Cristian **Pira**

Superconductive Cavities for Accelerators and Haloscopes

Meeting **SQMS** Italia

October 15, 2021

Outline

Introduction

State of the art

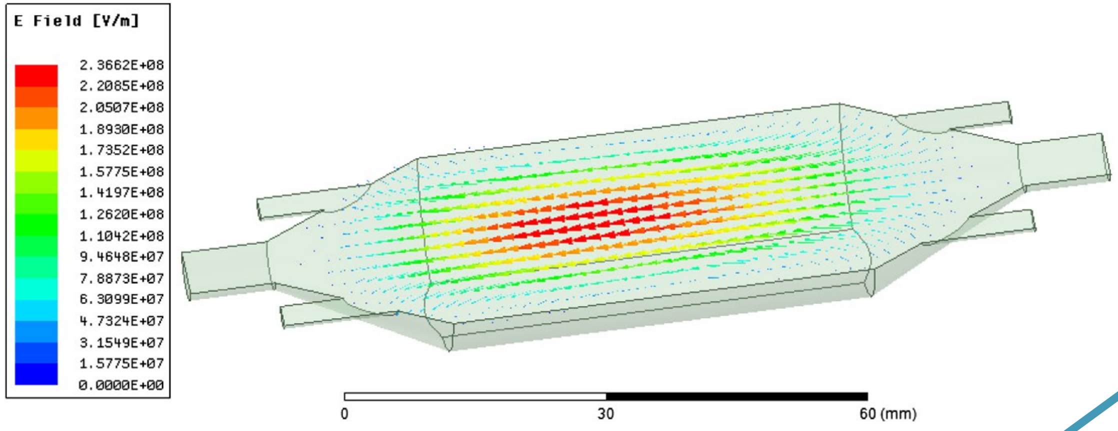
Future activities

Why Superconductive Haloscopes?

How to find axions?

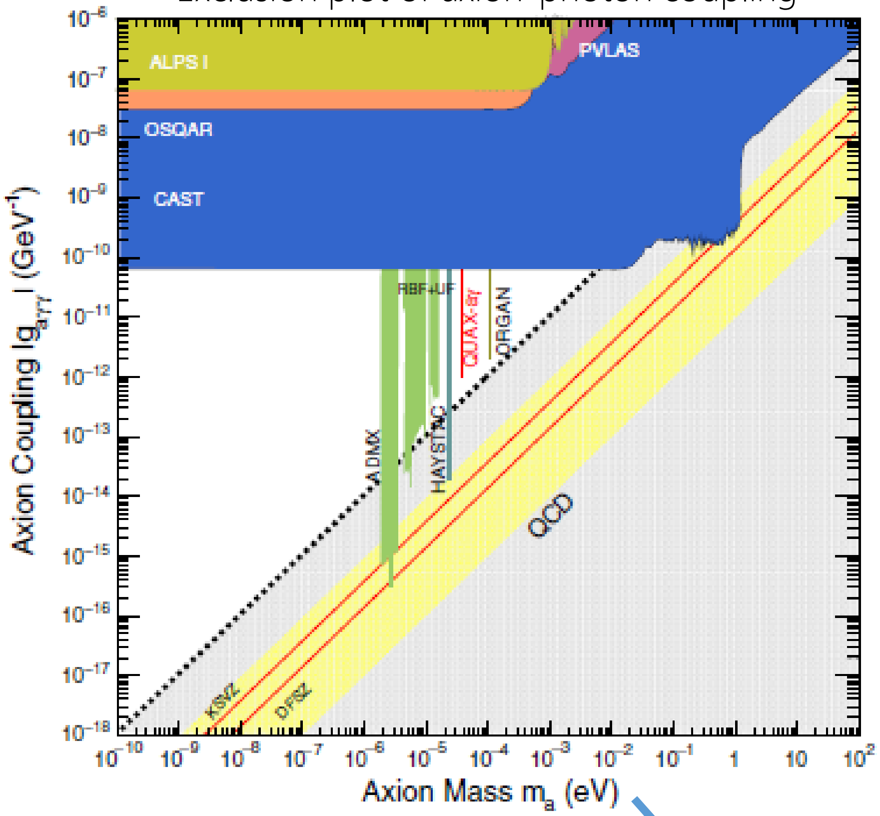
Electromagnetic coupling using a resonant cavity within strong DC magnetic field - **Primakoff effect**

(QUAX, ADMX, …)



Optimum **Q-factor** is $\sim$**10⁶**

Exclusion plot of axion-photon coupling

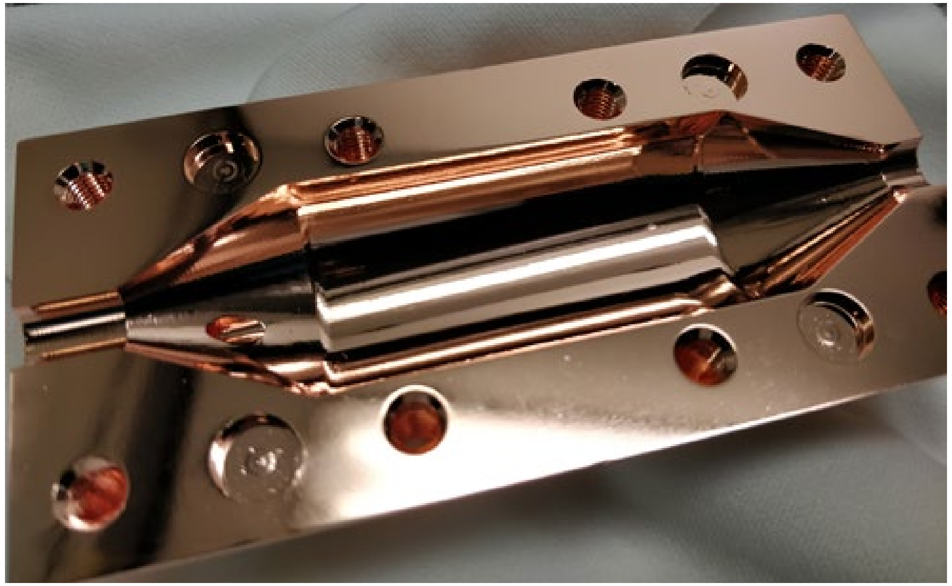


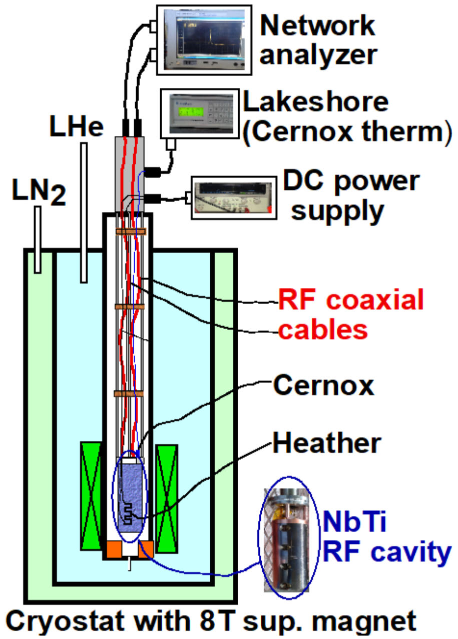
$$\nu_c = \frac{m_a c^2}{h}$$

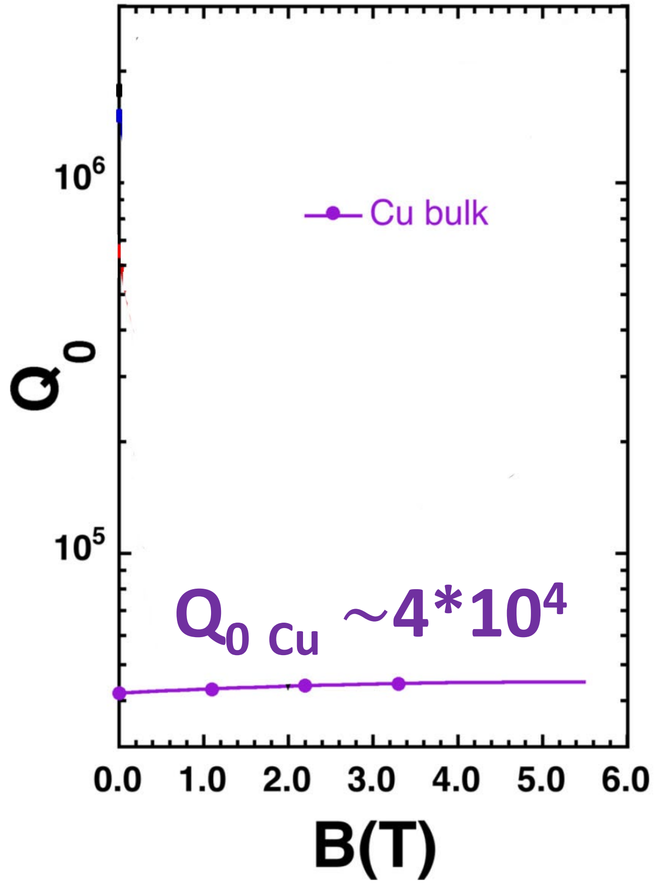
Resonant frequency of the cavity

Copper Haloscopes (QUAX)

Q factor of Cu haloscopes limited
by anomalous skin effect

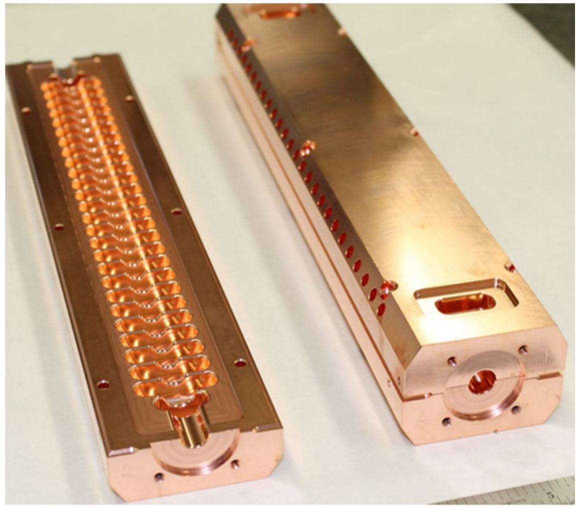






From Cu to Superconducting Cavities

SC cavities reduce the wall dissipation by many orders of magnitude compared to NC cavity



Cu $_{1.5\ \mathrm{GHz}}$: R_s (300 K) ~10 mΩ, R_s (4 K)~1.3 mΩ

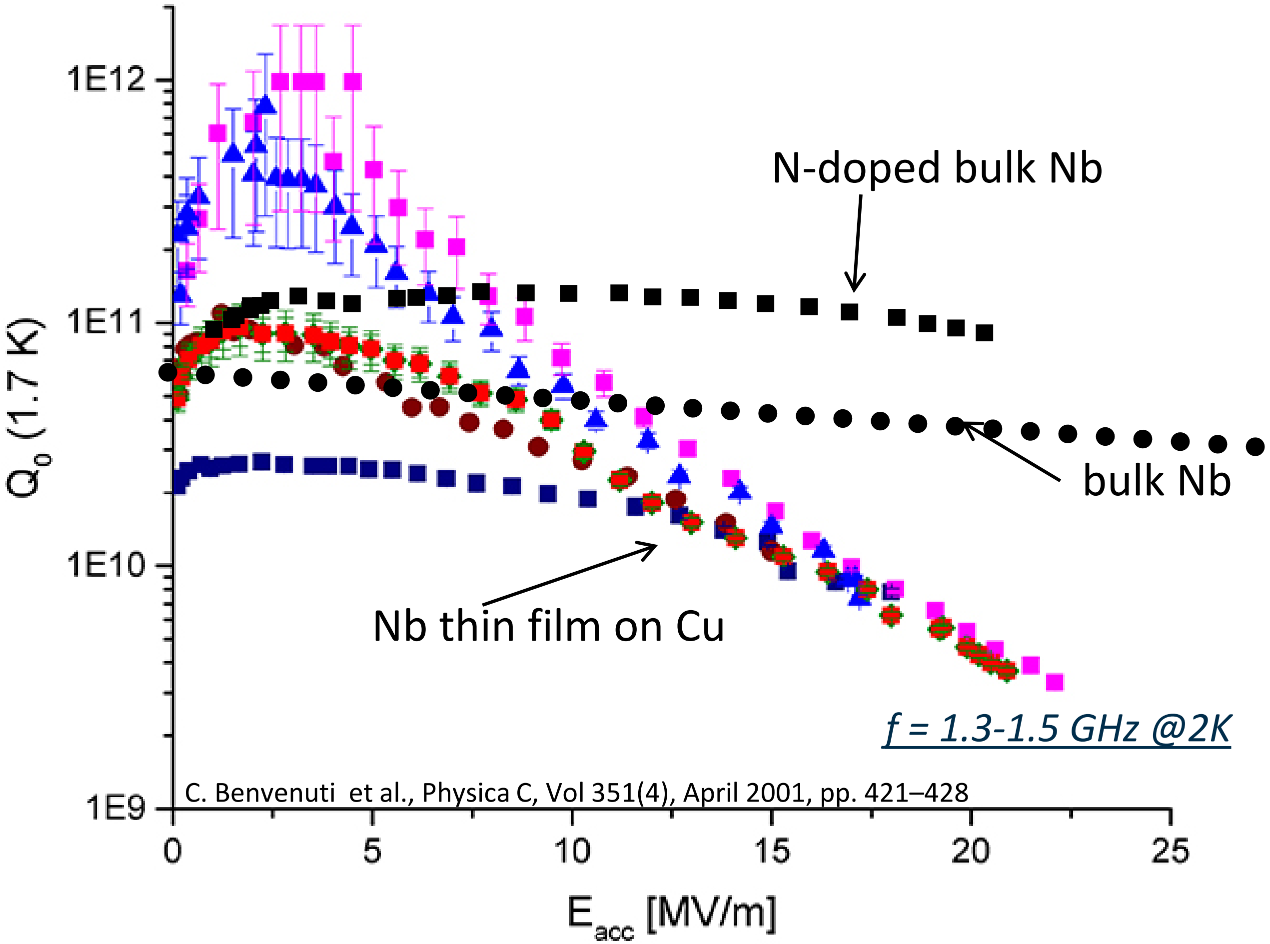
Nb $_{1.5\ \mathrm{GHz}}$: R_s (4 K)~500 nΩ, R_s (2 K)~20 nΩ

SC Cavities performances

Q values > 10^{10}

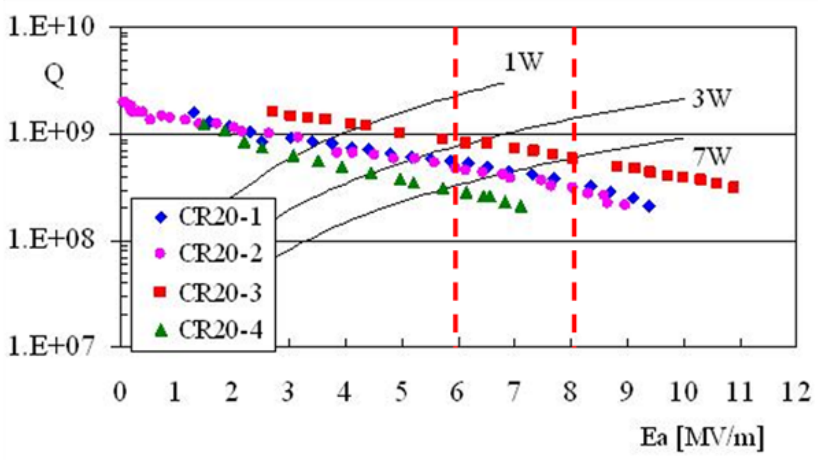
LHC: 400MHz 1-cell

E-XFEL: 1.3 GHz 9-cell



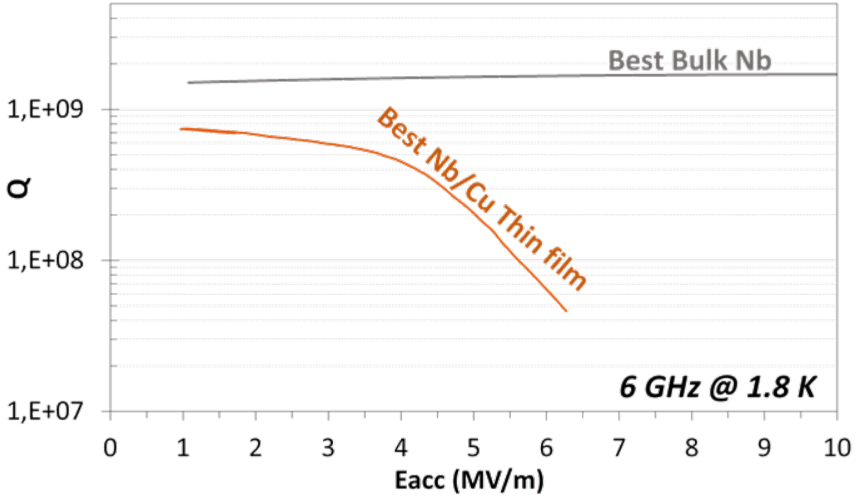
SC cavities performances (2)

Geometry and Coating technique dependent



Frequency dependent

$$R_{BCS} = \omega^2 \lambda^3 \sigma_0 \mu_0^2 exp\left(-\frac{\Delta}{k_b T}\right)$$



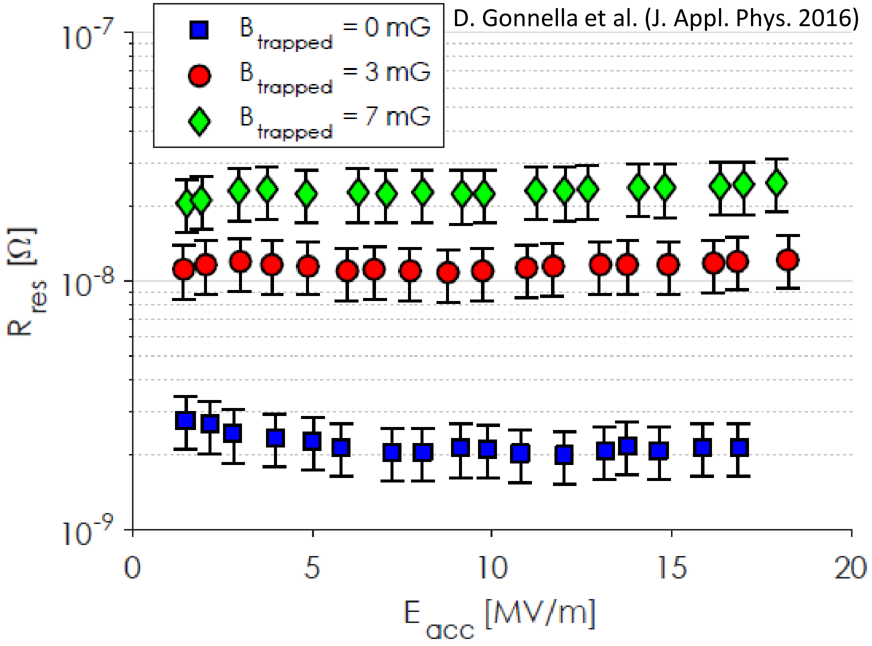
SC Cavities does not like Magnetic Field

Magnetic Hygiene is a fundamental part in cryostat design

Local shield for LCLS-II

S.K. Chandrasekaran, TTC workshop on flux trapping and magnetic field

D. Gonnella et al. (J. Appl. Phys. 2016)

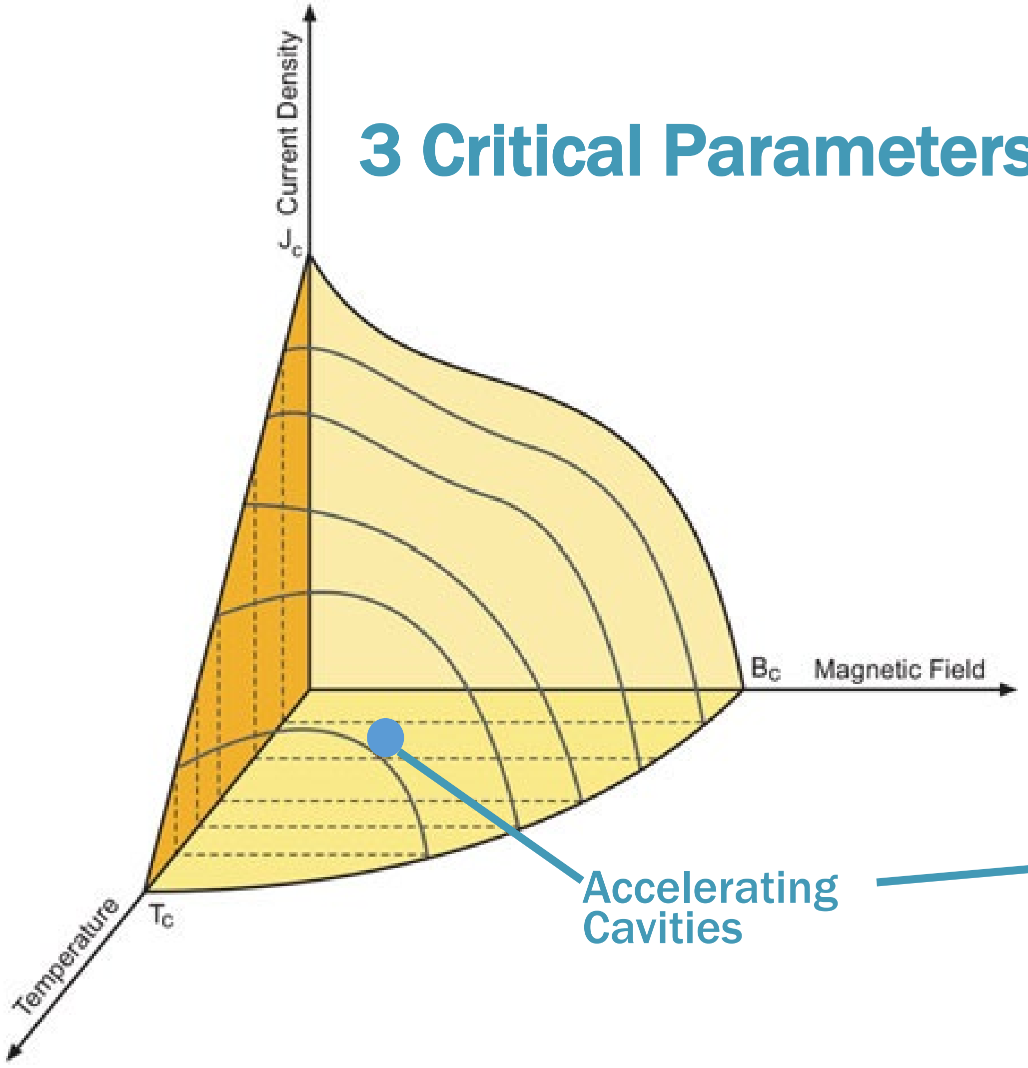


RF performances are sensitive to Trapped flux

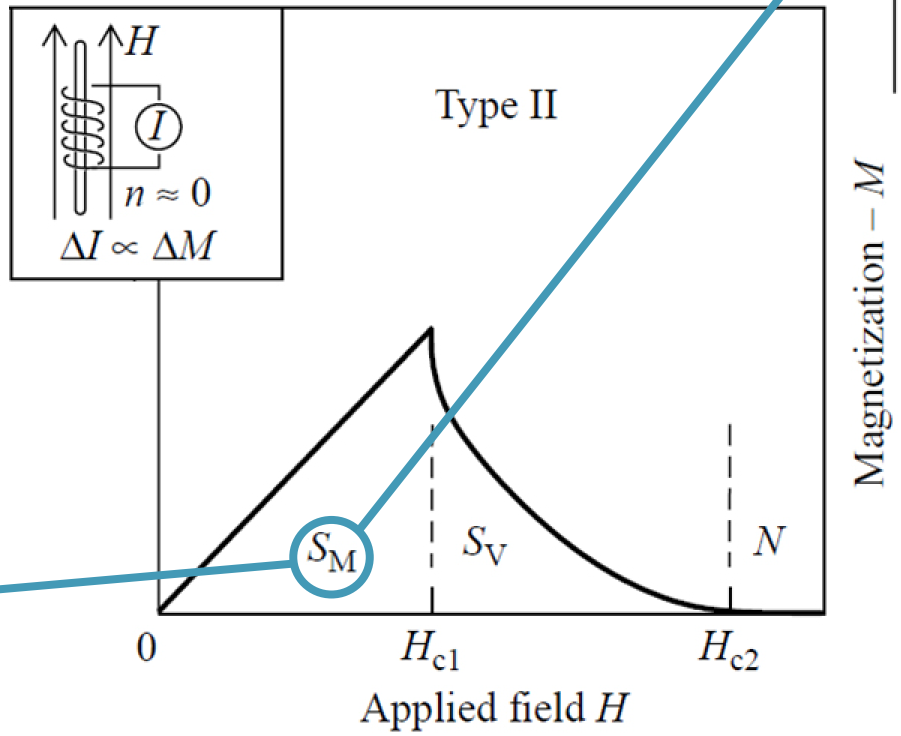
(Earth magnetic field, cavity cooling)

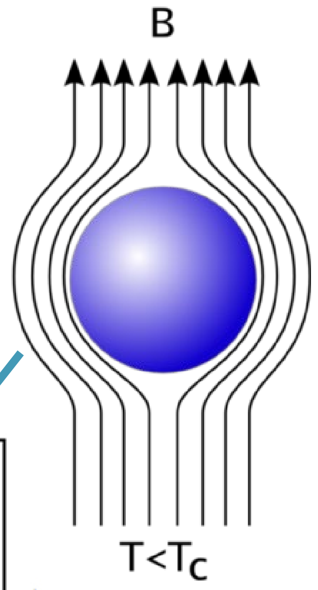
Basics of SRF

3 Critical Parameters inter-dependent



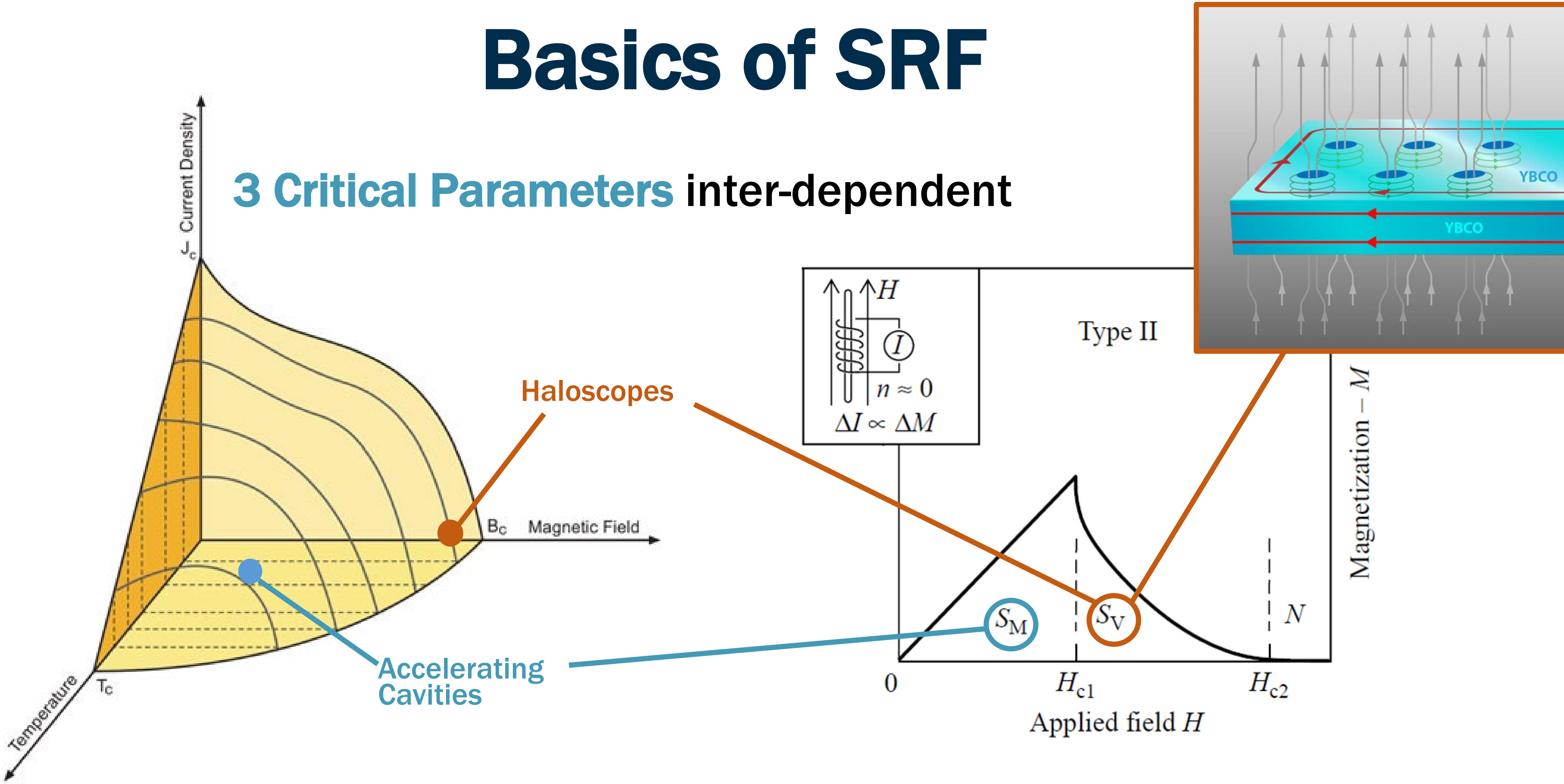
Accelerating Cavities





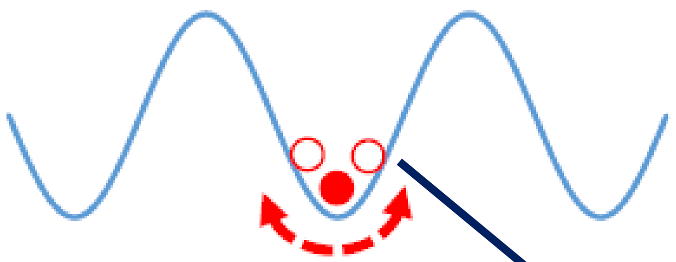
Basics of SRF

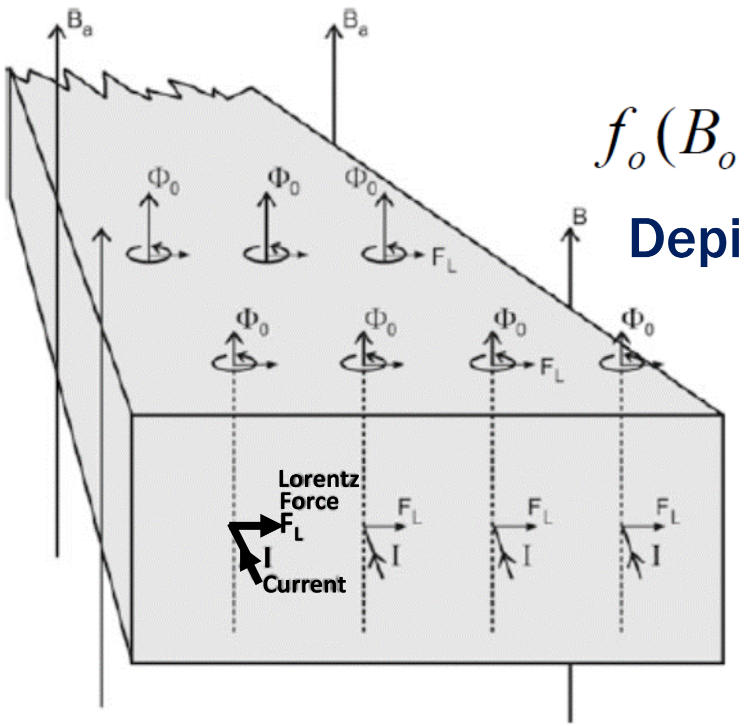
3 Critical Parameters inter-dependent



Basics of SRF (2)

$$\omega_o = \frac{k}{\eta}$$

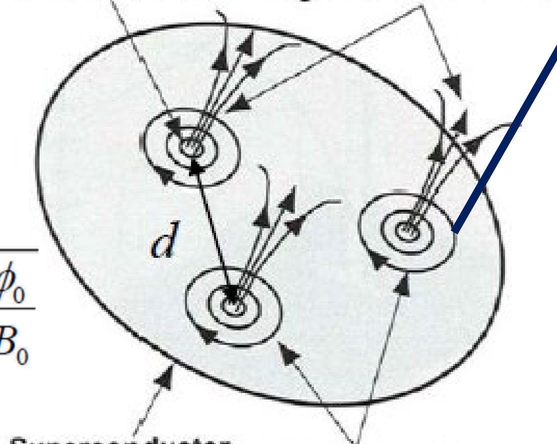




$$f_o(B_o) = \frac{\omega_o(B_o)}{2\pi} = \frac{\rho_n \sqrt{B_o} J_c(B_o)}{\sqrt{\varphi_o B_{c2}}}$$

Depinning frequency

Pinning center



$$d \propto \sqrt{\frac{\phi_0}{B_0}}$$

Pinning force

$$k = \frac{2\pi J_c \phi_0}{d}$$

Fluxon viscosity

$$\eta = \frac{\phi_o B_{c2}}{\rho_n}$$

The **motion** of the rigid **fluxon lattice** behaves as a **harmonic damped oscillator** (neglecting thermal creep)

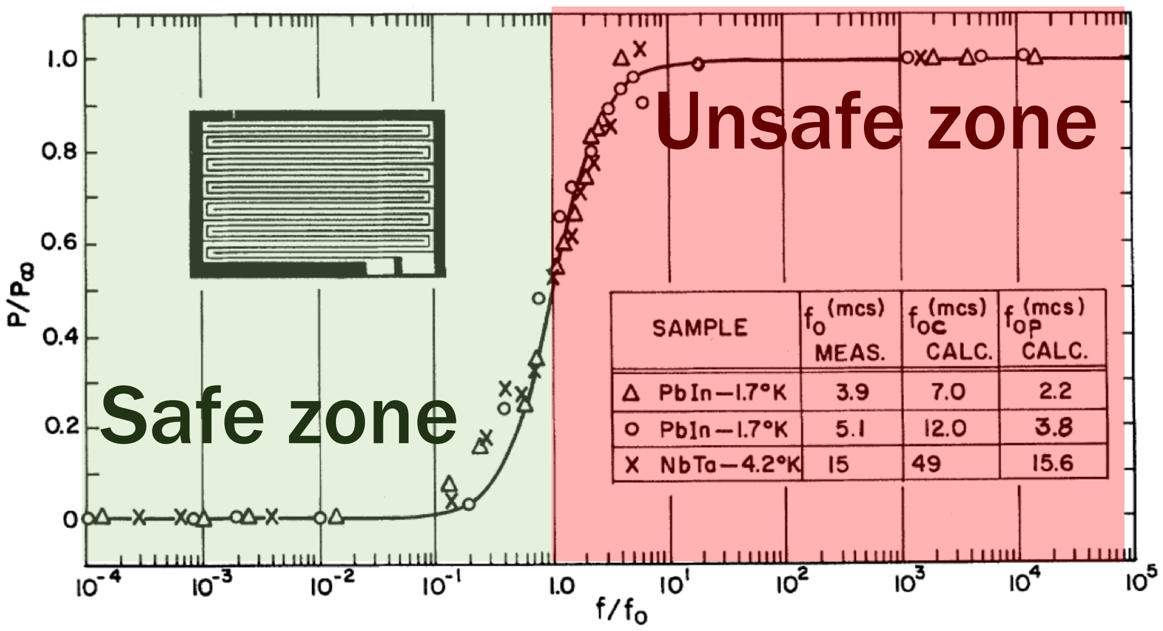
$$m\ddot{x} + \eta\dot{x} + kx = J_{rf}\phi_O$$

Gittleman and Rosenblum: Phys Rev. Lett. 16, 734 (1966)
Calatroni and Vaglio, IEEE Trans. Appl. Supercond. 27 (2017) 3500506

Basics of SRF (3)

Depinning frequency

$$f_o(B_o) = \frac{\omega_o(B_o)}{2\pi} = \frac{\rho_n \sqrt{B_o}\, J_c(B_o)}{\sqrt{\varphi_o B_{c2}}}$$



SC effective resistivity $\rho_{\text{eff}} = \rho_s + \rho_f$

Standard complex resistivity

$$\frac{1}{\sigma_1 - i\sigma_2}$$

oscillating fluxon contribution

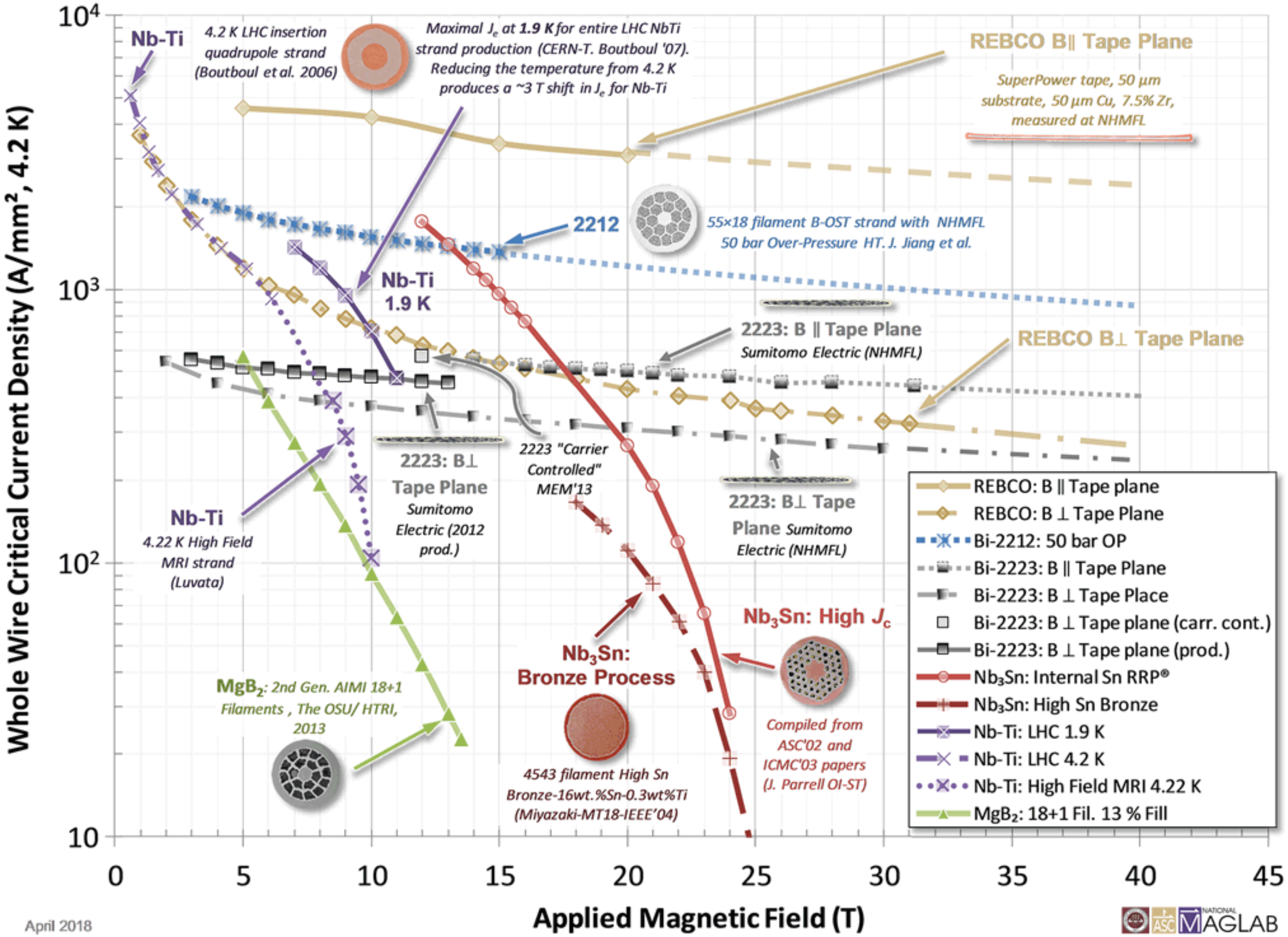
$$\rho_n \frac{B_o}{B_{c2}} \left(\frac{\omega^2}{\omega^2 + \omega_o^2} + i \frac{\omega \omega_o}{\omega^2 + \omega_o^2} \right)$$

If $f < f_0$ elastic vortex motion

If $f > f_0$ resistive vortex motion

Gittleman and Rosenblum: Phys Rev. Lett. 16, 734 (1966)
Calatroni and Vaglio, IEEE Trans. Appl. Supercond. 27 (2017) 3500506

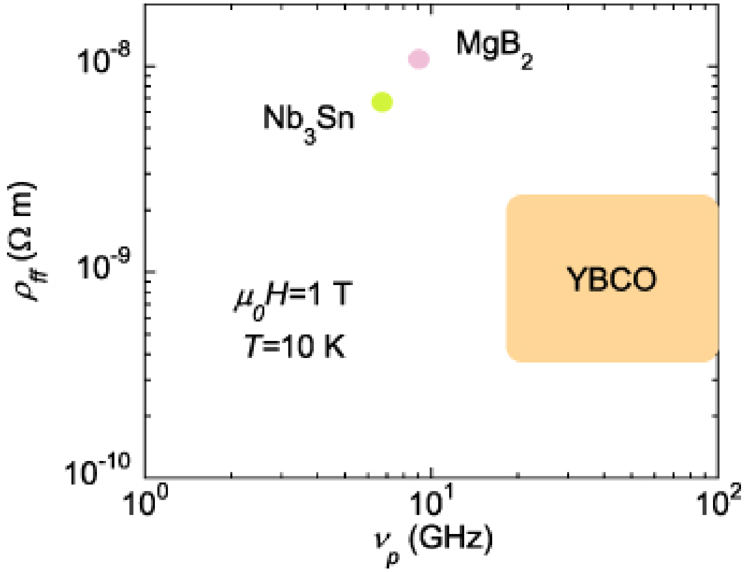
Zoo of Superconductors for Magnets



J_c may vary of order of magnitudes

H_{c2} has much smaller variation

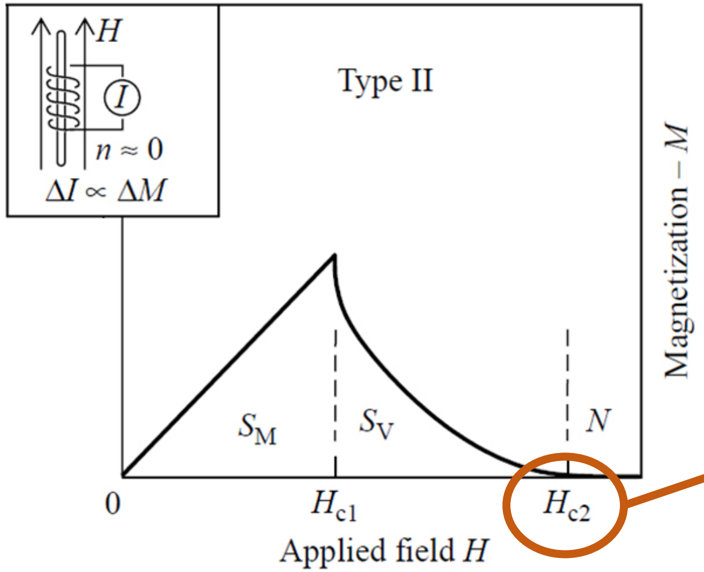
Very poor data in RF conditions



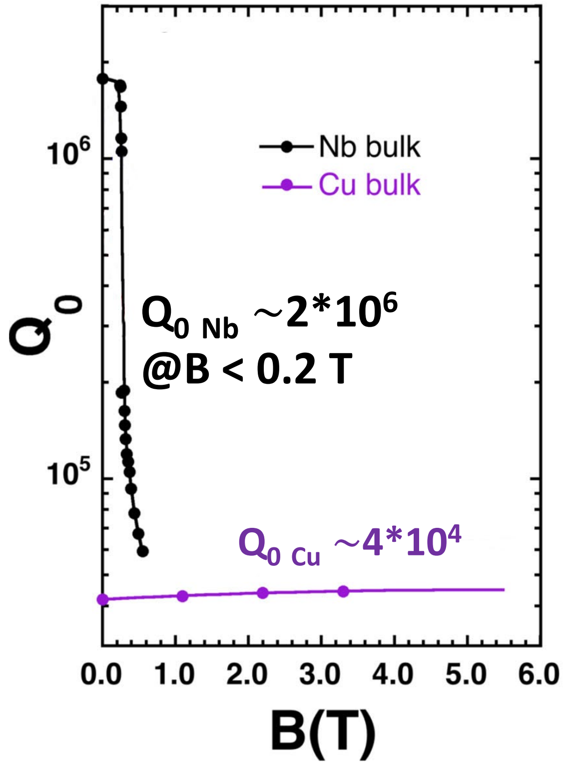
A. Alimenti et al, Supercond. Sci. Technol., (2020)

https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

SC materials choice



Nb



H_{c2} ~ 0.4 T

Not suitable!

SC material choice

Material	Tc	H_{c2}	Note
Nb	9.2 K	0.4 T	Not suitable at high field
NbTi	~ 9.5 K	~ 14 T	Simple preparation
NbN	~ 17.1 K	~ 15 T	Uniformity is a challenge
Nb_3Sn	~ 18.3 K	~ 30 T	Preparation is a challenge
REBCO	~ 93 K	~ 100 T	Available in tapes

State of the art

NbTi

Galactic axions search with a superconducting resonant cavity

D. Alesini,[1] C. Braggio,[2,3] G. Carugno,[2,3] N. Crescini,[4,3] D. D' Agostino,[5] D. Di Gioacchino,[1] R. Di Vora,[2,*] P. Falferi,[6,7] S. Gallo,[2,3] U. Gambardella,[5] C. Gatti,[1,†] G. Iannone,[5] G. Lamanna,[8] C. Ligi,[1] A. Lombardi,[4] R. Mezzena,[7,9] A. Ortolan,[4] R. Pengo,[4] N. Pompeo,[10] A. Rettaroli,[1,11,‡] G. Ruoso,[4] E. Silva,[10] C. C. Speake,[12] L. Taffarello,[2] and S. Tocci[1]

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[12]*School of Physics and Astronomy, Univ. of Birmingham, Birmingham, United Kingdom*

To account for the dark matter content in our Universe, post-inflationary scenarios predict for the QCD axion a mass in the range $(10-10^3)\,\mu$eV. Searches with haloscope experiments in this mass range require the monitoring of resonant cavity modes with frequency above 5 GHz, where several experimental limitations occur due to linear amplifiers, small volumes, and low quality factors of Cu resonant cavities. In this paper we deal with the last issue, presenting the result of a search for galactic axions using a haloscope based on a 36 cm^3 NbTi superconducting cavity. The cavity worked at $T = 4$ K in a 2 T magnetic field and exhibited a quality factor $Q_0 = 4.5\times10^5$ for the TM010 mode at 9 GHz. With such values of Q the axion signal is significantly increased with respect to copper cavity haloscopes. Operating this setup we set the limit $g_{a\gamma\gamma} < 1.03\times10^{-12}\,\mathrm{GeV}^{-1}$ on the axion photon coupling for a mass of about 37 μeV. A comprehensive study of the NbTi cavity at different magnetic fields, temperatures, and frequencies is also presented.

PACS numbers: 14.80.Va, 95.35.+d, 98.35.Gi, 74.78.-w

I. INTRODUCTION

The axion is a pseudoscalar particle predicted by S. Weinberg [1] and F. Wilczek [2] as a consequence of the mechanism introduced by R.D. Peccei and H. Quinn [3] to solve the "strong CP problem". Axions are also well motivated dark-matter (DM) candidates with expected mass laying in a broad range from peV to few meV [4]. Post-inflationary scenarios restrict this range to $(10-10^3)\,\mu$eV [4], where a rich experimental program will probe the axion existence in the next decade. Among

power deposited by DM axions is given by [6]

$$P_a = \left(g_\gamma^2 \frac{\alpha^2}{\pi^2}\frac{\hbar^3 c^3 \rho_a}{\Lambda^4}\right)\times\left(\frac{\beta}{1+\beta}\omega_c\frac{1}{\mu_0}B_0^2 V C_{mnl} Q_L\right), \quad (1)$$

where $\rho_a = 0.45\,\mathrm{GeV/cm^3}$ is the local DM density, α is the fine-structure constant, $\Lambda = 78$ MeV is a scale parameter related to hadronic physics, and g_γ is a model dependent parameter equal to -0.97 (0.36) in the KSVZ (DFSZ) axion model [11, 12]. It is related to the coupling appearing in the Lagrangian $g_{a\gamma\gamma} = (g_\gamma\alpha/\pi\Lambda^2)m_a$. The second parentheses contain the vacuum permeability μ_0, the magnetic field strenght B_0, the cavity volume V, its angular frequency $\omega_c = 2\pi\nu_c$, the coupling between cavity and receiver β and the loaded quality factor

Phys. Rev. D 99, 101101(R)
Published 1 May 2019

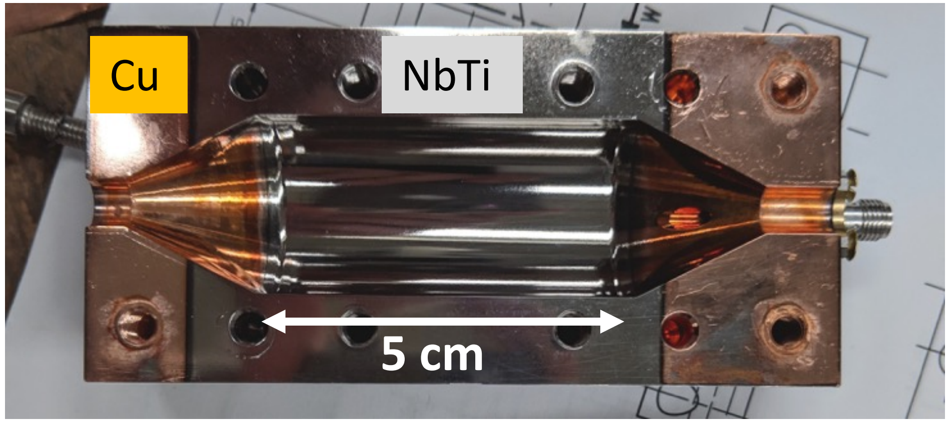
INFN NbTi

First SC haloscope

Collaboration between LNF and LNL

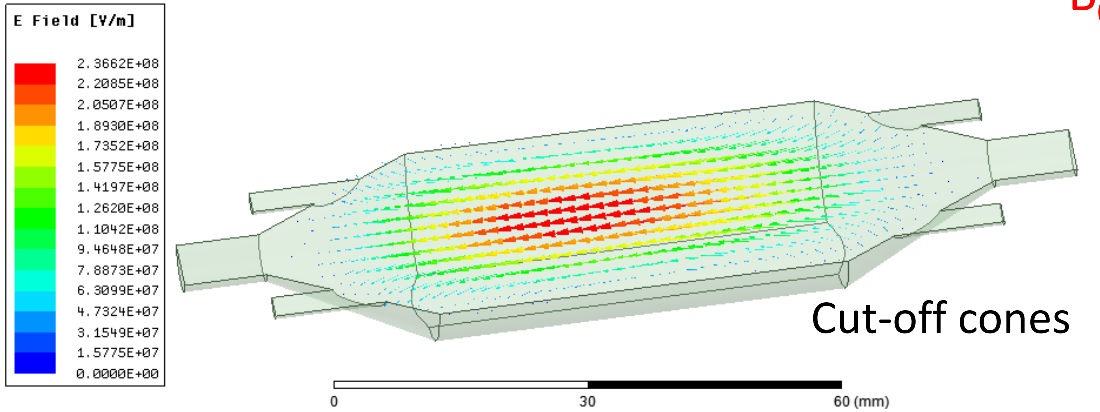
Cavity coated at LNL with 4 mm **NbTi layer**

Cu endcaps to reduce vortex motion dissipation



$$\frac{1}{Q_0} = \frac{R_s^{\mathrm{cyl}}}{G_{\mathrm{cyl}}} + \frac{R_s^{\mathrm{cones}}}{G_{\mathrm{cones}}}$$

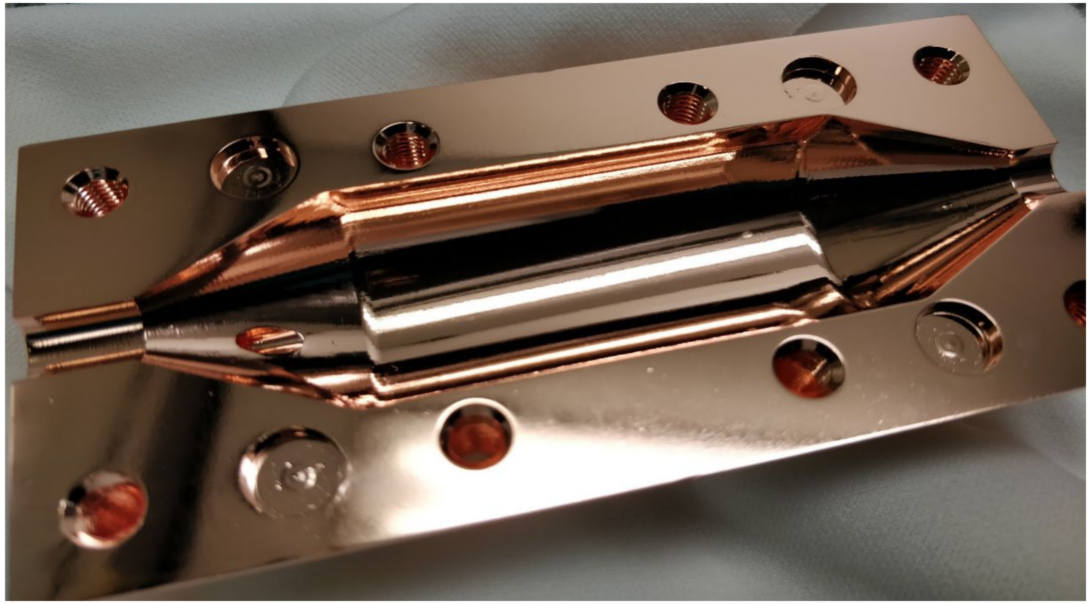
B_0



ν (TM010)	9.1 GHz
G_{cyl}	6270 Ω
G_{cones}	482 Ω
Rs^{Cu}	4.9 mΩ
Q_0^{Max}	1.3×10^6

Phys. Rev. D **99**, 101101(R) (2019)

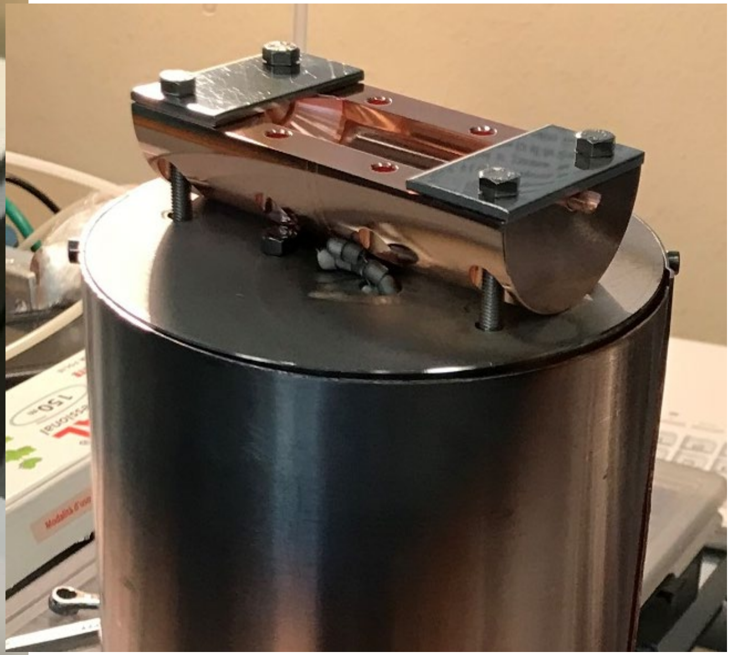
Surface Preparation



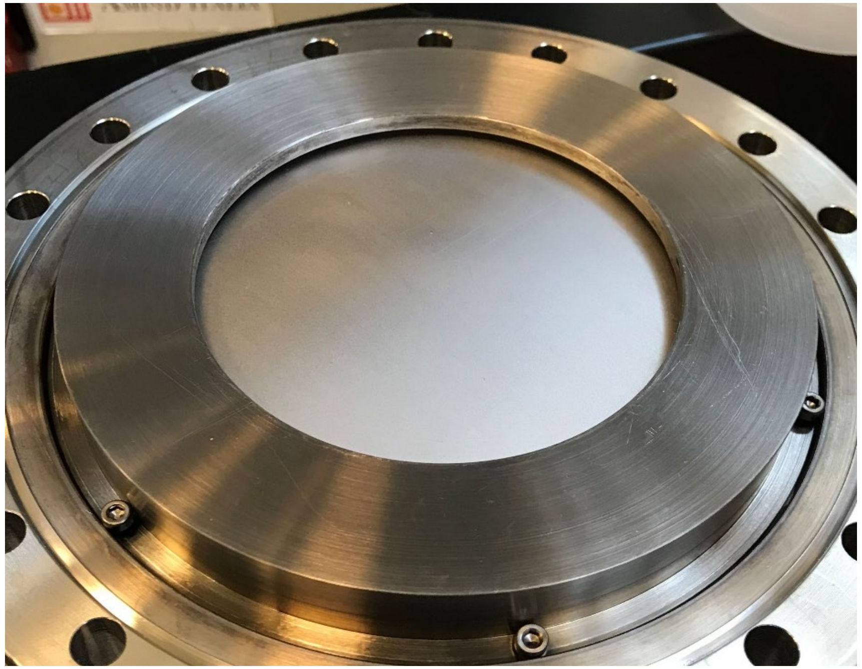
Half cavity after chemical polishing

1. Ultrasonic degreasing in Rodatel-30 soap
2. Ultrasonic in deionized water
3. **Electropolishing** in H_3PO_4: Butanol at 3:2 volume ratio
4. Chemical polishing in SUBU-5 solution
5. Surface passivation with sulfamic acid
6. Ultrasonic, ethanol rinsing and drying

NbTi Coating Set-up



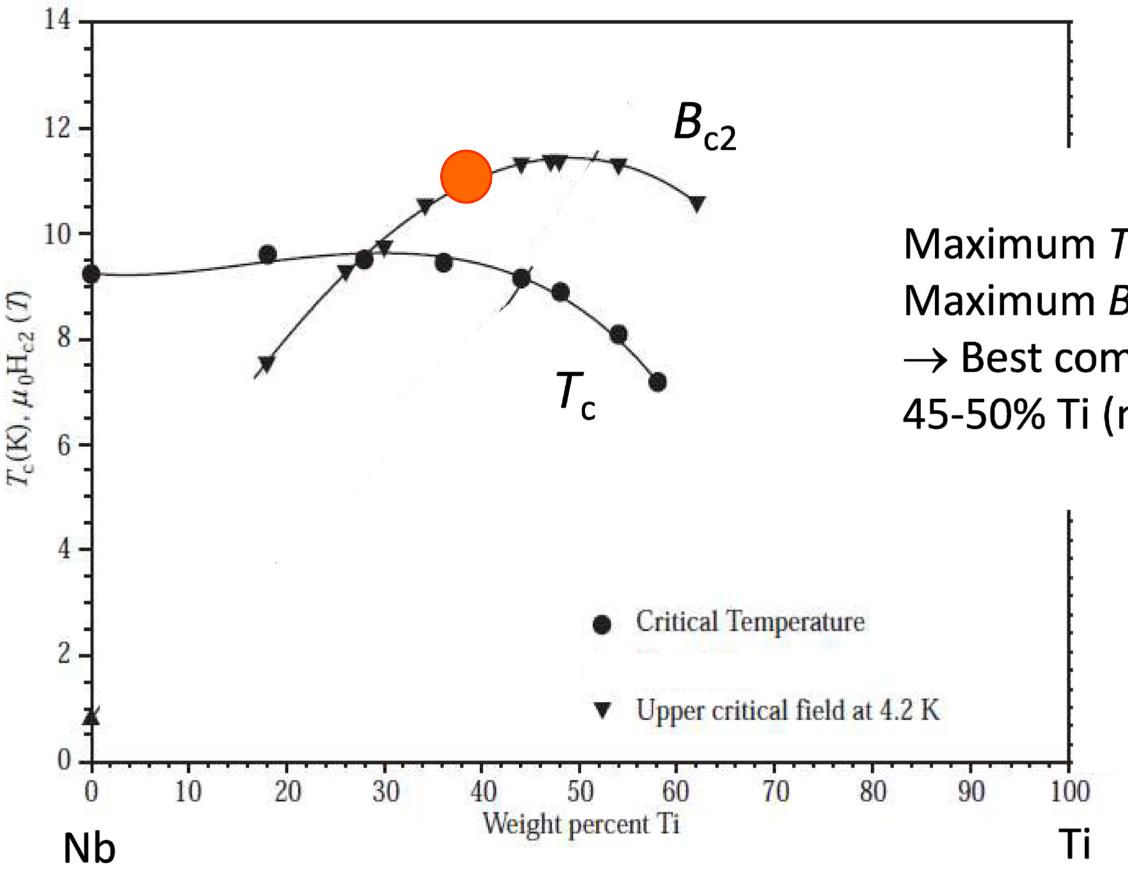
Half cavity on heatable sample holder



4 inches NbTi planar magnetron

Cavity dimension limited by CF150 flange

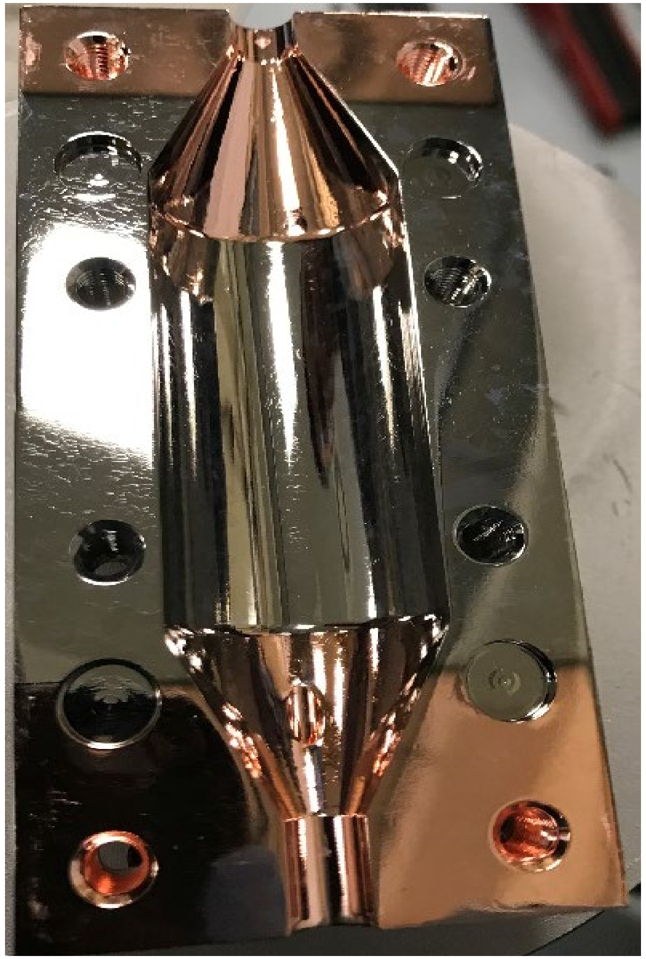
NbTi composition



Maximum T_c at 30% Ti
Maximum B_{c2} at 44% Ti
→ Best composition:
45-50% Ti (most 47%)

A NbTi sheet with a composition of 40% in Ti has been used

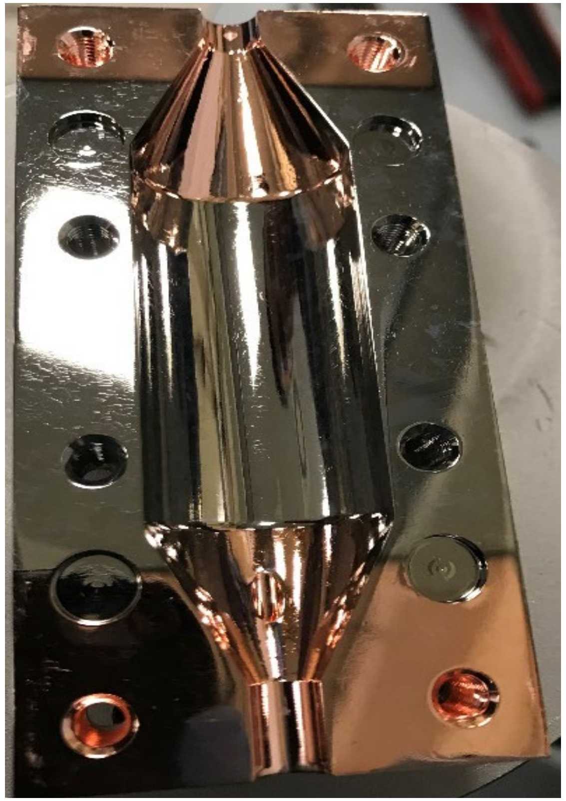
NbTi Coating Parameters

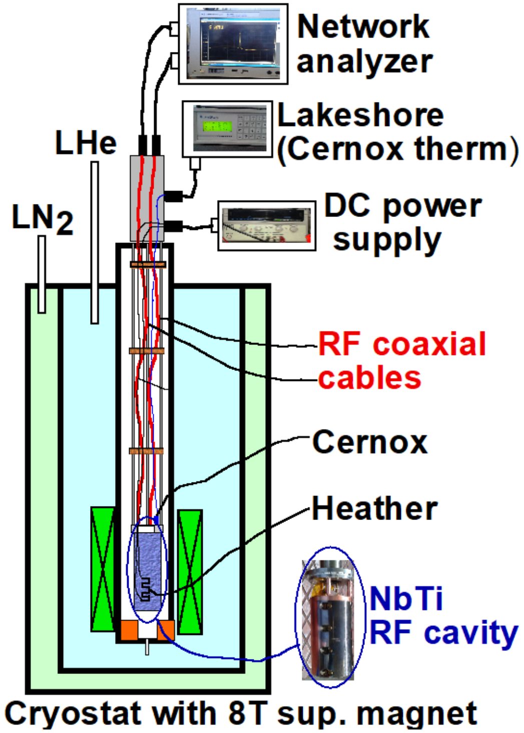


Coated half cavity

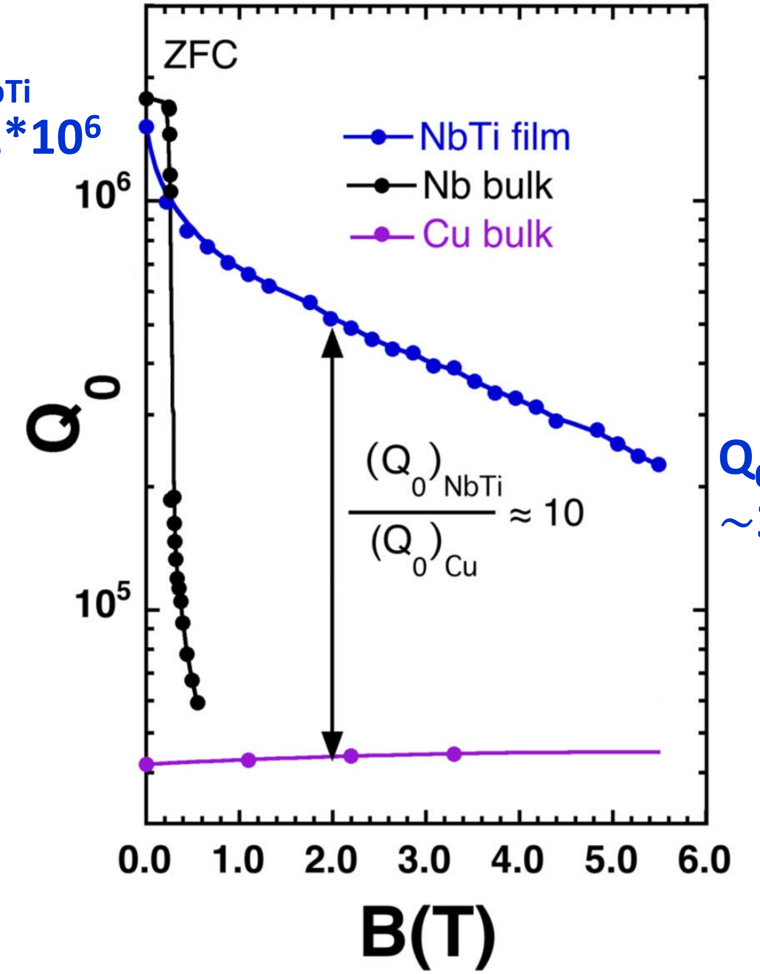
- **T process = 450 °C**
- P_{base} < 9 * 10^{-9} mbar
- $P_{process}$ = 8 * 10^{-3} mbar
- I = 1 A
- T = 30 min
- Thickness ~ 3 - 4 µm

NbTi results





$Q_{0\ NbTi}$ $\sim 1.2*10^6$



$Q_{0\ NbTi}$ $\sim 3*10^5$ @ 5 T

Room for improvements

Institute for Basic Science

REBCO

First prototype of a biaxially textured $YBa_2Cu_3O_{7-x}$ microwave cavity in a high magnetic field for dark matter axion search

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(Dated: March 29, 2021)

A high-quality factor microwave resonator in the presence of a strong magnetic field could have a wide range of applications, such as axion dark matter searches where the two aspects must coexist to enhance the experimental sensitivity. We introduce a polygon-shaped cavity design with bi-axially textured $YBa_2Cu_3O_{7-x}$ superconducting tapes covering the entire inner wall. Using a 12-sided polygon cavity, we obtain substantially improved quality factors of the TM_{010} mode at 6.9 GHz at 4 K with respect to a copper cavity and observe no considerable degradation in the presence of magnetic fields up to 8 T. This corresponds to the first demonstration of practical applications of superconducting radio frequency technology for axion and other research areas requiring low loss in a strong magnetic field. We address the importance of the successful demonstration and discuss further improvements.

PACS numbers:

The advancement of the superconducting radio-frequency (SRF) technology allows an RF resonator to obtain an extremely high quality (Q) factor and to be used in a broad scope of applications [1–4]. However, the presence of an external magnetic field could limit scientific productivity in many areas where a strong external magnetic field is absolutely necessary. The examples include the beam screen design at the future circular collider (FCC) [5, 6] and high Q-factor cavities in axion dark matter research. In particular, the axion dark matter conditions in dark matter axion search, the Q factor can be expected to be larger, because the vortex pinning becomes stronger at lower temperature (100 mK) and in a magnetic field parallel to a REBCO film [18–20]. A high depinning frequency (> 10 GHz) is also reasonable for a dark matter axion search which target frequency ranges up to 100 GHz.

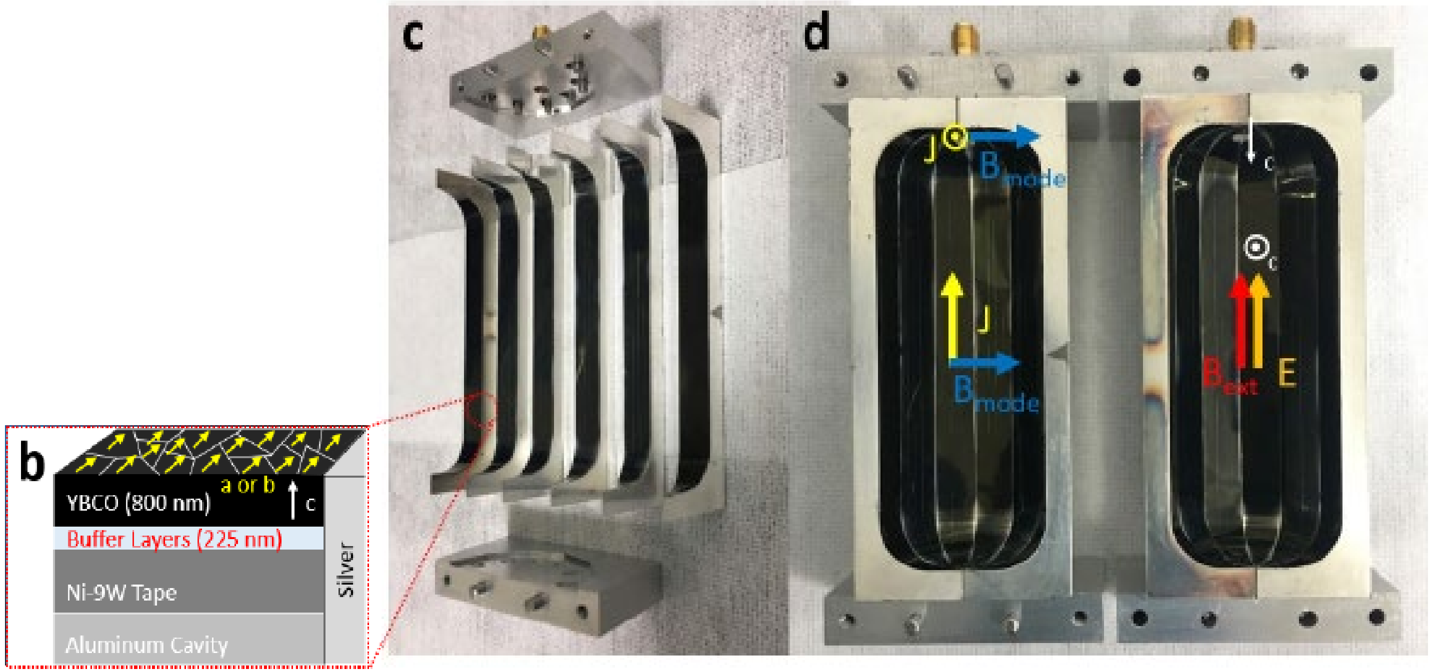
Fabricating a 3-D resonant cavity structure with 2G REBCO film poses large technical challenges because of its biaxial texture. Directly forming a biaxially textured

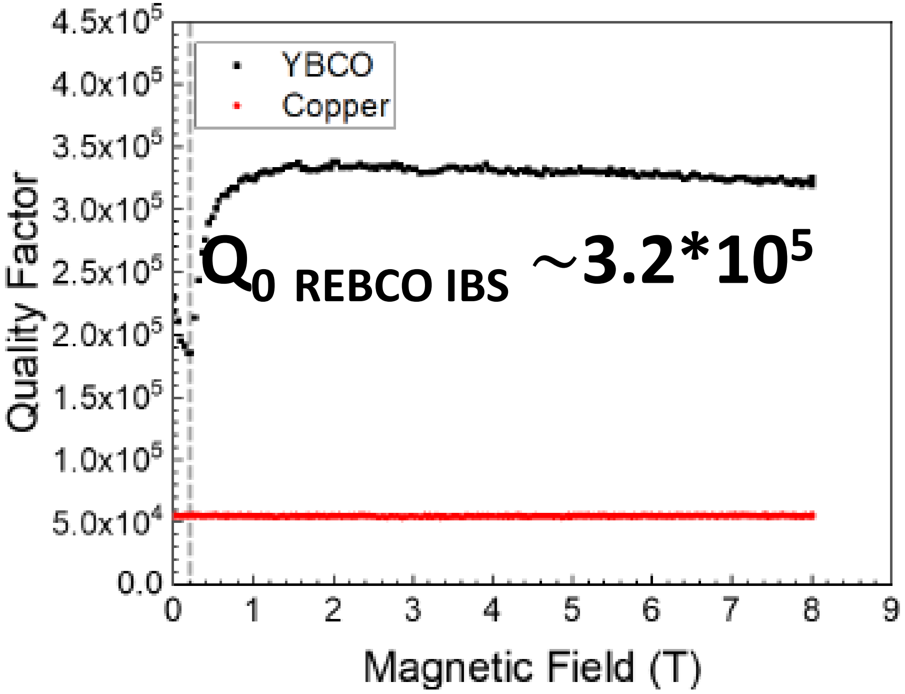
26 March 2021

arXiv:2103.14515

기초과학연구원 Institute for Basic Science

REBCO



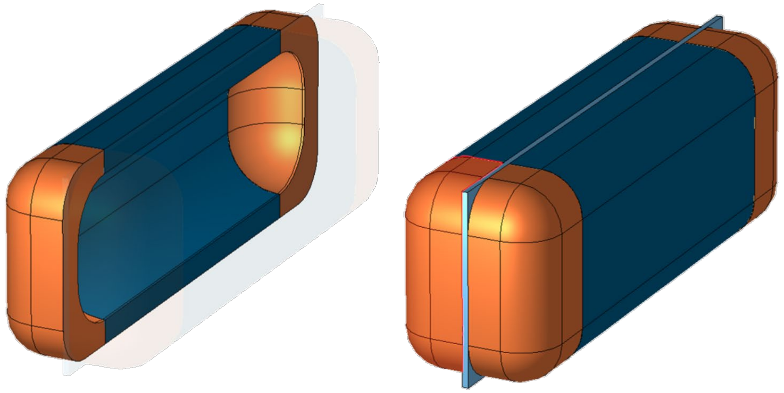


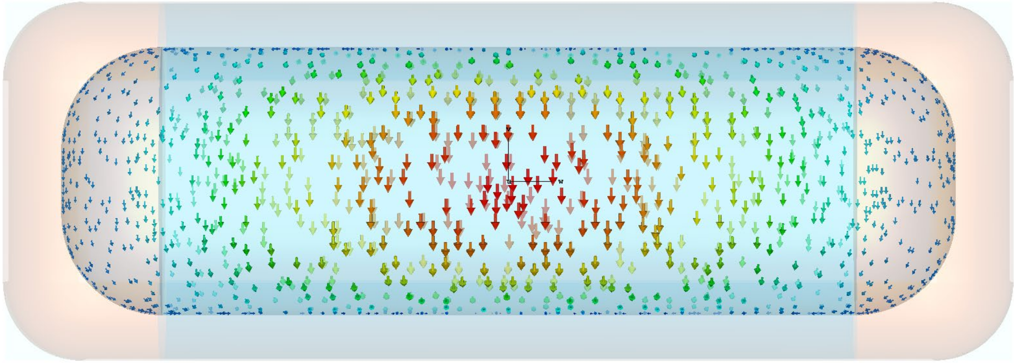
Q_0 REBCO IBS $\sim 3.2*10^5$

- 12 pieces polygon cavity
- Aluminum cavity (7 GHz)
- REBCO biaxially textured tapes (American Superconductor)

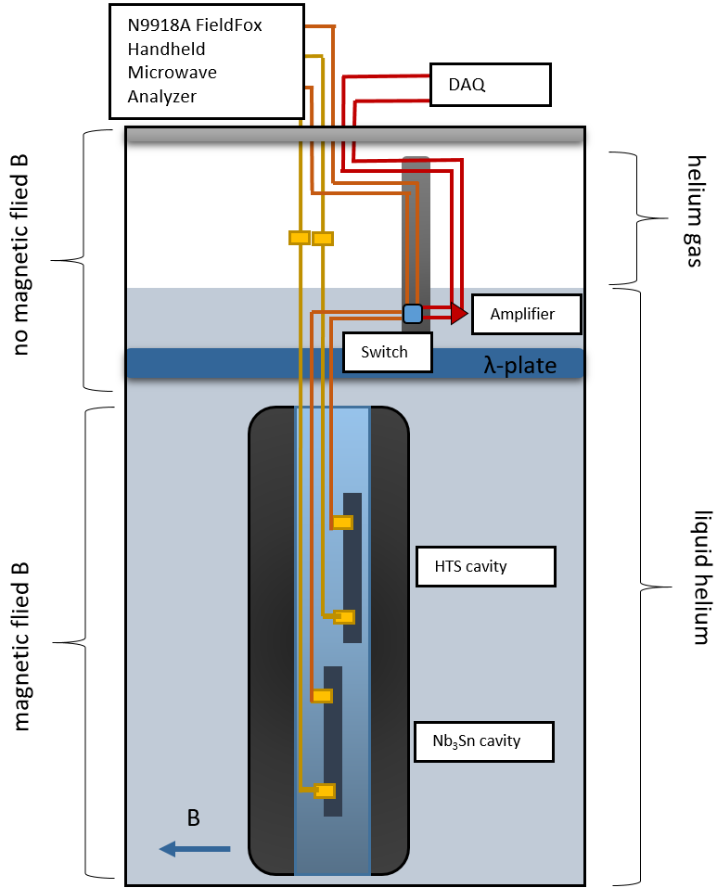
arXiv:2103.14515

REBCO





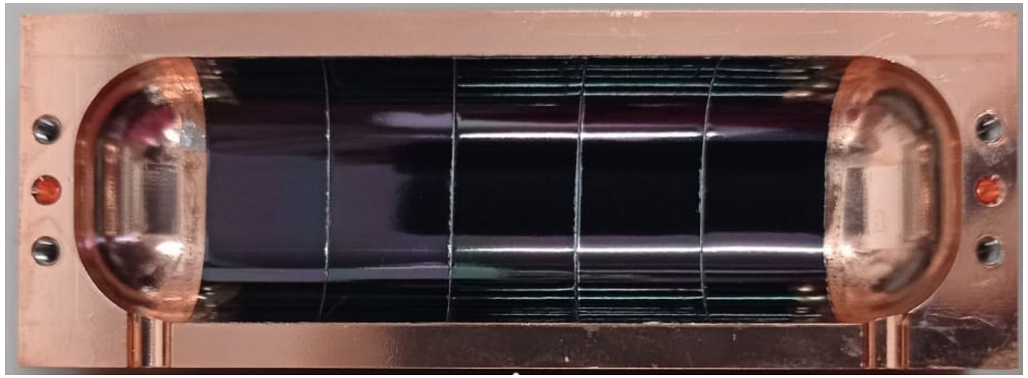
Different cavity geometry (9 GHz)

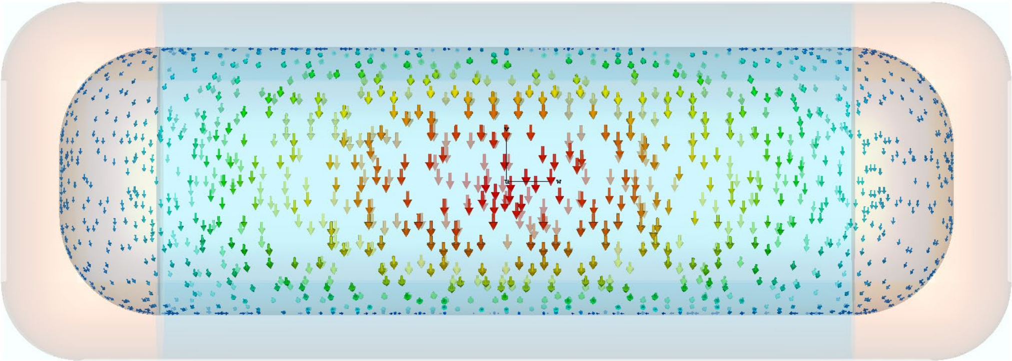


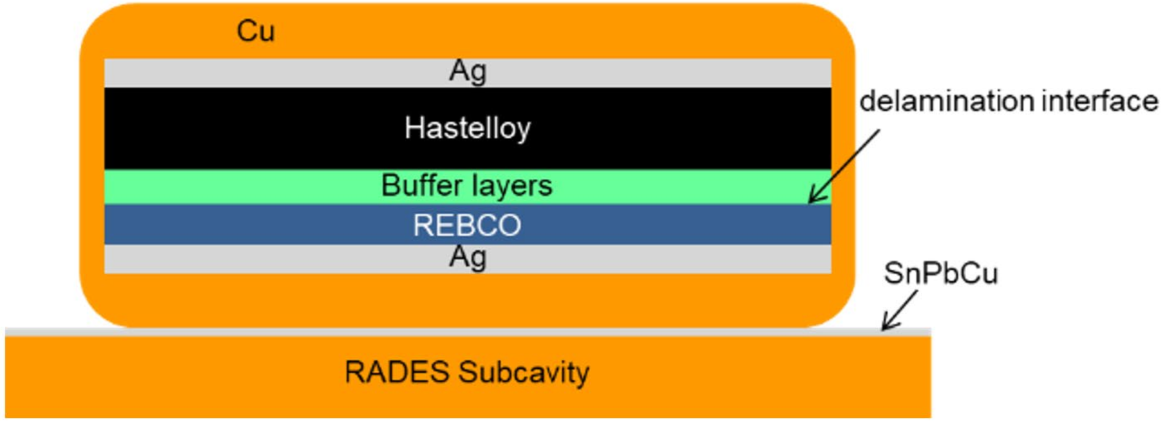
4 October 2021

arXiv:2110.01296v1

REBCO



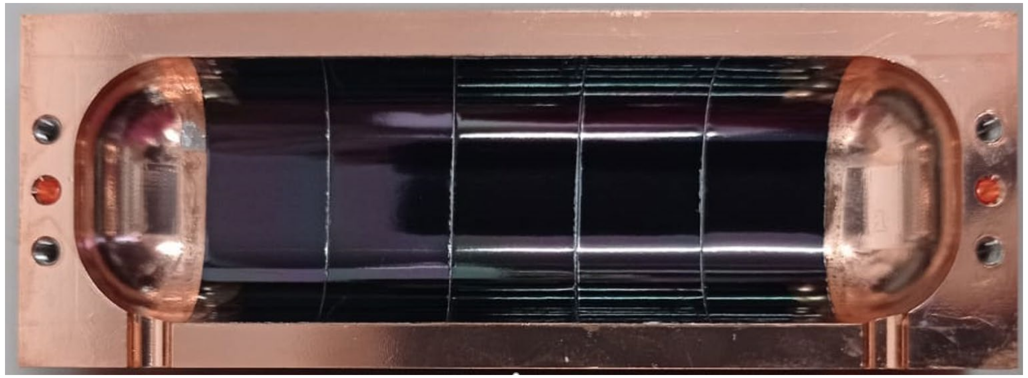


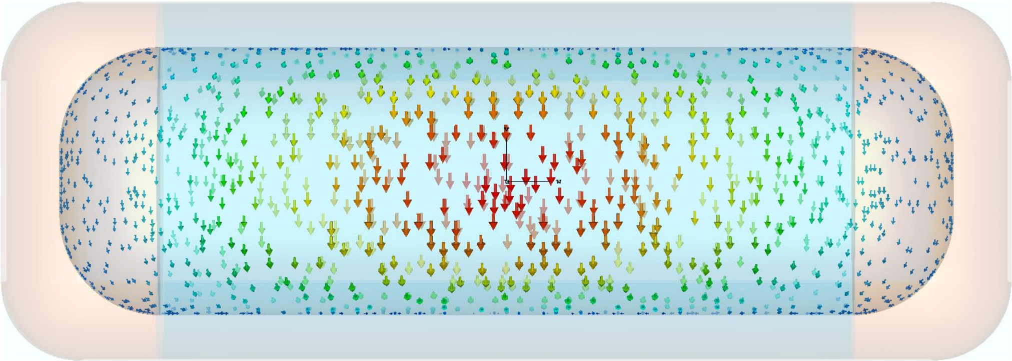


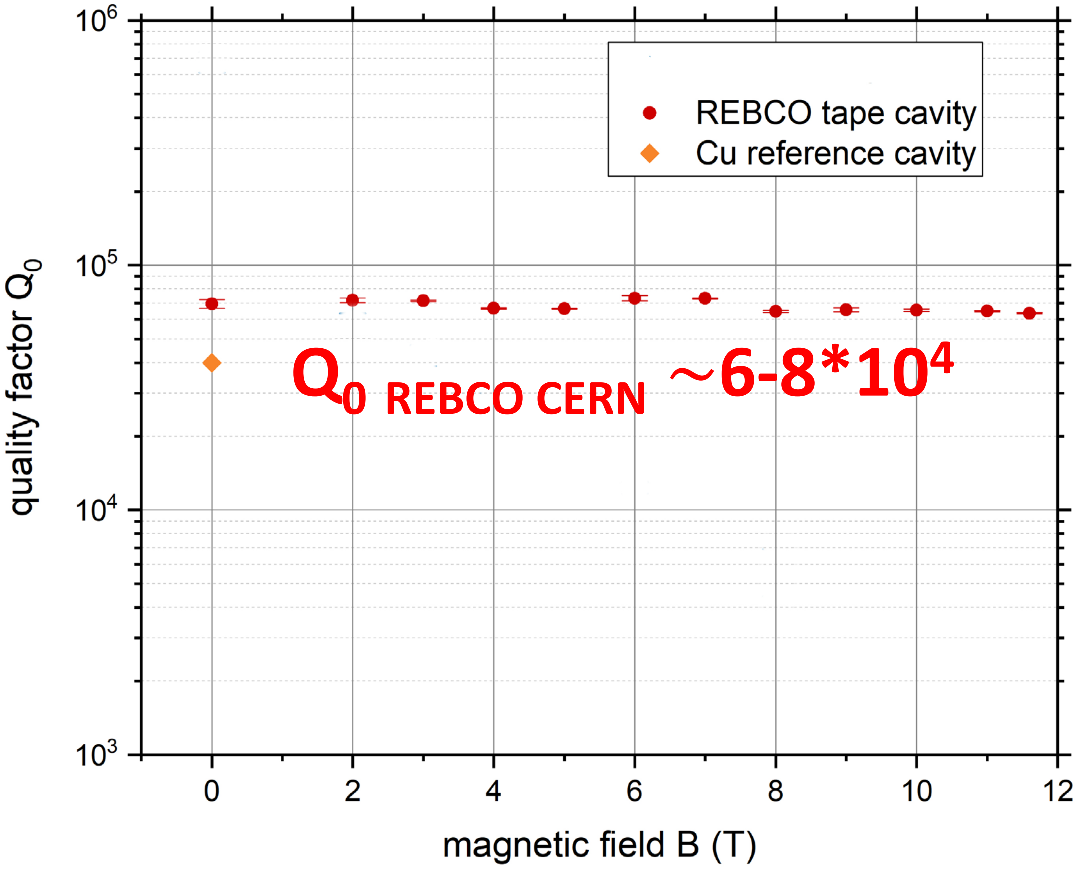
In commercial REBCO tapes SC is embedded

arXiv:2110.01296v1

REBCO

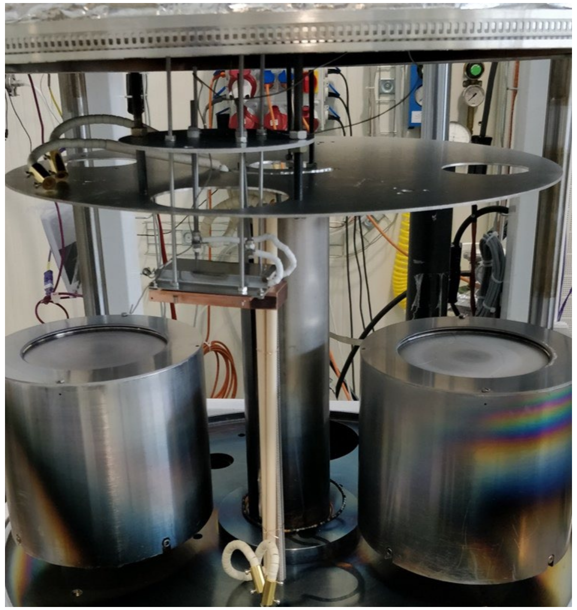


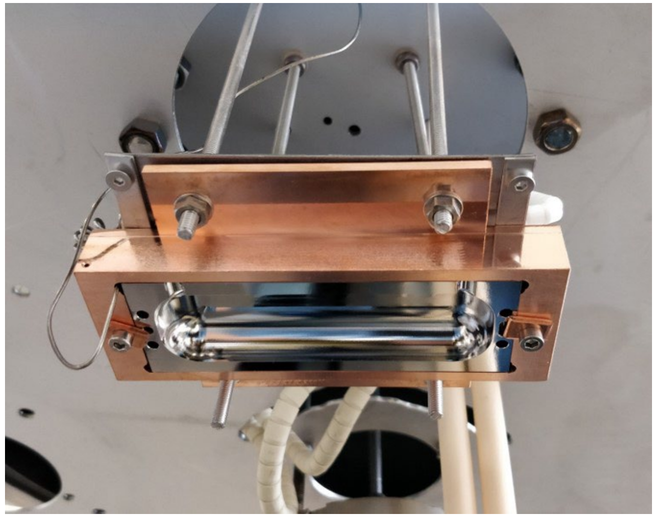


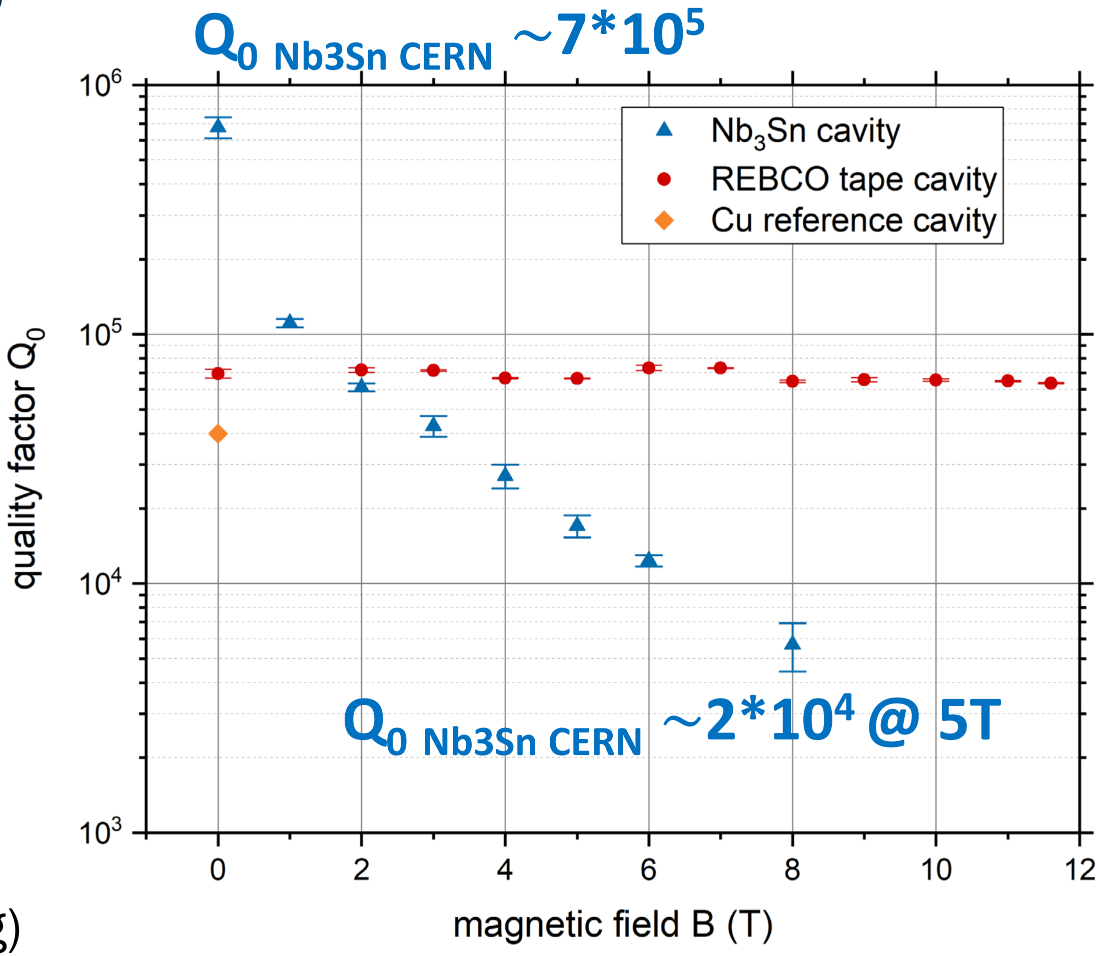


arXiv:2110.01296v1

Nb_3Sn







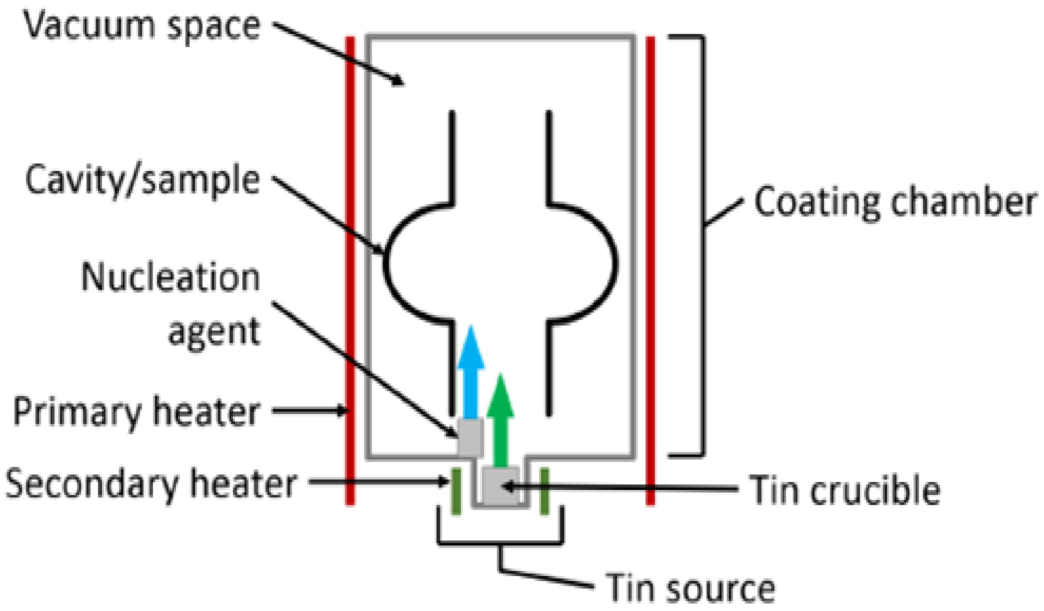
- **Nb_3Sn coating by Magnetron Sputtering**
- **Ta buffer layer** (to prevent Sn migration/film poisoning)
- **SS cavity** (T coating = 750 C)

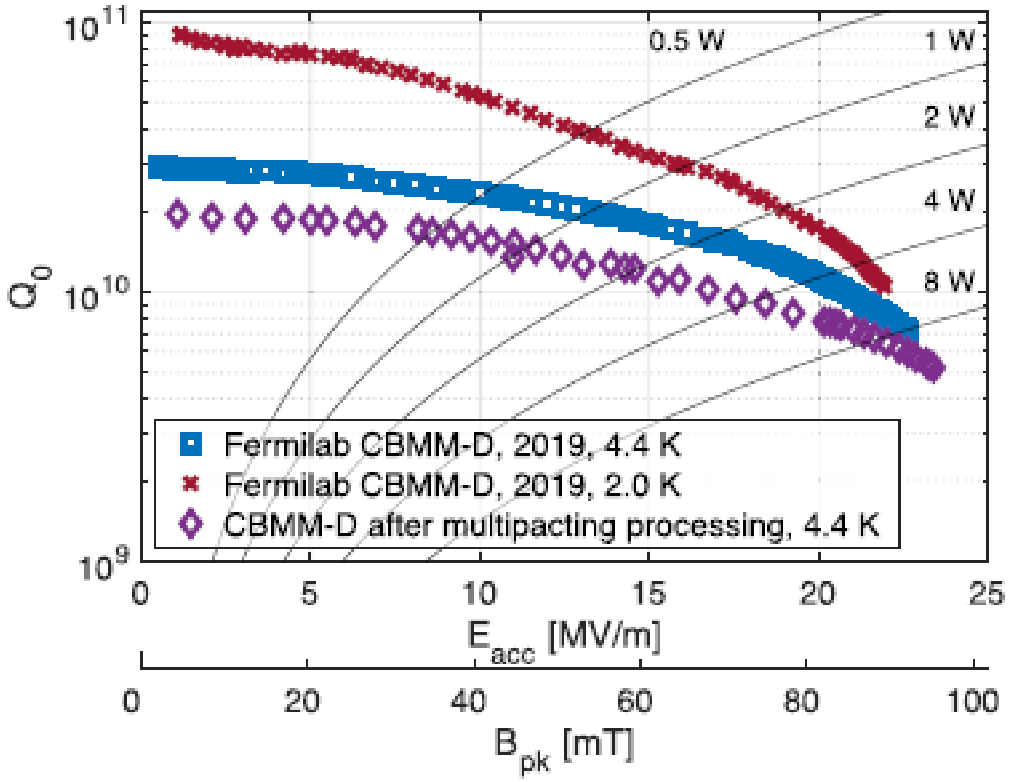
arXiv:2110.01296v1

Fermilab Nb_3Sn

Tin Vapor Diffusion

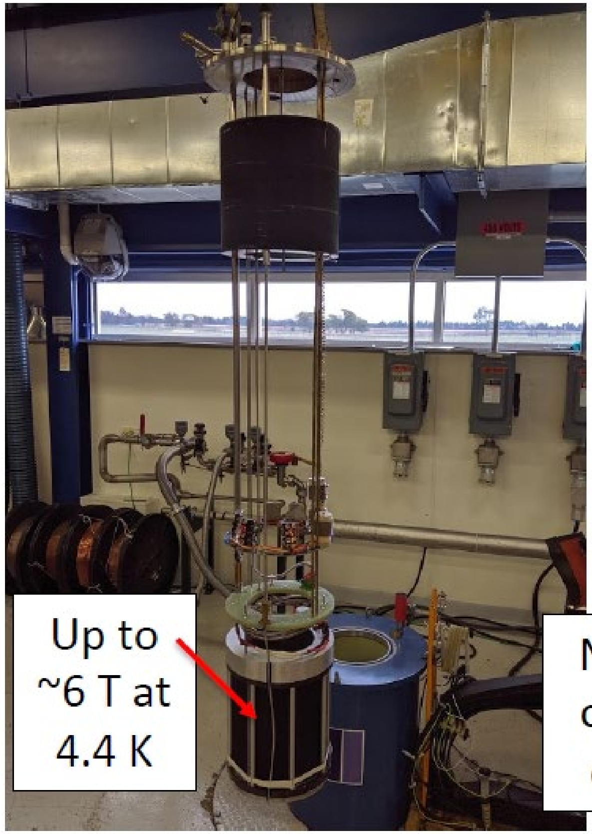
Very Mature Technique

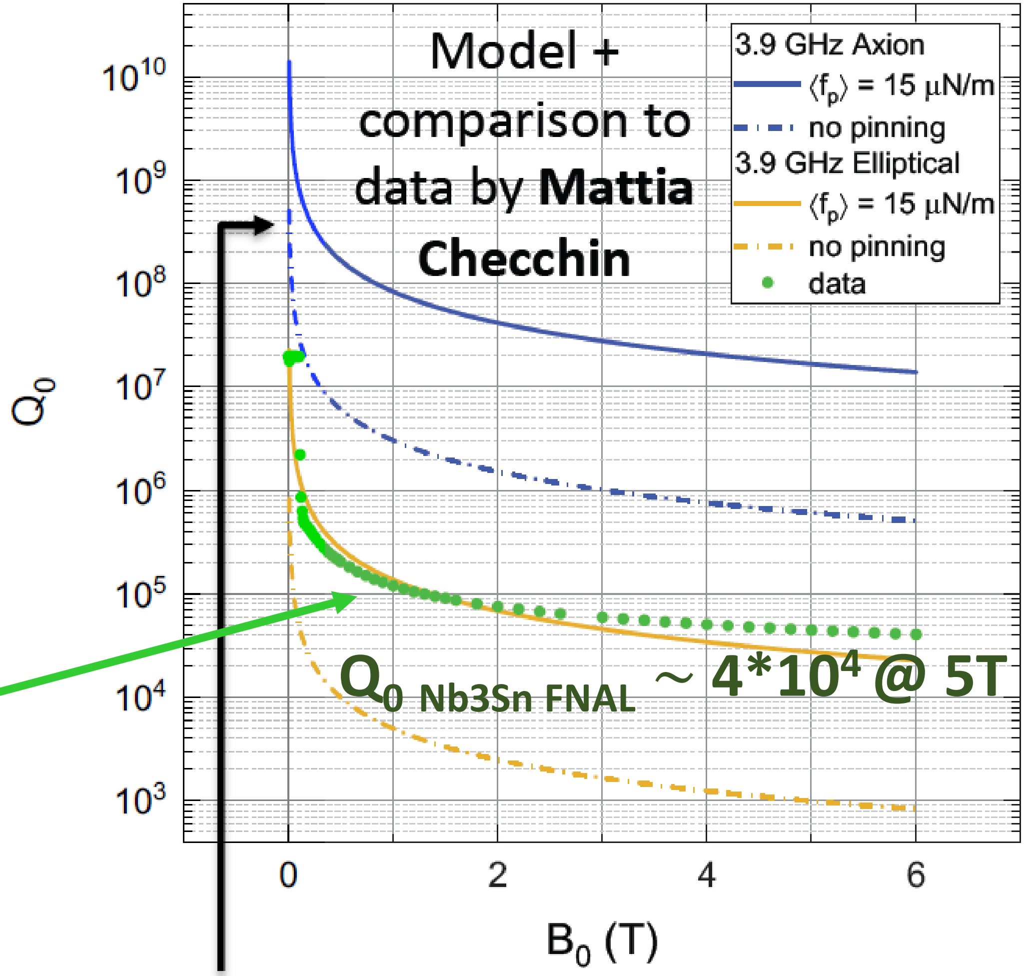




Quality factors up to 10^{11} @ 2K accelerating cavities

Fermilab Nb_3Sn



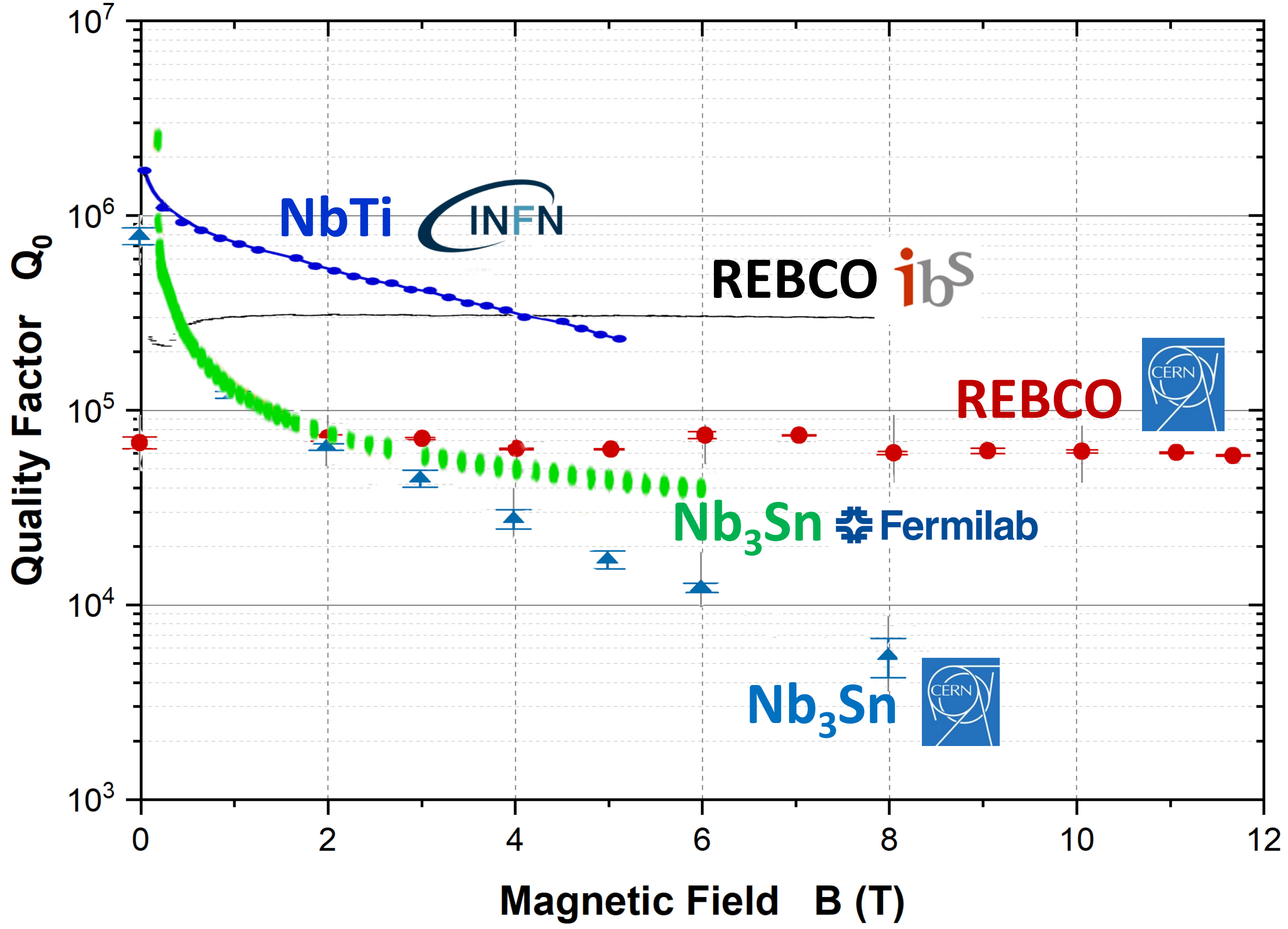


First evaluation on 3.9 GHz elliptical cavity

Not optimized geometry for DC high fields

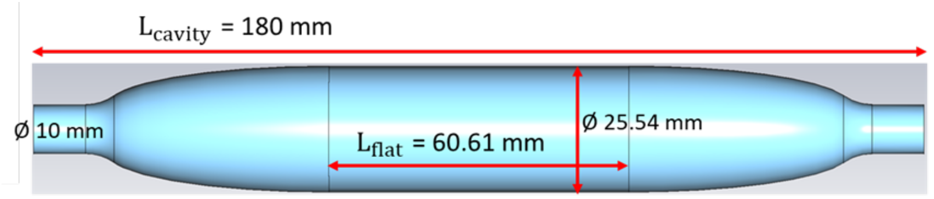
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

State of the Art Recall



What's next?

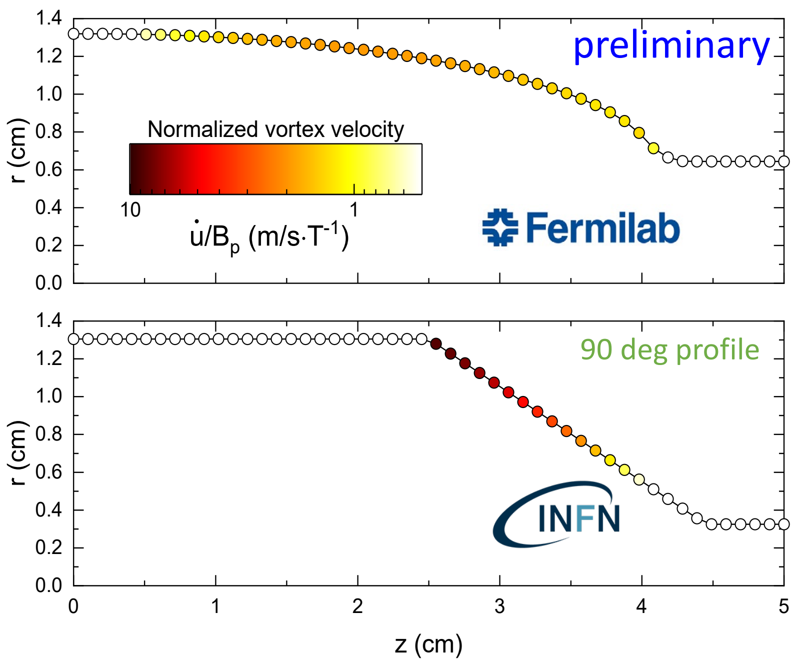
Fermilab Optimized Cavity Geometry

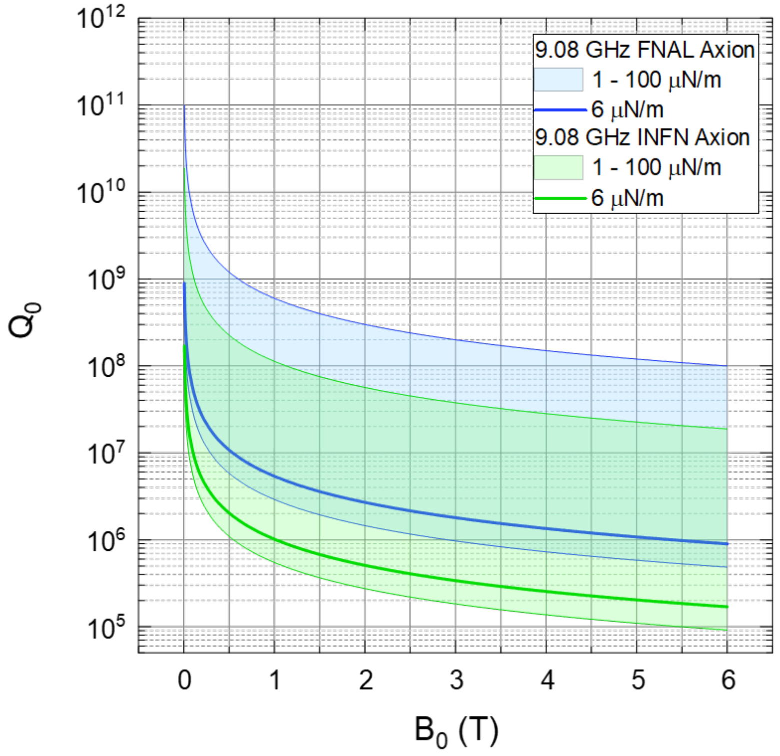


Optimized geometry with solenoid field. Ratio is 3.5

FNAL design expected to have 4.5 times higher Q than INFN design for same frequency and same material parameters

Elongated cones with lower angle



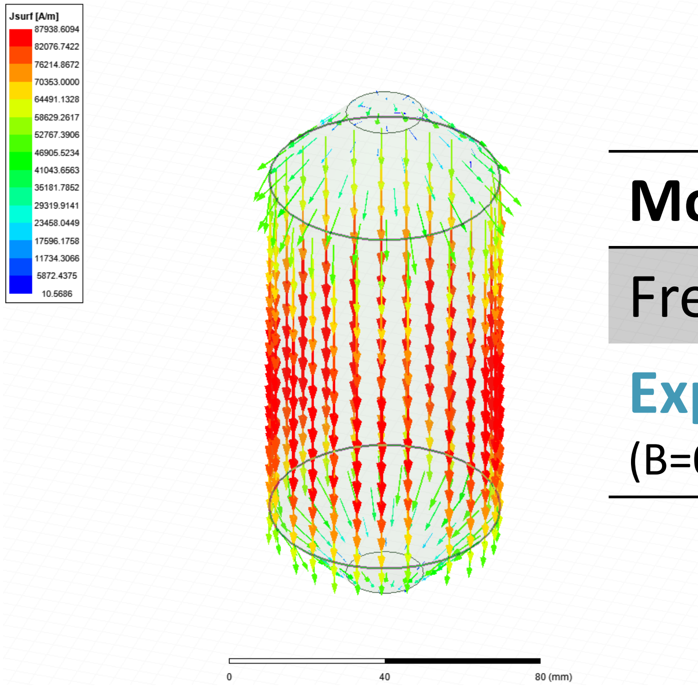


Fermilab Optimized Cavity Geometry

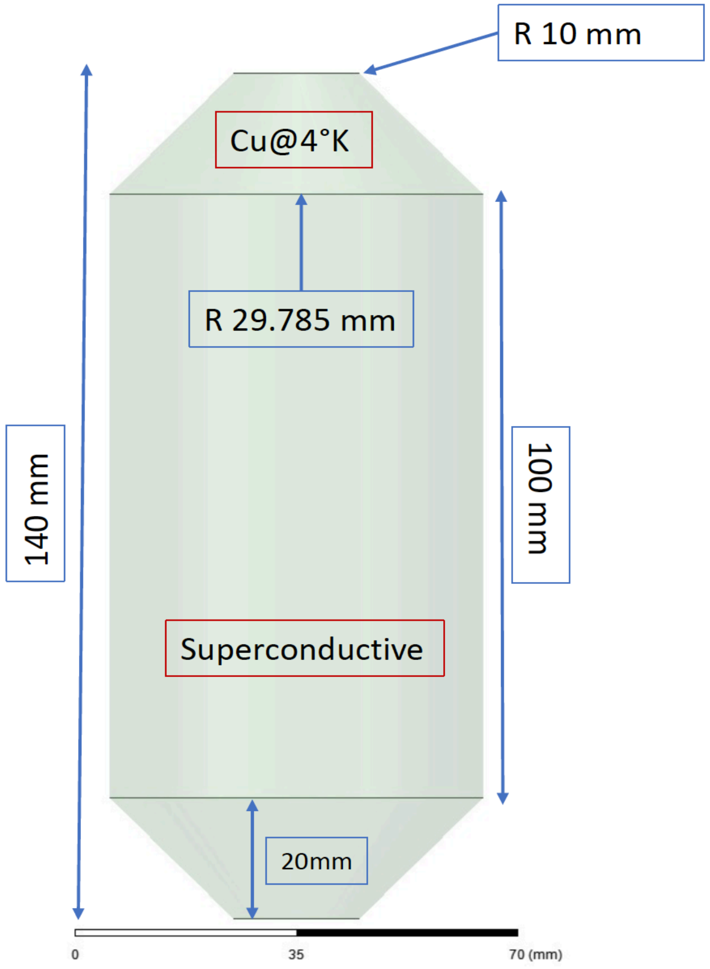
Designed to have surface currents highly parallel to applied field:
minimize *JxB* term in Lorentz force

NbTi Cavity at 3.9 GHz for FNAL

Fabrication at LNF
NbTi Sputtering at LNL
Measurements at FNAL at 4K in 6T magnet

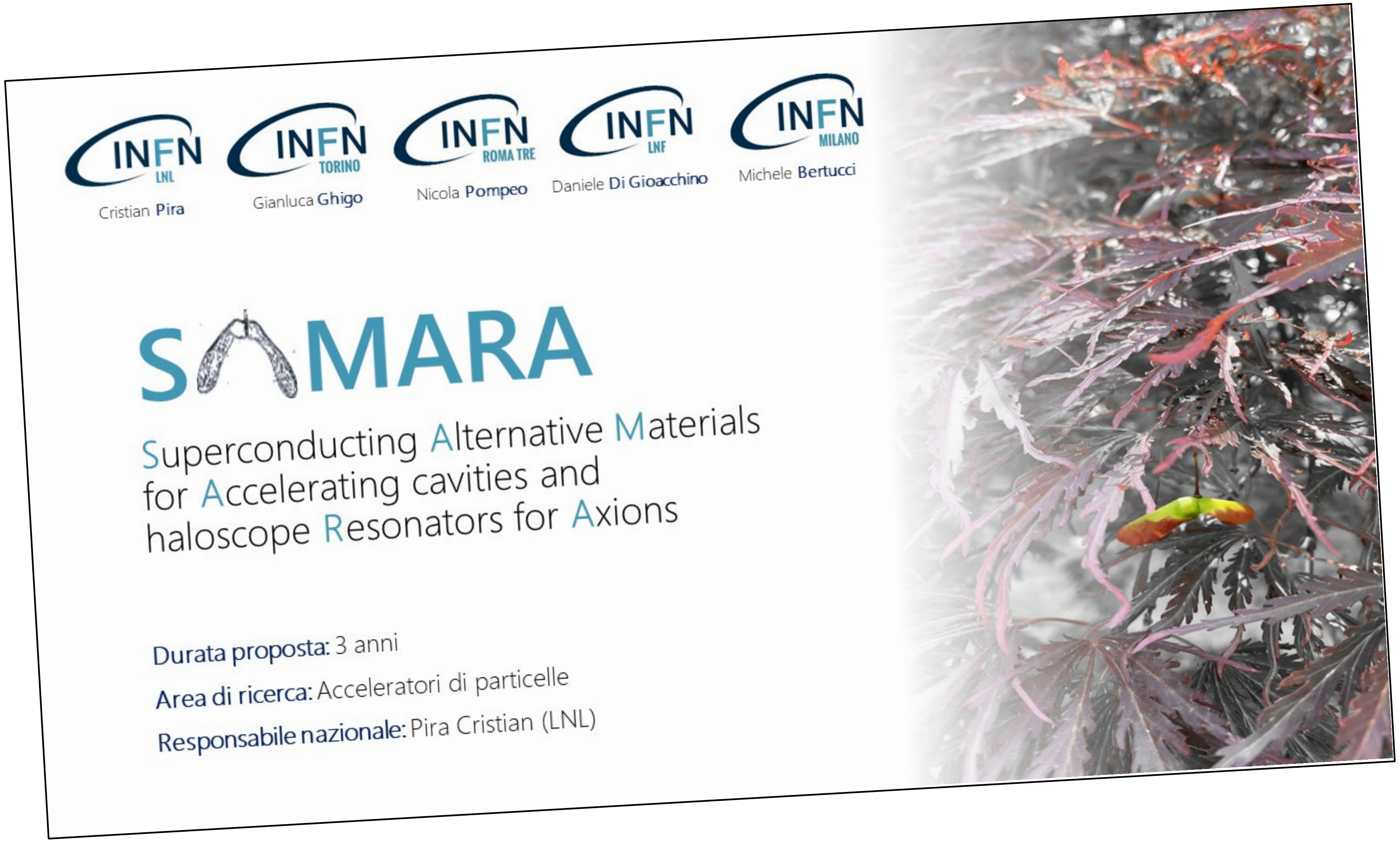


Mode	TM010
Frequency	3.965 GHz
Expected quality factor (B=0, NbTi walls, Cu endcaps)	**1.64×10^6**



Ansys Hfss simulations (S.Tocci, LNF)
Rs^{Cu}=2.8 mOhm, in Ansys obtained by using a conductivity of 2e+9 S/m

SAMARA INFN CSN5 new experiment



Established a **new collaboration** with **Roma Tre** (Enrico Silva) and **PoliTO** (Gianluca Ghigo)

Innovation: Nb_3Sn on Cu

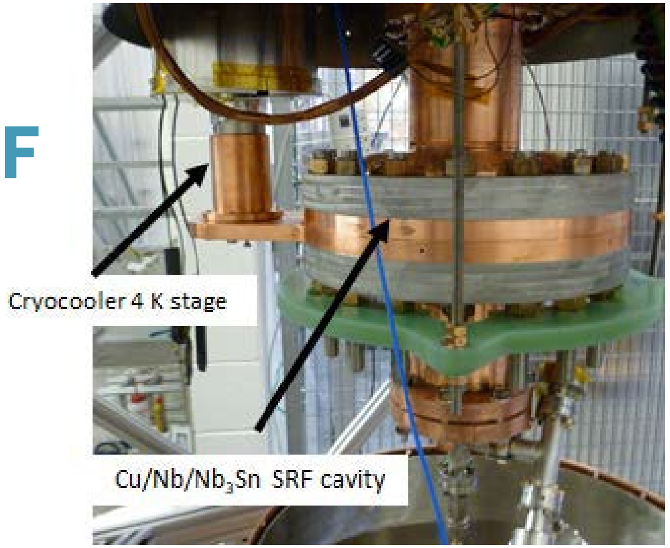
High thermal conductivity substrate is preferred in SRF

High performance of Nb_3Sn @ 4.2 K

Potential cooling by cryocooler

(proof of concepts already realized at Jlab on Nb_3Sn-**Nb**-Cu cavities)

New industrial applications for SRF accelerators



Innovation: Nb_3Sn on Cu

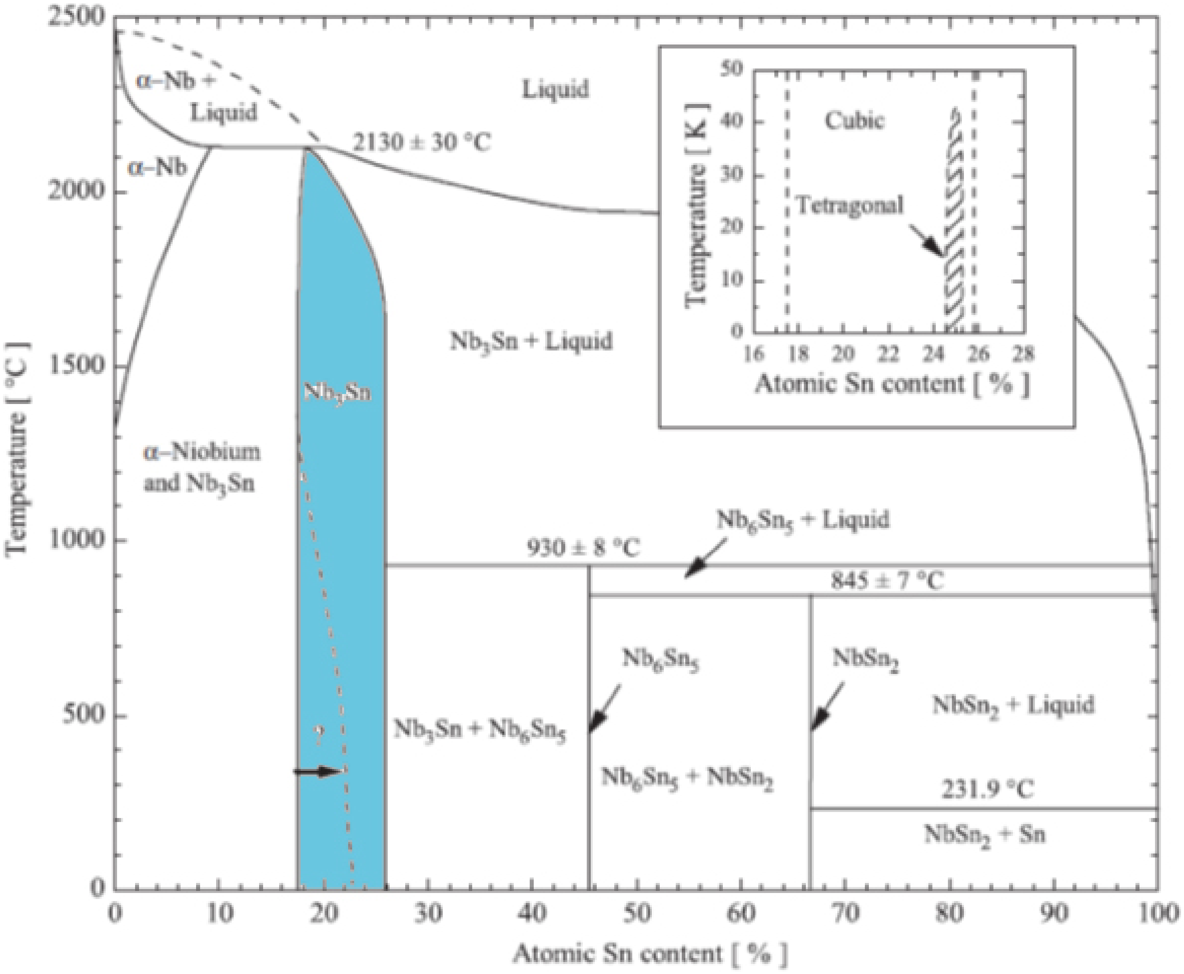
Sputtering is the most promising technique

Advantages:

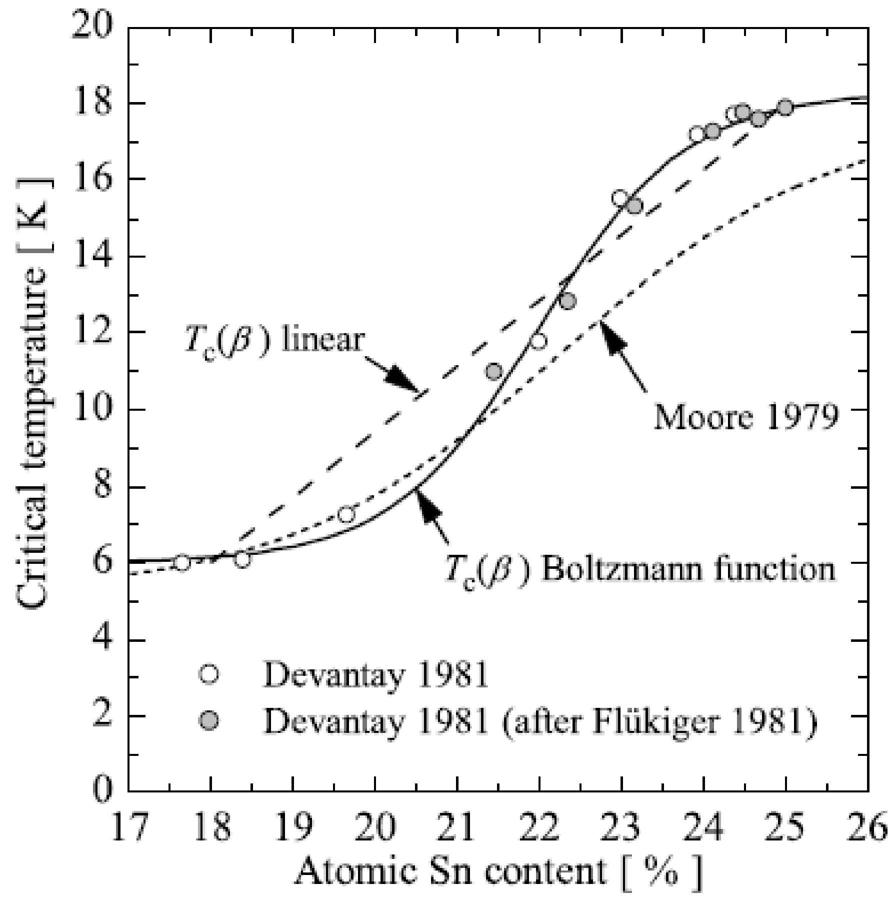
- Versatile technique
- LNL experience
- **Good stoichiometry already at 600 °C**
- **Small grain film → more pinning → best in high magnetic field**

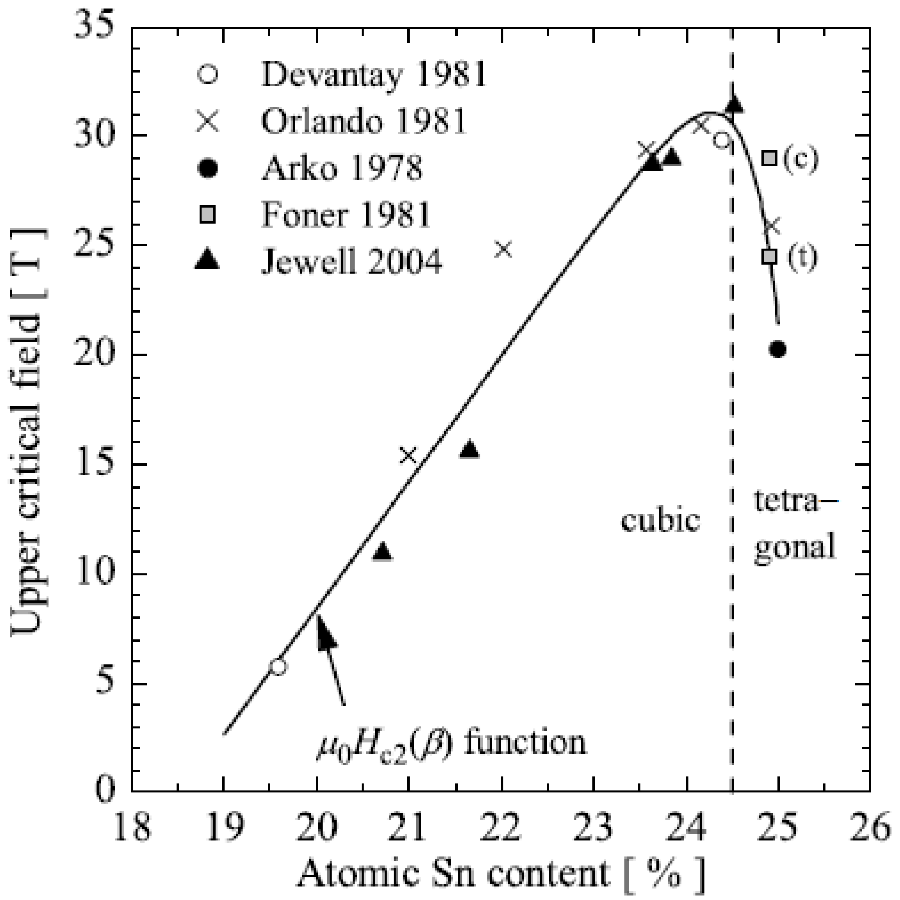
Challenges:

Nb_3Sn Challenging: Phase Diagram



Nb_3Sn Challenging: Stoichiometry





Innovation: Nb_3Sn on Cu

Sputtering is the most promising technique

Advantages:

- Versatile technique
- LNL experience
- **Good stoichiometry already at 600 °C**
- **Small grain film → more pinning → best in high magnetic field**

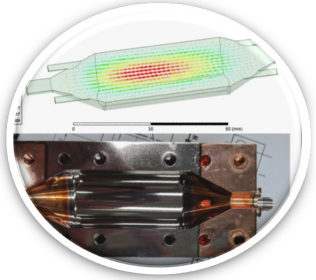
Challenges:

- Complex Phase Diagram
- Stoichiometry is critical
- Possible poisoning from Cu substrate
- Complex scaling to accelerating cavity

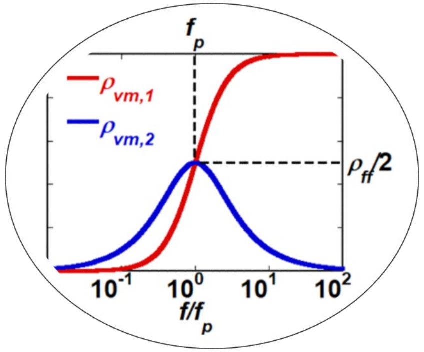
Not a problem with haloscopes!

SAMARA will develop and study Nb_3Sn for:

ACCELERATING CAVITIES

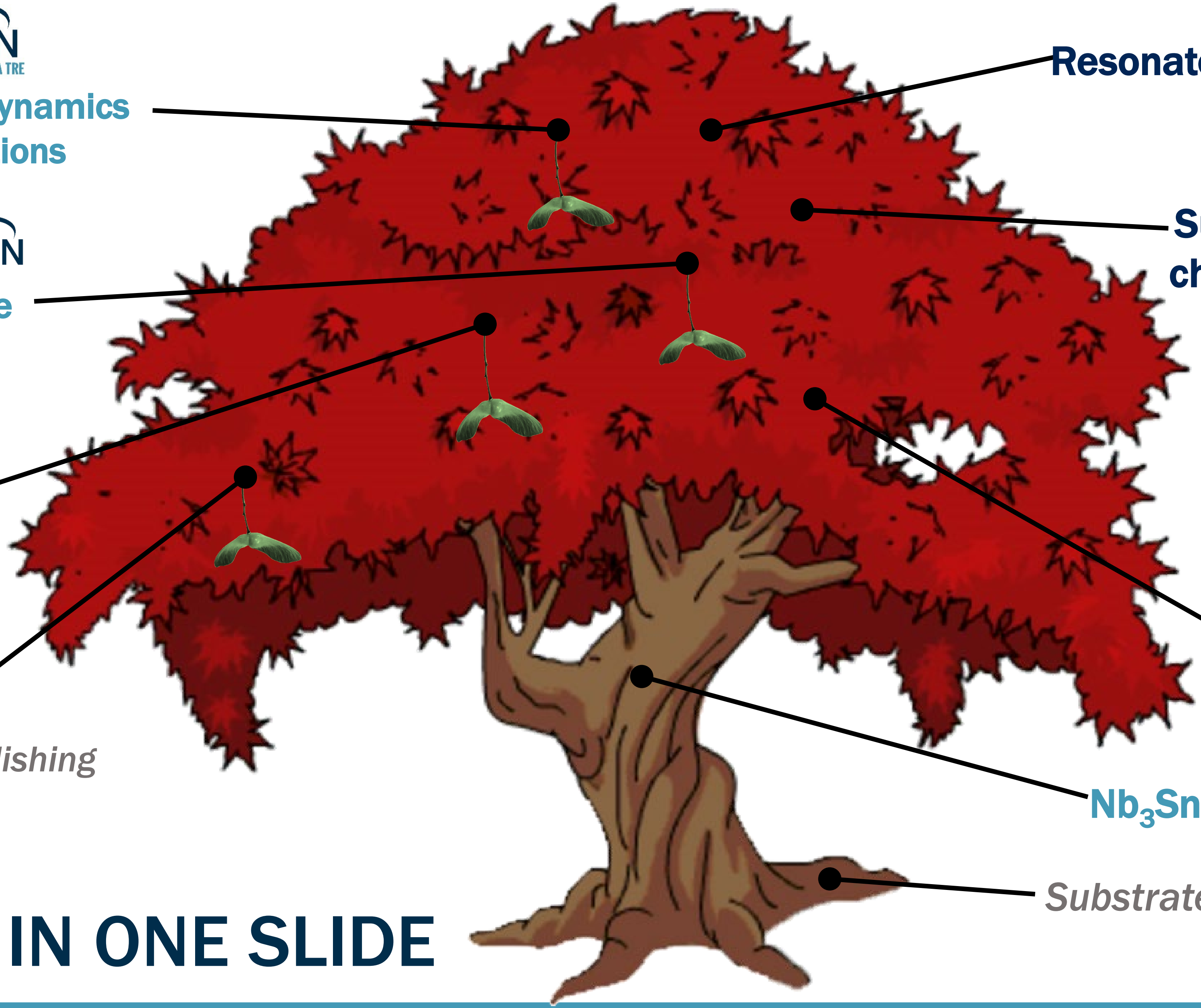


HALOSCOPE FOR AXION SEARCH



MODELLIZATION OF VORTEX DYNAMICS IN EXTREME CONDITIONS

SAMARA IN ONE SLIDE



Modelling of Vortex Dynamics
In extreme conditions

Nb_3Sn Haloscope

Nb_3Sn
accelerating cavities

Plasma Electrolytic Polishing

Resonators

Superconductive
characterizations

Morphological
characterizations

Nb_3Sn coatings

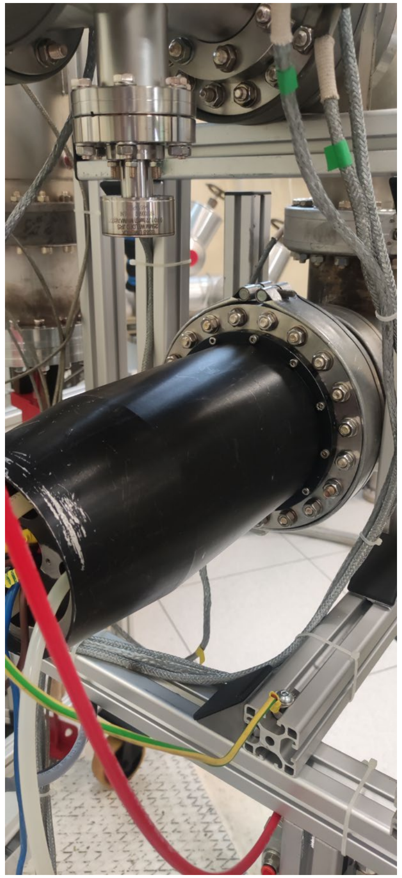
Substrate preparation

From old coating system to new one

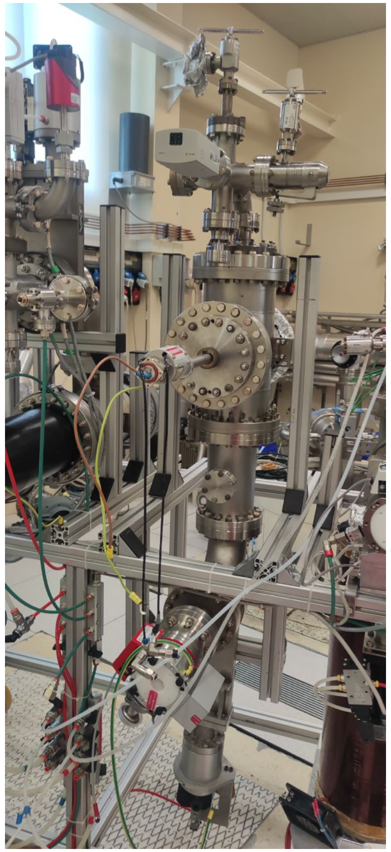
cristian.pira@lnl.infn.it

From old coating system to new one

Commercial 4 “ *magnetron source*

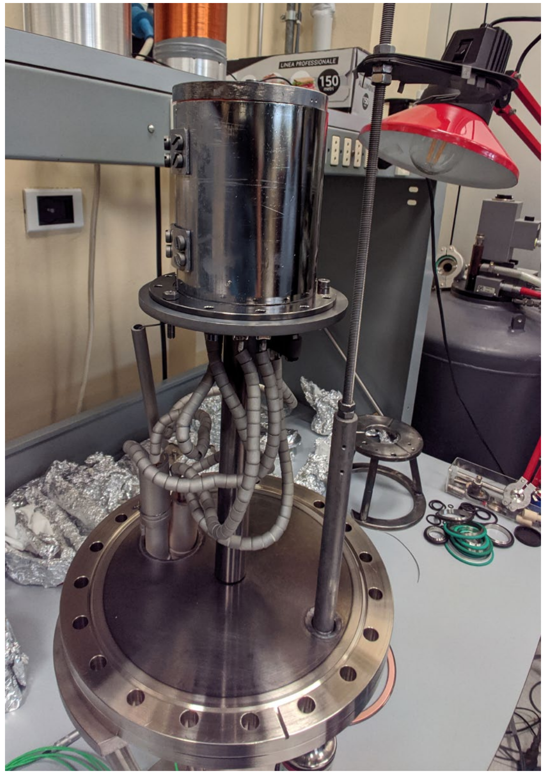


In house 4 “ *magnetron source*



1“ *MS sputtering system*

4“ *MS sputtering system*



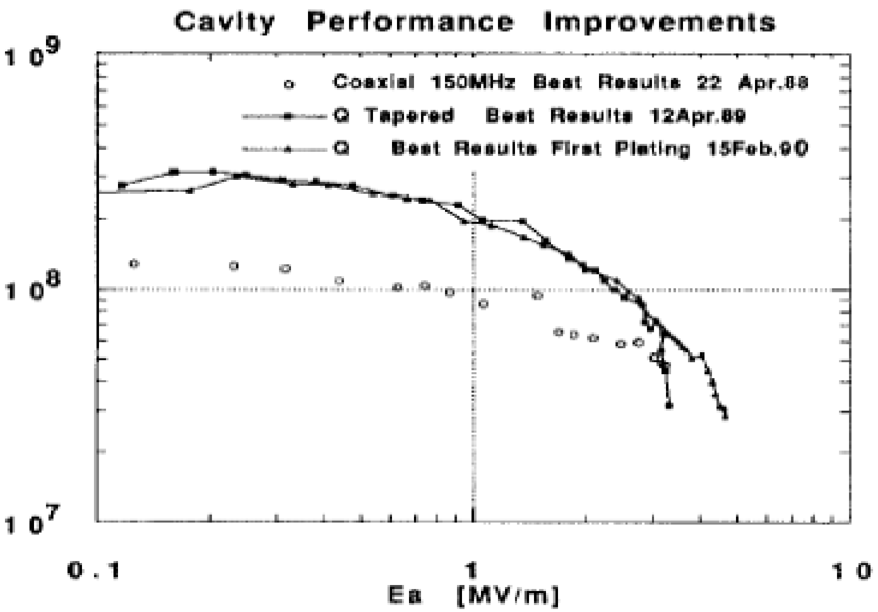
600 °C Sample holder

Final remarks

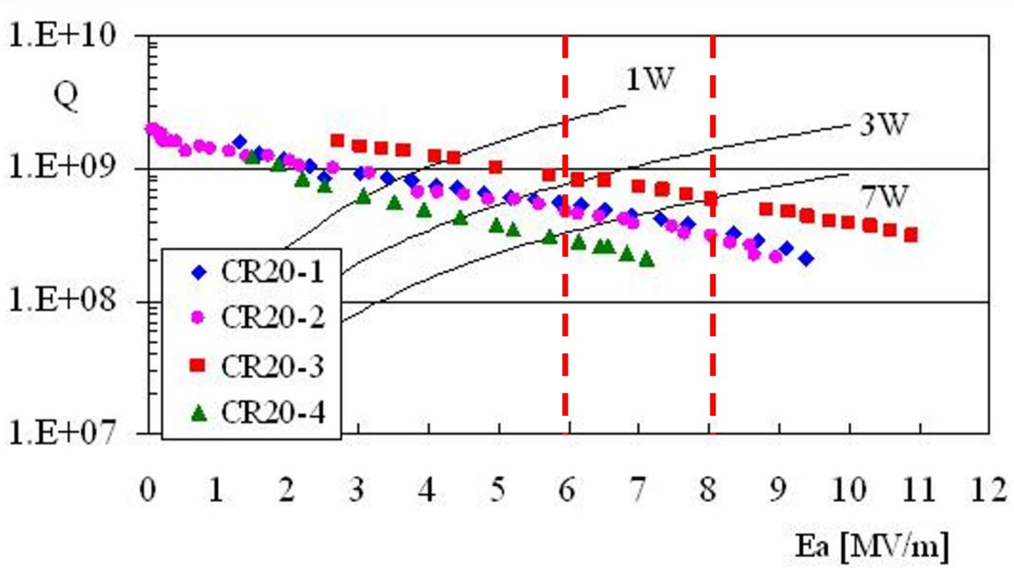
- First results with **SC haloscopes** have shown the feasibility of **RF operation in strong magnetic field**
- Necessary **more R&D**
- **Modelling** of vortex motion will help the R&D
- We are only at the **beginning…**

ALPI SC cavities performance evolution

Pb on Cu QWR (1988)



Nb on Cu QWR (1993)



Q and E_{acc} improved of one order of magnitude in 5 years

Thank you!