Properties of Superconducting Accelerator Cavities

Zachary Conway
July 10, 2007
Overview

- My background is in heavy-ion superconducting accelerator structures. AKA low and intermediate-velocity accelerator resonators

Outline
- RF Superconductivity
- RF Superconductivity in accelerators
- Part 2
Superconductivity

Leiden, ca. 1910

- 1911 – superconductivity discovered by Kamerlingh Onnes
- 1930’s:
  - Magnetic flux expulsion discovered by Meissner and Ochsenfeld
  - London equations (zero momentum state)
- 1950’s:
  - Ginsburg-Landau theory developed
  - Pippard: non-local electrodynamics
  - 1957 – Bardeen, Cooper, and Schrieffer theory
- Theoretical understanding opened the way for applications (SC magnets, quantized flux magnetometry, etc.)
- 1964 – SC resonators developed for accelerator applications at Stanford.
**Meissner Effect and the Superconducting Phase Transition**

The magnetic field penetrates into the superconductor a distance \( \lambda = 50\text{nm} \) for Niobium.

The phase transition is second order if there is no applied magnetic field (no latent heat), otherwise the transition is first order.
Penetration Depth – Coherence Length

\[ \kappa = \frac{\lambda}{\varepsilon} \]

- If \( k < \frac{1}{\sqrt{2}} \), the surface energy is positive (type I SC)
- If \( k > \frac{1}{\sqrt{2}} \), the surface energy is negative (type II SC)

Magnetic flux breaks into the smallest possible units which are flux-tubes or vortices containing a single quantum of magnetic flux \( P_0 = \frac{h}{2e} = 2E-15 \text{ W} \)

For Nb:
\[ \lambda_0 = 50 \text{ nm} \]
\[ \varepsilon_0 = 30 \text{ nm} \]
\[ \kappa = 1.66 \]

Ginzburg-Landau parameter \( \kappa = \frac{\lambda}{\varepsilon} \)

From Michael Tinkham’s “Introduction to Superconductivity”, 2nd edition
Type II Superconductors (The mixed state)

\[ H_{c2} = \sqrt{2} \cdot \kappa \cdot H_c \]
**SC materials and Applications**

DC applications (magnets): Type II, Mixed state
AC applications (cavities): Type I or II, Meissner State

Magnetization curves for type I and type II superconductors

\[ H = \frac{B}{\mu_0} - M \]

<table>
<thead>
<tr>
<th>Metal</th>
<th>( T_C )</th>
<th>( H_{c1} )</th>
<th>( H_c )</th>
<th>( H_{c2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb</td>
<td>7.2 K</td>
<td>*</td>
<td>803 G</td>
<td>*</td>
</tr>
<tr>
<td>Nb</td>
<td>9.2 K</td>
<td>1700 G</td>
<td>1950 G</td>
<td>3400 G</td>
</tr>
<tr>
<td>Nb(_3)Sn</td>
<td>18 K</td>
<td>380 G</td>
<td>5200 G</td>
<td>25,000 G</td>
</tr>
<tr>
<td>YBCO</td>
<td>95 K</td>
<td>**</td>
<td>12,000 G</td>
<td>10^6 G**</td>
</tr>
</tbody>
</table>

* Type I Superconductor  
** Extreme Type II

High frequency accelerator devices have been made out of these materials.
**Superconducting State**

- Electrons form Cooper-pairs through weak attractive interactions

- Electron pairs (bosons) condense into zero-momentum state where
  \[ p = (m^* v + e^* A/c) = 0 \]

- Conducting electrons can be described by a two-fluid model of the condensate (superconducting electrons) and excitations (normal electrons)

- The behavior of the condensate (superfluid) can be described by G-L theory

  \[
  \frac{1}{2m^*} \left( \frac{\hbar}{i} \nabla - \frac{e^*}{c} \vec{A} \right)^2 \psi + \beta |\psi|^2 \psi = -\alpha(T)\psi
  \]

- Processes involving the excitations (normal fluid) are central to the upper limits of EM fields and power dissipation which are critical to DC and RF applications.
RF losses in normal metals – normal and anomalous skin effect

- RF currents are confined to a surface layer of thickness $\delta$:

$$\delta = \sqrt{\frac{2}{\mu_0 \omega \sigma}}$$

- Giving an effective surface resistance of:

$$R_s = \frac{1}{\delta \sigma} = \sqrt{\frac{\mu_0 \omega}{2 \sigma}}$$

- Power loss into the metal surface is:

$$P = \frac{R_s}{2} \int_s \left| \vec{H}(\vec{x}) \right|^2 d\vec{a}$$

<table>
<thead>
<tr>
<th>T</th>
<th>Skin Depth (μm) Cu</th>
<th>Skin Depth (μm) Nb</th>
<th>Surface Resistance 8.2e-3 Ω/m² Cu</th>
<th>Surface Resistance 23e-3 Ω/m² Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>293 K</td>
<td>2.1 μm</td>
<td>6.1 μm</td>
<td>8.2e-3 Ω/m²</td>
<td>23e-3 Ω/m²</td>
</tr>
<tr>
<td>~30 K</td>
<td>0.2 μm</td>
<td>1.7 μm</td>
<td>7.9e-4 Ω/m²</td>
<td>6.3e-3 Ω/m²</td>
</tr>
</tbody>
</table>
**RF Surface Resistance vs Frequency**

\[
R_s(\text{NC}) = \sqrt{\frac{\mu_0 \omega}{2\sigma}}; \quad R_s(\text{SC}) = A(\lambda, \xi, \Delta(T)) \cdot \omega^2 \cdot e^{-\frac{\Delta(0)}{k_B T}}
\]
**SC thin film within a perpendicular magnetic field**

- Lorentz force $= \mathbf{J} \times \phi_0$ on the vortices causes “Flux Flow” and power dissipation.

- For DC applications, vortices must be pinned on defects.

$$\phi_0 = \frac{h}{2e} \approx 2 \cdot 10^{-15} \text{ W}$$

- For RF applications even pinned vortices wiggle about the pinning site and dissipate power.

- $R_s(\text{trapped flux}) \approx R_s(\text{anomalous}) \cdot (H_T/H_{c2}) \approx 0.3 \text{ nΩ/mG}$

"Lorentz force = $\mathbf{J} \times \phi_0$ on the vortices causes “Flux Flow” and power dissipation."

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**SC Surface Resistance**

**Penetration Depth – Skin Depth - Dispersion**

- SC surface resistance is lower by 3-5 orders of magnitude.
- Penetration depth does not vary appreciably with frequency (for frequencies much less than the band gap, 100GHz for Nb).
- Maximum SC RF field is $H \leq H_{sh} \approx H_c$

<table>
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<tr>
<th>T</th>
<th>Skin Depth</th>
<th>Surface Resistance</th>
<th>Cu</th>
<th>Cu</th>
<th>Nb</th>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td>1.7 μm</td>
<td>6.3e-3 Ω/m²</td>
<td>1.7 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.2 K</td>
<td>Penetration Depth</td>
<td>0.2 μm</td>
<td>7.9e-4 Ω/m²</td>
<td>3.2e-7 Ω/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Surface Resistance</td>
<td>0.05 μm</td>
<td>3.2e-7 Ω/m²</td>
<td>0.05 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 K</td>
<td>Penetration Depth</td>
<td>0.2 μm</td>
<td>7.9e-4 Ω/m²</td>
<td>6.5e-9 Ω/m²</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Surface Resistance</td>
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<td>6.5e-9 Ω/m²</td>
<td>0.05 μm</td>
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</table>
Cryogenic Refrigeration Efficiency

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<thead>
<tr>
<th></th>
<th>4.2 K</th>
<th>2 K</th>
</tr>
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<tbody>
<tr>
<td>Carnot Efficiency</td>
<td>1.4%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Mechanical Efficiency</td>
<td>0.3%</td>
<td>0.2%</td>
</tr>
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<td>230 W per Watt</td>
<td>830 W per Watt</td>
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</table>

$$\eta_c = \frac{T}{300 - T}$$
Summary So Far

- Depending on the frequency and temperature we can reduce RF losses by a factor of $10^4$ to $10^6$ by going from room temperature cooper to niobium at 2-4 K.
- Given the efficiency of present cryogenic refrigerators, the net wall-plug power savings can be in the range of 30 – 1000

- Playing the SC game might be worth while...
  - Field limits and breakdown
  - Detuning: microphonics and Lorentz detuning

- For the next 16 slides we will discuss basis features of cavities, SC cavities, and the nomenclature of SCRF

- We will wrap today up with an intensive review of R&D work dealing with matching the cavity RF field phase with the charged particle beam bunch
An RF cavity is a hole in a chunk of metal

TEM-Class

TM-class
Feature of superconducting TEM and TM structures

- TEM-class cavities exhibit higher shunt impedance
- TEM-spoke cavities are half the diameter at a given frequency
- TEM-class cavities have lower $E_{\text{peak}}$ for $\beta < 0.6$
- TM cavities have lower $E_{\text{peak}}$ for $\beta > 0.6$
- TM cavities have very large apertures
- TM generally have lower $B_{\text{peak}}$
115 MHz Quarter-Wave Cavity

$\lambda/4$ mode axial electric field

Velocity Acceptance (Transit Time Factor)
**SC cavity Thermal Properties**

<table>
<thead>
<tr>
<th>Total Heat Capacity (J/K)</th>
<th>293 K</th>
<th>4.2 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>20</td>
<td>15000</td>
</tr>
<tr>
<td>Nb</td>
<td>13600</td>
<td>22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermal Relaxation Time (3mm sheet)</th>
<th>293 K</th>
<th>4.2 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>200 msec</td>
<td>.03-0.3 msec</td>
</tr>
</tbody>
</table>
Thermal Stability and Nb purity

Is a normal region unstable?

i.e. is the temperature rise $\delta T < (T_c - T)$

Given by $dT = d\cdot 0.5\cdot R_s \cdot H_s^2 / K_{eff}$

$K_{eff} = \int K \cdot dT / (T_2 - T_1)$, so the maximum stable field region is given by

$H_s^2 = 2 \cdot d \cdot (T_c - T_B) \cdot (1 / K_{eff} \cdot R_s)$

Note that $R_s \sim \omega^{1/2}$ so $H_s \sim \omega^{-1/4}$ and thermal stability is better at lower frequencies.

At 1 GHz and 2K the limit is 50-500 Gauss depending on the purity of the material
Thermal-Magnetic Breakdown

SC cavity being pulsed to a high field level. Horizontal scale is 5 msec/div
Cavity Fabrication

Building a high-performance Nb cavity is an utterly unforgiving process. Very small defects (cracks, fissures, inclusions, weld-spatter) are very difficult to diagnose, and can destroy performance.

After fabrication, at least 100 μm of Nb is chemically removed from the RF surface to eliminate defects.
High-Pressure water rinsing
Effects of HPR

Cleaned with ethanol and Acetone, before HPR

After HPR at 1750 PSI

240 \mu
Cavity parameters all refer to a single eigenmode – the one used to accelerate particles

- $\omega$ = resonant frequency of the cavity

- $l_0$ = effective length of the cavity ($= n*\beta*\lambda/2$ or $(n-1)*\beta*\lambda/2$)

- $E_{acc}$ = the accelerating gradient: the energy gain per unit charge for a synchronous particle divided by the effective length of the cavity

- $U_0$ = the electromagnetic energy content of the cavity at $E_{acc} = 1.0$ MV/m: in general $U(E_{acc}) = U_0 * E_{acc}^2$

- $Q = \delta\omega/\omega = \omega\tau$ where $\delta\omega$ = the -3dB cavity bandwidth and $\tau$ = the decay time for the rf energy in the cavity (Power = Stored Energy / $\tau$)
Cavity parameters continued

- \( Q = \frac{\delta \omega}{\omega} = \omega \tau \) where \( \delta \omega \) = the -3dB cavity bandwidth and \( \tau \) = the decay time for the rf energy in the cavity (Power = Stored Energy / \( \tau \))

- \( G = Q \times R_s \) = geometric factor for the cavity: relates the cavity Q to the RF surface resistance of the cavity

- \( Z_{\text{shunt}} \) (sometimes labeled as R or \( R_s \)) = \( V^2/P \) and is usually given in the form \( Z_{\text{shunt}}/Q \) or \( R/Q \), notice that \( R/Q = \frac{I_0^2}{\omega \cdot U_0} \)

- Notice that the RF power dissipated in the cavity walls is given by:

\[
P = \frac{G(l_0 \cdot E_{acc})^2}{R_s \cdot \left(\frac{R}{Q}\right)}
\]
Elliptical cell cavity example

805 MHz, 6-cell elliptical-cell niobium cavity developed for $\beta = 0.47$ high intensity ion beams.
Measured axial electric field-tune for flatness

Bead pull measures $E^2$ along the beam axis

Transit-time factor shows the effects of adding cells to the cavity
### 6-cell cavity parameters

**TABLE I.** Parameters of the symmetric 6-cell $\beta_g = 0.47$ cavity. The rf quantities were calculated with SUPERFISH.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell mode</td>
<td></td>
</tr>
<tr>
<td>Phase advance per cell</td>
<td></td>
</tr>
<tr>
<td>Resonant frequency $f$</td>
<td>805 MHz</td>
</tr>
<tr>
<td>Cell-to-cell coupling $\equiv 2(f_{\pi} - f_0)/(f_{\pi} + f_0)$</td>
<td>1.5%</td>
</tr>
<tr>
<td>$E_p/E_a$</td>
<td>3.34</td>
</tr>
<tr>
<td>$cB_p/E_a$</td>
<td>1.98</td>
</tr>
<tr>
<td>$R_a/Q$</td>
<td>173 $\Omega$</td>
</tr>
<tr>
<td>Geometry factor $G$</td>
<td>136 $\Omega$</td>
</tr>
<tr>
<td>Active length $\equiv 6\beta_g c/(2f)$</td>
<td>527 mm</td>
</tr>
<tr>
<td>Inner diameter at iris (aperture)</td>
<td>77.2 mm</td>
</tr>
<tr>
<td>Inner diameter at equator</td>
<td>329 mm</td>
</tr>
</tbody>
</table>

$$U_0 = 0.635 \text{ J/(MV/m)}^2$$

$$B_p/E_A = 66 \text{ G/(MV/m)}$$
**6-cell cavity Q curves**

At 10 MV/m and 2K, the rf power input is 16 watts (into 2K helium).

The stored rf energy is 63.5 joules.
A good cavity is just a start...

- High performance SC cavities must be operated phase-locked to the charged particle beam bunches.

- SC cavities have much smaller bandwidths than their normal conducting counterparts. The power required to excite a cavity and accelerate the beam is:

\[
P_{rf} = \frac{V_c^2}{Z_{shunt}} \cdot \frac{(1 + \beta)^2}{4\beta} \cdot \left(1 + \left(\frac{2\delta\omega}{\Delta\omega_L}\right)^2\right) \cdot \text{beam loading}
\]

\[
\frac{V_-}{V_+} = \frac{\beta - 1}{\beta + 1}
\]
Break

- 20 minutes
**Triple-Spoke or Elliptical-Cell Resonators for $0.4 < \beta < 0.7$**

805 MHz  
$\beta = 0.47 \text{ TM}_{010}$

345 MHz  
$\beta = 0.50 \text{ TEM}$
**Triple-Spoke or Elliptical-Cell Resonators for 0.4 < β < 0.7**

- The transverse size of TM structures is of the order of $0.9 \lambda$ while for TEM structures it is on the order of $0.5 \lambda$, $\lambda = \frac{c}{f}$.

- At a fixed transverse size TEM structures operate at approximately half the frequency, this has several important consequences:
  - Lower BCS surface resistance
  - A TEM structure will have half the number of cells of a TM cavity of the same length and therefore will have a broader velocity acceptance.
  - Improved beam dynamics

- Improved mechanical stability
European Isotope Separation On-Line Radioactive Ion Beam Facility (EURISOL)

- Particle: $H^-$
- Kinetic Energy: 1 GeV
- Average Beam Power: 5 MW
- Mode of Operation: Continuous Wave (cw)

<table>
<thead>
<tr>
<th>Beta</th>
<th>f (MHz)</th>
<th># of Cav.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>352</td>
<td>22</td>
</tr>
</tbody>
</table>
High Intensity Neutrino Source (HINS)

<table>
<thead>
<tr>
<th>Particle</th>
<th>H⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic Energy</td>
<td>8 GeV</td>
</tr>
<tr>
<td>Average Beam Power (Peak)</td>
<td>2 MW (200 MW)</td>
</tr>
<tr>
<td>Duty Factor (Repetition Rate)</td>
<td>1% (10 Hz)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beta</th>
<th>f (MHz)</th>
<th># of Cav.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.22</td>
<td>325</td>
<td>18</td>
</tr>
<tr>
<td>0.40</td>
<td>325</td>
<td>33</td>
</tr>
<tr>
<td>0.63</td>
<td>325</td>
<td>42</td>
</tr>
</tbody>
</table>
## Advanced Exotic Beams Laboratory (AEBL)

<table>
<thead>
<tr>
<th>Beta</th>
<th>$f$ (MHz)</th>
<th># of Cav.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.39</td>
<td>345</td>
<td>16</td>
</tr>
<tr>
<td>0.50</td>
<td>345</td>
<td>54</td>
</tr>
<tr>
<td>0.63</td>
<td>345</td>
<td>24</td>
</tr>
</tbody>
</table>

### Color code:
- Black = existing facility
- Blue + green = AEBL baseline
- Red = Low-cost upgrade

### Particles
- Protons $\rightarrow$ Uranium

### Output Proton Kinetic Energy (Uranium)
- 578 MeV (201 MeV/u)

### Proton Beam Power
- 400 kW

### Mode of Operation
- Continuous Wave (cw)
ANL Triple-Spoke Cavities

β = 0.63
Triple-Spoke Cavity
345 MHz

β = 0.50
Triple-Spoke Cavity
345 MHz

102 cm
83 cm
Cavity RF Performance

- The RF power required to operate a cavity RF field phase-locked to the beam bunches is a function of:
  - The power delivered to the beam
  - The power required to control the cavity RF field phase and amplitude errors.
  - The power required to energize the cavity

- Dramatic improvements in the power required to energize and operate spoke-loaded cavities operating at a fixed beam current have been realized from 6 years of spoke-loaded cavity development.
$\beta = 0.63$ Triple-Spoke Cavity
$\beta = 0.63$ Triple-Spoke Cavity
Refrigeration

\[ \eta_c = \frac{T}{300 - T} \]

<table>
<thead>
<tr>
<th></th>
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<td>830 W per Watt</td>
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<table>
<thead>
<tr>
<th></th>
<th>Before Bake</th>
<th>After Bake</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Power @</td>
<td>4.2 K</td>
<td>2 K</td>
</tr>
<tr>
<td>( \beta = 0.63 )</td>
<td>180 W</td>
<td>70 W</td>
</tr>
<tr>
<td></td>
<td>100 W</td>
<td>8 W</td>
</tr>
</tbody>
</table>
\[ \beta = 0.5 \text{ Triple-Spoke Cavity} \]
\( \beta = 0.5 \) Triple-Spoke Cavity

Field Emission

10 n\( \Omega \) surface resistance

\( \sigma \)

\( E_{\text{acc}} \) (MVm)
The power required to energize and cool a cavity is only one part of the power required to operate a cavity.

Cavity RF frequency variations generate phase errors between the cavity RF field and the particle beam bunches.

More RF power is required to control the cavity RF field amplitude and phase when the RF frequency variations are a large fraction of the beam loaded cavity bandwidth.

Cavity RF frequency variations are due to external forces coupling to the cavity RF field.
Cavity RF Frequency Variations

Boltzmann-Ehrenfest Theorem

\[ \frac{\Delta f}{f} = \frac{\text{Mechanical Work}}{\text{Stored RF Energy}} \]

\[ \frac{\Delta f}{f} = \frac{\Delta U}{U} \]

Double-spoke cavity \( \Delta f/\Delta p = -76 \text{ Hz/torr} \)

\[ \Delta f \propto -\frac{1}{4} \int_{\Gamma} \left[ \mu_0 \left| \vec{H}_0(\vec{x}) \right|^2 - \varepsilon_0 \left| \vec{E}_0(\vec{x}) \right|^2 \right] u(\vec{x}, t) \, da \]

- Designed to balance the electric and magnetic field contributions to frequency shifts due to uniform external pressure.
Cavity RF Frequency Variations

Room temperature test results for $\beta = 0.5$ Triple-Spoke

measured $\Delta f/\Delta P$ (predicted) = -12.4(-8.7) Hz/torr

$\Delta f/\Delta P = -2.5(-0.3)$ Hz/torr ($\sim$30x improvement over double-spoke)

$\Delta f/\Delta P = -6.3(-4.7)$ Hz/torr

$\Delta f/\Delta P = -0.5(+5.4)$ Hz/torr
Cavity RF Frequency Variations

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity</td>
<td>0.5 TSR</td>
</tr>
<tr>
<td>$E_{\text{acc}}$</td>
<td>9.5 MV/m</td>
</tr>
<tr>
<td>RF Power</td>
<td>82 W</td>
</tr>
<tr>
<td>Temp.</td>
<td>4.2 K</td>
</tr>
<tr>
<td>$\sigma_{\text{rms}}$</td>
<td>0.58 Hz</td>
</tr>
</tbody>
</table>
Cavity RF Frequency Variations

- $\sigma_{\text{rms}} = 0.58$ Hz; $\Delta f/\Delta p = -2.5$ Hz/torr
- $\sigma_{\text{rms}} = 1.04$ Hz; $\Delta f/\Delta p = -12.5$ Hz/torr

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<td>Temp.</td>
<td>4.2 K</td>
</tr>
</tbody>
</table>
Cavity RF Frequency Variations

\[ \beta = 0.5 \text{ TSR } \sigma_{\text{rms}} = 0.58 \text{ Hz}; \text{ df/dp} = -2.5 \text{ Hz/torr} \]
\[ \beta = 0.4 \text{ DSR } \sigma_{\text{rms}} = 5.3 \text{ Hz}; \text{ df/dp} = -76 \text{ Hz/torr} \]

No \( \Delta f/\Delta p \) tuning
Cavity RF Frequency Variations

Cavity 0.5 TSR
E_{acc} 9.5 MV/m
RF Power 82 W
Temp. 4.2 K
σ_{rms} 0.58 Hz

Helium Bubbling

No Δf/Δp Tuning

Cavity 0.4 DSR
E_{acc} 7 MV/m
RF Power 9 W
Temp. 4.2 K
σ_{rms} 5.3 Hz
**Cavity RF Frequency Variations**

- Over-couple to the cavity with the power coupler
  - RF Power = $N \times \delta\omega_{\text{rms}} \times U$
- Fast Reactive Tuners
  - Damp the cavity bandwidth requiring additional RF power
- Fast Mechanical Tuners
  - No additional RF power requirements

![ANL 20 kW Triple-Spoke Fundamental Power Coupler](image-url)
**Fast Mechanical Tuners**

- We have done all we can to decouple the cavity RF frequency dependence on changes in the external pressure.

- This by itself is not sufficient for phase and amplitude stable operation at 4 K.

- At ANL mechanical fast tuners have been developed to compensate the low frequency cavity RF frequency errors due to low frequency microphonics.

<table>
<thead>
<tr>
<th>Tuner Actuator</th>
<th>Piezoelectric</th>
<th>Magnetostrictive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>APC</td>
<td>Energen</td>
</tr>
<tr>
<td>Operating Temp.</td>
<td>26 K</td>
<td>4 K</td>
</tr>
<tr>
<td>Length</td>
<td>11 cm</td>
<td>6.7 cm</td>
</tr>
<tr>
<td>Stroke @ 4 K</td>
<td>16 μm</td>
<td>100 μm</td>
</tr>
<tr>
<td>Push Force</td>
<td>4000 N</td>
<td>440 N</td>
</tr>
</tbody>
</table>
Fast Mechanical Tuners
Magnetostrictive Actuated Fast Tuner

- Magnetostrictive actuator designed and built by Energen, Inc.
- Response time ~6ms.
- Magnetostrictive rod coaxial with an external solenoid operating at 4K.
- Not designed for high frequency operation.
Piezoelectric Actuated Fast Tuner

- Response time <1ms.

- Layered piezo-ceramic material electrically connected in parallel operating at 26K with a resolution of 2nm purchased from APC.

- Not designed for high frequency operation.
Tuner/Cavity Transfer Function Measurement
ANL $\beta = 0.5$ TSR Magnetostrictive Tuner/Cavity Transfer Function

Cavity Response$(t) = \int_{-\infty}^{\infty} \left( \text{Transfer Function}(\omega) \ast I(\omega) \right) e^{-i\omega t} d\omega$
ANL $\beta = 0.5$ Triple Spoke Piezo/Cavity Transfer Function
Fast Mechanical Tuning
Fast Mechanical Tuning

- Cavity 0.5 TSR
- $E_{acc}$ 8.5 MV/m
- RF Power 110 W
- Temp. 4.5 K

Deliberately coupled cavity to external noise (ATLAS).
Fast Mechanical Tuning

- Cavity: 0.5 TSR
- $E_{\text{acc}}$: 8.5 MV/m
- RF Power: 110 W
- Temp.: 4.5 K


**Lorentz Detuning**

- Systems to control RF field phase errors in cw operation due to low frequency noise have been developed.

- Pulsed accelerators have an additional force detuning the cavities, the dynamic Lorentz force

- The Lorentz force is due to the cavity RF surface fields interacting with the RF surface currents

- The Lorentz force can cause cavity ringing at much higher frequencies than the cw helium bath bubbling
SCRF Cavity Frequency Variations

- FNAL $\beta_{geo} = 0.63$ triple-spoke cavity loaded-bandwidth ~ 800 Hz
  - $I_{pk}(I_{ave}) = 40$ (25) mA
  - $E_{acc} = 10.5$ MV/m
  - Stored Energy ~ 600 mJ
    - *Largest stored energy of all the spoke-loaded cavities*
  - Effective Length ~ 0.8 m

- Externally Driven Frequency Variations?
  - Microphonics?
  - Lorentz Force Detuning?

- Tests performed at ANL on a $\beta_{geo} = 0.5$ triple spoke cavity yield:
  - Microphonics ~ 0.58 Hz$_{rms}$
  - Lorentz Force Detuning ~ 1 kHz @ 10.5 MV/m
Lorentz Transfer Function Measurement

Diagram showing the setup for measuring the Lorentz transfer function. The diagram includes components such as Agilent 8644B, SR850 Lock-In Amplifier, Frequency Difference, Superconducting Cavity, and various amplifiers and couplers.
ANL $\beta = 0.5$ Lorentz Transfer Function

Cavity Response(t) = \int_{-\infty}^{\infty} \text{Transfer Function}(\omega) \ast \text{E}^2_{\text{ac}}(\omega) e^{-i\omega t} d\omega

$K_L = -11.5$ Hz/(MV/m)^2
ANL $\beta = 0.5$ TSR Pulsed Operation

Cavity Response($t$) = $\int_{-\infty}^{\infty} \left( \text{Transfer Function}(\omega) \cdot E_{\text{acc}}^2(\omega) \right) e^{-i\omega t} d\omega$
ANL $\beta = 0.5$ TSR Pulsed Operation
Lorentz Transfer Functions
Elliptical Cell Mechanical Tuning

- Piezo
- Tuning Frame
- Helium Jacket
- Nb Cavity
SNS Mechanical Tuning

Cavity $E_{acc}$ Amplitude
Frequency Variation Without Tuning
Frequency Variation With Tuning

FNAL Proton Driver Pulsed Operation

- RF power required to phase and amplitude stabilize the ANL $\beta = 0.5$ TSR when pulsed to 10.5 MV/m would be much greater than $200\text{ kW}_{\text{peak}}$

- Design changes may help
  - Cavity frequency variations due to the Lorentz force may decrease by a factor of 2 or 3
  - This will not improve by a factor of 10

- A mechanical fast tuner is necessary
Conclusions

- Superconducting triple-spoke-loaded cavity technology RF performance exhibits surface resistances < 10 nΩ at 2K after hydrogen degassing.

- Tuners still need to be developed to compensate the dynamic RF frequency variations due to pulsed operation of superconducting triple-spoke-loaded cavities

- Other mechanical fast tuner solutions were developed for specific SCRF applications
  - Pulsed operation: DESY X-FEL and SNS
  - Spoke cavity cw operation: AEBL

- This constitutes the only work (I know of) to date on pulsed spoke cavity operation
\[ \beta = 0.3 \]

Freq (MHz) | \( \beta = 0.5 \) | \( \beta = 0.63 \) |
--- | --- | --- |
| 345 | 345 |

\( l_{\text{eff}} \) (cm) | 65.2 | 82.2 |

\( G \) (Ω) | 85.7 | 93.0 |

\( R/Q = \frac{V^2}{PQ} \) (Ω) | 494 | 520 |

At an accelerating gradient of 1 MV/m:

| \( \beta = 0.3 \) |
--- |
Freq (MHz) | 855 |

\( l_{\text{eff}} \) (cm) = \( (n\beta\lambda/2) \) | 5.3 |

\( G \) (Ω) | 60 |

\( R/Q = \frac{V^2}{PQ} \) (Ω) | N/A |

At an accelerating gradient of 1 MV/m:

| \( \beta = 0.3 \) |
--- |
RF Energy (mJ) | 5.7 |

\( E_{\text{peak}} \) (MV/m) | 3.3 |

\( B_{\text{peak}} \) (G) | 78 |
Intermediate-Velocity Accelerator Cavities ($0.2 < \beta < 0.7$)

- Before 1990
  - Copper Accelerator Structures
    - Long structures with a narrow velocity acceptance
    - Require lots of power to operate cw
    - Peak fields limited by power dissipation in cavity (100kW/m²)
  - Drift tube linacs
    - Long structures optimized for a single ion species
    - Not flexible
  - Coupled cavity linacs
    - Long structure optimized for a single ion species
    - Not flexible
- After 1990
  - Structure were needed
Single-Spoke Cavities

Triple-Spoke Cavity Q-Disease

### SCRF Cavity Frequency Variations

- **JLAB**
  - Loaded Bandwidth = 200 Hz
  - Externally Driven Frequency Variations
    - Microphonics ~ 20 Hz

- **XFEL @ DESY (TESLA Cavities)**
  - Loaded Bandwidth = 500 Hz
  - Externally Driven Frequency Variations
    - Lorentz Force Detuning ~ 400 Hz (23.5 MV/m)
    - Microphonics ~ 40 Hz

- **SNS (Squeezed Tesla Cavities)**
  - $BW_L = 1100$Hz
  - Externally Driven Frequency Variations
    - Lorentz Force Detuning ~ 500 Hz (12 MV/m)
    - Microphonics ~ 15 Hz
Original RIA design called for the production of triple-spoke cavities with residual surface resistances on the order of 30 nΩ.

\[ R_s = R_{BCS}(f, T, \Delta) + R_{res} \]

After 6 years of spoke-loaded cavity development triple-spoke cavities can now be produced with residual surface resistances < 10 nΩ.
Triple-Spoke Cavity RF Requirements

- AEBL driver linac proposes to use 52 $\beta_{\text{geom}} = 0.5$ and 20 $\beta_{\text{geom}} = 0.63$ triple-spoke cavities to provide 470 MV of the ~870 MV total accelerating potential.

<table>
<thead>
<tr>
<th>$\beta_{\text{geom}}$</th>
<th>0.5</th>
<th>0.63</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{acc}}$ (MV/m)</td>
<td>9.5</td>
<td>9.5</td>
</tr>
<tr>
<td>Beam (kW)</td>
<td>4.4</td>
<td>5.3</td>
</tr>
<tr>
<td>Cavity (W @ 4.2K)</td>
<td>87</td>
<td>94</td>
</tr>
<tr>
<td>Cavity (W @ 2 K)</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>$\Delta f_L$ (Hz)</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>$\Delta f_{\text{rms}}$ (Hz)</td>
<td>0.58</td>
<td>???</td>
</tr>
</tbody>
</table>

Refrigeration efficiency decreases by x4 going from 4.2 K to 2 K.
Triple-Spoke Cavity 600°C Bake

\[ \beta = 0.63 \]

\[ Q @ 2 \text{ K} \]

\[ 1 \times 10^{10} \]

\[ 1 \times 10^{9} \]

\[ E_{\text{acc}} (\text{MV/m}) \]

After 600°C Bake

Before 600°C Bake
**Triple-Spoke Cavity 600°C Bake**

\[ \beta = 0.5 \]

![Graph showing Q @ 2K vs. E_{acc} (MV/m)]

- **After 600°C Bake**
- **Before 600°C Bake**
Triple-Spoke Cavity 600°C Bake

$R_{res} (\text{n}\Omega) @ 2\,K$

$B_{pk} (\text{Gauss})$

- $\beta=0.5$ TSR $R_{res}$ at 2K
- $\beta=0.63$ TSR $R_{res}$ at 2K
Results of first cold test of a production model double spoke cavity with an integral stainless steel housing holding the liquid helium bath. (M.P. Kelly et al, PAC 2003)

\[ \frac{\Delta f}{\Delta P} = -76 \text{ Hz/torr} \]
**Triple-Spoke Cavity RF Performance**

\[ \beta = 0.63 \text{ cavity with } 10\text{n}\Omega \text{ surface resistance} \]

\[ \beta = 0.5 \text{ cavity with } 10\text{n}\Omega \text{ surface resistance} \]

\[ Q @ 2K \]

\[ 1 \times 10^9 \]

\[ 1 \times 10^{10} \]

\[ E_{acc} (\text{MV/m}) \]

---

**Legend:**

- ■ \( \beta = 0.5 \text{ Cavity} \)
- ▲ \( \beta = 0.63 \text{ Cavity} \)
Cavity Power Requirements

- The power required to energize and cool a cavity is only one part of the power required to operate a cavity.

\[
P_{\text{generator}} = P_{\text{cavity}} \left( \frac{(\beta + 1)^2}{4\beta} \right) \left( 1 + \left( \frac{2Q_L \delta f}{\Delta f_L} \right)^2 \right)x g(\text{beam loading})
\]

\[
\frac{V_-}{V_+} = \frac{\beta - 1}{\beta + 1}
\]

- Where \( P_{\text{generator}} \) = output from RF amplifier required to drive the cavity, \( P_{\text{cavity}} \) = power required to energize the cavity to the operating field level, \( \beta \) = coupling strength, \( Q_L \) = loaded cavity quality factor, \( \delta f \) = difference between the resonator RF frequency and the RF drive frequency, \( \Delta f_L \) = loaded cavity bandwidth, \( g(\text{beam loading}) \) = function of the beam loading.
SCRF Cavity Frequency Variations

$\beta_{\text{geo}} = 0.5$ Triple-Spoke-Loaded Cavity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>345.23 MHz</td>
</tr>
<tr>
<td>$\beta_{\text{geom}}$</td>
<td>0.5</td>
</tr>
<tr>
<td>$L(3\beta\lambda/2)$</td>
<td>65.2 cm</td>
</tr>
<tr>
<td>QRs (G)</td>
<td>88.5 $\Omega$</td>
</tr>
<tr>
<td>R/Q</td>
<td>492 $\Omega$</td>
</tr>
<tr>
<td>Below for $E_{\text{ACC}} = 1.0$ MV/m</td>
<td></td>
</tr>
<tr>
<td>RF Energy</td>
<td>0.398 j</td>
</tr>
<tr>
<td>$B_{\text{PEAK}}$</td>
<td>86 G</td>
</tr>
<tr>
<td>$E_{\text{PEAK}}$</td>
<td>2.79</td>
</tr>
</tbody>
</table>
Advanced Exotic Beams Laboratory (AEBL)

<table>
<thead>
<tr>
<th>Beta</th>
<th>f (MHz)</th>
<th># of Cav.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>345</td>
<td>52</td>
</tr>
<tr>
<td>0.62</td>
<td>345</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particles</th>
<th>Protons =&gt; Uranium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Proton Kinetic Energy (Uranium)</td>
<td>578 MeV (201 MeV/u)</td>
</tr>
<tr>
<td>Proton Beam Power (Uranium)</td>
<td>400 kW (136 kW)</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>100% (cw)</td>
</tr>
</tbody>
</table>
Cavity RF Power Requirements

- The power required to energize and cool a cavity is only one part of the power required to operate a cavity.

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\[
\frac{V_-}{V_+} = \frac{\beta - 1}{\beta + 1}
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