Design Studies on the TESLA TW Positron Injector Linac and Beam Modeling

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Abstract The TESLA positron injector linac with a L-band TW normal conducting structure has been studied, which offers both higher shunt impedance and larger aperture. Main parameters of this injector linac have been designed by systematical beam modeling, and a satisfactory positron beam transmission and the beam performance at the output of the injector linac have been obtained.

Key words positron injector linac, L-band TW structure, beam modeling

1 Introduction

TESLA is one of the proposed future linear colliders, which employs the superconducting acceleration structure in L-band for its many advantages[1]. Its positron injector linac[2], however, should be made by the normal conducting structure to avoid its operation unreliability caused by a great amount of the lost positrons and electrons from the positron source. A design goal of an accelerating structure is usually to have high shunt impedance for high accelerating efficiency, and to have a large acceptance as well for a high beam transmission, particularly for a positron injector linac with large initial beam emittance and transverse momentum. Usually a structure in L-band has lower shunt impedance but larger aperture than that in S-Band. To have both higher shunt impedance and larger aperture in a L-band structure, a marvelous design study has been made[3]. The design strategy is to adopt a modified cup-like disc-loaded structure with optimum structure geometry and by changing the iris thickness cell-by-cell in an accelerating section. As a possible positron injector linac for TESLA, its main parameters have been designed by systematical beam modeling, including the phasing, the optimized solenoid focusing field, the space charge and the beam loading effects. Finally a satisfactory positron beam transmission and the beam performance at the output of the injector linac have been obtained.

2 Modified cup-like disc-loaded structure

A constant gradient TW structure with $2\pi/3$ operating mode was chosen for the structure to have a uniform power dissipation along the structure and a high accelerating efficiency. Given a frequency, for instance $f_0 = 1.3$ GHz, in order to have a reasonable shunt impedance Z_s, iris radius a and accelerating section length L_s, one has first to choose an attenuation constant τ_0, which defines the ratio of the output to the input power of the structure, and the power loss per unit length in the structure:

$$P_{out} = P_{in} \cdot e^{-2\tau_0}, \quad \frac{dp}{dz} = \frac{P_{in}}{L_s} \cdot (1 - e^{-2\tau_0}).$$

It is clear that the larger τ_0, the smaller the output power and hence the higher the power ratio. On the other hand, a smaller τ_0 gives a larger group velocity V_g of the structure, and hence gives a larger iris radius, (since $V_g \propto a^4$), and a larger transverse acceptance. A τ_0 of 0.55 is a good compromise as will be seen later.

Based on the "cup-like" cell structure as used in the de-

Received 24 September 2004, Revised 30 November 2004
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sign of the S-Band Linear Collider (SBLC) [4], which has the advantages of precise manufacturing and high shunt-impedance, we modified it so that each cell consists of "two half-cups", as shown in Fig. 1. There are two outer-curves with a radius R_b for each iris to further increase the shunt-impedance. In addition, we changed the iris thickness cell-by-cell, to obtain a larger iris radius while keeping the shunt impedance higher. The optimum cell geometry and its EM performance, calculated with MAFIA code[5], are listed in Table 1.

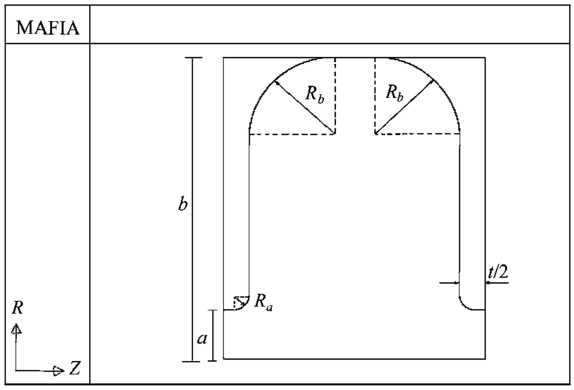

Fig. 1. A modified cup-like disc-loaded structure.

Table 1. The optimum geometry and its EM performance.

# cell	a/mm	b/mm	t/mm	V_g/c	Q	$Z_s/(\text{M}\Omega/\text{m})$
01	17.612	93.188	12.00	0.00301	2.259×10^4	51.20
02	17.486	93.182	12.15	0.00287	2.256×10^4	51.20
03	17.360	93.176	12.30	0.00273	2.252×10^4	51.19
04	17.234	93.170	12.45	0.00259	2.249×10^4	51.18
05	17.107	93.165	12.60	0.00247	2.246×10^4	51.18
06	16.981	93.160	12.75	0.00234	2.242×10^4	51.14
07	16.855	93.156	12.90	0.00223	2.239×10^4	51.14
08	16.729	93.152	13.05	0.00211	2.236×10^4	51.14
09	16.603	93.148	13.20	0.00200	2.232×10^4	51.10
10	16.477	93.144	13.35	0.00190	2.229×10^4	51.09
11	16.351	93.140	13.50	0.00180	2.226×10^4	51.07
12	16.224	93.137	13.65	0.00170	2.222×10^4	51.03
13	16.098	93.134	13.80	0.00161	2.219×10^4	51.02
14	15.972	93.131	13.95	0.00152	2.215×10^4	50.98
15	15.846	93.129	14.10	0.00144	2.212×10^4	50.95
16	15.720	93.127	14.25	0.00135	2.209×10^4	50.93
17	15.594	93.125	14.40	0.00128	2.205×10^4	50.89
18	15.467	93.123	14.55	0.00120	2.202×10^4	50.86
19	15.341	93.121	14.70	0.00113	2.198×10^4	50.81
20	15.215	93.120	14.85	0.00107	2.195×10^4	50.79
21	15.089	93.119	15.00	0.00100	2.191×10^4	50.79

In each cell of the above table, $R_b = 25$mm and $R_a = 4.75$mm are chosen.

The advantages of the designed structure are summarized as follows:

(1) It is a constant gradient structure and also an almost constant impedance structure.

(2) It has a high shunt-impedance $Z_s > 50$ MΩ/m, which is close to the values for the normal S-band structure.

(3) It has a large iris diameter of 35.2—30.2mm.

(4) It has a thick iris of 12—15mm, so the cooling channel can directly pass through the inside of the iris, to have a high cooling efficiency. This is very important in the case of high gradient and high duty cycle.

(5) The maximum surface electric field (at the radius R_a) in a cell is a factor of 1.98 of the averaged longitudinal electric field on the axis. That is acceptable to avoid the RF

breakdown.

A higher gradient (> 20 MV/m) is possible to be chosen for this structure. However, considering the L-band klystron with 10 MW output for instance, which is developed at DESY for the TESLA super-conducting main linacs, an accelerating gradient of 12 MV/m is adopted for the positron injector linac. With the shunt-impedance of 50 MΩ/m, a section length $L_s = 7\lambda = 1.61427$ m is preferred. Therefore each section consists of 21 cells. The average energy gain of the positron beam per section is about 19.4 MeV, the pulse RF power for the structure is about 6.97MW per section. Having 12 sections for the injector, it offers a final average energy of about 250MeV at the exit, in which the initial average beam energy of 15MeV at the injector input is included. The positron beam power extracted from a section is about 0.65MW, hence the total power needed for a section is about 7.62MW, and one has about 20% rf in reserve for beam loading compensations.

3 Modeling of positron beam dynamics

3.1 Positron beam parameters at the input of the injector linac

The TESLA positron source[6,7] had been designed by using the spent electron beam (250 GeV, after collision at the interaction point) to produce a positron beam, by passing the spent electron beam through a wiggler to produce photons, which will hit a thin target to yield the positron. This positron source is expected to have a higher positron yield and is much more complicated than a conventional concept of hitting a primary electron beam with an energy of a few GeV onto a thick target. Further design studies on the conventional positron source for the linear collider are underway. As an example of a L-band TW positron injector linac design, here we just use the available positron data from the TESLA designed source. However the design principle of the positron injector linac described here could be a good reference for others with the conventional positron source.

Due to the large transverse momentum and emittance of the positrons at the target, an Adiabatic Matching Device (AMD) had been designed, which immediately follows the target to realize a phase-space transformation. At the exit of the AMD[6], i. e. at the input of the injector: (1) a large electric charge, the number of positrons per RF pulse is > 2.8×10^{14}. The parasitic electron yield at the target is about a factor of 1.65 higher than the positron yield, due to the ionization; (2) a small spatial spot of about 10 mm, but with a large transverse momentum and large normalized emittance ($>5.0\times10^{-2}$m); and (3) a large energy spread of 2—60 MeV. The energy domain is 5—25 MeV and the average energy of the positron beam is about 15MeV. The positron bunch length is about ±20ps. The transverse and longitudinal beam performances at the input of the injector linac are shown in Fig.2.

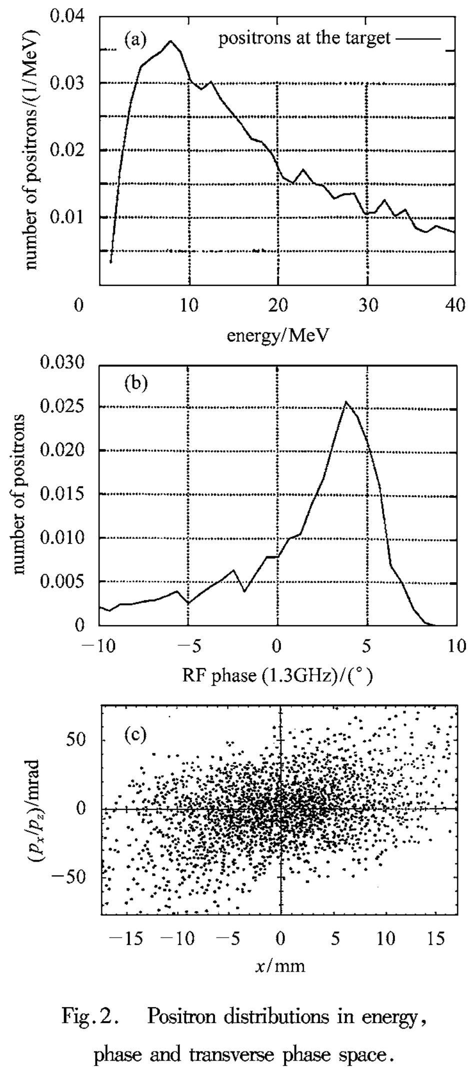

Fig.2. Positron distributions in energy, phase and transverse phase space.
(a) Energy distribution; (b) Phase distribution; (c) Transverse phase distribution.

3.2 Beam dynamics in the positron injector linac

The beam dynamics in the injector linac has been studied analytically and by simulations with the PARMELA code[8] as well.

Choice of the "synchronous phase"

Due to the large energy spread and the phase spread of the input beam, for the injector beam dynamics studies, we first have to define the "optimum synchronous phase" by shifting the RF phase to obtain an optimum effective acceleration, an optimum transmission and a reasonable beam performance. In the primary calculations, an accelerating gradient of $E_0 = 12$ MV/m and a longitudinal solenoid field of $B_z = 0.32$ T were used. The selection of the B_z value will be explained later. The space charge and beam loading effects were neglected to begin, which will also be discussed later.

Table 2. Beam performances with varying accelerating phase.

RF phase/(°)	particle transmission	average energy/ MeV	horizontal normalized rms emittance/($\times 10^{-3}$m)	vertical normalized rms emittance/($\times 10^{-3}$m)	energy spread/rms
0	21.5%	247.02	2.46	2.57	10.86%
-2	21.5%	247.78	2.47	2.53	10.57%
-4	21.5%	247.77	2.50	2.50	10.41%
-6	21.5%	247.71	2.50	2.50	10.22%

Table 2 lists the beam performance with different accelerating phase angles, obtained by the beam simulations with PARMELA. From this table one can see that the "optimum phase angle" in the injector linac has a range of a few degrees, due to the large input energy spread and phase spread.

Choice of the solenoid magnetic field

The number of positrons per pulse at the injector linac output would be a factor of about 2 higher than the one at the interaction point of the linear collider. The beam transmission from the target to the injector linac exit , η_t, has to fulfill: $0.7 \times 16.8 \times \eta_t = 2.5(e^+/e^-)$, where 0.7 is the capture efficiency of the spent electron's capture system, which is given by the energy spread of the spent electron beam (±3%) caused by the beamstrahlung at the interaction point; 16.8 e^+/e^- is the positron yield at the target[6]. Hence the transmission in the AMD and the injector linac should be > 21%.

Given the accelerating gradient and the iris radius, the beam transmission and its transverse performance at the injector output are dominated by the longitudinal magnetic field B_z of the solenoid surrounding the accelerating structure. Using the PARMELA code, we obtain the relations between η_t and B_z, as listed in Table 3. With this table one can see that to meet $\eta_t > 21\%$, one has to choose $B_z \geqslant 0.32$ T.

Table 3. Beam transmission vs solenoid field

B_z/T	AMD length/m	η_t
0.25	0.77	17.6%
0.32	0.59	21.5%
0.55	0.33	31.7%

Space-charge effects

The beam simulation with the PARMELA code shows that the space-charge effects on the beam performance, with the beam current mentioned above, are negligible due to the large beam emittance and the large longitudinal phase spread. If we take into account the electron bunches as well, which are overlapped in space with the positron bunches at the injector input, the space-charge rejection effects can be reasonably neglected.

Single-bunch beam loading effect

With ABCI code[9], we calculated the longitudinal wake W_l and the related loss factor k_l in a cell, as shown in Fig. 3, and $k_l = \frac{1}{q}\int W_l(z) \cdot i_b(z)\mathrm{d}z = -0.9992$V/pC. Hence the change of the energy distribution due to the wake in a cell, e.g. in the first cell (with maximum positron bunch charge) of the injector linac is $\Delta W_{max} = N_e^+ \cdot k_l = -40$ keV. This change of the energy distribution in a bunch is negligible compared with the already existing energy spread in a bunch. However it will affect the average energy of a bunch after passing through many cells. By using the loss factor K_l and taking into account the particle loss in the injector linac, the calculated change of the average energy at the output (totally 252 cells) will be a few MeV, which is consistent with the PARMELA simulation, as shown in Table 4.

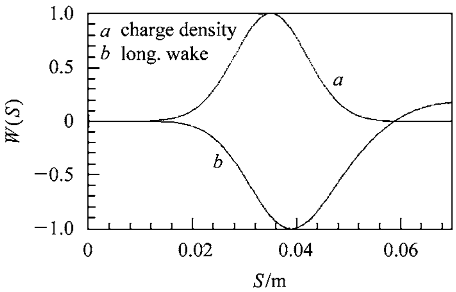

Fig.3. Longitudinal wake field in a cell.

Table 4. Energy gain with and without beam loading.

	average energy/ MeV	$\varepsilon_{n,x,rms}$/ ($\times 10^{-3}$m)	$\varepsilon_{n,y,rms}$/ ($\times 10^{-3}$m)	energy spread/ rms
$I = 51.0$ A without beam loading	247.7	2.5	2.5	10.6%
$I = 51.0$ A with beam loading	241.2	2.5	2.5	9.83%

Multi-bunch transient beam loading effect

During the beam pulse length of 800μs in the TESLA design[1], the beam power extracted from a section is about 0.65MW. To establish an unloaded gradient of 12MV/m, each section needs an RF power of 6.97MW. Thus without compensation for the transient beam loading, the bunch-to-bunch energy change in a section will be about 15%. A linear amplitude ramp over the pulse length can perfectly compensate the transient beam loading for a constant gradient section with almost constant shunt-impedance per unit length. An RF power of about 20% output from each klystron is reserved for this compensation.

4 Summary

A modified cup-like disc-loaded structure for a L-band positron injector linac has been designed. By adopting "two half cups" cell geometry and by changing the disc iris thickness cell-by-cell in each section, a large iris diameter of > 30mm and a high shunt impedance of > 50MΩ/m have been obtained simultaneously, meeting the requirements of high gradient and large acceptance.

A TW version of a possible positron injector linac for TESLA has been studied. The final beam performance is listed in Table 5, and shown in Fig.4. We can see that the number of positrons per pulse and the normalized transverse emittance ($1.9/1.9 \times 10^{-2}$m for 100% of the particles) well meet the required positron damping ring acceptance ($\pm 4.8 \times 10^{-2}$m). Regarding the energy spread, we need about ± 16 MeV energy cut (for energy spread of ± 6.5%) by using two bending magnets[2]. The beam simulation indicated that a ± 16MeV energy cut leads to a reduced phase spread of about ± 7.0 degrees, due to the fact that the positrons in the tail of a bunch have a lower energy than the core positrons (see Fig. 4 (e)). A remaining number of positrons is about 74%, hence the number of positrons per pulse at the injector linac output is a factor of 1.9 higher than the one at the interaction point.

The design principle of the positron injector linac described here could be a good reference for others with the conventional positron source.

Table 5. Positron beam performance at the injector linac output (after energy cut).

	design	required by damping ring
energy/MeV	248	~250
$\frac{\Delta W}{W}$	±6.5%	±6.5%
$\Delta\phi$	±7.0°	±7.5°
$\varepsilon_x/\varepsilon_y$(Norm.) $\times 10^{-2}$m, (100% particle)	1.9/1.9	≤4.8

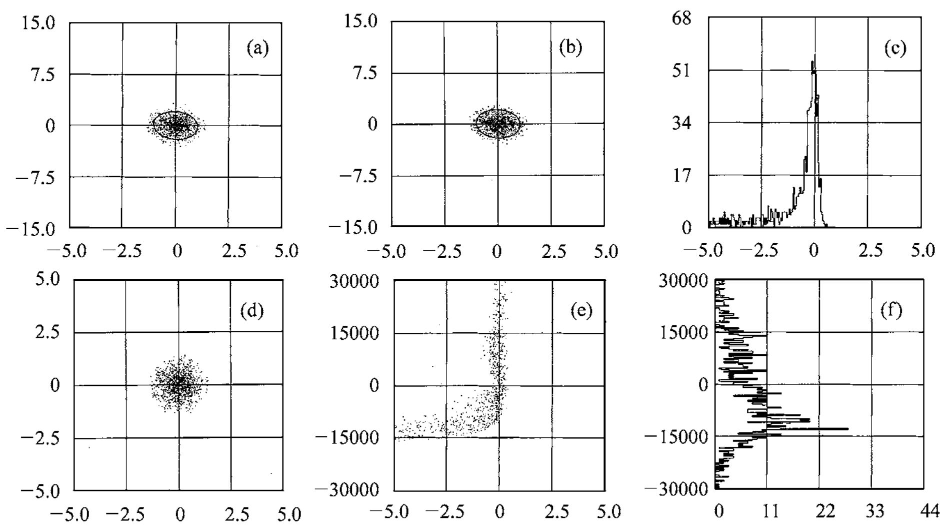

Fig.4. Positron beam performance at the PIL output.

(a) x-x' phase space; (b) y-y' phase space; (c) phase spectrum; (d) x-y beam cross section; (e) ΔW vs. $\Delta\phi$; (f) energy spectrum.

The authors wish to thank K. Floettmann for the very helpful discussions on this design study and for his support for the initial positron data given by his designed positron source. Thanks to R. Brinkmann, A. Gamp, V. Paramonov and D. Trines for the valuable discussions and concerns on this study.

References

1 TESLA Collaboration. TESLA Design Report. March, 2001
2 WANG S H et al. TESLA 99-03. March, 1999
3 JIN K et al. Nucl. Instrum. Methods Phys. Res., 2000, **A452**: 28—33
4 TESLA-CDR-500, DESY 1997-048, 614
5 MAFIA. The MAFIA Collaboration. December, 1996
6 Floettmann K. Investigations Toward the Development of Polarized and Unpolarized High Intensity Positron Sources for Linear Colliders, PhD. Thesis, DESY-93-161. 1993
7 Floettmann. K Positron Source: Conversion of Undulator Radiation. In: Chao, A, W, Tigner M. ed Handbook of Accelerator Physics and Engineering. Singapore: World Scientific Publishing, 1998. 433
8 Young Lloyd M. PARMELA-code, LA-UR-96-1835. 1998
9 Chin Y H. User's Guide for ABCI Version 8.8, LBL-35258. 1994

TESLA 行波正电子注入器和束流模拟

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摘要 TESLA 行波正电子注入器采用 L 波段常温加速结构,它同时具有高分路阻抗和大孔径的优点.经系统地束流模拟计算,设计了正电子注入器的主要参数.束流模拟结果表明,在注入器出口可获得满意的束流传输效率和优质的束流性能.

关键词 正电子注入器 L 波段行波加速结构 束流模拟

2004-09-24 收稿,2004-11-30 收修改稿

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