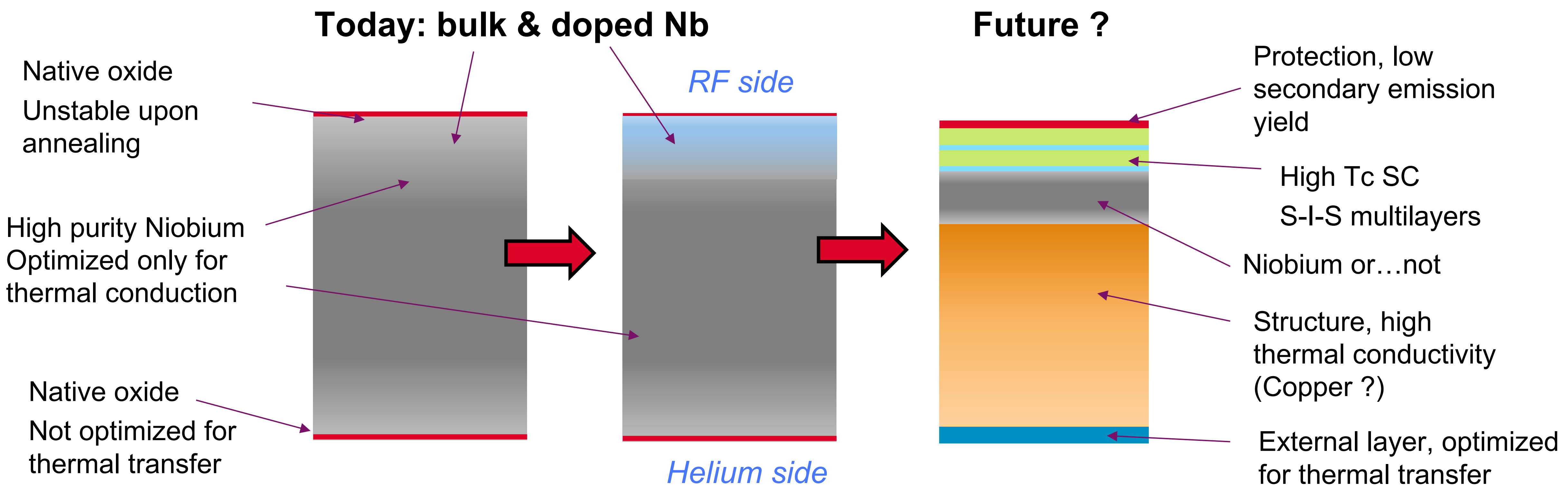
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

Thin films activities in the IFAST program

eeFACT 2022

Claire Antoine (CEA)

Desired: Tailored material for RF cavities

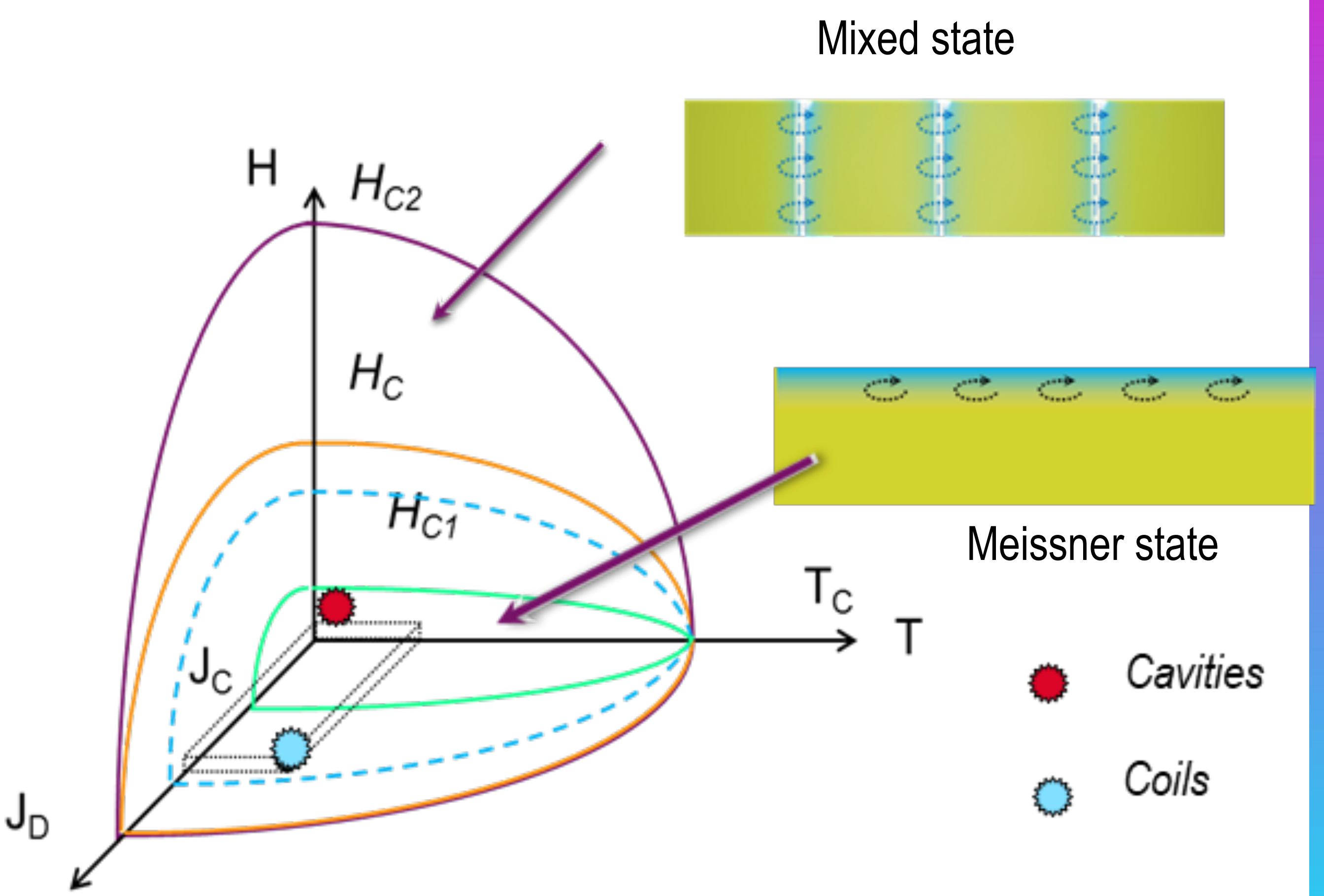


At stakes : COST REDUCTION !!!

- **Cooling power (any application); can we go to cryocooling ?**
- **High accelerating fields => shorter machines ?**

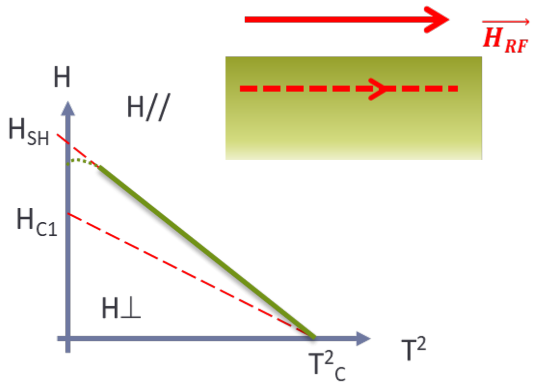
Superconductivity recalls

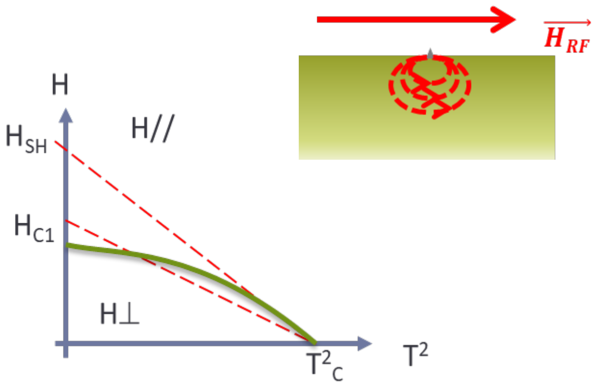
- ∃ thousands of SC
- In practice:
  - <10 are actually used
  - They are all type II
- Type II SC : 3 main Phases
  - Meissner state (SC, B=0)
  - Mixed state (SC + vortices (B≠0))
  - Normal conducting State
- Applications…
  - All applied SC are type II: i.e. low H_{C1} and high H_{C2} => operate in mixed state…
  - EXCEPT Nb for RF application !!!

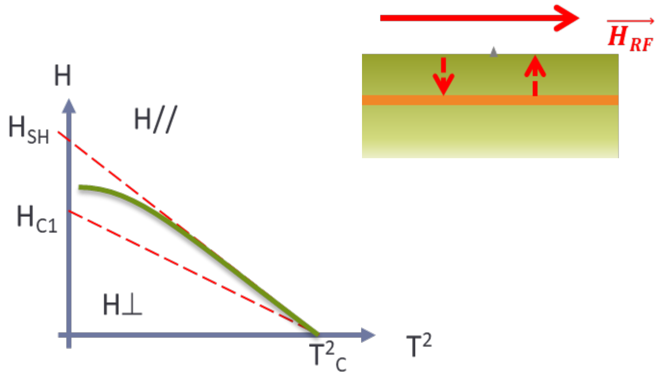


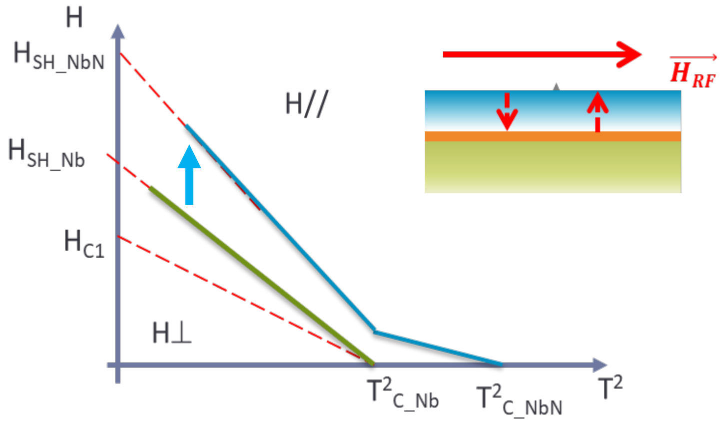
Multilayers (SIS) concept, or how to make theory face reality

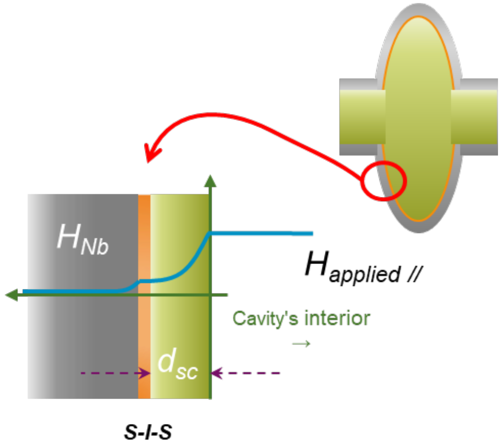
For the recall SRF cavity must operate in Meissner state !
No flux line please !

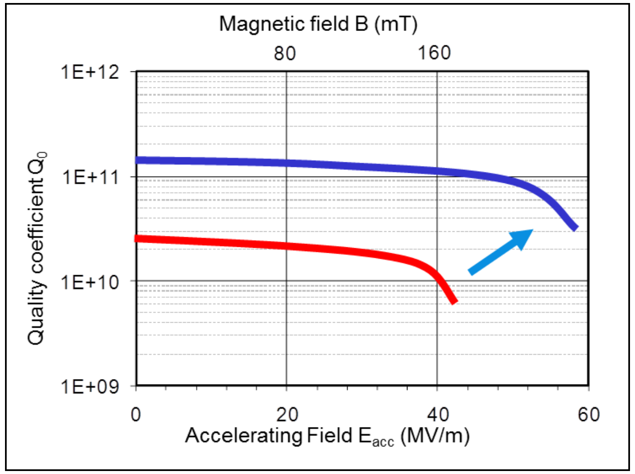












Some historical recalls about RF technology

Bulk Cu

= pure metal
Metallurgy
~ 6000 years

Bulk Nb

= pure metal
Metallurgy = ~ 6000 years
λ= 40 nm =>
+ Surface science: ~<100 years old

Higher Tc material

= Alloys, Compounds
+ Chemistry = ~ 250 years old
+ Surface science: ~<100 years old

Thin films

Nb or Compounds
CVD/PVD = ~ 50 years

Meta-material

multilayers
Advanced deposition techniques = ~ some years

Improving RF technology:

- **Huge challenges in material science**
- **Vast parameter space to be explored**
- **Underfinanced for years:**
  - **Accelerators considered as dirty hardware by fundamental material scientists**
  - **Material science considered as alchemy by (most) accelerator scientists**

Most developments, though, financed by Accelerator Community

Not enough (compared to e.g. magnet history)

Objectives for WP9 (task9.1)
Innovative superconducting cavities

Improve performance and reduce cost of SRF acceleration systems

- **We aim at building together a global strategy to be able to produce Superconducting RF (SRF) cavities coated with a superconducting films. Not only IFast, (informal) WW collaboration**
- **It includes pursuing the optimization and the industrialization:**
  - **Substrates preparation (Nb, Cu),** *e.g. PEP, metallographic polishing*
    - **Pre-and post treatment** *(laser, flash annealing)*
    - **The production of seamless copper cavities**
  - **The optimization deposition techniques: MS, PVD, ALD… to get Nb, NbN, Nb_3Sn, V_3Si… thick films (µm) and/or SIS Multilayers (nm)**
- **Produce and RF test prototypes of SRF cavities at 6 GHz: Easier to fabricate, handle, dissect to provide fast feedback**
- **Produce accelerator type 1.3 GHz cavities (feasibility assessment).**

Task 9.2: Seamless elliptical copper cavities

Task Leader: Cristian Pira (INFN)

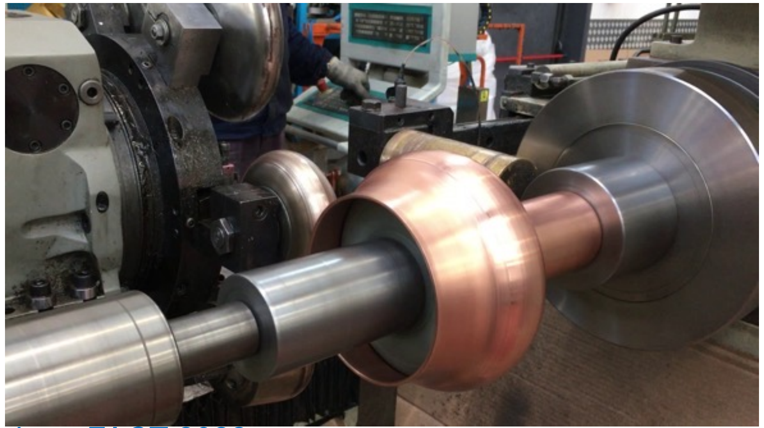
GOALS:

- **Move cavity forming process from semi-automatic to fully automatic using CNC machine**
- **6 GHz for task 9.3 and 1.3 GHz cavities for prototypes**

WHY ?

- **Need a lot of cavities for destructible tests**
- **Welding on copper definitively bad for films**
- **18 cavities realized 6 GHz , 1 @ 1,3,GHz**

Automatic spinning machine @ PICCOLI



Task 9.3 Part 1: Cavity Coating and Evaluation

Task Leader: Reza Valizadeh (UKRI)

GOALS:

- Quick deposition, quick testing, low cost (6 GHz)
- Optimization of process parameters with A15 material
- Evaluation of SRF performance by deposition of high Tc superconductor inside a 6-GHz copper cavity:

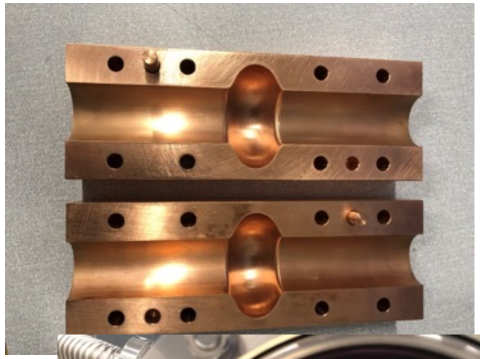
Nb_3Sn, NbTiN, NbN, MgB_2

WHY?

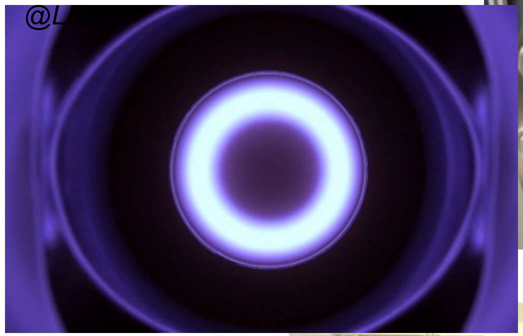
- Higher Tc SC are complex (compound) materials
- Composition needs to be adjusted to get best SRF performance
- Optimized recipes need then to be adapted for complex geometries

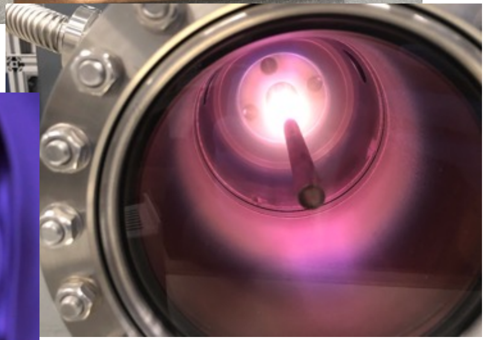
INFN 6 GHz cavity

Open 6 GHz cavity @ UKRI



Nb_3Sn 4" planar magnetron source @L





Nb magnetron target@ UKRI

Sputtering system @ USie

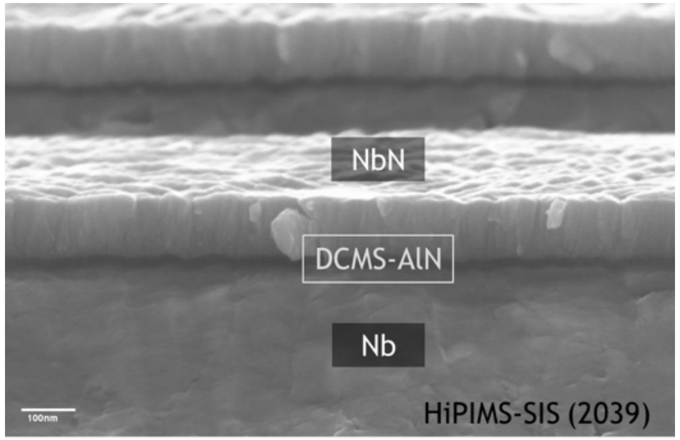
Task 9.3 Part Two: Planar Samples & QPR deposition

GOAL:

- **Optimise deposition parameters for other high T_c superconductor and provide sample for other partners for RF evaluation of their Thin Films**

WHY ?

- **Optimization of films still on going**
- **Alternative surface treatments**
- **Need to assess RF properties (see Task 9.6)**
- **Going from flat sample to complex shaped cavities is not straightforward => intermediate step**



HiPIMS-coated SIS structure on Si

Cu QPR sample before/after deposition

Task 9.4:Surface engineering by atomic layer deposition (ALD)

Task Leader: Thomas Proslier(CEA)

GOAL:

- **Deposition of functionalized layers :**
  - **Low secondary yield cap layer (↓ multipacting)**
  - **SIS multilayers**
  - **Dielectric surface engineering and doping**
- **Development of a 1.3 GHz deposition set-up**

WHY ?

- **ALD = highly conformational**
  - **=> adapted to complex shapes**
- **Chemical technique**
  - **=> wide range of compounds manageable in the same deposition set-up => in situ composite fabrication**
- **Can be used to upgrade Bulk Nb cavities**

Principle

- *Chemical precursors (gaz)*
- *Precursor 1 : adsorbed (chemisorbed) on the surface*
- *Purge (neutral gas): only 1 monolayer @ surface*
- *Precursor 2 : reacts w. precursor 1 directly on the surface => adapted to complex shapes like cavities (no line of sight issues)*

Task 9.4 results summary

Achievements :

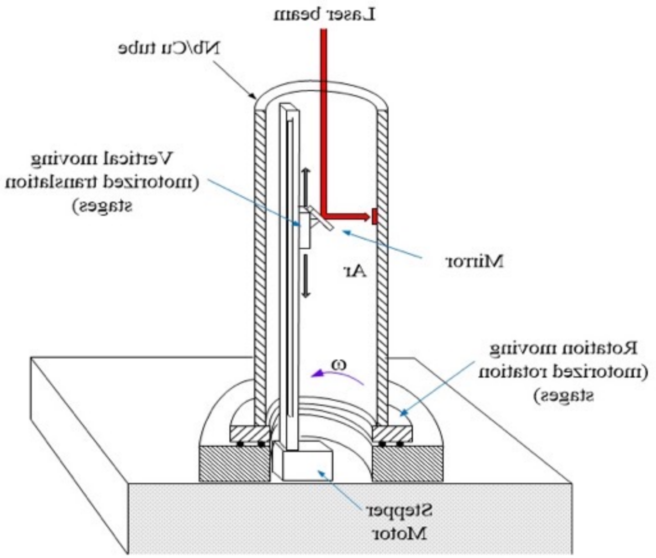
- Control and reduction by ALD of the secondary electron yield and the resulting multipacting mitigation.
- Control and optimization of the superconducting multilayer properties by ALD (Tc =15K).
- Homogeneous deposition and multilayer properties on Nb and Cu 1.3 GHz cavities.
- Compatible with cavity surface treatments (stability after HPR, thermal treatments…)
- New doping approach and dielectric layer engineering by ALD for bulk Nb.

New ALD system @CEA
Soon ready for 1.3 GHz cavity deposition
Compatible w. 700 MHz cavities

Atomic Layer deposition strength is its scalable capability: from bench to industrial scale (coupons to cavities and much more high aspect ratio and large surface objects).

Task 9.5: Improvement of mechanical and superconducting properties of RF resonator by laser radiation

Task Leader: Arturs Medvids (RTU)

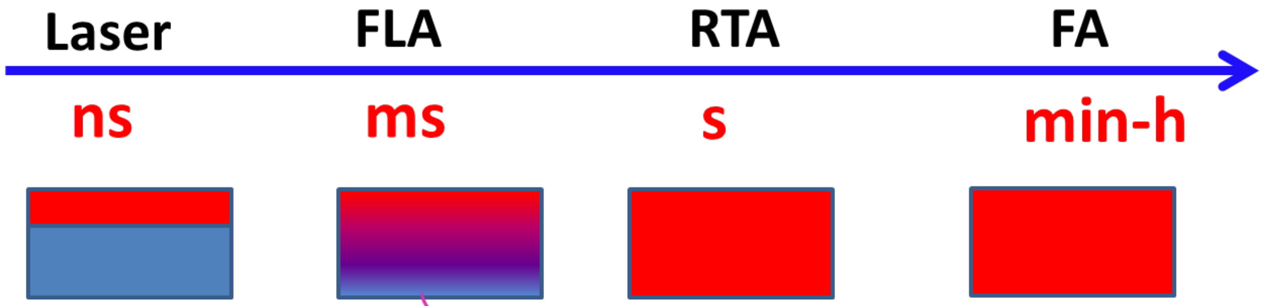


GOAL:

- **Pre-and Post-surface Laser treatment**
  - **On copper, to improve film deposition**
  - **On deposited films, to improve their crystalline quality**

WHY ?

- **Smoothing of surfaces**
- **Recrystallization**
- **Adhesion**
- **Decreasing porosities**



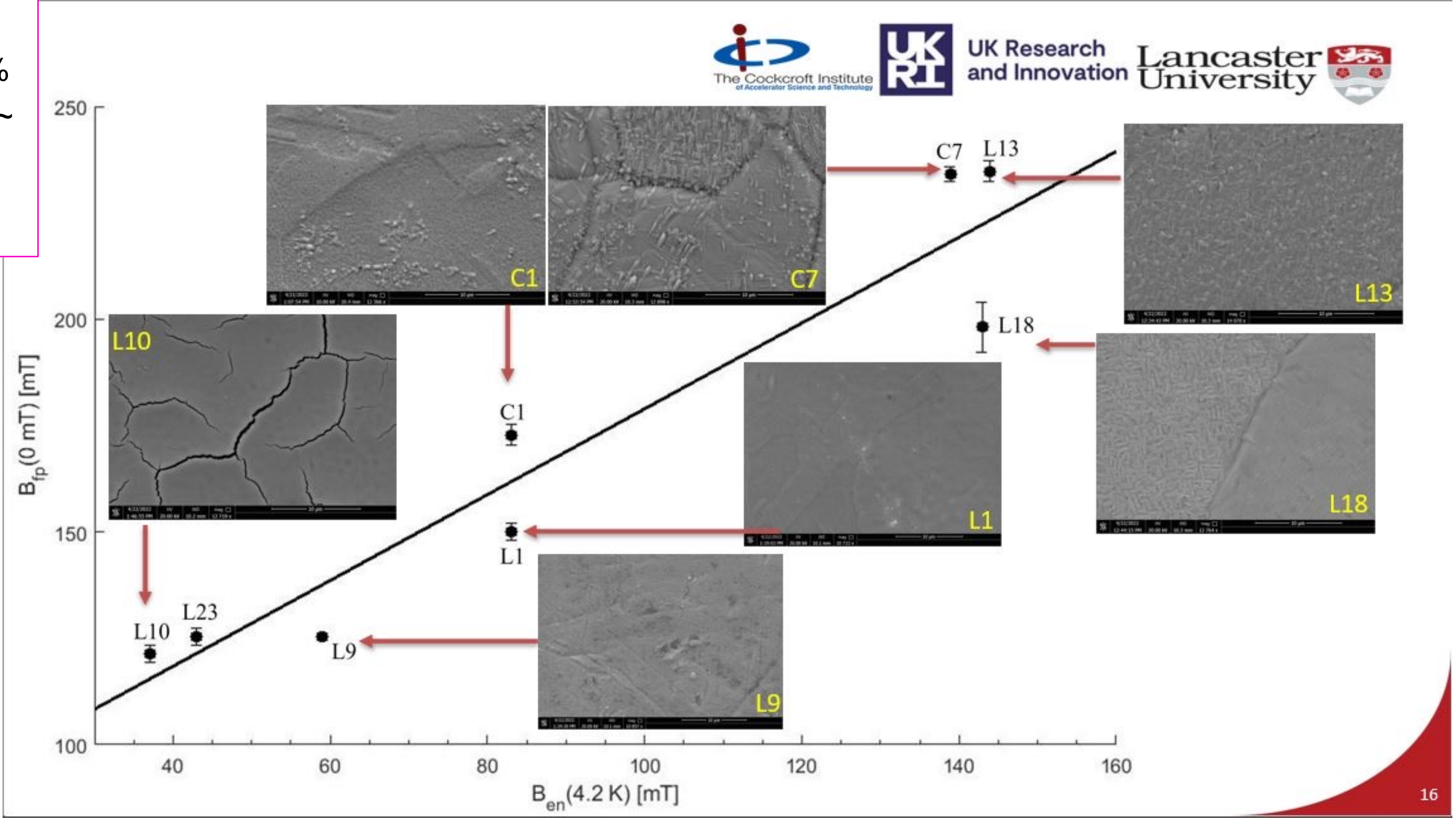
FLAsh lamp annealing :
New development w. HZDR

Assessment of the efficiency of laser treatment

Best Nb/Cu:

- Crystal size ↑ ~ 20%
- Adhesion Nb/Cu ↑ ~ 36%
- Roughness divided by >~2

https://indico.cern.ch/event/1140002/contributions/4783615/attachments/2436059/4172593/IFAST.WP9.5th.DTurner.FPE.pdf



Task 9.6: Optimization of flat SRF thin films production procedure

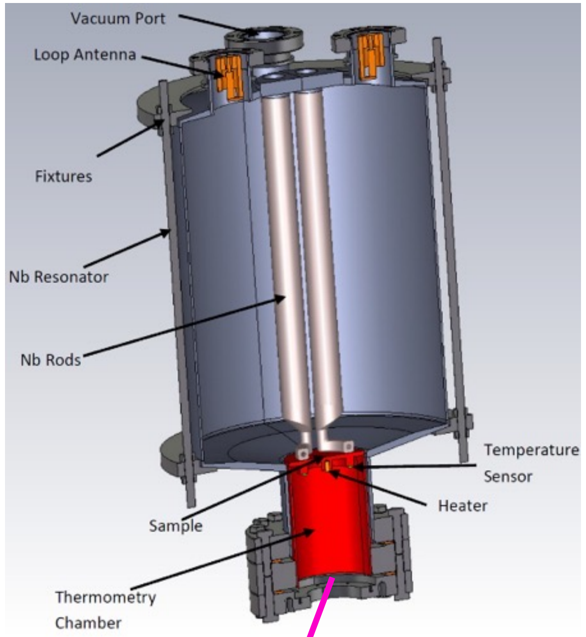
Task Leader: Oliver Kugeler (HZB)

GOAL:

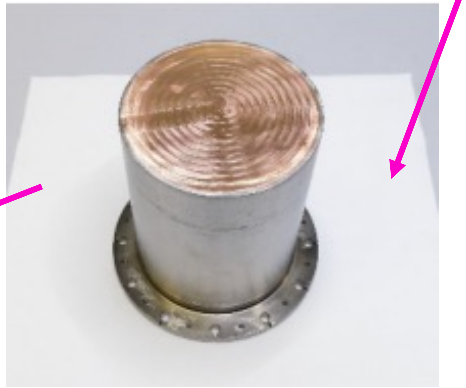
- **RF testing of the films developed throughout the WP9**
  - **Sample is small enough for easy handling**
  - **Sample is flat (one problem less in the way)**
  - **3 ≠ frequencies available : large exploration (R_{BCS} vs R_{res})**

WHY ?

- **Material characterization, even advanced are still not predictive of future RF behavior**



QPR



Flat sample for RF testing

Task 9.6:Optimization of flat SRF thin films production procedure

Lathe machining

Chemical or Electrochemical Polishing

Nb, NbN and SIS by HiPIMS

Nb, Nb3SN, SIS by DCMS or HiPIMS

Nb thick film by DCMS

, other partners...

Task 9.3

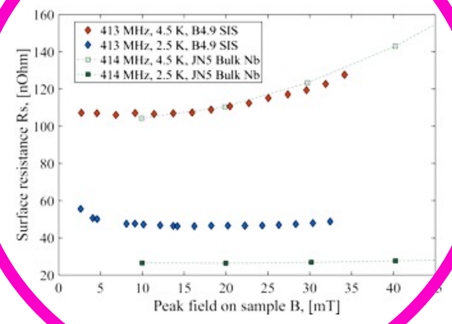
Task 9.6

MECHANICAL MACHINING

POLISHING

COATING

RF TEST

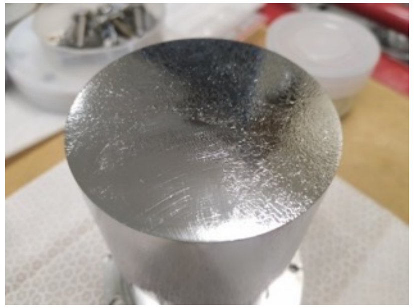


Courtesy of C. Pira (INFN) and E. Chyhyrynets

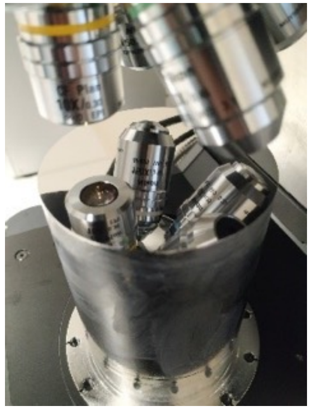
Task 9.6: Baseline measurement on QPR samples

Metallographic polishing @ CEA/IJCLab

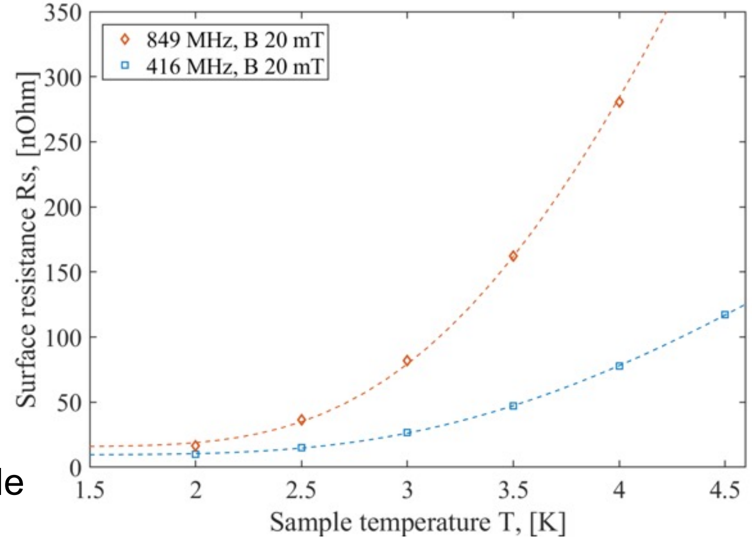
QPR sample milled from
ASTM0 large grain material
Poor RF performance,
In contaminations



Mirror polishing
at IJCLab

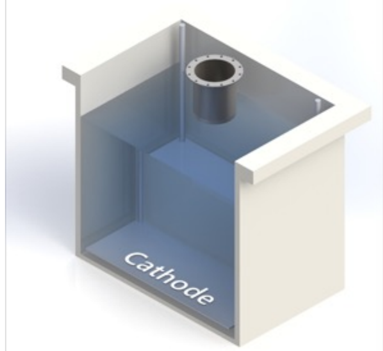


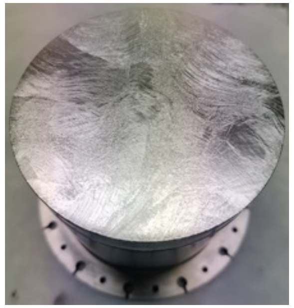
Pictures courtesy Oleksandr Hryhorenko (IJCLab)



Great RF performance of baseline sample
(9 Ohm residual resistance at 416 MHz)

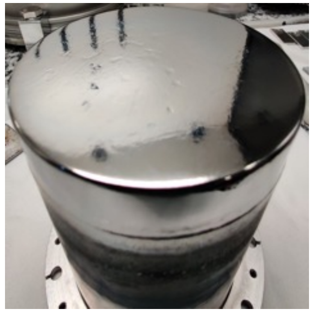
Plasma electropolishing samples@ INFN





Initial Nb QPR sample

Surface improvement after 10 min

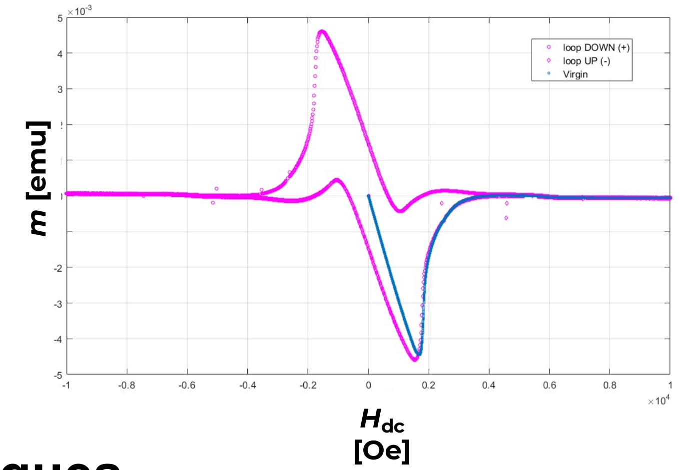


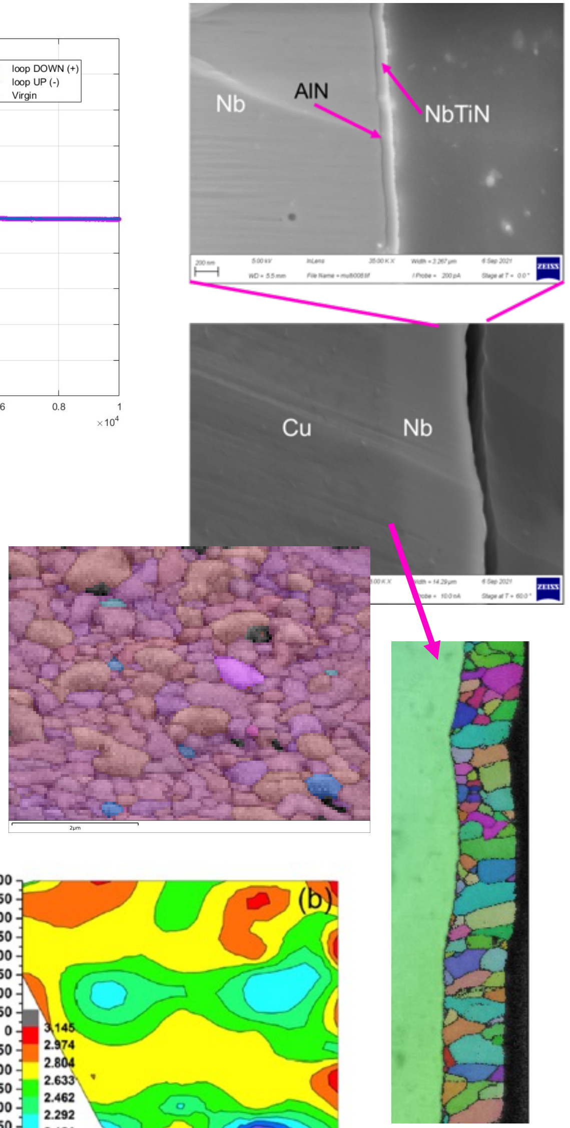
100-µm removal in 60 min.
Mirror finish

Interesting side effect:

Significant improvement of measurement accuracy (< 4 nW) by coating flanges too.

Ifast WP9 : Thorough material characterization needed!



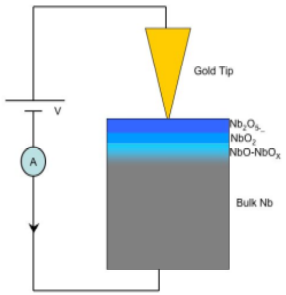


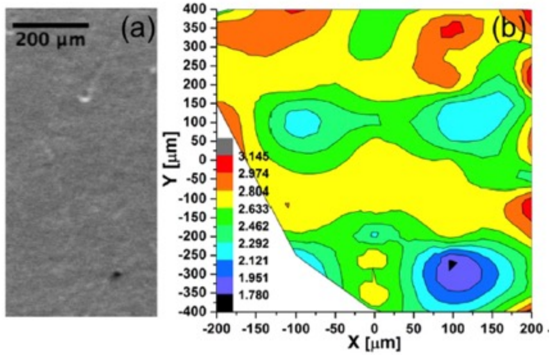
Classical material characterization …

- Opt. and confocal microscopy
- SEM, EDX and EBSD
- Ion beam miller for cross-section
- X-Ray, TEM … advanced characterization techniques
- Superconductivity: Tc, RRR, DC magnetometry, AC susceptibility

Home made (advanced) characterization tools:

- Flux penetration (@ UKRI, @ CEA) (=> E_{acc})
- Rs on small samples (7.8 GHz cavity @ UKRI)
- SC gap, DOS cartography
  (scanning tunnel microscope @ CEA)





CONCLUSION

→ Things are going according to IFAST WP9 plan

→ WW: thin films activities = few groups, few resources

→ Coordination and exchanges help to derive maximum benefit

→ Next generation of SRF material is “en route” with already very nice results on samples

→ We hope IFAST WP9 (and collaborators) to bridge the gap between lab R&D and 1rst prototypes development

→ If accelerator community wants SRF technology to evolve*, strong investments are needed in the near future

* Change of paradigm, not just mere improvement

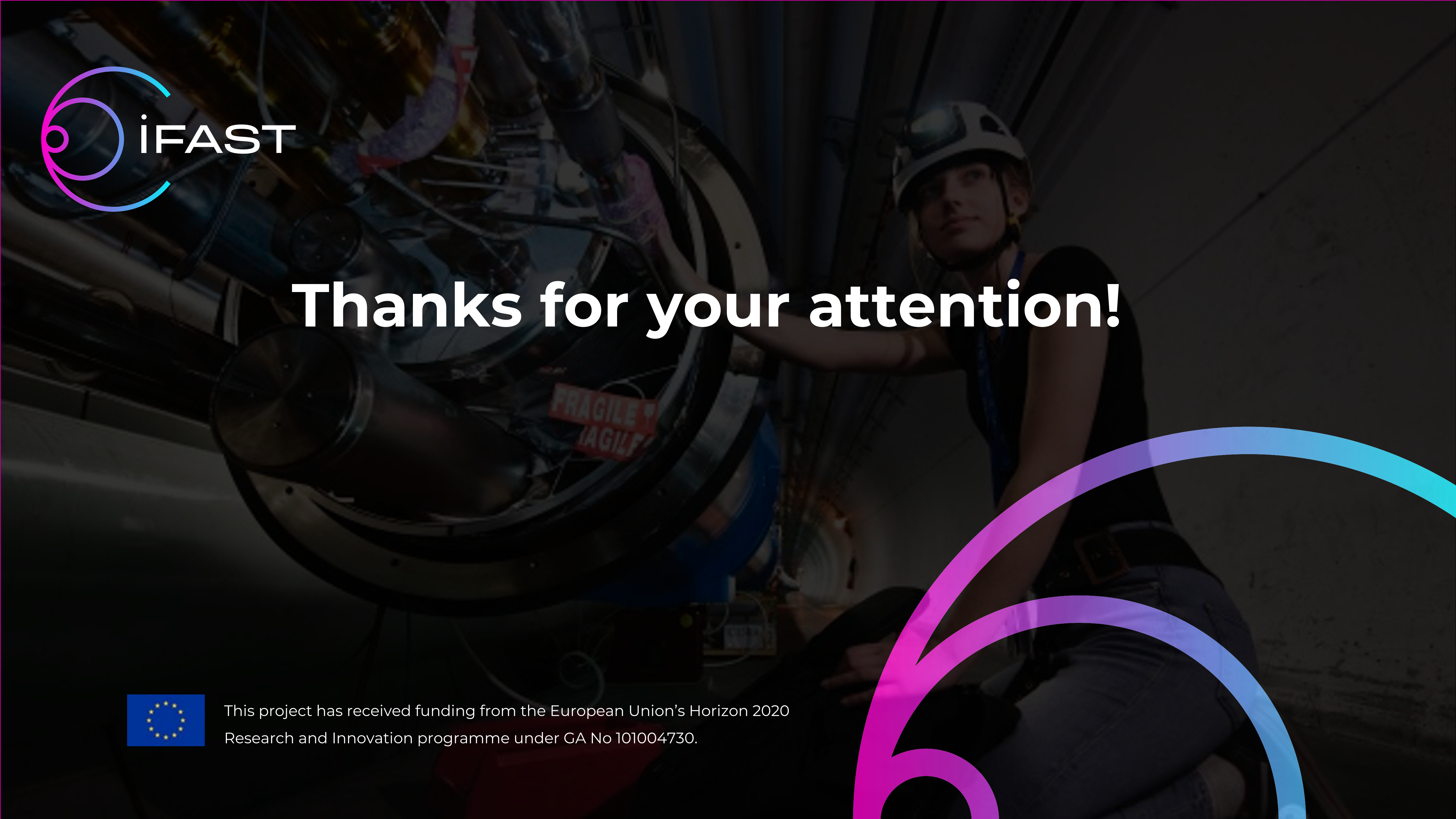
IFAST WP9:

- 9 countries
- 15 institutes
- >50 participants

+ Not officially:

CERN, DESY, (task 9.1)

	IFAST WP9 Partners	Leading	Participating
1	CEA (Saclay, France)	WP, Tasks 1 and 4	Task **1**, 2, **4**, 6
2	CNRS/IN2P3/IJCLab (Orsay, France)		Task 1, 4
3	IEE-SAS (Bratislava, Slovakia)		Tasks 2-6
4	INFN/LNL (Legnaro, Italy)	Task 2	Tasks 1, **2**, 3, 5, 6
5	*INFN/LASA (Milano, Italy)*		Tasks 2, 3
6	*Piccoli S.r.l. (Noale (VE), Italy)*		Tasks 2, 3
7	Helmholtz-Zentrum Berlin (Berlin, Germany)	Task 6	Tasks 1 and **6**
8	RTU (Riga, Latvia)	Task 5	Task **5**
9	University Siegen, (Siegen, Germany)		Tasks 2, 3, 6
10	UKRI/STFC/ASTeC (Daresbury, UK)	WP, Tasks 1 and 3	Tasks 1, 2, **3**, 5, 6
11	*Lancaster University (Lancaster, UK)*		Tasks 1 – 3, 6
12	*Jlab (Newport News, Virginia, USA)*		Tasks 1, 2
13	*PTI (Physical-Technical Institute, Minsk, Belarus)*		Tasks 1, 2
14	*MEPHI (National Research Nuclear University, Moscow, Russia)*		Tasks 1 - 3
15	*Helmholtz-Zentrum Dresden-Rossendorf (Dresden, Germany)*		Task 1 – 3, 5



iFAST

Thanks for your attention!

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