Experience with Control of Frequency, Amplitude, and Phase

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Abstract

In superconducting accelerators, requirements for frequency, amplitude, and phase control are different from those used for normal conducting cavities. Superconducting cavities have a very narrow bandwidth and are therefore highly sensitive to mechanical perturbations. Significant phase and amplitude errors are induced by the resulting frequency variations. Perturbations can be excited by microphonics, changes in pressure, or Lorentz forces. Slow (<1 Hz), large changes in frequency are typically corrected by a frequency tuner, while faster changes (>1 Hz) are corrected by modulation of the incident rf power in amplitude and phase. The basic principles of rf control systems used in superconducting electron accelerators and their operational performance have been presented by Gräf [1]. The present paper extends this earlier work. Operational experience gained at various accelerator facilities and performance details of the CEBAF rf control system are presented.

Introduction

The number of accelerator facilities using superconducting cavities is continually growing. Superconducting cavities allow for high gradients (typically 5 MV/m) and continuous wave (cw) operation. They are used to accelerate electrons, protons, and heavy ions in linacs and storage rings as shown in Table 1. Several other facilities are under construction or being commissioned.

Table 1: Accelerator facilities using superconducting cavities

Type	Facility				
Collider	KEK	CERN/LEP	DESY	CERN/SPS	
e^- linac	CEBAF	S-DALINAC	LISA	MACSE	HEPL
Heavy ion linac	ATLAS	STONY BROOK	ALPI		

Design considerations

The design of the rf system depends on the type of accelerator and the beam characteristics. Rf system requirements are derived from the beam requirements as shown in Figure 1. In most cases power requirements are determined by beam loading since rf power dissipation in the cavities is only a few watts. The choice of frequency is driven by cavity design, although energy spread induced by finite bunch length has to be taken into account. Amplitude and phase stability impose limitations on the achievable energy spread and can be improved using feedback techniques. Presently all accelerators using sc-cavities are operated cw, thereby simplifying feedback design. The proposed TESLA facility will operate in pulsed mode at cavity gradients of 25 MV/m. The Lorentz force will induce frequency changes exceeding the bandwidth of the cavity, therefore demanding a sophisticated control system to stabilize gradient and phase.

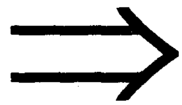
Beam parameters		**RF system requirements**
• Type of beam		• Type of cavity
• Energy		• Frequency
• Energy spread		• Power/cavity
• Beam current		• Amplitude stability
• Emittance		• Phase stability

Figure 1: RF system parameters are driven by beam parameters

Perturbations causing gradient and phase fluctuations of the accelerating field can be excited by the beam, fluctuations of the incident wave, or time-varying cavity deformation. The magnitude of the different types of perturbations can vary significantly between the different accelerators. Various sources are listed in Table 2.

Table 2: Sources of perturbations

• Beam loading
  • Beam current fluctuation
  • Pulsed beam transients
  • Multipacting and field emission
  • Excitation of HOMs
• Cavity drive signal
	• Cavity resonance frequency ($f_r = f_r(t)$)
	  • Microphonics (mechanical vibrations incl. ground motion, vacuum pumps, refrigerator, He-boiloff)
	  • (He-)pressure variations
	  • Radiation pressure (Lorentz force)

The perturbations in phase or amplitude are typically a factor 10 to 100 higher than required. The solution is active control for amplitude and phase of the accelerating field and control of the cavity resonance frequency. The various possibilities for the implementation of feedback systems are presented in reference[1].

<u>Implementations</u>

The main parameters of the rf system at the superconducting accelerator facilities are listed in Tables 3, 4, and 5. The largest installation is CEBAF, where 338 sc-cavities will be operated at average gradients exceeding 5 MV/m. Extensive operational experience with rf systems has been gained at the heavy ion linac Atlas and the electron-positron collider at KEK, both of which have been operating a significant number of cavities for several years. It is interesting to note that the rf systems in colliders drive multiple cavities with one power amplifier while linear accelerators employ separate drive systems for each cavity. This is due to the tighter control of amplitude and phase imperative in most linear accelerators.

<u>Performance of rf controls</u>

The performance of the rf control system is measured in terms of residual phase and amplitude fluctuations. Typically, phase fluctuation between 5° and 50° (peak-peak) and amplitude fluctuation in the few percent range have to be suppressed by two orders of magnitude. The performance of rf systems is shown in Table 6. In colliders, phase stability of the order of 1° rms is achieved, while the residual phase fluctuation in linear accelerators is about 0.1° rms. For amplitude stability the results are about 0.5% rms in colliders, 0.1% rms in heavy ion linacs, and 0.02% rms in linear electron accelerators.

Table 3: Rf system-related parameters of superconducting circular accelerators

Accelerator facility	KEK	CERN/LEP	DESY	CERN/SPS
Type of accelerator	e^-e^+ collider 8–29 GeV at 15 mA	e^-e^+ collider 20–46 GeV at 40 mA	e^- collider 26–40 GeV at 70 mA	$e^-, e^+, p, \bar{p}$ collider, booster
Cavity material (RRR)	Nb (200)	Nb (280) and Nb/Cu (30)	Niobium (280)	Niobium
Operating temperature (K)	4.2	4.2	4.2	4.2
Cavities installed (operational)	32 (32)	8 Nb + 4 Nb/Cu (8+4)	16 (16)	1 (1)
Number of cells	5	4	4	4
Frequency (MHz)	508	352	500	352
Q_0/Q_L	$2\cdot10^9$ / $1\cdot10^6$	$3\cdot10^9$ / $2.2\cdot10^6$	$2\cdot10^9$ / $2.4\cdot10^5$variable	$3\cdot10^9$ / N.A.
Design (average) operating gradient (MV/m)	5 (3.5 – 4.7)	5 (3.7) Nb, 6 (4) Nb/Cu	5 (4)	5 (5)
Normal operating gradient control range (MV/m)	2.5–4.5	2–4	1–5	4–6
Gradient control range for conditioning (MV/m)	0.1–9.0	1–7	1–7	N/A
Power amplifier	Klystron 1 MW	Klystron 1.2 MW	Klystron 1.6 MW	Tetrode 50 kW
# Cavities/power amplifier	4	16	16	1
Beam time (h)	25,000	several 100	15,000	30,000
Mechanical sensitivity (Hz/μm)	80	40	80	≈40
Pressure sensitivity (Hz/mBar)	30	8	-90	8
Gradient sensitivity (Hz/(MV/m)**2)				
Frequency predictability for first cooldown (kHz)	±100	±30	±90	
Frequency predictability for repeated cool down (kHz)		<5	±few kHz	
Tuning principle	length variation	length variation	length variation	length variation
Tuning mechanism	stepping motor + piezoelectric	thermal expansion + magnetostrictive	stepping motor	thermal expansion + magnetostrictive
Frequency range and settability of coarse tuner (kHz)	350	50	800	50
Frequency range and (settability) of fine tuner (Hz)	6000 (N.A.)	2000 (N.A.)	N.A.	2000 (N.A.)
Tuner control automated or manual	automated	automated	automated	automated
Bandwidth of tuner control (Hz)	10	< 1 Hz	< 1	

Table 4: Rf system-related parameters of superconducting linear electron accelerators

Accelerator facility	CEBAF	S-DALINAC	LISA	MACSE	HEPL
Type of accelerator	e^- recyclotron (5-pass) 0.5-4.0 GeV at 200 μA	e^- recyclotron (3-pass) 20-130 MeV at 20 μA	e^- linac 25 MeV linac for FEL	electron accelerator test facility	e^- recyclotron Nucl. Phys. and FEL
Cavity material (RRR)	Nb (300)	Nb (100 – 280)	Nb (100 – 200)	Nb	Nb
Operating temperature (K)	2.0	2.0	4.2	2.0	2.0
Cavities installed (operational)	306 (258)	10+1 (10+1)	4 (3)	4+1 (4+1)	7 (7)
Number of cells	5	20/5	4	4-5	7/23/55
Frequency (MHz)	1497	2997	500	1497	1300
Q_0/Q_L	$6\cdot10^9$ / $6\cdot10^6$	$2\cdot10^9$ / $3\cdot10^7$	$1\cdot10^9$ / $5\cdot10^6$	$5\cdot10^9$ / $5\cdot10^6$	$2\cdot10^9$ / $4\cdot10^6$
Design (average) operating gradient (MV/m)	5 (7.2)	5 (3.0)	5 (3.5)	5 (4–5)	5 (3.5/2.5)
Normal operating gradient control range (MV/m)	3–7	2–4		4–5	2–5
Gradient control range for conditioning (MV/m)	0.5–7	1–10 (variable coupler)		N.A.	0.1–9.0
Power amplifier	Klystron 5 kW	Klystron 0.5 kW	Klystron 15 kW	Klystron 5 kW	Klystron 10 KW
# Cavities/power amplifier	1	1	1	1	1
Beam time (h)	4,000	7,000	> 200	100	30,000
Mechanical sensitivity (Hz/μm)	500	500	60	500	N.A.
Pressure sensitivity (Hz/mBar)	-60(-10)	-15		-60	
Gradient sensitivity (Hz/(MV/m)**2)	-3	-4		-3	
Frequency predictability for first cooldown (kHz)	±20	±200		±50	13
Frequency predictability for repeated cool down (kHz)	±2	±20		±25	1
Tuning principle	length variation	length variation	length variation	length variation	length variation
Tuning mechanism	stepping motor	DC-motor+ magnetostrictive	stepping motor	stepping motor + magnetostrictive	stepping motor
Frequency range and settability of coarse tuner (kHz)	400 (0.002)	1000 (0.01)	600 (<0.01)	1500	25
Frequency range of fine tuner (Hz)		1500			
Tuner control automated or manual	automated	automated	automated	automated	N/A
Bandwidth of tuner control (Hz)	0.1	1			

Table 5: Rf system-related parameters of superconducting heavy ion accelerators

Accelerator facility	Atlas	Stony Brook	ALPI
Type of accelerator	Heavy in Linac	Heavy ion linac	Heavy ion linac
Cavity material (RRR)	Nb (20 – 200)	Pb/Cu	Pb/Cu
Operating temperature (K)	4.7	4.5	4.2
Cavities installed (operational)	62 (62)	42 (40)	32 (20)
Number of cells	N.A.	N.A.	N.A.
Frequency (MHz)	48,72,92,145	150.4	80, 160
Q_0/Q_L	typ. $2\cdot10^9/1\cdot10^7$	$1\cdot10^8$ / $1\cdot10^7$	$1\cdot10^8$ / $1\cdot10^7$
Design (average) operating gradient (MV/m)	3 – 4	3	3
Normal operating gradient control range (MV/m)	1 – 3.5		
Gradient control range for conditioning (MV/m)	1 – 8		
Power amplifier	200 W class A solid state	200 W class A solid state	100 W class A solid state
# Cavities/power amplifier	1	1	1
Beam time (h)	>50,000	30,000	some hours
Mechanical sensitivity (Hz/μm)	100		6
Pressure sensitivity (Hz/mBar)	2		
Gradient sensitivity (Hz/(MV/m)**2)	-100	-100	
Frequency predictability for first cool down (kHz)	< 10	<5	<10
Frequency predictability for repeated cooldown (kHz)	< 3	<1	<1
Tuning principle	Deformation	Deformation of bottom plate (QWR) or end cells (SLR)	Deformation of bottom plate
Tuning mechanism	He-pressure actuated	Stepping motor, screw, lever	Stepping motor +step reducer
Frequency range and settability of coarse tuner (kHz)	100 (0.001)	±5 kHz (QWR) ±20 kHz (SLR)	30 (0.002)
Frequency range and (settability) of fine tuner (Hz)	200 (2°rf phase)		
Tuner control automated or manual	automated	coarse tuner manual fine tuner automated	manual
Average tuner control (Hz/day)	> 1000 for slow tuner		
Bandwidth of tuner control (Hz)	< 1 for slow tuner		1

Table 6: Performance of rf control systems in superconducting accelerators

Accelerator facility		KEK	CERN/LEP	DESY	CERN/SPS	
Amplitude stability (fast errors >1 Hz)	σ_A/A	$\leq 5\cdot10^{-3}$	$\leq 5\cdot10^{-3}$	TBD	$\leq 1\cdot10^{-4}$	
Phase stability (fast errors >1Hz)	σ_ϕ	$\leq 2°$	$< 1°$	TBD	$\leq 0.3°$	
Microphonics noise	° (pk-pk)	±45°	TBD	TBD	TBD	
Stab. of aver. detuning angle	degrees					
Perturbations	source	LHe flow Cavity resonances	Pressure oscillations		LHe- evaporation	
Dominating frequencies	Hz	50			51,63,73	

Accelerator facility		CEBAF	HEPL	S-DALINAC	LISA	MACSE
Amplitude stability (fast errors >1 Hz)	σ_A/A	$2\cdot10^{-4}$ correlated $3\cdot10^{-5}$ uncorrelated	$2\cdot10^{-5}$	$4\cdot10^{-4}$		$1\cdot10^{-4}$
Phase stability (fast errors >1Hz)	σ_ϕ	$\leq 0.1°$	<<1°	0.2°		0.1°
Microphonics noise	° (pk-pk)	5 – 20		10 – 60	30 – 40	20
Stab. of aver. detuning angle	degrees	$< \pm 10°$		few		
Perturbations	source	compressor and cavity resonance		compressor and transfer line	thermo-acoustic cavity resonance	thermo-acoustic oscillations
Dominating frequencies	Hz	33, 58,61,65		none	approx. 30 Hz from resonance	65,30

Accelerator facility		Atlas	Stony Brook	ALPI		
Amplitude stability (fast errors >1 Hz)	σ_A/A	$1\cdot10^{-3}$	$1\cdot10^{-3}$	$1\cdot10^{-3}$		
Phase stability (fast errors >1Hz)	σ_ϕ	1°	0.1°	0.1°		
Microphonics noise	° (pk-pk)	$> 2\pi$				
Stab. of aver. detuning angle	degrees					
Perturbations	source	LHe flow, compressor resonance, vacuum pumps				
Dominating frequencies	Hz	30 – 80				

Operational experience

Superconducting rf systems have been operational in a large number of installations for several years and performance, reliability, and operability have been improved significantly during the past five years. Machine protection interlocks prevent the hardware from being damaged but can, if an overly sensitive trip level is set, reduce available beam time. It is therefore important to design interlocks for maximum noise immunity and implement procedures which allow to recover from interlock trips in a short time. Some of the experiences at the different facilities and special features of the rf systems are described below.

KEK

Amplitude and Phase Control	• Four cavities are controlled simultaneously using the vectorsum. Therefore the cavities must be tuned prior to lock of amplitude and phase • Large beam loading $(V_{br} = 10\,\mathrm{MV/m})$ has not presented an operational problem • The gradient is ramped from 0.9-4 MV/m during acceleration from 8 to 29 GeV • RF coupling between paired cavities is 0.1% of field
Frequency Control	• Initially tune each cavity at low gradient, then regulate on vector sum • Search mode for tuner when signal too small • Step response of piezoelectric tuner is approximately 20 ms and can correct simulated frequency steps of 250 Hz (≈40°) • Conditions at injection: α= -30° and ϕ ≈85°; change to α= -5° and ϕ ≈48° at flat top • Mechanical coupling between paired cavities is (7-10)% of frequency
Interlocks	• No beam loss when RF trips. Can be recovered without beam loss
Other	• Loaded Q ranges from $(0.71-1.3)\cdot 10^6$

CERN/LEP

Amplitude and Phase Control	• The scalar sum of 16 cavities is used for gradient control • Phase control only for output of klystron using fiber optic reference. Compensation for waveguide temperature
Frequency Control	• Need to know He-gasflow to return from parking condition
Interlocks	• Power coupler: local vacuum, electron current, 5 temperatures • HOM-coupler: temperature, fundamental power, total power
Other	• Power conditioning of fundamental coupler necessary

DESY

Amplitude and Phase Control	• Recently vector sum has been tested successfully. No amplitude and phase control needed at low beam current (<30 mA)
Frequency Control	• Tuning is not critical due to low loaded Q
Interlocks	• Input coupler, HOM coupler, cryo and vacuum • Quench detection using He-pressure

CERN/SPS

Amplitude and Phase Control	• Use of rf signal as reference; does not distinguish between phase and amplitude. Shunt impedance is low for protons, high for electrons • Very high gain of up to 130 dB allows for very tight control • Excitation of other passband modes is suppressed
Frequency Control	• Thermal tuner

CEBAF

Amplitude and Phase Control	• Meets correlated and uncorrelated noise specification except 60 Hz and harmonics where improvement by factor 2-3 is needed
Frequency Control	• Operate tuner while beam is accelerated • Presently manual detuning angle offset calibration required

Interlocks	• Arc, IR, quench, WG-vacuum, beam line vacuum, He-pressure, He-level, transmitted/incident power • Most frequent trips from IR, and WG vacuum
Other	• Observed slow drift of ±1% in energy. Period 20 minutes

HEPL

Amplitude and Phase Control	• Very low microphonic noise level due to rigid cavity design do not require high gain
Frequency Control	• N.A.

S-DALINAC

Amplitude and Phase Control	• Improved amplitude regulation by increasing power to gradient detector

MACSE

Amplitude and Phase Control	• Demonstrated gradient control using vector sum of four cavities. Achieved rms gradient stability of $1 \cdot 10^{-4}$ with beam. Same as with individual control but used beam measurement to adjust amplitude and phase of probe signals before summing
Frequency Control	• Operate tuner while beam is accelerated
Interlocks	• Vacuum, quench, He-pressure

ATLAS

Amplitude and Phase Control	• Control each resonator to $1 \cdot 10^{-3}$ and 1° • Tune for each beam and energy change
Frequency Control	• Increased tuning range
Interlocks	• As needed for data taking, not for machine protection

Experience with control of frequency, amplitude and phase at CEBAF

A description of the requirements and design of the CEBAF rf control system can be found elsewhere [2]. The perturbations that have to be controlled are summarized in Table 7.

Table 7: Perturbations in the CEBAF rf system

Type of perturbation	Characteristics
Microphonic noise	Phase fluctuations range from 3° to 15° (peak-peak). Factor of 3 difference observed between cavities in same cryomodule. Frequency range between 0.2 Hz and 200 Hz. Amplitude fluctuations up to 3% (rms) depending on average detuning angle
He-pressure fluctuations	Design $\Delta p \leq 0.1$ mbar at 2.0 K, sensitivity up to 60Hz/mBar
LHe-level	Typically (88±1)%, frequency changes insignificant
Drift of resonance frequency not He-pressure or level related	Probably mechanical relaxation following mechanical stress through beam pipe. Up to few 100 Hz/day during cryomodule installation
Klystron (incident signal)	Phase fluctuations approximately 1° rms at 720 Hz from ripple of HV-PS.
Phase noise from master oscillator	Approximately 0.4° rms (1 MHz bandwidth) resulting in significant PM-AM conversion when phase loop operated at high gain (>40 dB)
Schottky and 1/f noise from amplifiers	(10-30)W of power at klystron (33 dB gain) output (within bandwidth of several MHz) when no drive signal is present at input of preamplifier (53 dB gain). Noise in baseband circuits does not dominate
Long term (temperature) effects	Waveguides, coaxial cables, gradient detector cause changes of several degrees in phase and up to 0.1% in amplitude for 10°C temperature change
Beam loading	Approximately 5 MV/m at 5 × 200μA
Lorentz force	Resonance frequency changes by $-3\ \mathrm{Hz}/(\mathrm{MV/m})^2$

The dominating noise sources are microphonics for fast (>0.1 Hz) fluctuations and slow drifts due to temperature changes of cables and gradient and phase detector. A typical spectrum of the phase fluctuation is shown in Figure 2. A feedback system using the cavity field probe signal and controllers for amplitude and phase for the incident wave is used to correct fast errors while slow errors will be corrected using beam feedback.

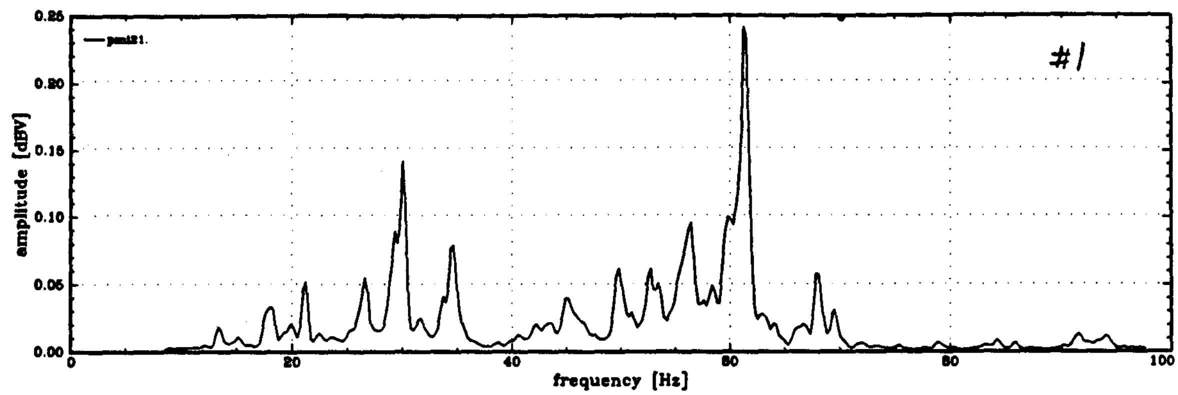


Figure 2: Typical spectrum of phase error signal

Gradient and phase control

The performance for control of fast errors exceeds specification except for correlated noise at 60 Hz and harmonics, which is two to three times higher than required. Slow phase errors along the linac are approximately 1° rms during an 8 hour period. A phase vernier system using beam feedback will correct long term drifts. The measured results are summarized in Table 8.

Table 8: Rf system performance at CEBAF

Type of error	Required	Measured
σ_A / A (fast gradient error)	$2 \cdot 10^{-4}$ uncorrelated $1.1 \cdot 10^{-5}$ correlated	$1.5 \cdot 10^{-4}$ uncorrelated $(2-3) \cdot 10^{-5}$ correlated
σ_f (fast phase error)	0.25° uncorrelated 0.13° correlated	0.08° uncorrelated 0.08° correlated
σ_s (slow phase error)	2.6°	$\leq$ 1°/(8 hours)

The spectrum of residual amplitude and phase fluctuations shows a significant contribution at frequencies >10 kHz. No contribution is observed above 1 MHz. Low frequency and broadband gain have to be optimized for minimum residual fluctuations. The residual noise depends also on the average detuning angle.

Gradient and phase calibration

Initial accuracy for the gradient calibration using the external Q of the field probe coupler is ±15%. Calibration with beam using the spectrometer yields ±2% accuracy. Several methods have been developed for the calibration of the accelerating phase. They employ the spectrometer, beam-induced transients (pulsed beam), beam induced voltage (cw), dead reckoning (calculation from cable length, etc.), and cancellation of beam-induced voltage with generator voltage. All methods yield ±2° to ±5° accuracy. At CEBAF beam-induced transients are used for initial phasing while automated phasing schemes use the spectrometer.

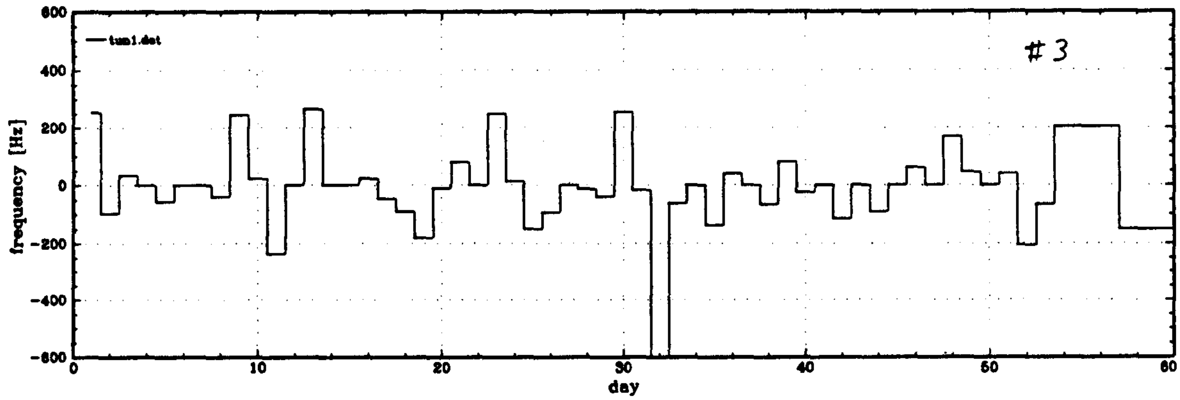


Figure 3: Typical frequency drift of a cavity during injector run.

Frequency control

The average frequency drift observed at CEBAF during previous runs in the injector is 85 Hz/day. The typical daily frequency drift of a cavity is shown in Figure 3. On the average, tuning requires 4,000 microsteps of the stepper motor per day with a limit of 50,000 steps/day to guarantee a useful lifetime exceeding 10 years. Presently implemented in the automated tuning algorithms is a tracking mode which activates the tuner when the detuning angle exceeds 10° and stops when it is within 3°. The tuner works well in the tracking mode, but the operator has to calibrate the detuning angle offset manually using a network analyzer. The detuning angle offset has to be calibrated quite frequently (in some instances once/day) due to control module changes, cable changes, He-pressure changes, or other reasons. The mechanical tuner has been proven reliable. Settability is better than 1 Hz and hysteresis effects are sufficiently small to allow for smooth tuner operation, as shown in Figure 4.

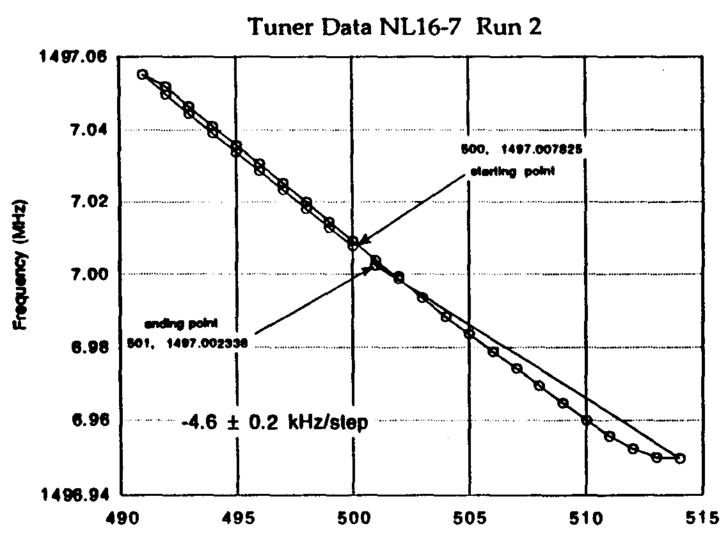


Figure 4: Typical tuner hysteresis

It is planned to add the functions "burst mode" and "sweep mode" to the tuner controller to allow for automated calibration of the detuning angle offset. The "burst mode" generates a bandwidth

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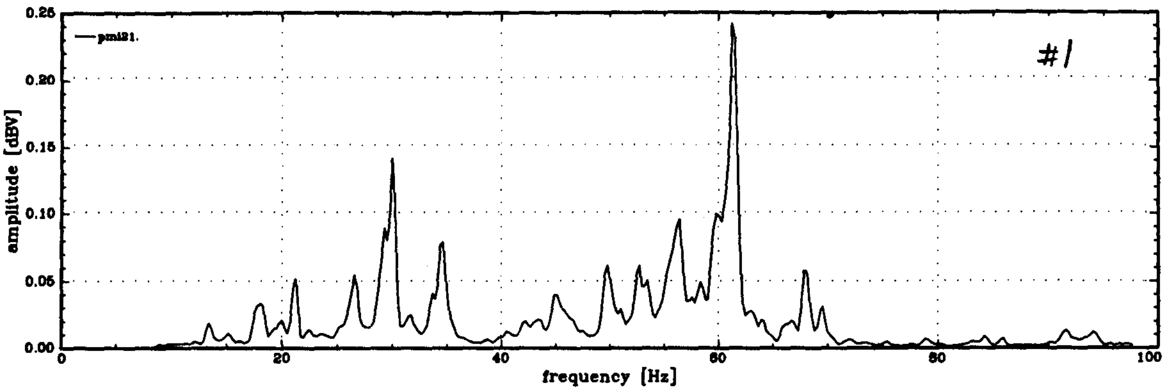

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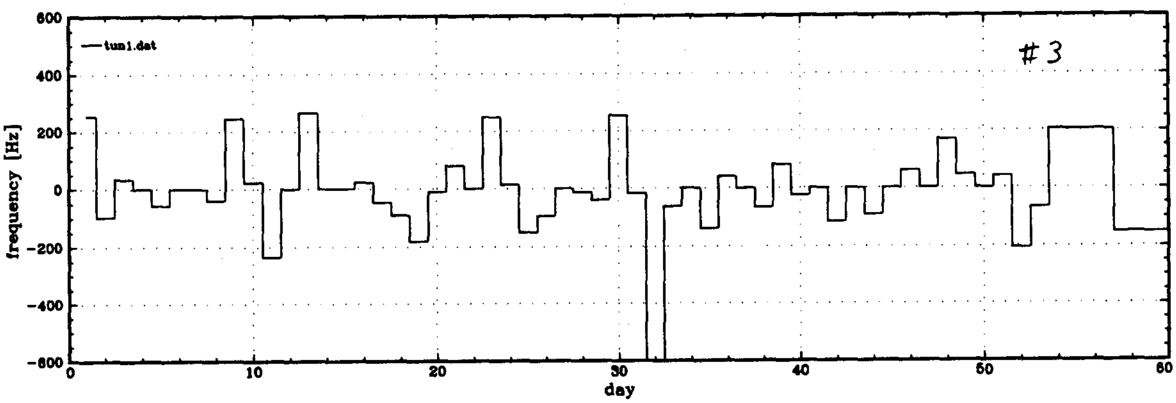

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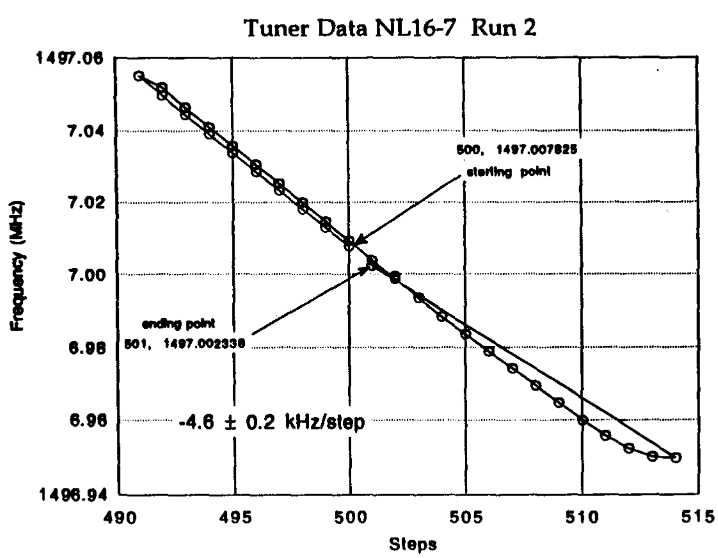

Figure 4: Typical tuner hysteresis

It is planned to add the functions "burst mode" and "sweep mode" to the tuner controller to allow for automated calibration of the detuning angle offset. The "burst mode" generates a bandwidth limited (±5 kHz) pseudorandom noise spectrum to drive the cavity. The noise burst lasts 18 μs; incident power is 300 W exciting a gradient of approximataly 0.5 MV/m. The actual cavity resonance frequency is determined from the 360° phase detector signal with an accuracy of better than 50 Hz. The frequency information is used for coarse tuning of the cavity to within ±125 Hz (bandwidth of cavity). The "sweep mode" measures the transfer function (phase) of the cavity with closed gradient loop. The transfer function is used to determine the cavity resonance frequency and therefore the detuning angle offset with an accuracy of better than ±3°. The detuning angle offset is then applied in the tracking mode to tune the cavity resonance to the operating frequency.

Conclusions

Several accelerators using superconducting cavities have been in operation for many years. The rf systems meet or exceed the requirements for amplitude and phase stability. A high degree of amplitude and phase stability requires significant efforts. Amplitude control is in general more difficult to achieve. A summary of the challenges for the various levels of stability is given in Table 9. It is assumed that typical conditions such as 5°-50° microphonic noise exist.

Table 9: Effort to achieve amplitude and phase control

Stability	One cavity per amplifier	Multiple cavities per amplifier
10^{-2} and 1°	simple(1)	moderate
10^{-3} and < 1°	moderate	difficult
10^{-4} and 0.1°	difficult	very difficult(2)

(1) Not simple for highly microphonic-sensitive heavy ion cavity structures
(2) Beam based calibration of phase and amplitude of vector sum components

RF system availability is a critical factor during accelerator operation. At many facilities it is determined by the rate of interlock trips. Automated fault recovery and a high degree of automation of rf controls can significantly reduce accelerator downtime in linear accelerators.

[1] H. D. Gräf, *Proceedings of the 5th Workshop on RF Superconductivity*, DESY M-92-01, Hamburg, Germany (1992) 317
[2] S. N. Simrock, *Proceedings of the 1991 Particle Accelerator Conference*, San Francisco, CA (1991), 2515