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CERN

RF CHARACTERIZATION TECHNIQUES OF 1.3 GHz CAVITIES

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INTRODUCTION

Introduction

Framework

The European Strategy for Particle Physics (ESPP) recommended to increase the R&D on high gradient accelerating structures, among others, in the context of the FCC project.

Desired FCC timeline :

One of our main objectives within the FS is to enlarge the range of machine parameters in which Nb/Cu can be competitive with the state of the art bulk Nb in terms of global cost optimization.

F. Gianotti, "Opening, CERN vision and plans until 2025 ", *FCC Week 2021* (2021).
M. Benedikt, "Roadmap for the FCC Feasibility Study", *FCC Week 2021* (2021).

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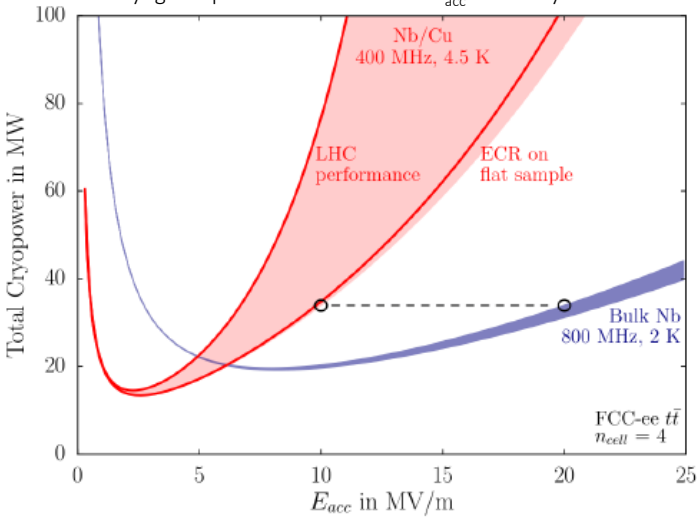
Introduction

Performance goals: *a moving target*

- R/D ongoing at CERN (joint effort between groups MME-VSC-RF) during the last years to push performance of Nb/Cu using 1.3 GHz mono cells, which are the international standard for SRF.
- Preliminary survey of materials and performance goals was done during CDR phase (see ref.)
- Nb/Cu HIPIMS coatings displayed optimized R_{BCS} below 300 nΩ at 1.3 GHz, and mitigated Q-slope.
- HIE-ISOLDE seamless QWR reached 120 mT at 100 MHz → no special field limits for Nb/Cu.
- By simple scaling and reasonable assumptions on R_{res} we can aim to R_s=50-90 nΩ (~3-5 10^9) at 400 MHz, 10 MV/m and 4.5 K.
- Performance targets and breakeven points are being reviewed for all frequencies considered for FCC, including 600 MHz, based on the recent developments of the 1.3 GHz program.

Cryogenic power as a function of E_{acc} in the cryomodule



S. Aull et al., Report number: CERN-ACC-2018-0019

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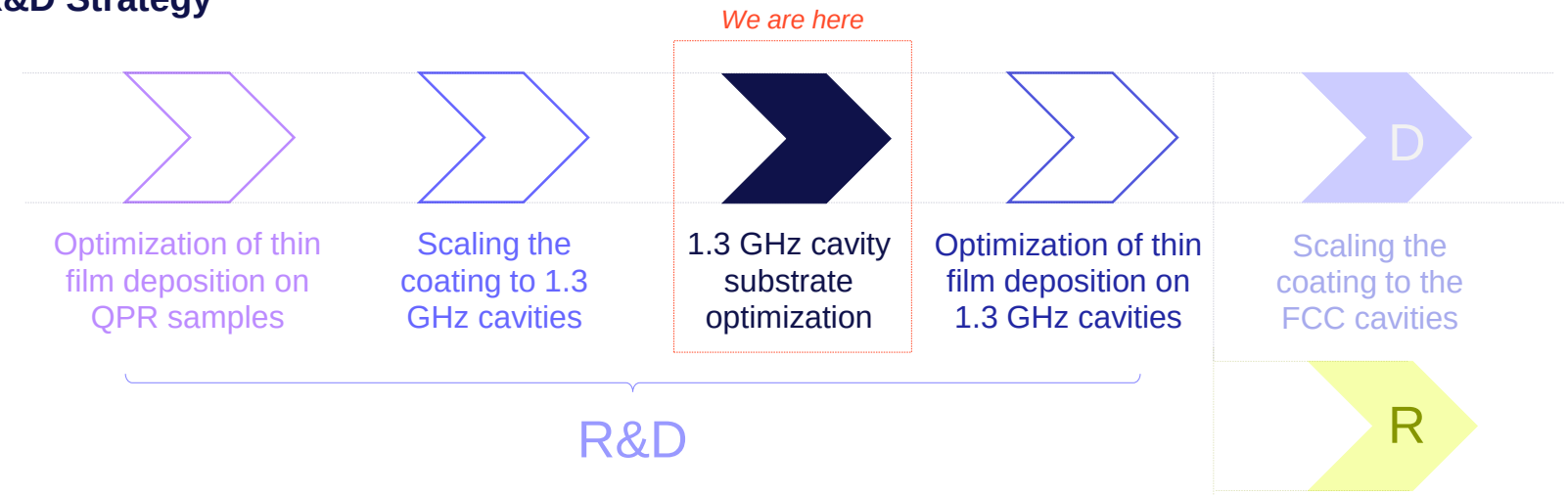
RF CHARACTERIZATION TECHNIQUES

RF Characterization Techniques

R&D Strategy



Push the Nb/Cu performance limits on 1.3 GHz cavities

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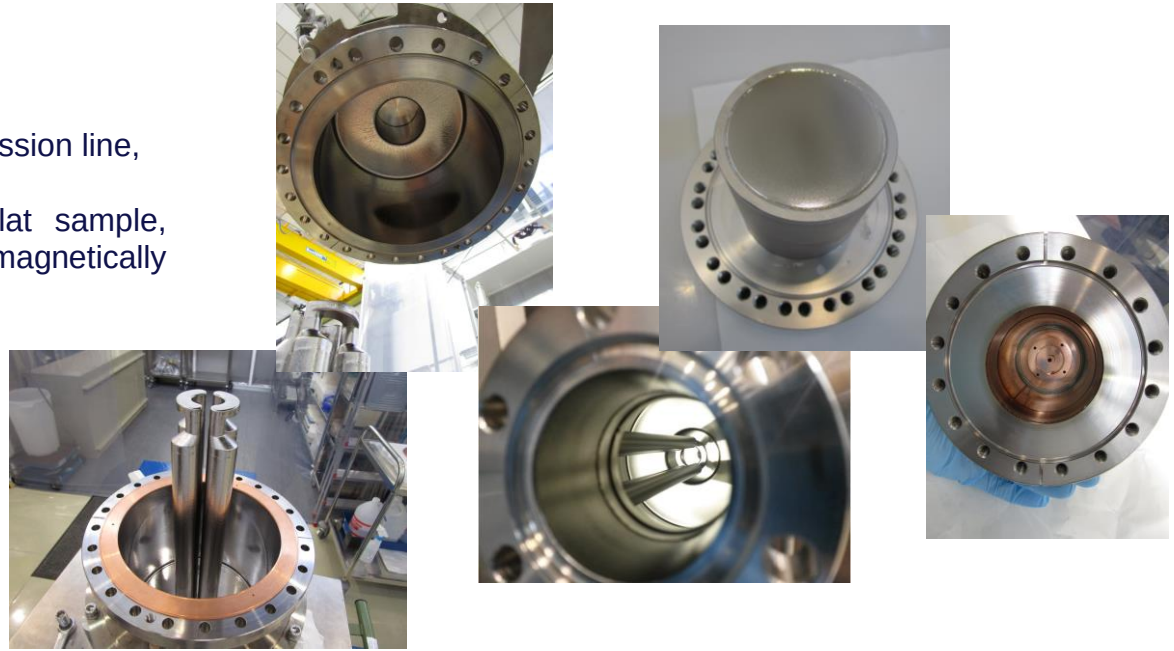
RF Characterization Techniques

Description

Quadrupole Resonator (QPR):

- Enclosed bulk Nb 4-wire transmission line,
- short-circuited by pairs,
- and coupled to the coaxial flat sample, which is thermally and electromagnetically isolated.



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RF Characterization Techniques

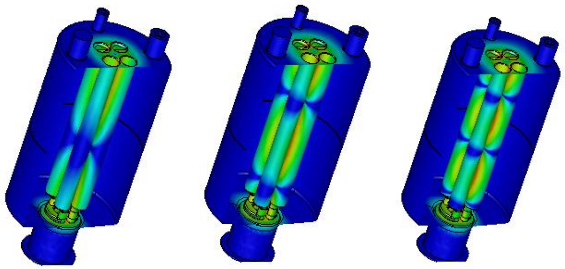
Description

Quadrupole Resonator (QPR):

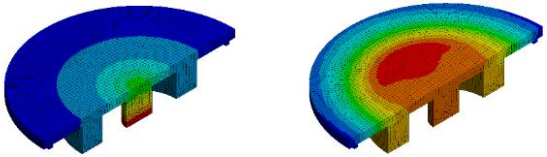
- Operating modes at 400, 800, and 1200 MHz.
- Three-antenna configuration:
  - Two *overcoupled* antennas operating critically coupling.
  - One *undercoupled* to calibrate the system.
- Thermal compensation to calculate the RF losses using:
  - one DC heater in the center,
  - four coaxial diode thermometers;

  in thermal contact with the sample and under UHV.
- Magnetic field compensation.

Accurate, wide ohmic range and stable RF measurements setting B_{pk} , T, and f lets to compare the fitted R_{res}, $\Delta(0)$, A_{BCS}, $\lambda(0)$, and T_c between samples.



$|H|$ 400MHz $|H|$ 800MHz $|H|$ 1200MHz



T=4.288 K from DC heater (0.021W) T=4.290 K from RF heat flux (0.021W)

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RF Characterization Techniques

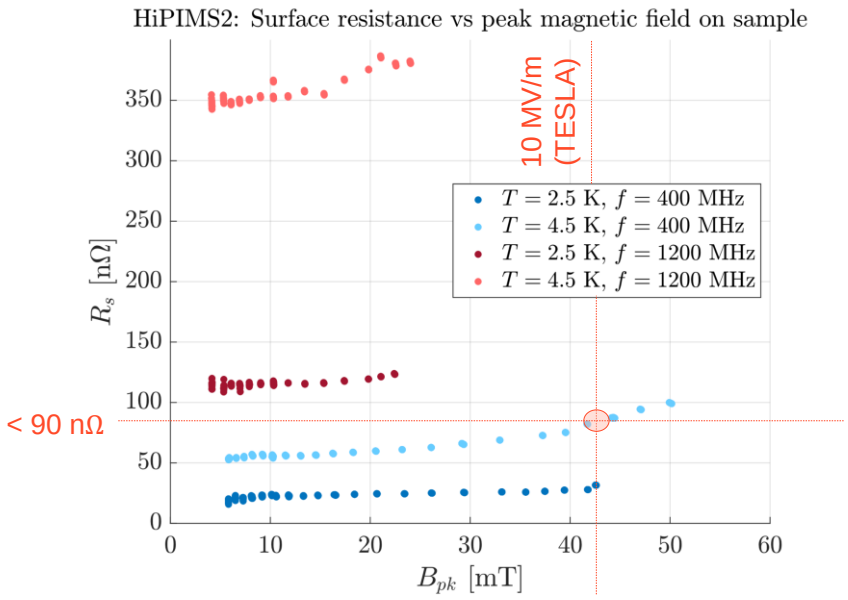
Results

Quadrupole Resonator (QPR):

HiPIMS2
- Mitigated Q-slope
- Relatively low residual

	400 MHz	1200 MHz
R_{res}	19.6 nΩ	100.8 nΩ

R_{res} ≅ 10 nΩ in best tested bulk Nb sample at 400MHz



L. Vega Cid, W. Venturini Delsolaro, G. Vandoni and G.J. Rosaz, "HiPIMS from QPR to 1.3 GHz cavities", *TTC2020* (2020).

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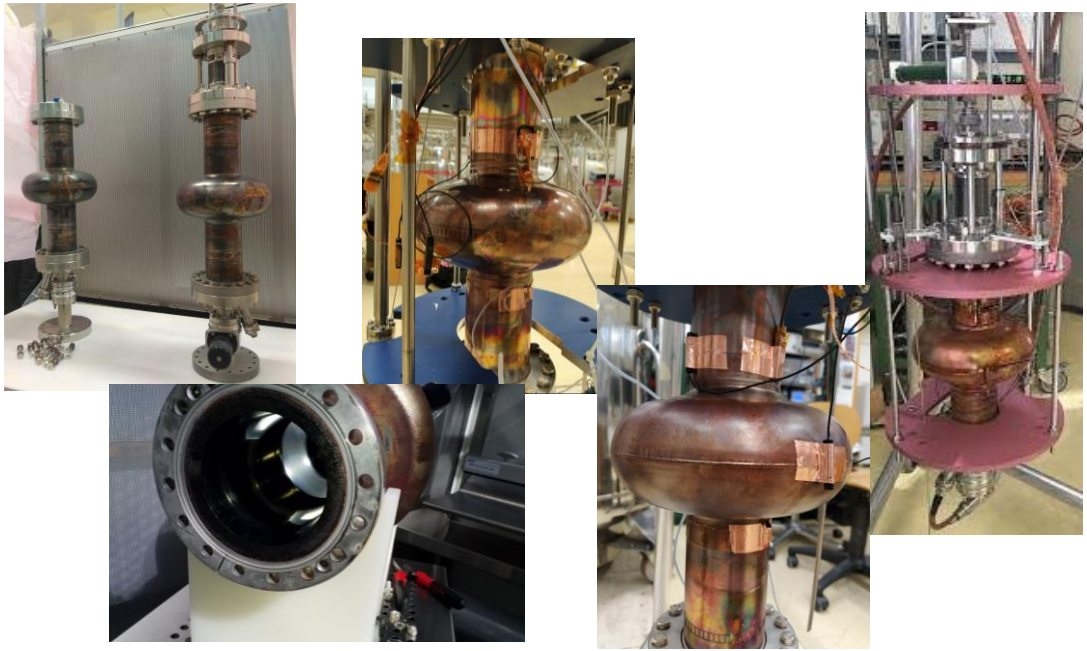
RF Characterization Techniques

Description

1.3 GHz cavity :

Substrates
- EB welded (W1)
- Seamless:
  - *Spun* (N1, N2, N3)
  - Bulk *machined* (BM1)
  - *Electroformed* (L1)

RF characterization
- Standard vertical test setup
- 4 fluxgates magnetometers
- 2 thermometers
- **Variable axial coupler:** to track the matching of the cavity during the test and so minimizing the measurement uncertainties.



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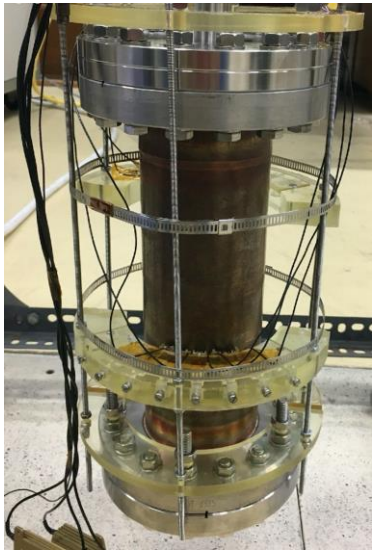
RF Characterization Techniques

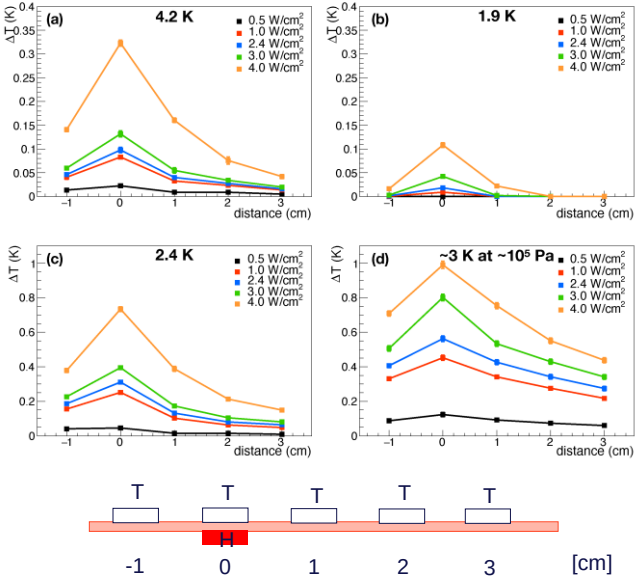
Diagnostic tools

Thermal mapping (T-map):

R&D studies:

- $\downarrow T_{bath} \Rightarrow \uparrow \Delta T$ (He-I).
- He-II $\Rightarrow \downarrow \Delta T$
- Subcooled He $\Rightarrow \uparrow \Delta T$





A. Bianchi, et al., "Thermal Mapping Studies on Nb/Cu SRF Cavities", paper THPCA007, *SRF'21* (2021).

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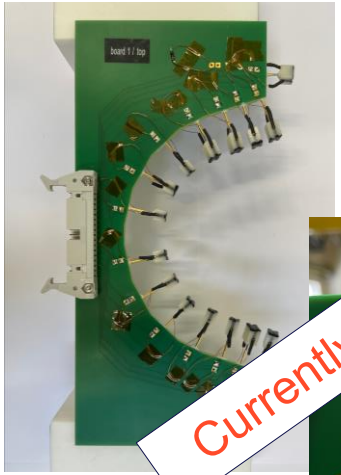
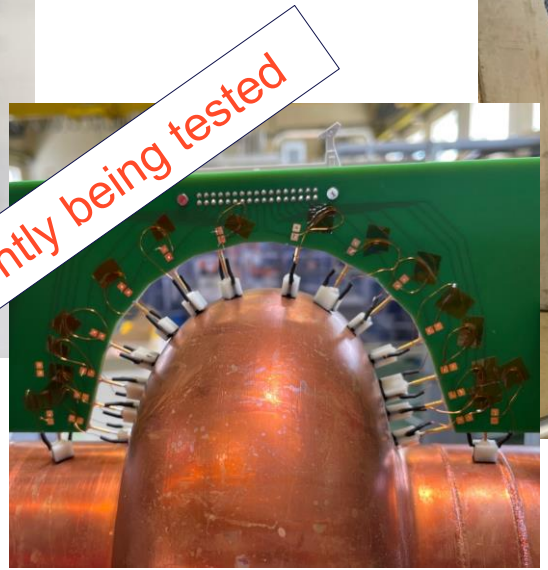
RF Characterization Techniques

Diagnostic tools

Thermal mapping (T-map):

Prototype under testing:
- 2 boards
- 16 thermometers/board





Currently being tested

A. Bianchi, et al., “Thermal Mapping Studies on Nb/Cu SRF Cavities”, paper THPCA007, *SRF’21* (2021)

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RF Characterization Techniques

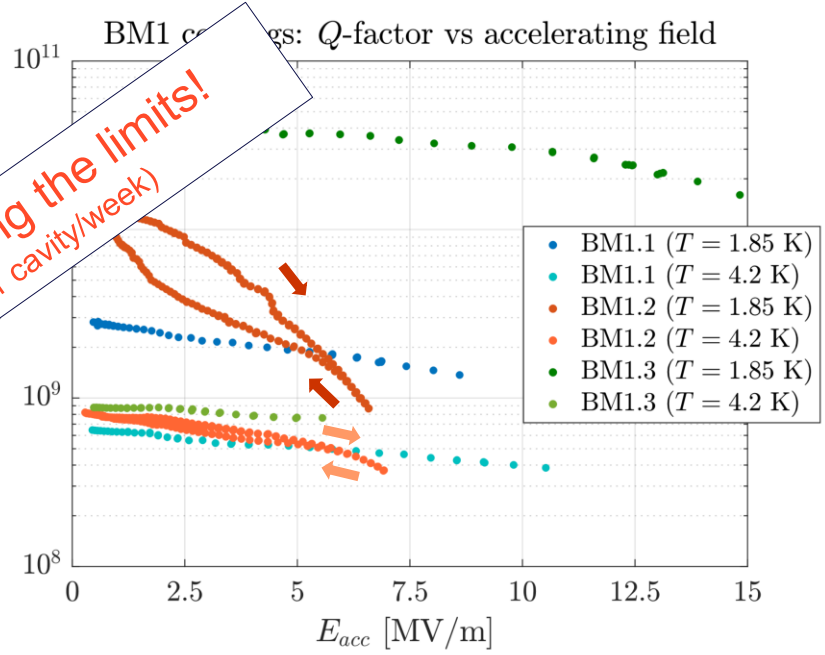
Results

1.3 GHz cavity (BM1 substrate) :

	BM1.1	BM1.2	BM1.3
R_{res}	95.6 nΩ	19.9 nΩ	4.4 nΩ
A_{BCS}	1.68e5 nΩ·K	1.56e5 nΩ·K	1.44e5
$\Delta(0)/k_B$	20.19 K	20.11 K	
$\lambda(0)$	53.96 nm	51.73 nm	m
T_c	9.317 K	9.312 K	9.321 K

Tests limited due to radiation interlock.

Keep on pushing the limits!
(testing rate: 1 cavity/week)



G.J. Rosaz, L. Vega Cid, W. Venturini Delsolaro, P. Vidal García, et al., "Seamless 1.3 GHz Copper Cavities for Nb coatings: Cold Test Results of Two Different Approaches", paper TUPTEV009, *SRF'21* (2021).

G.J. Rosaz, et al., "Superconducting Thin Film Studies at CERN", *FCC Week 2021* (2021).

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CONCLUSIONS AND FUTURE LINES

Wrap-up

The QPR has proved to be a very useful tool to compare different coatings and to optimize the coating recipe. In addition, it provides a unique testing environment in which the main physical parameters of the surface impedance (B_{pk}, T, and f) can be controlled.

For the Nb/Cu program, once reliable copper substrate become available, the optimization must continue using 1.3 GHz cavities.
The QPR is still used for the new materials (A15 on Cu), which are at a less advanced stage of development.

Thermal and magnetic mapping, and optical inspection tools are under development and will be instrumental for the scaling up to FCC frequencies.

The recent excellent results of the 1.3 GHz cavity are extremely encouraging, confirming that very low surface resistance can be maintained up 15 MV/m in Nb/Cu films. It is planned to study the high field behavior and the sensitivity to trapped flux in one of the vertical cryostats in SM18.

Progress was and is slowed down by ageing infrastructure and limited resources, which jeopardize the tight quality control which is necessary for SRF technology.

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Thank you for your attention

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RF Characterization Techniques

Description

Quadrupole Resonator (QPR) :

$$R_S = \frac{2{\mu_0}^2 P_{dis}}{\int_S |B|^2 dS} = \frac{2{\mu_0}^2 (P_{DC1} - P_{DC2})}{\int_S |B|^2 dS} = \frac{2{\mu_0}^2 c_1 (P_{DC1} - P_{DC2})}{c_2 U} =$$

$$= \boxed{R_S = \frac{{\mu_0}^2 c_1 (P_{DC1} - P_{DC2})}{c_2 (\tau P_L)}}$$

Simulations

$$\begin{cases} c_1 = \dfrac{B_{pk}^2}{\int_S |B|^2 dS} \\ c_2 = \dfrac{B_{pk}^2}{U} \end{cases}$$

RF measurables

$$\begin{cases} \tau \\ P_L = 2(P_F \pm \sqrt{P_F P_R}) \cong 2P_F \end{cases}$$

Control loop

$$\begin{cases} P_{DC1} \text{ (RF OFF)} \\ P_{DC2} \text{ (RF ON)} \end{cases}$$

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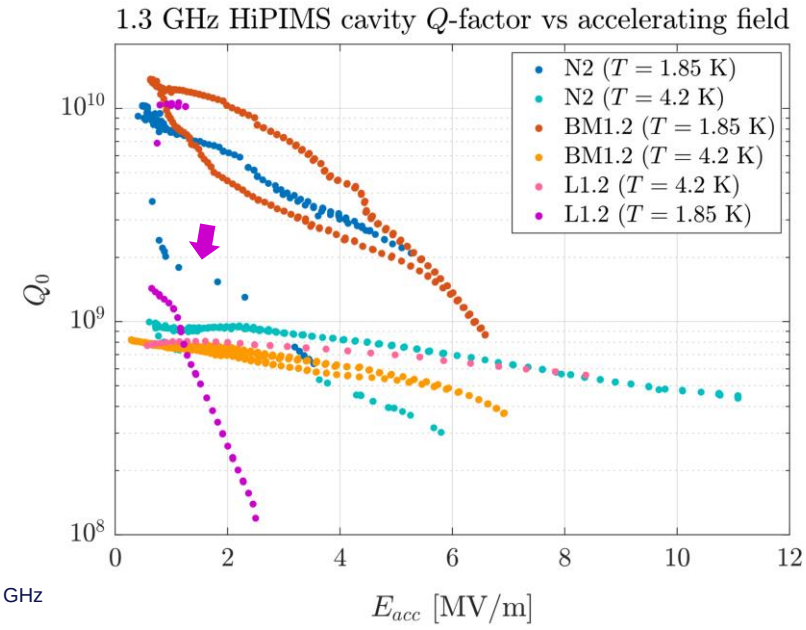
RF Characterization Techniques

Results

1.3 GHz cavity :

	N2	BM1.2	L1.2
R_{res}	32.4 nΩ	19.9 nΩ	23.9 nΩ
A_{BCS}	1.0e5 nΩ·K	1.7e5 nΩ·K	1.6e5 nΩ·K
max E_{acc} at 4.2 K	> 10 MV/m (Q switch)	< 10 MV/m (FE)	< 10 MV/m (FE)
Q-drop	X	X	?



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