HIGH POWER 325 MHZ VECTOR MODULATORS FOR THE FERMILAB HIGH INTENSITY NEUTRINO SOURCE (HINS)*

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Abstract

One of the goals of the low energy 60 MeV section of the HINS H^- linac [1] is to demonstrate that a total of ~40 RF cavities can be powered by a single 2.5 MW, 325 MHz klystron. This requires individual vector modulators at the input of each RF cavity to independently adjust the amplitude and phase of the RF input signal during the 3.5 ms RF pulse. Two versions of vector modulators have been developed; a 500 kW device for the radiofrequency quadrupole (RFQ) and a 75 kW modulator for the RF cavities. High power tests showing the vector modulator phase and amplitude responses will be presented.

INTRODUCTION

The first high power microwave phase shifters using ferrite-loaded coaxial structures were first described more than forty-five years ago [2,3]. Recently, there has been renewed interest in the field with advances in technology and materials. The possibility of powering multiple RF cavities from a single RF source has become a viable alternative to the traditional single RF source per cavity [4,5]. At Fermilab we are in the process of building a 60 MeV H^- linac to be used as the front end of a future High Intensity Neutrino Source (HINS). The linac is designed to accelerate 20 mA of beam current in either 1 ms pulses at a 10 Hz rate or 3 ms pulses at a 2.5 Hz rate. The first 30 MeV section of this new linac will have a 2.5 MeV RFQ, two bunching cavities, 16 room temperature CH type (3 & 4 spoke) cavities, and 18 superconducting single spoke cavities all being driven by a single 2.5 MW, 325 MHz klystron (Toshiba E3740AFermi.) Here there will be one vector modulator between the klystron and each cavity to independently control the phase and amplitude of the RF drive signal to its coupling loop. For the room temperature cavities these vector modulators will serve two purposes. First, they will be used to correct for cavity tuning errors caused by cavity heating and cooling water temperature fluctuations. Second, they will provide a means of compensating the effects of beam loading. To meet these goals we have developed two versions of high power vector modulators using fast ferrite loaded coaxial phase shifters. A 75 kW version will be used for all of the room temperature RF cavities. The RFQ which requires a larger 500 kW model.

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VECTOR MODULATORS

A photograph of one of the 75 kW vector modulators is shown in Figure 1. The 325 MHz signal from the klystron enters port 1 of a –3 dB quad hybrid (Dielectric Communications) where it is equally split with a 90° phase difference between ports 2 and 3. Two shorted 1.625″ OD coaxial, ferrite-loaded phase shifters, described below, are attached to ports 2 and 3 and provide full reflections with phase shifts $\varphi 2$ and $\varphi 3$ respectively. The desired phase shift is produced by a variable solenoidal magnetic field along the axis of the coaxial line which is used to adjust the permeability, μ, of the ferrite. These reflected signals are recombined at the output (port 4) of the quad hybrid with a resulting output phase of $(\varphi 2 + \varphi 3)/2$ and power proportional to $\cos^2 (\varphi 2 - \varphi 3)/2$. A 3 port 75 kW circulator (D & M Co. Ferrit-Quasar) with a 5 kW water cooled RF load (Altronic) is connected between the quad hybrid output and the RF cavity to isolate the phase shifters from any power being reflected from the cavity during the cavity filling time or under cavity detuning conditions.

The higher power vector modulator to be used with the RFQ is similar to the one described above except that the components are physically larger. The –3 dB quad hybrid (Micro Communications) has a coaxial design with 6″ EIA flanges and is filled with SF_6 to prevent sparking. The two phase shifters are 3.125″ OD, ferrite-loaded, shorted coaxial lines and are also filled with SF_6. A high power 3 port coaxial/stripline circulator (D & M Co. Ferrit-Quasar) is used to prevent the reflection of power back to the phase shifters.

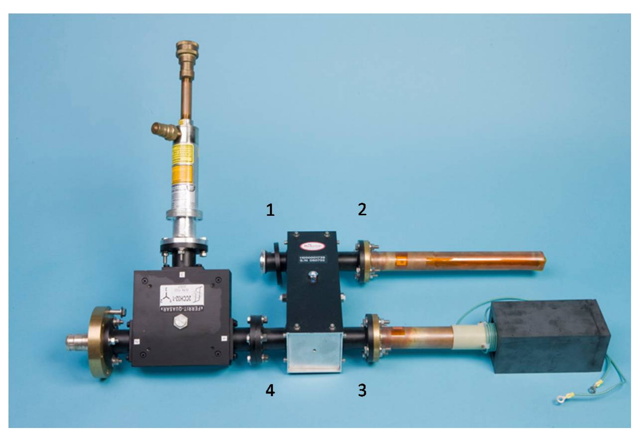

Figure1: Photograph of a 75 kW vector modulator.

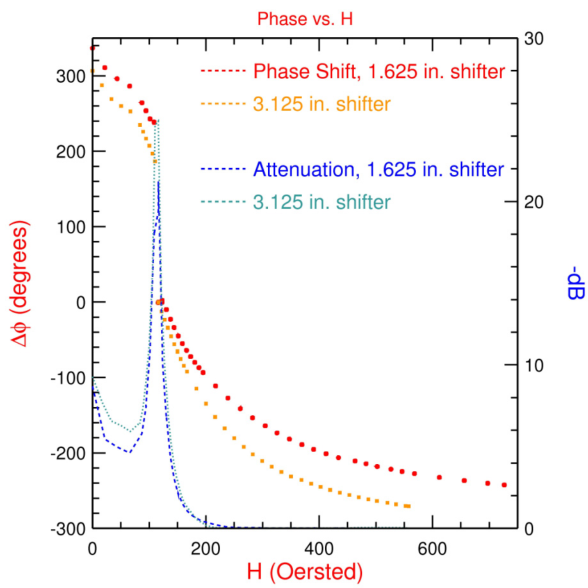

Figure 2: Phase shifter attenuation and phase shift vs. internal bias field, H, inside the garnet cores.

PHASE SHIFTERS

The phase shifters are OFHC copper shorted coaxial lines filled with a 5″ long section of aluminum doped yttrium-iron garnet (TCI Ceramics type AL-400) which has a saturation magnetization ($4\pi Ms$) of 400 gauss. The 75 kW version uses a 1.5″ OD x 0.65″ ID x 5″ long garnet cylinder at the shorted end over a 0.65″ diameter center conductor. The center conductor diameter is then increased to 0.880″ for a quarter of a wavelength (9.08″) to form a $Z_0 = 33\ \Omega$ matching section between the garnet filled region and the standard $Z_0 = 50\Omega$ port of the quad hybrid. The OFHC copper center conductor/garnet cylinder is assembled using a shrink fit technique where the center conductor is first cooled to LN_2 temperature and then inserted into the garnet cylinder. The phase shifter coaxial line outer conductor is a standard 1.625″ OD, 50Ω line (1.527″ ID) whose OD has been reduced to 1.567″ over the 9″ length closest to the short. Both this 9″ section and the bottom copper shorting plate have a 0.0197″ wide slot machined through the copper to reduce eddy current effects. The shorted end of the phase shifter containing the garnet cylinder is surrounded by a solenoid wound from 47 turns of 12 AWG stranded copper THHN wire on a 1.812″ OD G10 form. A magnetic flux return made from 0.75″ thick ferrite blocks (TCI Ceramics material G4) helps to increase the phase shifter frequency response.

The larger version phase shifter uses a 3.0″ OD x 0.65″ ID x 5″ long AL-400 garnet cylinder along with a Z_0 = 46Ω matching section. Here also, the outer conductor has a 0.020″ thick wall and a 9″ long slot. The biasing solenoid is 62 turns of 12 AWG wire on a 3.316″ OD G10 form with a G4 ferrite flux return. Each solenoid is independently powered by a 300V, 300A, 2 quadrant switching supply with a switching frequency of 250 kHz. A Praeg [6] style filter on the supply output, currently set to roll off at 40 kHz, is necessary to reduce the 250 kHz ripple that would otherwise be seen on the vector modulator outputs.

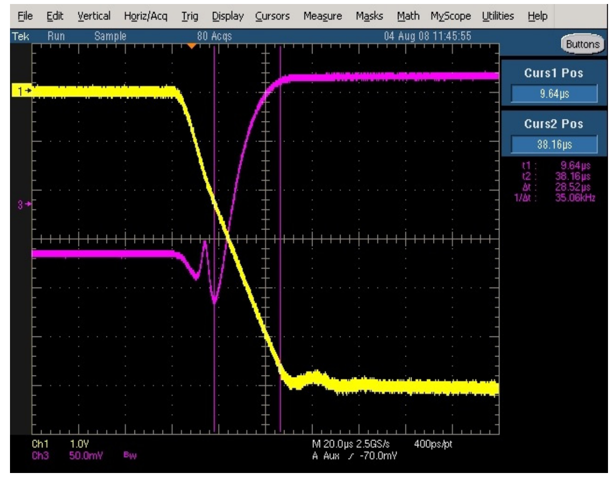

Figure 3: Time response of the 75 kW phase shifter biasing solenoid current (CH1 @ 50A/div.) and reflected phase (CH3 @ ~30 deg./div.) to a fast step (risetime< 1 μs) in the current program. The time scale is 20μs/div.

TUNING RANGE

Figure 2 shows a low power measurement of the round trip phase shifts and RF losses at 325 MHz for the 1.625″ OD and 3.125″ OD shifters plotted as a function of the internal biasing field, H. The maximum solenoid current for both cases was 300A during the 4ms pulse. The abrupt step in phase shift corresponds to the garnets going through gyromagnetic resonance. In Figure 2 the scale of H is normalized so that the gyromagnetic resonance at 325 MHz corresponds to the theoretical value of 2.8 MHz/oersted or H = 116 oersted. Below and at resonance the RF losses at 325 MHz are large which makes this region unsuitable for high power operation. However, above H ~ 200 oersted RF losses drop below -0.2 dB (typically < -0.1 dB) and high power operation becomes practical. Using –0.2 dB loss as an acceptable figure, the useable phase shift range is seen to be ~120 degrees.

FREQUENCY RESPONSE

Figure 3 is a scope trace showing the low power phase shifter response to a fast step used as the input program (0 to 300A) to the solenoid pulsed power supply. The rate of rise of the solenoid current is seen to be limited by the 300V maximum output of the supply and the ~45 μH inductance of the solenoid coil. The measured phase shift was obtained with an HP 86205A directional bridge and HP 10514A mixer, used as a phase detector at 325 MHz, comparing the input and reflected RF signals. Above resonance the average phase slew rate is ~ 6°/μs.

The small signal (+/- 10°) frequency response of the 1.625″ OD and 3.125″ OD shifters, centered at midrange, is shown in Figure 4. The open loop case (triangles) can be compared to a case with feedback (squares). The feedback error signal was obtained by comparing the measured reflected phase to a reference. The error signal was then amplified and summed back into the bias solenoid current program. The 1.625″ OD shifter open loop bandwidth is seen to be ~ 15 kHz which was extended to > 35 kHz with the phase feedback.

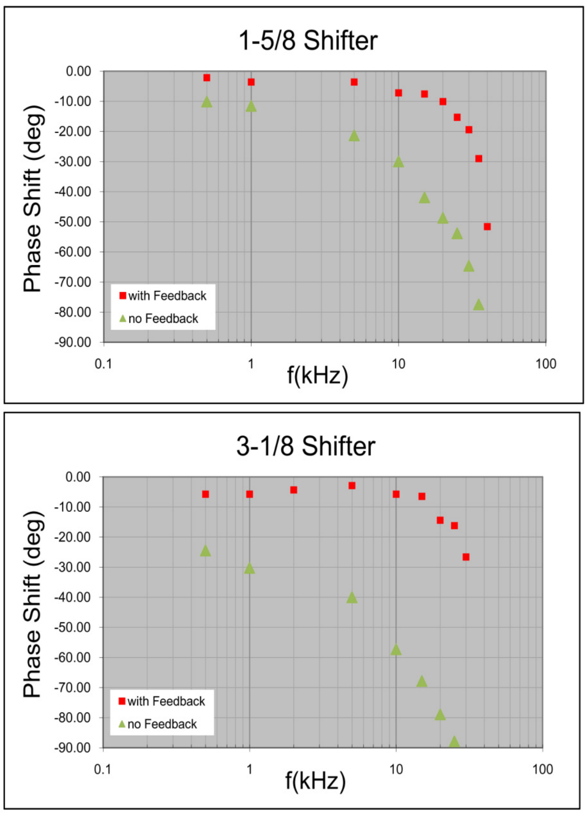

Figure 4: Phase shifter frequency responses with and without feedback.

HIGH POWER OPERATION

Figure 5 illustrates the amplitude modulation capability of the 75 kW vector modulator during a 2 ms RF pulse without any phase feedback. With a constant 50 kW input power to the vector modulator, the output power is stepped from 25kW (φ2 - φ3 = 90°) to the full 50 kW (φ2 - φ3 = 0°). During the first portion of the pulse, the 25 kW of unwanted power is directed back towards the circulator at the output of the 2.5 MW klystron where it is absorbed in the circulator load.

Both the 75kW and 500 kW phase shifters have successfully operated at their design power levels along with the 75 kW circulators. However; we have encountered some breakdown problems at the ~ 400 kW power level in the larger circulator. This circulator is currently being modified to reach the full 500 kW level.

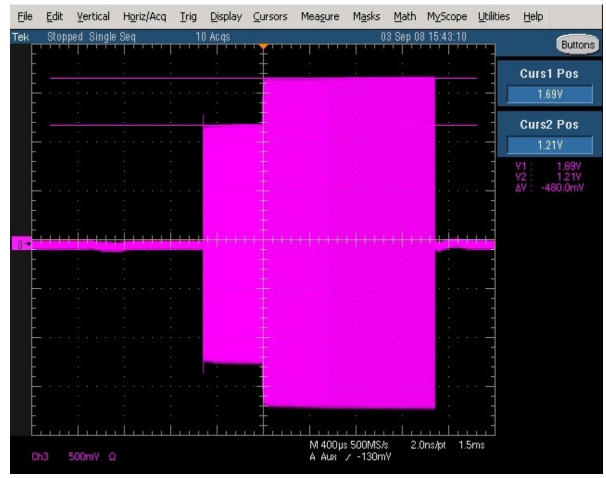

Figure 5: Vector modulator 325 MHz RF output amplitude being increased from 25 kW to 50 kW during a 2 ms pulse without any phase feedback. The time scale is 400µs/div.

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