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.

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 ($\sim 3-5 \times 10^9$) 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.
RF CHARACTERIZATION TECHNIQUES
RF Characterization Techniques

R&D Strategy

- Optimization of thin film deposition on QPR samples
- Scaling the coating to 1.3 GHz cavities
- 1.3 GHz cavity substrate optimization
- Optimization of thin film deposition on 1.3 GHz cavities
- Scaling the coating to the FCC cavities

We are here

R&D

Push the Nb/Cu performance limits on 1.3 GHz cavities

Horizon 2020
European Union Funding for Research and Innovation
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.
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.
RF Characterization Techniques

Results

Quadrupole Resonator (QPR):

HiPIMS2
- Mitigated $Q$-slope
- Relatively low residual

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>$R_{\text{res}}$ (nΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 MHz</td>
<td>19.6 nΩ</td>
</tr>
<tr>
<td>1200 MHz</td>
<td>100.8 nΩ</td>
</tr>
</tbody>
</table>

$R_{\text{res}} \approx 10$ nΩ in best tested bulk Nb sample at 400MHz

HiPIMS2: Surface resistance vs peak magnetic field on sample

$R_{\text{res}} \leq 90$ nΩ

$R_{\text{res}} \approx 10$ nΩ in best tested bulk Nb sample at 400MHz

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.
RF Characterization Techniques

Diagnostic tools

*Thermal mapping* (T-map):

R&D studies:
- $T_{\text{bath}} \Downarrow \Rightarrow \uparrow \Delta T$ (He-I).
- He-II $\Rightarrow \downarrow \Delta T$
- Subcooled He $\Rightarrow \uparrow \Delta T$

RF Characterization Techniques

Diagnostic tools

*Thermal mapping (T-map)*:

Prototype under testing:
- 2 boards
- 16 thermometers/board
RF Characterization Techniques

Results

1.3 GHz cavity (BM1 substrate):

<table>
<thead>
<tr>
<th></th>
<th>BM1.1</th>
<th>BM1.2</th>
<th>BM1.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{res}}$</td>
<td>95.6 nΩ</td>
<td>19.9 nΩ</td>
<td>4.4 nΩ</td>
</tr>
<tr>
<td>$A_{\text{BCS}}$</td>
<td>1.68e5 nΩ·K</td>
<td>1.56e5 nΩ·K</td>
<td>1.44e5 nΩ·K</td>
</tr>
<tr>
<td>$\Delta(0)/k_B$</td>
<td>20.19 K</td>
<td>20.11 K</td>
<td></td>
</tr>
<tr>
<td>$\lambda(0)$</td>
<td>53.96 nm</td>
<td>51.73 nm</td>
<td>50.30 nm</td>
</tr>
</tbody>
</table>

Tests limited due to radiation interlock.

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


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.
Thank you for your attention
RF Characterization Techniques

Description

Quadrupole Resonator (QPR):

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

Simulations

\[ c_1 = \frac{B_{pk}^2}{\int_S |B|^2 dS} \]
\[ c_2 = \frac{B_{pk}^2}{U} \]

RF measurables

\[ \tau \]
\[ P_L = 2(P_F \pm \sqrt{P_F P_R}) \approx 2P_F \]

Control loop

\[ P_{DC1} \quad \text{(RF OFF)} \]
\[ P_{DC2} \quad \text{(RF ON)} \]
RF Characterization Techniques

Results

1.3 GHz cavity:

<table>
<thead>
<tr>
<th></th>
<th>N2</th>
<th>BM1.2</th>
<th>L1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{res}$</td>
<td>32.4 nΩ</td>
<td>19.9 nΩ</td>
<td>23.9 nΩ</td>
</tr>
<tr>
<td>$A_{BCS}$</td>
<td>1.0e5 nΩ·K</td>
<td>1.7e5 nΩ·K</td>
<td>1.6e5 nΩ·K</td>
</tr>
<tr>
<td>max $E_{acc}$ at 4.2 K</td>
<td>&gt; 10 MV/m (Q switch)</td>
<td>&lt; 10 MV/m (FE)</td>
<td>&lt; 10 MV/m (FE)</td>
</tr>
<tr>
<td>$Q$-drop</td>
<td>X</td>
<td>X</td>
<td>?</td>
</tr>
</tbody>
</table>

1.3 GHz HiPIMS cavity $Q$-factor vs accelerating field

