13

Multiple Bunch Issues

Contents

13.1 Introduction

Obtaining the full design luminosity in the NLC requires that a train of about 90 bunches be accelerated on each machine pulse while preserving the emittance and stability of the beam. Operating a linear collider in multibunch mode has an impact on the entire machine. Many of the multibunch issues have already been discussed at some length in previous chapters. In this chapter we give a general overview of multibunch issues, and we will point out the most crucial multibunch problems, *i.e.*, those problems that have significantly affected the overall machine design and required the most effort to solve. One important example is control of multibunch emittance growth in the main linacs; this strongly impacts the design of the accelerator structures. We summarize the proposed solutions to the problems posed by multibunch operation.

Multibunch issues exist in the SLC, since there are three bunches (the e^+ and e^- colliding bunches, and the e^- bunch used to produce the positron bunch for the next machine pulse) accelerated down the SLC linac on each machine pulse, and there are two bunches circulating in the damping rings during normal operation. However, this is a small number of bunches compared to the 90 bunches per pulse in the NLC design, and the bunches are closer together in the NLC (1.4-ns apart, as opposed to about 60 ns in the SLC linac). Multibunch issues also exist in long-pulse operation of the linac at SLAC. Multibunch beam break-up was encountered when the SLAC linac was turned on, and detuning of the dipole modes was used to help control it. Also, it was necessary to control the energy spread of the long-pulse beam.

Furthermore, the NLC main linacs are at higher frequency (11.424 GHz) compared to 2.856 GHz in the SLC linac. We have chosen to go to this higher (X-band) frequency in the main linacs of the NLC, because of the savings in power and the higher accelerating gradient obtainable. Even if we had not chosen X-band, control of multibunch beam break-up would still be an issue, but it is nevertheless much more severe at X-band. The X-band accelerator structure is smaller and closer to the beam, resulting in much stronger wakefields in the main linacs of the NLC, unless additional measures are taken to reduce these wakefields. This has been the major force driving the design of new types of accelerator structures for the NLC, namely the Gaussian-detuned structure and the damped detuned structure (DDS) discussed in Chapters 7 and 8. Once the design and fabrication techniques are developed for the main linac accelerator structures, it is also convenient to apply them to the design of the accelerator structures for the other lower-frequency linacs (S-band and L-band) that are part of the NLC design.

Regulation of the bunch charges is a second very important issue, because of its impact on multibunch energy control, particularly in the main linacs. As was discussed in Sections 7.4.5 and 8.2.8, the method chosen for multibunch energy control is to fill the accelerator structure with a field profile that simulates that of the beam-loaded steady-state in the structure. The ideal profile depends on the charge in the bunches. If the charge of each of the bunches in a train jitters by as little as a percent from pulse to pulse, this compensation of the beam loading in the main linac is upset. This places tight tolerances on the sources and may also necessitate collimation and feedforward systems to control the charge profile over the length of each train.

A third major multibunch issue is polarization of the electron beam. We wish to obtain a train of 90 bunches of electrons with at least 80% polarization. A gun with a strained GaAs cathode capable of achieving this is under development. Although such a gun is somewhat beyond what has been achieved at present, it is believed to be well within reach on the timescale needed for NLC.

These three problems—control of long-range transverse wakefields, regulation of average current from pulse to pulse, and obtaining high polarization from the e^- source—are the multibunch-related beam dynamics issues which we have identified as most critical. In addition, the development of new instrumentation, in particular new diagnostics such as structure beam position monitors, will be critical to the success of multibunch operation in the NLC. In the next section, we will turn to a survey of these and other multibunch issues starting from the beginning and proceeding to the end of the machine.

13.2 Major Impacts of Multibunching

Multibunch issues are in general closely tied to other issues in the NLC design. For example, interbunch and intrabunch dynamics cannot be considered completely independently of each other. As noted above, the transverse dipole wake left in a linac by the bunches at the front of a train exerts transverse forces on subsequent bunches, and thus directly affects the growth of the projected multibunch emittance at the end of the linac. However, other effects come into play in determining the final emittance. The longitudinal wake left by a given bunch affects the energy and energy spread of subsequent bunches in the train. The transverse single bunch emittance can be blown up by the combination of intrabunch energy spread and transverse kicks, since particles of different energies will filament onto different trajectories unless the dispersion is zero. On the other hand, single-bunch filamentation can damp the motion of the bunch centroid and thus reduce its effectiveness as a driver of the transverse wake. For these and other reasons, single-bunch and multibunch trajectory correction and emittance control are strongly interrelated and must often be considered together.

Because of the many inter-relationships between multibunch issues and other issues, and because it was logical to organize the bulk of this design report according to geographical regions, many of the studies dealing with multibunch issues have been discussed at length in other chapters. However, in this section, for the convenience of the reader who wants an overview of multibunch effects in the NLC, we summarize the major findings of these studies and refer the reader to sections of the design report containing further details. Since some features of the design having to do with multibunching rely heavily at this time on simulations, we summarize briefly some of the simulation methods used in obtaining the results presented here and in other chapters. We will describe the solutions found to the multibunch problems and indicate where we expect further work will be concentrated as the detailed implementation of these solutions evolves.

The final goal of the NLC is to obtain two opposing trains of bunches with suitable properties for doing experiments at the interaction point (IP). The nth bunch in each train must meet its counterpart in the other train sufficiently close to the nominal IP. Thus the transverse offsets in x and y from the nominal incoming orbits must be small compared to the respective transverse bunch sizes. The two bunches meeting at the IP at a given time should pass through each other with maximum overlap. The centroid energy deviation and the energy spread of each bunch should each be no more than a few tenths of a percent. Perhaps the most difficult tolerance is that the projected multibunch emittances in each train are to be kept close to the desired transverse single-bunch emittances of $\gamma\epsilon_x = 4 \times 10^{-6}$ m-radand $\gamma\epsilon_y \approx 10^{-7}$ m-rad. Obtaining these properties at the IP requires careful control of various parameters in the other regions of the machine. In addition to tolerances on machine components, there will be a need for feedback, feedforward, special instrumentation, and beam-based correction techniques to operate in multibunch mode.

13.2.1 Electron and positron sources

There are several important multibunch issues that must be considered in designing the e^- and e^+ sources (for details on the electron and positron sources, see Chapters 2 and 3). One is bunch-to-bunch charge uniformity within a given train. Another is train-to-train total charge uniformity. The electron gun must be capable of producing a train of 90 bunches that are only 1.4-ns apart, and the population of each bunch needs to be up to 2.8×10^{10} (NLC-IIc with 20% overhead). Furthermore, the polarization of the electron beam should be at least 80%.

A laser modulator using rf-driven resonant Pockels cells is used to turn the approximately 100-ns DC laser pulse into a train of nearly square pulses with period 1.4 ns and width 1 ns. It will also be possible to obtain trains with bunch-to-bunch spacing of 2.8 or 5.6 ns, rather than the nominal 1.4 ns.

As was noted in the previous section, the train-to-train charge jitter tolerance is very tight because of its effect on multibunch beam-loading and thus on keeping the overall energy spread of each train within tolerance. A conventional DC gun (with a strained GaAs cathode to produce polarized electrons) has been chosen for the baseline NLC design, but an rf gun, which could inject flat, smaller-emittance beams, is under consideration as a possible upgrade. One major reason (though not the only one—survival of the cathode is probably the most important reason) for choosing the DC gun over the rf gun is the difficulty of achieving the laser intensity stability tolerance in the higher-bandwidth laser that would be required in the rf gun, in order to obtain bunch trains with the required charge intensity stability. The tolerance of $< 0.5\%$ rms laser intensity stability is not easy to obtain even for the baseline NLC polarized electron source. However, it is expected that it can be obtained by improvements to a feedforward system of the type used in the oscillator for the existing SLAC polarized gun.

A intensity-limiting aperture that scrapes away about 17% of the beam before it enters the injector bunching section will be used to reduce the intensity jitter below the very small required tolerance of about 0.5%. This tolerance is what is required to achieve the desired beam loading compensation in the X-band main linacs.

Beam-loading compensation in the various accelerator structures that are part of the e^- and e^+ sources is another significant multibunch issue in this region. Two basic methods of beam-loading compensation were considered. One possible energy compensation scheme (Δt scheme) is to turn the beam on before the structure has completely filled. The additional filling of the structure while the beam is passing through compensates the linear part of the beam loading. The slope of the SLEDded rf pulse can also be adjusted to compensate the quadratic "droop" in energy over the train.

Another possible scheme (Δf scheme) utilizes additional cavities driven at $\pm\Delta f$ away from the nominal central frequency. The resulting variation in phase from bunch to bunch can be used to cancel some of the variation in beam loading.

The Δf scheme has the advantage of being relatively easy to tune (by changing the amplitude of the fields in the Δf accelerator sections). However, the Δt scheme was selected for most of the source linacs because the Δf scheme gives a single bunch energy spread that is too large. A combination of the Δt and Δf schemes will be used in the e^+ capture linac, the e^- capture section, and the bunch compressor S-band prelinac.

Long-range transverse wakefields must be kept small enough to prevent multibunch beam blow-up in the source linacs. Satisfactory control of the multibunch emittance was achieved by using Gaussian-detuned structures for the positron booster linac (see Section 3.6.1) and the electron injector linac (see Section 2.4.5).

Multibunching also presents additional demands on the positron target (see Section 3.4), which must be capable of withstanding the peak and average power in the e^- beam impinging upon it. The design will be based on that of the positron target of SLC, with improvements to allow higher beam power and better intensity stability.

13.2.2 Damping rings

The damping rings of the NLC are larger and more complicated to design than those of the SLC. Each SLC damping ring contains at most two bunches at a time, while the NLC damping rings each contain four trains of about 90 bunches each; the beam loading in the NLC damping rings is much heavier than in SLC. Also, since the bunches are not distributed uniformly about the circumference (there is a gap between trains to allow time for the kickers to inject and extract a train from the ring on each machine pulse), there is a variation in the synchronous phase along each bunch train.

The required emittances of the bunches extracted from the damping rings are $\gamma\epsilon_x = 3 \times 10^{-6}$ m-radand $\gamma\epsilon_y = 3 \times 10^{-8}$ m-rad. The number of electrons per bunch in the damping ring of NLC-I is about 1×10^{10}, and goes up to about 1.3×10^{10} for NLC-II and NLC-III. The maximum charge per bunch in the most extreme design variations under consideration is about 1.5×10^{10}, which for four 90-bunch trains in a ring of circumference $\sim$220 m, leads to a maximum average current of about 1.2 A.

The two main damping rings (one for electrons and one for positrons) each damp four 90-bunch trains at a time, with one train being extracted and one train immediately injected in its place on each machine pulse. The reason for simultaneously injecting and extracting a train from each ring on each machine pulse is to minimize transients in the rf cavities that would be produced by changes in the average ring current. In addition to the main damping ring, there is a pre-damping ring for the positrons which damps three 90-bunch trains at a time.

Although the trains are separated by many buckets, they can still affect each other through long-range wakefields, unless these wakefields are quite heavily damped. Injection and extraction of bunch trains must be done with minimal disturbance of other trains in the ring. There are gaps of about 60 ns between trains, so the kicker rise and fall time must be comfortably less than this, and ringing of the kicker pulse must be minimized. The separation of 60 ns between trains is about equal to the rise and fall times of the kickers existing at present in the SLC. A flattop of about 130 ns is needed to accommodate the 90-bunch train. None of the requirements on the kickers are especially difficult, although the positron pre-damping ring kicker will need to kick more strongly due to the relatively large aperture.

Beam loading and synchronous phases

As noted above, the beam loading seen by the damping ring rf system will vary in time, due to gaps between trains, and the synchronous phases of the bunches in a train are different due to the different amount of beam loading seen by each bunch. Unless the bunch-to-bunch variation in beam loading is compensated within the ring (*e.g.,* by a special higher-harmonic cavity in addition to the regular rf cavities), it must be compensated further downstream, presumably in the bunch compressors. The variation in phases along the bunch train is very nearly linear if no phase compensation is performed in the damping ring. The present bunch compressor design is able to perform compensation for this phase variation (see Section 5.4.7). However, two methods of compensating the phases while still in the damping ring are also being considered, in an effort to simplify the requirements on the bunch compressors. One possibility is to vary the generator voltage as a function of time; this requires that the klystron have sufficient power and bandwidth and is currently under study. Another possibility is to use passive, lower-frequency harmonic cavities to partially compensate the phase variation (see Section 4.4.4); the main disadvantage of this scheme is that the pattern of synchronous phases versus bunch number becomes very nonlinear, and it would be difficult to remove the residual phase variation downstream, if this were necessary.

The variation in synchronous phases due to changes in charge of a bunch train has also been studied in simulations (see Section 4.4.4). Even for a change in average charge of 5%, the resulting phase variations could be easily compensated by a damping ring phase feedback system.

Coupled-bunch Instabilities

In addition to the effect on the synchronous phases, the longitudinal wakefields (both the fundamental and higher-order modes in the cavities) produce longitudinal coupled bunch instabilities. Preliminary rf cavity design and coupled-bunch simulations (see Section 4.4.5) indicate that it should be possible to damp the longitudinal higher-order modes (HOMs) to keep the threshold for longitudinal coupled-bunch instabilities comfortably below the radiation damping rate.

The transverse wakefields, due to both the rf cavities and the resistive wall of the vacuum chamber, can produce transverse coupled-bunch instabilities in the damping rings. Assuming that the cavity HOMs are damped to have Qs less than 300$\sim$500, then the resistive-wall impedance dominates. A bunch-by-bunch feedback system will be needed to damp any modes that are not suppressed by radiation damping, coherent head-tail damping, or Landau damping. Even if there is sufficient damping present that all the normal modes of oscillation are stable, interference between modes can produce transient blow-up of the beam. This transient behavior can be important in damping rings since the storage times are short. In addition, for sufficiently strong wakes and long trains of bunches, the transient could be large enough to cause beam loss at injection. A bunch-by-bunch feedback system along the lines of that designed for the PEP-II B-factory at SLAC will be used to suppress these effects.

Several coupled-bunch simulation programs have been used in calculating longitudinal and transverse coupled-bunch instabilities in the damping rings. Some are based on a semi-analytic, normal-modes approach, in which the bunches need not be symmetrically placed on the circumference. Interference between the modes can produce transient blow-up of the beam even if all these modes are long-term stable. Given the coherent frequencies and normal modes, the Laplace transform can be used to obtain the motion of the bunches, taking the initial conditions into account [Thompson 1991a]. Alternatively one may use a computer tracking method to obtain the offset of each bunch as a function of time. This is straightforward and computationally efficient provided that the number of bunches is not too large and the wakefields do not persist for too many turns. Several tracking codes are in use for NLC damping ring calculations [Thompson 1991b, Thompson 1991c, Byrd 1993].

A new code to investigate coupled-bunch mode-coupling was also developed [Berg 1995]; however, this turns out not to be a significant effect in the damping rings (see Chapter 4).

Ions and other effects

A possible multibunch issue in the damping rings (and also in the main linacs) stems from the fact that the bunches in a train are coupled not only by long-range wakefields but also by the fields due to ions in the beam line [Raubenheimer 1995]. If there is significant collisional ionization and if ions remain trapped between the passage of successive bunches, then bunch-to-bunch coupling can be mediated by the ions (similar to the way that surrounding structures mediate transverse wakefields). Ions can also produce a focusing variation between bunches, which may lead to filamentation of the trajectories of different bunches. Control of these effects may put stringent requirements on the vacuum in the damping rings and linacs, according to simulations of the beam dynamics with ions present. It should be noted that our concerns about ions are based mainly on simulation results, and experimental studies of the effects of ions on multibunch operation are needed.

Calculations predict that ions produced by the beam scattering with residual gas in the electron damping ring vacuum chamber can produce a fast transverse instability within a bunch train (see Section 4.4.6). Simulations and analytical estimates suggest that a vacuum pressure of 10^{-9} Torr or better may be required to control this instability. If this is not adequate, additional gaps in the bunch train may be used to clear the ions, but obviously this is a somewhat inelegant solution. Other solutions, such as "detuning" the ion frequencies or lowering the equilibrium emittance may be possible. More work, including experimental tests, is still needed.

A different multibunch instability may occur in the positron damping ring (see Section 4.4.7). This occurs when an electron cloud is produced in the vacuum chamber from photoelectrons and their collisions with the walls to produce secondary electrons. This electron cloud can couple to the transverse motion of the bunches and lead to an instability. There is some evidence for such an instability in the KEK Photon Factory and in CESR. Theoretical predictions of the coupled-bunch instability growth rates [Ohmi 1995] agree approximately with what has been observed. Present estimates for the NLC positron main damping ring give a characteristic growth time scale of about 200 ns. If this estimate is correct, it should be taken into account in the feedback systems being designed to combat coupled-bunch instabilities. Estimates also need to be made for this possible instability in the pre-damping ring.

Experience obtained in high-current, multibunch storage rings currently in operation or under construction is of course important to the design of the NLC damping rings. The electron-positron instability will be studied in the APS as it begins operation with positrons and in the PEP-II Low Energy Ring (LER). The ion-electron instability will be studied at the ALS, the PEP-II LER, and the KEK Accelerator Test Facility.

13.2.3 Bunch compressors

The main multibunch issue in the bunch compressor is compensation of the multibunch beam loading. Multibunch beam break-up must also be controlled in the various linacs that are part of the compressor design; these are discussed in the next section.

Compensation of beam loading

As noted above, the bunch compressors may need to perform the compensation of phase offsets produced by differential bunch-to-bunch beam loading in the damping rings. In addition, there is beam loading in the bunch compressors themselves, and the resulting bunch-to-bunch energy differences must be kept sufficiently small. It is possible to compensate the multibunch beam loading in the bunch compressor by using two rf systems having slightly different frequencies; this was assumed in the initial design studies and satisfactory results were obtained (see Section 5.4.7). However this "Δf" scheme of beam loading compensation has the disadvantage of being somewhat nonlocal, since the beam energy spread grows between the off-frequency compensation sections. As in the injectors, a combination of this "Δf" method and the "Δt" (early injection) method will be used to obtain even better results.

13.2.4 Control of multibunch beam break-up in low-frequency linacs

The transverse emittance of the multibunch trains must be controlled in the low-frequency linacs, throughout the front end of the NLC (in the sources and compressor regions). The multibunch beam break-up can be controlled by using Gaussian-detuned or damped detuned structures, as in the main linac. The pre-linacs are at lower frequency than the main linacs, so the wakefields are not as strong. However the beam is at lower energy, which makes it more susceptible to wakefield kicks. Simulations show that methods similar to those studied for the main linacs, namely the use of detuned or damped detuned accelerator structures, will control the break-up.

In some of the S-band (2.856 GHz) linacs, detuning alone may not be quite sufficient to control multibunch beam break-up. Thus an S-band damped detuned structure (DDS) is being designed for use in all the S-band linacs. It will have a total detuning frequency spread of about 6%. The modes will be damped to Qs of about 1000.

In the L-band (1.428-GHz) positron linac, Gaussian detuning with a 10% total spread is sufficient to control multibunch beam break-up (see Section 3.6.1).

13.2.5 Main linacs

As was noted at the beginning of this chapter, one of the most important issues in the design of the main-linac accelerator structures is control of the transverse wakefield. The achievement of an X-band accelerator structure that will accomplish this has been one of the major efforts in the design of the NLC. This damped detuned structure (DDS) has been discussed at greater length in Chapters 7 and 8. The structures are detuned by varying the individual cell dimensions in such a way that there is an approximately gaussian (truncated) distribution of frequencies of the fundamental dipole mode. The dipole modes in the structures are damped via ports leading into manifolds running parallel to the structures. Construction of the first DDS is nearing completion, and DDSs will be part of the complement of accelerator structures for the NLCTA.

Calculation and measurement of long-range wakefields

Calculation of the long range wakefields in the new accelerator structure designs being proposed for the NLC has been the focus of much effort. Over the past several years, increasingly sophisticated models of the wakefields in increasingly complex accelerator structures have been developed.

A fairly good representation of the long range wake was obtained in initial simple models of detuned structures, by regarding the structure as a collection of uncoupled oscillators corresponding to the synchronous modes of the periodic structures that one could construct from each of the cells in the structure. However, a more complete and accurate treatment includes the effects of the small couplings between the oscillators. A discussion of two such models [Bane 1993], a single-passband model and a model which takes into account the mixing of the two lowest dipole passbands, was given in Section 7.4.2. These are equivalent circuit models that give the best representation we have so far obtained for the wakefields in the detuned accelerator structure without damping (except for copper losses, which are taken into account in the models via perturbation theory).

These coupled, equivalent circuit models can be further extended to include the interaction between the accelerator structure and the damping manifolds in a damped detuned structure (DDS). The first such models treated the manifolds as coaxial lines, ignoring the periodicity introduced by the openings from the cells into the manifold [Kroll 1994]. Only a single passband was included in most of this work. A more complete model has now been developed that takes into account the mixing of the two lowest dipole passbands, as well as the periodicity of the manifold [Jones 1996].

A crucial element in the design of the NLC main linacs is an accelerator structure in which the transverse wakefields are greatly reduced below those that would occur in a conventional disk-loaded structure. Experimental verification of the performance of such structures is therefore essential. The Accelerator Structure Setup (ASSET) facility in the SLC has been used to measure the wakefields in a Gaussian detuned X-band structure (see Section 8.2.10). Damped detuned structures will also be tested in ASSET as they become available during the coming months.

Beam dynamics simulations in main linacs

The results of beam dynamics simulations in the main linacs, including multibunch effects, have been discussed extensively in Chapter 8, and we will not repeat that discussion here. In this section we will briefly describe the simulation tools used to obtain those results. These simulations incorporate the calculated long range wakefields, to calculate the multibunch beam blow-up to be expected, the bunch train injection tolerances, structure misalignment tolerances, and the effects of various correction schemes. As was noted in Chapters 7 and 8, it has been found that the structure internal misalignment tolerances are very tight, due to the effect on multibunch emittance growth. Also, control of the multibunch energy spread imposes tight tolerances on the variation of train current from pulse to pulse.

Several codes have been used to study multibunch beam break-up in the main linac and in the other linacs in the NLC. These include: LINACBBU [Thompson 1990], MBLINAC [Thompson 1991d], and LTRACK [Bane 1987]. A program that can handle combined single- and multibunch emittance control and trajectory correction was developed [Kubo 1995] and used to make the initial studies on these issues.

The main simulation tool used so far to study multibunch energy compensation in the main linacs is the program MBENERGY [Thompson, 1993]. In this simulation, one may take account of input rf pulse shaping and timing, the dispersion of the rf pulse as it transits the structure, the longitudinal distribution of charge within the bunches, the long range wake (LRW) including both the fundamental (accelerating) mode and higher order modes (HOMs), the short range wake (SRW), and phasing of the bunches with respect to the crests of the rf.

Ion effects may be important not only in the damping rings, but also in the main linacs [Raubenheimer 1992]; the basis for this expectation is almost entirely calculations and simulations. Results of these simulations are described in Section 7.4.6 and suggest that the vacuum tolerances in the main linac will be very tight, although achievable.

A new linac code, the Linear Accelerator Research (LIAR) code has recently been developed [Assmann 1996] to do the many detailed tolerance studies that will be needed over the coming months. This code is designed to flexibly accommodate new features, and is now beginning to be used for multibunch tolerance studies. It will be possible with this code to do more complete simulations that incorporate multibunch effects along with other effects to get a more accurate assessment of the many tolerances required to preserve the emittance of the multibunch beam.

13.2.6 Final focus, interaction region, and beam dumps

There are not any multibunch problems in the final focus region that are as difficult as those that must be faced in other parts of the machine. However, multibunching does have an impact on the design of the final focus, interaction region and beam dumps.

“Parasitic encounters”, *i.e.*, kicks on bunches in the incoming train due to bunches in the outgoing train, must be kept sufficiently small. This is the main reason for the introduction of a crossing angle at the interaction point. The crossing angle would entail a significant loss of luminosity since the bunches are long and thin, if the bunches were allowed to be non-parallel when they collide.

To avoid this loss in luminosity, special rf cavities are used to rotate the bunches away from their direction of travel just before they collide, so that the longitudinal axes of opposing bunches will be parallel when they pass through each other. It has been checked that these “crab cavities” do not produce unacceptable kicks due to bunch-to-bunch wakefields (see Section 11.7.2).

Another component affected by multibunch operation is the beam dump, which must be able to absorb the large amount of power in the multibunch beam. The requirements on the beam dumps are very stringent, due to the large amount of total charge, small emittance, and high energy of the beam. A dump using water as the main absorbing material has been designed (see Section 11.A) to handle the electromagnetic shower from the multibunch beam of up to 750 GeV.

13.3 Machine Protection and Operations

The long bunch trains at design emittance are capable of seriously damaging certain components (including the main linac accelerator structure) on a single pulse. Thus, start-up and recovery procedures will be strongly influenced by multi-bunch issues (see Chapter 16 and Section 7.8). The control system must be capable of handling a variety of bunch patterns and modes of operation, and the stability (*e.g.*, temperature of certain components) of the machine must be preserved as one cycles through the various modes of operation.

Even a single bunch at the design emittance may be capable of damaging the machine. It is anticipated that sacrificial titanium spoilers and collimators would be placed so as to prevent damage to crucial machine components. Such spoilers would be able to withstand a single bunch of nominal emittance and intensity, but not a full nominal-emittance bunch train. One must begin with single bunches having relatively large emittance and work up from there as the machine is tuned.

Note also that once operation with the full bunch train has been established at nominal emittance, the repetition rate must be kept high enough that the beam trajectory cannot change too quickly between pulses. Changes must be monitored and the beam must be shut off or have its emittance blown up before the trajectory wanders far enough to damage accelerator structures or other critical components.

Controlling the emittance, energy, energy spread, and trajectories of all the bunches in a train of 90 bunches is not trivial, even in simulations. There are a number of aspects of multibunch running that will require detailed online simulation and control. One such example is fine-tuning the input rf pulse in linac accelerator sections, as part of a feedback system to improve the multibunch energy compensation. Obviously this is only one of many examples—the control system software will be required to do detailed online simulations related to emittance control, trajectory correction, feedback, etc throughout the machine.

13.4 Instrumentation Specifications

Meeting the required specifications at the IP also imposes certain requirements on instrumentation of various parts of the machine. These include: BPMs that can resolve bunches (or a few bunches) within a train, multibunch emittance measurement stations, multibunch energy measurement stations, and fast kickers (bandwidth sufficient to correct alignment of trains). Design of such instrumentation is underway, and discussions are given in Sections 7.3.4 and 7.10. and in Chapter 15.

The tolerances on the alignment of the structures with respect to the beam are very tight due to the need to control the transverse multibunch wake; the tolerance is only a few microns on some scales. Thus, one of the most important issues is instrumentation of the accelerator structure to measure its offsets with respect to the beam, via detection and analysis of the beam-induced dipole wakefield. This method of measuring the alignment of the structures by looking at signals derived from the dipole wake is discussed in Section 7.10.3. and experimental tests of the method are being carried out in the SLC.

13.5 Experimental tests related to multibunch issues

A crucial element in the design of the NLC main linacs is an accelerator structure in which the transverse wakefields are greatly reduced below those that would occur in a conventional disk-loaded structure. Experimental verification of the performance of such structures is therefore essential. The Accelerator Structure Setup (ASSET) facility in the SLC has been used to measure the wakefields in a Gaussian detuned X-band structure (see Section 8.2.10). Damped detuned structures will also be tested in ASSET when they become available.

We of course wish to verify the multibunch beam dynamics simulation results as soon as possible, and so a number of multibunch beam dynamics experiments will be done in NLCTA (see Section 8.2.9), including detailed tests of the multibunch energy compensation scheme and measurements of multibunch beam breakup. Studies of the latter will be greatly facilitated by an upgraded injector for NLCTA that produces a bunch train with a charge per bunch and bunch spacing similar to that in the NLC designs.

Experience obtained in high-current, multibunch storage rings currently in operation or under construction is of course important to the design of the NLC damping rings. Bunch-by-bunch feedback systems similar to that needed to suppress transverse coupled bunch instabilities in the NLC damping rings are being built for the PEP-II B-factory and other high-current storage rings.

13.6 Summary and Conclusions

The proposed NLC design relies heavily on multibunching to achieve the design luminosity. Some of the resulting tolerances are very tight—two important examples are the alignment of the X-band accelerator structures in the main linacs, and variations in the bunch populations from pulse to pulse. However, we believe that they are achievable by the methods we have proposed.

Experience at the SLC provides considerable guidance in pursuing solutions to the problems posed by multibunch operation. While in some ways SLC experience is limited by the fact that the number of bunches per pulse is small compared to that in NLC, there is much that can be done in SLC that is directly relevant, particularly in the characterization of the long-range wakefields and in the development of instrumentation. Experience with high-current storage rings, such as PEP-II, which have average currents even greater than that proposed for the NLC damping rings will also be valuable, especially in refining the design of feedback systems for the NLC damping rings. As has already been emphasized, one of the most crucial elements of the NLC design is an accelerator structure for the X-band main linacs that adequately controls the transverse wakefields. Here we must rely on simulations to guide the design and ongoing experimental tests to verify that the structures work as planned. Tests in the SLC will also be important to the development of instrumentation, such as structure beam position monitors that use measurements of the induced dipole wakefields to infer the alignment of the structures with respect to the beam.

Our goal so far has been to find satisfactory conceptual solutions to the problems we will encounter in multibunch operation at the NLC. Considerable detailed design and engineering remains to be done, for example, on the various feedback systems that will be required to control the multibunch emittance and energy spread throughout the machine, as well as the associated instrumentation. Another major focus will be to continue the detailed engineering of the most practical ways to manufacture the large number of accelerator structures for the X-band linacs.

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