Tuners, Microphonics, and Control Systems in Superconducting Accelerating Structures

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Introduction

In the textbook image of an accelerating cavity, superconducting or not, the axial electric field in the cavity is a sine wave with constant magnitude and phase. The field is timed (phased) so that the bunches of charged particles which pass through the cavity each receive the desired acceleration. Often the bunches are synchronized to be at the position of maximum field when the sine wave reaches its maximum, so that the greatest average acceleration is achieved. When longitudinal focussing is needed, the beam is retarded somewhat.

Manufacturing tolerances, thermal stresses, acoustic noise, and cooling fluid pressure fluctuations all conspire to make the field in the cavity not precisely what the accelerator physicist has in mind. Tuners and control systems are the tools used to fight back: they regulate the field in the cavity to the desired magnitude and phase.

Amplitude and phase stability are usually of greater concern in superconducting cavities than in copper cavities. The reasons are many:

1. Superconducting cavities allow, and often have, much higher loaded Q's.
2. Superconducting cavities are more conducive to continuous operation, and energy stability is more meaningful in a continuous beam machine; therefore the requirements on phase control are often more stringent.
3. Cold structures generally have lower mechanical losses, and are therefore more strongly resonant.
4. The cryogenic system required to keep the cavities superconducting is itself a noise source.

History

Possibly the first time that several cavities were independently phased to a master oscillator for an accelerator is described by Schultz, 1947 [1]. This system ran "open loop," without feedback from the cavity field.

Early copper accelerators, with their low-Q pulsed operation and multiple cavities per klystron, in general did not have feedback from the cavity field. The Stanford HEPL Superconducting Electron Accelerator seems to be the first to have per-cavity electronic feedback (Suelzle, 1968 [3]). While this accelerator was not a rousing success, its control system was ahead of its time.

Ponderomotive Instabilities

At high gradient, and continuous operation, open loop control is susceptible to a ponderomotive instability. This process (in copper cavities) was first described by Karliner in 1967 [2]. The loop that becomes unstable involves radiation pressure deforming the cavity, which then goes out of tune and loses its coupling to the power source. The field decays, the cavity relaxes, the field builds up again, and the cycle continues. Karliner's paper mentions that feedback techniques are required to control the problem.

The first description of ponderomotive instabilities in a superconducting accelerator comes from Schulze, 1971 [6]. He also calls for the use of electronic feedback to cure the instability.

Ponderomotive oscillations plagued the superconducting helix community for years. Papers abound describing the proposed solutions, and eventually the successful conquering of the problem [27].

Feedback

The key to achieving stable gradient and phase is feedback. A probe must be placed in the cavity itself to sense the present cavity status. Electronic control is then given the responsibility to correct for any measured disturbance. There are two general classes of corrections possible.

1. Purely electronic.
   a. The forward wave of RF power from the High Power Amplifier is modulated in amplitude and phase.
   b. An external variable reactance is added to the cavity, changing the system resonant frequency to that desired.
2. Mechanical deformation of the cavity.
   a. Motor driven. Included are tuners which only change the position of a tuning plunger in the cavity.
   b. Piezoelectric tuners. A high voltage is applied to a piezoelectric crystal, which deforms and presses on the wall of the cavity.
   c. Magnetostrictive tuners. Like a piezoelectric tuner, except a magnetic field is applied to magnetostrictive material.
   d. Thermal Tuners. Heat is added to a material with known (high) coefficient of thermal expansion.
   e. Bath pressure control. Most high-β cavities are sensitive to fluctuations in bath pressure. Control can be either in the form of additional heat (from a resistor in the bath), or in the form of setting a control valve position.

See table 1 for a summary of the feedback schemes which have been described in the literature.

One control approach does not fall neatly into these categories. When the ponderomotive coupling is high (as with a low-β helix), amplitude control will stabilize the frequency of the cavity by damping mechanical motion. In this case the cavity itself is being used as a transducer. This has been used to damp high-Q mechanical modes of a helix [6], [10].

Electronic Control

The electronic modulation of forward power has been implemented in a number of ways. Perhaps the easiest implementation to understand has two separate control loops, one for amplitude and one for phase. This is listed as P in table 1.

Most of the phase noise in the system comes from the change in the resonant frequency of the cavity. When that frequency is not centered on the operating frequency, additional drive amplitude is required to maintain the cavities field. Thus, both loops have to respond to the noise source. This effect can be bypassed (to first order) by arranging the phase feedback to compensate for the reduced sensitivity of the cavity off resonance. This is easily done with a complex phasor modulator (CPM) as is described in detail in Ben-Zvi, 1986 [32]. This approach has demonstrated a factor of four improvement in amplitude stability at CEBAF over the more ordinary phase feedback [43].

Rather than separate out the magnitude and phase error, one can configure the two feedback loops to lock the real and imaginary part of the complex field vector of the cavity, as described by Dick, 1977 [20]. Negative vector feedback is easily converted to positive feedback, which turns the circuit into a self-excited oscillator for testing or startup.

Forward power modulation systems like these make additional demands on the high power amplifier when the noise amplitude approaches or exceeds the bandwidth of the cavity. Helices, in particular, would require orders of magnitude more RF drive than would be required without feedback. In this case (especially because of the relatively low frequencies involved) laboratories have found it more cost-effective to use a variable reactance device. Large amounts of power still flow from the cavity to the control element, except now the control element is passive and inexpensive. A PIN diode switch alternately opens and shorts a coaxial line to the cavity, and the duty cycle will determine the average reactance added to the cavity. The standard circuitry is explained well in Despe, 1973 [16]. A more sophisticated control circuit, which borrows some concepts from forward wave modulated systems, is described by Hochschild, 1973 [18]. The losses between the cavity and the room-temperature control element limit the amount of frequency shifting that can be achieved. Variable reactance systems have been built to correct for frequency shifts of a hundred bandwidths.

From theoretical considerations one can place limits on the amount a feedback system can reduce microphonic noise. A stable, broadband feedback system separated from the cavity by l meters must have no gain at $f_b = c/4l$ Hz and above. In this expression, c is the velocity of electrical signals in the interconnecting cables. Other considerations, like available high power amplifier bandwidth, may limit f_b to lower values. A standard, unconditionally stable feedback loop has linearly rising gain at lower frequencies, so that noise at frequency f can be reduced by a factor of f_b/f. More aggressive feedback (conditionally stable) can, in principle, increase the possible reduction to $(f_b/f)^2$. Narrow band noise can be reduced more easily than wideband noise. The performance limit of an adaptive feedback network is computed by replacing f above with the width of the noise peak; the center frequency is immaterial.

Mechanical Tuners

Piezoelectric and magnetostrictive tuners are considered 'fast' tuners. Fast tuners respond in milliseconds, usually limited by the mechanical resonances in the accelerating structure. For example, the magnetostrictive tuner at CERN (Cavallari, 1987 [38]) has a response time of about 50 milliseconds.

Bath pressure control, motor driven tuners, and thermal tuners are considered 'slow' tuners. Slow tuners are not expected to operate at time scales faster than a few seconds. They are incorporated when the tuning range of the fast tuner plus electronic tuning is not enough to compensate for unpredictability or drift in the static frequency setting.

Tuners, in particular motor driven tuners, originated simply as remote controlled, manually operated devices used for setting up at the start of a run. Suelzle, 1968 [3] and Hoffswell, 1971 [7] proposed the idea of actively coupling the tuner control to the phase measurement system. Ben-Zvi, 1972 [9] was perhaps the first to describe a working system with mechanical tuning feedback. This system is slightly unusual in that the mechanical tuning (piezoelectric) is the *only* feedback incorporated. The other extreme is a system described by Ceperley, 1977 [22], which has electronic phase control, a motor driven tuner, a piezoelectric fast tuner, and bath pressure stabilization.

Microphonic Environment

Each laboratory has its own experience with microphonic background which is picked up by the cavities. One generalization is that the noise sources are narrow band. Synchronous motors run at a frequency harmonically related to the AC line frequency. Their torque is proportional to the phase difference between the rotor and the field. In an asynchronous motor, the torque is proportional to the difference in frequency between the rotor and the field, so in normal operation the rotation rate is typically 95% to 99% of the equivalent synchronous motor rate. In both synchronous and asynchronous motors, the peak width is usually much less than 1 Hz. At CEBAF, for instance, strong peaks have been observed at 16 Hz, 17 Hz, 18 Hz, 30 Hz, and 58.5 Hz. Power transformers generally broadcast the most noise at the second harmonic of the line frequency. Strong 120 Hz noise is common at CEBAF.

Power spectra of frequency noise observed in cavities have been published by Benaroya, 1972 [14]; Peebles, 1973 [15]; Cauvin, 1987 [37]. Some people have provided estimates of ambient vibration in their laboratory. Aron, 1973 [17] estimates 10 cm/sec^2 on the floor under the cryostats. Benaroya, 1972 [14] observes 2 cm/sec^2 rms in his laboratory, mostly in the 120 to 160 Hz band. Fischer, 1985 [30] discusses unavoidable low frequency background noise.

The cavity responds to mechanical motion by changing its resonant frequency (f_r). If external excitation is provided, for example by a changing bath pressure, a sensitivity S could be measured:

$$S = \Delta f_r / F$$

where F is the excitation, the change in pressure in this example. Sensitivities can be measured for a variety of forces, such as Ponderomotiv force, bath pressure, axial displacement, piezoelectric tuner drive, and mangnetostrictive tuner drive. This response varies with mechanical frequency, so that S is a function of f_m. Note the ambiguity in talking simply about 'frequency.' Under sinusoidal excitation,

$$f_r = f_0 + a \cdot \sin(2\pi f_m t),$$

where both a and f_m are frequencies in the Hz to kHz range.

On rare occasions, the frequency response of one of these functions is actually measured and published. Indirect measurements of the ponderomotive term were published by Schulze, 1972 [12]. Measurements of a magnetostrictive tuner's frequency domain sensitivity are published by Cavallari, 1987 [38].

The easiest quantity to measure in a laboratory, and the one with the most significance to the operation of an accelerator, is the microphonic induced frequency shift in a cavity. Table 2 lists some measured values that have been published. Unfortunately, this single number folds together a great many physical details, and has little predictive power for a new set of cavities in a new laboratory.

The background noise has a spectrum consisting of a number of sharp peaks (less than 1 Hz wide) in the 10 to 500 Hz band. In this band there will also be a number of sharp mechanical resonances (also less than 1 Hz wide) within the cavity and its cryostat. The exact location (±5% in frequency) of these resonances can be considered unpredictable due to manufacturing tolerances. A high stability machine can not be expected to operate properly if a noise source and a mechanical resonance overlap. At this point the astute reader may correctly deduce that luck plays an important role in the operation of a superconducting accelerator.

A separate issue in a large machine ($N^{1/2} \gg 1$, where N is the number of cavities) is whether microphonic noise is correlated or uncorrelated from cavity to cavity, see Leeman, 1987 [36]. The requirements for correlated noise are a factor of $N^{1/2}$ more stringent than for uncorrelated noise. CEBAF expects to encounter both types. Expectations of manufacturing variability from unit to unit, and considerations discussed by Fischer, 1985 [30] lead one to think that most vibration induced noise will be effectively uncorrelated.

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Reference	Tuner	Control	Resonator	Laboratory
Suelzle '68 [3]		P	High-β	Stanford-HEPL
Hoffswell '71 [7]		P	High-β	Illinois
Ben-Zvi '72 [9]	P		Re-entrant	Stanford
Dick '72 [10]		X	Helix	Caltech
Schulze '72 [12]		X	Helix	Karlsruhe
Jones '72 [13]	R		Helix	Oak Ridge, Karlsruhe
Peebles '73 [15]		X	Helix	Oak Ridge
Despe '73 [16]		X	Helix	Argonne
Hochschild '73 [18]		X	Helix	Karlsruhe
Dick '76 [19]		V	Split-Ring	Caltech, Stony Brook
Dick '77 [20]		V	Split-Ring	Caltech, Stony Brook
Ceperley '77 [22]	RBP	P	Re-entrant	Stanford
Hochschild '77 [25]	R		Helix	Karlsruhe
Delayen '77 [26]		V	Split-Ring	Caltech
Ben-Zvi '86 [32]	R	C	Quarter-Wave	Stony Brook
Aab '87 [35]	P	C	High-β	Darmstadt
Cauvin '87 [37]		XP	Mod-Helix	Saclay
Cavallari '87 [38]	MT		High-β	CERN
Fugitt '87 [39]		P	High-β	CEBAF
Bernard '88 [40]	MT	V	High-β	CERN
Boussard '88 [41]	MT	V	High-β	CERN
Simrock '89 [43]		C	High-β	CEBAF

Tuner Key:
- R Motor Driven
- B Bath Pressure
- P Piezoelectric
- M Magnetostrictive
- T Thermal

Control system key:
- X Variable Reactance
- P Phase-Amplitude loops
- C CPM-Amplitude loops
- V Vector loop

Table 1. Index to descriptions of various types of tuners and control systems.

Reference	p-p noise	Center freq.	Resonator	Laboratory
Dick '72 [10]	400 Hz	30 MHz	Helix	Caltech
Fricke '72 [11]	24000 Hz	90 MHz	Helix	Karlsruhe
Benaroya '72 [14]	500 Hz	63 MHz	Helix	Argonne
Dick '76 [19]	600 Hz	238 MHz	Split Ring	Caltech, Stony Brook
Benaroya '77 [21]	120 Hz	97 MHz	Split Ring	Argonne
Hochschild '77 [25]	350 Hz	108 MHz	Helix	Karlsruhe
Shepard '77 [24]	80 Hz	98 MHz	Split Ring	Argonne
Delayen '77 [26]	100 Hz	150 MHz	Split Ring	Caltech
Zieher '81 [28]	350 Hz	142 MHz	Mod. Helix	Karlsruhe
Doolittle '88 [42]	30 Hz	1497 MHz	High-β	CEBAF

Table 2. Observed levels of microphonics.