A DIPLEXER TO OPERATE TWO CAVITY EIGENMODES IN PARALLEL

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Abstract

To fulfil the demand of future high power and high luminosity FEL and storage ring sources, an intensive electron beam with short bunch length, small emittance and large bunch charge is required. Normal conducting (NC) laser driven radio frequency (RF) photocathode guns can deliver 1 nC bunches with an emittance of 1 π µrad. But to realize the demand on high average currents, a superconducting (SC) RF gun appears to be the best solution. First long term operation has been demonstrated at FZD [1]. In difference to the NCRF guns, the application of static magnetic fields near the cathode is not possible. Instead, the use of the magnetic field of a transverse electric (TE) mode in parallel to the accelerating mode was proposed. Numerical simulations have shown that this RF focusing can be applied to compensate the emittance growth [2].

This contribution will introduce a possibility to use the existing coaxial RF coupler of TESLA like cavities, as a RF power input for TE modes in parallel to its normal operation. The additional coupler component outside the module accomplishes the task of combining two different frequencies from different sources to one load. Thus, it corresponds to the working principle of a high power RF diplexer. Based on the $3^{1/2}$ cell Rossendorf SRF-Gun [3], a concrete technical implementation and results of its operation at the cold SRF-Gun cavity will be presented.

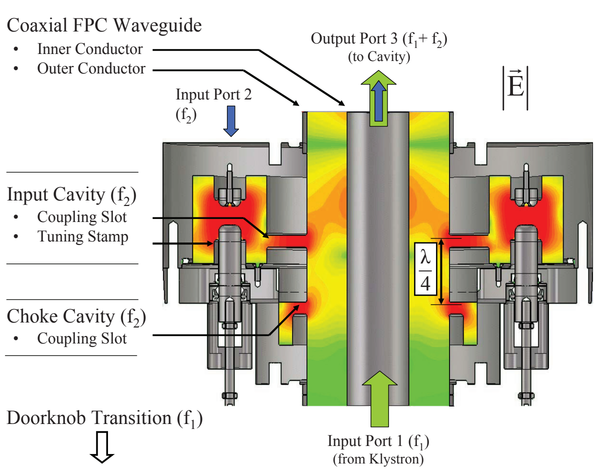

Figure 1: Cross section of the coaxial diplexer consisting of an input cavity and a reflecting choke cavity. The picture shows the simulated magnitude of the electric field @ 2.5 GHz for a random phase.

INTRODUCTION

In all presented SRF-Gun projects [4] so far, the emittance compensation is done by normal conducting and in parts also by superconducting static solenoid lenses placed at the output of the superconducting resonator. In this regard, the TE mode application offers some advantages:

- The magnetic field maximum can be placed near the cathode, which improves the compensation effect.
- No additional µ-metal shielding is needed, especially in contrast to the proposed SC solenoids.
- No additional mechanical adjustment is necessary.

In contrast to the π-mode, the magnetic field can be generated by a few hundred watts of RF power, which can easily be provided by commercial solid state amplifiers. Moreover, there is no phase stabilization and frequency tuning required. Only the stabilization of the amplitude needs to be realized. More theoretical background and different examples of engineering are presented in [5].

PRELIMINARY ANALYSIS

The focal length of the RF lens is composed by two parts. The static component just depends on the amplitude of the RF field, while the dynamic component varies with the frequency of the mode and its phase relation to the bunch [5]. The last part disappears under certain frequency and phase conditions of the mode, but in general the principle applies, the higher the frequency the smaller the dynamic fraction. Thus, a possibly high frequency should be chosen. However, this is not possible because the cut-off frequencies of the TE_{11} (2.25 GHz) and TM_{01} (2.94 GHz) waveguide modes are setting the upper limit, to avoid unnecessary damping. For this reason a TE_{011} cavity mode out of the first TE monopole pass band was chosen for closer consideration. The mode was previously identified by the bead pull analysis. The resonance frequency of f_2 = 2.5 GHz turns out to be favourable, because the commercial data communication in this field provides measurement- and amplifier technology at low cost.

To use the TE mode, it needs to be excited in parallel to the accelerating RF field. In principle, this task can be done by both the HOM couplers and the main coupler (FPC). Preliminary investigations at room temperature have shown that HOM couplers are inappropriate for this purpose. Their measured external quality factor of Q_{ext} = 4E+06 is too low. The FPC instead, met the required criterion for low power demand and a bandwidth of about 10 Hz. Its measured coupling factor is in the order of the intrinsic one. Since the main coupler is also a carrier of the fundamental mode (f_1 = 1.3 GHz), a possibility to transport two different high-frequency waves at the same signal path is required. In RF technology, such components are known as frequency diplexers and available in different versions. Unfortunately, none of the commercially available models meet the given boundary conditions and thus an in-house development was required.

BOUNDARY CONDITIONS

The complete signal path from klystron to FPC via WR650 waveguides and waveguide transition is optimized for a frequency of f_1 = 1.3 GHz and a power of at least 10 kW. This results in some problems especially at higher frequencies. The WR650 waveguide carries at least six higher waveguide modes at the frequency of the selected TE_{011} pass band near f_2 = 2.5 GHz. This results in an unpredictable mode coupling in the waveguide bends and in the coaxial waveguide transition to the FPC. As a consequence the transmission loss increases unacceptably. For this reason, a rectangular waveguide diplexer is excluded. At first glance the same is true also for the coaxial FPC, because it also carries the TE_{11} mode of circular waveguides. In the lower part of the coupler its cut-off frequency is about 1.76 GHz, but because of the decreasing diameter the frequency rises to about 3 GHz. For this reason an excitation of the TE_{11} waveguide mode in the lower part of the FPC will result in an unacceptable high attenuation at 2.5 GHz. To avoid this problem, the simplest way is to ensure the rotational symmetric excitation of the undamped coaxial TEM waveguide mode. In summary, the diplexer needs to fulfil the following boundary conditions:

1. Generation of a rotationally symmetric TEM field distribution even though the coaxial waveguide has a multimode character.
2. High isolation and low insertion loss between both frequencies and thus suitability for high RF power up to 10 kW CW (L-Band).
3. Simple and cost effective integration into the existing waveguide structure without changing the resonator or other cold parts of the coupler.

BASIC CONCEPT

The boundary conditions mentioned above are fulfilled by a cylindrical cavity structure, called “Cavity Diplexer”. The structure is arranged around the lower warm part of the coaxial waveguide. A 3D cross section including a MWS© field simulation is shown in Figure 1. The inner radius of the input cavity is specified by the mantle of the waveguide (outer conductor), while the outer one is defined by the axially symmetric TM_{0x0} Eigen mode frequency f_2 that need to be coupled in. The excitation of this mode is done either inductive or capacitive using one or more adjustable antennas. A gap in the mantle of the waveguide provides the coupling to the input cavity. The resulting energy transport is divided into two equal parts (3dB) to port 1 and port 3. The height of the gap determines the coupling bandwidth, i.e. the smaller the gap the smaller the bandwidth. A second resonator (choke cavity) placed at a distance of λ/4 next to the first one, interacts as an imaginary short-circuit. Thus, the RF wave running to port 1 is fully reflected and constructively superimposed with the second part running to port 3. For best reflectivity the field of the choke mode needs to be axially symmetric and its frequency has to be equal to the input cavity. The advantage of this concept is the well defined coupling to the TEM fundamental wave even if a coaxial multimode waveguide carries more than one mode, as it is the case in the warm part of the SRF-Gun FPC at f_2 = 2.5 GHz.

PRACTICAL REALIZATION

RF Modelling

To adapt the basic diplexer concept to the real world of the SRF-Gun, the modelling and optimization was done by CST Microwave Studio©. Out of this development process, the following expediencies can be separated.

To fulfil the first boundary condition, it is reasonable to create the input cavity for the TM_{020} mode resonance at 2.5 GHz. Higher monopole modes would unnecessarily increase the diameter, while the geometry of a TM_{010} mode at the same frequency does not provide enough room for tuners and input antennas. However, this leads to a problem in satisfying the second boundary condition, because the TM_{010} mode is in the range of the frequency f_1. In order to still realize a high isolation and low insertion loss at the same time, this mode has to be selectively detuned to lower frequencies. This is done by changing the volume ΔV in significant field areas (see Eq. 1), as it is stated by the Slater theorem [6].

$$\omega^2 = \omega_0^2 \left(1 + \int_{\Delta V} \left(H_N^2 - E_N^2 \right) dV \right) \tag{1}$$

According to this, the volume reduction in a region of the electric field E_N consequently causes a negative frequency shift. Since both modes have different field distributions, the troubling mode can be detuned while the frequency of the desired one keeps nearly unchanged.

To realize the focussing field strength of about 300 mT, an RF power up to few 100 W is needed. This power is symmetrically divided by a Wilkinson Power Splitter to both capacitively coupled coaxial 50 Ω SMA input antennas. To suppress an unwanted excitation of the TM_{120}-dipol mode (f_{TM120}=2.57 GHz) beside to the TM_{020} frequency the phase angle needs to be equal in both feed lines. To compensate for manufacturing tolerances in both the input and the choke cavity two axially movable tuning plugs are provided. Additionally, these plugs enable a slight separation between the TM_{020} and the TM_{120} mode resonances; otherwise they would have the same frequency.

CAD Construction

Based on the MWS© optimized volume model, the CAD engineering was expanded to fulfil additional requirements. Beside the typical demand on ease of assembly and mechanical stability, all materials, feed troughs and seals are suitable for a high vacuum down to 1E-07 mbar. In order to reduce RF losses and to avoid high peak fields, the entire inner surface is polished and all edges are provided with a radius of 1-3 mm.

The diplexer is realized as a warm part outside of the cryomodule. In order to allow subsequent installation the interfaces to both the doorknob transition and the main coupler are designed to keep those untouched. Hence, the diplexer easily fits to the SRF-Gun which finally fulfils also the last requirement mentioned above. After finishing the design, the complete 3D CAD model was transferred back into MWS© to verify the s-parameters once again (see upper part of Fig. 2). Compared to the simplified model only small deviations were noted. Also further simulations concerning multipacting, electric peak fields and the thermal behaviour did not indicate any restriction of the application.

MEASUREMENTS

After machining and clean room assembly, the s-parameters were determined experimentally. For this purpose an idealized test setup was used to ensure the rotational symmetry by using special coaxial measurement transitions. Compared to the previously simulated results the measurements demonstrate an excellent agreement. Both, the isolation damping and the insertion loss correspond to the predictions and thus completely fulfil all requirements (Fig. 2).

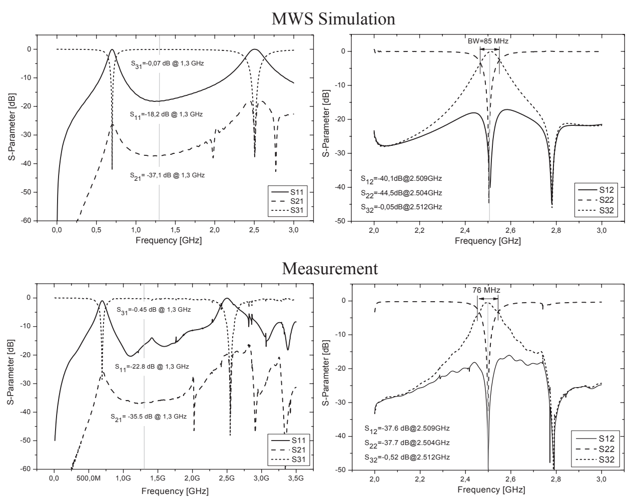

Figure 2: Comparison of the simulated and measured s-parameter set using port 1 (left diagrams) and port 2 (right diagrams) for RF power input. Reflection and transmission coefficients are marked for both frequencies f_1 and f_2.

Cold Cavity

The following installation at the SRF-Gun was carried out without any problems. The diplexer perfectly fits into the FPC signal path (see Fig. 3). During the subsequent RF tests both modes were excited in parallel for the first time. About 10 W (f_2 = 2.5 GHz) could be transferred into the cavity. The power was divided onto both input antennas. The corresponding reflection coefficient seen by the amplifier was S_{11} = 0.7. A better matching can be achieved by using a double-stub tuner working as a matching network. The axial field strength of the TE_{011} mode achieved in this way was limited to 10 - 20 mT. The reason is that most of the RF power is transferred out of the HOM coupler or dissipated in normal conducting parts. For example, a significant increase in temperature was detected at the beam pipe. Both effects will be examined more closely in the future.

Nevertheless, the preliminary results show that the investigated SRF-Gun cavity is not suitable for TE mode focusing. The achievable field is still too low to observe any improvement of the beam quality. In this regard a cavity is under fabrication at the Jefferson Laboratory, whose modified coupler section will not show any of these damping mechanisms [7].

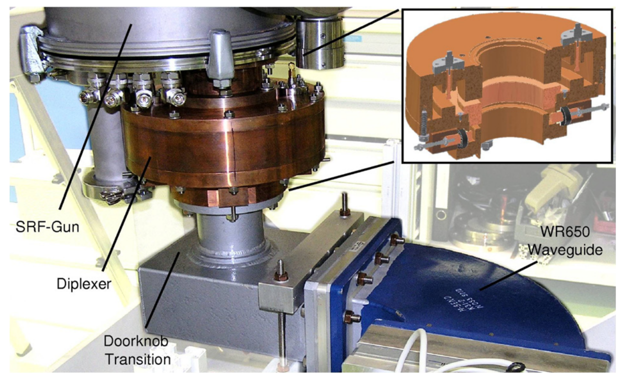

Figure 3: The diplexer after its assembly in between the doorknob transition and the SRF-Gun cryomodule.

SUMMARY

The diplexer presented here was able to fully confirm its anticipated functionality during both the S-parameter measurement and the cold test at the SRF-Gun cavity. During this test a TE mode was excited in parallel to the fundamental mode while the normal operation kept unaffected. The achieved field strength of the TE mode was limited by damping of the assembled HOM couplers and normal conducting parts inside the cavity beam pipe. The new cavity combined with the developed diplexer will be a promising candidate to demonstrate the focussing effect of TE modes at superconducting electron sources for the first time.

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