Summary of the NLC Accelerator Working Group*

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ABSTRACT

The NLC (Next Linear Collider) accelerator working group was concerned with a presentation and thorough discussion of the prospects for achieving a 0.5 TeV linear collider and an examination of issues related to energy upgrades to attain 1.0 to 1.5 TeV in the center-of-mass. The contents of the talks and subsequent discussions are summarized in this paper. Highlights of R&D efforts toward the NLC that were underway during the Snowmass workshop are described. Finally, some of the recent results and issues from the Stanford Linear Collider (SLC), relevant to the design of a future linear collider, are also described. Further detail on most subjects can be found in the recently published "Zeroth-Order Design Report for a Next Linear Collider" (ZDR).

I. INTRODUCTION

In this paper, we will summarize the NLC Accelerator Working group at Snowmass '96. The group primarily discussed the Next Linear Collider (NLC) [1, 2] which is a future electron/positron linear 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 (cms) energy of 500 GeV and ultimately upgraded to 1.5 TeV cms.

In the subsequent sections of this paper, we will first outline the NLC design that was presented to the working group; note that more detailed descriptions of the NLC design can be found in Refs. [1, 2], both of which will be included on the CDROM version of these proceedings. In addition, a short description of the NLC can be found in plenary talk by D. Burke [3] which is also included in these proceedings.

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Next, we will summarize the discussions in the NLC working group. This included a detailed presentation of the design and it's limitations, discussions of the performance of the Stanford Linear Collider (SLC) and the implications for the NLC design, an update of the parameter set for 1.5 TeV, and the development of a concept for a 5 TeV linear collider, based on 34 GHz rf power sources, that would fit on the NLC site and would utilize much of the NLC infrastructure.

Throughout this discussion, we will describe recent NLC R&D results that are relevant. This includes extensive ground motion measurements to verify the required stability, measurements of the dipole wakefields to verify the performance of the Damped-Detuned accelerator Structures (DDS), and tests of the rf structure BPMs that are needed to align the structures to the beam trajectory. It also includes the development and fabrication of the X-band structures, klystrons, and rf pulse compressors that are needed to accelerate the beams with gradients in excess of 50 MV/m.

In addition, we will also discuss many of the recent developments at the SLC. The SLC has been extremely important to the design of the NLC because, as the only existing linear collider, it provides invaluable operational experience. In particular, we will discuss the performance of the beam-based feedback systems, the beam collimators, beam jitter issues, beam emittance control, and sub-micron beam diagnostics.

It should be noted that much of the material reported here is described in greater detail in other papers submitted to this conference and elsewhere and thus the appropriate references are included throughout. In addition, because of space limitations, we only briefly describe the design of the NLC and, instead, concentrate on the R&D that is supporting the design; as stated earlier detailed descriptions of the NLC design can be found in Refs. [1, 2], both of which will be included on the CDROM version of these proceedings.

II. NLC DESIGN

The Next Linear Collider (NLC) [1, 2, 3] is a future electron/positron linear 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 (which could be decreased to 350 GeV to study the top quark) and to be adiabatically upgraded to 1 TeV cms. At the onset, the entire infrastructure will be constructed to support the 1 TeV cms upgrade. An upgrade to 1.5 TeV could later proceed either by a straight-forward 50% extension of the linac length, a trombone is incorporated into the design to facilitate this extension, or by improvements in the rf technology, increasing the acceleration gradient; the final focus and collimation sections have been designed with sufficient length to operate with 750 GeV beams for the upgrade to 1.5 TeV cms.

The initial rf system for the 500 GeV cms design is based on components that have been developed or can be expected in the near future. Specifically, it is composed of 50 MW X-band klystrons, SLED-II rf pulse compressors, and Damped-Detuned accelerator Structures (DDS) that reduce the long-range transverse wakefields through a combination of weak damping and detuning of the dipole mode frequencies. The upgrade to 1 TeV is based on expected improvements in the rf technology and would proceed by replacing the 50 MW klystrons with 75 MW klystrons and doubling the number of modulators and klystrons.

The NLC design, shown schematically in Fig. 1, contains all of the components found in the SLC. There are sources, damping rings, and bunch compressors to produce the low emittance beams, long linacs to accelerate the beams to the desired energies, and collimation sections and final foci to produce the small spots needed at the IP. In this paper, we cannot describe the various components of the design and instead we refer to the recent design study that was completed and documented in the "Zeroth-Order Design Report for the Next Linear Collider" [1]. This is a complete systems study with engineering support in crucial areas to verify feasibility.

The NLC design incorporates many of the hard lessons from the SLC. Throughout the design, we have been careful to provide substantial operating margins on all the subsystems; if all the subsystems perform as designed, the luminosity would be roughly three times higher than that specified. In addition to providing some overhead on the luminosity, this was done in an attempt to ensure the stability and reliability that is required to operate a linear collider; sub-systems that operate at their limit rarely provide the stability that is desired. Similarly, tolerances were specified to attain the design luminosity over a large range in operating parameters, such as bunch charge and beam emittance. Designing the collider to operate over a large range in parameter space, and not just at a single point, will allow the performance to be optimized during operation without sacrificing luminosity. Finally, the NLC design includes extensive beam collimation sections and detailed diagnostic layouts and tuning procedures; all of these have been added onto the original SLC design as operational experience has been gained. The

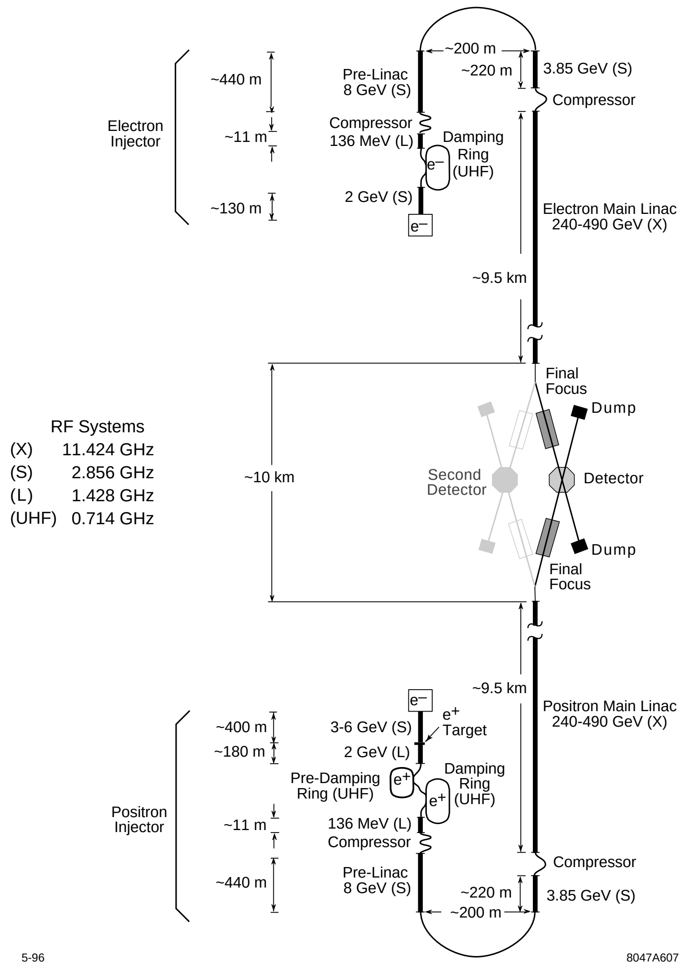

Figure 1: Schematic of the NLC; from Ref. [1].

NLC design was reviewed by an external committee in March of 1996 and, as we are discussing, it was presented to the NLC Working group at the 1996 DPF/DPB Snowmass meeting. At this time, a larger engineering effort is being started to further study the reliability issues as well as studying the issues associated with manufacture of large numbers of components. The next goal is to produce a cost estimate and schedule.

III. NLC ACCELERATOR WORKING GROUP

The NLC Accelerator Working Group was concerned with a presentation and thorough discussion of the prospects for achieving a 0.5 TeV linear collider, and an examination of issues related to energy upgrades in the 1.0 to 1.5 TeV cms energy range. The discussions concentrated on the design of the NLC that is described in the ZDR [1].

In specific, the NLC sub-group met seven mornings. The topics of these sessions were:

1. NLC Design Overview and SLC Experience (6/27),
2. Linac Design and Dynamics (6/28),
3. X-band RF Systems (7/1),
4. Polarized Electron and Positron Injectors (7/3),

5. Gamma-Gamma Interaction Region (7/5),
6. Beam Delivery and Interaction Region (7/9),
7. Systems Issues (7/10).

In addition to these morning sessions there were five talks presented at the accelerator group afternoon plenary sessions. These talks were:

- NLC Overview—John Irwin,
- X-band RF Systems Overview—Ron Ruth,
- Beam Delivery Systems Overview—Frank Zimmermann,
- Major Concerns (SLC Discrepancies, Cost Determination, Reliability Studies, Outstanding Design Questions)—David Burke,
- System Integration—Tor Raubenheimer.

In the following, we will describe the highlights of each of the NLC morning sessions and then we will discuss some of the additional work that was performed or presented in other sessions. In addition, we will present some of the recent results from the NLC R&D program and the SLC; these results will be described in subsections following the discussion of the appropriate working group session. Some of these R&D results were presented at Snowmass while in other cases the experimental plans were described but the results had not yet been obtained. Most of the more recent results were presented at the 1996 Linac Conference in Geneva, Switzerland; references are provided throughout.

A. Session: Design Overview (6/27)

The first morning was spent introducing the NLC design and then discussing some of the results and issues that have been found at the SLC and how these results have been incorporated into the NLC design:

- SLC–Nan Phinney
- NLC Summary–Tor Raubenheimer

The SLC had a long and difficult commissioning period and still has not quite reached the design luminosity. Over the years, numerous systems have been upgraded and/or installed as the operational experience has increased. This includes extensive reliance on beam-based feedback systems, multiple layers of collimation systems, and numerous additional and redundant diagnostics. In addition, there have been important advances in understanding the sources and effects of wakefields, the effects of beam jitter, which primarily limits the beam diagnostics and not the luminosity, and the importance of highly reliable and stable operation which is required to tune the collider subsystems and attain the luminosity.

These later issues are perhaps the most important lessons from the SLC. Because a linear collider is a pulsed device, every beam pulse will differ slightly from the preceding. This complicates the interpretation of the diagnostics and can limit the convergence of the complex beam-based tuning procedures. In the NLC ZDR, it is estimated that roughly 25% of the ideal luminosity is lost due to the finite resolution of the tuning diagnostics; this would be further decreased if there are significant sources of instability in the beam. Thus, it is extremely important to have a stable and reliable platform upon which the sub-systems can be tuned and optimized. As mentioned, at this time, the NLC design effort is concentrating on clearly defining the reliability issues and the tuning/recovery procedures.

B. Session: Linac Design and Dynamics (6/28)

The next morning was spent discussing the main linacs that accelerate the beams from a few GeV to the final beam energy between 250 GeV to 750 GeV. The talks concentrated on the NLC design with the exception of that by H. Padamsee who suggested combining the TELSA superconducting linac with the NLC final focus system to get very high luminosity:

- Linac Experience and Design–C. Adolphsen
- Tesla–NLC Combination–H. Padamsee
- Mechanical Design Considerations–G. Bowden
- Operations and Performance–R. Assmann

The primary points made during the discussion of the NLC linac were: first, the linac is aligned using beam-based procedures, similar to those used in the Final Focus Test Beam at SLAC (FFTB) presently. This relies upon having high resolution 1 μm Beam Position Monitors (BPMs) and remote magnet movers—both of which have been demonstrated at the FFTB. In addition, although by design the wakefields in the NLC linac are a smaller perturbation on the beam dynamics than they are in the SLC linac, the accelerator structures must be aligned to within 15 μm of the beam trajectory. This will be done by directly measuring the induced dipole modes in the accelerator structures and using remote movers to center them; this dipole mode monitor was tested in July 1996 and the experimental results are discussed in Section III.C.2.

Second, another topic that has received significant study is the thermal and vibrational stability of the magnet and accelerator support systems. The thermal stability is required to prevent movement of the magnets or bowing of the accelerator structures as the thermal loads and/or tunnel temperature change. At this time, detailed computer models, using finite element techniques, are being used to study the heat flow around the structures and in the tunnels in an attempt to quantify and minimize the effects. Given the FFTB experience, vibration of the supports is thought to be less of an issue and is discussed further in Section III.G.1 where we describe the recent ground motions measurements at SLAC.

Finally, there was a detailed discussion of the simulation procedures that have been used to verify the emittance degradation through the linacs; this topic is described further in Ref. [4] submitted to these proceedings. The simulations have been benchmarked against experience in the SLC and include the beam-based feedback systems that are needed to stabilize the trajectory over time as well as the various beam-based alignment algorithms. The simulated emittance growth along the linac is significantly less than what actually has been budgeted. Furthermore, the NLC simulations have not included the global emittance correction techniques, such as the beam trajectory bumps that are commonly used in the SLC—see Section III.B.1, with the assumption that these techniques can be held in reserve to further reduce the emittance dilution. At this time, the simulation programs are being used to help quantify the reliability requirements and determine the operational limits when many of the magnet movers and BPMs are not functioning properly.

Other issues that are relevant to the NLC design are all operational questions that are being answered at the SLC. In the next sub-sections, we describe recent results from the emittance control techniques in the SLC, the present operation of the beam-based feedbacks that will be necessary in the NLC, and the 'anomalous' beam jitter that has plagued the SLC and has been a concern for the NLC design.

1. SLC Emittance Control

For a number of years, beam trajectory bumps have been used, in the SLC, to correct for emittance dilutions due to transverse wakefields. The principal is straightforward: one induces a betatron oscillation with an amplitude and phase so that the effect of the wakefields cancels the effects of the wakefields due to the steering errors and misalignments. The oscillations are optimized to minimize the beam emittance at an emittance diagnostic downstream of the oscillation. In practice, a number of bumps must be used in the SLC to prevent the emittance dilutions from filamenting due to the energy spread in the beam.

Using these techniques, the emittance dilution can be reduced from roughly 1000% in the vertical plane to roughly 100%. The problem with such global emittance correction techniques, where two large effects are being used to cancel each other, is that they are very sensitive to the optics between the sources of dilution and the cancellation and these optics change as the energy profile along the linac changes. This reduces the stability of the emittance correction and, in the SLC, it is found that the trajectory bumps must be tuned roughly once every eight hours.

There have been a number of attempts to reduce the sources of the dilutions, thereby reducing the magnitude of the trajectory bumps and improving the stability. Most recently a technique referred to as two-beam Dispersion-Free steering has been used to reduce the steering errors. The results have been mixed but in many cases the technique appears to reduce the required bump amplitude by over 50% and the dilution without bumps is reduced from approximately 1000% to 200% [5]. In addition, numerous emittance diagnostics have been added along the length of the linac to make the correction more local. Another approach of improving the stability of the emittance correction is to stabilize the optics. Two techniques are being tried: first, reduce the sensitivity of the hardware to thermal fluctuations and, second, use a diagnostic pulse to monitor the optics in the linac. Unfortunately, it has not yet been determined how to correct the observed optical fluctuations.

Finally, it should be noted that these problems will be minimized in the NLC design. First, the design is not relying on the use of global emittance correction techniques to constrain the emittance dilution. Second, there are numerous emittance and, perhaps more importantly, energy diagnostics along the length of the linac. These will help stabilize the linac optics. Lastly, both the linac tunnel and the klystron gallery, which contains most of the local electronics will be in temperature controlled tunnels; this differs from the SLC where the klystron gallery is above ground and diurnal temperature fluctuations of $50°$F are not uncommon.

2. SLC Beam-Based Feedbacks

Another topic that is extremely important for the NLC is the use of beam-based feedbacks. The SLC utilizes over 30 fast beam-based feedback loops to control and stabilize the beams and most future linear collider designs are even more heavily reliant on the beam-based feedback systems. Unfortunately, during the previous SLC runs, it was found that the gain, and thereby the frequency response, of the feedback systems had to be reduced substantially to prevent the feedbacks from oscillating [6]. This was found to be especially true in the linac where many feedbacks are "cascaded" to prevent them from interfering with each other. The principle of the cascade is that each feedback transmits what it measures to the next downstream feedback with the assumption that the trajectory deviation will be corrected and thus the downstream system should not respond to it. To allow the cascade system to adapt to changes in the optics and the energy profile along the linac, the cascade transfer matrices are calculated adaptively from the natural beam jitter.

Studies during the 1994-95 and 1996 collider runs, identified three primary performance limitations:

- Feedback loop transfer matrices had significant errors — partly due to optics modification from transverse wakefields,
- Cascade assumes purely linear transport matrices through the linac and thus the feedback systems only talk to the next downstream feedback but wakefields and chromatic effects make the linac transport nonlinear,
- Cascade adaption does not correctly account for the finite BPM resolution yielding incorrect transfer matrices between feedback systems.

After these problems were identified, near perfect performance was attained at low currents, where the wakefields are less important, and when the cascade matrices were calculated from dedicated oscillations where the measurements were not limited by the finite BPM resolution. This was important because it verified the feedback principles although it suggested that the algorithms need to be modified. In the future, at the NLC, the cascade matrices will likely be calculated from dedicated oscillations and the cascade system will be modified to account for the nonlinearity of the beam transport through the linac.

While diagnosing the performance limitations, another important realization was made, namely, that different feedback algorithms have dramatically different sensitivities to errors. The SLC beam-based feedbacks do not use very aggressive algorithms. The cross-over frequency, below which the feedback damps rather than amplifies incoming oscillations, is $\frac{1}{30}f_{rep}$, where f_{rep} is the sample rate. In the past, members of the linear collider community have suggested using far more aggressive feedback systems. For example, the simple double-dead-beat system, which uses the two previous measurements to estimate the next, has a higher cross-over frequency, $\frac{1}{6}f_{rep}$, and a faster rate of damping. Unfortunately, these systems were found to be extremely sensitive to errors. In fact, even relatively small changes to the SLC feedback algorithms were seen to perform much worse when realistic errors were included. At this time, the details of the error sensitivity are not understood and this requires additional study.

3. SLC Transverse Beam Jitter

Transverse beam jitter has two effects: it decreases the luminosity by decreasing the overlap of the two colliding beams and, more importantly, it makes the diagnostics more erratic and harder to interpret, thereby decreasing the effectiveness of the tuning procedures. During the previous SLC runs, many sources of transverse beam jitter have been traced and eliminated [7]. The primary diagnostic used to trace the jitter sources is the accumulation of Beam Position Monitor (BPM) readings on 1000s of sequential pulses. Of course, this requires extensive controls and eliminates the possibility of multiplexing the BPMs.

Unfortunately, there still remained an undetermined 'white noise' source in the SLC, that caused the vertical trajectory jitter to grow uniformly along the length of the linac by roughly $0.3\sigma_y$. While damaging to SLC operation, this was also a significant concern for NLC operation since there was fear that the jitter source would not demagnify as the beam emittance is decreased. There had been a number of candidates considered for this jitter, including dark current in the linac structures that drive transverse wakefields, higher-order correlations on the injected beam that then, due to the transverse wakefields, cause the motion of the bunch centroid to increase [8], and the more prosaic effect of 10% bunch length fluctuations [9] that arise from the sawtooth instability in the damping rings [10]. This later effect, where the variation of the bunch length changes both the loading due to the longitudinal wakefield and the deflections due to the transverse wakefields, describes the observed jitter well [11]. Measurements have confirmed that there is a high degree of correlation between the linac jitter and the sawtooth signal from the damping rings [8]. If indeed this is the source, it should be less of an issue in the NLC than in the SLC, even though the beam emittance is much smaller in the NLC, because the transverse wakefields have a smaller effect on the beam dynamics.

C. Session: X-band RF Systems (7/1)

On Monday, the X-band rf systems for the NLC were described. The discussion started with the status of the NLC Test Accelerator (NLCTA) which is constructed to test all the rf components required for the NLC. This includes the klystrons, structures, rf pulse compression systems, and the accelerator structures. Next, the X-band klystrons, rf pulse compressors, and accelerator structures were described in detail. This was followed by a discussion of the theory of the Damped-Detuned accelerator Structures (DDS), methods for phasing the klystrons, and finally, a discussion of the manufacturing issues involved in constructing the NLC.

- Status and NLCTA–Ron Ruth
- Klystrons–R. Phillips
- Pulse Compression–P. Wilson
- Accelerator Structures–J. Wang
- Structure Theory–N. Kroll

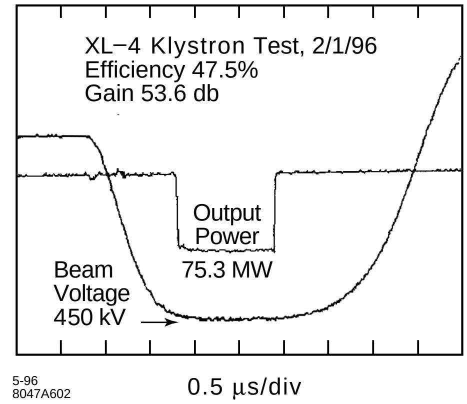

Figure 2: Power output of XL4 klystron.

- RF Phasing–K. Jobe
- Manufacturing Issues–T. Lavine

Most of the components required for the 500 GeV cms NLC are already available—the recent R&D results are summarized below in Sections III.C.1–III.C.3. This includes the klystrons, the rf pulse compressors, the accelerator structures, and all of the ancillary components such as efficient mode converters, low loss waveguide, $90°$ waveguide bends, *etc.*. A major effort is currently underway to optimize the component designs for manufacture. A collaboration has been started with the Design for Manufacture group at Stanford University to begin studying these issues. Already there have been suggestions on methods of significantly reducing the cost of manufacturing the accelerator cells and the klystrons. The collaboration is being expanded to include LLNL and work is continuing in this effort.

1. X-band Klystrons

As described, the NLC will initially rely on 50 MW klystrons which will then be upgraded to 75 MW klystrons to achieve a full 1 TeV in the center-of-mass. At this time, the XL series of X-band klystrons are producing the required 50 MW pulses [12]. The latest klystron in the XL series, the XL4, produces 75 MW with an efficiency of 48%; an output pulse is illustrated in Fig. 2. The tube is very robust with stable output power and an infrequent fault rate. Furthermore, the performance of the XL series has been in close agreement with the simulation results giving confidence in our ability to design klystrons with the aid of computer simulation.

Unfortunately, the XL klystrons all use solenoidal focusing and these solenoids are both expensive and consume a significant amount of power. Thus, a Periodic Permanent Magnet (PPM) focused klystron, shown schematically in Fig. 3, has been developed [13]. This is a lower perveance tube with potentially higher efficiency. In recently completed initial tests, this klystron produced $1.5\,\mu$s pulses of 52 MW at 55% efficiency; this exceeds the requirements for the NLC. In addition, the klystron produced 300 ns pulses of 60 MW at 63% efficiency. At the higher power, the length of the pulse was limited due to rf breakdown and thus the klystron has been opened and

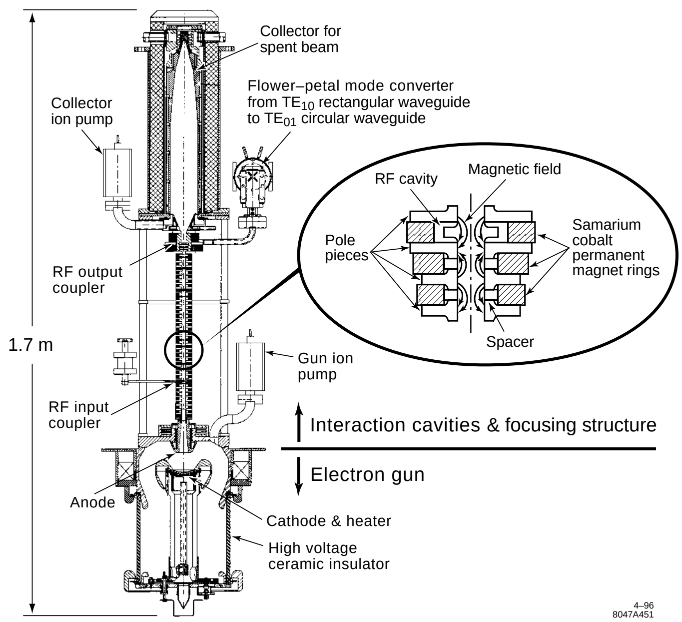

Figure 3: Schematic of PPM klystron; from Ref. [1].

the cavities are being coated with TiN. The next PPM klystron is being designed to produce 75 MW with $> 60\%$ efficiency which will meet the requirements for the 1 TeV cms NLC upgrade.

2. *Damped-Detuned Accelerator Structures*

To control beam-breakup of the long bunch trains in the NLC linacs, the long-range transverse wakefields in the accelerator structures must be reduced. This is done by a combination of detuning the dipole modes so that there is a $\sim$10% Gaussian spread in the frequencies, causing the dipole modes to rapidly decohere, and damping the dipole modes with Q's of roughly 1000 to prevent the modes from recohering at a later time. The damping is added to the Damped-Detuned Structures (DDS) by coupling each cell to four manifolds running along the length of the structures as illustrated in Fig. 4. Recent measurements of the transverse wakefields in the DDS structures, which were in excellent agreement with theory, showed that the wakefield is damped below the limit required for the NLC [14]; additional optimization of the matching into the manifold loads should reduce the wakefields even further.

The four damping manifolds also provide a straightforward method of measuring the induced dipole modes. In the NLC, the accelerator structures, which will be mounted on remote movers, need to be aligned to the beam trajectory by minimizing these measured dipole mode signals with high resolution. Furthermore, because the frequencies of the dipole modes vary along the length of the structure, one can determine what portion of the structure is misaligned. This technique was tested during the recent wakefield measurements [15]. The analysis of the resolution was complicated by a very large kink in the structure due to an unfortunate construction error. Regardless, the measurements reproduced the measured alignment, including the kink. Further analysis is required but the initial results look extremely promising.

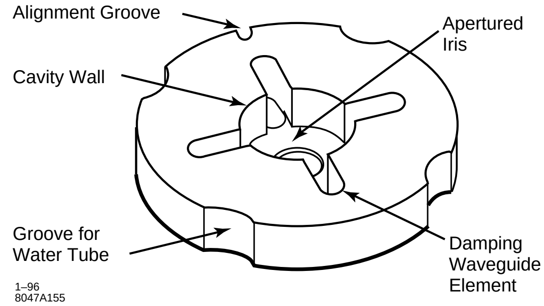

Figure 4: Schematic DDS structure; from Ref. [1].

3. *NLC Test Accelerator*

Finally, the NLC Test Accelerator (NLCTA) [16] is designed to both test all of the rf components required for the NLC and to verify the beam loading compensation technique that is needed to control the energy spread along the NLC bunch train. It consists of a 70 MeV X-band injector, a magnetic chicane, and six 1.8 m X-band (11.4 GHz) accelerator structures that are designed to suppress the long-range transverse wakefields. The X-band injector and the six main accelerator structures will be powered with four 50 MW X-band klystrons, whose peak power is compressed with SLED-II pulse compressors, producing a 50 MV/m acceleration gradient.

As of September 1996, the entire NLCTA beamline, except for the six accelerator structures, has been installed and is under vacuum. Beam from the gun has been accelerated to 60 MeV in the injector and transported to the final dump. Commissioning will begin this fall as the additional klystrons and accelerator structures are installed [17].

D. Session: Injectors (7/3)

The next working session was devoted to the positron and polarized electron injector systems. These include the sources, the damping rings, and the bunch compressors which are all required to prepare the beams for injection into the main X-band linacs. The talks were:

- Polarized Electron Source–D. Yeremian
- Positron Source–H. Tang
- Damping Rings–T. Raubenheimer
- Photoelectron Instabilities–J. Rogers
- Bunch Compression–F. Zimmermann
- Polarized Positrons–R. Brinkmann

Both the positron and polarized electron sources are based on the present SLC sources. The positrons are created by accelerating an electron beam to 3–6 GeV, directing it onto a target, and collecting positrons from the resulting electromagnetic shower. The NLC source would use a rotating target rather than a trolling target, like that used in the SLC, to reduce intensity fluctuations caused by the induced eddy currents. Unfortunately, the rotating target system requires a differential pumping scheme and vacuum tight seals along the target drive shaft to allow the drive motor to operate at atmosphere. A prototype of this system will be tested soon.

The polarized electron source uses a strained $GaAs$ photocathode to produce 80% polarized electrons and a sub-harmonic bunching system similar to that operating at the SLC. One potential problem which arises in the polarized electron source is the 'charge limit' that has been observed on the present polarized cathodes [18]. This limit occurs when free electrons accumulate on the cathode surface and prevent additional charge from being emitted. The presently observed limit on the cathodes that produce 80% polarization is about 1/3 the charge that is required in the 1 TeV cms NLC design. In contrast, the charge limit on the cathodes with 60% polarization substantially exceeds the 1 TeV NLC requirements. This arises because the relaxation time, the time it takes the excess charge to disperse, is much shorter in the cathodes with 60% polarization.

Since high polarization $> 80\%$ is required in the NLC, there are three solutions to the charge limitation that are being considered: (1) use of a modulated doping technique to keep the relaxation time low near the surface of the cathode similar to that of the 60% polarization cathodes, (2) improve the handling techniques, never exposing the cathodes to atmosphere, and (3), if these first two solutions are difficult or fail, increase the cathode area. This last solution is a brute force approach that will certainly work although it may lead to a small degradation in the beam emittance from the injector.

Next, there are three damping rings: a main ring for the electrons and both a pre-damping ring and a main ring for the positrons. The pre-damping ring has a straight-forward design with a large acceptance to capture the beams from the positron source and damp them to roughly the same emittance as that coming from the electron source. The main damping rings are very similar to the present generation of synchrotron radiation sources such as the Advanced Light Source at Berkeley. Details of the designs can be found in Ref. [1]. Many of the required concepts and tuning techniques will be tested at the ATF damping ring at KEK which is a prototype of a damping ring for a future linear collider. In addition, the rings will operate in a new parameter regime where some new instabilities, such as a single pass beam-ion instability [19] or a beam-photoelectron instability [20], may become important; these will also be studied at the ATF.

Finally, R. Brinkmann described the a method of generating polarized positrons that is being considered for TESLA design. The concept is, after the IP, to send the spent electron beam through roughly 100 meters of helical undulator. This will generate a beam of circularly polarized photons with energies of 10–20 MeV. The photon beam is then directed to a thin target where they create e^+/e^- pairs. By capturing the high energy positrons from the target, one can get beams with polarizations greater than 80%. It was suggested that this technique might be easier to implement in the NLC design than in TELSA.

This concept is presently being investigated. There is some reluctance to utilize the spent electron beam in this manner because it strongly couples the positron beam to the electrons. This is similar to the present method of positron production at the SLC where a secondary electron beam is generated at the source, damped in the damping rings, and accelerated behind the production electron beam. At an energy of 30 GeV, the scavenger beam is deflected onto the positron target. Unfortunately, there have been numerous difficulties at the SLC related to this method of positron production because it strongly couples the electron and positron sources. For example, the technique slows the fault recovery because one first has to recover the electrons and then recover the positrons. Similarly, jitter in the electron beam charge and energy is amplified and becomes worse in the positron beam. The situation in the NLC would be further complicated by the large energy changes, due to the beamstrahlung, that occur as the beams go in and out of collision; the beams are scanned through collision during every beam-beam deflection scan which is the primary diagnostic for tuning and monitoring the performance of the final focus.

For these reasons, most of our efforts are directed at using an alternate source of electrons combined with either a very high field short period undulator or backscattered radiation. Alternatively, it may be possible to utilize the electron beam before the IP and, in this way, avoid the variations induced during the beam-beam deflection scans.

E. Session: Gamma-Gamma IR (7/5)

One the NLC working group sessions was devoted to discussing the option of having gamma-gamma collisions at one of the two interaction regions (IR) of the NLC; this is the topic of Appendix B in the ZDR [1]. A γ-γ IR would extend and complement the physics capability of a linear collider. For example, it is uniquely suited for direct measurement of the partial decay width of a Higgs boson into two gamma quanta. Work on this option has been carried out by an informal collaboration of scientists from LBNL, LLNL, SLAC, Rochester U., U. of Tennessee, Hiroshima U., KEK, and BINP since March 1995. The session was organized as follows:

- Introduction to parameters–K.-J. Kim
- Compton scattering and IP–M. Xie
- Laser optical path–D. Klem
- Remarks on sweeping magnet–G. Bowden
- Backgrounds and detectors–A. Weidemann
- Electron final focus and wake fields–J. Irwin
- Solid state lasers–M. Perry
- E-144 experiment–K. Shmakov

The high energy gamma-photons for the γ-γ collision are produced via Compton back scattering of focused laser beams on the high energy electron beams of the linear collider. The high energy photon beams are then brought into collision with either the opposing photon or electron beams. The interaction region consists of two conversions points (CPs) where the Compton conversion occurs, and the interaction point (IP) where the collisions occur. The collider can be operated in the γ/e^- and e^-/e^- mode; provision has been left in the NLC design to operate with two polarized electron beams instead of positrons and polarized electrons.

The electron beam parameters up to the final focus system are taken to be the same as for the e^+/e^- collisions. However the final focus system is modified so that the beta functions in the horizontal and vertical directions are the same, about 0.5 mm. This modification is difficult and has not received extensive study like the primary e^+/e^- final focus, but, it leads to a geometric e^-/e^- luminosity of about twice that of the nominal e^+/e^- design. After conversion, the γ-γ luminosity, within 20% of the maximum energy, is about 10^{33} cm^{-2} s^{-1}.

The simulation of the γ-γ IR is more complicated than in the e^+/e^- case. At this time, three simulation codes are being developed and are in reasonable agreement with each other; these results are summarized in a paper by T. Takahshi, *et. al.* in these proceedings.

One of the difficulties with the γ-γ option arises from the close proximity of the CPs to the IP. A possible mirror arrangement to bring the laser pulses to the conversion point and to dispose of them in the tight space limited by the vertex chamber, the masking, and quadrupoles was presented. Details can be found in a contribution to these proceedings by D. Klem. Using a set of spherical mirrors and a quarter wave plate, a solution was found in which each laser pulse could be used twice.

It is desirable to introduce a magnet between the CP and the IP so that the e^- beam could avoid the IP. There is a preliminary design of this magnet based on pulsed coil technology by G. Silvestrov and V. Telnov. G. Bowden discussed the mechanical vibration of such a magnet in a strong solenoidal field.

The synchrotron radiation entering the IR from upstream may damage the mirrors, and the secondaries generated in the mirrors may present further background to the detector. Bauer and Weidemann found that the problems appear manageable with a reasonable model. They also studied the implication of not using a sweeping magnet when measuring the Higgs two photon decay width, and concluded that, in this case, the sweeping magnet is not essential.

Finally, the laser system requirements are extremely challenging. The laser needs a pulse energy of 1 joule in a pulse length of a few picoseconds with an average power of 10 to 20 kW and variable polarization. A solution based on a solid state laser was presented. High power diode lasers for pumping and lasing material that can handle high thermal loading are already under development as part of both military and civilian projects. Advanced solid state materials, either athermal glass hosts or new crystals specifically engineered for diode pumping, are also being developed. Based on these developments, the laser needed for a gamma-gamma collider can in principle be built out of 1 kW unit cells.

F. Session: Beam Delivery and IR (7/9)

The beam-delivery section must prepare and focus the beams to the tiny spots required at the IP. This includes extensive beam collimation to prevent backgrounds from flooding the detector, a short arc to provide both the 20 mrad crossing angle and the separation for the two IP's, the final focus system, and the detector and interaction region (IR). The talks given in the working group session on beam delivery system design were:

- Collimation–J. Irwin
- Final Focus Design–F. Zimmermann
- IP Design–G. Bowden
- IP Depolarization–D. Schroeder
- Detector Backgrounds–T. Markiewicz

Since collimation was found to be essential for the SLC, there has been considerable emphasis on its inclusion in the NLC. The original SLC design contained no provision for collimation, so that a system had to be designed to fit into an already existing beamline. Elements were added in stages: 1) clean-up collimators in the final focus region, 2) primary collimators at the end of the linac, and 3) secondary collimation at the beginning of the SLC arc. Recently studies of the SLC system have been undertaken to confirm important design concepts [21].

As for the SLC, the NLC collimation system has primary, secondary and clean-up collimation, with the clean-up collimation in the final focus system, and the primary and secondary collimation at the end of the linac before the 10 mrad arcs. The important issues in the collimation system are: collimator wakefields, estimates of tail populations, collimator survival, chromatic correction, aberrations, and transport system properties between collimators, especially from secondary collimators to final focus system collimators.

These issues are detailed in the ZDR. There is an outstanding theoretical question regarding the wakefields from tapered flat collimators. In addition, there appears to be a significant discrepancy between the measured wakefields in the SLC and those expected; see Section III.F.1. For these reasons, a test facility is being constructed at SLAC to study collimator wakefields [22].

The collimation system is followed by a 10 mrad arc and a beamline section referred to as the skew correction section. This latter section consists of a repetitive lattice providing for 4 skew quadrupoles at four orthogonal phase locations followed by four laser wire scanners to measure beamsizes at four orthogonal phase locations, with roughly equal beam sizes at all measurement sites. The skew correction system is able to verify the beam quality before entrance into the final focus system, and non-invasively monitor changes in upstream beam conditions. The intention of this section is to provide a pedigreed beam, stable against changes in waist, skew, or dispersion aberrations, for the final focus system.

The final focus system is patterned after the successful FFTB design. It consists of a horizontal chromatic correction section, then a beta exchange section followed by the vertical chromatic correction section, and finally, the final telescope and final doublet. The complete beam delivery system has been designed with sufficient length to accommodate a 750 GeV beam for the 1.5 TeV upgrade. As illustrated in Fig. 5, the upgrade path requires two horizontal displacements (+/- 25 cm maximum from the 500 GeV design) of beamline magnets.

The final focus final doublet elements are the most sensitive elements, both in strength and position, and the support and design of these elements is of particular importance. Furthermore, the final doublet must operate over a wide range of incoming beam energies. The current design consists of three elements, starting from the IP: a vertically focusing permanent magnet, a variable strength superconducting magnet (vertically focusing at higher energies), and a conventional iron horizontally focusing magnet. A $Sm\,Re\,Co$ (sumarium, rhenium, cobalt) permanent magnet has been chosen because of its high field strength, small size, and excellent field stability under changes of temperature. The superconducting element provides energy adjustability and can sit in the fringe field of the detector solenoid, while the conventional iron element is completely outside of the solenoid region. Because of the tight vibration tolerances, these elements will be linked to bedrock with a laser interferometer, generally referred to as an optical anchor. The support system will likely consist of both active and passive elements and experiments are underway to determine the best design [23]. Recently reported interferometric experiments have obtained a resolution of 1 pm for distance changes between two optical cubes separated by 1 m.

Extensive consideration has been given to the procedures and diagnostics necessary to tune the system. The final focus system contains an IP-image point in the beta-exchange section where the beam quality can be determined before entering the vertical chromatic correction and final telescope. Finally, the IP itself is tuned using the beam-beam deflection scans and extensive diagnostics in the dump line that is downstream of the IP. Furthermore, beam orbit is monitored at critical positions with 0.1 micrometer high resolution BPMs; see Section III.G.2.

Special attention must be given to dilutions (sources of luminosity loss) within a final focus system. Dilutions arise from: collimator and beam pipe wake fields, synchrotron radiation in bends and in the final doublet, changes in element strength, high- and low-order aberrations including bandwidth effects, aberration tuning time, beamline element movement, beam-based alignment tuning time, crab-cavity adjustment and phase difference jitter, incoming beam jitter, and bunch arrival time differences. In the NLC design, these dilutions amount to roughly a 30% loss in luminosity, a substantial fraction of which is due to the finite resolution of the diagnostics and the time required to tune the system. It is believed that an overly large dilution due to horizontal synchrotron radiation losses in final focus system bends can be reduced in the next design iteration. A contribution to these proceedings [24] describes work foreseen in improving the beam delivery system design for a conceptual design report (CDR).

The detector background studies [25] include determination of muon backgrounds from all collimators, synchrotron radiation from bends and quadrupoles, the e^+/e^- pairs and hadronic backgrounds from the IP, and determination of the luminosity spectrum caused by beamstrahlung, energy spread, and initial state radiation.

The insertion of magnetized toroids around the beam line (referred to as muon spoilers), similar to toroids that were inserted in the SLC final focus beamline, reduce the expected muons through the detector to less than one per bunch train. Masks after the last bending magnet in the final focus system protect the IR region from upstream synchrotron radiation. A large exit-quadrupole beam aperture, which is possible because of the 20 mrad crossing angle, allows synchrotron radiation produced in the entrance final doublet elements to pass out of the IR region.

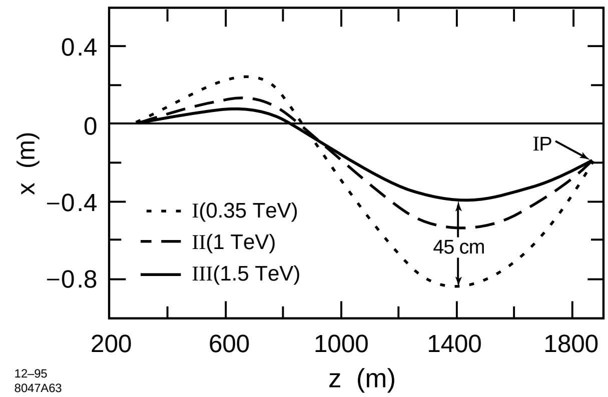

Figure 5: Alignment of the NLC final focus for different ranges of beam energy—case I extends from 350 GeV cms to 700 GeV cms, case II extends from 500 GeV cms to 1.2 TeV cms, and case III covers the range from 1 TeV cms to 1.5 TeV cms; from Ref. [1].

Tungsten masks inserted around the final doublet, protect the detector from the back-scatter produced by e^+/e^- pairs incident on the quadrupole faces. Finally the NLC parameters have been chosen so that beamstrahlung-induced smearing of the luminosity spectrum is not substantially worse than smearing due to initial-state radiation.

1. SLC Collimator Wakefields

During the 1994-1995 SLC run, it was noticed that optimal luminosity was found when the beams had large wakefield tails at the end of the linac. It was suggested that these wakefield dilutions were required to cancel some wakefield dilutions further downstream and this led to a study of the beam collimators [26].

Over the years, the SLC has installed a large number of collimators to reduce the backgrounds in the detector and this is also felt to be essential for a future linear collider. On inspection at the end of the 1994-95 run, it was found that many of these collimators were badly damaged. The collimators had been coated with a layer of gold to reduce the number of backscattered particles. Unfortunately the thermal contact between the gold layers and the body of the collimators was insufficient and the beam melted a very irregular channel through the gold [27]. This caused transverse wakefields that were roughly 25–50 times larger than expected. Most of these damaged collimators were replaced for the 1996 run. To prevent similar damage, the replacement collimator jaws were coated with either vanadium or TiN. Both of these coatings have resistivities that are roughly 10 times larger than that of the gold but it was thought that they would have much better survival.

Measurements made during the 1996 SLC run [27] showed that the geometric component of the transverse wakefield was in agreement with the results of MAFIA calculations but the resistive wall wakefield of both the vanadium-coated collimators and the undamaged gold-coated collimators was roughly a factor of four higher than expected. The reasons for this discrepancy are still not explained and a facility is being planned at SLAC to test different collimator geometries and materials to gain further understanding [22].

G. Session: Systems Issues (7/10)

The last session consisted of a collection of subjects that pertain to many machine sections. This includes a discussion of the beam polarization, the beam diagnostics, ground motion, machine protection systems, and conventional facilities:

- Polarization Transport–F. Zimmermann
- RF BPMs–C. Adolphsen
- Laser BSMs–M. Ross
- Conventional Facilities–C. Corvin
- Ground Motion–C. Adolphsen
- Machine Protection–M. Ross

Polarized beams are important for physics reach and potential, and are an integral part of the NLC design. The e^- source is a strained $GaAs$ photocathode producing over 80% polarization. It will be very similar to the SLC, though perhaps larger and with graded doping, to provide higher current. The polarization from the gun is longitudinal. By using solenoids and a bend prior to entering the damping ring, the polarization is rotated to the vertical direction. In the damping ring one must avoid spin-resonance conditions. Upon exiting the damping ring, the polarization is rotated back to the longitudinal direction using a bend sandwiched between a pair of solenoids. This latter system is designed to have a range sufficient to provide an arbitrary polarization direction and thereby compensate any polarization rotations that may arise downstream. Primary sources of depolarization occur in the bunch compressor, because of the large energy spreads there, and at the IP itself. At the IP, both the strong fields from the counter-moving bunch and scattering can cause depolarization. In session F, D. Schroeder showed that the depolarization due to scattering would be negligible. The dominant effect proves to be the rotation at the IP which results in a depolarization of about 1.4%.

Wire scanners, which determine beam sizes, have been crucial to the understanding, control and improvement of the SLC. But metalic or carbon wires have proved useless for small beam sizes and/or large beam intensities, because the small wires are destroyed by the beam. Laser wires can provide the same information, are not destroyed by intense beams, and have other useful features. Their intensity can be optimized to match beam conditions, or they may be operated at low intensity in a parasitic mode where, for example, IR detector backgrounds are important. Also they can be pulsed to look at a single bunch or a set of bunches within a bunch train. One laser can provide a beam for many wire scanners. A laser wire has been recently commissioned in the SLC; see subsection III.G.3 below.

1. *Ground Motion Measurements*

Because the NLC operates with low emittance beams which are focused to small spot sizes, there was concern that fast ground motion could cause beam jitter, leading to a significant loss in luminosity, while slower ground motion could prevent one from ever being able to properly align and tune the collider. Recent measurements at SLAC of the fast ground motion ($0.01\,\mathrm{Hz} < f < 100\,\mathrm{Hz}$), using very high resolution seismographs, have confirmed the amplitude of the ground motion but have shown that the large amplitude motion is highly correlated [28]. Such motion has relatively little impact on the design and, with the exception of the final doublets which may need additional stabilization, the motion would cause an insignificant ($< 2\%$) source of luminosity loss. Of course, the design must be engineered carefully to ensure that any additional ‘cultural’ noise is minimized. One example of such engineering is the design of the magnet supports at the Final Focus Test Beam (FFTB) at SLAC. Measurements show that the difference between the motion of the magnets and the nearby ground is less than 1 nm, even when all systems are powered and have cooling water [29].

At much lower frequencies, it has been suggested that the ground has a diffusive behaviour which can be described by the ATL rule [30]. This slow uncorrelated motion would cause the beam trajectory to drift with time requiring additional steering and tuning. Measurements of the motion of the magnets in the FFTB beamline at SLAC over a period of 180 hours found motions much smaller than previously reported [31]. This emphasizes the importance of site selection, although the FFTB tunnel could not be considered a quiet or ideal location. Finally, detailed simulations of the NLC linacs show that this slow ground motion should not significantly impede the operation of the collider [32].

2. *RF Beam Position Monitors*

The small IP spot size of the NLC leads to strict tolerances on beam stability resulting from beamline element motion. The beamline stability can be monitored by BPMs. The desired resolution for the FFTB BPM was 1 micrometer, and the standard stripline BPMs were successfully redesigned and fabricated to meet this requirement. For the NLC the required resolution is about a factor of 10 smaller, about $0.1\,\mu$m. Further improvement of the stripline is possible, but rf BPMs offer additional flexibility in that they can be compact, inserted in small spaces, and more readily protected from beam halos and spray. An experiment was recently undertaken on the FFTB [33] to determine the feasibility of this device. Three identical rf BPMs were mounted in succession at a beta minimum point in the final telescope. The first experimental results indicate a resolution for this first rf BPM device of about 40 nm.

3. *Sub-Micron Beam Diagnostics*

During the 1996 SLC/SLD run, additional diagnostic tools were commissioned including the “laser wire” [34] which was installed inside the SLD detector. The laser wire is created by focusing an intense 349 nm laser to narrow spot, about 380 nm with a Rayleigh length of $5\,\mu$m. The e^-/e^+ beam is then scanned across the laser and the beam size is inferred from the rate of Compton backscattering. During the end of the 1996 SLC run, the laser wire was commissioned and found to have a width of 400–500 nm, roughly 20% greater than design but still more than sufficient for SLC operation. In the NLC, such devices will be needed throughout the linacs and final focus to measure the beam emittance.

Another important diagnostic is a technique of inferring the individual beam sizes at the IP using both the beam-beam deflection scans, which just yield the convoluted size of the two beams, and the BPMs to measure the energy loss of the outgoing beams [35]. This technique will be very important at the NLC where, at present, the beam-beam deflection is the only diagnostic capable of resolving the beam sizes at the IP.

H. Related Talks in Other Sessions

In addition to the talks described above, several talks closely related to the subject of the NLC working group were given in other parallel working groups. For completeness we mention them here and give a brief introduction to their content.

- Outstanding Issues in Collimator Wakes—J. Irwin
- Margins in the 1.5 TeV NLC—R. Ruth
- A 5 TeV Linear Collider on the NLC Site—J. Irwin
- A 34 GHz rf system for a 5 TeV linear collider—P. Wilson

As mentioned before, an experiment is now being planned at the SLC to measure wakefields for tapered collimators with various tapers, geometries, and surface materials [22]. Though theory appears unambiguous for round tapers, there is an uncertainty for parallel plane tapers. Current theoretical estimates suggest a linear dependence on the width of the parallel planes of the taper [36]. Also, previous measurements at the SLC have indicated a resistive-wall wake four times larger than theory—see Section III.F.1. These wake fields can have a dramatic effect on the apertures that can be collimated and it is important to have experimental validation.

Although the ZDR design is based on an eventual upgrade to 1.5 TeV cms, neither the 1.5 TeV parameters nor the upgrade path were fully described in the published report. These parameters and a choice of upgrade paths were described in a talk by R. Ruth to the Strong Coupling Working Group. For parameters consult this talk [37]. The linac upgrade path will depend on experience in development of X-band klystrons. If the gradient can not be increased by 50% above the 1 TeV design, the linac may be extended by displacing the 180° arc of the second bunch compressor, sometimes referred to as the trombone. The injector complex remains unchanged. The "margins" referred to in the title of this talk are: i) intensity overhead in injectors, ii) gradient overhead in the rf structures, iii) potential for increased rf efficiency, iv) space already allocated for beam delivery systems (the ZDR contains a complete optics design for 1.5 TeV cms, v) conservative spot size dilutions in 1.0 TeV ZDR design, vi) magnets sized for 1.5 TeV cms energy, and vii) moderate beam-beam effects.

A scenario to construct a 5 TeV linear collider on the NLC site using 34 GHz rf was developed during the Snowmass workshop as a contribution to the 5.0 TeV Linear Collider Working Group [38]. P. Wilson, in a talk to that group, argued that 34 GHz is a modest extension of 11 GHz, in that many rf components can be scaled, and there is already experience at 30 GHz at CERN and LBNL/LLNL. The rf acceleration structures would have an unloaded gradient of 250 MV/m and a loaded gradient of 190 MV/m. Since the latter is more than 3 times the loaded gradient for the conservative 1.5 TeV cms parameter set, the linac would fit in the same tunnel as that upgrade.

The 5 TeV parameter set presented in this talk maintained a quadratic scaling of luminosity with energy, achieving $L = 2.5 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ with a wall plug power allowed to increase from 200 MW to 300 MW. The number of beamstrahlung photons per electron is constrained to be about 1.5. The energy spread in the beam rises to about 30%, but 25% of the luminosity spectrum is still in the incident energy peak. The single bunch charge is smaller, at 2.5×10^9, and the vertical spot size is decreased to $0.3\,\mathrm{nm}$. This vertical spot size is felt to be achievable because of the correlations that have been determined in ground motion, and the high precision demonstrated for optical anchors and rf BPMs [33]. The emittances required to produce the desired spots are roughly a factor of three smaller than those in the present NLC design and could probably be obtained with minor modifications to the damping ring systems.

The modifications anticipated for the components of each subsystem were described. Briefly: the injector is easier than NLC; the damping ring would fit in the same vault, with perhaps weaker bends and stronger focusing; the bunch compression factor is the same; the linac dynamics needs study, but the wakefield dilutions appear to be sufficiently small since N is down by factor of 5; the collimation length is sufficient if one goes to an "active" protection scheme; the big bend appears to be of sufficient length if combined function magnets are used for the bend; the final focus length is sufficient if L^* is reduced to 0.67 m; the IR crossing angle is still much larger than the kink instability threshold; and the IP will have a larger upsilon parameter implying many more soft pairs exiting along the solenoid axis. In summary, the potential for this upgrade on the NLC site appears promising. Of course, at this stage an enormous amount of work remains before such a design could be considered seriously, the most important being the development of the high frequency klystron.

IV. SUMMARY

The design of a Next Linear Collider (NLC) was presented to the1996 DPF/DPB Snowmass meeting in plenary and working group sessions. This paper has tersely described the talks presented to the Next Linear Collider (NLC) Working Group. Further details of the content of these talks can be found in the "Zeroth-Order Design Report for the Next Linear Collider" (ZDR), the text of which is included in the CDROM version of these proceedings. The ZDR is a complete design study for an NLC with engineering support in crucial areas and is the culmination of more than a decade of effort.

The ZDR design leans strongly on the experience at the SLC, and many margins have been included, so as to arrive at a conservative design. Recent experience at the SLC has also been briefly described in this summary, such as experience with beam-based feedback systems, laser wire development, collimation system measurements, and efforts to control emittance and jitter.

Additionally, recent and current R&D that is relevant to the NLC has been outlined. This includes a successful start to the NLC Test Accelerator (NLCTA) commissioning, an X-band PPM klystron performing as predicted, promising X-band damped detuned (DDS) structure wake field and alignment measurements, a successful rf BPM test, and measurements showing a very high degree of correlation in ground motion.

Near-term planned R&D has also been noted. These include collimator wakefield measurements, optical anchor development, and active and passive support experiments for final doublets.

Finally, talks given in parallel working groups at Snowmass were briefly described. These included 1.5 TeV parameters and upgrade scenario and parameters for a 5 TeV collider on the NLC site.

V. ACKNOWLEDGEMENTS

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