SLAC–PUB–12692
July 2007

ILC RF System R&D *

Chris Adolphsen
Stanford Linear Accelerator Center, Stanford University, Stanford CA 94309

Abstract

The ILC Linac Group at SLAC is actively pursuing a broad range of R&D to improve the reliability and reduce the cost of the L-band (1.3 GHz) rf system. Current activities include the development of a Marx-style modulator and a 10 MW sheet-beam klystron, construction of an rf distribution system with adjustable power tap-offs and custom hybrids, tests of cavity coupler components to understand rf processing limitations, simulations of multipacting in the couplers and optimization of the cavity fill parameters for operation with a large spread of sustainable cavity gradients. Also, a prototype positron capture cavity is being developed for the ILC injectors. This paper surveys the results from the past year and notes related L-band R&D at other labs, in particular, that at DESY for the XFEL project.

Presented at the 2007 Particle Accelerator Conference,
Albuquerque, New Mexico, June 25-29, 2007

* Work supported by Department of Energy contract DE–AC02–76SF00515.

ILC RF System R&D*

Chris Adolphsen
Stanford Linear Accelerator Center, Stanford University, Stanford CA 94309 USA

Abstract

The ILC Linac Group at SLAC is actively pursuing a broad range of R&D to improve the reliability and reduce the cost of the L-band (1.3 GHz) rf system. Current activities include the development of a Marx-style modulator and a 10 MW sheet-beam klystron, construction of an rf distribution system with adjustable power tap-offs and custom hybrids, tests of cavity coupler components to understand rf processing limitations, simulations of multipacting in the couplers and optimization of the cavity fill parameters for operation with a large spread of sustainable cavity gradients. Also, a prototype positron capture cavity is being developed for the ILC injectors. This paper surveys the results from the past year and notes related L-band R&D at other labs, in particular, that at DESY for the XFEL project.

INTRODUCTION

The development of modulators, klystrons, rf distribution systems, SC cavity power couplers and normal-conducting injector accelerators for the ILC are surveyed below. The emphasis is on the research at SLAC although parallel, and often complimentary programs, are noted for the European XFEL project. More detailed accounts of these efforts can be found in the numerous contributions to this conference on these subjects, which are referenced herein.

MODULATORS

The ILC baseline modulator is a pulse transformer type with an LC 'bouncer' circuit for droop compensation [1]. It nominally produces 120 kV, 130 A, 1.6 ms long HV pulses at 5 Hz to drive a 10 MW klystron. The design was originally developed at FNAL for TESLA, and it has since been industrialized by DESY, with 11 units in operation there (8 built by European vendors). Currently DESY is expanding their vendor base in preparation for an order of about 30 units for XFEL (which will run at 10 Hz), and is creating a facility at Zeuthen to do long term testing of two modulators and klystrons. They are also doing reliability testing of km-length cables under pulsed operation (10 kV, 1.6 kA), as is required for XFEL (but not the ILC). One of their new units will be of a pulse step design where 0.5 kV cells are added in series to drive the transformer [2]. The turn-on of some of the cells is delayed to compensate the droop, thus eliminating the need for a bouncer circuit.

Both FNAL and KEK have recently acquired pulse transformer modulators. A unit was built at FNAL that has long pulse (5 ms) capability to allow use in both their neutrino source and ILC programs. It incorporates a state-of-the-art IGBT switching circuit built by SLAC [3]. The KEK version was built by Japanese industry for their Superconducting Test Facility (STF) program [4].

Although pulse transformer modulators have thus far run fairly reliably, they have very large and heavy oil-filled transformers, and the switching is done at the low voltage (10 kV), high current (1.6 kA) end, which increases the losses. In an effort to find a better design at a lower cost, SLAC is evaluating three modulators that do not use large step-up transformers. One is the SNS High Voltage Converter Modulator, which employs a high efficiency, 20 kHz DC-to-DC switching circuit in a compact layout [5]. A production unit on loan from SNS has been in use at SLAC for over a year with few problems. While it is efficient, its droop compensation system is not used as the required changes to the poly-phase circuit timing can lead to overheating of the IGBT switches.

Another modulator being assessed is a direct switch unit being developed through the US SBIR program [6]. It uses a multiplier circuit to produce the full voltage, which is then applied by a direct solid-state switching element to the klystron. As in the baseline design, droop is compensated with a bouncer circuit. The first unit is due to be delivered to SLAC by the end of 2007 for evaluation.

The last modulator is a Marx design where the goal is also to significantly improve reliability. In this approach, a series of capacitors are slowly charged in parallel and then discharged in series to form the pulse. A full-scale, air-cooled prototype is being built at SLAC [7]. It consists of a series of 12 kV main cells (large circuit boards mounted on a common backplane) and vernier cells for regulation and droop compensation. Its modular design lends itself to high reliability (extra cells are included to automatically replace ones that fail), and to mass production assembly techniques, which should provide significant cost savings (up to 50%) over the baseline design. The prototype is nearly complete, and the unit so far has operated at full voltage and current, although at low pulse rate and with only partial droop compensation. Full spec operation is expected by the end of 2007.

Besides the Marx development at SLAC, a shorter pulse (100 μs), and somewhat lower voltage (90 kV) version was built and successfully operated recently for a company supporting NATO radar systems [8]. Also, an

* Work Supported by DOE Contract DE-AC03-76F00515.

Figure 1: Photo of the SLAC Marx Modulator with 10 of the 18 cards installed.

SBIR-funded Marx modulator for the ILC is being built and is expected to be completed by summer 2008 [9].

KLYSTRONS

The ILC baseline rf source is a 10 MW Multiple Beam Klystron (MBK) developed originally for TESLA. Three klystron vendors in collaboration with DESY have each produced a version that achieved 10 MW peak power [10-13]. These designs attain high efficiency (up to 66%) by using six or seven beams to reduce the space charge forces that limit rf bunching (single beam tubes typically have 40% - 45% efficiencies). However, the prototypes so far have either not proven robust at full power or have not been tested long enough at full power to completely qualify them for the ILC. Nonetheless, the basic approach appears sound, and DESY has recently contracted the three vendors to build second generation prototypes for XFEL that will be supported horizontally (instead of vertically) to fit in the accelerator tunnel (they will typically run at 5 MW at XFEL, but at 10 Hz). SLAC in collaboration with KEK is also acquiring a 10 MW MBK for long-term evaluation at full power for the ILC.

As an alternative, the SLAC Klystron Group is developing a Sheet Beam Klystron (SBK). In this tube, a flat beam is used to reduce the space charge forces, which should produce an efficiency similar to that of the MBK's. The tube will also be 'plug' compatible with the MBK's, have a 40:1 beam aspect ratio and utilize permanent magnets for focusing (reducing the ILC power consumption by about 4 MW). Its rectangular geometry and many fewer parts make it simpler to manufacture. This should reduce the per-klystron cost, and because there are fewer joining operations during fabrication, the tube yields should also be higher. Production SBK's are estimated to be about 30% longer (3.1 m) than the MBK's, but 30% narrower (0.7 m) and about five times lighter (420 kg) from not having the large solenoid magnets.

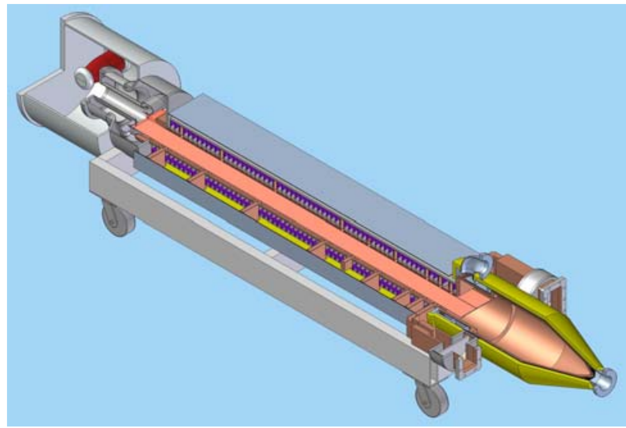

Figure 2: Cut-away illustration of the Sheet Beam Klystron with permanent magnet focusing.

The development plan is to produce a 'beam tester' (no rf cavities) by the end of 2007 and a full SBK by mid-2008. The beam tester will be used to verify the predicted beam transport. With it, the beam current density will be measured just after the gun (at the expected beam size minimum) and after the beam has passed two-thirds along the magnetic circuit. The klystron will be produced in parallel to speed development, so there will be little feedback from the beam tester. This program benefits from the Klystron Group's design and fabrication efforts that led to successful beam transport in a 91 GHz SBK (no commercial SBK's exist at any frequency).

Much of the recent L-band work has focused on understanding and perfecting the 3-D gun design. Extensive studies of the center 2-D beam slice, 3-D emission and magnetic field effects were performed to become familiar with the MICHELLE gun code and to compare with previous 2-D tools (EGUN). Much was learned about the limitations of the code and the various trade-offs in emission, field solutions and ray tracing accuracies. Code refinements by the vendor have led to significant advances in the accuracy of the code.

After this study, electrostatic modeling of the full 3-D gun began, and the focus electrode and anode shapes were adjusted to produce the desired beam shape and current density. The next phase will be to adjust the magnet stack entrance to match the electrostatic electron beam focusing for smooth beam transport. Concurrently, the magnetic structure is being simulated in 3-D using both the ANSYS and MAGNET finite element codes, with much effort devoted to achieving the unique focusing field requirements of a sheet beam. RF-electron beam interaction simulations have been performed using the PIC code MAGIC to optimize the rf circuit parameters (cavity tuning, gap spacing, etc.) for efficiency and output power. The 3-D geometries of the cavities were designed using the ANALYST finite element code. This code was also used to design rf input and output couplers for the cavities. Final touches to the full 3D rf and transport simulations will be made after the magnet stack simulations have achieved an optimal input match condition. A high power output window was designed using CASCADE, ANSYS, HFSS and ANALYST. The SLAC Advanced Computations Department is currently studying the multipactor behavior of this window design.

With the majority of the electrical design work complete, the mechanical design phase has started, including the modeling of parts with Solid Edge and the generation of drawings for the production of the beam tester and klystron. Using shape input from the 3-D electron gun simulations and ANSYS thermal analyses to determine the heater design and power requirements, the cathode design was completed, and parts are being ordered.

RF DISTRIBUTION

In the ILC baseline design, the rf power from each 10 MW klystron is distributed to 26 cavities via a series of fixed tap-offs along waveguides that run parallel to the beam line. There is a circulator in each cavity feed line for isolation, followed by a three-stub tuner for phase control (the cavity Q_{ext} can also be adjusted with this tuner, but this will nominally be done by moving the coaxial antenna in the cavity power coupler). This distribution system design is based on that used at the TTF facility (now FLASH) at DESY. However, the DESY systems contain off-the-shelf components that are not necessarily optimized for this application. Also, by delivering the same power to each cavity, they are inefficient if there is a large spread in sustainable gradients as the poorest performing cavity limits the overall gradient.

A more versatile and less costly rf distribution system for ILC is being developed at SLAC [14]. The expensive circulators are eliminated and the cavities are instead powered in pairs using 3-dB hybrids. This still isolates the cavities, but allows some power (up to ~ 0.1%) to return to the klystron in the event of an rf fault in a single cavity or coupler. This level does not exceed the klystron VSWR specification, and the klystron power would likely be shut off anyway to limit the damage at the fault location. Another change is the use of a Variable Tap-Off (VTO) system to feed each cavity pair. For this purpose, a rotatable, polarized TE11-mode circular/oval waveguide section has been designed that, together with pair of three-port mode 'launchers/selectors,' can produce any fractional power split at constant rf phase (see Fig. 3). In the ILC, their orientations would be set initially based on the cavity performances before cryomodule installation, and then adjusted based on the in-situ results (hopefully one time only). A further cost cutting measure is to replace the 3-stub tuners with simpler phase shifters or eliminate them all together, as the waveguide phase length is fairly insensitive to temperature. Finally, with the large number of waveguide flanges, a means of welding the waveguides together is being sought to reduce cost and improve reliability.

Recently, VTO and 3-dB hybrid prototypes were built using an aluminum dip-brazing technique. The 'cold' test results show the devices work as designed with better than 40 dB isolation in the 3-dB hybrid output ports. The 'hot' testing has started, and the VTO with a 1:3 split is operating stably with 4 MW, 1.2 msec, 5 Hz pulses while filled with dry nitrogen at atmospheric pressure.

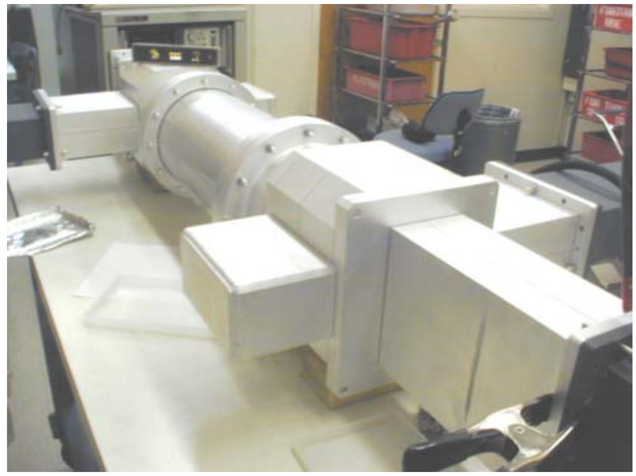

Figure 3: Photo of a 1.6 m long Variable Tap Off (VTO) undergoing 'cold' tests.

Other waveguide parts are also being acquired to assemble an eight cavity distribution system based on the VTO/hybrid concept for the first cryomodule being assembled at FNAL. However, circulators will be supplied so that cavity and LLRF feedback system performances can be compared with and without them. They are also needed to accelerate beam as the phase length between cavities in the first cryomodule does not allow both acceleration at a fixed phase and the effective use of the 3-dB hybrids to port the combined cavity reflected power to a load (future cryomodules will have a cavity spacing that allows both).

For the ILC, using one circulator and one VTO per cavity allows maximum flexibility to accommodate a large spread of sustainable gradients. Currently there is a 22-34 MV/m uniform distribution of gradients for production-like cavities. For the ILC in this case, each cavity could operate at its maximum gradient during the beam period with only a 7% increase in rf power on average relative to that if all cavities ran at the mean gradient of 28 MV/m. The cavity power levels and Q_{ext}'s would be adjusted for this purpose and the additional reflected power would be absorbed in the circulator loads. However, this distribution system is relatively expensive, and studies were done recently to determine the impact on gradient with simpler systems [15]. For example, if the cavities are feed in pairs via 3-dB hybrids and similarly performing cavities are grouped, the gradient is reduced by about 1% using one VTO per pair but no circulators, and by about 3% without either VTO's or circulators. In these cases, the gradient is constrained to be flat on average for the 26 cavities to < 0.1% rms during the beam period. With this information, tradeoffs in cost and operational complexity are being evaluated.

For the XFEL rf distribution system, DESY has also improved on the TTF design [16]. Because of the limited space in the single tunnel linac for XFEL, a planar distribution has been adopted that includes inline T-shaped waveguide splitters that feed pairs of cavities. Each splitter contains two posts that can be positioned during fabrication to provide any fractional spilt. Thus they can be customized if the gradient limits of the associated cavity pairs are know in advance. DESY has also developed a waveguide phase shifter with a moveable C-shaped insert to replace the 3-stub tuner. However, their choice of cavity spacing, which allows bi-directional beam acceleration, requires having a circulator per cavity. At KEK, one of their four-cavity cryomodules will be fed by a tree-like distribution system using 3-dB hybrids, while the other will use a TTF-like system with circulators. Thus, they will also be able to compare the system performance with these two approaches.

CAVITY POWER COUPLERS

To power a SC cavity in the ILC, the rf will be channeled from a waveguide through coaxial tubes to an antenna-like structure near the cavity entrance. The design of this power coupler is complex due to requirements on cleanliness, temperature gradient, vacuum, Q_{ext} adjustability and high voltage isolation. The TTF-3 coupler design used at DESY is the ILC baseline choice, and while over fifty such couplers have been operated successfully for tens of thousands of hours, the power levels have been generally below the 300 kW level required by the ILC [17-18]. Another concern is the multipacting that is observed near this power level in the 40 mm OD sections attached to the cavities (the couplers were originally designed for 230 kW operation at the lower TESLA gradient). The resulting outgassing could lead to rf breakdown at the windows, and some of the electrons from the amps of current generated could migrate into the cavities and be accelerated. Finally, the couplers are expensive to fabricate, which has prompted efforts to simply the design.

At LAL Orsay, which assembles and rf processes the couplers used at DESY, two alternative designs are being developed, called TW60 and TTF5 [19]. Their minimum coaxial OD was increased to 62 mm so multipacting occurs at higher power, and for TW60, a disk like window is used to simplify fabrication. These designs still allow the antennae to be moved to adjust the Q_{ext} of the cavities, which is likely to be critical for maximizing gradient as discussed above. KEK is also testing two different coupler designs, one of which uses capacitive coupling through a window to simplify the geometry and improve thermal isolation, and one based on the geometry used at Tristan, with disk windows and a larger (60 mm) minimum OD [20-21]. However neither has a movable antenna, and unlike the others, the center conductor cannot be HV biased to suppress multipacting. This latter change makes the design much simpler, and would probably be acceptable for the ILC if a larger OD is adopted.

At SLAC, a joint program with LLNL is underway to better understand multipacting and rf processing limitations of the TTF-3 couplers [22]. For this purpose, a coupler component test stand has been built that allows coaxial sections to be powered (see Fig. 4). Various sections are being built to assess the impact of coatings, bellows, and windows on the rf processing speed. Currently, 610 mm long, 40 mm OD straight stainless steel sections are being powered to study the multipacting that occurs in the high field coupler sections. Various signals (vacuum, electron probe and light) are monitored as the rf power is increased, and after repeated power cyclings (up to 1-2 MW) with progressively longer pulses (up to 1 msec), the multipacting bands become more apparent. These multipacting power levels are in fair agreement with those predicted in simulations at SLAC [23]. The electron probe signals are particularly interesting as they have a delayed turn-on with respect to the rf pulse. This delay varies with power and vacuum level and may be due to insufficient electrons to seed the multipacting. In fact, adding a microsecond long, high power spike to the rf pulse, which likely produces field emitted electrons, leads to the immediate turn on of the multipacting after the spike.

Another coupler program at SLAC is to assemble and rf process units fabricated in industry for the cavities that will be ‘dressed’ at FNAL. Building on the experience of the Orsay group, SLAC is in the process of acquiring a class-10 cleanroom and producing the necessary fixtures and processing facilities to handle up to 30 couplers a year.

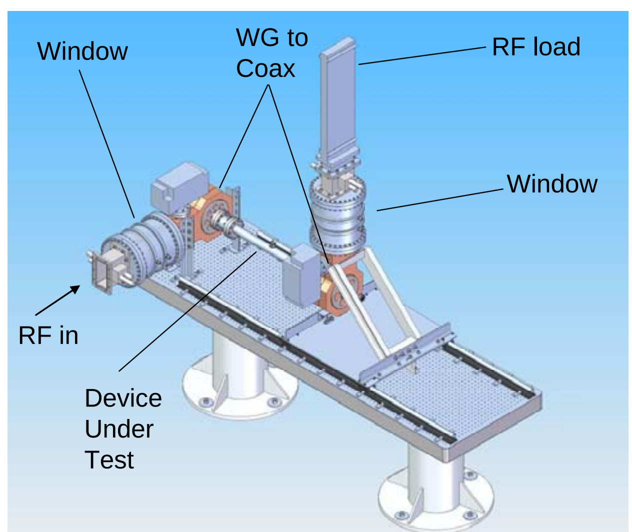

Figure 4: Illustration of the coupler component test stand.

NC ACCELERATOR STRUCTURES

The ILC injectors include normal-conducting (NC) accelerator structures as the beam losses and required solenoidal focusing prevent of use of superconducting rf technology. In particular, a positron capture cavity is required after the target that has a large aperture (60 mm) and operates at about 15 MV/m for a good positron yield. The baseline design is to use an 11 cell, π-mode standing wave cavity for this purpose. The surface fields will be close to the sustainable limits for the 1 ms long rf pulses. Also, about 5 kW of average power will be dissipated in each of the 11 cm long cells, which can significantly detune the cavity due to the average power heating.

A prototype cavity has been built after extensive design iterations of the cooling channels were done to limit the detuning. This prototype has a unity beta, a Q_0 of 29,000 and 5 cells (instead of 11) to match the current power source capability (5 MW) at SLAC. With about 20 gpm of water flowing around each cell, no active temperature regulation will be required to compensate the detuning during the ~ 1 °C warm up after rf turn-on (about 20% of the input power will be reflected initially). To maintain a constant gradient during the pulse, only a few percent adjustment to the input power will be required. Recently, the cavity went through its final tuning and it is now being installed in NLCTA for high power operation, including beam acceleration.

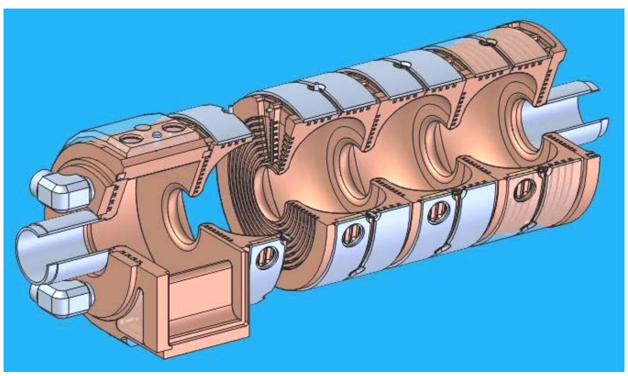

Figure 5: Cut-away illustration of the Positron Capture Cavity.

ACKNOWLEDGMENTS

Special thanks to Erik Jongewaard and Daryl Sprehn of SLAC for providing text on the SBK development, and to Stefan Choroba from DESY for sharing information on the XFEL rf system development.

REFERENCES

[1] Stefan Choroba, ‘Design and Status of the XFEL RF System,” TUXC03, these proceedings.
[2] J. Alex, et al, “A New Klystron Modulator for XFEL based on PSM Technology,” WEPMN073, these proceedings.
[3] M. Nguyen and R. Cassel, “High Power Switch for the SMTF Modulator,” WEPMS044, these proceedings.
[4] H. Mori, “Developments of Long-pulse Klystron Modulator for SCRF Test Facility,” THIBKI04, these proceedings.
[5] W. Reass, et al, “Converter-Modulator Design and Operations for the ILC L-band Test Stand,” WEPMS028, these proceedings.
[6] M. Kempkes, et al, “A High Voltage Hard Switch for the International Linear Collider,” WEPMN113, these proceedings.
[7] Greg Leyh, “Development and Testing of the ILC Marx Modulator,” TUOAC02, these proceedings.
[8] R. L. Cassel, et al, “A High Power Dynamically Flexible Pulse Width Radar Modulator,” Paper 8D2, PPPS-2007, June, 2007.
[9] M. Kempkes, et al, “Marx Bank Technology for the International Linear Collider,” THOBKI02, these proceedings.
[10] V. Vogel, et al, “Testing of 10 MW Multibeam Klystrons for the European X-ray FEL at DESY,” WEPMN013, these proceedings.
[11] Y.H. Chin, et al, “Development of 10 MW L-Band Multi-Beam Klystron (MBK) for the European X-FEL Project,” WEPMN023, these proceedings.
[12] K. Hayashi, et al, “Klystron Development by TETD,” THIBKI03, these proceedings.
[13] A. Balkcum, et al, “RF Sources for the ILC,” THIBKI01, these proceedings.
[14] C. Nantista et al, “An RF Waveguide Distribution System for the ILC Test Accelerator at Fermilab’s NML,” WEPMS043, these proceedings.
[15] K.L.F Bane et al, “RF Distribution Optimization in the Main Linacs of the ILC,” WEPMS037, these proceedings.
[16] V. Katalev and S. Choroba, “Compact Waveguide Distribution with Asymmetric Shunt Tees for the European XFEL,” MOPAN015, these proceedings.
[17] T. Treado and S. Einarson, “Power Couplers For The ILC,” THIBKI02, these proceedings.
[18] Dave Wilcox, “European Industry's Potential Capabilities for High Power RF Systems for the Future ILC,” THIBKI05, these proceedings.
[19] Alessandro Variola, “High Power Couplers for Linear Accelerators,” TH2001, LINAC 2006, Aug. 2006.
[20] Kenji Saito, “R&D Status of KEK High Gradient Cavity Package,” WEPMN032, these proceedings.
[21] Eiji Kako, et al, “Construction of the Baseline SC Cavity System for STF at KEK,” WEPMN027, these proceedings.
[22] B. Rusnak, et al, “High-Power Coupler Component Test Stand Status and Results,” WEPMS017, these proceedings.
[23] Lixin Ge, et al, “Multipacting Simulations of TTF-III Coupler Components,” WEPMS041, these proceedings.