Superconducting Cavity for Dark Matter Axion Search

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Dark Matter Axion Search & Superconducting Cavity R&D

II
Superconductor in a High Magnetic Field & Material Evaluation

III
Biaxially-Textured ReBCO Tapes, Polygon Geometry & First Prototype

IV
2.3 GHz Half-million Quality Factor ReBCO Cavity & Commissioning Run

V
Future Plan for Enhanced Axion Search using the ReBCO Cavity

(Credit: ESO/L. Calçada)
Dark Matter Axion Search (Axion Haloscope)

\[ P_{\alpha \gamma \rightarrow \gamma} = g_{\alpha \gamma \gamma} \frac{\rho_a}{m_a^2} B^2 V \omega_0 C \frac{Q_a Q_c}{Q_a + Q_c} \]

Kim et al. JCAP03(2020)066

Sikivie PRL(1983)1415

(Credit: ESO/L. Calçada)
Revisiting Quality Factor

➢ Definition of Quality Factor

\[ Q = \frac{\omega_0 U}{P_{loss}} \]

Angular Frequency \( \omega_0 \) Internal Energy \( U \)

Quality Factor \( Q \)

Total Energy Loss \( P_{loss} \)

➢ Decomposing Origins of Energy Loss

\[ P_{surf} \propto R_s \]

Surface Current Loss

\[ \frac{1}{Q} = \frac{P_{loss}}{\omega_0 U} = \frac{1}{\omega_0 U} \left( P_{surf} + P_{vol} + P_{rad} \right) \]

Volume Loss \( P_{vol} \)

Wave Propagation (Radiation) \( P_{rad} \)
Revisiting Quality Factor

➢ Definition of Quality Factor

\[ Q = \frac{\omega_0 U}{P_{\text{loss}}} \]

Angular Frequency \( \omega_0 \) \( U \) Internal Energy

Quality Factor \( Q \) Total Energy Loss

➢ Decomposing Origins of Energy Loss

\[ P_{\text{surf}} \propto R_s \]

\[ \frac{1}{Q} = \frac{P_{\text{loss}}}{\omega_0 U} = \frac{1}{\omega_0 U} \left( P_{\text{surf}} + P_{\text{vol}} + P_{\text{rad}} \right) \]

Surface Current Loss

Volume Loss

\( \tan\delta \) Low Loss Tangent

Low Loss Tangent

Controlled by Geometric Design

Low Loss

High Q
Revisiting Quality Factor

Definition of Quality Factor

\[ Q = \frac{\omega_0 U}{P_{loss}} \]

Decomposing Origins of Energy Loss

\[ P_{surf} \propto R_s \]

- **Low Surface Resistance** → Superconductor (SC)

\[ 1 \left( \frac{1}{Q} \right) = \frac{P_{loss}}{\omega_0 U} = \frac{1}{\omega_0 U} \left( P_{surf} + P_{vol} + P_{rad} \right) \]

- **High Q**

2021 Patras Workshop
Dark Matter Axion Search (Axion Haloscope)

Photon ($\gamma$) → Virtual Photon ($\gamma'$)

$P_{\alpha\gamma\rightarrow\gamma'} = g_{\alpha\gamma\gamma'} \frac{\rho_\alpha}{m_\alpha^2} B^2 V \omega_0 C \frac{Q_a Q_c}{Q_a + Q_c}$

Dark Matter Halo

Our Galaxy

High Magnetic Field

Axion Mass

Axion Quality Factor

Kim et al. JCAP03(2020)066

Sikivie PRL(1983)1415

(Credit: ESO/L. Calçada)
Superconductor in a High Magnetic Field

Three Phases of Type II Superconductor

- An external magnetic field can degrade Superconductivity.
- In a mixed state, type 2 SCs make vortices inside.
- Vortex pinning can make a low dissipative surface. (low $R_s$)
- SC Materials with a higher upper critical field ($H_{c2}$) have higher melting field ($H_m$) of vortices.
- High-temperature superconductors (HTS) are promising for making high Q factor cavities for axion haloscope.
## Material Evaluation

<table>
<thead>
<tr>
<th></th>
<th>$R_s$ (B = 0 T) (Ohm)</th>
<th>$R_s$ (B = 8 T, $∥c$) (Ohm)</th>
<th>Critical Field ($H_{c2}$)</th>
<th>Depinning Frequency</th>
<th>Film Fabrication Method</th>
<th>Cavity Fabrication</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OFHC Cu (Metal)</strong></td>
<td>~ 7E-3</td>
<td>~ 7E-3</td>
<td>None</td>
<td>None</td>
<td>Yes</td>
<td>Machining</td>
</tr>
<tr>
<td><strong>NbTi (LTS)</strong></td>
<td>~ 1E-6</td>
<td>~ 4e-3</td>
<td>~ 13 T</td>
<td>~ 45 GHz</td>
<td>Deposition (No Texture Requirement)</td>
<td>Deposition</td>
</tr>
<tr>
<td>Gatti et al. PRD(2019)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bi-2212 (HTS)</strong></td>
<td>~ 1E-5</td>
<td>?</td>
<td>&gt; 100 T ($∥ab$)</td>
<td></td>
<td>Weak Pinning</td>
<td></td>
</tr>
<tr>
<td>Bi-2223 (HTS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TI-1223 (HTS)</strong></td>
<td>~ 1E-5</td>
<td>~ 1e-4</td>
<td>&gt; 100 T ($∥ab$)</td>
<td>12 – 480 MHz</td>
<td>Deposition (No Texture Requirement)</td>
<td>Deposition</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ReBCO (HTS)</strong></td>
<td>~ 1E-5</td>
<td>~ 1e-4</td>
<td>&gt; 100 T ($∥ab$)</td>
<td>10 – 100 GHz</td>
<td>Deposition (Biaxial Texture)</td>
<td>1. Deposition 2. Using Tapes</td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
</table>

- **Critical Field ($H_{c2}$)**: The critical field is the magnetic field at which the material transitions from a superconducting state to a normal state.
- **Depinning Frequency**: The frequency at which the depinning of defects occurs.
- **Film Fabrication Method**:
  - Deposition (No Texture Requirement)
  - Deposition (Biaxial Texture)
  - Machining
- **Cavity Fabrication**: Indicates the method used for cavity fabrication.

**References**:
- Calatroni et al. SUST (2017)
- Romanov et al. Scientific Reports (2020)
- Ormeno et al. PRB (2001)
- Gatti et al. PRD (2019)
Biaxially Textured ReBCO Tape


- Biaxially-textured Rare-earth Barium Copper Oxide (ReBCO) films consist of strong links.
- It shows good performance of surface resistance in a high magnetic field at low temperature.
- Its depinning frequency is also high enough. (> 10 GHz)
- There are many providers that fabricate biaxially-textured ReBCO tapes.
Biaxially Textured ReBCO Tape

➢ Biaxially-Textured ReBCO films have anisotropy of surface resistance due to their crystal structure.

➢ The surface resistance of a film is maximized when the c axis of a crystal and the direction of an external magnetic field is parallel to each other.

➢ Directions of a ReBCO crystal should be considered to design a cavity.

How to make 3D surface with tapes?
Making 3D Surfaces with Tapes

CAPP’s Solution
Polygon Shape: From Planar Surfaces to a 3D Surface

12 Polygon, 12 Tapes

16 Polygon, 32 Tapes
The Advantages of the Polygon Cavity

Tape Direction: Minimized Surface Resistance
Vertical Cut: Avoiding Contact Problem

- Electric and Magnetic Field
- 6.85 GHz

- Surface Current
- Electric and Magnetic Field

Maximum current at the middle (parallel to ab)

Θ = 90 deg

9mm

Surface Resistance

Tape Direction: Minimized Surface Resistance
Vertical Cut: Avoiding Contact Problem

- Electric and Magnetic Field
- 6.85 GHz

- Surface Current
- Electric and Magnetic Field

Maximum current at the middle (parallel to ab)

Θ = 90 deg

9mm

Surface Resistance
First Prototype Cavity

- (2019) First Prototype HTS Cavity (with Prof. Dojun Youm)
  - (March 8\textsuperscript{th}) Q \approx 150,000 at 8 T
  - (August 15\textsuperscript{th}) Q \approx 330,000 at 8 T (Improved Tape Edge)

ArXiv: 1904.05111
ArXiv: 2103.14515
PRApplied Submitted
2.3 GHz Axion Search Cavity

➢ (2019 – 2020) 2.3 GHz ReBCO Cavity (Dr. Seongtae Park)
2.3 GHz Axion Search Cavity

➢ 2.3 GHz ReBCO Cavity (Dr. Seongtae Park)

✓ (December 8th, 2019) $Q \sim 340,000$ at 8 T

✓ (January 18th, 2020) $Q \sim 500,000$ at 8 T (Using Different Tape)
Tuning System

Simplified Tuning Simulation

- **h** = depth

<table>
<thead>
<tr>
<th>Resonant Frequency (Hz)</th>
<th>Q Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.80E+09</td>
<td></td>
</tr>
<tr>
<td>1.90E+09</td>
<td></td>
</tr>
<tr>
<td>2.00E+09</td>
<td></td>
</tr>
<tr>
<td>2.10E+09</td>
<td></td>
</tr>
<tr>
<td>2.20E+09</td>
<td></td>
</tr>
<tr>
<td>2.30E+09</td>
<td></td>
</tr>
<tr>
<td>2.40E+09</td>
<td></td>
</tr>
</tbody>
</table>

- **TE112**
  - No Mode Crossing

- **TM010**
  - Small Q Drop

- **TE111**

<table>
<thead>
<tr>
<th>Form Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.25E+09</td>
</tr>
<tr>
<td>2.27E+09</td>
</tr>
<tr>
<td>2.29E+09</td>
</tr>
<tr>
<td>2.31E+09</td>
</tr>
</tbody>
</table>

- **Small C Drop**

2021-06-15

2021 Patras Workshop
### Testing in a CAPP-PACE Chain

<table>
<thead>
<tr>
<th></th>
<th>HEMT Run</th>
<th>JPA Run</th>
<th>SC Run (Plan)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency Range</td>
<td>2.457 – 2.749 GHz</td>
<td>2.27 – 2.30 GHz</td>
<td>2.27 – 2.30 GHz</td>
</tr>
<tr>
<td>Magnetic Field (B)</td>
<td>7.2 T</td>
<td>7.2 T</td>
<td>7.2 T</td>
</tr>
<tr>
<td>Volume (V)</td>
<td>1.12 L</td>
<td>1.12 L</td>
<td>1.5 L</td>
</tr>
<tr>
<td>Quality Factor (Q₀)</td>
<td>100,000</td>
<td>100,000</td>
<td><strong>500,000 – 1,000,000</strong></td>
</tr>
<tr>
<td>Geometrical Factor (C)</td>
<td>0.51 – 0.66</td>
<td>0.45</td>
<td>0.51 – 0.65</td>
</tr>
<tr>
<td>System Noise (Tₜₚₛ)</td>
<td>1.1 K</td>
<td><strong>200 mK</strong></td>
<td><strong>200 mK</strong></td>
</tr>
<tr>
<td>Scan Rate (Arb.)</td>
<td>1</td>
<td>18</td>
<td><strong>150 – 300</strong></td>
</tr>
</tbody>
</table>

\[ \propto B^4V^2C^2Q₀/T_{sys}^2 \]

About to Submit (Mr. Jinsu Kim et al.)

About to Submit (Mr. Jinsu Kim et al.)

Scan Rate (Arb.) \( \propto B^4V^2C^2Q₀/T_{sys}^2 \)
Commissioning Run Parameters

- Cavity Volume: 1.5 L
- Average Magnetic Field: 6.9 T
- Q Factor: 500,000
- JPA Gain: 17 dB
- HEMT Gain: 65 dB
- Tuning Range: 2.282 - 2.294 GHz
- Coupling Constant: 2.8 – 3.8
- Cavity Temperature: 100 mK
- System Noise: 300 mK
Commissioning Run

- Commissioning run is successfully finished.
  - Period: (2021) Feb 10\textsuperscript{th} 19:30 ~ Feb 15\textsuperscript{th} 14:30
  - Experiment Parameters
    - JPA Noise Measurement (Every 1 MHz)
    - NA (Span 50 kHz, IFBW 100 Hz, 501 points): \(Q_L, \beta\), Every 20 steps
    - SA (60 sec, Span 100 kHz, RBW 100 Hz, 1000 points)
    - Cavity Tuning (5 kHz), JPA Tuning (17 dB Gain, Every 10 times)

![Diagram of Center Frequency vs. Date]

![Diagram of Unloaded Quality Factor vs. Resonant Frequency (Hz)]
Plan for Improving 2.3 GHz ReBCO Cavity

➢ Next Version Cavity

- Quality Control of Tapes (targeting $Q_0 \sim 1,000,000$)

- Cavity Temperature Reduction: $100\text{mK} \rightarrow 50\text{mK}$
  - Brass Body $\rightarrow$ Copper Body (Improving Thermalization)

- Defected area minimized

- Cut by Machine

- Mechanical Polishing

- Safe

- 5 – 10 um

- 300 – 400 um

- 100 um
Target Sensitivity

JPA Run Target: 2.8 KSVZ (About to Submit)

Superconducting Cavity Run Target: 1 KSVZ

HEMT Run Target: 9 KSVZ (Published)
Summary

➢ Superconducting Cavity R&D at CAPP aims to enhance axion search with a high Q factor cavity using superconductors.
➢ ReBCO is one of the most promising materials for realizing a high Q cavity in a high magnetic field.
➢ CAPP successfully developed a half-million Q factor ReBCO cavity with a 2.3 GHz resonance frequency working in an 8 T magnetic field.
➢ The commissioning run with the 2.3 GHz ReBCO cavity was successfully finished.
➢ CAPP-PACE team is now planning to take 1 KSVZ data with the next version of the 2.3 GHz ReBCO cavity.
Superconductivity in a High Magnetic Field

Gittleman & Rosenblum Model

\[ \eta \dot{x} + k_p x = J \times \Phi_0 n_c. \]

\[ \rho_v = \rho_{ff} \frac{1}{1 + iv_0/\nu} = \frac{B\Phi_0}{\eta} \frac{1}{1 + iv_0/\nu}. \]

\[ Z_{fl} = Z(T, B) - Z(T, 0) = \Delta Z = \sqrt{2\pi v} \mu_0 \rho_v. \]

Lower Surface Resistance at Low Temperature

Biaxially textured ReBCO tapes has good properties for high Q cavity for axion Search
ReBCO Film at mK temperature

➢ Surface Resistance Study

Anti-ferromagnetism (AFM)
Gd Atom Spins
Néel Temperature ~ 2.2 K

\[ R_{s}, 0 \text{ T, 100 mK, 10.18 GHz} \approx 1e-5 \]
\[ R_{s}, 0 \text{ T, 100 mK, 2.3 GHz} \approx 5.1e-7 \]
\[ Q_{\text{idealBBQ, 100 mK}} \approx 7.83e8 \]
Surface Resistance Study

\[ Q_{\text{add}} \approx 600,000 \]

\[ 4.2 \text{ K: } Q \approx 530,000 \]

\[ Q_{\text{ReBCO}}, 4.2 \text{ K} \approx 4,500,000 \]

\[ Q_{\text{idealBBQ}}, 0 \text{ T}, 4.2 \text{ K} \approx 3,200,000 \]
Cavity Q Factor Analysis

➢ Surface Resistance Study

ReBCO loss can be reduced by additional pinning center (APC). Ex) Fujikura APC, THEVA APC

Additional loss can be reduced by improved delamination, and polishing tapes mechanically.

\[ Q_{\text{ReBCO}} \sim 3,000,000 \] at 8 T

\[ Q_{\text{add}} \sim 600,000 \]