

# Overview of the X-band R&D Program\*

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## Abstract

An electron/positron linear collider with a center-of-mass energy between 0.5 and 1 TeV is recognized as an important complement to the physics program of the LHC. The Next Linear Collider (NLC) is being designed by a US collaboration (FNAL, LBNL, LLNL, and SLAC) which is working closely with the Japanese collaboration that is designing the Japanese Linear Collider (JLC). The NLC/JLC main linacs are based on normal conducting 11 GHz rf. This paper will discuss the status of the NLC design. Results from the ongoing R&D programs, including the recently uncovered high gradient damage problem, will be discussed along with changes to the optical design and collider layout which were made to enhance the collider capabilities.

## 1 INTRODUCTION

The Next Linear Collider (NLC) [1, 2] is a future electron/positron collider that is based on copper accelerator structures powered with 11.4 GHz X-band rf. It is designed to begin operation with a center-of-mass energy of 500 GeV or less, depending on the physics interest, and to be adiabatically upgraded to 1 TeV cms with a luminosity in excess of  $3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ . The initial construction will include infrastructure to support the full 1 TeV cms to ensure a straightforward upgrade path. A schematic of the NLC is shown in Fig. 1. The collider consists of electron and positron sources, two X-band main linacs, and a beam delivery system to focus the beams to the desired small spot sizes. The facility is roughly 30 km in length and supports two independent interaction regions (IRs).

The NLC proposal was started by SLAC and later joined by LBNL, LLNL, and FNAL. SLAC has formal Memoranda of Understanding (MOUs) with these laboratories and with KEK in Japan to pursue R&D towards a linear collider design. In particular, there has been a close collaboration with KEK for several years concentrated primarily on X-band rf development. The JLC linear collider [3] and the NLC have developed a set of common parameters with very similar rf systems; a status report on the progress of this collaboration was published recently [4]. Work at Fermilab is focusing on the main linac beam line while the efforts at LBNL and LLNL are focused on the damping ring complex, the modulator systems and the gamma-gamma interaction region.

In the following, we will first describe recent developments in the NLC X-band rf systems and then discuss some

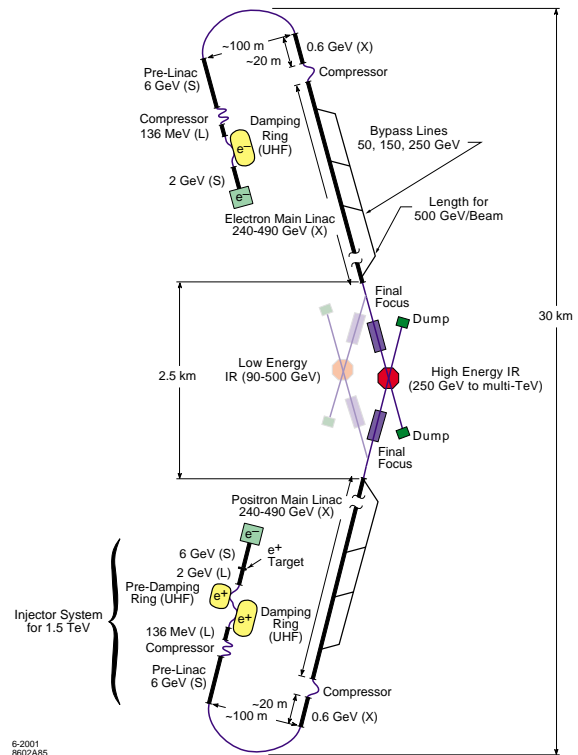


Figure 1: Schematic of the NLC.

of the modifications that have been made to the optical design. Next, we will describe some recent modifications to the collider layout that could allow the facility to collide beams with energies as high as 5 TeV once the appropriate rf systems are developed. Finally, we will discuss the NLC luminosity goals and our future plans.

## 2 X-BAND RF SYSTEM

The rf system for the NLC design operates at a frequency of 11.424 GHz to support the higher acceleration gradients needed for TeV-scale colliders. Currently, the NLC rf system is in its third design iteration. The evolution of the rf system has been driven by costing models that have been developed for the collider and by the results from the ongoing R&D programs. The present cost estimate for the rf system has decreased by roughly 50% from that in the 1996 cost model!

The first iteration of the rf system was based on conventional thyratron switched modulators, 50 MW Periodic Permanent Magnet (PPM) focused klystrons, the SLED-II pulse compression system and a Damped-Detuned (DDS) accelerator structure. This configuration was described in the NLC ZDR [1] and is the technology used in the NLC Test Accelerator (NLCTA). The NLCTA began op-

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eration in 1997 and verified the beam loading compensation scheme to be used in the NLC as well as the basic rf configuration [5].

The current generation of the rf design is based on solid-state modulators with an rf pulse length of  $3\ \mu\text{s}$  instead of  $1.5\ \mu\text{s}$  from the klystrons. These parameters reduce the required number of klystrons and modulators by a factor of two. In addition, the rf system uses an enhancement of the DLDS scheme where the rf power is propagated in multiple modes to reduce the amount of waveguide required. In this current design, the rf system for each 250 GeV linac consists of 117 modules each of which contains a modulator, eight 75 MW X-band klystrons, an rf pulse compression unit, and 48 accelerator structures. Finally, the accelerator structures are 0.9-m in length, roughly half the length of the previous designs, which we believe will reduce the breakdown damage effect that limited the accelerator gradient. It should be noted that, with the exception of the change in the accelerator structure length, all of these rf system modifications have been driven for reasons of efficiency and cost reduction. If an operating system were needed on a more rapid time scale, it would be possible to use earlier versions of the rf components. In the following, we will discuss each of the components in more detail.

### 2.1 Solid State Modulator

Recent improvements in high power Isolated Gate Bipolar Transistor (IGBT) switches have made it possible to consider a solid state modulator design. The switches have relatively fast rise and fall times ( $<200\text{ns}$ ) and can switch a few kA at a few kV [6]. The voltage contributions from a number of switches can be added together inductively in a manner similar to that in an induction linac. This design has the potential for much better efficiency than the 60-70% typical of the conventional modulators such as those operating in the NLCTA.

The NLC design uses a stack of 80 induction cores, each with two IGBT switches and a 3-turn transformer to generate over 2 kA at 500 kV [7]. This modulator would drive 8 klystrons at once with an estimated cost that is roughly half the cost of the conventional modulator and with an overall efficiency of roughly 80%. At this time, a full stack of 80 induction cores has been assembled and testing will begin in the fall of 2001.

### 2.2 75 MW PPM X-band Klystrons

The NLC program has constructed roughly 10 X-band 50 MW klystrons referred to as XL-4s. However, conventional klystrons, such as the XL-4, use a large solenoid magnet to focus the beam between the gun and the collector. This magnet requires 20 kW of power which is comparable to the average rf output power, effectively decreasing the klystron efficiency. To improve the efficiency, a new generation of klystrons using periodic permanent magnet (PPM) focusing have been developed. In these PPM klystrons, the focusing is generated with rings of permanent magnet material which generate a periodic axial field.

At this time, a couple of PPM klystrons have been built. The most recent model was a 75 MW PPM tube which produced over 72 MW with a pulse length of  $3.1\ \mu\text{s}$  and an efficiency of roughly 55%, consistent with simulations [8]. At this output level, the pulse length was limited by the modulator output and the repetition rate was limited to 10 Hz because the klystron body was not cooled. A second 75 MW PPM klystron has been constructed to operate with a  $3\ \mu\text{s}$  pulse length and 120 Hz repetition rate; it will be tested in the fall of 2001. In addition, the PPM klystron program at KEK has recently demonstrated a 75 MW PPM klystron with a  $1.5\ \mu\text{s}$  pulse length [9].

### 2.3 Delay Line Distribution System

The klystrons most efficiently generate a pulse that is longer and lower power than that needed for the structures. To optimize the system, the rf pulse must be compressed temporally before being sent to the accelerator structures. The SLED-II system, in operation at the NLCTA, compresses the klystron pulse by a factor of 6 but the efficiency is only about 70% so the peak power is only increased by a factor of 4.

To improve on this efficiency, the DLDS system was proposed at KEK [10]. In this system, the power from eight klystrons is summed and divided into equal time intervals. It is then distributed up-beam to eight sets of accelerator structures that are spaced appropriately so that the beam-to-rf arrival time is the same in each case. The power is directed to each different group of structures by varying the relative rf phases of the eight klystrons. The intrinsic efficiency of this system is 100% although wall losses and fabrication errors will likely reduce it to  $85 \sim 90\%$ .

To reduce the length of waveguide required, a multi-mode version of this system has been developed in which the power is distributed through a single circular waveguide, but in two or more different modes. To test the components at their design power levels, the NLCTA has been upgraded to produce 240 ns long pulses of 800 MW and testing will begin at the end of FY01.

### 2.4 Accelerator Structures

The accelerator structures for NLC have been studied for many years, much of this in collaboration with KEK. A good summary of the structure development history is given in Ref. [11]. There are three requirements on the structure design: first it must transfer the rf energy to the beam efficiently, second, it must be optimized to reduce the short-range wakefields which depend on the average iris radius, and third, the long-range transverse wakefield must be suppressed to prevent multibunch beam breakup (BBU).

The original structure design for the NLC was based on relatively long structures of 1.8-m. Unfortunately, in testing these at high power, a major problem in the design was uncovered. The NLC design calls for a gradient of 70 MV/m to attain a center-of-mass energy of 1 TeV with a reasonable length linac. In the past, short X-band structures were operated at gradients of over 100 MV/m and

single X-band cells have operated at gradients of 150~200 MV/m but it is only recently that sufficient X-band rf power has been available to test the full structures at their design gradient. During these recent tests, damage has been observed after 500 hours of operation. The onset of damage appears to occur at a gradient of 45 ~ 50 MV/m [12].

The two primary differences between these 1.8-m structures and those tested earlier at much higher gradients is the structure length and the group velocity of the rf power in the structure. The NLC structure had a group velocity of 12% at the input end while the other structures had group velocities between 5% and 1% and had lengths less than 0.9-m. A simple theoretical model has been developed which may correlate the damage with group velocity.

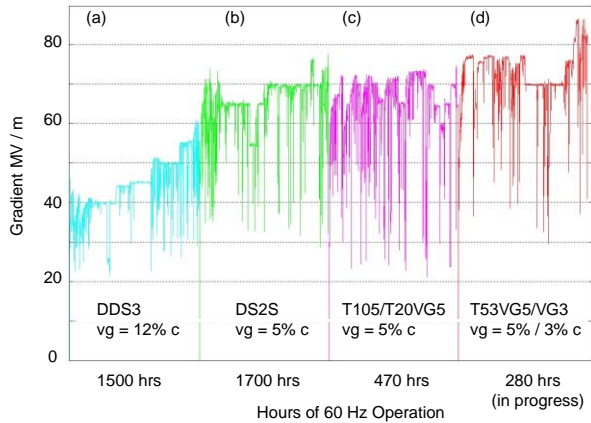


Figure 2: Processing voltage history for (a) DDS3 1.8-m structure, (b) a 0.5-m DS2S structure which was cut from the end of one of the 1.8-m structures, (c) a 1.05-m and a 0.2-m structure, and (d) 0.5-m structures with 5% and 3% peak group velocities.

To study this gradient limitation, SLAC, KEK, and LLNL have constructed 5 structures with different group velocities and lengths. In addition, one of the 1.8-m structures has been cut in two and the last  $\frac{1}{3}$  of the structure, where the maximum group velocity is 5%, was tested. All of the low group velocity structures have reached gradients  $>70$  MV/m. The gradients attained in these low group velocity test structures is compared against that attained in one of the recent 1.8-m structure in Fig. 2. One can see clearly that the low group velocities rapidly process to much higher gradients than the longer structure. In each case, a negligible amount of damage was observed during the rapid processing of the structures to high fields and no damage has been observed during the subsequent nominal operation [12].

Based on these results, we are changing the design for the NLC structures to have a maximum group velocity of 3 ~ 5% like that in the test structures and a length of 0.9-m which is half that of the previous design[13]. However, unlike the test structures, we still want to maintain a relatively large average iris radius of  $a/\lambda \sim 0.18$  to minimize the short-range wakefields. With standard structure design, this large iris radius leads to a large group velocity of 12%.

To reduce the group velocity while maintaining the large  $a/\lambda$ , the structure will have a phase advance of  $150^\circ$  per cell and the iris thickness will be increased. A version of this modified structure will be tested at the NLCTA in early 2002.

This structure will look very much like a full NLC structure however it will not have the components necessary to control the long-range transverse wakefields. In the NLC design, the long-range transverse wakefield is suppressed through a combination of detuning the dipole modes and weak damping. 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. The signals from this manifold also can be used to determine the beam position with respect to the accelerator structure to micron-level accuracy.

This long-range wakefield control has been studied in detail and four damped-detuned accelerator structures (DDS) have been built with the most recent structure using rounded cells. Measurements of the rf properties of the structures [14, 15] have confirmed: (1) the cell fabrication techniques which can achieve sub-MHz accuracy, (2) the wakefield models and wakefield suppression techniques, (3) the rf BPMs which are necessary to align the structures to the beam and prevent emittance dilution, and (4) the rf design codes which have sub-MHz accuracy [16]. Because of this previous experience, we are confident that it will be straight-forward to include the long-range wakefield control after the gradient performance is verified. We expect to be testing full prototype structures by the end of 2002.

### 3 OPTICAL DESIGN CHANGES

Over the last year, a number of changes have also been made to the optical design to reduce the collider cost and/or improve the collider performance. In this section, we will discuss the design for the beam delivery system (BDS) which has evolved significantly in the last few years. Other changes include modifications to the bunch compressor system [17], small changes to the beam parameters, possibly placing much of the control electronics directly into the linac tunnels, extensive use of permanent magnets[18], and the modified civil construction techniques to reduce costs.

#### 3.1 Beam Delivery System

The beam delivery system (BDS) includes the beam collimation section and the final focus. Both of these systems have been completely redesigned over the last two years, resulting in a design that is more robust and is 25% the length of that presented in 1999.

The beam collimation system has two purposes: it must collimate the beam tails to prevent backgrounds at the IP and it must protect the downstream components against errant beams. In the previous design, the beam collimation section was designed to survive any mis-steered or off-energy *incoming* beam. This is a difficult constraint be-

cause the beam density is normally so high that the beam will damage any material intercepted [19]. The resulting collimation design had to be roughly 2.5 km to collimate 500 GeV beams and the system energy bandwidth was only 1% with very tight optical tolerances—so tight that very small misalignments within the system could cause the beams to damage the beam line components.

In a pulsed linac, the beam energy can change from pulse-to-pulse however large changes to the beam trajectory which are not due to energy errors are much less frequent. We have taken advantage of this fact and redesigned the collimation system to passively survive any off-energy beam but to allow on-energy beams with large betatron errors to damage the collimators. The betatron collimators will be ‘consumable’ collimators which can be rotated to a new position after being damaged [20]; based on SLC experience, we expect the frequency of the errant betatron errors to be less than 1000 times per year. The net effect of this change in the design specification is that we now have a design that is roughly 25% the length with much looser tolerances and a larger bandwidth [21].

Another issue that constrains the collimator system design is the wakefields due to the collimators themselves. The collimators are planar devices with very shallow tapers which are expected to minimize the wakefields but make it difficult to perform either direct MAFIA-type or analytic calculations. We have installed a facility to measure these wakefields in the SLAC linac [22]. Initial results show much smaller wakefields than predicted from analytic estimates although the measurements are consistent with MAFIA calculations. We will be using the facility to test additional collimator designs, including some designed at DESY, over the next year.

In addition, a novel concept of using octupole doublets at the entrance to the final focus will fold the beam tails into the core of the beam at the phase of the final doublet[23]. This technique will increase the required transverse collimation depths by a factor of two per octupole stage. The present design uses two stages to gain a factor of four in the collimation depth.

Second, we have completely redesigned the final focus system (FFS). The previous FFS was based on the lattice of the Final Focus Test Beam (FFTB) at SLAC which was constructed from separate modules for the chromatic correction and made full use of symmetry. Although this makes the design of the FFS simpler, it has the disadvantage of making the FFS quite long—1.8 km for 750 GeV beams.

A new design has been adopted where the chromatic correction of the strong final magnets is performed locally at these magnets [24]. This results in a compact design with many fewer elements which has better performance than the previous version. In particular, the new FFS has a larger energy bandpass with comparable alignment tolerances and a more linear transport which should make it less sensitive to beam tails.

Finally, the scaling of the length with beam energy in

Table 1: Design parameters for the NLC at 500 GeV and 1 TeV

PARAMETER NAME	Stage 1	Stage 2
CMS Energy [GeV]	500	1000
Luminosity [ $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ ]	20	34
Lum. within 1% of $E_{cms}$ [%]	55	44
Repetition rate [Hz]	120	120
Bunch Charge [ $10^{10}$ ]	0.75	0.75
Bunches per pulse	190	190
Bunch separation [ns]	1.4	1.4
Effective Gradient (MV/m)	48	48
Injected $\gamma\epsilon_x/\gamma\epsilon_y$ [ $10^{-8}$ m-rad]	300 / 2	300 / 2
IP $\gamma\epsilon_x/\gamma\epsilon_y$ [ $10^{-8}$ m-rad]	360 / 3.5	360 / 3.5
IP $\beta_{tx}/\beta_{ty}$ [mm]	8 / 0.01	10 / 0.12
IP $\sigma_x/\sigma_y$ [nm]	245 / 2.7	190 / 2.1
IP $\sigma_z$ [ $\mu\text{m}$ ]	110	110
Pinch Enhancement	1.43	1.49
Beamstrahlung [%]	4.7	10.2
Photons per $e^-/e^+$	1.2	1.3
Linac length [km]	6.3	12.8

this new design is much weaker than in the earlier design. The present FFS is only 700 m in length but can focus 2.5 TeV beams while an equivalent conventional design would have to be roughly 10 km in length. This change makes it much more reasonable to consider a multi-TeV collider using an advanced high-gradient rf system such as the CLIC design [25]. We have taken advantage of this possibility in the NLC design by eliminating the bending between the main linacs and one of the two interaction regions to prevent synchrotron radiation from diluting the emittance of a very high energy beam. Thus, once a high gradient rf system is developed, the NLC could be upgraded to a multi-TeV facility in a cost effective manner, reusing much of the infrastructure and beam line components.

## 4 LUMINOSITY

The NLC has been designed to provide a luminosity of  $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  at a center-of-mass energy (cms) of 500 GeV and a luminosity in excess of  $3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  at 1 TeV cms [2]. These design luminosities include derating factors for the expected errors and dilutions and make use of some of the tuning techniques developed at the Stanford Linear Collider [26] and the Final Focus Test Beam [27]. The design luminosity values are roughly a factor of two below the intrinsic luminosity the collider can support assuming that all components operate perfectly, however, it should be noted that there is not significant margin at these design values. The IP parameters are listed in Table 1 and a full description of the luminosity parameters, the tuning techniques, and the alignment tolerances can be found in Ref. [2].

## 5 SUMMARY

Over the last year, the NLC collaboration has been focused on new technology developments and design changes to reduce the facility cost. We are making extensive changes to our baseline rf system and to the beam line optics to support the higher luminosity operation and the two interaction regions. We have also uncovered a high gradient limitation in our accelerator structure design and are vigorously investigating solutions—although earlier structure designs have operated at gradients well over 100 MV/m, the present structures are limited to gradients between 45 to 50 MV/m. Finally, we have also modified the collider layout so that it does not preclude upgrading the facility to a multi-TeV collider once an appropriate rf system has been developed.

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