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R&D of Accelerator Structures at SLAC*

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Abstract The research activities for accelerator structures at SLAC are reviewed including the achievement via the main linac design for the Next Linear Collider (NLC), the program adjustment after the decision of the International Linear Collider (ILC) to be based on superconducting technology, and the work progress for the ILC, photon science at SLAC and basic accelerator structure studies.

Keywords linear collider, normal conductivity, superconductivity, wakefield, damping, detuning.

1 Introduction

The mission of the RF Structures Group at SLAC is to design, engineer, and test variety of accelerator structures with superior properties in high RF efficiency, strong Higher Order Mode (HOM) suppression and good high gradient performance. Our activities span design theory and practice, structure related beam dynamics studies, fabrication technology, RF measurements, and high power experiments.

There are two major challenges in developing accelerator structures for linear colliders[1]. The first is to demonstrate stable, long-term operation at the high gradient (65 MV/m) in order to optimize the machine cost. The second is to strongly suppress the beam induced long-range wakefields, which is required for achieving high luminosity. Fifty X-Band accelerator structures with various RF parameters, cavity shapes, phase advance per cell and coupler types have been fabricated and tested since 2000.

After the decision was made to select superconducting technology for the future linear collider, we quickly adjusted our R&D program to embrace the ILC opportunity with enthusiasm as well as to support SLAC photon science projects.

2 From the NLC to the ILC

2.1 Two Options

With the advent of the SLAC $e^- e^+$ linear collider in the 100 GeV center-of-mass energy range, the research and development on even higher energy machines of this type started around the world. The TeV-Energy Superconducting Linear Accelerator (TESLA) was based on superconducting accelerator technology – so called “cold machine”. The Next Linear Collider (NLC/GLC) was based on normal conducting technology - “warm machine”. Both technologies can achieve the goals. They have been pursued by dedicated and talented collaborations of physicists and engineers from around the world.

2.2 International Linear Collider (ILC)

In 2004 the ICFA formed the International Technology Recommendation Panel (ITRP) - a major step toward new international global machine. The recommendation was presented to ILCSC&ICFA in August 2004 at Beijing. The ILC has been recommend to be based on superconducting RF technology. The 1st ILC accelerator workshop was held in November 2004 at KEK with 220 participants from three regions (Asia/Europe/North America). The Global Design Effort (GDE) was established in March 2005. The 2nd ILC accelerator workshop was hold in August 2005 at Snowmass, US.

3 Achievements from NLC Structures

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3.1 Damped Detuned Structure

As a technology breakthrough, the Damped and Detuned Structures for the NLC main linac can be applied to any low emittance, high beam loading accelerators. Detuning requires that each cell of the structure has a slightly different dipole frequency such that the net wakefield decreases rapidly and smoothly during the period between bunches. In order to prevent partial recoherence of the mode excitations, a weak mode damping is introduced by coupling each cell through longitudinal slots to four TE11 circular waveguides (manifolds) that run parallel to the structure. Moreover, manifold damping functions as structure position monitor with micron transverse sensitivity and frequency multiplexed longitudinal resolution of the order of several cells.

Figure 1. Prototype structure for the NLC main Linac.

3.2 Theoretical Wakefield Analysis

We have developed a two-band circuit model for theoretical analysis of HOM wakefield and interaction between beam and RF structure, emittance growth, tolerances of structure alignment and dimensions[2]. Figure 2 shows a wonderful agreement between the predicted structure wakefields and the measurement results obtained in the early 2005.

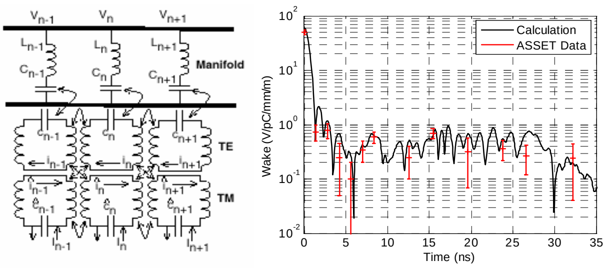

Figure 2. Circuit model of wakefield damping (left), wakefield as a function of time behind the driving bunch (right).

3.3 Design Integration of Accelerator Parameters

We have systematically studied the parameters optimization including phase advance per cell, group velocities, total length, attenuation factor for highest RF efficiency. All structure 3-D dimensions can be calculated with sub-micron precision.

3.4 Fabrication technologies

We have mastered the advanced fabrication technologies for normal conducting (NC) accelerator structures including precision machining, diffusion bonding and long structure alignment. No tuning was needed for structure final assembly[3].

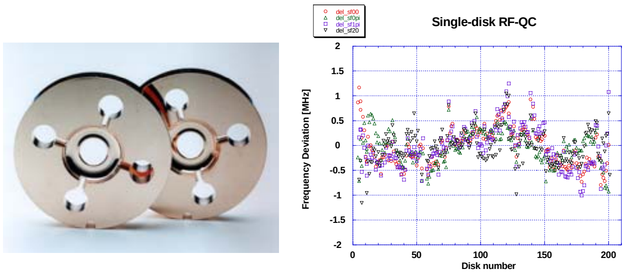

Figure 3. Precision machined discs (left) and measured data showing frequency accuracy of RMS=0.4 MHz (right).

3.5 High Gradient Operation

After more than thirty structures were tested with over 20,000 hrs of high power operation, we improved the design and structure preparation procedures, the RF breakdown rate was less than 1 per 10 hours at 65 MV/m average gradient and 60 Hz, 400 ns RF pulses for the 60 cm prototype structures[4].

4 Research Program for the ILC

4.1 Accelerator Structures for the ILC e^+ Sources

Due to the extremely high energy deposition from positrons, electrons, photons and neutrons behind the positron target, the 1.3 GHz pre-accelerator has to use normal conducting structures up to energy of 250 MeV. There are many challenges in the design of the ILC positron injector system such as obtaining high positron yield with required emittance, achieving adequate cooling for heating from high RF power and particle losses, and sustaining high gradients during millisecond-long pulses in a strong magnetic field. Considering issues of feasibility, reliability and cost saving, our new design contains both standing-wave and traveling-wave L-band accelerator structures[5].

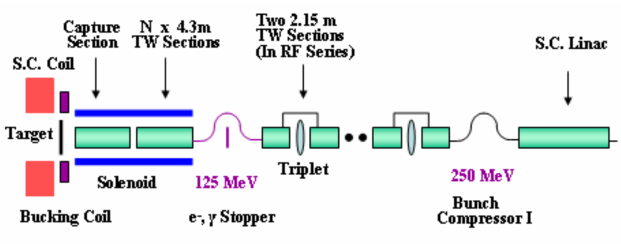

Figure 4. Schematic layout of the ILC positron source.

4.1.1 Types of accelerator structures

Three types of accelerator structures have been carefully studied and designed.

- 11-cell π mode SW structure

The structure for e^+ capturing with high gradient (15MV/m) is a π mode SW structure with 11 cells. The advantages are effective cooling, high shunt impedance with larger aperture (60 mm), low RF pulse heating, apparent simplicity and cost saving.

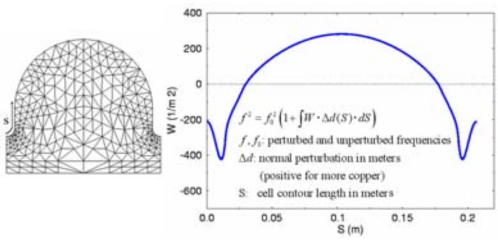

Figure 5. Cell profile of SW structure (left) and the frequency perturbation weighting function along cell surface (right).

- 4.3 m 3π/4 mode TW structure

The "phase advance per cell" has been used for optimization in designing large aperture, constant gradient TW structures with high RF efficiency. The advantages are lower pulse heating, easy installation for solenoids, no need for RF reflection protection (circulators), apparent simplicity and cost saving.

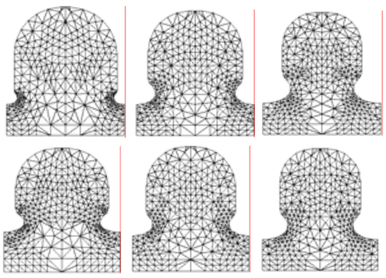

Figure 6. Profiles of 1st, middle and last cell for 4.3m structure, regular (upper three) and special section (bottom three).

Also, we've designed a special 4.3 m TW section with larger iris (6 cm) and thicker disc (1.7 cm), which can be used as a section right after the e^+ target of undulator-based source in order to realize deceleration scheme for higher positron yield.

- Pair of two 2.2 m 3π/4 mode TW structures

In order to insert quadrupole triplets for transverse focusing of e^+ with energy >125 MeV, we plan to divide the regular 4.3 m TW structure into two ~2.2 m sections and install them with proper drift space. The RF power from output coupler of the first section feeds to the second section.

4.1.2 Cooling and Mechanical Design

The proposed cooling channels are machined into the outer cylindrical surface and the planar end surface of the cell's copper body. A copper cover is brazed over the planar end surface and a stainless steel cylinder is brazed to the outer surface of the copper body. A full cell is formed by brazing two of half cell assemblies together at the cavity iris and the full section is assembled from full cell subassemblies.

To determine the detuning at operating temperature, an axisymmetric representation was modeled using the finite element code ANSYS. Both cell surface RF losses and the average volumetric heating due to particle losses were considered in the simulations.

The cavity detuning was calculated by applying the Slater perturbation method based on the normal cavity surface displacements obtained from ANSYS and weighting factors shown in the right figure of Fig. 5.

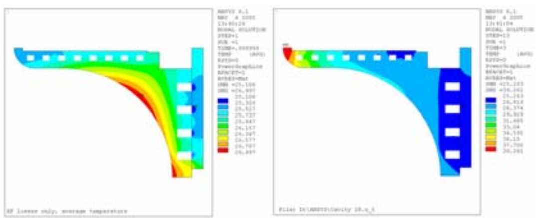

Figure 7. ANSYS thermal model with average RF losses (left). and thermal model with average RF and particle losses (right).

The feasibility has been theoretically analyzed. The mode spacing near to π mode is wide enough for stable operation; the influence of cell phase difference due to RF power flow is negligible; the RF amplitude and phase variation due to fabrication errors and heating is tolerable; the temperature increase due to RF pulse heating is safe for high gradient operation.

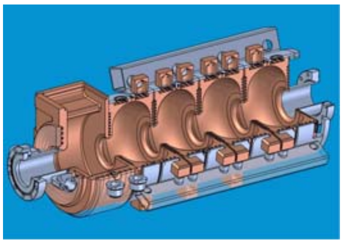

Figure 8. L-Band SW test accelerator structure.

4.1.3 Positron Capture studies

The traditional approach for positron capturing has been to arrange the phase and amplitude of fields in the capture section(s) to accelerate the positrons as fast as possible. The higher the accelerator field, the less the beam debunches due to the initial energy spread of the positrons. At 1.3 GHz to get reasonable positron yield into a 15^{O} bunch for this case requires an accelerating gradient of 12 MeV/m or greater.

As shown in Figure 9, another approach is to initially decelerate the positrons and arrange the phase and amplitude of fields so that the distribution in longitudinal phase space of the incoming positrons lay along one of the orbits in longitudinal phase space. Thus the positrons approach a small spread in asymptotic phase as their energy increased.

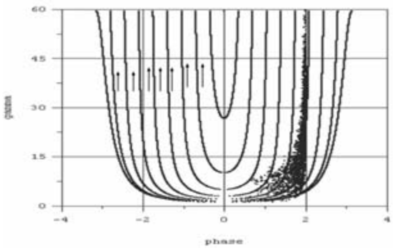

Figure 9. Phase space for positrons interring accelerator.

Simulations for the ILC indicate that this approach can increase the yield of positrons into a 1% spectrum at 5 GeV by about 40%. These simulations were done without bunch compression. The optimum gradient in these capture-with-deceleration simulations was found to be about 6 MeV/m. With this gradient, a single 10 MW klystron can drive up to 6 meters of structure.

4.2 Theoretical modeling of wakefield and emittance dilution for the ILC.

The progress of the bunches in high energy linear colliders is disrupted by the trailing wakefield left behind each driving bunch and this can lead to a severe dilution in the luminosity of the colliding beams. In an ideal structure the horizontal and vertical modes of the dipole wakefield are degenerate. Inevitable manufacturing errors may remove the degeneracy and create two dipole eigenmodes of slightly different frequencies lying in diagonal planes. These dipole wakefields will couple the horizontal and vertical motions of the beam. We have investigated the consequences on the final emittance dilution of the beam for this coupling in L-band superconducting linear colliders. Means to ameliorate the severe emittance dilution that occurs due to this mode coupling have included splitting the horizontal and vertical phase advance per cell of the linac lattice. The vertical tune remains fixed at a phase advance of 60 degrees per cell whereas the horizontal has been varied from 70^{O} to 90^{O}. In all cases the emittance dilution has been reduced to the order of 20%.

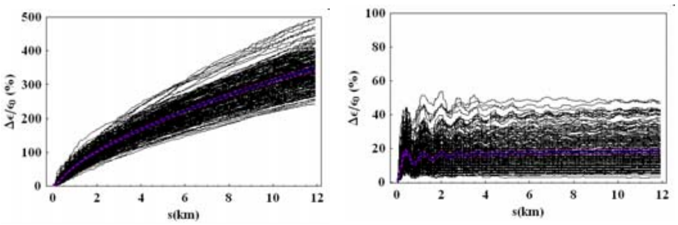

Figure 10. Equal tune of 60-60 in both planes of the lattice (left) and splitting tune of lattice 90-60 in x-y plane (right).

5 Other Structure Research Program

5.1 Support photon Science

We are actively participating in the S-Band structure related work for the LCLS project including design discussions for microwave gun, modification of the accelerator sections with double RF feeds and microwave measurements. We have designed and fabricated a horizontal bead pulling setup. Two 9.5 ft sections and six 10 ft sections have been evaluated. We've provided some important suggestions for the LCLS injector engineering. We will measure and characterize two RF deflectors and perform complete microwave measurement and tuning of the 1st microwave gun. The analysis of test results will contribute to the future upgraded gun design.

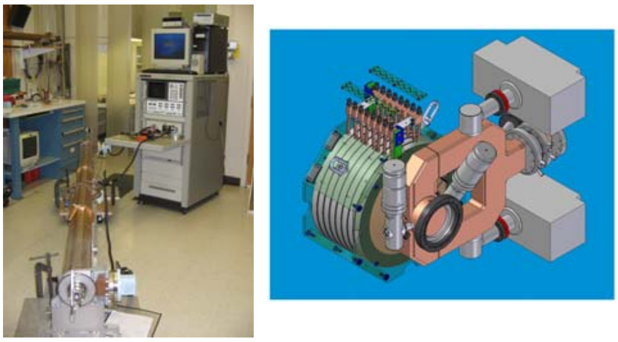

Figure 11. Microwave evaluation of a S-Band structure (left) and LCLS microwave gun to be fabricated and tested (right).

5.2 Wire Measurement

A wire-based structure experimental method is being developed to quickly and inexpensively analyze the wakefield suppression properties of accelerator structures[6]. In order to automate the measurement, the position of a 300-micron thick brass wire is moved by micro-stepping motors and controlled by a measurement software. The data acquisition with a HP8510 network analyzer has been successfully accomplished on a SW20PI-L standing wave accelerator structure. The recorded S-parameters are used to compute the impedances for monopole band and higher dipole mode bands.

5.3 Micro Linac Structures

The Micro Linac is a small, SW linac intended as a low cost radiography source with dosage larger than 100 Ci to replace radioactive sources, which can potentially be used for “dirty bombs”. We have contributed both the electrical and mechanical design for these accelerator structures.

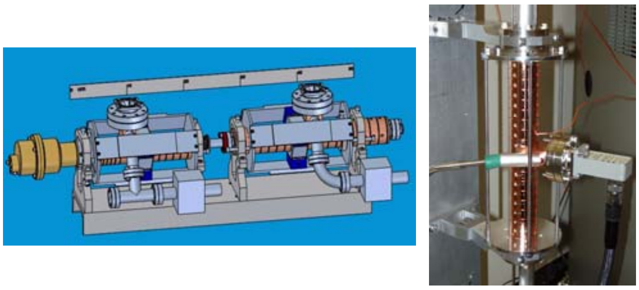

Figure 12. MicroLinac assembly (left) and an SW section under test.

6 Acknowledgements

Many SLAC scientists and engineers have joined as a strong team and contributed to the structure R&D.

This symposium gives me a wonderful opportunity to meet many talented scientists and students of top Chinese institutions. I am grateful to the organization committee members for their great support and help.

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加速器结构在 SLAC 的研究和发展

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摘要 评述近年来加速器结构在 SLAC 的研究和发展。内容包括：通过下一代直线对撞机(NLC)的研究取得的成果；在决定国际直线对撞机采用超导主加速器以后研究工作的调整和进展。

关键词 直线对撞机，常温导体，超导体，尾场，阻尼，失谐。