AN S-BAND SUPERCONDUCTING LINEAR COLLIDER

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Abstract

In this paper a parameter list is proposed for an S-band (3 GHz) superconducting linear collider (SSLC) which escapes from the dark current problem at an accelerating gradient of 25MV/m. Detailed beam dynamics simulations are carried out, which reveal the main features of a 3 GHz SSLC.

1 INTRODUCTION

Nowadays there are six projects for future linear colliders, TESLA, SBLC, NLC, JLC, VLEPP, and CLIC, among which the TELSA project is the only superconducting machine. Since the TESLA designed accelerating field 25MV/m is far above the electron emission capture field strength 15MV/m, the captured electrons may be accelerated to a very high energy before finally hitting the cavity walls (the distance between the two adjacent quadrupoles will be almost 50 meters at the end of the main linac). This intrinsic defect can be avoided by pushing the rf frequency higher because the critical capturing electric field strength increases linearly with the rf frequency. In this paper we propose an S-band superconducting linear collider. In section 2, beam parameters are determined from the physical constraints at the interaction point. In section 3, superconducting cavity parameters and the critical field for electron capture varying with the working frequency are discussed. Beam dynamics simulation results are shown in section 4.

2 BEAM PARAMETERS

The luminosity of two gaussian head-on colliding beams is given by

$$L_0 = \frac{f_{rep} N_b N_e^2}{4\pi\sigma_x^* \sigma_y^*} H_{D_x} H_{D_y} \tag{1}$$

where f_{rep} is the repetition frequency of the bunch train, N_b is the number of bunches in the train, N_e is the number of particles per bunch, $\sigma_x^* = (\epsilon_x^* \beta_x^*)^{1/2}$, $\sigma_y^* = (\epsilon_y^* \beta_y^*)^{1/2}$, $\beta_{x,y}^*$ and $\epsilon_{x,y}$ are the values of the beta functions at the IP and the emittances, respectively, and $H_{D_{x,y}}$ are the pinch enhancement factors which are functions of the so-called disruption parameters $D_{x,y}$ of a bunch. According to ref. 1 one can determine the colliding beam parameters starting from the physical constraints at the IP:

$$\sigma_x^* = \frac{\pi r_e^3 H_{Had}}{2.6\delta_B^* \alpha H_{D_y} n_\gamma \sigma_{\gamma\gamma\to Had}} \tag{2}$$

$$\sigma_y^* = \frac{r_e n_\gamma^3}{41.5\delta_B \alpha^3} \tag{3}$$

$$\sigma_z^* = \frac{(n_\gamma)^2 \gamma r_e}{4.6\delta_B^* \alpha^2} \tag{4}$$

$$R^* = \frac{\sigma_x^*}{\sigma_y^*} = \frac{16\pi\alpha^2 r_e^2 N_{Had}}{H_{D_y} (n_\gamma)^4 \sigma_{\gamma\gamma\to Had}} \tag{5}$$

$$\beta_x^* = \frac{3.5\pi\gamma r_e^3 N_{Had}}{\delta_B H_{D_y} \sigma_{\gamma\gamma\to Had} n_\gamma^2} \tag{6}$$

$$\beta_y^* = \sigma_z^* \tag{7}$$

$$\gamma\epsilon_x = \frac{\pi r_e^3 N_{Had}}{23.4 H_{D_y} \delta_B \alpha^2 \sigma_{\gamma\gamma\to Had}} \tag{8}$$

$$\gamma\epsilon_y = \frac{n_\gamma^4 r_e}{374\delta_B \alpha^4} \tag{9}$$

$$N_e = \frac{\pi r_e^2 N_{Had}}{5.2 H_{D_y} \sigma_{\gamma\gamma\to Had} \delta_B \alpha^2} \tag{10}$$

$$\frac{N_e}{\sigma_x^*} = \frac{n_\gamma}{2\alpha r_e} \tag{11}$$

$$f_{rep} N_b = \frac{L_0 (n_\gamma^*)^2 \sigma_{\gamma\gamma\to Had}}{N_{Had}} \tag{12}$$

$$P_b = \frac{\pi e W_{cm} r_e^2 n_\gamma^2 L_0}{10.4 H_{D_y} \delta_B \alpha^2} \tag{13}$$

where $r_e = 2.82 \times 10^{-15}$ m is the classical electron radius, α is the fine structure constant, γ is the ratio of the colliding particle energy to its rest energy, $\sigma_{\gamma\gamma\to Had}$ is the $\gamma\gamma \to$ hadron total cross section, δ_B^* is the maximum tolerable beamstrahlung energy spread, n_γ is the mean number of beamstrahlung photons per electron, N_{Had} is the maximum tolerable number of hadronic events per crossing, and H_{D_y} is almost a constant, about 1.5 with $D_y = 9$ which is used later in this paper. Finally, we arrive at the stage that once γ, n_γ , N_{Had} and L_0 are given, one can determine the values of σ_x^*, σ_y^*, R^*, σ_z^*, N_e, β_x^*, β_y^*, ϵ_x^*, ϵ_x^*, and $f_{rep} N_b$.

3 CHOICE OF THE RF FREQUENCY OF SUPERCONDUCTING STRUCTURES

Different from the normal conducting structures, superconducting linacs are more sensitive to the dark current problems. When the field emitted electrons are captured by the rf field, these electrons can be accelerated to a very high energy before hitting the superconducting cavity walls or being over deflected by the quadrupoles. Since the distance between the two adjacent quadrupoles is very large, especially for the end half of the main linac, the probability for these electrons to be accelerated and lost inside the low temperature cavities is very large. The energy deposited by the electrons on the cavity wall demands extra refrigerator power to maintain the working temperature, or even causes quench. The theoretical critical accelerating fields at which the field emission electrons begin to be captured in standing and travelling wave accelerating structures are proportional to the operating frequency, or explicitly, E_{crit}^{SW}(MV/m)= $12f$(GHz), and E_{crit}^{TW}(MV/m)= $6f$(GHz), where SW and TW stand for standing wave and travelling wave, respectively. Fig. 1 shows the accelerating fields of the existing projects compared with the critical accelerating fields. It is clear that TESLA is the only project under the danger of dark current and one has to push the operating frequency higher to avoid the problem. An S-band (3 GHz) Superconducting Linear Collider (SSLC) seems interesting and merits to be a candidate which has a critical dark current accelerating field of 36 MV/m which is much higher than the designed 25 MV/m accelerating gradient of TESLA and not far from the 40 MV/m envisaged to upgrade E_{cm} to 1 TeV. The field emission electron phase capture regions for 1.3 GHz and 3 GHz standing wave structures are shown in Fig. 2.

To compare the machine performances of TESLA and an S-Band Superconducting Linear Collider (SSLC), we recall some basic knowledges about superconducting cavities. It is known that the accelerating mode quality factor is inversely proportional to the cavity surface resistance R_s which consists of two parts, BCS surface resistance and residual surface resistance (R_{BCS} and $R_{resid.}$). For Nb cavity at $T = 1.8^{\circ}$K, one has[2]

$$R_s = R_{BCS} + R_{resid.}$$

$$= \frac{6.64 \times 10^{-25}}{T}\omega^2 exp(-1.75\frac{T_c}{T}) + 10(n\Omega) \qquad (14)$$

where $T_c = 9.2^{\circ}$K, and ω is the angular rf frequency.

4 BEAM DYNAMICS

The focusing channel for the main linac is a FODO type with the beta function scaling as $\beta_0(\gamma/\gamma_0)^{1/2}$, where β_0 and γ_0 are the beta function and the normalized beam energy at the beginning of the main linac. Since the length of the cryostat can not vary in a continuous way, this scaling law is followed step by step. With the $\beta_{0,max} = 17m$ and the phase advance $\mu = \pi/2$, one needs eight different types of FODO structures. The half lengths of this eight FODO cells are $1l_0$, $2l_0$, $3l_0$, $4l_0$, $5l_0$, $6l_0$, $7l_0$, and $8l_0$, respectively, where $l_0 = 5$m. The number of the corresponding FODO cells are 38, 32, 30, 28, 28, 27, 27, and 24, respectively. By using the improved program (the old version has been used in ref. 3), one gets the multibunch and the single bunch emittance blow-up behaviours. Assuming that the quadrupole and structure misalignments are 40μm and

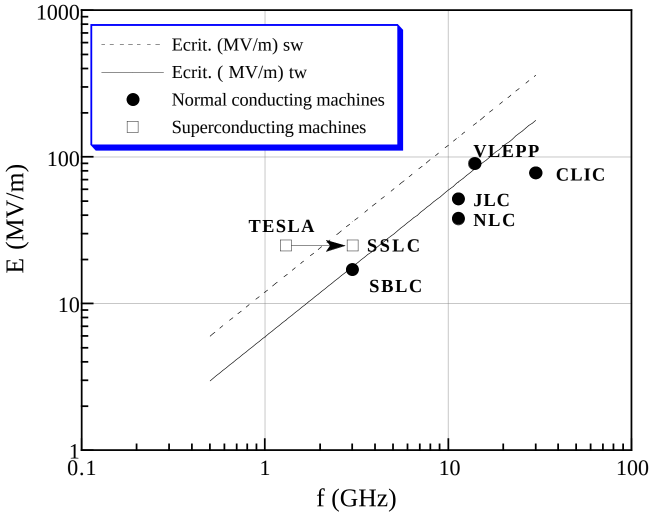

Figure 1: The accelerating fields of different projects vs operating frequencies.

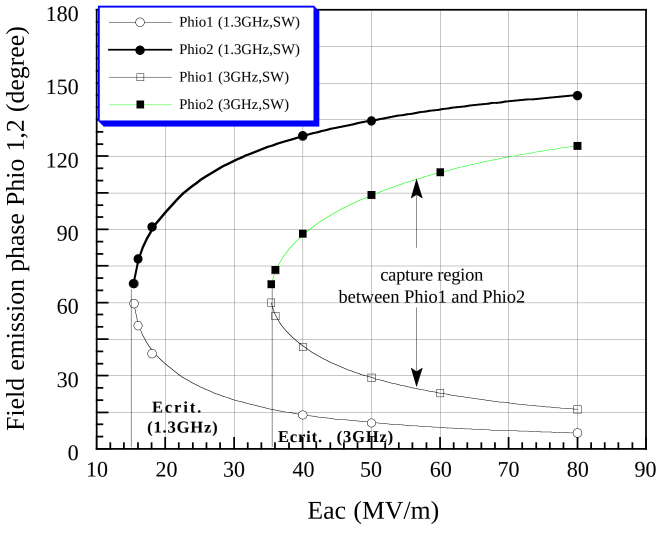

Figure 2: The field emission electron phase capture regions vs the accelerating field for the 1.3 GHz and 3 GHz standing wave accelerating structures.

180μm, respectively, and the quality factor of the first dipole mode is $Q_{01} = 4 \times 10^4$, one gets the multibunch emittance growth of 6$\%$. As for the single bunch emittance growth, a single bunch has been divided into 100 slices. Assuming that the quadrupole and structure misalignments are 10μm and 180μm, respectively, one gets single bunch emittance growth up of 100$\%$ after one-to-one correction. If the Dispersion Free and Wake Free correction techniques are used, the single bunch emittance blow-up can be reduced by more than an order of one (which has not been done in this paper). We conclude that the structure and the quadrupole tolerances are in the order of 200μm and 20μm, respectively. The energy spread with a single bunch is about 0.3$\%$ which is ten times smaller than the beamstrahlung energy spread.

5 CONCLUSION

In this paper we propose a 3 GHz S-band Superconducting Linear Collider (SSLC) to escape from the dark current problem at 25 MV/m accelerating gradient (since it has a critical capture field of 36MV/m). A beam parameter list has been proposed which is used in the machine design considerations. It is suggested that the HOM quality factor be damped lower than 10^5, the quadrupole and the cavity misalignment tolerances be about 20 μm and 200 μm, respectively. The energy spread within a single bunch is about 0.3$\%$. The peak rf power through the main coupler is 36kW, and the total wall plug ac power (including the refrigerator power) is less than 80 MW.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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	SSLC
Energy (c. of m.) (GeV)	500
RF frequency (GHz)	3
Luminosity w/pinch (10^{33}cm^{-2}s^{-1})	5
Linac repetition rate (H$_z$)	5
No. of particles/bunch (10^{10})	1.43
No. of bunches/pulse	1400
Bunch separation (nsec)	800
Beam power/beam (MW)	4.02
$\gamma\epsilon_x/\gamma\epsilon_y$ (m-rad$\times 10^{-8}$)	898/8.86
β_x^*/β_y^* (mm)	19/0.187
σ_x^*/σ_y^* (nm) before pinch	590/5.82
σ_z^* (μm)	187
σ_x^*/σ_z	3.16×10^{-3}
Disruptions D$_x$/D$_y$	0.09/9
Υ_0	0.068
δ_B $(\%)$	3
n$_\gamma$ per electron	1
N$_{Had}$ per crossing	0.3
Unloaded gradient (MV/m)	25
Beam loaded gradient (MV/m)	25
τ_e (μs)	1071
τ_{fill} (μs)	257
τ_{rf} (μs)	1328
Wavelength (m)	0.1
R/Q (Ohom/m)	2484
Unloaded Q_0	1.5×10^9
Loaded Q_L	3.5×10^6
Iris size (a/λ)	0.15
Cavity length (m)	0.5
Klystron power (MW)	1.2
Structures per klystron	32
Number of klystrons (two linacs)	1250
Number of structures (two linacs)	40000
Average pulse current (mA)	2.88
β_0 (m)	17
η_{rf}^b (%)	81
η_{ac}^{rf} (%) Ac power of refrigerators is excluded	32
η_{ac}^b (%) Ac power of refrigerators is excluded	26
Average Rf power (MW) (two linacs)	10.1
AC power for the rf power (MW) (two linacs)	31.5
AC power of refri. (MW) (two linacs)	41
Total AC power (MW) (two linacs)	72
Structure misalign. tolerances (μm)	195

Table 1: SSLC is proposed in this paper. The efficiency of the refrigerator is assumed to be $\eta_{refri} = 20\%\eta_{Carnot} = 0.0012$.