FAST FERROELECTRIC PHASE SHIFTER DESIGN FOR ERLs *

S.Yu.Kazakov,[a,b] S.V.Shchelkunov,[c] V.P.Yakovlev,[a,d] A.Kanareykin,[e]
E.Nenasheva,[f] J.L.Hirshfield[a,c]

[a]*Omega-p,Inc., 199 Whitney Ave., New Haven, CT 06511, USA*
[b]*High Energy Accelerator Research Organization, KEK, Tsukuba, Ibaraki 305-0801, Japan*
[c]*Beam Physics Laboratory, Yale University, 272 Whitney Avenue, New Haven, CT 06511, USA*
[d]*Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[e]*Euclid Concept LLC, Solon, Ohio 44139, USA*
[f]*Ceramics Ltd., St. Petersburg, 194223, Russia*

Abstract

Fast phase shifters are described that use a novel BST ceramic that can rapidly change its dielectric constant as an external bias voltage is changed. These phase shifters promise to reduce by ~10 times the power requirements for the RF-source needed to drive an energy recovery linac (ERL). Such phase shifters will be coupled with SRF cavities so as to tune them to compensate for phase instabilities, whether beam-driven or those caused by microphonics. The most promising design is presented, which was successfully cold-tested and demonstrated a switching speed of ~30 ns for 77 deg, corresponding to <0.5 ns per deg of RF phase. Other crucial issues (losses, phase shift values, etc) are discussed.

INTRODUCTION

In ERLs there are several factors which significantly affect the required wall-plug power. With small beam loading, RF power requirements are determined by Ohmic wall losses, imbalance between beam currents, and microphonics. Compensation for the latter two typically requires a rapid change in coupling between the cavity and feeding line, and attendant high bandwidth, leading to need for significant additional RF power. If beam loading is not small, there are beam-driven phase instabilities for which compensation will also demand additional power.

Compensation can be either by changing the cavity geometry to offset detuning caused by phase instabilities and/or microphonics [1,2], and/or to apply a corrective phase shift to the reflected RF wave that is reintroduced to the cavity so as to cancel phase instabilities [3,4]. The first strategy is accomplished by internal or external motors, or fast internal mechanical piezoelectric tuners. The second approach utilizes fast ferrite or ferroelectric phase shifters that are external to the cryomodules, whereas piezoelectric and other mechanical tuners require operation at cryogenic temperatures and thus permit only limited access in the event of a failure. Further, piezoelectric devices have mechanical resonances which may interfere with control system performance if their own resonance frequency overlaps with the microphonics excitation to be controlled [5]. It is unknown if piezo-electric tuners are efficient enough at high frequencies.

Ferrite phase shifters [6,7,8] are presently limited in their response time to ~30 μs, while the required response time may be only a few μs. The limitation comes mainly from the eddy currents in the ferrite material [7].

Need for μs response time is dictated by the phase and amplitude stability requirements of ~ 0.06 deg and 3e-4, as cited for the Cornell ERL [9]; requirements are similar for the electron cooler project at BNL [10]. The gain in the control feedback loop should be high enough, and its bandwidth wide enough, to insure this high degree of stability. This translates to a bandwidth of about 1 MHz, and rules out contemporary ferrite tuners.

The authors have studied several designs for a fast electrically-controlled ferroelectric phase shifter for ERL applications. The device is to allow changing the RF-coupling during the cavity filling process in order to effect significant power savings, and also to provide rapid compensation for beam imbalance and allow for fast stabilization against phase fluctuations caused by microphonics and beam-driven instabilities. This capability should allow a reduction by about an order-of-magnitude in the required power from the RF source.

POSSIBLE RF POWER SAVINGS

The RF power P_g required to maintain an accelerating voltage V is given by [11]

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

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 average phases of the accelerating and decelerating beams compared with the RF phase; and I is the beam current. The value $\delta\omega = \omega_0 - \omega$ is determined by the amplitude of uncontrolled noise.

In [10,12], an example is given for a cooler linac having two cavities with $Q_0 \approx 4.5\times10^{10}$ at 2°K and $r/Q \approx$ 400 Ohms/cavity, I = 50mA×2 = 100 mA and $V \approx$25 MV.

---

*Work supported by DoE, Office of High Energy Physics.

(The beams go through the linac twice.) The intrinsic RF power required for is, for parameters listed above,

$$P_{\text{int}} = \frac{V^2}{Q_0 (r/Q)} = 9\,\text{W}.$$

If the accelerated and decelerated beams are well balanced, and the beams are in phase with the RF field, the required power is determined by the peak frequency variations caused by microphonics [2], namely

$$P_g = \frac{V^2}{4Q_l (r/Q)} \left[1 + \left(2Q_l \frac{\delta\omega}{\omega} \right)^2 \right],$$

where Q_l is loaded quality factor, $Q_l = Q_0/(1+\beta)$. One finds the optimal value of the loaded quality factor, $Q_{opt} = \omega/2\delta\omega$, and the minimum required power is proportional the peak cavity detuning, namely

$$P_g = \frac{V^2}{(r/Q)} \frac{\delta\omega}{\omega} = 0.55\text{kW} \times df\,[\text{Hz}],$$

where $\delta f = \delta\omega/2\pi$ is the peak microphonic cavity detuning in Hz. If, for example, the peak cavity detuning is reduced to 30 Hz (a typical value), the required input power would be ~17 kW for four 5-cell cavities.

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 can be seen from (1). The required power in this case is

$$P_g = \frac{V^2}{(r/Q)} \left(\frac{\delta\omega}{\omega} + \frac{(r/Q) I \delta\varphi}{2V} \right) = 0.55\text{kW} \times df\,[\text{Hz}] + 22kW \times \delta\varphi[°].$$

With, for example, $\delta\varphi = 1°$ and $\delta f = 30$ Hz, the required power would be about 40 kW. Obviously, it is crucial to provide means for compensation of phase instabilities to keep the RF-power requirements to a minimum.

FERRO-ELECTRIC MATERIAL AS BASIS OF THE PROPOSED DEVICE

Recently, ferroelectric (FE) devices for fast switching applications have received close attention, and are already used up to 100 kW peak in military systems [13], phased-array radars [14], and communication systems [15]. FE's have a dielectric permittivity $\varepsilon(\mathbf{E})$ that depends on electric field **E**, and can be rapidly altered by application of an external bias-voltage pulse. The response time would be limited by that of the external bias circuit. The minimum intrinsic switching time demonstrated is less than 1 ns [15]. Modern bulk ferroelectrics, e.g. $Ba_xSr_{1-x}TiO_3$ (barium strontium titanate or BST) with $\varepsilon \sim 500$, have sufficiently high electric-breakdown strength (100-200 kV/cm) and require an acceptable bias electric field (~20-50 kV/cm) to effect a 20-30% change in ε. Loss tangent for commercially-available samples is about ~1.5×10^{-3} at 1 GHz [14].

Euclid Concepts LLC recently developed and tested a modified bulk FE [16] based on a composition of BST ceramics, magnesium compounds, and rare-earth metal oxides. The availability of this FE already allows one to create a high-power RF phase shifter with the peak power required for ERL.

Properties of modified BST FE ceramic are in Table1.

Table 1

dielectric constant, ε	~460
tunability, $\varepsilon\partial/\partial E_{\text{bias}}$	> 2/(kV/cm)
intrinsic response time	< 10 ns
loss tangent at 1.3-1.4 GHz, $tg(\delta)$	2×10^{-3}
loss tangent at 700-900 MHz, $tg(\delta)$	1.1×10^{-3}
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
coefficient of thermal expansion	10.1×10^{-6} /ºK
temperature tolerance, $\partial/\varepsilon\partial T$	3 /ºK

For the proposed devices, the FE ceramic is manufactured in the form of rings [Fig.1.a] or bars [Fig.1.b]. To measure the loss-tangent for ring-like samples, the setup shown in Fig. 2 was used [17]. Measurements on the bars were done with the bars suspended along the axis in a long metal pipe.

Figure 1a. FE ceramic ring Ø106 ×2.8×22 mm.

Figure 1b. FE ceramic bars (6 ×5×108 mm).

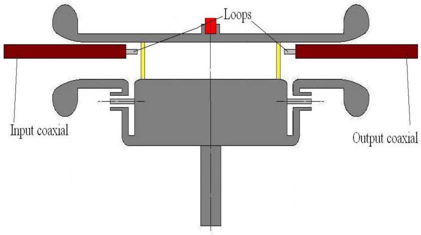

Figure 2. Setup to measure FE ring loss tangent.

Fig. 3 presents results of tunability measurements. The lower portion of the curve indicates low tunability at lower applied voltages. Presently, efforts are underway to reduce the loss tangent at 1.3 GHz, without undue sacrifice of tunability.

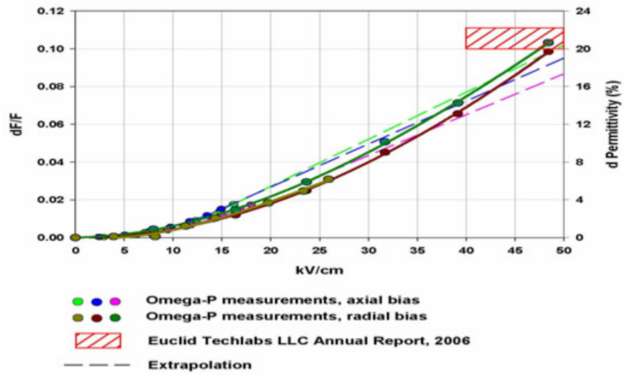

Figure 3. Tunability measurements on modified BST ring.

PHASE SHIFTER DESIGN

Three configurations have been considered: coaxial, planar/coaxial hybrid, and sandwich-in-waveguide; all for 500 kW pulse and 4-5 kW average powers, figures dictated by ILC parameters that we have chosen as the base line. Below we describe the last of these which was successfully built, and cold-tested.

The sandwich-in-waveguide configuration employs standard WR650 waveguide as a host for three sets of two narrow FE bars and two matching ceramic slabs ($\varepsilon \sim 21$), as shown in Fig. 4a. Each set rests on a metal plate, with a second metal plate above, as seen in Fig. 4b.

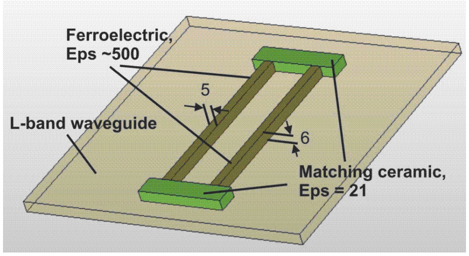

Figure 4a. Arrangement for one set of FE bars (grey) and ceramic slabs (green). Dimensions are in mm.

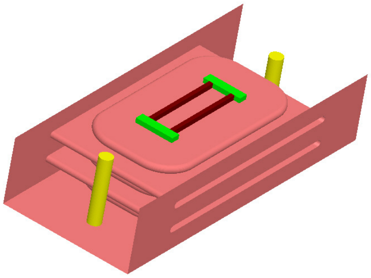

Figure 4b. WR650 waveguide with top removed to show three sandwiches and matching rod.

Alternate plates are joined to a feed-thru to provide the desired bias, while other plates are grounded. When assembled, dimensions are 8.2 × 16.5 × 30 cm. The mode spectrum is sparse, and can be controlled by changing the geometry. For matching to the structure, dielectric rods (alumina with ε ~9.8) are placed before and after the sandwiches. Frequency response is shown in Fig. 5.

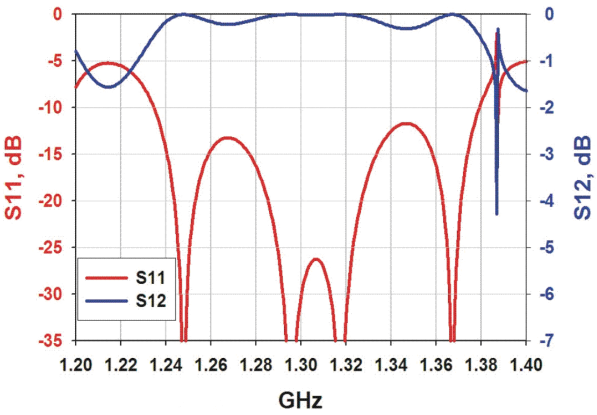

Figure 5. Frequency response for sandwich geometry with $\varepsilon \sim 470$; it is nearly the same for $470 < \varepsilon < 500$.

Table 2 lists design parameters of the phase shifter for 500 kW of pulsed and 4 kW of average power.

Table 2

FE permittivity ε at $V_{\text{bias}} = 0$,	460
∂(phase)/$\partial\varepsilon$, deg	4
max. DC electric field, kV/cm giving Δ(phase) = 120 deg	15
total loss, %	$2.8 + 6\times10^{3}\tan\delta$
max. E-field in FE, kV/cm	3
max. E-field in ceramic, kV/cm	5.9
max. E-field in air, kV/cm	6.1
phase shift, deg, at 15 kV/cm bias	120
FE pulse heating with loss tan 5×10^{-4}	0.2 °K, for $\Delta\varepsilon = 0.6$
FE av. heating with loss-tan 5×10^{-4}	0.9 °K for $\Delta\varepsilon = 2.7$
FE pulse heating with loss-tan 2×10^{-3}	~0.4 °K for $\Delta\varepsilon = 0.6$
FE av. heating with loss-tan 2×10^{-3}	~3.5 °K for $\Delta\varepsilon = 2.7$

LOSS, PHASE SHIFT, AND SWITCHING SPEED MEASUREMENTS

Low-power RF measurements were made using only one of the three sandwiches in a waveguide that has the same width as WR650, but tapered to one-third the standard height, as shown in Fig. 6. The center electrode can be biased electrically.

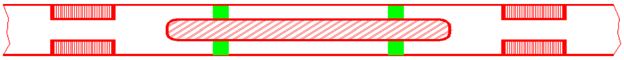

Figure 6. A cross-sectional side-view of the one-third structure used for tests. Green lines represent matching slabs. FE rods are not seen in this cross-section.

The loss tangent of ferroelectric bars is measured for the uncoated bars (manufactured from the same batch used to make the bars coated with gold, as used in the 1/3 model. The value of loss tangent is determined to be ~2×10^{-3}, suggesting that the 1/3 scaled tuner model may suffer a transmission loss no better than ~0.7 dB. In actuality, the measured transmission is worse. The best value obtains only when one uses either freshly applied liquid indium-gallium or soldered the bars to the waveguide walls using In. However, we were not able to apply more than 4 kV to the soldered configurations; hence we discuss below only the structures assembled with liquid Ia-Ga. It is found that in the configurations with fixed structure height, when the top and bottom walls are tethered by bolting to the side walls, transmission drops when the voltage increases [see Fig. 7a]. However, in a configuration where the top wall is resting without tethering on the ceramic bars under 200-400 lbs load, the transmission does not change much at all as shown in Fig 7b (in some cases, it becomes even higher). However, in general, the transmission level is lower because of leakage radiation through the gaps formed between unbolted walls. This suggests the presence of piezoelectric effects that shrink the bars and degrade the quality of the bar-wall surfaces contacts.

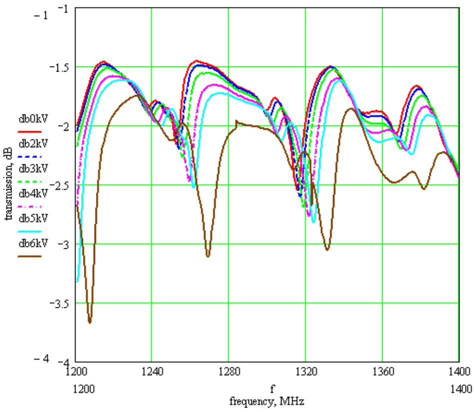

Figure 7.a. The transmission drops when the voltage grows in the configurations with fixed structure height [see the magnitude change at 1,3GHz]

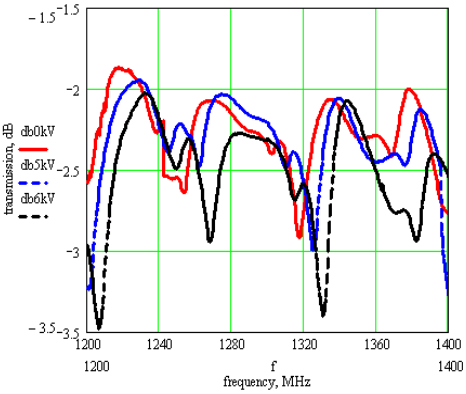

Figure 7.b. At 1,3GHz (middle of the plot), the transmission does not change so much (sometimes get higher) if top wall is resting under 200-400 lbs load on the ceramic bars, and thus the structure height is not fixed

It is anticipated that successful brazing of the ferroelectric and matching dielectric bars will eliminate losses beyond those in the bulk ceramics and metallic walls, as well as to lead to transmission being independent of applied voltage. As of now, several brazing attempts have revealed that the gold coating of the bar surfaces suffers badly when subjected to rapidly rising temperature and, in addition, the brazing atmosphere must be thoroughly controlled to avoid traces of oxygen. Tests were made with gold-plated ferroelectric bars and matching slabs; contact to copper walls was provided by liquid In-Ga alloy or In solder. Results of measurements of phase shift are presented in Fig. 8; these are seen to be in good agreement with simulations. Hysteresis is evident.

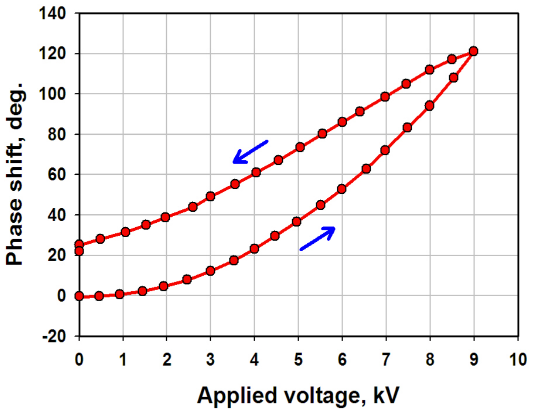

Figure 8. Measured phase shift of RF signal transmitted through one-third section *vs.* applied bias voltage.

A vital property of any tuner is its response time, which for many accelerator applications should be less than 100 ns. Measurements of response time were made using the arrangement shown in Fig. 9. The high voltage rise/fall times from the available pulse generator were in the range of ~100 ns (measured as the time difference from 5% to 95% of the voltage maximum). Switching speed measurements (each averaged over 16 shots) were processed by subtracting data with RF off from data taken with RF on, and are shown in Fig. 10.

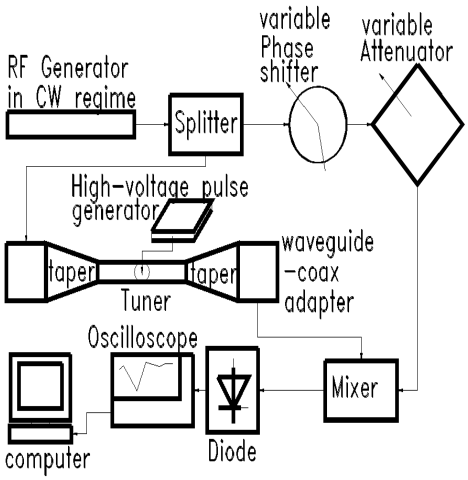

Figure 9. The signal from the RF generator at 1,290 MHz is split in two. One portion is directed through a phase shifter and attenuator directly to a mixer, while the second portion is fed through the tuner input port, passes through the tuner, picked up at the tuner output port, and then is fed to the mixer. The resulting signal from the mixer is detected by a diode and monitored at an oscilloscope, and also captured by a computer for further signal processing (mainly FFT).

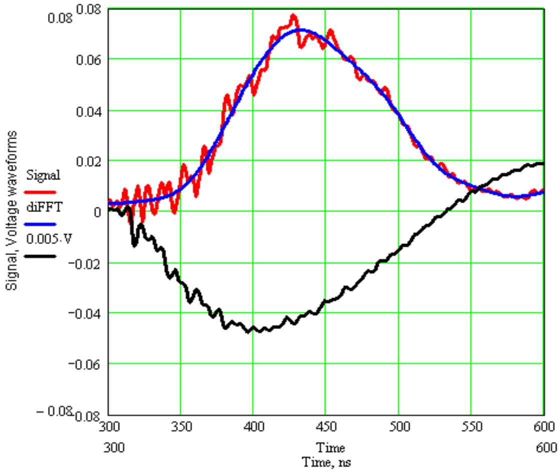

Figure 10. Time-response of phase shifter. Red curve (convex) is the difference between data with RF off and RF on. Blue curve is FFT/IFFT processed signal. Black curve (concave) is the high-voltage pulse with its peak value of ~9.7 kV. It is seen that the time delay between the peak voltage and the peak variation in phase is 28 ns. This value excludes delays in cables. The difference signal of 67 mV from the mixer corresponds to a phase change of 77°. (One horizontal division is 50 ns)

The difference signal of 67 mV from the mixer corresponds to a phase change of 77°. From these data, where the response time of the phase shifter is dominated by the 90 ns rise time of the voltage pulse, one can infer that the response time to a step function voltage would be equal to or less than the delay time, namely approximately 30 ns. This could be interpreted to correspond to an average switching rate of less than 0.5 ns for each degree of RF phase.

CONCLUSIONS AND PLANS

An RF-wave phase shifter based on a novel BST FE ceramic has been shown capable of delivering rapid phase switching (perhaps < 100 ns for shifts of ~180 degrees), while being suitable for high-power applications. That makes it an attractive candidate to externally tune the SRF-cavities for ERLs to reduce (at least by an order of magnitude) the RF-power requirements that arise because of phase instabilities of different origin, including microphoncs as one of many.

The conducted research has revealed that several material issues must be addressed, including brazing, provisions to limit breakdowns at high bias voltages, and re-designing the FE ceramic for L-band with low losses.

The planned work also includes: 1) further developing the design for planar-coax geometry because it promises simplicity (relative to other designs) and thus low cost; and 2) proceeding with high-power tests. These efforts are underway.

Lastly, we note that the tuner has been already connected to a 1.3 GHz cavity [that is a mock-up of the superconducting RF-gun cavity designed to be used in the electron cooling project at BNL, see [2] and confirmed the capability of tuning of its resonance frequency.

ACKNOWLEDGEMENTS

This work was supported by the Office of High Energy Physics, US Department of Energy. We also acknowledge the help of Timergali Khabiboulline (FNAL), Harald Hahn (BNL) and E.M. Choi (formerly of BNL).

REFERENCES

1. S. Simrock., et al., “First Demonstration of Microphonic Control of a Superconducting Cavity with a Fast Piezoelectric Tuner”, PAC2003, Portland, May 11-16, 2003, p.470.
2. M. Liepe and S. Belomestnykh, “Microphonics Detuning in the 500 MHz Superconditing CESR Cavities,” PAC2003, Portland, May 11-16, 2003, pp.1326-1328.
3. Y. Kang, et al., “Reactive RF Tuning for Compensation of a Detuned Accelerating Cavity,” Linac 2002, Gyeongju, Korea, 2002, pp.733-735.
4. Martin Dohlus, DESY, Feb. 2004
5. T. Zwart, et al., “Optimal RF System For Lightly Loaded Superconducting Structures”, Proceedings of the 2004 FEL Conference, pp. 542-545
6. D. Valuch, et al., “First Results With A Fast Phase And Amplitude Modulator For High Power RF Applications,” EPAC2004, pp. 959-961.
7. D. Horan, et al., “Fast-Ferrite Tuner Operation On A 352-MHz Single-Cell RF Cavity At The Advanced Photon Source,” PAC2003, pp. 1177-1179.
8. B. Foster, et al., “High Power Phase Shifter,” PAC2005, PAC2005, Knoxville, May 16-20, 2005, p. 3123-3125.
9. V.P. Yakovlev, et al., “1.3 GHz Electrically-Controlled Fast Ferroelectric Tuner,” EPAC2006, Edinburgh, June 26-30, 2006, pp. 487-489.
10. I. Ben-Zvi, “The ERL High-Energy Cooler for RHIC”, EPAC2006, Edinburgh, 2006, pp. 940-944. *See also* R. Calaga, “SRF Cavities for High Current ERLs,” BNL, January 23, 2006
11. O.A. Nezhevenko, V.P. Yakovlev, “Cumulative Interaction in the Deflection Cavities of a High-Power Magnicon Amplifier,” *IEEE Transactions On Plasma Science*, vol. 28, No. 3, June, 2000, pp 542-549.
12. D. Wang, et al., “Design of a Superconducting Linac Cavity for High-Current Energy Recovery Linac Operation,” PAC2003, Portland, May 11-16, 2003, pp. 1300-1302.
13. L.C. Sengupta, “Bulk Ceramic Ferroelectrics and Composites: Manufacture, Microwave Properties and Applications,” IMS2000.
14. D. Webb, “Applications of Ferroelectrics in Military Systems,” IMS2000.
15. A.B. Kozyrev et al. Technical Physics Letters, v. 24, pp.19-25, (1998).
16. A. Kanareykin, et al., “Low-Loss Ferroelectrics for Accelerator Application,” EPAC2006, Edinburgh, June 26-30, 2006, pp. 3251-3253.
17. S.Yu. Kazakov, et al.,“First Measurements of RF Properties of Large Ferroelectric Rings for RF Switches and Phase Shifters,” PAC2007, Albuquerque, June 25-29, 2007.