RESEARCH AND DEVELOPMENT FOR AN X-BAND LINEAR COLLIDER*

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Abstract

At SLAC and KEK research is advancing toward a design for an electron-positron linear collider based on X-Band (11.4 GHz) rf accelerator technology. The nominal acceleration gradient in its main linacs will be about four times that in the Stanford Linear Collider (SLC). The design targets a 1.0 TeV center-of-mass energy but envisions initial operation at 0.5 TeV and allows for expansion to 1.5 TeV. A 10^{34} cm $^{-2}$ s $^{-1}$ luminosity level will be achieved by colliding multiple bunches per pulse with bunch emittances about two orders of magnitude smaller than those in the SLC. The key components needed to realize such a collider are under development at SLAC and KEK. In this paper we review recent progress in the development of the linac rf system and discuss future R&D.

1 INTRODUCTION

For the next generation electron-positron linear collider, one wants to generate at least one TeV center-of-mass collisions to complement the physics reach of the Large Hadron Collider (LHC) that is being constructed at CERN. At SLAC and KEK research has been focused on a collider design that uses X-Band (11.4 GHz) rf technology to achieve this goal [1,2]. The design has evolved largely from the experience gained from operation of the Stanford Linear Collider (SLC) where S-Band (2.9 GHz) rf technology is used to accelerate beams to about 50 GeV. Increasing the rf frequency allows for higher gradients (72 MeV/m versus 17 MeV/m in the SLC) which keeps the machine cost from becoming prohibitive at the higher energies.

To be efficient, multiple bunches (95) will be accelerated on each rf pulse (120 Hz repetition rate). There will be about 10^{10} particles per bunch and the bunch spacing will be 2.8 ns. These 0.6 A beams will reduce (load) the gradient in the 1.8 m long X-Band accelerator structures by 16%. Including energy overhead, the effective gradient in the structures will be 55 MeV/m. The structures will fill 86% of the lineal distance along the main linacs so 10.4 km long beam lines will be required to accelerate the electron and positron beams from their 10 GeV injection energies to 500 GeV. However, the collider will be operated initially with a 500 GeV center-of-mass energy where only the first half of each of the opposing linacs will contain rf components, and the beams will 'drift' through the remaining halves.

The main components of the linac rf system are the modulators that power the klystrons, the 75 MW klystrons that generate the rf, the distribution system that transports the rf to the accelerator structures, and the structures themselves. In the following sections, we review the designs, recent R&D and future development plans for these components.

2 MODULATORS

The modulators that are used in the SLC are conventional line-type with pulse-forming networks (PFN). These networks are composed of discrete inductors and capacitors that are slowly charged and then rapidly discharged (via a thyratron) through a step-up transformer to generate the high voltage pulse needed to drive an SLC klystron. A similar approach is being pursued at SLAC to produce the 490 kV, 260 A, 1.5 μs long pulses required for the X-Band klystrons that are being developed [3]. The current design has a single modulator powering two klystrons through a 14:1 transformer. A prototype version has been built using high-energy-density glass-type capacitors, and tested with a single S-Band klystron at a lower voltage (290 kV) to produce the same impedance as two X-Band klystrons. In this configuration, 89% of the stored energy is transferred from the modulator to the klystron, and 82% of the transferred energy is within the 1.5 μs long pulse flattop, between the pulse rise (350 ns) and fall (450 ns) periods. The charging power supply used in the test was not particularly efficient; however, if the goal of 90% is achieved, the overall energy transfer efficiency from AC to usable klystron beam power would be 66%.

To improve efficiency, KEK is working with a Blumlein modulator configuration [2]. Here a step-up transformer of half the turns-ratio as the conventional configuration sits between two PFNs of the appropriate impedance to double the primary voltage. In principle, this should yield a faster rise time due to the lower leakage inductance of the transformer [4]. However, tests thus far with klystron loads have yielded values comparable to the SLAC results. Both groups will continue to upgrade their test setups to improve

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efficiency, reduce costs, and handle the full klystron pulse requirements.

One drawback of these modulator designs is their use of thyratrons which in general have relatively short lifetimes (10-20 khour) and require periodic tuning. As an alternative, a solid-state induction-type modulator is being developed at SLAC and LLNL that has the potential of better reliability and higher efficiency [5]. The basic idea is to sum many low voltage sources inductively to yield the desired klystron voltage. This has been realized by having each source drive a transformer made from a 4.5 inch ID, by 11.5 inch OD, by 2 inch thick Metglass core. The cores are stacked so the secondary windings, which sum the output voltages, can be threaded through their IDs. Each source is essentially a capacitor that is slowly charged and then partially (20%) discharged through a solid-state switch to generate the pulse.

Recent improvements in Isolated Gate Bipolar Transistor (IGBT) switches, which are used in electric trains for example, have made this induction scheme conceivable. They have relatively fast rise and fall times (< 100 ns between 10% and 90%) with turn-off occurring after a fixed delay of about 100 ns from the end of the gate pulse. Tests so far have been done with resistive loads: a single source has directly (no core) switched 1.5 kA at 2 kV, and an 18 kV pulse has been generated inductively through a six-core stack with single-turn primaries and a four-turn secondary.

Although the switching times are fast in these cases, the rise and fall times in actual operation will be somewhat longer due to the combination of the modulator leakage inductance and the klystron capacitance. Simulations have shown that a 1:1 turns-ratio is needed to produce fast enough rise and fall times (≈ 200 ns) to yield an overall efficiency of 75%. Part of this efficiency would come from including circuitry in each source that would recover much of the stored energy remaining in stray inductances and capacitances after the IGBTs shut off.

For the 1:1 turns-ratio design, one hundred 5 kV, 2 kA sources are summed to drive 8 klystrons. IGBTs capable of switching such power are expected to be available soon. Failure of any single source should be benign; the core will saturate and be nearly transparent to the pulse. Some overhead in voltage capability will be included to offset such a loss. Also, the sources will be independently timed to better shape the pulse, for example, to offset the natural droop. One potential problem in driving many klystrons is that an arc in one will be fed by the stored energy in the others (the circuit itself can be shut off in time to not be a problem). Adding inductors in the power feeds that fan out to the klystrons should reduce the discharge power to a manageable level. In the next year a more realistic prototype will be built to better evaluate this induction modulator scheme.

3 KLYSTRONS

During the past decade at SLAC and KEK, research has been directed at developing X-Band (11.4 GHz) klystrons in the 50 to 130 MW range [1,2,6,7,8]. Until the last few years these klystrons have used large solenoid magnets to focus the beam in its path from the gun through the bunching and output sections to the collector. However, the power used by these magnets, around 20 kW, is comparable to the average rf output power so it has a big impact on efficiency. This has prompted the development of a focusing scheme that uses permanent magnets so there is no associated power loss.

Before discussing this scheme however, we review results from the latest and perhaps last generation of solenoid-focused X-Band klystrons that SLAC and KEK will develop. They operate with a perveance (I [Amps] / $V^{3/2}$ [Volts]) of 1.2×10^{-6} and contain four-cell traveling wave output cavities. At SLAC, the XL4 klystrons are the culmination of its 50 MW klystron development program. Six of these tubes have been built, and they are used as X-Band rf sources for component testing and beam acceleration in the Next Linear Collider Test Accelerator (NLCTA). They reliably generate 1.5 μs long, 50 MW pulses with a 41% beam-to-rf efficiency. In a brief test, one klystron produced 75 MW, 1.2 μs long pulses at 48% efficiency. At KEK, the XB72K #9 tube, which was developed with BINP, has recently produced 72 MW with a 31% efficiency although the pulse length was limited to 200 ns by the modulator. KEK, in collaboration with Toshiba, has also recently completed assembly of a tube that is expected to produce 126 MW, 1.5 μs long pulses at 48% efficiency. It uses longer cavity cells with a lower Q_{ext} to be able to operate at higher currents for the same cavity surface fields. Testing of this tube has just started.

At SLAC, permanent magnet tubes are now being developed. In these designs, about 40 magnet rings with alternating polarities are interleaved with iron pole pieces to generate a periodic (i.e., sine-like) axial field along the ≈ 0.5 meter region between the gun anode and beam collector. The resulting focusing strength is proportional to the RMS of this axial field. About 2 kG can be achieved practically, which is smaller than the ≈ 5 kG field in the solenoid-focused tubes. This has led to a lower perveance (0.8×10^{-6}) design where the space charge defocusing is smaller. To handle the increased voltage drop along the output cavity, it was lengthened to five cells. The lower perveance has the advantage of increasing efficiency through improved bunching, but it makes the modulator harder to build due to the higher voltage hold-off (490 kV). The efficiency goal for these Periodic

Permanent Magnet (PPM) klystrons is at least 60% when generating 75 MW, 1.5 μs long pulses at 120 Hz.

Thus far, SLAC has built a 50 MW PPM klystron using samarium cobalt magnets. This tube has produced 2 μs long pulses with a 55% efficiency at the design power. A 75 MW PPM tube has also been built but has had operational problems that are thought to arise in part from using magnets that do not fully meet specifications. A switch to NbFeB magnets was made for machining and cost reasons, but they proved harder to manufacture within the desired magnetic tolerances. The present program is to improve the operation of this tube and concurrently to build a new version that is more suited for mass production. It should be completed by the end of 1999. At KEK, a 75 MW PPM tube that was designed and built by BINP was tested with limited success. Work there has recently focused on more accurate klystron modeling using the MAGIC code. These studies have resulted in a better understanding of existing tubes and will be used as the basis for designing the first PPM tube at KEK.

4 RF DISTRIBUTION

The function of the rf distribution system is to transport the klystron output power to the accelerator structures. This task is made more difficult by the fact that the klystrons optimally generate a lower power and longer pulse than that needed for the structures. In past linac designs and in the NLCTA, the solution was to use pulse compression, namely the SLED II system which is a delay line version of the SLAC Linac Energy Doubler (SLED) [1]. It consists of a 3 dB hybrid divider that routes the klystron output power equally to two delay lines made of circular waveguide. These lines are shorted at the far end and have irises at the near end that partially reflect the rf. During operation in the NLCTA, for example, the two 40 m long lines are resonantly filled during the first 5/6th of the 1.5 μs long klystron pulse, and then effectively discharged through the remaining hybrid port by a 180º reversal of the klystron phase during the last 1/6th of the pulse. This yields a shorter (1/6th as long), higher power pulse that is used to power two NLCTA accelerator structures. Although it works well, it is not particularly efficient; about 30% of the power goes to the structures during the filling of the delay lines, so the power gain is about four.

Although there are more efficient pulse compression methods, the scheme now being pursued sums the power from four pairs of klystrons, 'slices' it into four equal time intervals, and then distributes it up-beam to four sets of accelerator structures that are appropriately spaced so that the beam-to-rf arrival time is the same in each case. Hence no power is wasted although there are still resistive wall losses.

In the original version of this Delay Line Distribution System (DLDS), which was proposed by KEK, the power is summed with 3 dB hybrid combiners and distributed up-beam through individual circular waveguides to each set of structures [2,9]. The power routing is accomplished by varying the relative rf phases of the four sources. In the circular waveguides, the power is transported in the low-loss TE_{01} mode as is done in the SLED II delay lines. To reduce the length of waveguide, a multimode version of this system has been proposed at SLAC in which the power is distributed through a single circular waveguide, but in four different modes [10]. In this case the power from the four klystron pairs is sent to a 'launcher' that generates the modes based on the relative rf phases of the four inputs. During operation, the phases are varied to excite the four modes sequentially in equal time intervals. The circular waveguide modes are TE_{01}, TE_{12H}, TE_{12V} and TE_{21} where the H and V subscripts refer to horizontal and vertical polarizations. Three of modes travel up-beam and are extracted at appropriate locations to arrive 100 ns (the structure filling time) before the beam. Each 'extractor' couples out only one mode and passes the remaining modes. The fourth mode (TE_{21}) is extracted at the launcher. KEK is considering a similar scheme but with the power distributed in two circular waveguides where two modes (TE_{01}, TE_{12H}) are launched and extracted in each waveguide.

For the rf transport between the klystrons and launcher, and between the extractors and the structures, the TE_{01} circular waveguide mode is used. The extracted power in each case feeds three contiguous accelerator structures. To power a contiguous array of structure triplets, nine DLDSs (a nonet) are interleaved to form a 225 m long sector. The sector length is set by the 1.5 μs klystron pulse length and the relative beam-to-rf group velocity (about 2c). Twenty-two sectors are required to produce a 500 GeV beam.

An important requirement of this distribution system is its power handling capability. With eight 75 MW klystrons, 600 MW of rf power will be launched, extracted and 'taped-off' in thirds to feed 200 MW to each structure. Based on operational experience, the goal is to keep the surface fields in all transport components below about 40 MeV/m [11]. Recently, two planar-style 3 dB hybrids and several rectangular (TE_{10}) to circular (TE_{01}) mode converters were successfully tested to 420 MW with 150 ns long pulses. To test components at their design power level and beyond, the NLCTA is being upgraded to produce 800 MW, 240 ns long pulses.

Concepts for the launcher, extractors and bends are in hand and development programs have begun at SLAC and KEK. In addition to reducing the surface fields, the designs aim for a power reduction of < 1% in each component due to mismatches and resistive wall losses. Overall, a klystron-to-structure transfer efficiency of about 85% is expected where only a small portion of the power loss occurs in the long circular waveguides. This assumes no mode conversion in these sections. A joint experiment is under way to verify that such conversion losses are small, especially from rotation of the polarized modes.

5 ACCELERATOR STRUCTURES

SLAC and KEK have enjoyed an active collaboration in X-Band accelerator structure development for more than five years. This has led to a common structure design that uses an electrical scheme developed at SLAC and assembly techniques pioneered at KEK. The electrical design addresses both the requirement of efficient beam acceleration and the need to suppress the long-range transverse wakefield generated when a beam travels off-axis through the structure. Unless the wakefield is reduced by about two orders of magnitude, the coupling of the bunches in a multibunch train will resonantly amplify any betatron motion of the train by a significant amount. This difficult goal has been met by using a combination of two methods.

The first to be developed was mode detuning whereby the frequencies of the lowest (and strongest) band of dipole modes are systematically varied along the 206 cell structure to produce a Gaussian distribution in the product of the mode density and the mode coupling strength to the beam [12]. With this detuning, the modes excited by an off-axis bunch add deconstructively, yielding an approximately Gaussian falloff in the net wakefield generated after each bunch. A sigma of 2.5% was chosen for the 206-mode frequency distribution to produce more than a hundred-fold wakefield suppression by 1.4 ns, the nominal bunch spacing in the early linear collider designs.

This detuning works well to suppress the wakefield for about the first 30 ns, after which its amplitude increases due to a partial recoherence of the mode excitations. This has led to the introduction of weak mode damping to offset this rise [13]. The damping is achieved through the addition of four single-moded waveguides (manifolds) that run parallel to the structure and couple to the cells through slots. For each dipole mode, the power flow to the manifolds occurs in that region of the structure where the cell-to-cell phase variation of the mode matches that of the manifold mode. When terminated into matched loads, the manifolds reduce the mode Q's from about 6000 to 1000, enough to keep the wakefield from significantly increasing again.

To date, three of these Damped Detuned Structures (DDS) have been constructed. The cells for the most recent version were manufactured at LLNL using diamond-point turning. The mating surfaces of the cells were machined flat to < 0.5 µm and smooth to < 50 nm. The cells were then assembled in Japan using a two-step diffusion bonding technique. In the first step, the cells were stacked on an inclined V-block and pressed by 600 kg of force for 48 hours in a 180 °C environment. This procedure partially bonded the surfaces which prevented cell-to-cell slippage when the stack was placed upright to be fully bonded. For this step, the stack was placed under 24 kg of force at 890 °C for 4 hours.

The straightness of the resulting structure varied with scale, increasing from a few µm cell-to-cell to a few hundred µm over its 1.8 m length. However, the long wavelength (> 0.5 m) offsets were reduced by counter bowing the soft copper structure. A straightness of +/- 20 µm was achieved, yielding an overall alignment that meets the requirements of the linear collider design. In this design, the long wavelength alignment of the structures will be set and maintained by the support system. The structures will be attached to girders in sets of three with a single rf feed per girder that is 'tapped-off' to each structure. Each girder will have remote adjustment capability and will be positioned to best center the beam in the three structures based on the information obtained from processing the dipole mode signals from the structure manifolds. Thus, only the internal alignment of the structures along the girders will have to be established with precision (about +/- 20 µm) and be kept stable. Studies of long-term stability have been done with mock structures on a prototype girder. They show that the desired level of alignment is maintainable in an operating-like environment.

In the most recent DDS prototype, the rf match through the output ports of the manifolds was improved and the dipole frequency profile was changed slightly to increase the wakefield suppression. To gauge the effect of these changes, the long-range wakefield of the structure was measured in the Accelerator Structure Setup (ASSET) facility in the SLAC Linac [14]. Here a positron beam was used to induce a wakefield in the structure and an electron beam was used to 'witness' it. The measurements show larger than expected values for the wakefield, particularly at short times (< 20 ns). This increase is thought to be the result of systematic errors in the cell dimensions. Errors of roughly the size required to explain these data were observed in a sample of cells measured for QC purposes prior to assembling the structure.

Centering tests were also done in ASSET in which the dipole signals were used as a guide to position the positron beam. Measurements of the resulting short-range wakefield (< 300 ps) indicated that the beam had been centered to < 20 µm in the structure which is roughly the requirement during linear collider operation. However, monopole-like components of the transverse wakefield were also observed and need to be understood.

The next structure that will be built will have rounded shaped cavities instead of the cylindrical shape used so far. This increases the shunt impedance of the structure by 12% which yields a 6% increase in the rf-to-beam efficiency. This rounded-DDS or RDDS will have an average iris radius equal to 18% of the X-Band wavelength. This value was derived from a joint SLAC and KEK study to optimize the linac performance. The main design difficulty thus far has been in damping the modes in the few cells at the downstream end of the structure that cannot be coupled to the manifolds due to space limitations. Several solutions are being considered including adding individual absorbers in these cells. Otherwise, the electrical design is nearly complete; SLAC and KEK will jointly build and test an RDDS by the end of 1999.

The suppression of the long-range wakefield is not the only difficult structure performance requirement. The structures must also operate reliably at a high gradient, about 70 MeV/m. Three structures have been rf conditioned to this level, the most recent one up to 85 MeV/m after 440 hours of operation [15]. It is a 1.3 m long, diamond-turned structure built at KEK to study detuning. During its conditioning, the rf power was slowly increased until a breakdown occurred in which > 5 MW of power was reflected back toward the source. The rf was then shut off for 2-4 minutes to allow the structure to pump down, and then it was slowly ramped up again. This procedure was continually repeated under computer control during most of the conditioning period.

At the highest gradient, the dark current emitted from the downstream end of the structure was about 5 mA and the mean time between breakdowns was less than a minute. Reducing the power to yield a 70 MeV/m gradient reduced the dark current to about 0.5 mA and increased the periods between breakdowns to several hours. Even at the highest gradient, however, the loading due to the dark current should not have been significant.

Another dark current related concern is the excitation of transverse fields. To the extent that such fields are the result of excitations of the lowest band of dipole modes, an estimate of their size was made by measuring the dipole signals from a manifold of a DDS during rf conditioning to 70 MeV/m. No significant signals were observed (except during breakdown) which puts a limit on the transverse field amplitude that is within the tolerance required in the linear collider design. The latest DDS prototype will be conditioned in the near future as part of a more systematic program to understand high gradient limits in the structures.

6 SUMMARY

The four major components of an rf system for an X-Band linear collider - the modulators, klystrons, rf distribution system and accelerator structures - are being actively developed at SLAC and KEK. Once their designs are more mature, an integrated rf system with eight klystrons will be built that will serve as a model element of a full-scale linac.

7 REFERENCES

[1] "Zeroth-Order Design Report for the Next Linear Collider," SLAC Report 474 (1996).

[2] "JLC Design Study," KEK (April 1997).

[3] R. Koontz et al., "NLC Klystron Pulse Modulator R&D at SLAC," http://www.slac.stanford.edu/grp/kly/mkw/nlc.htm (June 1998).

[4] M. Akemoto et al., "Pulse Transformer R&D for NLC Klystron Pulse Modulator," SLAC-PUB-7583 (July 1997).

[5] Dick Cassel, talk presented at the Third Modulator-Klystron Workshop at SLAC (1998), see http://www.slac.stanford.edu/grp/kly/mkw/.

[6] G. Caryotakis, "Development of X-Band Klystron Technology at SLAC," SLAC-PUB-7548 (May 1997).

[7] D. Sprehn et al., "Periodic Permanent Magnet Development for Linear Collider X-Band Klystrons," these proceedings.

[8] Y. H. Chin, "Modeling and Design of Klystrons," these proceedings.

[9] H. Mizuno, "RF Pulse Compression for Linear Colliders," these proceedings.

[10] S. Tantawi et al., "A Four-Port Launcher for a Multi-Moded DLDS Power Distribution System," these proceedings.

[11] A. Vlieks et al., "High Power RF Component Testing for NLC," these proceedings.

[12] K. A. Thompson et al., "Design and Simulation of Accelerating Structures for Future Linear Colliders," *Particle Accelerators* **47**, 65-109 (1994) and SLAC-PUB-6032 (Nov. 1993).

[13] R. H. Miller et al., "A Damped Detuned Structure for the Next Linear Collider," SLAC-PUB-7288 (Sept. 1996).

[14] C. Adolphsen et al., "Wakefield and Beam Centering Measurements of a Damped and Detuned X-Band Accelerator Structure," to be presented at PAC99.

[15] R. Loewen et al., "SLAC High Gradient Testing of a KEK X-Band Accelerator Structure," to be presented at PAC99.