700 MHZ LOW-LOSS ELECTRICALLY-CONTROLLED FAST FERROELECTRIC PHASE SHIFTER FOR ERL APPLICATIONS*

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Abstract

A fast, electrically-controlled phase shifter is described with parameters suitable for operation with the SC acceleration structure of the Energy Recovery Linac (ERL) for the electron cooling system of Relativistic Heavy Ion Collider (RHIC) at BNL. The phase shifter is a key element of the external RF vector modulator that is capable of fast tuning of the cavities to compensate for microphonics, Lorentz force and beam instabilities in a way that can possibly lead to an order of magnitude reduction in the required RF power. The phase shifter is based on a shortened low-impendence coaxial line containing ferroelectric rings. The dielectric constant of the ferroelectric rings is altered by applying a 0 to 4.2 kV voltage that provides an RF phase shift from 0° to 180°.

INTRODUCTION

The RF power requirement for cavities in an SRF linac is determined by the accelerating gradient maintained in the cavity and the beam loading. Additional power is required for corrections of phase errors which arise from Lorentz force detuning, and other uncontrolled sources of detuning [1,2]. In Energy Recovery Linacs the beam loading is very small, and the power requirements are determined mainly by unbalanced beam currents, and by cavity resonance frequency variations arising because of microphonics.

There are two means that may be used in order to confront this problem [3]. The first is to use a piezoelectric frequency tuner [4,5] that changes the cavity length such a way that the detuning caused by microphonics is nearly-perfectly compensated. The device must allow correction of micron-scale cavity deformations at frequencies up to about 100 Hz. However the piezoelectric tuner should operate at cryogenic temperatures and doesn't allow access inside the cryostat in case of a failure. In addition, the piezoelectric tuner has its own mechanical resonances that may create additional problems for the control system [3]. A second means for neutralizing microphonics is to use an external tuner to redirect the reflected RF power back to accelerating structure [3,6]. Early on, ferrite tuners were suggested for this application [7,8,9]. The tuning frequency for this device will have an upper cut-off at a few kHz that comes mainly from eddy currents inside the RF structure [7]. ERLs have a stringent requirement for amplitude and phase stability. For example, the Cornell ERL's amplitude stability is to be not worse than $\pm 3\times 10^{-4}$, and phase stability must be within ±0.06° [10]. Thus the gain in the control feedback loop should be high enough, and its bandwidth wide enough, to insure this high degree of stability. For the Cornell ERL, this translates to a bandwidth of about 1 MHz [10]. Thus when an external tuner is used, it's bandwidth also has to be in this range, corresponding to a tuner response time of about 1 μsec. This rules out ferrite tuners with their narrow bandwidth. Similar considerations apply to the BNL ERL [11]. The design of a fast electrically-controlled 700 MHz, 25 kW phase shifter is considered for RHIC ERL applications that is based on a ferroelectric elements [12]. The phase shifter will allow for fast stabilization against phase fluctuations due to microphonics and other uncontrolled fluctuations. The tuner allows a reduction of about ten times in the required power from the RF source, and provides rapid compensation for beam imbalance.

GENERAL

The superconducting 700 MHz Energy Recovery Linac (ERL) for the RHIC electron cooler should provide acceleration of a 50 mA electron beam from 4.7 MeV up to 54.5 MeV, and then its subsequent deceleration to the injection energy [11]. ERL contains a SC RF gun, the SRF linac having four 5-cell accelerating SC cavities, and two 180° turns. The accelerated beam goes through the cavities twice. Operating in the electron cooler system, the SRF linac must provide the required energy spread and emittance of the beam that in turn, determine the required amplitude and phase stability. The control system of the linac should provide this stability. The RF power P_g required to maintain the accelerating voltage V is determined by well-known formula describing the RF cavity excitation by external RF source in the presence of beam loading (see, for example [10]):

$$P_g = \frac{V^2(1+\beta)^2}{4\beta Q_0 (r/Q)}\left[\left(1+\frac{I_{\mathrm{Re}}(r/Q)Q_0}{V(1+\beta)}\right)^2+\left(\frac{Q_0}{1+\beta}\left(\frac{\omega_0}{\omega}-\frac{\omega}{\omega_0}\right)-\frac{I_{\mathrm{Im}}(r/Q)Q_0}{V(1+\beta)}\right)^2\right], \quad (1)$$

where ω_0 is the cavity resonance frequency; Q_0 is it's unloaded quality factor; β is the coupling factor, for SC cavity β>>1; r/Q is the cavity impedance; $I_{Re} = I(\cos\delta\varphi_a - \cos\delta\varphi_d)$, $I_{Im} = I(\sin\delta\varphi_a - \sin\delta\varphi_d)$, $\delta\varphi_a$ and $\delta\varphi_d$, are the

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average phases of the accelerating and decelerating beams compared with the RF phase, respectively; and I is the beam current. For the cooler linac having two cavities with $Q_0 \approx 4.5 \cdot 10^{10}$@2K and r/Q = 404 Ohms/cavity, I = 50mA×2 = 100 mA and $V \approx 25$ MV (the beams will go through the linac twice) [11]. The value $\delta\omega = \omega_0 - \omega$ is determined by the amplitude of uncontrolled noise. While beam loss within reasonable limits gives no significant increase in required power, the phase error $\delta\varphi$ of the beams does, because in this case the beam introduces an additional reactance proportional to $\delta\varphi$ as it can be seen from (1). For parameters mentioned above in this case the required power P_g is equal to

$$P_g = 0.55\text{kW}\times df\,[\text{Hz}] + 22\ \text{kW}\times\delta\varphi\,[^\circ] \qquad (2)$$

With, for example, $\delta\varphi$ =1° and δf= 30 Hz, the required power is about 40 kW.

The fast, electrically controlled tuner that is described here for the RHIC electron cooler SRF linac may be based on a related tuner for ILC application [12] that employs a magic-T with two coaxial phase shifters containing ferroelectric elements, and allows fast electrically-controlled coupling and phase changes. The phase shifter itself may be designed as a coaxial line containing a half-wave ferroelectric ring [12] with matching elements and terminated by a coaxial resonator, as shown in Fig. 1. Applying bias voltage between the central and outer conductors of the coaxial line effects a change in dielectric permittivity of the ferroelectric ring, which in turn causes a phase advance of the RF wave in the phase shifter, and thus a change in coupling between the cavity and the RF source. The design contains matching alumina rings necessary to decrease the electric field in the ferroelectric ring. The end capacitor allows one to apply bias voltage to the central electrode. This phase shifter can also be used in other systems for SRF cavity control based on adjustments of an external tuner, for example in the resonant ring [3] developed for ERLs.

In a preliminary conceptual design, the ferroelectric ring has a length L_f = 75.9 mm (4 wavelengths in the material) and is surrounded by two identical alumina matching rings having lengths L_c = 33.7 mm. The length of the end coaxial resonator is L_r = 210 mm. The inner diameter of the coaxial line d = 106 mm, the gap between inner and outer conductor dr = 2.7 mm. Note, that ferroelectric rings with this size have been already supplied for the X-band phase shifter [13]. A photograph of a sample ring is shown in Fig. 2. For a 700 MHz tuner the inner and outer cylindrical parts of ring should be metallized. One can see metallization of the end surface that is necessary to apply bias voltage. In general, ferroelectric surface metallization increases the response time of a material. The technology of metallization allows a ferroelectric response time of less than 10 nsec [13]. Parameters of the ferroelectric material are shown in Table I.

In the conceptual design shown above, each phase shifter should sustain an average input power P of 25 kW. For this high average power the temperature effects are important and will influence a final design. It may be shown, that in order to minimize the temperature rise, one should employ a low-impedance line. For the ring considered above, the impedance of the air part of the coaxial line is 3 Ohms, and the temperature rise is 4 °C, an acceptable value. Because of it, the operating point is chosen to be +10°C. Note that in contrast to the ILC tuner [12] that operates in a pulsed RF system, this design has no problems with pulse heating and, thus, allows higher temperature rise (that is compensated by proper choice of operating point), and, thus, higher average power.

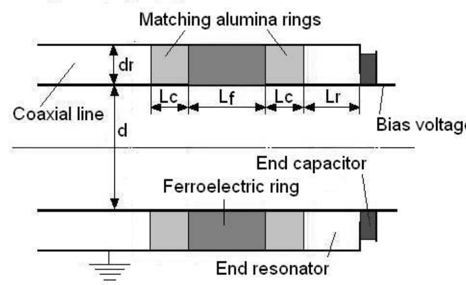

Figure 1: Schematic of the ferroelectric phase shifter.

Figure 2: A sample of a metallized ferroelectric ring with a diameter of 104.2 mm, a thickness of 2.6 mm, and a length of 20.4 mm.

Table I: Properties of ferroelectric ceramics

dielectric constant, ε	~550
tunability, $\Delta\varepsilon_{bias}$	>30@15 kV of the bias field
response time	< 10 ns
loss tangent at 0.7 GHz, δ	~5×10^{-4}
breakdown limit	200 kV/cm
thermal conductivity, K	7.02 W/m-ºK
specific heat, C	0.605 kJ/kg-ºK
density, ρ	4.86 g/cm^3
coeff. of thermal expansion	10.1×10^{-6} ºK^{-1}
temperature tolerance, $\partial\varepsilon/\partial T$	3 ºK^{-1}

The calculated field profile along the coaxial phase shifter is shown in Figure 3. The phase shifter provides a phase change of about 170° when the bias voltage changes from 0 to 4 kV, and the dielectric constant changes from 500 to 470. The maximum bias electric field does not exceed 15 kV/cm. The amplitude of RF electric field is 3 kV/cm, small compared to the maximum bias field, and small nonlinear effects can be easily compensated by use of a fast feedback system [7]. Total losses in the phase shifter are -0.65 dB. Power losses in the phase shifter elements for an incident power of 25 kW are shown in Table II.

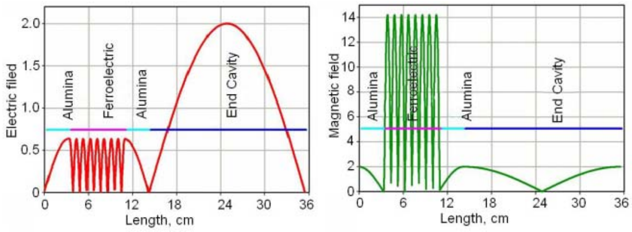

Figure 3: Electric and magnetic field amplitudes along the phase shifter normalized to the incident wave amplitude for different dielectric constants of the ferroelectric. Note that the normalized amplitude of the electric field in the ferroelectric ring is 0.6 compared to 2 in the air part of the phase shifter.

Table II: Power losses in the phase shifter

source of losses	losses, W
ferroelectric ring	708
metal surrounding the ferroelectric ring	2531
two alumina rings	1.2
metal surrounding the two alumina rings	23
end cavity	143
Total	3427, or -0.64 dB
power reduction factor	7.3

Thus, the total losses in the tuner are about 13.7%. These losses determine the power reduction factor that may be achieved with the tuner: the power required from the RF source will be not 50 kW/cavity, but 3.4×2=6.8 kW/cavity (almost none of the incident power will be reflected to the load, but will dissipate in the tuner). Thus, the power reduction factor is 50 kW/6.8 kW = 7.3. It should be stressed that, if the ferroelectric ring is two times thicker, the losses in the ring will the same, but the losses in the metal surrounding the ring will be two times smaller. Furthermore, if expectations concerning the material loss factor are confirmed, the temperature rise will be 6 °C, which is still acceptable, the losses will be less than 0.4 dB, and the power reduction factor will be greater than 11.

The tuner design includes waveguide-to-coaxial transformers for both phase shifters that require an impedance transformer from 50 Ohm to ~3 Ohms. In Fig. 4 a cut-away drawing of the phase shifter is shown. One can see the waveguide-coaxial transformer, the impedance transformer, a termination capacitor that allows the bias on the central electrode of the coax, and the cooling system. The total capacitance of the phase shifter containing ferroelectric and alumina rings is 41 nF, and the total energy that should be supplied in order to create a bias voltage of 4 kV is 0.33 J. The maximum average power for both phase shifters is only about 60 W for compensating microphonics at frequencies up to 100 Hz without any energy recovery circuit. An alternative concept for the L-band ferroelectric phase shifter is based on use of a radial line reflector instead of the coaxial line reflector, and is depicted in Fig. 5. As can be seen, this design requires metallization on the flat edges of the ferroelectric and alumina rings, rather than on the cylindrical surfaces; the former technique is already well developed. Furthermore, assembly of this structure with either brazing or clamping of the rings between the planar surfaces of the two metallic elements would seem to be more straightforward than for cylindrical surfaces as in the structure shown in Fig. 5.

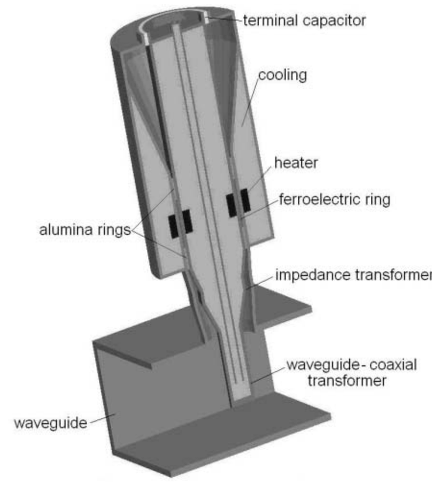

Figure 4: Cut-away drawing of the phase shifter.

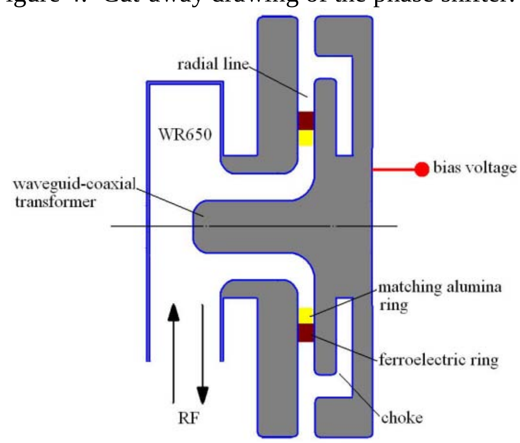

Figure 5: An alternative phase shifter concept employing a TEM radial line reflector.

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