SUPERCONDUCTING TRAVELLING WAVE RING WITH HIGH GRADIENT ACCELERATING SECTION

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Abstract

Use of a superconducting travelling wave accelerating (STWA) structure [1] instead of a standing wave cavity has major advantages in increasing the accelerating gradient in the ILC. In contrast with standing wave cavity STWA requires feedback loop, which sends wave from the structure output to input, making a superconducting travelling wave ring (STWR). One or few input couplers need to excite STWR and compensate power dissipations due to beam loading. To control travelling wave regime in the structure two independent knobs can be used for tuning both resonant ring frequency and backward wave. We discuss two variants of the STWR with one and two feed couplers.

INTRODUCTION

The principal goal of this work is to study travelling wave superconducting (SC) accelerator concepts to increase the accelerating gradient of a SC structure and, therefore to reduce the length (and hence the cost) of the accelerator. A superconducting travelling wave accelerator (STWA) allows the increase in the accelerating gradient of a superconducting structure larger by a factor of 1.2÷1.4 over than that of the TESLA and alternative designs with a new shape: low-loss or re-entrant [2].

As described in the February 7, 2007 ILC Reference Design Report (RDR) [2], the accelerating gradient is to be about 31.5 MeV/m, the c.m. energy 500 GeV, and the ILC collider length 31 km. To reach the required energy of 500 GeV the accelerating system should have the length of 22 km and includes of about 16,000 one-meter long 9-cell superconducting cavities. Groups of 8 or 9 such cavities would be installed in a cryomodule. Any improvements in cavity performance will have big impact to the cost and efficiency of the ILC project. Two new proposed cavity designs: low-loss and re-entrant cavities aims to increase accelerating gradient or the gradient acceptance margin.

As show in the Table 1, the travelling wave accelerating structure has the best performances with respect to the surface magnetic and electric fields and the field uniformity along the accelerating structure. For the same gradient STWA has of ~ 24 % lower magnetic fields compare with TESLA type cavity. TW structure has much lower sensitivity to the frequency errors of the individual cells. In the current ILC designs the length of SW structure is limited to 1 m, mostly because of field flatness requirements. As a result, there is an unavoidable space (gap) between 1 m long structures of about 280 mm that reduces the effective gradient by about 22 %. The TW structure has no such fundamental limitation and the length of STWA structure may be up to the length of cryomodule (10 m) if technology of the SC cavity fabrication and surface processing allows it. This means that the effective accelerating gradient can be increased up 22 %, giving an overall 46 % gain over the ILC SW structure. Presented STWA structure has a 60 mm aperture and phase advance per cell of 105º, which was chosen for the technological reasons.

Table 1: Comparison between TESLA, Low-Loss, Re-Entrant and STWA Structures

Cavity Parameters	TTF	LL60	RE60	STWA(105º)
Aperture [*mm*]	70	60	60	60
k_{cc}(*) [%]	1.9	1.52	1.57	3.35
E_{peac}/E_{acc}	2.0	2.36	2.28	1.94
$H_{peac}/E_{acc}[mT/MV/m]$	4.15	3.61	3.54	3.05
R_{sh}/Q [Ω]	1036	1206	1140	1808
$G\cdot R_{sh}/Q$ [Ω^2]	30800	37970	41208	39075

(*) Cell to cell coupling factor.

BASIC CONCEPTS

Application of a superconducting accelerating structure with nonzero group velocity requires recuperation of the RF energy, i.e. the transmitted wave has to be returned to the section without any reflection from the input and output ports. Appearance of the reflected wave in the accelerating section increases the total surface electric and magnetic fields at the same accelerating gradient and accordingly reduces the KE and KH ratios. In 1949 the original idea of resonant ring with "warm" TW accelerating section was proposed by R.-Shersby-Harvie and Mullett [3]. The superconducting travelling-wave accelerator with feedback was considered in series of SLAC publications in 1968-1971 [4, 5], where the advantages of the TW accelerating scheme with feedback over the conventional SW SC systems were discussed.

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-couplers 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 [6, 7].

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. 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.

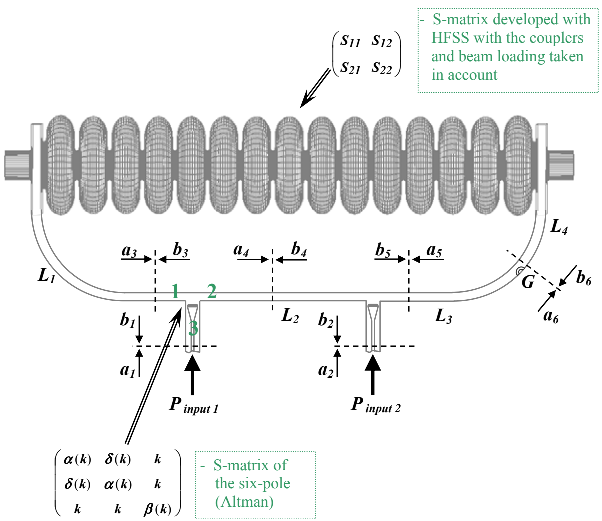

Figure 1: Two-coupler model of the resonant travelling wave ring with STWA cavity.

The following notation is used:

L_1, L_2, L_3, L_4 – the length of the waveguide sections between the resonance 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 into 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. 1. 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 (see, for example, ref. [8]).

The proposed model can be fully described by a system of equations with the right-hand element at the any point along the frequency scale. The bandwidth is rather narrow, of ~ 10^{-6} for these types of devices (T-joint and matcher) and the S-matrix elements do not depend on the frequency. The feedback waveguide are 160 mm wide and exhibit normal dispersion. S-matrix of the resonance ring $M(f)$ is equal:

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

Where: $\varphi_n = 2\pi L_n/\lambda_{wg}$ - phase; L_n – the length of waveguide sections; f –excitation frequency.

$$M(f)\times\begin{pmatrix} a_3(f) \\ b_3(f) \\ a_4(f) \\ b_4(f) \\ a_5(f) \\ b_5(f) \\ a_6(f) \\ b_6(f) \end{pmatrix} = \begin{pmatrix} 0 \\ -a_1\cdot k_1 \\ -a_1\cdot k_1\cdot e^{-0.5i\varphi_2} \\ -a_2\cdot k_2\cdot e^{-0.5i\varphi_2} \\ -a_2\cdot k_2 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$ - system of linear equations of the resonance ring

Beam loading – $S_{12}(f) = S_{21}(f) = S_{12}(HFSS)\cdot\sqrt{1-\frac{(R_{sh}/Q)\cdot I_{beam}}{E_{acc}}\cdot\frac{2\pi}{\beta_{gr}}}$

The transmission coefficient of the $S(f)$ – matrix of the accelerating structure is multiplied by the absorption coefficient of beam loading. I_{beam} is the average pulse beam current, E_{acc} is the accelerating gradient, β_{gr} the group velocity of the operation mode of accelerating structure.

After choosing input coupling, matcher reflection and relative phase and amplitudes of the input waves we can adjust the resonant ring, i.e. 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 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. Fig. 2 shows the

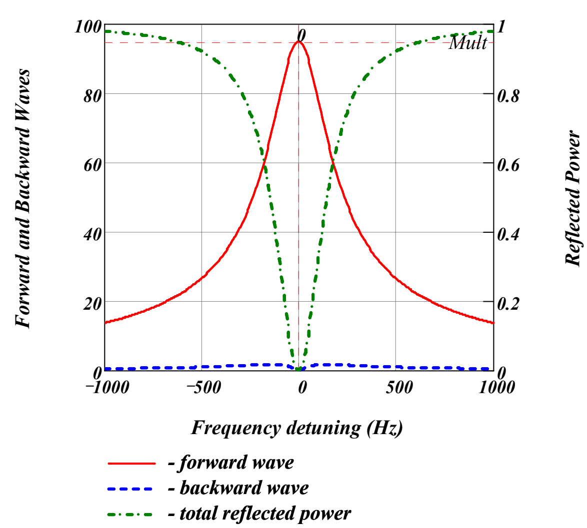

Figure 2: Amplitudes of forward wave, backward wave and total reflected power vs frequency detuning of the resonant ring.

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 backward wave into the section and reflected power from the resonant ring 1 %, the required tolerance of the ring parameters is presented in Tab. 2. As shown in the Table 2, 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 0.6 μm.

Table 2: Tolerance Requirements of the Two-Coupler Resonant Ring Parameters

Parameter	**Tolerance**
$\Delta L/L$ – feedback loop length	$4.5{\cdot}10^{-7}$
$\Delta L_2/L_2$	$3.5{\cdot}10^{-2}$
$\Delta L_4/L_4$	$2.4{\cdot}10^{-6}$
$\Delta k/k$ – inputs coupling	0.0214
$\Delta\varphi$ – inputs phase difference	± 1 deg
$\Delta G/G$ – matcher reflection	$4{\cdot}10^{-5}$
$\Delta Q_{ext}/Q_{ext}$ – loaded Q factor	0.13
Δf_0 – resonant frequency detuning	±15 Hz

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 non-directional input and special matcher, which splits the normal SW mode of resonant ring in two frequency shifted SW modes. 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 it proved that it is better to use an additional matcher G_2 (see Fig. 3) to adjust independently the reflection from the TW section. Table 3 shows the similar results of one-coupler ring modelling to the previous two-coupler scheme.

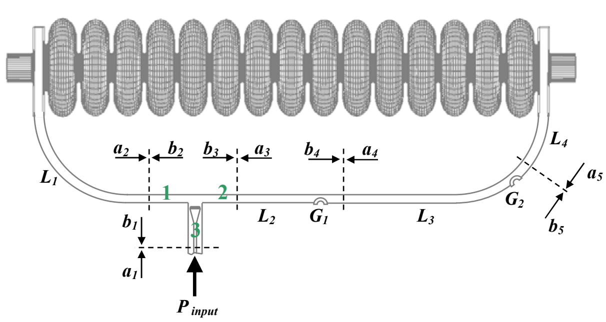

Figure 3: One-coupler model of the resonant travelling wave ring with STWA cavity.

Table 3: Tolerance Requirements of the One-Coupler Resonant Ring Parameters

Parameter	**Tolerance**
$\Delta L/L$ – feedback loop length	$4.5{\cdot}10^{-7}$
$\Delta L_2/L_2$	0.01
$\Delta L_3/L_3$	$4.1{\cdot}10^{-5}$
$\Delta L_4/L_4$	$2.6{\cdot}10^{-5}$
$\Delta k/k$ – input coupling	0.096
$\Delta G_1/G_1$ – first matcher reflection	$6{\cdot}10^{-5}$
$\Delta G_2/G_2$ – second matcher reflection	$1.07{\cdot}10^{-5}$
$\Delta Q_{ext}/Q_{ext}$ – loaded Q factor	0.13
Δf_0 – resonant frequency detuning	±15 Hz

CONCLUSION

The numerical model of the STWA structure with the feedback and input couplers is developed and tested. The model includes beam loading effects, and allows analysis of different schemes of structure excitation, tuning, tolerance requirements and beam loading. The two- or more coupler schemes can be exploited for excitation of a long SC TW section with high RF power consumption. The one-coupler scheme is beneficial for short (~ 1m) STWA, which can be used to replace ILC cavity.

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