FIRST RESULTS WITH A FAST PHASE AND AMPLITUDE MODULATOR FOR HIGH POWER RF APPLICATION

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Abstract

In a high energy and high power superconducting proton linac, it is more economical to drive several cavities with a single high power transmitter rather than to use one transmitter per cavity. However, this option has the disadvantage of not permitting individual control for each cavity, which potentially leads to instabilities. Provided that it can be built at a reasonable cost, a fast phase and amplitude modulator inserted into each cavity feeder line can provide the necessary control capability. A prototype of such a device has been built, based on two fast and compact high power RF phase-shifters, magnetically biased by external coils. The design is described, together with the results obtained at high and low power levels.

INTRODUCTION

For an RF system in particle accelerators it is more economical to drive several accelerating (superconducting) cavities with a single high power transmitter rather than to use one transmitter per cavity. This option has the disadvantage of not permitting individual control of the field in each cavity. When driven by a high gradient pulsed RF field, Lorentz forces can excite periodic mechanical deformations which detune the cavity. Unfortunately, the mechanical resonant frequencies of the cavities are generally in the same frequency range as the pulsing signal. These facts lead to instabilities and potentially to loss of control over the cavities [1] [2]. If a fast phase and amplitude modulator can be built at reasonable cost, and be inserted into each cavity feeder line, it could provide the necessary control capabilities (see figure 1).

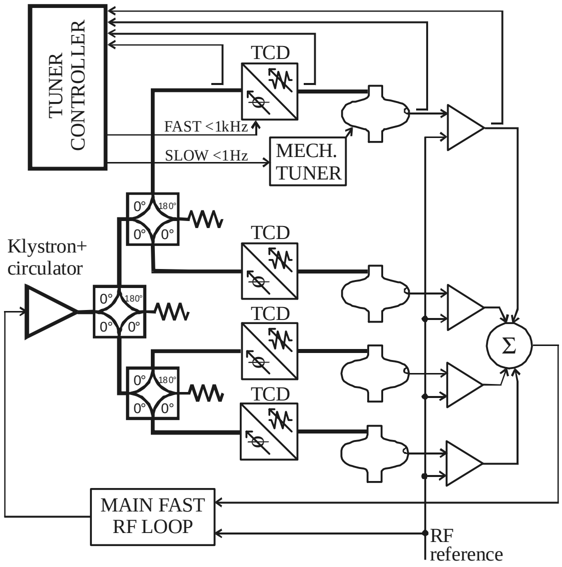

Figure 1: Proposed layout of a RF system. The complete tuner system is drawn only for the top cavity (TCD – Transmission Controlling Device)

For the Superconducting Proton Linac (SPL), a new linear accelerator being studied at CERN [3], a prototype of such a device has been developed and built. It is based on two fast and compact high power RF phase-shifters, magnetically biased by external coils [4]. The design is described, together with the results obtained at high and low power levels. Some of the technical parameters of the modulator and phase-shifters are given in table 1.

Table 1: Parameters of the modulator and phase-shifters

Parameter	**Value**
Operating frequency	352 MHz
Peak power (per modulator/cavity)	250 kW
RF pulse duration (duty cycle)	< 5 ms (25 %)
Pulse repetition frequency	50 Hz

RF PHASE AND AMPLITUDE MODULATOR

The RF phase and amplitude modulator splits the incident RF wave into two identical components. These are individually phase shifted and combined again to one output wave. When driving phase-shifters “in phase”, only the *phase* of the signal changes. When driving phase-shifters in “anti-phase”, only the *amplitude* of the signal changes. By a combination of these two modes, both phase and amplitude of the RF wave can be controlled simultaneously.

Two different designs were studied. The advantages and disadvantages of each type are described in the next paragraphs.

Transmission type modulator (type one)

The setup shown in figure 2 is more complex consisting of two 3dB hybrids, two transmission type phase-shifters and two dummy loads. As a 3dB hybrid a magic tee, rat race or any type of a quadrature hybrid might be used. The transmission of this device is described by formula:

$$\frac{V_{OUT}}{V_{IN}} = \frac{\Phi_1 + \Phi_2}{2} \tag{1}$$

where $\mathbf{\Phi_1}=F_1e^{-j\varphi1}$, $\mathbf{\Phi_2}=F_2e^{-j\varphi2}$ are the transmission coefficients of the phase-shifters. As we can see, the transfer function is not dependent on the load connected to the output of the modulator. Then for lossless phase-shifters ($F_1=F_2=1$), the transmission controlling capabilities will be described by the magnitude:

$$\mathrm{Mag}(S_{21}) = \sqrt{\frac{1+\cos(\varphi_1-\varphi_2)}{2}} \qquad (2)$$

and phase:

$$\mathrm{Arg}(S_{21}) = -\frac{\varphi_1+\varphi_2}{2} \qquad (3)$$

of the transfer function.

Apart from increased complexity, the disadvantage of the setup using two-magic tees is the need for transmission type phase-shifters. For frequencies around 352MHz and power levels of 250kW, it is very difficult, if not impossible, to build transmission type, fast phase-shifters for a reasonable price and having reasonable power requirements for the tuning drive (see more detailed information in the section about the fast ferrite phase-shifter).

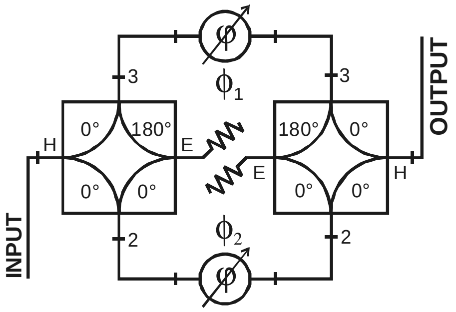

Figure 2: Transmission type of modulator

Reflective type of modulator (type two)

The setup shown in figure 3 consists of only one 3dB hybrid, and two resonant reflective phase-shifters. This is the smallest and lowest cost configuration.

A device of this type does not use any dummy loads. The difference between the incident and transmitted wave is reflected back towards the generator. The transmitter (e.g. klystron) is usually protected by a circulator, hence the wave reflected at the modulator input (S_{11}) presents no problem. Since the modulator device is fully reciprocal, the wave coming back from the cavity is partly re-reflected by a factor $S_{22}=S_{11}$ at the modulator output and the transfer function is dependent on the load connected – as shown by formula (4).

$$\frac{V_{OUT}}{V_{IN}} = \frac{\Phi_1-\Phi_2}{2-\Gamma(\Phi_1+\Phi_2)} \qquad (4)$$

where $\mathbf{\Phi_1}=F_1e^{-j\varphi 1}$, $\mathbf{\Phi_2}=F_2e^{-j\varphi 2}$ are the reflection coefficients of the phase-shifters and $\mathbf{\Gamma}=Ge^{-j\gamma}$ is the reflection coefficient of the load. It can be shown that a modulator with an arbitrary load will not be easily controllable, and in the worst case the whole system can become unstable.

For the "matched case" ($\mathbf{\Gamma}=0$) the transmission function S_{21} becomes the same as for the system using transmission type phase-shifters, described by the formulas (2) and (3). However in this case φ_1 and φ_2 will represent the phase of the phase-shifter's reflection coefficient, instead of the phase of the transmission coefficient as in the first case.

A superconducting cavity resonator, with negligible beam loading, acts as a short circuit reflecting the full incident wave back to the generator. As mentioned above, for proper operation of the modulator, the output has to be matched in any condition. This might be realised e.g. by inserting a "small" circulator between the output of the modulator and the cavity (see figure 3).

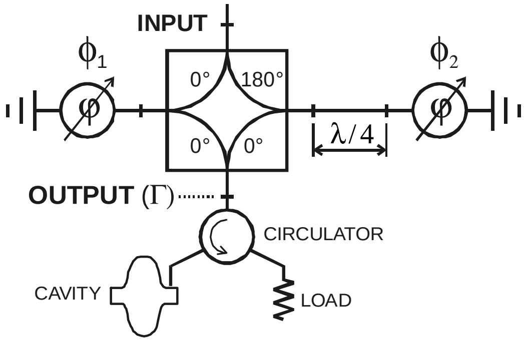

Figure 3: Reflective type of modulator (with additional circulator)

When using a circulator in the cavity feeder line, both types of modulator will show the same properties. For a low frequency application (352MHz), this configuration has the same controlling capabilities as the "one klystron per cavity" configuration and can cost less.

FAST FERRITE PHASE-SHIFTER

For the transmission type phase-shifter working at 352MHz, a phase-shift of only 10 to 15 degrees per 10 cm of strip-line length was achievable. Since this would demand a very long and expensive structure, we have chosen a single-port resonant type of phase-shifter.

In collaboration with the German company Advanced Ferrite Technology (AFT) two prototypes of such a fast ferrite phase-shifter have been designed and built.

The phase-shifter device consists of a high power, ferrite loaded strip-line structure, which is magnetically biased by a pair of external coils (see figure 4). To achieve low RF losses in the ferrite region, high-quality RF ferrites specially developed by AFT for these purposes were used. With the correct bias point and a uniform field

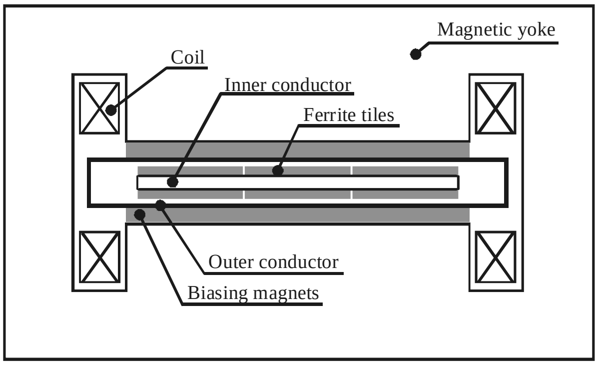

Figure 4: Cross section of the RF structure

(the working point is set above the gyromagnetic resonance), very low losses in the ferrite region were achieved. From measurements at high power it was shown that the RF losses in the low impedance strip-line structure are dominant in comparison to the ferrite losses.

The tuning speed of the phase-shifter is determined by the ability of the tuning magnetic field to penetrate into the ferrite region. The microwave part of the device requires a very rigid design (heat transfer, RF tightness). On the other hand, the magnetic design requires all structures surrounding the ferrite region to be as thin as possible (to minimize eddy currents).

A good compromise between these two requirements was found following numerous computer simulations using the ANSOFT's Maxwell 3D code. Inside the device, a special slotted structure suppressing the eddy currents is used. The inner and outer conductor of the strip-line structure is made of stainless steel, coated by a 20 µm thick silver layer.

Due to the large amount of energy stored in the coils, which must be shuffled between the coils and the power supply during the tuning process, a full four quadrant power supply has to be used.

MEASURED PERFORMANCE

For a tuning current range of –12 to +12A a phase-shift of 130 degrees was achieved. Phase tuning is very close to a linear function of the current, which is an advantage for the control system. The measured tuning frequency response of the ferrite tuner is shown in the figure 5, the high frequency cut-off coming mainly from the remaining eddy currents inside the RF structure.

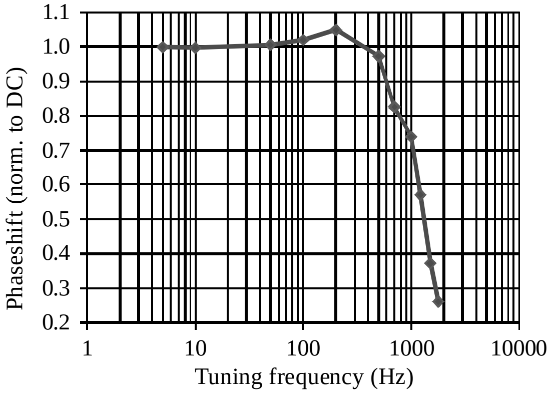

Figure 5: Tuning speed of the ferrite phase-shifters

A full tuner of the reflective type was built and tested. The transmission controlling capabilities of the tuner when working into a matched load is shown in figure 6. A photo of the phase-shifter device mounted on the WR-2300 waveguide is shown in figure 7.

ACKNOWLEDGEMENTS

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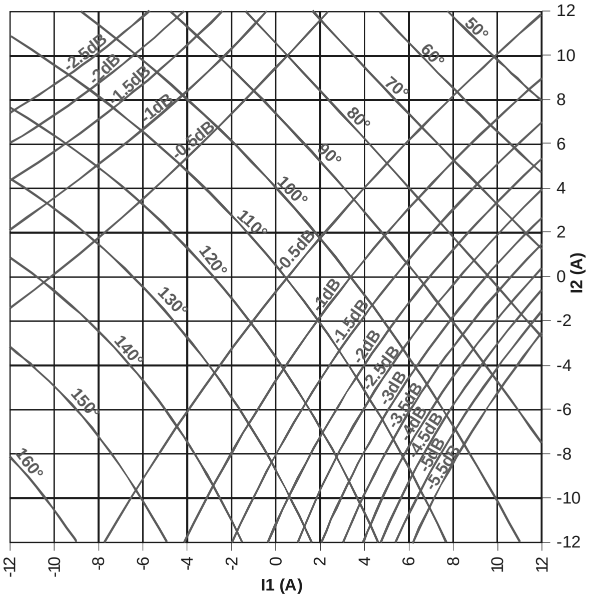

Figure 6: Measured transmission controlling capabilities. I_1 and I_2 are the phase-shifter's tuning currents.

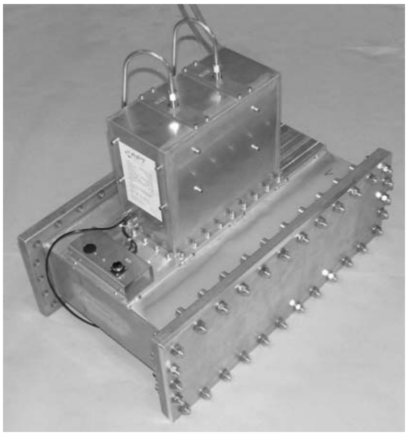

Figure 7: A built prototype of the phase-shifter

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