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ФИЗИКА И ТЕХНИКА УСКОРИТЕЛЕЙ

DEVELOPMENT OF A SUPERCONDUCTING TRAVELLING WAVE ACCELERATING CAVITY WITH HIGH GRADIENT[1]

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In the ILC project the required accelerating gradient is higher than 30 MV/m [1]. For current technology the maximum accelerating gradient in superconducting (SC) structures is limited 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 and cell shape (Re-Entrant structure). These features allow gradients in excess of 56 MV/m to be obtained for a single-cell cavity. Further improvement of the coupling to the beam may be achieved by using a travelling wave (TW) SC structure with small phase advance per cell. Calculations show that an additional gradient increase by up to 46% is possible if a $\pi/2$ TW SC structure is employed. However, a TW SC structure requires a SC feedback waveguide to return a few GW of circulating RF power from the structure output back to the structure input. We discuss variants of the superconducting travelling wave ring (STWR) with one and two feeding couplers.

В проекте международного линейного коллайдера ILC требуется иметь ускоряющий градиент выше 30 МВ/м. Для существующей технологии изготовления сверхпроводящих ускоряющих структур градиент ограничен в основном величиной высокочастотного (ВЧ) магнитного поля на поверхности ускоряющей секции. Для того чтобы повысить ускоряющий градиент, делают более равномерное распределение магнитного ВЧ-поля на поверхности ускоряющей ячейки (Re-Entrant-структура) или увеличивают связь ускоряющей компоненты поля с пучком, изменяя апертуру и форму ячейки (структура с малыми потерями, DESY). Эти усовершенствования позволили получить градиент 56 МВ/м на одиночной ускоряющей ячейке. Дальнейшее увеличение связи ускоряющего поля с пучком может обеспечить использование сверхпроводящей (СП) ускоряющей структуры на бегущей волне (БВ) с меньшим, чем в структуре на стоячей волне, набегом фазы на ячейку. Расчеты показывают, что возможно дополнительное увеличение ускоряющего градиента до 46 %, если использовать СП БВ-структуру на рабочем типе $\pi/2$. Однако такая структура потребует применения СП волноводного кольца обратной связи для возвращения нескольких гигаватт ВЧ-мощности с выхода ускоряющей секции обратно на ее вход. Мы рассмотрели варианты сверхпроводящего кольца с бегущей волной, использующего один и два ввода ВЧ-мощности.

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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 ILC. As described in February 7, 2007 ILC Reference Design Report (RDR) [1], the accelerating gradient is to be about 31.5 MV/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 include of about 16,000 one-meter long 9-cell superconducting cavities. Any improvements in cavity performance will have big impact on the cost and efficiency of the ILC project. Two new proposed cavity designs: Low-Loss and Re-Entrant cavities aim to increase accelerating gradient or the gradient acceptance margin.

We have developed an accelerating structure for the ILC based on a high gradient superconducting travelling wave accelerating (STWA) cavity that will allow higher acceleration gradients, a main goal of the superconducting accelerating community.

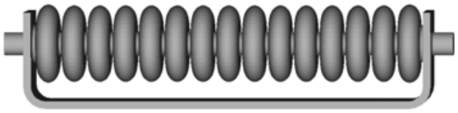

Fig. 1. Schematic example of a travelling wave structure with a feedback waveguide and feedback couplers. The input coupler is not shown

Although the basic idea of a superconducting TW resonant ring accelerator structure (see Fig. 1) is in itself not new [2–4], there have not been any known and published attempts to apply this design to ILC. A number of innovative ideas were required in the details of the technology in order to develop the TW design with parameters competitive with the current SW TESLA solution for ILC.

CONCEPTUAL DESIGN

Shape Optimization. The cell shape in the STWA structure presented in Fig. 2 has been optimized to reach the maximum accelerating gradient while keeping the magnitude of surface magnetic and electric fields less than the experimentally verified limits for superconductors. The magnitudes of the electric and magnetic fields demonstrated experimentally in the Re-Entrant shape cavity design for ILC [5] have been chosen as a reference. A STWA cavity with a 80–120° phase advance per cell has been studied, taking into account the technological limitations on diaphragm thickness as well. In order to understand the maximum increase in the accelerating gradient, we compared the optimized travelling wave structure with the standing wave Re-Entrant structure, in which the previous record values of gradient have been achieved [6]. We considered the version of Re-Entrant structure having an aperture of 70 mm, where the gradient achieved was 54 MV/m. Note that the single-cell Re-Entrant cavity with a 60 mm aperture demonstrated an even higher gradient of 59 MV/m.

While optimizing the SC TW structure, we used the following evident constraints: (1) the structure should have the same surface magnetic RF fields as those of the 70 mm Re-Entrant structure; (2) the structure should exhibit a maximal surface RF electric field that does not exceed the field in the 70 mm Re-Entrant structure; (3) the diaphragm thickness should not be less than 10.5 mm.

Numerical simulations of the cell showed that with the limitations mentioned above, an optimal value of the phase advance per cell was found that provided the maximum accelerating gradient. The STWA cavity cell shape is presented in Fig. 2. The maximal gain in accelerating gradient is of about 24% for a phase advance per cell in the range of 100–105°. A phase advance of 105° is preferable to 100° because of its smaller number of cells [7]. This advantage is an increased accelerating gradient up to a factor 1.24 while maintaining the same Re-Entrant surface field enhancement parameters.

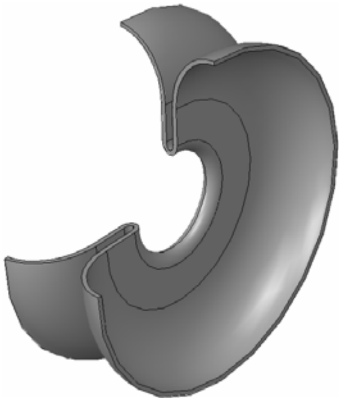

Fig. 2. Cell geometry of the superconducting TW accelerating structure

Table 1. **Comparison between TESLA, Low-Loss, Re-Entrant and STWA structures**

Cavity parameters	TTF	LL60	RE70	STWA-105°
Aperture, mm	70	60	70	60
k^{*}_{cc}, %	1.9	1.52	1.57	3.35
$E_{\mathrm{peac}}/E_{\mathrm{acc}}$	2.0	2.36	2.4	1.94
$H_{\mathrm{peac}}/E_{\mathrm{acc}}$, mT/MV/m	4.15	3.61	3.78	3.05
R_{sh}/Q, Ω	1036	1206	1140	1808
$G \cdot R_{\mathrm{sh}}/Q$, Ω^2	30800	37970	33762	39075

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[*] Cell-to-cell coupling factor.

Field Flatness Studies. The field flatness parameters for SC SW and TW (105 and 90°) 1–16 m long accelerating structures have been simulated. We have found that any SC travelling wave structure with length < 15 m will have a flatness better than the TESLA 1 m long cavity.

We define the *flatness* parameter as flatness $= (\max(E_s) - \langle E_s\rangle)/\langle E_s\rangle$, where $\max(E_s)$ and $\langle E_s\rangle$ are the maximum and average values of the accelerating gradient in cavity cells. For the TESLA nine-cell cavity it is required that this parameter should be better than 5%. Frequency errors in each cell result in gradient variations along the structure. Flatness depends on cell-to-cell frequency errors, the coupling between cells k, and the number of cells in the structure.

After production the cell-to-cell frequency errors are typically too large to provide the required field flatness and the cavity is tuned to get the correct frequency and good field flatness (on the order of few %). But after the final chemistry, HPR, welding to the helium vessel, cool-down and frequency tuning in the cryostat we will also have the uncontrolled changes in cell frequencies which will disturb the flatness.

Table 2. **Field flatness comparison for accelerating structures. N is the number of cells per unit length. The coupling coefficient k and relative frequency spread $\delta f/f$ are assumed to be the same in all cases**

Cavity parameters	TESLA (180°)	STWA (105°)
Coupling, %	1.88	3.344
N per 1 m	9	15
flatness (N, k, $\delta f/f$)	$1.05N^{3/2}\left(\frac{\delta f/f}{k}\right)$	$1.3N^{0.6}\left(\frac{\delta f/f}{k}\right)$
flatness ($L_{\text{cavity}} = 1$ m), %	5	0.65
flatness ($L_{\text{cavity}} = 2$ m), %	15.8	1.0
flatness ($L_{\text{cavity}} = 4$ m), %	30.5	1.5
flatness ($L_{\text{cavity}} = 8$ m), %	>50	2.26
flatness ($L_{\text{cavity}} = 16$ m), %	—	3.42

The results of the flatness simulations are shown in Table 2. The flatness even in the 16 m long TW structure is better than in the 1 m long standing wave TESLA structure.

Coupling Section Development. The design of the L-band coupling section for the SCTW accelerating cavity with a feedback waveguide is presented in Fig. 3. A rectangular waveguide type of coupling section has been chosen and the method of impedance boundary conditions has been used for the coupling section parameter optimization. Single-cell, four-

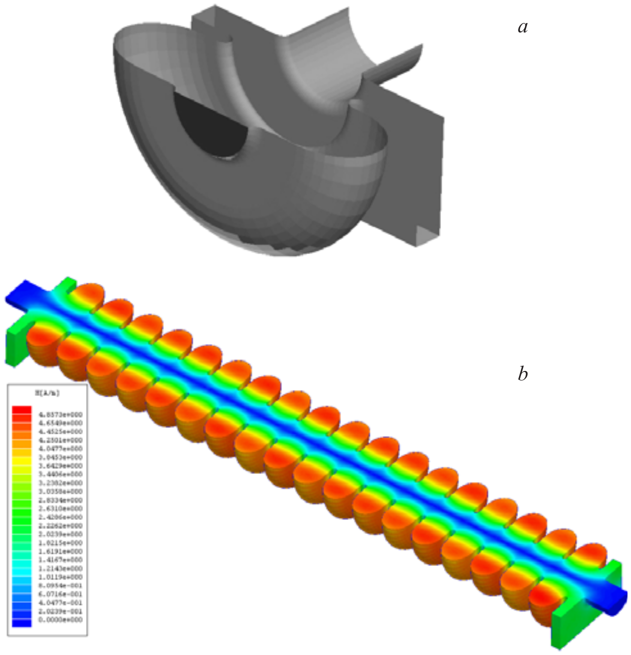

Fig. 3. *a*) Transverse cuts through the rectangular waveguide coupling section for the L-band SCTW accelerating structure, side view; *b*) magnetic field of the 18-cell SCTW cavity with the optimized coupling section

cell and 18-cell configurations have been considered. The optimized coupling section provides no field enhancement at the coupling cells and the feedback waveguide is 20 mm width.

Modeling of the Travelling Wave Regime. A theoretical model [8] of the STWA structure including feedback and input couplers is being developed and tested. The model includes beam loading effects, and allows analysis of tuning, tolerance requirements and beam loading.

The first scheme (see Fig. $4, a$) uses only one non-directional input and special matcher (G_n), 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 90° with respect to each other. Their superposition is a travelling wave propagating along the ring. The second scheme (see Fig. $4, b$) uses two input couplers that excite independently both partial standing waves comprising the resulting travelling wave. Each input coupler supplies half of the total power. The phases of the partial modes are shifted by of about $\pi/2$.

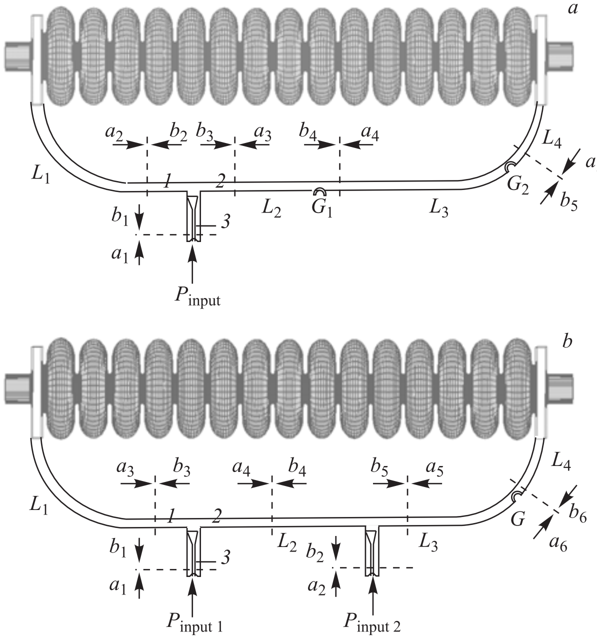

Fig. 4. One- (*a*) and two-coupler (*b*) models of the resonant travelling wave ring with STWA

If we suppose an acceptable level of backward wave into the section and reflected power from the resonant ring 1%, the most precision and accuracy are needed for resonant ring frequency detuning. For a 1330 mm ($4\lambda_{\rm wg}$) waveguide loop length the acceptable error is 0.6 μm. It means $dL/L \sim 4.5 \cdot 10^{-7}$ for waveguide loop length or ± 15 Hz 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

As shown above, 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 structure has of $\sim 24\%$ lower magnetic fields compared with TESLA-type cavity. The TW structure has much lower sensitivity to the frequency errors of the individual cells. In the current ILC design 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 a 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 to 22%, giving an overall 46% gain over the ILC SW structure.

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