ELECTRO-MECHANICAL INTERACTIONS IN SUPERCONDUCTING SPOKE-LOADED CAVITIES

BY

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DISSERTATION

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ABSTRACT

This dissertation reports an investigation of the mechanical and electromagnetic properties of a β = 0.4 double-spoke-loaded and a β = 0.5 triple-spoke-loaded superconducting cavity at Argonne National Laboratory. These cavities are of interest in new heavy-ion and proton linear accelerators. We present a powerful method for characterizing arbitrary time-dependent Lorentz force induced detuning of superconducting cavities; the convolution of the Lorentz transfer function and the cavity accelerating gradient. Using the β = 0.5 triple-spoke-loaded superconducting cavity the Lorentz transfer function is shown to accurately predict the cavity response to RF field pulses. We present experimental data characterizing the microphonic-noise of the β = 0.4 double-spoke-loaded superconducting cavity and the subsequent design and testing of the β = 0.5 triple-spoke-loaded superconducting cavity. The β = 0.5 triple-spoke-loaded superconducting cavity rms microphonic-noise is less than 0.5 Hz, an improvement by an order of magnitude over the β = 0.4 double-spoke-loaded superconducting cavity. Finally, electro-mechanical frequency and phase control methods to compensate the microphonic-noise of superconducting spoke-loaded cavities are presented. The techniques and methods developed here advance characterization and tuning techniques which are beneficial for all superconducting cavities and enable the use of spoke-loaded cavities in future accelerators.
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Chapter 1

Introduction

1.1 Purpose

The experiments described in this dissertation develop frequency and phase control methods for spoke-loaded superconducting cavities for ion accelerators. The radio-frequency (RF) field in accelerator cavities must be operated with stable amplitude and phase locked to the ion-beam bunches. The accuracy and precision to which the cavity RF field amplitude and phase can be controlled determine:

- The reliability and availability of beam for experiments
- The beam quality
- Beam losses (activation of the accelerator)

Cavity mechanical deformations drive RF eigenfrequency variations. Superconducting cavities are highly sensitive to mechanical deformations due to the small loaded-cavity bandwidths found in some of their accelerator applications. Cavity RF field phase and amplitude errors occur when the RF frequency variations are a large fraction of the loaded-cavity bandwidth.

The RF frequency variations, of the electromagnetic eigenmode use to accelerate particles, of a $\beta = 0.4$ double-spoke-loaded cavity and of a $\beta = 0.5$ triple-spoke-loaded cavity have been measured and will be presented. An analysis of the data led to the development of fast tuning systems, culminating in the demonstration of phase control of a $\beta = 0.5$ triple-spoke-loaded cavity operating under realistic conditions.

Chapter 1 continues with a discussion of the attraction of RF superconductivity for many accelerator applications and a brief history of the field to motivate the work in the subsequent chapters.

Chapter 2 introduces the parameters used to describe superconducting cavity RF performance and response to mechanical vibrations. After introducing these parameters the coupling between the cavity RF field and an arbitrary driving force is introduced followed by the experimental apparatus and methods used to measure these parameters.
Chapter 3 presents a powerful method for studying and analyzing the dynamic detuning in superconducting cavities driven by the dynamic Lorentz force, the radiation pressure of the cavity fields. This method, in principle, could be used to characterize the dynamic detuning of a cavity subject to any type of time-dependent driving RF waveform. This technique provides a simple, direct tool for characterizing the electromechanical properties of superconducting cavities operated with time-dependent RF field amplitudes.

Chapter 4 presents experimental measurements which characterize the microphonic-noise of a $\beta = 0.4$ double-spoke-loaded cavity and a $\beta = 0.5$ triple-spoke-loaded cavity operated at fixed RF field amplitudes. The $\beta = 0.5$ triple-spoke-loaded cavity was designed after the $\beta = 0.4$ double-spoke-loaded cavity and the microphonic-noise was less than that of the phase noise of the RF oscillator used for the measurements.

The experimental measurements presented in chapters 3 and 4 demonstrate that spoke-loaded cavities are rigid mechanical structures, i.e. no low-frequency mechanical eigenmodes couple to the cavity RF field, but their rigidity does not limit RF frequency variations to levels acceptable for phase stable operation. As a result, frequency and phase control systems are required to operate superconducting spoke-loaded cavities with stable amplitude and phase-locked to the particle beam.

Chapter 5 presents the development and implementation of fast mechanical frequency and phase control systems for spoke-loaded cavities operating in the continuous-wave mode. The techniques and methods developed here advance tuning techniques which are beneficial for all superconducting cavities and enable the use of spoke-loaded cavities in future accelerators.

Chapter 6 summarizes the results presented in this dissertation.

1.2 Features Specific to Superconducting RF Cavities

The superconducting state of matter is typically described by its direct current (DC) characteristics: perfect conductivity and perfect diamagnetism [1-5]. However, the use of superconductors in accelerator cavities involves alternating currents (AC) with frequencies ranging from a few megahertz (MHz) to a few gigahertz (GHz). Above absolute zero, AC surface currents in a superconductor dissipate energy [5-11]. This is because a finite fraction of the electrons are in the normal conducting state. A time-
dependent supercurrent requires an electric field to accelerate and decelerate the superconducting electron pairs. This electric field also exerts a force on the normal-conducting electrons which scatter from impurities and dissipate power, similar to the anomalous skin effect in metals. For niobium below 4.6 K and for frequencies much less than 100 GHz, a good approximation to the Bardeen-Cooper-Schrieffer (BCS) surface resistance is given by [12, 13]:

$$R_{BCS} (\Omega) = 2 \times 10^{-4} \frac{1}{T(K)} \left( \frac{f(GHz)}{1.5} \right)^2 e^{-17.76/T(K)}$$

1.1

$R_{BCS}(\Omega)$ is the fit of the RF surface resistance predicted by the BCS theory expressed in Ohms, $\Omega$. $T(K)$ is the temperature in Kelvin, and $f(GHz)$ is the RF frequency of the surface field in gigahertz. At 2 K a superconducting niobium cavity operating at 345 MHz can have a BCS surface resistance as low as 0.7 n$\Omega$, almost $10^6$ times smaller than the 0.4 m$\Omega$ surface resistance attainable with normal-conducting copper under the same conditions [13]. The small RF surface resistance of superconducting cavities results in cavity quality factors ($Q$) which are $10^5$ to $10^6$ times greater than achievable in

Figure 1.1: The surface resistance of copper and niobium as a function of frequency.
normal conducting cavities. The cavity quality factor defined in terms of the electromagnetic stored energy, \( U \), the power loss, \( P \), and the frequency, \( \omega \), is defined as:

\[
Q = \omega \cdot \frac{U}{P} \tag{1.2}
\]

The beam requirements are the primary factor in determining the design of an accelerator cavity. The RF surface resistance determines the RF power required to achieve the design goals. The following discussion reviews several definitions and formulae quantifying the relationships between the various geometric, electromagnetic, and material properties of an RF cavity [13-15].

First, the RF surface resistance determines the RF power, \( P \), required to generate the cavity field as:

\[
P = \frac{R_s}{2} \int_{S} \left| \vec{H}(\vec{x}) \right|^2 \, da \tag{1.3}
\]

where \( R_s \) is the RF surface resistance, \( \vec{H}(\vec{x}) \) is the time-averaged cavity magnetic field, and the integral is taken over the RF surface of the cavity, \( S \). Substituting 1.3 into 1.2 allows us to calculate the intrinsic cavity quality factor, \( Q \):

\[
Q = \omega \cdot \frac{U}{P} = \frac{1}{R_s} \cdot \frac{\mu \cdot \omega \cdot \int_{V} \left| \vec{H}(\vec{x}) \right|^2 \, dv}{\int_{S} \left| \vec{H}(\vec{x}) \right|^2 \, da} \tag{1.4}
\]

where the cavity electromagnetic stored energy \( U \) is proportional to the integral in the numerator, which is taken over the entire cavity volume, \( V \). Notice that this formula can be factored into two components: the RF surface resistance, and a factor independent of the cavity material, defined as the first of two factors which are determined entirely by the cavity geometry, i.e. the cavity geometric factor \( G \), given by:

\[
G = \frac{\mu \cdot \omega \cdot \int_{V} \left| \vec{H}(\vec{x}) \right|^2 \, dv}{\int_{S} \left| \vec{H}(\vec{x}) \right|^2 \, da} \tag{1.5}
\]

Now, expressing the cavity power in terms of the effective accelerating voltage, \( V \), we can define shunt impedance, \( R_{sh} \), as:
In the literature, the commonly given quantity is \( R_{sh}/Q \), the geometric shunt impedance, which is also independent of the surface resistance of the material used to form the cavity.

\[
R_{sh} = \frac{V^2}{P}
\]

Equation 1.6 factors the expression giving the RF power required to provide an accelerating voltage \( V \) into two terms: the surface resistance, depending on the material and temperature, and another term depending entirely upon the cavity geometry.

Equation 1.6 shows that for any cavity geometry the \( 10^5 - 10^6 \) times smaller RF surface resistance of superconducting materials would decrease the RF power required to generate a given cavity voltage by \( 10^5 – 10^6 \).

1.3 The Early Development of Superconducting Cavities

The first proposal to fabricate particle accelerator cavities out of superconducting materials came three years after the basic understanding of the RF properties of superconductors was laid out by the BCS theory of superconductivity [5, 10]. In 1961, Banford and Stafford presented a paper in which they described the feasibility and advantages of an array of superconducting lead cavities for a 1.5 GeV proton linear accelerator [16, 17]. They found that a normal-conducting copper accelerator would require 276 MW of power and a superconducting lead accelerator would required 5 MW (5 kW RF power + refrigeration). There were many technical and scientific problems to be addressed before construction of a superconducting lead accelerator could proceed, but their analysis showed the capital and operating cost savings afforded by using a superconducting accelerator.

The first sign of how difficult it could be to fabricate, test, and operate superconducting cavities came from two superconducting niobium cavities tested at CERN in 1962 [18]. The cavities were both 280 MHz quarter-wave resonant lines. The
RF losses were large and the effort was discontinued after two years where it was noted that the material purity and the surface finish were two limiting factors on the resonators RF performance [19, 20].

In 1965, a three cavity 2856 MHz superconducting accelerator 4 inches long was successfully operated at Stanford University [21]. The accelerator produced a 1 µA 500 keV electron beam. This was the first step in an ambitious project which resulted in an accelerator based on superconducting RF materials. The project produced a useful linac. Perhaps more importantly, the Stanford project successfully developed solutions to many technical problems of superconducting cavities [22].

1) Cryostat design
2) Helium refrigeration below 2 K
3) Resonator design and fabrication
4) Resonator RF Performance
5) Resonator Phase Control
6) Beam Break-up

Even though the superconducting cavity accelerating gradients were limited by electron loading to levels below 3 MV/m they were used for many years in the 600 MeV electron microtron at the University of Illinois at Urbana-Champaign [23]. The electron microtron at the University of Illinois at Urbana-Champaign was the first use of the Stanford superconducting cavities.

Soon after Stanford began its ambitious effort RF superconductivity was applied to the acceleration of protons at the Nuclear Research Center in Karlsruhe, Germany [24]. Their focus was constructing a stand-alone superconducting driver linac for a π-meson production facility. The Karlsruhe project developed several classes of superconducting cavities for the acceleration of particles with velocities in the range $0.04 < \beta < 0.8$ ($\beta = \frac{v}{c}$) [25]. One of these cavity geometries, the helically-loaded cavities, achieved acceptable accelerating gradients of 2-4 MV/m (a similar helically-loaded cavity cross-section is shown later in figure 1.4) [26]. The poor mechanical stability and small loaded bandwidth of the helically-loaded cavities, made them extremely sensitive to RF frequency variations, making control of the RF phase extremely difficult. Finally, in 1972, after a substantial effort, two helically-loaded cavities accelerated a $\beta = 0.06$ proton...
beam [27]. To continue to discuss the development of superconducting cavities, it is useful to discuss some of the basic RF field limits of superconducting RF cavities: thermal stability, field emission, and phase control.

1.4 RF Field Limits

1.4.1 Thermal Stability

The Stanford superconducting accelerator project was the first of many laboratory efforts focused on superconducting accelerator development. One aspect of the development work focused on increasing the maximum achievable RF field in superconducting cavities [13, 28, 29]. For example, considerable effort was directed at determining the phenomena responsible for limiting the RF field due to regions of the cavity surface with high magnetic fields. The experiments demonstrated that the breakdowns were due to the ohmic heating of the cavity surface and not the local magnetic field exceeding the critical field of the superconductor [30]. In 1979 researchers at CERN developed a technique to indirectly map the temperature of the cavity RF surface and subsequently demonstrated that local surface defects resulted in cavity quenches well below the superconducting critical magnetic field at the cavity surface [31, 32]. Examples of surface defects include impurities in the superconducting material used to fabricate the cavity and steel from tools used to machine the cavity [13].

Surface defects in a superconducting RF cavity are fundamentally different from defects in superconducting magnets (flux pinning sites) [4, 15, 33]. In general, a DC supercurrent is determined by the surface resistance, following the path of zero resistance, and flows around a normal conducting region. An RF supercurrent is determined not by the surface resistance but by the reactive impedance of the electromagnetic field. Hence, an RF supercurrent will flow through surface defects, resulting in the ohmic heating of the defect. If the temperature of the defect exceeds the critical temperature of the superconducting material the surrounding superconducting material quenches and the normal-conducting region grows.

Researchers at Cornell University suggested that the field at which a superconducting cavity quenches could be increased if the thermal stability of the cavity were improved. Improved thermal stability is achieved by increasing the material purity in order to increase the thermal conductivity of the superconducting material [33]. As a result, ever
higher purity niobium has been used to manufacture superconducting cavities. In the literature it is common to measure the niobium purity in terms of the residual resistance ratio, RRR [13].

\[
RRR = \frac{\rho_{273 \text{K}}}{\rho_{4.2 \text{K}}}
\]

where \(\rho_{273 \text{K}}\) and \(\rho_{4.2 \text{K}}\) are the normal-conducting resistivity of niobium at 273 K and 4.2 K respectively. Figure 1.2 shows the variation in thermal conductivity with RRR and table 1.1 summarizes the effect of the major impurities of niobium by giving the expected RRR of niobium with 1 ppm by weight of each impurity [28].

In the early 1990s the Continuous Electron Beam Accelerator Facility (CEBAF) was built with a design goal of producing superconducting cavities with accelerating gradients of 5 MV/m [34]. By increasing the purity of the niobium used to manufacture the cavities and also by eliminating surface defects, many cavities produced for CEBAF

<table>
<thead>
<tr>
<th>Element</th>
<th>RRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>4230</td>
</tr>
<tr>
<td>O</td>
<td>5580</td>
</tr>
<tr>
<td>C</td>
<td>4380</td>
</tr>
<tr>
<td>H</td>
<td>2640</td>
</tr>
<tr>
<td>Ta</td>
<td>1,140,000</td>
</tr>
</tbody>
</table>

Table 1.1: Expected niobium RRR for 1 ppm by weight of impurity.

Figure 1.2: Temperature dependence of niobium thermal conductivity with increasing purity. Notice that as the purity increases so to does the RRR.
attained accelerating gradients of 10 MV/m [17]. This advance in the technology provided the options of increasing output energy or reducing the linac length and overall cost by a factor of two, an impact of several tens of millions of dollars on a project of this scope.

1.4.2 Field Emission

After the introduction of high purity niobium the principal mechanism limiting the accelerating gradient was RF losses caused by field-emitted electrons. In the early 1970s, research lead by R.V. Latham at the University of Aston in the United Kingdom, showed that field emission in high-voltage vacuum insulated electrodes was largely due to micron and sub-micron sized particles on the cavity surface [35, 36]. It was not until the mid 1980s and early 1990s that superconducting cavity research focused on cleaning and processing the superconducting cavities to remove small particulates from the cavity surface [17, 37, 38].

- Ultrasonic cleaning and high-pressure ultrapure water rinsing in very-low-particulate cleanrooms of the cavities and their peripheral hardware remove particulates from the cavity RF surface.
- Very-low-particulate cleanroom drying and assembly prevent particulates from migrating back into the clean cavities.
- High pulsed power processing after final assembly was developed to eliminate field emission during cavity tests.

A substantial amount of work was dedicated to the processing and cleaning of $\beta = 1$ elliptical-cell superconducting cavities and has culminated in a 59 MV/m accelerating gradient with a few design changes [39]. This corresponds to peak surface fields of 2065 Gauss (lower critical field of niobium = 2000 Gauss) and 125 MV/m.

The very-low-particulate clean techniques employed to clean and assemble superconducting cavities were first developed by the semiconductor industry to process wafers and dies with surface areas ranging from 0.1 cm$^2$ to ~100 cm$^2$ [40-42]. In general, if clean very-low-particulate semiconductor techniques are directly applied to superconducting cavities the cleanliness will be degraded. Superconducting cavities are much more difficult to clean than relatively-small flat silicon wafers which are hydrophobic because:
• The surface area of superconducting cavities is relatively large ($10^4$ cm$^2$).
• Superconducting cavities have complex shapes and the inside surface is not easily accessible for cleaning.
• Niobium is hydrophilic. Anything dissolved in the water used to clean the cavities will stick to the surface.

This increases the size and complexity of superconducting cavity very-low-particulate processing facilities. This raises the cost of using superconducting cavities. For example, superconducting cavities typically require 100+ hours per cavity to clean and dry. This lengthens the assembly time and requires skilled technicians. However, the performance of clean superconducting RF cavities is at least a factor of 2 better than unclean cavities.

1.4.3 Phase Control

The difficulties encountered in controlling the phase of superconducting helically-loaded cavities are an instance of “the defect of the virtue” of superconducting cavities, which because of their very low losses, have very small bandwidths [43]. Mechanical vibrations can drive variations in the cavity RF frequency. When the variations are a large fraction of the loaded-cavity bandwidth, RF field amplitude and phase errors can result. Cavity mechanical vibrations driven by forces which couple to the cavity RF field are covered in detail in chapter 2, but briefly introduced in this subsection for clarity.

The coupling of mechanical deformations to the cavity RF field can be described by the Boltzmann-Ehrenfest theorem [44]. Using the Boltzmann-Ehrenfest theorem, the adiabatic invariant of a resonant cavity is given by the ratio of the stored energy divided by the resonant frequency, $U/f$. For variations in the cavity parameters which take place over time scales much larger than the RF period:

\[
\Delta \left( \frac{U}{f} \right) = 0
\]  

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

where $\Delta U$ is the work done on the cavity RF field by a mechanical deformation and $\Delta f = f - f_0$ is the resonant RF frequency shift due to the work $\Delta U$.  

10
There are two important types of cavity mechanical deformations which couple to the cavity RF field: microphonics and Lorentz force detuning [43, 45-47]. Microphonics is the general term used to describe the process where resonant cavities couple mechanical vibrations driven by external forces into unfavorable RF frequency and phase errors. Lorentz force detuning refers to the process where variations in the cavity RF field amplitude couple to the RF phase through the cavity mechanical structure. For example, the pressure exerted by a magnetic field alone is given by $\mu H^2/2$, corresponding to a pressure of approximately 5 psi for an RF resonator with a 1 kG oscillating surface magnetic field. If the field amplitude decreases to 0.5 kG the pressure would decrease to 2.5 psi resulting in a change in the mechanical structure of the resonator which changes the RF frequency. Lorentz force detuning is a relatively new term. In the 1970s through the 1980s it was referred to as the ponderomotive force.

RF accelerators couple power to a charged particle beam through the RF electric field in a string of resonant cavities [14]. The RF field of each and every resonant cavity must be phase-locked to the beam bunches. This is accomplished by locking the resonant cavities to a stable external oscillator, and at the same time synchronizing the beam bunches with the oscillator. When the cavity RF frequency diverges from the stable external oscillator, the phase relationship between the cavity RF field and a particle bunch is altered, introducing time and energy errors in the beam.

The precession of phase error of a cavity relative to an external stable oscillator is given by:

$$\frac{d\Delta \phi(t)}{dt} = \Delta \omega(t)$$

where $\Delta \phi(t) = \phi(t) - \phi_0$, $\phi(t)$ is the phase of the cavity RF field at time t, $\phi_0$ is the synchronous phase, $\Delta \omega(t) = \omega(t) - \omega_0$, $\omega(t)$ is the frequency of the cavity at time t, and $\omega_0$ is the frequency of the external reference oscillator. In general, equation 1.12, leads to the condition that a large frequency error can be tolerated but only for a very short time, and vice versa.

Three techniques have been developed to control the RF phase of superconducting cavities.
1) Overcouple to the cavity. This reduces the loaded-cavity $Q$, increasing the bandwidth and permitting operation at a fixed frequency in the presence of RF frequency fluctuations [46].

2) Couple the cavity RF field to a variable reactance circuit, in the literature this is referred to as reactive tuning. An ideal reactive tuner does not load the cavity $Q$. In practice there are RF losses in reactive tuners and the loaded-cavity $Q$ is reduced. Reactive fast tuners were developed for heavy-ion accelerator cavities which operate at low stored energies and low frequencies. Reactive fast tuners have not been developed for frequencies much larger than 100 MHz or for cavities operating at stored energies greater than a few joules [48].

3) Employ a mechanical fast tuner to introduce a controllable RF frequency variation to maintain the phase relationship between the cavity RF field and the beam. This technique does not damp the loaded-quality factor of the cavity and requires no additional RF power [49-51].

Overcoupling to the cavity RF field requires a control system to provide a reactive RF power given by [46]:

$$ P_{\text{required}} = f(\delta \omega/\Delta \omega_0) \cdot \delta \omega_{\text{max}} \cdot U \approx \delta \omega_{\text{max}} \cdot U \quad \text{if} \quad \delta \omega \gg \Delta \omega_0 $$$$ 1.13

where $\delta \omega = \omega - \omega_0$ measures how far off resonance the cavity is driven, $\Delta \omega_0$ is the intrinsic cavity bandwidth, $U$ is the cavity stored energy, and $f(\delta \omega/\Delta \omega_0)$ is graphed in figure 1.3 (copied from ref. [46]).

Controlling the phase of a superconducting cavity is different than controlling the phase of a normal conducting accelerator cavity. Because of the large amount of RF power dissipated in the walls of normal conducting accelerator cavities they operate with loaded bandwidths on the order of $10^5$ Hz. Superconducting cavities operate with loaded bandwidths determined by the beam loading and are on the order of $10^3$ Hz or less. Consequently, normal conducting cavities can tolerate larger RF frequency variations than superconducting cavities.
A superconducting TEM-class $\beta = 0.5$ triple-spoke-loaded cavity operating with a typical accelerating gradient of 10 MV/m has a stored energy of 40 J and requires 36 W of RF power to operate at 2 K [52]. A peak RF frequency variation of 1 Hz in this cavity would require an additional 250 W of RF power for phase-stable operation. An equivalent normal conducting cavity would only require an additional 13 mW to the 5 MW required for operation, a negligible amount.

As a result, overcoupling to the cavity is useful for cavities with small RF frequency deviations relative to the loaded bandwidth and with small stored energies; refer to equation 1.13. As the RF frequency deviations increase, the RF power required to control the cavity RF field amplitude and phase increases dramatically in cavities which operate at high gradients and high stored energy. It is in this range of applications that external tuners (reactive or mechanical) are useful for reducing the capital and operating costs of a superconducting accelerator.

1.5 The Development of Superconducting Heavy-Ion Accelerators

In the early 1970s, four different laboratories started to develop superconducting accelerators to boost the energy of heavy-ions from electrostatic tandem Van de Graaf...
accelerators [53, 54]. Research groups at Argonne National Laboratory, the California Institute of Technology, and Karlsruhe worked on developing helically-loaded superconducting cavities (figure 1.4). Although high RF fields were achieved the poor mechanical stability of the helically-loaded cavities continued to limit the achievable accelerating gradient. As a result the Karlsruhe group decided to use normal-conducting RF cavities to boost the energy of a tandem Van de Graaf accelerator [55].

Development at the California Institute of Technology started with a helically-loaded cavity and subsequently focused on alternatives to helically-loaded cavities [48, 53]. In 1974, improved mechanical rigidity and RF performance were obtained with a spiral-loaded superconducting cavity and followed one year later by a split-ring cavity (figure 1.4) [56, 57]. The improved mechanical stability of the split ring resonator simplified the phase stabilization and reduced the amplitude of the RF frequency variations.

The Stanford superconducting RF cavity group worked on developing cylindrically symmetric, re-entrant cavity geometries [58]. This work successfully developed a pair of cavities. Because of their short accelerating gaps (2-3 cm) a large number of cavities were required for a linear accelerator and development was discontinued.

Out of these four types of cavities only split ring resonators were used to boost the energy of tandem Van de Graaf accelerators, but this early work lead to the successful development and use of the quarter-wave resonator [54, 59-61]. Both the quarter-wave resonator and the split-ring resonator can be found in 11 superconducting heavy-ion energy-booster accelerators. The success of these accelerators coupled with the major progress in the understanding of nuclear physics research led to the proposal of several higher-energy heavy-ion and proton superconducting accelerators (a conference dedicated to these proposals is detailed in ref. [62]). Early research in superconducting
RF cavities focused on both heavy-ion accelerators ($\beta < 0.2$) and on electron accelerators ($\beta = 1$) [17]. Only in the early 1990s did the development of cavities in the intermediate-velocity range ($0.2 < \beta < 0.8$) begin [63-66].

1.6 Intermediate-Velocity Cavities

There are two distinct classes of superconducting resonators which have been proposed for the acceleration of intermediate-velocity ($0.4 < \beta < 0.8$) heavy-ions [63, 65-67]. The first cavity class is the so-called multiple-cell elliptical-cell cavities, formed from several weakly-coupled cylindrical cells with each cell supporting a cylindrically symmetric Transverse Magnetic $010$ mode ($TM_{010}$). This cavity class is geometrically similar to the cavities used to accelerate $\beta = 1$ particles, and match reduced particle velocities by reducing the length of the cells. The second cavity class is designed around cavities with one or more half-wave loading elements, similar to the spokes of a wheel. Each loading element supports a Transverse Electromagnetic (TEM) half-wave mode. The spoke-loaded cavities which are the focus of the experiments in this dissertation are included in this class of cavity. The TM and TEM class cavities differ in several significant areas (figure 1.5, table 1.2) [63, 66].

![Figure 1.5: A 345 MHz TEM-class triple spoke loaded resonator and an 805 MHz TM-class elliptical cell resonator.](image)
First, the transverse dimension of the TM-class cavities is approximately 0.9λ, where λ is the free space wavelength of the accelerating mode. The transverse dimension of TEM-class cavities is approximately 0.5λ. Hence, at a fixed operation frequency the transverse dimension of a TEM-class structure is half that of a TM-class structure. Also, at a fixed transverse size, the TEM-class structures will resonate at half the frequency. Operating at half the frequency the TEM-class cavities will have half of the number of accelerating cells as a TM-class cavity per unit length. This increases the longitudinal acceptance and increases the stable area of longitudinal particle motion within the bunch.

Second, the electromagnetic field in each cell of a TM-class cavity is coupled to its nearest neighbors through the beam line irises. The coupling between the cavity cells is proportional to the area of the iris and to achieve the required level of coupling the iris size must be large (7 – 8 cm in diameter). Increasing the area of the beam line irises reduces the cavity shunt impedance and increases the peak surface fields at larger iris diameters. Typically values of TM-class cell-to-cell coupling factors are approximately 2%, resulting in a highly intolerant design to mechanical deformations (< 1 mm). TEM-class cavities are strongly coupled through the magnetic fields supported by each of the loading elements. The cell-to-cell coupling of TEM-class cavities is typically between 20 – 30%. The larger cell-to-cell coupling in TEM-class cavities results in cavity designs more tolerant to mechanical deformations.

Third, the electromagnetic stored energy density in TM-class cavities is large over most of the cavity volume. This results in a large stored energy at a fixed accelerating gradient relative to the TEM-class structures which localize the regions of large electromagnetic stored energy to regions along the beam line (predominantly electric field) and at the base of the spokes (predominantly magnetic field). At the same operating frequency TEM-class cavities have approximately half the volume. Hence, at a

<table>
<thead>
<tr>
<th>Attribute</th>
<th>TM-Class</th>
<th>TEM-Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Magnetic Field</td>
<td>Lower Surface fields for β &gt; 0.6</td>
<td>Lower Surface fields for β &lt; 0.6</td>
</tr>
<tr>
<td>Mechanical Structure</td>
<td>Not Rigid</td>
<td>Rigid</td>
</tr>
<tr>
<td>Cell-to-cell coupling</td>
<td>1-3%</td>
<td>20-30%</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>Larger Energy Content at Given Gradient</td>
<td>Smaller Energy Content at Given Gradient</td>
</tr>
<tr>
<td>Cleanability</td>
<td>Geometrically Simple Design</td>
<td>Complex geometric Designs</td>
</tr>
<tr>
<td>$R_{2n} \cdot R_3$</td>
<td>Better for β &gt; 0.6</td>
<td>Better for β &lt; 0.6</td>
</tr>
</tbody>
</table>

Table 1.2: Attributes of TM and TEM-class superconducting cavities.
fixed accelerating gradient and operating frequency the TEM-class cavities operate with reduced stored energies. This increases the shunt impedance of the TEM-class cavities and reduces the RF power required to stabilize the phase and amplitude of the cavity RF field in the presence of relatively large RF frequency variations, frequency variations which are a sizable fraction of the cavity loaded-bandwidth.

Fourth, intermediate-velocity TM-class cavities are not as mechanically rigid as TEM-class cavities. Large deflections of the cavity wall due to external forces lead to significant RF frequency variations. This causes phase errors between the cavity RF field and the particle beam bunches. Rigid structures should have smaller deflections and accordingly smaller RF frequency variations.

Finally, the peak surface magnetic field of spoke loaded resonators increased as the cavity geometry is changed to accelerate high-velocity ions. Above $\beta = 0.65$ the peak surface magnetic field of TM-class resonators is lower.

1.7 The RF Performance of Spoke-Loaded Cavities

Clean processing and handling techniques were recently applied to intermediate and low-velocity TEM-class superconducting cavities and have profited from the research dedicated to TM-class $\beta = 1$ cavities. In 2001 the effects of high-pressure rinsing a $\beta = 0.4$ superconducting single-spoke cavity at Argonne National Laboratory were published [68]. The results showed an increase by a factor of 2 in the maximum achievable accelerating gradient.

Using clean techniques spoke-loaded superconducting cavities reach peak accelerating gradients greater than 10 MV/m with peak surface electric and magnetic fields exceeding 30 MV/m and 800 G respectively [52, 69, 70]. The peak surface fields are still less than those obtained in elliptical-cell cavities and there may be more gains to be made in spoke-loaded cavities. The total research and development effort devoted to spoke-loaded cavities amounts to a small fraction of the work focused on improving elliptical-cell cavities and because of this the RF performance of spoke-loaded cavities lags behind $\beta = 1$ elliptical-cell cavities. At present levels of performance, superconducting spoke cavities are the technology of choice for continuous-wave ion/proton linear accelerators and for applications which require a high quality beam for
velocities $0.3 < \beta < 0.65$, but microphonic-noise and Lorentz force induced RF frequency variations are still problematic for phase control.

- Techniques which rely on overcoupling to phase-stabilize spoke-cavity RF fields have been developed but are inefficient.

- Reactive fast tuners developed for heavy-ion accelerator cavities have not been developed for frequencies much larger than 100 MHz or for cavities operating at stored energies greater than a few joules. As a result, they are currently not an option for spoke-loaded cavities.

- Mechanical fast tuners have been developed for pulsed TM-class superconducting cavities, but prior to this dissertation, no mechanical tuning systems have been developed for superconducting spoke-loaded cavities or any superconducting cavity operated in the continuous-wave mode.
Chapter 2

Background and Experimental Methodology

2.1 Introduction

This chapter discusses the parameters, theory, and experimental methodology used to obtain the experimental results discussed in the following chapters. Chapter two is separated into three parts.

- First, the superconducting cavities and parameters relevant to this dissertation are introduced.
- Second, these parameters will be used in the presentation of the theoretical background relating experimentally measurable quantities to the interactions between electromagnetic and mechanical eigenmodes.
- Finally, the experimental apparatus and methodology used to characterize the coupling of the cavity mechanical and electromagnetic eigenmodes will be presented. In particular, the Lorentz transfer function will be discussed. In chapter 3, the Lorentz transfer function will be shown to be a powerful tool in analyzing cavity electro-mechanical behavior.

2.2 Multi-Spoke-Loaded Cavity Structures

The experiments in this dissertation utilize two superconducting niobium prototype cavities produced as part of the Rare-isotope Accelerator Project at Argonne National Laboratory. The two TEM-class, 345 MHz, cavities are a 345 MHz TEM-class $\beta = 0.4$ double-spoke-loaded resonator (DSR) and a $\beta = 0.5$ triple-spoke-loaded resonator (TSR) (see figure 2.1) [52, 69-71]. The cavity names stand for the number of spokes which can support TEM-like standing waves (figure 2.2) and $\beta$ is the particle velocity which the cavity was optimized to accelerate (figure 2.5). The structural dimensions and relevant electromagnetic properties of the two multi-spoke loaded cavities are summarized in tables 2.1 and 2.2.
2.3 Spoke-Loaded Cavity Electromagnetic Properties

2.3.1 The 345 MHz Eigenmode

A cavity electromagnetic field is formed from standing waves with discrete frequencies, the electromagnetic normal modes, such that the boundary conditions for Maxwell’s equations are satisfied at the cavity surface [72]. Both the $\beta = 0.4$ DSR and the $\beta = 0.5$ TSR use the lowest frequency electromagnetic eigenmode to accelerate charged particles. The 345 MHz mode of the $\beta = 0.5$ TSR is shown in figure 2.3.
electromagnetic properties of the $\beta = 0.4$ DSR and the $\beta = 0.5$ TSR are summarized in table 2.2. The cavity electromagnetic modes were modeled using CST Microwave Studio simulation software [73].

### 2.3.2 The Accelerating Gradient

When the 345 MHz eigenmode is excited each spoke can be viewed as a half-wave TEM transmission line grounded at both ends with a voltage maximum and a current minimum located at the center of the spoke, figure 2.2 [65]. The 345 MHz eigenmode is also referred to as the pi-mode, since the relative phase of the electric field differs by $\pi$ radians in adjacent gaps [13, 14]. A snapshot of the $\beta = 0.5$ TSR 345 MHz eigenmode RF electric and magnetic field is shown in figure 2.3 for a cavity stored energy of 1 J. 1 J was chosen, not because it is a typical operating value (= 40 J), but to present the graph in the notation currently used in the literature.

The energy coupled to a charged particle with an accelerator cavity is equal to the work done on the particle by the axial electric field, following the notation of Delayen [74]:

$$\Delta W = q \int_{-\infty}^{\infty} E_z(0,0,z) \sin(\alpha + \phi) \, dz$$  

2.1
where $q$ is the particle charge, $E_z(0,0,z)$ is the axial electric field, $\omega$ is the angular frequency of the electromagnetic field ($=2\pi f$), $\phi$ is the phase of the electric field relative to its peak accelerating magnitude at $t = 0$, the z-axis is chosen to lie along the beam path, and the field profile was assumed to be odd with respect to the center of the cavity (see figure 2.4 for plots of the axial electric field). In the case of an even field profile, as is the case for the $\beta = 0.4$ DSR, the term $\sin(\omega t + \phi)$ is replaced with $\cos(\omega t + \phi)$. From this the definition of the cavity voltage gain is:

$$V_{\text{acc}} = \frac{\Delta W}{q} = \int E_z(0,0,z) \sin(\omega t + \phi) \, dz$$  \hspace{1cm} 2.2$$

Graphs of the voltage gain as a function of the particle velocity are shown in figure 2.5. Notice that the energy gain is maximized for an ion traveling at $\beta = 0.5$ for the TSR and at $\beta = 0.4$ for the DSR. These values are defined as the geometric $\beta$ of the cavity, $\beta_{\text{geom}}$, and correspond to the particle velocity with the maximum voltage gain.

The cavity accelerating gradient, $E_{\text{acc}}$, is defined as:

$$E_{\text{acc}} = \frac{V_{\text{acc}}}{l_{\text{eff}}}$$  \hspace{1cm} 2.3$$

where $l_{\text{eff}}$ is the effective length of the cavity [74].

In the literature, several definitions are used for the cavity effective length. This dissertation will use the notation recently proposed by Delayen [52, 74, 75]:

$$l_{\text{eff}} = n \cdot \frac{\beta \cdot \lambda}{2}$$  \hspace{1cm} 2.4$$

where $n$ is equal to either the number of accelerating cells in a TM-class cavity or, in the case of TEM-class cavities, the number of loading elements. For example, the effective length of the proposed International Linear Collider (ILC) 1.3 GHz ($\beta = 1$) nine-elliptical-cell cavity is $9 \cdot 1 \cdot \lambda / 2 = 103.8$ cm [76]. Some references, primarily older, use the exterior or interior physical length of the cavity. For example, the interior length of a quarter-wave coaxial-line resonator ($n = 1$) discussed in is 20.3 cm, instead of $n \cdot \beta \cdot \lambda / 2 = 15.5$ cm [77].
Figure 2.3: Snapshots of the $\beta = 0.5$ TSR 345 MHz mode electric (top) and magnetic (bottom) field. The figure was generated with CST Microwave Studio simulation software at a stored energy of 1 J.
Figure 2.4: Axial electric field of the $\beta = 0.4$ DSR (top) and the $\beta = 0.5$ TSR (bottom) operating at a stored energy of 1 J.
Figure 2.5: Energy gain versus particle velocity for the $\beta = 0.4$ DSR (top) and the $\beta = 0.5$ TSR (bottom) operating at a stored energy of 1 J.
2.4 Electromagnetic and Mechanical Mode Interactions

2.4.1 Introduction

This section introduces the physics which describe the coupling process between the RF field and the mechanical eigenmodes. This is necessary because the walls of a superconducting cavity are not infinitely rigid. Consequently, the mechanical structure of a cavity is described by a complete set of mechanical eigenmodes and cavity RF frequency variations are due to external forces driving mechanical oscillations which couple to the cavity RF field.

First, the two fundamental points are introduced: the Boltzmann-Ehrenfest theorem and the linear equation of motion for the cavity mechanical eigenmodes. The Boltzmann-Ehrenfest theorem relates a change in the cavity frequency to the work done on the electromagnetic field. It will show that the changing in frequency is linear in the displacement of the cavity surface. Hence, changes in the cavity frequency must obey the same differential equation which describes the mechanical eigenmodes. It is the transfer functions of the linear equation of motion which are experimentally measured to characterize the coupling between the cavity RF field and the mechanical eigenmodes. The experimental results which measure the parameters used in this derivation are presented in chapters 3, 4, and 5.

2.4.2 The Boltzmann-Ehrenfest Theorem

Following the derivation of Schulze [45], first, consider a one-dimensional mechanical system which undergoes a periodic motion and whose properties depend on the parameter $\lambda$. If $\lambda$ does not change much over a period of the motion, $T$:

$$T \frac{d\lambda}{dt} \ll \lambda$$

Then, according to the Boltzmann-Ehrenfest theorem, the ratio of the parameter $\lambda$ and the stored energy, $U$, is a constant to as many orders in the rate of change of $\lambda$ as $\lambda$ has continuous derivatives [44]. This constant is referred to as an adiabatic invariant of the motion of $\lambda$.

For the simple harmonic oscillator the parameter $\lambda$ is the eigenfrequency of the oscillation, $\omega_0$, and the adiabatic invariant is $U/\omega_0$. This is analogous to changing the
eigenfrequency of one of the electromagnetic eigenmodes in a loss-free resonant cavity with eigenfrequency $\omega$ and stored energy $U$.

Applying the Boltzmann-Ehrenfest theorem to the case of a resonant cavity and using the notation of Schulze in the limit where [45]:

$$\frac{2\pi}{\omega} \frac{d \omega}{dt} \ll \omega$$

yields:

$$\Delta \left( \frac{U}{\omega} \right) = \frac{\Delta U}{U} - \frac{\Delta \omega}{\omega} = 0$$

2.7

When the walls of the resonator are displaced by a small amount $\ddot{u}(\vec{x},t)$ the electromagnetic force performs work on the resonator field. The energy for the work done is subtracted from the electromagnetic stored energy:

$$\Delta U + A = 0$$

2.8

The electromagnetic force density acting on the resonator surface can be determined from the Maxwell stress tensor through the surface fields and is found to be:

$$\vec{F}(\vec{x},t) = \left[ \frac{\varepsilon}{2} \vec{E}(\vec{x},t) \cdot \vec{E}(\vec{x},t) - \frac{\mu}{2} \vec{H}(\vec{x},t) \cdot \vec{H}(\vec{x},t) \right] \cdot \hat{n}(\vec{x},t)$$

2.9

where $\hat{n}$ is the inward unit normal vector at all points on the cavity RF surface. The work done on the system is found by integrating the dot-product between the force density and the surface displacement, $\ddot{u}(\vec{x},t)$, over the resonator surface, $S$:

$$A = \int_S \left( \vec{F}(\vec{x},t) \cdot \ddot{u}(\vec{x},t) \right) da$$

2.10

The electromagnetic energy is given by the integral of the magnetic and electric energy density over the entire volume of the resonant cavity, $V$:

$$U = \int_V \left( \frac{\varepsilon}{2} \vec{E}(\vec{x},t) \cdot \vec{E}(\vec{x},t) + \frac{\mu}{2} \vec{H}(\vec{x},t) \cdot \vec{H}(\vec{x},t) \right) d^3x$$

2.11

Using equations 2.7 - 2.11 the change in eigenfrequency due to the work done on the resonator electromagnetic eigenmode is:
\[
\frac{\Delta \omega}{\omega} = -\int_s \left( \frac{\varepsilon}{2} \mathbf{E}(\bar{x},t) \cdot \mathbf{E}(\bar{x},t) - \frac{\mu}{2} \mathbf{H}(\bar{x},t) \cdot \mathbf{H}(\bar{x},t) \right) \mathbf{u}(\bar{x},t) \cdot \mathbf{u}(\bar{x},t) \, da
\]

This is also called Slater’s formula [78, 79]. As a result when the surface of the resonator is deformed inward in a region where the surface field is predominantly electric (magnetic) rather than magnetic (electric) the resonant frequency of the excited cavity mode decreases (increases).

### 2.4.3 Electromagnetic and Mechanical Eigenmode Coupling

Equation 2.12 relates the displacement of the cavity surface to a change in the RF frequency. This section presents the derivation of the equation of motion for cavity mechanical eigenmodes and relates it to the RF frequency variation of a cavity resonator.

The $\beta = 0.5$ triple-spoke-loaded cavity is a complex mechanical system. Simpler equations are obtained by expressing the deflections and the force density in the basis of the mechanical eigenmodes, $\phi_\alpha(\bar{x},t)$, as was done by Karliner, Shapiro, Schulze, and Delayen [45, 47, 80-82]. Let the inward normal vector on the cavity surface be, $\bar{e}(\bar{x},t)$, and the surface displacement is:

\[
\bar{u}(\bar{x},t) = u(\bar{x},t)\bar{e}(\bar{x},t)
\]

and the projected force is:

\[
F(\bar{x},t) = \bar{F}(\bar{x},t) \cdot \bar{e}(\bar{x},t)
\]

and the generalized coordinates $q_\alpha$ and $F_\alpha$ are defined in terms of the mechanical eigenmodes, $\phi_\alpha$, as:

\[
F_\alpha(t) = \int_S (F(\bar{x},t)\phi_\alpha(\bar{x},t)) \, da
\]

\[
q_\alpha(t) = \int_S (u(\bar{x},t)\phi_\alpha(\bar{x},t)) \, da
\]

\[
\int_S (\phi_\alpha(\bar{x},t)\phi_\beta(\bar{x},t)) \, da = \delta_{\alpha\beta}
\]

The total work done on the electromagnetic field is a sum over all of the mechanical eigenmodes. Hence, the total work done on the system can be represented as the summation:
The Lagrange equation of motion for the $\alpha^{th}$ mechanical mode is:

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_\alpha} \right) - \frac{\partial L}{\partial q_\alpha} + \frac{\partial \kappa}{\partial \dot{q}_\alpha} = F_\alpha \tag{2.19}$$

With the assumption, that the mechanical power loss, $\square$, is small relative to the reactive power. Expanding the potential energy, the kinetic energy, and the power loss in terms of the generalized coordinates:

$$V = \frac{1}{2} \sum_\alpha c_\alpha q_\alpha^2 \tag{2.20}$$

$$T = \frac{1}{2} \sum_\alpha c_\alpha \left( \frac{\dot{q}_\alpha}{\Omega_\alpha} \right)^2 \tag{2.21}$$

$$\kappa = \sum_\alpha \frac{\Omega_\alpha c_\alpha}{Q_\alpha} \left( \frac{\dot{q}_\alpha}{\Omega_\alpha} \right)^2 \tag{2.22}$$

where for a mode $\alpha$, $c_\alpha$ is the elastic constant, $\Omega_\alpha$ is the mechanical eigenfrequency, and $Q_\alpha$ is the quality factor. $Q_\alpha$ is the ratio of the reactive mechanical power to the power loss in the mechanical resonance and it must be much greater than 1 for equation 2.19 to be valid.

Substituting equations 2.20 - 2.22 into 2.19:

$$\frac{d^2 q_\alpha}{dt^2} + \frac{2\Omega_\alpha}{Q_\alpha} \frac{dq_\alpha}{dt} + \Omega_\alpha^2 q_\alpha = \frac{\Omega_\alpha^2}{c_\alpha} F_\alpha \tag{2.23}$$

Recall, from equations 2.9 and 2.15 that the frequency shift of the cavity is proportional to the displacement of the cavity wall which, in turn, is proportional to the generalized coordinate of motion. It follows that:

$$\Delta \omega_\alpha \propto \frac{\omega F_\alpha}{U} q_\alpha \tag{2.24}$$

As a result the total eigenfrequency shift, $\Delta \omega$, can be expressed as the sum of the frequency shifts due to the contributions of each individual mechanical eigenmode, $\Delta \omega_\alpha$: 

$$A = \sum_\alpha F_\alpha \cdot q_\alpha \tag{2.18}$$
\[ \Delta \omega = \sum_{a} \Delta \omega_{a} \quad 2.25 \]

Substituting 2.24 into equation 2.23 gives:

\[ \frac{d^{2}\Delta \omega_{a}}{dt^{2}} + \frac{2\Omega_{a}}{Q_{a}} \frac{d\Delta \omega_{a}}{dt} + \Omega_{a}^{2} \Delta \omega_{a} = -\frac{a\Omega_{a}^{2}}{c_{a}U} F_{a}^{2} \quad 2.26 \]

This equation has an important experimental consequence, in that \( \Delta \omega \) and \( \Delta \omega_{a} \) can easily be measured experimentally, whereas the mechanical eigenmodes are extremely difficult to measure and characterize [45].

2.5 Experimental Methods

2.5.1 Introduction

This section will provide a detailed description of the experiments and methods used to characterize the interaction between the electromagnetic eigenmode used to accelerate particles and the mechanical eigenmodes.

1) The lumped parameter approximation to a resonant cavity under test will be presented, introducing the measurement of the cavity \( Q \)-curve and of the systematic error. A \( Q \)-curve is a graph of the cavity quality-factor as a function of the accelerating gradient.

2) The methodology used to characterize microphonic-noise will be discussed. This will focus on the hardware and methods used to measure cavity RF frequency deviation relative to an external oscillator.

3) The methodology used to measure cavity detuning due to the Lorentz force will be discussed. This requires the simultaneous measurement and correlation of the cavity accelerating gradient, RF frequency, and input power.

4) The methodology used to characterize the performance of fast mechanical tuners will be discussed.

Results from the microphonics measurements and the Lorentz detuning measurements will be presented in chapters 3 and 4, while the fast mechanical tuner measurements are the focus of chapter 5.
2.5.2 The Lumped Parameter Approximation

Circuits can be divided into two classes: circuits which are composed of lumped-elements, or distributed circuits. Lumped-element circuits combine discrete resistors, inductors, and capacitors which have dimensions that are much smaller than the electromagnetic wavelength; while distributed circuits are formed from objects which have dimensions comparable to the electromagnetic wavelength. In a parallel RLC circuit the electric field of a capacitor is used to store electric energy while the magnetic field of an inductor is used to store magnetic energy. In a cavity resonator the electric and magnetic energy is stored in the same volume rather than in two distinguishable spaces.

For drive frequencies close to the resonant frequency, it has been shown that distributed cavity resonators can be quantitatively approximated by lumped-element parallel RLC circuits. This is called the lumped-parameter approximation. Analytically it is convenient to approximate the distributed circuit with a lumped-parameter model. Refer to figure 2.6 for a block diagram of the lumped parameter approximation to a resonant cavity [83].

The measurement of the cavity $Q$, field level, and dissipated power will be described using the lumped parameter approximation [13, 83, 84]. The parallel RLC circuit, within the dashed box shown in figure 2.9, is used to approximate the cavity electromagnetic properties. The cavity input impedance when driven at a frequency $\omega$ is given by:

$$
\frac{1}{Z_{12}} = \left( \frac{1}{R_0} + \frac{1}{i\omega L_0} + i\omega C_0 \right)
$$

where $R_0$, $L_0$, and $C_0$ are the cavity lumped resistance, inductance, and capacitance respectively. The power delivered to the resonator is:

![Figure 2.6: The lumped parameter approximation to a cavity coupled to an external generator and a pick-up probe.](image)
\[ P_m = \frac{|V|^2}{2 \cdot Z_{in}} = \frac{|V|^2}{2} \left( \frac{1}{R_0} - i \omega \cdot C_0 \left( 1 - \frac{1}{\omega^2 \cdot L_0 \cdot C_0} \right) \right) \quad 2.28 \]

For a fixed cavity voltage the power delivered to the resonator is a minimum when:

\[ \omega = \frac{1}{\sqrt{L_0 C_0}} = \omega_0 \quad 2.29 \]

As a result, on resonance the stored energy, intrinsic cavity \( Q \), and dissipated power are:

\[ U_0 = \frac{C_0 \cdot |V|^2}{2} \quad 2.30 \]

\[ Q_0 = \frac{R_0}{\omega_0 \cdot L_0} = \frac{\omega_0}{\Delta \omega_0} \quad 2.31 \]

\[ P_0 = \frac{|V|^2}{2 \cdot R_0} \quad 2.32 \]

where \( \Delta \omega_0 \) is the intrinsic bandwidth of the system. From this the RF energy decay time can be calculated and is given by:

\[ \tau = \frac{U_0}{P_0} \quad 2.33 \]

When the cavity is coupled to a transmission line the lumped parameter approximation is shown in figure 2.14. The intrinsic-cavity \( Q \) defined in equation 2.31 is a characteristic of the RLC resonant circuit without any additional loading effects due to external circuitry. However, a resonant cavity is always tested with a pick-up coupler and an input power coupler. This has the effect of damping the overall \( Q \) of the system. The damped \( Q \) is referred to as the loaded-cavity \( Q \), \( Q_L \). Now the total power required to operate the cavity \( (P) \) is equal to the sum of the power dissipated in the cavity \( (P_c) \), the power coupled out of the cavity by the pick-up coupler \( (P_1) \), and the power coupled out of the cavity by the input power coupler \( (P_2) \). Now \( Q_L \) can be written as:

\[ \frac{1}{Q_L} = \frac{P}{\omega \cdot U_0} = \frac{P_c + P_1 + P_2}{\omega \cdot U_0} = \frac{1}{Q_0} + \frac{1}{Q_{ext1}} + \frac{1}{Q_{ext2}} \quad 2.34 \]

where the external quality factor of the couplers is equal to the ratio of the power removed from the cavity by the coupler divided by the product of the energy stored in the cavity times the drive frequency. The coupling factor is defined as:
Physically, the coupling factor is related to the reflection coefficient, $\Gamma$, for a wave propagating toward the cavity:

$$\Gamma = \frac{1 - \beta}{1 + \beta}$$

2.36

The coupling strength of the pick-up coupler is chosen to be much less than 1, $\beta \ll 1$, to avoid damping the intrinsic cavity $Q$. The pick-up used in the experiments described in this dissertation was measured at room temperature to have $Q_{\text{ext}} = 2.6 \times 10^{11}$ when mounted on the $\beta = 0.5$ TSR and $Q_{\text{ext}} = 3.5 \times 10^{11}$ when mounted on the $\beta = 0.4$ DSR, these measurements are accurate to 50% and lead to an error of less than 1% when measuring the cavity RF performance. Both cavities were tested at and below 4.5 K with variable input power couplers. The $\beta = 0.4$ DSR variable power coupler $Q_{\text{ext}}$ could be varied over the range $2 \times 10^8 < Q_{\text{ext}} < 3 \times 10^{10}$ and the $\beta = 0.5$ TSR variable power coupler $Q_{\text{ext}}$ could be varied over the range $5 \times 10^6 < Q_{\text{ext}} < 5 \times 10^9$, these measurements are accurate to 3%.

Now when the RF power is turned off the RF stored energy will decay in a time defined as the loaded decay time, $\tau_L$:

$$Q_L = \omega \cdot \tau_L$$

2.37

also the cavity stored energy can be determined because it is proportional to the cavity power in the steady state:

$$P_c = \frac{dU(t)}{dt} = -\frac{U}{\tau_L}$$

2.38

Finally, the cavity accelerating field is determined:

$$E_{acc} = \sqrt{\frac{U}{U_0}}$$

2.39

where $U_0$ is the stored energy when the cavity has an accelerating gradient of 1 MV/m, table 2.1.

The forward and reflected RF powers are measured with a dual-directional coupler located 5 meters away from the input coupler. The actual value of the forward (reflected)
power at the cavity/coupler interface is the measured power value multiplied (divided) by the attenuation factor of the transmission lines, input coupler, and dual-directional coupler. The relative error for the forward and reflected power is given by:

\[
\frac{\Delta P}{P} = \sqrt{\left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta P_{\text{measured}}}{P_{\text{measured}}}\right)^2}
\]  

2.40

where \(A\) is the attenuation factor and \(P_{\text{measured}}\) is the power measured by the power meter. The relative error of the attenuation factor and the measured power are both 2%. These numbers apply to both the forward and reflected power corresponding to an overall uncertainty in their measurement of 3%.

The relative error for the intrinsic quality factor of the cavity when measured at low field levels is given by:

\[
\frac{\Delta Q_0}{Q_0} = \frac{\Delta \tau_0}{\tau_0}
\]  

2.41

where the decay time uncertainty is typically 3%. The relative errors of the \(Q\) and accelerating gradient at high field levels are given by:

\[
\frac{\Delta Q}{Q} = \sqrt{\left(\frac{\Delta U}{U}\right)^2 + \left(\frac{\Delta P}{P}\right)^2}
\]  

2.42

\[
\frac{\Delta E_{\text{acc}}}{E_{\text{acc}}} = \sqrt{\left(\frac{\Delta U}{U}\right)^2}
\]  

2.43

For the experiments discussed here the relative error is approximately 5% for the \(Q\) and 4% for \(E_{\text{acc}}\).

2.5.3 \(Q_0\) versus \(E_{\text{acc}}\) Measurement

A schematic of the hardware used to measure the \(Q\) and \(E_{\text{acc}}\) is shown in figure 2.7 (adapted from ref. [84]). The measurement system utilizes a phase-locked loop to lock the cavity frequency to an external oscillator (HP8644B). This is necessary because the \(Q\) of the superconducting cavity at 4 K is typically \(10^9\) or more and the cavity RF bandwidth is less than 0.4 Hz [52, 71].

The cavity pick-up signal is used as the feedback signal for the phase-locked loop [85]. The pick-up signal and a signal coupled from the external oscillator are transmitted to a doubly balanced mixer. The IF output of the mixer is filtered with a low
pass filter such that the signal controlling the oscillator frequency modulation is proportional to the phase difference between the cavity signal and the external oscillator.

The relative error of the signal amplitudes measured with the oscilloscope increase with the voltage. To circumvent this error growth the signal amplitudes measured with the oscilloscope are kept constant with a step attenuator and a limiting amplifier. The actual signal amplitude is then equal to the product of the calibration value and the attenuation of the step attenuator.

The cavity $Q$ as a function of the accelerating gradient is shown in figure 2.8 for the $\beta = 0.4$ DSR and the $\beta = 0.5$ TSR. The horizontal axis is the accelerating gradient in MV/m and the vertical axis is the logarithm of the measured cavity quality factor. For reference, there is an additional curve on each graph of the cavity $Q$ a function of the accelerating gradient at a fixed power:

$$Q = \omega \frac{U_0 \cdot E_{acc}^2}{P_{\text{fixed}}}$$

2.44
Figure 2.8: Q curves for the $\beta = 0.4$ DSR (top) and the $\beta = 0.5$ TSR (bottom).
2.5.4 RF Frequency Deviation Measurement

The RF frequency of a superconducting cavity is measured by comparing the pickup signal from the cavity to an external reference oscillator with a cavity resonance monitor (CRM) [67]. This section will first discuss the CRM and then discuss the measurement of the cavity RF frequency relative to an external oscillator.

2.5.4.1 The Cavity Resonance Monitor

A block diagram of the CRM is shown in figure 2.9. The CRM takes as an input two signals:

\[ f_1(t) = A \sin(\omega t + \phi_1) \]
\[ f_2(t) = A \sin(\omega t + \phi_2) \]

First, \( f_1(t) \) is split into two components with a relative phase difference of 90°, and \( f_2(t) \) is split into two in phase components:

\[ f_1(t) \Rightarrow f_1^{\phi_1} (t) = \frac{A}{\sqrt{2}} \sin(\omega t + \phi_1) \quad ; \quad f_1^{90\phi_1} (t) = \frac{A}{\sqrt{2}} \sin(\omega t + \phi_1 - \pi/2) \]
\[ f_2(t) \Rightarrow f_2^{\phi_2} (t) = \frac{A}{\sqrt{2}} \sin(\omega t + \phi_2) \quad ; \quad f_2^{90\phi_2} (t) = \frac{A}{\sqrt{2}} \sin(\omega t + \phi_2) \]
Second, two doubly balanced mixers form the product of two of the split signals and the mixer outputs are each filtered with a low-pass filter. Generating the signals:

\[ X(t) = f_1^{\phi_1}(t) \cdot f_2^{\phi_2}(t) = \frac{A^2}{4} \cos(\Delta \omega \cdot t + \Delta \phi) \]  
\[ Y(t) = f_1^{\phi_1}(t) \cdot f_2^{\phi_2}(t) = \frac{A^2}{4} \sin(\Delta \omega \cdot t + \Delta \phi) \]

where \( \Delta \omega = \omega_1 - \omega_2 \) and \( \Delta \phi = \phi_1 - \phi_2 \). Finally, the output voltage is calculated:

\[ f_{out}(t) = X(t) \frac{dY(t)}{dt} - Y(t) \frac{dX(t)}{dt} \]

\[ X(t) \frac{dY(t)}{dt} = -\Delta \omega \frac{A^4}{16} \sin^2(\Delta \omega \cdot t + \Delta \phi) \]

\[ Y(t) \frac{dX(t)}{dt} = \Delta \omega \frac{A^4}{16} \cos^2(\Delta \omega \cdot t + \Delta \phi) \]

\[ f_{out}(t) = -\Delta \omega \frac{A^4}{16} \]

where \( f_{out}(t) \) is the output of the CRM, the frequency deviation signal, which is proportional to the frequency difference between the two input signals.

The precision of the frequency deviation signal is limited by the reference oscillator phase-noise. To characterize the reference oscillator phase-noise 345 MHz output signals from two Hewlett-Packard 8644B synthesized signal generators were input to the CRM; the HP8644B being the reference oscillator used in the experiments presented in this dissertation. The CRM frequency deviation signal was sampled at 5 kHz for 5 min and the results are displayed in figure 2.10. The probability density (histogram) of the reference oscillator’s phase-noise is graphed on top. The horizontal axis is the RF frequency deviation signal and the vertical axis is the product of 20 and the logarithm of the ratio of the number of counts in the histogram bin to the total number of counts in the data set:

\[ dB_{counts} = 20 \log \left( \frac{\text{Number of Counts in the Bin}}{\text{Total \# of Data Points}} \right) \]

The lower plot is the spectrum of the CRM RF frequency deviation signal. The horizontal axis is the FFT frequency in hertz of the time domain data and the vertical axis
Figure 2.10: Frequency error on the output of two HP8644B synthesized signal generators: probability density (top) and frequency spectrum (bottom).
is the amplitude of the RF frequency deviation. The axes scales were chosen to coincide with the scales used in chapters 4 and 5 of this dissertation. Notice that at low FFT frequencies the output of the HP8644B is stable and the rms frequency deviation of two reference oscillators is 0.33 Hz.

2.5.4.2 Determination of the Cavity RF Frequency Deviation

Figure 2.11 displays the measurement layout used to determine the RF frequency of a cavity relative to an external oscillator, the cavity RF frequency deviation.

- The superconducting cavity is phase-locked to an external oscillator.
- The cavity RF frequency deviation from an external oscillator is measured with the CRM.
- A LABView data acquisition system samples the output of the CRM.

Figure 2.11: Block diagram of the electronics used to measure the frequency deviation of the cavity RF field from an external oscillator with a cavity resonance monitor, chapter 4.
2.5.5 Lorentz Transfer Function Measurement

The Lorentz transfer function will be covered in detail in chapter 3. To measure the Lorentz transfer function sinusoidal modulations of the cavity RF frequency, sinusoidal modulations of the cavity RF field amplitude, and the relative phase between these modulations must be simultaneously measured [86]. A block diagram of the measurement system is shown in figure 2.12.

First, the cavity $Q_0$ is typically $10^9$ or greater, corresponding to an RF decay time at 345 MHz of 0.5 seconds [52, 71]. It is necessary to measure variations in the RF field amplitude which occur over time scales comparable to 1 ms. To measure these variations the cavity $Q$ is damped with the input power coupler to $10^7$, $\tau_L = 4.5$ ms. RF field amplitude modulations are generated by amplitude modulating the forward power exciting the cavity. The amplitude modulation signal is provided by a lock-in amplifier.

Second, the cavity RF frequency modulation is measured with a CRM.

---

Figure 2.12: Block diagram of the Lorentz transfer function measurement, chapter 3.
Finally, the frequency modulation signal is measured with the lock-in amplifier which measures both the amplitude of the RF frequency modulation and its relative phase to the forward power modulation. The cavity RF field amplitude is monitored with an RF amplitude detector which outputs a voltage proportional to the input RF signal amplitude. LABView is used to simultaneously monitor all of the data [87].

2.5.6 Mechanical Fast Tuner Experimental Methods

There are three distinct experimental measurements performed with the mechanical fast tuner which will be covered in chapter 5. The systematic error for all of these measurements is characterized in section 2.5.4.1.

1) The mechanically coupled fast tuner/cavity system is characterized by correlating sinusoidal tuner amplitude modulations with the corresponding cavity RF frequency modulation (figure 2.13).

2) The mechanical fast tuner is used to damp the microphonic-noise induced RF frequency variations (figure 2.14).

3) The mechanical fast tuner is used to phase lock the cavity RF field to an external reference oscillator (figure 2.15).

2.5.6.1 Fast Tuner/Cavity Transfer Function

The mechanically coupled fast tuner/cavity system characterization requires the simultaneous measurement of the RF frequency modulation of the cavity RF field and the amplitude modulation of the signal driving the fast mechanical tuner [51]. A block diagram of the transfer function measurement is shown in figure 2.13.

1) An external reference oscillator is phase-locked to the cavity RF frequency.

2) A lock-in amplifier is used to generate the sinusoidal waveform used to drive the fast mechanical tuner. This results in a sinusoidal modulation of the cavity RF frequency.

3) The cavity RF frequency deviation from an external oscillator is measured with a CRM. The cavity RF frequency deviation amplitude and phase relative to the signal driving the fast mechanical tuner are measured with the lock-in amplifier. This data is discussed in detail in chapter 5.
Figure 2.13: Block diagram of the coupled tuner/cavity transfer function, chapter 5.

Figure 2.14: Negative frequency feedback system for damping RF frequency variations with a fast mechanical tuner.
2.5.6.2 Fast Tuner Microphonic-Noise Damping

To damp the microphonic-noise of a spoke-loaded cavity the fast mechanical tuner is driven by the instantaneous frequency difference between the cavity and the external oscillator (figure 2.14). These experiments are discussed in chapter 5.

1) An external reference oscillator is phase-locked to the cavity RF frequency.
2) The cavity RF frequency deviation from an external oscillator is measured with a CRM.
3) The CRM output voltage is used to drive the fast mechanical tuner.

The mechanical tuner

2.5.6.3 Fast Tuner Phase Control

To this point all of the experiments discussed use a phase-locked loop to lock an external oscillator to the cavity RF field. The phase control experiments discussed in chapter 5 use a specially engineered analog phase controller designed and built at Argonne National Laboratory [88]. A block diagram of the experimental layout is shown in figure 2.15. The phase controller performs two functions.

1) The amplitude of the cavity pick-up signal is measured with an amplitude detector. The amplitude controller compares the amplitude of the cavity pick-up signal to a DC voltage equal to the cavity pick-signal strength at a fixed cavity RF field level. The amplitude controller either increases or decreases the forward power exciting the cavity to maintain a constant field level.
2) The phase of the cavity RF field relative to an external oscillator is measured. The phase control module then actuates the fast mechanical tuner and shifts the phase of the RF signal exciting the cavity to either advance or regress the RF phase of the cavity to match the external oscillator.
Figure 2.15: Phase control block diagram of the cavity RF field with the fast mechanical tuner.
Chapter 3

Lorentz Force Detuning

3.1 Introduction

Two distinguishable sources of cavity mechanical deformations which couple to the cavity RF field are microphonics and the Lorentz force [43, 45-47]. This chapter will present experimental results which characterize the coupling between the electromagnetic eigenmode used to accelerate particles, 345 MHz, and the mechanical eigenmodes when the interactions are driven by the Lorentz force. This is relevant to the pulsed operation of spoke cavities where the time-dependent Lorentz force can drive large variations in the cavity resonant frequency when it excites mechanical modes.

Chapter 3 presents the Lorentz transfer function and its applications. The Lorentz transfer function will be shown to be a powerful tool useful for the study and analysis of detuning in superconducting cavities when the detuning is driven by the Lorentz force.

Chapter 3 is separated into 4 parts.
1) Lorentz force detuning is discussed.
2) The Lorentz transfer function is defined and the experimentally measured Lorentz transfer function of the \( \beta = 0.5 \) TSR is presented.
3) One of the two modes of accelerator operation, pulsed operation, is introduced. The \( \beta = 0.5 \) TSR Lorentz transfer function is used to predict the pulsed response of the cavity and the prediction is compared to experimentally measured values.
4) The results presented in chapter 3 and the results of the data compared to elliptical-cell cavities are discussed.

3.2 Lorentz Force Detuning

Lorentz force driven interactions limiting either the maximum achievable accelerating gradient or the precision of the amplitude and phase control in beam-loaded accelerator cavities is not a new problem. Lorentz detuning was first noticed in a normal-conducting 25 MHz cavity at the Novosibirsk electron-positron storage ring VEPP-2 in 1966 [80, 81]. The loaded bandwidths of the superconducting cavities developed in the late sixties and seventies were typically one hundred times smaller than the Novosibirsk cavity [17, 53]. This exacerbated the problem of phase locking a superconducting cavity’s RF field
to the beam bunches in the presence of both Lorentz force and microphonic induced RF frequency variations. At that time, researchers developed tuners and control systems capable of counteracting the detuning and controlling the RF field phase and amplitude in the presence of both microphonic and Lorentz force induced detuning [46, 48]. These cavities operated with small stored energies relative to the proposed operating parameters of spoke-loaded accelerator cavities (10 – 40 J).

The technological advances of spoke-loaded superconducting accelerator cavities now allows for the production of cavities capable of imparting voltage gains of 4 to 9 MV to particles traveling between \(0.35 < \beta < 0.65\) [52, 68, 69]. Operating in this region, the peak surface field magnitudes are approximately 30 MV/m and 800 G, which correspond to pressures of 15 torr and 10 torr respectively. This deforms the cavity wall and shifts the resonant frequency by hundreds of hertz as the cavity RF field pulses [89].

Another consequence of operating at the gradients necessary to impart 4 to 9 MV to the particle beam is the large stored energy, greater than 10 J in multi-spoke cavities. The control systems successfully employed in early superconducting accelerator cavities have not been developed to operate with cavities operating at high-stored energies and high loaded-cavity \(Q\) in the pulsed mode of operation. This chapter represents the first step in characterizing the pulsed mode of operation of superconducting multi-spoke loaded cavities in order to develop the control systems necessary to control the RF field amplitude and phase.

### 3.3 The Lorentz Transfer Function

To characterize the coupling between the cavity RF field and the mechanical eigenmodes driven by the Lorentz force, a transfer function is experimentally measured. The transfer function is a mathematical expression which expresses the relationship between the input and output of a linear time-invariant system [90, 91]. It is important to point out that the transfer function contains all of the information required to determine how a linear time-invariant system will respond to an arbitrary time-dependent stimulus.

In section 2.4 it was shown that the RF frequency variations due to oscillations in mechanical eigenmode \(\alpha\) driven by a generalized force \(F_{\alpha}\) obey [45, 47]:

\[
\frac{d^2 \Delta \omega_{\alpha}}{dt^2} + \frac{2 \Omega_{\alpha}}{Q_{\alpha}} \frac{d \Delta \omega_{\alpha}}{dt} + \Omega_{\alpha}^2 \Delta \omega_{\alpha} = -\frac{\alpha \Omega_{\alpha}^2 F_{\alpha}^2}{c_a U}
\]  

3.1
and the total RF frequency shift of the excited electromagnetic eigenmode is:

$$\Delta \omega = \sum \Delta \omega_{a}$$  \hspace{2cm} (3.2)

The electric and magnetic field components of the resonator electromagnetic eigenmodes are not independent but are related through Maxwell’s equations. Both the magnitude of the electromagnetic force acting on the cavity walls and the energy stored in the electromagnetic eigenmode are proportional to the second power of the accelerating gradient.

$$F_{a} = f_{a} \cdot E_{acc}^{2}$$  \hspace{2cm} (3.3) \\
$$U = U_{0} \cdot E_{acc}^{2}$$  \hspace{2cm} (3.4)

Substituting equations 3.3 and 3.4 into equation 3.1 gives:

$$\frac{d^{2} \Delta \omega_{a}}{dt^{2}} + \frac{2\Omega_{a}}{Q_{a}} \frac{d\Delta \omega_{a}}{dt} + \Omega_{a}^{2} \Delta \omega_{a} = -\frac{\omega U_{0} \Omega_{a}^{2} f_{a}^{2}}{c_{a}} E_{acc}^{2}$$  \hspace{2cm} (3.5)

and in the frequency domain equation 3.5 is:

$$\Delta \omega_{a} (\Omega) = \frac{-\omega U_{0} \Omega_{a}^{2} f_{a}^{2} (\Omega)}{(\Omega_{a}^{2} - \Omega^{2}) + \frac{2i\Omega_{a}}{Q_{a}}} \ast \frac{E_{acc}^{2}}{\Omega_{a}} = 2\pi \cdot k_{a} (\Omega) \cdot E_{acc}^{2} (\Omega)$$  \hspace{2cm} (3.6) \\
$$\Delta \omega = 2\pi \cdot \Delta f = 2\pi \cdot \left( \sum \frac{k_{a}(\Omega)}{\Omega_{a}} \right) \cdot E_{acc}^{2} (\Omega)$$  \hspace{2cm} (3.7)

where the factor of $2\pi$ was included to switch from angular frequency, $\omega$, to frequency $f$, $E_{acc}^{2} (\Omega)$ is the accelerating gradient of the excited electromagnetic eigenmode in the frequency domain, parameterized by the variable $\Omega$, and the Lorentz transfer function is the sum of the transfer functions of all the mechanical eigenmodes:

$$Lorentz \ Transfer \ Function = \sum_{a} k_{a}(\Omega)$$  \hspace{2cm} (3.8)

Notice that the time-domain RF frequency response of the cavity is simply the convolution of the Lorentz transfer function and any arbitrary $E_{acc}^{2} (\Omega)$.

Equation 3.7 was derived to show that the Lorentz transfer function is both a measurable quantity and that it contains all of the physics of the interactions between the electromagnetic eigenmodes and the mechanical eigenmodes. The Lorentz transfer function correlates an RF field amplitude modulation with the consequent Lorentz force.
induced RF frequency modulation. Measuring the Lorentz transfer function yields all of the information necessary to calculate the RF frequency variations due to changes in the RF field amplitude and this is done without directly characterizing every mechanical eigenmode of the coupled cavity/cryomodule mechanical system and its coupling strength to the cavity RF field, an almost impossible task.

Two methods are employed to experimentally measure the Lorentz transfer function in the frequency domain [90]. The first experimental method employs a function generator and an oscilloscope [86]. The function generator generates the signal used to amplitude modulate the forward power, which causes an amplitude modulation of the cavity field. Then both the frequency modulation signal and the RF field pick-up signal are input into the oscilloscope allowing for the RF field modulation amplitude, the resulting frequency modulation, and their relative phase shift to be measured as a function of the amplitude modulation frequency. This method is use to measure the Lorentz transfer function at amplitude modulation frequencies within a few hertz of mechanical mode eigenfrequencies which couple to the cavity RF field, i.e. 320 Hz and 220 Hz. Another experimental method, which is more efficient, employs a lock-in amplifier (figure 2.12). The lock-in amplifier measures the signal amplitudes and relative phase shift directly and can be programmed to sweep the forward power modulation frequency to automate the measurement.

The $\beta = 0.5$ TSR Lorentz transfer function amplitude and phase are graphed in figure 3.1 [89]. The horizontal axis is the amplitude modulation frequency, referred to as the vibration frequency. The top half of the plot is the amplitude of the cavity RF frequency modulation divided by:

$$\Delta E^2 = E_{acc,max}^2 - E_{acc,min}^2$$

where $E_{acc,max}^2$ and $E_{acc,min}^2$ are the maximum and the minimum of the accelerating gradient sinusoidal amplitude modulation respectively. The lower half of the graph is the relative phase difference between the cavity RF field amplitude modulation and the cavity RF frequency modulation.
Figure 3.1: The measured $\beta = 0.5$ triple-spoke cavity Lorentz transfer function.
3.4 Pulsed Cavity Detuning

Pulsed operation is characterized by a cyclic rapid excitation of the cavity RF field using a pulsed RF power source, the rapid excitation of the cavity being followed by a similarly rapid decay when the power is turned off. In general, pulsed operation offers two features which may be advantageous for particle accelerator applications [92]:

1) Pulsed operation reduces the cryogenic refrigeration cooling power.
2) Pulsed operation may permit an increase in the cavity operating gradient.

The Lorentz transfer function can be used to predict the response of the cavity RF frequency to any time-dependent RF field amplitude, including RF field pulses. Using equation 3.7, the response of the cavity RF frequency to any arbitrary time-dependent RF field amplitude is given by:

\[ f(t) = \int_{-\infty}^{\infty} k(\Omega) \cdot E_{\text{acc}}^2(\Omega) \cdot e^{-i\Omega t} d\Omega \quad 3.10 \]

Hence, the convolution of the Lorentz transfer function and the second power of the accelerating gradient yield the time-domain response.

The predicted and the measured response to a pulsed cavity field are graphed in figure 3.2 for several different pulse durations and amplitudes. The horizontal axis is time in milliseconds. The upper plot is the experimentally measured cavity RF frequency deviation from an external oscillator and the response predicted by the Lorentz transfer function. The lower plot shows the squared field pulse which drives the cavity RF frequency deviations.

Finally, the measured and predicted response to repeated pulsing of the cavity RF field at 1 Hz and at 30 Hz is plotted in figure 3.3. Notice that the horizontal time-axis is not continuous on the top plot. This was done to show the predicted and measured response after two uninterrupted pulses.
Figure 3.2: The RF frequency deviation of the $\beta = 0.5$ TSR cavity from an external oscillator due to pulsing the cavity field.
Figure 3.3: The RF frequency deviation of the $\beta = 0.5$ TSR from an external oscillator due to repeated pulsing of the cavity field.
3.5 Discussion of the Lorentz Transfer Function

Sections 3.3 and 3.4 demonstrated a powerful method for studying and analyzing dynamic Lorentz detuning in superconducting cavities. It was shown that the Lorentz transfer function completely characterized the coupling between the cavity RF field and the Lorentz force by accurately predicting the pulsed response of the $\beta = 0.5$ TSR. In general, this technique provides a simple and direct tool for characterizing the electromechanical properties of Lorentz detuned superconducting cavities and can be used to characterize the dynamic detuning of any cavity subject to any type of time-dependent RF field amplitude modulation.

For example, the measured Lorentz transfer function of the $\beta = 0.5$ TSR (figure 3.1) and the $\beta = 0.4$ DSR (figure 3.4) offer insights into the mechanical structure of multi-spoke loaded cavities which would otherwise required the characterization of the cavity mechanical eigenmodes. The Lorentz transfer function of both the $\beta = 0.5$ TSR and the $\beta = 0.4$ DSR show that the cavity RF fields do not couple to low-frequency mechanical eigenmodes. This is an extremely important result. It will be shown in chapter 4 that microphonic-noise is primarily due to low-frequency non-resonant mechanical vibrations. Hence, the Lorentz force does not couple to microphonic-noise. Compare this result to that of an 805 MHz elliptical-cell superconducting cavity developed for the Spallation Neutron Source (figure 3.5) [86]. The RF field of the elliptical-cell cavity couples to low-frequency mechanical vibrations and as a result microphonic-noise can drive mechanical eigenmodes.

Finally, a 5 kW peak pulsed power 345 MHz RF amplifier was available for the experiments presented in section 3.4. To pulse the $\beta = 0.5$ TSR to 10.5 MV/m in 1.5 ms at 10 Hz, operating parameters for the proposed Fermi National Accelerator Laboratory 8 GeV proton driver linear accelerator, would require a peak RF power of 45 kW [92, 93]. Figure 3.6 graphs the predicted response of the $\beta = 0.5$ TSR to these pulse parameters using the Lorentz transfer function presented in 3.3 (figure 3.1). Notice, at the end of the pulse (when the cavity is accelerating beam), the Lorentz force is predicted to shift the cavity RF frequency by approximately 400 Hz, half of the cavity 800 Hz loaded bandwidth. This corresponds to a 25% increase in the RF power required to phase-stabilize the cavity with overcoupling alone.
Figure 3.4: The Lorentz transfer function of a $\beta = 0.4$ double-spoke-loaded cavity.

Figure 3.5: The Lorentz transfer function of a $\beta = 0.63$ elliptical-cell cavity developed for the Spallation Neutron Source.
Figure 3.6: The $\beta = 0.5$ TSR Lorentz transfer function prediction for a 1.5 ms 10 Hz 10.5 MV/m pulse train. These are the operating parameters for the FNAL 8 GeV proton driver linac, one future accelerator which includes spoke-loaded cavities in the proposal.
Chapter 4

Microphonic Induced RF Frequency Variations

4.1 Introduction

This chapter presents the experimental results used to characterize the microphonic-noise induced RF frequency variations of a $\beta = 0.4$ DSR and a $\beta = 0.5$ TSR. The chapter is separated into four parts.

1) A general discussion of continuous-wave operation and the impact of microphonic-noise on the operation of spoke-loaded cavities will be discussed.

2) The microphonic-noise of the $\beta = 0.4$ DSR RF frequency will be presented.

3) The microphonic-noise of the $\beta = 0.5$ TSR will be presented. In particular, how the mechanical design of the $\beta = 0.5$ TSR was modified to lessen the coupling between the cavity RF field and adiabatic changes in the external pressure will be discussed.

4) Chapter 4 will conclude with a discussion of the results.

4.2 Continuous-Wave Operation

The mode of accelerator operation in which the cavity RF field amplitude is constant is referred to as continuous-wave operation. Continuous-wave operation is often possible only with superconducting cavities, because of their low RF losses and high-$Q$. As a result, the small-loaded bandwidth found in some superconducting cavity applications makes them extremely sensitive to mechanical deformations. The dominant driver of mechanical deformations in the continuous-wave mode of operation is microphonic mechanical vibrations.

Continuous-wave operation offers many useful characteristics for particle accelerators.

- A larger fraction of the beam is captured from electrostatic pre-accelerators [54].
- The peak current in a continuous wave accelerator is typically 1% or less than found in a pulsed accelerator operating at the same average current [13].
- Smaller peak beam currents result in smaller peak event rates. Hence, experimental detectors may be made more sensitive and not saturate.
• Transient heating of high-power targets is eliminated [94].
• Time-dependent Lorentz detuning of the cavities is not a problem.

It is the subset of cavity RF frequency variations which are a large fraction of the loaded bandwidth that are a concern for continuous-wave accelerators, referred to as microphonic-noise [89, 95]. For example, microphonic-noise dominates the RF power requirements for continuous-wave energy-recovery linacs (a small beam current due to the cancellation of two large currents) and for heavy-ion linacs with small beam currents [47].

Several techniques have been developed to control the cavity RF phase in the presence of microphonic-noise.

• Overcouple to the cavity. This introduces additional cavity damping increasing the loaded cavity bandwidth and the RF power required to drive the cavity at a fixed gradient in the presence of microphonic-noise [46].
• Determine and eliminate the sources of the microphonic-noise [89].
• Change the mechanical design of the cavity to decrease the coupling between the cavity RF field and the mechanical vibrations driven by the microphonics [89, 96, 97]. This is the focus of this chapter.
• Employ a mechanical tuner to controllably deform the cavity. This is the focus of chapter 5.

4.3 The $\beta = 0.4$ Double-Spoke-Loaded Resonator Microphonic-Noise

4.3.1 $\beta = 0.4$ Double-Spoke-Loaded Resonator Microphonic-Noise Measurements

The $\beta = 0.4$ DSR was the first multi-spoke-loaded cavity fabricated and tested. The $\beta = 0.4$ DSR was designed to minimize the cavity coupling to adiabatic changes in the external pressure by reinforcing the cavity end walls [96, 97]. Each of the cavity end walls was reinforced with 12 support gussets. This reduces the deflection of the rigid end walls and, hence, reduces the microphonic-noise. The effect of adiabatic pressure changes on the cavity RF frequency ($\Delta f/\Delta p$) was measured to be $+65$ Hz/torr [95]. $\Delta f/\Delta p$ is the parameter cited in the literature to specify the coupling strength between the cavity RF field and the external pressure. For a picture of the $\beta = 0.4$ DSR with the reinforced end walls refer to figure 2.1.
The $\beta = 0.42$ DSR microphonic-noise was measured at 4.2 K and at several cavity field levels: at 1 MV/m, requiring a 0.3 watt RF input and at 7 MV/m, requiring 16 W of RF input [95]. The microphonic-noise at both of the input power levels is graphed in figures 4.1, 4.2, and 4.3.

Figure 4.1 graphs the time-domain microphonic-noise data. Time is plotted on the x-axis and the instantaneous difference in frequency between the $\beta = 0.4$ double-spoke cavity and a stable reference oscillator is plotted on the y-axis.

The projection of the time-domain data into 0.77 Hz wide bins on the frequency deviation axis is plotted in figure 4.2 and is referred to as the probability density. The y-axis of the probability density is:

$$f(y) = 20 \times \text{LOG} \left( \frac{\text{# of observations in the bin}}{\text{total # of observations}} \right)$$

4.1

The solid points are the experimental data while the solid lines are the results of a least
squares fitting of the data with a Gaussian of the form:

\[
\text{fit}(y) = \frac{A}{\sqrt{2\pi\sigma_{\text{rms}}^2}} e^{-y^2/(2\sigma_{\text{rms}}^2)}
\]

where \(A\) is the amplitude and \(\sigma_{\text{rms}}\) is the standard deviation. Notice the 70% increase in the amplitude of the cavity RF frequency variation with the input power increasing from 0.3 W (1 MV/m) to 16 W (7 MV/m).

Figure 4.3 shows the microphonic-noise Fourier spectrum. The x-axis is the cavity mechanical vibration frequency and the y-axis is the peak cavity RF frequency deviation amplitude. For reference, a line corresponding to the peak frequency deviation required to drive a \(\pm 0.3^0\) phase precession is added to the graph; \(\pm 0.3^0\) is the design goal for the cavities in the proposed AEFL driver linac [98, 99]. The slope of the line follows equation 1.12, that is, large frequency deviations can be tolerated but only for a short
Consequently, notice that low-frequency vibrations dominate the cavity RF phase error.

4.3.2 Coolant Boiling as a Driver of Microphonics

In order to determine if the low-frequency vibrations of the cavity were driven by liquid helium boiling a series of measurements were performed to determine if the variations in the helium vapor pressure and the $\beta = 0.4$ DSR RF frequency variations were correlated [100]. A pressure measurement system with a resolution of 1 mtorr was installed to measure the vapor pressure of the liquid helium bath. The $\beta = 0.4$ DSR RF frequency deviation from an external stable oscillator and the external pressure deviation from atmospheric pressure were simultaneously measured at 4.2 K and at input powers of 5 W, 14 W, and 22 W. The experimental data is presented in figures 4.4, 4.5, 4.6, and 4.7.
Figure 4.4 graphs the time-domain data at each of the three input power levels. Time is plotted on the x-axis in seconds. There are two distinct vertical axes for each plot: on the left is the difference between the vapor pressure of the helium coolant and atmospheric pressure, while the simultaneous frequency difference between the $\beta = 0.4$ double-spoke cavity and a stable reference oscillator is on the right.

Figure 4.5 shows the probability density of the pressure and frequency variations for the three input power levels. The microphonic-noise probability density is on top and the external pressure fluctuation probability density is the lower graph. The vertical axes both follow equation 4.1. The x-axis of the top graph is the RF frequency deviation from an external oscillator. The x-axis of the lower graph is the helium vapor pressure deviation from atmospheric pressure. As the input power increases both the variations in the helium pressure and the $\beta = 0.4$ DSR RF frequency increase.
Figure 4.6 graphs the vibration spectrum of the microphonic-noise and pressure deviations for the three input power levels. The top graph is the vibration spectrum of microphonic-noise and the lower graph is the vibration spectrum of the helium vapor pressure deviation. The x-axis is the Fourier transform frequency of the time-domain data, referred to as the vibration frequency. The y-axis of the top plot is the peak amplitude of the microphonic-noise. The y-axis of the lower plot is the peak amplitude of the helium vapor pressure deviation. Notice that the amplitude of both the microphonic-noise and the pressure deviations are highest at low vibration frequencies and decrease at higher vibration frequencies. Also, the frequency spectrum of microphonic vibrations below 5 Hz is very similar to that of the low frequency helium pressure deviation.

Figure 4.7 shows the cross-correlation between the $\beta = 0.42$ DSR RF frequency variations and the helium vapor pressure for the three input power levels. The cross-correlation at the lag time $t$ between the RF frequency variation ($f_i$) and the helium pressure variation ($p_i$) was calculated as:

$$
Corr(t) = \frac{\sum_{i=0}^{N-1} f_i p_{i-t}}{\sqrt{\sum_{i=0}^{N-1} (f_i - \bar{f})^2 \sum_{i=0}^{N-1} (p_i - \bar{p})^2}}; -N+1 < t < N-1
$$

where $N$ is the number of samples collected, the $f_i$ are the microphonic-noise data points, the $p_i$ are the helium pressure deviation data points, $\bar{f}$ is the mean value of the microphonic-noise, and $\bar{p}$ is the mean value of the helium pressure deviation. When the lag index $i+t$ is less than 0 or greater than $N-1$ the value of $p_{i+t}$ is assumed to be zero.

The denominator in equation 4.3 was chosen to normalize the cross-correlation function to ±1. If the cross-correlation function equals 0 there is no correlation between the data, and if the cross-correlation function equals 1 the data is highly correlated. A large negative cross-correlation corresponds to a large correlation between one data set and the inverse of the other data set. All of the cross-correlation graphs show a large correlation for very small lag times ($-0.01 < t < 0.01$) which rapidly falls off with larger lag times. This is indicative of the two signals being correlated in time with a random driving force driving the signal variations.
This data has two consequences:

- The $\beta = 0.47$ DSR RF frequency deviation from a reference oscillator is highly correlated with changes in the helium vapor pressure.
- The RF power dissipated in the cavity appears to be driving both the variations in the $\beta = 0.42$ RF frequency and the helium vapor pressure.

4.3.3 The Impact of Microphonic-Noise on the $\beta = 0.4$ Double-Spoke Cavity

The proposed AEBL driver linac proposes to use 16 superconducting $\beta = 0.4$ DSR in a section of the accelerator with fairly large beam loading. The AEBL driver linac design gradient for the $\beta = 0.4$ DSR is 9.2 MV/m with an effective length of 39 cm [98, 99]. Then each cavity will provide 3.6 MV of accelerating potential to the beam. The AEBL driver linac design requires the acceleration of a 0.7 mA proton beam. The $\beta = 0.4$ DSR beam loaded cavity bandwidth is:

$$\Delta f_L = \frac{f_0}{Q_L} = \frac{P}{2\pi U} = \frac{0.7 mA \cdot 3.6 MV}{2 \cdot \pi \cdot 12.8 J} = 31 \text{Hz}$$  \hspace{1cm} (4.4)$$

Figure 4.3 puts a lower limit on the range of microphonic-noise at 50 Hz (this is a generous estimate since the design gradient input power = 22 W not 16 W as shown in this figure). An estimate of the RF power required to overcoupling to the $\beta = 0.4$ DSR and drive the cavity at a fixed frequency in the presence of this level of microphonic-noise is given by equation 1.13; RF power = $\Delta \omega \cdot U$. This estimates the RF power to be 4 kW, a 60% increase in power; corresponding to a similar increase in capital and operating costs.

Continuing to increase the mechanical rigidity of the $\beta = 0.4$ DSR is likely to reduce the amplitude of the microphonic-noise. This will increase the cavity fabrication cost and may decrease the cavity thermal conductivity. Alternative options are developed and are presented in the following sections of chapter 4 and in chapter 5. The following sections of chapter 4 discuss how design changes, which decouple the cavity RF field from adiabatic pressure changes, reduce the microphonic-noise of a cavity. Chapter 5 presents fast mechanical tuning systems which introduce a controllable RF frequency variation which cancels the microphonic-noise. Neither of these techniques damps the cavity RF field, i.e. overcoupling. Hence, the RF power required to phase lock the cavity RF field to the particle beam bunches may be reduced.
Figure 4.5: The probability density of RF frequency and pressure variations of the $\beta = 0.42$ DSR operating at input powers equal to 5 W, 14 W, and 22 W.
Figure 4.6: The spectrum of RF frequency and pressure variations of the $\beta = 0.42$ DSR operating at input powers equal to 5 W, 14 W, and 22 W.
4.4 The $\beta = 0.5$ Triple-Spoke-Loaded Resonator Microphonic-Noise

4.4.1 The $\beta = 0.5$ Triple-Spoke-Loaded Resonator Mechanical Design

The next multi-spoke-loaded cavity designed and fabricated was the $\beta = 0.5$ TSR. The $\beta = 0.5$ TSR was designed to minimize the coupling between the cavity RF frequency and adiabatic changes in the external helium pressure [52, 89]. This was accomplished by balancing the cavity RF frequency shift due to deformations in regions of predominantly magnetic surface field with those due to the regions of predominantly electric surface field. Refer to equation 2.12 for the cavity frequency shift [78, 79]:

$$\Delta f = \frac{\int \left( \mu |\vec{H}(\vec{x})|^2 - \varepsilon |\vec{E}(\vec{x})|^2 \right) da}{\int \text{ Stored Energy}}$$

The $\beta = 0.5$ TSR was constructed with mechanical support gussets on both of the end-walls and the cylindrical wall of the cavity. The support gussets stiffen the cavity and

![Graph showing cross-correlation functions](image-url)
reduce the deformation of the walls due to changes in the helium bath pressure but are not intended to make the cavity infinitely rigid. Instead the support gussets balance the magnetic and the electric field contributions to the cavity RF frequency shift.

For a 1 atmosphere pressure increase between the cavity exterior and interior, the radial inward displacement of the cylindrical portion of the cavity wall, where the RF surface fields are primarily magnetic rather than electric result in a +100 kHz increase in the $\beta = 0.5$ TSR cavity frequency [96]. Notice that the total change in the $\beta = 0.5$ TSR RF frequency also contains a decreasing contribution from the regions of the cavity of primarily electric surface fields, the cavity end walls.

Initially, several of the reinforcing ribs were intentionally oversized, leaving a residual $\Delta f/\Delta p$ of -12.4 Hz/torr; the design guiding the rib placement predicted a shift of -10.5 Hz/torr. The residual $\Delta f/\Delta p$ was kept to allow for a fine tuning of $\Delta f/\Delta p$ by cutting away sections of the oversized support gussets after characterizing the cavity microphonic induced RF frequency variations at 4 K. After modifying the support ribs, the RF frequency shift was measured to be 2.2 kHz over 680 torr whereas the modeled result predicted a 3.7 kHz shift.

4.4.2 Measured $\beta = 0.5$ Triple-Spoke-Loaded Resonator Microphonic-Noise

The $\beta = 0.5$ TSR microphonic-noise was experimentally characterized by exciting the cavity and comparing the cavity RF frequency to an external stable oscillator with a CRM [52, 89]. The microphonic-noise for input powers of 20 W and 100W are shown in figures 4.8 and 4.9.

Figure 4.8 graphs both the microphonic-noise in the time domain and the Fourier transform of the data. There are four separate graphs in this figure. On the left, the time-domain data is graphed with the horizontal axis corresponding to time in seconds and the vertical axis corresponding to the cavity RF frequency deviation from an external oscillator. On the right, the Fourier transform of the time-domain data is graphed. The horizontal axis is the vibration frequency and the vertical axis is the peak RF frequency deviation. Again, a line corresponding to the peak RF frequency deviation amplitude required to drive a $\pm 0.3^0$ phase precession is include for reference.
Figure 4.9 graphs the probability density of the cavity RF frequency variations at each input power level. The horizontal axis is the RF frequency deviation and the vertical axis follow equation 4.1. Notice two features of these graphs:

1) The rms frequency deviation does not change as the power is increased.
2) The rms frequency deviation is approximately equal to the noise on the reference oscillator used in the measurement, section 2.5.4.

Essentially, these measurements are comparing the reference oscillator to a superconducting cavity with relatively little phase noise. The reference oscillator used for these experiments was one of the most stable oscillators commercially available on the market, HP8644B. Oscillators have been developed with less phase noise but are not commercially available and require the use of sophisticated engineering techniques [101].
4.5 Discussion of Chapter 4 Results

Chapter 4 presented the microphonic-noise of a $\beta = 0.4$ DSR and a $\beta = 0.5$ TSR operated in the continuous-wave mode. First, the microphonic-noise of a $\beta = 0.4$ DSR was presented. It was found that the $\beta = 0.4$ DSR microphonic-noise was due to low frequency mechanical vibrations due to boiling in the liquid helium bath. Second, a design technique useful for decoupling the RF field of a cavity from adiabatic changes in the external pressure was presented. This resulted in the development of a $\beta = 0.5$ TSR with a $\Delta f / \Delta p$ of -2.5 Hz/torr, an significant decrease relative to the $\beta = 0.4$ DSR $\Delta f / \Delta p = +65$ Hz/torr [89, 100].

Table 4.1 compares the microphonic-noise properties of several different superconducting accelerator cavities [25, 52, 89, 95, 102, 103]. Table 4.1 lists the operating frequency of the cavities, the peak microphonic-noise, the temperature of the liquid helium bath the microphonic-noise was measured, the input power at which the
microphonic-noise was measured, and the additional RF power (equation 1.13) required to overcouple to the cavity to phase-lock the RF field to an external oscillator.

Notice that the $\beta = 0.63$ elliptical-cell cavity was tested at 2 K, not 4.2 K. Below 2.17 K liquid helium undergoes a phase change, becoming a superfluid. Superfluid liquid helium does not boil. This eliminates the low vibration frequency microphonic-noise due to boiling in the liquid helium bath, see section 4.3.2.

Table 4.1 is only intended to illustrate the improved mechanical stability of the $\beta = 0.5$ TSR relative to other reduced-$\beta$ cavities. The number of published microphonic-noise studies is very small and this comparison would benefit from more data.

<table>
<thead>
<tr>
<th></th>
<th>Helically-Loaded</th>
<th>Split-Ring</th>
<th>$\beta = 0.63$ Elliptical-Cell</th>
<th>$\beta = 0.4$ Double-Spoke</th>
<th>$\beta = 0.5$ Triple-Spoke</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resonant Frequency</strong></td>
<td>108 MHz</td>
<td>97 MHz</td>
<td>805 MHz</td>
<td>345 MHz</td>
<td>345 MHz</td>
</tr>
<tr>
<td><strong>Peak Microphonic-Noise</strong></td>
<td>250 Hz</td>
<td>80 Hz</td>
<td>10 Hz</td>
<td>30 Hz</td>
<td>2.5 Hz</td>
</tr>
<tr>
<td><strong>Measurement Temperature</strong></td>
<td>4.2 K</td>
<td>4.2 K</td>
<td>2 K</td>
<td>4.2 K</td>
<td>4.2 K</td>
</tr>
<tr>
<td><strong>Input Power</strong></td>
<td>1 W</td>
<td>1 W</td>
<td>13 W</td>
<td>12 W</td>
<td>100 W</td>
</tr>
<tr>
<td>$\Delta \omega \cdot U$</td>
<td>2000 W</td>
<td>120 W</td>
<td>7000 W</td>
<td>4700</td>
<td>1200</td>
</tr>
<tr>
<td><strong>Figure</strong></td>
<td>1.4</td>
<td>1.4</td>
<td>1.5</td>
<td>2.1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Table 4.1: Comparison of the microphonic properties of several reduced-$\beta$ accelerator cavities.
Chapter 5

Frequency and Phase Control of Superconducting Spoke-Loaded Resonators

5.1 Introduction

Chapter 5 discusses the fast mechanical tuning of the $\beta = 0.5$ TSR. The chapter is separated into 5 parts.

1) A brief introduction motivating the development and use of fast mechanical tuners in superconducting cavities with RF frequency variations which are a large fraction of the cavity beam-loaded bandwidth.

2) The development of a piezoelectric-actuated fast mechanical tuner will be discussed. Measurements of the transfer function of the mechanically coupled fast tuner and cavity system will be presented.

3) Experimental results using the piezoelectric fast mechanical tuner to control the cavity frequency will be presented.

4) Experiments will be presented which demonstrate cavity phase control with a piezoelectric fast mechanical tuner.

5) The results presented in chapter 5 will be discussed.

Fast mechanical tuning will be shown to be a useful technique for damping microphonic induced RF frequency variations in the $\beta = 0.5$ TSR and reducing the RF power required to phase-lock the cavity to the particle beam. This leads to a large reduction in the RF power required to operate the superconducting spoke cavities in an accelerator which in turn can reduce the capital and operating cost of the accelerator.

5.2 Applications of Fast Mechanical Tuners

RF accelerators couple power to a charged particle beam through the RF electric field in a string of resonant cavities [13, 14]. The RF field of each and every resonant cavity must be phase-locked to the beam bunches. This is accomplished by locking the resonant cavities to a stable external oscillator, and at the same time synchronizing the beam bunches with the oscillator [46]. When the cavity RF frequency diverges from the stable external oscillator, the phase relationship between the cavity RF field and a particle
bunch is altered, introducing time and energy errors in the beam. Refer to section 1.6 for a detailed discussion of the frequency error induced phase precession.

Three techniques have been developed to control the RF phase of superconducting cavities.

4) Overcouple to the cavity and use negative phase feedback to control the cavity RF field. This reduces the loaded-cavity $Q$, to increase the bandwidth, permitting operation at a fixed frequency in the presence of eigenfrequency fluctuations [46].

5) Couple the cavity RF field to a variable reactance circuit, in the literature this is referred to as reactive tuning [48]. An ideal reactive tuner does not load the cavity $Q$. In practice there are RF losses in reactive tuners and the loaded-cavity $Q$ is reduced. Reactive fast tuners were developed for heavy-ion accelerator cavities which operate at low stored energies and low frequencies. Reactive fast tuners have not been developed for frequency much larger than 100 MHz or for cavities operating at stored energies greater than a few joules. As a result, they are currently not an option for spoke-loaded cavities.

6) Employ a mechanical fast tuner to introduce a controllable RF frequency variation to maintain the phase relationship between the cavity RF field and the beam. This technique does not decrease the loaded-cavity quality factor and requires no additional RF power. These tuners were successfully developed for TM-class elliptical-cell cavities operated in the pulsed mode [49-51]. This work represents the first application of fast mechanical tuners to spoke-loaded cavities and also the first application to continuous-wave operation of superconducting cavities [89].

5.3 The Piezoelectric Fast Mechanical Tuner

5.3.1 The Coupled Fast Mechanical Tuner and Cavity System

The mechanical tuner tested here used a piezoelectric actuator. An electric potential gradient is generated when a piezoelectric material is mechanically stressed [104]. Conversely, applying a potential difference to a piezoelectric material causes internal mechanical stress. A piezoelectric actuator is a device which converts electrical energy into precise mechanical motion; the mechanical motion being proportional to the applied voltage. In this application the motion (~10 µm) is used to deform the accelerator cavity.

Piezoelectric actuators possess several useful technical features:
• Fast response time; piezoelectric actuators deform within a few microsecond of changing the control voltage.

• High displacement resolution; piezoelectric actuators can deform ~10 μm with a 0.01 μm resolution.

• No magnetic field; piezoelectric actuators are an electric device and do not generate magnetic fields. Consequently, there is no degradation of the cavity RF performance due to an external applied magnetic field.

• Low power consumption; piezoelectric actuator performance is similar to that of a capacitor (~1000 nF). In practice there are electrical losses in the piezoelectric material which amount to several watts of heating.

• Operate at < 4.2 K; piezoelectric actuators will operate in the cryogenic cavity environment.

The piezoelectric actuator used in these experiments was an APC International Ltd. PSt 1000/25/100 mounted in a homemade guide assembly. This piezoelectric actuator is composed of layered piezoelectric material electrically connected in parallel. At 4.2 K the piezoelectric actuator capacitance is 2300 μF and the stroke length is 10 μm.

The piezoelectric fast tuner guide assembly, shown in figure 5.1, preloads, guides, and supports the piezoelectric actuator. The piezoelectric fast mechanical tuner was mounted on the β = 0.5 TSR by bolting the actuator assembly to a conflate flange on the integral stainless steel helium jacket, see figure 5.1. The fast tuner deforms the cavity surface in a region of predominantly surface magnetic field near the base of the middle spoke [96].

During operation the fast mechanical tuner actuator expands and contracts, pushing between the niobium wall of the cavity and the stainless steel helium jacket. The motion of the piezoelectric fast tuner couples to the mechanical eigenmodes of the mechanically coupled piezoelectric fast tuner and cavity system. The characterization of the piezoelectric fast tuner and cavity electromechanical coupling is presented in the next section.
The Piezoelectric Fast Tuner Transfer Function

In order to characterize the fast tuner performance, the correlation between the amplitude and frequency of the piezoelectric fast tuner control voltage and the amplitude and relative phase of the cavity RF frequency modulation is measured [51]. The measurement was performed by sweeping the frequency of the signal driving the fast tuner and simultaneously recording the relative phase and amplitude of the resulting cavity RF frequency modulation. The amplitude of the correlation measurement and relative phase between the cavity RF frequency modulation and piezoelectric fast tuner drive signal is graphed in figure 5.2 and is referred to as the piezoelectric fast tuner transfer function.
The horizontal axis is the amplitude modulation frequency of the electrical signal driving the piezoelectric fast tuner, referred to as the vibration frequency. The top graph is the amplitude, defined as the ratio of the amplitude of the sinusoidal cavity RF frequency modulation to the amplitude of the sinusoidal amplitude modulation on the piezoelectric drive. The lower graph is the relative phase between the cavity RF frequency modulation and the piezoelectric drive amplitude modulation.

The piezoelectric fast tuner transfer function completely characterizes the electromechanically coupled piezoelectric fast tuner and $\beta = 0.5$ TSR. The piezoelectric fast tuner transfer function can be used to predict the cavity response for any arbitrary waveform driving the piezoelectric actuator.

Notice, that at low frequencies no mechanical eigenmodes of the mechanically coupled cavity and fast tuner are excited. At 117 Hz the motion of the piezoelectric fast tuner couples to a mechanical eigenmode, the amplitude of the response changes.

![Piezoelectric fast tuner transfer function](image)

Figure 5.2: Piezoelectric fast tuner transfer function amplitude (top) and relative phase shift (bottom). This transfer function relates the amplitude modulation of the piezoelectric fast tuner drive signal to the frequency modulation of the cavity RF field.
dramatically and for drive frequencies greater than 117 Hz the relative phase between the drive signal and the cavity RF frequency modulation shifts by 180°. This limits the performance of the piezoelectric fast tuner to low frequencies. For example, the total cavity RF frequency is the sum of the microphonic-noise and the controllable shift due to the piezoelectric fast tuner, given by:

\[ \Delta f_{\text{total}} = \Delta f_{\text{microphonic}} + \Delta f_{\text{tuner}} \]  

where the controllable \( \Delta f_{\text{tuner}} \) is chosen to be 180° out of phase with the microphonic-noise, \( \Delta f_{\text{microphonic}} \), and the two signals cancel. When the phase of \( \Delta f_{\text{tuner}} \) shifts by 180° the two terms in equation 5.1 add instead of cancel. Hence, the mechanical tuner will add to the total cavity RF frequency deviation instead of subtracting.

At low-frequencies the amplitude and phase response of the piezoelectric fast tuner transfer function are flat enough to damp the microphonic-noise presented in chapter 4 and to phase-lock the cavity to an external oscillator.

5.4 Piezoelectric Fast Tuner Used to Damp RF Frequency Noise

This section discusses measurements where the piezoelectric fast tuner is used to damp the microphonic-noise induced RF frequency variation of the \( \beta = 0.5 \) TSR cavity (the experimental layout is shown in section 2.5.5).

1) These measurements were performed with the \( \beta = 0.5 \) TSR intentionally coupled to an external vibration source to drive the microphonic vibrations. The external vibration source being the ATLAS accelerator helium refrigeration system.

2) The \( \beta = 0.5 \) TSR cavity was operated without any negative fast tuner frequency feedback for five minutes to determine the background noise of the coupled cavity/helium refrigeration system.

3) Immediately following the background measurement the piezoelectric fast mechanical tuner was used to cancel the \( \beta = 0.5 \) TSR microphonic-noise.

Figure 5.3 graphs the time domain data collected with and without a mechanical fast tuner. The horizontal axis is the time in seconds and the vertical axis is the RF frequency deviation of the cavity from an external oscillator. Notice that the mechanical tuner damps all of the large frequency excursions of the cavity.
Figure 5.4 graphs the probability density of the RF frequency deviations with and without mechanical tuning. The horizontal axis is the RF frequency deviation of the cavity from an external source binned into 0.12 Hz wide bins and the vertical axis is the number of counts on a logarithmic scale (refer to equation 4.1). Notice that when the piezoelectric fast tuner is active the frequency deviation probability density is bimodal. This corresponds to a sinusoidal variation in the cavity resonant frequency, which in this case is at 8 Hz. This was found to be a helium thermal-acoustic oscillation in the cryostat used to test the cavity. This is not an intrinsic feature of the cavity/tuner system but is unavoidable when using the equipment available for these tests.

Finally, figure 5.5 graphs the vibration spectrum of the RF frequency variation with and without piezoelectric feedback. The horizontal axis is the mechanical vibration frequency in hertz and the vertical axis is the RF frequency deviation amplitude, both axes use a logarithmic scale. For reference, the peak frequency deviation at a given vibration frequency required to generate a $0.3^\circ$ phase error, the AEBL design goal, is include on the graph.

To avoid exciting mechanical eigenmodes with the piezoelectric fast tuner a low pass filter is included in the feedback loop. The -3dB point of the filter used was 20 Hz; consequently, the piezoelectric fast tuner would only damp RF frequency variations which were driven by low frequency mechanical vibrations. Notice in figure 5.5 that the spectrum of RF frequency deviations is significantly damped only at low frequencies.

For reference, applying equation 1.13, the RF power required to phase-stabilize the $\beta = 0.5$ TSR, in the absence of beam loading, and without the piezoelectric fast mechanical tuner, would be at least 7.5 kW at an operating gradient of 10 MV/m. 10 MV/m is the proposed operating gradient found of the $\beta = 0.5$ TSR in the AEBL driver linear accelerator. The fast mechanical tuner reduces the required RF power to 3.3 kW at 10 MV/m, a reduction by a factor of two, which could provide a similar savings in capital and operating costs.
Figure 5.3: The $\beta = 0.5$ TSR cavity RF frequency variation plotted as a function of time. The $\beta = 0.5$ TSR input power = 110 W ($E_{acc} = 8.5$ MV/m) at 4.5 K. The top graph is data taken in the absence of any piezoelectric fast tuner feedback. The bottom graph is data taken with the piezoelectric fast tuner damping the total RF frequency deviation of the cavity.
Figure 5.4: The $\beta = 0.5$ TSR cavity RF frequency variation spectral densities with the input power = 110 W ($E_{acc} = 8.5$ MV/m) at 4.5 K with and without piezoelectric damping of the RF frequency variations.

Figure 5.5: The $\beta = 0.5$ TSR cavity RF frequency variation vibration spectrums with the input power = 110 W ($E_{acc} = 8.5$ MV/m) at 4.5 K with and without piezoelectric damping of the RF frequency variations.
5.5 Piezoelectric Fast Tuner Phase Control

5.5.1 Phase Control Experiments Overview

This section presents experimental data which characterizes the piezoelectric fast tuner as a phase controller (the experimental setup is discussed in section 2.5.6).

1) The cavity is coupled to an external source of microphonic noise.

2) A baseline measurement of the microphonic-noise induced RF frequency variations is presented. The baseline data is presented to quantitatively access the performance of the piezoelectric fast tuner as a phase controller.

3) The performance of a fast tuning system which utilizes the piezoelectric fast tuner to control the phase of the $\beta = 0.5$ TSR will be presented.

5.5.2 Baseline Microphonic-Noise Induced RF Phase Errors

The $\beta = 0.5$ TSR microphonic-noise measured before phase-locking the cavity to an external source is characterized in figures 5.6, 5.7, and 5.8. The RF power source used for these experiments was limited to 3 kW at 345 MHz. The operating field level of 2.5 MV/m was determined to be the maximum accelerating gradient at which the cavity RF field could be phase-locked to an external source with 3 kW. Higher fields could have been reached if more RF power was available.

Figure 5.6 graphs the time-domain frequency-deviation data measured at 2.5 MV/m. The horizontal axis is time and the vertical axis is the frequency deviation from an external oscillator.

Figure 5.7 is the RF frequency deviation probability density. The data is counted in 0.77 Hz wide bins. The vertical axis is defined in equation 4.1 and the horizontal axis is the frequency deviation.

Figure 5.8 is the frequency deviation spectrum. The vertical axis is the frequency deviation and the horizontal axis is the cavity mechanical vibration frequency. For reference, lines corresponding to the RF frequency deviation amplitude required for a 0.3° and a 3.0° phase precession, at a single vibration frequency, are included on the graph.
Figure 5.6: The $\beta = 0.5$ TSR microphonic-noise prior to phase-lock experiments. The accelerating gradient is 2.5 MV/m and the cavity input power is 4 W.

Figure 5.7: The probability density of the $\beta = 0.5$ TSR microphonic-noise prior to phase-lock experiments. The accelerating gradient is 2.5 MV/m and the cavity input power is 4 W.
The layout for the piezoelectric fast tuner phase control experiment was presented in section 2.5.6. This section quantitatively characterizes the phase control performance of the piezoelectric fast tuner.

1) The gain of the amplifier which drives the piezoelectric fast tuner is variable. Decreasing the gain decreases the response of the piezoelectric fast tuner resulting in larger cavity RF phase errors.

2) The gain of the amplifier which drives the piezoelectric fast tuner is incrementally decreased and the RF power required to control the $\beta = 0.5$ TSR RF field phase is recorded.

3) Experimental Data characterizing the cavity RF frequency variation and RF phase precession will be presented.

First, for simplicity this dissertation is defining the maximum gain at which the amplifier driving the piezoelectric fast tuner can operate, without exciting any instability in the feedback loop, as 1. These experiments were performed with the maximum gain of

![Figure 5.8: The $\beta = 0.5$ microphonic-noise spectrum prior to phase-lock experiments. The accelerating gradient is 2.5 MV/m and the cavity input power is 4 W.](image)
1, at 75% of this gain (gain = 75%), and at 50% of the maximum gain (gain = 50%). The amplitude of the signal driving the piezoelectric fast tuner is

The lowest RF power level required to phase stabilize the cavity was obtained with a gain of 1. Figures 5.9 to 5.12 present the experimentally measured performance of the piezoelectric fast tuner operated at a gain of 1.

Figure 5.9 graphs the time domain RF frequency deviation and the RF phase precession measured with a piezoelectric fast tuner driver amplifier gain of 1. The horizontal axis is the time in seconds. The upper plot is the RF phase precession and the lower graph is the RF frequency deviation.

Figure 5.10 graphs the RF frequency deviation probability density. The horizontal axis is the RF frequency deviation amplitude and the vertical axis is the number of counts in each 0.77 Hz wide bin as defined in equation 4.1. Notice that the distribution is bimodal, i.e. there are two humps. This is due to the peak in the RF frequency deviation spectrum at 12 Hz and is driven by thermal-acoustic oscillations of the liquid helium coolant.

Figures 5.11 and 5.12 graph the RF frequency deviation and the RF phase precession spectrums respectively. The horizontal axis in both graphs is the mechanical vibration frequency. The vertical axes are the RF frequency deviation amplitude and the RF phase precession amplitude respectively. For reference, figure 5.11 includes two lines corresponding to the RF frequency deviation amplitude required for a 0.30° and a 3.0° phase precession due to a single frequency. Notice that no RF frequency deviation peaks reach the 3.0° RF phase precession line while the maximum measured RF phase error is 3.0°. The total RF phase error is an integral over the complete vibration spectrum, not only the phase error due to a single vibration frequency.

Table 5.1: Summary of the fast mechanical tuning results.

<table>
<thead>
<tr>
<th>RF Power</th>
<th>Peak Frequency Deviation</th>
<th>Peak Phase Error</th>
<th>Feedback Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 W</td>
<td>15 Hz</td>
<td>3.0°</td>
<td>-1</td>
</tr>
<tr>
<td>1200 W</td>
<td>23 Hz</td>
<td>3.0°</td>
<td>-0.75</td>
</tr>
<tr>
<td>3000 W</td>
<td>39 Hz</td>
<td>3.0°</td>
<td>-0.5</td>
</tr>
</tbody>
</table>
Figure 5.9: The time domain phase-error and frequency deviation of the $\beta = 0.5$ TSR cavity when operated coupled to an external noise source. The upper graph is the phase-error and the lower graph is the frequency deviation.

Figure 5.10: The frequency-deviation probability density of the $\beta = 0.5$ TSR when operating phase locked at 2.5 MV/m.
Figure 5.11: The frequency deviation spectrum of the $\beta = 0.5$ TSR phase errors when operating phase locked at 2.5 MV/m.

Figure 5.12: The vibration spectrum of the $\beta = 0.5$ TSR phase errors when operating phase locked at 2.5 MV/m.
5.6 Discussion of Chapter 5 Results

Chapter 5 presented the results of the development of a piezoelectric fast mechanical tuner.

- It was demonstrated that the piezoelectric fast tuner developed here is useful for the compensation of the low-frequency non-resonant microphonic-noise characterized in chapter 4.
- The piezoelectric fast tuner is useful for damping the RF frequency deviation of a spoke-loaded cavity coupled to a cryogenic helium refrigeration system. The helium refrigeration system is similar to what is found around present superconducting accelerators.
- The piezoelectric fast tuner is useful for continuous-wave operation phase control when the RF frequency deviations are driven by microphonic-noise.

A piezoelectric fast tuner was chosen due to the successful application of similar piezoelectric fast tuners to pulsed elliptical-cell cavities: piezoelectric fast tuner compensation of Lorentz detuning was first demonstrated at the DESY FLASH accelerator and subsequently at the U.S. Spallation Neutron Source[49-51]. This dissertation represents the first application of fast mechanical tuners to superconducting cavities operated in the continuous-wave mode and to spoke-loaded cavities.

The piezoelectric fast tuner was also mechanically coupled to the $\beta = 0.4$ DSR and tested. The mechanically coupled piezoelectric fast tuner and the $\beta = 0.4$ DSR transfer function is shown in figure 5.13. Below 200 Hz the piezoelectric fast tuner does not excite mechanical eigenmodes and should be useful for damping the microphonic-noise induced RF frequency variations.

There are several drawbacks to employing piezoelectric based fast mechanical tuners.

- In general, piezoelectric actuators are high voltage devices (~ 1 kV). In the experiments presented here tuner failure due to electrical arcing was common.
- Piezoelectric actuators are fabricated from ceramic compounds.
  - Ceramics have very low thermal conductivities and to reduce the heat leak from room temperature to the cryogenic cavity the piezoelectric actuator is operated in ultra-high vacuum ($< 10^{-8}$ torr) and mounted within a low-thermal conductivity guide assembly. Consequently, any
electrical energy dissipated during operation is not removed from the piezoelectric actuator. This may lead to the failure of the piezoelectric actuator and additional heating of the cavity.

- The stroke of a piezoelectric actuator at 4.2 K is less than 15% of the room temperature value.

To overcome these limitations another class of actuator was developed. This actuator class is based upon magnetostrictive materials. Table 5.2 presents a comparison of the properties of piezoelectric and magnetostrictive actuators.

Applying a magnetic field to a magnetostrictive material causes internal mechanical stress. A magnetostrictive actuator is a device which converts electromagnetic energy into precise mechanical motion; the mechanical motion being proportional to the magnetic field magnitude. The actuator tested here had a stroke of 100 µm at 4.2 K. The magnetostrictive actuated mechanical fast tuner (figure 5.14) was tested on the $\beta = 0.5$ TSR [89, 105]. The mechanically coupled magnetostrictive fast tuner and the $\beta = 0.5$ TSR transfer function is shown in figure 5.15. Its performance is very similar to that of the piezoelectric fast tuner indicating that it should damp the low-frequency non-resonant microphonic-noise problematic for phase stable operation.

Finally, notice that neither the piezoelectric actuated nor the magnetostrictive actuated fast tuners will compensate RF frequency deviations at mechanical vibration frequencies above ~100 Hz. High frequency mechanical vibrations are driven by the time-dependent Lorentz force encountered in the pulsed mode of operation.

Table 5.2: A comparison of the properties of piezoelectric and magnetostrictive actuated fast mechanical tuners.

<table>
<thead>
<tr>
<th>Tuner Actuator</th>
<th>Piezoelectric</th>
<th>Magnetostrictive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temp.</td>
<td>Greater than 4 K</td>
<td>2 to 4 K</td>
</tr>
<tr>
<td>Length</td>
<td>Long (6 - 12&quot;)</td>
<td>Short (~4&quot;)</td>
</tr>
<tr>
<td>Stroke @ 4 K</td>
<td>&lt; 10 µm</td>
<td>&gt; 100 µm</td>
</tr>
<tr>
<td>Push Force</td>
<td>4000 N</td>
<td>440N</td>
</tr>
</tbody>
</table>
Figure 5.13: The mechanically coupled $\beta = 0.4$ DSR and piezoelectric fast tuner transfer function.

Figure 5.14: The magnetostrictive fast tuner actuator and guide assembly. The actuator is on the right.
Figure 5.15: The mechanically coupled $\beta = 0.5$ TSR and magnetostrictive fast tuner transfer function.
Chapter 6

Summary

6.1 Introduction

This dissertation discussed the experimental characterization of the coupling between the 345 MHz accelerating electromagnetic eigenmode and the mechanical eigenmodes of a $\beta = 0.4$ DSR and a $\beta = 0.5$ TSR with a focus on the development of frequency and phase control techniques.

- A powerful method for studying and analyzing Lorentz detuning in superconducting cavities has been developed, as was demonstrated in chapter 3.
- The microphonic-noise induced RF frequency variations of a $\beta = 0.4$ DSR were characterized and found to be due to adiabatic changes in the external pressure due to helium boiling at 4.2 K.
- The $\beta = 0.5$ TSR was designed to decouple the cavity from adiabatic changes in the external helium pressure. The microphonic-noise induced RF frequency variations were found to be at the level of the phase noise on the output of the external oscillator used for the measurement.
- Fast mechanical tuning systems were developed, culminating in the demonstration of RF phase control of a triple-spoke cavity operated under realistic operating conditions.

Chapter 6 will conclude with a summary of the results presented in this dissertation.

1) The Lorentz detuning results presented in chapter 3.
2) The microphonic-noise results presented in chapter 4.
3) The frequency and phase control systems developed in chapter 5.

6.2 Summary of Lorentz Detuning

Chapter 3 presented data demonstrating that the Lorentz transfer function completely characterized the coupling between the cavity RF field and the Lorentz force by accurately predicting the pulsed response of the $\beta = 0.5$ TSR. In principal, this method could be used to characterize the dynamic detuning of a cavity subject to any type of time-dependent driving waveform, not just a simple RF field pulse.
In general, the technique of convoluting the Lorentz transfer function with the second power of the RF field amplitude provides a simple, direct tool for characterizing the electromechanical properties of superconducting cavities. The absence of the Lorentz force coupling to low-frequency spoke-loaded cavity mechanical eigenmodes was demonstrated with the Lorentz transfer function.

6.3 Summary of Microphonic-Noise Induced RF Frequency Variations

Chapter 4 introduced the microphonic-noise induced RF frequency variations of a $\beta = 0.4$ DSR and a $\beta = 0.5$ TSR. It was shown that:

- The maximum amplitude of the RF frequency variations of the $\beta = 0.4$ DSR, at realistic accelerating gradients, would be at least $\pm25$ Hz, and was heavily dependant upon the input power.

- The microphonic-noise induced RF phase errors were due to low-frequency (<20 Hz) non-resonant pressure fluctuations due to boiling in the liquid helium coolant at 4.2 K.

- The design of spoke-loaded cavities could be tailored to decouple the cavity RF field from adiabatic changes in the external pressure. By designing the $\beta = 0.5$ TSR with support gussets, which do not make the cavity infinitely rigid, but instead balance the RF frequency changes due to cavity deformations in regions of predominately high surface magnetic fields with deformations in regions of predominately high surface electric fields.

- Consequently, the microphonic-noise induced RF frequency variations of the $\beta = 0.5$ TSR were found to be independent of the input power and were greatly reduced relative to the $\beta = 0.4$ DSR cavity.
6.4 Summary of Developed Frequency and Phase Control Systems

Chapter 5 presented the development of frequency and phase control methods for superconducting cavities.

- A piezoelectric fast tuner was developed to compensate low-frequency non-resonant microphonic-noise. In general, microphonic-noise induced RF frequency variations are the dominate driver of cavity RF phase errors in continuous-wave accelerators.

- The piezoelectric fast tuner was shown to damp the previously mentioned microphonic-noise. For vibration frequencies below 20 Hz, the piezoelectric fast tuner decreased the RF frequency deviations of a $\beta = 0.5$ TSR by a factor of 8.

- The piezoelectric fast tuner was shown to reduce the RF power required to phase-lock the $\beta = 0.5$ TSR to an external stable source.

- The response of the $\beta = 0.4$ DSR to a piezoelectric fast tuner was presented and was appropriate for damping microphonic-noise.

- An alternative mechanical tuner based on a magnetostrictive rod actuator was coupled to the $\beta = 0.5$ TSR and shown to also be appropriate for damping microphonic-noise.

- No mechanical tuners have been developed for pulsed spoke cavities.
List of References


92. An 8 Gev superconducting injector linac design study part II (FNAL-TM-2169), G.W. Foster, Chou, W., and Malamud, E., Editor. 2003, FNAL: Batavia, IL.


Curriculum Vitae

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Research Interests
My research focuses on hardware development for superconducting niobium cavities. Primarily, this involves the development of spoke-loaded niobium superconducting cavities, mechanical tuners, and fundamental power couplers. Adaptations of this hardware may be used in the FNAL HINS proton driver linac and the ANL Advanced Exotic Beams Laboratory driver linac, AEBL, to phase and amplitude stabilize both the pulsed and cw modes of cavity operation in the presence of RF frequency variations.

I am also involved in experimentally evaluating the overall performance of new TEM-class superconducting cavities currently under development at Argonne National Laboratory for the proposed AEBL driver linac. My work with these cavities involves their chemical processing, cleaning, assembling, and rf testing using current state of the art techniques.
Publications


Presentations

1) “Electromechanical Properties of Spoke-Loaded Superconducting Cavities,” invited talk at the 13th International Workshop on RF Superconductivity, Beijing, China, October 2007.

2) “Superconducting Multi-Spoke-Loaded Accelerator Cavities,” Fermi National Accelerator Laboratory Accelerator Physics and Technology Seminar, Batavia, IL, August 2007.


9) “Status of the $\beta = 0.5$ Superconducting Triple-Spoke-Cavity RF Testing,” LBNL Engineering Division Seminar, Berkeley, California, October 2006.