# PROGRESS TOWARDS DEVELOPMENT OF AN L-BAND SC TRAVELING WAVE ACCELERATING STRUCTURE WITH FEEDBACK*

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## *Abstract*

In the ILC project the required accelerating gradient is higher than 30 MeV/m. For 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 single-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 $\pi/2$ 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. The test cavity with the feedback is designed to demonstrate the possibility of achieving a significantly higher gradient than existing SC structures.

## INTRODUCTION

The most serious problem of ILC is its high cost, resulting in part from the enormous length of the collider. This length is determined mainly by the achievable accelerating gradient in the RF system of the ILC. In turn, the accelerating gradient in a SC structure is limited mainly by quench, i.e., by the maximum surface RF magnetic field [1]. The following techniques have been developed to increase the gradient: (1) development of surface processing in order to avoid the field enhancement caused by surface microstructure. A recently developed electro-polishing technique [2] permits micro-tips only less than 0.1 micrometer [2]; (2) Improvement of niobium material. For example, large grain and mono-crystal materials are currently being considered [3]; (3) improvement of the structure shape in order to decrease the surface magnetic field for a given accelerating gradient. There are two ways to decrease the magnetic field: (1) develop a homogeneous magnetic field distribution over the cavity surface (Low-Loss structure [4], Ichiro structure [4], and Re-Entrant structure [5, 7]); (2) improvement of the beam interaction with the structure like increasing the transit time factor (Re-Entrant structure [5, 7]). The maximum gradient achieved in the one-cell cavity is 54 MeV/m for an aperture of 70 mm [5] and 59 MeV/m for 60 mm [6].

### *SW and TW Designs for ILC: Pros and Cons.*

Standing Wave (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 $\pi$, but a SW $\pi$-structure has the following limitations [8, 9]:

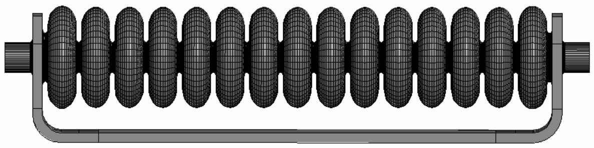

Figure 1. Example of a traveling wave structure with a feedback waveguide and feedback couplers. The input coupler is not shown.

(a) A considerably small transit time factor; the higher the factor, the higher the acceleration gradient.
(b) Poor stability of the field distribution versus small geometrical perturbations. The field perturbation gives the field enhancement in the structure and limits the acceleration gradient. The field perturbation limits the number of the cells in the structure that leads to (1) small structure length (9 cells for ILC); (2) a large number of input couplers and HOM dampers; (3) a large number of gaps between the structures and thus (4) an effective acceleration gradient reduction.
(c) Trapped modes. If the cells of the structure have the same length, the field in the end cells is the same as in the regular cells only for the operating mode. For all another modes the maximal field may be not in the end cells, but in the regular cells. It may happen that the field in the end cells is small, preventing high-order mode (HOM) extraction – the so-called trapped modes.

*An alternative approach is a superconducting traveling wave acceleration structure (STWA).* Recently a SC Traveling Wave Accelerating structure with feedback waveguide intended for ILC applications has been suggested [8]. The STWA structure schematic is presented in Fig. 1.

## GENERAL

Initially the superconducting traveling-wave accelerator with feedback was considered in [10], where the advantages of the TW accelerating scheme with feedback over the conventional SW SC systems were noted and discussed.

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The proposed SCTW structure possesses the following benefits by comparison with the standing wave design:

(a) A higher transit time factor and higher acceleration gradient for the same surface RF magnetic field magnitude compared to SW designs. The gain in the accelerating gradient of the *ideal* $\pi/2$ traveling wave accelerating structure is 42% by comparison with the SW design [11].

(b) High stability of the field distribution along the structure with respect to geometrical perturbations. This allows (1) a much longer structure, up to the length of a cryostat (~10 m); (2) many fewer input couplers are required, up to two couplers per cryostat; (3) there are no gaps between short cavities, providing an additional effective increase in the gradient;

(c) The TW structure has no trapped modes for the lower dipole mode pass band. Only two HOM dampers for a long TW structure are required.

(d) In the case of breakdown the SC TW structure with feedback demonstrates the same behavior as the SW structure i.e., while at breakdown the power from the source is reflected back from the structure and not dissipated in the structure destroying the niobium walls [12].

Meanwhile, employing the SC TW design also has some significant trade-offs: (1) a STWA has a negligibly small RF field attenuation, and thus, use of high power feedback is necessary. (2) The tuning procedure is more complicated than for SW structure, because it is necessary to tune the two partial SW modes that compose the traveling wave. (3) Tuning requires control of the VSWR in the structure. (4) The corresponding technology to fabricate and process the longer SC structure with its feedback waveguide needs to be developed; (5) a high-power coupler needs to be designed to feed a long SC TW structure.

The most favorable phase advance per cell from the point of view of stability is about 90°. However, for a real structure the gain would be limited for two main reasons: (1) the aperture needs to be large enough in order to provide an acceptably low magnitude of the transverse wakefield. For ILC applications the aperture diameter is 60 mm; (2) the coupling diaphragm thickness is limited to satisfy the requirements of diaphragm welding by electron beams. The SC TW structure is a result of a compromise between electrodynamic properties and technological feasibility, and has a phase advance per cell of 105°. It allows an increased transit time factor and finally, a maximum gradient that is 24% higher than that of a re-entrant structure.

Let us consider a mechanism of travelling wave excitation in the superconducting resonant ring with TW accelerating section. 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. It should be noted that the well known feed scheme with one directional coupler doesn't work in this case, because under the power multiplication factor of the SC TW resonator ~ $10^4$, the requirements for the coupler directivity and inner ring reflection become impracticable. Both suggested schemes use non directional (standard TTF-III) couplers. Those methods of travelling wave excitation are successfully used for RF sources with circular beams deflecting in a rotating RF field - gyrocons and magnicons.

The first scheme uses two input couplers that excite independently both partial standing waves comprising the resulting traveling wave. Each input coupler supplies half of the total power. The phases of the partial modes are shifted by of about $\pi/2$. In addition, the first scheme (see Fig. 2) 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.

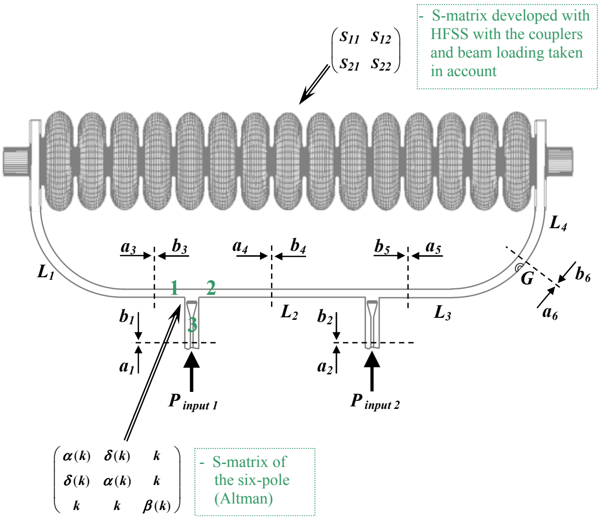

Figure 2. Two-coupler model of the resonant travelling wave ring with the STWA cavity.

The following notation is used:

$L_1$, $L_2$, $L_3$ and $L4$ – the length 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.

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. 2. The S-matrix of the structure and the feedback coupler is calculated numerically. The beam loading is taken into account. The input coupler is described by six-pole matrix.

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. The feedback waveguides are 160 mm wide and exhibit normal dispersion.

The S-matrix of the resonance ring *M(f)* =

$$\begin{pmatrix} -1 & S_{11}\cdot e^{-2i\varphi_1} & 0 & 0 & 0 & 0 & S_{21}\cdot e^{-2i(\varphi_1+\varphi_4)} & 0 \\ \alpha_1 & -1 & 0 & \delta_1\cdot e^{-0.5i\varphi_2} & 0 & 0 & 0 & 0 \\ \delta_1\cdot e^{-0.5i\varphi_2} & 0 & -1 & \alpha_1\cdot e^{-i\varphi_2} & 0 & 0 & 0 & 0 \\ 0 & 0 & \alpha_2\cdot e^{-i\varphi_2} & -1 & 0 & \delta_2\cdot e^{-0.5i\varphi_2} & 0 & 0 \\ 0 & 0 & \delta_1\cdot e^{-0.5i\varphi_2} & 0 & -1 & \alpha_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & iG\cdot e^{-2i\varphi_3} & -1 & 0 & \sqrt{1-G^2}\cdot e^{-i\varphi_3} \\ 0 & 0 & 0 & 0 & \sqrt{1-G^2}\cdot e^{-i\varphi_3} & 0 & -1 & iG \\ 0 & S_{12}\cdot e^{-2i(\varphi_1+\varphi_4)} & 0 & 0 & 0 & 0 & S_{22}\cdot e^{-2i\varphi_4} & -1 \end{pmatrix}$$

where $\varphi_n = 2\pi L_n/\lambda_{wg}$ - phase; $L_n$ – the length of waveguide sections; $f$ –excitation frequency. The system of linear equations of the resonance ring then are

$$M(f)\times\begin{pmatrix} a_3(f) \\ b_3(f) \\ a_4(f) \\ b_4(f) \\ a_5(f) \\ b_5(f) \\ a_6(f) \\ b_6(f) \end{pmatrix} = \begin{pmatrix} 0.5\cdot\sqrt{(R_{sh}/Q)\cdot I_{beam}\cdot\omega\cdot L_n/E_{acc}\cdot\beta_{gr}\cdot c} \\ -a_1\cdot k_1 \\ -a_1\cdot k_1\cdot e^{-0.5i\cdot\varphi_2} \\ -a_2\cdot k_2\cdot e^{-0.5i\cdot\varphi_2} \\ -a_2\cdot k_2 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$0.5\cdot\sqrt{(R_{sh}/Q)\cdot I_{beam}\cdot\omega\cdot L_n/E_{acc}\cdot\beta_{gr}\cdot c}$ is the beam radiation into the accelerating section, $I_{beam}$ is the average pulse beam current, $\omega$ is the angular frequency, $E_{acc}$ is the accelerating gradient, $\beta_{gr}$ is the group velocity of the operation mode of accelerating structure, and $c$ is the speed of light.

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. We present here numerical simulation results for the resonance ring with the 15 cell accelerating structure (~1m length). The reflection coefficient $S_{11}$ is -30.46dB at 1300MHz, phase advance is 105º, $R_{sh}/Q$ = 1808 Ω, loaded with the beam current $I_{beam}$= 9mA at the accelerating gradient 31.5 MeV/m. Fig. 2 shows the well tuned resonance ring where the backward wave magnitude at the segments $L_1$, $L_2$ and $L_3$ is ~ $10^{-4}$ of the forward wave.

If we suppose an acceptable level of the backward wave into the section is 5% of the forward wave and the acceptable additional power for maintenance of accelerating gradient 10% of nominal level, the required tolerance of the ring parameters is presented in Table 1.

Table 1: Tolerance requirements of the two-coupler resonant ring parameters

| **Parameter** | **Tolerance** |
|---|---|
| $\Delta L/L$ – Waveguide Loop Length | $3.23\cdot10^{-6}$ |
| $\Delta L_2/L_2$ – Distance between Couplers | $3.7\cdot10^{-2}$ |
| $\Delta L_4/L_4$ - .. between Tuner and Section | $2.6\cdot10^{-5}$ |
| $\Delta k/k$ – Input Ports Coupling | 0.0475 |
| $\Delta\varphi$ – Ports Phase Difference | ± 2.86 deg |
| $\Delta G/G$ – Matcher Reflection | $4.07\cdot10^{-4}$ |
| $\Delta Q_{ext}/Q_{ext}$ – Loaded $Q$ Factor | 0.33 |
| $\Delta f_0$ – Resonant Frequency Detuning | ±106 Hz |

As shown in the Table 1, the most precision and accuracy is needed for resonant ring frequency detuning.

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.

## CONCLUSION

A Superconducting Traveling Wave Accelerating (STWA) structure is suggested for the Main Linac of the ILC. The STWA structure has crucial advantages in comparison with the standing wave designs (SW) like the recently developed Re-Entrant cavity that in turn has significant advantages over the 9-cell TESLA cavity. This advantage is an increased accelerating gradient to up to a factor 1.24 while maintaining the same magnetic and electrical surface field ratios $E_{peac}/E_{acc}$ and $B_{peak}/E_{acc}$ as the Re-Entrant cavity. Furthermore, the proposed SC TW acceleration method will provide accelerating parameters that allow much longer accelerating structures to be built, also critical for the effective gradient enhancement. The length of the SW accelerating structure is limited by the strong sensitivity of the field flatness along the structure to dimension errors. The proposed TW structure does not have this limitation. If manufacturing and surface processing technology allow, the STWA structure is a strong candidate technology for a 10 m long STWA section that is limited only by the cryomodule length. This means that the effective accelerating gradient if a TW structure is employed can be increased by 22%, giving an overall 46% gain over the SW ILC structure. The proposed modification will result in a total accelerating structure length reduction by a factor of 1.46.

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