X-band Linear Collider R&D Update
and
Supplemental material on some Questions submitted to KEK

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This material is jointly submitted by the GLC and NLC Collaborations.

GLC Collaboration
NLC Collaboration

Update on recent X-band R&D

Structure Gradient Performance:

The eight accelerator structures in the NLCTA have operated about 1000 hours since the ITRP meeting at SLAC. The average trip rate of the 8 structures has continued to decline, and is now 0.085 per hour at 65 MV/m (the goal is < 0.1 per hour). This rate is about a factor of two smaller than that measured at the same gradient one month ago and reported at the ITRP meeting at KEK.

6/20/04 Update of Eight Structure Operation

(Statistics Based on Latest 150 hours of Operation)

Structure	Manufacturer	Gradient (MV/m)	Trip Rate (#/hr)
H60vg4S17-FXD1A	FNAL	65.4	0.18
H60vg3S17-FXC5	FNAL	64.5	0.10
H60vg4S17-3	KEK/SLAC	65.4	0.04
H60vg3S17-FXC3	FNAL	64.5	0.04
H60vg3-FXB6	FNAL	64.8	0.00
H60vg3-FXB7	FNAL	66.7	0.19
H60vg4S17-1	KEK/SLAC	63.2	0.10
H60vg3R17	SLAC	64.8	0.04
Average		64.9	0.085
Average One Month Ago		64.9	0.163

Structure Operation:

In computing a trip rate goal of 0.1 per hour, it is assumed that after a breakdown, the rf is shut off and then ramped to full power and pulse width in 10 seconds. This recovery procedure is needed during processing, but a less disruptive procedure can be used in normal operation. For example, tripping off only after two consecutive breakdowns (i.e., a ‘two-strikes’ trip) has been used in past operation of the NLCTA. Recently a structure was run for a week without single-pulse trip protection. Only 2 of the 19 breakdowns that occurred were on consecutive pulses. Operation with the ‘two-strikes’ trip logic would thus reduce the trip rate by an order-of-magnitude.

Measurement of kicks from structure breakdowns:

The effect of rf breakdown on the beam trajectory has now been measured at the NLCTA in two structures operating at a 90 MV/m gradient and 240 ns pulse width. The transverse kick of the beam due to rf breakdown fields was found to be small, with a limit of 30 keV/c. This is somewhat larger than the beam transverse momentum in the X-band LC, but an order-of-magnitude smaller than the kick size that would cause the beam to hit the collimators. This means that breakdowns will not interrupt normal beam operations.

Klystron Operation:

During May and June, PPM tube XP3-4 has continued to operate at full specifications and has now run ~ 80 hours at 75 MW, 1.6μs and 120 Hz.

At SLAC, we heard that no further large scale tests are necessary, and that GLCTA and NLCTA could be modestly expanded to handle needed prototype testing. With such a large increase in the size of the produced systems needed relative to today's experience, how can we be convinced that such a large extrapolation will work?

Summary: The components of the warm X-band technology can be tested individually during their development and final production in facilities dedicated to high-volume Quality Control (QC). The GLC/NLC groups plan to establish this capability as part of the industrialization process. Extensions of the NLCTA and GLCTA are planned to test design interfaces, integration, and operation of complete accelerator systems.

Response: As part of our overall risk analysis of the collider project, we have analyzed potential ways that the project could fail to achieve its performance requirements, when and how those failures will be detected, and have built steps into the project plan to mitigate the effects of failures. The response to this question is made in terms of this analysis.

RF Components and System Tests: The performance of the Main Linac X-band rf technology has been demonstrated. However, it is fully anticipated that extensive testing of components will be done as their design and fabrication techniques are improved to reduce costs and enhance reliability and serviceability. The warm X-band technology naturally separates into isolated components that can be individually tested. For example, testing of modulators and klystrons can be, and in fact is best, done in dedicated stand-alone stations. This makes it possible to include test instrumentation that will not be installed in the actual accelerator, and for the testing to be done by personnel with experience with the components under test. Development and build-up of needed QC capabilities is planned to occur (and costs included) during the first years of the project as an integral part of the industrialization of the components. Approximately one percent (40) of the final complement of klystrons will be produced and tested as the TDR is being completed. (For example, see the talk by J. Cornuelle at the meeting of the ITRP at SLAC.)

During production, it is expected that testing will be carried out by the companies that manufacture the components, and the models include the anticipated costs to establish and carry-out QC as part of the production. For example, it is planned that every klystron will be “burned-in” before it is delivered to the project. A similar approach is planned, and costs included, for QC of components in the low-level rf drive (TWTAs) and instrumentation, and for QC of the microwave properties of SLED-II components and accelerator structures.

There remains a need to test interfaces between components as their designs change, and to test integration and operation of the entire accelerator system. The GLC/NLC plan is to extend the NLCTA and GLCTA test accelerators to include five to ten times as many complete X-band accelerator units as presently available (the schedule and budget includes a total of eight systems). This will be done during the project initialization phase (first 3-4 years) as new components become available. Since the purpose of this testing is to confirm system design and operations, it is not necessary to replicate these systems more extensively.

These facilities will also partially support high-power processing of accelerator structures (particularly during the initial industrialization phase). Augmented by dedicated accelerator processing stations as additional production modulators and klystrons become available, the two facilities will meet the need for QC during the production of accelerator structures. For the purposes of constructing a model schedule and budget for the project, high-power processing of structures during the major production run has been planned to be done on site or at participating institutions.

Operating two similar test stations GLCTA and NLCTA will allow us to maintain close interactions with the regional industries. The existing collaboration between GLC and NLC groups, together with the coordination by GDI, will ensure timely exchanges of technical information between the activities in both places. Overall, we consider the parallel and concurrent operation of multiple test stations at KEK, SLAC and elsewhere as the best approach for facilitating the final engineering design efforts and industrialization of RF components with a number of industry participants who are equally competent yet distributed around the world.

Instrumentation, Alignment, and Emittance Control Tests: The critical instrumentation and controls needed to build the X-band collider have been demonstrated at the SLC, FFTB, and ATF with performance better than or close to those required. This includes instrumentation needed to measure beam properties as well as instrumentation needed for control of collider hardware such as girder supports and movers. Alignment techniques have also been demonstrated and the needed hardware and software developed. The test facilities have tested integration of beam instrumentation, magnets, and accelerator structures into working systems. It is established that the performance requirements are within the capability of existing engineering solutions. The various elements and the demonstrations done to date are discussed in our answer to ITRP Question 7.

There remains a risk that the beam emittance could increase more than desired in the full main linac. This risk is mitigated by the fact that the techniques used to control emittance dilution in the X-band design correct the errors directly at their sources, rather than globally. Since corrections are done “locally”, simulations can more reliably extrapolate performance from tests of individual elements to the full machine. For example, the quadrupole magnets and Q-BPMs are aligned locally to each other by the beam-based alignment procedure. Also, each rf girder is aligned independently of all other girders using information from the local S-BPMs. Beam steering is a global technique, but is similar to what is performed in all operating accelerators, and is therefore low risk.

The X-band project could still fail to maintain the performance requirements in the final engineering, design, and construction of the individual elements. However, the plan is to finish the production design of the linac girders early in the industrialization stage of the project, and fabricate sufficient numbers to populate the extensions of the NLCTA and GLCTA. Beam tests at these facilities, and at the ASSET facility in the SLAC linac, will verify final electro-mechanical designs, instrumentation performance, and control of wakefields. Control of the quality of the production run of linac girders should be straightforward, and the more complicated QC of accelerator structures has been described in the answer to Question 7.

There remains the ultimate question of potential inaccuracies in the beam simulations used to extrapolate the local corrections to the global performance of the machine. Construction of a stand-alone test facility to directly verify the simulations of emittance growth in either an X-band or L-band linac would be quite difficult. The warm and cold linacs are designed to limit the vertical emittance growth to < 50% of the injected normalized emittance of 2×10^{-8} m-rad. In absolute units, this is a very small amount of growth. Typical beam size measurements are made at the 10% level due to the finite measurement resolution, beam jitter, and non-gaussian beam tails. It would take ~50 GeV of acceleration to verify design performance.

The most uncertain factors in the simulation of emittance growth in the X-band linac are unaccounted systematic errors that might appear in the beam instrumentation. These can be addressed early in the project with more extensive studies in the SLAC linac and with the ATF beam in the GLCTA. The GLC/NLC project plan also provides for acceleration of low-emittance beams to the first linac diagnostic station (beam energy of 50 GeV) one to two years prior to completion of the entire linac. While this is still rather late in the project, the impacts of reworking the instrumentation could be absorbed in the project contingency.

What R&D will be conducted on DLDS pulse compression? How much time could be spent on this and still switch the baseline design from SLED2 to DLDS? What is the cost of the R&D? What is the potential cost savings if DLDS is chosen?

Response: Use of the DLDS system instead of SLED-II for the main linac RF power compression and distribution has several implications to the development, construction and operation of the X-band LC. Some benefits are noted as follows:

- The DLDS can be designed and built in such a way that it does not affect the bunch train structure and beam current specifications. Its implementation is transparent to the design of the rest of the X-band LC, such as the beam sources, pulse compressors, collimators and the beam delivery systems.
- The DLDS, with the same RF pulse length, offers an improvement of the power efficiency of ~15%, compared to SLED-II.
- The DLDS system is able to compress longer klystron pulses (2.4 μs or 3.2 μs) without loss of efficiency, contrary to the case with SLED-II, where the pulse length of 1.6 μs is considered the optimum. If the modulator and klystrons can produce longer pulses, then the DLDS system with higher compression ratios will
    - Reduce the number of power sources (modulators, klystrons, low-level rf drive and controls),
    - Improve the modulator efficiency (~14%) at longer pulse length,
- Overall, the DLDS has the potential for a substantial reduction in the operating costs, by decreasing the linac rf power consumption by as much as 25% and by reducing the number of klystrons replaced by half.

The potential issues are as follows:

- The ability of the pulse compression components to transport the maximum power in the system needs to be established.

  The basic components and concepts of the DLDS system are the same as those in the SLED-II Baseline, and the SLED-II prototype was designed to produce the maximum power of 600 MW needed in the DLDS system. The prototype successfully reached 580 MW during commissioning before an endurance run at 510 MW was started to fully demonstrate the baseline requirement of 475 MW in time for the ITRP meeting at SLAC. Tests of the SLED-II at power levels above 600 MW will be done in the near future.

- The ability of the DLDS system to safely handle the total stored energy needs to be established.

  It must be shown that a DLDS system is robust against damage during breakdowns. With an input pulse of 1.6 μs and a pulse compression ratio of four, a DLDS system stores the same amount of energy as the SLED-II system operating at 600 MW. Therefore, tests of operation with these parameters will be complete when the SLED-II prototype is operated at higher power levels.

- The ability of the RF power sources to handle pulse lengths longer than 1.6 μs needs to be established.

  The ultimate value of the DLDS option depends on the length of the rf pulse that can be generated by the modulator and klystron, and the number of klystrons that can be combined by the DLDS. The present IGBT modulators and SLAC XP klystrons are designed to generate pulses of up to 3.2 μs. PPM klystrons have been tested up to 2.4 μs, but running to date has been limited to 1.6 μs pulses to establish the validity of the SLED-II Baseline design.

The GLC/NLC groups plan to pursue the DLDS according to the following path:

1. We note that the X-band SLED II Baseline is fully responsive to the needs of the linear collider providing e^+e^- collisions at $E_{CM} = 0.5 \sim 1$ TeV. The primary focus of development activities by the GLC/NLC groups in the next years is to establish the final engineering designs and industrialization of the required components for SLED-II, consistent with the time chart that has been outlined by ILCSC.

2. Testing of klystrons and IGBT modulators, with pulse lengths up to 3.2 μs, will be done on the time-available basis, in as much as it does not negatively impact the Baseline efforts in 1.

3. With the development status of the efforts in 1 and 2, a review will be made on the possibility of building a prototype DLDS system either at NLCTA or at GLCTA.

4. By the time the international TDR is complete at the end of 2007, a decision will be made concerning whether or not we would implement DLDS at the X-band LC, and if so when.

Costs needed for this R&D are in the budget given in the answer to ITRP Question 25.

I would like to understand what SLACs plan is to involve the accelerator community into the construction of a LC if the decision is warm. What will or can motivate the majority of the accelerator physicists to work on this technology (which they have to, because an NLC will take the majority of the budget).

Response: There are a very large number of accelerator physicists around the world already committed to participate in an X-band LC. To begin with, there is a very strong collaboration between the NLC and GLC through the International Study Group. SLAC currently has ~90 FTEs spread over 150 people working on NLC R&D and about half as many additional people spread over the collaborating laboratories (BNL, FNAL, LBNL, LLNL) and universities. This would be expected to double if the X-band LC project is launched. GLC has ~55 FTEs spread over 80 people, and would expect that to grow to 120-200. The recently announced UK initiative in Accelerator R&D included nearly eleven million Pounds over three years for the UK LC Accelerator Beam Delivery (LC-ABD) collaboration. This group plans to participate in the LC independent of technology, and will grow to about 30 FTEs spread over 50 people. The recent EuroTev proposal to the EU led by DESY and CERN includes a substantial LC effort, over 100 FTEs per year, and explicitly plans to participate in whichever technology is chosen. Together this represents a significant fraction of the people needed during the initial design phases of the project.

In addition, others in the accelerator physics community would likely be motivated to participate. The linear collider is more than just two linacs and there are many challenging accelerator issues beyond the main linac rf. The damping rings are significant projects in themselves and would be attractive to accelerator physicists from the light sources and flavor factories. The electron and positron sources have challenges which would be attractive to other segments of the accelerator community. NLC is already collaborating with LHC on innovative collimation systems. The strong synergies between the X-band LC and CLIC might attract further joint efforts with CERN. Global systems such as instrumentation, machine protection, feedback or controls are also attractive to accelerator physicists from a wide spectrum of facilities.

The integration and coordination of all contributing groups will be the task of the Global Design team. If the decision is warm, the existing relationships among the American, Asian and European groups could allow an immediate start on a global conceptual design.