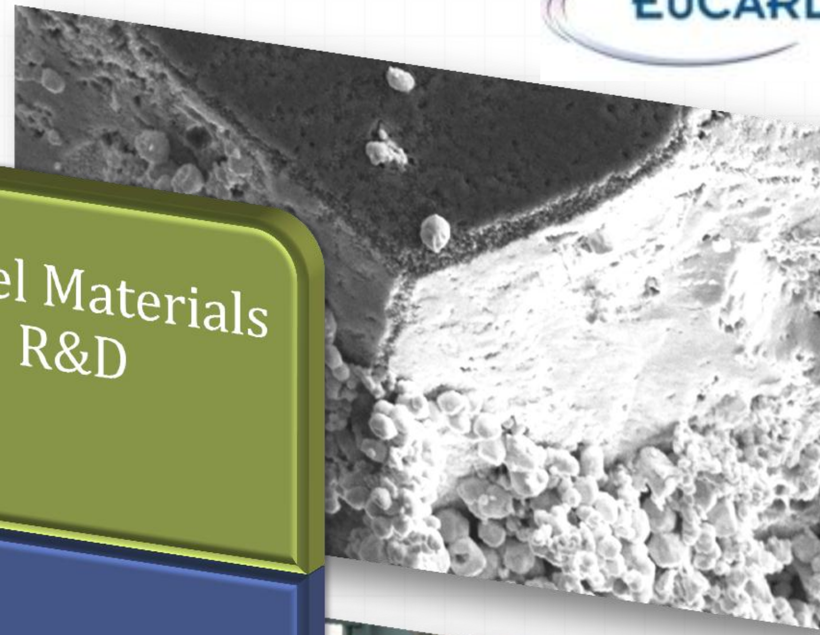
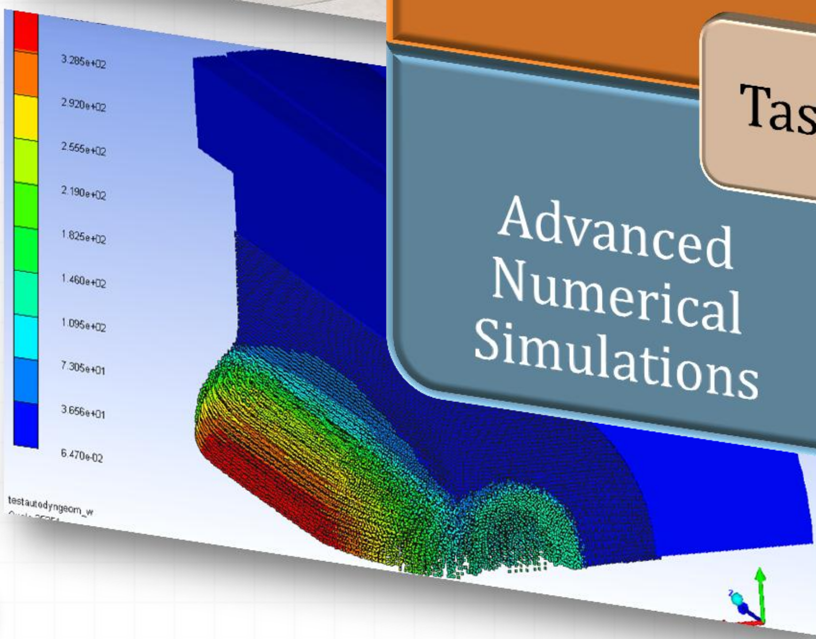
OUTLOOK

- Phase II Activities in EN-MME
- Phase II Collimator design principles
- R&D for Phase II Advanced Materials
- HiRadMat Materials Test

PHASE II ACTIVITIES IN MME

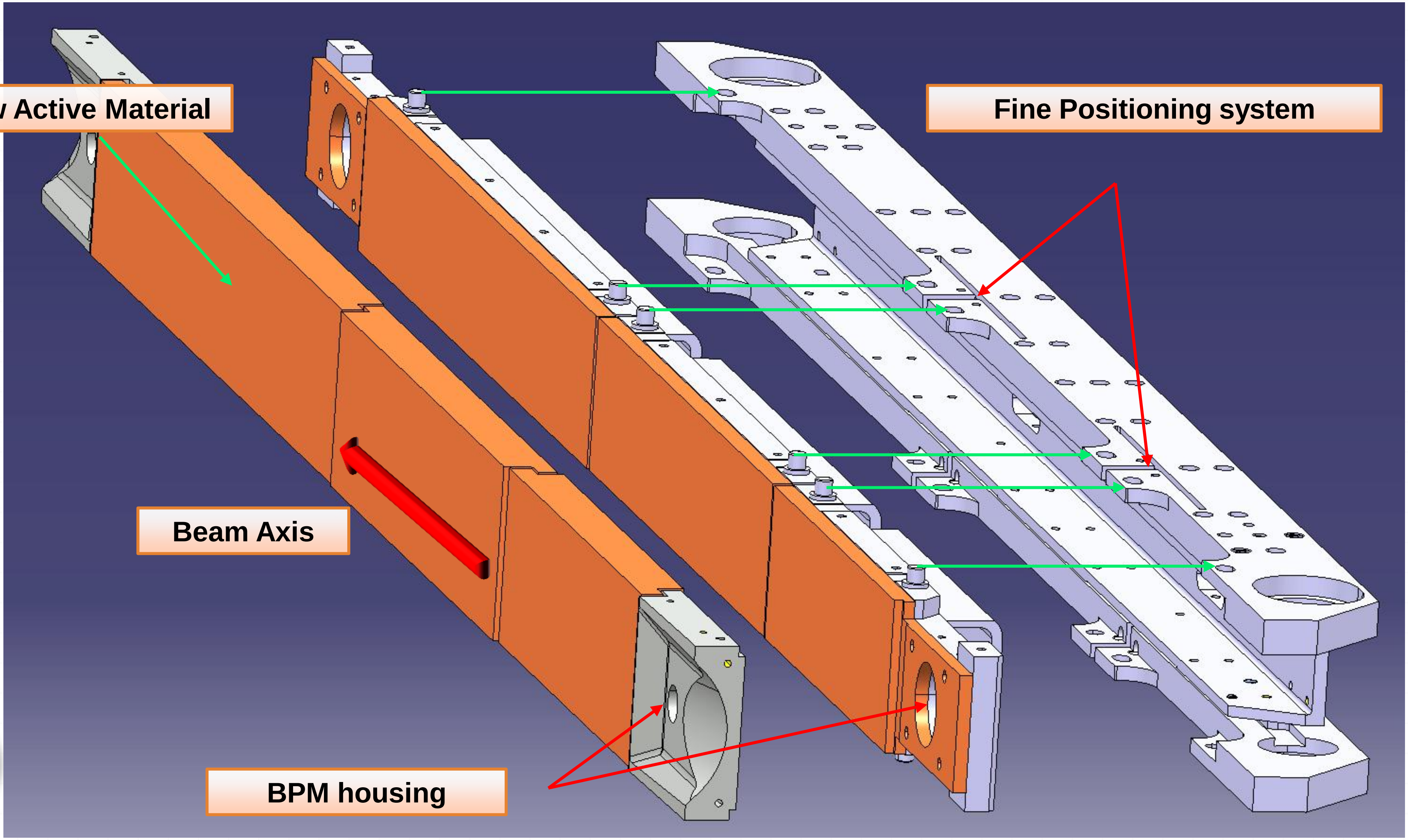




- Prototype Design & Manufacturing
- Novel Materials R&D
- Advanced Numerical Simulations
- Material Testing

Task 8.2

PHASE II COLLIMATOR DESIGN PRINCIPLES



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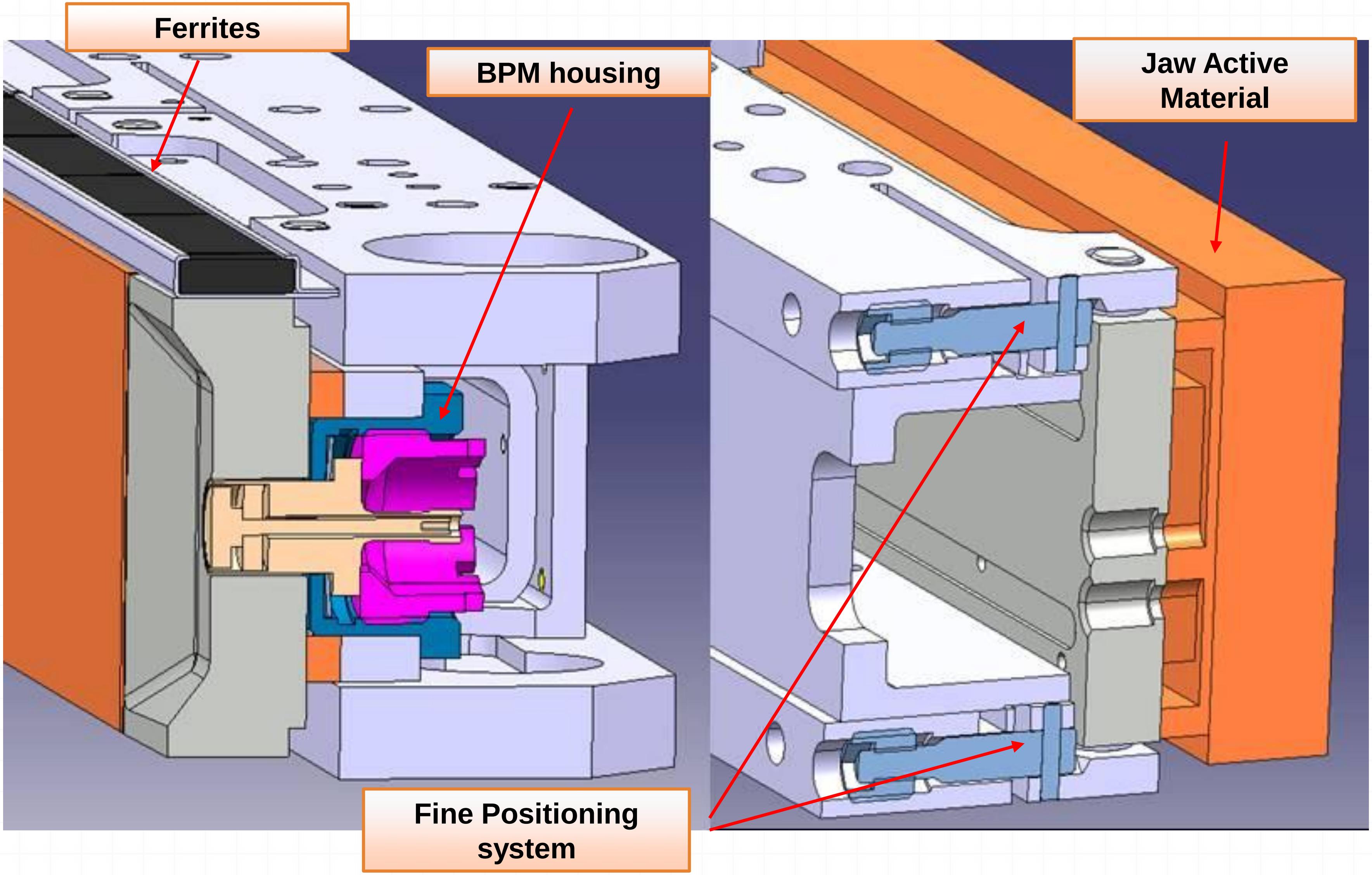
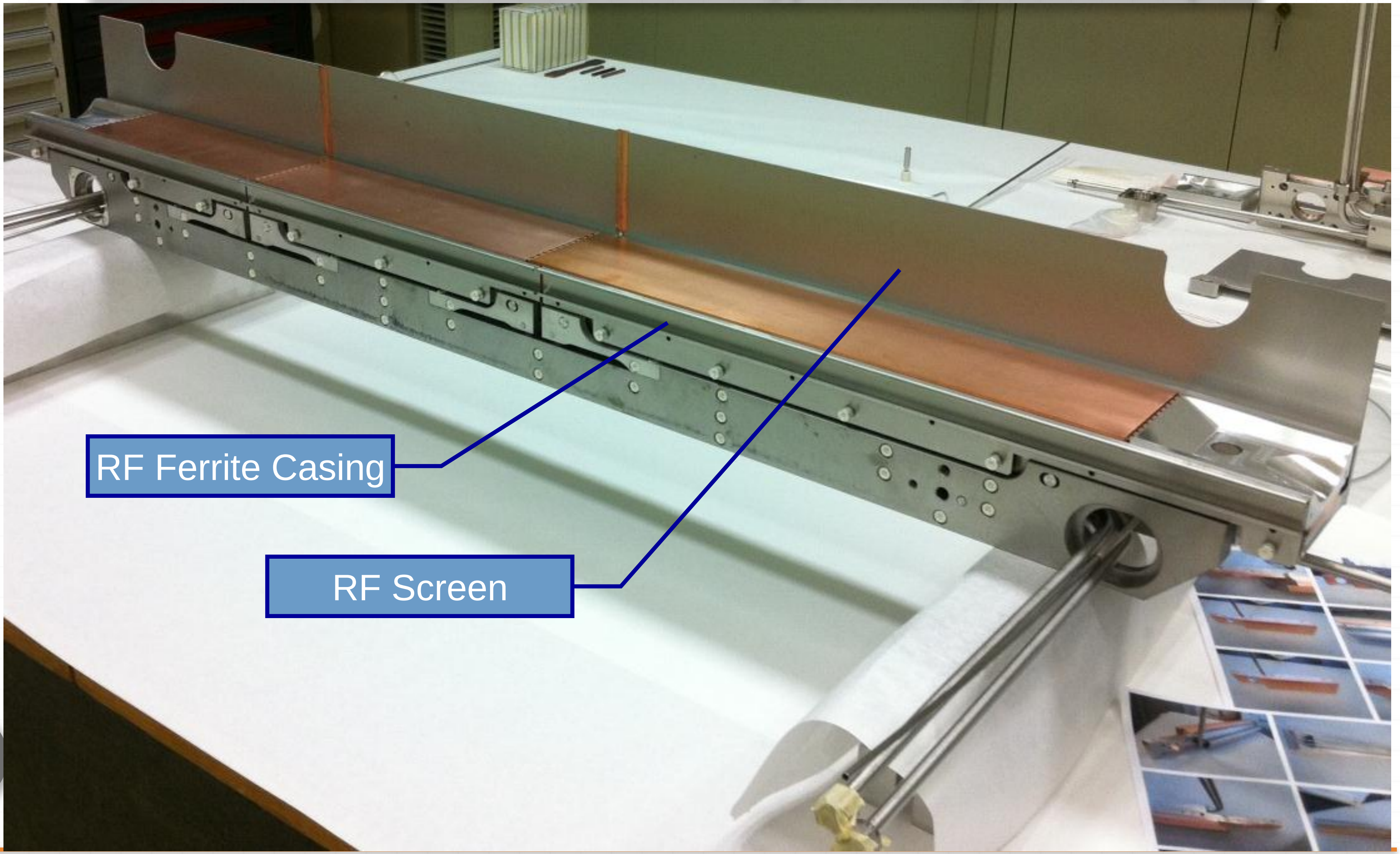


PHASE II COLLIMATOR PROTOTYPE

Assembled Jaw of Phase II 1st Prototype; active jaw in Glidcop



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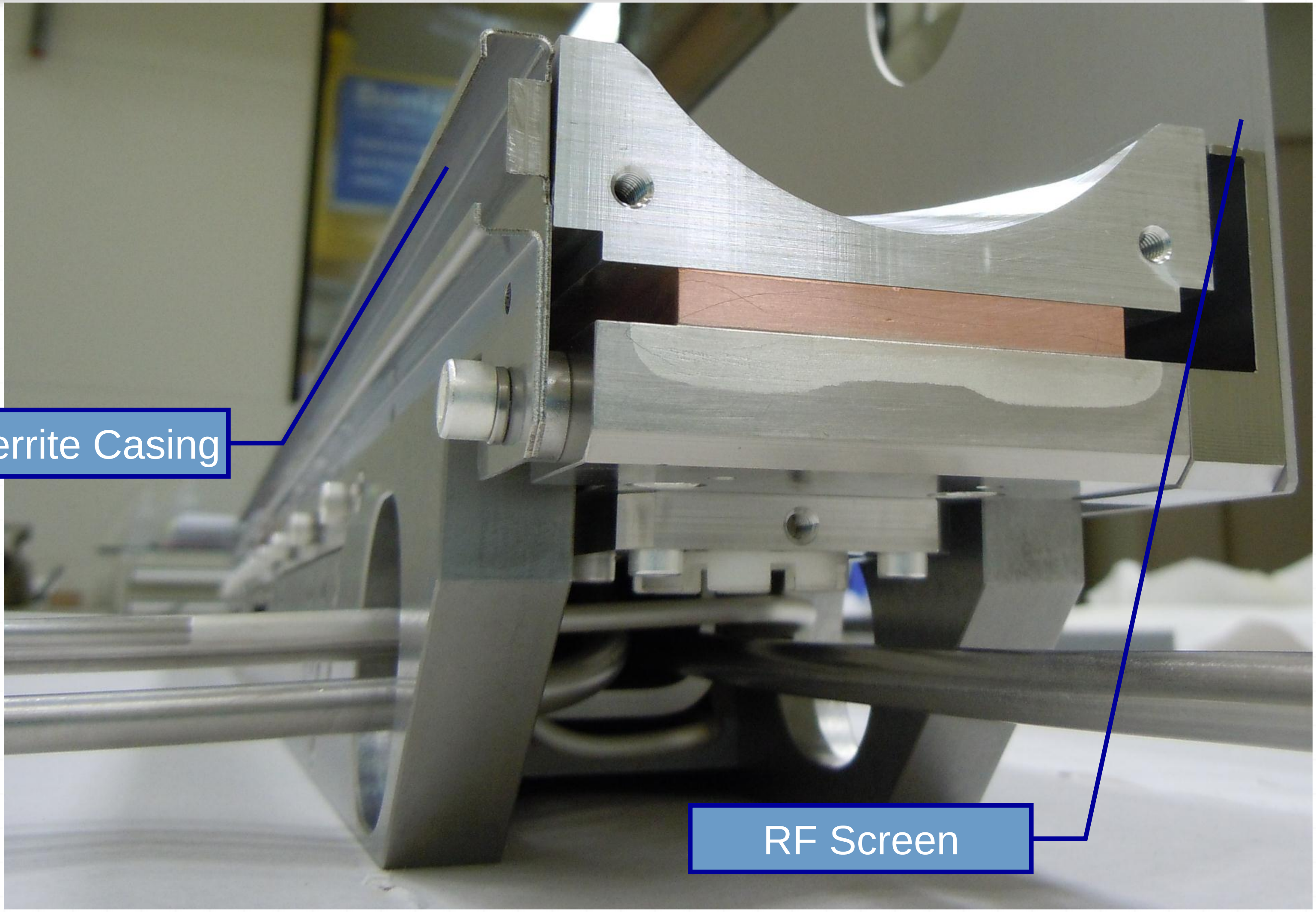

Material Requirements for LHC Phase II Collimators

- **Reduce RF impedance**
  Maximize **Electrical Conductivity**
- **Maintain/improve jaw geometrical stability in nominal conditions**
  Maximize the stability indicator **Steady-state Stability Normalized Index (SSNI)**
- **Maintain Phase I robustness in accidental**
  Maximize the robustness indicator **Transient Thermal** ... **ex TSNI)**
- **Improve cleaning efficiency (absorption ra**
  Increase Radiation and nuclear Interaction Lengths, i.e
- **Improve maximum operational temperatu**
  Increase **Melting Temperature**.

Note Conflicting requirements as to Density

γ

$\frac{k}{\rho\alpha}$

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

Z

T_m

Additional "standard" requirements include ...

- Radiation Hardness, UHV Compatibility, Industrial producibility of large components, Possibility to machine, braze, join, coat ..., Toughness, Cost ...

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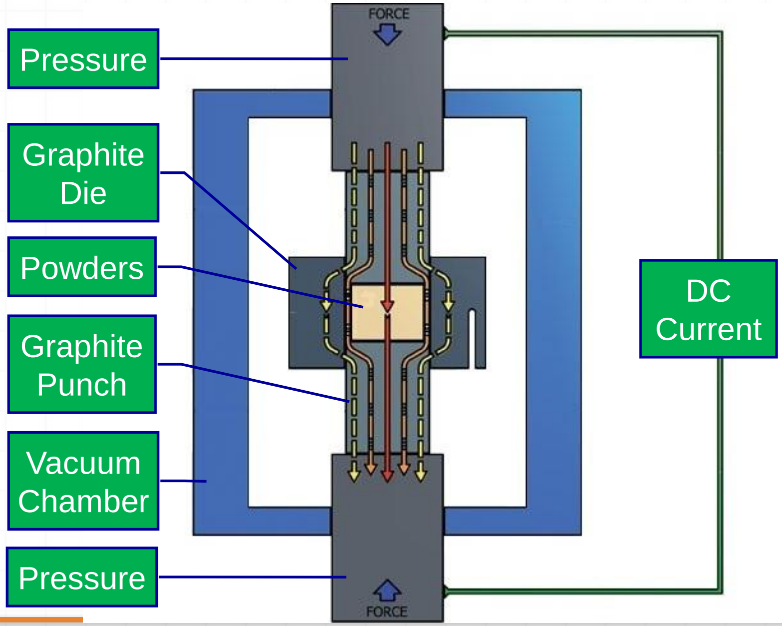
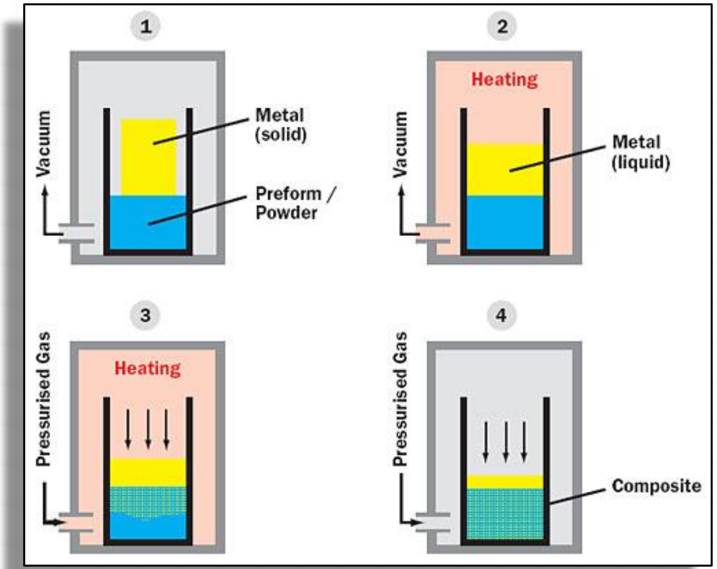
Metal Matrix Composites

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





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PHASE II MATERIALS RANKING

Material	C-C	Mo	Glidcop ®	Cu-CD	Mo-CD	Ag-CD	Mo-Gr
Density [kg/m^3]	1650	10220	8900	~5400	~6900	~6100	~5600
Atomic Number (Z)	6	42	29	~11.4	~17.3	~13.9	~13.1
T_m [°C]	3650	2623	1083	~1083	~2623	~840	~2520
SSNI [kWm^2/kg]	24	2.6	2.5	13.1 ÷ 15.3	6.9 ÷ 10.9	11.4 ÷ 15.4	*7.4 **
TSNI [kJ/kg]	793	55	35	44 ÷ 51	72 ÷ 96	60 ÷ 92	*115 **
Electrical Conductivity [MS/m]	0.14	19.2	53.8	~12.6	~9.9	~11.8	*1 ÷ 18 ***

worse — better

** Estimated values*
*** γ=18 MS/m with Mo surface coating*

- **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.
- **Molybdenum-graphite,** currently under development and characterization, shows very promising figures of merit.

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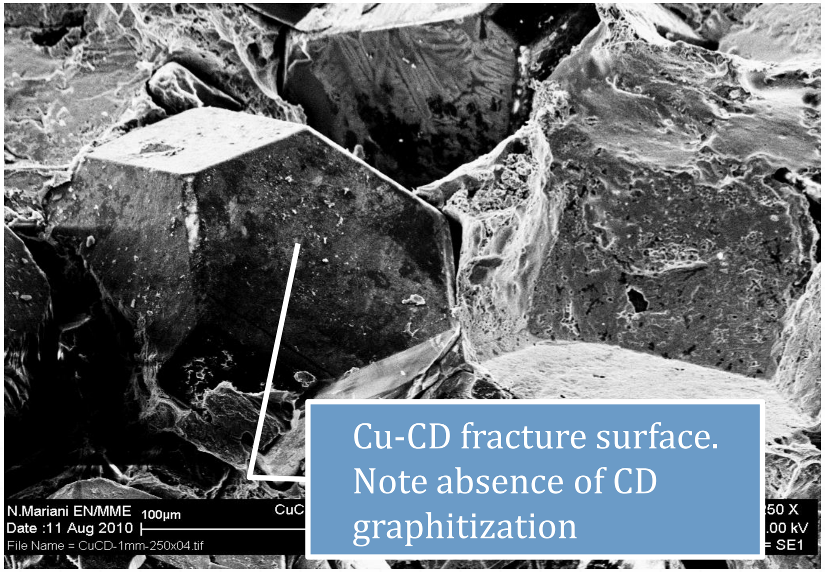
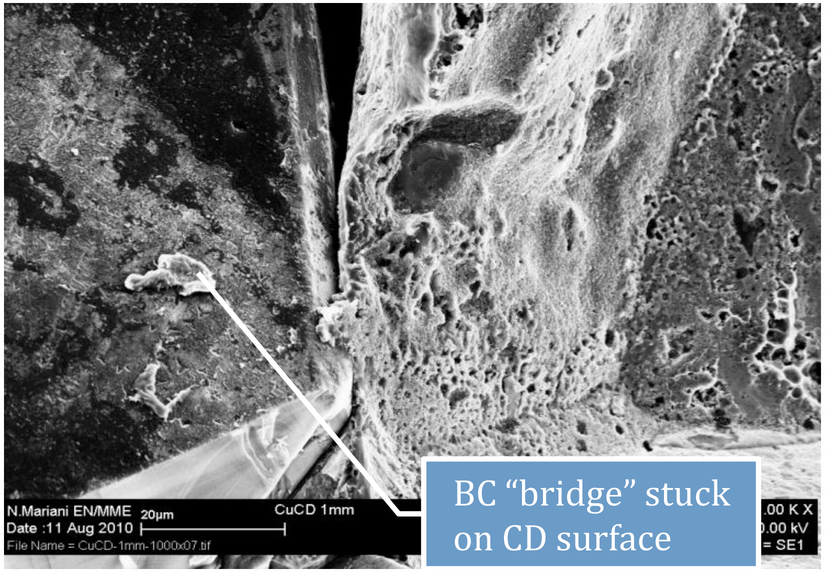
CU-CD COMPOSITES

- 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**)





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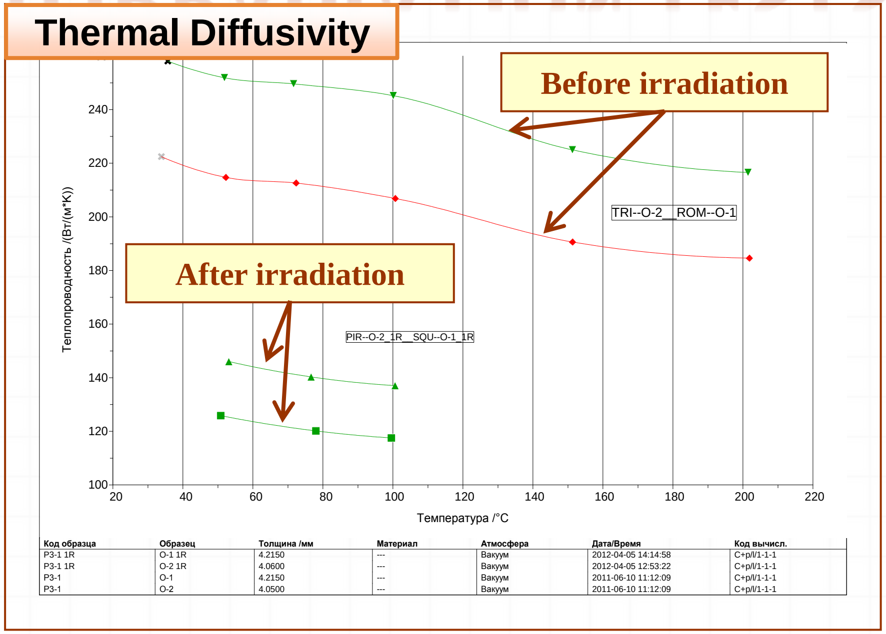
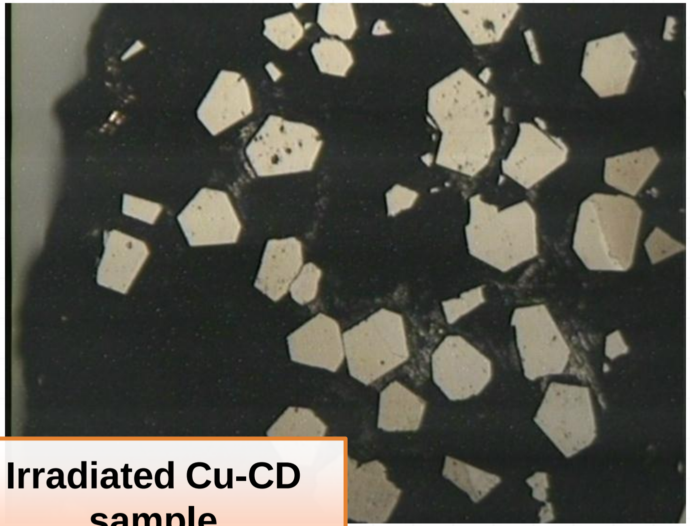
CU-CD IRRADIATION TESTS

- **Irradiation studies** on Cu-CD at Kurchatov Inst.
- 30 MeV protons, Φ = 1E17 p/cm^2.
- Properties measured **before and after irradiation**.
- Results obtained for **k, γ, CTE, E**.
- **Yield stress and elongation** still to come.



Property at T_a	Before Irradiation	After Irradiation	Variation %
CTE [ppm/m/K]	7,8	8,3	– 6%
k [W/m/K]	580	330	– 43%
γ [MS/m]	10 ± 0.2	9.8 ± 0.2	–
E [GPa]	240 ± 50	330 ± 30	+ 40%



Irradiated Cu-CD sample

MO-CD COMPOSITES

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Liquid Phase Sintering (LPS)

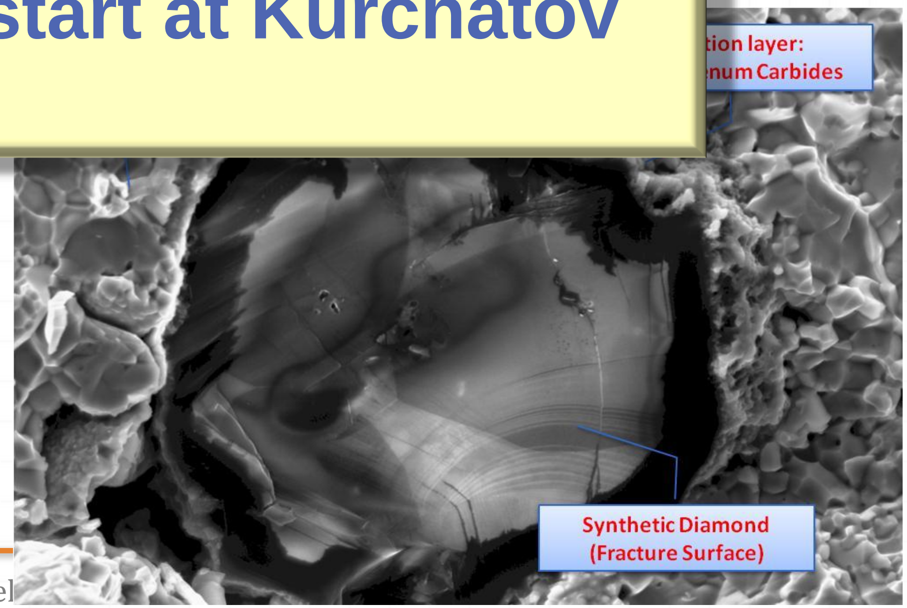
- ↑ Addition of low-melting phase (Cu or Cu-Ag) to fill in the pores between Mo and CD
- ↑ Good mechanical strength (400+ MPa) and Thermal Conductivity (185 W/mK)
- ↓ Max $T_{Service}$ limited by low-melting phase (Cu)

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

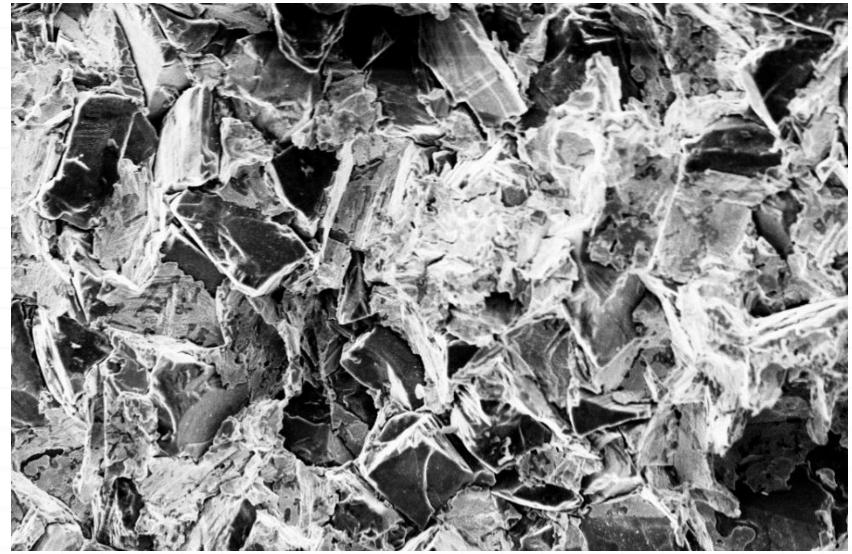
…bided.

Irradiation tests to start at Kurchatov



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.

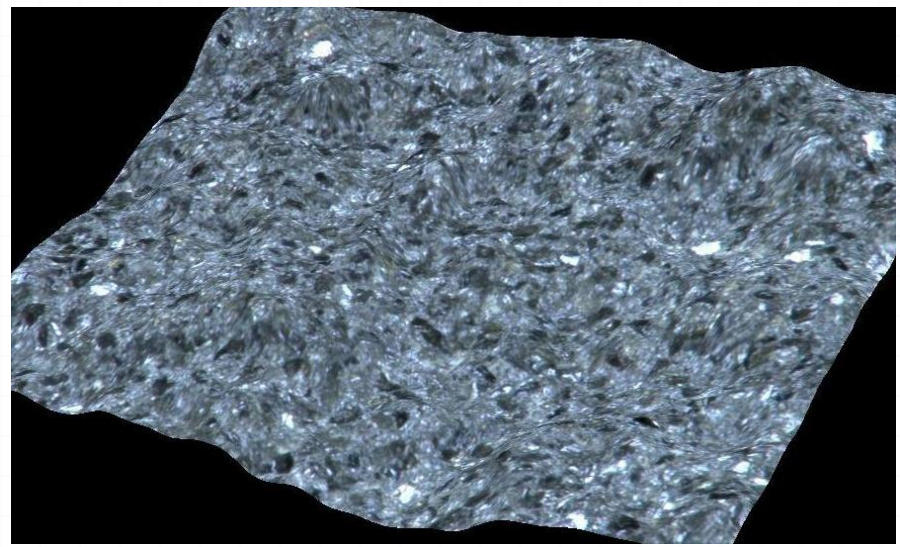
↑ High Flexural Strength (**~500 MPa**) and toughness.

↑ 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.



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MO-GR COMPOSITES

Why Graphite?

- Low CTE
- Low Density
- High Thermal Conductivity
- High Melting (degradation) point
- High Shock wave dumping

Compared to Mo-CD:

- ↑ No low melting phase (Cu in LPS Mo-CD)
- ↑ Lower Density
- — Similar Thermal Conductivity
- ↑ No reinforcement degradation
- ↑ Lower Costs
- ↓ Mechanical strength not yet satisfactory

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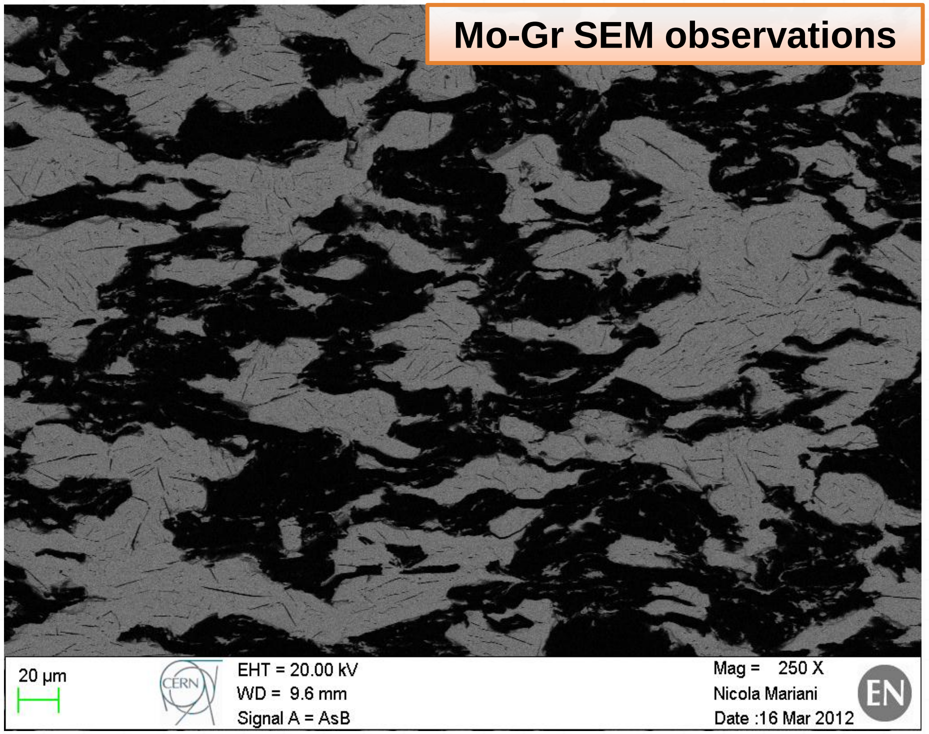
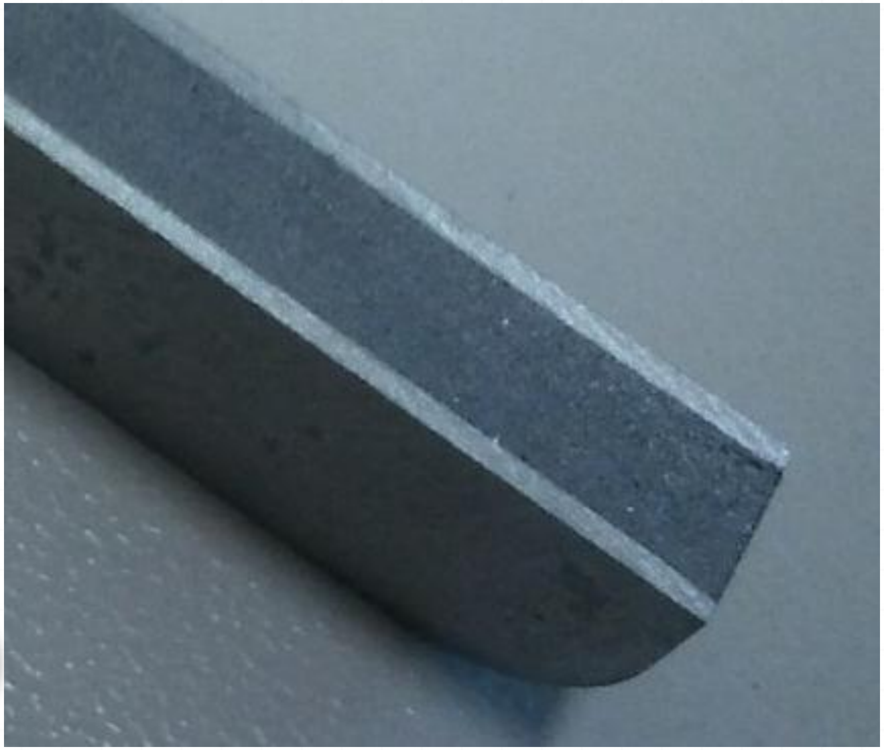


Mo-Gr SEM observations

- Mo-GR under intense development program.
- Material properties can still be improved by optimizing base materials, composition and processes.

MO-GR/MO SANDWICH

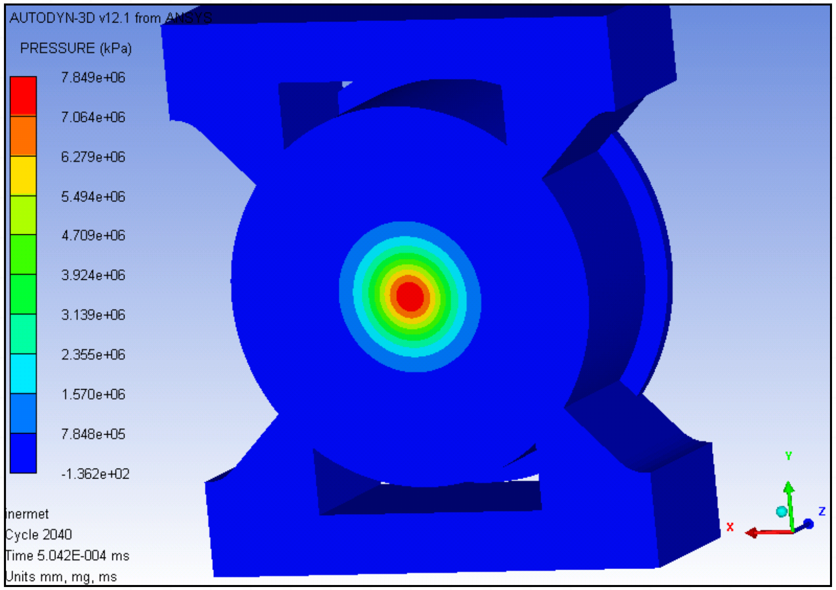
- Solution to increase electrical conductivity of the composite up to **18 MS/m: sandwich structure**;
- Molybdenum – Graphite core with two surface layers of **high electric conductive pure Mo**;
- Sandwich with **1 mm thick** Mo layers;
- Coating thickness can be decreased to < 0.1 mm: **optimal thickness to be defined with RF team!**



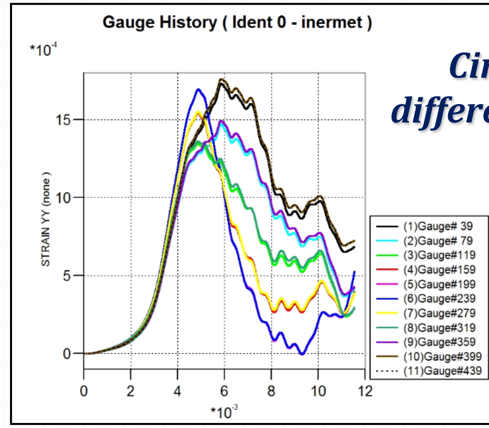
Density (g/cm3)	Electrical Conductivity (MS/m)	Thermal Conductivity (W/mK)	Flexural Strength (Mpa)
6.68	18	-	260

NUMERICAL SIMULATIONS

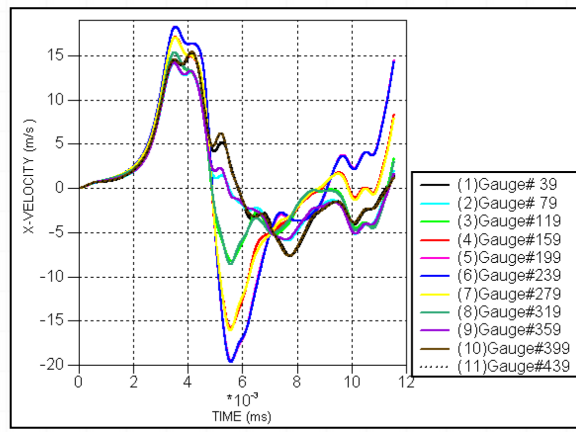
- **Explicit calculations performed on Inermet180, Copper OFE and Molybdenum samples**
- **Calculation on Inermet180 shown below: representative case (σ = 2.5 mm, bunch intensity = 1.5E11 particles)**



Pressure wave after 500 ns



Circumferential strain in different longitudinal positions



Radial velocity on the external face in different longitudinal positions

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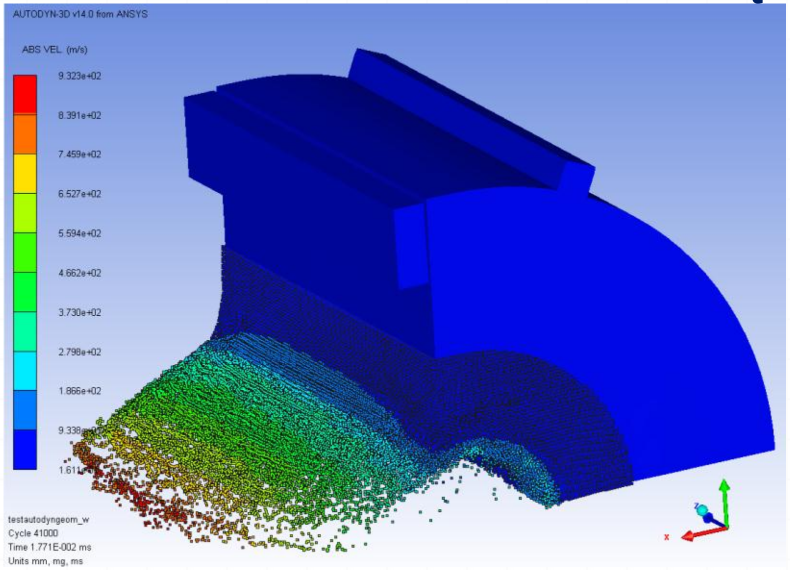
NUMERICAL SIMULATIONS

- **SPH calculations on different beam scenarios to determine spray behaviour, thus:**
  - **window covering (due to vaporized material)**
  - **material density change**
  - **load on Be window**
  - **Acquisition feasibility**

70 bunches
0.25 mm
t=17μs



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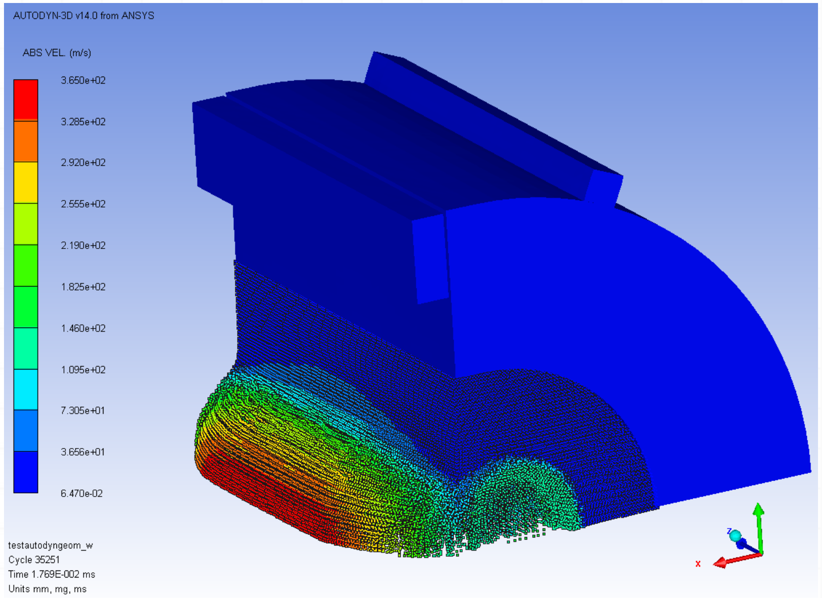

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MATERIAL TESTS IN HIRADMAT

- **In the HiRadMat facility**, novel materials under development for Phase II can be tested under the **extreme conditions** they may encounter in case of accidental beam impacts.

Objectives:

- Gather, mostly in **real time**, **experimental data** on these materials properties (EOS, Strength models, Failure Models).
- **Benchmark** advanced numerical simulations.
- To the best of our knowledge, such an extensive test has never been **done before**.


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Switzerland

EDMS NO.	REV.	VALIDITY
1178003	2.0	DRAFT

REFERENCE
LHC-TC-ES-0004

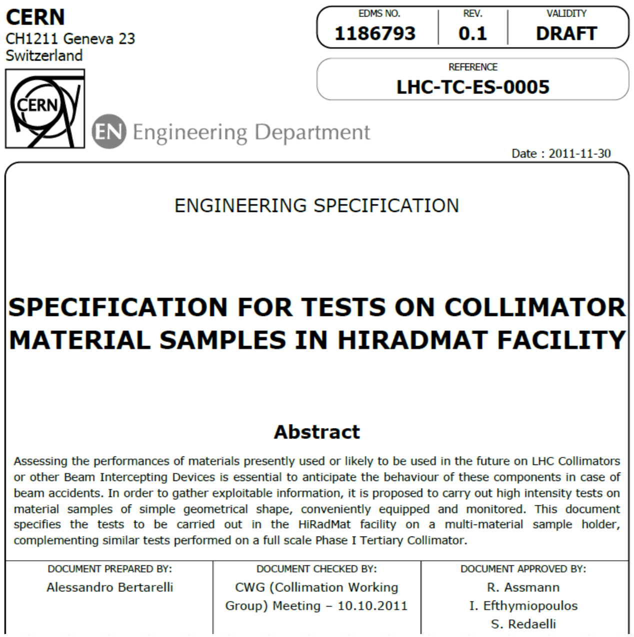
ENGINEERING SPECIFI

REQUIREMENTS FOR 2012 ASSEMBLED COLLIMAT COLLIMATOR MATERIAL S HIRADMAT FAC

ABSTRACT:

The robustness of complete collimators in case of bean their installation in the LHC.
Additionally, assessing the performances of materials p in future LHC Collimators or other Beam Intercepting I behaviour of these components in extreme conditions.
This document describes the tests to be performed in the HiRadMat facility on a Phase I Tertiary Collimator (T Collimator prototype and a series of material sampl mounted on a multi-material sample holder.

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:
R. Assmann, A. Bertarelli, A. Rossi	O. Aberle, R. Assmann, V. Baglin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Date : 2011-11-30

ENGINEERING SPECIFICATION

SPECIFICATION FOR TESTS ON COLLIMATOR MATERIAL SAMPLES IN HIRADMAT FACILITY

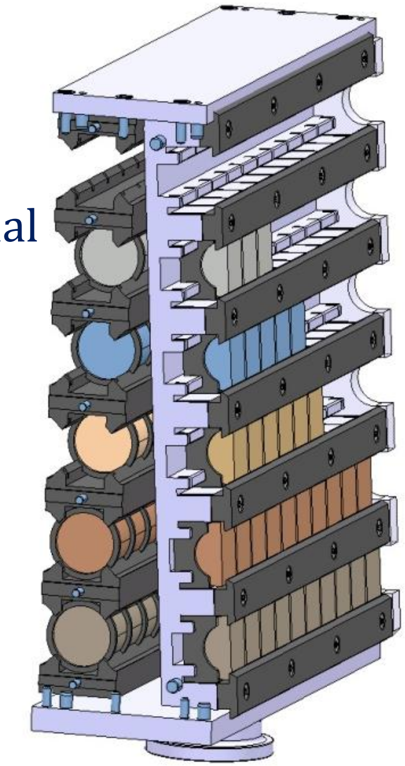
Abstract

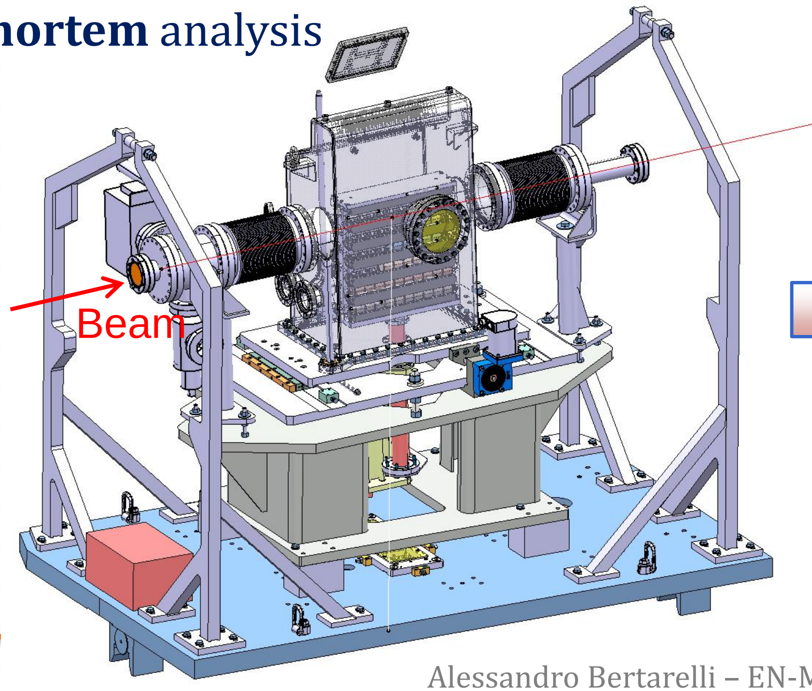
Assessing the performances of materials presently used or likely to be used in the future on LHC Collimators or other Beam Intercepting Devices is essential to anticipate the behaviour of these components in case of beam accidents. In order to gather exploitable information, it is proposed to carry out high intensity tests on material samples of simple geometrical shape, conveniently equipped and monitored. This document specifies the tests to be carried out in the HiRadMat facility on a multi-material sample holder, complementing similar tests performed on a full scale Phase I Tertiary Collimator.

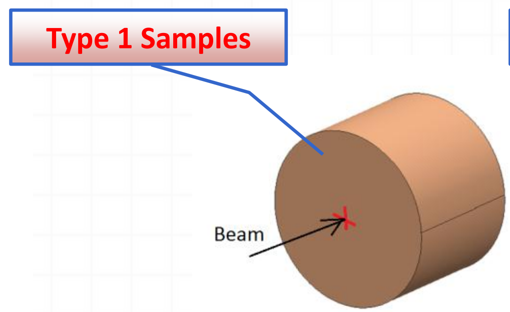
DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
Alessandro Bertarelli	CWG (Collimation Working Group) Meeting – 10.10.2011	R. Assmann, I. Efthymiopoulos, S. Redaelli

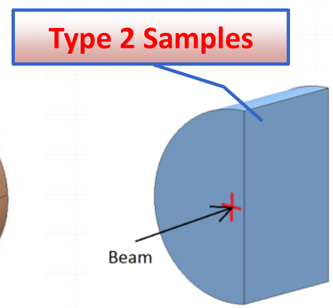
TEST SPECIFICATIONS

- Characterize **six different materials** (Inermet180, Glidcop, Molybdenum, Copper-Diamond, Molybdenum-Diamond, Molybdenum-Graphite)
- **Medium intensity** and **high intensity** tests, with different material samples for each material (Type 1, Type2)
- Each sample holder tier can host up to **10 specimens**
- Extensive **real time data acquisition**
- **Post mortem** analysis









TEST SPECIFICATIONS

- Beam energy: **440 GeV**
- Bunch spacing: **25 ns**
- Protons/bunch: 1.5E11
- Beam size: **2.5x2.5 mm²** (medium intensity) or **0.25x0.25 mm²** (high intensity)
- Up to **72 bunches** (~4 LHC bunches), limited by Be window.
- Total expected number or protons **~ 1.3E14**

Irradiation History for Inermet180 (Tungsten)

Target	Protons per bunch	Bunches per pulse	Beam size (σ_x x σ_y) [mm x mm]	Number of pulses	Time before next pulse [min]
Type 1 sample Tungsten	5e10	1	2.5 x 2.5	2	20
"	1.5e11	1	"	1	15
"	1.5e11	2	"	1	15
"	1.5e11	4	"	1	15
"	1.5e11	6	"	1	15
"	1.5e11	20	"	1	15

Target	Protons per bunch	Bunches per pulse	Beam size (σ_x x σ_y) [mm x mm]	Number of pulses	Time before next pulse [min]
Type 2 sample Tungsten	5e10	1	0.25 x 0.25	2	20
Type 2 sample Tungsten	1.5e11	60	0.25 x 0.25	1	30

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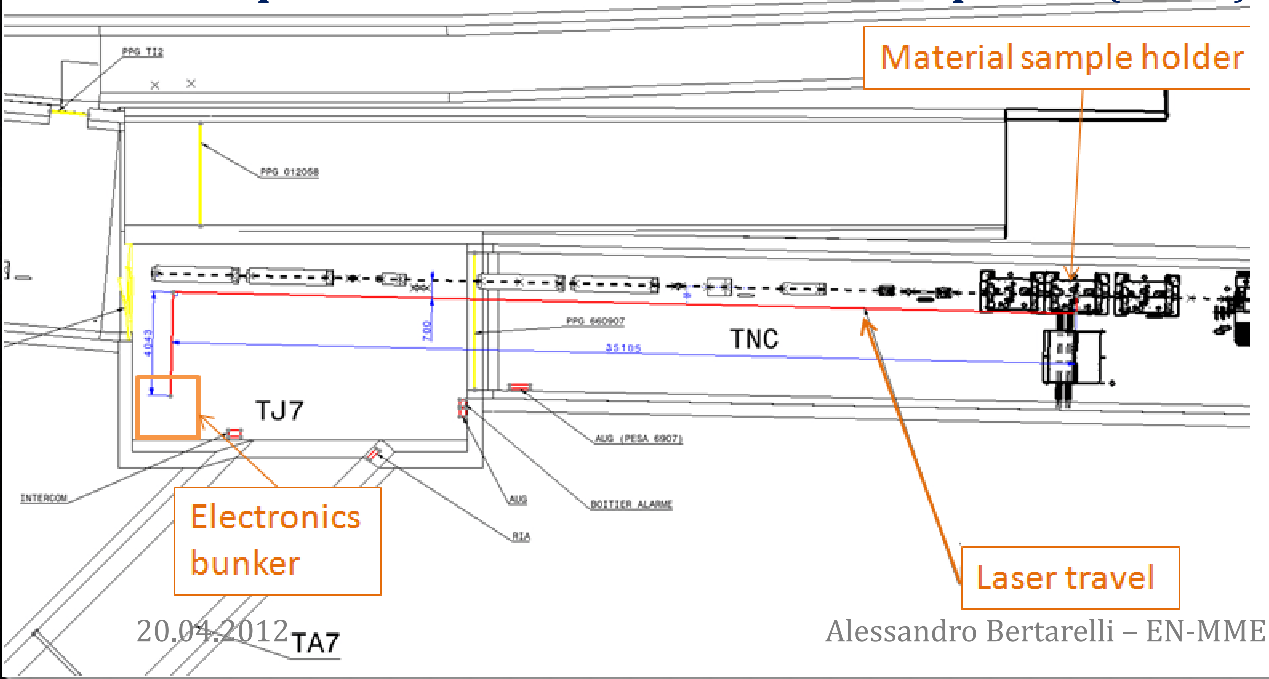
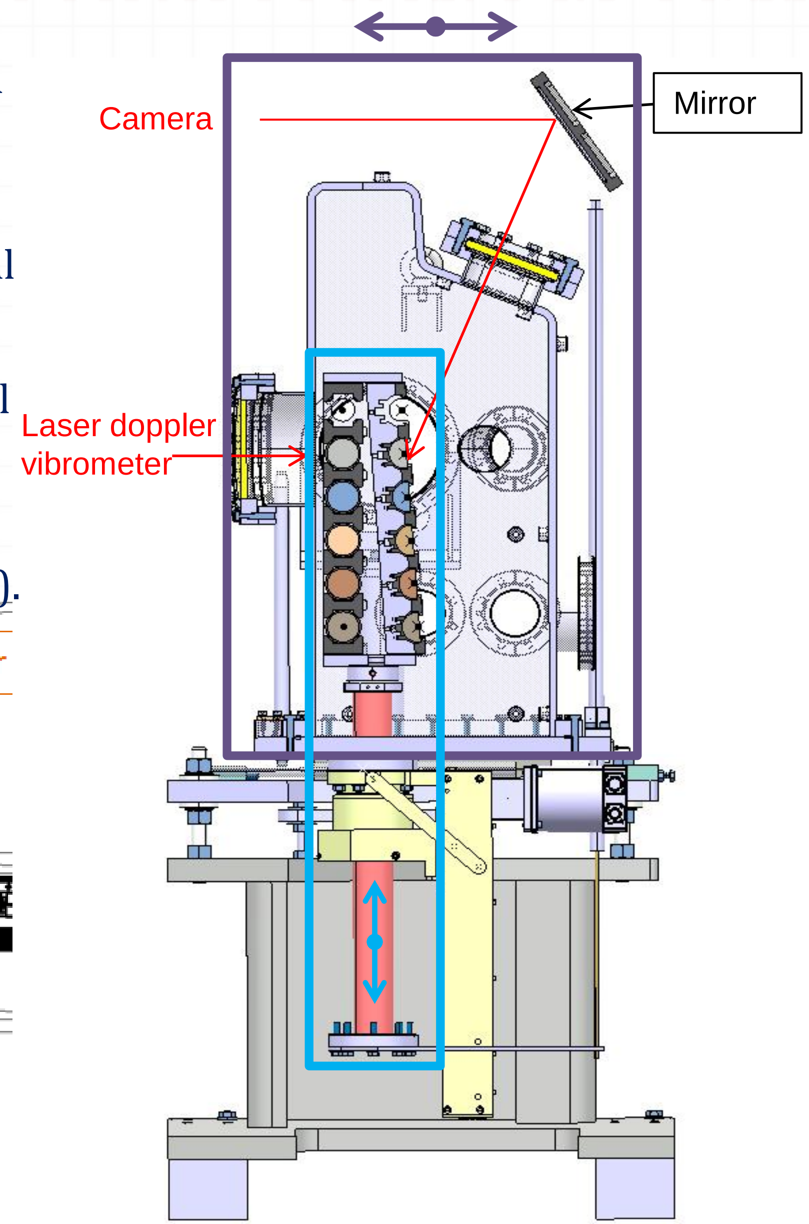
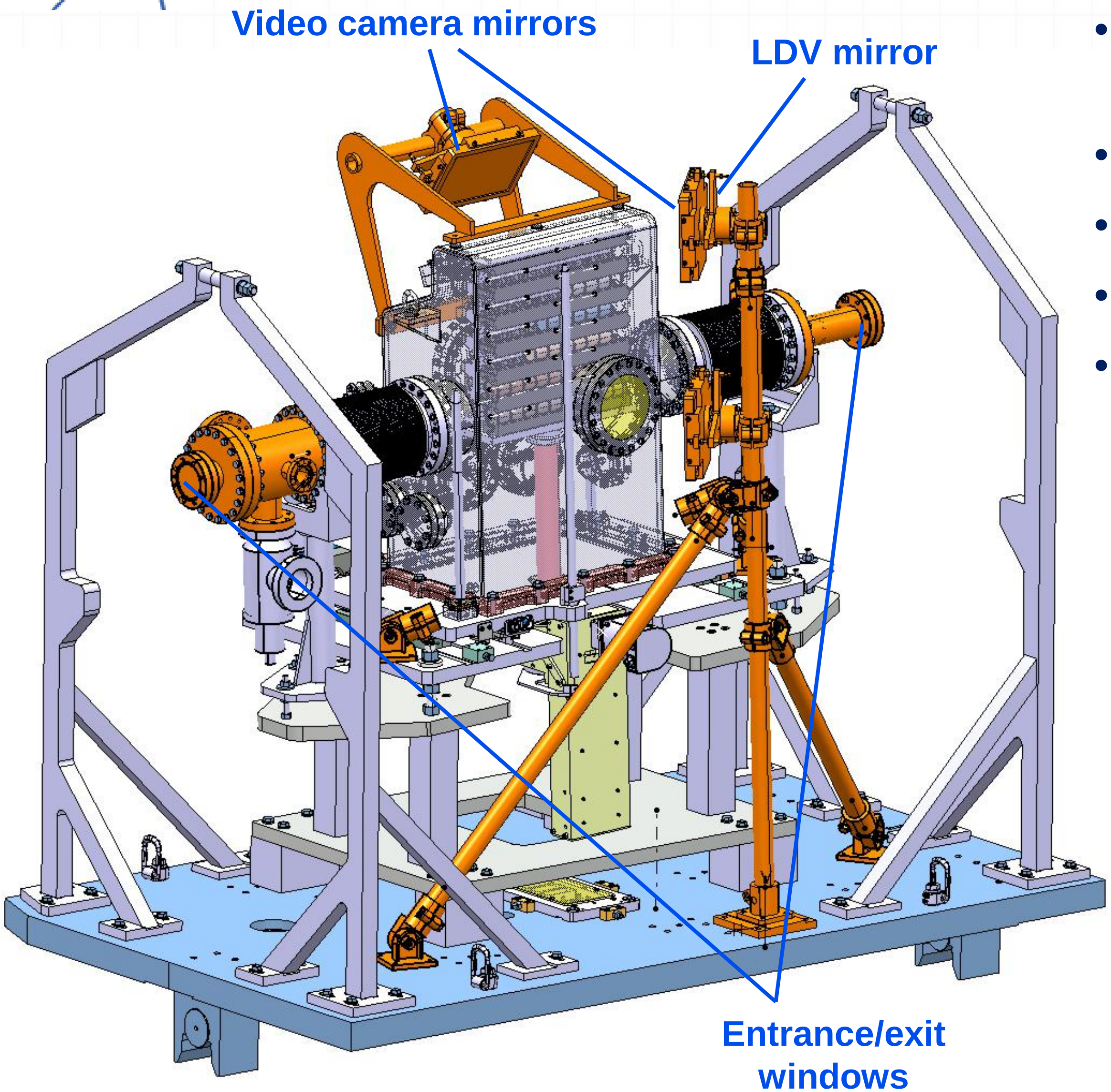
DATA ACQUISITION SYSTEM

- **LDV** (remote): measures radial velocity of outer cylindrical surface (type 1 samples). Sampling rate > 2.5 MHz
- **High Speed Camera** (remote): acquires live images of impacted type 2 samples. Capture rate up to 30kfps. Critical issue is sufficiently powerful lighting.
- **Strain gauges** (in situ): measures circumferential and axial strains generated on outer surface (type 1 and 2). Acquisition rate > 2.5 MHz.
- **Temperature** and v**acuum** sensors, **microphones** (in situ).

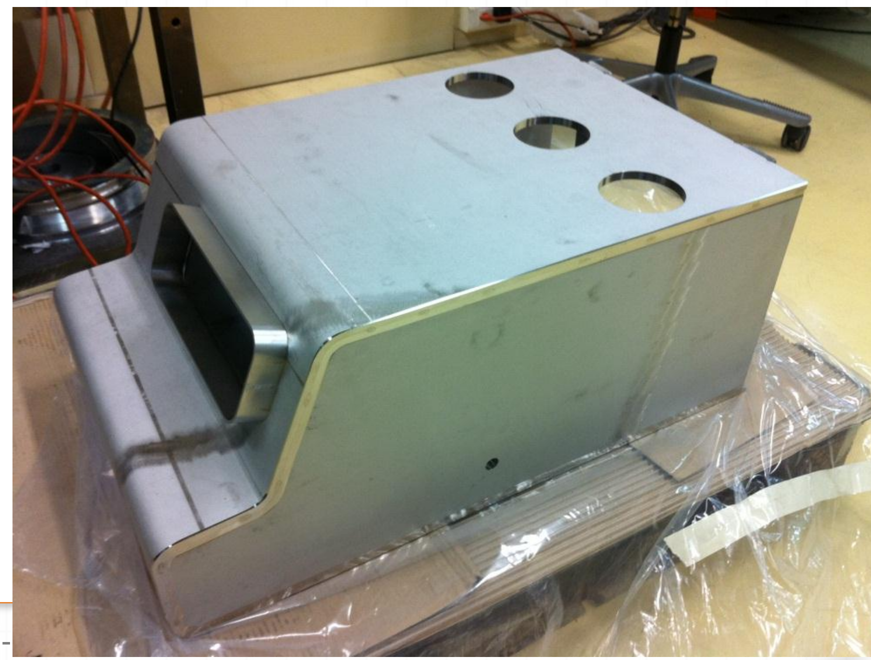




PROJECT STATUS

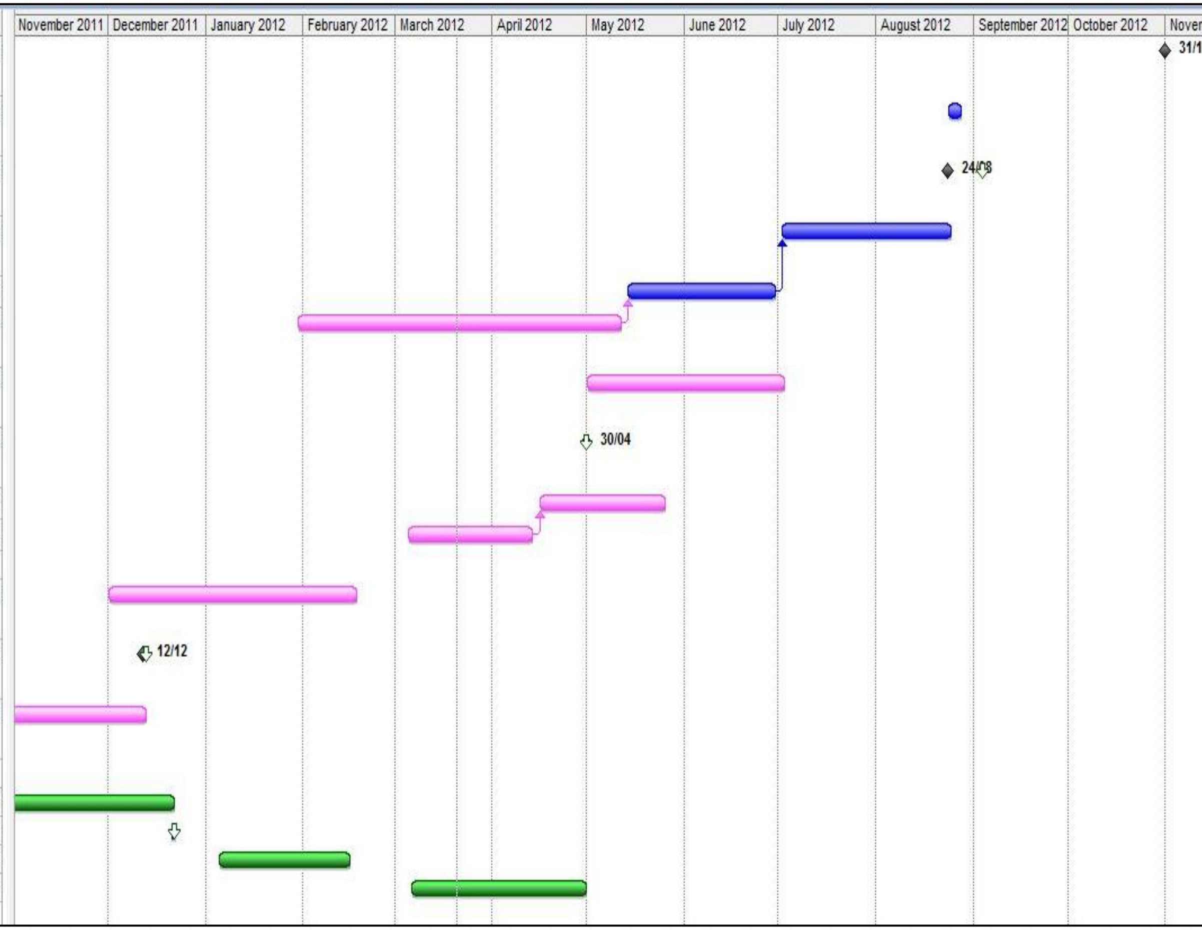


- Design very advanced, details finalization.
- Manufacturing has started.
- All main data acquisition choices made.
- New LDV purchased.
- Material samples ordered and partly delivered.



PLANNING

Task Name	Duration	Start	Finish
Last proton in LHC	0 days	Wed 31/10/12	Wed 31/10/12
Installation & run of equipment	2 days	Fri 24/08/12	Mon 27/08/12
Equipment ready to run	0 days	Fri 24/08/12	Fri 24/08/12
Validation & test of equipment	40 days	Mon 02/07/12	Fri 24/08/12
Dimensional control and Equipment alignment	35 days?	Mon 14/05/12	Fri 29/06/12
Manufacturing of mechanical sub-elements	75 days	Mon 30/01/12	Fri 11/05/12
Mechanical assembling	45 days	Tue 01/05/12	Mon 02/07/12
External sub-components received	0 days	Mon 30/04/12	Mon 30/04/12
Manifacturing of last sub-elements	30 days?	Mon 16/04/12	Fri 25/05/12
Last sub-elements design (mirrors, Be windows, vacuum pumping port)	30 days?	Mon 05/03/12	Fri 13/04/12
Equipment drawings delivery	57 days	Thu 01/12/11	Fri 17/02/12
End of the 3D design	0 days	Mon 12/12/11	Mon 12/12/11
Start of the design	66 days	Mon 12/09/11	Mon 12/12/11
Study of instrumentation adapted	78 days?	Mon 05/09/11	Wed 21/12/11
Instrumentation elements chosen	1 day?	Wed 21/12/11	Wed 21/12/11
test of equiping sample with gauges	1.5 mons	Thu 05/01/12	Wed 15/02/12
equiping all samples with gauges	2 mons	Tue 06/03/12	Mon 30/04/12



CONCLUSIONS

- EN-MME Phase II Collimator modular design permits the maximum flexibility on the choice of the active jaw material.
- A first prototype, with Glidcop jaws, is being built by MME.
- Several novel materials are under study and development for the Phase II jaw.
- MMC combining metal properties with those of graphite or diamond are particularly appealing.
- Figures of Merit were defined, allowing to pinpoint “best” candidates and to set ambitious goals.
- Cu-CD, Mo-CD and Ag-CD were studied and successfully produced. Size challenge has been met for Cu-CD and Mo-CD.
- Promising results have been achieved in the last months on Mo-Gr development; substantial room for improvement seem to exist.
- Radiation hardness assessment is almost completed for Cu-CD, still to come for the other selected materials.
- Beam tests under extreme conditions foreseen at CERN’s HiRadMat facility.
- Design of HiRadMat test bench finalized. Procurement and production ongoing.