RF R&D for muon collider needs and opportunities

Alexej Grudiev (CERN)

25/02/2021

Workshop on Muon collider testing opportunities

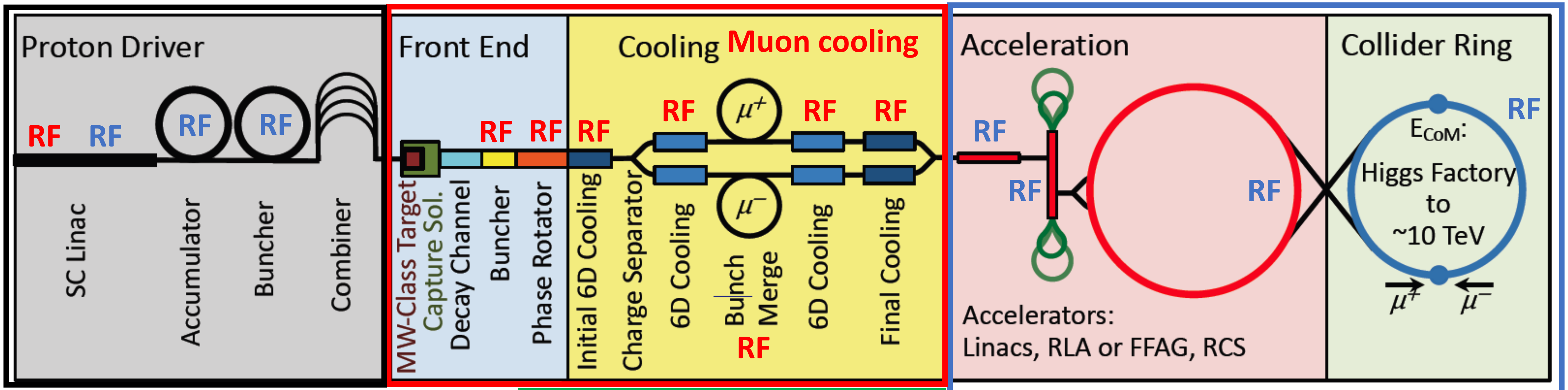
Outline

- Muon collider layout and RF
  - MAP scheme: proton driven muon source
  - LEMMA scheme: positron driven muon source
- RF system for proton driver
- RF system for positron driver
- RF system for muon cooling
- RF system for acceleration and collider

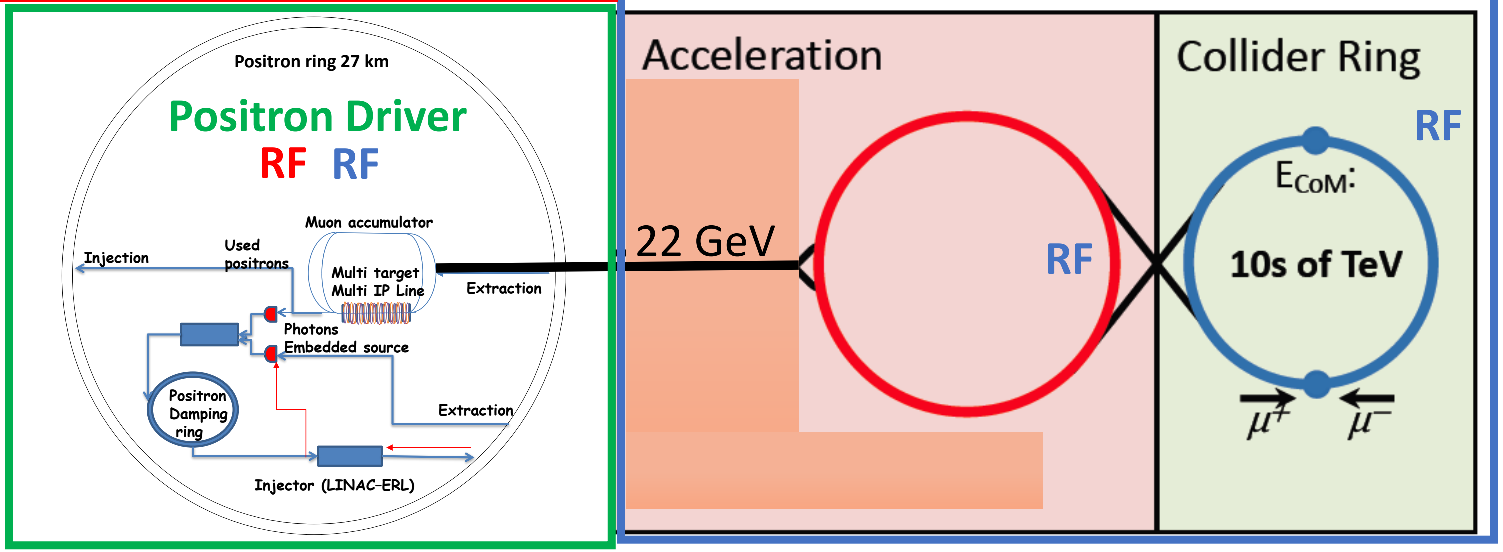
Muon Colliders and RF systems

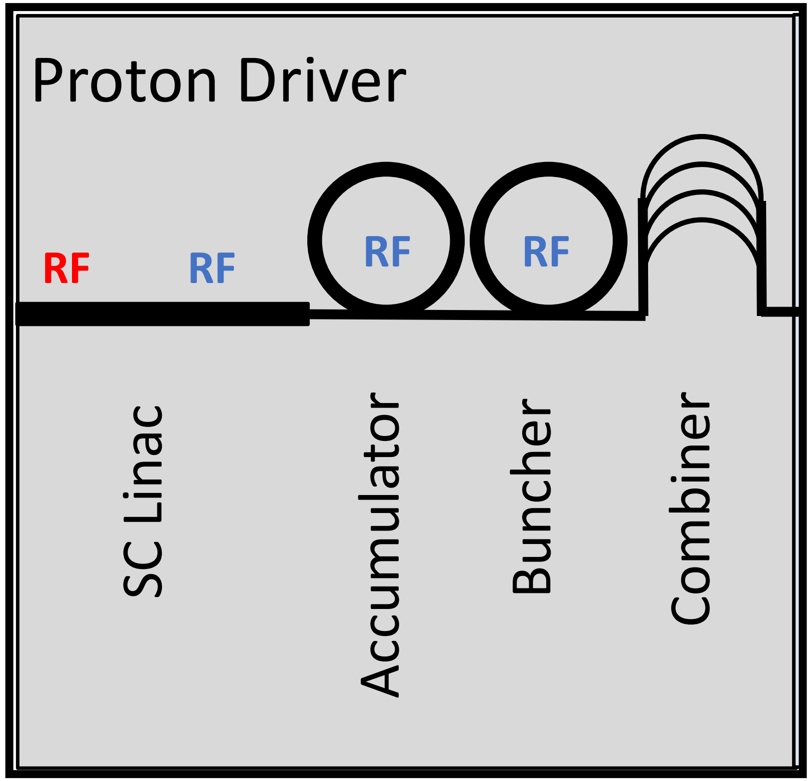
Proton driven Muon Collider Concept (MAP collaboration)

Acceleration and collider rings



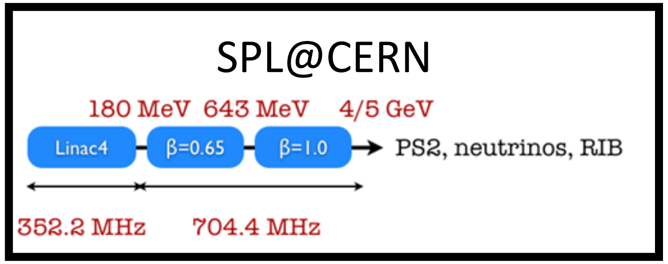
Positron driven Muon Collider concept (LEMMA)





Challenges:
- Few MW beam power
- ….

State of the art RF technology (SNS, ESS, SPL, …)



Required RF Test facility for feasibility demonstration
- **NO**

Challenges:

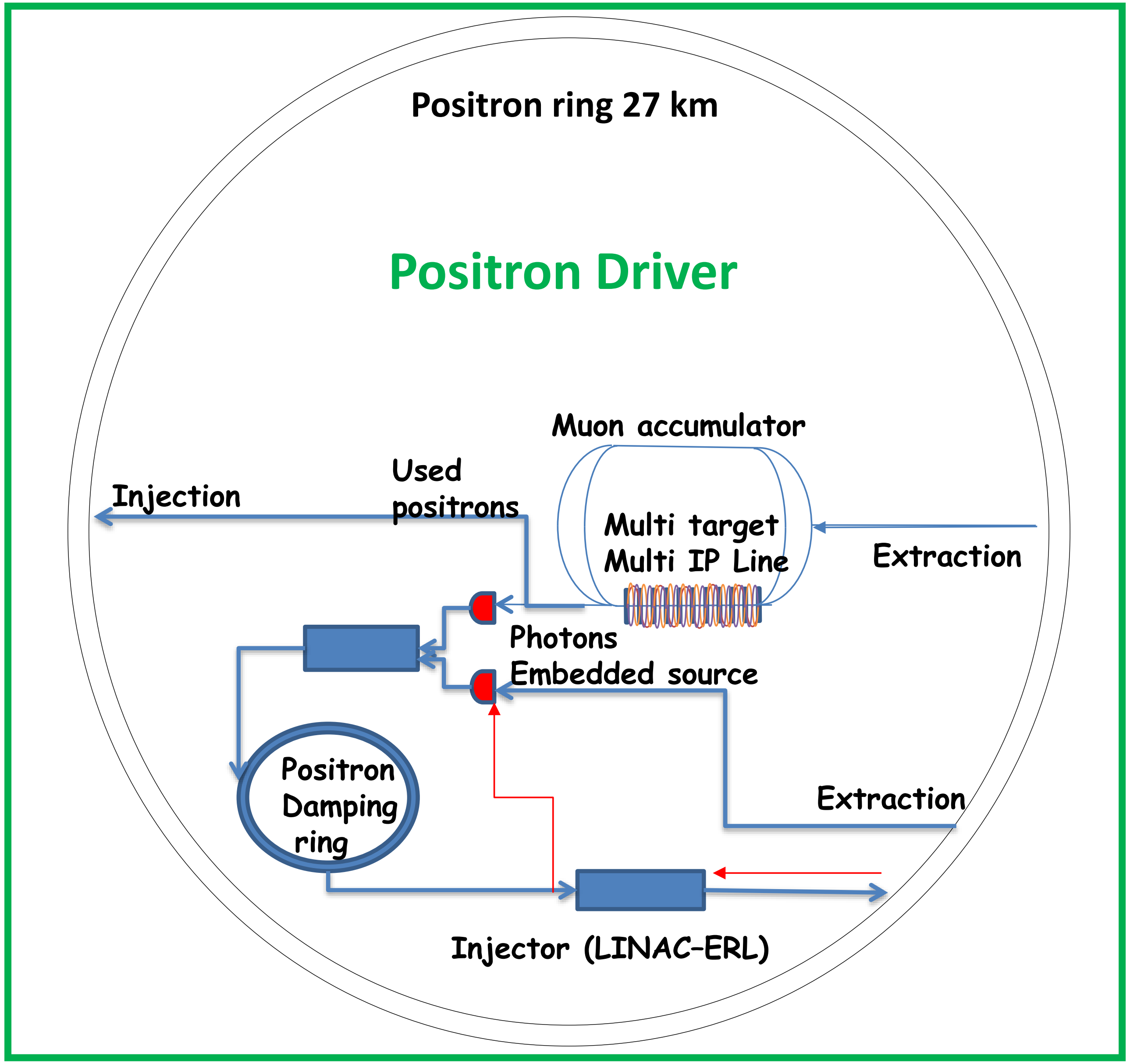
- Positron production
- Target
- Muon accumulation and merging
- ….

State of the art RF technology for electron positron linacs:

- Normal conducting: S-, C-band (LCWS, SwissFEL,…)
- Superconducting: L-band (XFEL, ILC,…)

Required RF Test facility for feasibility demonstration

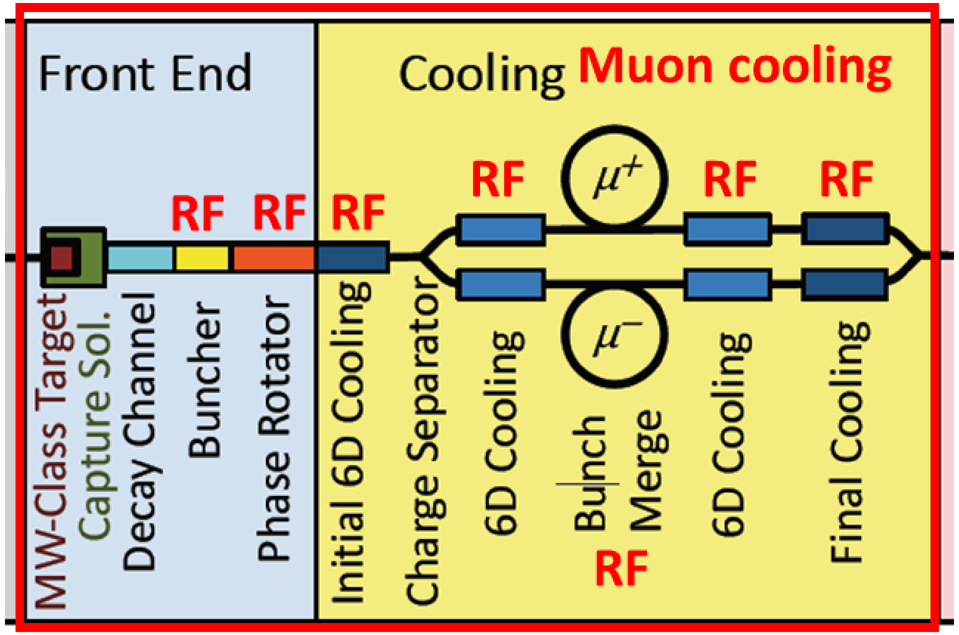
- **NO**

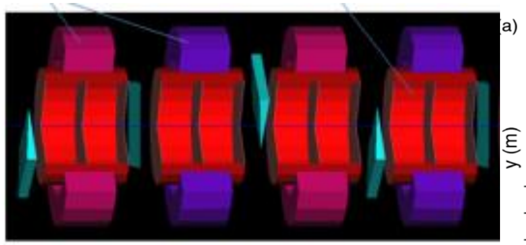


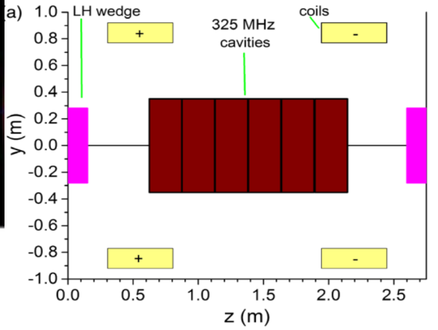
RF system for muon capture and cooling

Summarized from:
David Neuffer
Chris Rogers

Region	Length [m]	N of cavities	Frequencies [MHz]	Peak Gradient [MV/m]	Peak RF power [MW/cav.]
Buncher	21	54	490 - 366	**0 - 15**	1.3
Rotator	24	64	366 – 326	**20**	2.4
Initial Cooler	126	360	325	**25**	**3.7**
Cooler 1	400	1605	325, 650	**22, 30**	
Bunch merge	130	26	108 - 1950	**~ 10**	
Cooler 2	420	1746	325, 650	**22, 30**	
Final Cooling	140	96	325 - 20		
Total	**~1300**	**3951**			=> ~12GW







- **It is a very large and complex RF system with high peak power**
- **Very high bunch charge: (40->4)e12 => Collective effects (?)**

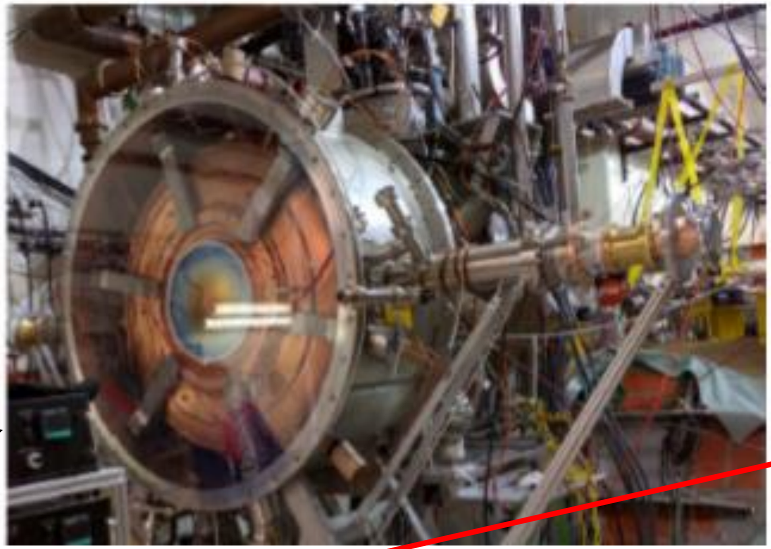
RF cavities for muon cooling

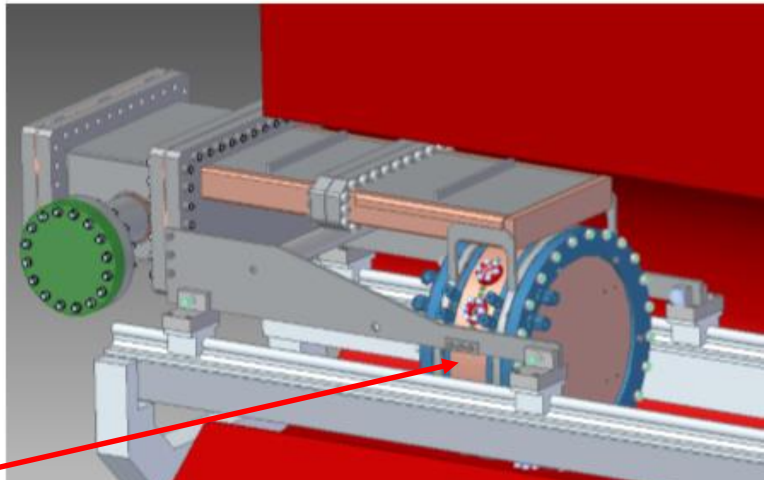
Challenges:

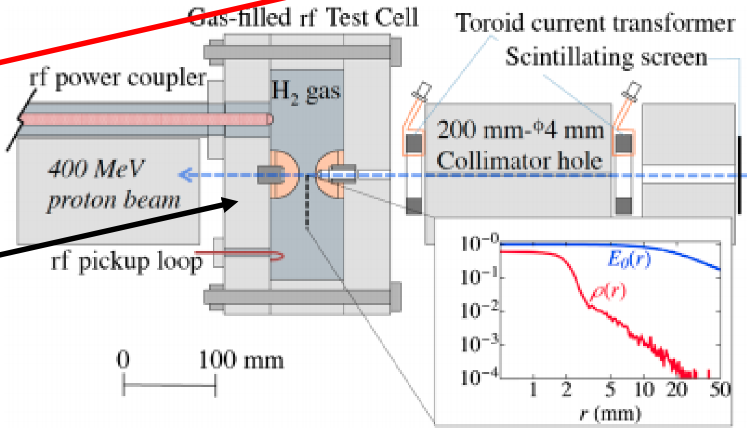
- High Gradient
- High magnetic field
- High radiation
- Technology far from been common

State of the art :

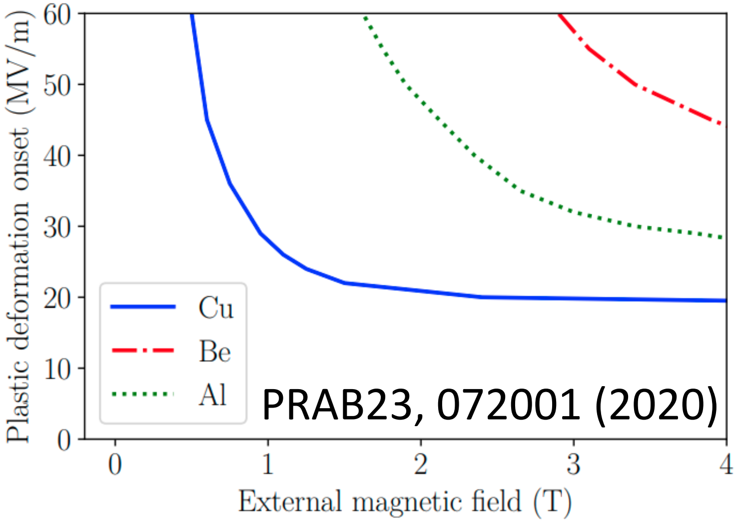
- MICE 200 MHz RF module prototype: 4T, **10 MV/m**, 1ms@1Hz
- 800 MHz **beryllium** RF cavity: 3T, **>50 MV/m**, 30us@10Hz
- 800 MHz **Gas** filled RF cavity: Small gap, 3T, **>50 MV/m**







PRAB19, 062004 (2016)



PRAB23, 072001 (2020)

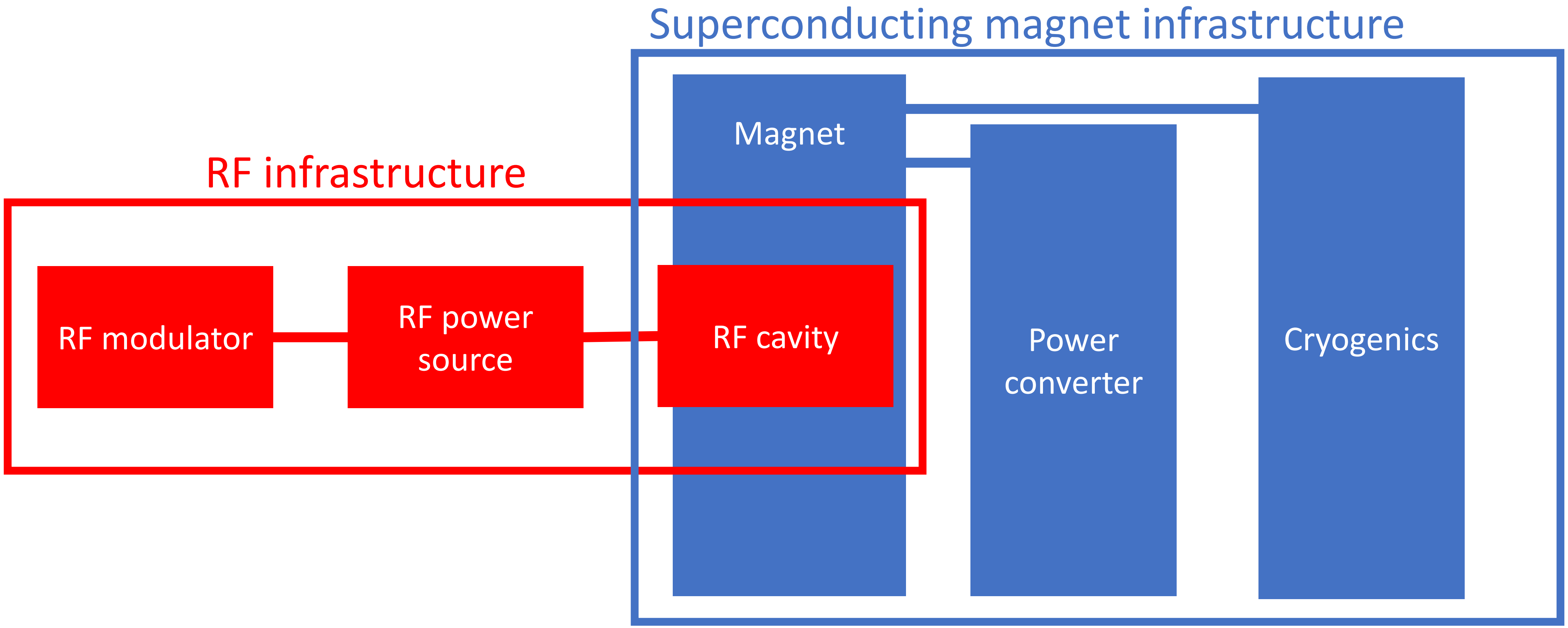
R&D directions and test facilities

- **High gradient RF test facility with magnetic field up to ~10T (NO BEAM)**
- Stage 1: Test cavities for technology development
  - Frequency: 200 - 800 MHz
  - Magnetic field: 0 - 10T, different field configurations
  - Different materials: Cu, Be, Al, …
  - Different temperatures: 300K -> 70K ->…
  - Different gases and pressure
- Stage 2: Prototype(s) for muon cooling test facility
  - Design of realistic cavity prototypes: frequency, beam aperture, integration
  - Parameters defined based on the results of Stage 1 and the design of the muon cooling test facility
  - Validation of high gradient in magnetic field performance
- **Muon cooling test facility**
  - Validates performance with the beam

Required RF Test facility for feasibility demonstration

- **YES**

What kind of facility we need



Proposal mentioned by Johannes Bernhard

proposal_rf.dvi (inspirehep.net)

A study of high gradient 201 MHz cavities in strong magnetic fields for the MICE experiment[1]

R. Bertoni[*], A. Blondel[†], M. Bogomilov[**], M. Bonesini[*], S.B. Bracker[‡], A. Bravar[†], A.D. Bross[§], S. Chattopadhyay[¶], L.M. Cremaldi[‡], A. DeMello[‖], S. Gilardoni[††], J.-S. Graulich[†], P. Hanlet[‡‡], G. Hanson[§§], F.D. Ingram[¶¶], D.M. Kaplan[‡‡], D. Li[‖], K. Long[***], G. Lucchini[*], M. Martini[††], M. Miller[¶¶], E. Montesinos[††], A. Moretti[§], A. Moss[†††], D. Neuffer[§], E. Norbeck[¶¶], J. Norem[‡‡‡], Y. Onel[¶¶], D. Orestano[§§§], M. Popovic[§], G. Prior[††], R.A. Rimmer[¶¶¶], C. Rogers, D.A. Sanders[‡], D.J. Summers[‡], E. Tiras[¶¶], L. Tortora[§§§], Y. Torun[‡‡], V. Verguilov[†], S. Virostek[‖] and M.S. Zisman[‖]

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STFC Rutheford Appleton Laboratory, Didcot, UK

Abstract. The early sections of the neutrino factory current design comprise high gradient normal conducting radio-frequency (RF) cavities embedded in high magnetic field. The performance of these cavities is known to degrade with magnetic field; but the exact nature of the phenomenon, its reproducibility and limitations are not well known. It is proposed to make use of the superconducting M1 magnet at CERN and surrounding infrastructure to test this behaviour. In a first step, which is the object of the present proposal, the 201 MHz RF cavities for the Muon Ionization Cooling Experiment (MICE) will be tested in a systematic way. The ten cavities built at Lawrence Berkeley National Laboratory (LBNL) will be brought to CERN and tested inside a standalone vacuum vessel, presently under design, to an accelerating gradient of the order of 10 MV/m or more as a function of magnetic field up to 3 T. The rate and spectrum of emission of electrons and x-rays will be measured. The experimental setup and instrumentation are described. The request from CERN amounts to 6 man months of technical manpower and up to 419 kCHF. On a longer time scale these measurements, which are complementary to those performed at Fermi National Accelerator Laboratory (Fermilab) for the neutrino factory and muon collider projects, can open the way to systematic studies of normal conducting cavity materials, in synergy with other projects involving warm RF cavities.

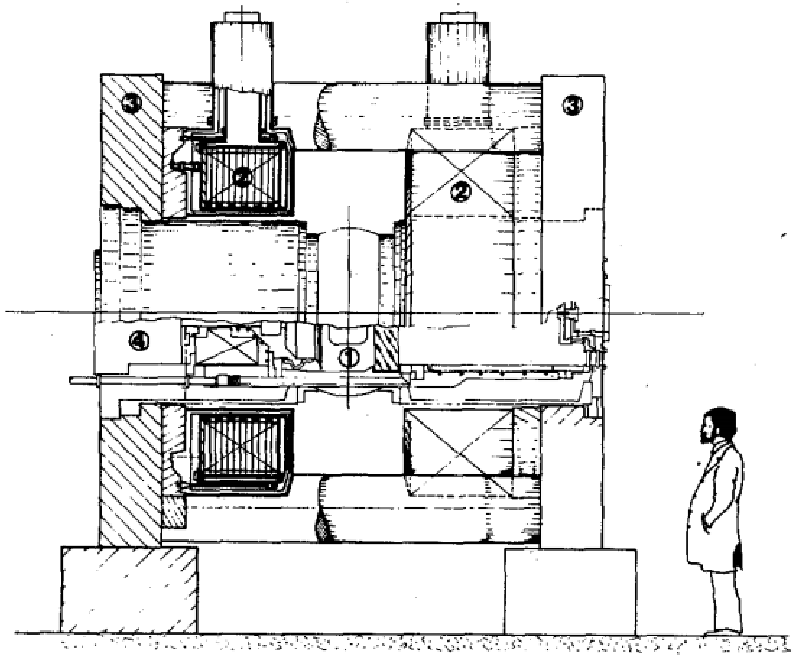
Contact: gersende.prior@cern.ch

718 IEEE TRANSACTIONS ON MAGNETICS, VOL. MAG-17, NO. 1, JANUARY 1981

SUPERCONDUCTING MAGNET FOR EHS

H. Desportes, R. Duthil, J.C. Gélébart, C. Leschevin, C. Lesmond.

CEA/Saclay, DPh/PE-STIPE (France)



① R.C.B.C.
② COILS
③ IRON YOKE
④ EXPANSION SYSTEM

Fig. 1 - Schematic view of RCBC and superconducting magnet.

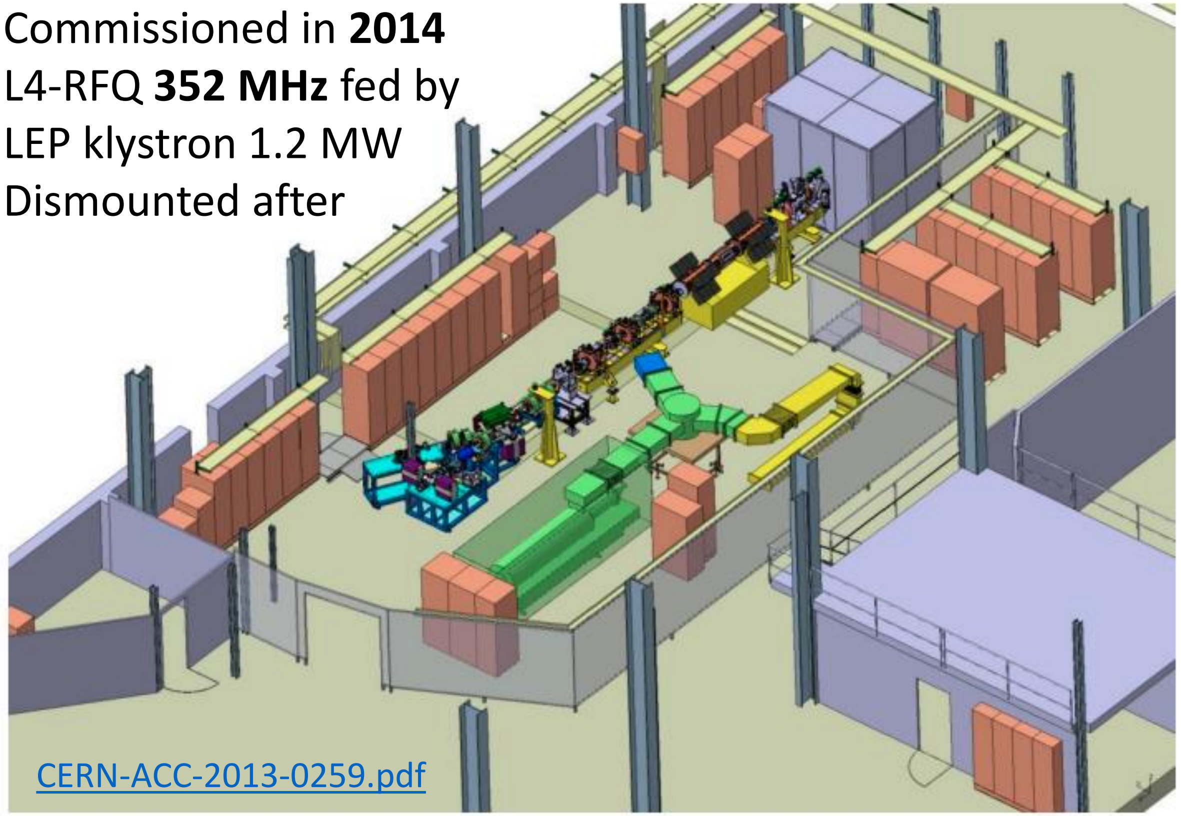
TABLE I

Room temperature bore	1.4 m
Room temperature gap between coils	0.82 m
Acceptance angle from central plane	±18°
Overall O.D. of cryostats	2.8 m
Winding I.D.	1.65 m
Winding O.D.	2.4 m
Axial length of each coil winding	0.46 m
Distance between windings	1.13 m
Number of double pancakes per coil	13
Number of turns per double pancake	84
Conductor dimensions	14.8 x 8.6mm^2
Spacing between pancakes	3 mm
Nominal current	4000 Amps
Central field	3 T
Peak field on the conductor	5.8 T
Total Amp x turns	8.74 10^6
Stored energy	55 MJ
Conductor weight	8 tonnes
Total weight per coil (at 4.2 K)	12 tonnes

- **Proposal might be reconsidered**
- **RF must be brought to the magnet**
- **Cost estimate 2010: ~0.5MCHF**

RF test infrastructure at CERN: an example
CERN 3 MeV test stand with L4-RFQ RF station

Commissioned in **2014**
L4-RFQ **352 MHz** fed by
LEP klystron 1.2 MW
Dismounted after



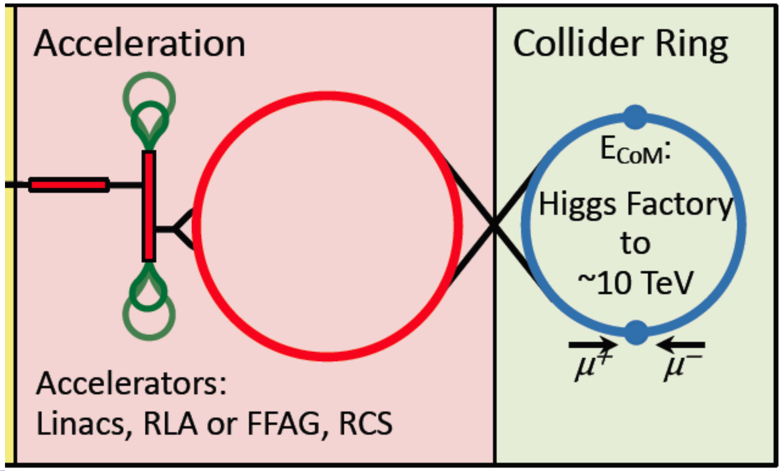
CERN-ACC-2013-0259.pdf

Figure 2 View of the 3 MeV test stand in the PS South Hall extension

- **L4-RFQ Spare project** – a new project initiated in **2020**
- Short-term goals:
  - Construct a spare copy of L4-RFQ (2021 – 2022)
  - Commission new RFQ with RF and beam in reinstalled 3 MeV test stand (2022 – 2023)
  - Make L4-RFQ spare available for replacement in L4
- Long-term goals: Develop a new RFQ with better expected performance in terms of
  - beam acceptance
  - resilience to RF breakdowns under H- irradiation
- There is a potential for synergies:
  - High gradient under irradiation (p, H-)
  - Different material (Cu, CuCrZr, CuBe, Ta, Nb, Ti6Al4V)
  - Resources, infrastructure
- **NO MAGNET, NO CRYOGENICS**
- **NO RADIATION SCHELDING**

Acceleration

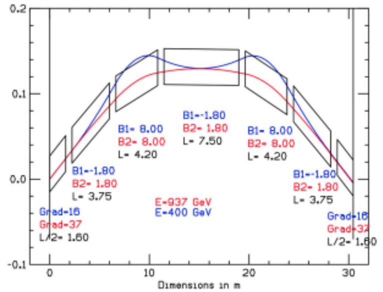
- Limited muon lifetime requires **highest** possible acceleration rate
- Although the rate is defined mainly by the magnets ramping rate, the SRF must follow with required **(very high) voltage**
- Small number of turns (~100) for very high collision energy ~10 TeV requires very high **voltage: ~100 GV**
- It operates in quasi pulsed mode;
  - RF is on only during acceleration (~ 10 ms)
  - Transients
- Longitudinal bunch compression/manipulation require **additional voltage**
- **Highest gradient for 'compact' RF system**



Muon Acceleration to 4 TeV in the LEP Tunnel

- LEP Tunnel. Neuffer, Shiltsev, JINST 13 (2018) T10003
  Interleave 16T (13%) and ramping ∓1.9T (87%) dipoles

Tunnel	Circ. m	B(max) T	Pack Frac	RF GV	orbits	freq. Hz	muon surv	E_{final} TeV
ISR	942	1.8	0.78	1	48	1260	0.81	0.063
SpS	6900	1.8	0.76	15	26	360	0.85	0.45
LEP	26 700	3.7	0.85	50	71	70	0.83	4



Interleaved ramping/fixed superconducting dipole example. arXiv:0707.0302
Lucien Cremaldi is running Bob Palmer's 2007 path length Basic code
Must adjust muon orbital radius to stay in phase with the SRF

Monday, 5 October 2020
Muon Collider Meeting
CERN (page 11)
Don Summers
U. of Mississippi–Oxford

Acceleration (cont.)

- Very large bunch charge:
  - In collider ring: $2x10^{12}$
  - In accelerators: $(4\text{->}2)x10^{12}$
- Short bunch length: 1 mm
- Cause strong **collective effects** which must be mitigated
  - **Large Aperture**
  - **Highest possible gradient**
  - Novel designs

Tentative Target Parameters

FCC-ee	Parameter	Unit	3 TeV	10 TeV	14 TeV
	L	10^{34} cm^{-2}s^{-1}	1.8	20	40
0.2	N	10^{12}	2	2	2
	f_r	Hz	6	4	4
	P_{beam}	MW	5.8	12.8	17.9
	C	km	4.5	10	14
	<B>	T	7	10.5	10.5
	ε_L	MeV m	7.5	7.5	7.5
	σ_E / E	%	0.1	0.1	0.1
2.4	σ_z	mm	5	1.5	1.07
	β	mm	5	1.5	1.07
	ε	µm	25	25	25
	$\sigma_{x,y}$	µm	3.0	0.9	0.63

Scaled from MAP parameters

Emittance is constant
$$\sigma_E \sigma_z = \text{const}$$

Collider ring acceptance is constant
$$\frac{\sigma_E}{E} = \text{const}$$

Bunch length decreases
$$\sigma_z \propto \frac{1}{\gamma}$$

Betafunction decreases

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

D. Schulte   Muon Colliders, CERN, July 3, 2020   6

Single bunch beam loading (energy spread):
Energy spread ~ Loss factor x Bunch charge

R&D directions for SRF for muon acceleration

- Highest possible gradient
  - Pulsed operation of ~0.1ms (LA) -> ~10ms (RCS) may help
- Large aperture, low loss factor
- Design of the cavities combining the above (contradicting) points must be driven by
  - High gradient considerations
  - Longitudinal beam dynamic requirements
  - Overall design of the RF system
  - Efficiency and Cost
- The design might need (must have) high gradient validation

Required RF Test facility for feasibility demonstration

- **MAYBE (YES)**

Acknowledgements

- I would like to acknowledge usage of material from:
  - MAP collaboration: Muon Accelerator Program
  - International Muon Collider Collaboration: Accelerator Design

Thank you !

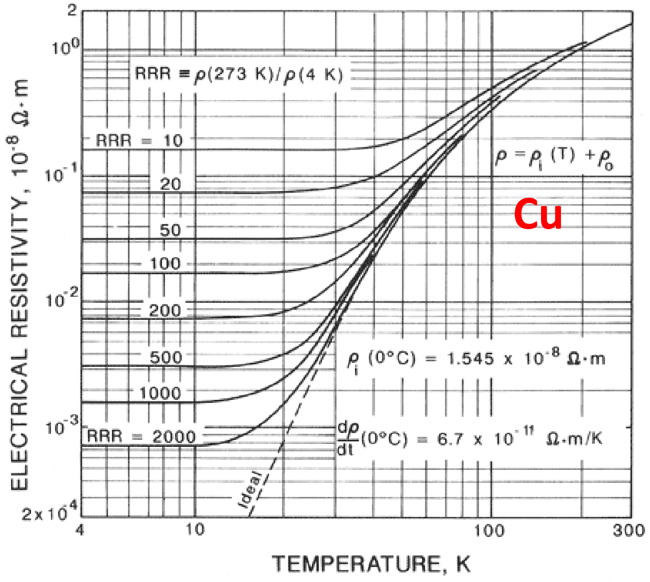
Spare slides

Cryogenic operation of NC cavities

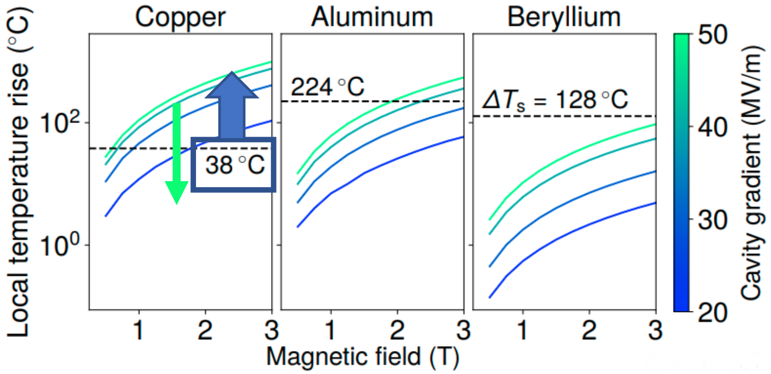
[RF technology challenges discussion, MC workshop, 2019 (cern.ch)]

Cavities are already in the cryogenic environment of the SC solenoids

- Higher gradients require even higher RF power:
  - V=const, G x 2 => P x 2
- **Low temperature reduce ohmic losses: P x 1/3 or even lower**



- RF breakdown (BD) strength in high magnetic field depends on thermo-mechanical properties
- Field emission induced pulsed heating model predicts (PRAB 23, 072001):



Local temperature rise

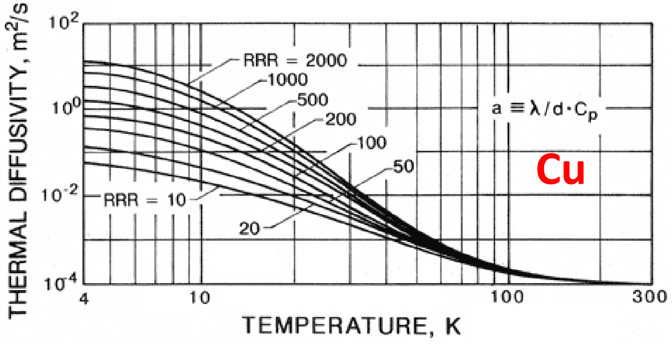
$$\Delta T = \frac{2\alpha_d}{qK_{th}R_f^2} \times \int_0^{\tau_{add}} Idt' \left(\int_0^{R_f} dR' \frac{1}{4\pi\alpha_d(t-t')} R' e^{-\frac{R^2+R'^2}{4\alpha_d(t-t')}} I_0\left(\frac{RR'}{2\alpha_d(t-t')}\right)\right) \times \left(\int_0^D dz' \frac{1}{\sqrt{4\pi\alpha_d(t-t')}} \left[e^{-\frac{(z-z')^2}{4\alpha_d(t-t')}} + e^{-\frac{(z+z')^2}{4\alpha_d(t-t')}} \right] \frac{dE}{dz'} \right)$$

Threshold: (38K for Cu@300K)

$$\Delta T_s = \frac{(1-\nu)\sigma_y}{\epsilon\alpha}$$

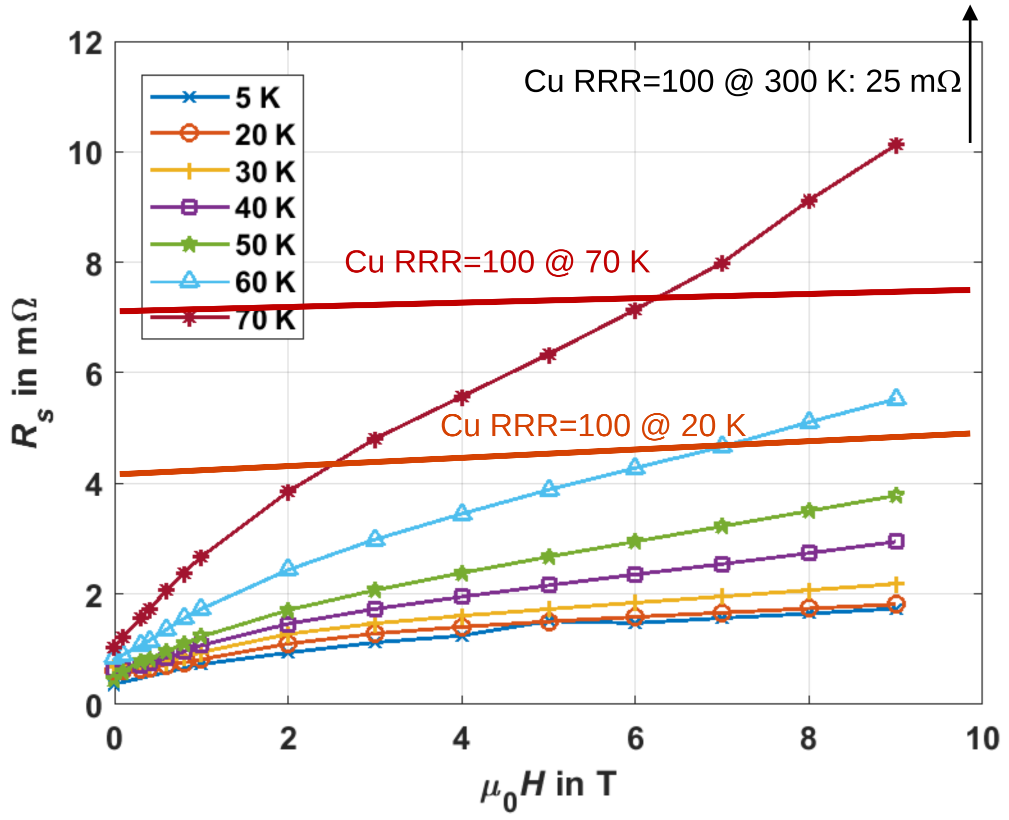
- **Low temperature improves thermal and mechanical properties**

=> Higher BD strength



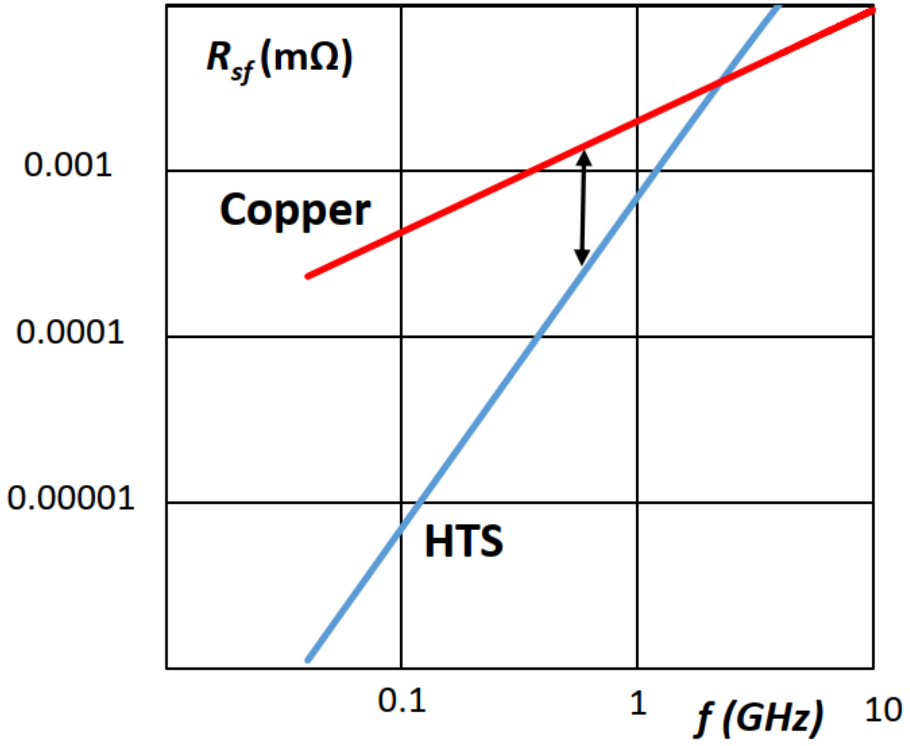
HTS for RF applications

HTS coated conductor at 8 GHz



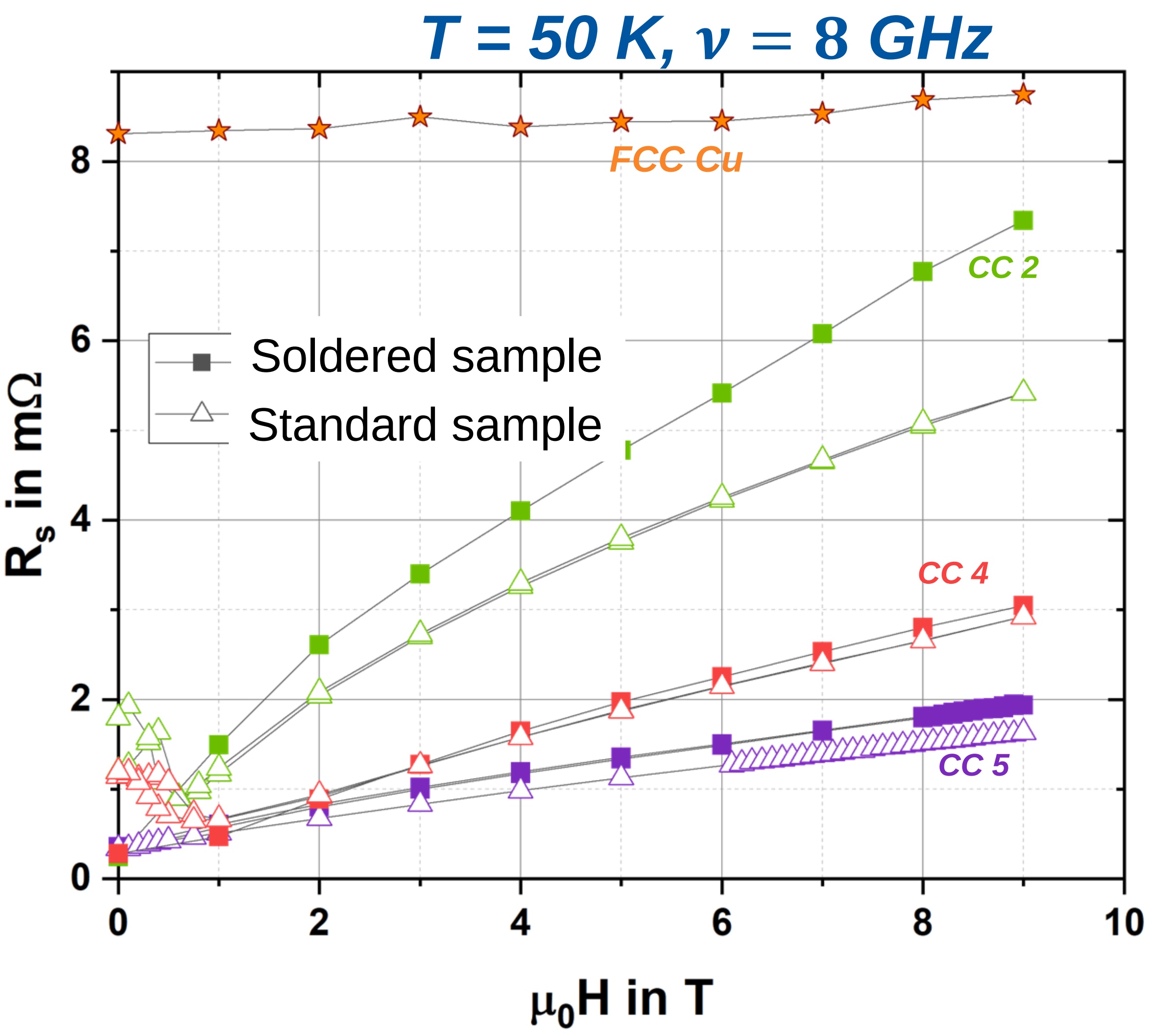
T Puig *et al* 2019 *Supercond. Sci. Technol.* **32** 094006

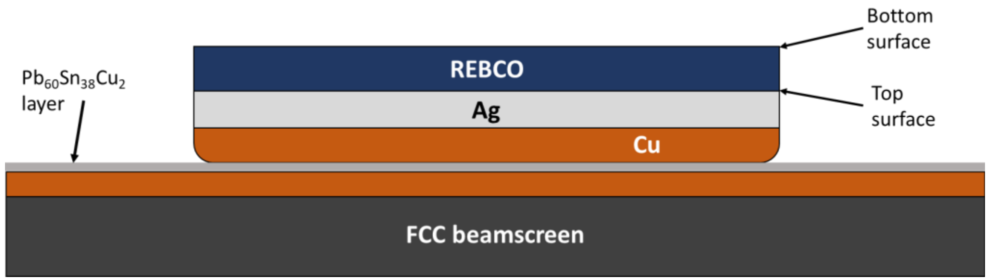
Frequency scaling HTS vs Cu at 9 T



From: Teresa Puig – ICMAB. Developments of HTS Coated Conductors for the FCC-hh beam screen impedance mitigation

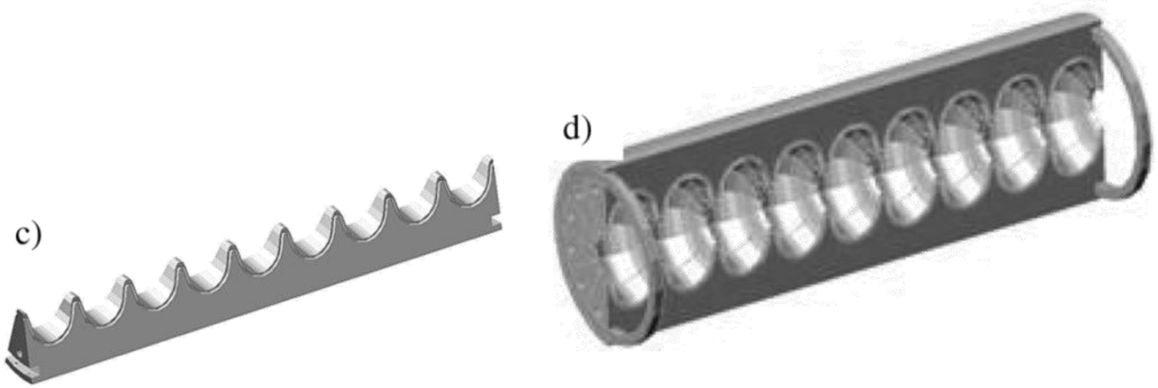
Soldering of HTS coated conductors





Soldering mostly preserves properties

This could be used in a cavity made in sectors



Peter McIntyre, Nathaniel Pogue, and Akhdiyor Sattarov

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 19, NO. 3, JUNE 2009

Initial acceleration

- Limited muon lifetime requires highest possible accelerating gradient to reach higher energies
- Large emittance require large acceptance
  - Additional voltage
  - Low frequency
  - Large aperture
- Very large bunch charge: ~5x10^{12} causes collective effects which must be addressed
- Transmission and decay beam losses
- Strong focusing magnets with large apertures
  - Stray magnetic fields
  - Low filling factor
  - Cryogenic NC RF might help in the linac