REBCO Coatings for High-Gradient RF Applications

Sergio Calatroni, on behalf of the Collaboration.

Outline

- HTS cavities at low gradient, in a strong magnetic field
  - The present: FCC beam screens and RADES axion detectors

- HTS cavities at high-gradient
  - The goal of the new iFAST collaboration CERN – KIT – ICMAB

- HTS cavities in both high-gradient and strong magnetic field
  - The future?

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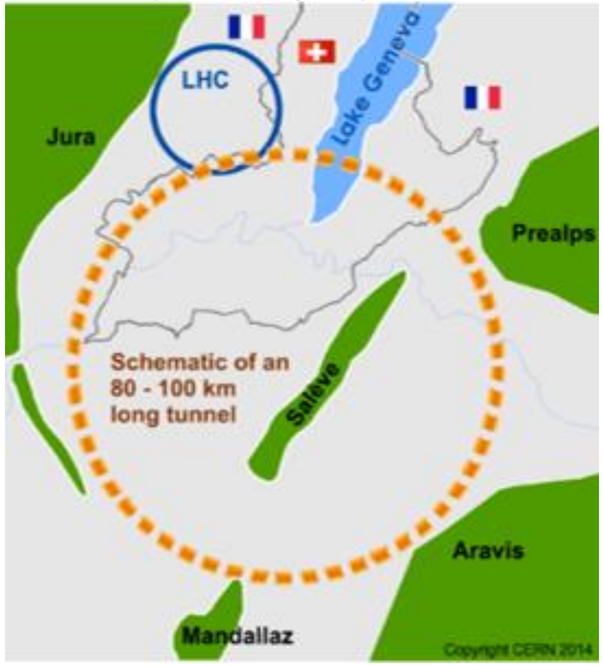
FCC integrated program

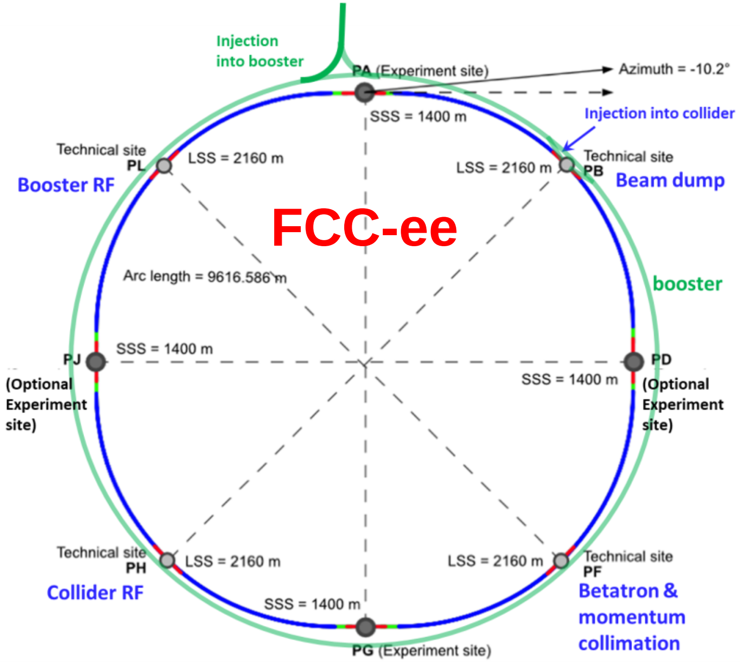
FUTURE CIRCULAR COLLIDER

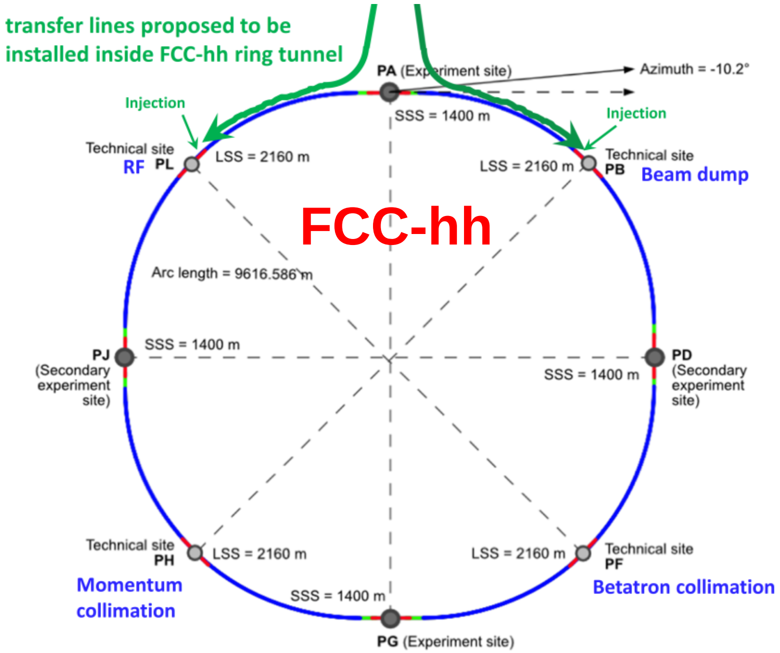
Link to last FCC week

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as “energy upgrade” of FCC-ee)
- common civil engineering and technical infrastructures, building on and reusing CERN’s existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC





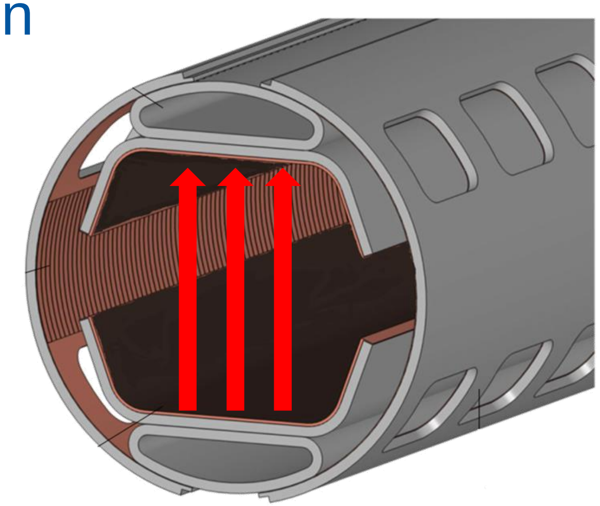


2020 - 2040 **2045 - 2063** **2070 - 2095**

From M. Benedikt, FCC Study leader

HTS for the FCC-hh beam screen

- FCC-hh, a proposed 100 TeV p-p collider at CERN, with 16 T dipoles operated at 1.9 K
- A beam screen held at 50 K, to protect the dipoles from synchrotron radiation ~30 W/m/beam (LHC < 0.2 W/m)
- HTS materials instead of copper in the FCC-hh beam screen, to improve beam stability (-> impedance) at 50 K
- Bunched particle beams produces RF fields, up to ~1 GHz
- 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 (2.5×10^8 A/m^2)
    - Surface resistance R_s better than for copper
- Compatible with accelerator environment
    - Minimize dipole field distortion due to persistent currents
    - UHV compatible, low SEY, lifecycle assessment, etc..



16 Tesla !

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

Two material choices

Manufacture the screen using REBCO tapes soldered to the screen

Coat the inside of the screen with Tl-1223 films

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

ALBA

IFAE
Institut de Física d'Altes Energies
EXCELENCIA SEVERO OCHOA
BIST Barcelona Institute of Science and Technology

UPC
CommSensLab
EXCELENCIA MARÍA DE MAEZTU
2017 - 2020

EASITrain

CERN

SPIN

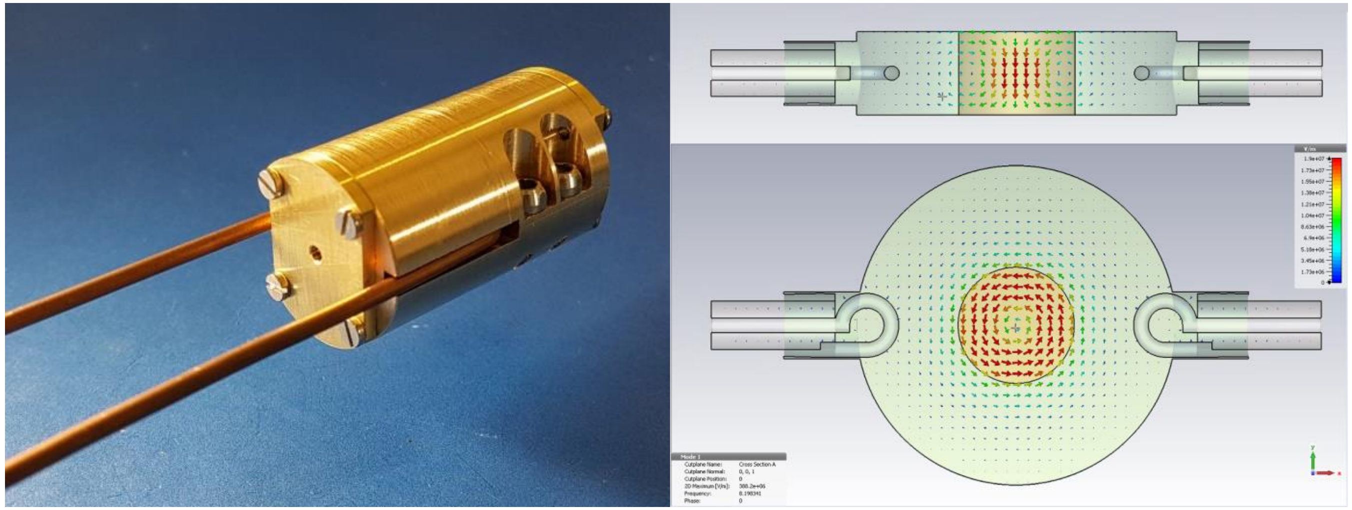
ROMA TRE
UNIVERSITÀ DEGLI STUDI

ATOMINSTITUT

TU WIEN
TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

USTEM

Validation of RF performance (UPC - ICMAB)



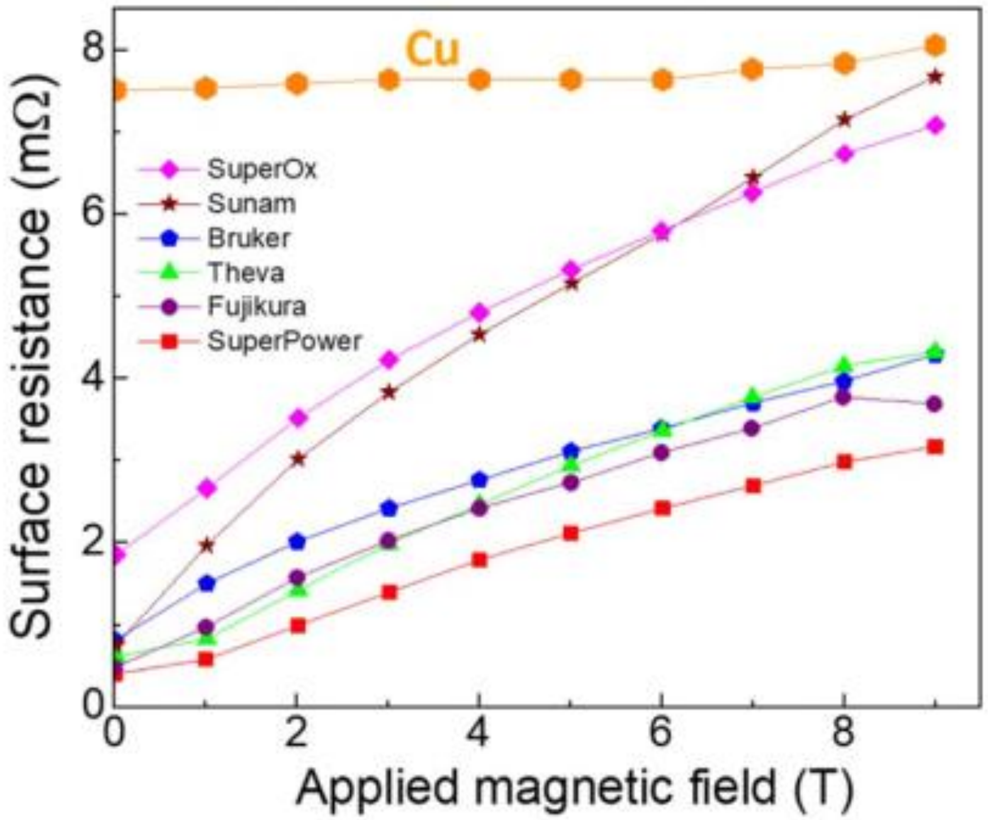


Figure 3. Magnetic field dependence of the surface resistance at 8 GHz and 50 K. Up to 9 T, CCs' R_s outperforms that of copper.

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

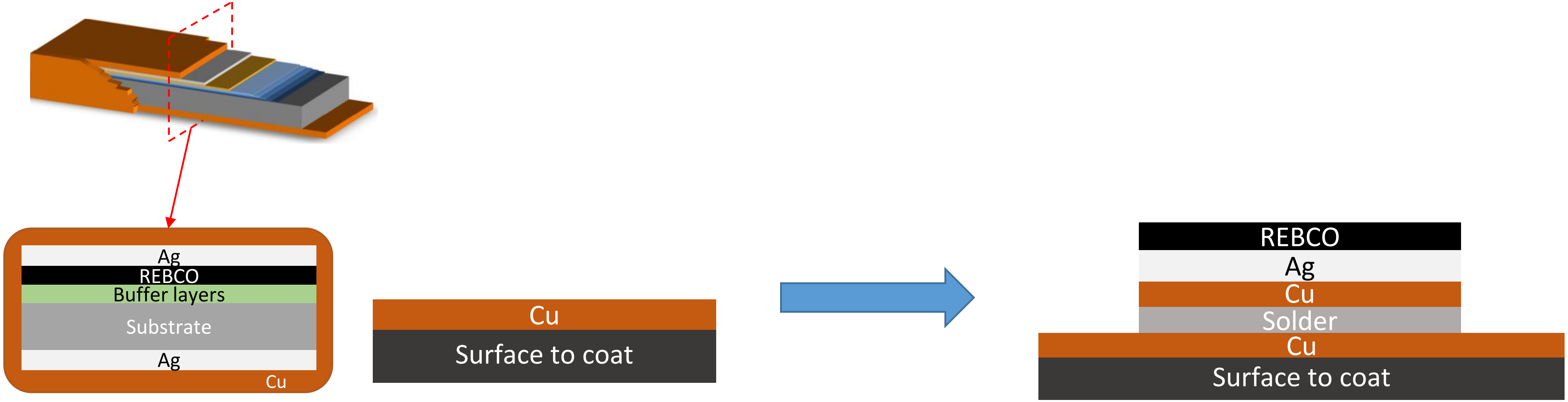
R_S is microstructure dependent

Puig et al, SuST 32, 094006 (2019)

FUTURE CIRCULAR COLLIDER

Surface currents equivalent to 0.1 MV/m of a typical accelerating cavity

HTS coated conductor soldering and delamination



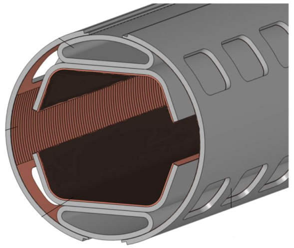
Ag
REBCO
Buffer layers
Substrate
Ag
Cu

Cu
Surface to coat

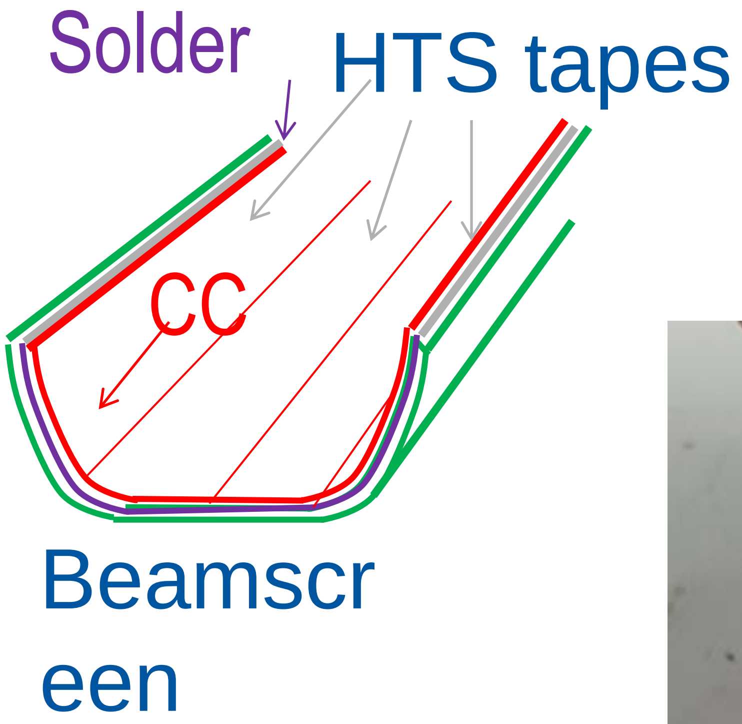
REBCO
Ag
Cu
Solder
Cu
Surface to coat

N. Lamas et al., to be published

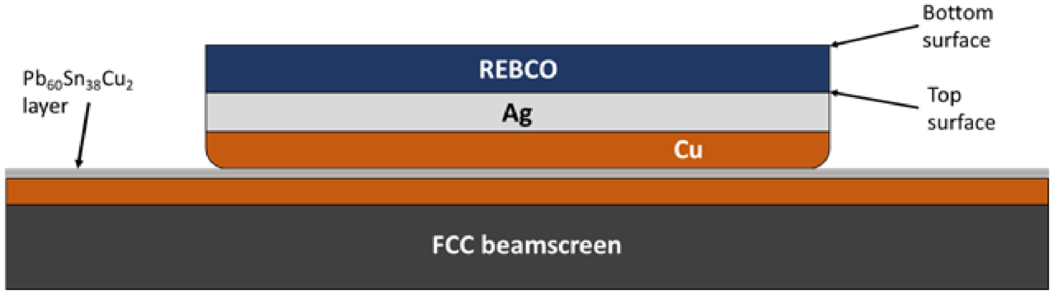
Developed in the context of FCC-hh impedance reduction by coating the beam screen with HTS tapes



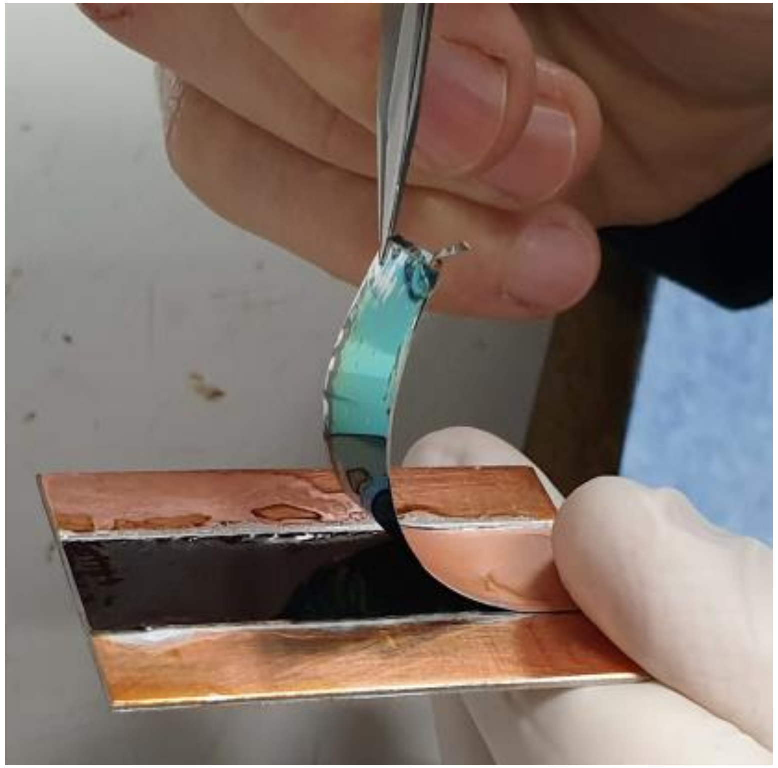
Development of soldering technology

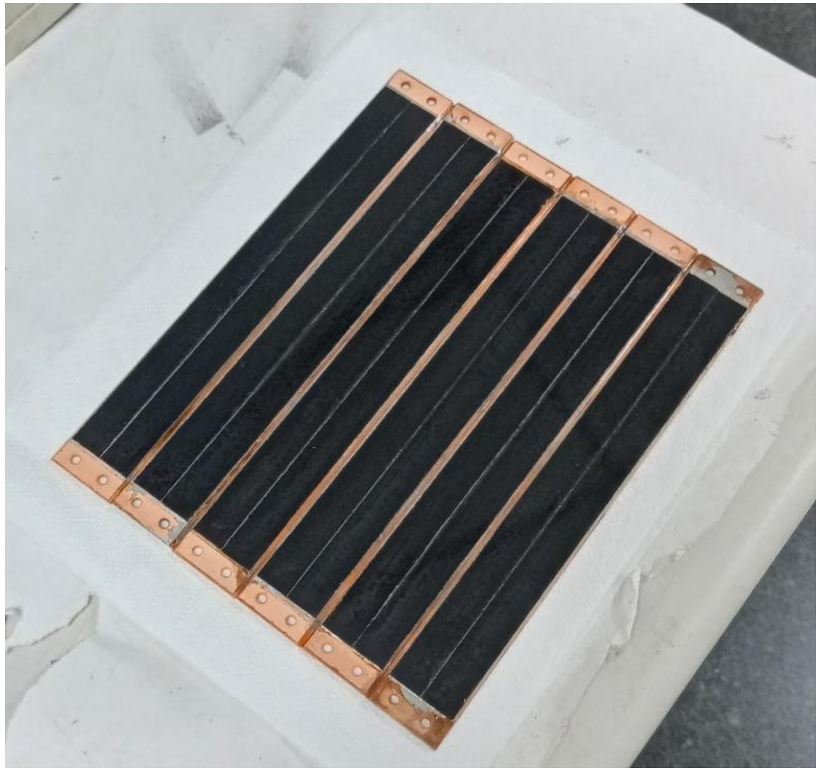


2x80 km of beam screens to be coated with HTS



Solders based on Sn / Pb / Cu / Bi & In temperatures < 220ºC

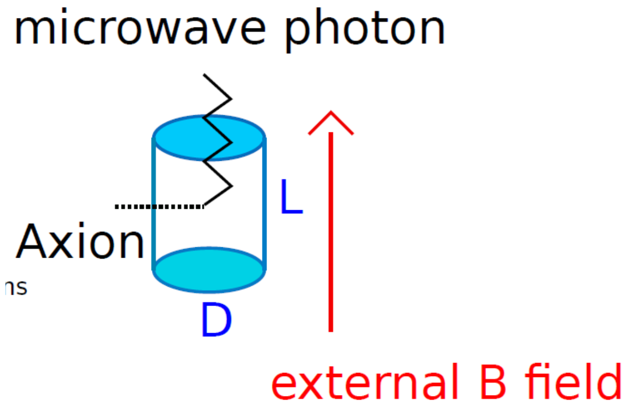




HTS for axion searches

Motivation:

Axion haloscope



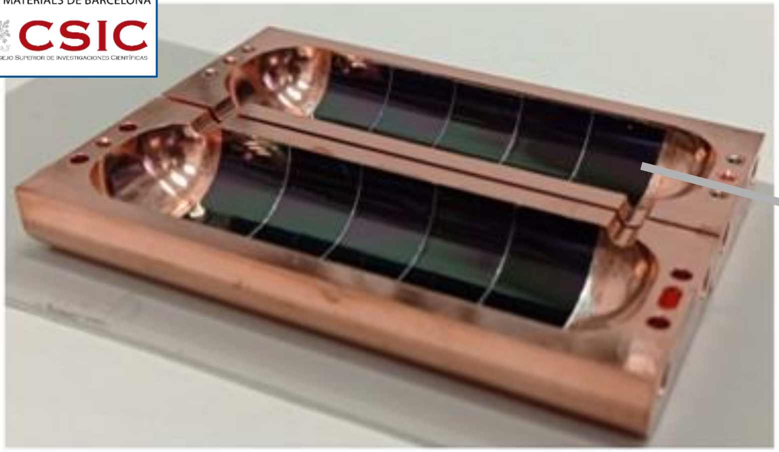
$$\mathcal{F} \sim g_{A\gamma}^{4} \, \boldsymbol{Q} \, T_{sys}^{-2} V^{2} G^{4} m_{A}^{2} \, \boldsymbol{B}^{4}$$

Increase Q copper coating → superconducting coating

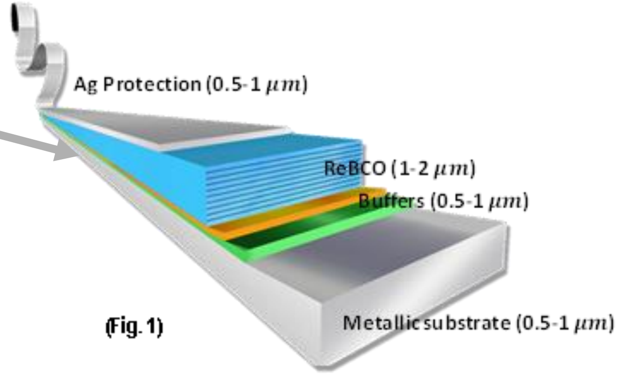
Requirement: High quality factor in a high magnetic field

First real cavity, f≈9 GHz

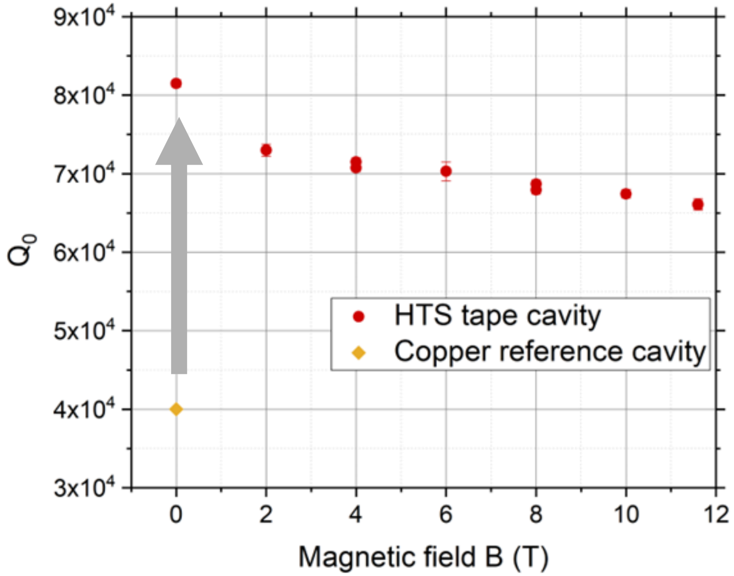
- We have developed a technology for applying 2D HTS tapes to 3D RF “RADES” cavities demonstrating the potential of HTS for RF applications J. Golm et al., IEEE TAS, Vol. 32, No. 4, (2022) 1500605



12 mm-wide HTS tapes

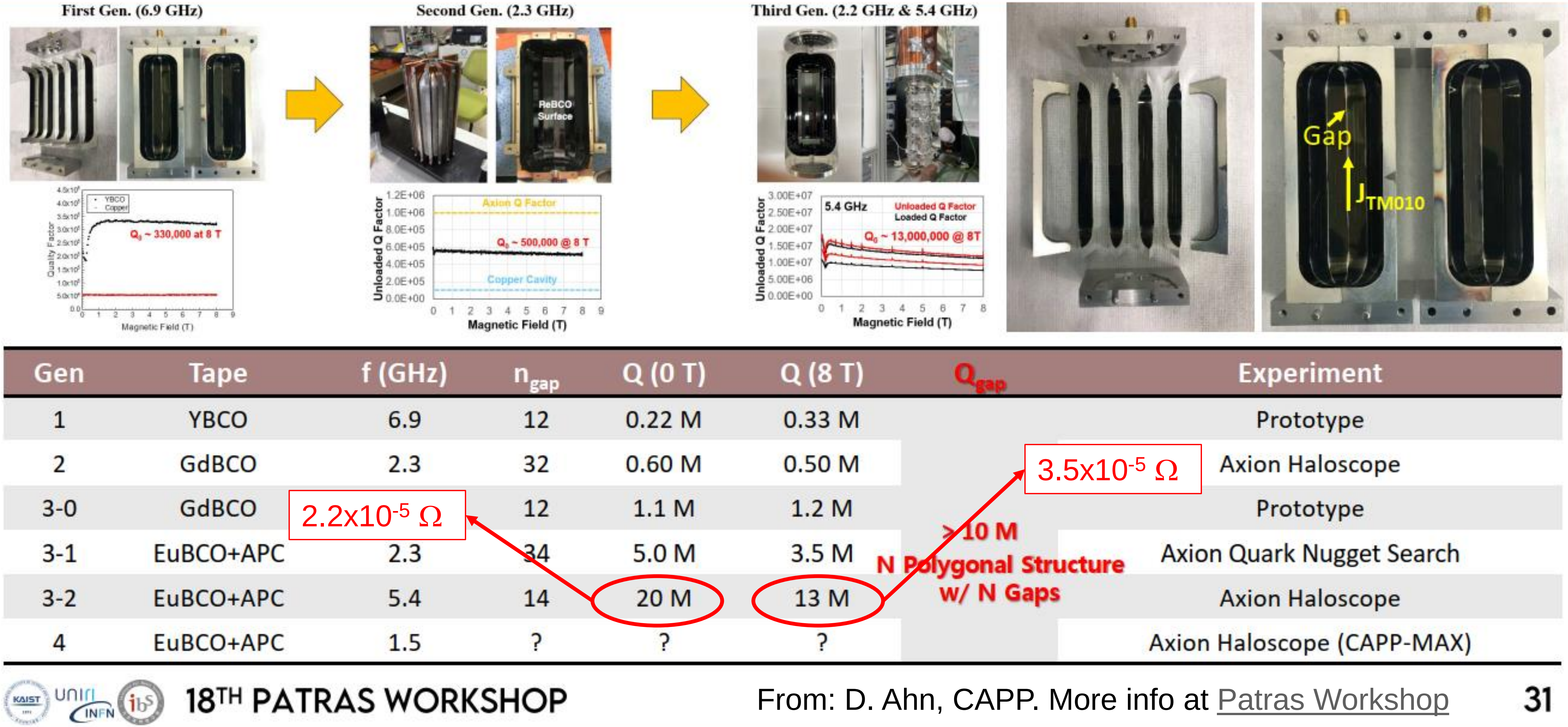


2x improvement of RF quality factor compared to copper
(newer prototype 5x improvement)



RADES cavity for axion searches

Other results from CAPP



Gen	Tape	f (GHz)	n_{gap}	Q (0 T)	Q (8 T)	Q_{gap}	Experiment
1	YBCO	6.9	12	0.22 M	0.33 M		Prototype
2	GdBCO	2.3	32	0.60 M	0.50 M	> 10 M N Polygonal Structure w/ N Gaps	Axion Haloscope
3-0	GdBCO		12	1.1 M	1.2 M		Prototype
3-1	EuBCO+APC	2.3	34	5.0 M	3.5 M		Axion Quark Nugget Search
3-2	EuBCO+APC	5.4	14	20 M	13 M		Axion Haloscope
4	EuBCO+APC	1.5	?	?	?		Axion Haloscope (CAPP-MAX)

2.2x10^{-5} Ω

3.5x10^{-5} Ω

18TH PATRAS WORKSHOP

From: D. Ahn, CAPP. More info at Patras Workshop

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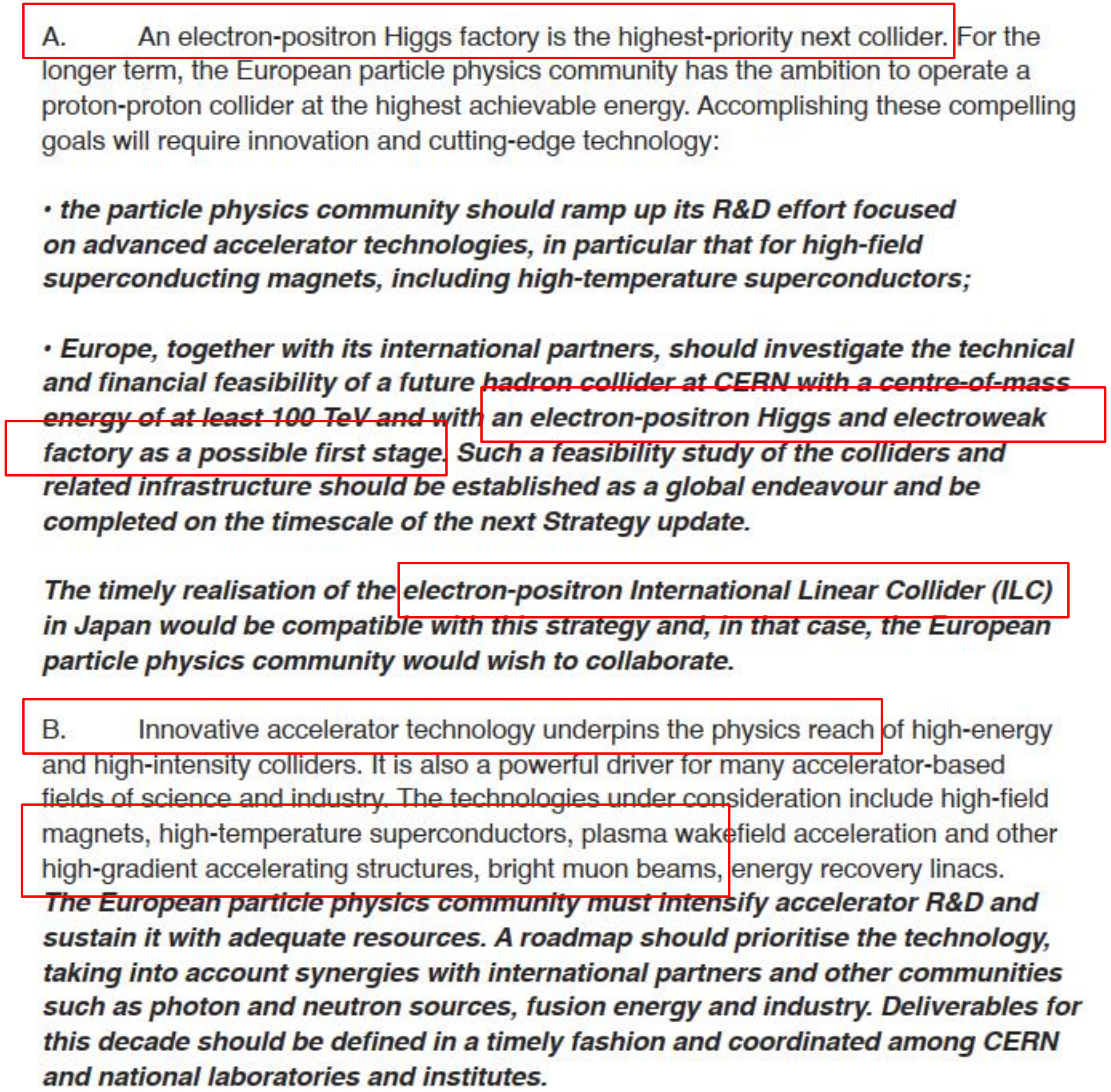
The European Strategy for Particle Physics
High-priority future initiatives



A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

FCC-ee

- ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

ILC

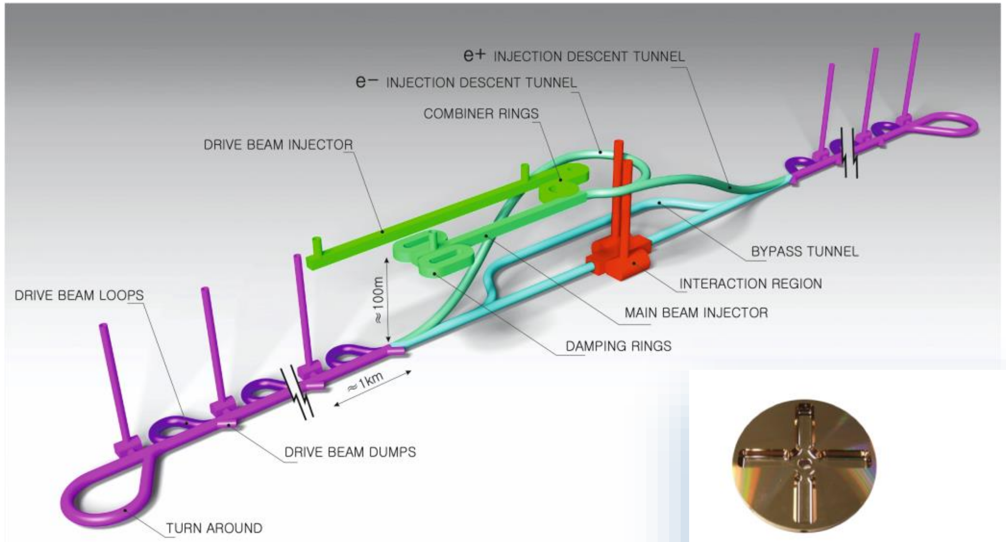
The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

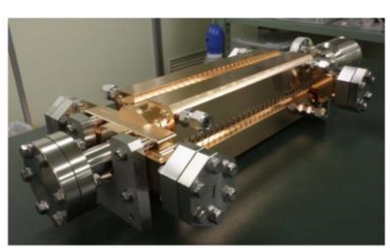
CLIC, etc.

B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. ***The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.***

The Compact Linear Collider (CLIC)

Recent talks: eeFACT-I1 and eeFACTI2





Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)

- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)

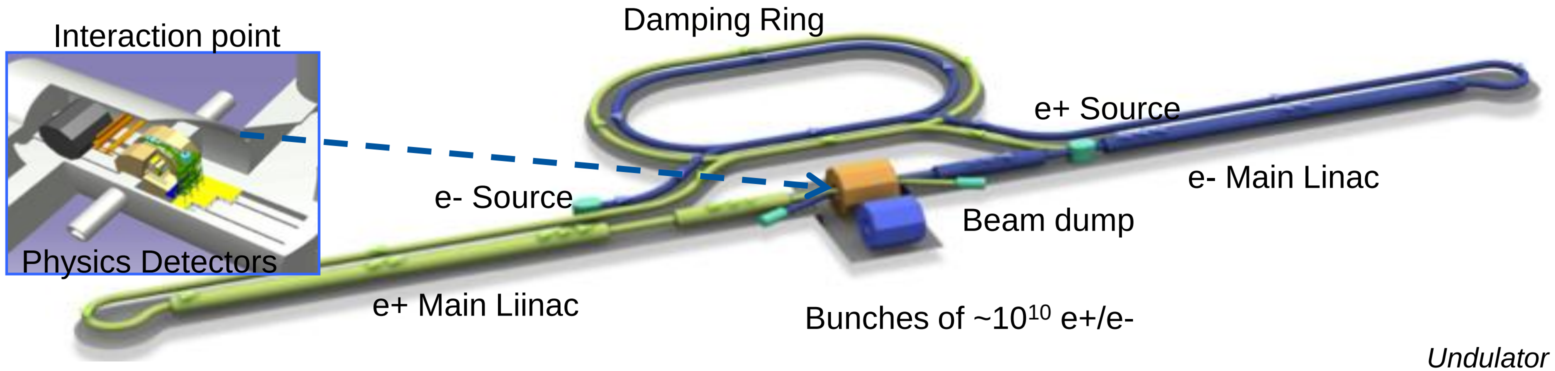
- CDR in 2012 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.

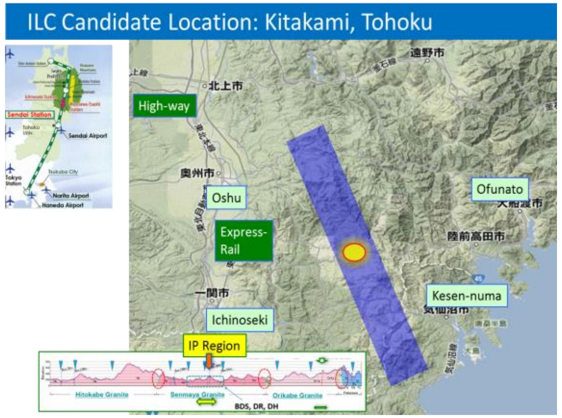
The CLIC accelerator studies are mature:
- Optimised design for cost and power
- Many tests in CTF3, FELs, light-sources and test-stands
- Technical developments of “all” key elements

From: Steinar Stapnes

The ILC250 accelerator facility

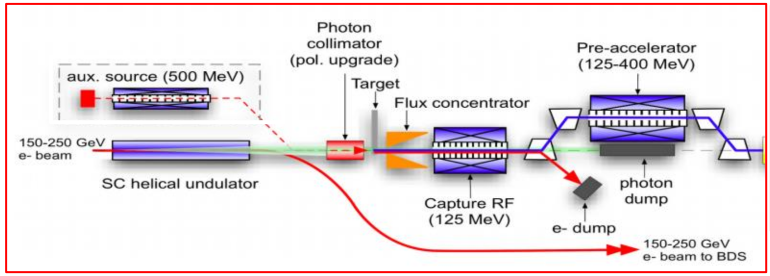
Recent talks: eeFACT-I1 and eeFACTI2

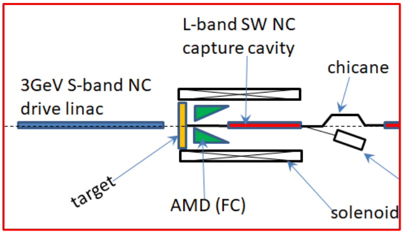




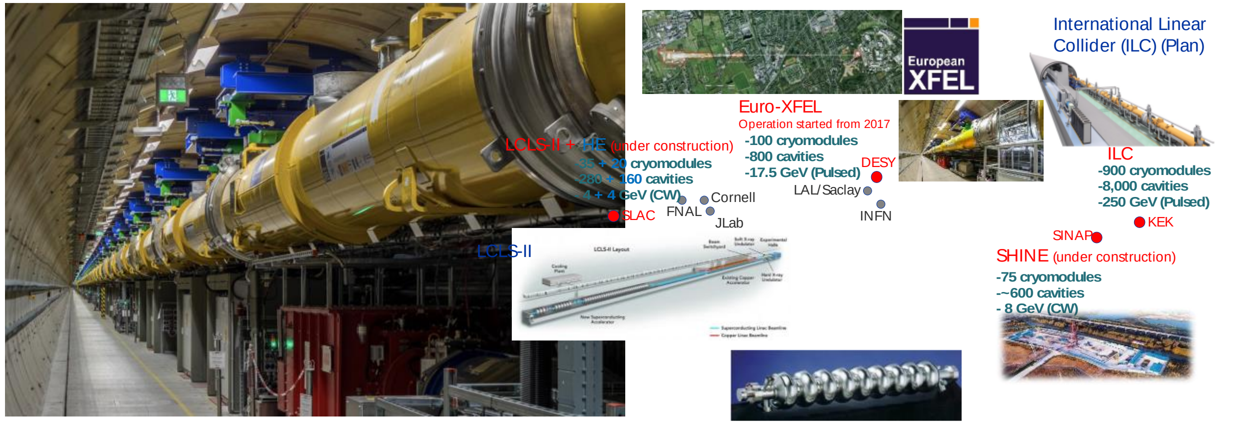
- Creating particles — Sources
  - polarized elections/positrons
- High quality beam — Damping ring
  - low emittance beams
- Acceleration — Main linac
  - superconducting radio frequency (SRF)
- Collide them — Final focus
  - nano-meter beams
- Go to — Beam dumps

Undulator positron source





Electron driven positron source



LCLS-II + HE (under construction)
-35 + 20 cryomodules
-280 + 160 cavities
- 4 + 4 GeV (CW)
SLAC
FNAL
Cornell
JLab
LCLS-II

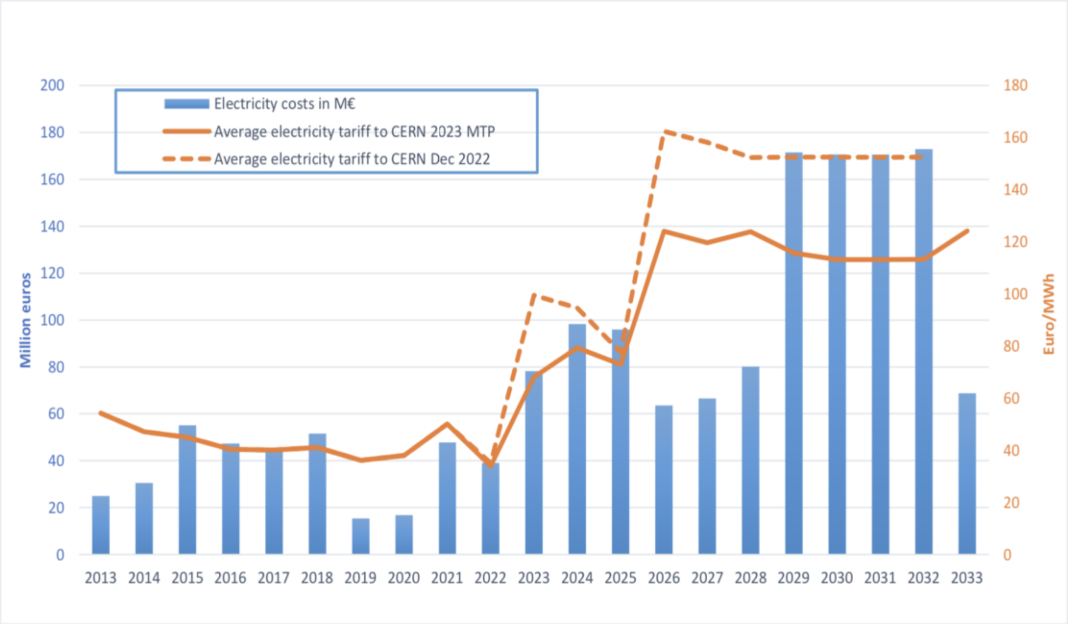
Euro-XFEL
Operation started from 2017
-100 cryomodules
-800 cavities
-17.5 GeV (Pulsed)
DESY
LAL/Saclay
INFN

International Linear Collider (ILC) (Plan)
ILC
-900 cryomodules
-8,000 cavities
-250 GeV (Pulsed)
KEK

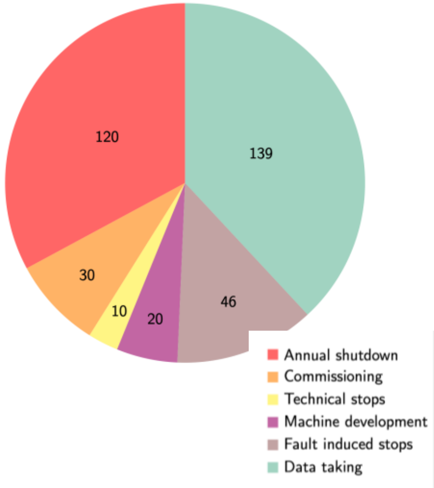
SINAP
SHINE (under construction)
-75 cryomodules
-~600 cavities
- 8 GeV (CW)

From: Steinar Stapnes

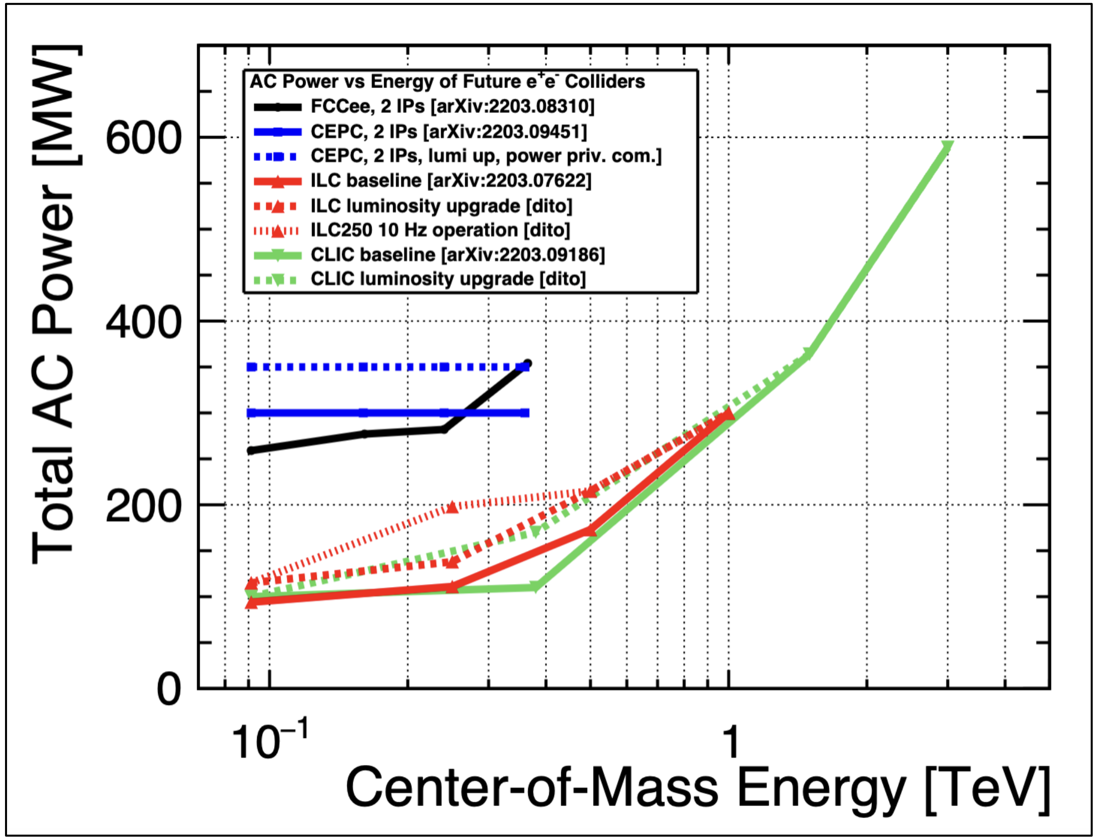
Power and energy: LHC and future machines



Very uncertain but MTP assumes 120 MCHF/TWh beyond 2026. With “standard” running scenario (on the right) every 100 MW corresponds to ~0.6 TWh annually, corresponding to ~75 MCHF annually.



From: Steinar Stapnes



Linear collider studies predict roughly similar power consumption for equivalent machines (ILC vs CLIC)

How can SC and NC have the same power consumption?

- Linear collider RF systems fall in two categories

SC niobium, $Q_0 \approx 10^{10}$, 35 MV/m, CW

NC copper, $Q_0 \approx 10^4$, 100 MV/m, pulsed

- Despite the ~10^6 difference in quality factor (~10^3 considering cryo efficiency), pulsing at low duty factor allows reducing the average consumption for NC accelerating structures down to the SC level – which cannot be effectively be pulsed
- In our study, we want ultimately to verify whether HTS in pulsed RF mode allows a further power gain compared to both Nb and Cu

Cryo-cooled copper -> HTS ?

More info on C^3 here

New kid on the blocks: the C3 study @ SLAC is based on cryogenically cooled copper, to increase gradient and save on RF power

A potential advantage could come from combining the advantage of higher gradients at lower temperatures, with the higher Q factor of HTS coatings -> **energy efficiency**

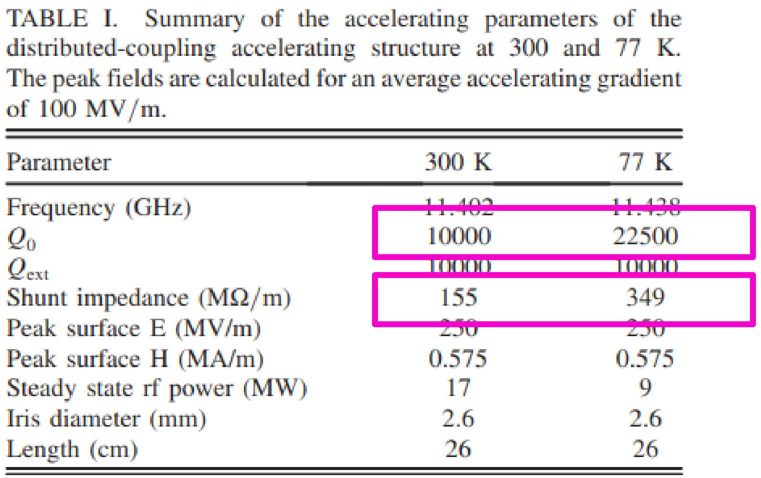


TABLE I. Summary of the accelerating parameters of the distributed-coupling accelerating structure at 300 and 77 K. The peak fields are calculated for an average accelerating gradient of 100 MV/m.

Parameter	300 K	77 K
Frequency (GHz)	11.402	11.438
Q_0	10000	22500
Q_{ext}	10000	10000
Shunt impedance (MΩ/m)	155	349
Peak surface E (MV/m)	250	250
Peak surface H (MA/m)	0.575	0.575
Steady state rf power (MW)	17	9
Iris diameter (mm)	2.6	2.6
Length (cm)	26	26

E. Nanni et al., PRAB 24, 093201 (2021)

Cryoplant efficiency (Carnot + engineering)

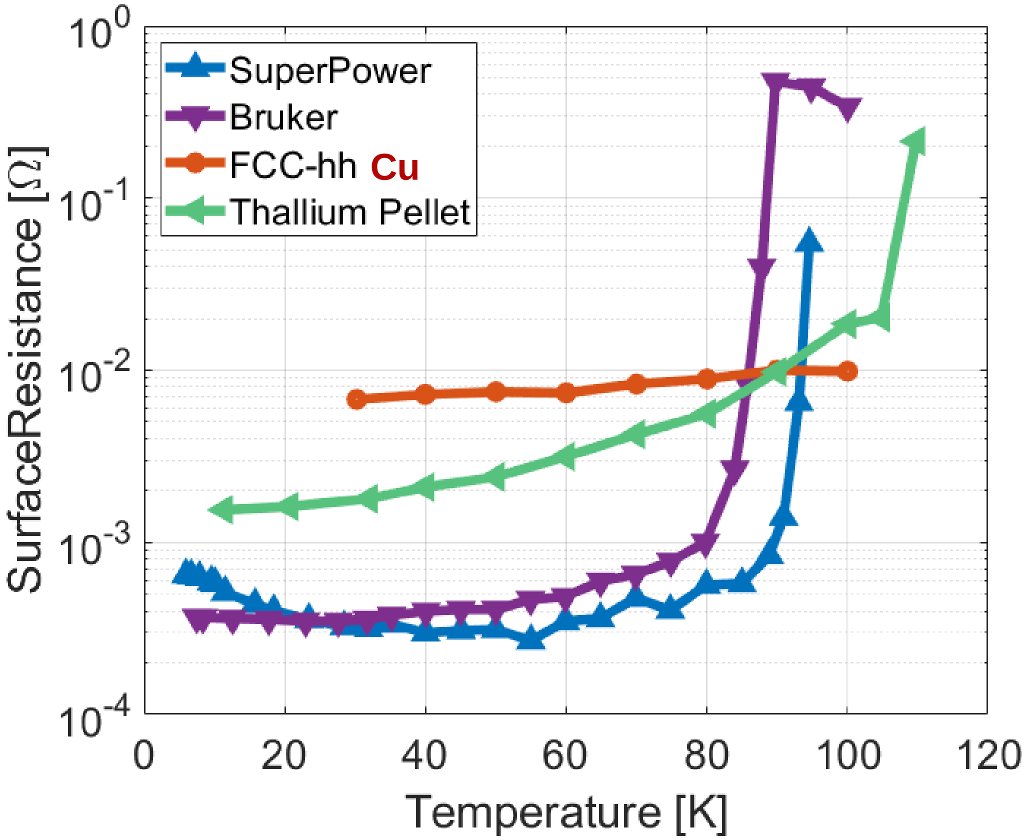
SRF temperature	Ratio W_{300K}/W_{cryo}
77 K	13
50 K	20
4.2 K	230
1.9 K	920

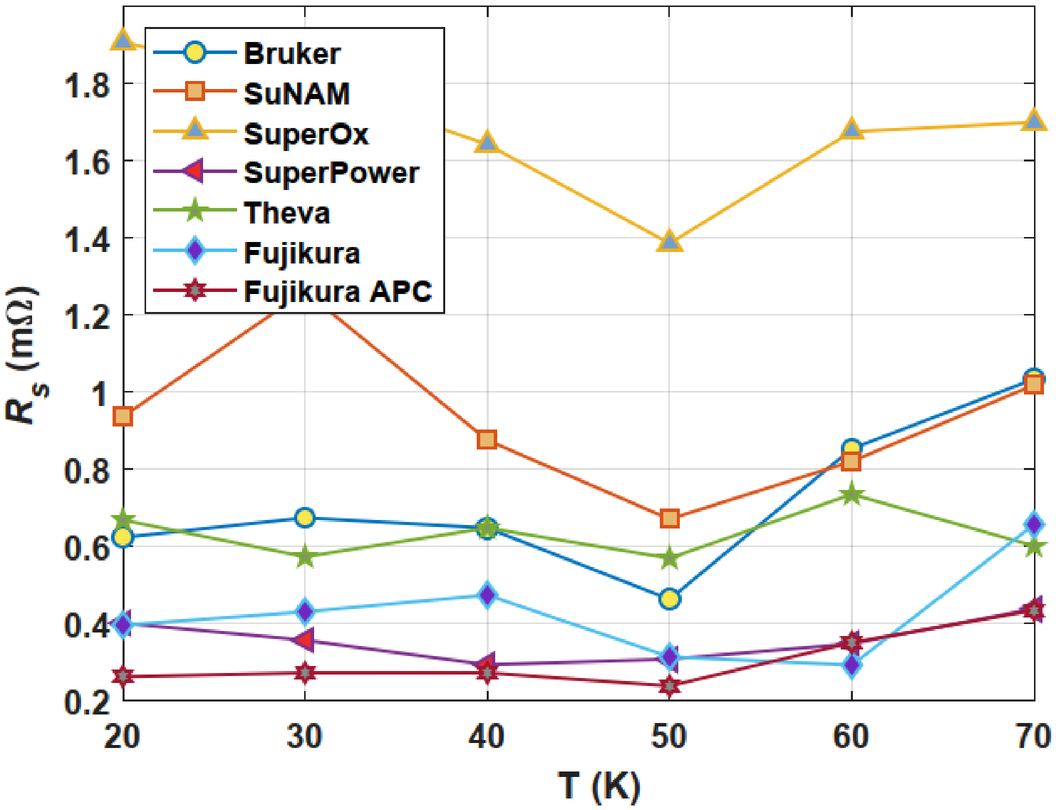
Thanks to T. Koettig, CERN

A factor x10 improvement in Q factor compared to copper could pave the way for energy savings

Low-power measurements

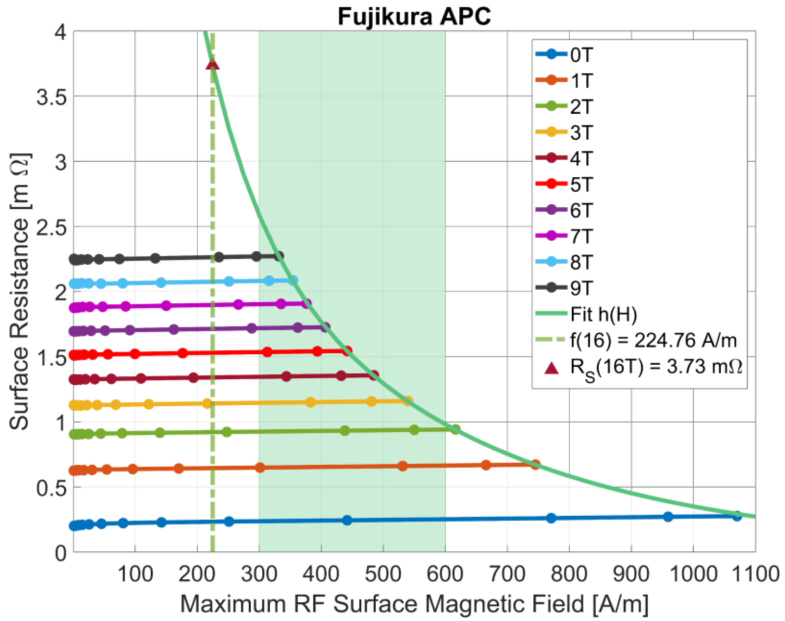
- An improvement larger than x10 compared to copper (Rs=8mΩ) has been measured on samples of tapes (8 GHz) at low RF power

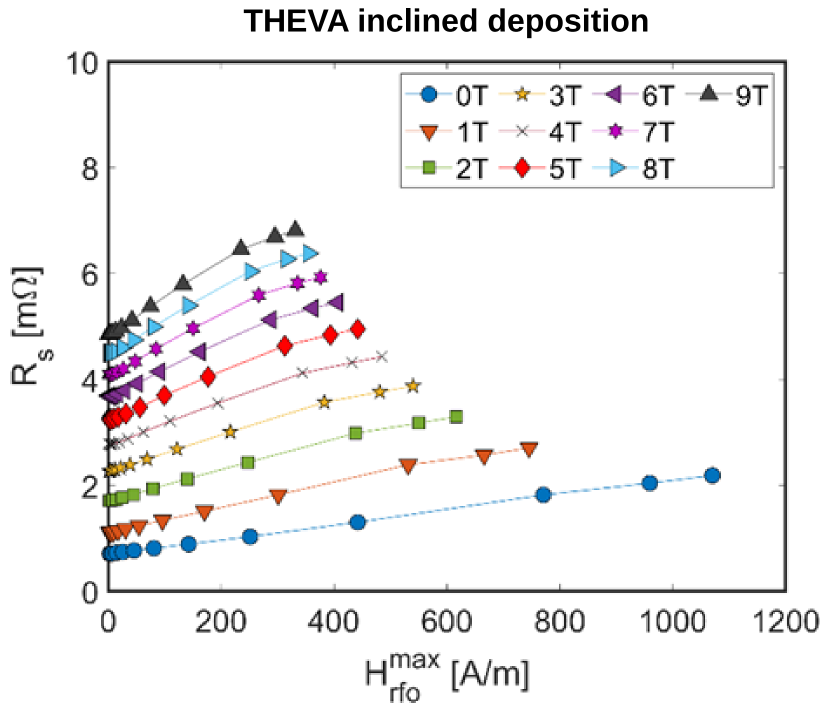


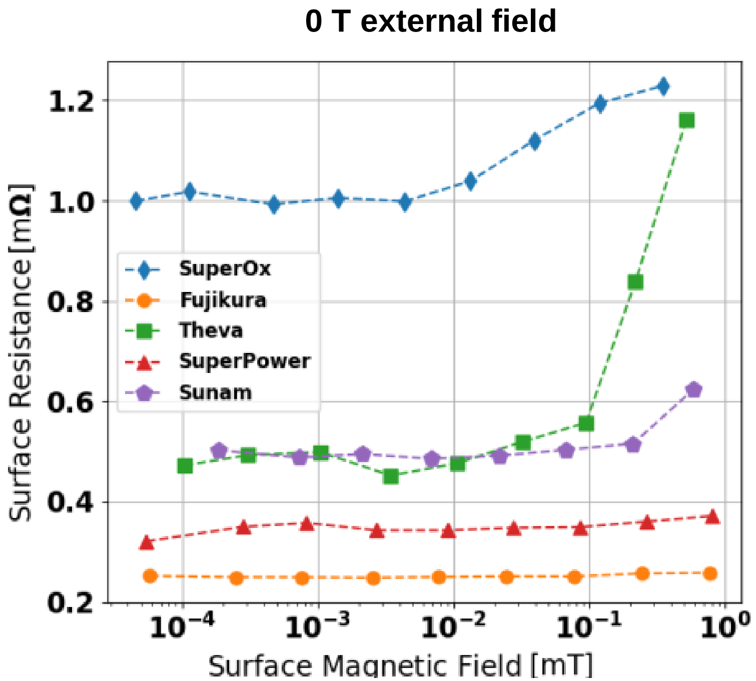


Adapted from Romanov et al, Sci. Rep. (2020) 10:12325

Testing at higher RF power





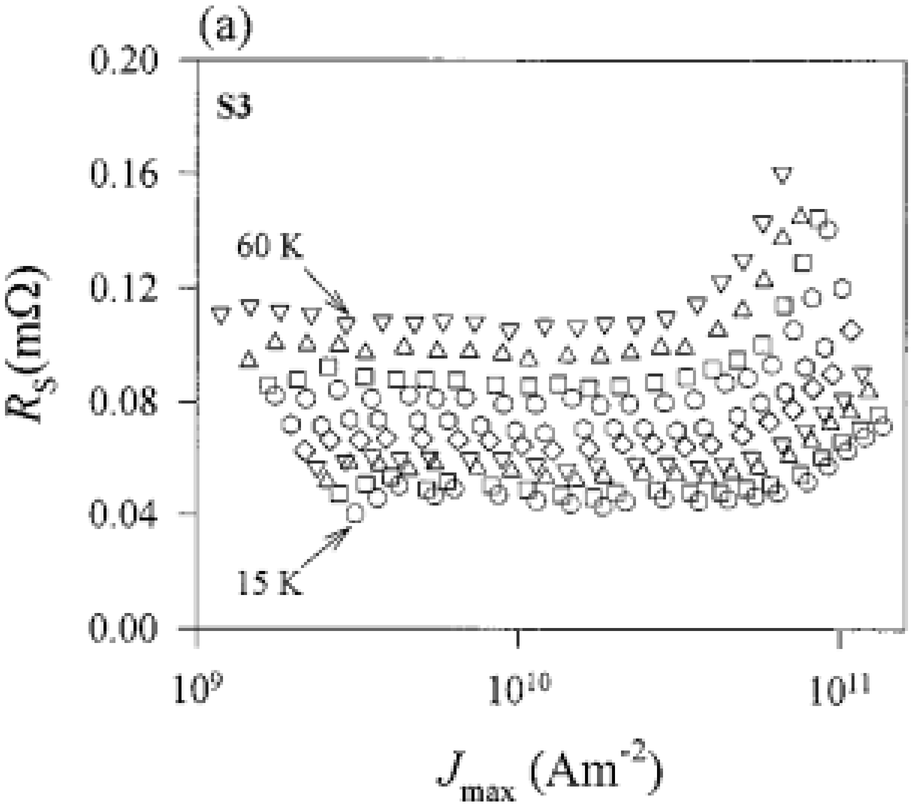


HTS coated conductors at 8 GHz (dielectric resonator) and 50 K

Patrick Krkotic, PhD dissertation, UPC Barcelona 2022

Literature review

- There are very few measurements on HTS at high RF currents (mostly microstrip resonators). But physics is proven.



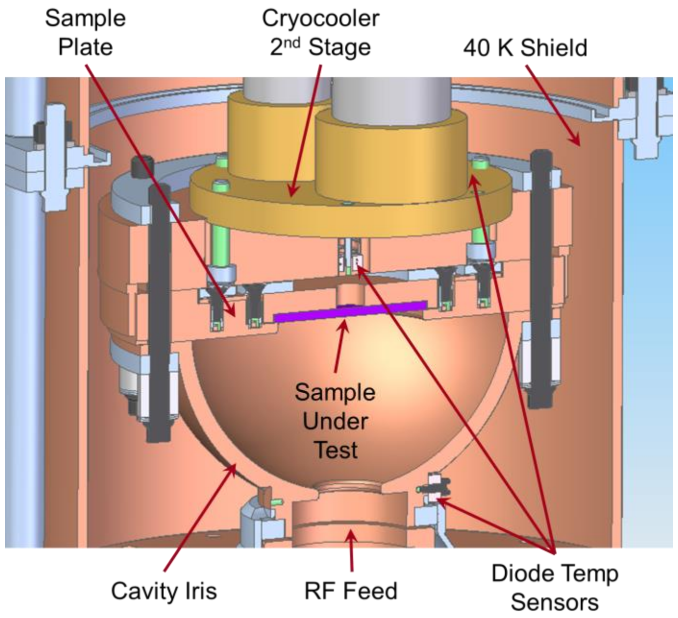
~10^{11} A/m^2 RF current (microstrip resonator, 200 µm, 350 nm thick, 8 GHz)

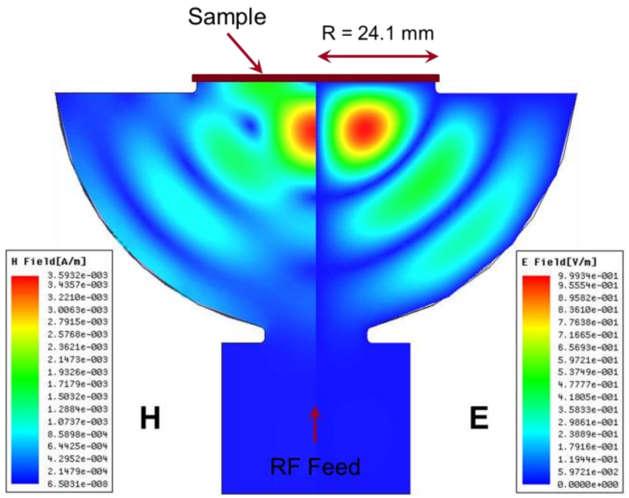
Powell et al. Journal of Applied Physics 86, 2137 (1999)

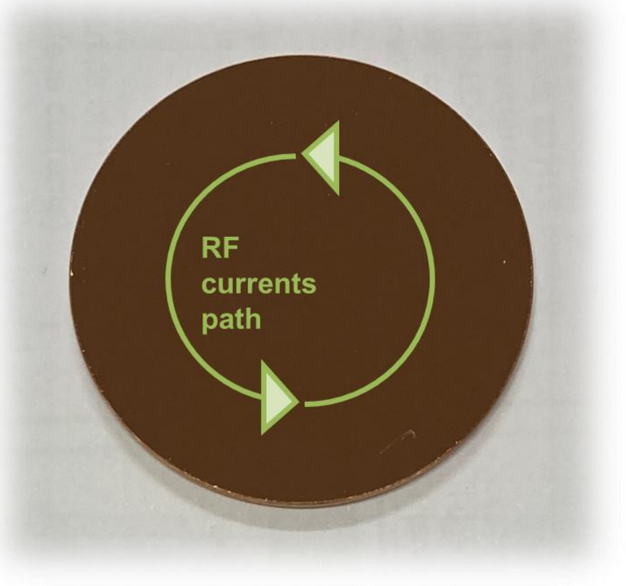
For 1 µm thickness this is equivalent to 10^5 A/m (≅ 0.1 T ≅ 25 MV/m)
Entering the “high-gradient” range

High-gradient testing at SLAC – supported by I.FAST IIF

- “Mushroom” cavity. Can achieve H_{peak} of about 360 mT – $2.9\text{x}10^5$ A/m (equivalent to ~80 MV/m in a standard accelerating cavity) using 50 MW XL-4 Klystron at 11.4 GHz.
- Zero E-field on the sample
- Maximum H-field on the sample
- Sample accounts for ⅓ of total cavity loss





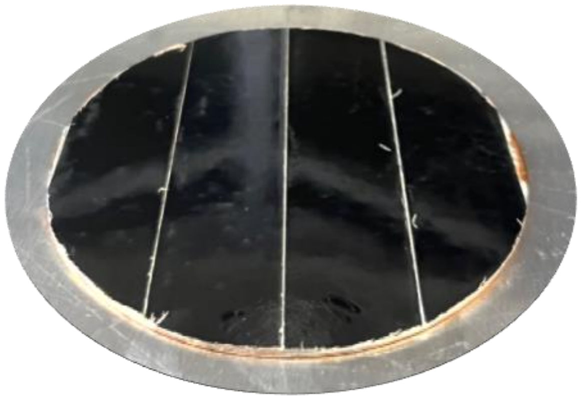


Goal: demonstrate high-gradient pulsed operation of HTS, at cryo-temperatures

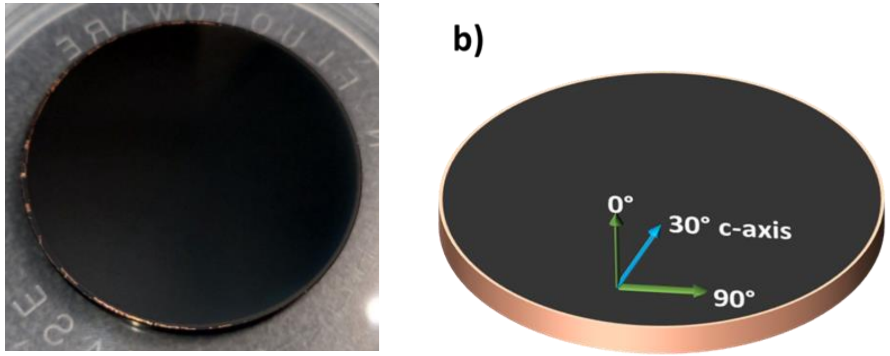
First results at SLAC, at low gradient

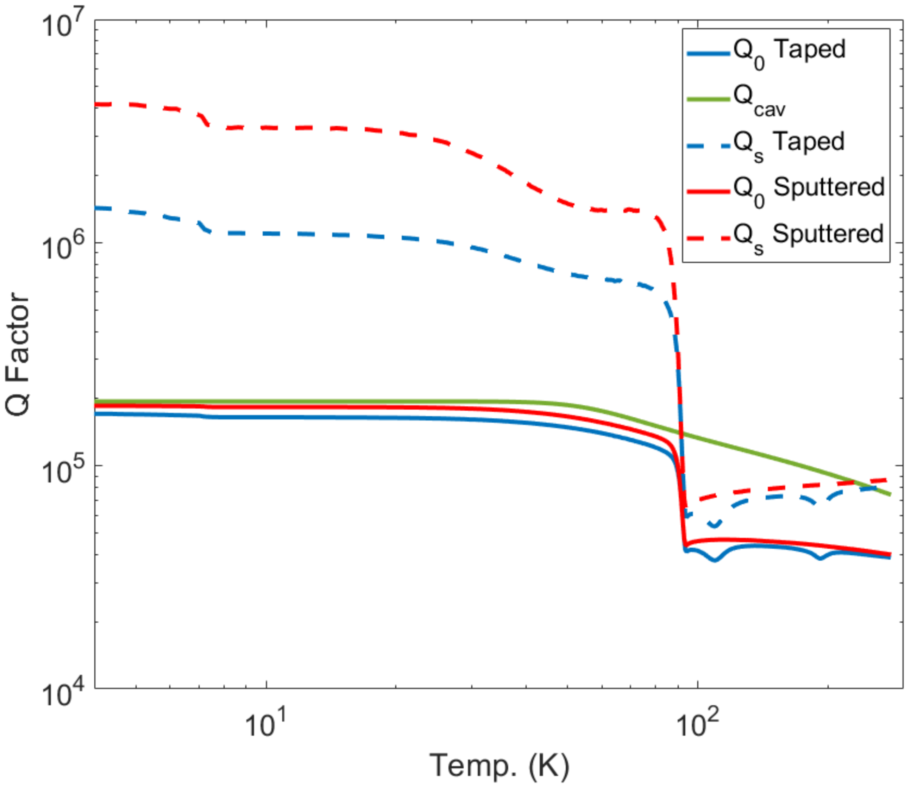
Two HTS measurements, after calibration measurements with Cu and Nb

Soldered REBCO-CCs on copper (Fujikura by CSIC-ICMAB)



Directly grown REBCO on MgO on copper (CERACO)





R_s Cu ≅ 17 mΩ
R_s REBCO tapes ≅ 1.7 mΩ
R_s REBCO PVD ≅ 1.0 mΩ

Preliminary SLAC results at high-gradient

YBCO RF from TWT

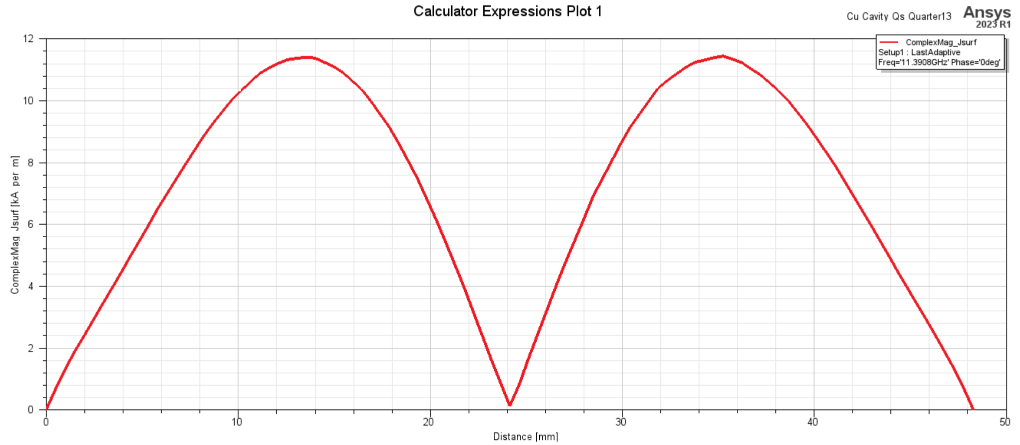
TWT is 1.6 kW @ 11.7 µs

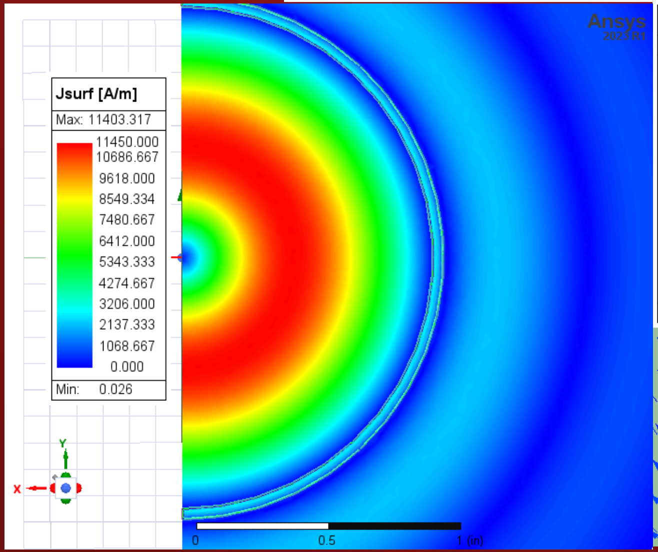
Q_{tot} is 75k and f_0=11.43 GHz

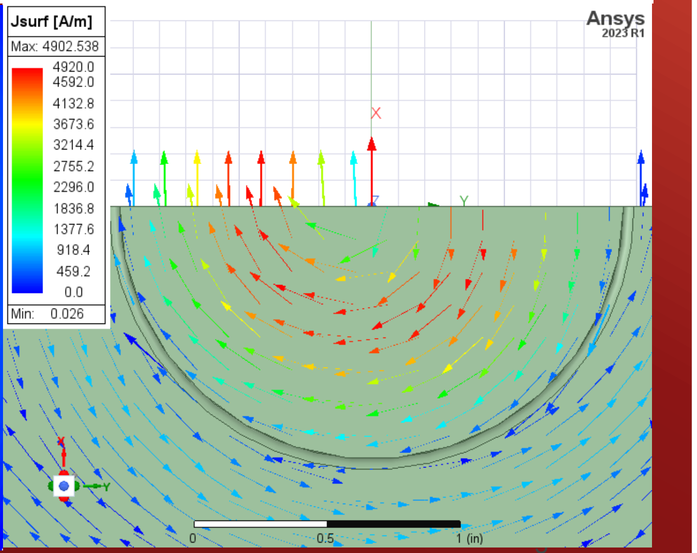
=> fill time is 13.4 µs

Tape sample has surface currents of 10 kA/m

Equivalent to ~3 MV/m

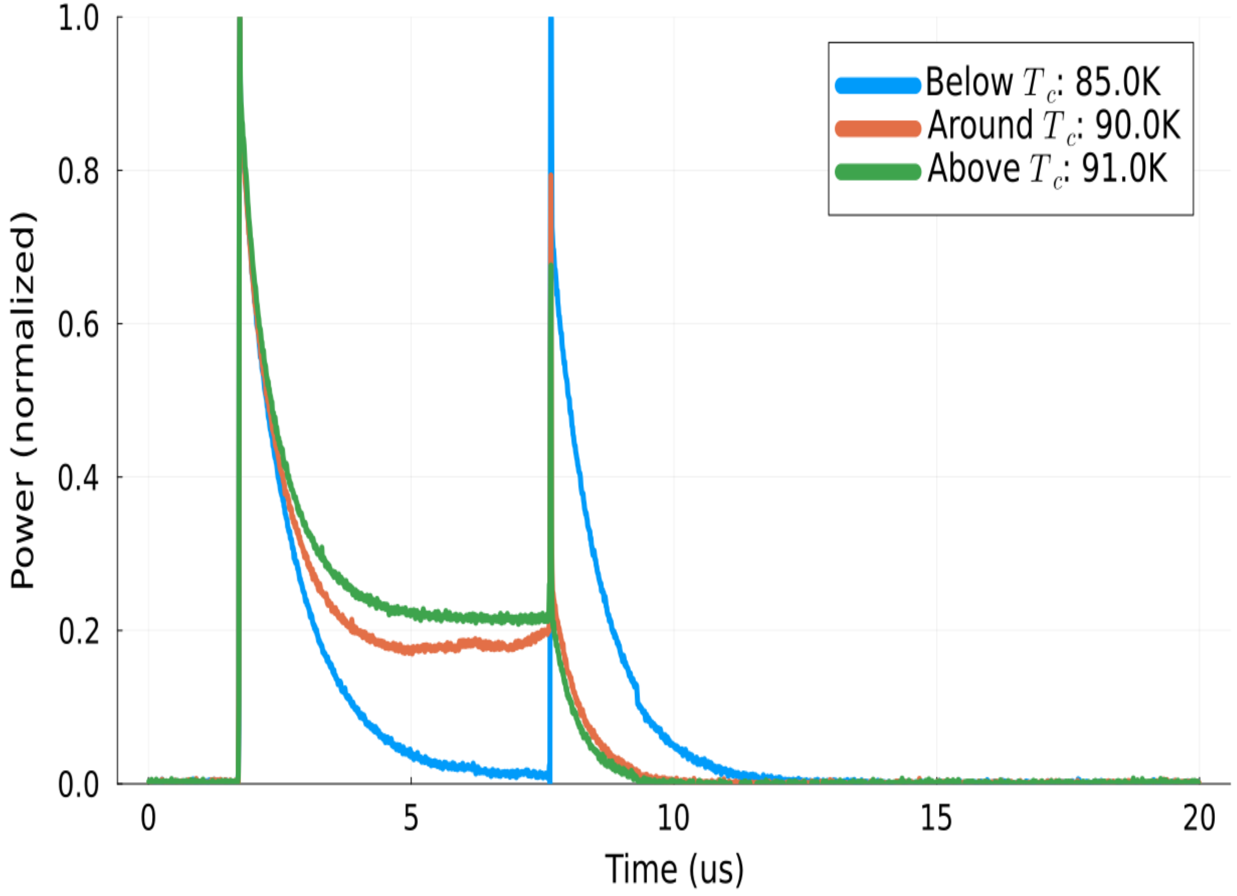


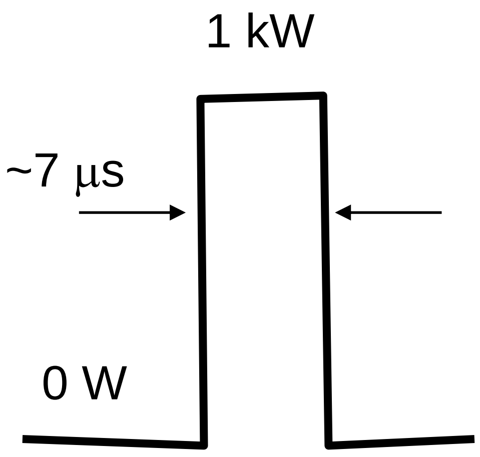




From: Mitch Schneider

Preliminary SLAC results at high-gradient: different temperatures



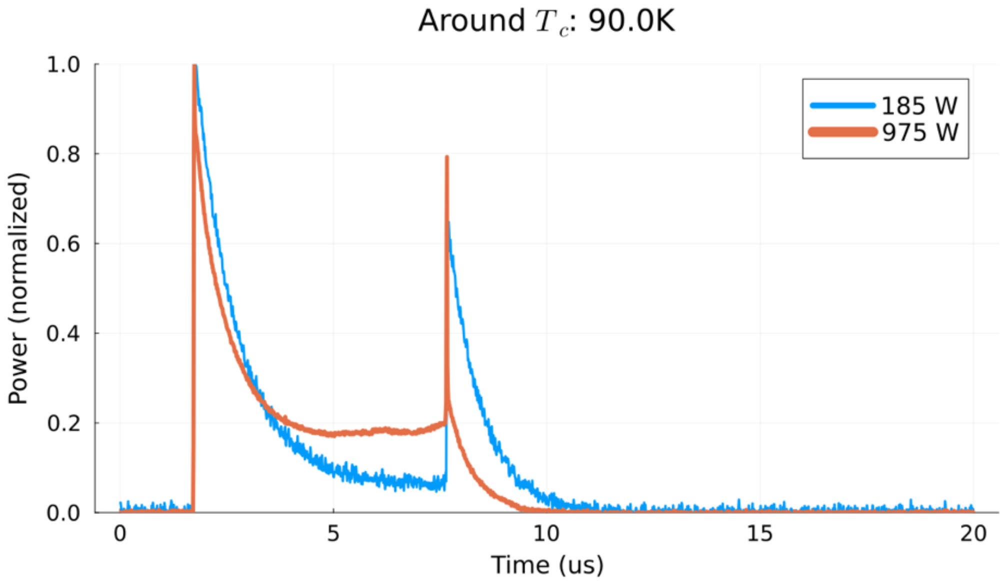


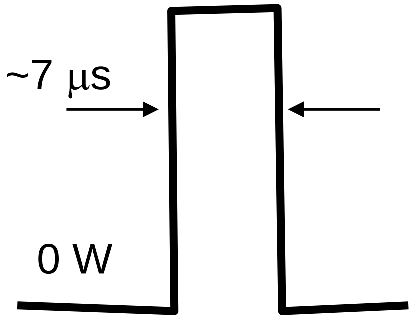
Power pulse

From: Mitch Schneider

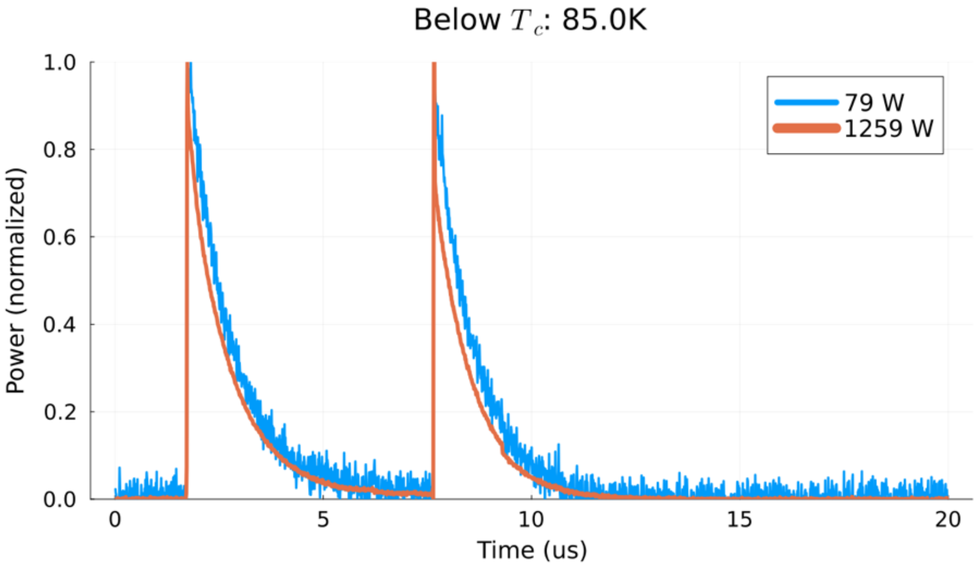
Preliminary SLAC results at high-gradient: different powers

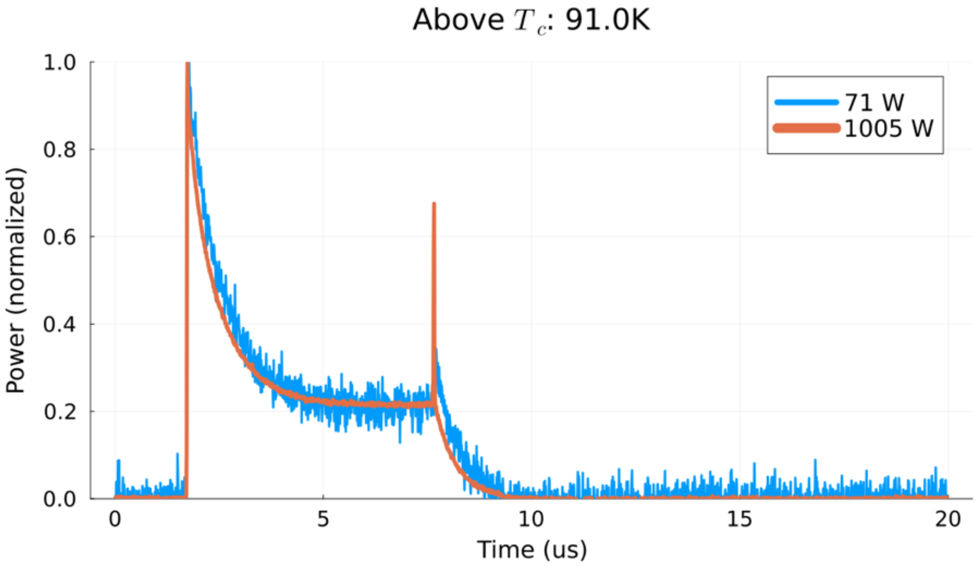
From: Mitch Schneider


Around T_c: 90.0K



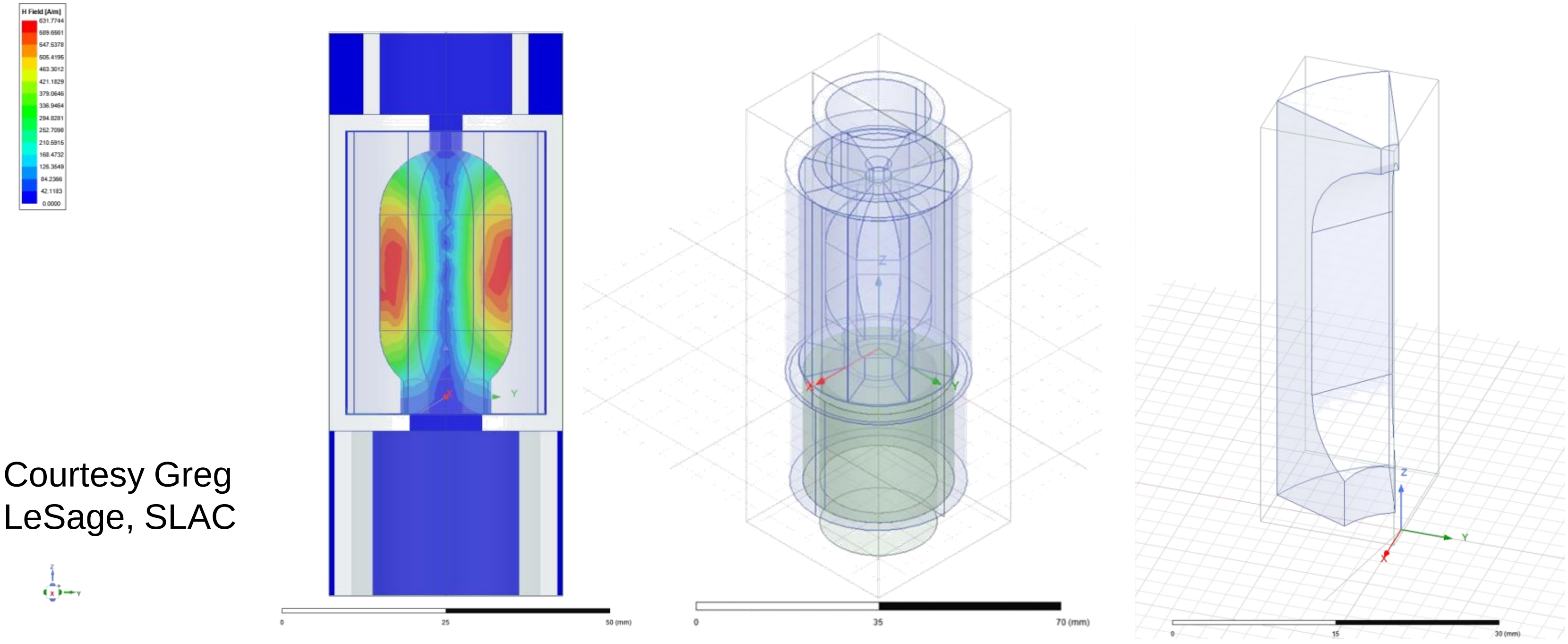
Power pulse


Below T_c: 85.0K

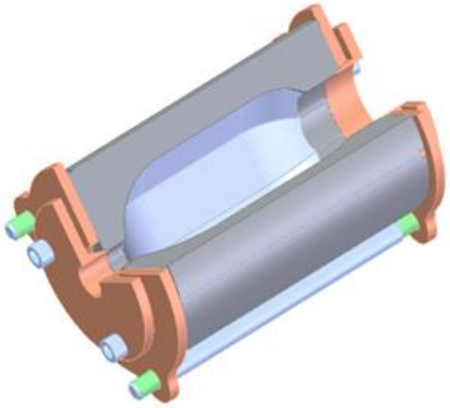

Above T_c: 91.0K

First device validation – supported by I.FAST Innovation Fund

- Next goals: develop large-size tapes (50 mm wide) in collaboration with KCT, to be first tested on discs at SLAC. Two-years plan funded by IIF
- (Ideally: REBCO coating directly on 3D objects)
- Device validation: X-band pulse compressor (SLAC) as first “real” RF device



Courtesy Greg LeSage, SLAC

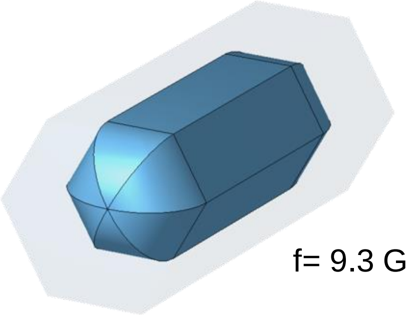


Pulse compressor

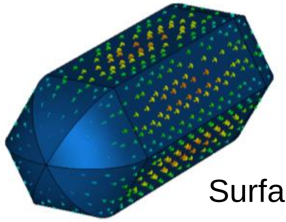
- Coating will be performed by CSIC-ICMAB

Axion cavity as earlier demonstrator

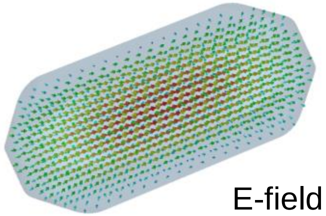
- Approach being validated also for axion detection cavities in RADES collaboration having a similar geometry
- Copper body manufactured at Mainz University, adapted to 12 mm wide coated conductors, coated by CSIC-ICMAB



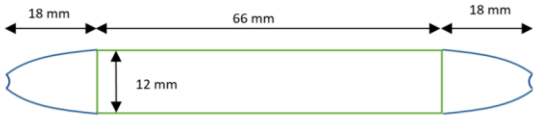
f= 9.3 GHz

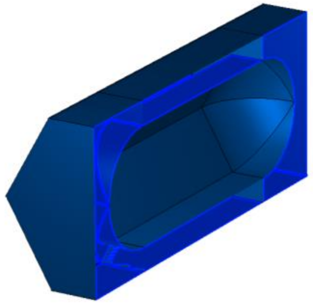


Surface currents

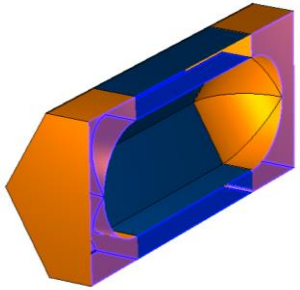


E-field





Q_0 = 356 070



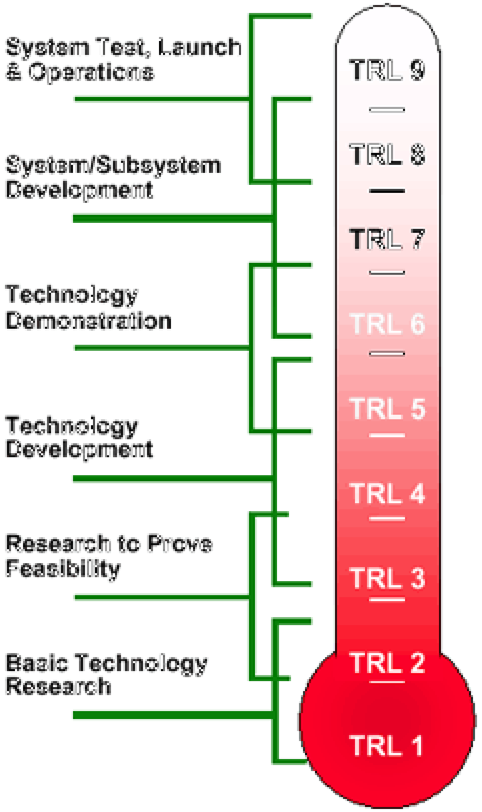
Q_0 = 268 520 (75%)

Work plan from 4/2023 to 4/2025

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
WP 1 (CERN)								
Coordination activities	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Samples and substrates procurement	🟩	🟩 M1						
RF low power characterization of segmented cavities (small tapes)			🟩	🟩	🟩 D1			
Final report						🟩	🟩	🟩 D2
WP 2 (KCT)								
Design and fabrication of sample holder system	🟦	🟦	🟦	🟦 M1				
HTS coating of large samples					🟦	🟦	🟦	🟦 D1
WP3 (CSIC-ICMAB)								
Coating on discs and segmented cavities for benchmarking (small tapes)	🟨	🟨	🟨	🟨 D1				
Measurement of superconducting properties of large size tapes					🟨	🟨	🟨	🟨 D2
SLAC supporting partner								
RF high power characterization of 3D coated HTS discs in their mushroom cavity			🟧	🟧	🟧	🟧	🟧	🟧

Industrial application prospect

- At the end of this study, we aim at consolidating TRL4.
- Prototype pulse compressor with SLAC will demonstrate TRL6.
  - Timescale: 2-3 years after completion of this study
  - Need a further round of funding
  - This will include the design, fabrication and coating, and its validation in a high-power RF bench test bench.
- Future accelerator projects will drive achieving further TRLs and drive commercialization.
  - Industry will be involved for construction of devices
  - Other companies may be involved for hardware manufacturing



Addressing the European Green Deal

Benefits

fresh air, clean water, healthy soil and biodiversity

renovated, energy efficient buildings

healthy and affordable food

more public transport

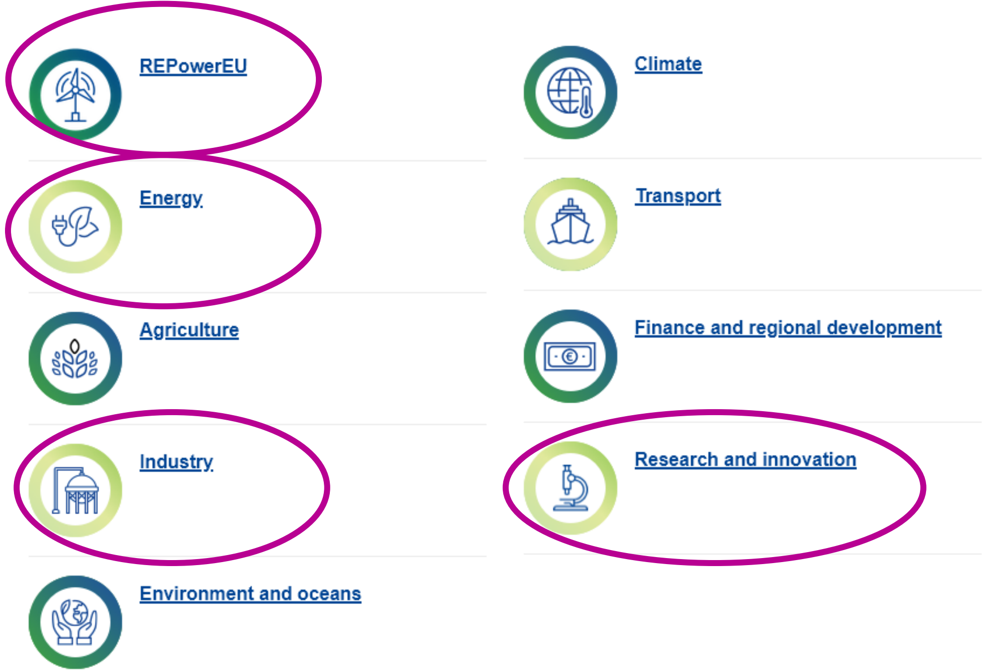
cleaner energy and cutting-edge clean technological innovation

longer lasting products that can be repaired, recycled and re-used

future-proof jobs and skills training for the transition

globally competitive and resilient industry

Actions



REPowerEU

Climate

Energy

Transport

Agriculture

Finance and regional development

Industry

Research and innovation

Environment and oceans

- New-generation collider linacs are expected to use hundreds of MW of electricity
- Energy savings from HTS are in line with current policies of societal impact minimization

Resources and budget

- CERN:
  - Provided resources: two senior physicist (scientific coordination, 0.2 FTE) and one senior Fellow (follow up, measurements, 0.5 FTE)
  - Requested resources: 10 kEUR (sample manufacturing)
- KCT:
  - Provided resources: one senior scientist (design, procurement, coating, 1 FTE)
  - Requested resources: 100 kEUR (80 kEUR manpower for coating operations, 20 kEUR sample holder manufacturing)
- CSIC-ICMAB:
  - Provided resources: one senior scientist (0.2 FTE), and one PhD student (0.5 FTE)
  - Requested resources: 50 kEUR (40 kEUR PhD student and manpower for coating and characterization work, 10 kEUR consumable)

Ratio for the requested IIF funds: 120 kEUR personnel and labour / 40 kEUR material

- Final deliverable is a report on the demonstrated achieved performance, and on the prospects for scalability to accelerator-scale RF devices.

Budget table

	Manpower	**Materials**	**Total**
CERN		10 kEUR	10 kEUR
KCT	80 kEUR	20 kEUR	100 kEUR
CSIC-ICMAB	40 kEUR	10 kEUR	50 kEUR
			160 kEUR

Outline

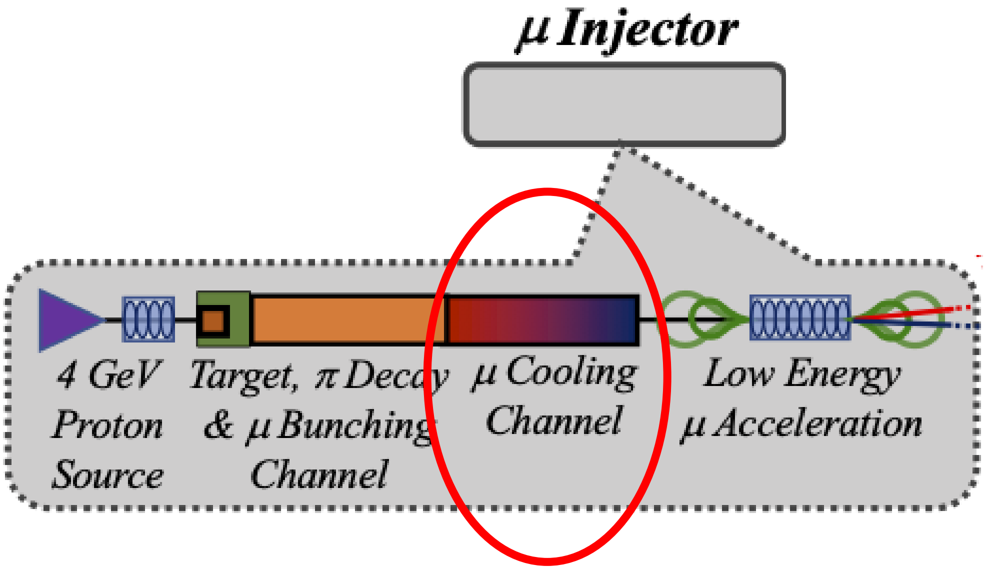
- HTS cavities at low gradient, in a strong magnetic field
  - The present: FCC beam screens and RADES axion detectors

- HTS cavities at high-gradient
  - The goal of the new iFAST collaboration CERN – KIT – ICMAB

- HTS cavities in both high-gradient and strong magnetic field
  - The future?

Muon collider

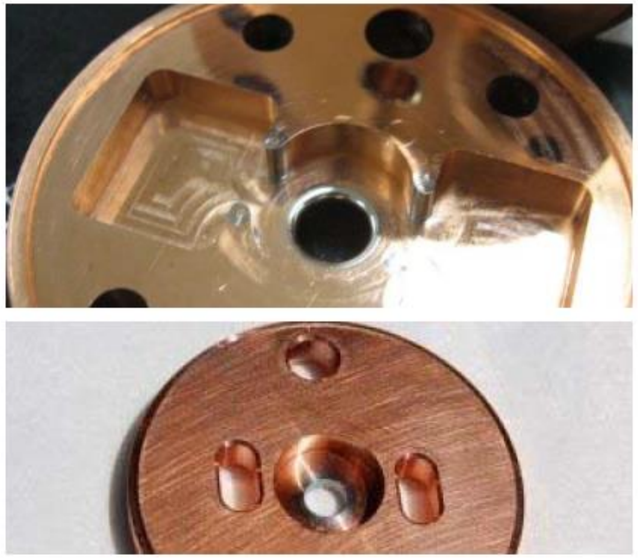
- Muon cooling system requires RF cavities operating at high-gradient AND in a strong magnetic field.



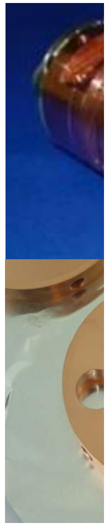
- Normal conducting copper, possibly cryo: baseline option
- Superconducting: High-Temperature Superconductors (HTS) ?

Possible practical implementation of HTS tape-coated cavities

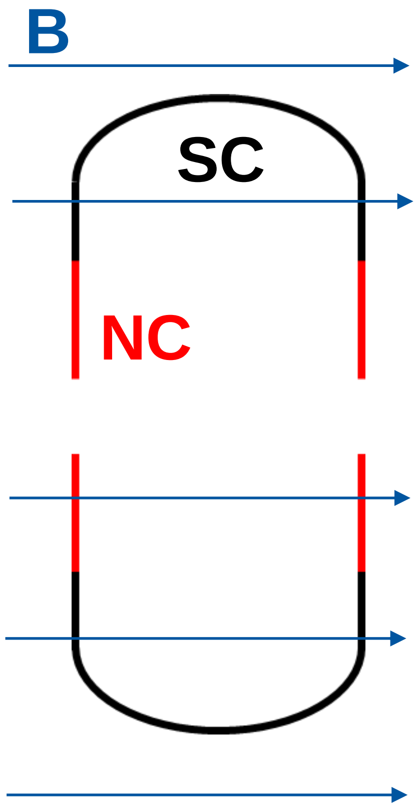
- How could a future cavity look like? Bimetallic cavities

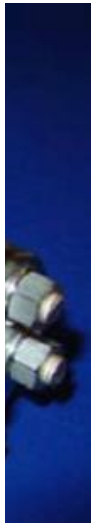


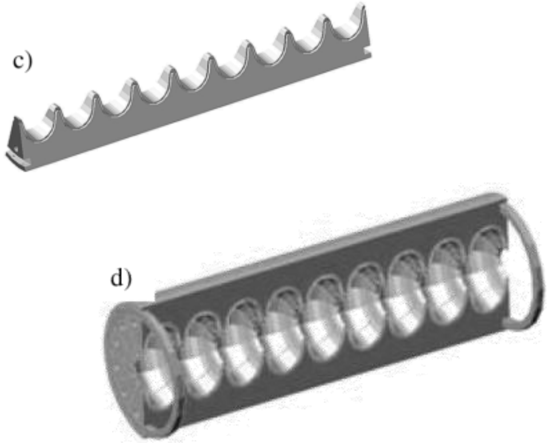
J. Haimson, WEPMS085,
PAC07 (s.steel inserts)



C







P. McIntyre et al., IEEE
TAS 19 (2009) 1380

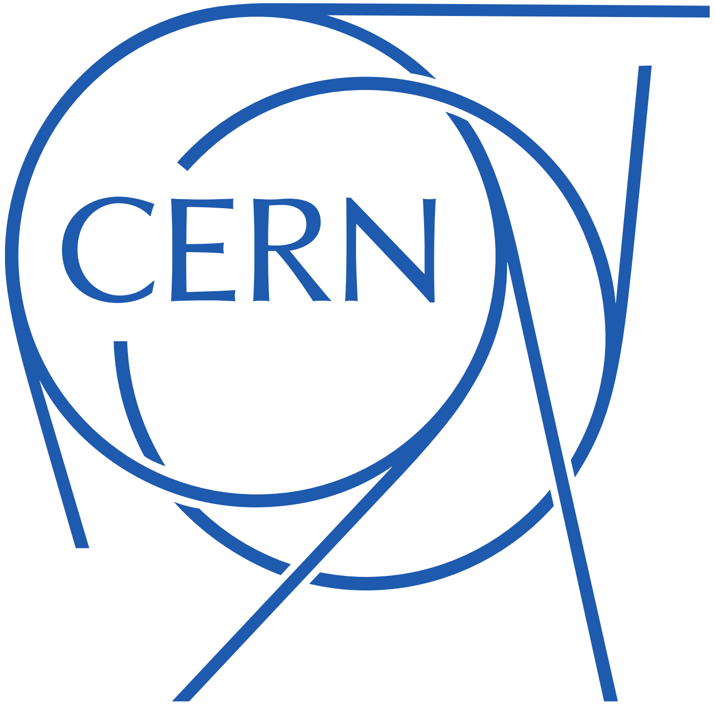
Composite cavities exist and have ed.

Joints at low-current regions are standard practice even in SRF cavities (ie QWRs)

Segmentation at zero-current region is possible, see device being designed at SLAC

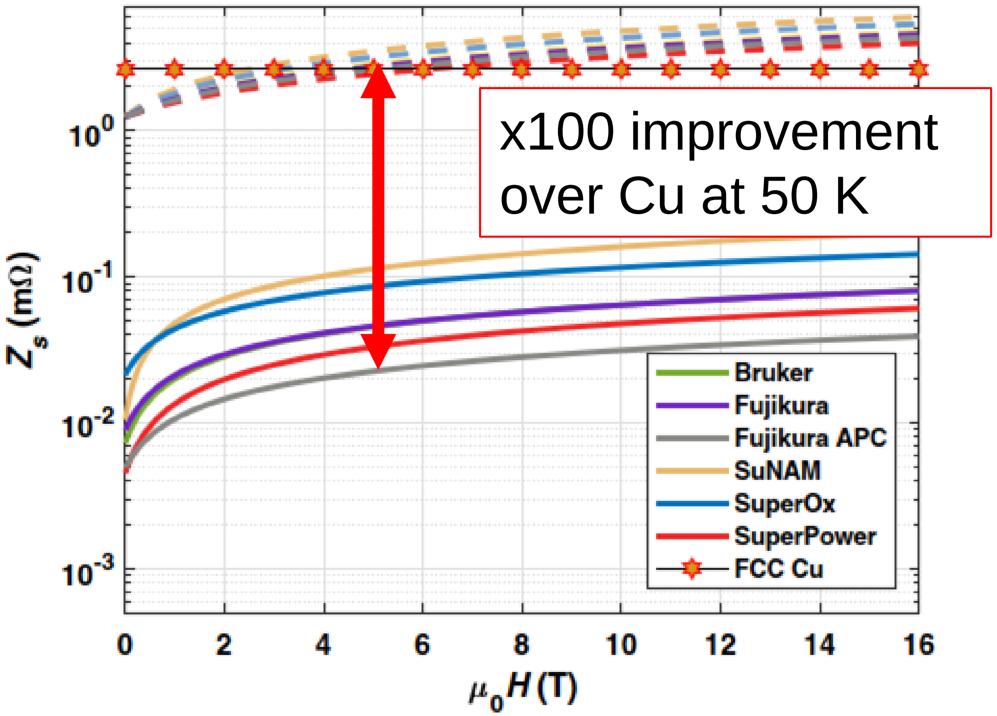
Final remarks

- No data exist for HTS at high-gradient (either samples or cavities): experiments needed
- Fabrication technologies for real cavities must be developed: wider soldered tapes (iFAST collaboration "HIGHEST"), and perhaps eventually develop a direct HTS coating technique on copper
- Overall energy efficiency would have to be studied, considering: operating temperature, cryo-efficiency, possible Q-factor, pulsed operation


CERN

Scaling to lower frequency

REBCO scaled to 1 GHz at 50 K

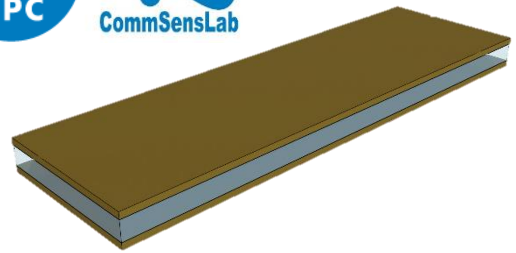


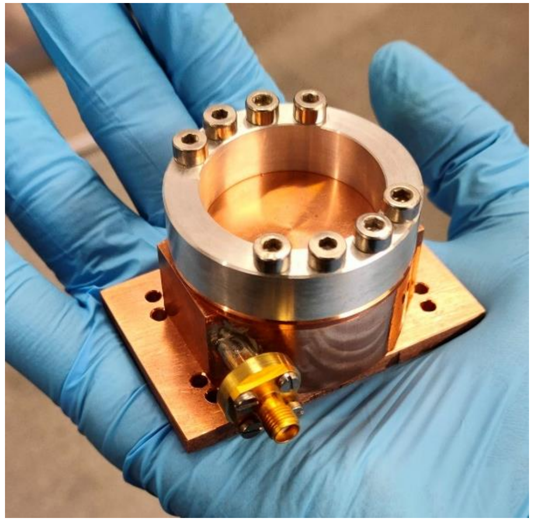
x100 improvement over Cu at 50 K

Romanov et al, SciRep 10:12325 (2020)

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

A parallel-plate resonator is being commissioned to test samples at ~1 GHz





38x12 mm samples
50 mm bore
16 T
$X_s(T)$ at all frequencies

Will demonstrate real experimental frequency scaling on samples

Surface impedance: the key

τ Risetime of beam instabilities

$$\frac{1}{\tau} \propto -\mathrm{Im}|\Delta\omega| \propto \frac{I_b M}{EL}\mathrm{Re}(Z_T)$$

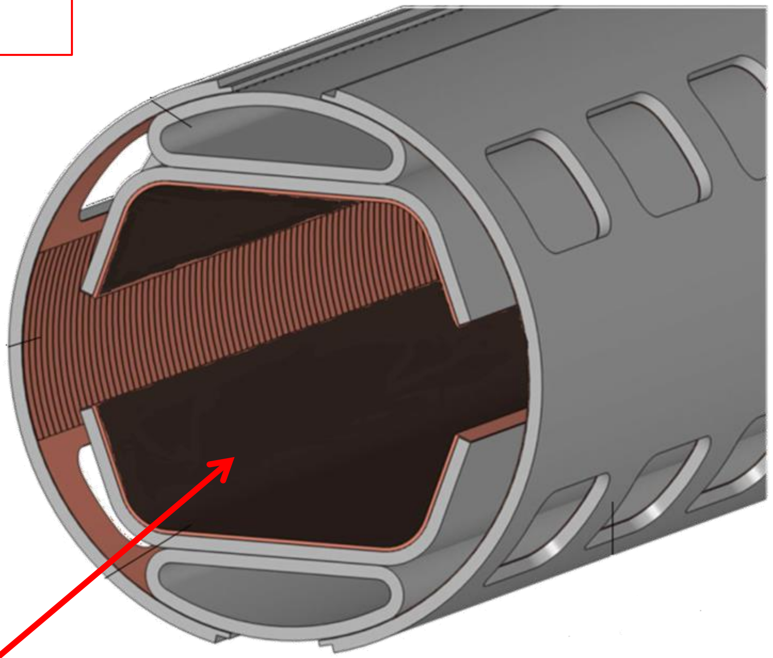
$$\mathrm{Re}(Z_T) = \frac{R\,c}{\pi b^3\ f} R_S = \frac{R\,c}{\pi b^3\ f}\sqrt{\rho\mu_o \pi f}$$

Z_T Transverse impedance (property of the beam)

R_S Surface resistance (property of the surface)

τ: instabilities rise-time
$\Delta\omega$: betatron tune-shift
I_b: bunch current
M: number of bunches
E: beam energy
L: bunch length
R: accelerator radius
c: speed of light
b: vacuum chamber radius
f: wakefields frequency
ρ: electrical resistivity

What could be better than copper at 50 K?



High-Temperature Superconductors (HTS)

New kid on the blocks: the C3 study @ SLAC

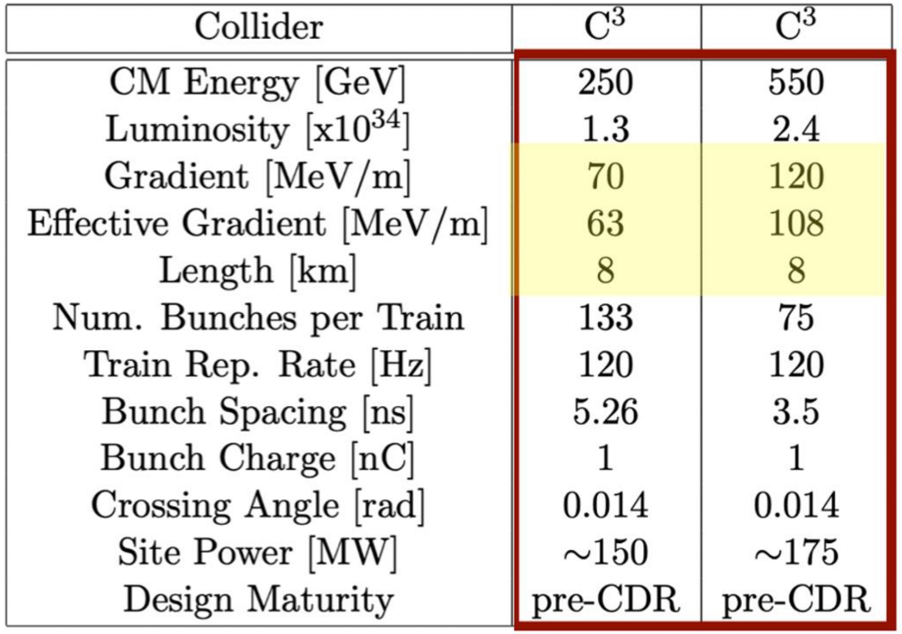
More info here

8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

Large portions of accelerator complex compatible between LC technologies

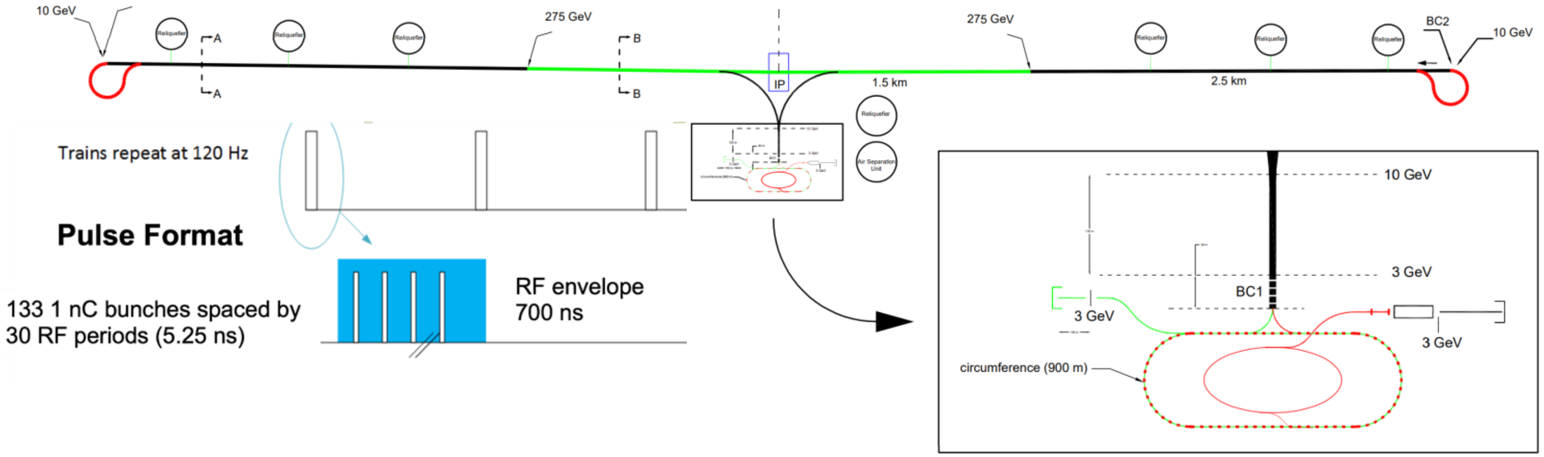
- Beam delivery / IP modified from ILC (1.5 km for 550 GeV CoM), compatible w/ ILC-like detector
- Damping rings and injectors to be optimized with CLIC as baseline
- Cryogenically cooled – 77 K (liquid nitrogen)

C^3 Parameters



Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [$\times 10^{34}$]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

C^3 - 8 km Footprint for 250/550 GeV (to scale)



Trains repeat at 120 Hz

Pulse Format

133 1 nC bunches spaced by 30 RF periods (5.25 ns)

RF envelope 700 ns

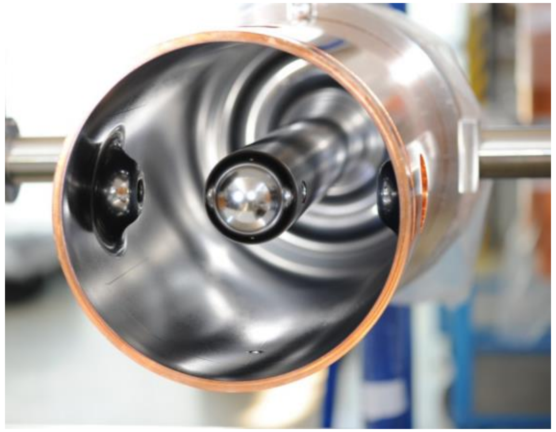
Cooling allows for increase in accelerating gradient, and savings in RF power infrastructure

From: Emilio Nanni

Flux pinning

- 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
- Earth magnetic field should not be an issue for HTS (to be verified)

Literature review - II

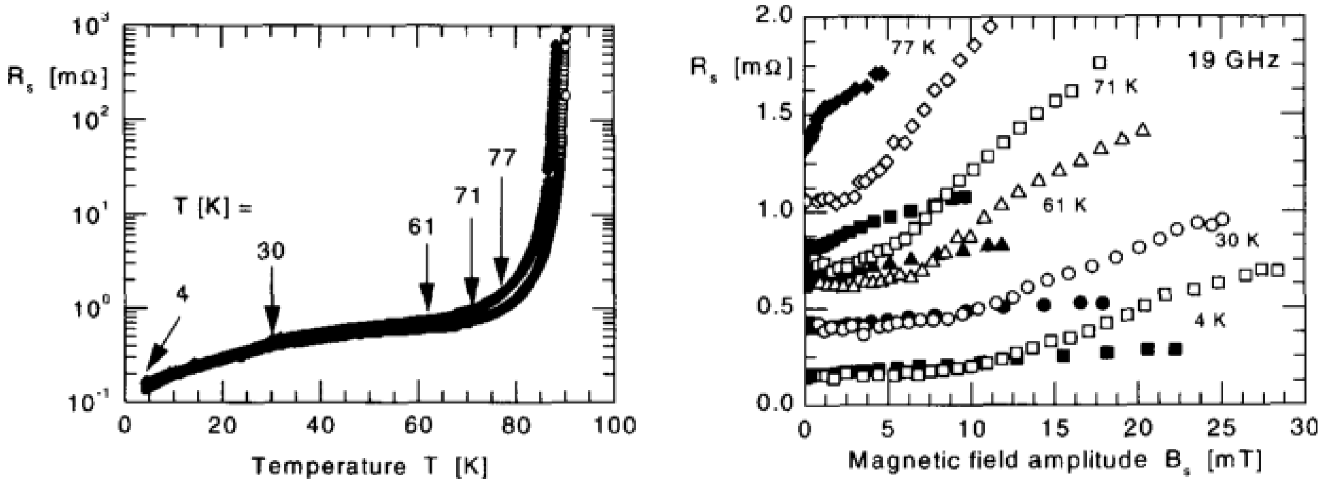


Fig. 4.1. Temperature dependence at 19 GHz (*left part*) of the surface resistance a ⌀2″ laser-ablated film (*diamonds*, "L49", [23]) and a ⌀1″ DC-sputtered film (*circles*, "S145", [24]). The *right part* displays the field dependences $R_s(B_s)$ of both films at the temperatures indicated by *arrows* in the left part. *Filled (open) symbols* refer to the laser-ablated (sputtered) films.

23. T. Kaiser: Dissertation, University of Wuppertal, Report WUB-DIS 98-13 (1998).
24. T. Bollmeier, W. Biegel, B. Schey, B. Stritzker, W. Diete, T. Kaiser, G. Müller:

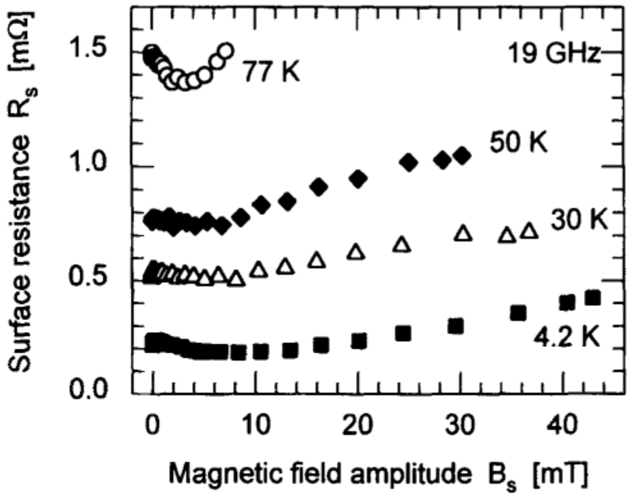
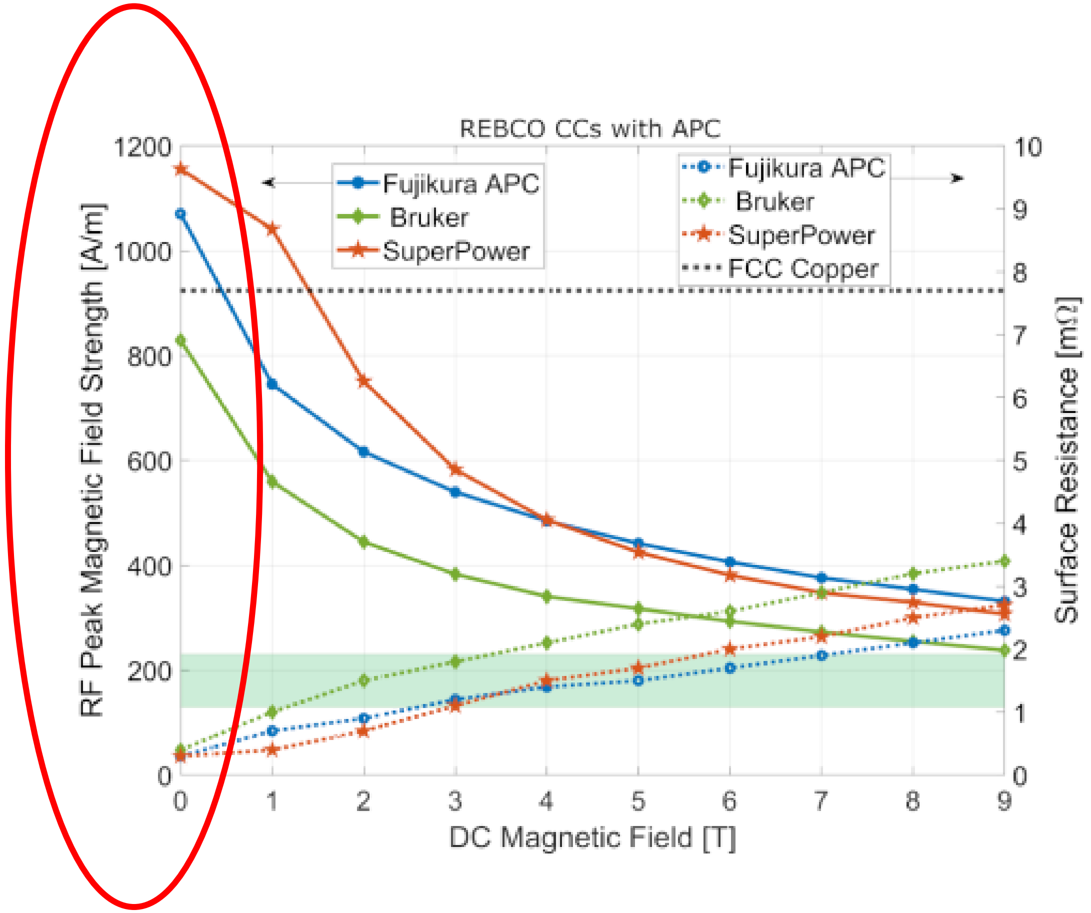
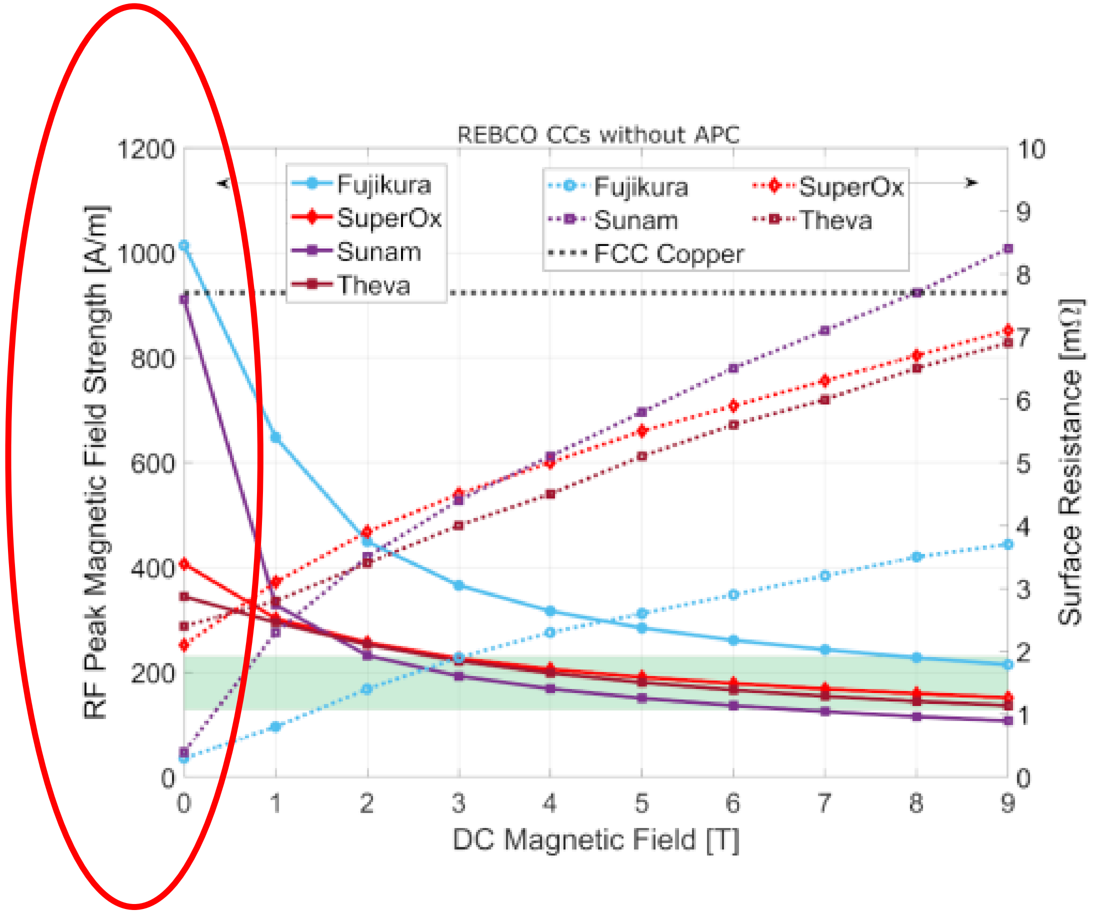


Fig. 4.31. Anomalous microwave field dependences $R_s(B_s)$ at 19 GHz for the two DC-sputtered films S178 ($T = 77$ K, *circles*) and S373 ($T = 4.2$ K (*squares*), 30 K (*triangles*) and 50 K (*diamonds*)) [23].

From: M. Hein, "High-Temperature-Superconductor Thin Films at Microwave Frequencies" (Springer Tracts in Modern Physics, 155)

HTS tape at 8 GHz (dielectric resonator) and 50 K





Patrick Krkotic, PhD dissertation, UPC Barcelona 2022

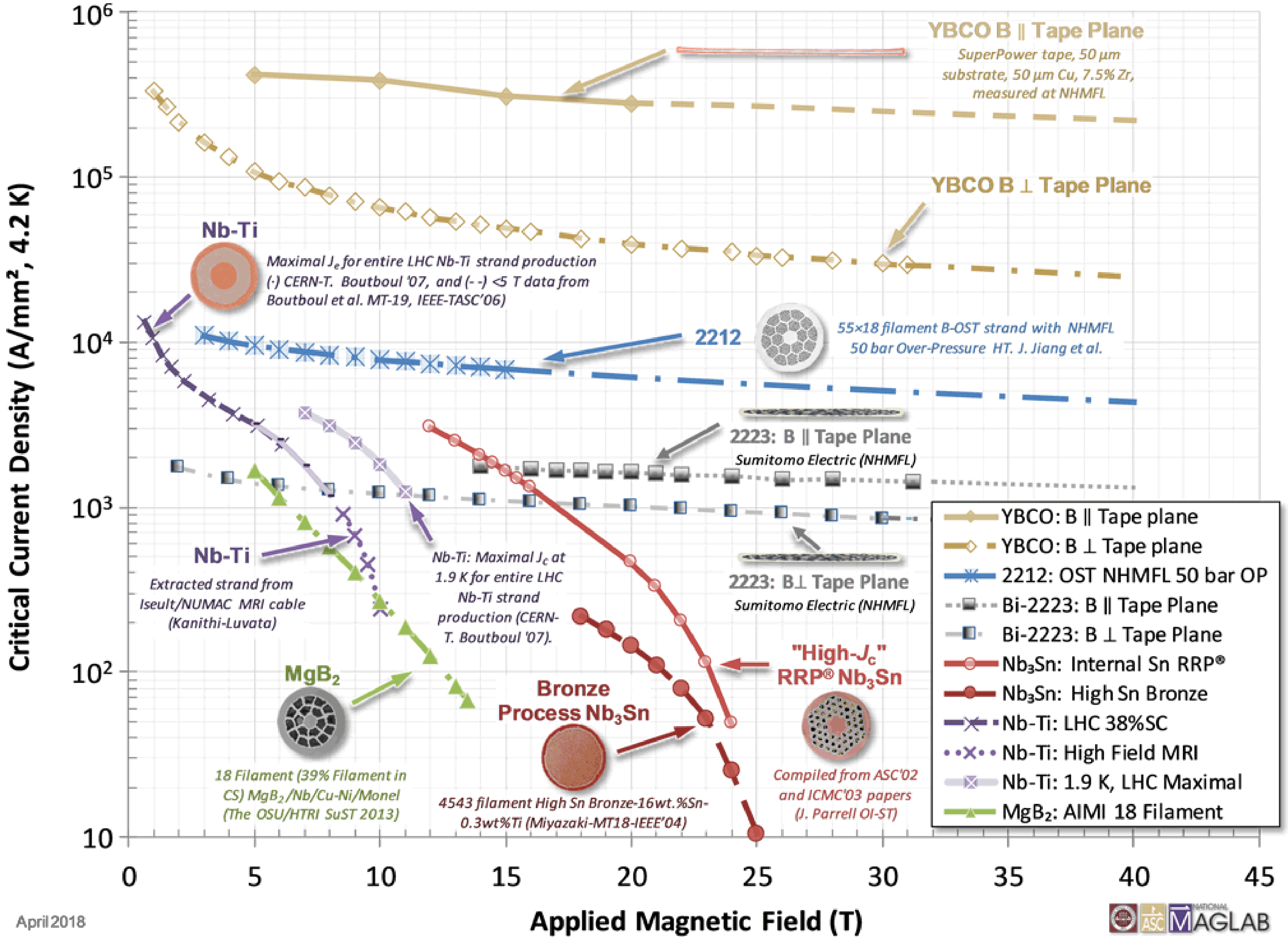
Zoo of superconductors

J_c may vary of orders of magnitude.
H_{c2} has much smaller variation.

YBCO most promising candidate

NbTi – NbTiN possible candidates at B < 10T

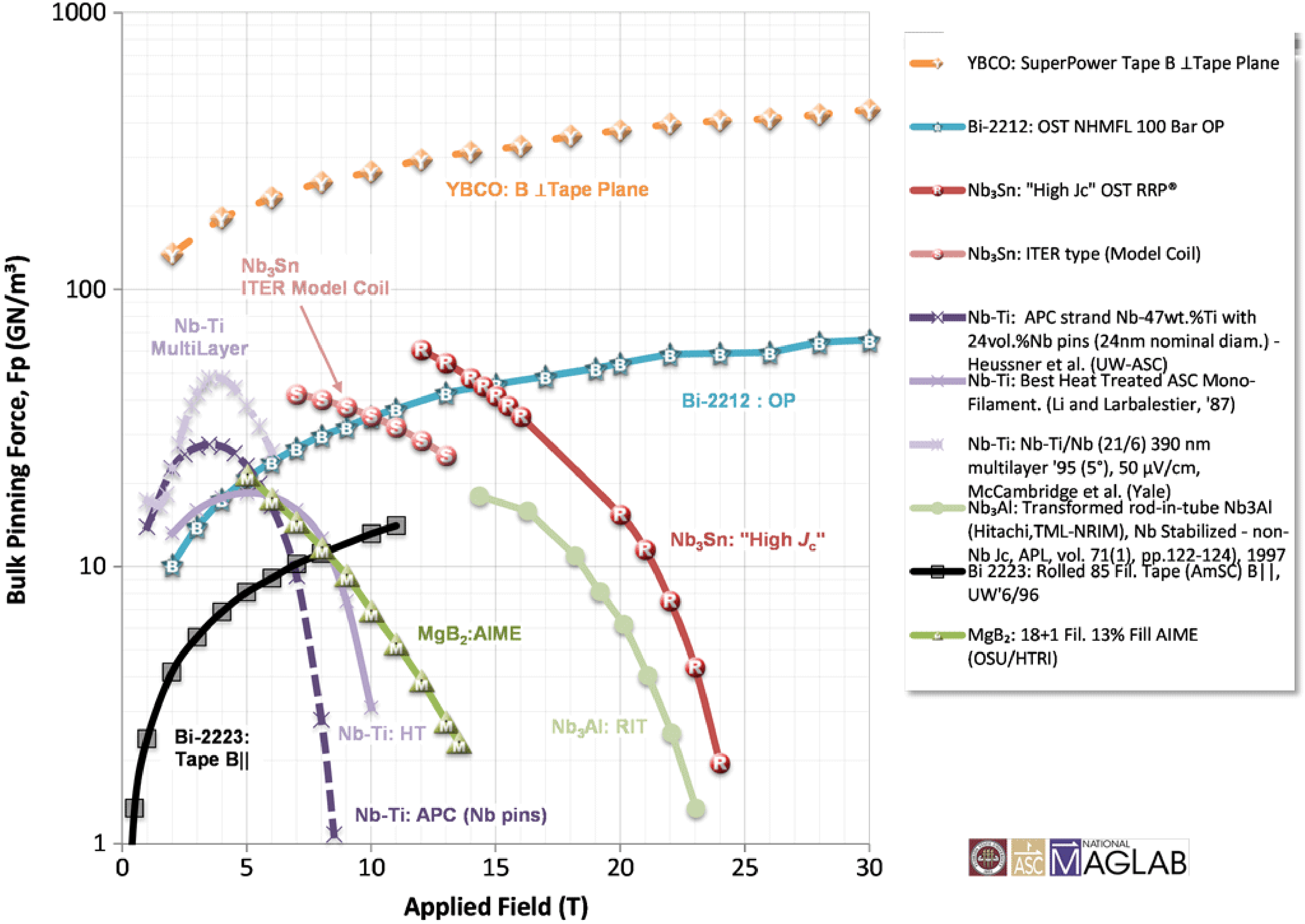
Nb_3Sn for B < 15 T



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

Zoo of superconductors

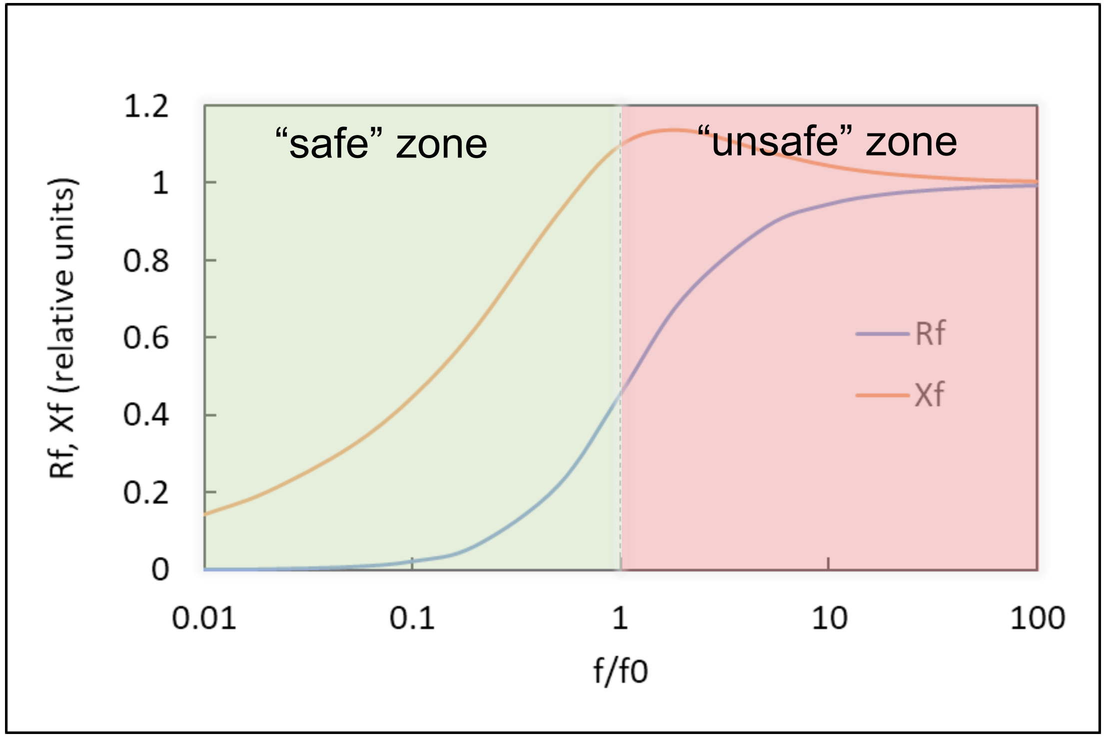
Pinning force



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

Effect of magnetic field: fluxon losses in RF

Surface resistance, reactance due to vortex motion



Case $f < f_o$

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

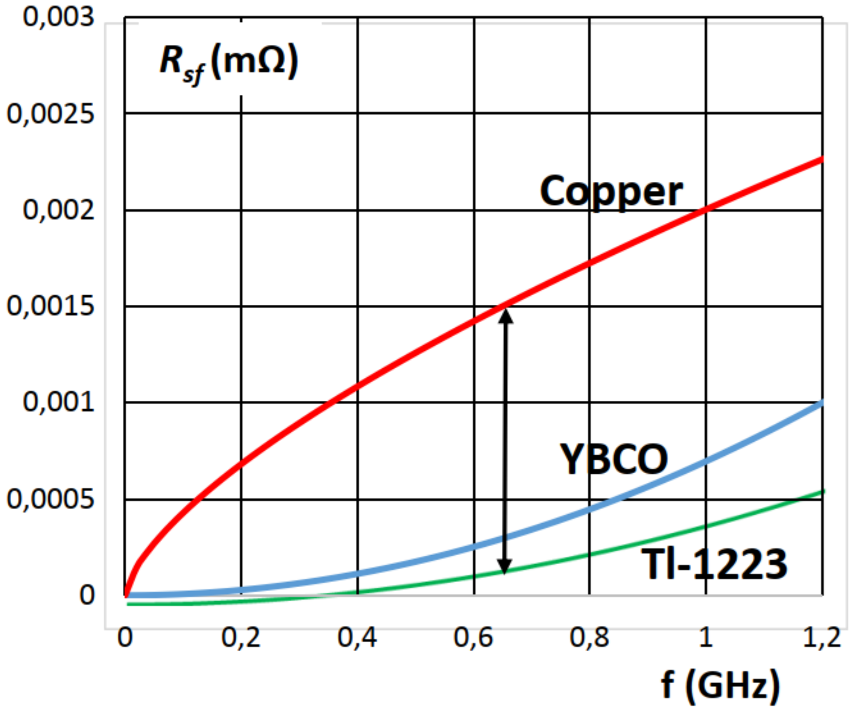
$$R_f = \frac{R_n}{\sqrt{2}}\sqrt{\frac{B_o}{B_{c2}}}\left(\frac{f}{f_0}\right)^{3/2} \qquad B_0 \square B_{c2}$$

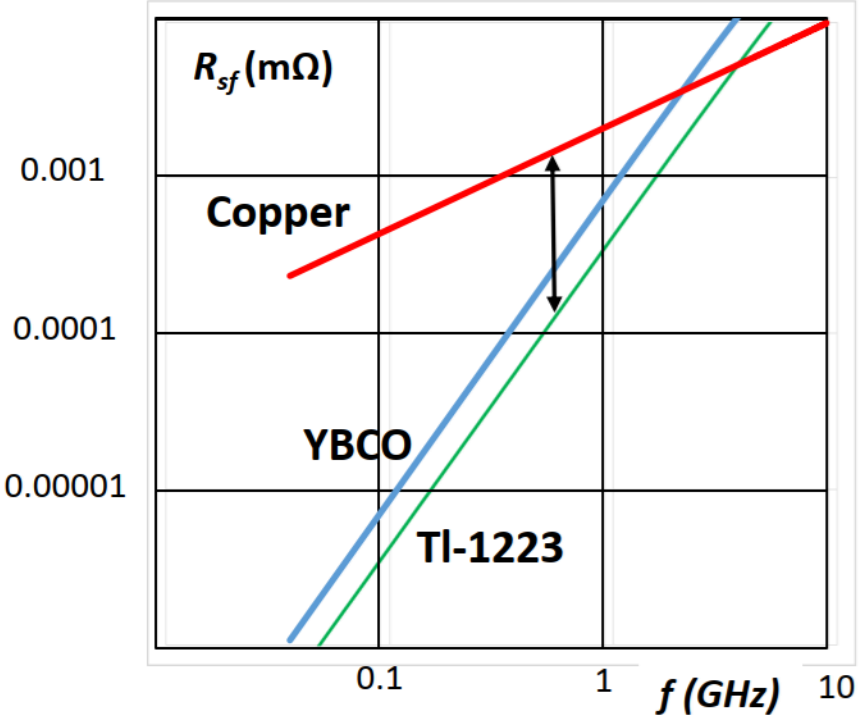
$$f_o(B_o) = \frac{\omega_o(B_o)}{2\pi} = \frac{\rho_n\sqrt{B_o}\,J_c(B_o)}{\sqrt{\varphi_o}\,B_{c2}}$$

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

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

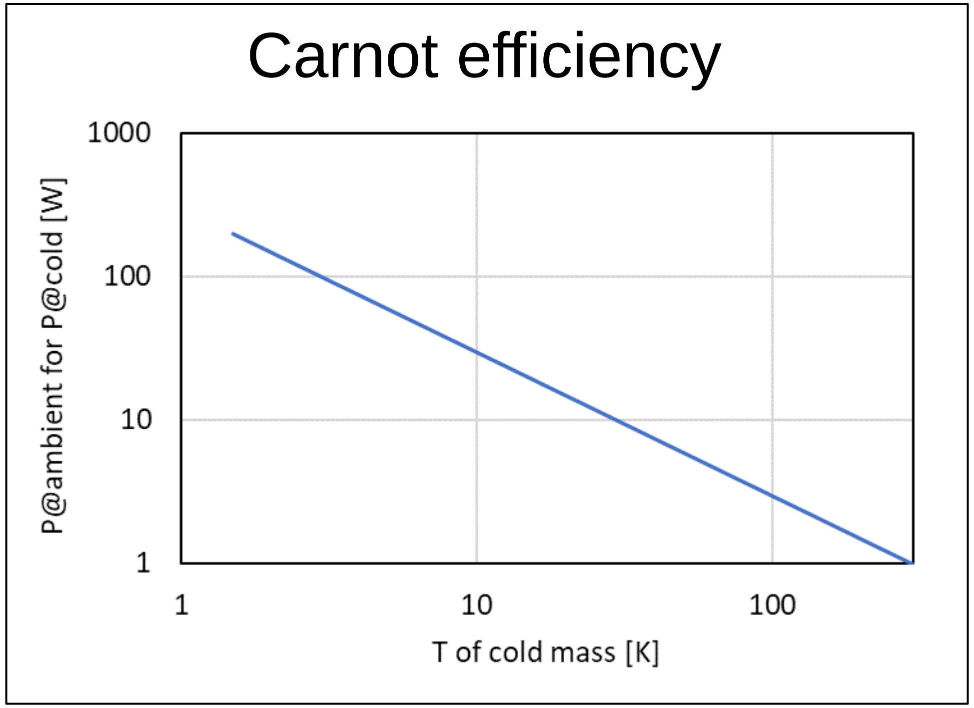


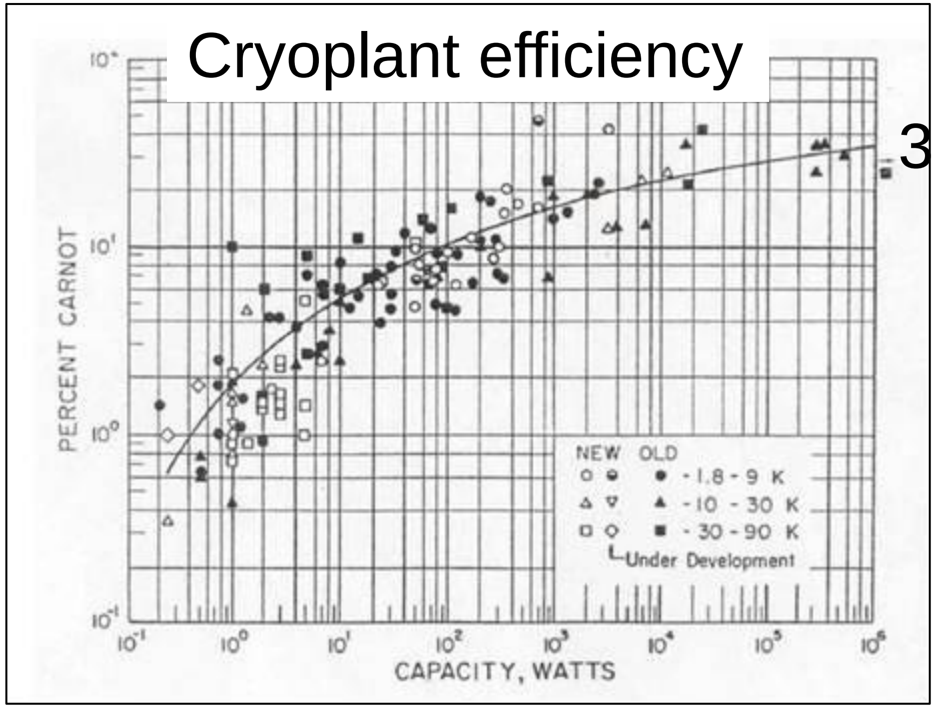


For HTS the Rs scales as f^2

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

Cryogenic losses: SRF aimed at energy saving compared to NRF



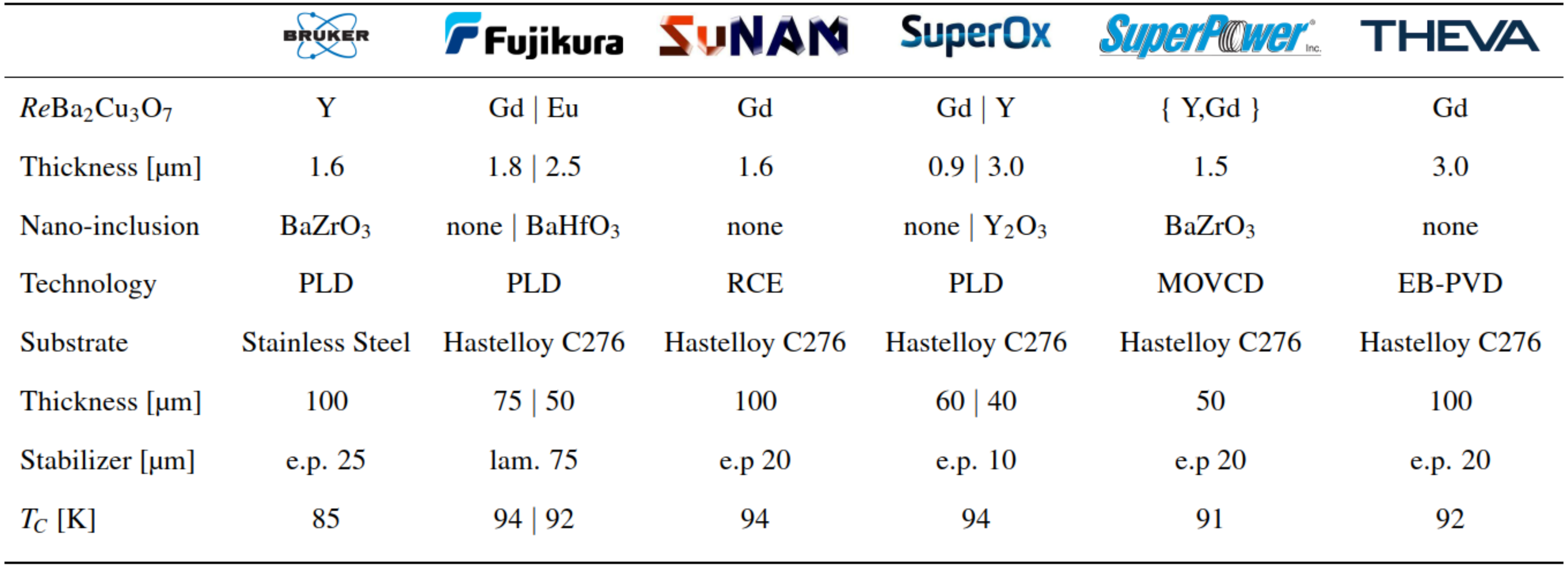


30%

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

HTS coating technologies



	BRUKER	Fujikura	SuNAM	SuperOx	SuperPower Inc.	THEVA
$ReBa_2Cu_3O_7$	Y	Gd | Eu	Gd	Gd | Y	{ Y,Gd }	Gd
Thickness [μm]	1.6	1.8 | 2.5	1.6	0.9 | 3.0	1.5	3.0
Nano-inclusion	$BaZrO_3$	none | $BaHfO_3$	none	none | Y_2O_3	$BaZrO_3$	none
Technology	PLD	PLD	RCE	PLD	MOVCD	EB-PVD
Substrate	Stainless Steel	Hastelloy C276	Hastelloy C276	Hastelloy C276	Hastelloy C276	Hastelloy C276
Thickness [μm]	100	75 | 50	100	60 | 40	50	100
Stabilizer [μm]	e.p. 25	lam. 75	e.p 20	e.p. 10	e.p 20	e.p. 20
T_C [K]	85	94 | 92	94	94	91	92

Patrick Krkotic, PhD dissertation, UPC Barcelona 2022