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ILC Linac R&D at SLAC [*]

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Since the ITRP recommendation in August 2004 to use superconducting rf technology for a next generation linear collider, the former NLC Group at SLAC has been actively pursuing a broad range of R&D for this collider (the ILC). In this paper, the programs concerning linac technology are reviewed. Current activities include the development of a Marx-style modulator and a 10 MW sheet-beam klystron, operation of an L-band (1.3 GHz) rf source using an SNS HVCM modulator and commercial klystrons, design of a more efficient and less costly rf distribution system, construction of a coupler component test stand, fabrication of a prototype positron capture cavity, beam tests of prototype S-band linac beam position monitors and preparations for magnetic center stability measurements of a prototype SC linac quad.

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INTRODUCTION

Seven ILC linac technology related programs based at SLAC are reviewed below. SLAC is the center for the ILC Americas rf system development, which includes all elements in the main linacs between the ‘wall plug’ and the cavity couplers, and the normal-conducting injector accelerators.

MODULATORS

The ILC baseline modulator is a pulse transformer type with an LC ‘bouncer’ circuit for droop compensation. Although several of the baseline pulse transformer modulators have been built and operated without major reliability problems, 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. The goal of the SLAC modulator program in the next year is to evaluate alternative designs that could reduce the modulator size, weight and cost while increasing reliability and energy efficiency.

The ILC alternate modulator choice is a Marx Generator design [1]. In this approach, which is being developed at SLAC, a series of capacitors are slowly charged in parallel, and discharged in series to form the pulse. It uses no transformer and all switching is done at the lower load current (130 A). The modulator consists of a series of 12 kV main cells (large circuits boards mounted on a common backplane) and 900 V vernier cells for regulation and droop compensation. These circuits are summed to produce the required 120 kV, 1.6 msec flat pulses at 5 Hz. 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 (~ 40%) over the baseline design. A full-scale prototype is under construction and initial testing is expected by the end of 2006. For this prototype, one cell has been fabricated, operated at full specification and shown to survive a shorted load.

Another design being evaluated is the SNS High Voltage Converter Modulator, which employs a high efficiency, 20 kHz switching circuit in a compact layout [2]. A production unit on loan from SNS has been installed and brought into operation at the SLAC L-band Test Stand (see below). Its main drawback is that droop compensation has yet to be successfully implemented. The unit at SLAC may eventually be modified to produce flat pulses for 10 MW klystron testing. Yet another modulator being considered is a direct switch unit being developed by Diversified Technologies through SBIR funds. 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 Marx approach, the pulse transformer is avoided, and as in the baseline design, droop is compensated with a bouncer circuit. The first unit is due to be delivered to SLAC at the end of 2006 for evaluation.

KLYSTRONS

The existing ILC high power rf source prototypes consist of three vendor-produced 10 MW Multiple Beam Klystrons (MBKs) that were built in a collaboration with DESY. These designs achieve high efficiency (~ 65%) 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, these prototypes have not yet proven robust or have not been tested long enough to fully qualify them. The SLAC Klystron Group is instead investigating the merits of a new class of sources known as Sheet Beam Klystrons (SBKs). In these tubes, a flat beam is used to reduce the space charge forces, which should produce an efficiency similar to that of the MBKs.

The current plan is to produce two prototype SBKs at SLAC in the next two years. This effort will benefit from the Klystron Group’s recent design and fabrication efforts that led to successful beam transport in a 91 GHz SBK (no commercial SBKs exist at any frequency). The ILC prototypes, which will be ‘plug compatible’ with the MBKs, will have a 40:1 beam aspect ratio and will utilize

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permanent magnets for focusing (reducing the ILC power consumption by about 4 MW). The rectangular geometry of these klystrons and their many fewer parts makes them simpler to manufacture than the MBKs. This should reduce the per-klystron cost, and since there are fewer joining operations during fabrication, the tube yields should also be higher. Overall, the tubes will about 30% longer (3.1 m), but 30% narrower (0.7 m) and about five times lighter (420 kg) from not having the large solenoid magnet.

Much work has been done over the past three years in perfecting 3-D klystron simulations using recently developed software modeling packages for the gun, beam transport and rf power formation and extraction. The basic SBK rf design is complete and the first prototype is scheduled to be fabricated by the fall of 2007. Future plans also call for acquiring and testing second generation 10 MW MBKs.

L-BAND TEST STAND

To gain experience with L-band sources and rf components at SLAC, construction of an L-band test stand was started in 2005 at the Next Linear Collider Test Accelerator (NLCTA). For this facility, a 140 kV converter-style modulator was borrowed from SNS (see above), and an SDI-legacy, 10 MW, 160 kV, short-pulse klystron was purchased from Titan. At 120 kV, this source produces 3.3 MW, 1 msec, 5 Hz rf pulses, which have been used to test a high power circulator and waveguides that are pressurized (3 bar) with nitrogen (instead of SF6) to suppress rf breakdown. Recently the modulator was modified to allow higher current (90 A) operation with a newly acquired 5 MW, 128 kV Thales 2104C klystron (this tube has been the ‘workhorse’ for testing at DESY and FNAL).

The L-band Test Stand is controlled by an EPICS-based low-level rf system and will provide power to two experimental test areas. One will be used to rf process coupler components and couplers, and the other will be located in the NLCTA beam enclosure to test prototype positron accelerator cavities (both programs are described below).

RF DISTRIBUTION

To distribute the rf power from a klystron to the cavities in the ILC linacs, the baseline design is to have a series of tap-offs along a waveguide that runs parallel to the beam line. There would be a circulator in each cavity feed line followed by a three-stub tuner to allow control of the cavity phase and Q_{ext}. Currently the DESY rf distribution systems use off-the-shelf components that are not necessarily optimized for this application. Also, delivering the same power to each cavity is inefficient with the ~ 5 % rms spread in cavity operating gradients that is expected (i.e., the worst cavity limits the gradients of the others).

At SLAC, four changes to the rf distribution design are being considered. The circulators would be eliminated as they are a big cost item, and the cavities would instead be powered in pairs using 3-dB hybrids. This would still isolate the cavities, but would allow some power (< 1%) to return to the klystron in the event of an rf fault in a single cavity or coupler, which should be benign. A second change would be to use a variable tap-off system to feed the cavity pairs. One proposal is to have rotatable, polarized TE11 circular waveguide sections between the cavities whose orientation would be adjusted (one time only) after the relative cavity performance was measured. Another cost cutting measure is to replace the 3-stub tuner with a simpler phase shifter that would be adjusted once the system is set up, and would not require further changes. Finally, with the large number of waveguide flanges, a means of welding the waveguides together is being sought to reduce cost and improve reliability. At present, an rf design for a variable tap-off system has been completed and some initial waveguide welding tests have been done. The plan next year is to assemble an eight cavity feed system for the first FNAL cryomodule. It would incorporate these proposed changes if they prove practical to implement and robust in high power tests at SLAC (circulators would be supplied for the initial cryomodule operation to ensure full cavity isolation).

CAVITY POWER COUPLERS

The power coupler designs for the ILC linac cavities are complex devices due to the required cleanliness, temperature gradient, vacuum isolation and tunability requirements. A joint LLNL and SLAC program is underway to better understand the rf processing limitations of the ILC baseline TTF-3 couplers. Various coupler sections will be tested to assess the impact of coatings, bellows, and windows on the rf processing time. Currently, a general purpose waveguide (WR650) to coax adaptor and reusable inner coaxial conductor are being fabricated to power the test sections.

In the program proposed for next year, the TTF-3 design will be evaluated and a modified version will be built with the goal of improving its conditioning time and lowering its manufacturing cost. Plans are also underway to process couplers that will be used for the cavities being built for cryomodules at FNAL.

NC ACCELERATOR STRUCTURES

The standing-wave ILC positron capture cavities are required to have a large aperture (60 mm) and operate at about 15 MV/m for a good positron yield. The surface fields will be close to the sustainable limits for the 1 ms long, 1.3 GHz rf pulses. In addition, 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 pulsed and average power heating.

A prototype cavity is being 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 30,500 and 5 cells (instead of 11) to match the current power source capability (5 MW) at NLCTA. With about 20 gpm of water flowing around each cell, no active temperature regulation will be required to compensate the detuning during the 0.8 °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 will require only a few percent adjustment to the input power. The fabrication of this cavity and a newly designed input coupler window are underway, and they are expected to be high power tested this fall. Next year, a 2.2 m long traveling-wave structure will be designed, which will be a prototype for the first half of a 4.3 m structure with 46 mm diameter irises that would be used accelerate the beams in the warm sections of the ILC injectors.

SC QUADRUPOLE MAGNET AND BPM

To preserve the small emittances in the ILC linacs will require beam-based alignment of the quads. The simplest technique proposed requires that the alignment of the magnetic center of each quad be first measured relative to the electrical center of the nearby BPM. This involves changing the quad strength and recording the resulting beam kick. To achieve the desired accuracy, the quad magnetic center cannot move by more than a few microns when the field strength is changed by 20%. The large aperture of ILC Linac quads (78 mm) may make achieving this stability difficult, especially if high gradient magnets with coil-defined fields are used. The beam-based alignment procedures also require large aperture beam position monitors (BPMs) with micron-level resolution.

The goal at SLAC is to develop a SC quad and BPM that meet these requirements. To this end, an ILC Linac prototype SC quad built at CIEMAT in Spain has been obtained from DESY [3], and a warm-bore cryostat is being built for it at SLAC. The 0.66 m long magnet has a $\cos(2\phi)$ coil design that produces a 60 T/m field gradient with a 100 A supply current (DESY verified its basic performance in a vertical dewar test). At SLAC, its magnetic field will be characterized with a rotating coil similar to that developed for NLC prototype quads. This system will have a submicron level sensitivity to motion of the quad magnetic center.

In a parallel program, a slotted-waveguide-style, 2.9 GHz, cavity BPM has been designed, and three prototypes constructed and tested at End Station A at SLAC [4]. These BPMs were made with a 36 mm aperture, which is about half of the nominal ILC size. This choice made testing this design concept simpler, and it would be advantageous to adopt this aperture size for the ILC. The BPM geometry naturally suppresses monopole mode signals, and it was carefully designed so the neighboring modes are well separated in frequency. The slotted-waveguide geometry was also chosen because the inner BPM surfaces can be easily cleaned, which is necessary to maintain the contaminant-free environment in which they will need to operate. A low cavity Q_{ext} was chosen (~ 500) to allow clean bunch-to-bunch signal separation in the ILC (the signal drops to 0.2% of its initial level after 337 ns, the nominal ILC bunch separation).

The prototype BPMs preformed well in beam tests with 29 GeV, 300 micron-long single bunches of 1.5e10 electrons. Resolutions of 400-800 nm were achieved when down-mixing the signals to 73 MHz and digitizing them at 100 MHz. There were no signs of monopole mode signal leakage, although the out-of-phase signal components were somewhat large (5-50 microns equivalent). This is thought to be due to the pitch and yaw angles of the BPMs, which were not precisely aligned during installation (the alignment will be improved for the next run). Next year, if no broad consensus is reached to reduce the large BPM apertures (80 mm) for the ILC Linacs, a triplet of full aperture, L-band (1.5 GHz) BPMs will be built. Also, more quad prototypes will be tested, both with a rotating coil and with beam using the prototypes BPMs to monitor changes in the beam trajectory when the quad strength is changed.

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REFERENCES

[1] G. E. Leyh, “The MARX Modulator Development Program for the International Linear Collider,” SLAC-PUB-11868, June, 2006.

[2] W. Reass, et al, “High-Frequency Multimegawatt Polyphase Resonant Power Conditioning,” *IEEE Trans. on Plasma Science*, Vol. 33, Issue 4, Part 1, Aug. 2005.

[3] F. Toral, et al., “Fabrication and Testing of a Combined Superconducting Magnet for the TESLA Test Facility,” *IEEE Transactions on Applied Superconductivity*, Vol. 16, No. 2, June 2006.

[4] M. Woods, et al, “Test Beam Studies at SLAC End Station A for the International Linear Collider,” MOPLS067, these proceedings.