FAST PHASE AND AMPLITUDE MODULATOR FOR HIGH POWER RF APPLICATION

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Abstract:

In a high power RF system for particle accelerators, it is more economical to drive several superconducting cavities with a single high power transmitter, rather than use one transmitter per cavity. However, this solution requires the use of a fast RF phase and amplitude modulator connected between the transmitter and each cavity to allow independent control of the RF field.

1. INTRODUCTION

For an RF system of 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 however the disadvantage of not permitting individual control of the field in each cavity. When driven by a pulsed RF field, Lorentz forces excite periodical mechanical deformations which detune the cavity. Unluckily, the mechanical resonant frequencies of the cavities are in the same frequency range as the pulsing signal. These facts leads to instabilities and potentially to loss of control over the cavity [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).

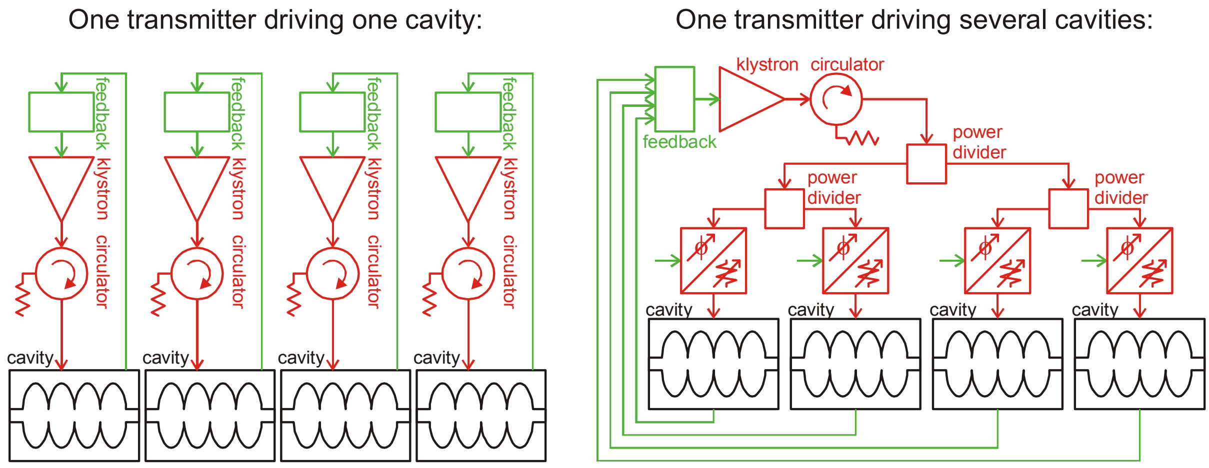


Fig. 1: Particle accelerator RF systems

For the Superconducting Proton Linac (SPL) [3], a new linear accelerator being studied at CERN, 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 SPL RF system are given in table 1.

Operating frequency	352MHz	Pulse repetition frequency	50Hz
Peak cavity power	250kW	Number of cavities	100-150
Transmitter power	max. 1.2MW	Cavities per amplifier	4
RF pulse duration	<5ms	Q_{ext} of the cavity	$2x10^6$

Table 1: Basic technical parameters of the SPL accelerator RF system

2. RF PHASE AND AMPLITUDE MODULATOR

The RF phase and amplitude modulator splits the incident RF wave into two identical in-phase components. These are phase shifted and combined again into one output wave. When driving phase-shifters “in phase”, the phase of the signal can be controlled. When driving phase-shifters “in anti-phase”, the amplitude of the signal can be controlled. By a combination of these two tuning modes, both phase and amplitude of the RF wave can be controlled simultaneously. Two different setups of the phase and amplitude tuner have been studied.

2.1. Modulator type one

Setup #1 (see figure 2), is more complex, and consist of a two magic tees, two transmission type phase-shifters and two dummy loads. This structure can handle easily any output load, because the difference between incident and outgoing power is dissipated in one of the magic tee’s loads. A modulator of this type is matched on both sides for all working points.

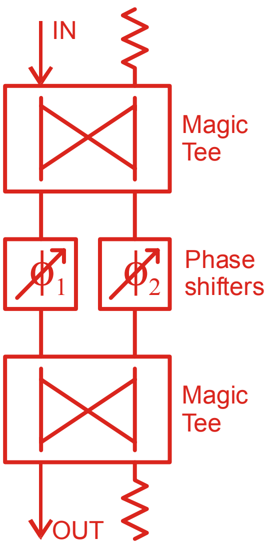


Fig. 2

Apart from increased complexity, the disadvantage of the two-magic tees setup is the use of the transmission type phase-shifters. For frequencies around 352MHz and power levels of 250kW, it is very difficult, if not impossible to build fast phase-shifter for a reasonable price (detailed information is in chapter 3).

The transmission of the device is described by formula:

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

and phase-shift of the device is given by:

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

The phase and amplitude control capabilities are shown in figure 3. Due to the limited range of the phase shift, provided by the phase-shifters, it is necessary to set a correct working point for each of the phase-shifters. In contrast to formulas {1} and {2}, the values shown in figure 3 are applicable for a permanent offset of a 90° applied to phase-shifter φ_2.

2.2. Second type of modulator

The setup #2 (see figure 4), consists of only one magic tee, and two reflecting phase-shifters. This is the smallest and lowest possible cost configuration.

A device of this type does not use any dummy loads, and the difference between the incident and transmitted wave is reflected back to the generator. Due to the circulator inserted between the klystron and the modulator, the wave reflected at the modulator input (S_{11}) presents no

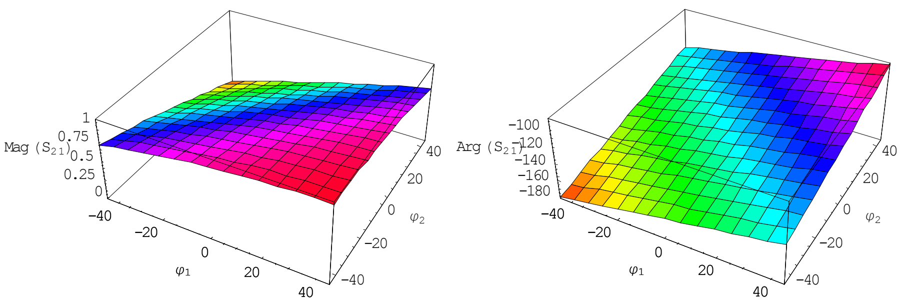


Fig. 3: Control capabilities of the device of first type

problem. Since the modulator device is fully reciprocal, the wave coming back from the cavity is partly re-reflected by a factor of $S_{22}=S_{11}$ at the modulator output. This means, the device's ports are not matched anymore.

A superconducting cavity resonator, with negligible beam loading, acts as a short circuit reflecting the full incident wave back to the generator. The transmission line between the modulator and the cavity will be unmatched at both ends. A detailed mathematical description of such a modulator is very extensive, so it will not be presented here. The system is not easily controllable and in the worst case can lead to instabilities. Its detailed behavior has to be studied further.

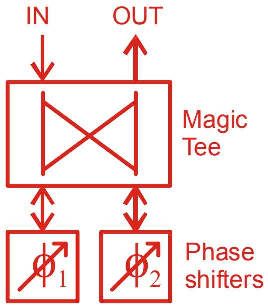


Fig. 4

Even when considering the very complex control system required, this configuration seems able to compete in terms of cost with the "one klystron per cavity" RF system configuration.

3. FAST FERRITE PHASE-SHIFTER

In collaboration with the German company Advanced Ferrite Technology (AFT) two fast ferrite phase-shifters were built. The phase-shifter device consists of the high power, ferrite loaded stripline structure, which is magnetically biased by the pair of external coils (see figure 5). To achieve low RF losses in the ferrite region, high-quality RF ferrites chosen from the AFT production line were used. With a correct bias point and a uniform field (the working point is set above the gyromagnetic resonance), very low losses in the ferrite region were achieved. By measurements at high power it was shown, that the RF losses in the stripline structure are dominant in comparison with 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 (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 stripline structure is made of stainless steel, coated by a 20μm thick silver layer.

Due to a 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 is used.

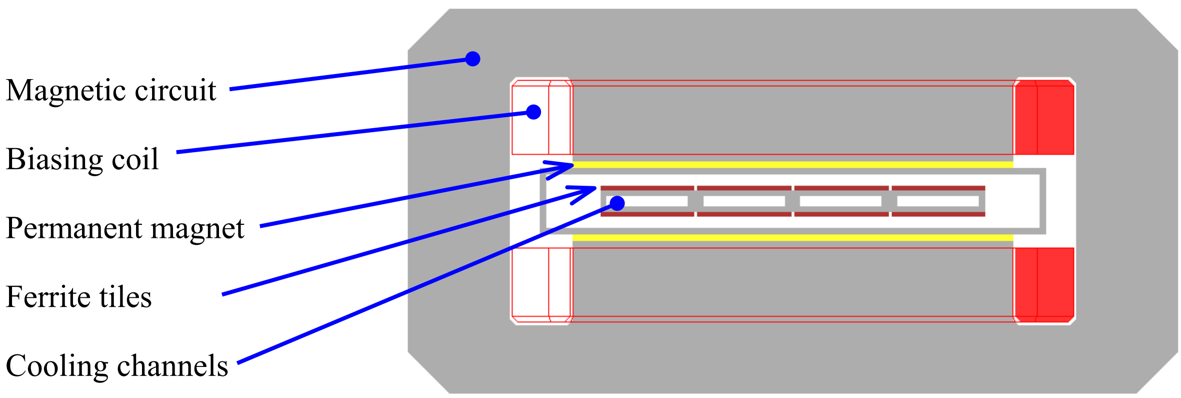
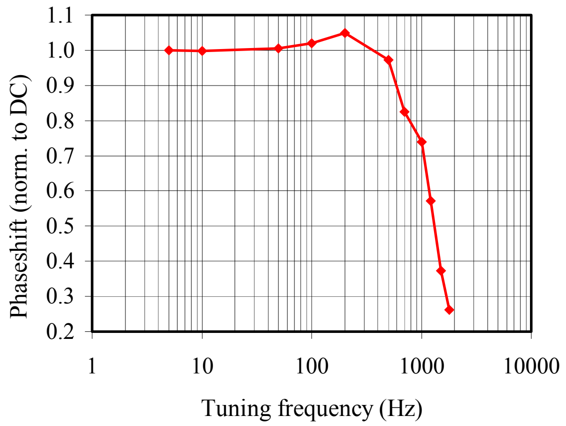


Fig. 5: Cross section of the phaseshifter's stripline structure



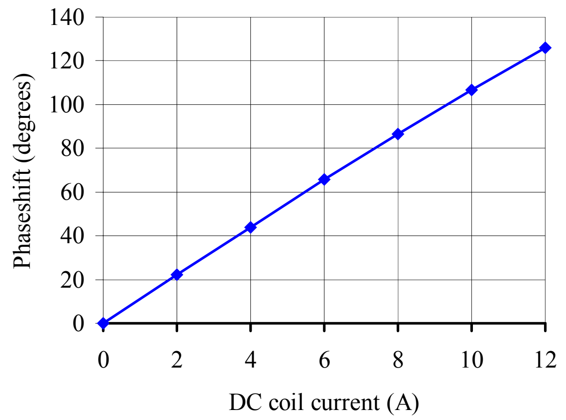


Fig. 6: Measured parameters of the phase-shifters

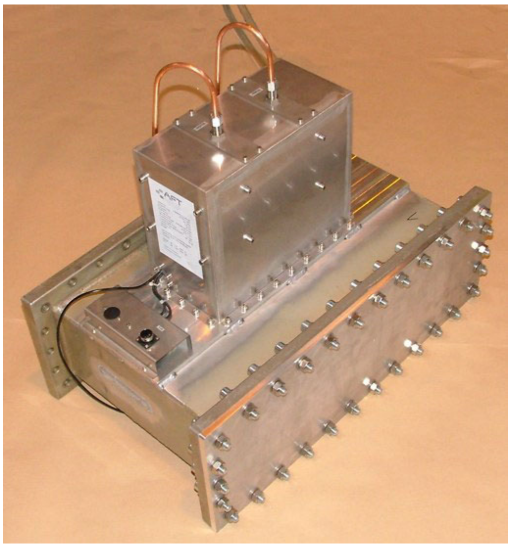


Fig. 7: Assembled phase-shifter

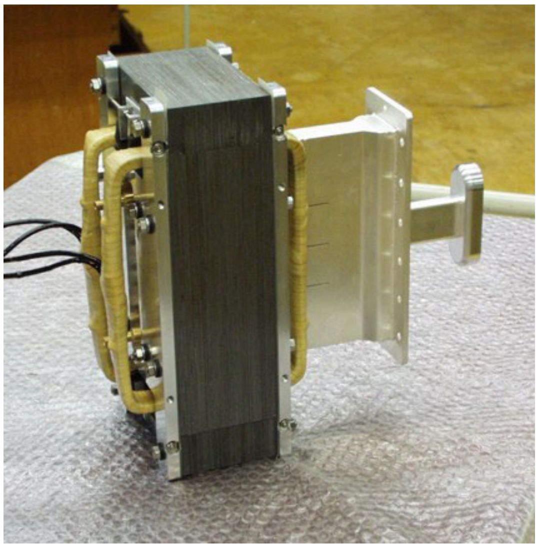


Fig. 8: Stripline structure

4. ACKNOWLEDGEMENTS

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