SUPERCONDUCTING TRAVELING WAVE CAVITY TUNING STUDIES*

R. Kostin[1†], A. Kanareykin[1], St. Petersburg Electrotechnical University LETI, St.Petersburg, Russia
P. Avrakhov, Euclid Techlabs, Bolingbrook, IL, USA
V. Yakovlev, N. Solyak, Fermilab, Batavia, IL, USA
[1]also at Euclid Techlabs, Bolingbrook, IL, USA

Abstract

Superconducting traveling wave cavity (SCTW) can provide 1.2-1.4 times larger accelerating gradient than conventional standing wave SRF cavities [1]. Firstly, traveling wave opens the way to use other than Pi-mode phase advance per cell which increase transit time factor. Secondly, traveling wave is not so sensitive to cavity length as standing wave, which length is limited to 1 meter because of field flatness degradation. 3 cell SCTW cavity was proposed [2] and built for high gradient traveling wave demonstration and tuning studies. This paper describes analytical model that was used for cavity development. Tuning properties and requirements are also discussed.

INTRODUCTION

The accelerating gradient in RF cavities plays a key role in high energy accelerators [3], since the cost of the project is highly dependent on its length. The current design of an SRF based linear collider uses superconducting Tesla type [4] accelerating cavities with accelerating gradients of 31 MV/m. The Tesla cavity length is restricted to 1 meter because of field flatness degradation and consists of only 9 cells. There is an unavoidable gap between cavities which decreases the average accelerating gradient.

A superconducting traveling wave cavity (SCTW) was proposed to increase the accelerating gradient [1]. However, it requires a feedback waveguide to transfer RF power from the output of the cavity back to its input section. Traveling wave (TW) cavities have lower field flatness sensitivity to the cavity length and, thus can be much longer. Our investigations showed [5] that a 10 meter long TW cavity would have a better field flatness than even a 1 meter standing wave (SW) cavity if it can be fabricated and cleaned with the required tolerances. Thus, if the technology allows building such a long cavity it might increase the accelerating gradient by 22% eliminating beam pipes empty of RF power between cavities. A TW cavity can operate at any phase advance, and, as is well known, a smaller phase advance provides a higher transit time factor. We investigated the phase advance dependence on the accelerating gradient of the SCTW cavity and it was found that 105 degrees gives an optimal accelerating gradient gain of 24% [5]. Overall, a TW cavity may increase the gradient by up to 46% compared to a conventional SW cavity.

The first approach to a TW cavity was a single cell cavity. It was manufactured to prove the feasibility of cleaning the feedback waveguide. The cavity was cleaned at Argonne National Lab and tested at Fermilab at the vertical test stand in liquid helium. A 26 MV/m accelerating gradient was reached [5], which is comparable to Tesla single cell cavities with the same treatment. This opened the way to build a next generation TW cavity – a 3-Cell SCTW cavity [2] to demonstrate operation in the TW regime in a superconducting cavity with a high gradient. Two cavities were built. Traveling wave was successfully adjusted in one of them at room temperature [6]. The other cavity will be tested in liquid helium and requires siffening ribs on the waveguide. The welding process will be finished by Fall 2016.

Tuning properties of the 3-Cell TW cavity were investigated [7, 8]. Analytical model of 3-Cell traveling cavity which was used in these studies is presented and discussed in the paper. It was found that suppression of microphonics caused by external pressure variation is possible by power redistribution in the input couplers. A feeding scheme with power redistribution capability is proposed and discussed. A 2D tuner required for Lorentz force compensation was designed, manufactured and tested [9]. Its analytical representation in the model is also presented.

ANALYTICAL MODEL

Analytical model was created to investigate traveling wave adjustment in resonator with feedback waveguide and at the same time include effects of mechanical deformations, such as microphonics, Lorentz force and tuner. The model is based on S-matrix formalism and utilizes S-parameters calculated in finite element (FE) codes. The model is suitable for any resonator but will be discussed in details on example of the 3-cell SCTW cavity which schematic is depicted on Figure 1.

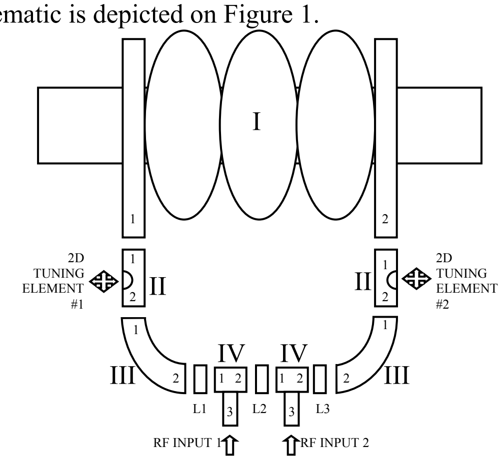

Figure 1: 3-Cell schematic for analytical model.

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† r.kostin@euclidtechlabs.com

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The 3-Cell SCTW cavity analytical model contains four main elements: particle acceleration part (I), tuner (II), waveguide bend (III) and a power coupler (IV). Straight waveguide inserts (L_i) can be added mathematically between those elements. As well known, cavity with feedback waveguide resonant frequency corresponds to its electrical length which should be multiple of 2π. Thus, cavity can be adjusted mathematically by changing electrical length of the inserts without any additional calculations in FEM software. Also, main elements position along the cavity can be changed by the inserts which is very helpful and does not require any calculation. It is only required to solve a matrix equation of the model to get information about circulating waves in the cavity. The matrix equation of the 3-Cell analytical model is shown below.

$$\begin{pmatrix}
-1 & 0 & S_{12}^{I} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{11}^{I} \\
0 & -1 & S_{22}^{I} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{21}^{I} \\
0 & S_{11}^{II} & -1 & 0 & S_{12}^{II} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & S_{21}^{II} & 0 & -1 & S_{22}^{I} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & S_{11}^{III} & -1 & 0 & S_{12}^{III} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & S_{21}^{III} & 0 & -1 & S_{22}^{III} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & S_{22}^{IV} & -1 & 0 & S_{21}^{IV} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & S_{12}^{IV} & 0 & -1 & S_{11}^{IV} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{22}^{IV} & -1 & 0 & S_{21}^{IV} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{12}^{IV} & 0 & -1 & S_{11}^{IV} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{22}^{III} & -1 & 0 & S_{21}^{III} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{12}^{III} & 0 & -1 & S_{11}^{III} & 0 \\
S_{21}^{II} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{11}^{III} & -1 & 0 \\
S_{11}^{II} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{12}^{II} & 0 & -1
\end{pmatrix} \times \vec{a} = \begin{pmatrix}
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ S_{23}^{IV}\cdot A \\ S_{13}^{IV}\cdot A \\ S_{23}^{IV}\cdot B \\ S_{13}^{IV}\cdot B \\ 0 \\ 0 \\ 0 \\ 0
\end{pmatrix}$$

A and B in the excitation vector are the signals from RF input 1 and 2. They are complex numbers, i.e. they have amplitude and phase and it is possible to change them for tuning purposes. S-parameters of the main elements were calculated in frequency range. It is also possible to implement S-parameters dependence on any external effect which can change them. For example, it can be external pressure variation (microphonics), Lorentz force or waveguide deformation by a tuner. All of these effects were integrated in the model. Thus, S-parameters in the model are functions of frequency and external parameters, such as pressure, acceleration gradient, and amplitude of waveguide deformation. The effect of external pressure variation was analyzed and it was found that it can be compensated by amplitude and phase redistribution (A and B signals) in input cavity ports [7, 8]. Lorentz force compensation requires waveguide deformation with the tuner. Not only is amplitude of reflection produced by the tuner important but also a phase. That is why the tuner called "a 2d tuner", because it can deform the waveguide and it is also capable to move along the waveguide. Required amplitude of reflection obtained by amplitude of deformation, phase of reflection obtained by position of waveguide deformation. The tuner was successfully built and tested [9].

S-PARAMETERS CHANGE BY "2D TUNER"

A coupled multi-physics analysis was done in order to insert the tuner into the model. The model consists of the part of the waveguide, its vacuum volume and a ball bearing #6904 which deforms the waveguide. Material properties of the waveguide correspond to Nb at 2K. S-parameters of non-deformed waveguide were found at first. Then the model was transferred to static structural analysis where the wall deformation was simulated. After that, the deformed geometry was sent back to electromagnetic module to analyze S-parameters change. It was found that S-parameters amplitude and phase linearly depend on the amplitude of deformation, and can be characterized by the curve slope which different for different frequencies and is depicted on Figure 2.

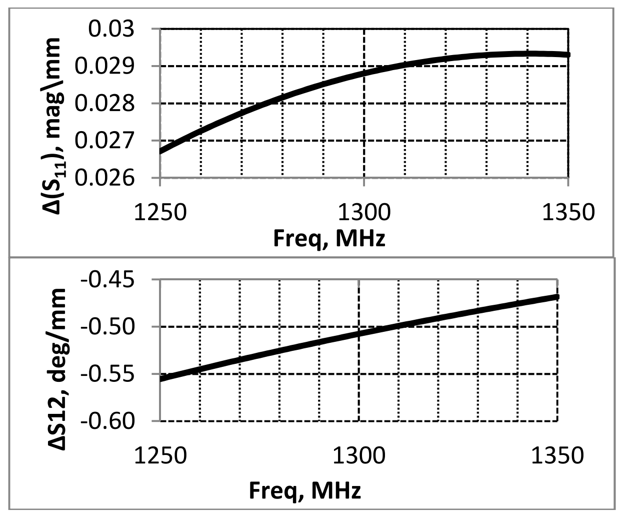

Figure 2: Normalized reflection and phase change as a function of frequency.

TRAVELING WAVE AT ROOM TEMPERATURE

The analytical model was used to predict the required parameters for traveling wave excitation in the 3-Cell SCTW cavity for room temperature test, which was successfully done [6]. It was found that amplitude and phase variation of input signals was enough to highly damp a backward wave which is shown on Figure 3. Input signal parameters found from the model was used in HFSS simulation and a TW regime was obtained, see Figure 5.

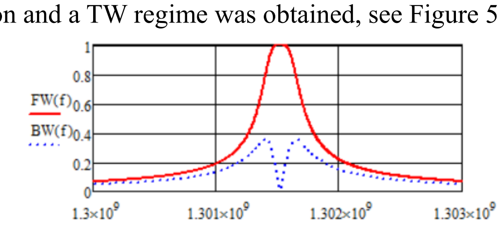

Figure 3: Normalized amplitudes of forward (FW) and backward (BW) waves in the 3-Cell cavity at room temperature with highly damped backward wave.

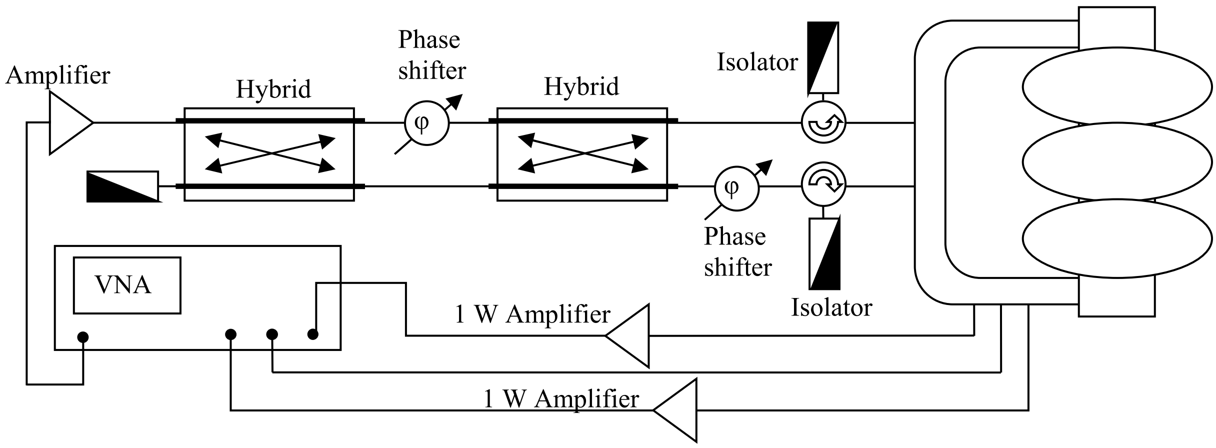

Figure 4: 3-Cell superconducting traveling wave cavity feeding and measurement scheme.

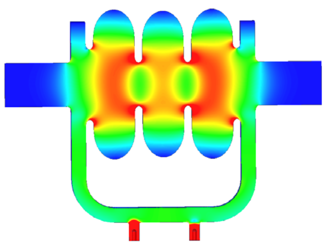

Figure 5: Distribution of E-field complex magnitude in the 3-Cell traveling wave cavity at room temperature.

FEEDING SCHEME

One of the tuning features of a superconducting traveling wave cavity with feedback waveguide with at least two power couplers is a redistribution of amplitude and phase in the couplers. As long as 3-Cell superconducting traveling wave cavity will be tested in helium at Fermilab vertical test stand with a 500W RF power supply all the components of feeding scheme should be able to withstand up to 300W CW RF power. A feeding scheme capable to withstand this level with power redistribution feature is depicted on Figure 4. It consists of a main power amplifier, two hybrids, two trombone phase shifters, two isolators (circulator with RF load) in a feeding part of the scheme. The first hybrid equally divides the input signal between two channels but adds 90/180 degree phase advance to one of them. One of the phase shifters is located between two hybrids. It is possible to redistribute power in the second hybrid in any proportion by changing phase on the first phase shifter. The second phase shifter is required to set a proper phase between two channels. A measurement part of the scheme consists of two low power amplifiers. They are required only for room temperature test. The measurement signals go directly to VNA for further post processing, i.e. their sum and difference with 90 degree phase advance is required to restore information about traveling in both direction waves. This step can be done by hybrid and is more attractive. Hybrid can be installed closer to the cavity and summarize/subtract signals much earlier eliminating phase errors.

CONCLUSION

A special analytical model, based on S-matrix formalism was created to analyze traveling wave excitation in 3-Cell superconducting traveling wave cavity at different conditions. The model includes such effects as microphonics, Lorentz force detuning and influence of a 2D tuner. The tuner was calculated by coupled electromagnetic and structural analysis which simulates effect of waveguide wall deformation on propagating H_{10} mode S-parameters. The model was used to find traveling wave parameters at room temperature and HFSS simulation showed the TW regime at the predicted frequency with the predicted amplitude and phase input signals. A special feeding scheme with power redistribution capability was proposed and discussed in the paper. This scheme was successfully used for traveling wave excitation in 3-Cell niobium traveling wave cavity at room temperature [6].

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