Some aspects in accelerator structure studies at SLAC*

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Abstract Recent progress in the accelerator structure studies at SLAC is reported. This paper covers the room temperature accelerator structures for the ILC e^+/e^- sources; RF structures for some photon science projects including RF deflectors and the LCLS RF gun; the high gradient accelerator R&D in a global CLIC collaboration for the future multi-TeV linear colliders.

Key words e^+ sources, e^- sources, RF deflector, RF gun, light source, linear collider, high gradient

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1 Introduction

Stanford Linear Accelerator Center (SLAC) is operated by Stanford University for the Department of Energy's Office of Science. SLAC is open to all scientists worldwide. The Laboratory's mission is to design, construct and operate state-of-the-art electron accelerators and related experimental facilities in unclassified fundamental research of particle physics, astrophysics and photon science.

Accelerator science program at SLAC is well advanced in very broad aspects including: Advanced electron guns and high brightness X-ray free electron laser – Linear Coherent Light Source (LCLS) project; Participation in R&D of the future high energy colliders – the International Linear Collider (ILC), the Compact Linear Collider (CLIC) and the Large Hadron Collider (LHC); Generation of high-current, low emittance electron and positron storage rings; High gradient RF accelerator technologies; Ultrahigh gradient acceleration based on laser or beam-driven plasma wakefield techniques; Advanced beam physics and beam test facilities and so forth.

My talk would only cover what I have recently directly participated and heavily involved. The issues are the following:

1) L-Band Room Temperature Structures for the ILC e^+/e^- Sources and Structure High Power Test.

2) X-Band RF Deflector Studies.

3) S-Band LCLS gun Design and Tuning.

4) Collaboration with the CLIC and KEK on X-Band Accelerator Structures R&D and High Gradient Tests.

2 L-band room temperature accelerator structures for the ILC e^+/e^- sources and high power test

For the ILC engineering design, we have proposed the system designs for both e^+/e^- sources.

2.1 Basic RF system design

2.1.1 Positron source[1]

The positron source relies upon an intense source of high energy photons impinging upon a metal target. The photons generated by synchrotron radiation in a helical undulator through the interaction of relativistic electrons must be of sufficient energy, typically of order 10 MeV, to generate electron-positron pairs that can escape from the target material and be captured and accelerated. The target is followed by an Optical Matching Device (OMD) which has a field which tapers from 5T to 0.5 T over 20 cm. Due to the extremely high energy deposition from positrons, electrons, photons and neutrons, the 1.3 GHz capture section and pre-accelerator have to use normal conducting structures up to energy of 400 MeV.

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The capture region is composed of two 1.27 m SW accelerator sections at accelerating gradient of 15 MV/m and three 4.3 m TW accelerator sections at gradient of 8.5 MV/m in order to capture and accelerate the positron beam to 125 MeV. The positrons are accelerated to 400 MeV in a pre-accelerator region, which is composed of eight 4.3 m TW sections at 8.5 MV/m. All accelerator sections are surrounded with 0.5 Tesla solenoids as shown in Fig. 1.

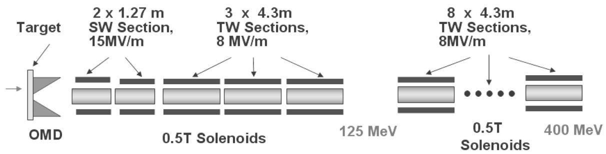

Fig. 1. System design for the ILC positron source.

2.1.2 Electron source[2]

The ILC requires a highly polarized electron beam. We have to use DC gun with GaAs-type cathode for the present design because the low emittance RF gun with GaAs-type cathode is extremely sensitive to vacuum contamination and back bombardment by electrons and ions. The capture region is composed of two SW sub-harmonic prebunchers (216.7 MHz and 433.3 MHz respectively) and a TW 5-cell buncher at 1.3 GHz. The electrons are accelerated to 76 MeV in a pre-accelerator, which is composed of two 4.3 m TW sections at 8.5 MV/m accelerating gradient. All accelerator sections are surrounded with 0.5 T solenoids as shown in Fig. 2.

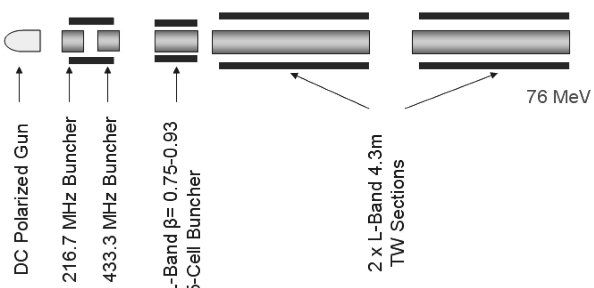

Fig. 2. System design for the ILC electron source.

2.2 Types of accelerator structures

2.2.1 1.3 GHz SW accelerator structure

The capture section has been designed to be simple π mode 11-cell SW accelerator structure. The mode and amplitude stability under various cooling conditions for this type of structure have been theoretically verified. Fig. 3 shows a cutaway view of the SW structure and Table 1 gives the important RF parameters.

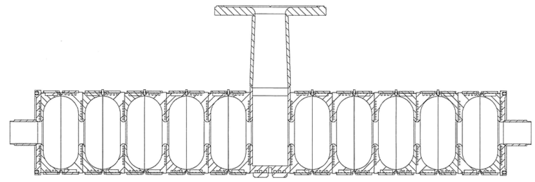

Fig. 3. 11–cell SW structure.

Table 1. Parameters of the capture section.

structure type	simple π mode
cell number	11
aperture 2a	60 mm
Q	29700
shunt impedance r	34.3 MΩ/m
E_0 (8.6 MW input)	15.2 MV/m

2.2.2 1.3 GHz TW accelerator structure

All TW sections are designed to be 4.3 m long $3\pi/4$ mode constant gradient accelerator structures. In order to obtain a good RF efficiency, the "phase advance per cell" was used to optimize the RF efficiency for designing this type of large aperture TW structure. Comparing with standing wave structures, the advantages are lower pulse heating, easy installation for long solenoids, no need to use circulators for RF reflection protection, apparent simplicity and cost saving. Fig. 4 shows the shapes for three typical cells and Table 2 gives the important RF parameters.

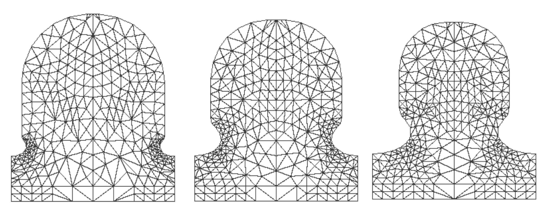

Fig. 4. Profiles of the 1st, middle and last cell for the 4.3 m TW structure.

Table 2. Parameters of the TW structure.

structure type	TW
cell number	50
aperture 2a	46 mm
attenuation τ	0.98
Q	24842—21676
group velocity Vg/c	0.62%—0.14%
shunt impedance r	48.60—39.45 MΩ/m
filling time T_f	5.3 μs
power dissipation	8.2 kW/m
E_0 (at 10 MW input)	8.5 MV/m

2.3 5-Cell SW structure for high power test

In order to test the RF and thermal properties at full gradient using a 5 MW klystron for the capture section, we designed a 5-cell structure as shown in

Fig. 5. Its fabrication process and microwave measurement set-up are shown in Fig. 6 and the recorded field distribution along its axis is shown in Fig. 7.

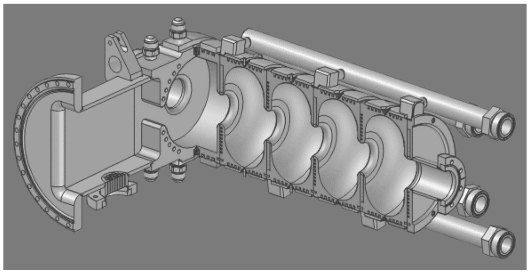

Fig. 5. Cutaway view of L-Band Test SW structure.

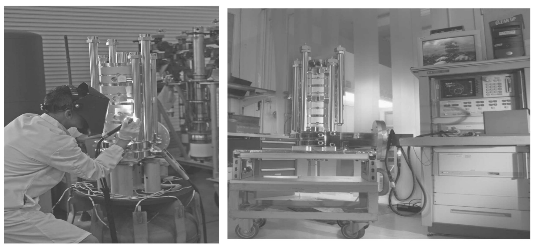

Fig. 6. Welding cooling system after brazing the SW test structure (left) and microwave measurement setup (right).

Finally, the SW test accelerator was installed in a L-Band test facility for high power test as shown in Fig. 8.

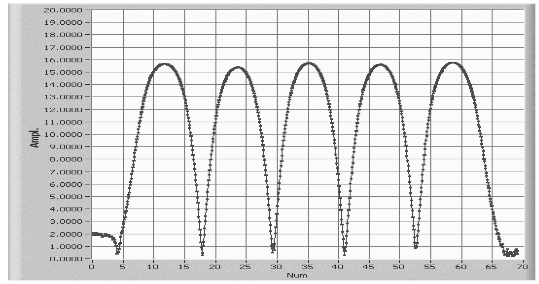

Fig. 7. Plot of measured electrical field along the 5-cell SW accelerator axis by bead pulling.

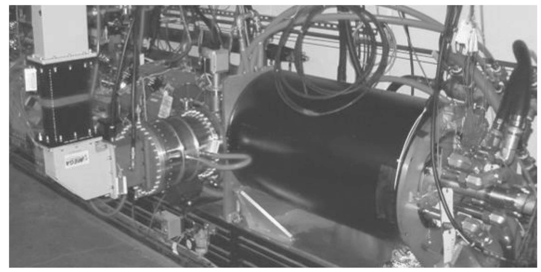

Fig. 8. The SW accelerator structure under high power test.

The high power processing was done for the total of 530 hours ($\sim 5.5\times10^6$ pulses) in the sequences: 160 hours for 100 μs pulse width, 20 hours for 200 μs pulse width, 70 hours for 400 μs pulse width, 280 hours for 1000 μs pulse width[5]. Fig. 9 shows the waveforms for some typical RF breakdown events.

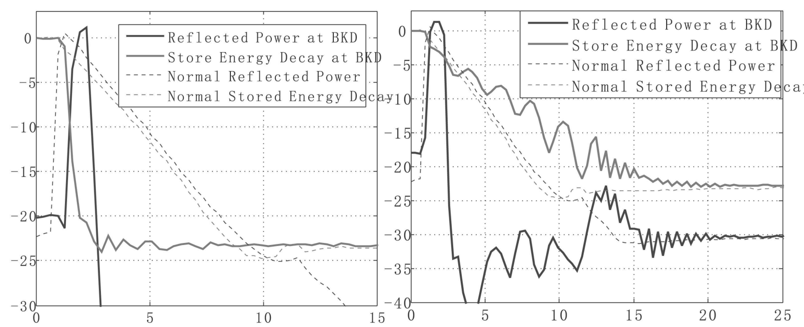

Fig. 9. Recorded waveforms for hard even (left) and soft event (right).

3 X-band RF deflector studies

3.1 Deflector for beam measurement

In order to characterize the extremely short bunch of the LCLS project, we need to extend the time-resolved electron bunch diagnostics to the scale of 10—20 fs[3]. The time resolved diagnostics are made possible using a transverse RF deflector cavity. Using the LCLS beam parameters with full beam energy 13.6 GeV, necessary peak vertically deflecting voltage of a X-Band section to produce a 10-fs temporal resolution bunch is 33 MV. Table 3 gives some important RF design parameters.

3.2 Deflector for fast RF kicker

It has been proposed to convert the SLAC B-factory to be a very strong FEL light source. In order to pick up single bunches from the bunch-train, we need to have an ultra-fast RF kicker. There are 1746 bunches circulating in an orbit with 2200 meters circumference in the B-factory. The bunch spacing is two RF periods with 1.26 m in space or 4.2 ns in time. Therefore, the most challenging design issues are to

Table 3. RF parameters for a 1.5 m deflector.

structure type	TW DLWG
mode	$2\pi/3$ backward wave
aperture 2a	10.00 mm
cavity diameter 2b	29.74m
cell length d	8.7474 mm
disk thickness	1.45 mm
quality factor Q	6400
kick factor k	2.986×1016 V/C/m/m
transverse shunt impedance $r_\perp$	43.17 MΩ/m
group velocity Vg/c	−3.165%
total length	1.5 m
filling time	158 ns
attenuation factor τ	0.885
input peak RF power	30 MW
deflecting voltage	38.9 MV

obtain less than 6 ns RF filling time and more than 5 MV vertical deflecting voltage. Fig. 2 shows the plots of the calculated group velocity and transverse shunt impedance as a function of cell geometries. By enlarging the aperture, the filling time can be reduced, but the power needed for certain deflecting voltage increases. Table 4 lists all most important parameters for a 0.75 m ultra-fast RF kicker with filling time 4.8 ns and 5 MV deflecting voltage at 400 MW X-Band 11424 MHz input power.

Table 4. RF parameters for a fast kicker.

structure type	TW DLWG
mode	$2\pi/3$ forward wave
aperture 2a	27.0 mm
cavity diameter 2b	35.14 mm
cell length d	8.7474 mm
disk thickness	1.45 mm
quality factor Q	9763
kick factor k	1.052×1016 V/C/m/m
transverse shunt impedance $r^\perp$	2.39 MΩ/m
group velocity Vg/c	52.4 %
total length	0.75 m
filling time	4.77 ns
attenuation factor τ	0.0176
Input peak RF power	400 MW
deflecting voltage	5 MV

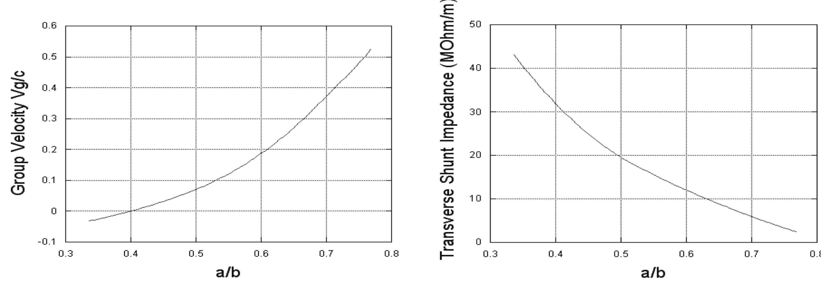

Fig. 10. Group velocity (left) and transverse shunt impedance as a function of the ratio of cell aperture with cell diameter (a/b).

4 S-band LCLS gun design and tuning

In order to provide the LCLS project with a laser-driven high brightness electron gun with superior performance, several important design features are as follows:[4]

1) Dual RF feeds to eliminate any transverse RF field asymmetry due to the flow of RF power.

2) A racetrack shape in the full cell to correct for quadrupole fields introduced by the dual feed.

3) Increased mode separation from 3 to 15 MHz to reduce beating between the 0-mode and π-mode.

4) The elliptical iris shape to reduce its maximum surface field to be lower than the cathode field.

5) Cooling channels capable of dissipating 4 kW of average RF power. (At 120 Hz this corresponds to a cathode peak field of 140 MV/m).

6) The cathode designed for rapid replacement with a new mounting allowing for adjustment of the RF seal and resonance frequency while the gun is under vacuum.

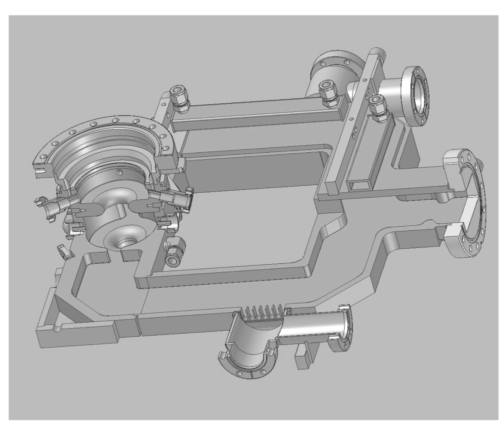

Fig. 11. Cutaway view of the LCLS RF gun.

Figure 11 Shows a cutaway drawing of the gun body with the dual feed waveguides to the full cavity.

The field distribution along the gun axis is measured using the beam drop method and its setup is shown in Fig. 12.

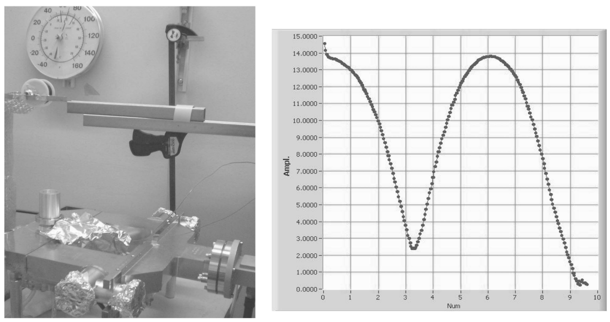

Fig. 12. Bead drop measurement setup (left) and electrical field distribution along axis (right).

As a measure of the field balance, $E_{\text{Full Cell}}/E_{\text{Cathod Cell}}$ as a function of separation between 0-mode and π-mode is shown in Fig. 13. This was obtained by deforming the cathode plate using a differential screw at the center of cathode plate.

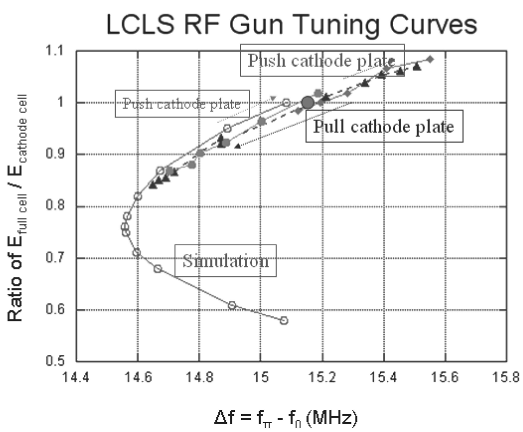

Fig. 13. Electrical field balance as a function of separation between 0-mode and π-mode.

A tuning ridge of 3.8 mm wide and 1.0 mm tall was designed at the outer diameter of the cathode cell to allow tuning of the gun resonance frequency and field balance. Three successive cuttings were made by machining off this ridge based upon the bead drop measurements for the resonant frequencies and field distribution plots until a perfect field balance was obtained. After installing the final cathode, what we needed to do was just to deform the cathode plate to make the modes separation to be ~15.17 MHz as indicated by a red dot in Fig. 13. These tests are essential to establish the procedure for in situ tuning of the gun on the beam line when the cathode is changed and a bead drop cannot be performed. Using the above tuning procedures, all the wall tuners were never used for ensuring the field azimuthal symmetry, only the operation temperature was slightly adjusted by 2℃ than the design value. The final RF tune parameters in comparison with the design values are listed in Table 5.

Table 5. Design and measured parameters of the LCLS gun.

RF parameters	design	measured
f_π	2856 MHz	2856 MHz
Q_0	13960	$\sim$14000
β	2.1	2.03
mode Sep. Δf	15 MHz	15.17 MHz
field balance	1	1

5 Collaboration with the compact linear collider (CLIC) on X-band accelerator structures and high gradient tests

Linear collider is the only option for realizing electron–positron collisions at TeV energies. At present, there are two global collaborations in developing two different technologies for linear colliders. The ILC based on superconducting RF system at a nominal accelerating gradient of 31.5 MV/m is a machine with a centre-of-mass energy of 500 GeV and a possible future upgrade to 1 TeV. The CLIC based on normal conducting RF system at very high electric fields of 100 MV/m is a machine with a centre-of-mass energy of 3 TeV. Such high fields require high peak power and hence a novel power source — an innovative two-beam system is adopted, in which a drive beam supplies energy to the main accelerating beam. Initiated at CERN, CLIC is now closely collaborating with 26 institutes including SLAC.

The design of linac structures is one of the most challenging items being developed for CLIC[6]. The CLIC study aims to demonstrate a prototype accelerating structure with an average loaded gradient of 100 MV/m at 12 GHz, which are quite similar with the goals of the NLC main linac developed at SLAC in the past years. In order to reach a sufficient luminosity for the collider a bunch train of 312 bunches has to be accelerated with good efficiency. Therefore the structure needs to be equipped with heavy higher order mode damping and the gradient should be sustainable for 230 ns. They have to be able to withstand the very high accelerating fields of 100 MV/m in RF pulses without being damaged by unavoidable

RF breakdowns and pulsed RF heating.

In order to obtain the best performance, broad range of RF parameters including structure length, cell geometries, group velocities, HOM damping schemes and coupler types are under investigation. A total of five disk-loaded structures and two quadrant structures have been made by SLAC/CERN/KEK joint effort. More than twenty test structures are being planned to be made and high power tested in this collaboration. Fig. 14 shows the best accelerating structure produced so far.

Fig. 14. X-Band structure T18_VG2.6_DISK.

The parameters of this structure are listed in Table 6 and the microwave measured results are shown in Fig. 16.

This structure was high power tested for a total of 1400 hours using an automated conditioning system. A total of 2148 breakdowns were accumulated throughout the experiment. The pulse length was extended in several steps from 50 ns to 230 ns. The results summarized in Fig. 15 were the breakdown probability plotted as functions of the average unloaded gradient along the structure and pulse widths. The CLIC goal for a 3 TeV machine is a trip rate of 3×10^{-7} per meter at 100 MV/m loaded gradient. An average unloaded gradient of 109 MV/m corresponds to a loaded gradient of 100 MV/m for the present CLIC beam parameters.

Table 6. RF parameters for TW test structure.

frequency	1.424 GHz
cells	18+input+output
filling time	36 ns
$a_{\rm in}/a_{\rm out}$	4.06/2.66 mm
$V g_{\rm in}/V g_{\rm out}$	2.61% c/1.02% c
S_{11}	0.035
S_{21}	0.8
phase advance	120°/per cell
average gradient	55.5 MW →100 MV/m

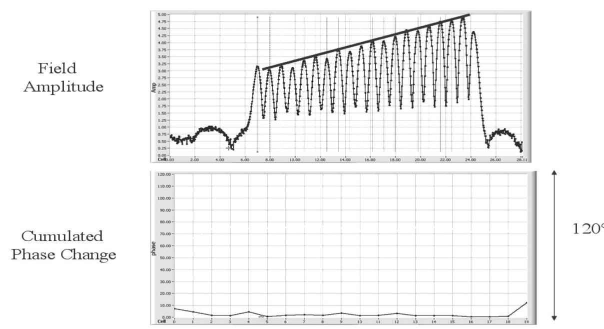

Fig. 15. Field (top) and phase (bottom) measurement results for the test structure using beam pull technology.

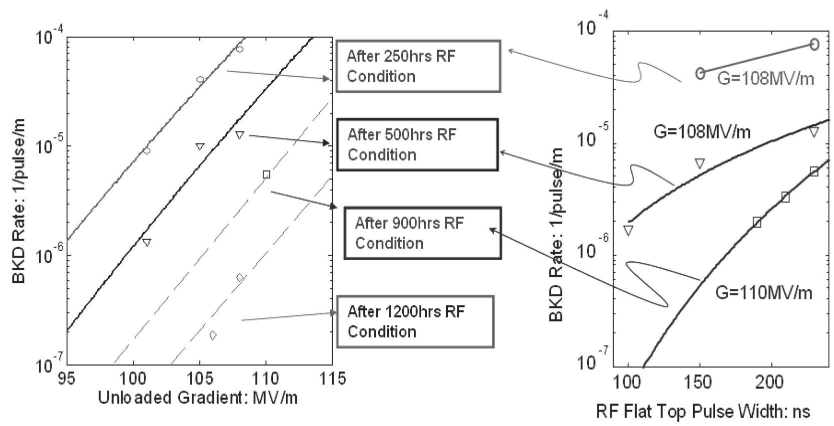

Fig. 16. The breakdown probability are plotted as functions of the average unloaded gradient (left) and pulse width (right).

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