Summary of Session 7: Tuning, Feedback and Diagnostics

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Abstract

We summarise the main issues and conclusions of the session devoted to tuning, feedback and diagnostics.

1 INTRODUCTION

The need for feedback systems at today's advanced accelerators is self-evident. In order to maintain small emittances in storage rings, high luminosity at colliders, and stable beams in linac applications such as free-electron laser (FEL) X-ray sources, a large number of machine parameters must be maintained within narrow tolerances on a scale and frequency that are beyond the level of human operator intervention. Effects requiring feedback compensation include:

- environmental changes such as temperature, pressure or hydrostatic drifts;
- seismic ground motions;
- cultural 'noise' such as facilities-induced vibrations due to eg. water pumps or electrical feedthrough, and human activities such as motor traffic.

Compared with operator intervention, the deployment of automated feedback systems can allow a fast response where needed, speedier recovery from downtime and improved efficiency; operators can thereby be freed to study more complex or subtle problems. Feedback systems can be integrated with automated or semi-automated tuning procedures, and both tuning and feedback rely on accurate state information about the accelerator that must be provided by advanced diagnostic tools. Ideally the feedback systems and tuning strategies should therefore be designed congruently with the diagnostic tools and facilities.

2 LINEAR COLLIDERS

2.1 The SLAC Linear Collider

An enormous amount was learned during the decade of operation of the SLAC Linear Collider (SLC) [1]. The main message is: if it can be measured, feed back on it! Feedback was barely considered in the first design studies, but by the end of SLC operations feedback systems had been deployed across the entire machine, in every major subsystem: the electron gun, booster, damping rings, linac, arcs and the interaction region (IR). The requirement to deliver high integrated luminosity to the SLD experiment provided a huge impetus for the development of tuning tools, most of which had to be 'retro-fitted' into the existing controls architecture. In developing these tools SLC was effectively used as a test-bench for 'experiments' with feedback, including controlled 'ping' tests as well as study of sample and control rates, gain factors, corrector speeds and measurement/model errors.

A powerful suite of software tools has been developed for Linear Collider simulations [2, 3]. These are based on MATLAB for the feedback routines and LIAR/DIMAD for beam transport and wakefield effects. Ground-motion models have been devised based on real data and 'ATL' models [2].

Linac feedback: One of the major feedback implementations at SLC was the cascaded adaptive feedback system employed in the linac. Each feedback station sent its measured state in terms of beam position and angle to the next station downstream; the transfer matrices between stations were calculated adaptively from pulse-to-pulse. However, in controlled experiments in which a disturbance was purposely introduced, it was found that overshoot and ringing built up over a timescale of tens of machine pulses (frequency 120 Hz). For the Next Linear Collider (NLC) a 'many-to-one' cascade is proposed, whereby each feedback station is in communication with a number of others, and feeds information to a distributed set of correctors. Simulations show that such a scheme can damp out oscillations within a few pulses [1].

One problem found at SLC was that requiring the feedback to fit BPM measurements did not always result in the minimum r.m.s. position. This can arise due to BPM noise and offsets, as well as modelling errors and numerical stability of the found solution. The current strategy for the NLC is to fit the corrector settings that minimise the r.m.s. BPM readings; this appears to give stable and improved solutions [1, 3].

Another issue is that correction of local beam centroid position does not correct local beam tilt (induced, for example, by wakefields): the tail of the beam effectively sees the 'wrong' correction. The employment of a distributed set of BPMs for each feedback station can allow the tilt to be determined and corrected.

Luminosity optimisation: At SLC five 'knobs' were used routinely for luminosity tuning: the x and y waist positions, the x and y dispersions, and the x-y coupling. Initially each knob was scanned so as to minimise the beam size as deduced from beam-beam deflection scans. However, with the availability of fast luminosity monitors, a better method was found to be to 'dither' each knob in turn so as to maximise locally the luminosity, which is the 'bottom line' requirement. This technique should find wide applicability at future linear colliders.

2.2 Future Linear Colliders

Introduction: At NLC it is planned to employ:

- Pulse-to-pulse feedback for stabilising the orbit and energy in the injector, linac and beam delivery system (BDS), maintaining collisions [3], correcting the beam angle at the interaction point (IP), and specialised systems (source laser intensity, polarisation etc.).
- Dither feedbacks, operating over several pulses, for IP tuning and linac emittance bumps [1], as well as determining the setpoint for the beam-beam deflection curve (see below).
- 'Slow' feedback, operating on the timescale of many pulses (seconds → minutes) is envisaged for steering the linac orbit and the damping rings.
- An intra-train feedback system that must operate on a timescale significantly less than the 270ns-long bunchtrain; this will be used to remove residual train-to-train offsets, as well as to straighten out relative bunch position offsets within the train.

A flexible control system with full connectivity and high bandwidth will be required to implement and integrate these systems in a coherent fashion.

Pulse-to-pulse feedback: Important applications include preservation of small beams at the IP and maintainance of collisions [3]. The latter is clearly beneficial also for the operation of the intra-train feedback as it will help to reduce the dynamic range requirement of that system. Extensive algorithm development and simulations have been performed for the NLC/JLC, CLIC and TESLA machine designs [3], taking into account the plant noise model, the actuator response model and sensor noise, and using three ground-motion models of varying severity [2]. The deflection curve, and therefore optimal setpoint, change with ground motion and will almost certainly have to be measured and updated adaptively in real life (see below). Although, in the case of the most benign ground-motion model, the pulse-to-pulse feedback can minimise luminosity loss to below 5% of nominal for all three machines, for the worst-case model considered the loss of luminosity is severe: roughly 45% (NLC), 60% (TESLA) and 75% (CLIC).

Intra-train feedback: An intra-train beam position correction feedback system is being considered for use in the interaction regions of all the future linear collider designs. It will be required to remove residual electron-positron relative beam displacements, caused by ground motion of the final-focus quadrupoles, that are not ameliorated by active stabilisation or corrected by the pulse-to-pulse feedback. The basic idea is that the relative position offset of early bunches in the train is amplified by the beam-beam deflection so as to provide a detectable position signal in a BPM a few metres downstream of the IP. A suitable correction signal can then be calculated, and applied via an upstream fast kicker, so as to move the later bunches into nominal relative alignment.

The demands on the intra-train feedback are somewhat different for TESLA than for JLC/NLC/CLIC. In the TESLA case there 2820 bunches, each separated by 337ns: the long train containing thousands of bunches provides a relatively easy environment and a digital feedback processor scheme can be considered. In the JLC/NLC case there are only 192 bunches, each separated by 1.4 or 2.8ns, and in the CLIC case there are 154 bunches separated by 0.7ns. Such short trains containing only O(100) bunches demands, with today's technology, an analogue electronics approach, and puts stringent requirements on the latency of the BPMs, electronics and amplifier-kicker components.

Results of the simulation of the performance of such a system were presented [4] for NLC, TESLA and CLIC. The simulations incorporate:

- beam transport from the exit of the damping rings, through the linac and beam delivery system to the IP,
- the beam-beam interaction dynamics,
- the components of the feedback hardware system, including risetimes and delays, modelled using Simulink,
- the production of both electromagnetic and hadronic backgrounds through the beam-beam interaction, as well as knock-on backgrounds caused by the presence of the feedback components, modelled within the overall interaction region layout using GEANT.

In all cases a significant fraction of the nominal luminosity can be recovered [4]. However, the choice of gain is an interesting issue: too low and the feedback corrects slowly, too high and the correction oscillates; in both cases a significant luminosity is lost. Furthermore, the beam-beam deflection curve (angular kick vs. e^+e^- position offset) is highly non-linear for offsets larger than a few σ_y, and it changes with other beam parameters such as charge, bunch-length, σ_x etc. In practice the gain might be chosen adaptively by feed-forward from the pulse-to-pulse feedback system, and the deflection curve will probably need to be measured regularly.

These issues have been discussed in contributions to this workshop [5, 6]. It has been shown by simulation (for NLC) [5] that a beam-beam deflection scan within a single train is possible; this even opens the possibility of intra-train dither feedback! The non-linearity of the deflection curve can be handled by an appropriate non-linear amplifier or 'linearizer' to improve the transfer function between measured relative beam offset and corrective kick [6]; this allows a convergence of the correction in fewer latency periods, and thereby reduces the luminosity loss. A prototype linearizer with the desired characteristics has been built.

An entertaining complication for this feedback system is provided by the 'banana effect', whereby coherent linac wakefield effects can induce a non-gaussian beam profile at the IP. For such banana-shaped beams the optimal luminosity does not always occur for zero offset between the two beam centroids, which would be the result of perfect intra-train feedback. If a fast luminosity measurement were available it would be possible to employ a dither feedback (see above) so as to optimise the luminosity after the beams have been nominally centred. This seems feasible for TESLA, with a resulting recovery in luminosity at the 20% of nominal level [4], i.e. almost the full amount lost due to the banana effect. However, this looks very challenging for NLC/JLC and CLIC unless a running luminosity measurement can be provided to the feedback circuit on a 10-nanosecond timescale.

3 DAMPING RINGS AND LIGHT SOURCES

Common issues: The ATF at KEK has been a key experiment in developing understanding of the tuning required to produce nanometer-sized beams, in particular for linear colliders, and has been a test-bed not just for damping rings but also for technologies to be employed in IP stabilisation. Compared to 3rd-generation light sources, which have similar goals of trying to achieve small coupling and emittance, and maintaining a high degree of stability for the beams extracted from them (whether electron or photon), the following issues are of particular and common concern:

- *Lattice tuning*. The ultimate resolution of stabilisation methods is limited in part by the knowledge of and ability to correct the linear machine model. In particular, the diagnosis and quantification of quadrupole gradient errors (using LOCO in particular [7]), and the associated correction of β-beat to a few % have been important [8, 9]. Frequency Map Analysis has been a popular tool to confirm machine-model agreement [7].

- *Control of the residual vertical dispersion and betatron coupling*. Automated procedures for correction using model response matrices have been very successful, achieving overall coupling values less than 0.1%, and a residual vertical dispersion limited to around 5 mm by a variety of instrumental effects, notably EBPM resolutions and instrumental errors when measuring such small vertical emittances [9], as well as the ability to align magnetic centres to better than $20\mu m$ [10]

- *Closed-orbit control*. R.m.s. corrected orbit deviations $< 1\ mm$ are now routinely obtained using EBPMs with short-term resolutions of a few μm, typically using global correction and single-value decomposition methods [7, 9].

- *Slow and fast orbit feedback* has been adopted by most light sources to obtain control of the relative beam position at important source points already at the sub-μm level and at frequencies up to 1 kHz, and global SVD correction is generally the method of choice [7], if technology and signal pathlengths permit; local correction is used to some extent but can suffer from significant cross-talk when very small corrections are needed [7]. It should be noted that at some light sources (for instance at the ALS), that physical EBPM drifts occur to the extent that slow correction hampers rather than helps stability.

Ground motion and environmental factors: In addition to the above, movement of the accelerator elements via movements of their supports or changes in temperature has long been problematic, and yet still relatively poorly understood. A two-dimensional model of ATL has been one recent way to model ground motion both in damping rings and light sources [7], and these simulations have informed specifications of the girder alignment and of foundation and ground slab requirements, although there is much debate as to their validity and so their usefulness. The ATF is similar to modern light sources in that their girder mounting and adjustment requirements are basically the same, and experience of installed alignment systems, for instance at the Swiss Light Source have been invaluable [8]. Good temperature control of the accelerator ring tunnel to 0.5 K or better is already known to strongly aid stability, but lately more attention has been paid to the influence that external environmental changes in temperature, wind and precipitation can have on the accelerator building, and of how to decouple this from the accelerator elements [8]; for instance, new buildings are taking great care to decouple the outer shell from the slab on which the accelerator lies [11].

High-current operation: A particular issue for damping rings is understanding emittance increase with beam current. Intrabeam scattering is expected to increase beam emittance significantly, and extensive theoretical development and experiments have been performed, in particular at the Advanced Light Source, which have greatly improved confidence that the theory is believable [9]. Remaining uncertainties concern the measurement of bunch volume, to wit:

- Bunch length variation with current is not well measured, but is in line with expectations.

- Transverse emittance measurement is performed via extraction line scanners, which are limited by how well the spurious vertical dispersion in the line can be corrected.

- The effect of impedance on emittance growth with current.

Diagnostic instrumentation: Instrumentation development has of course gone hand in hand with increasing requirements from both damping rings and light sources, with position and emittance monitoring in particular being common issues for both types of accelerator. Both types of accelerator are also being used to improve diagnostic instrumentation to be used at linear collider IPs [12], notably the laser wire scanner and intra-train feedback systems [4].

Current issues for diagnostics can be summarised as follows:

- *EBPM resolution* has to steadily improve over time, and systematic effects are being investigated [10]. New designs such as the cavity BPM [10] show promise in achieving resolutions very much less than $1\mu m$, but significant development remains to be done. With more traditional button-type EBPMs resolutions of $100nm$ can be obtained at higher currents [11], and are limited by mechanical stability.

- *Wire scanners* are limited by being able to physically make a small wire, and by knowledge of the beam optical properties at the measurement points [9]. Laser-wire scanners are of course under intense scrutiny, and have been dealt with in a mini-workshop [12].

- *Transverse cavities* are presently experiencing a renaissance, and could be a good method for measuring bunch lengths in transfer lines [10], although SR-based streak cameras or other non-destructive methods must be used in rings [11].

- *Innovative optical methods* are being used to measure transverse beam profiles, notably the development of OTR and ODR screens and the use of SR interferometric methods. These instruments presently rival wire scanners in resolution [9].

- *Electro-optic methods* could in principle give a very high resolution bunch length measurement, but at present these devices are in the experimental stage and not reliable instruments [10]

4 REFERENCES

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