IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

Irradiation Effects on High-Temperature Superconducting Coated Conductors

Teresa Puig[1]

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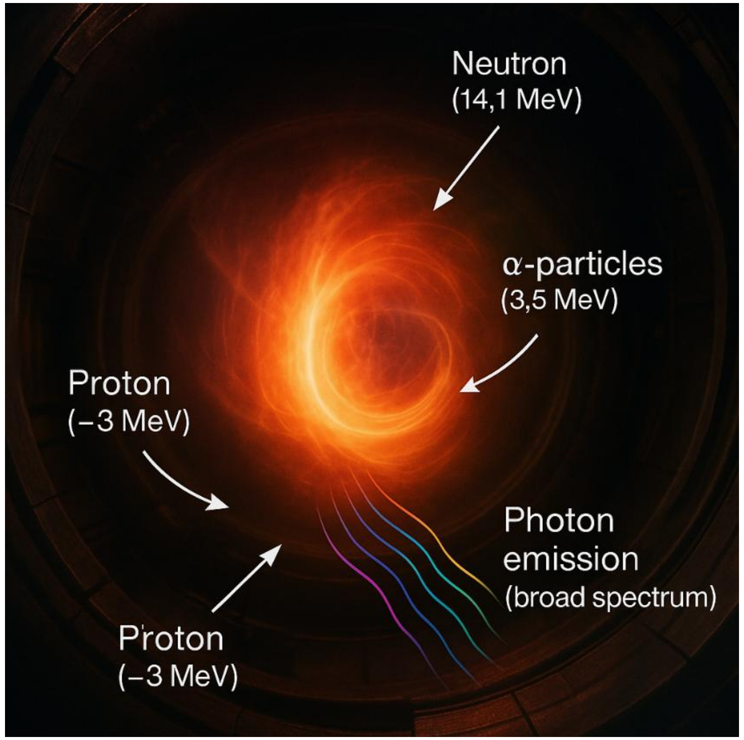
Work is supported by

Radiation Sources in Fusion Reactors

D + T → α (3.5 MeV) + n (14.1 MeV)



Primary products

Massive particles that interact with strong and week nuclear forces

Can cause damage through DPA displacement and nuclear heating

→ **Neutrons** (14.1 MeV)

-Materials interaction:
- Atomic displacement damage
- Activation → **β-electrons** and delayed **γ-rays**
- Transmutation → **γ-rays, α/β particles**

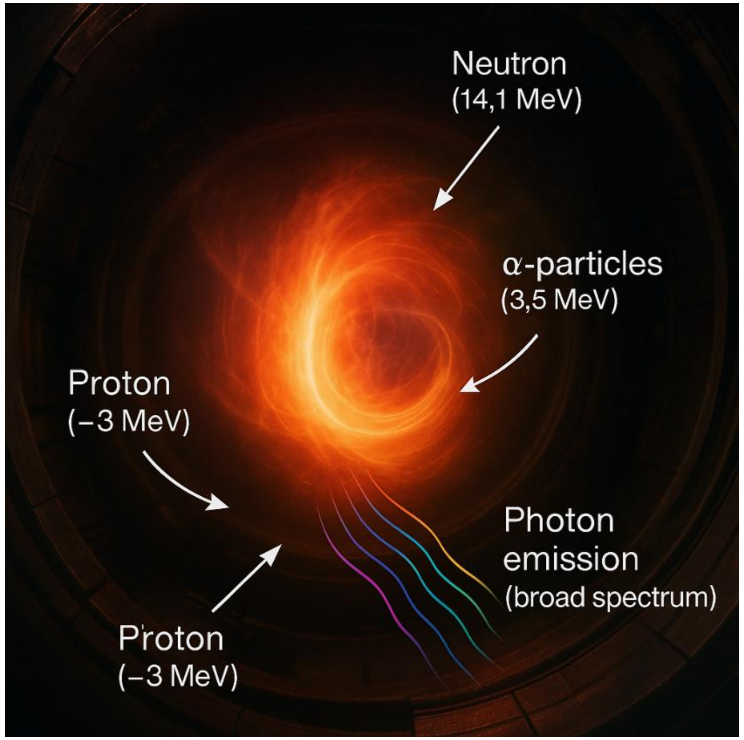
→ **α-particles** (3.5 MeV) mostly confined in plasma, but some scape due to collisions, turbulences, imperfections

→ **Protons** (~3 MeV from D-D reaction) can escape plasma

-Materials interaction:
- Displacement damage
- Activation

Radiation Sources in Fusion Reactors

D + T → α (3.5 MeV) + n (14.1 MeV)



Massless particles that interact using electromagnetic forces

→**Photons** emitted by the plama and surrounding materials (broad spectrum)

Can cause damage through nuclear heating and ionization interactions depending on the energy

- **Infrared to visible (~1.6 - 3 eV)** → no electronic excitation, photothermal effects
- **UV /VUV (~3 - 100 eV)** → Surface excitation, photodesorption, bond breaking, photoionization, surface damage, redistribution of carriers
- **Soft X-rays (~100 eV - 10 keV)**→ ionization photoelectric effect, local heating, desorption
- **Hard X-rays (10 keV - ~ 1 MeV)** → Ionization Compton scattering, heating, atomic displacement, lattice defects
- **Gamma rays (> 100 keV (typically > 1 MeV)** → pair particle –antiparticle production, transmutation

Different radiation environments need to be studied ex situ and in-situ at realistic doses and effects and defects have to be identified over those already existing in the material

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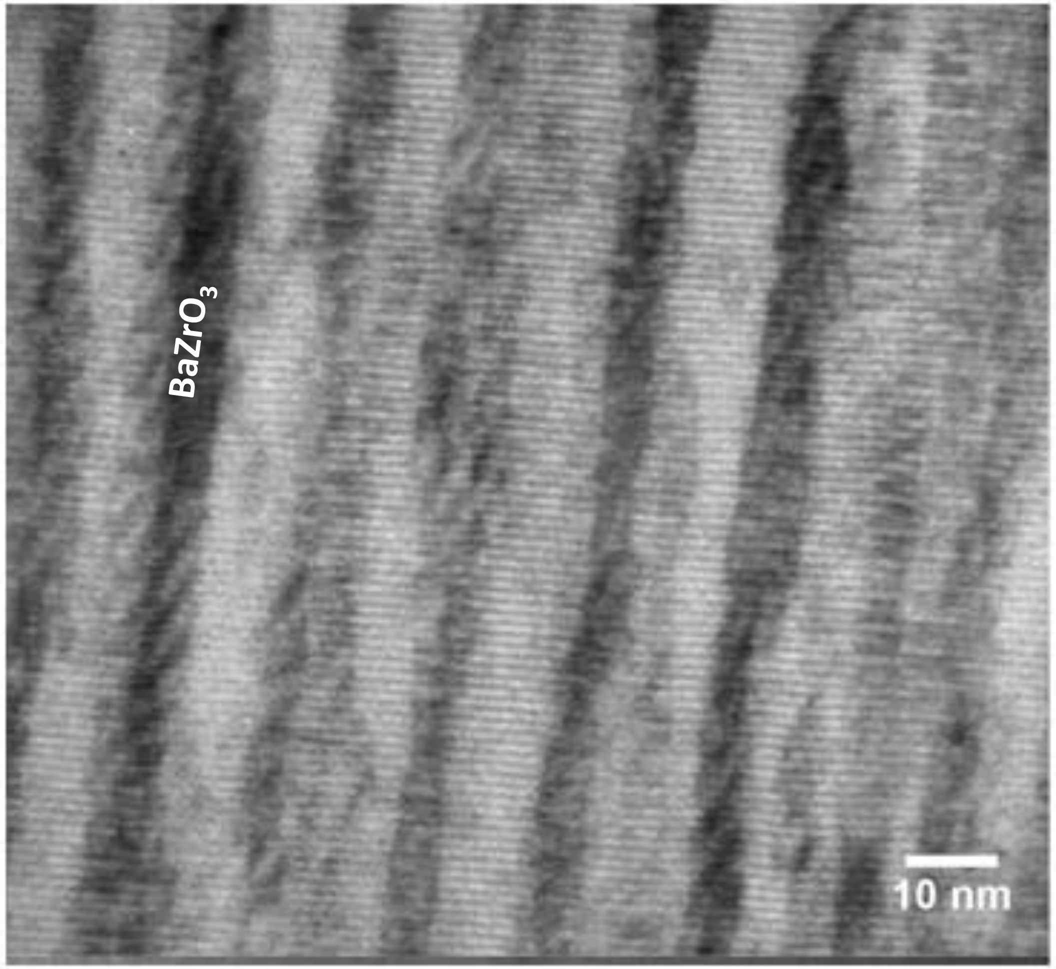
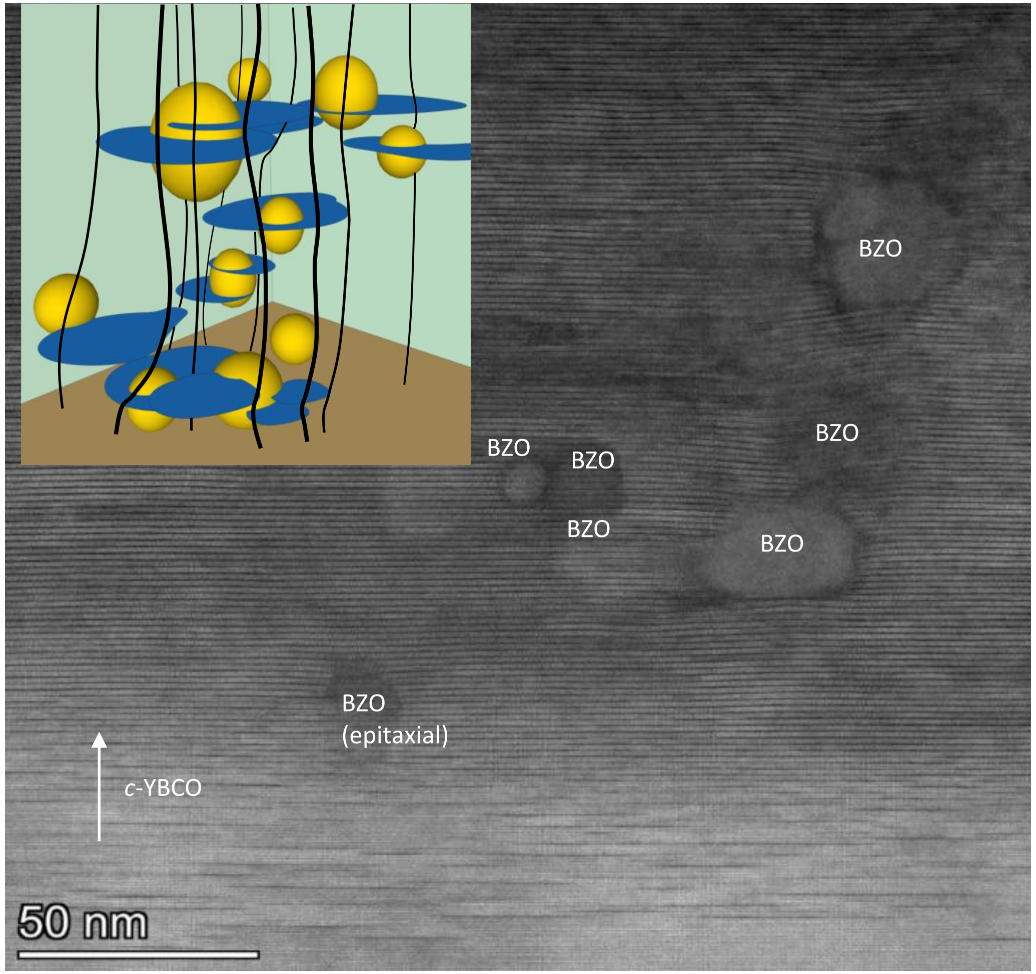
Complex microstructure of REBCO Coated Conductors





Atomic vancancies
Dislocations
Stacking Faults
Twin boundaries
Nanoparticles
Nanorods
...

Irradiation:
Displacent of O
Point defects
Cluster defects
Amorphization
Local structural disorder
Chemical changes
...

T. Puig et al, Nat Rev Phys (2024), Majkic, G. *et al*. *SUST* (2020), L. Soler et al., Nat Comm (2020)

Altogether are defects with different dimensionality, with cooperative and competitive interactions which may be beneficial but also destructive

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Vortex Pinning in HTS Coated Conductors vs Damage by irradiation

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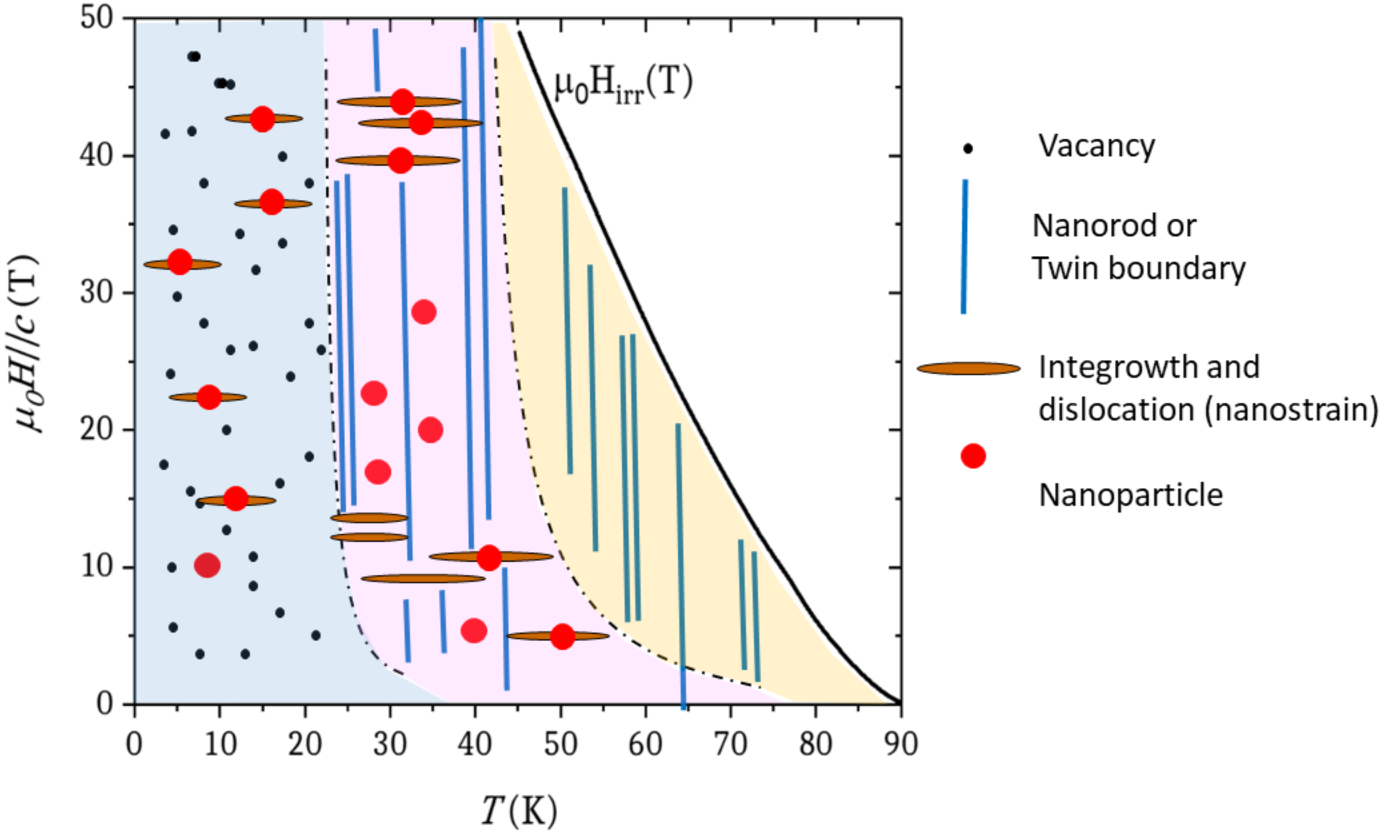
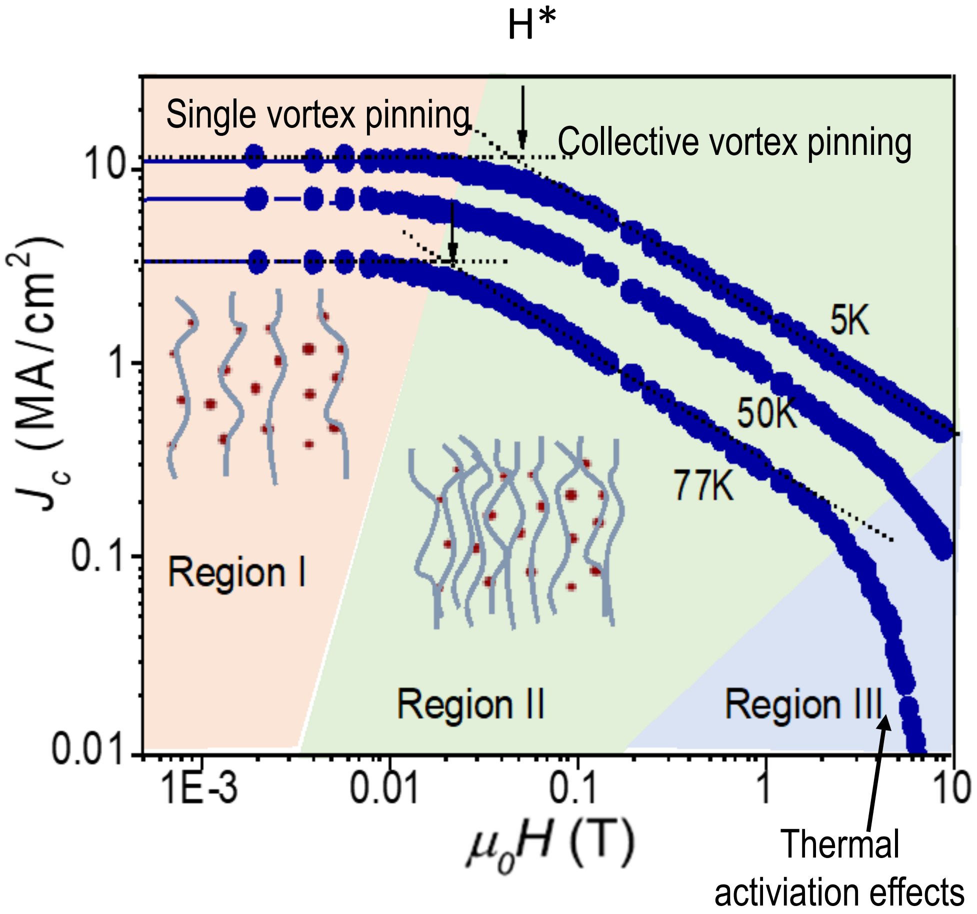


T. Puig et al, Nat Rev Phy (2024)



- **Important to classify the defects behaviour in terms of effectiveness at different T, H**
- **Evaluate the contribution of irradiation defects depending on the type of radiation**
- **Identifying the damage thresholds**

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Outline of Irradiation studies on REBCO CC and films

1. Experiments ex-situ and in-situ with **Hard X-rays (10 -250 keV) at the ALBA synchrotron inside accelerator**

→ Total deposited photons between 10^{15} and 10^{18}

→ Doses < 0.1 MGy

→ Evaluation of T_c R_s

2. In-situ experiments with **Soft X-rays (3-20 keV) at NOTOS beamline of ALBA synchrotron**

→ Total deposited photons between 10^{10} and 10^{15}

→ Doses ≤ 0.4 MGy

→ T_c, J_c and R_s in-situ evaluated

Initiated for the **HTS beam screen FCC-hh collider** studies
Capabilities are ready for other studies like fusion environments

3. Irradiation using **2 MeV electron beams from a Van de Graaff accelerator**

→ At room temperature and real-time electrical resistance monitoring

→ Doses up to 10 MGy

→ It will be upgraded for in-situ irradiation at cryogentic temperatures

4. Irradiation with **1.5 MeV gamma** particles from **Co-60 source**

→ At room temperature

→ Doses of 1 MGy

Just starting
Results are being evaluated

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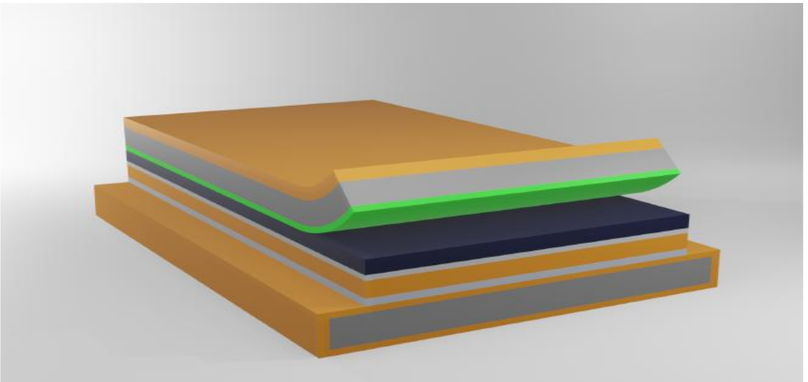
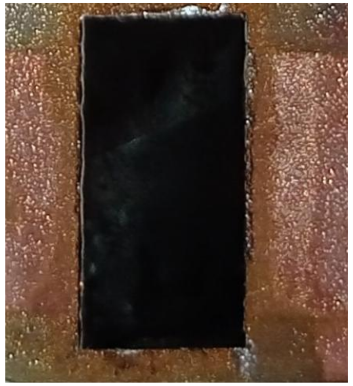
Samples in this study

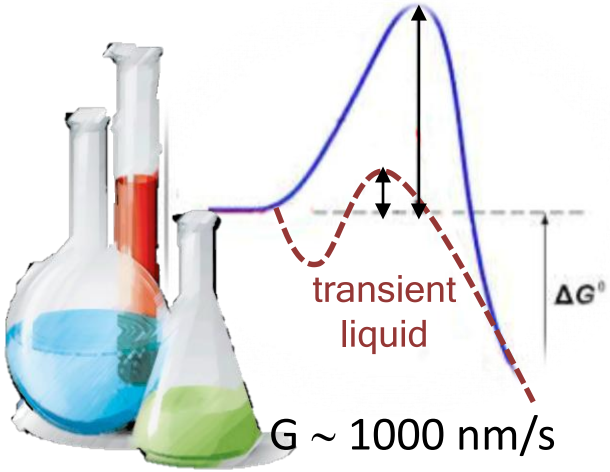
1) REBCO surfaces after substrate delamination of commercial Coated Conductors from Theva, Fujikura, Superpower, Sunam, SuperOx, Bruker with and w/o APC used for **BS- FCC-hh study** (different growth methods, different microstructure)

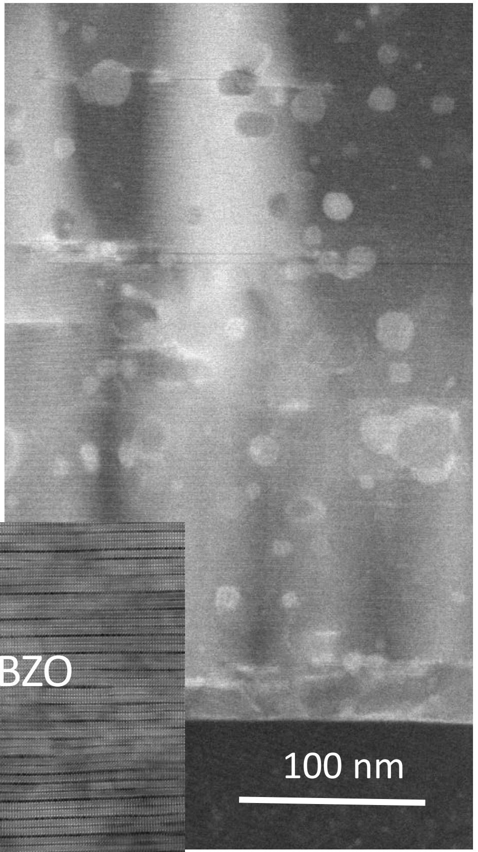


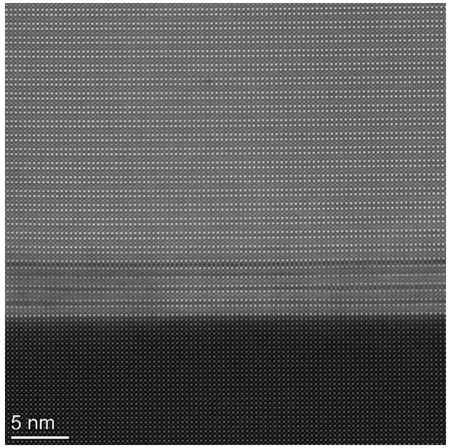


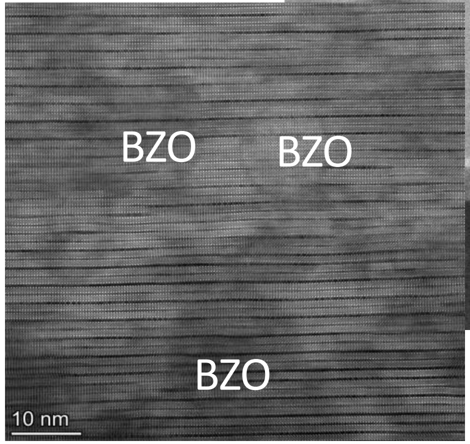
Beam screen- FCC-hh prototype

2) YBCO TLAG (transient Liquid Assisted grown) films prepared at ICMAB with different microstructures









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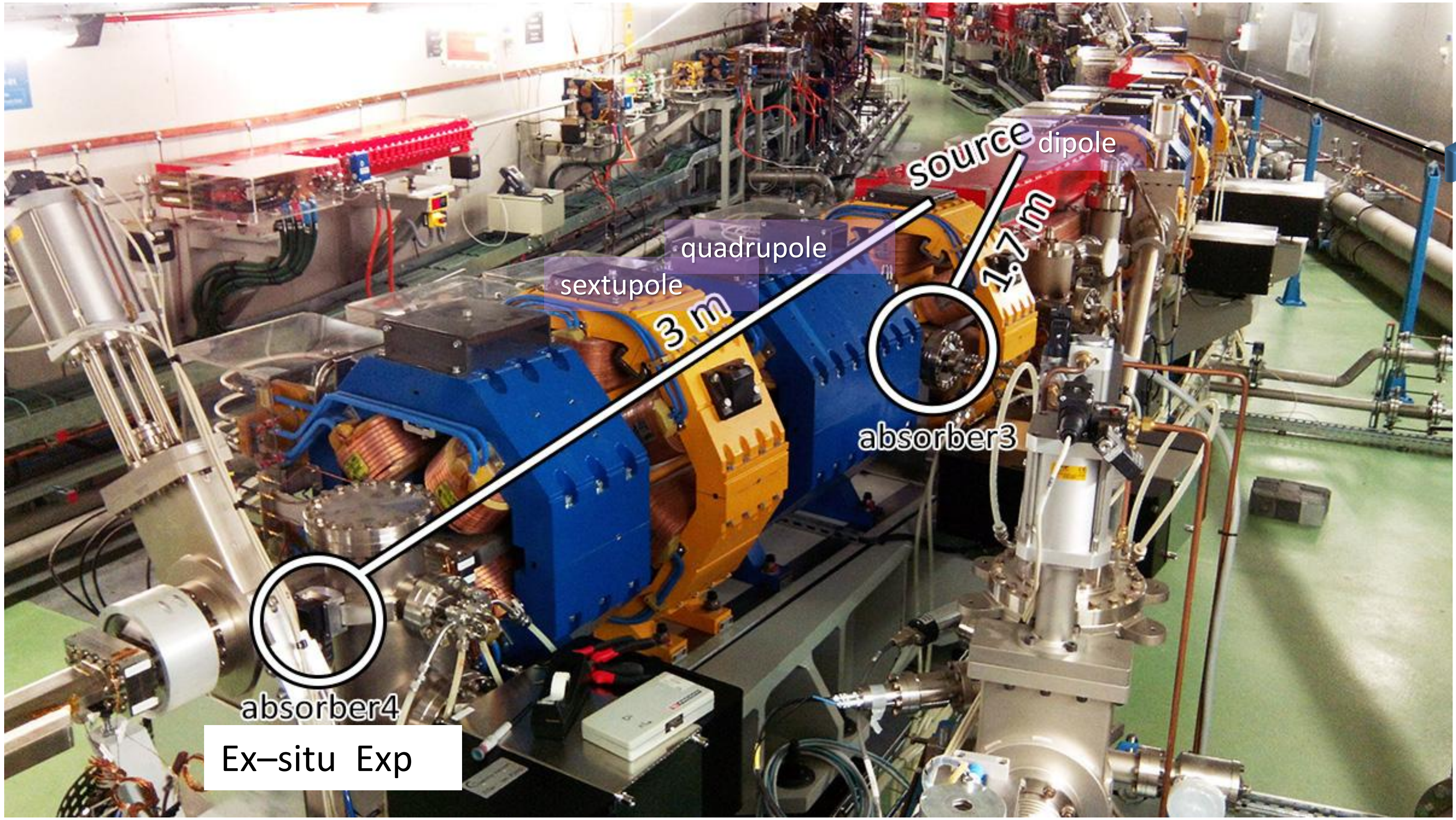
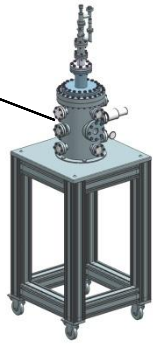
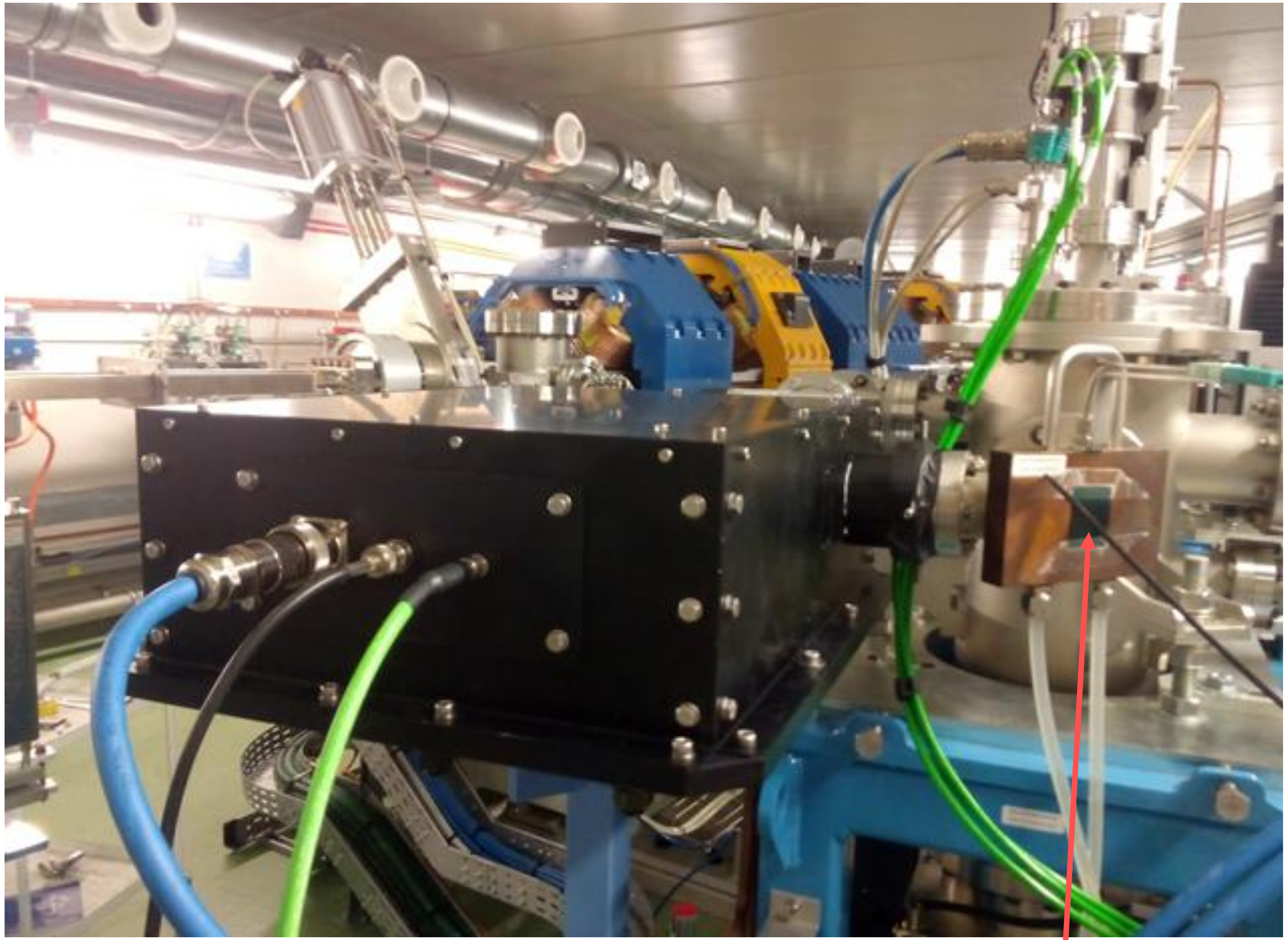
ALBA synchtrotron installation for Hard X-rays irradiation: ex-situ and in-situ

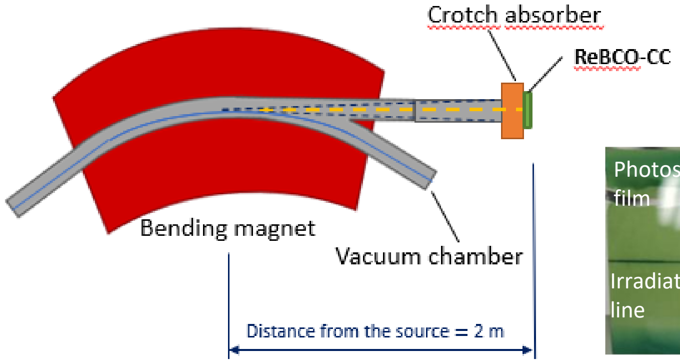
Diagnostics beamline inside the accelerator

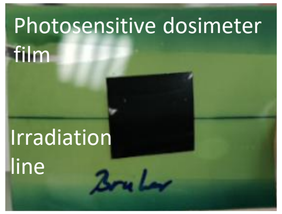


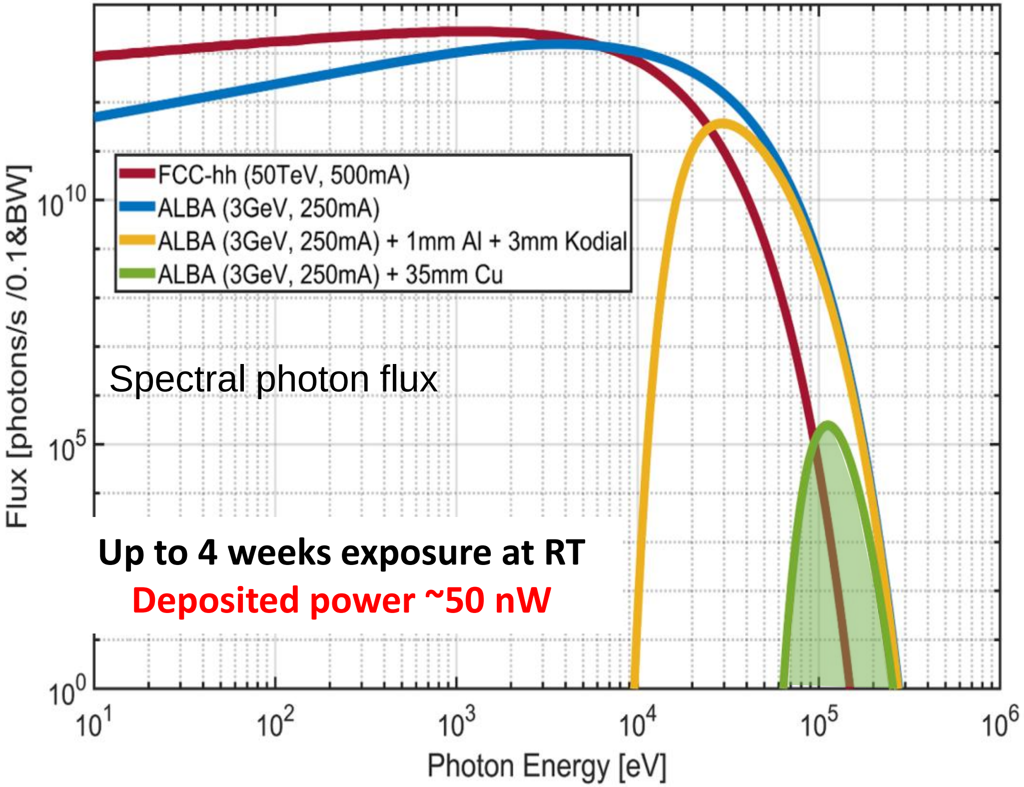


Ex-situ experiments (70 keV $<E_\gamma<$ 250 keV)









REBCO samples attached to the water cooled 35 mm Cu crotch absorber

Ex-situ experiments after irradiation with 70 keV $<E_\gamma<$ 250 keV

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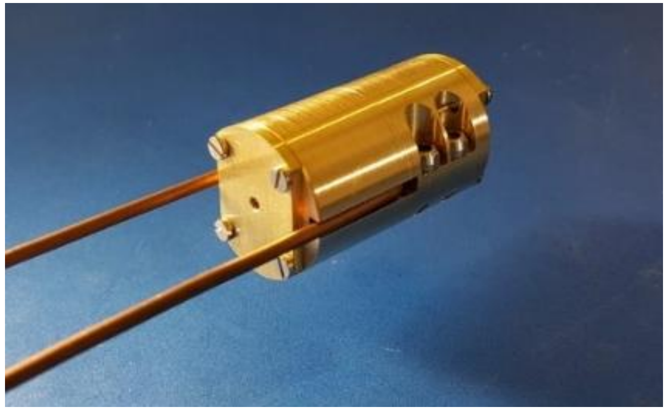
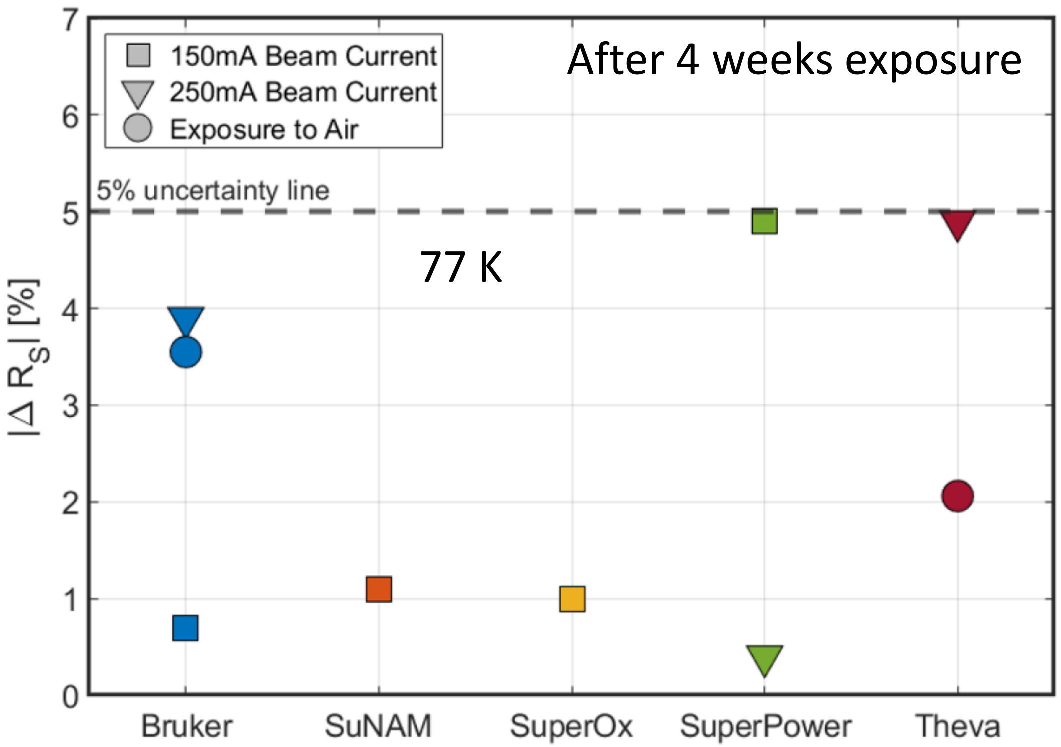
Surface Resistance results

Electron beam current, I_{beam} (mA)	**Deposited Power density, Q_{dep} (µW/cm²)**	Total deposited photons (10^{14} ph)	**Total deposited Fluence, F_{dep} (10^{15} ph/cm²)**	REBCO provider thickness (µm)	Time (h)	Abs Fluence, F_{abs} (10^{12} ph/cm²)	**Dose (kGy)**
150	**0.4**	6.3	**5,2**	0.9-3	552	1.4 - 4.8	**0.4**
250	**0.7**	10	**8,8**	0.9-3	552	2-4 - 11,7	**0.7**



Hakki-Coleman dielectric resonator
TE_{001} mode at 8 GHz

T. Puig et al, Supercond. Sci. Tech. (2019)
A. Romanov, et al. Scientific Reports (2020)



Under these conditions, hard X-rays do not generate permanent damage: R_s is not affected for D< 0.7 kGy

P. Krkotic et al, SUST 36, 105009 (2023)

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Ex situ experiments after irradiation with 70 keV < E_γ < 250 keV

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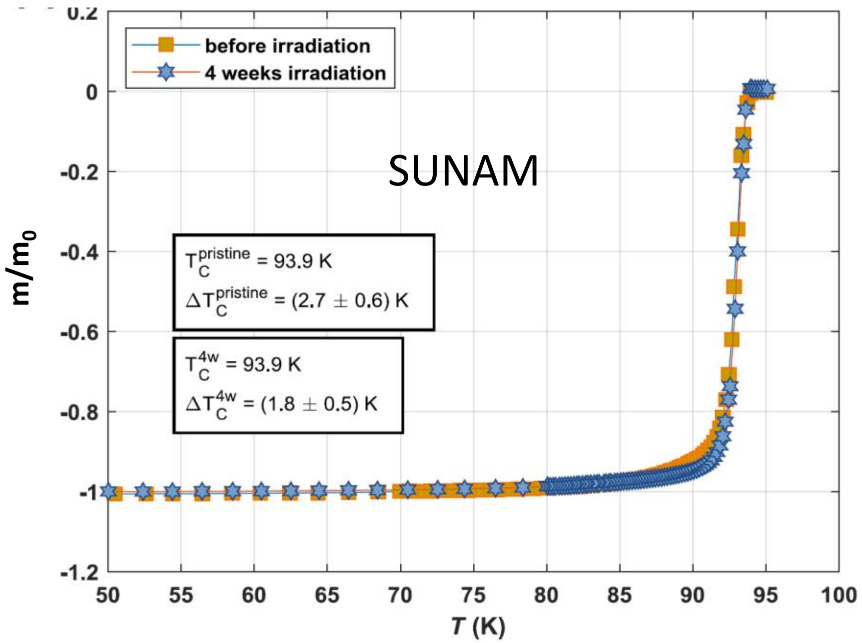
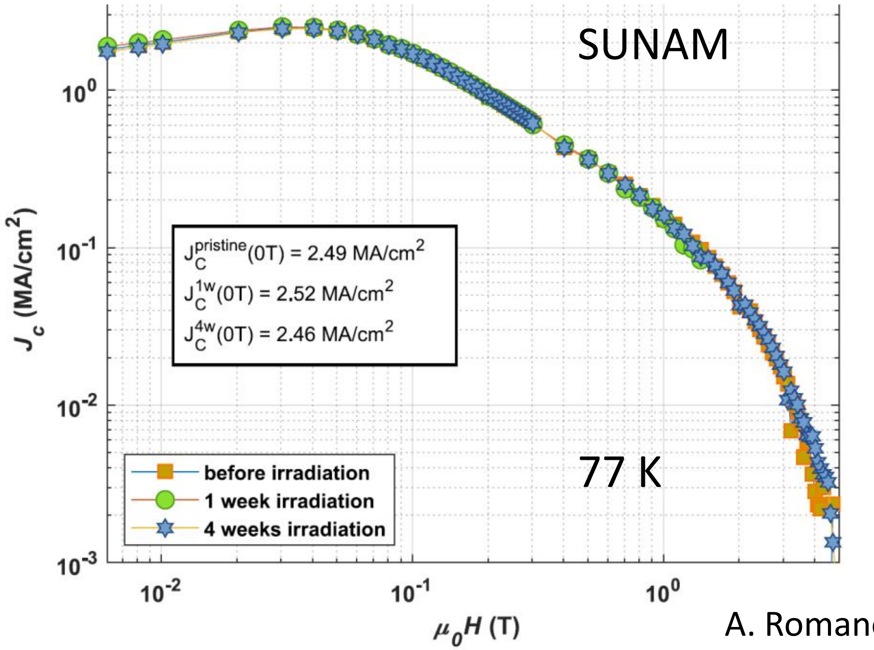
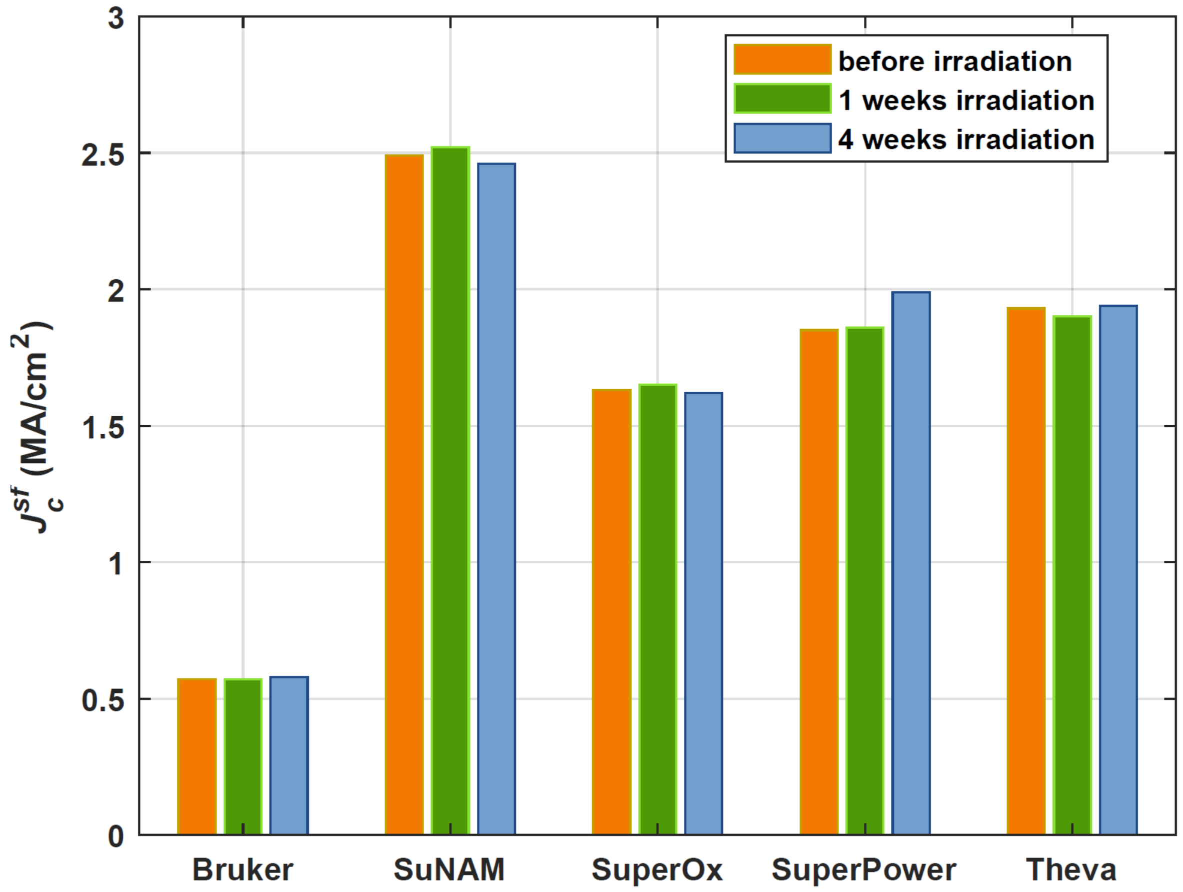




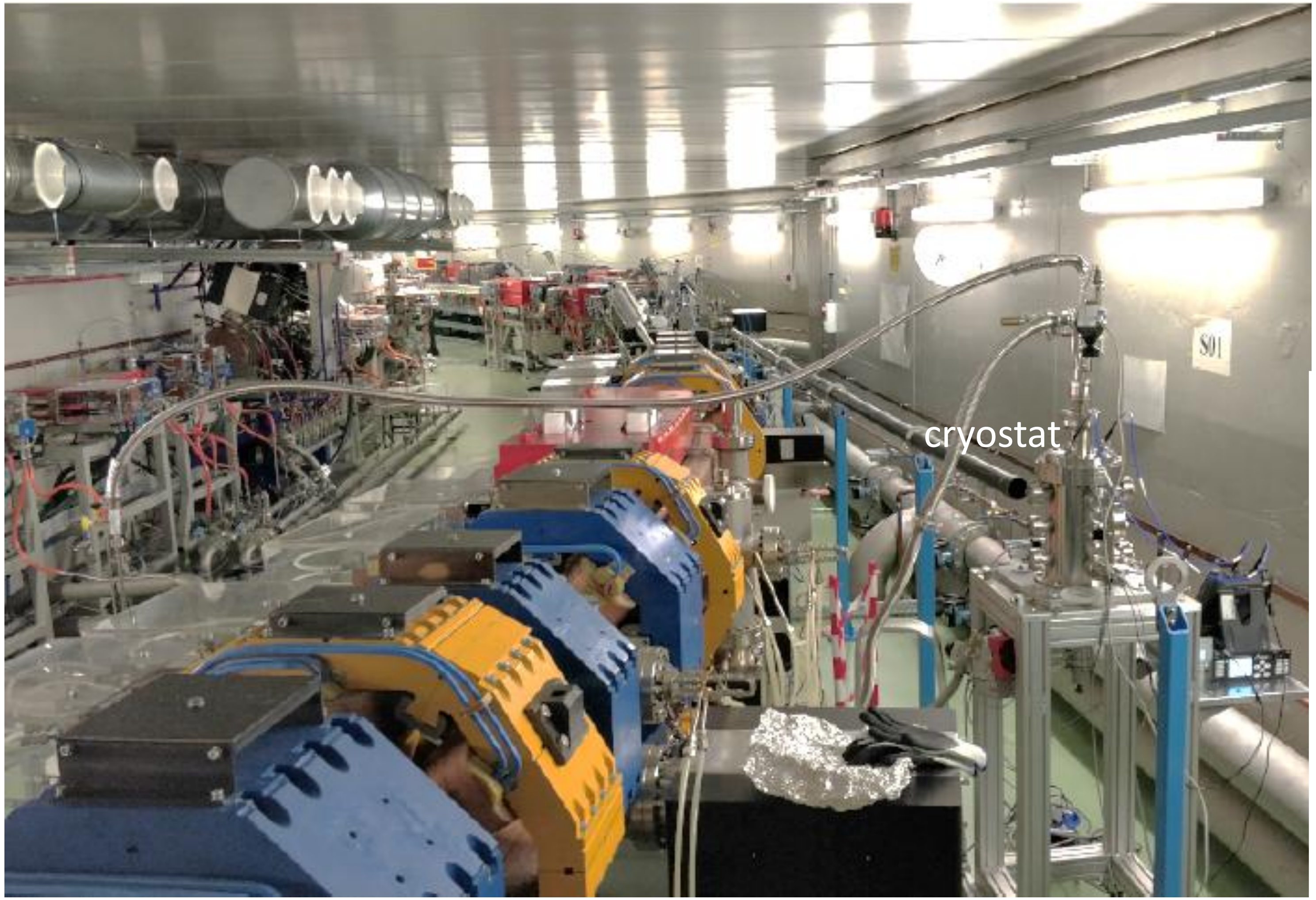
A. Romanov, PhD Thesis

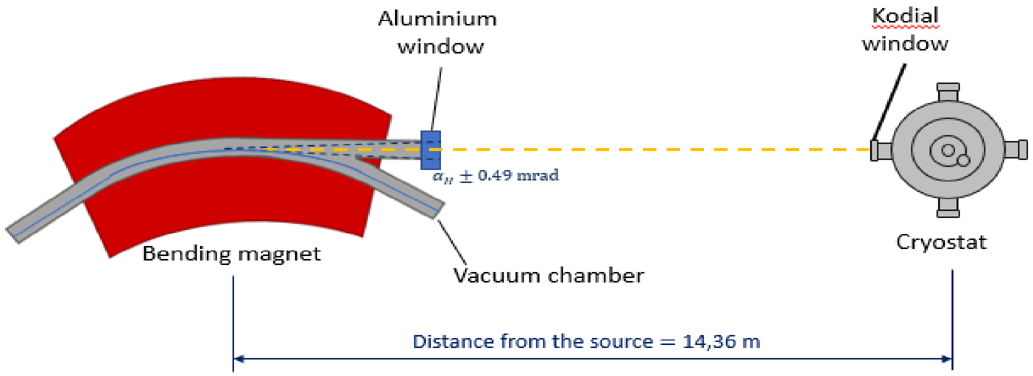


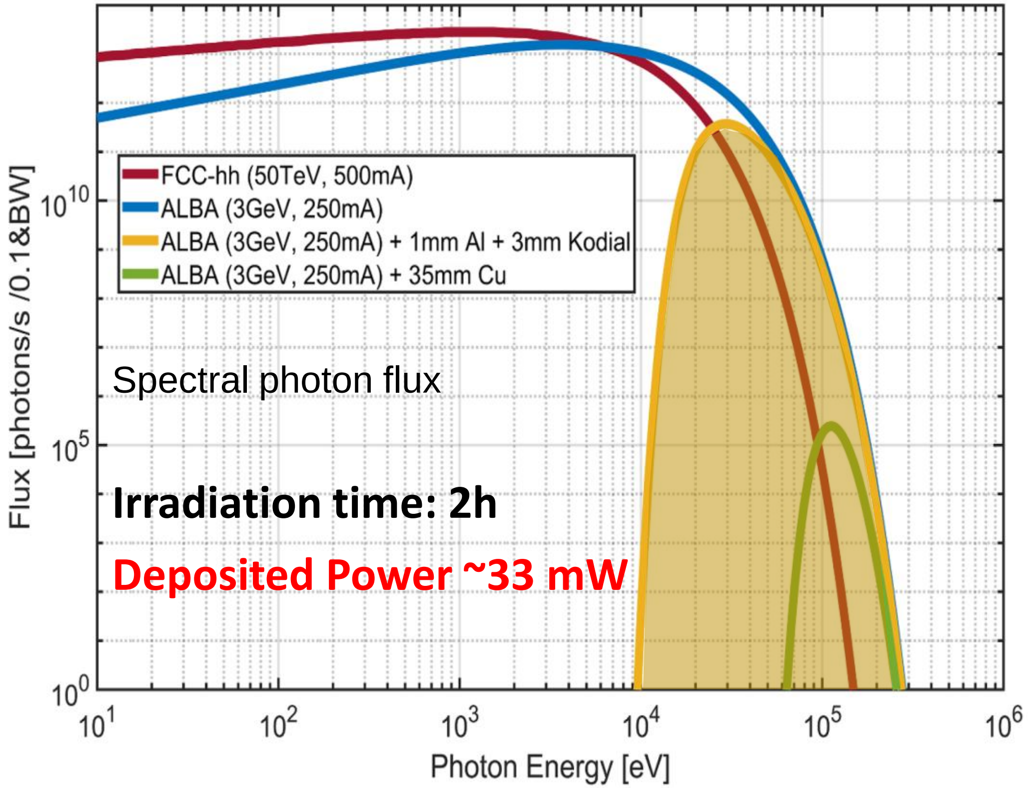
Differences within 5%

Under these conditions, hard X-rays do not introduce permanent damage: T_c and J_c^{sf} are not affected for D < 0.7 kGy

In-situ Hard X-ray experiments (10 keV <E_γ< 250 keV)







Irradiation time: 2h

Deposited Power ~33 mW

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In-situ Hard X-ray experiments (10 keV $<E_\gamma<$ 250 keV)

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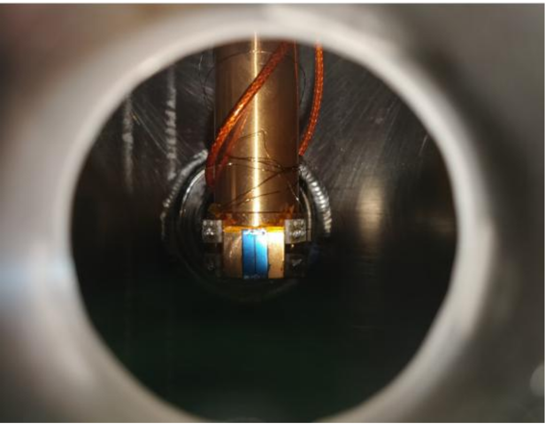
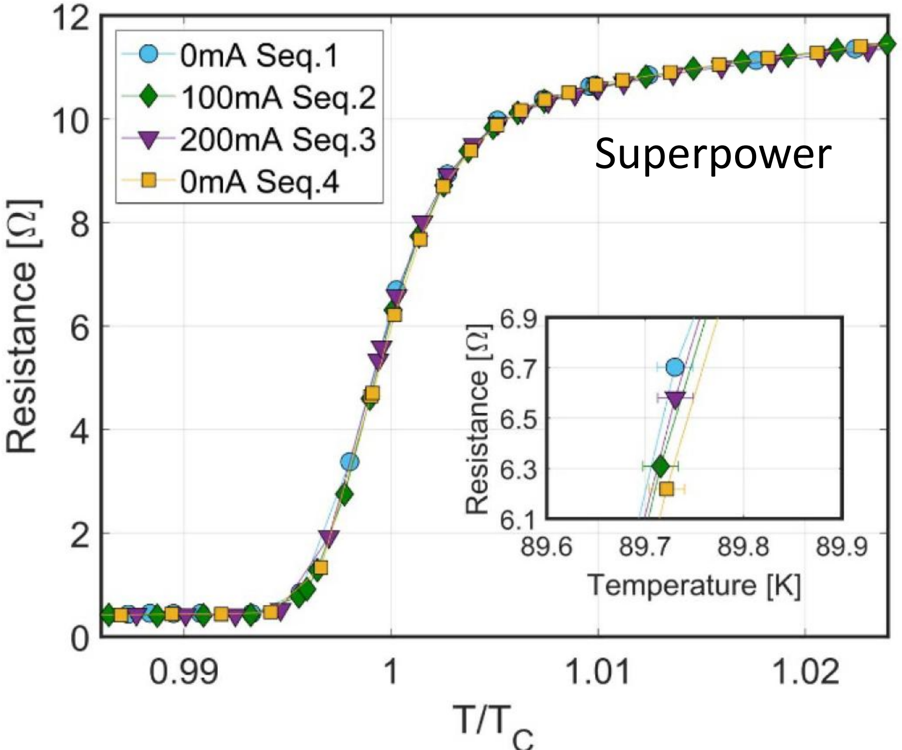
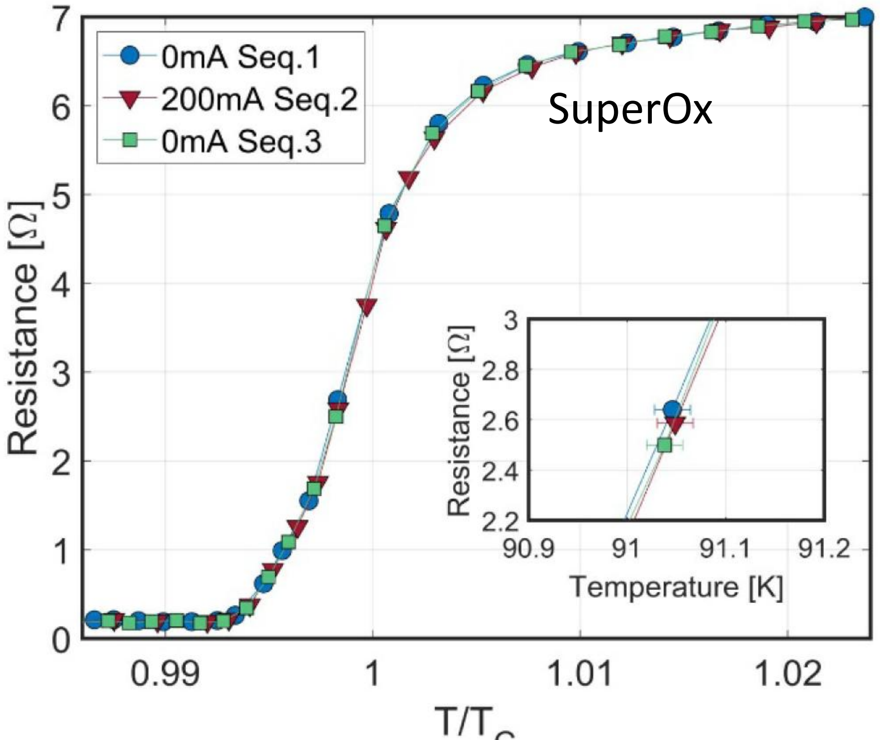


Electron beam current, I_{beam} (mA)	**Deposited Power density, Q_{dep} (W/cm^2)**	Total deposited photons (10^{18} ph)	**Total deposited Fluence, F_{dep} (10^{19} ph/cm^2)**	REBCO provider thickness (µm)	Time (h)	Abs Fluence, F_{abs} (10^{17} ph/cm^2)	**Dose (kGy)**
100	**0.7**	1.5	**3**	0.9-1.5	2	1.7- 2.7	**46**
200	**1.3**	3	**6**	0.9-1.5	2	3.3-5.5	**92**

measurements on 1 mm-10 mm bridge



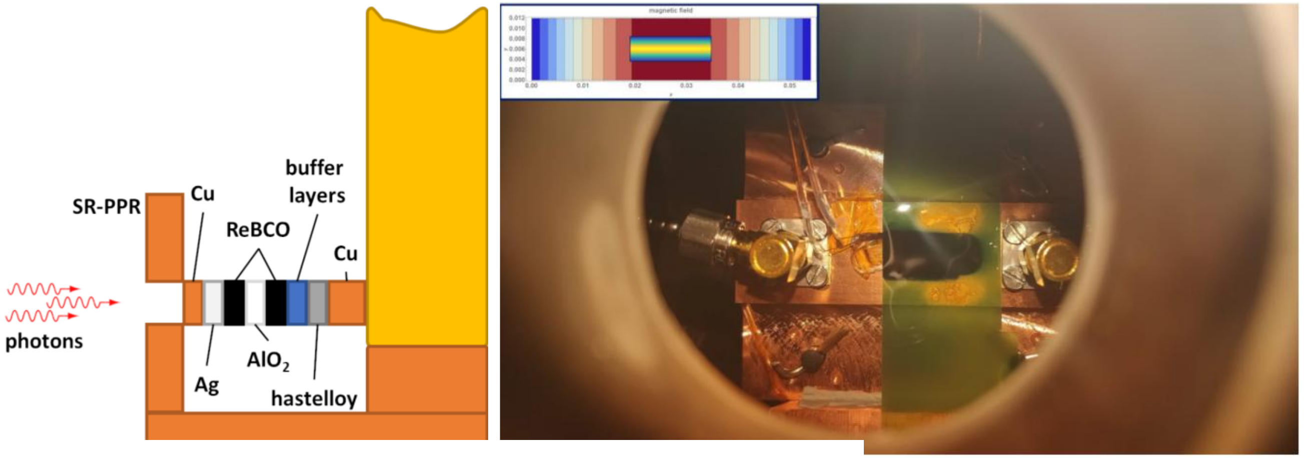


Under these in-situ conditions (D < 100 kGy), hard X-rays do not induce sufficient heating neither other damage

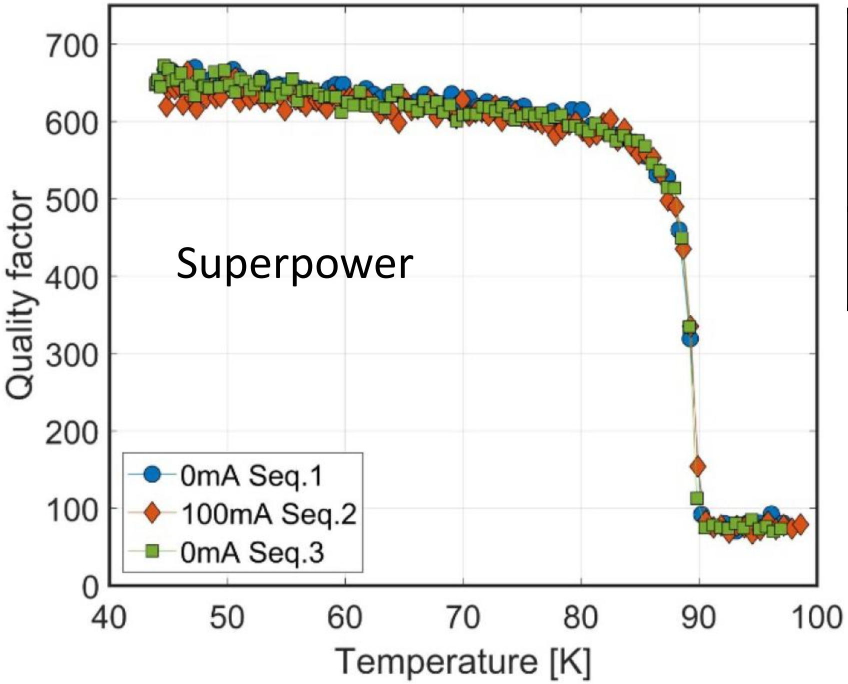
P. Krkotic et al, SUST 36, 105009 (2023)

In-situ Hard X-ray experiments (10 keV <E_γ< 250 keV)

Surface Resistance mesurements



Parallel Plate Resonator at 1.2 GHz for Surface Resistance measurements in the cryocooler with a radiation window



Electron beam current, I_{beam} (mA)	**Deposited Power density, Q_{dep} (W/cm²)**	Total Deposited photons (10^{18} ph)	**Total Deposited Fluence, F_{dep} (10^{19} ph/cm²)**	REBCO provider thicknes s (μm)	Time (h)	Abs Fluence,F_{abs} (10^{17} ph/cm²)	**Dose (kGy)**
100	**0.6**	2.2	**2.8**	1.5	2	2.5	**42**

Under these in-situ conditions (D<50 kGy), hard X-rays do not induce heating neither other type of damage

P. Krkotic et al, SUST 36, 105009 (2023)

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In-situ Hard X-ray experiments (10 keV <E_γ< 250 keV)

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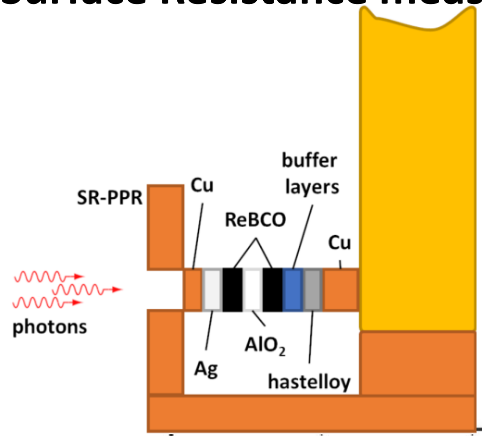
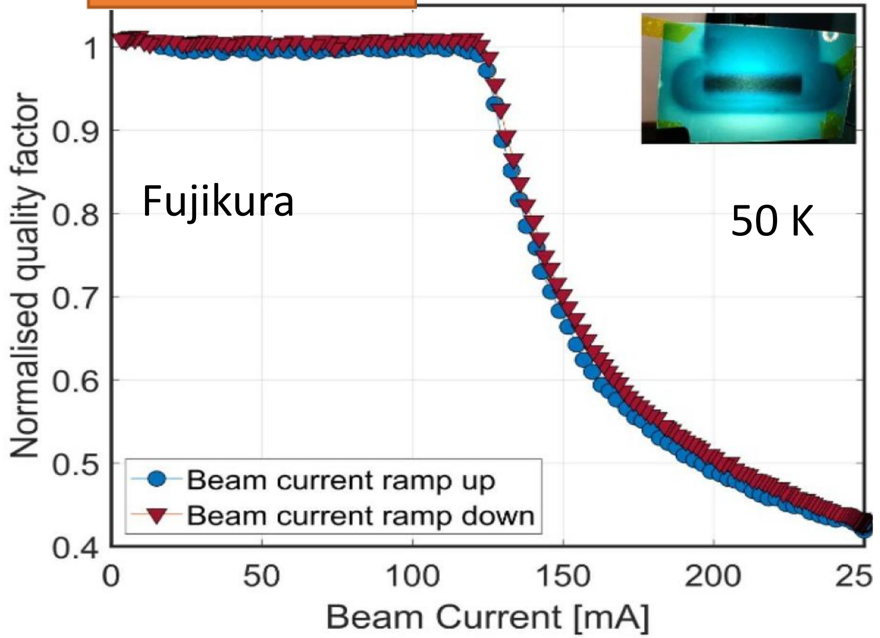
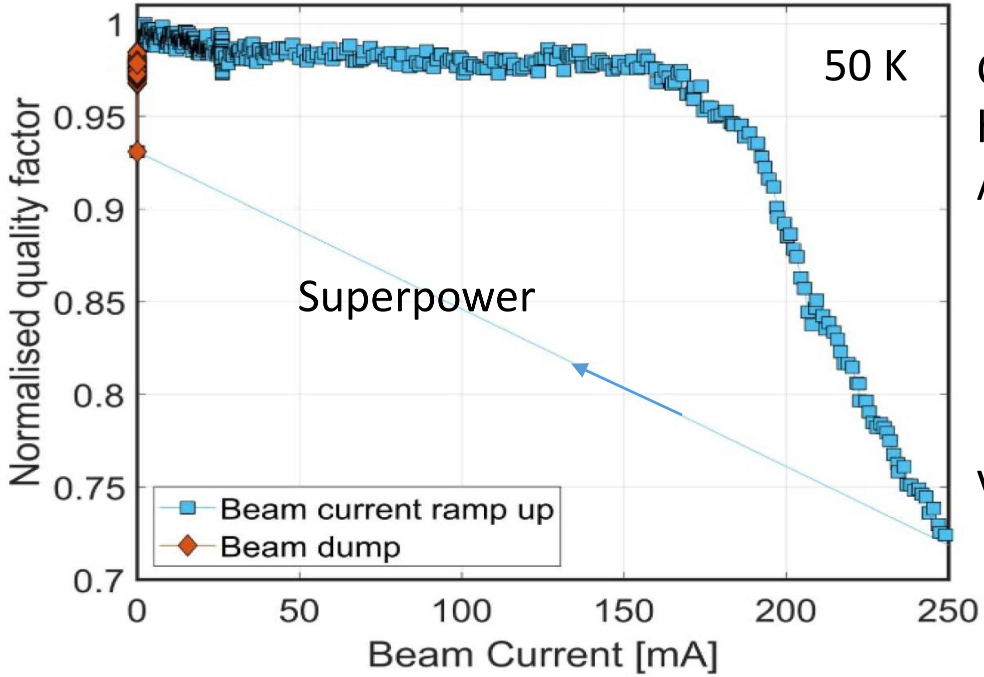
Surface Resistance meas.



Electron beam current, I_{beam} (mA)	**Deposited Power density, Q_{dep} (W/cm^2)**	Total Deposited photons (10^{18} ph)	**Total Deposited Fluence, F_{dep} (10^{19} ph/cm^2)**	REBCO provider	Time (h)	Abs Fluence,F_{abs} (10^{17} ph/cm^2)	**Dose (kGy)**
130	**0.8**	2.9	**3.6**	Fujikura	2	3.3	**55**
160	**1**	3.5	**4.5**	Superpower	2	4	**67**





Compatible with local heating as simulatied by ANSYS thermal solver

Very fast recovery

Reversible effect confirming no permanent damage

At 50 K, a threshold between no impact and no sufficient evacuation of the absorbed heat was identified at D~ 60-70 kGy, but this possible heating did not cause permanent damage

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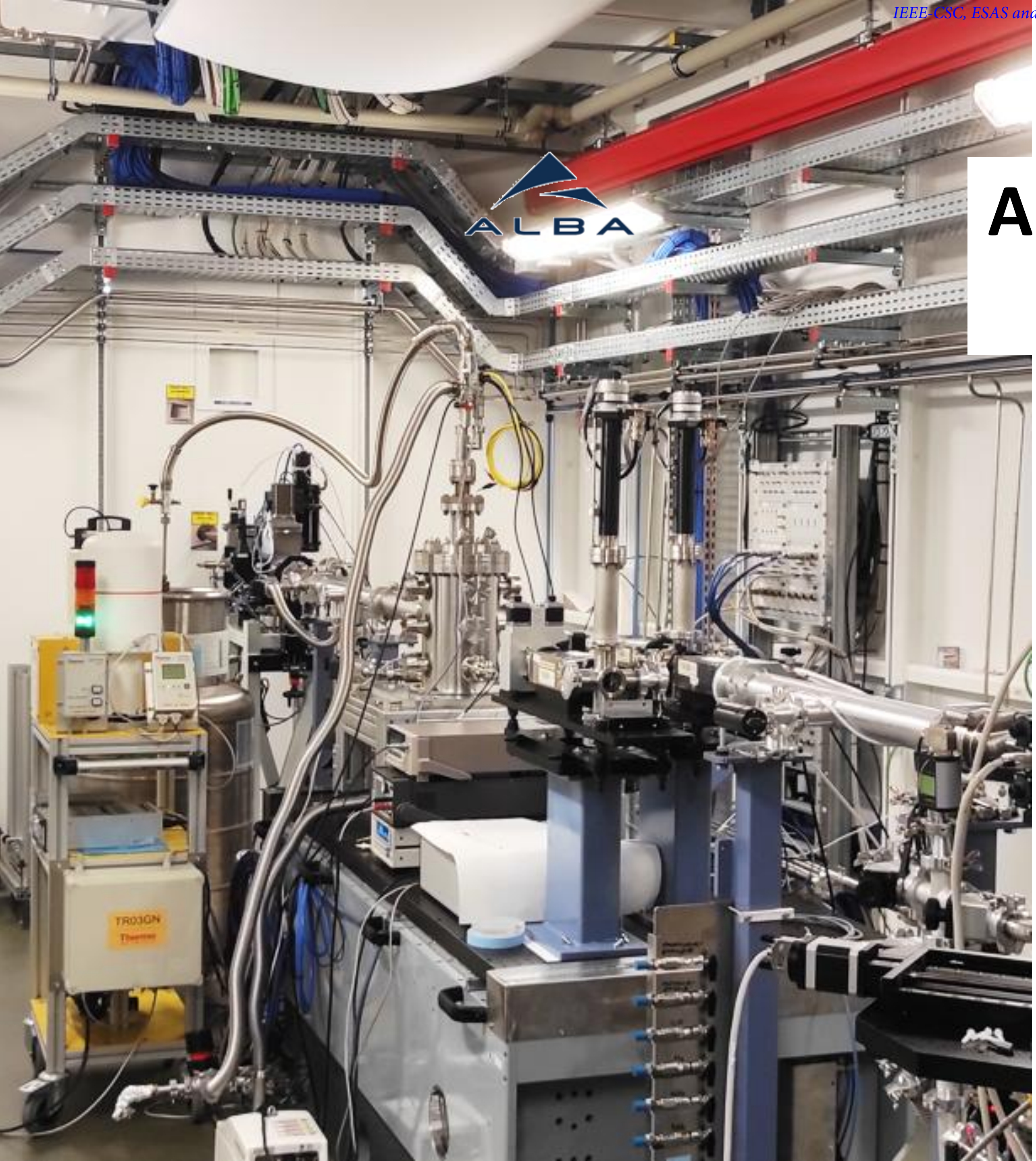
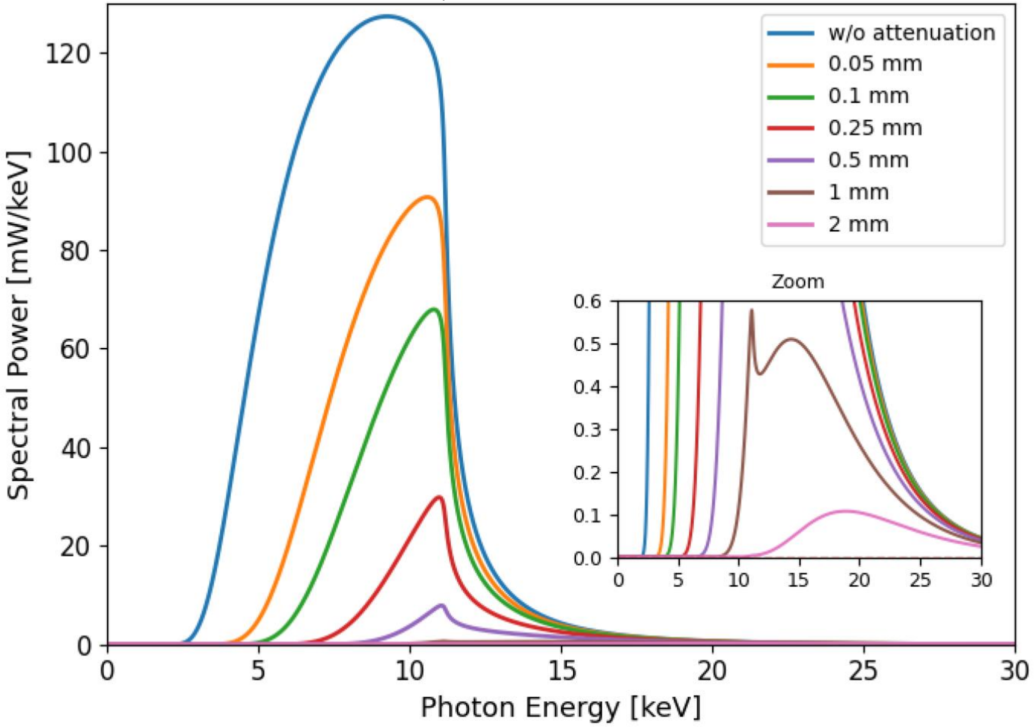


ALBA synchtrotron installation for Soft X-rays irradiation: in-situ

Metrology BL (BL16-NOTOS)

(3 keV < E_γ < 20 keV)



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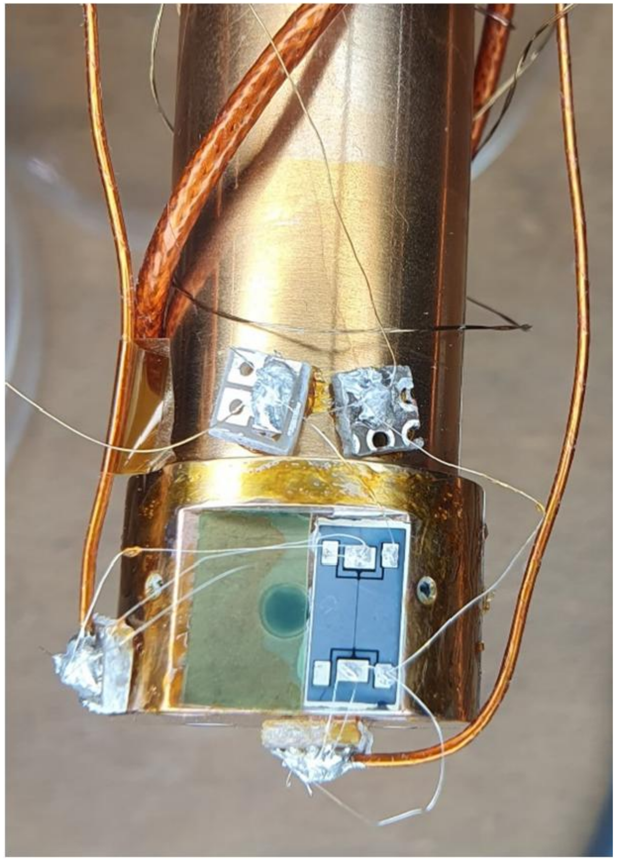
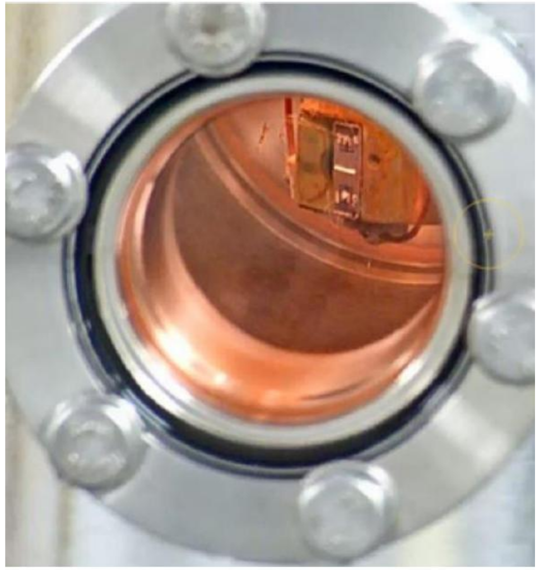
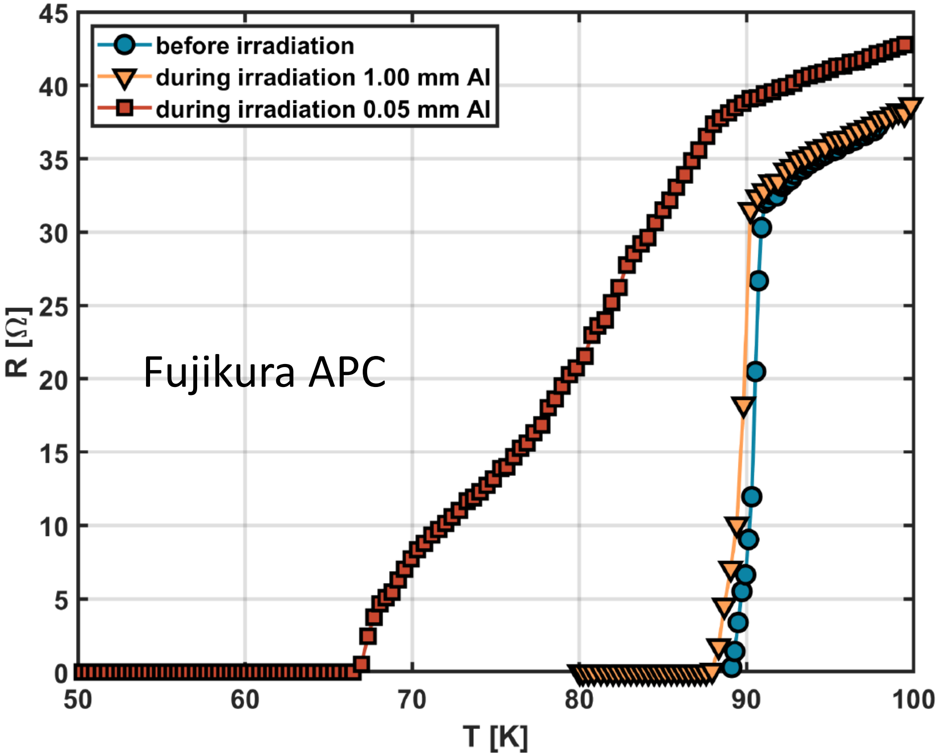
In-situ experiments (3 keV < E_γ < 20 keV)





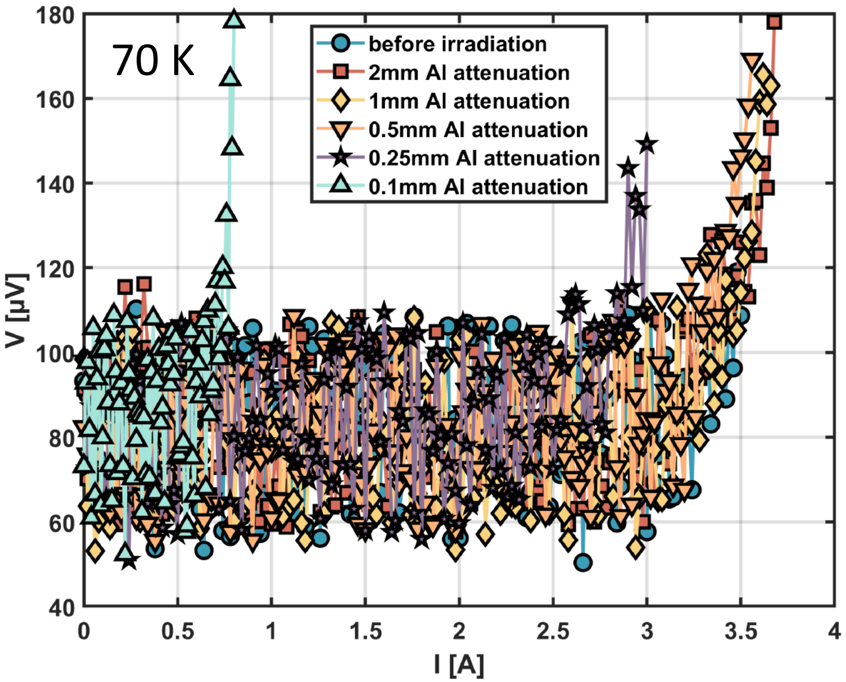


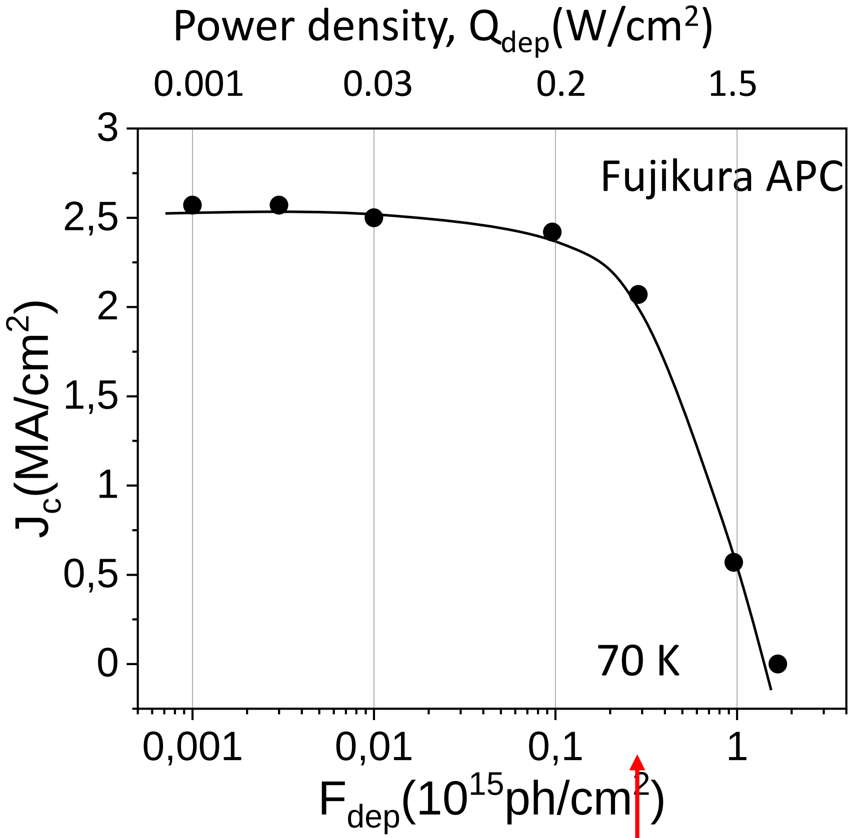
Al filter (mm)	**Deposited power density, Q_{dep} (W/cm^2)**	Total deposited photons (10^{12} ph)	**Total Deposited Fluence, F_{dep} (10^{15} ph/cm^2)**	REBCO provider thickness (μm)	Dose (kGy)
0.05	**2.5**	2,4	**1.7**	2.5	30 – 40
1	**0.03**	0.01	**0.01**	2.5	~0.2

Conditions for not proper evacuation of absorbed heat was identified at D~30-40 kGy

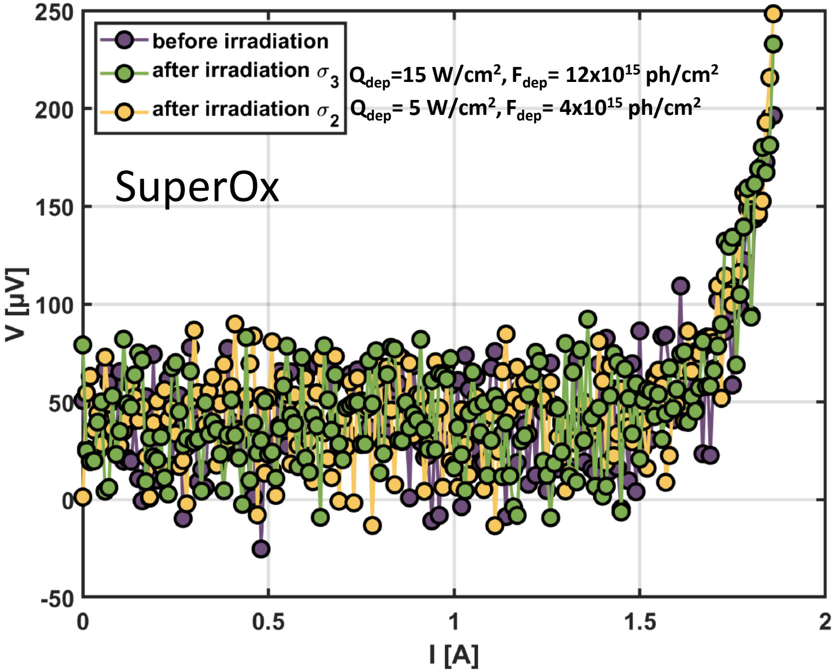
P. Krkotic et al, to be published

I(V) during irradiation with (3 keV <E_γ< 20 keV)





D~ 10-13 kGy



J_c decreased with irradiation compatible with local heating in agreement with ANSYS simulations

No permanent damage was observed even at 10^{16} ph/cm² (D~0.4 MGy)

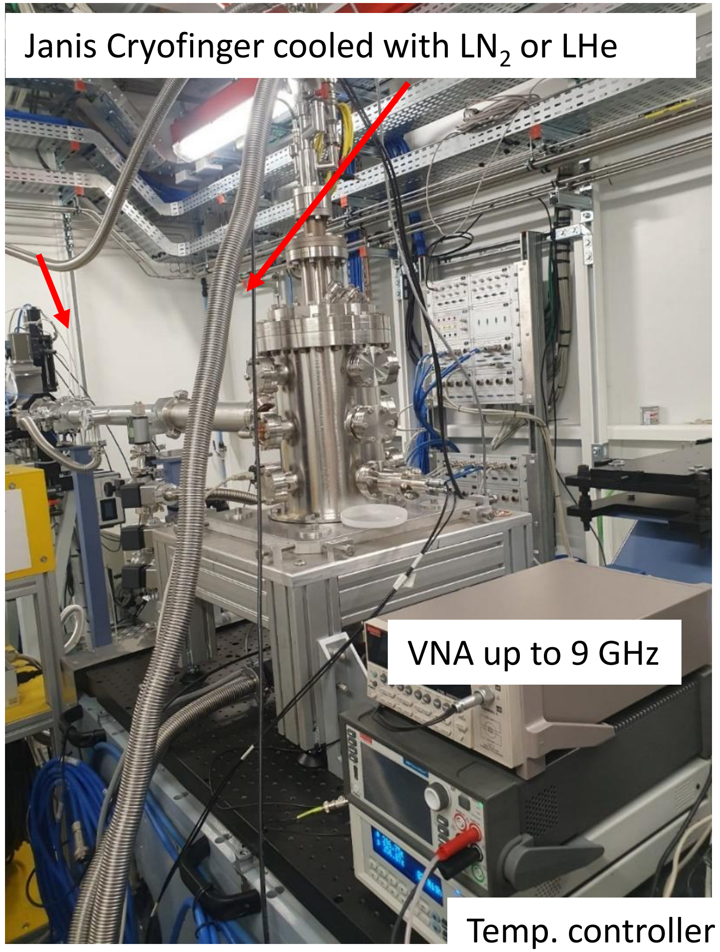
J_c decrease (probably by induced heating) was observed at D~10 kGy, but no permanent damage was achieved even at D~0.4 MGy

P. Krkotic et al, to be published

In-situ experiments (3 keV < E_γ < 20 keV)

Surface Resistance mesurements in NOTOS beamline

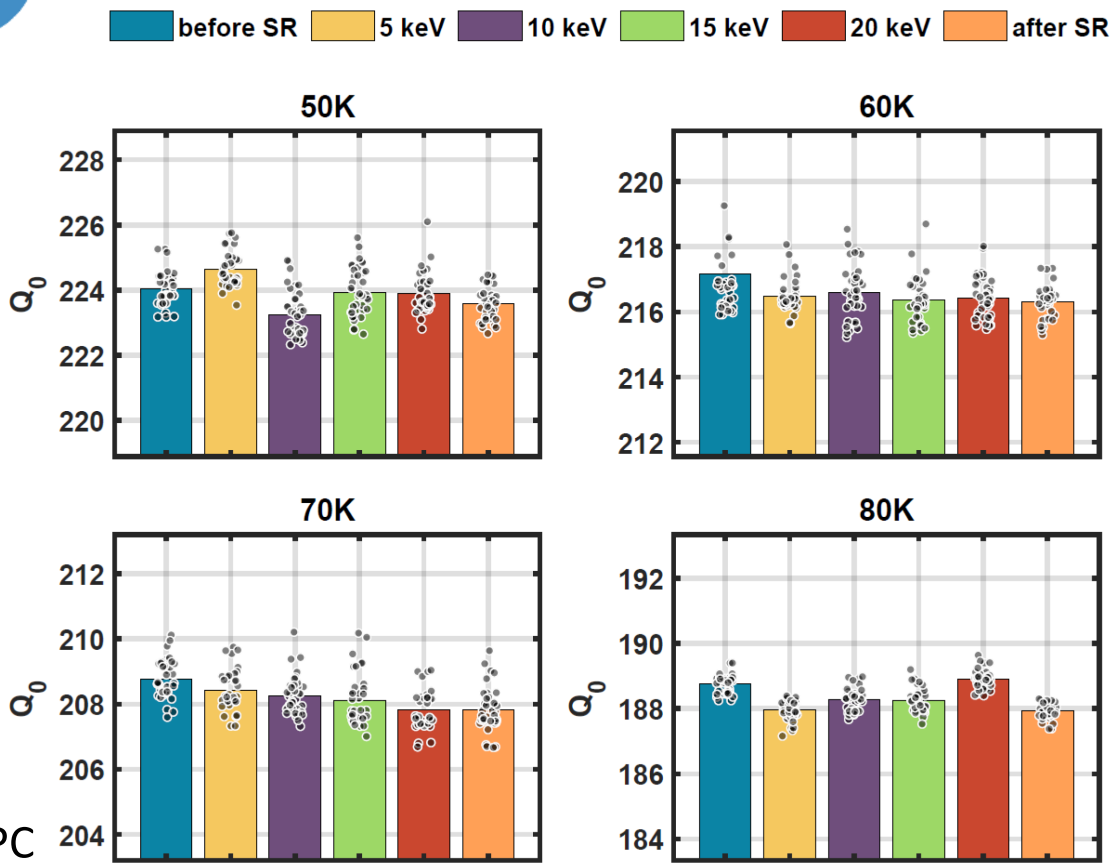
ALBA · ICMAB (Institut de Ciència de Materials de Barcelona) · Excelencia Severo Ochoa · CSIC (Consejo Superior de Investigaciones Científicas) · UPC



Temp. controller

Parallel Plate Resonator at 1 GHz
Al_2O_3 dielectric sandwiched with 2 delaminated REBCO samples

At F_{dep} = 3×10^{11} ph/cm^2 and Q_{dep} = 0.6 mW/cm^2



Fujikura APC

P. Krokotic et al, to be published

SR under these low doses does not have a measurable impact on the RF performance of the REBCO-CC samples neither permanent damage

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

Overall from all these Hard and Soft X-ray experiments at ALBA synchrotron, we concluded that HTS was compatible with the irradiation thresholds of FCC-hh beam screen

These capabilities are ready and can be upgraded to evaluate photon irradiation for fusion environemnts

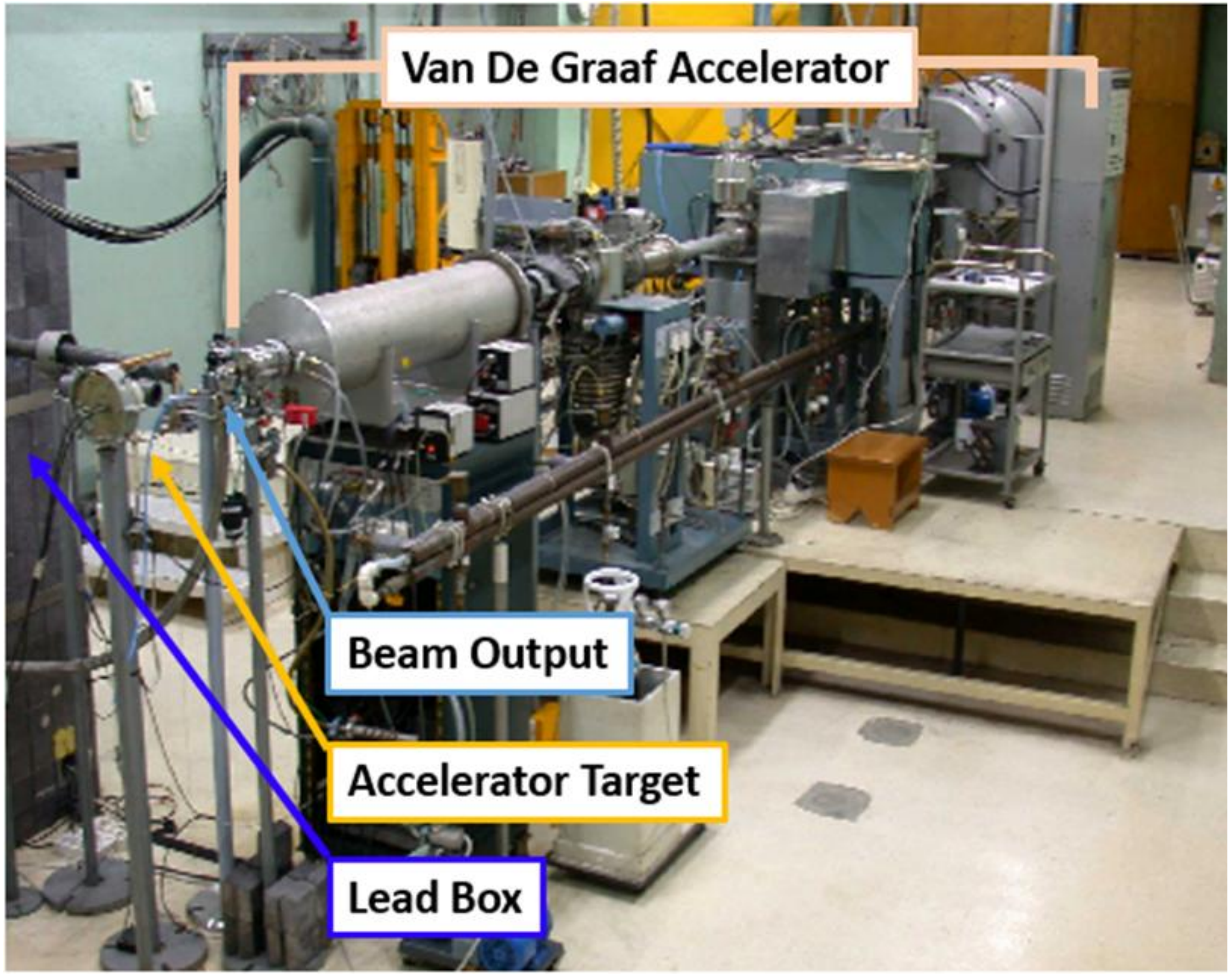
EUROfusion
Realising Fusion Electricity

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Installations at CIEMAT: National Fusion Laboratory
2 MeV Van der Graff electron accelerator

ICMAB INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA EXCELENCIA SEVERO OCHOA

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS



It will accomodate a cryocooler in the near future

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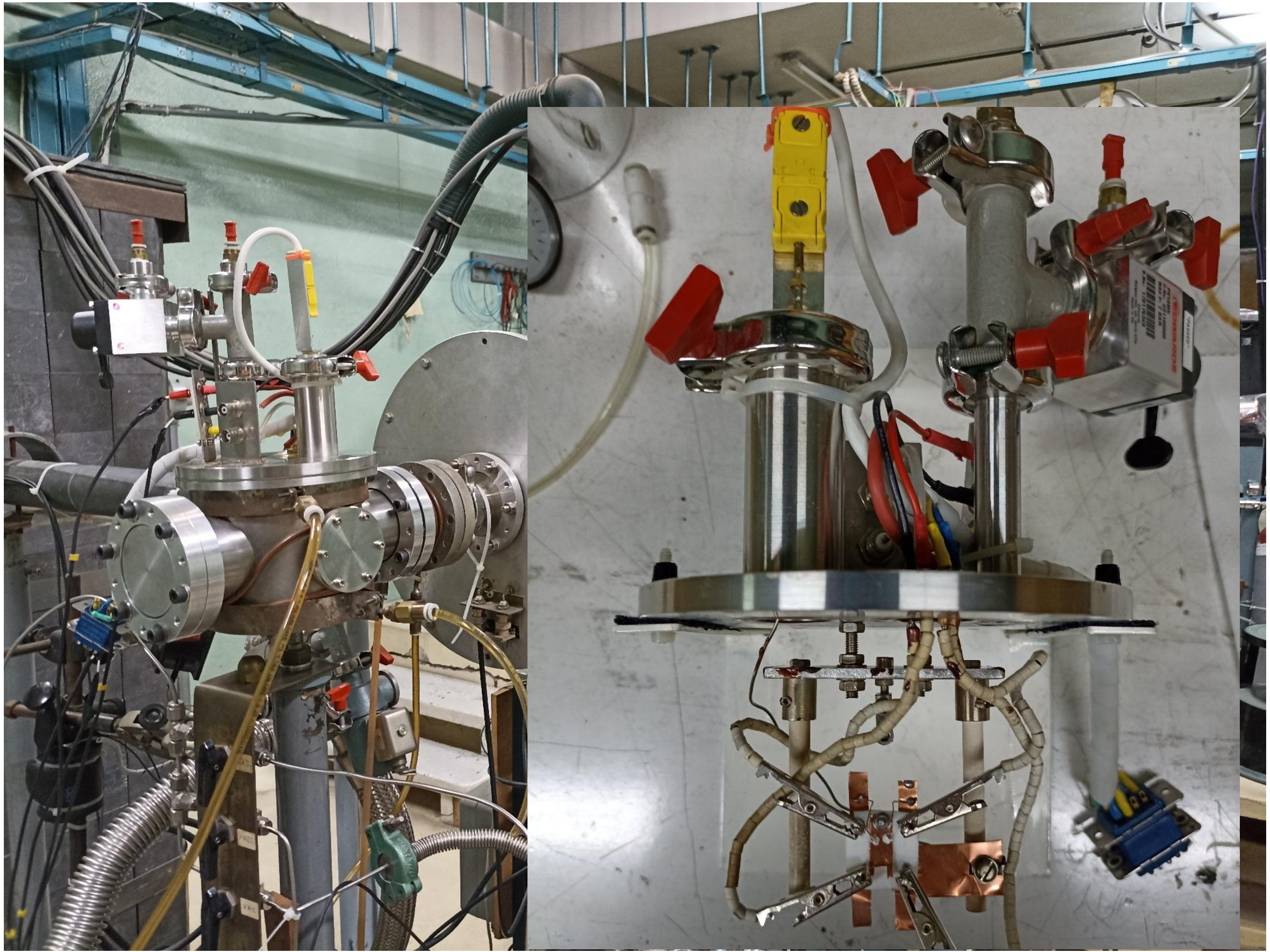
EXCELENCIA SEVERO OCHOA

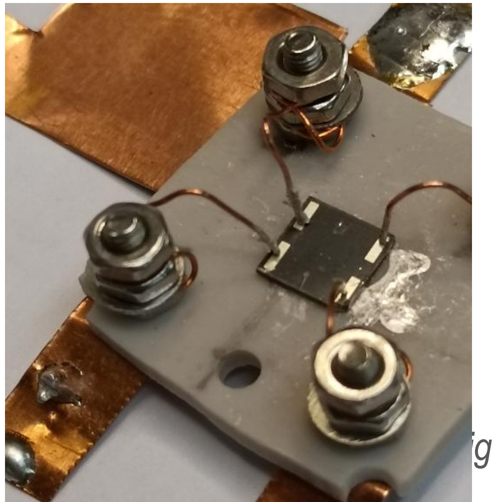
CSIC

Irradiation chamber in the Van der Graaf

with controlled atmosphere (vacuum, He, O_2, …) ≤ **10 MGy**

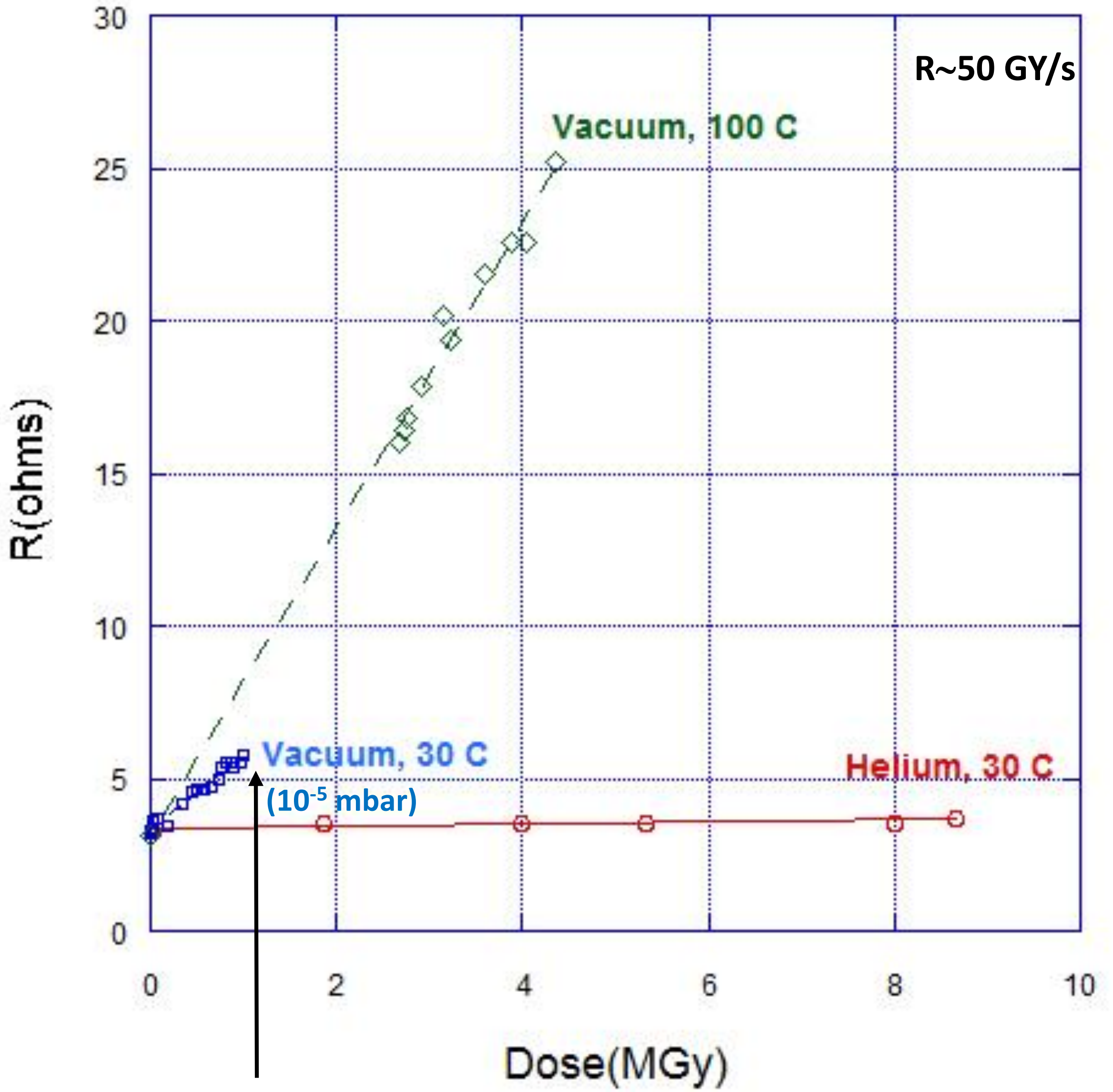


In-situ sample resistance monitoring during irradiation at RT



IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at IREF 2025, Gallipoli, Italy, June 2025.

Irradiation with 2 MeV electrons: On going studies



$F_{dep}=1.6\times10^{15}$electrons/cm^2

Irradiation at RT

- Material is differently modified during irradiation depending on the environment conditions

- Posible loss of oxygen induced by ionization radiation in vacuum conditions

- Properties after irradiation to be analyzed and compared to those before irradiation on the same sample:
  - Normal state properties (Van der Pauw): nH at 100 K, $\rho(T)$
  - Superconducting properties (SQUID): T_c, $J_c(T, H)$
  - XRD and TEM
  - Flux creep: starting a collaboration with L. Civale and MIT

Conclusions

- **Considering that massive and massless particles are relevant in fusion reactors, REBCO Coated Conductors and YBCO films have been irradiated with different irradiation sources, energies, fluences and doses**

- **Ex situ and in-situ Hard X-ray** (10 -250 keV) have shown no permanent damage effects up to 0.1 MGy. Only in some conditions local heating was observed in surface resistance

- **In-situ Soft X-ray** (3-20 keV) have shown reversible damage (probably due to local heating) at D ~10 kGy and no permanent damage even at G~0.4 MGy

- **Cooling power and sample heat extraction was one of the major identified issues in the in-situ photon irradiation experiments**

- **2 MeV electron** irradiation at RT up to 10 MGy have shown changes in resistance during irradiation depending on the atmosphere, vacuum being the worse scenario. Effect probably coming from loss of oxygen due to ionizaton effects

- **1.5 MeV γ-rays** irradiation at RT up to 1 MGy has been carried out and results are under evaluation

- Different radiation sources **capabilities are available** and being upgraded for carrying out irradiation studies on HTS for fusion