NEW MATERIALS AND DESIGNS FOR HIGH-POWER, FAST PHASE SHIFTERS

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Abstract

In the 100 MeV H^- Linac to be constructed at Fermilab, the use of fast ferrite high power phase shifters will allow all of the accelerating RF cavities to be driven by a single 2.5 MW, 325 MHz klystron. This results in substantial cost savings. The shifters are coaxial with aluminum doped Yttrium Iron Garnet (YIG) ferrite. In combination with branch line couplers, they will provide independent phase and amplitude control for each cavity. This is achieved by adjusting the solenoidal magnetic field applied to the ferrite. We report on our results in both low power (timing) and high power tests, for both 3″ and 1-5/8″ OD phase shifters. The low power measurements demonstrate that the rate of phase shift is well within the spec of 1 degree/μs. The high power tests were performed at the Advanced Photon Source at Argonne National Lab. We measured phase shifts and the failure point (applied power) for tuners in various configurations. In addition, we performed phase and amplitude measurements for a setup consisting of a 1-5/8″OD phase shifter along with a prototype branch line coupler.

INTRODUCTION

As part of the ongoing R&D at Fermilab for a High Intensity Neutrino Source (HINS) [1], a 100 MeV H^- linac is being constructed in the Fermilab meson detector building. One of the novel features of this accelerator is that the entire RF power at 325 MHz is supplied by a single 2.5 MW pulsed klystron (Toshiba E3740A.) The RF components consist of an RFQ with two input couplers, two bunching cavities, 16 room temperature triple spoke cavities, and 29 superconducting single spoke cavities (18 at β = 0.22 and 11 at β = 0.4.) With the exception of the RFQ which will require a total input power > 400 kW, all of the other 47 RF cavities require less than 50 kW of input power to accelerate the maximum beam current of 26 mA. The accelerator is designed to operate with either 1 ms RF pulses at 10 Hz or 4 ms pulses at 2.5 Hz.

In order to maintain the correct amplitude and phase control for each of the 48 cavities, every cavity will have its own high power vector modulator. Each vector modulator consists of a four port branch line coupler with two fast ferrite phase shifters on ports 2 and 3. Input port 1 is connected to a directional coupler which taps off the correct amount of RF power from the main 2.5 MW klystron feed. Output port 4 is connected to the cavity through a circulator and a short coaxial transmission line. By independently varying the phase shift through each of the shifters connected to ports 2 and 3, both the amplitude and phase of the output signal at port 4 can be simultaneously adjusted.

PHASE SHIFTER DESIGN

High power fast phase shifters have been previously designed and built in three different configurations: coaxial [2], stripline [3,4,5,6], and waveguide [7,8,9]. The coaxial design offers two distinct advantages. They can be used over a wide frequency range, being limited only by the appearance of higher order modes. They also offer a more efficient, compact design since the ferrite can fill the entire region between the conducting boundaries. The waveguide versions appear to have the advantage of operating at higher peak power levels.

Boxer et. al. [2] first demonstrated a coaxial high power design at 1350 MHz with a 10% bandwidth. They obtained a 360° phase shift for a 300 kW, 1 μs pulse at a repetition rate of 500 Hz through an 18″ long, 7/8″OD coaxial transmission. The coax line was fully loaded with a low loss magnesium manganese ferrite-aluminate,TT1-103, which was perpendicularly biased by a solenoidal magnetic field.

Several differences exist between the original design by Boxer et. al. [2] and the coaxial phase shifters described in this paper. Used with the branch line couplers, the new shifters must operate in the full reflection mode creating a standing wave with twice the maximum peak voltage across the line. The RF pulse length is up to 4000 times longer in the present application and the operating frequency is 325 MHz instead of 1350 MHz. The new phase shifter with its characteristic impedance Z_0 near 50Ω is a wideband device that has been high power tested at 352 MHz and 1300 MHz. The other notable difference is that the magnesium manganese ferrite used in the original design has been replaced with an aluminum doped yttrium iron garnet.

The fast ferrite phase shifters described in this paper are all shorted stubs (coaxial transmission lines shorted at one end) that operate in the normal TEM coax transmission line mode. A section of the coax line near the shorted end is fully filled with ferrite (garnet.) This line section is inserted into a varying solenoidal H field whose direction is perpendicular to both the E and B RF fields in the TEM mode (hence the term “perpendicularly biased”.) Above the gyromagnetic resonance which occurs when the RF frequency f = 2.8 MHz/oersted x H, losses in the ferrite become extremely low. Low power network analyzer S11 measurements have shown losses as low a 0.3 dB/m. The fast phase shift is obtained by changing the garnet’s relative permeability μ by varying the magnitude of the external H field.

The first new coaxial design was based on the requirement of operating with an input of several hundred kW for a 4 ms pulse, a ± 45° phase shift range, a tuning slew rate of 1°/μs, and a characteristic impedance $Z_0 \approx 50\Omega$. Since the relative permeability μ of the garnet changes as a function of the applied magnetic field H, the requirement that $Z_0 = 50\Omega$ cannot be strictly maintained throughout the entire tuning range. Using a relative dielectric constant ε = 14 for the garnet and a core OD/ID ratio = 6 gives $Z_0 = 50\Omega$ at a relative permeability μ = 3. A 3″OD for the garnet cores was chosen so that they could fit inside a standard 3-1/8″ OD coaxial copper transmission line that has a peak power rating of 440 kW and a maximum frequency of 1588 MHz.

Three different aluminum doped yttrium iron garnets from three different vendors were initially evaluated. Sample toroids 3.0″OD X 0.5″ID X 0.5″ thick of GA-58 (Ferrite Domen), AL-400 (TCI Ceramics), and G-510 (Transtech) with 4πMs = 570, 383, and 537 gauss respectively were tested to verify losses and phase shift vs. external bias field over a frequency range from 325 MHz to 1300 MHz. All three materials had low losses and produced the expected phase shifts. The availability of AL-400 from TCI in larger size cylinders, suitable for our phase shifters, was the determining factor in choosing AL-400 for the final design.

Figure1: Components of the three types of phase shifters with a 12″ ruler for scale.

Final Designs

Three different prototype shifters have been built. The inner coax conductors and garnet cylinders for the three types are shown in Fig. 1. Type I is an attempt to make a shifter with a characteristic impedance Z_0 as close as possible to 50Ω. It consists of a 3″OD X 0.5″ID X 2.5″long AL-400 garnet cylinder inserted into an 11” long standard 3-1/8″OD copper coax line. A 2.5″ long section of the inner conductor of the coax line has been machined down to a diameter of 0.5″ to fit inside the garnet cylinder. The assembly is a shrink fit process in which the copper inner conductor is cooled to liquid nitrogen temperature before inserting it into the room temperature garnet cylinder.

Types II & III were made to double the available phase shift range using longer lengths of garnet. Due to manufacturing constraints imposed by the requirement of longer garnets, the nominal $Z_0 = 50\Omega$ geometry could not be maintained. To produce the longer cylinders the cylinder wall thickness had to be reduced. Both types II & III use coaxial quarter wave matching sections (at 325 MHz) in an attempt to match the garnet portions of the line to a standard 50Ω impedance. Type II fits inside a 15″ long 3-1/8″ coax line. The garnet is 3″OD X 1.1″ID X 5″ long. The inner diameter of the quarter wave matching section is 1.69″. Type III is a lower power, smaller diameter version that fits inside a 14.75″ long 1-5/8″OD coax line. The garnet cylinder is 1.5″OD X 0.65″ID X 5″ long. The matching section has an ID of 0.88″.

High Power Testing at 1300 MHz

The original proposal for a HINS called for an 8 GeV linac where the low energy end operated at 325 MHz and the high energy β = 1 section at 1300 MHz. Given the ability of the coaxial phase shifters to operate at both frequencies and the availability of a 5 MW pulsed 1300 MHz klystron at Fermilab's A0 photoinjector, preliminary high power tests were done at 1300 MHz. The device tested was similar to the Type I design except five cores 3″OD X 0.5″ID X 0.5″ thick were slipped over the copper center conductor (.488″OD). A ~1/16″ radius was ground on the inner edges of the garnet cores to reduce sparking. The ~0.006″ gap between the garnets and copper shaft was filled with two layers of corona resistant, 0.003″ thick Kapton™ CR300 film. As a final precaution against arcing, the entire 11″ section of coax line was filled with Rtemp™ fluid (ε = 2.2.) Using 25 μs wide pulses with a peak power of 600 kW, a phase shift range of ~40° was measured.

High Power Testing at 352 MHz

During the past 18 months while Fermilab's 325 MHz, 2.5 MW klystron test facility was under construction, we were fortunate to be able to make many high power tests at Argonne's APS 352 MHz spare/test station [10]. The APS RF test station consists of a 1.1 MW CW klystron operating at 351.93 MHz. For our measurements, the test area was reconfigured to operate in a pulsed mode with pulse widths up to 4 ms long and peak power up to ~500 kW. The pulse repetition rate was set to 1 Hz.

A WR2300 waveguide to 6-1/8″ coax transition followed by a 6-1/8″ to 3-1/8″ reducer was used to connect our apparatus to the test station output. RF power levels were measured using directional couplers located in the main WR2300 waveguide connected to an HP power meter. The power meter readings were calibrated with the klystron running into a matched load against thermometry measurements of the input and output cooling water to the load.

A water-cooled solenoid, energized by a 0 – 1000A dc supply, was used to provide the external bias H field for the phase shifters. A minimum constant current of 320A (H= 454 oersted) was maintained through the coil to guarantee operation in the low loss region above gyromagnetic resonance.

The procedure for high power testing consisted of starting at a power of ~10 kW and gradually increasing the power level while changing the dc current through the biasing solenoid to vary the phase shifter over its entire useful range. This was repeated until breakdown or arcing was observed. Internal arcing in the phase shifter assembly was easily detected by looking at the output of a discriminator that compared the diode–detected forward and reflected RF signals from directional couplers installed in the main WR2300 waveguide. A sudden decrease in the reflected power, corresponding to energy being dissipated in the garnet portion of the shifter, could be detected on a time scale of a few μs.

Phase shift measurements through the garnet phase shifters were made using the direct RF waveforms from forward and reflected directional couplers installed in the WR2300 waveguide. The directional coupler signals were connected to two channels of a Tektronix 3054B digital oscilloscope which automatically computed the phase shift between the channels.

Experimental Results

Fig. 2 shows both the phase shift and attenuation of two low level RF signals at 325 MHz and 352 MHz passing through a Type III (1.5″OD x 5″ long garnet) and being reflected back from the shorted end of the line. The data points were obtained from network analyzer (Agilent 8753ES) S11 measurements as the external bias field H was varied. Superimposed on the low level measurements in Fig. 2 are individual data points taken during 352 MHz high power tests with 4 ms pulses at power levels of 10, 25, 50, 75, and 100 kW. Good agreement is seen between the high and low power data. The test was stopped at the 100 kW level due to arcing across the coax line in the quarter wave matching section. Fig. 3 shows similar data for the Type II shifter at 100 and 200 kW. The Type II shifter failed at slightly more than 200 kW when arcing occurred through small hairline cracks in the garnet that were present when the cylinder was manufactured.

Fig. 4 shows the same measurements as the two previous figures except that they were made on the Type I (3″OD x 2.5″long garnet, Z_0 ~ 50Ω) shifter. The highest power data point corresponds to 420 kW. Tests on the Type I shifter concluded when the APS RF test facility reached its maximum pulsed mode output of ~500 kW.

Since the smaller OD (Type III) phase shifters function well to 80 kW, these will most likely be the choice for all of the vector modulators, with the exception of the modulator for the RFQ, in which Type I or II will be used.

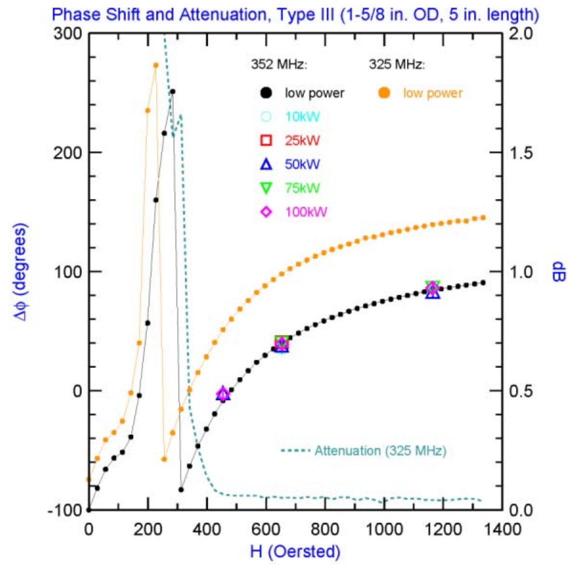

Figure 2: Type III phase shift and attenuation.

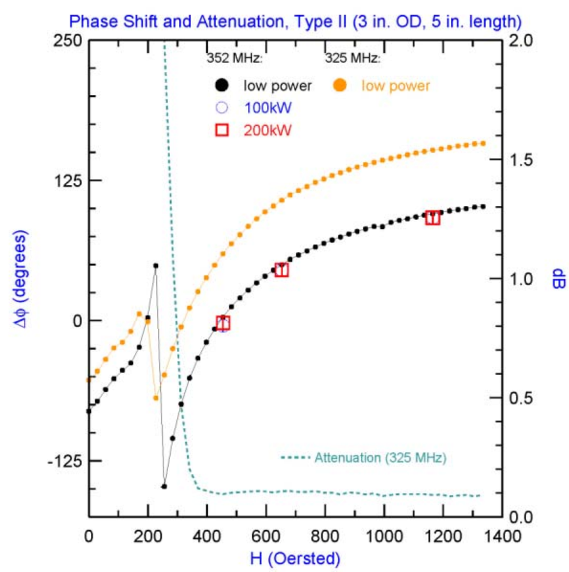

Figure 3: Type II phase shift and attenuation.

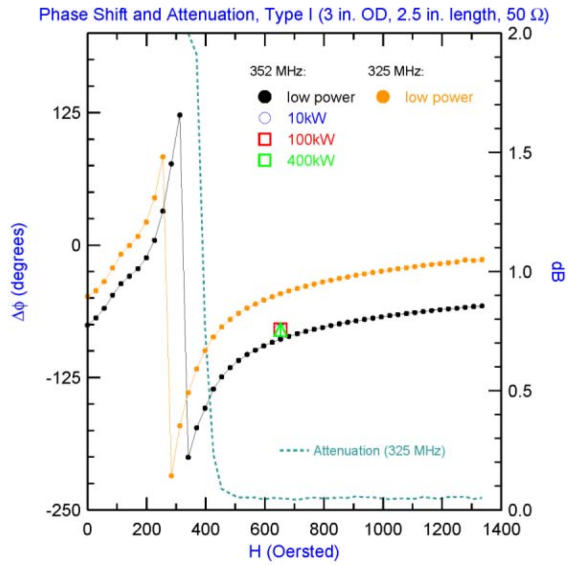

Figure 4: Type 1 phase shift and attenuation.

Figure 5: Type III phase shifter (slotted) with solenoid used for low power fast response tests.

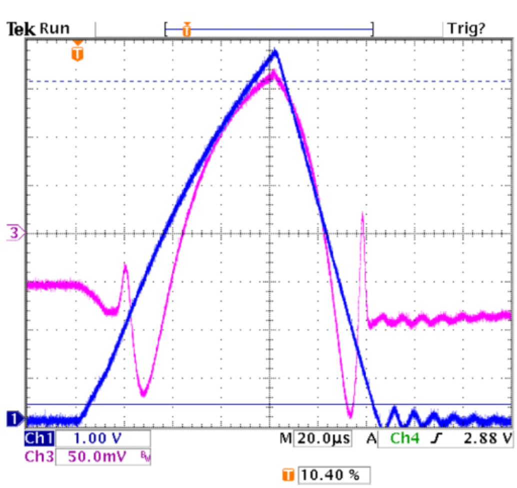

Figure 6: Type III fast phase shift (CH3 @ ~17°/div) and solenoid bias current (CH1 @ 50A/div) as a function of time (20µs/div).

Fast Response Measurements

Besides the available phase shift tuning range, the other important phase shifter parameter is its time response or slew rate. To eliminate induced currents due to the time varying magnetic bias field H and increase the shifter slew rate response, a 1/16″ wide, 8″ long slot was machined through the outer conductor of a 1-5/8″OD shifter starting at the shorted end. 47 turns of #12 AWG insulated wire were then wound in a single layer solenoid around the outer conductor as shown in Fig. 5.

To measure the phase shifter time response an HP 86205A 50Ω directional bridge was inserted between a 325 MHz signal source and the phase shifter input. The reflected signal from the shifter was then combined with the source reference signal using an HP 10514A mixer acting as a phase detector. The mixer output was then sent through a 20 MHz low pass filter to remove any residual 325 MHz component and then displayed on a Tektronix 3034B scope. The pulsed current through the solenoid was monitored using a HITEC model RA500 (bandwidth = 250 kHz) current transformer.

Fig. 6 shows two scope traces of the solenoid current (CH1 @ 50A/div) and the resulting phase shift (CH3 @ ≈ 17 degrees/div.) Approximately 20µs after the start of the current ramp the garnet passes through the gyromagnetic resonance region indicated by the rapid phase reversal. As the current ramp continues rising towards 375A the shifter enters its normal operating region characterized by very low losses. After 80 µs the current reaches 375A and then starts to decrease, returning back to zero in 40µs. The useful phase shift range above resonance is seen to be about 110°. Traversing this region in ~ 50µs gives an average slew rate of 2.2°/µs, twice as fast as the original design specification.

Vector Modulator Measurements

In the final high power test, a branch line coupler and phase shifter were combined into a vector modulator. Figures 7 & 8 show the results of tests at Argonne's APS of a branch line coupler [11] with a Type III phase shifter connected to port 2 and a fixed coaxial short on port 3. Figures 7 and 8 show the change in output power and phase at port 4 as a function of the phase difference between ports 2 & 3, as the input power to port 1 was varied from 20 kW to 160kW. Figure 7 shows the expected $\cos^2(\Delta\varphi/2)$ power dependence while figure 8 shows the output phase shift proportional to $\Delta\varphi/2$. Here $\Delta\varphi$ is defined as the phase shift difference between ports 2 and 3.

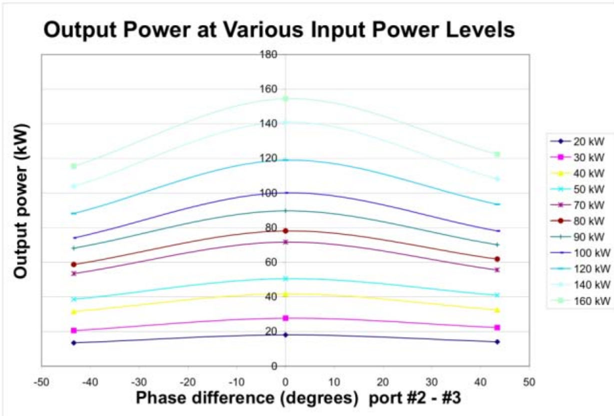

Figure 7: Vector modulator output power as a function of phase shift difference.

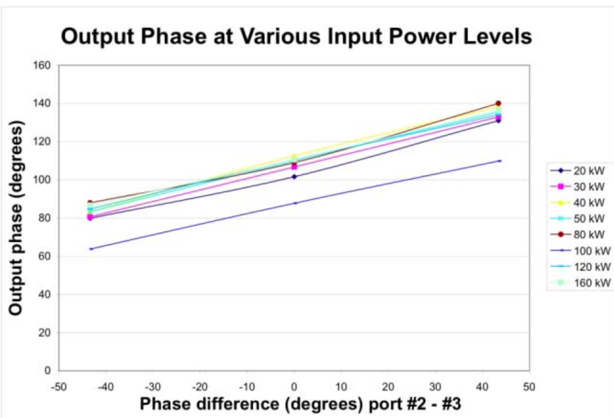

Figure 8: Vector modulator output phase as a function of phase shift difference.

CONCLUSIONS

Three types of high power (100's of kW), fast (> 2°/μs) ferrite phase shifters have been demonstrated in the full reflection mode. Using aluminum doped yttrium iron garnet cylinders in a coaxial geometry, phase shift ranges up to 120 degrees with losses less than 0.1 dB have been obtained.

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