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Quadrupole Centering and Beam Steering in the Next Linear Collider Main Linacs[1]

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Accurate measurement of quadrupole-to-BPM center offsets and use of this information in an auto-steering algorithm are two essential components of emittance preservation in the Next Linear Collider main linac. We present the results of an analytic/simulation study of possible statistical and systematic limitations on the measurement of quad-BPM center offsets. These results are incorporated in a simulation study of a potential main linac steering algorithm which relies entirely on remote-controlled magnet and RF-structure positioning devices to minimize emittance dilution. The effects of ground motion during the alignment process are also considered.

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Abstract

Accurate measurement of quadrupole-to-BPM center offsets and use of this information in an auto-steering algorithm are two essential components of emittance preservation in the Next Linear Collider main linac. We present the results of an analytic/simulation study of possible statistical and systematic limitations on the measurement of quad-BPM center offsets. These results are incorporated in a simulation study of a potential main linac steering algorithm which relies entirely on remote-controlled magnet and RF-structure positioning devices to minimize emittance dilution. The effects of ground motion during the alignment process are also considered.

1 INTRODUCTION

In order to achieve its luminosity goals, the Next Linear Collider (NLC) must collide trains of bunches with extremely small emittances: typically, $\gamma\epsilon_{x,y} = 4.5 \times 0.085$ mm.mrad at the IP [1]. This in turn implies that the NLC injector complex must produce a train of bunches with similarly small emittances on every machine pulse, and these emittances must be preserved throughout the sequence of bunch compression, acceleration, collimation, and demagnification which occur downstream of the damping rings.

The X-band main linacs of the NLC each contain approximately 750 quadrupoles and 5,000 RF accelerator structures in a length of 10 km per linac. The principal challenge to emittance preservation in the main linacs is misalignment of the structures and quadrupoles: misaligned structures dilute emittance through their strong short-range wakefields, while misaligned quadrupoles dilute emittance by generating dispersion. In high-performance linacs the latter effect is enhanced by the use of a large head-tail energy spread to achieve damping of the single-bunch beam break-up instability [2]. In order to achieve the desired emittances, the RMS beam offset from the magnetic centers of the quads and the electrical centers of the RF structures must be on the order of microns. Such tight tolerances can only be achieved through beam-based techniques.

The NLC main linacs have been designed to permit high-precision alignment of all components to the beam axis:

- Each quadrupole contains an x/y BPM captured in its bore, with a resolution of 1 μm at the design bunch charge (10^{10})
- Each RF structure contains a higher-order-mode (HOM) manifold; measurement of the amplitude and phase of the HOM signal at a given frequency permits the beam position to be determined at any point in the structure with 5 μm resolution, and present plans call for 3 readouts per structure (upstream/middle/downstream)
- Each quadrupole is mounted on a remote-controlled translation stage with x/y/roll degrees of freedom, and 50 nm stepsize
- Each 3-structure RF girder is mounted on a remote controlled translation stage with x/y/roll degrees of freedom at one end and x/y at the other (providing pitch and yaw), with 300 nm stepsize.

The intention of the design is that the translation stages will be used to continually correct the positions of the quads and RF structure girders during normal operation. In order to do this, it is necessary to determine the relationship between the BPM readings and the beam-to-element offset and then to use the BPM readings in an algorithm to determine the optimal motions of the elements to minimize the emittance.

2 BPM OFFSETS

The RF structure BPM uses direct measurement of the parameter of interest (the amplitude of the dipole wakefield) to determine the beam position in the structure: the amplitude gives the absolute distance from the center and the phase determines the sign of the offset (alternately the zero-point in the structure can be determined by measuring the zero-crossing of the HOM phase signal). Since the structure position measurement uses a single signal and directly measures the quantity of interest, it is expected that the offset of the BPM will be a small fraction of its resolution, and measurements of several damped-detuned structures (DDS) support this expectation [3].

Quadrupole BPM offsets are more problematic because they typically use the difference of two large signals to measure the position, which requires extreme stability of each signal's calibration. Even after calibration, the BPM's zero position may not correspond to the zero-field axis of the associated quadrupole: recent installations have achieved an RMS quad-BPM offset of 100–200 μm [4]. For the NLC such performance is quite unacceptable: Figure 1 shows the resulting emittance when the NLC main linac is steered using BPMs with various RMS quad-BPM offsets, using a robust steering algorithm reported elsewhere [5]. In the simulations for Figure 1, all relevant parameters other than quad-BPM offset were perfect (element strengths, BPM resolutions, etc.). Figure 1 indicates that a

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quad-BPM offset substantially worse than 2 μm RMS is not acceptable.

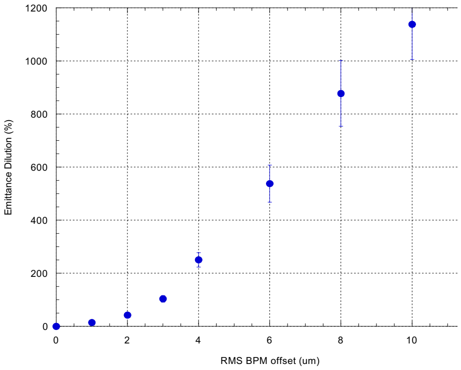

Figure 1: Emittance dilution as a function of the RMS quad-BPM offset, due to residual dispersion after steering the NLC linac.

Quad-BPM offsets smaller than 100 μm are typically achieved by quad shunting: since an offset beam in a quad receives a dipole kick, varying the quadrupole strength varies the dipole kick, resulting in position changes which can be measured on downstream BPMs. The NLC linacs have excellent optical functions for performing such a measurement, excellent BPM resolution, and an immense number of BPMs to measure the variation in the dipole kick. Consequently, a very modest variation in quadrupole strength is sufficient to measure the quad-BPM offset with sub-micrometer precision: typically 2% of the nominal strength suffices [6].

The use of quadrupole shunting is limited by a systematic effect: if the magnetic center of the quadrupole moves in the xy plane when the magnet's strength is varied, this produces a varying dipole kick which is basically indistinguishable from the static offset which is to be measured. The fit error introduced by this motion is inversely proportional to the fractional strength change of the quad: if the quad is reduced in strength by 10% and the center moves 1 μm in the process, the fitting algorithm will converge on a position which is 10 μm from the actual zero-field axis of the magnet at its design strength. Simulation studies of model NLC electromagnets have indicated that permeability mismatches in the poles of solid-core quads could introduce fitting errors ranging from 2 μm to 12 μm, depending on the nominal quad strength [6].

In the present NLC design, the quad-BPM offset measurement is complicated by the possible use of hybrid iron-permanent magnets in the first few sectors of the main linac. The present design uses a set of rare-earth cobalt magnets wrapped around shaped iron pole-pieces to generate the main field, and a small set of movable permanent magnets to tune the field strength [7]. When such a magnet's strength is varied via the tuner elements, the change in the dipole kick measures only the effect of the tuner elements; any dipole kick due to mismatches in the main PM elements is static and thus not measured.

The problem of BPM offset measurements for the hybrid main linac quads can be addressed in any of several ways:

- The NLC linacs can make aggressive use of closed orbit bumps to globally correct dispersion and/or wakefield dilutions. This approach was used routinely in the SLC, and typically reduced the emittance dilution in the linac by a factor of 10 [8]. Such bumps require periodic retuning (at a frequency of several times per day), and complicate the task of the linac feedback and steering algorithms.
- The linacs could make use of changes in the beam energy to permit measurement of the quad offsets without changing quad strengths, via *dispersion-free steering* (DFS) [9]. This technique would introduce a systematic effect which is similar to the one being addressed: RF deflections which vary as the energy is varied. This can be addressed by reducing the beam energy by 20% at a given point in the linac, and then measuring the deflections downstream of that point – the RF deflections become a change in the initial conditions which can be extracted in fitting.
- The acclerator complex can be designed to permit either electrons or positrons to be injected into either linac on a pulse-by-pulse basis, which would permit *two-beam dispersion-free steering* (TBDFS), a technique which proved tremendously useful in the later stages of the SLC [10]. This would require a central injector complex, redesigned second-stage bunch compressors, and changes to the beam delivery system.
- The large head-tail energy spread can be eliminated, which will reduce the severity of the emittance dilution by roughly a factor of 3-4. If this is done it will be necessary to add RF quadrupoles to the linac to provide the damping of emittance dilution presently generated by the correlated energy spread. There is some concern that RF quadrupoles will also have difficult alignment tolerances, but one might imagine that RFQ's with HOM damping manifolds might be as simple to align as RF accelerator structures.

3 LINAC STEERING

Once the quad-BPM offsets are determined, it becomes possible to steer the main linac, via the magnet and girder translation stages, to optimize the emittance. In the limit where the quad-BPM offsets are measured with micron-scale precision and accuracy, this can be done via an algorithm which minimizes the RMS BPM readings. In addition to minimizing the BPM readings, the algorithm must constrain the long-wavelength misalignment of the linac, in order to avoid movers "ranging out;" it should avoid introducing unwanted sources of dilution (such as DC steering correctors); and it should operate as quickly as possible. The algorithm we use to satisfy these criteria is the "french curve" algorithm reported previously [5]. We assume that the hardware capabilities are as described above, and that the RMS of the quad-BPM offsets is 2 μm. For these conditions, the algorithm typically reduces the emittance dilution to 40% in simulations performed using the program LIAR [11].

It is important to note that the algorithm performance is not degraded when the magnet translation stage step size is increased by a factor of 6 (to 300 nm), and the emittance dilution increases from 40% to 60% when the RF structure BPM resolution is degraded by a factor of 2 (to 10 μm). This implies that, for the present parameters, the emittance dilution is dominated by residual dispersion in the linac, which in turn is caused by the quad-BPM offsets – the offsets presently limit the performance of the steering algorithm.

The studies above were performed for a static accelerator, in which only the remote-controlled translation stages generate motion. In reality the NLC will be subject to continual ground motion in several forms, which will constantly drive the linacs out of alignment. We simulated the effect of continual ground motion during the alignment process using the "ATL" model of Shiltsev *et al* [12]. In the simulation we assumed an ATL coefficient of $5 \times 10^{-7}\ \mu\mathrm{m}^2/\mathrm{m}/\mathrm{sec}$, the "canonical ATL" value for NLC, which is low but achievable based on measurements at various sites. We further assumed that the linac is aligned piecewise from upstream to downstream in a continuous cycle, and that the cycle requires 60 minutes. For this set of parameters, the normalized vertical emittance at the end of the linac reaches an equilibrium value of 0.064 mm.mrad – a dilution of 110%. The emittance dilution from 60 minutes of ATL motion without linac steering is 240%; thus, the alignment algorithm reduces the dilution by roughly a factor of 2.

There are several paths which can be taken to reduce the emittance dilution to acceptable values. First, the time permitted to complete one cycle could be reduced to 30 minutes. A second potential improvement would be the implementation of steering feedbacks similar to those used at SLC, which can reduce the amplitude of slow orbit drifts substantially [13, 14]. A third approach is to align several segments of the linac simultaneously, while using feedbacks to keep the launch conditions constant for each segment. Finally, it is worth noting that the ATL model of ground motion may not be the most accurate. It has been noted that for short times the ATL model predicts a relative motion of two objects which is greater than their absolute motion due to typical wave spectra in the ground [15]. Preliminary studies of linac steering which use a more realistic ground motion model have begun.

4 CONCLUSIONS

The problem of emittance dilution in the main linacs of the NLC can be reduced, to good approximation, to the problem of beam centering in the magnets and RF structures of the linac. The main linacs are in principle designed to permit continual remote-controlled steering of the beams to the center of every element with high precision, but in order to accomplish this it is necessary to determine the relationship between the readings on the BPMs (especially the magnet BPMs) and the actual beam-element offset.

For electromagnets, the quad-BPM offset can be measured by shunting the magnet, and the desired statistical resolution can easily be achieved. The technique is limited by a systematic error related to motion of the magnetic center as a function of quad strength, and additionally the present design of main linac quads makes extensive use of permanent magnets which are not amenable to quad shunting measurements of this type. Several techniques exist which may permit the quad-BPM offsets to be accurately measured despite these difficulties.

The quad-BPM offsets are the main source of emittance dilution when a robust steering algorithm is used on a static linac. When ground motion corresponding to the ATL model is included in the simulations, the resulting emittance dilution is unacceptably large due to the long time required to align the linac in a monotonic, upstream-to-downstream fashion. The emittance dilution may be overestimated due to limitations in the ATL model at short time intervals, and can potentially be addressed by a more clever alignment algorithm and the addition of steering feedbacks. Work on these areas is continuing.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

[1] http://www-project.slac.stanford.edu/lc/local/AccelPhysics /Parameters/nlc_param.htm

[2] V.E. Balakin, A.V. Novokhatsky, V.P. Smirnov, Proceedings *HEACC-88*, 119 (1988).

[3] C. Adolphsen *et al*, Proceedings *PAC-99* 3477 (1999)

[4] S. Smith, P. Tenenbaum, S.H. Williams, NIM **A431** 9 (1998).

[5] P. Tenenbaum, Proceedings *PAC-99* 3459 (1999).

[6] P. Tenenbaum, T.O. Raubenheimer, PRST-AB **3** 052801 (2000).

[7] C. Adolphsen, private communication.

[8] J.T. Seeman, F.-J. Decker, I. Hsu, Proceedings *HEACC-92* 879 (1992).

[9] T.O. Raubenheimer, R.D. Ruth, NIM **A302** 191 (1991).

[10] F.-J. Decker *et al*, Proceedings *EPAC-98* 454 (1998).

[11] R. Assmann *et al*, Proceedings *LINAC-96* 464 (1996).

[12] V. Shiltsev, Proceedings *IWAA-95* 352 (1995).

[13] L. Hendrickson *et al*, Proceedings *PAC-95* 2389 (1995).

[14] L. Hendrickson, these proceedings.

[15] A. Seryi, these proceedings.