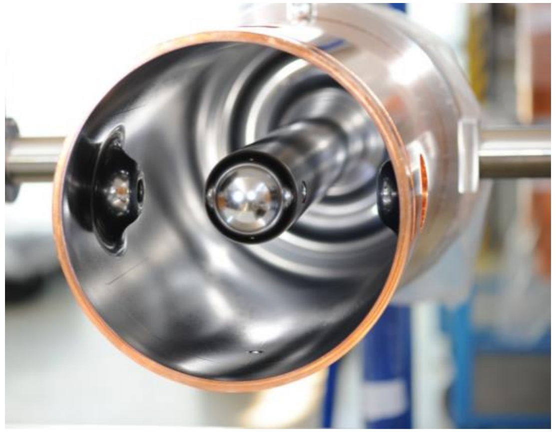
SRF technology under strong magnetic field

Sergio Calatroni – CERN
With contributions from
many Collaborators

Setting the scene

- Typical SRF accelerator cavities are made of niobium

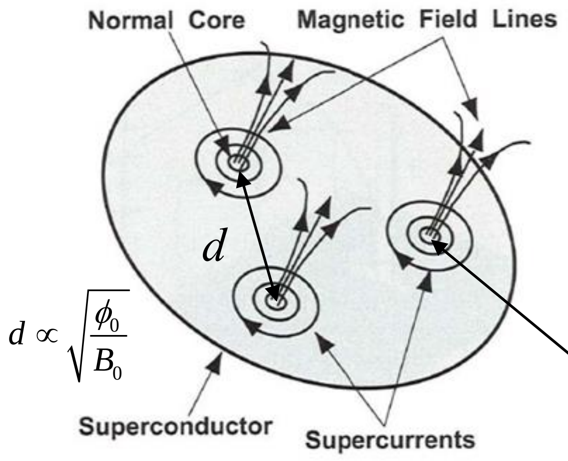
Strong magnetic shielding needed



Limited or no magnetic shielding

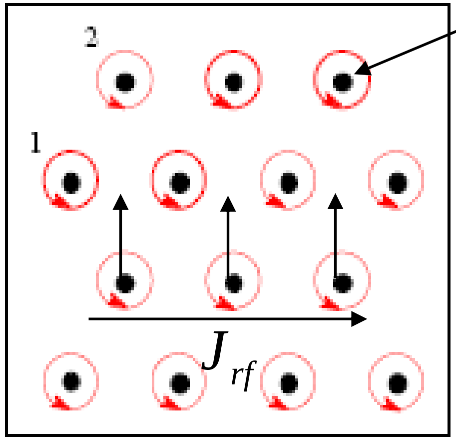
- Effect of external magnetic field on SRF accelerating cavities is mostly due to flux pinning, weak pinning in bulk Nb and strong in Nb/Cu
- Niobium critical field $H_{c2} < 1$ T, superconductivity is lost at higher fields

Some theory background: fluxon motion in RF



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

Pinning centers

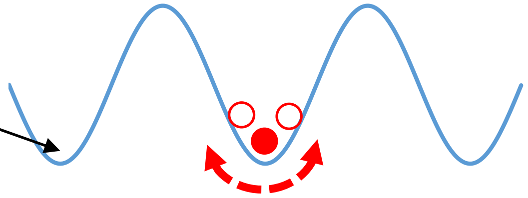


B field is normal to surface: worst case

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

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

Very simplified model
Useful for estimates
and scaling



$$\eta=\frac{\phi_o B_{c2}}{\rho_n} \qquad k=\frac{2\pi J_c\phi_0}{d} \qquad \omega_o=\frac{k}{\eta}$$

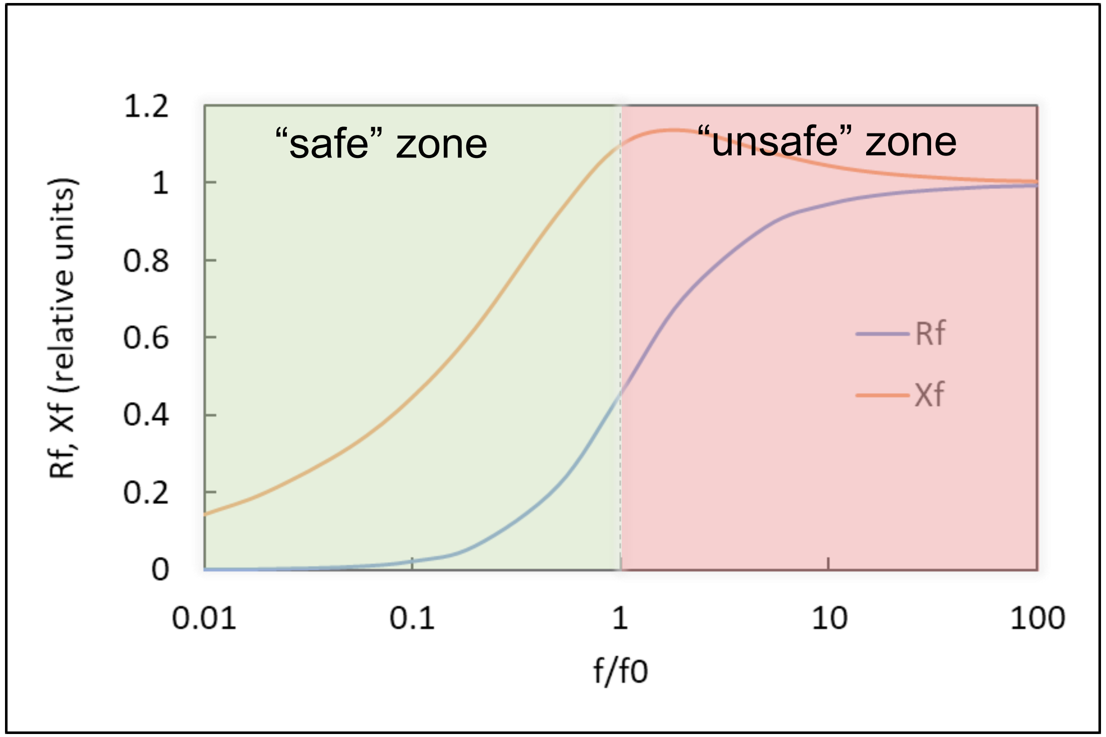
The “depinning frequency”

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

Gittleman and Rosenblum: Phys Rev. Lett. 16, 734 (1966)
Calatroni and Vaglio, IEEE Trans. Appl. Supercond. 27 (2017) 3500506
Coffey, Clem PRL 67, 386 (1991)
Brandt PRL 67 2219 (1991)
Silva et al, PRB 78, 094503 (2008)

Effect of magnetic field: fluxon losses in RF

Surface resistance, reactance due to vortex motion



Case $f < f_o$

$$R_f = \frac{\rho_n}{2\lambda} \frac{B_o}{B_{c2}} \frac{f^2}{f_0^2} \qquad B_0 \square \; B_{c2}$$

$$R_f = \frac{R_n}{\sqrt{2}} \sqrt{\frac{B_o}{B_{c2}}} \left(\frac{f}{f_0} \right)^{3/2} \qquad B_0 \square B_{c2}$$

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

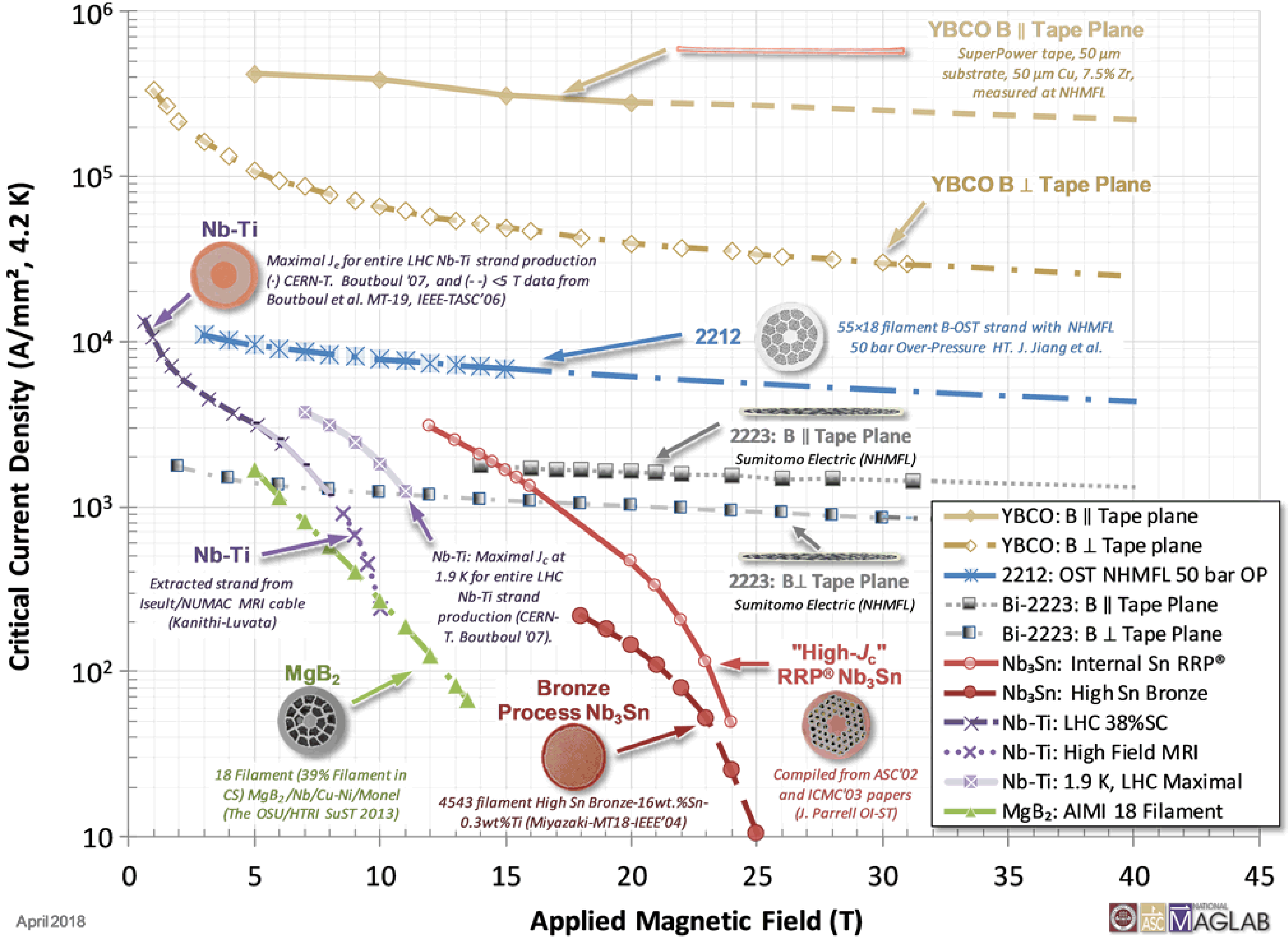
To maximize f_0 and minimize fluxon losses we need high J_c materials

Zoo of superconductors

J_c may vary of order of magnitudes.
H_{c2} has much smaller variation.

YBCO most promising candidate

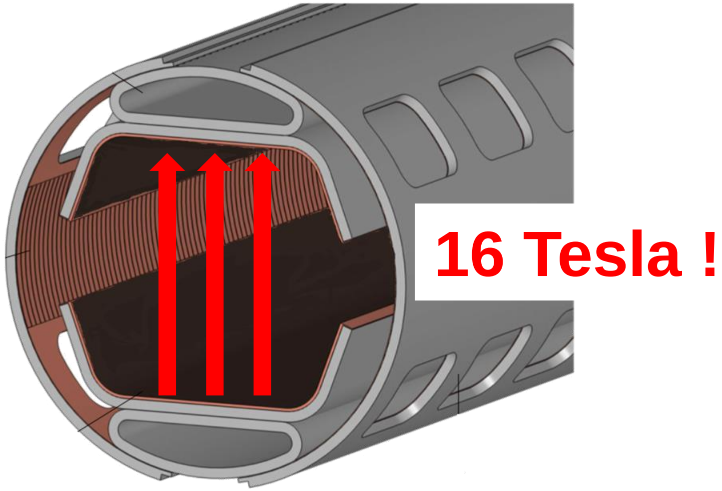
Remember: our benchmark is copper



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

HTS for the FCC-hh beam screen

- Recent work motivated by the need of HTS materials for replacing copper in the FCC-hh beam screen, to reduce beam coupling impedance.
- Beam produces RF fields
- Extremely challenging requirements:
    - HTS must operate at 50 K and 16 T
    - Critical fields Hc_2 , H_{irr} >> 16T
    - $J_c > 25$ kA/cm^2 (2.5x10^8 A/m^2)
    - Surface resistance R_s better than for copper
- Compatible with accelerator environment
    - Minimize dipole field distortion due to persistent currents (Note 1)
    - UHV compatible, low SEY, lifecycle assessment, etc..



Calatroni, IEEE TAS 26, 3500204 (2016)
Calatroni et al, SuST 30, 075002 (2017)

How to make it in practice ?

Manufacture the screen using REBCO tapes soldered to the screen

Coat the inside of the screen with Tl-1223 films

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INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA
EXCELENCIA SEVERO OCHOA
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

ALBA

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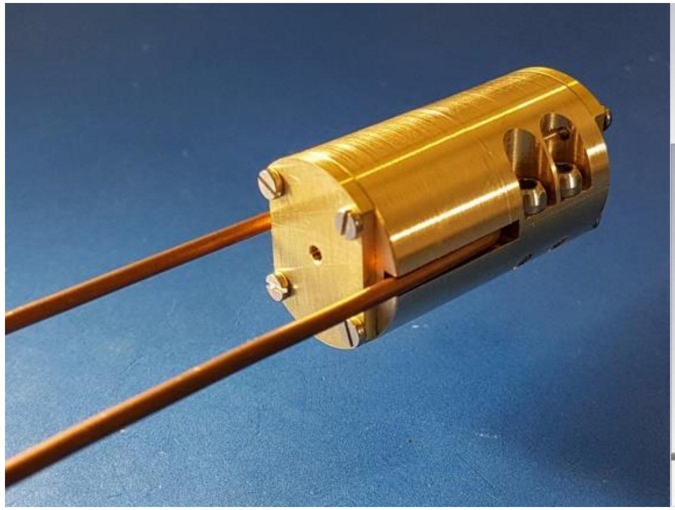
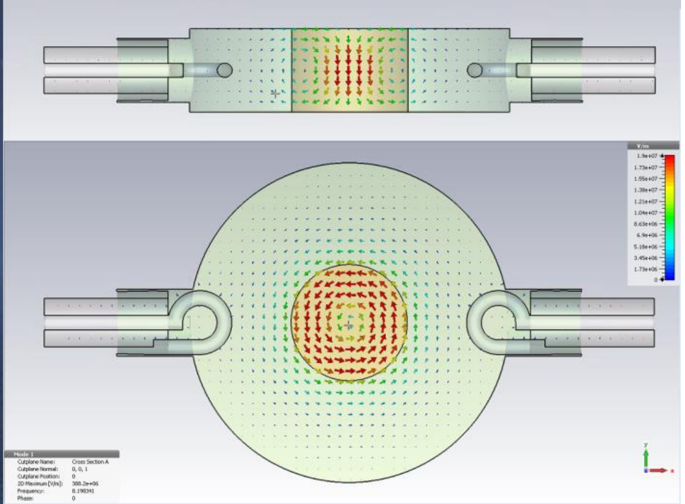
Validation of RF performance (UPC - ICMAB)





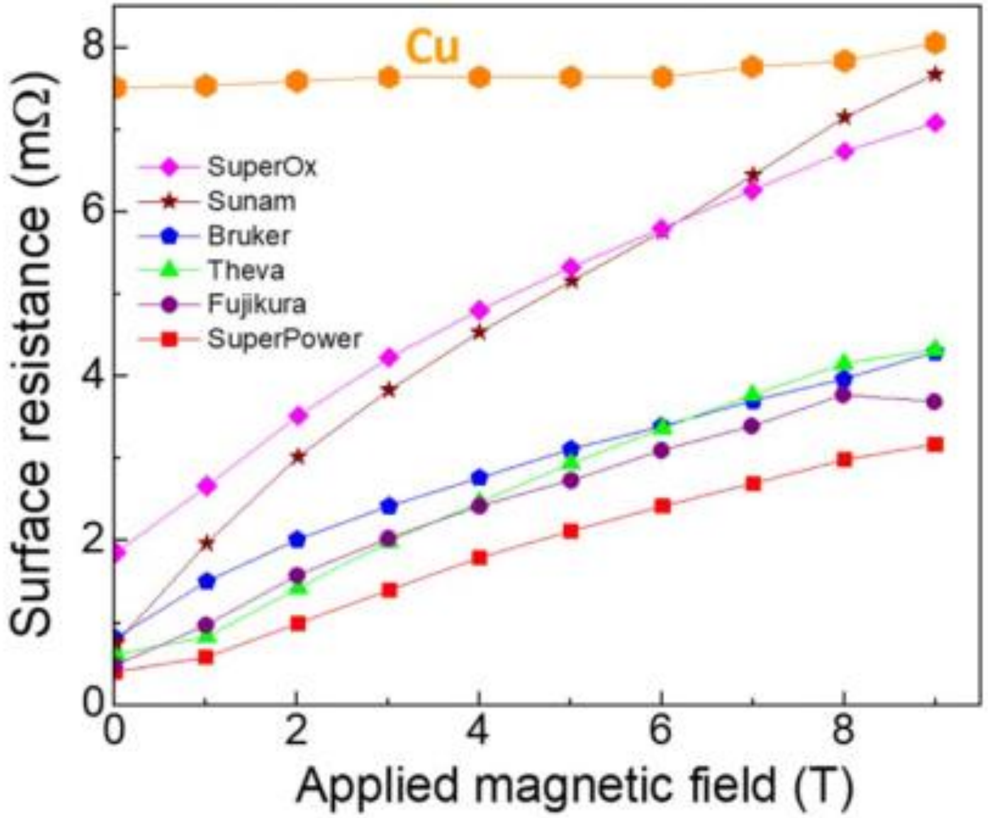


Figure 3. Magnetic field dependence of the surface resistance at 8 GHz and 50 K. Up to 9 T, CCs' R_s outperforms that of copper.

In house developed 8.05 GHz cavity resonator compatible with 25mm bore 9 T magnet at ICMAB

REBCO CCs outperform Cu at 50K and up to 9T
R_S is microstructure dependent

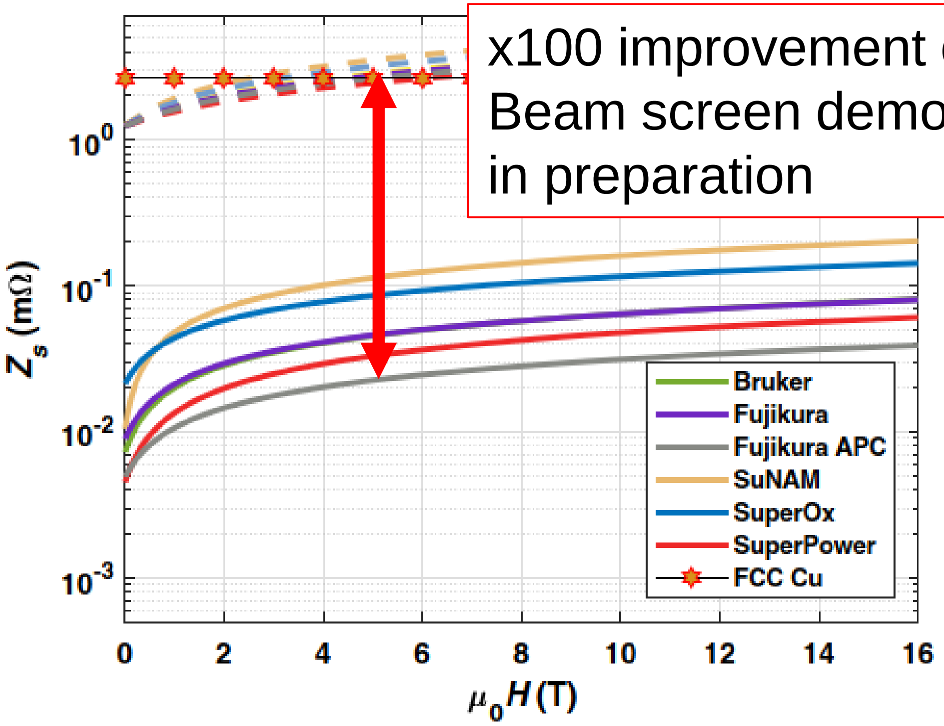
Puig et al, SuST 32, 094006 (2019)

Note 2: surface currents equivalent to 0.1 MV/m of typical accelerating cavity

Scaling to lower frequency

Romanov et al, SciRep 10:12325 (2020)

REBCO scaled to 1 GHz at 50 K



x100 improvement over Cu
Beam screen demonstrator in preparation

Note 3: For HTS Rs scales as f^2
For Cu Rs scales as $f^{1/2}$

Copper properties

NRF temperature	Rs copper @ 325 MHz	Rs copper @ 1000 MHz
300 K	4.8 mΩ	8.3 mΩ
77 K	1.7 mΩ	3 mΩ

Cryoplant efficiency (Carnot + engineering)

SRF temperature	Ratio W_{300K}/W_{cryo}
77 K	13
50 K	20
4.2 K	230
1.9 K	920

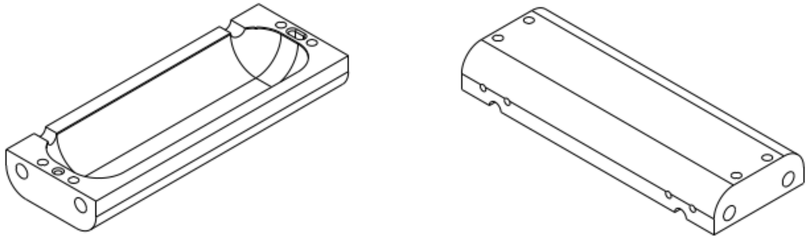
Thanks to T. Koettig, CERN

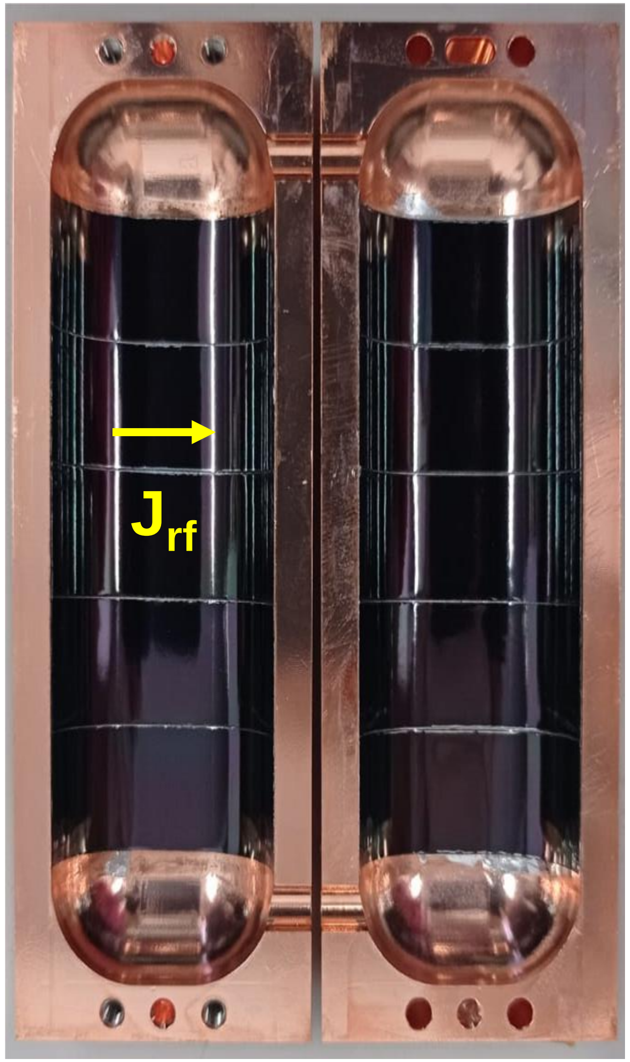
$$P = \frac{1}{2} R_s H^2$$

Note 4: predicted energy gain must take into account cryo efficiency

RADES: Relic Axion Detector Exploratory Setup

9 GHz cavity for Axion detection





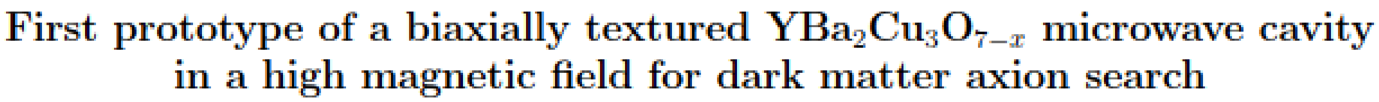
Copper

REBCO coated conductors (soldered)
Same as previous slides

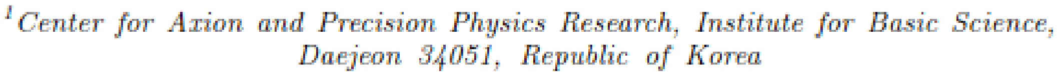
Nb$_3$Sn by sputtering

First test in 11T magnet scheduled for next week!

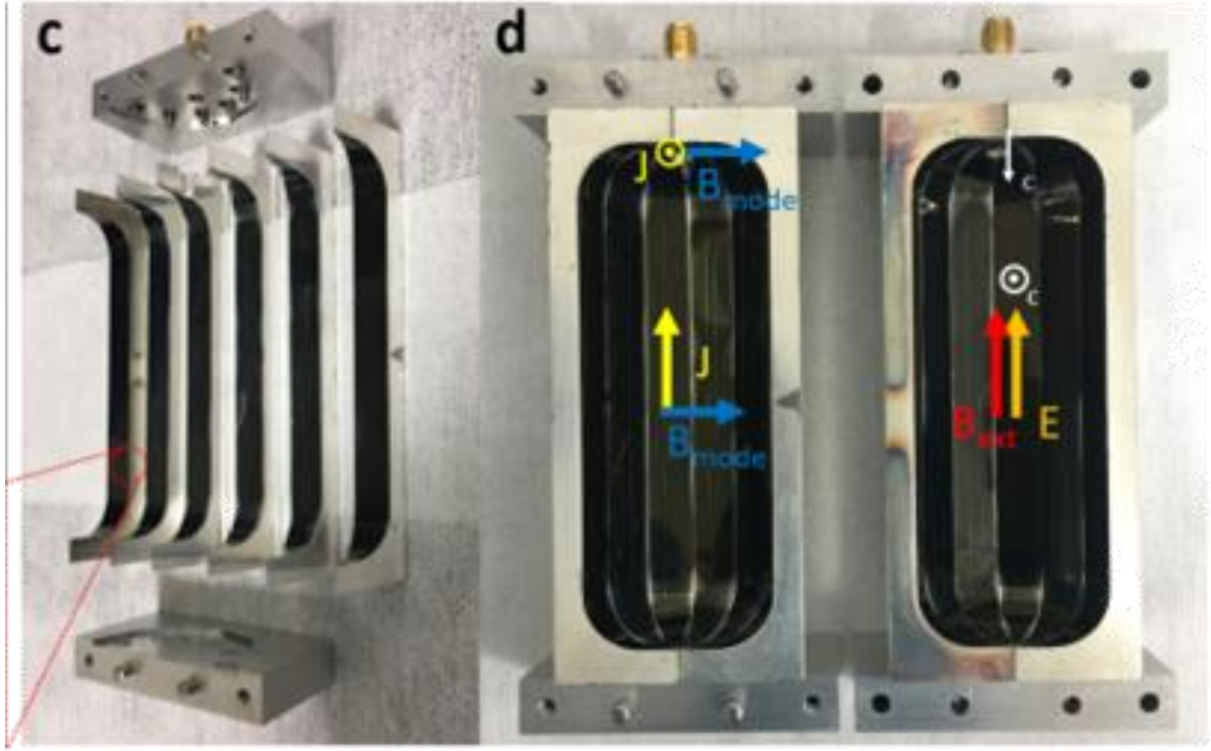
CAPP: axion searches

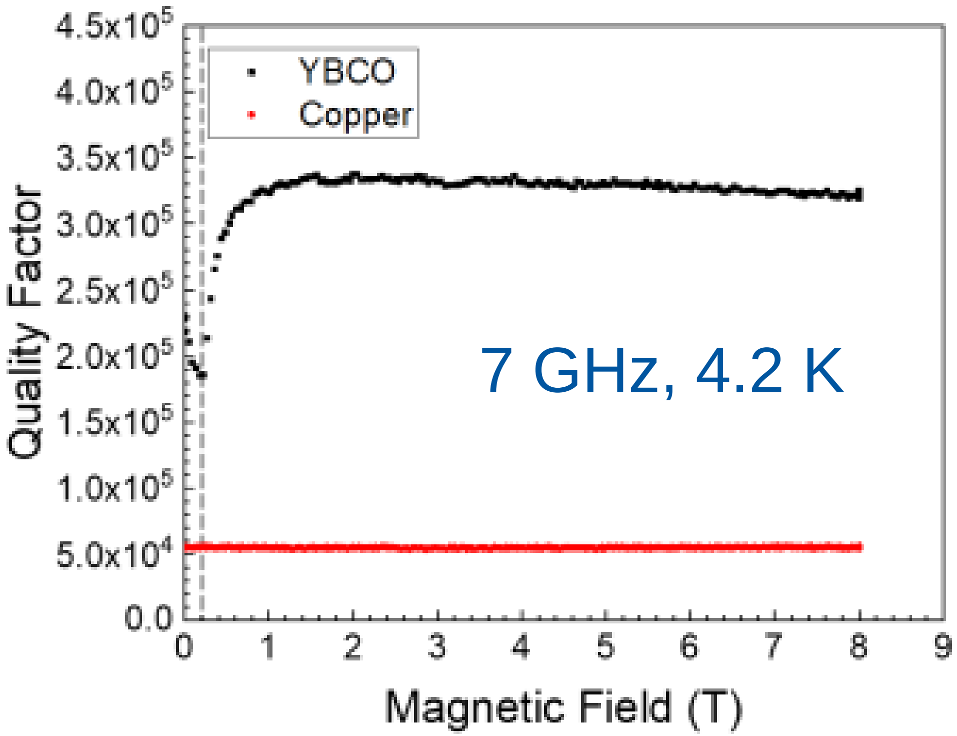


First prototype of a biaxially textured $YBa_2Cu_3O_{7-x}$ microwave cavity in a high magnetic field for dark matter axion search



[1]*Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Republic of Korea*





7 GHz, 4.2 K

REBCO coated conductors glued to aluminum support

arXiv:2103.14515v1

INFN: NbTi and NbTiN cavitie for axion searches

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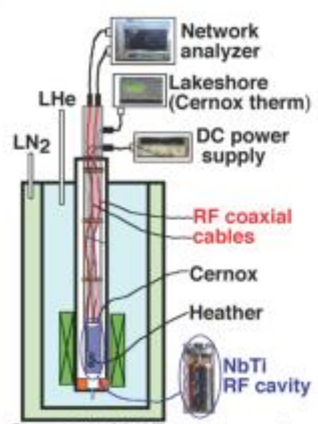
Microwave Losses in a DC Magnetic Field in Superconducting Cavities for Axion Studies

RF cavity
2 Cu semi-cells+NbTi film



Cryostat with 8T sup. magnet

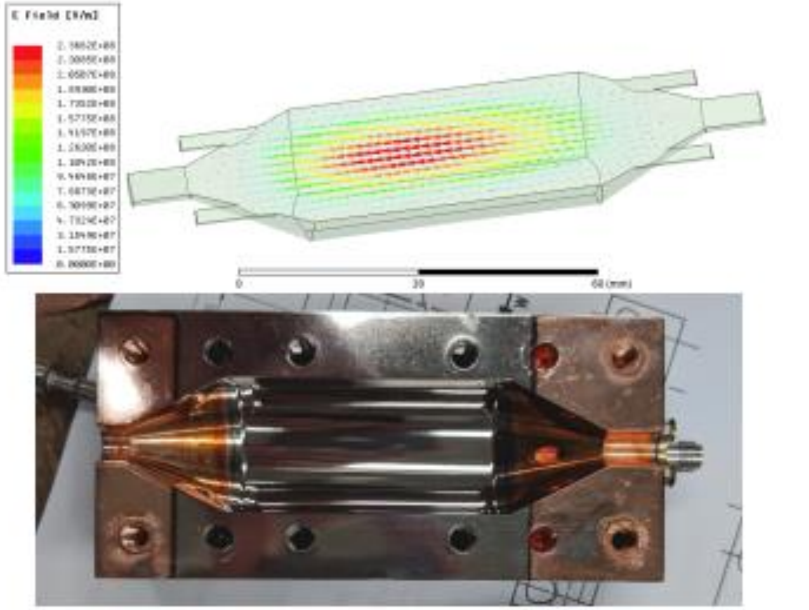
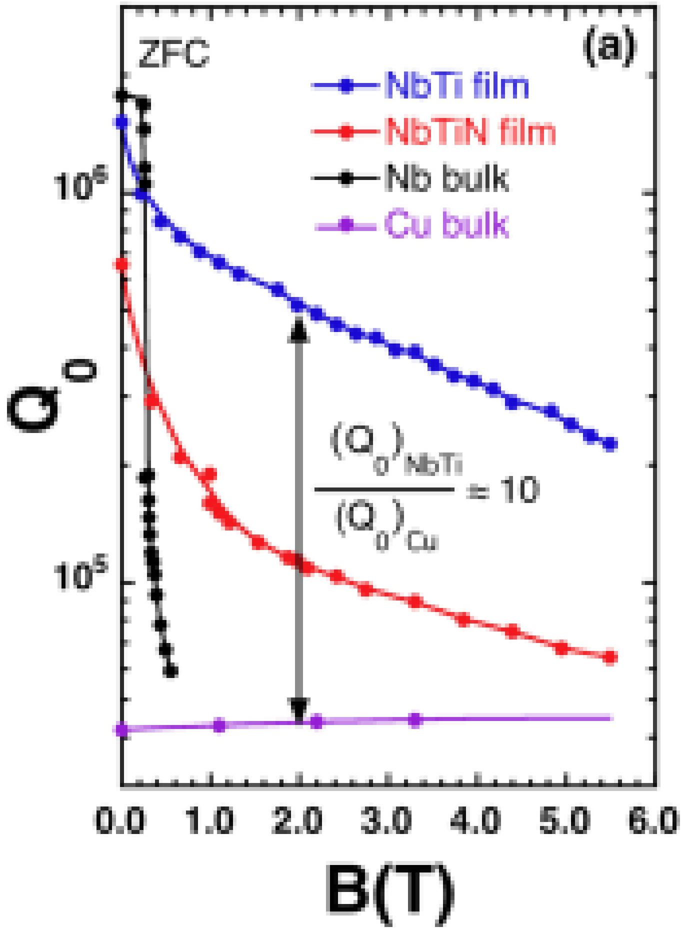
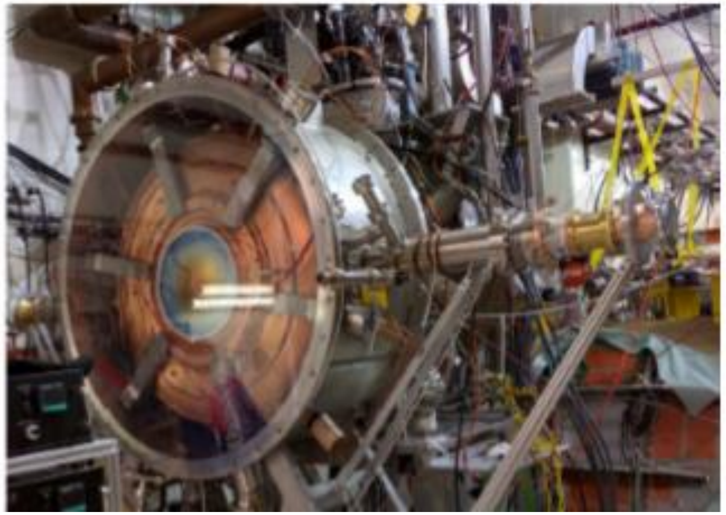


FIG. 1: The upper image represents the electric field of 9.08 GHz TM010 mode in arbitary amplitude units, while the lower photo is one of the two halves of the superconducting cavity.

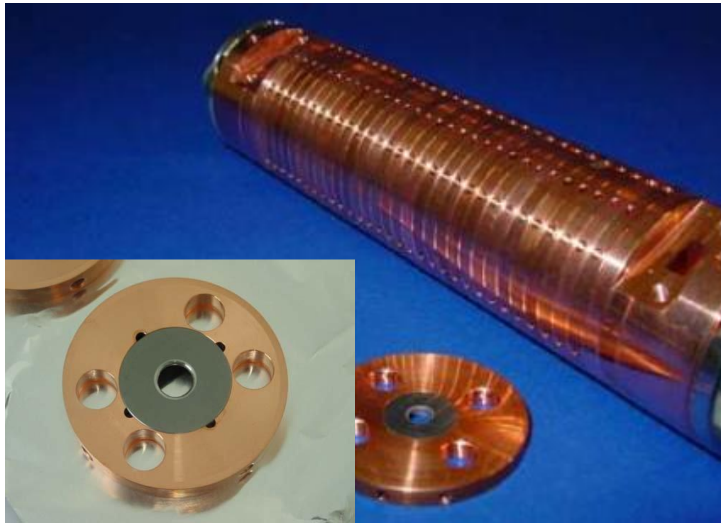


x10 improvement over copper at 4.2 K

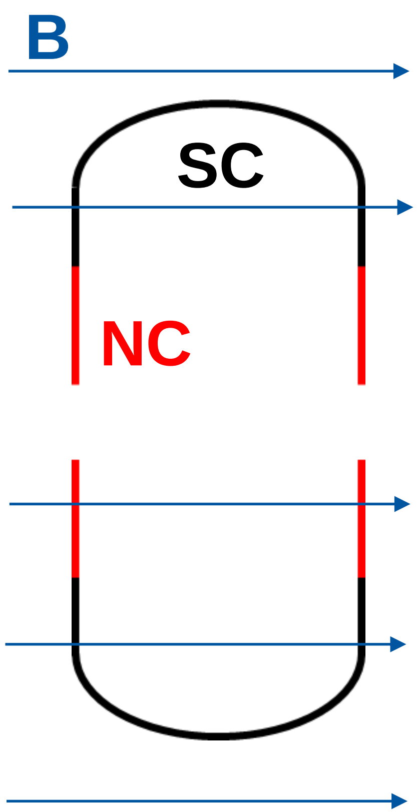
Composite cavities, field emission and bre



MICE 200 MHz RF module
prototype: 4T, **10 MV/m**, 1ms@1Hz



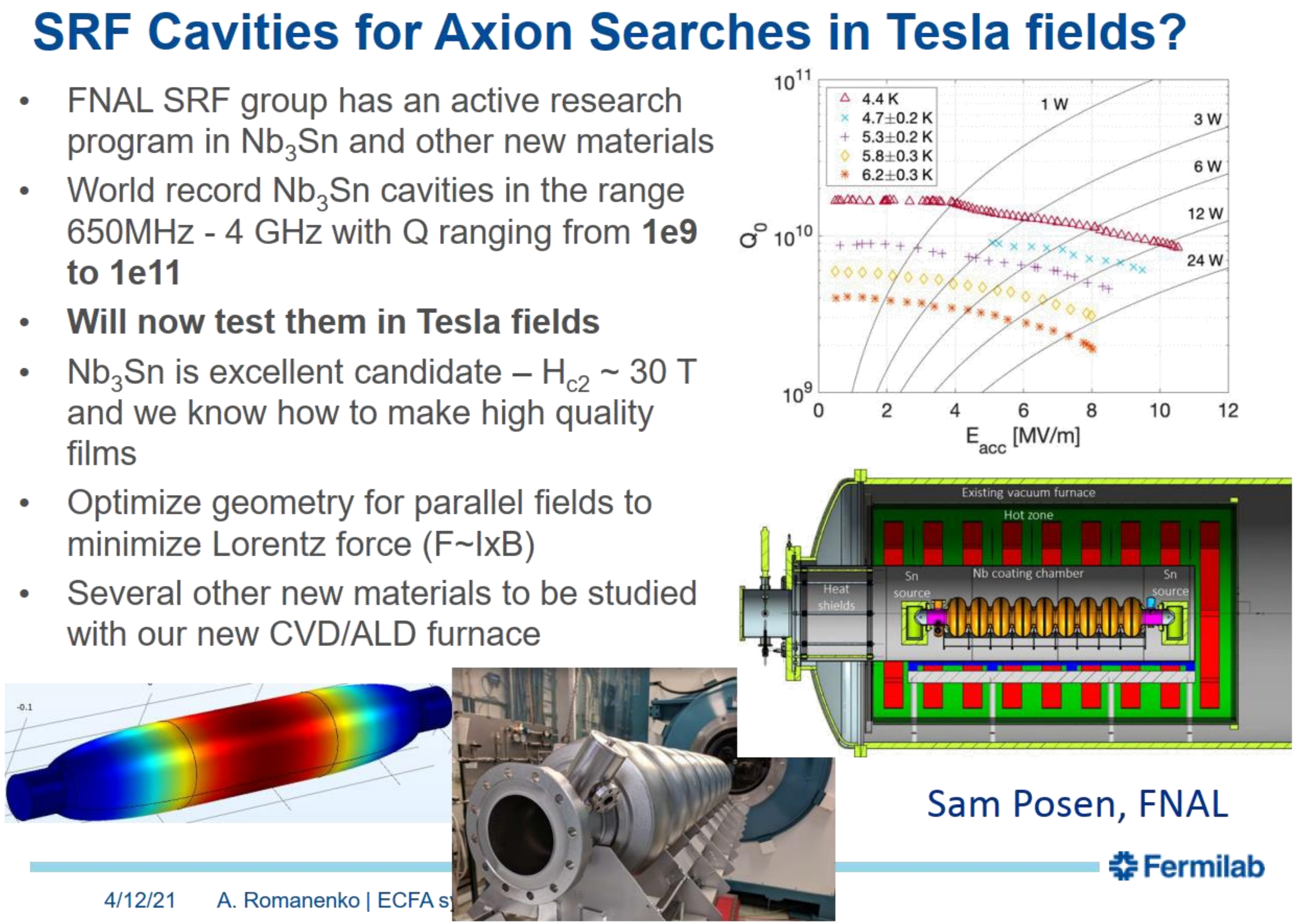
CLIC Mo-iris prototype



HIE-ISOLDE cavities

Composite cavities exist and have been demonstrated.
Joints at low-current regions are standard practice even in SRF cavities (ie QWRs)
Segmentation at zero-current region is possible

Nb_3Sn @ 1.3 GHz in strong magnetic field: to be tested at FNAL



SRF Cavities for Axion Searches in Tesla fields?

- FNAL SRF group has an active research program in Nb_3Sn and other new materials
- World record Nb_3Sn cavities in the range 650MHz - 4 GHz with Q ranging from **1e9 to 1e11**
- **Will now test them in Tesla fields**
- Nb_3Sn is excellent candidate – H_{c2} ~ 30 T and we know how to make high quality films
- Optimize geometry for parallel fields to minimize Lorentz force (F~IxB)
- Several other new materials to be studied with our new CVD/ALD furnace

Sam Posen, FNAL

Fermilab

4/12/21 A. Romanenko | ECFA s

Will bring important insights:

- Experimental data, instead of relying upon extrapolation
- Operation at high E-field
- Ideally, Nb_3Sn from vapor tin diffusion should then be compared to Nb_3Sn from sputtering

A few notes

- Note 1: minimize perturbation to B field
  - Bulk SC material would shield B field due to persistent currents. Thin films are required
- Note 2: operation at high RF field
  - Most data available on small samples, typically O(1 MV/m) field maximum
  - Real cavities with alternative LTS (Nb3Sn, NbTi, NbTiN) performed reasonably at high field in the past, but no data with external magnetic field
- Note 3: frequency scaling
  - No known (to me) experiment at sub-GHz frequency.
  - Real experiments are needed, to avoid relying upon scaling
- Note 4: cryogenic efficiency
  - Overall energy gain to be assessed, for each material at its ideal operating temperature.

Final remarks and possible experiments

- Developments for FCC-hh beam screen and Axion cavity detectors have shown the feasibility of RF operation of HTS (and some LTS as well) in a strong magnetic field

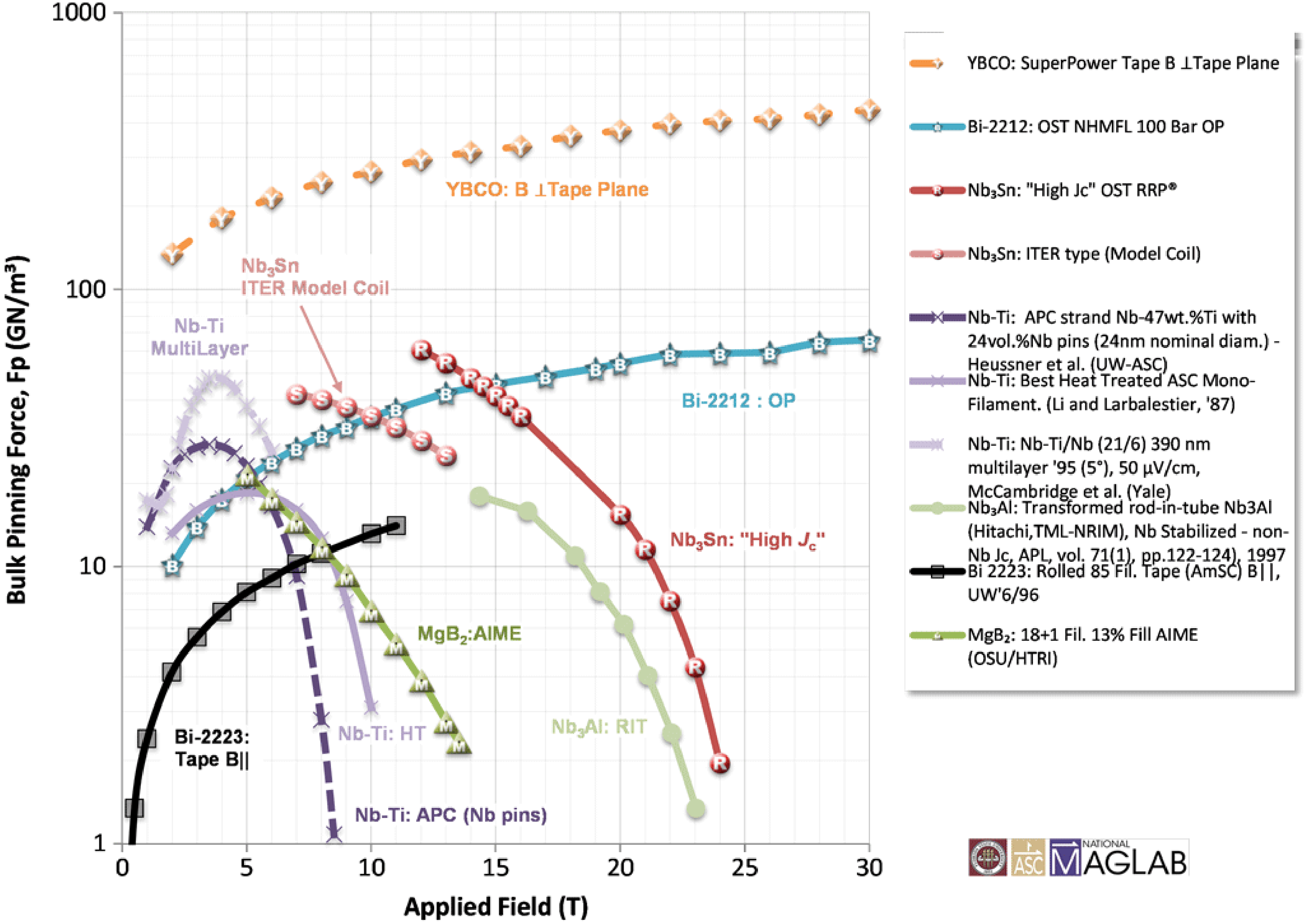
- Experimental data at low frequency and high RF field are missing. Possible experiments:
  - HTS “Coated Conductor” cavity at ~1 GHz frequency
  - Nb_3Sn cavity at 1.3 GHz (and other frequencies) from FNAL
  - Nb_3Sn by sputtering (different pinning regime)
  - NbTi/NbTiN thin films?

- To be obtained from these experiments:
  - Behavior at fields of several MV/m
  - Total energy efficiency, including projected cryoplant consumption
  - Verification of pulsed operation
  - Study of fabrication technologies

CERN

Zoo of superconductors

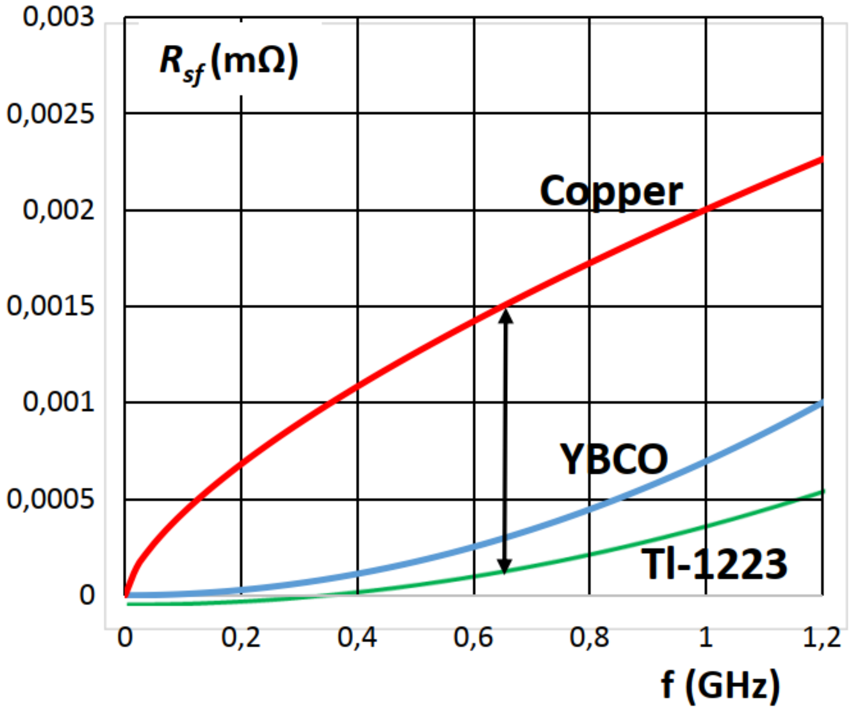
Pinning force

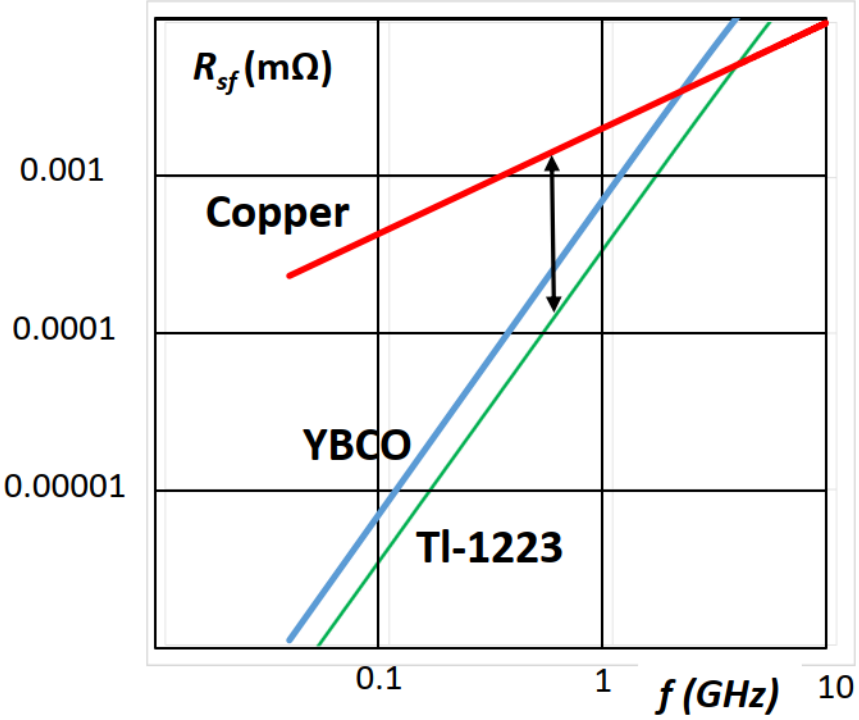


https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

Predicted surface resistance of HTS in 16 T field

YBCO	T_c=92K	T=50K	B_0=16T	$J_c(50,16)=7.5\times10^9 Am^{-2}$	$B_{c2}(50)$=40T	$\rho_n=60\mu\Omega cm$	f_0=10GHz
Tl-1223	T_c=125K	T=50K	B_0=16T	$J_c(50,16)=1\times10^{10} Am^{-2}$	$B_{c2}(50)$=80T	$\rho_n=80\mu\Omega cm$	f_0=14GHz

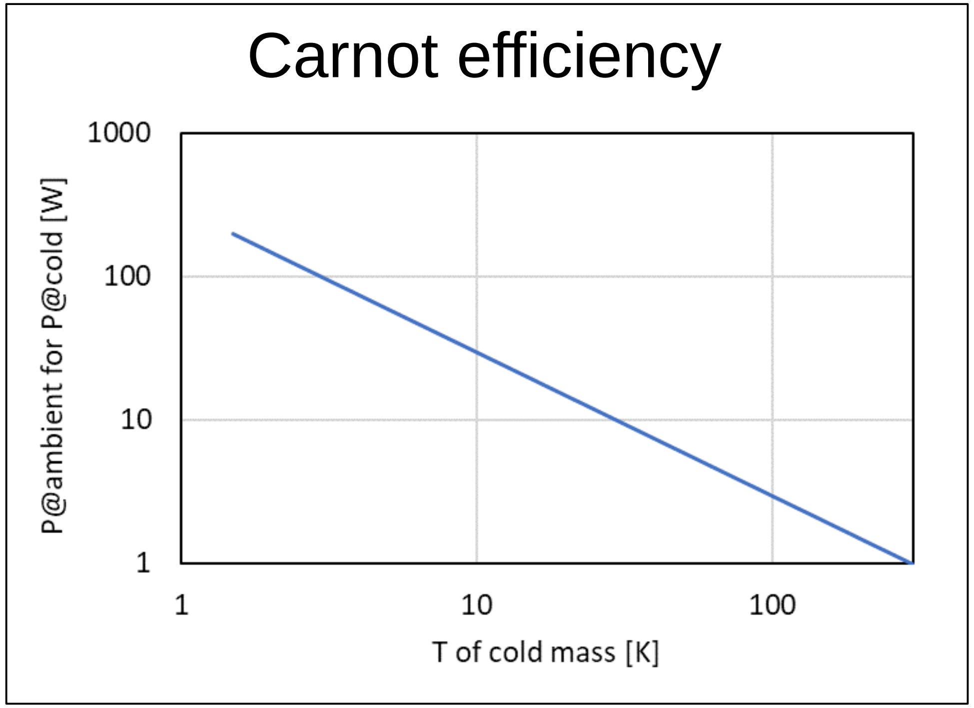


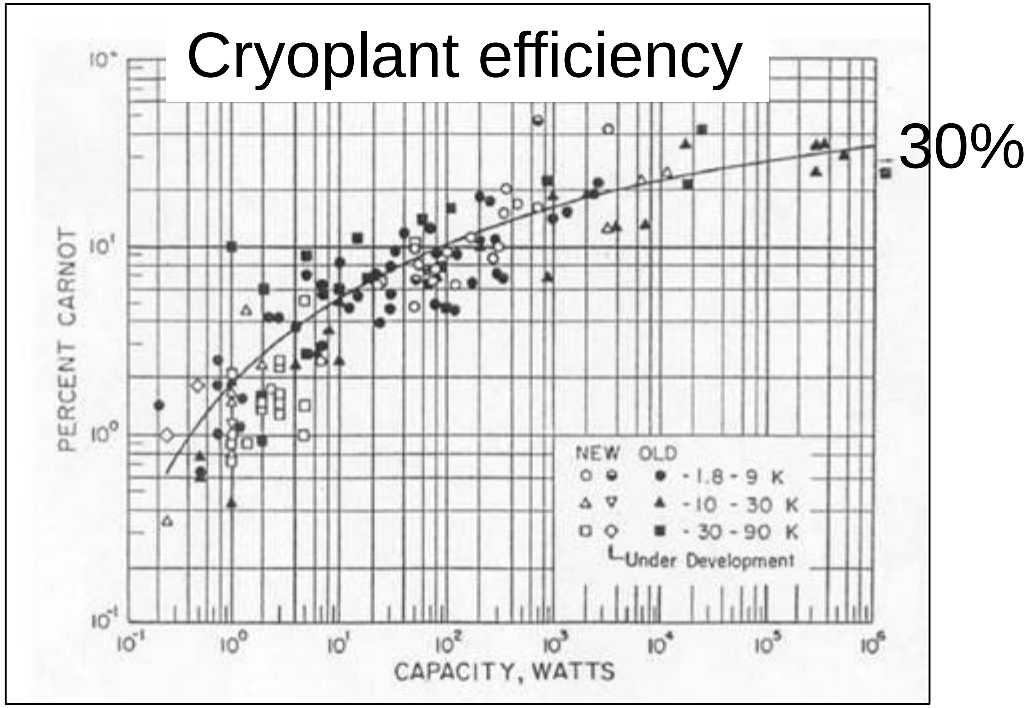


For HTS the Rs scales as f^2

For Cu the Rs scales as $f^{1/2}$

Cryogenic losses: SRF aimed at energy saving compared to NRF





Power consumption for 1 W @ 77 K	13 W
Power consumption for 1 W @ 20 K	50 W
Power consumption for 1 W @ 4.2 K	230 W
Power consumption for 1 W @ 1.9 K	920 W

Thanks to T. Koettig, CERN

Test of Nb3Sn films up to 12 T

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Surface Impedance Measurements on Nb_3Sn in High Magnetic Fields

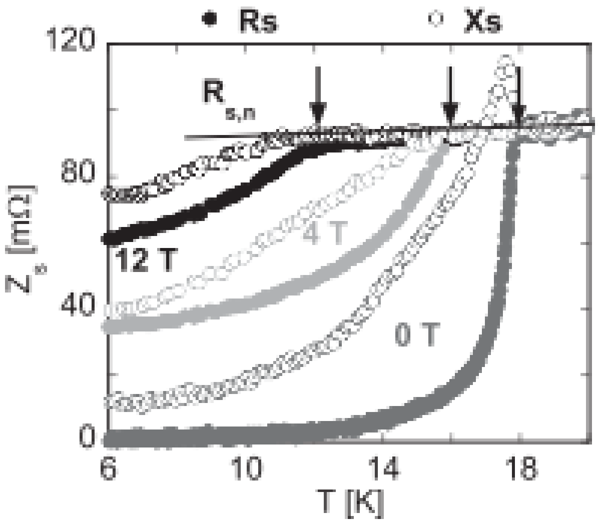


Fig. 2. Z_s measured at fixed $\mu_0 H$, depicted in the figure, and varying T. Full circles: R_s; empty circles: X_s. Colors: black, $\mu_0 H = 12$ T; light gray, $\mu_0 H = 4$ T; dark gray, $\mu_0 H = 0$ T. Vertical arrows indicate $T_{c2}(H)$.

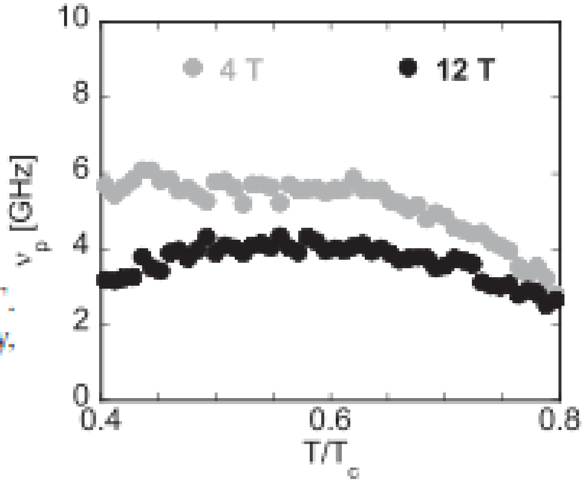
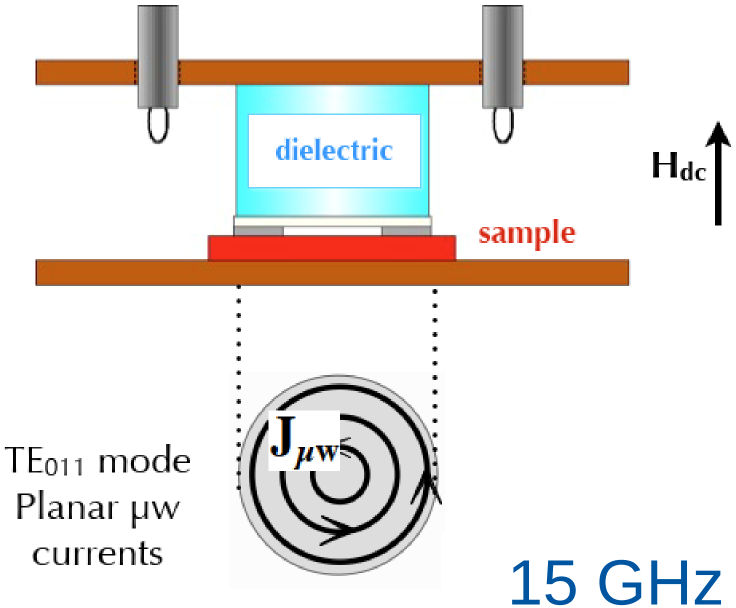


Fig. 4. The depinning frequency ν_p at $\mu_0 H = 12$ T (black points) and at $\mu_0 H = 4$ T (gray points). The ν_p is almost constant up to 0.65 T_c.



15 GHz