EXCITATION OF A TRAVELING WAVE IN A SUPERCONDUCTING STRUCTURE WITH FEEDBACK*

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Abstract

The accelerating gradient required for the ILC project exceeds 30 MeV/m. With current technology the maximum acceleration gradient in SC structures is determined mainly by the value of the surface RF magnetic field. In order to increase the gradient, the RF magnetic field is distributed homogeneously over the cavity surface (low-loss structure), and coupling to the beam is improved by introducing aperture "noses" (re-entrant structure). These features allow gradients in excess of 50 MeV/m to be obtained for a singe-cell cavity. Further improvement of the coupling to the beam may be achieved by using a TW SC structure with small phase advance per cell. We have demonstrated that an additional gradient increase by up to 46% may be possible if a π/2 TW SC structure is employed. However, a TW SC structure requires a SC feedback waveguide to return the few GW of circulating RF power from the structure output back to the structure input. Advantages and limitations of different techniques of exciting the traveling wave in this structure are considered, including an analysis of mechanical tolerances. We also report on investigations of transient processes in the SC TW structure.

INTRODUCTION

The principal goal of this project is the development and experimental demonstration of a Superconducting Traveling Wave Accelerating structure. The proposed SC TW structure has crucial advantages compared to standing wave (SW) designs like the recently developed re-entrant cavity (that in turn has significant advantages over the original 9-cell TESLA cavity). The primary STWA advantage is an increased accelerating gradient, up to a factor 1.24 while maintaining the same cavity magnetic and electrical surface field ratios E_{peak}/E_{acc} and B_{peak}/E_{acc} as the re-entrant SW structure. In this project, a SC TW Accelerating structure is being manufactured. We plan to optimize the proposed SC TW cavity geometry to achieve the maximum available accelerating gradient for a given cavity surface field strength. A collaboration of Euclid Techlabs, AES, Inc. and FNAL is currently working to design and manufacture a prototype single-cell superconducting cavity with the feedback waveguide required for operation of the traveling wave device.

GENERAL

A variety of techniques have been developed to increase the achievable accelerating gradient in the RF system of the ILC [1-7]. The maximum gradient demonstrated in a one-cell cavity is 54 MeV/m for an aperture of 70 mm [5] and 59 MeV/m for an aperture of 60 mm [6]. SW SC 9-cell RF cavities are planned to be used in the ILC Main Linac. The phase advance per cell in this design is π, but a SW π-structure has the following limitations [8, 9]: (a) a considerably small transit time factor; (b) poor stability of the field distribution to small geometrical perturbations. (c) trapped modes.

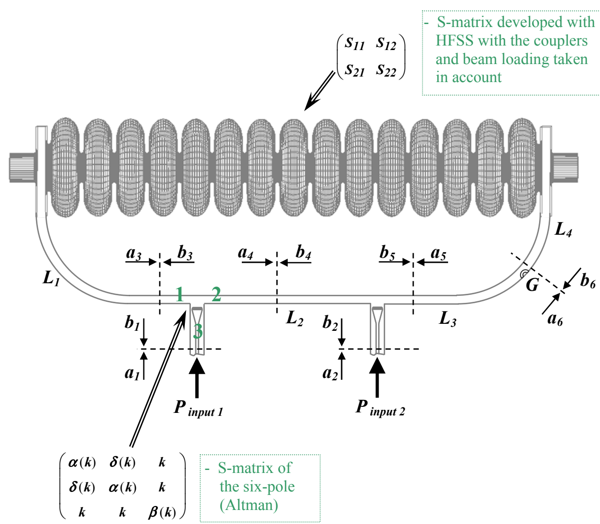

Figure 1: Two-coupler model of the resonant travelling wave feedback ring and STWA cavity.

An alternative approach is a superconducting traveling wave acceleration structure (SCTW). Recently a SC TW structure with feedback waveguide intended for ILC applications has been suggested [8,9]. Initially the superconducting traveling-wave accelerator with feedback was considered in [10]. The SCTW structure schematic with a two coupler powering scheme is presented in Fig. 1. The proposed SC TW structure benefits have been discussed in [11,12]. Meanwhile, employing the SC TW design also has some significant trade-offs: (1) a SCTW structure has a negligibly small RF field attenuation, and thus, use of high power feedback is necessary; (2) a tuning procedure especially designed for the TW SC structure has to be developed.

The resonant ring can be fed by one, two or more RF couplers depending on the accelerating section length and acceptable power level of the couplers. We will examine in detail one- and two-coupler feed schemes.

The first scheme uses two input couplers that excite independently both partial standing waves comprising the

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resulting traveling wave. Each input coupler supplies half of the total power. The phases of the partial modes are shifted by of about π/2. In addition, the first scheme (see Fig. 1) includes the structure, the feedback couplers, the feedback waveguide, and a special matching element ("matcher") that compensates reflections caused the input couplers, system imperfections, tuning errors, etc.

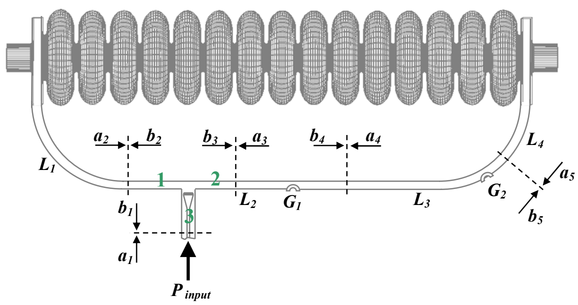

Figure 2. One-coupler model of the resonant travelling wave ring with the SC TW structure.

The following notation is used: L_1, L_2, L_3 and L_4 – the lengths of the waveguide sections between the resonant ring elements; G – matcher reflection coefficient; $\alpha(k)$ – reflection from the shoulders 1 and 2 of the T-joint; $\beta(k)$ – reflection from the shoulder 3; $\delta(k)$ – transmission from the shoulder 1 to shoulder 2; k – transmission from the shoulder 3 to 1 and 2 of the T-joint.

Table 1: Parameters of the two input coupler powering scheme.

Parameter	Tolerance	P_{add} (%)	U_b/U_f(%)
$\Delta L/$	$3.23\cdot10^{-6}$	10	0.03
$\Delta L_2/L_2$	$3.7\cdot10^{-2}$	5	5
$\Delta L_4/L_4$	$2.59\cdot10^{-5}$	0.25	5
$\Delta k/k$	0.0475	0.95	5
$\Delta\varphi$	± 2.86 deg.	0.12	5
$\Delta\Gamma/\Gamma$	$4.07\cdot10^{-4}$	0.25	5
$\Delta Q_{ext}/Q_{ext}$	0.33	10	0
Δf_0	± 106 Hz	10	1.17

The scattering matrix formalism is used for the system analysis. Each element is characterized by its own scattering matrix that depends on the element properties and its location in the system as shown in Fig. 1. The S-matrix of the structure and the feedback coupler is calculated numerically [12,13]. Beam loading is taken into account. The input coupler is described by a six-pole matrix. The feedback waveguides are 160 mm wide and exhibit normal dispersion.

The proposed model can be fully described by a system of equations with the right-hand element at any point along the frequency scale. The bandwidth is rather narrow, ~ 10^{-6} for these types of devices (T-joint and matcher) and the S-matrix elements do not depend on the frequency [12,13].

The system of linear equations of the resonance ring has been published in [12,13]. We present here the preliminary numerical simulation results for the resonance ring with a 15 cell accelerating structure ~1 m length. After choosing the input coupling, matcher reflection and relative phase and amplitudes of the input waves we can adjust the resonant ring, i.e. for zero power reflection and zero backward wave into the TW section. The reflection coefficient is -30.46 dB at 1300 MHz, φ = 105º, R_{sh}/Q = 1808 Ω, loaded with the beam current I_{beam}= 9mA at the accelerating gradient 31.5 MeV/m.

Consider the first powering scheme (Fig.1) that uses two input couplers that excite both partial standing waves independently. The results of the modeling are shown in Table 1, where $\Delta L/L$ – waveguide loop length, $\Delta L_2/L_2$ – distance between couplers, $\Delta k/k$ – input port coupling, $\Delta\varphi$ – port phase difference, $\Delta G/G$ – matcher reflection, $\Delta Q_{ext}/Q_{ext}$ – loaded Q factor, Δf_0 – resonant frequency detuning.

Table 2: Single input coupler powering scheme parameters.

Parameter	Tolerance	P_{add} (%)	U_b/U_f(%)
$\Delta L/L$	$2.42\cdot10^{-7}$	0.06	5
$\Delta L_2/L_2$	$4.5\cdot10^{-3}$	1	5
$\Delta L_4/L_4$	$2.76\cdot10^{-5}$	0.27	5
$\Delta k/k$	0.1	4.76	5
$\Delta G_1/G_1$	$2\cdot10^{-2}$	0.23	5
$\Delta G_2/G_2$	$1.6\cdot10^{-4}$	0.23	5
$\Delta Q_{ext}/Q_{ext}$	0.047	0.06	5
Δf_0	± 8.1 Hz	0.06	5

If we suppose that an acceptable level of backward wave present in the section is 5% and the margin of power does not exceed 10%, the required tolerance of the ring parameters is presented in Table 1. The third and fourth columns show the additional power required for keeping the fixed accelerating gradient and to control the value of backward wave at the accelerating section with the tolerances presented in the second column. As shown, the most precision and accuracy is needed for resonant ring frequency detuning. For a 1330 mm ($4\cdot\lambda_{wg}$) waveguide loop length the acceptable error is dL/L ~ $3.23\cdot10^{-6}$ or ±106 Hz detuning of the resonant ring frequency.

It should be noted that with the proposed powering scheme there is no necessity for a high tuning frequency adjustment of the accelerating section itself at the chosen operational mode. The bandwidth of the coupling section of the structure and the additional phase advance due to the cavity frequency shift give a much smaller effect (by a few orders of magnitude) than the resonance ring frequency shift or the backward wave detuning. It is enough to control the overall resonant frequency and the backward wave suppression to achieve the standard operational parameters.

The second scheme uses only one input coupler and special matcher, which splits the normal SW mode of resonant ring into two frequency shifted SW modes, Fig 2.

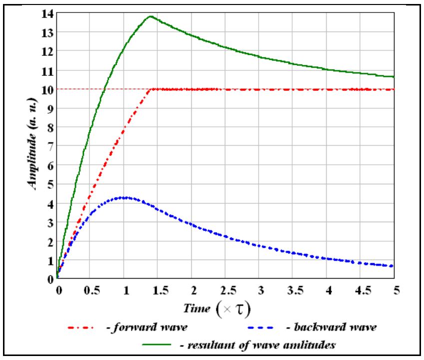

Figure 3: Transition process for the single coupler powering scheme with beam loading: (a) forward (red), backward (blue) and resultant (green) wave amplitudes at the resonance ring.

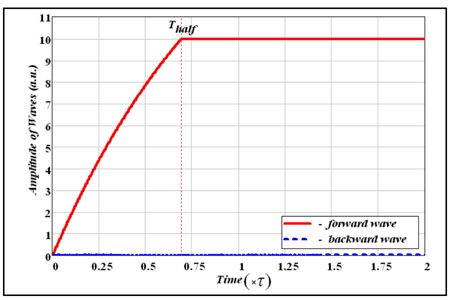

Figure 4: Transition process for the two coupler powering scheme with beam loading: (a) forward (red), backward (blue) wave amplitudes at the resonance ring.

These modes are excited with equal amplitudes and phase advance of 90º with respect to each other. Their superposition is a travelling wave propagating along the ring. Our investigation showed that it is better to use an additional matcher G_2 to independently adjust the reflection from the TW section.

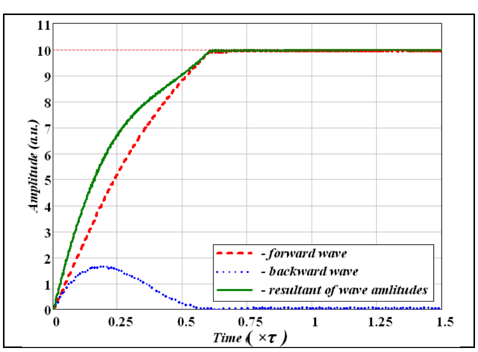

Figure 5: Transition process for the single coupler powering scheme with beam loading if the structure is tuned with the matcher: forward (red), backward (blue) and resultant wave amplitudes at the resonance ring.

Table 2 presents the parameters of the one coupler feed scheme. Note the ±8 Hz resonant ring frequency detuning of the single coupler powering design, Table 2. The tolerance analysis showed that two-coupler scheme is more stable versus the structure parameter perturbations. At the same time, one can utilize this more simple and inexpensive powering scheme if a matcher (piezo-tuning element) is employed.

Fig. 3 and Fig. 4 present the transition process of the beam loaded single coupler and two coupler powering schemes. One can see that two coupler scheme, Fig.4, exhibit significant advantages over the one-coupler feed, Fig.3 resulting in increased field enhancement for the one-coupler feed transition process. Fig. 5 shows the same process as Fig.3 but with a piezo-matcher used for reflection control for the transition time period that allows elimination of the over voltage enhancement for the one-coupler powering scheme as well.

CONCLUSION

Two methods of traveling wave excitation were considered in a Superconducting Traveling Wave Accelerating (STWA) structure with feedback waveguide: two-coupler and one-coupler schemes. A mathematical model was developed for both cases. Conditions are determined for pure traveling wave excitation in the system. The tolerance analysis was made for both cases, and it was shown that the two-coupler scheme is more stable with respect to perturbations of structure parameters. Transient processes of structure excitation were considered, and it is shown that the one-coupler scheme is not suitable because of a strong overvoltage during the transient process. The two-coupler scheme does not have this disadvantage. However, in order to use the simplicity of the one-coupler scheme compared to two-coupler scheme, a special fast tuning element (matcher) is suggested that changes the reflection properties during the transient process. It is shown that this fast matcher allows elimination of the overvoltage during the process of the structure filling.

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