1.3 GHZ ELECTRICALLY-CONTROLLED FAST FERROELECTRIC TUNER*

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Abstract

A fast, electrically-controlled tuner is described with parameters suitable for operation with the 9-cell SC accelerator structure of ILC. The tuner is based on a magic tee and two phase shifters that contain ferroelectric rings. The dielectric constant of the ferroelectric rings is altered by applying a 4.2 kV DC pulse that provides an RF phase shift from 0° to 180°. This in turn allows a change of the input signal amplitude from zero to its maximum value, or a change in phase from 0° to 360° during the RF pulse. It is shown that the possibility of changing the cavity coupling to the input line during the RF pulse allows significant RF power savings, up to 12.5 MW for the 800 GeV ILC option. In addition, fast electrically-tuned amplitude and phase control with a feed-back system should be useful to compensate for possible phase deviations of the input RF fields in each cavity of ILC to match the cavity with the feeding transmission line as the beam load varies.

INTRODUCTION

There is broad agreement in the high energy physics community that a linear e^+e^- collider with a center-of-mass energy E_{cm} = 500-1000 GeV, and a luminosity $\geq 10^{34}$ cm^{-2}-s^{-1} is of fundamental importance for the future development of particle physics [1,2]. In the TESLA concept [3], which is considered to be the basis for ILC, two main linear accelerators each include approximately 10,000 one-meter long 9-cell superconducting cavities. The accelerating gradient is about 25 MeV/m and the c.m. energy is 500 GeV. The average AC mains power consumed by the RF system at 500 GeV c.m. energy is thus about 70 MW. Refrigerators take an additional 8.5 MW to dissipate heat from RF losses in the structures, plus static heat load compensation [3]. In order to reduce the cavity filling time and thus to conserve RF power, utilization of an external fast tuner was proposed [4,5] that would change the coupling of the cavity with the RF circuit during each pulse. This tuner would also reduce the power required for refrigeration. Simple estimates show that utilization of a fast tuner allows a reduction in filling time from 420 μs down to about 300 μs, and thus to reduce the average power required for the RF system by 9% [5]. In addition, utilization of a fast tuner allows quick extraction of RF from the superconducting sections after the RF pulse ends, thereby decreasing the cavity heating and the refrigerator power consumption by 16% [5]. The maximum total AC power savings could then be up to ~8 MW for the 500 GeV option of TESLA. A further use of fast tuning is to stabilize the necessary precise phase differences between cavities in near-real-time, to compensate for fluctuations due to microphonics and Lorentz-force cavity distortions. Early on, ferrite tuners were suggested for such applications [6,7]. These ferrite tuners are designed to provide fast phase and amplitude modulation of the drive signal for individual superconducting cavities. However, the tuning frequency for this device has an upper cut-off at 2 kHz that comes mainly from eddy currents inside the RF structure [7]. Its shortest switching time is thus about 1 msec. For ILC applications, switching times must not exceed a few 10's of μs. One must thus conclude that ferrite tuners are unlikely to be developed with fast enough switching rates for use with ILC. A fast electrically-controlled L-band tuner based on a ferroelectric phase shifter is proposed with the parameters suitable for operation with 9-cell SC cavity of ILC. The phase shifter will allow coupling changes during the cavity filling process in order to provide significant power savings, and will allow for fast stabilization against phase fluctuations. Modern bulk ferroelectrics, such as $Ba_xSr_{1-x}TiO_3$ (barium strontium titanate or BST) with $\varepsilon \sim 500$, have high enough electric breakdown strength (100-200 kV/cm) and do not require too high a bias electric field (~20-50 kV/cm) to effect a significant change (20-30%) in ε. The loss tangent already achieved for large bulk samples is about 6×10^{-3} at 11 GHz [8], that scales to less than 10^{-3} at 1.3 GHz, assuming the well-known linear dependence between loss tangent and frequency [9]. 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. Note that the possibility of fast electrically-controlled coupling is desirable for ILC in order to match the cavity with the feeding transmission line as the beam load varies. Also, fast electrically-tuned amplitude and phase control with a feed-back system is useful in order to compensate possible phase deviations of the input RF fields in each cavity. This difficulty is magnified in ILC, since one klystron is to drive 36 cavities, and RF fields in all cavities must have precisely-fixed phase differences with respect to one another, plus uniform amplitudes. Such fast amplitude and phase control may also be useful also in providing a wide change in the beam energy, as is likely to be necessary for collider operation.

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GENERAL

In TESLA, for a c.m. energy of 500 GeV, about 600 RF stations in the main linacs are required in order to provide RF power for all accelerating cavities [3]. At each RF station three cryomodules are fed by a 10 MW klystron in order to provide an accelerating gradient of 23 MeV/m. The klystron has two rf output windows and has to supply thirty six 9-cell cavities, which are installed in the three modules. For RF distribution, a linear system branching off identical amounts of power for each cavity from a single line by means of directional couplers is to be used. Circulators would be used to protect the klystrons against reflected power at the start of the RF pulse during filling of the cavity and at the end of the pulse. The particle beam pulse consists of 2820 micro-pulses spaced by 0.337 μs, resulting in a macro-pulse duration of 950 μs. To fill the cavity with RF, an additional 420 μs is needed. The simplest case to analyze is when the coupling is initially n times higher than the nominal value ($n > 1$), is then reduced to nominal during the filling process, and then is increased back during the cavity discharge. as shown in Fig. 1.

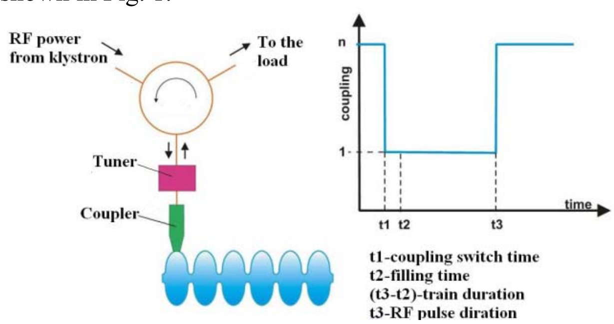

Figure 1: Coupling change during the cavity filling process. Here $n\beta$ is the initial coupling that is changed instantaneously at $t = t_1$ to the nominal value of coupling β. The RF pulse starts at $t = 0$ and ends at $t = t_3$.

In Figure 2 the total AC power savings are shown as a function of n for both the 500 GeV TESLA option (TESLA-500) and the 800 GeV TESLA option (TESLA-800). For example, for $n = 5$ the total AC power savings will be about 5.3 MW for TESLA-500, and 12.5 MW for TESLA-800. One can see that further increase in n doesn't give significant power savings, and it is not reasonable to use an initial coupling five times higher than the nominal value. A possible device [6] to allow fast electrically-controlled coupling and phase changes can be based on a magic-T with two coaxial phase shifters containing ferroelectric elements, as shown in Fig. 3. Changing the phase shifts from -90° to +90° will change the transmission coefficient from 0 to 1, and the phase from -180° to 180°, independently. For a symmetric magic-T, the power level at each phase shifter is only half of the total power incident on Port 4, which thereby reduces the temperature rise that must be accounted for in the design. The phase shifter itself may be designed as a low-impedance coaxial line containing a half-wave ferroelectric ring with matching elements and terminated by a coaxial resonator, as shown in Fig. 4. Applying bias voltage between the central and outer conductors of the coaxial line effects a change in dielectric permittivity of the ferroelectric ring, which 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.

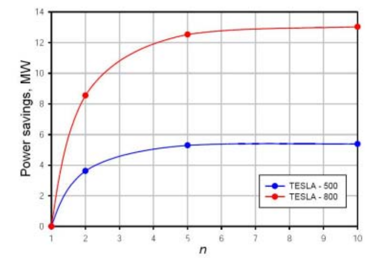

Figure 2: The total AC power savings *vs*. n.

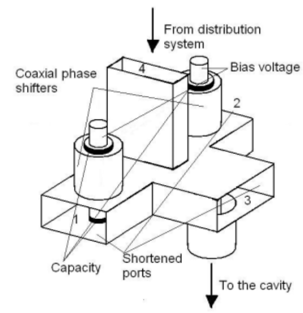

Figure 3: Schematic of a device to produce fast cavity coupling changes based on a magic-T and two phase shifters containing ferroelectric elements. This device is not under vacuum, and is located outside of the cryostat.

In a preliminary conceptual design, the ferroelectric ring has a length L_f = 20.95 mm and is surrounded by two identical alumina matching rings having lengths L_c = 18.2 mm. The length of the end coaxial resonator is L_r = 115 mm. The inner diameter of the coaxial line d = 106 mm, the gap between inner and outer conductor dr = 2.8 mm. Note, that ferroelectric rings of this size have been developed for an X-band phase shifter [10]. A photograph of a sample ring is shown in Fig. 5.

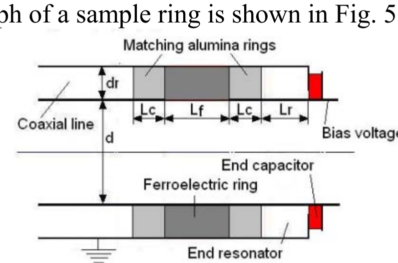

Figure 4: Schematic of the ferroelectric phase shifter. The design contains matching alumina rings necessary to decrease the electric field in the ferroelectric ring. The end capacitor allows apply bias voltage to the central electrode.

In the conceptual design described above, the phase shifter should sustain a peak input power of 500 kW at a duty factor of 6.5×10^{-3}, or an average power of 3.25 kW

[2]. For this high average power thermal effects are important and will influence a final design.

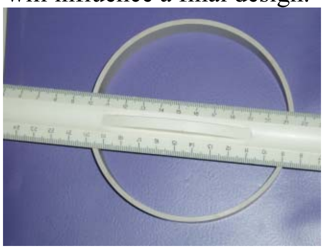

Figure 5: A sample of a ferroelectric ring with a diameter of 106 mm, a thickness of 2.8 mm, and a length of 22 mm, as fabricated by Euclid Concepts for Omega-P.

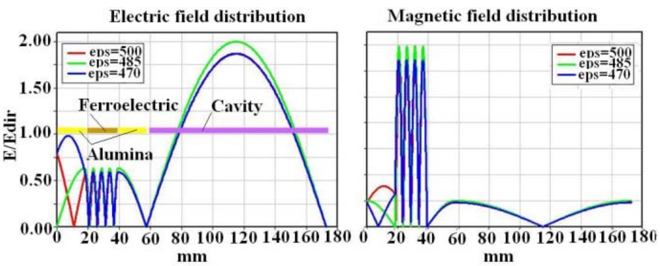

Figure 6: The electric and magnetic field amplitudes along the coaxial phase shifter normalized to the incident wave amplitude for differing dielectric constant of the ferroelectric.

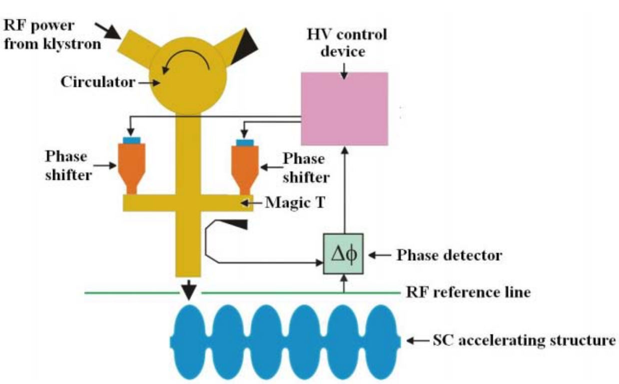

Figure 7: A possible schematic of the control system with its local feedback loop.

The calculated field profile along the coaxial phase shifter is shown in Fig. 6. The phase shifter provides a phase change of 90° when the bias voltage changes from 0 to 4.2 kV, with the dielectric constant changing from 500 to 470. The phase shifter with two ferroelectric rings provides a phase change of 180°. The maximum bias electric field does not exceed 15 kV/cm. This value is still acceptable for a non-vacuum device, but it would be desirable to reduce the peak field to the conventional level of 10 kV/cm. For the present design, the temperature rise is 0.3°C, an acceptable value, for loss tangent of 0.5×10^{-3} and thermal conductivity of 7 W/m-°K. The temperature rise during the pulse (pulse heating) is 0.1°C for specific heat of the chosen ferroelectric of 0.65 kJ/kg-K and density of $4.86\cdot10^{3}$ kg/m^3. All these small deviations as well as nonlinear effects can be easily compensated by a simple fast feedback system [6] shown in Fig. 7.

The tuner design includes waveguide-coaxial transformers for both phase shifters (see Fig. 3), similar to that used TTF-III power coupler [11]. The coaxial impedance in the TTF-III design is 50 Ohms. Thus, an impedance transformer from 50 Ohm to ~3 Ohms is required. Preliminary conceptual design of a transformer with such a high transformer ratio is shown in Fig. 8. The total capacitance of the phase shifter containing the two ferroelectric and two alumina rings is 25 nF. For both phase shifters the maximal average bias power would be a very modest 48 W.

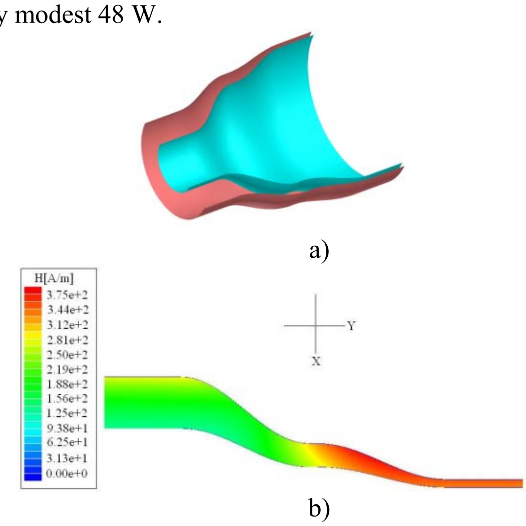

Figure 8: Geometry of the impedance transformer from 50 Ohms to 3 Ohms (a) and the field pattern (b).

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