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

Millisecond flash lamp treatment for SRF accelerating cavities

IIF Evaluation - CERN 16 November 2022

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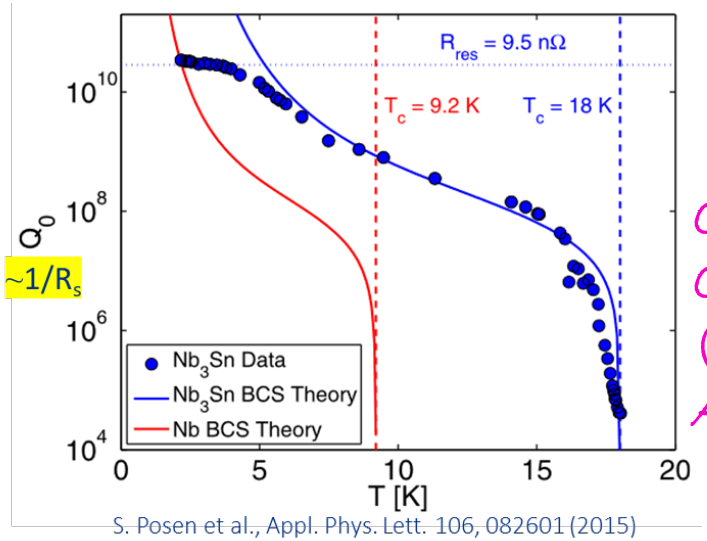
Nb_3Sn motivation

Nb_3Sn looks a good choice For SRF cavities

Material	Tc	H_{sh}
Nb	9.2 K	0.2 T
Nb_3Sn	18.3 K	0.4T

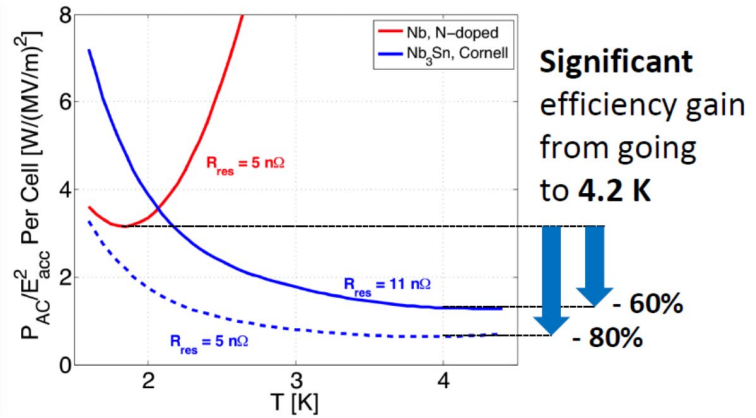
DOUBLE ACCELERATING FIELD

60% DECREASE IN CRYOGENIC COSTS



S. Posen et al., Appl. Phys. Lett. 106, 082601 (2015)

CRYOCOOLER COOLING POSSIBLE (INDUSTRIAL APPLICATIONS)



Significant efficiency gain from going to **4.2 K**

- 60%

- 80%

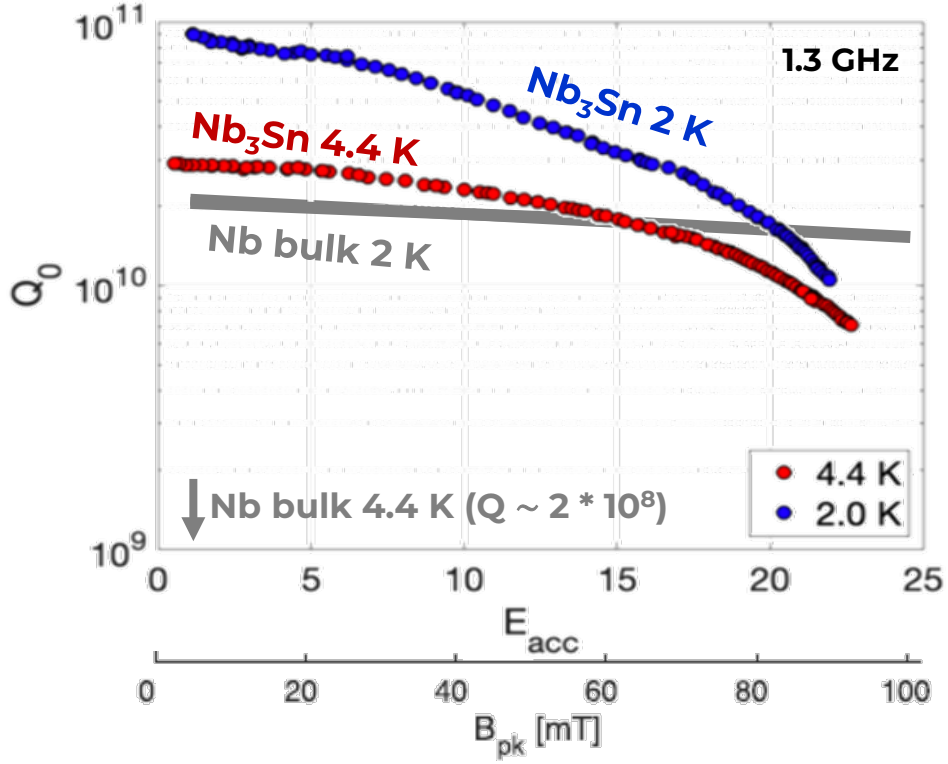
Nb_3Sn State of the art

Nb_3Sn on Nb by Tin Vapour Diffusion already show performances at 4.2 K comparable to bulk Nb at 2K

Nb cavity as substrate:

- expensive
- Bad thermal conductivity

(strong limitation for industrial applications that require Cryocoolers)

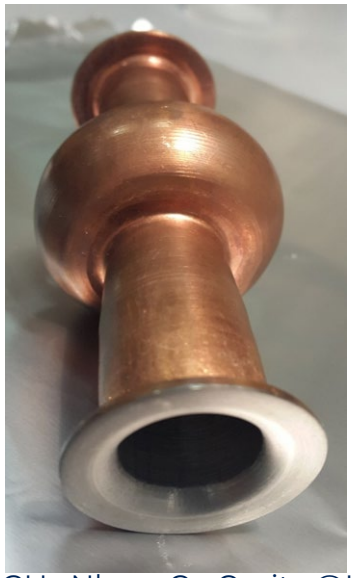


S. Posen, SRF 2019 proceedings (elaborated)

Nb_3Sn on Cu by Sputtering

- **Similar to Nb on Cu** cavities
- **Solve** the **Low Thermal Conductivity issue** of Nb substrate
- A first prototype of 1.3 GHz cavity is under developing in **iFAST WP9**

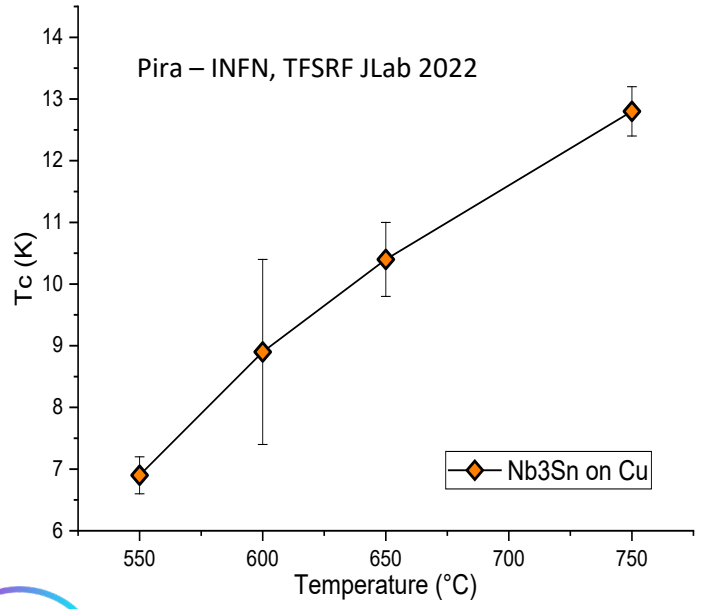
- **Low melting point of Cu** is a limitation
- 650 °C can be considered a limit in a Cu cavity
- Diffusion of Cu into Nb_3Sn



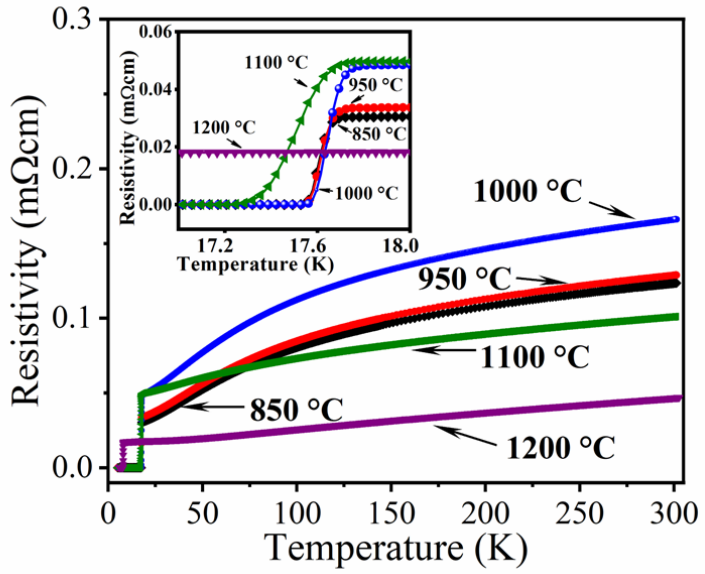
6 GHz Nb on Cu Cavity @LNL

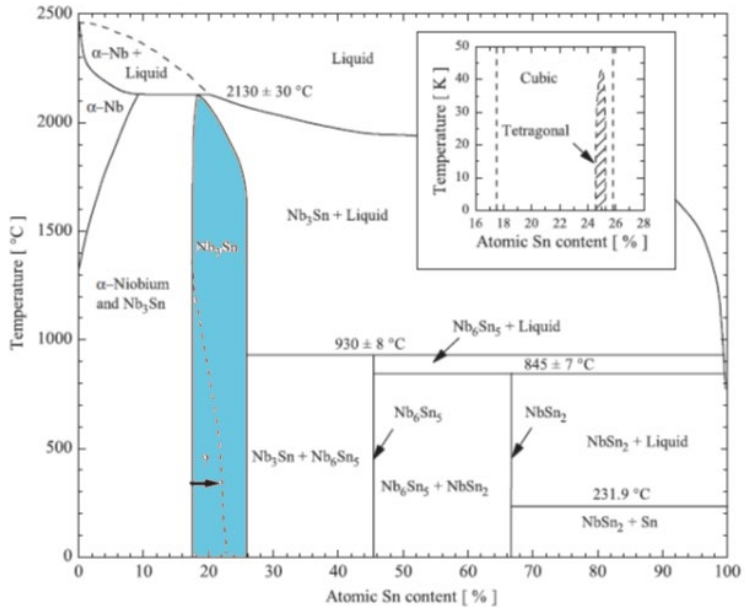
Nb_3Sn on Cu by Sputtering

- Nb_3Sn coating **Tc increase with substrate temperature deposition**
  (Stewart Leith – CERN, TFSRF JLab 2022), (Pira – INFN, TFSRF JLab 2022)
- Optimal T seems ~950 °C → Tc= 17.9 K (in Nb_3Sn on Nb by sputtering)
  (Nizam Sayeed - Jlab, SRF 2021)



M.N. Sayeed et al. https://doi.org/10.1016/j.jallcom.2019.06.017





Nb_3Sn phase diagram

Goal

Develop a novel thermal process to improve performances of SC coating by suppressing (reducing) Cu substrate heating

Millisecond-flash-lamp-annealing (FLA)

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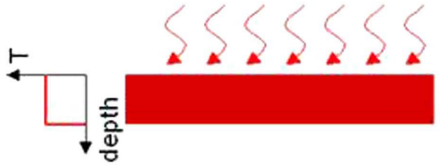
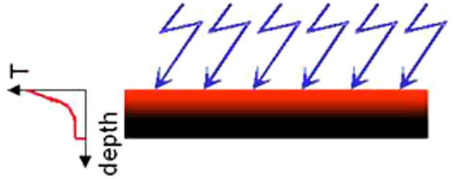
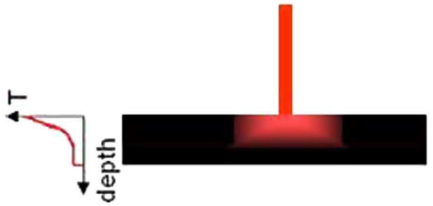
Millisecond-flash-lamp-annealing (FLA)

RTP	FLA	Laser
		
• whole wafer heated	• only surface heated	• only surface heated
• $T_{RS} \approx T_{FS}$	• $T_{RS} << T_{FS}$	• $T_{RS} << T_{FS}$
• 1 –100 s	• 0.5 – 20 ms	• 1 – 1000 ns, ms for cw
• up to 1300°C	• up to 2000°C	• up to 2000°C
• halogen lamps	• Xe flash lamp	• XeCl excimer (308 nm) KrF excimer (248 nm)
• broad spectrum ~ 800 nm	• broad spectrum ~ 400 nm	• discrete lines (interference effects!)
• one shot-one wafer	• one shot-one wafer	• point or line scan

L. Rebohle, S. Prucnal, W. Skorupa, Semicond. Sci. Technol. 31 103001 (2016).

FLA Advantages compared to standard annealing

- FLA is an innovative process for thermal pre- and post-treatment of functional coatings and sensitive substrates in millisecond range time scale.

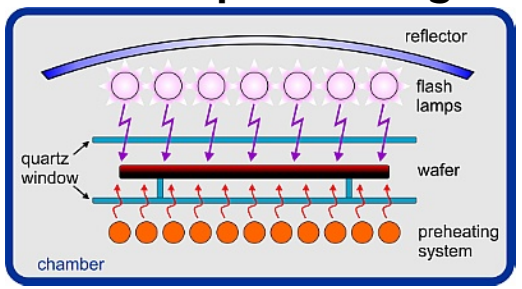
- The thermal load and hence the temperature throughout the entire substrate is much lower compared to conventional annealing.
  This produces two advantages in respect to standard annealing (state of the art for sputtering processes):

  1. **Suppresses the diffusion of Cu into SC layer**
     A diffusion barrier (Nb or Ta film) between Nb_3Sn and Cu may **no longer be needed**
  2. **Higher annealing temperature possible on SC coating**
     On Nb_3Sn we expect an **improvement of Tc** from 10-16 K to 18 K

Tc range for Nb_3Sn on Cu with standard annealing up to 650 °C

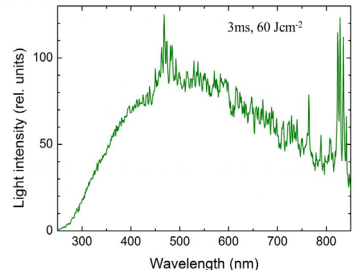
Tc of Nb_3Sn on Nb by sputtering annealed at 950°C

Flash Lamp Annealing



FLA parameters

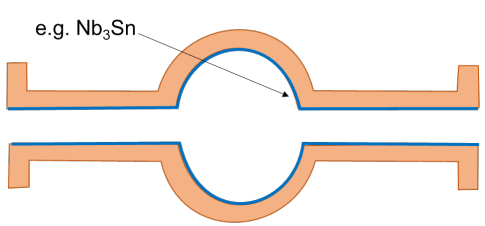
Max. T ≈ 2000 °C
Pulse length – 0.4 – 23 ms
Max. E = 145 Jcm^{-2}
Sample size – 12” or 40x40cm

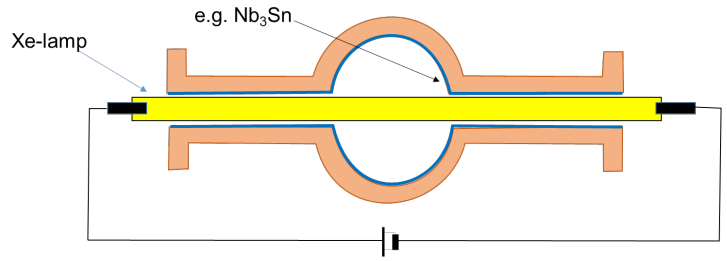


Spectrum of the flash lamps

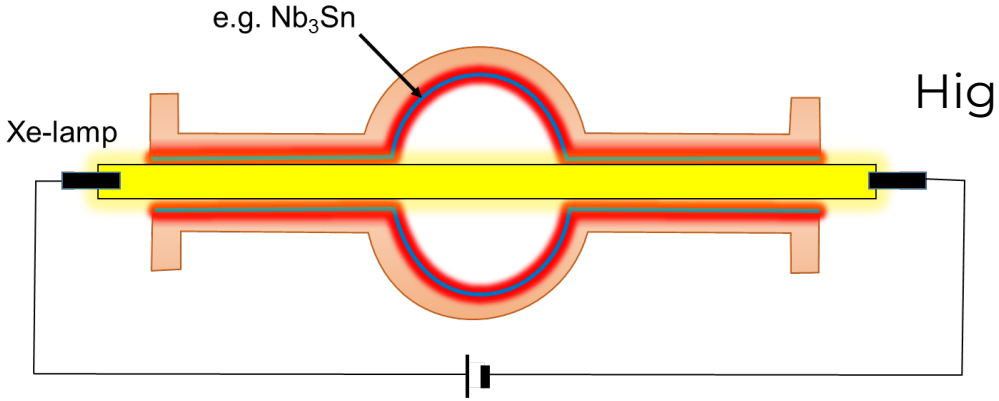
How to implement in a cavity?

1. Nb_3Sn coating of Cu-cavity: 6 GHz (or 1.3 GHz)

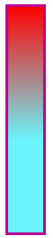




2. Flash Lamp Annealing of high Tc coatings



High T (K)

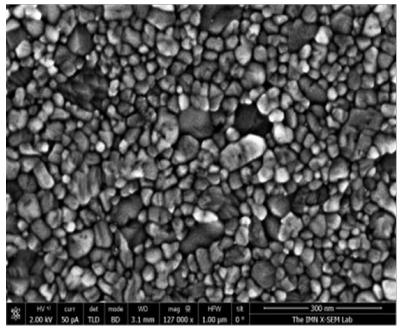


Temperature distribution
in flashed cavity 20 ms

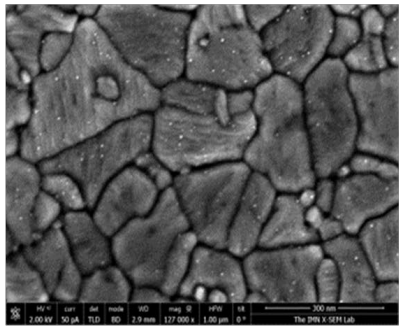
Proof of concept

Recrystallization of magnetron sputtered TiO_2 thin film on Si-substrate
With FLA grain dimension enhancement and lower roughness

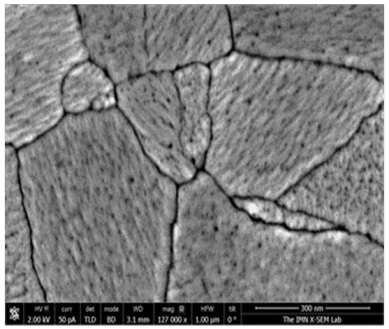
Furnace annealing 600 °C_30 min



Flash Lamp Annealing 80 Jcm^{-2} 20ms

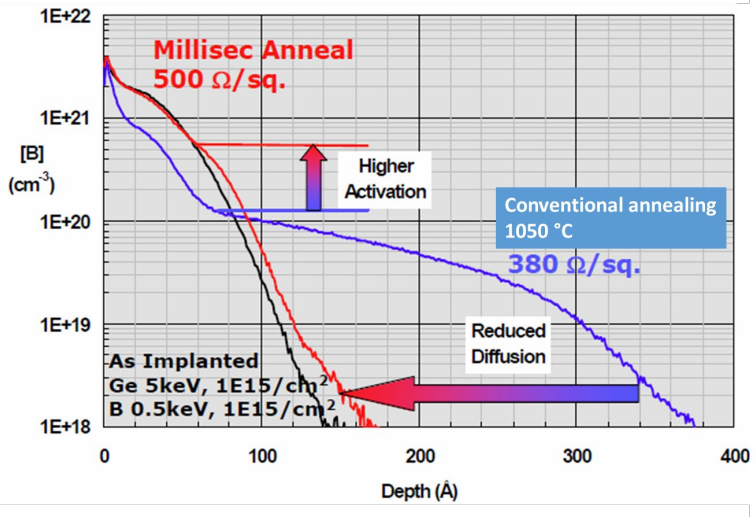


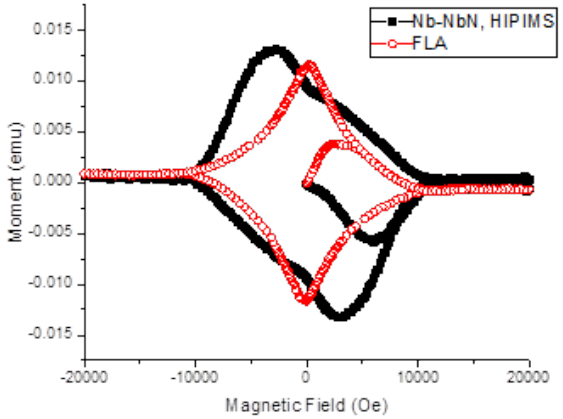
Flash Lamp Annealing 120 Jcm^{-2} 20 ms



Courtesy of Raul Gago (CSIC Madrid, Spain)

FLA reduce diffusion of dopants in semiconductors **compared with standard annealing**





FIRST TEST ON SC SAMPLE

2 micron Nb-NbN multy layer on Cu substrate coated by STFC

2.2 ms FLA treatment

The FLA produce a narrower hysteresis curve
(material crystallinity improved)

Expected results (technology validation)

- On planar samples:
  1. Nb on Cu: grain size enlargement of Nb, Cu substrate almost unaffected
  2. **improvement of the Tc** up to 18 K in Nb_3Sn on Cu films

- On 6 GHz cavities:
  3. **treatment uniformity** along the cavity (check by grain size measurement on Nb and on Cu cavity)
  4. **Q value of $1*10^9$ at 4.2 K** for Nb_3Sn on Cu 6 GHz cavity by RF test (same performances of Nb at 2 K)

Point 4 success strongly depend on iFAST task 9.3

Workplan

PLANAR SAMPLES

Coatings of SC (Nb_3Sn, NbTiN, …) on Cu planar substrate

INFN iFAST **WP9 partners**

Flash lamp annealing of planar samples

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Characterisation

- XRD
- SQUID
- RBS
- SEM-EDS
- Scratch test

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

iFAST **WP9 partners**

PICCOLI srl TORNERIA IN LASTRA METALLICA

6 GHz Cavities forming by spinning

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

FLA of a 6 GHz cavity

6 GHz FLA implant design, production and test

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

INFN iFAST **WP9 partners**

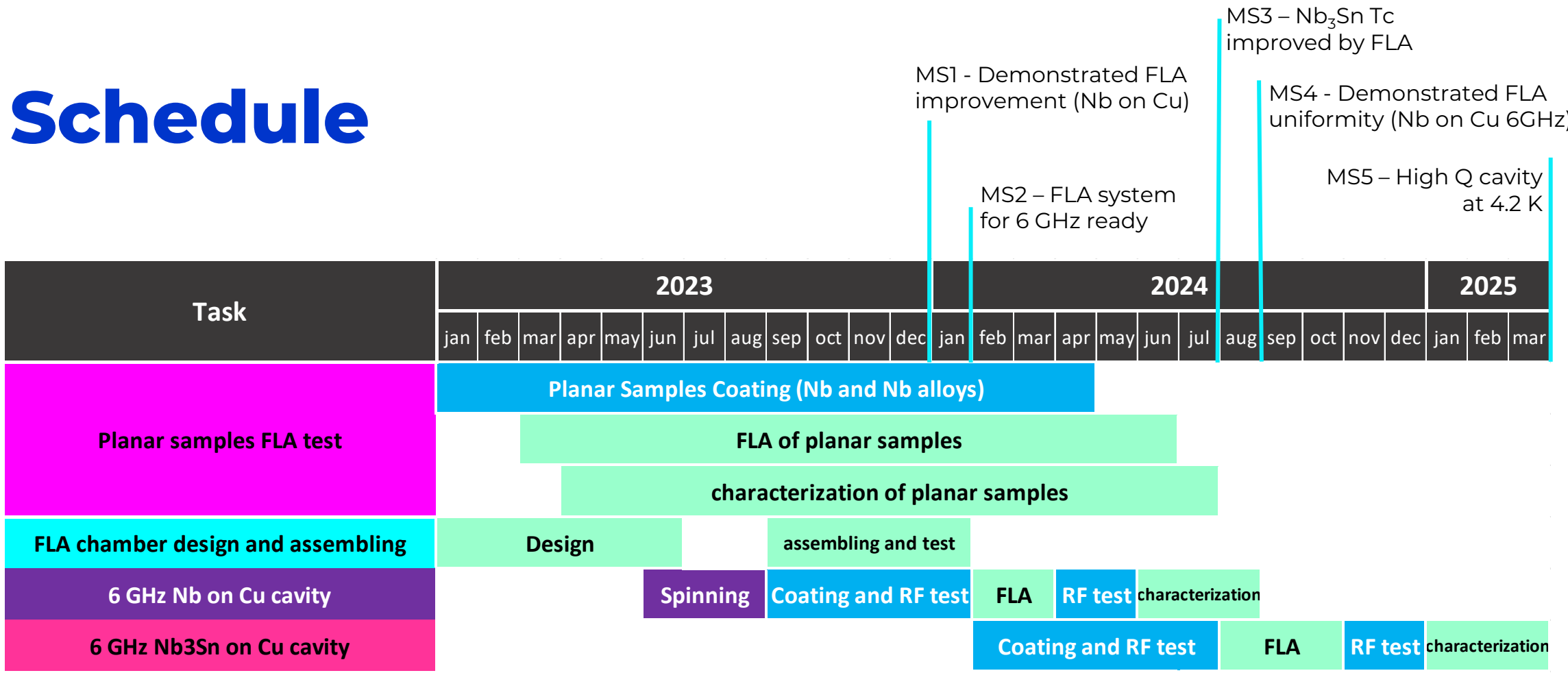
Polishing and Coating of 6 GHz cavity

6 GHz RF test

INFN

6 GHZ CAVITIES

Schedule


MS1 - Demonstrated FLA improvement (Nb on Cu)
MS2 – FLA system for 6 GHz ready
MS3 – Nb_3Sn Tc improved by FLA
MS4 - Demonstrated FLA uniformity (Nb on Cu 6GHz)
MS5 – High Q cavity at 4.2 K
Task
2023
2024
2025
jan feb mar apr may jun jul aug sep oct nov dec jan feb mar apr may jun jul aug sep oct nov dec jan feb mar
Planar samples FLA test
Planar Samples Coating (Nb and Nb alloys)
FLA of planar samples
characterization of planar samples
FLA chamber design and assembling
Design
assembling and test
6 GHz Nb on Cu cavity
Spinning
Coating and RF test
FLA
RF test
characterization
6 GHz Nb3Sn on Cu cavity
Coating and RF test
FLA
RF test
characterization

Budget

REQUEST	MOTIVATION	COST
Personnel costs	2 year person	96 500
Equipment and consumables	FLA system for 6 GHz	13 500
TOTAL		**110 000**

Co-funding	MOTIVATION	COST
Personnel	6 months researcher	50 000
	Helium, Lamps	20 000
TOTAL		**70 000**

REQUEST	MOTIVATION	COST
Personnel costs	iFAST contract extension	20 000
Equipment and consumables	Targets, Helium, samples	20 000
TOTAL		**40 000**

Co-funding	MOTIVATION	COST
Personnel	6 months researcher	30 000
TOTAL		**30 000**

REQUEST	MOTIVATION	COST
Personnel costs	iFAST contract extension	3 000
Equipment and consumables	Cavities production	7 000
TOTAL		**10 000**

TOTAL CO-FUNDING 100 k€
(Funding rate = 0.49)

TOTAL BUDGET REQUEST 160 k€

TRL

- A working 6 GHz cavity can be considered as **TRL4**

- To reach TRL6 process must be scaled to 1.3 GHz cavity.
  - FLA scaling is not critical, but first must be demonstrated the possibility to coat Nb3Sn on a 1.3 GHz cavity (final goal of iFAST task 9.2, expected in 2025)
  - 2027-2030 can be a reasonable date

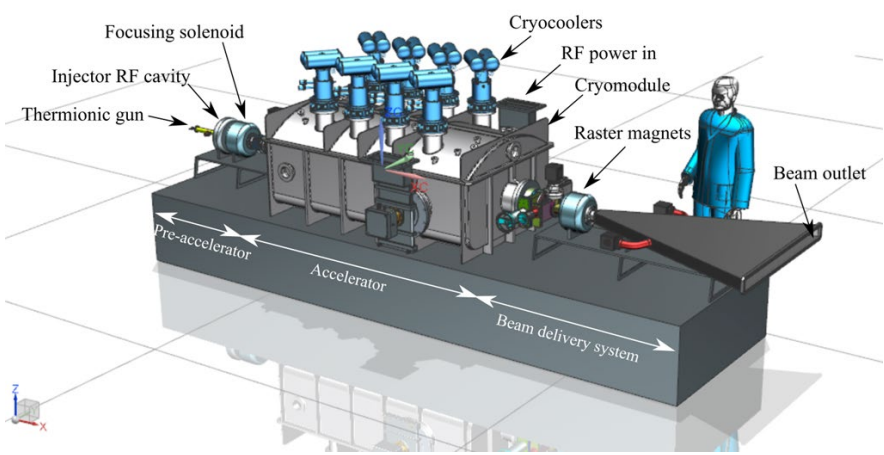
2 Addressable Markets

1) SRF Cavities

- **High Energy Particle Accelerators**

Companies like Zanon Research & Innovation Srl and RI Research Instruments GmbH, which work in synergy with large international laboratories are potential end users of our technology

- **New industrial Applications of SRF cavities**
  - **Nb_3Sn on Cu allows cryocooler cooling** by eliminating complex and expensive cryogenics
  - **Conduction-cooled SRF accelerator can move SRF to industrial application** (proof of concepts ongoing in USA):
    - Treat Municipal Waste & Sludge
      (Eliminate pathogens in sludge, destroy organics, and pharmaceuticals in wastewater)
    - In-situ cross-link of materials
    - Medical sterilization without Co60

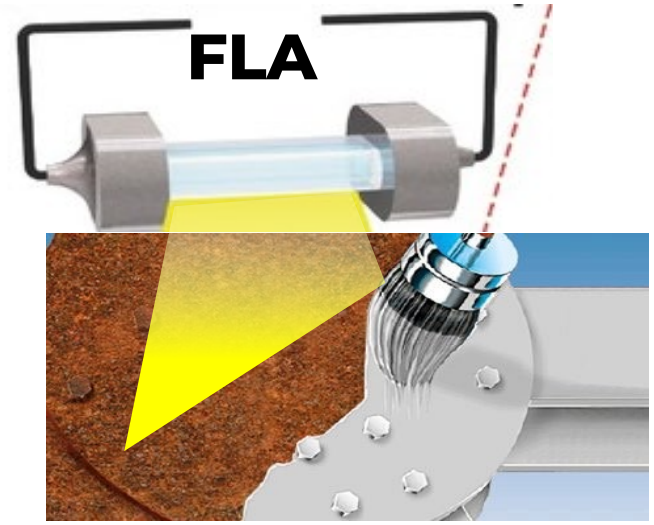


Jayakar Thangaraj (Fermilab), TTC 2022 Aomori

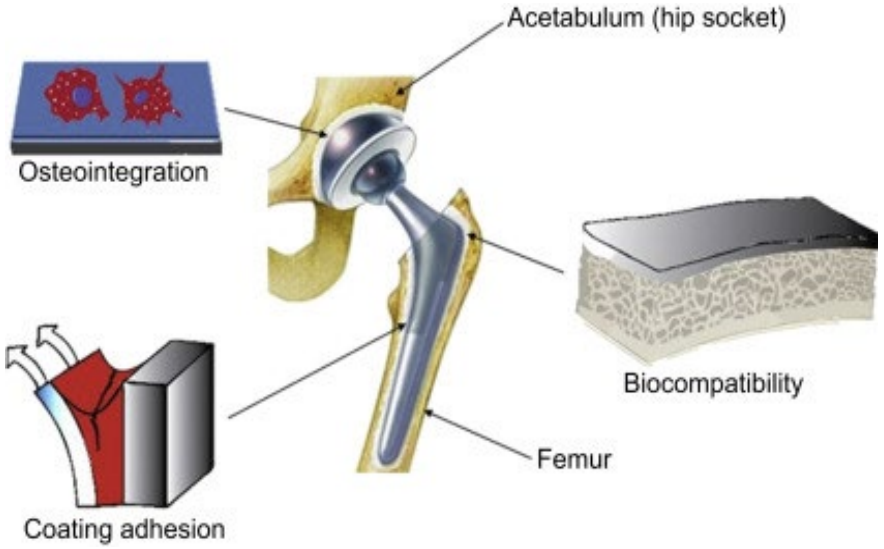
2 Addressable Markets

2) FLASH LAMP ANNEALING

Flash lamp annealing can be applied to numerous applications



Activation of anticorrosion coatings

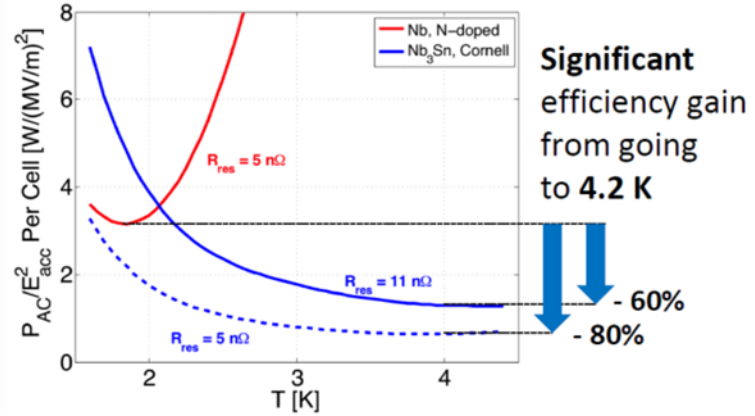


Improving the tribological properties of biocompatible implants

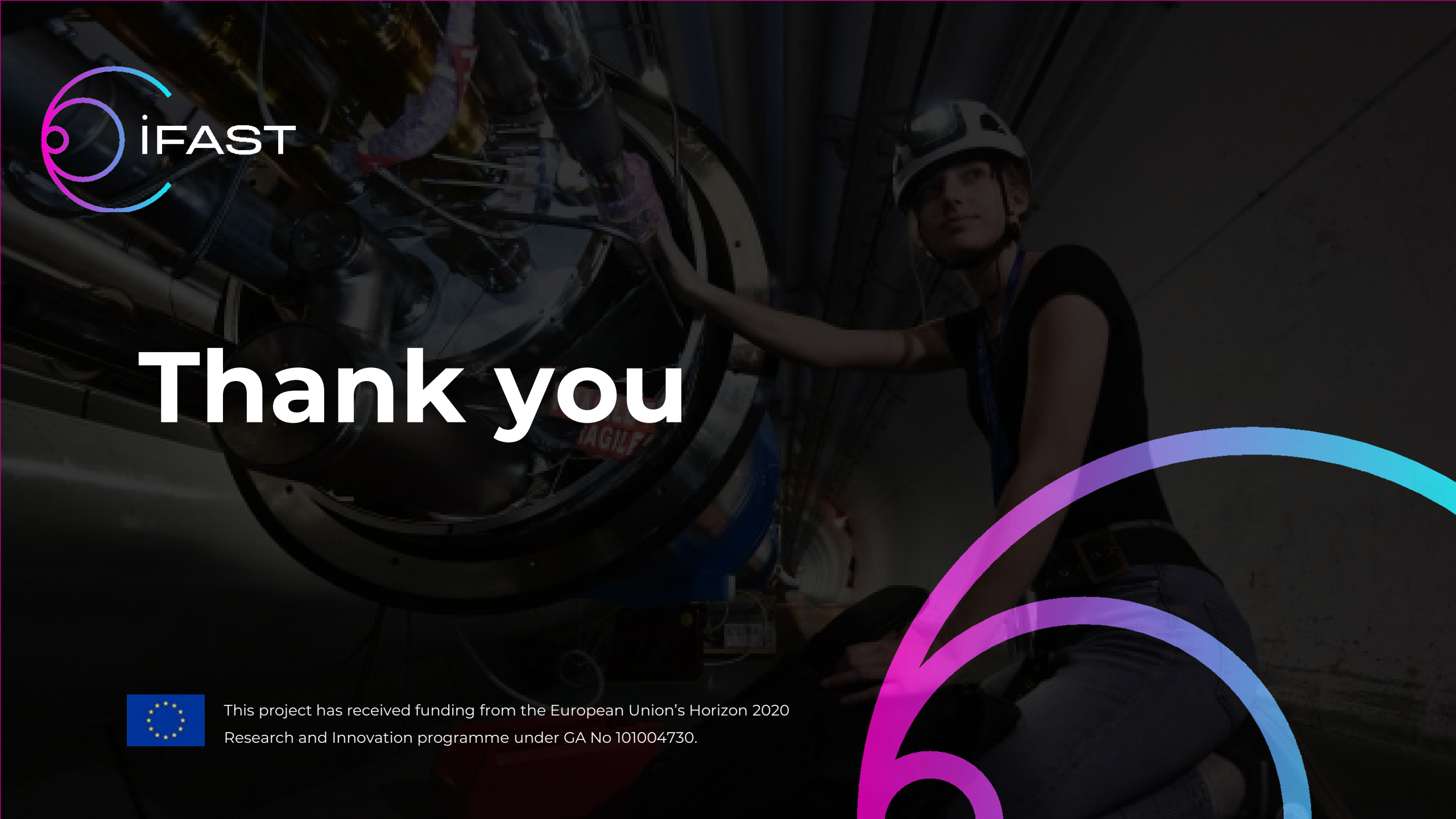
Sustainability

Our technology will significantly **reduce the environmental impact** and **energy-costs** of SRF accelerator technology:

- The goal is to realize SC resonant cavities operating at higher T than bulk Nb **reducing cryogenic power costs by 60%**
- The thermal load and hence the temperature throughout the entire substrate is much lower compared to conventional annealing: **FLA is less energy-intensive (20-30% power reduction (1)**, resulting in a reduction of **CO_2 emissions**



(1) Rovak GmbH experience on Semiconductors



Thank you

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