HIGH POWER FERROLELECTRIC SWITCHES AT CENTIMETER AND MILLIMETER WAVE LENGTHS*

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Abstract

High-power ultra-fast, electrically-controlled switches for accelerator applications in the centimeter and millimeter wavelength ranges that employ ferroelectric elements are discussed. Examples of fast switches and phase shifters for pulse compression and power distribution systems at X– and Ka- band are presented.

INTRODUCTION*

Future linear accelerators with high accelerating gradient [1] rely on pulse compression to achieve the high peak RF power levels required to drive the accelerator structures (500-600 MW in ~ 400 nsec pulses at X-band, for example). A number of RF pulse compression systems have been under consideration recently including versions of the Delay Line Distribution System (DLDS) [2], and SLED-II [3]. The mechanisms upon which these compressors operate are *passive*, in that no element in the compressor structure has time-dependant properties. Common limitations of these systems are their relatively low compression ratio (~4:1), and/or their very long runs (100's of km) of low-loss vacuum waveguide [4]. In an attempt to circumvent these limitations, various concepts of *active* RF pulse compression have recently received attention [5,6,7] To date, none of the tested versions of active pulse compressors have achieved power levels high enough for accelerator application.

Electrically–controlled ferroelectric elements represent an attractive option for either active pulse compression and/or power distribution systems [8,9]. Ferroelectric elements have an **E**-field-dependent dielectric permittivity $\varepsilon(\mathbf{E})$ that can be very rapidly altered by application of a bias voltage pulse. The switching time in most instances would be limited by the response time of the external electronics that generates the high-voltage pulse, and can therefore be in the nsec range. Modern bulk ferroelectrics, such as barium strontium titanate (or BST), have high enough dielectric breakdown fields (100-200 kV/cm) and do not require too high a bias electric field (~20-50 kV/cm) to effect a significant change in ε [10]. Ferroelectrics are already successfully used in RF communication technology and radar applications. Euclid Concepts, LLC recently developed and tested for Omega-P a bulk ferroelectric [11] that has a permittivity ε = 500, and a 20% change in permittivity for a bias electric field of 50 kV/cm. The best loss tangent already achieved is 4×10^{-3} at 35 GHz that should correspond to 1.3×10^{-3} at 11 GHz [10]. Development of production techniques for this material continues, with the expectation of further lowering of the loss tangent to values of less than 1×10^{-3}.

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FERROELECTRIC SWITCHES

1. In active pulsed compressors with resonance switches, the RF source supplies electromagnetic energy to fill a low-loss storage cavity coupled through an electrically-controlled resonance switch to a load (the accelerating structure). Compressor operation involves two steps: *first*, that of energy storage when the coupling to the storage cavity is small in order to provide good efficiency of filling; and *second*, that of energy extraction when the coupling is high to provide fast energy discharge into the accelerating structure. The coupling of the storage cavity with the RF source is controlled by changing the resonance frequency of the switch cavity. A schematic diagram of a proposed active pulse compressor is shown in Fig. 1. This example is based on the design of Omega-P's two-channel Active Bragg Compressor (ABC) [12] that employs resonance plasma switches. As shown in Fig. 1, two cylindrical TE_{01}-mode storage cavities (*8*) are each coupled through an electrically-controlled switch cavity (*7*).

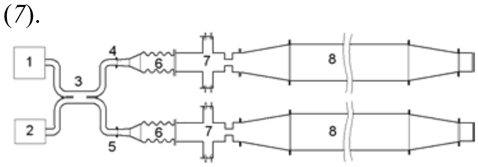

Figure 1: Schematic diagram of the two-channel ABC.

Waveguides (*4* and *5*) are fed from the RF source (*1*) after the source power is split using a 3-dB hybrid coupler (*3*). Mode converters (*6*) transform the mode from TE_{10}-rectangular to TE_{01}-circular. Compressed output pulses are combined and absorbed in the load, i.e. the accelerator structure (*2*). Main design parameters of the proposed ferroelectric active pulse compressor are given in Table 1.

Table 1: Parameters of the active pulse compressor.

operating frequency f_0	11.424 GHz
input power P_o	50 MW
input pulse duration t_f	1 μsec
power gain k	10
peak output power $P_{out} = kP_o$	500 MW
output half-height pulse duration $t_{0.5}$	~40 nsec

The entire proposed ferroelectric switch arrangement is shown in Fig. 2, including the matching diaphragm and two TE_{031} switch cavities containing ferroelectric rings. Two cavities are necessary in order to reduce both RF electric fields and losses in the ferroelectrics. The cavity resonance frequency is altered by application of a bias voltage pulse across the ferroelectric rings. The two cavities are located in an external evacuated chamber. In order to apply biasing voltages up to 100 kV, part of the end walls of each cavity are separated from the rest of the cavity by circular non-radiating slots. Parameters found for the X-band switch cavity are listed in Table 2.

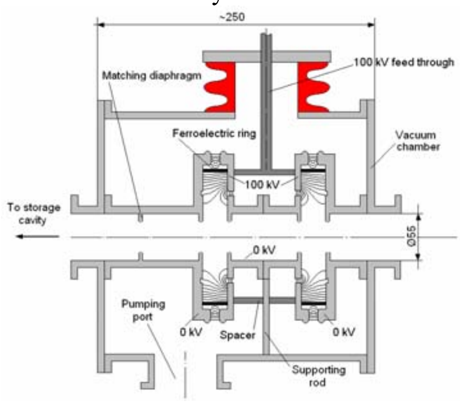

Figure 2: A conceptual arrangement of the X-band ferroelectric switch, showing the bias electric field lines. Dimensions are in mm.

In the energy storage regime, when both switch cavities have resonance frequencies of about 11.350 GHz, transmission at the operating frequency is about –14 dB that provides optimal coupling of the storage cavities with the line. In the energy extraction regime, the ferroelectric permittivity of the switch cavities is decreased from 500 to 400, and the resonance frequencies are close to the operating frequency. At resonance the transmission of both cavities is close to 100%.

Table 2: Parameters of TE_{031} switch cavity.

operating mode	TE_{031}
cavity length, mm	20
ferroelectric ring width, mm	20
ferroelectric ring inner diameter, mm	106
ferroelectric ring radial thickness, mm	3
maximum electric field in ferroelectric, kV/cm	16

2. In order to develop RF technology in the millimeter wavelength domain for a future CLIC-like multi-TeV electron-positron linear collider, it is necessary to test in realistic regimes accelerating structures and high power RF components, and to determine limits of breakdown and metal fatigue. The typical required power for such tests at Ka-band falls in the range of 200-300 MW with a pulse width of 70-150 nsec [13]. This goal can be achieved by creation of a long pulse RF source and then employing an RF pulse compressor. For example, if one has an RF power source of 30-50 MW with a pulse width of 0.5-1 μsec, and if one could develop an active pulse compressor with a compression ratio of 10:1, it would be possible to achieve the required power of 200-300 MW in ~100 nsec pulses. Development of an active pulse compressor with a ferroelectric switch is partly motivated by the first successful test results of the 34.3 GHz third-harmonic magnicon amplifier [14,15]. The main design parameters of the proposed Ka-band active pulse compressor with ferroelectric switches are given in Table 3. A design concept for the ferroelectric switch cavity is scaled from that shown in Fig. 2. Parameters found for the switch cavity are listed in Table 4.

Table 3: Parameters of the 34.272 GHz active pulse. compressor.

operating frequency, MHz	34.272
output power, MW	200
input power, MW	30
output pulse width, nsec	70
input pulse width, nsec	700
compression ratio	10
efficiency, %	67.5
bias voltage, kV	35

Table 4: Parameters of 34.272 GHz TE_{031} switch cavity.

operating mode	TE_{031}
cavity length, mm	6.7
coupling iris diameter, mm	9.3
coupling diaphragm thickness, mm	3
ferroelectric ring width, mm	6.7
ferroelectric ring inner diameter, mm	35.7
ferroelectric ring radial thickness, mm	0.95

3. In principal, the most efficient power combining system should be DLDS. However, in its original incarnation, DLDS required ~300 km of waveguides and waveguide components [4]. It has been recognized that a substantial reduction in the length of waveguides could be achieved if an *active* DLDS system could be developed. Fig. 3 illustrates the layout of an active DLDS for the case of one waveguide feed for four accelerator modules [4]. The key element is a high power microwave switch, which must quickly divert ~500 MW of power sequentially from a main feed line in and out of the accelerator modules.

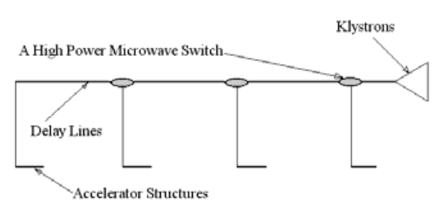

Figure 3**:** Schematic for an active DLDS that feeds four accelerator modules [4].

High-power microwave switches must be able on command to redirect the full microwave power from a main feed line to one accelerator module after another within the RF pulse, with a switching time of tens of ns. One possible scheme for such a switch is shown in Fig. 4. The circuit consists of two 3-dB hybrid couplers and an electrically-controlled phase shifter. In this circuit, input power is supplied to one waveguide at the left. The hybrid splits the input power into two equal portions

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which, with the phase shifter unbiased, combine into one of the right-most output channels. In order to switch RF power from one output to the other, one has to change the phase difference between the two input signals by 180°. This phase shifter should thus be designed to operate with at least half of the full RF power (500/2 = 250 MW).

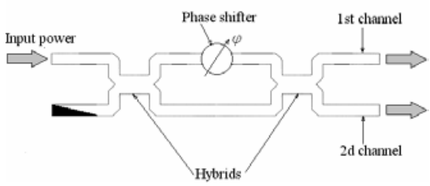

Figure 4: A possible arrangement of a switch for an active DLDS.

Table 5: Parameters of an X-band phase shifter.

operating frequency, GHz	11.424
bias voltage for ~200° phase shift, kV	100
number of cavities	4
cavity operating mode	TE_{031}
waveguide mode	TE_{01}
transmitted (switched) power, MW	250 (500)
peak power losses ($\tan\delta = 0.0013$), MW	18 (3.6%)
efficiency, %	> 96
RF electric field in ferroelectric, kV/cm	24

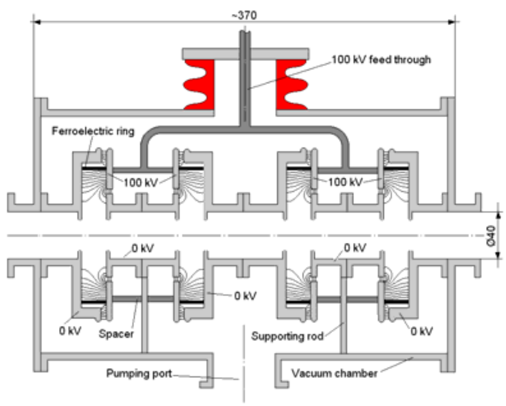

Figure 5: A concept of an X-band phase shifter design, showing the bias electric field lines. Dimensions in mm.

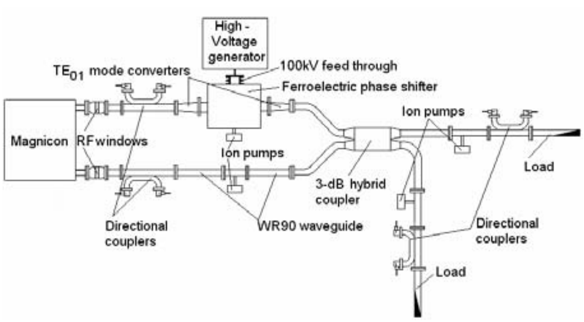

Figure 6: Arrangement for testing the X-band phase shifter up to 50 MW.

As with the switch considered above, a phase shifter can be constituted as a set of RF cavities partially-filled with ferroelectric whose dielectric constant is electrically-controlled. A change in resonance frequency of the cavities causes a phase change for the transmitted signal. The cavities should sustain the full power of 250 MW without breakdown, and should possess low dielectric losses. These requirements limit the maximum available phase shift that can be achieved in one cavity to about ~50°. Thus, in order to achieve the required phase shift of 180°, a sequence of four identical cavities should be used. In order to achieve maximum transmission over a wide frequency range, a quarter-wave filter-like arrangement may be used. The results for optimized parameters found for the phase shifter are listed in Table 5. A design concept for the phase shifter that will be suitable for high-power use is shown in Fig. 5. The four cavities are located in an external evacuated chamber. Evaluation of the phase shifter with RF power levels up to 50 MW using the Omega-P/NRL 11.4 GHz magnicon [16] is currently planned. The arrangement of the test bed for evaluation of the phase shifter is shown in Fig. 6. Because the magnicon has two outputs with equal power [16], the test bed for the phase shifter doesn't require a power splitter. The power from the two outputs is combined in a 3-dB hybrid [7]. Finally the power from the outputs of the two hybrids is absorbed in high-power SLAC-type vacuum loads. Varying the biasing pulse generator will allow redirection of the full magnicon power from one output arm of the 3-dB hybrid to the other.

CONCLUSIONS

New ultra-fast, X-band and Ka-band electrically-controlled ferroelectric switches have been designed as key elements of high-power active pulse compression systems for future linear accelerators. Construction of a 50 MW X-band phase shifter is now underway.

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