HIGH POWER PHASE SHIFTER

B. Foster, I. Gonin, T. Khabiboulline, A. Makarov, N. Solyak, I. Terechkine#, and D. Wildman
FNAL, Batavia, IL 60510, U.S.A.

Abstract

One of the approaches to power distribution system of a superconducting proton linac that is under discussion at Fermilab requires development of a fast-action, megawatt-range phase shifter. Using two phase shifters with a waveguide hybrid junction can allow independent control of phase and amplitude of RF power at the input of each superconducting cavity of the linac. This promises significant saving in number of klystrons and modulators required for the accelerator. A prototype of a waveguide version of a phase shifter that uses Yttrium-Iron Garnet (YIG) blocks was developed and tested. This report presents design concept of the device and main results of simulation and proof-of-principle tests.

INTRODUCTION

One of major conceptual features of the proton superconducting linac under development at Fermilab (usually referred to as Proton Driver or PD) is using one klystron to feed many accelerating cavities. Although this concept is attractive due to significant cost saving it suggests, some work to justify this approach is required.

RF power filling time of a superconducting cavity in the linac depends on its RF properties, which are different for different cavities. Because the end of the filling period must be synchronized with the moment when the head of the beam reaches the cavity, input power must be individually adjusted.

Action of Lorenz forces and acoustic vibrations of cavity walls result in detuning. To keep the amplitude and phase of accelerating RF field within optimal range, fast control of these quantities is needed.

So, having a device that can control both amplitude and phase of input power would be very useful.

This kind of a device can be built based on a four-port waveguide hybrid junction or Magic “T”. Power entering the input port can not immediately exit through the output port because of a different polarization; instead, the power splits equally between the two side ports. If these ports end with shorted stubs, one can obtain independent control of amplitude and phase of the output RF power by changing average and differential length of the shorted stubs. If blocks of ferrimagnetic material are placed inside the side stubs, external magnetic field (bias field) can be used for the phase shift and power control. For more effective control, the magnetic field strength must be in the vicinity of the electron spin resonance [1]. Some ferrite-like materials, like YIG, show very low RF power loss even quite close to the resonance.

#terechki@fnal.gov

Known examples of using ferrite shifters in high power systems for phase and power control cover frequency range from ~100 MHz to ~3000 MHz with typical power of several hundred kW and different styles of implementation: based on a strip line, coaxial line, or waveguide (see [1-4], for example).

Accelerating cavities of PD use two frequencies: 325 MHz and 1300 MHz. Input power reaches 320 KW with duty factor of 1.5%. A desire to avoid using additional insulators between cavities and the power-regulating devices leads to the requirement of using a Mega-Watt-range phase shifter to have adequate electrical breakdown properties of the device. At this power range, removing heat from the ferrite blocks can become a major concern, so careful design and modelling of the device is needed.

This paper presents main results of 1300 MHz waveguide-based phase shifter modelling and testing.

PHASE SHIFTER CONCEPT

To ensure simultaneous filling with RF power of all superconducting cavities in the linac and compensation for acoustic and Lorenz force detuning, each phase shifter in the regulating devices at the input ports of the cavities must have working range of ±45° degrees. Because reaction time of the device must be small in comparison with the RF pulse duration, a transparent to changing magnetic field waveguide and sufficiently fast and powerful power supply are required. It is also important to ensure effective removal of heat from each ferrite block.

A concept of the phase shifter design that allows meeting major requirements stated above is as following:

1. Two YIG blocks of moderate thickness are located along opposite sides of a shorted waveguide and have good thermal contact with the side walls, which are made water-cooled.
2. There is a separate magnetic circuit for each of the two YIG blocks in the waveguide, so that the magnetic filed is only created in the desired area around the blocks.
3. The top and bottom walls of the waveguide are made of a material with high specific resistance and plated with thin layer of copper (or silver) from inside.

This concept is illustrated by a sketch in Figure 1.

Cross-section of the ferrite blocks is trapezoidal to reduce electrical field in gaps between the block and the horizontal walls of the waveguide. Length of the blocks, if not shaped in the longitudinal direction, is limited by onset of longitudinal resonances.

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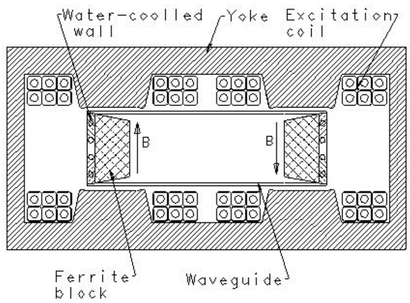


Figure 1: Phase shifter concept.

Figure 2 shows simulated S11 plot accompanied by field distribution pictures for two adjacent longitudinal resonances: half-wave and one-wave. Working zone must be chosen between the resonances, where power loss is sufficiently small.

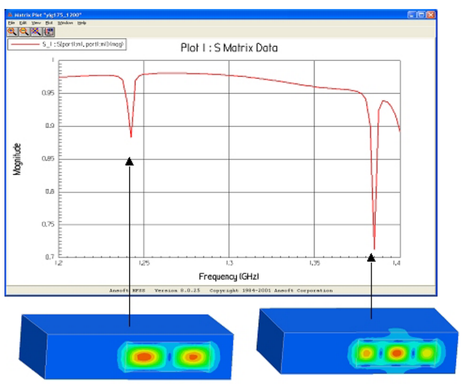


Figure 2: Longitudinal resonances.

Good thermal contact between the blocks and the side walls is a key to making a reliable device. Thickness of the YIG blocks must be chosen carefully. Thinner blocks significantly simplify heat removal, but provide modest phase shift. Possibility of increasing thickness of the blocks is limited by excitation of transverse resonance modes that leads to increased power loss near the borders of the working frequency region.

Direction of the bias magnetic field for one ferrite block in the waveguide is opposite to that for another block. This arrangement was made to suppress resonance excitation of the high order modes in phase shifter. These modes are well coupled to fundamental waveguide mode if directions of bias magnetic field in the ferrite blocks are the same and decoupled if these directions are opposite. Unbalance of bias magnetic field and non-identical properties of material in each block result in incomplete decoupling, so a provision must be made to allow some adjustment of the bias field strength in the blocks.

PHASE SHIFTER MOCKUP

Because none of the known devices could reach 1 MW power level, before starting any serious design efforts, it was necessary to prove that phase shifter can handle required power. For this purpose, a simplified version (a mockup) of a phase shifter was built (Figure 3).

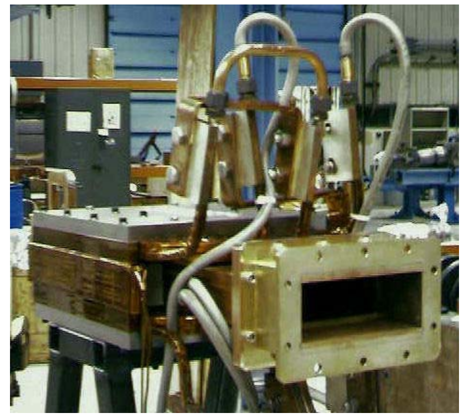


Figure 3: Phase Shifter mockup.

A reduced height WG650 waveguide was used for the mockup. A quarter wave intermediate-height section ensured proper matching with a standard-height waveguide feeder. Magnetic core was made of low-carbon steel and had cross-sectional profile as shown in Figure 1. The length of the core was 300 mm. Uniformity of field in the block region was ~5% with field unbalance for the two YIG blocks ~1%. Excitation coils were wound of water-cooled square copper wire, so a DC power supply could be used. Correlation between the coil current and bias magnetic field in the blocks is shown in Figure 4.

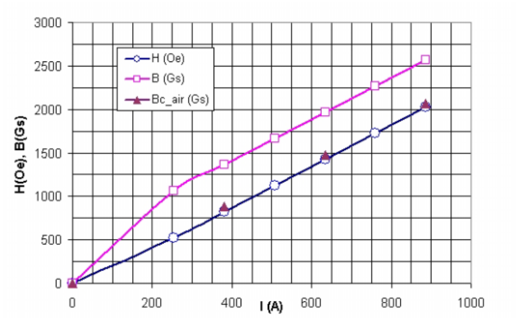


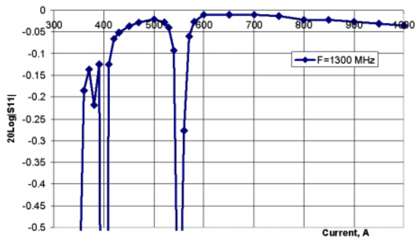
Figure 4: Magnetic system performance

Ferrite blocks were attached to the side walls of the waveguide by using high thermal conducting paste OMEGATHERM®"201".

Before making high power test, RF properties of the phase shifter were measured using a network analyser. Corresponding power loss and phase diagrams are shown in Figure 5 as function of excitation current. These diagrams show low loss zone in the current interval between 400 A and 550 A with integrated phase shift of about 90° which is consistent with the requirements. Power loss level is less than 0.1 dB in the working zone.

Satisfactory results of low level RF measurements allowed us to switch to high power RF test.

a)



b)

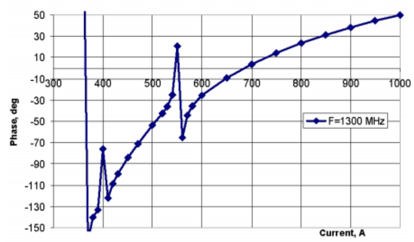


Figure 5: RF power loss (a) and phase (b) diagrams.

HIGH POWER TEST

High power test was set using equipment available at the Photo-Injector laboratory (FNPL) at FNAL. Power from 1.3 GHz, 5 MW, 200 µs klystron was brought to the phase shifter through an insulating circulator. Direct and reflected power was measured by taking corresponding signals from a directional coupler. Klystron power was regulated by adjusting voltage.

Phase shift measurements made at the power level of 100 kW are shown in Figure 6.

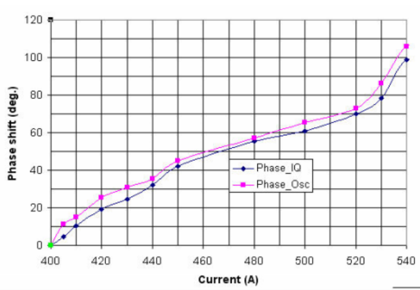


Figure 6: Phase shift vs current at 100 kW.

Two different curves correspond to different techniques of the phase shift measurement: by direct oscilloscope observation of forward and reflected RF signals and by using digital means of phase measurements existing at FNPL. The two methods gave similar results (integrated phase shift of ~90°), consistent with what was obtained by using the network analyser (Figure 5). In the case when the waveguide was filled with air at normal atmospheric pressure, maximal power level was limited due to sparking in the waveguide that developed when the bias field was set near boundaries of the working zone. This effect limited the phase shift range, as it is shown in the left part of the graph in Figure 7. Again, two curves correspond to different methods of phase measurement.

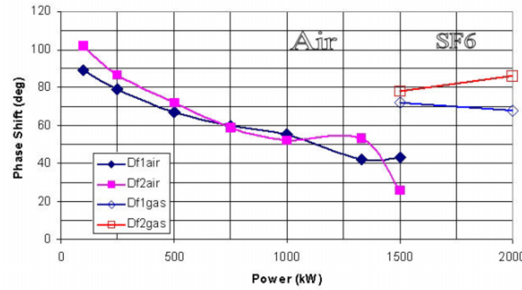


Figure 7: Phase shift range as function of input power

Adding SF_6 into the waveguide fully suppressed sparking and allowed reaching 2 MW input power level, which was well above of the goal power.

FUTURE WORK

While testing the prototype of the Phase Shifter, resonance effects were identified that were related to misalignments of the ferrite blocks and non-symmetry of the bias magnetic field. Understanding these effects and their elimination are the natural next steps to make.

Testing the device using longer RF pulse (up to 5 ms of pulse duration is planned for the Proton Driver) and with nominal maximal and average power must be done before dynamic properties of the device are addressed.

To switch from DC mode of operation to fast changing control field, steel in the magnet core must be replaced with soft ferrite. Setting central working point using permanent magnets is also considered.

ACKNOWLEDGMENTS

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