Beam Department

Engineering Department

Workshop on Radiation Effects in Superconducting Magnets and Materials 2014 (RESMM'14)

Wroclaw University of Technology, Poland

12th – 15th May 2014

Radiation damage studies for the LHC collimator materials

Elena Quaranta

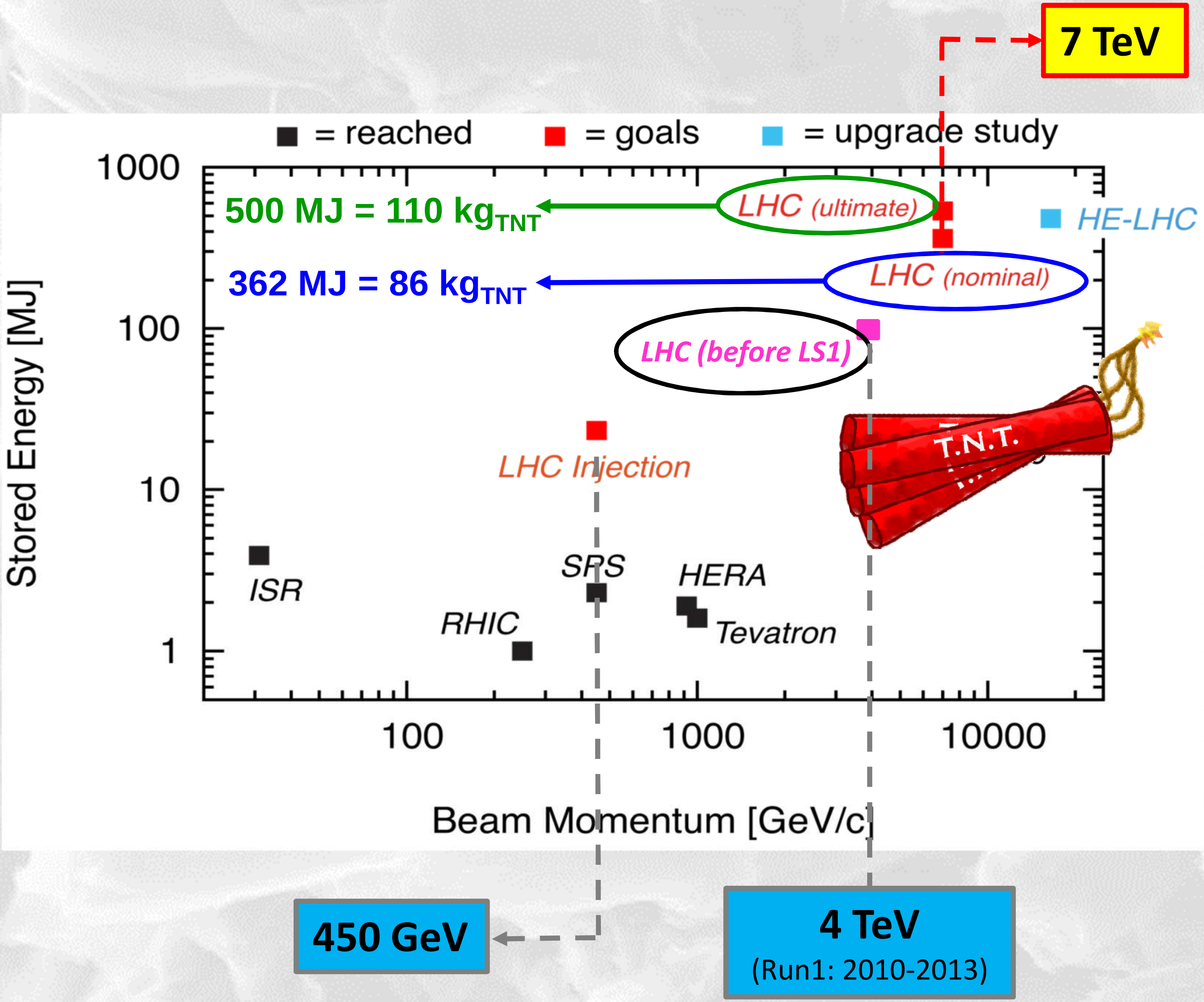
on behalf of LHC collimation team and EN-MME group

CERN, Geneva, Switzerland

Outline

- LHC Collimation System: strengths and weaknesses
- Do we need to change something?
- Material R&D for Future Collimation Upgrade
- Overview of Material Tests
- Conclusions

LHC energy challenge

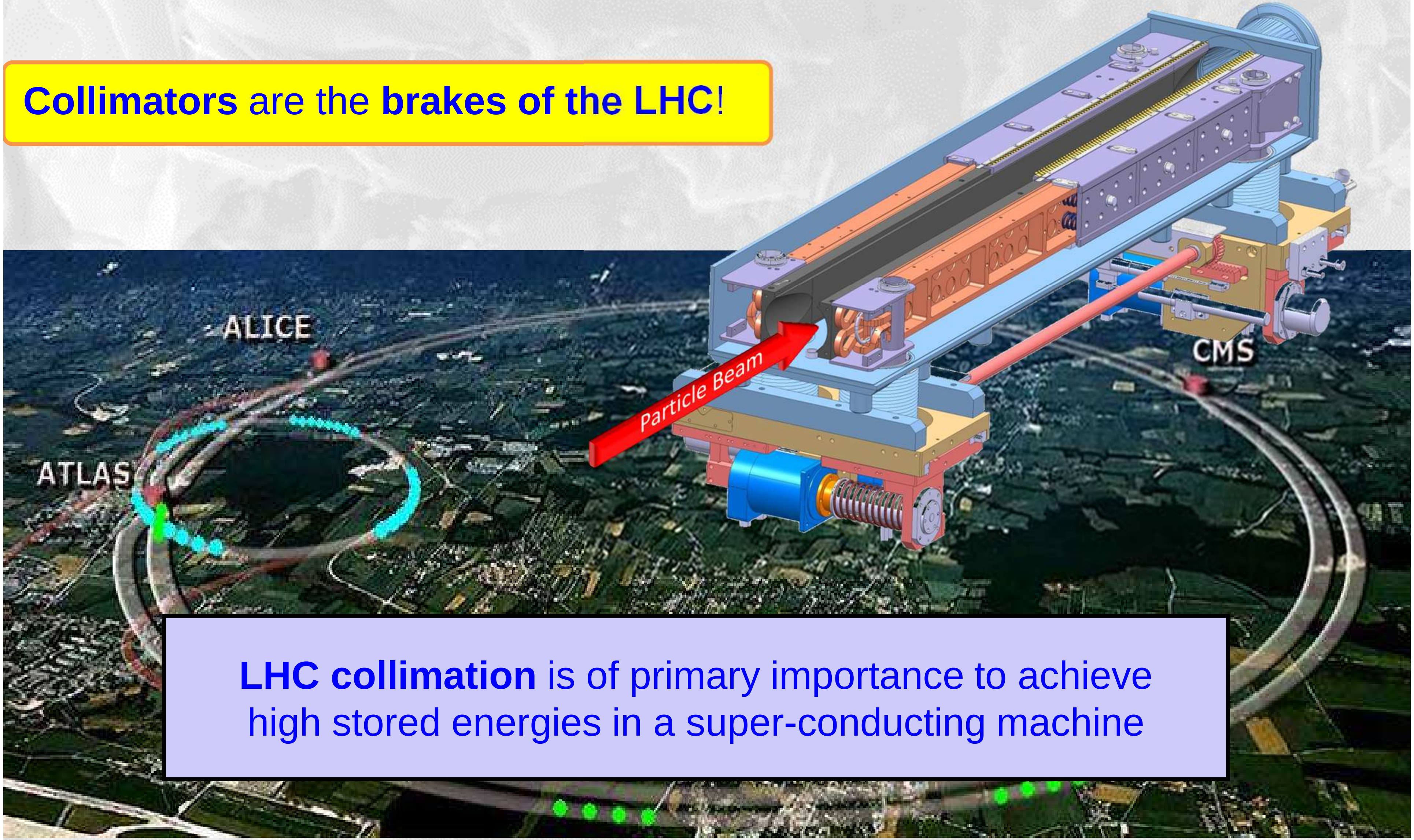


We need the best brakes!

Good brakes allow you to **go faster and safer**!

We need the best brakes!

Collimators are the **brakes of the LHC**!



LHC collimation is of primary importance to achieve high stored energies in a super-conducting machine

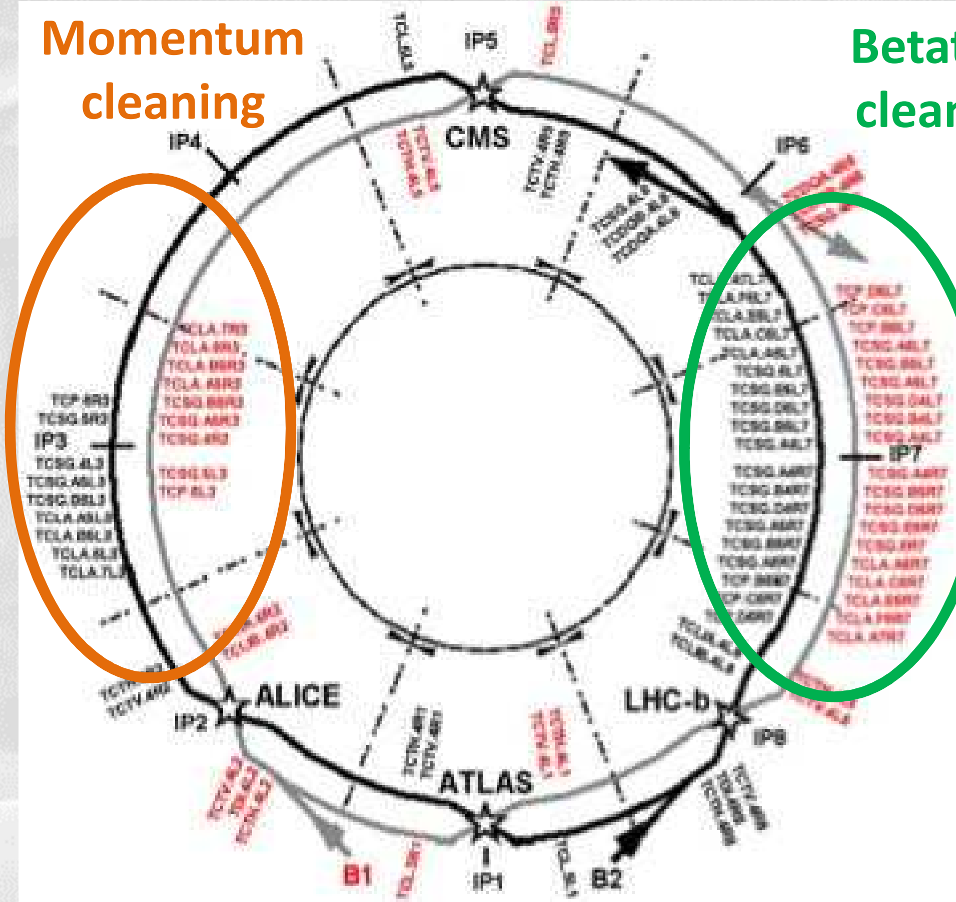
LHC collimation layout

- **Two warm cleaning insertions:**
  IR3: momentum cleaning
  - 1 Primary (H)
  - 4 Secondaries (H/S)
  - 4 Shower Abs. (H/V)

  IR7: betatron cleaning
  - 3 Primaries (H/V/S)
  - 11 Secondaries (H/V/S)
  - 5 Shower Abs. (H/V)

- **Local cleaning at triplets**
  - 8 tertiaries: 2 per IP per beam

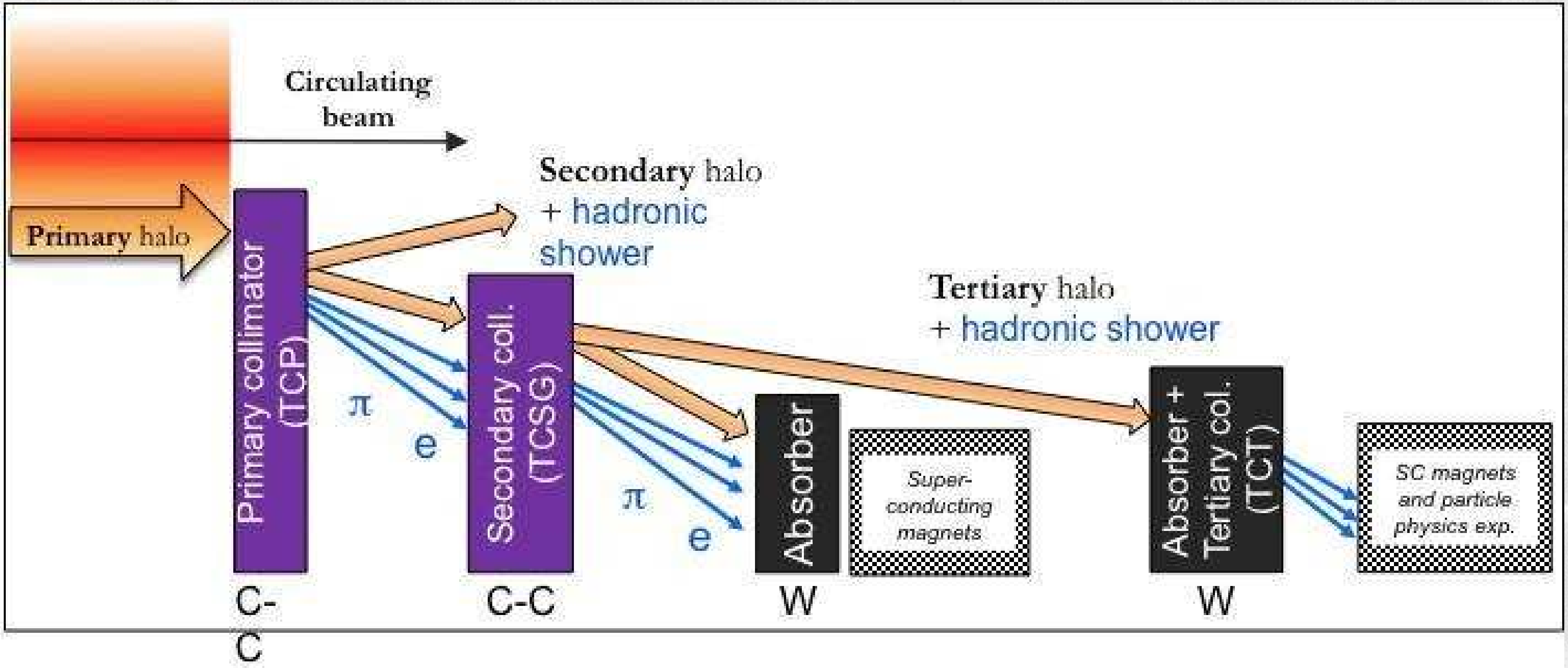
- **Physics debris absorption**
  - 2 TCL (1 per beam IP1/IP5)



8 passive absorbers for warm magnets in IP3/IP7
Transfer lines (13 collimators)
Injection and dump protection (10 collimators)

Total of 108 collimators (100 movable)

The multi-stage collimation system



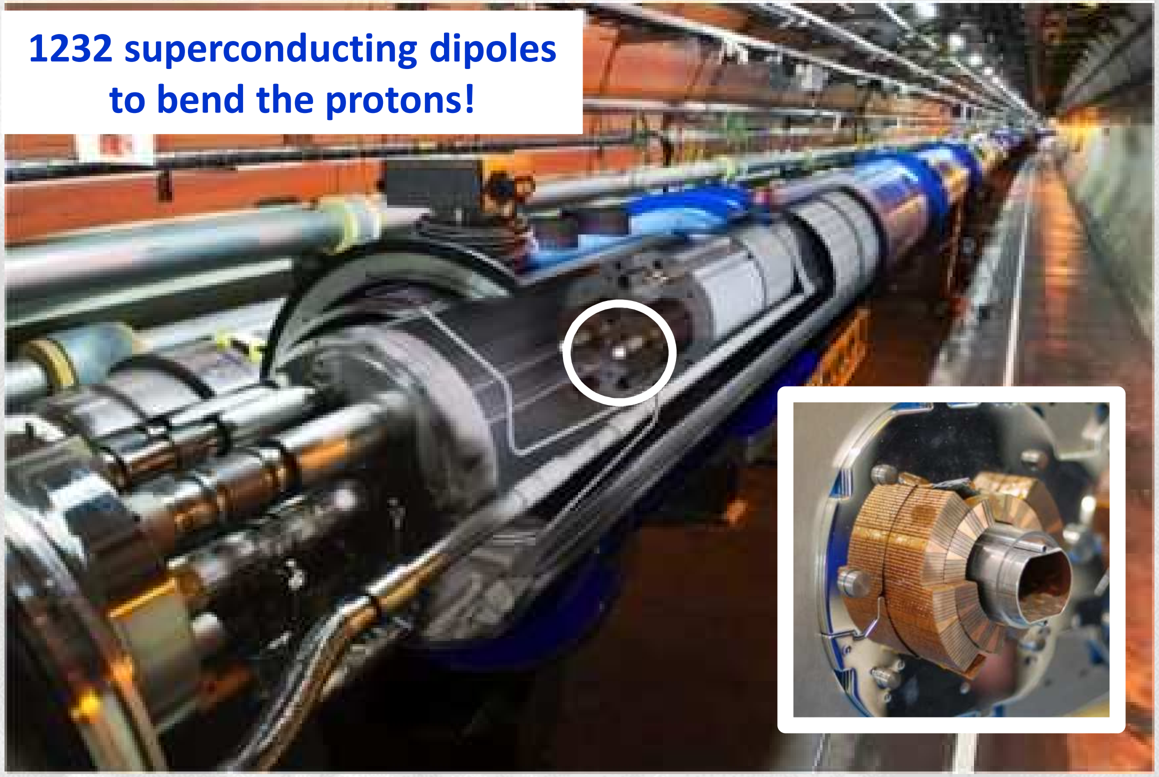
Collimation hierarchy has to be respected in order to achieve satisfactory…

…**Cleaning**: removal of unavoidable halo during standard operation

…**Machine Protection**: avoid damage during abnormal operation or failures

...and to minimize background signal in the experimental areas

Need for…high CLEANING EFFICIENCY



Collimation cleaning inefficiency

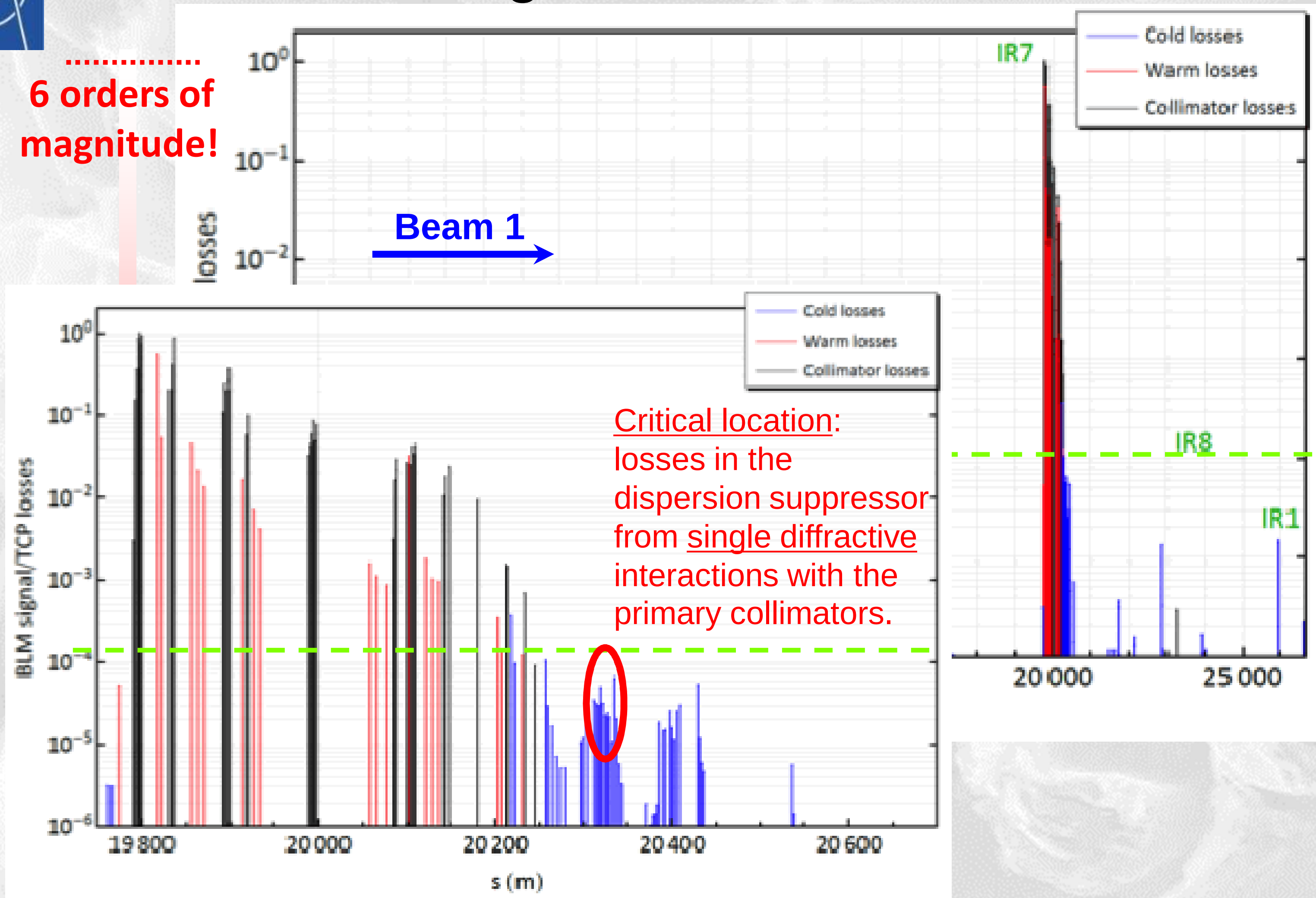
$$\eta_c = \frac{N_{loss}}{\Delta s \cdot N_{abs}}$$

Out-of-core particles (halo) might be lost in machine aperture, quenching the SC magnets.

Cold magnets must stay below their quench limit!

Collimation system MUST guarantee → **HIGH CLEANING EFFICIENCY** (less than 2 particles out of 10000 allowed to escape)

Need for…high CLEANING EFFICIENCY

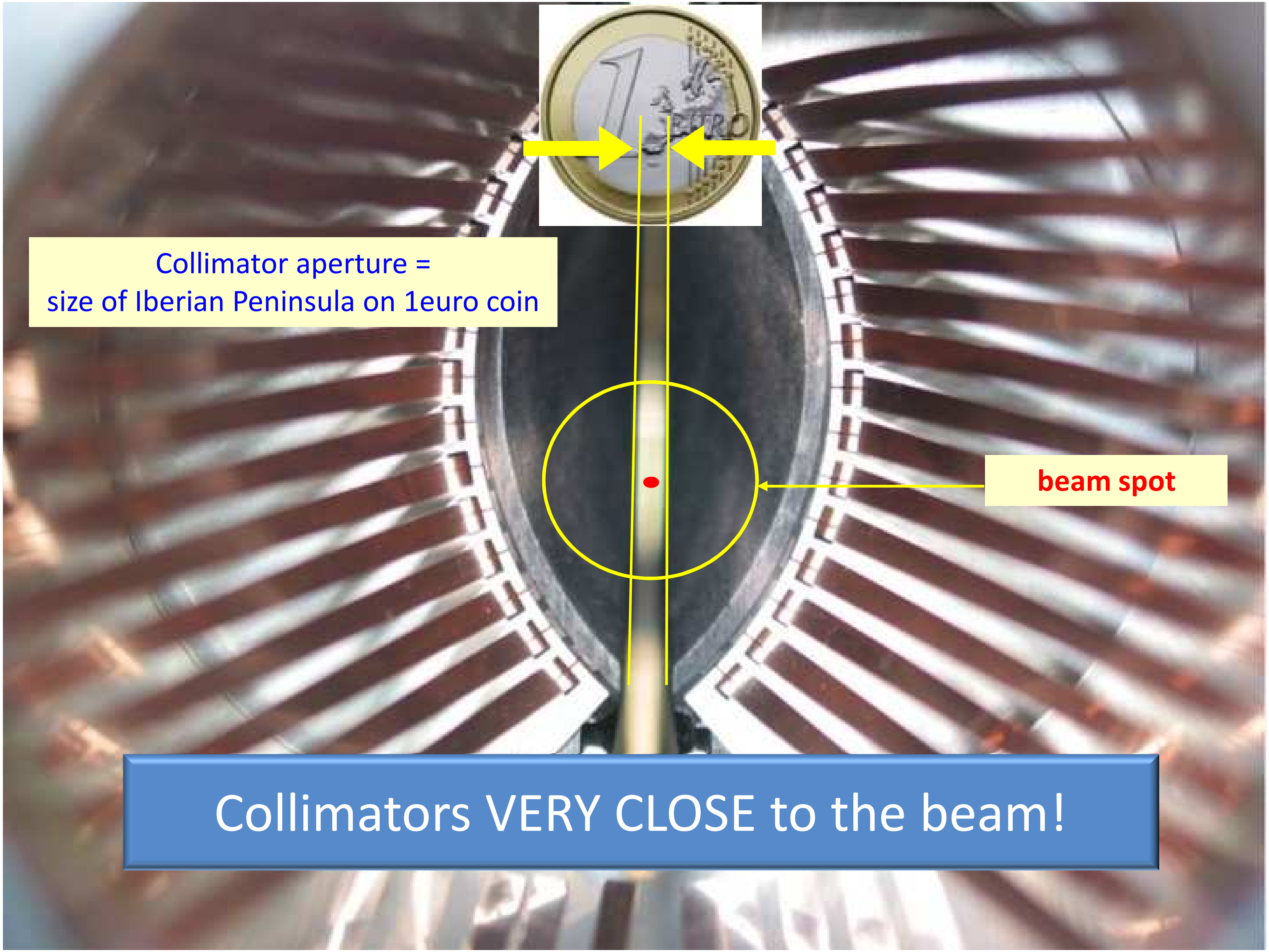


NB: η_c is appox. by ratio of BLM signal to losses at TCP

Cleaning Inefficiency at quench limit

at 4TeV (meas. 28/11/12)

LHC "Run 1" 2010-2013: No quench with circulating beam, with stored energies up to 145 MJ per beam!

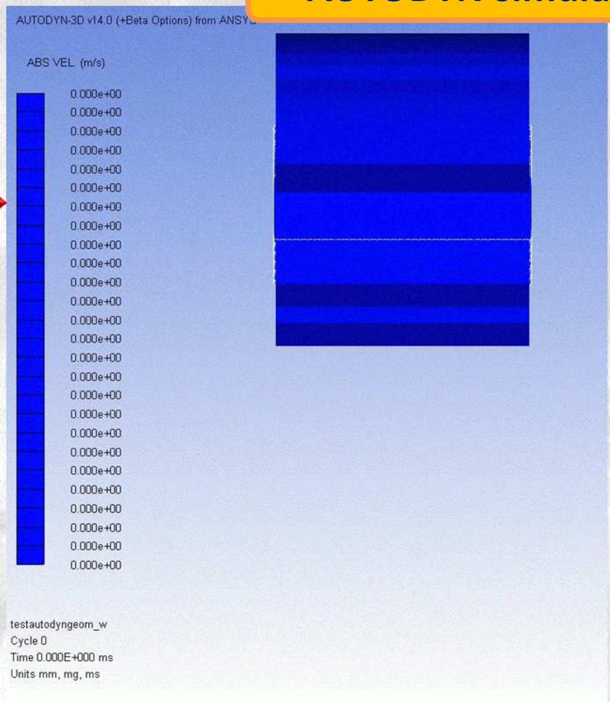

Collimator aperture =
size of Iberian Peninsula on 1euro coin
beam spot
Collimators VERY CLOSE to the beam!

Need for...ROBUSTNESS

Beam-induced material damages due to
- instantaneous **high intensity impacts** (failure scenarios)
- **long-term irradiation**

AUTODYN simulation

Beam



Beam

Collimators MUST be: **ROBUST to withstand high intensity beam impact in case of failure**

Need for… RADIATION HARDNESS

Beam-induced material damages due to
- instantaneous **high intensity impacts**
- **long-term irradiation** (normal operation)

Collimators are subject to high level of radiation doses during the normal LHC operation which lead to DRAMATIC CHANGES in the material properties:

- Decrease in thermal conductivity
- Increase in electrical resistivity → Does it affect the machine IMPEDANCE?
- Increase in Young’s modulus

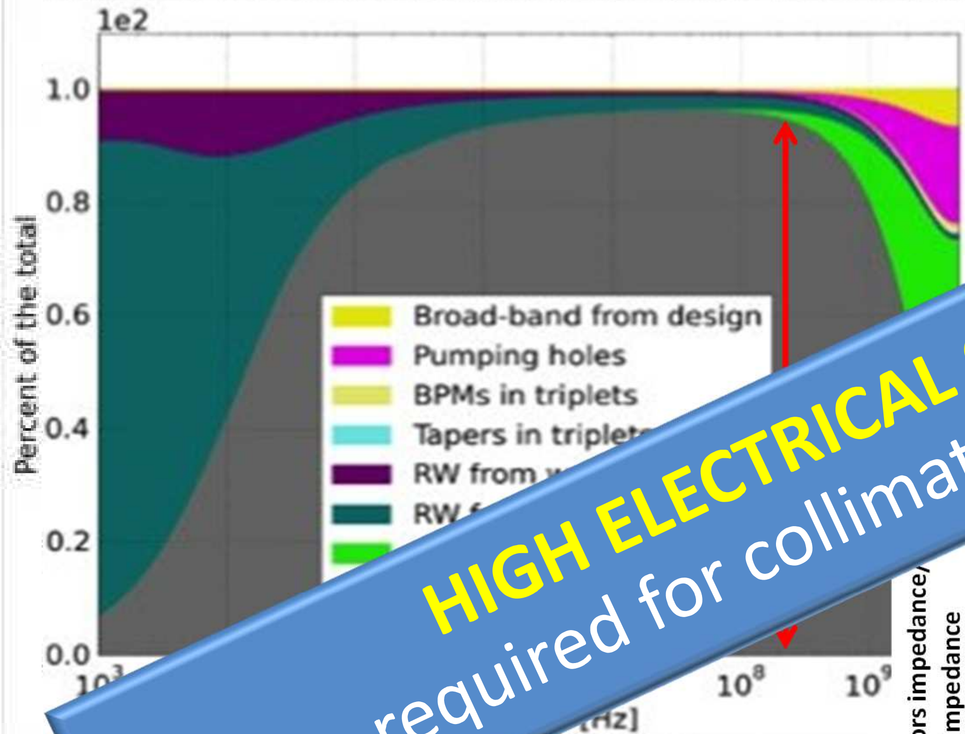
IMPEDANCE: why collimators are critic?

Like the wakes of a ship diffuse in the ocean and perturbs the ships behind…

…bunched charged particles passing through an insulator experience an high electrical resistance, which might generate instability for the next bunches…

IMPEDANCE: why collimators are critic?

Close distance of collimator material to beam induces strong impedance for the LHC beam: possible instabilities and higher losses.



Collimator material give t

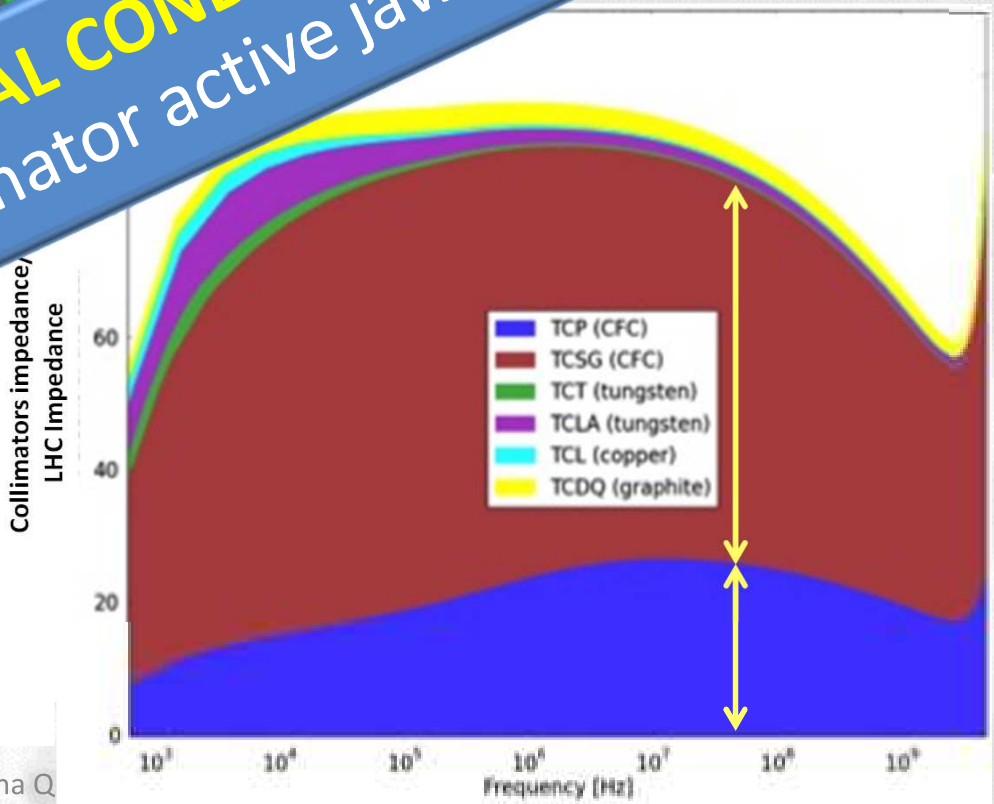
contributor to whol

Electrical r

ide

... μΩm for CFC material).

The biggest part of collimator impedance is due to **CFC collimator**, mainly secondaries (TCSGs)



HIGH ELECTRICAL CONDUCTIVITY
is required for collimator active jaw material

Need for… RADIATION HARDNESS

Beam-induced material damages due to
- instantaneous **high intensity impacts**
- **long-term irradiation** (normal operation)

Collimators are subject to high level of radiation doses during the normal LHC operation which lead to DRAMATIC CHANGES in the material properties:

- Decrease in thermal conductivity
- Increase in electrical resistivity → Does it affect the machine IMPEDANCE?
- Increase in Young's modulus

Property degradation contributes in REDUCING the collimator LIFETIME…

…we might need to replace the collimator earlier than the foreseen!

Collimator materials MUST → **MINIMIZE the WORSENING of phys/mech properties due to radiation-induced effects**

LHC collimator will not last forever!

- ☑ **How much will the present collimators last?**
- ☑ **How to estimate their lifetime?**
- ☑ **How do their physical-mechanical properties degrade?**

What we know in terms of…

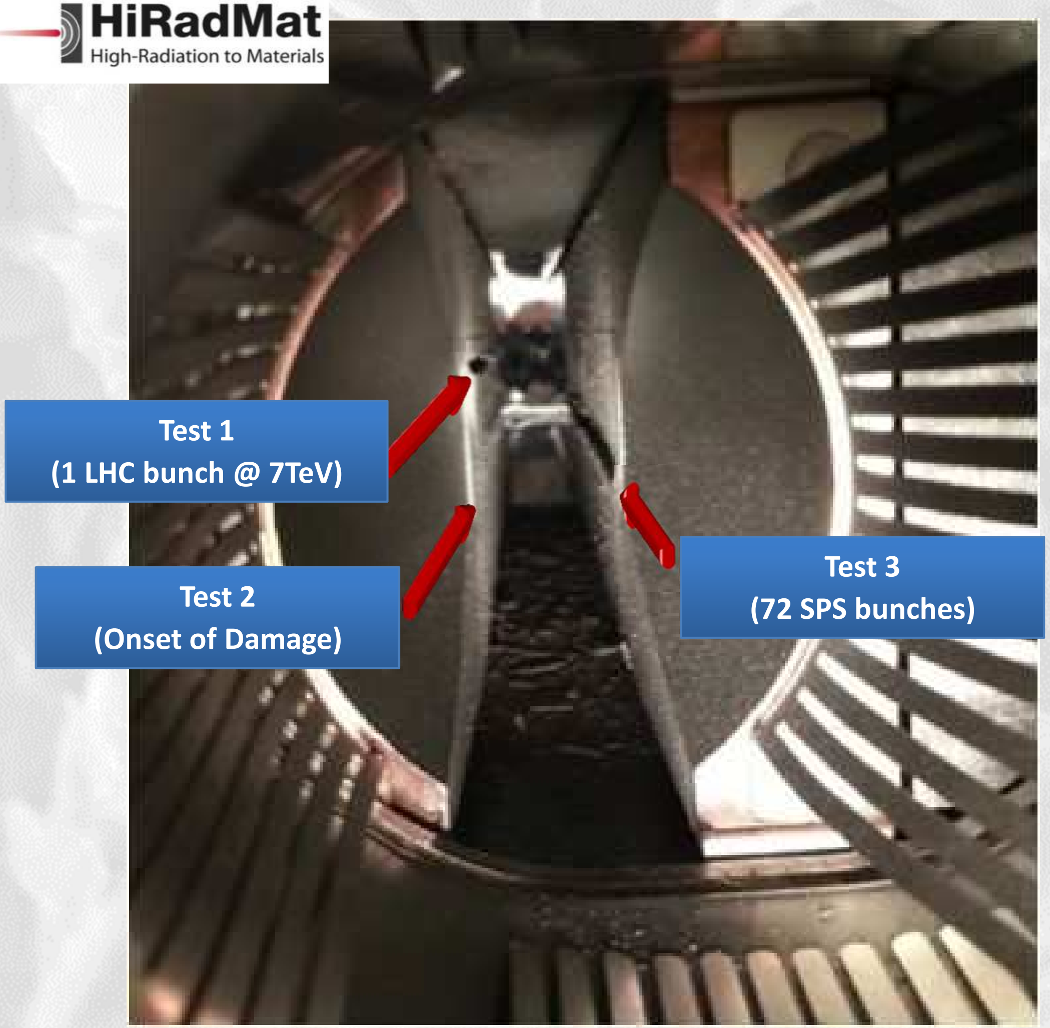
- **ROBUSTNESS**, in case of failure on TCTs:
  - ✓ **HRMT09** in HiRadMat facility at CERN

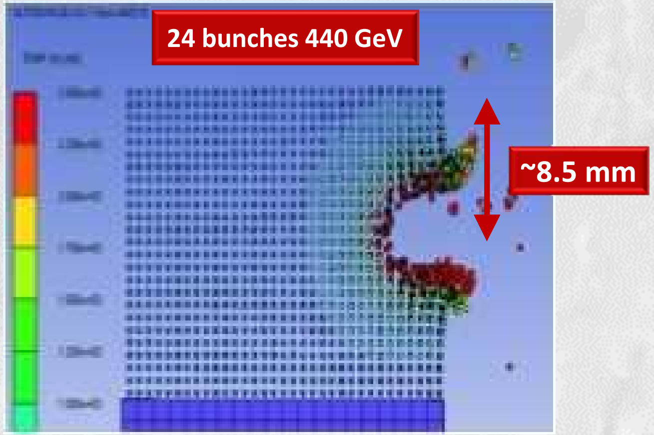
- **DOSES**, in terms of property degradation:
  - ✓ **CFC irradiation** (and post-irradiation analysis) at RRC-KI, BNL and GSI (on-going)

HRMT09 experiment (@CERN)

Objective: **verify the robustness and performance integrity of a fully assembled tertiary collimator (W-based) in case of direct beam impact (destructive test).**

HiRadMat
High-Radiation to Materials





- Good matching between tests and simulations (e.g. groove height)
- Impressive **quantity of tungsten ejected** (partly bonded to the opposite jaw, partly fallen on tank bottom or towards entrance and exit flanges)
- **Vacuum degraded**
- **Tank contaminated**

Radiation Tests on CFC (@NRC-KI)

CFC samples (AC-150) were tested at Kurchatov Institute under radiation environment of 10^{17}-10^{19}p/cm^2 of up to 30 MeV.

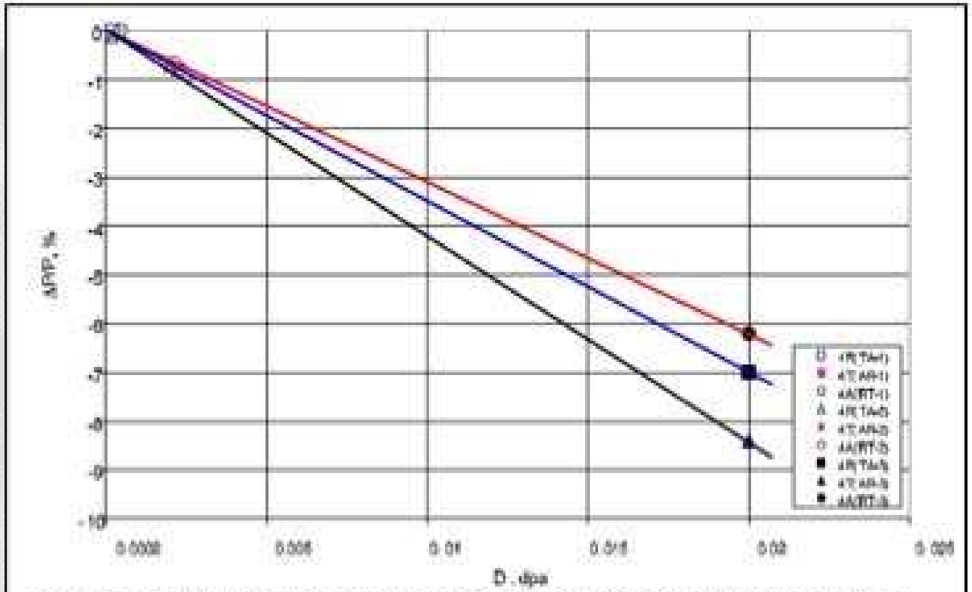


Fig.48. The relative change in density of samples for AC-150 material depending on the doses.

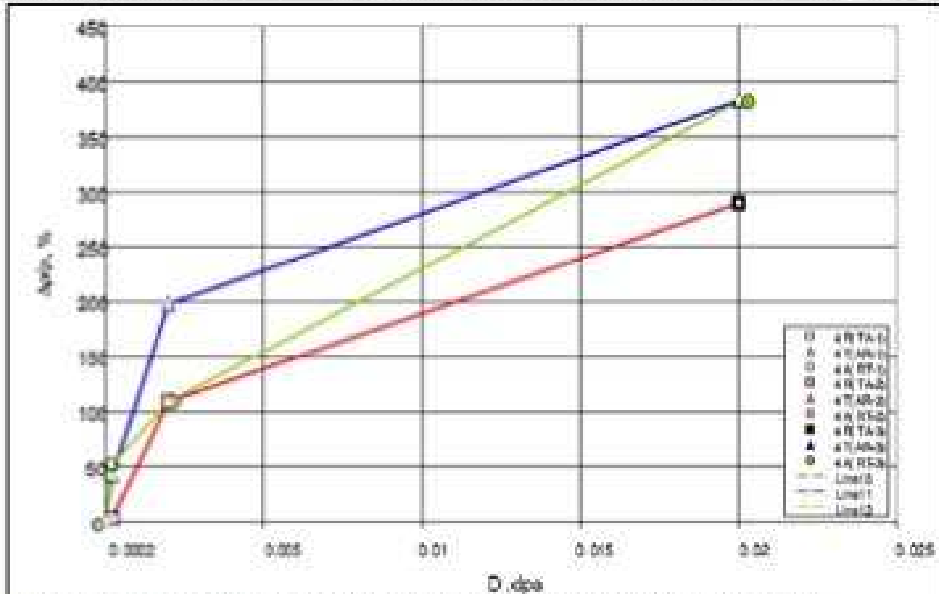


Fig. 50. The relative change in resistivity of samples for AC-150 material depending on the doses.

Courtesy of A. Ryazanov

Dramatic property degradation was observed:

- Δ volume = +1.5%
- Δ elastic modulus = +50%
- Δ thermal conductivity = -70/80%
- **Δ electrical resistivity = +350%!!!**

Factor UNACCEPTABLE for LHC collimator material!!

Do we need to change?

High worsening of electrical properties in CFC collimators poses strong constrain in terms of beam performance in the LHC.

Remember: high contribution of CFC collimator to total impedance (see slide 14)

Which are the ALTERNATIVES???

R&D on NOVEL ADVANCED MATERIAL is on-going…

R&D focused on **Metal Matrix Composites** (**MMC**) with **Diamond** or **Graphite** reinforcements.

The goal is to combine the properties of Diamond and Graphite (**high *k*, low** ρ and **low CTE**) with those of Metals ($\boldsymbol{\sigma_{el}}$, …).

Metal Matrix Composites

- Materials investigated are **Copper-Diamond** (Cu-CD), **Molybdenum-Diamond** (Mo-CD), **Silver-Diamond** (Ag-CD), **Molybdenum-Graphite** (Mo-Gr)
- Most **promising materials** are **Cu-CD** and **Mo-Gr**.
- Ag-CD and Mo-CD are limited by, respectively, low melting temperature and insufficient toughness.

Mo-CD

Ag-CD

Mo-Gr

Cu-CD

Copper-Diamond Composite

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

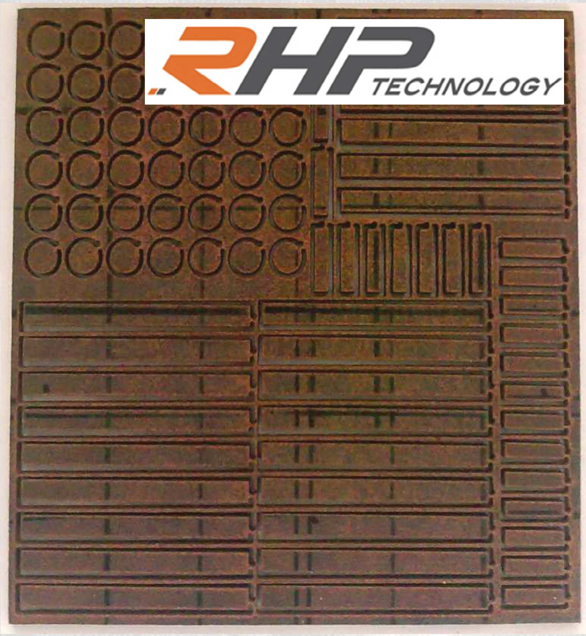
↑ No diamond degradation (in reducing atmosphere graphitisation starts at **~ 1300 °C**)

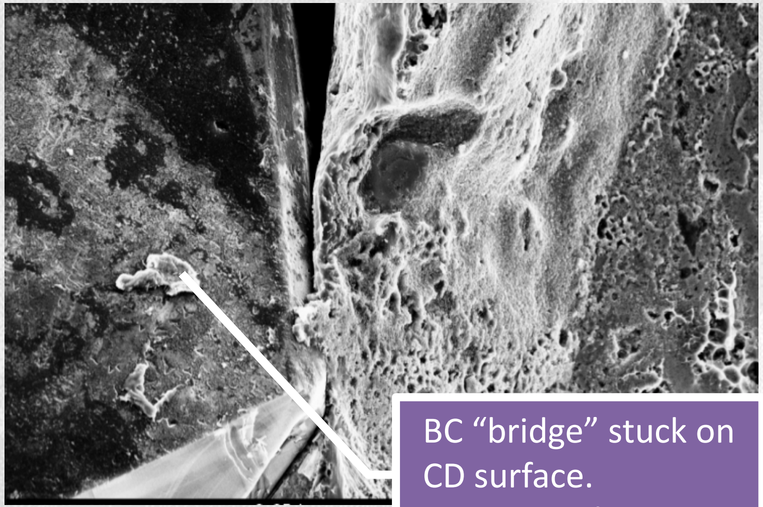
↑ Very good thermal (**~490 $Wm^{-1}K^{-1}$**) and electrical conductivity (**~12.6 MSm^{-1}**)

↔ 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**) may limit 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**)





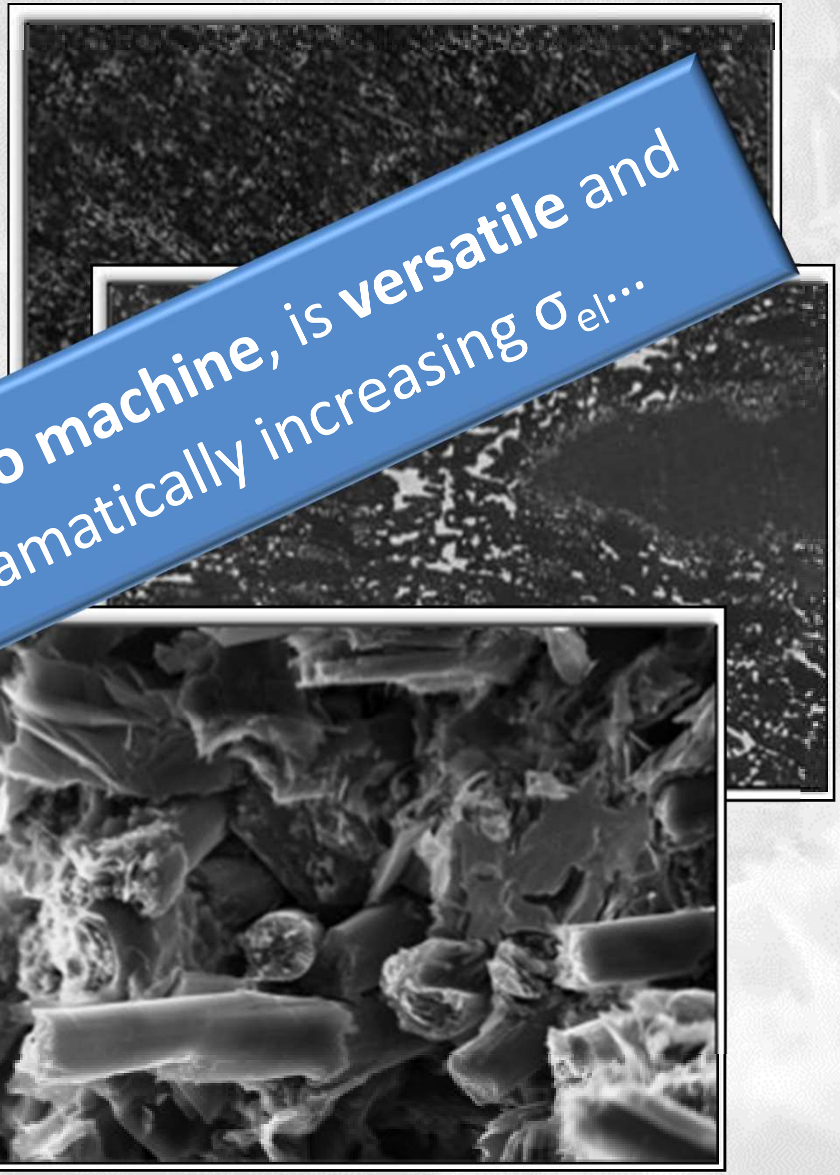
BC "bridge" stuck on CD surface.
No CD graphitization

Molybdenum-Graphite Composite

- Co-developed by **CERN** and **Brevetti Bizz** (Italy)

Composite Features

- Very high melting point (**2500+°C**)
- Low Density (can be tailored)
- **Very high thermal conductivity** (>700
- Highly stable (forms MoC_1
- Fair electrical cond
- Mechani



Particularly appealing as it is **easy to machine**, is **versatile** and can be **coated with a Mo layer** dramatically increasing σ_{el}…

Which is the best choice?

To define the material for a future secondary collimator jaw, we need to:

- Quantify **robustness** in case of accident
- Understand **behaviour** (change of property) in highly **irradiation environment**

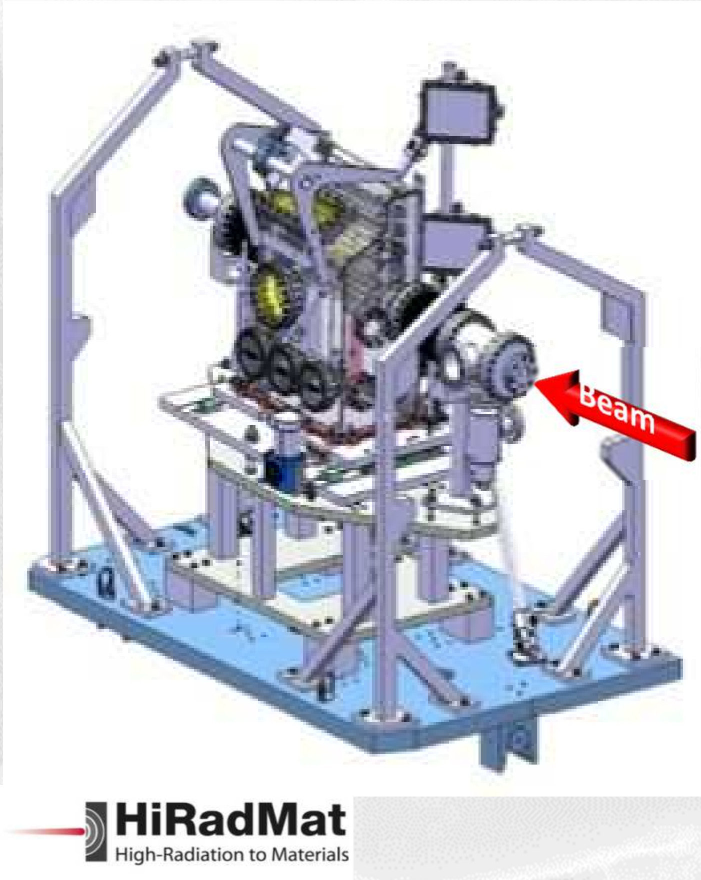
We need help from

the community of experts!

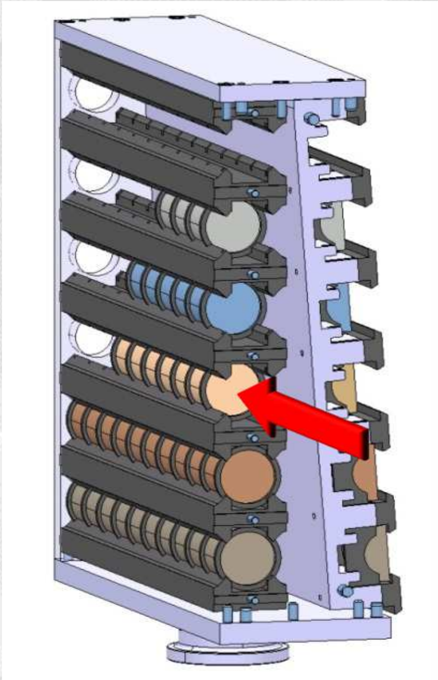
…where are we now?

HRMT14 experiment (@CERN)

Objective: Controlled beam test on a multi-material test bench hosting a variety of specimens conveniently instrumented for online and offline measurements.



- **Six different materials** (Inermet 180, Glidcop, Mo, Cu-CD, Mo-CD, Mo-Gr)



- **Medium intensity** and **High intensity** tests, with different material samples for each material (Type 1, Type2)

HRMT14 (@CERN): Results

Inermet 180, 72 bunches

Molybdenum, 72 & 144 bunches

Glidcop, 72 bunches (2 x)

Copper-Diamond
144 bunches

Molybdenum-Copper-Diamond
144 bunches

Molybdenum-Graphite (3 grades)
144 bunches

Irradiation studies on CuCD at KI

Effect of **30 MeV proton** irradiation
(**Φ = 10^{17} p/cm²**) on physical properties

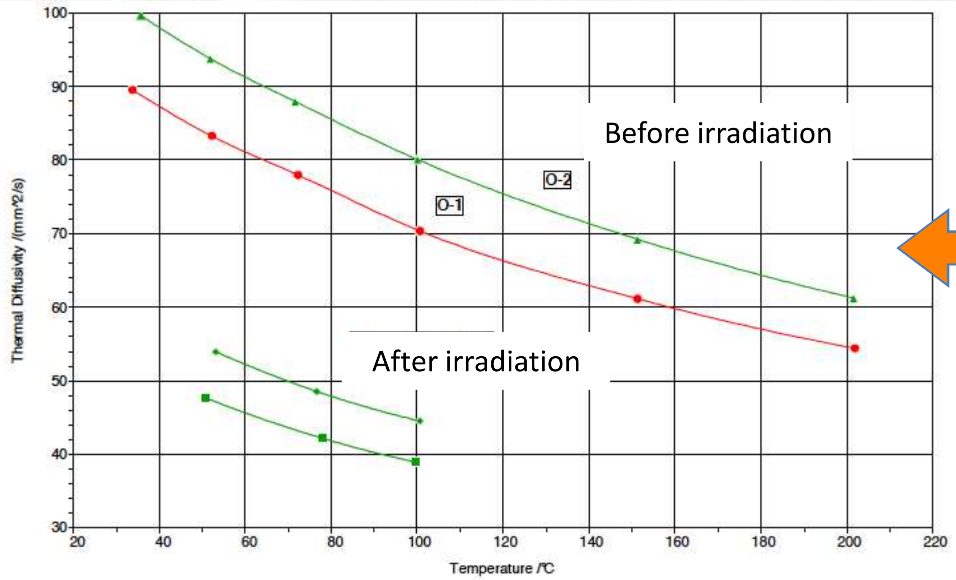


Figure 4.8 - Temperature dependence of the thermal diffusivity of the O-1 and O-2 Copper Diamond samples before and after the first irradiation by fast protons with the energy 30 MeV and dose of irradiation $\Phi_1 = 10^{17}$p/cm².

Thermal Conductivity Reduction

Courtesy of A. Ryazanov

Young's Modulus Increase

Property at T_a	Before Irradiation	After Irradiation	Δ %
CTE [10^{-6} 1/K]	7,8	8,3	+ 6%
k [W/m/K]	490	279	– 43%
γ [MS/m]	10 ± 0.2	9.8 ± 0.2	–
E [GPa]	240 ± 50	330 ± 30	+ 40%

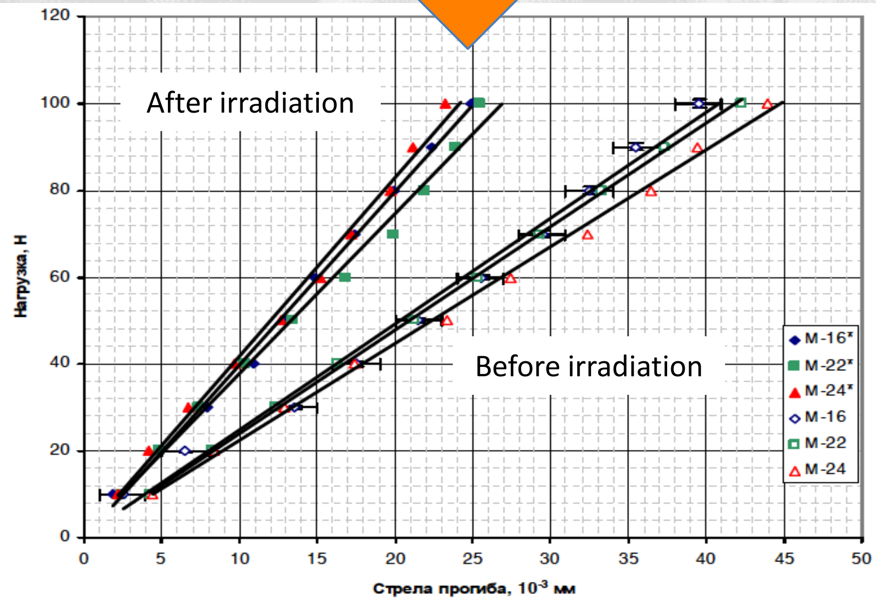


Figure 5.3 The initial parts of the "load - deflection" curves of the original (◊, □, Δ) and the first irradiation by protons with the energy 30 MeV and dose of irradiation $\Phi_1 = 10^{17}$p/cm² (♦, ■, ▲) samples during the elastic modulus (UM, UM *) measurement.

Irradiation studies on CuCD at KI

Effect of **30 MeV proton** irradiation (**Φ = 10^{18} p/cm^2**) on physical properties

Courtesy of A. Ryazanov

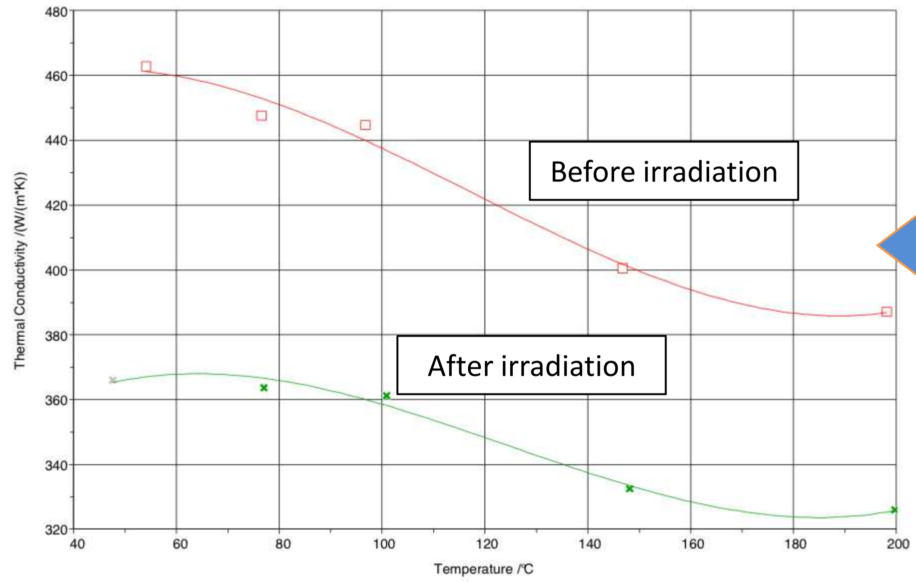


Figure 4.11 Temperature dependence of the thermal conduction of the sample O-8 before and after the second irradiation with the energy 30 MeV and dose of irradiation $\Phi_2 = 10^{18}$p/cm^2.

Thermal Conductivity Reduction

Young's Modulus Decrease

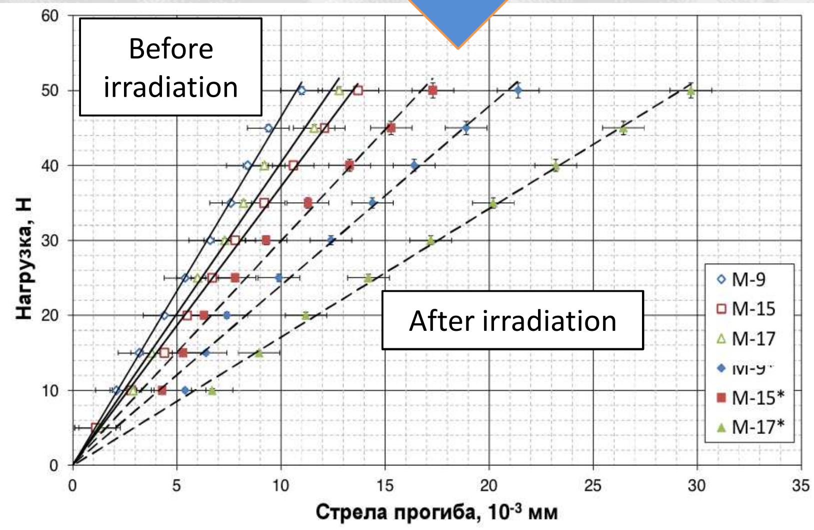
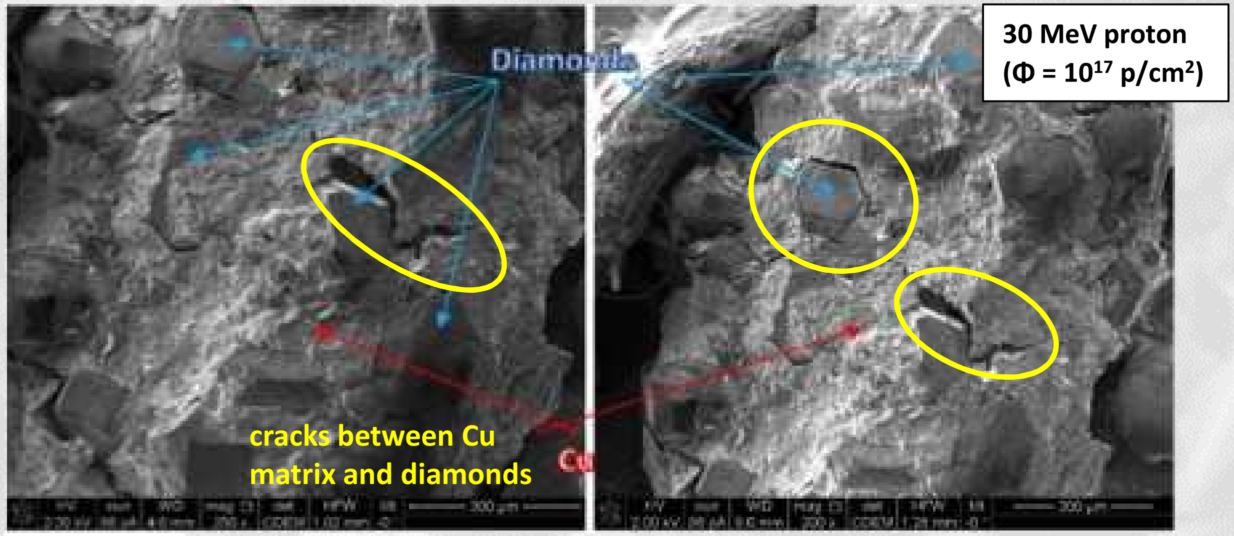


Figure 5.5 - The initial parts of the "load - deflection" curves of the initial (◊, □, Δ) and irradiated (♦, ■, ▲) samples under the elastic modulus (UM, UM *) the measurements of Copper Diamond samples after the second irradiation by protons with the energy 30 MeV and dose of irradiation $\Phi_2 = 10^{18}$ p/cm^2 (high dose).

Property at T_a	Before Irradiation	After Irradiation	Δ %
CTE [10^{-6} 1/K]	8.5	11.5	+ 35 %
k [W/m/K]	460	365	– 20%
γ [MS/m]	9.4 ± 0.2	10.3 ± 0.2	+ 10 %
E [GPa]	200± 18	114 ± 6	- 43%

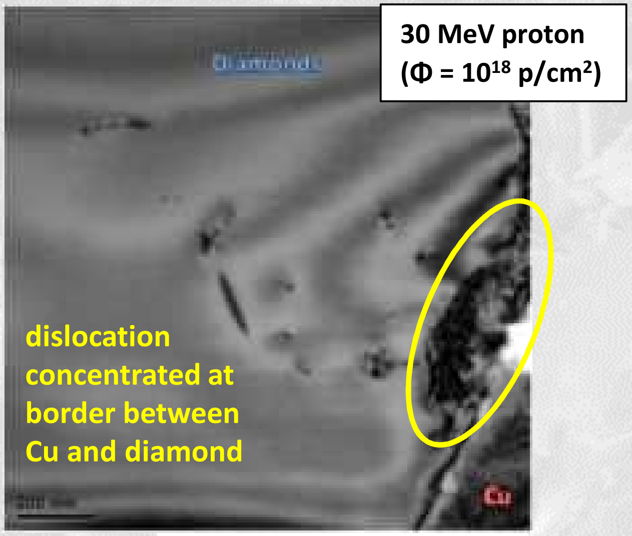
Irradiation studies on CuCD at KI

Observation and study of radiation-induced effects.

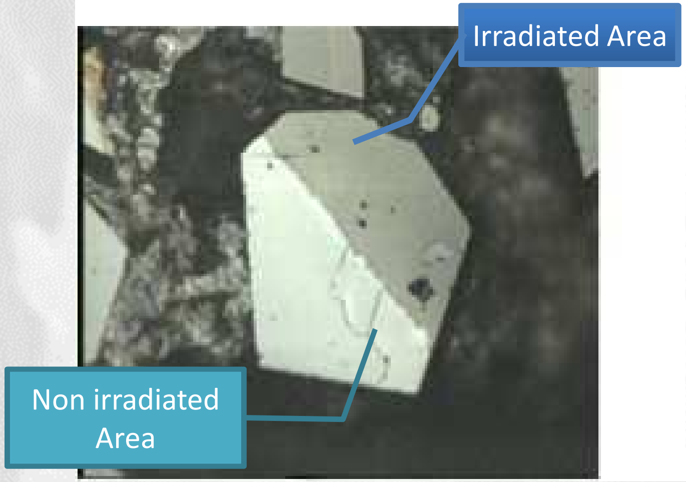


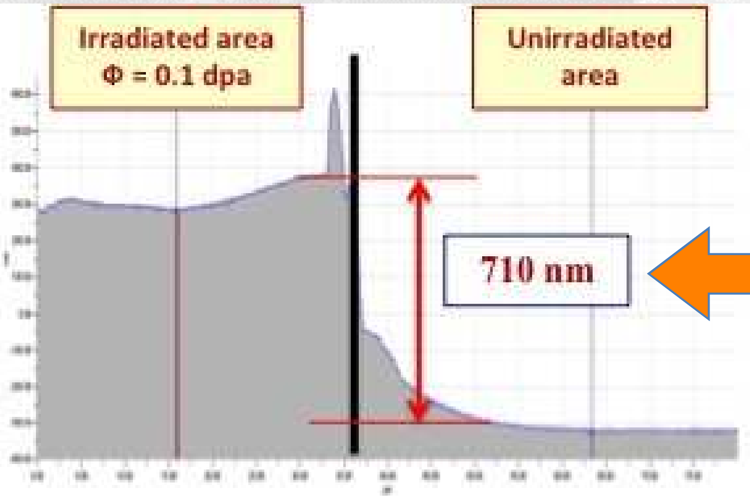
SEM images

Courtesy of A. Ryazanov



Bright Field (BF) TEM image



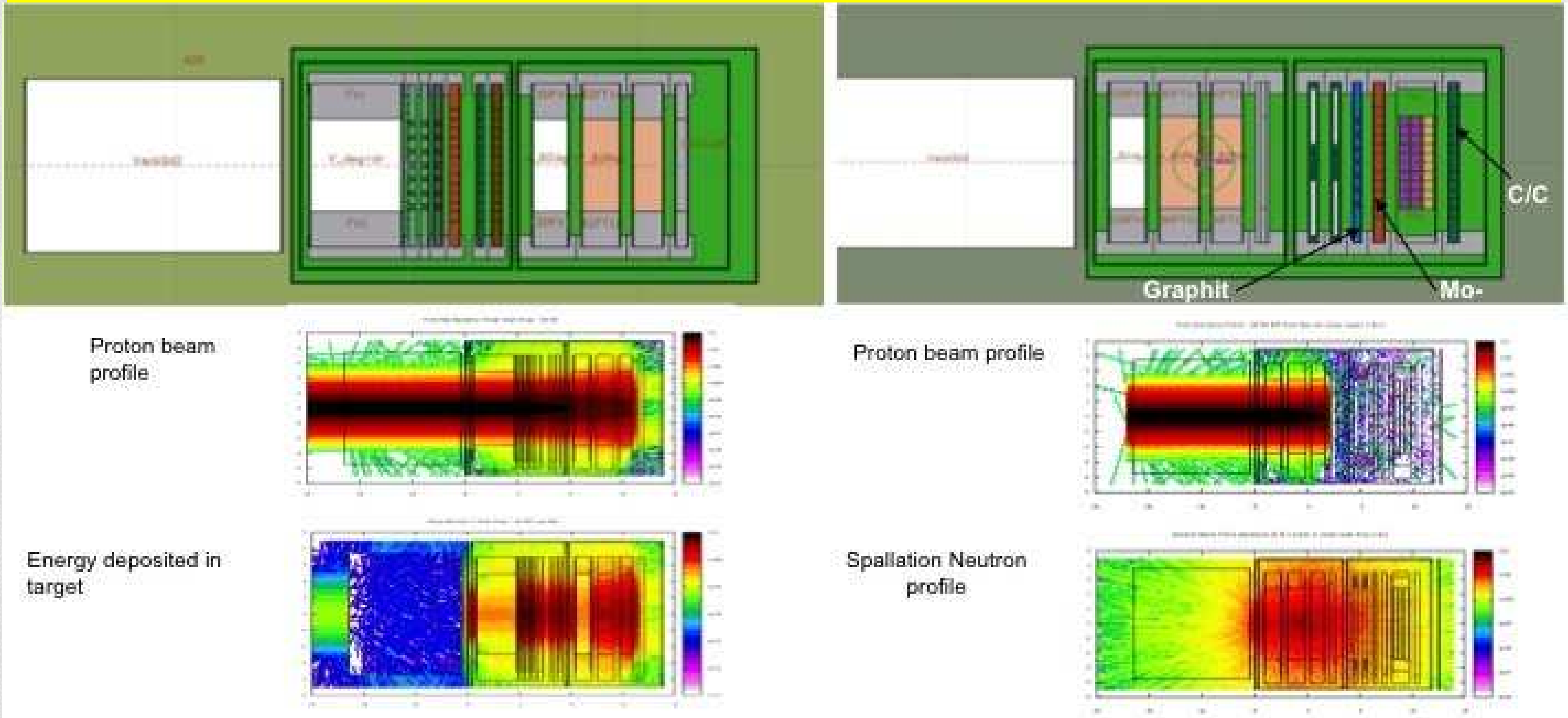


Swelling Measurement on Diamond by 26 MeV carbon-ion Irradiation

Irradiation campaign at BNL

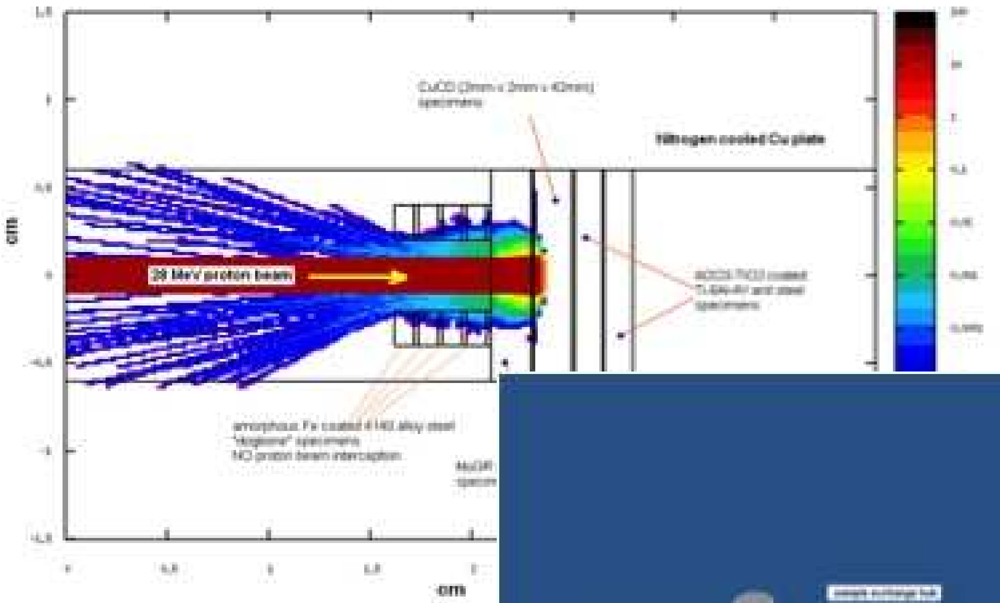
- ON-GOING irradiation and post-irradiation studies on Molybdenum, Glidcop, CuCD, MoGRCF
- Focus on radiation-induced damage and degradation of key physical and mechanical properties as well as damage annealing potential

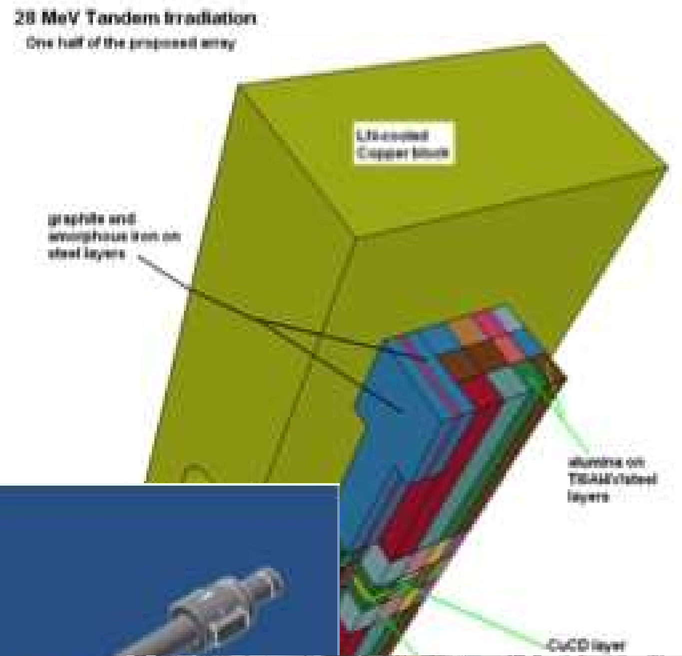
200 MeV proton and spallation neutron (by ~120 MeV protons) irradiation @**BLIP**



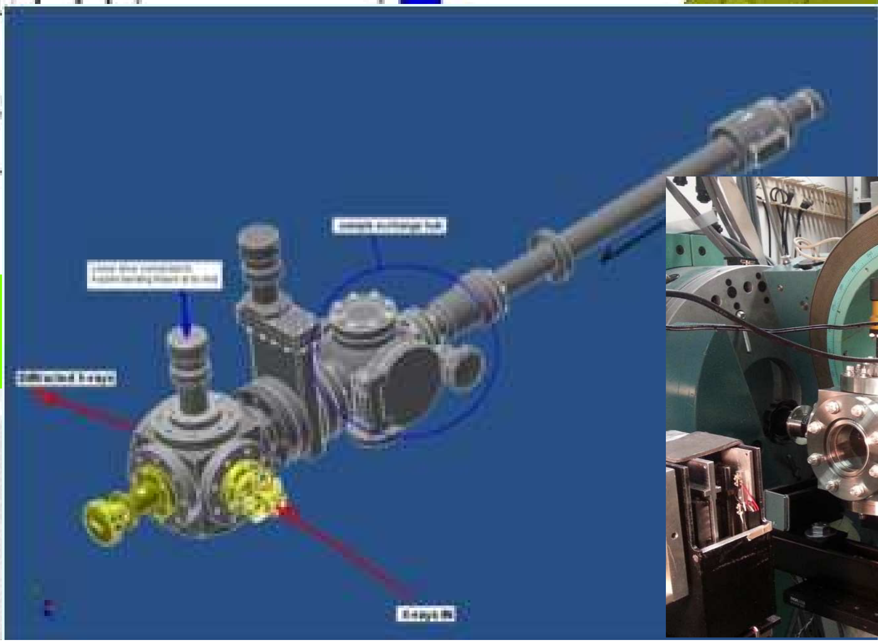
Irradiation campaign at BNL

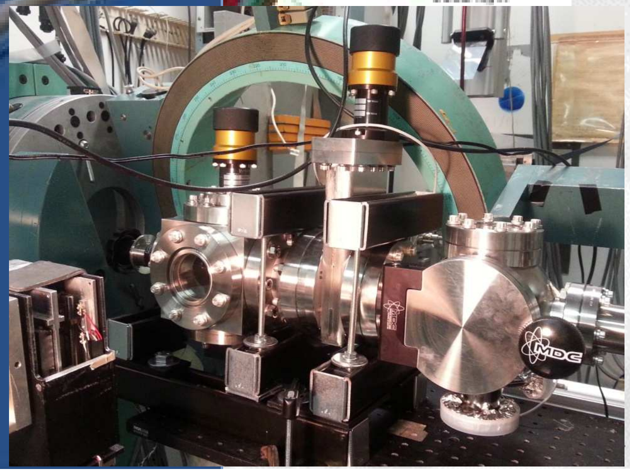
28 MeV proton irradiation for very localized proton-induced damage @**Tandem van de Graaff**





studies @ **NSLS**
(100-200 keV X-rays)

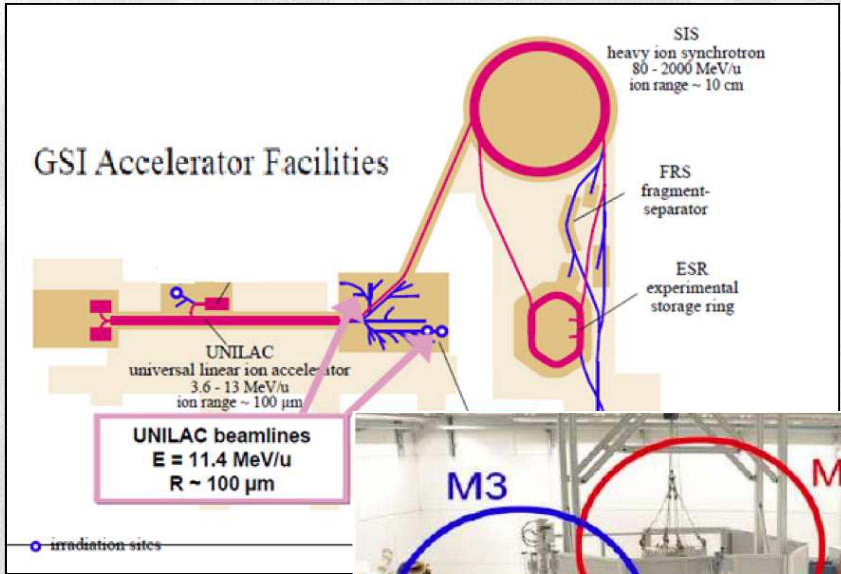




EuCARD²: Irradiation tests at GSI

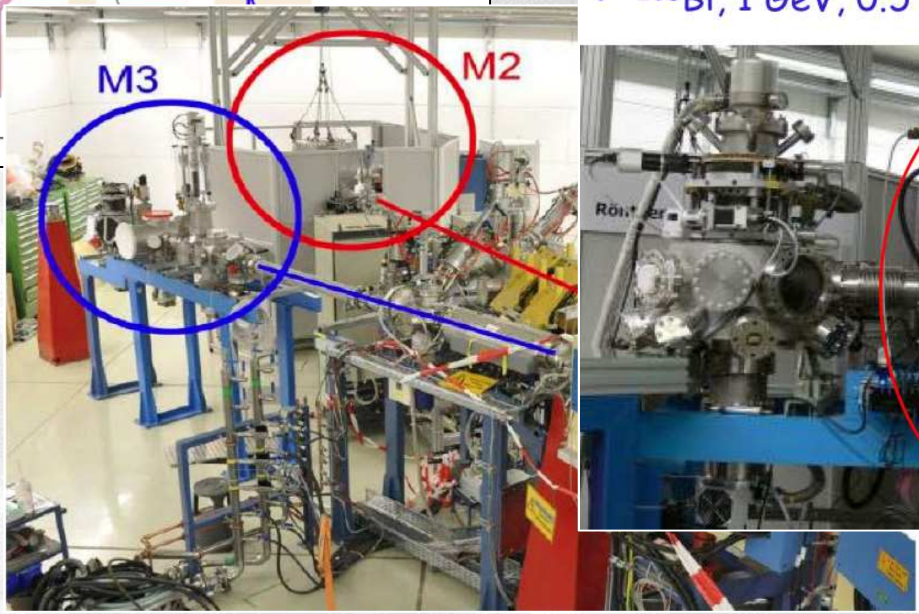
In the framework of **EuCARD-2** project.

***WP11**:Collimator Materials for fast High Density Energy Deposition.*

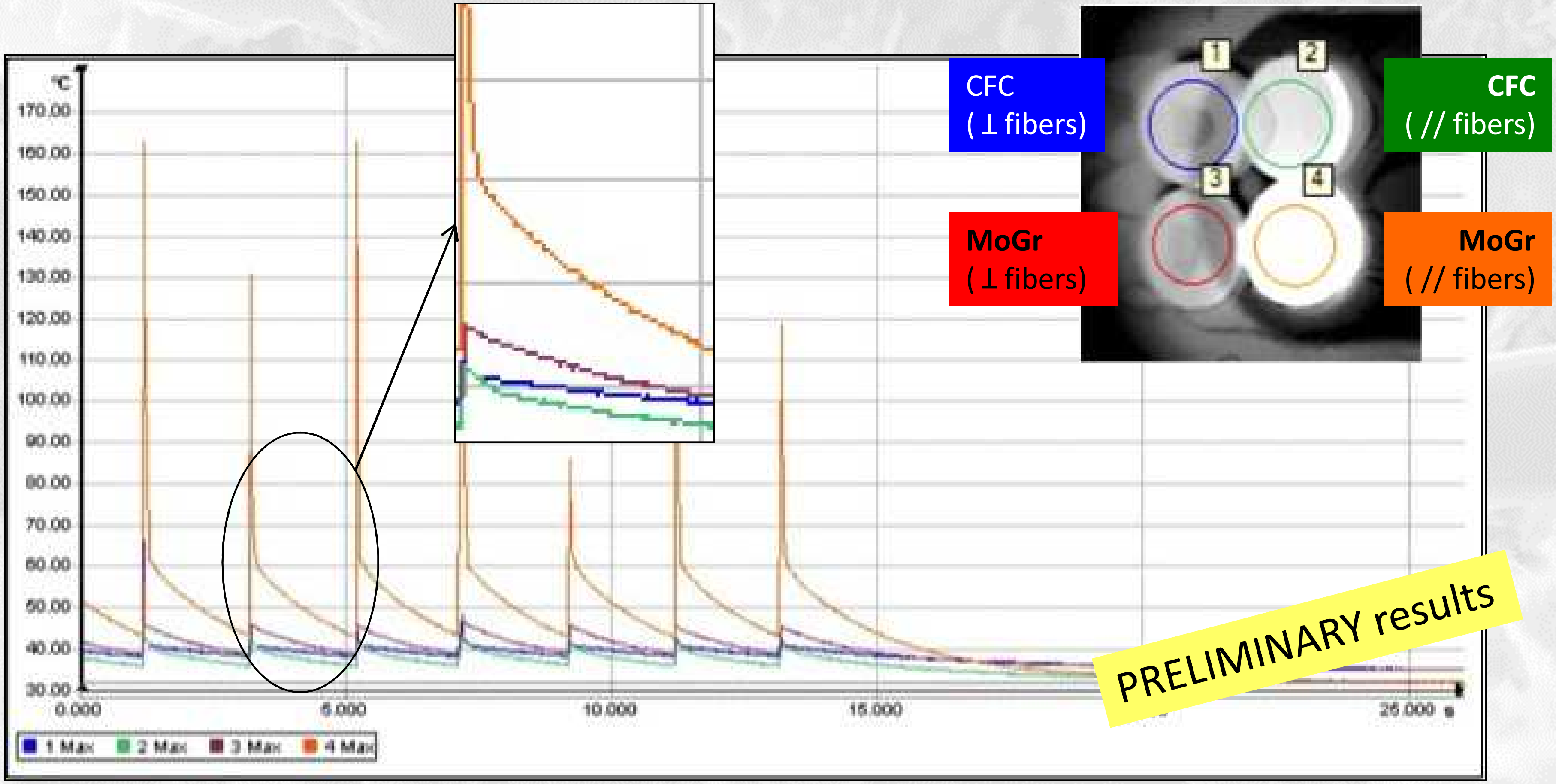


On-Line tests and **Post-Mortem** analysis on CFC, CuCD and MoGr samples are ON-GOING at UNILAC facility at GSI (Germany) to assess property degradation under heavy-ions irradiation.

- ^{238}U, 1.14 GeV, 0.5 ms, 0.6 Hz, 4x10^{9} ions/cm^{2} s
- ^{208}Bi, 1 GeV, 0.5 ms, 3.4 Hz, 1.2x10^{9} ions/cm^{2} s



Thermal conductivity degradation monitoring after **1GeV ^{238}U** irradiation (**$\Phi = 10^{13}$ i/cm²**): on-line measurement through thermal camera - estimation of time constant at cooling.



Courtesy of M.Tomut

Summary

☑ **Study on LHC Collimation Materials:**

- Analysed strengths and weaknesses
- Performed tests to assess robustness of TCTs and radiation hardness on CFC collimators
- Considerated possible changes

☑ **Material R&D for Future Collimation Upgrade**

- **MoGr seems to be most promising material!**
- Irradiation tests still on-going at KI, BNL and GSI

But questions are still open…

How to estimate collimator LIFETIME?

Is DPA the only indicator to rely on?

Any suggestion from the expert community is welcome…

BE Beam Department

EN Engineering Department

BROOKHAVEN NATIONAL LABORATORY

EuCARD^2

GSI

...as well as questions & comments!

CERN

LHC Collimation Project CERN

Beam Department

Engineering Department

Backup Slides

Material Requirements

Maximize **Electrical Conductivity**

Maximize **Thermal Conductivity**

Minimize **Coefficient of Thermal Expasion**

Maximize **Strength** and **Robustness**

Maximize **Operational Temperature**

Ensure **Radiation Hardness**

Ensure **industrial feasibility** of large components

Produced at **affordable costs**

Tentative roadmap

Long Shutdown 1
NO BEAM

SPS physics

LHC physics

mid 2014
Final material choice for TCSx

end 2014

end 2015

2016

- **Studies** of **new** collimator **materials**
  - Modybdenum-based materials
  - further studies of Me-GR composites
- Identification of interesting **scenarios to simulate** at nominal LHC energy
  - normal machine operation
  - accidental conditions
- Understanding of performance limitations (***SixTrack** simulations*)

- Identification of main performance limitations from tests in HiRadMAT facility (with BNL collaboration for post-irradiation analysis) and beam measurements in LHC
- Understanding of possible **solutions**
- Extrapolation of the results for **HL-LHC**

Installation of 1 TCSx in LHC

Test of TCSx in LHC