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Next Linear Collider Design Status

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NEXT LINEAR COLLIDER DESIGN STATUS*

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Abstract

The layout of the Next Linear Collider (NLC) has been revised to provide greater physics capabilities and to make the design more cost effective. The basic rf unit for the main linacs uses a solid-state modulator to drive eight 70 MW klystrons with a $3\,\mu s$ pulse length. The rf power is distributed with a multi-mode Delay Line Distribution System (DLDS) to 8 girders of accelerating structures. This configuration improves the AC to rf efficiency while reducing the number of modulators and klystrons required by a factor of two. Using a new compact design for the final focus, the NLC now has two different Interaction Regions (IR), one for high energy (250 GeV-1 TeV cms) and one for low energy (90-500 GeV cms). The high energy IR has minimum bending to support an eventual upgrade to 3-5 TeV cms. The low energy IR is optimized for precision studies at the Z-pole, W-pair, Top and possibly Higgs threshold. The design allows for beam to be shared between the two IRs and the possibility of 180 hz operation is under study. The present design provides flexibility for a variety of upgrade and staging scenarios from initial operation at low energy to a future extension to multi-TeV.

1 INTRODUCTION

The Next Linear Collider (NLC) [1] 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. A schematic of the NLC, which is not to scale, 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. There are two independent interaction regions (IRs), a high energy IR eventually upgradeable to multi-TeV and a low energy IR optimized for precision measurements at 90-500 GeV. The facility is roughly 30 km in length and has two 13 km long X-band linacs, long enough to accelerate the beams to 500 GeV for collisions at 1 TeV cms. The collider is intended to begin operation at a lower energy, in which case the linac tunnels would only be partially filled with accelerator structures and rf power sources. In addition, there are bypass lines to deliver low-energy beam to either IR as desired.

The NLC proposal was started by SLAC and later joined by LBNL, LLNL, and FNAL. Work at Fermilab

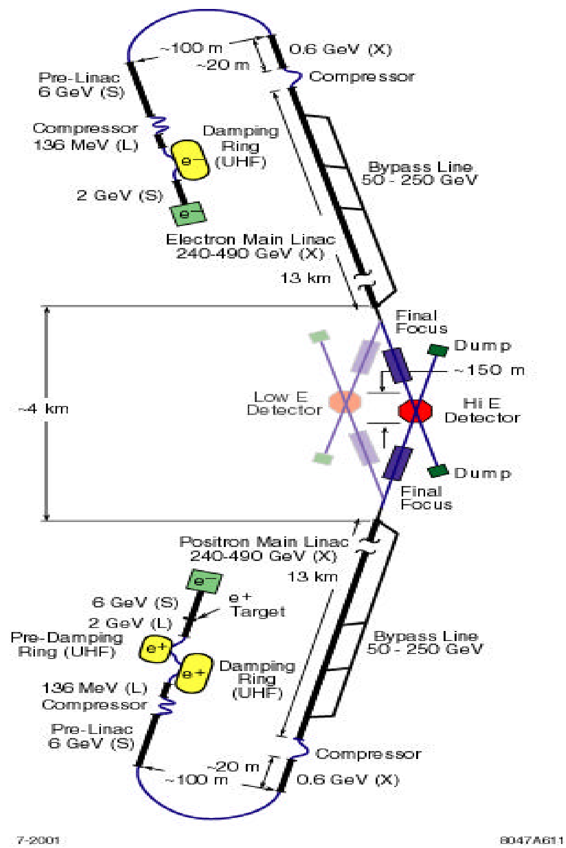

Figure 1: Schematic Layout of the NLC.

will focus on the main linac beam line while the efforts at LBNL and LLNL center on the damping ring complex, the modulator systems and the gamma-gamma interaction region. In addition, there has been a close collaboration with KEK for several years concentrated on X-band rf development. The JLC X-band linear collider [2] 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 in 2000 [3].

Over the last two years, the NLC layout has been revised to provide greater physics capabilities and to make the design more cost effective [4]. The two NLC IRs are asymmetric, with the high energy IR directly in line with the linacs. The total bending angle is minimal to support an eventual upgrade to 3-5 TeV cms. The bw energy IR is optimized for precision studies at the Z-pole, W-pair, Top or Higgs threshold. This design provides flexibility for a variety of upgrade and staging scenarios from initial operation at low energy to a future extension to multi-TeV. The NLC design luminosity has been revised upward to reflect the true design parameters and

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take full advantage of recent R&D results. At the same time, the original cost estimate has been reduced by about 30% through the use of new technologies (permanent magnets, solid-state modulators, *consumable* collimators), more compact optics (bunch compressors, Final Focus, collimation) and new layouts to share housings.

2 PARAMETERS

The NLC was initially designed to provide a luminosity in excess of $10^{34}/cm^2/s$ at 1 TeV cms. To ensure this luminosity, the design included a large operating space with numerous margins and overheads. For example, the injector system was specified to produce 50% more charge than required, and the beam emittance dilution budgets were in excess of 300%. These were based on conservative component tolerance specifications without including the impact of the emittance tuning techniques pioneered at the Stanford Linear Collider (SLC) [5], which successfully reduced the emittance dilutions by an order-of-magnitude. All systems were designed to meet the tightest tolerances for the full range of parameters. The design luminosity when all subsystems perform as specified is roughly a factor of four higher than the initial goal, similar to the TESLA luminosity estimates which are based on similar assumptions.

A set of design parameters for the NLC at different energies are listed in Tables 1 and 2. Table 1 lists the luminosity and IP parameters for 500 GeV and 1 TeV cms operation while Table 2 gives the luminosity at lower collision energies.

CMS Energy (GeV)	**500**	**1000**
Luminosity (10^{33})	20	34
Repetition Rate (Hz)	120	120
Bunch Charge (10^{10})	0.75	0.75
Bunches/RF Pulse	190	190
Bunch Separation (ns)	1.4	1.4
Eff. Gradient (MV/m)	50.2	50.2
Injected $\gamma\varepsilon_x$ / $\gamma\varepsilon_y$ (10^{-8})	300 / 2	300 / 2
$\gamma\varepsilon_x$ / $\gamma\varepsilon_y$ at IP (10^{-8} m-rad)	360 / 3.5	360 / 3.5
β_x / β_y at IP (mm)	8 / 0.10	10 / 0.12
σ_x / σ_y at IP (nm)	245 / 2.7	190 / 2.1
σ_z at IP (um)	110	110
Pinch Enhancement	1.43	1.49
Linac Length (km)	6.3	12.8

Table 1: NLC parameters for 500 GeV and 1 TeV cms

To preserve the small beam emittance during acceleration, the X-band structures must be designed to minimize wakefields, and both the structures and the focusing quadrupoles must be aligned to very tight tolerances. The wakefield properties of prototype structures have been measured precisely in the ASSET test facility and agree well with the calculations. Structures have been fabricated which meet tolerances far tighter than those required for NLC. The required alignment accuracy has also been demonstrated in ASSET. Beam-based alignment techniques developed for the SLC and FFTB have achieved close to the necessary accuracy, and extensive simulations indicate that these techniques are capable of preserving the emittance through a 10 km linac with diagnostics and correction hardware which need to be only a factor of 3 to 5 better than that used at the FFTB. The FFTB also demonstrated the validity of the final focus optics and achieved a demagnification of the beam size greater than required for NLC. All of these results have led to improvements in the design and increased confidence in its capabilities.

CMS Energy (GeV)	**92**	**250**	**350**
Luminosity (10^{33})	3.5	9.4	13.2
Repetition Rate (Hz)	120	120	120
Bunch Charge (10^{10})	0.75	0.75	0.75
σ_x / σ_y at IP (nm)	630 / 6.2	380 / 3.8	320 / 3.2
Beamstrahlung δ_B (%)	0.18	1.1	2
Photons per e+/e–: n_γ	0.49	0.79	0.92
Polarization loss (%)	0.08	0.21	0.34

Table 2: NLC parameters for low energy operation

The new NLC layout with two asymmetric IRs lends itself to consideration of two further options to expand the physics flexibility of the collider. The baseline design has always been to deliver luminosity to one IR at a time, but it may be desireable to have both detectors taking data simultaneously, particularly if the injectors and low energy portion of the main linacs could operate at 180 hz with lower energy beam to one IR. Simultaneous operation requires pulsed extraction from the linac, and for different center of mass energies, separate collimation systems. 180 hz operation requires new damping rings to accommodate the shorter damping time, possibly two smaller 90 hz rings. There are also issues with cooling the X-band klystrons at high rate. Neither option is mature enough to be part of the NLC baseline design but both are being studied as possible future enhancements.

3 OPTICS AND LAYOUT

Recently, a number of changes have also been made to the optical design to reduce the collider cost and/or improve the collider performance. The beam delivery system (BDS) has new designs for the beam collimation, final focus, and interaction region layout. The new BDS is more robust and is half the length of the previous design. The injector systems have also been modified to reduce cost by minimizing tunnel length.

3.1 Beam Collimation System

The beam collimation system has two purposes: it must collimate the beam tails to prevent backgrounds at the IP, including those generated by the collimation system itself, and it must protect the downstream components against errant beams. In earlier designs, the beam collimation section was designed to survive any mis-steered or off-energy *incoming* beam. This is a difficult constraint because the beam density is normally so high that the beam will damage any material intercepted. The resulting collimation design for 500 GeV beams was 2.5 km long with optical tolerances too tight for operational comfort.

In a pulsed linac, the beam energy can change from pulse-to-pulse, but large trajectory changes which are not due to energy errors are much less frequent. The new collimation system takes advantage of this fact and is designed 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' and can be rotated to a new position after being damaged [6]. Based on SLC experience, the frequency of errant betatron errors should be much less than 1000 times per year. With this revised design specification, the collimation system is half as long with much looser tolerances and a larger bandwidth [7].

3.2 Final Focus

Conventional final focus designs (FF) for linear colliders have been 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 FF simpler, it has the disadvantage of making the FF 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 [8]. The new, more compact design has many fewer elements and better performance. In particular, the new FF has a larger energy bandpass with comparable alignment tolerances and a more linear transport that should make it less sensitive to beam tails. Because of the better performance, it is possible to increase L*, the free space from the final magnet to the IP, from 2 m to 4.3 m. This will simplify the design of the interaction region and the interface with the high energy physics detector.

Finally, the length of the FF scales much more weakly with beam energy in this new design. The new FF can focus 2.5 TeV beams in only 700 m length, while an equivalent conventional design would have to be 3 km long. 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 [9]. To capitalize on the multi-TeV potential of the new design, it was also necessary to eliminate other bending between the linac and the high energy IP. In the new asymmetric layout, the linacs are no longer collinear but are oriented with a shallow 20 mrad angle between them to produce the desired crossing angle at the high energy IR without additional bending. The beams to the second IR are bent by about 25 mrad. This IR has a larger 30 mrad crossing angle for compatibility with a possible $\gamma\gamma$ option.

3.3 Interaction Region Layout

The beamline for the high energy IR is 2.5 km from the end of the linac. This distance includes a long 1.4 km collimation region, the 800-m final focus and an additional 300 m 'stretch' to accommodate the beamlines for the low-energy IR. The low-energy IR beamline splits off at the end of the collimation and includes the 25 mrad bend and a shorter 500 m final focus. Both beamlines share the same collimation system but, as a future upgrade, parallel collimator beamlines could be installed in the same tunnel. In the present layout, the two IRs are separated by about 20 m transversely and 440 m longitudinally to provide vibration isolation and shielding so either IR hall may be accessed while the other is in operation.

3.4 Injector Systems

There are two separate injector complexes to produce the electron and positron bunch trains. These have evolved in response to R&D results and cost optimization. In the present layout, the electron booster and prelinac are housed in the same tunnel to minimize infrastructure costs. The positron drive linac, booster and prelinacs also share a common tunnel and support buildings. The energy of the second bunch compressor has been lowered to 8 GeV to reduce the overall length and cost [10]. Recent data from the failure of the SLC positron source indicates that multiple positron targets are required to keep the energy deposited in each target below the threshold for material damage. In the present NLC design, the drive beam electrons are split by an rf separator and directed onto 3 of 4 multiplexed targets and positron capture sections. The bunches are then recombined into the desired 190-bunch train format.

The concept of a central injector complex was investigated for possible cost savings, and many configurations with and without shared components were considered. Any centralized injector requires long, low-emittance transport lines to bring the beams to the end of the main linacs and extra tunnels to connect into the linac housing and into the second bunch-compressor 180° turnaround. These additions more than offset any potential savings. The most cost effective location for the injectors is near the low-energy ends of the linacs as in the original ZDR design. A central injector design is being developed for the Fermilab deep tunnel site because it has the advantage of being located entirely on land already owned by the laboratory.

4 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. The rf system consists of four main components: the modulators which convert the line ac into pulsed dc power for the klystrons, the klystrons which convert the dc pulses into rf pulses at 11 GHz, the pulse compression system which temporally compresses the rf pulse while increasing the peak power, and the accelerator structures which transfer the rf power to the particle beam.

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 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 technology is used in the NLC Test Accelerator (NLCTA), which began operation in 1997. It would be adequate to build a 500 GeV machine today but it is not optimized for a final energy of 1 TeV or higher.

The present NLC rf design is based on solid-state modulators, 75 MW PPM X-band klystrons, the Rounded DDS (RDDS) accelerator structure which has 12% higher shunt impedance and the Delay Line Distribution System (DLDS) pulse compression scheme which has significantly higher efficiency than the SLED-II system. The rf pulse length has been increased to 3 μs instead of 1.5 μs, which reduces the required number of klystrons and modulators by a factor of two. The latest configuration uses an enhancement of the DLDS scheme where the rf power is propagated in two orthogonal 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 24 accelerator structures. The present cost estimate for the rf system has decreased by roughly 50% compared to an implementation with NLCTA technology.

4.1 Solid State Modulator

Recent improvements in high power Isolated Gate Bipolar Transistor (IGBT) switches have made it possible to develop a solid state modulator design. The NLC modulator 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. Each modulator will drive 8 klystrons with an estimated cost that is roughly half that of the conventional modulator and with an overall efficiency greater than 75%. Another advantage is that the reliability of the system can potentially be much higher. Failure of a single IGBT should be benign since the core saturates and becomes nearly transparent to the pulse, and additional IGBT units are included to offset such a loss.

As a first step to a full-scale solid-state modulator, a stack of ten cells was built and used to power a SLAC 5045 S-band klystron. Since then a full-scale prototype induction modulator has been built by a collaboration of SLAC, Livermore and Bechtel, Nevada. This unit is under test using four 5045 S-band klystrons operating as loads. It will be operated up to the rating of the loads, which is 420 kV at 1,800 A peak, 3.2 μs and 120 Hz. It will then be upgraded and moved to the NLCTA to power 75 MW PPM klystrons as they become available.

4.2 75 MW PPM X-band Klystrons

Conventional klystrons use a large solenoid magnet to focus the beam between the gun and the collector. Unfortunately, the magnet requires 20 kW of power which is comparable to the average rf output power, effectively decreasing the klystron efficiency. To avoid this 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 are interleaved with iron pole pieces to generate a periodic axial field.

In 1996, SLAC built a 50 MW PPM klystron which produced 2 μs long 50 MW pulses with a 55% efficiency. Next, a 75 MW PPM tube was built and was able to produce over 75 MW with a pulse length of 2.8 μs and an efficiency of roughly 55%, consistent with simulations. At this output level, the pulse length was limited by the modulator output and the repetition rate was limited to 10 Hz due to inadequate cooling of the klystron. A second 75 MW PPM klystron designed to operate at the full 3 μs pulse length and 120 Hz repetition rate has been built and will be tested in 2002. This klystron incorporates Design For Manufacture improvements to make it more suitable for mass production.

4.3 Delay Line Distribution System

The klystrons most efficiently generate a lower power and longer pulse than that needed in the structures to accelerate the beam. 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 [11]. 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 would reduce that to 85-90%.

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. In the current configuration, each waveguide transports two modes, reducing the length of waveguide by roughly a factor of two. Future studies will investigate both the possibility of transporting four modes in one waveguide and the utility of active rf switching techniques which might allow all the power to be transported in a single waveguide. Finally, to test the components at full design power, the NLCTA has been upgraded to produce 240 ns long pulses of 800 MW and testing will begin in 2002.

4.4 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. [12]. 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.

To optimize the rf efficiency, the structure cells are rounded, reducing the linac length by roughly 6% when compared to a simple disk-loaded waveguide like that in the SLAC linac. To reduce the short-range wakefields, the average iris radius was chosen to be $a/\lambda \sim 0.18$, leading to a relatively large group velocity ranging from 12% in the front of the structure to 2% at the exit. 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 can also be used to determine the beam position with respect to the accelerator structure to micron-level accuracy.

Four 1.8 m long damped detuned accelerator structures (DDS) have been built with the most recent structure using rounded cells. Measurements of the rf properties of the structures 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.

4.5 High Power Damage

Unfortunately, a major problem in the structure design was encountered in 1999 once sufficient rf power was available to test the full 1.8 m structures at their design gradient. 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. This is well below what has been achieved in the past with numerous short X-band structures which reached gradients of over 100 MV/m. In long structures, damage was observed at a gradient of 40-50 MV/m after 500 hours of operation. These structures have two primary differences compared to the earlier higher gradient tests, the structure length and the group velocity of the rf power in the structure. A possible model suggests the damage is correlated with group velocity.

To study the gradient limitation, SLAC and KEK began an intensive program of R&D on structures with different group velocities and lengths. One of the 1.8-m structures was cut in two and the last 1/4 of the structure, where the maximum group velocity is 5%, was tested. This short structure reached a gradient of 70 MV/m 10 times faster than the full length structures and, after about 1000 hours of operation, no evidence of rf damage was observed. Other structures with different lengths and initial group velocities of 3% and 5% have been tested with encouraging results. In addition, different cleaning techniques during fabrication, different processing methods, and different structure and coupler designs are being investigated. On the assumption that the correlation of gradient with group velocity is correct, design is proceeding on a replacement structure for the NLC which could be constructed quickly if testing confirms the initial results. The replacement structure would be shorter, either 60 or 90 cm long, and have a lower group velocity using a phase advance of 150° per cell instead of the standard 120° to keep the average iris radius large.

5 CONCLUSIONS

In the last few years, the NLC collaboration has focused on new technology developments and design changes to reduce the facility cost and enhance its flexibility. The luminosity has increased to reflect the full design capabilities. While there has been excellent progress on developing prototype rf components, a high gradient limitation in the accelerator structure design has been discovered. An intensive R&D program is underway to investigate the problem and find a structure design to meet the NLC goal of 70 MV/m. Extensive changes to the baseline rf system and to the beam line optics have reduced the collider footprint while maintaining the energy reach of the facility. A significant advantage of the new collider layout is that it is potentially upgradeable to a multi-TeV collider once an appropriate rf system has been developed.

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