BEAM DIAGNOSTICS CHALLENGES FOR BEAM DYNAMICS STUDIES

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Abstract

This seminar reviews the performance and limitations of present beam instrumentation systems in relation to beam dynamics studies, and gives an overview of the main requirements from the accelerator physics community for new or improved measurements that need an R&D effort on beam diagnostics.

INTRODUCTION

Beam dynamics studies are an essential element in the smooth running of all accelerators. Such efforts are important for the commissioning of a machine, modifying initial design parameters to increase performance, and to understand the issues and challenges that arise during accelerator exploitation [1].

Routine measurements during standard operation, such as adjustment of the orbit and optimisation of the tune, coupling and chromaticity are not addressed in this seminar, although some of the diagnostic devices used for such measurements will be covered. The emphasis is instead on specific measurements during machine set-up, such as the measurement and correction of the machine optics in both synchrotrons and linacs or transport lines. Also discussed are more advanced measurements for the understanding of impedance and space charge effects, detecting instabilities, and the identification of sources driving the diffusion of particles to high oscillation amplitudes.

MEASURING THE MACHINE OPTICS FUNCTIONS IN SYNCHROTRONS

The measurement and correction of optics parameters has been an area of intensive study since the advent of strong focusing synchrotron accelerators, where perturbations from field imperfections and misalignments became a concern. Traditionally, colliders have led the development of methods for optics control based on turn-by-turn centroid position data, while lepton storage rings have focused on closed-orbit-response techniques [2]. Both of these methods rely heavily on the use of the beam position system of the accelerator, and are now often driving its requirements.

Turn-by-turn Techniques

In 1983 a major achievement took place in the CERN-ISR, where the Beam Position Monitors (BPMs) were used successively around the collider to measure the relative amplitude and phase advance of the β-function by observing the amplitude and phase of induced betatron oscillations [3]. This was the first time that machine optics had successfully been reconstructed from individual BPM data, at that time using a BPM system that was entirely based on analogue technology.

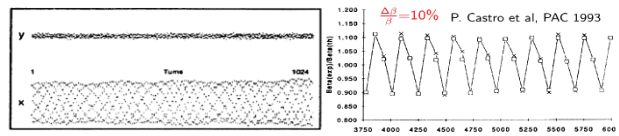

Figure 1: LEP β-beating example. Left: turn-by-turn BPM data. Right: Δβ/β for a section of the machine.

The first optics measurements using digital, turn-by-turn BPM data were performed at CERN-LEP (Fig. 1) [4]. The β-function at each BPM location was extracted from the phase advance between 3 BPMs, assuming a good knowledge of the focusing elements in between (Eq. 1).

$$\beta^{BPM1}_{measured} = \beta^{BPM1}_{model}\left(\frac{\{cot\varphi_{12}-cot\varphi_{13}\}_{measured}}{\{cot\varphi_{12}-cot\varphi_{13}\}_{model}}\right) \quad (1)$$

This method, known as “β from phase”, was also used in CESR (Cornell, USA) in 2000 to minimize the β-beating, the difference between the measured β and the design β (Δβ/β), with an rms of only 2% [5]. This is still one of the best optics correction achieved in a lepton collider.

One of the limitation of this method is its reliance on good quality BPM data. Identifying BPMs giving poor readings or BPMs with excessive noise was therefore very important. A major step forward in achieving a more robust analysis was taken at SLAC in 1999, where singular value decomposition (SVD) techniques were used to isolate faulty BPMs and identify noise components affecting the oscillation data [6].

The 3 BPM method developed at LEP has recently been extended for the LHC to take into account any number of BPMs [7], resulting in a much better overall resolution in the measurement of the β-functions.

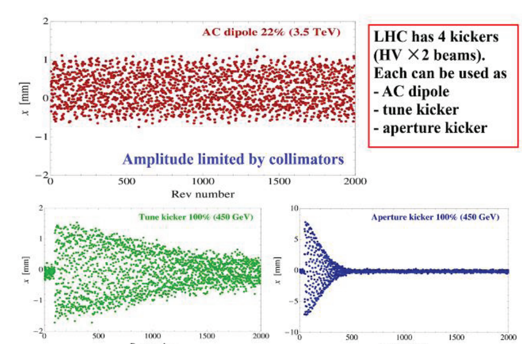

Figure 2: Examples of excitation for optics measurements in the LHC. Top: AC-dipole excitation. Bottom: Examples of single kicks at injection energy.

In order to initiate a sufficient large centroid motion to be visible on a turn-by-turn basis with the BPM system, the beams typically need to be kicked to relatively high

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amplitude using a fast magnetic or electro-magnetic kicker. The disadvantage of this technique is that the oscillations are often quickly damped, which lead to significant emittance blow-up in hadron machines. The former is a big drawback for optics measurement as the amount of useful BPM data available is then highly limited. An alternative excitation technique uses an "AC Dipole" excitation, originally developed at RHIC (BNL, USA) for crossing polarisation resonances [8]. Here, a forced oscillation is put onto the beam near the betatron tune, but still outside the tune spread. If performed adiabatically, this leads to a steady, high amplitude oscillation without emittance blow-up, which is excellent for turn-by-turn optics measurements (Fig. 2).

Closed-Orbit-Response Techniques

Measurement of optics functions in synchrotron light sources is dominated by the use of closed orbit response techniques. This involves exciting individual dipole corrector magnets, measuring the orbit and using analysis routines such as LOCO (Linear Optics from Closed Orbits [9]) to extract the lattice optics functions. Using such techniques SOLEIL (France) and DIAMOND (UK) have been able to measure and correct the β-beating to an rms value of less than 0.4%.

Closed orbit response measurements typically take longer that turn-by-turn measurements, as each of the hundreds of corrector magnets in the ring needs to be excited individually and the corresponding orbit measured. Nevertheless, recent advances in automating these techniques now allow such a measurement to be carried out in under a minute in some synchrotron light sources. This is unfortunately not scaleable to the LHC, where the slow response of the thousand or so superconducting corrector magnets would imply very long measurement times.

With recently improved BPM electronics now providing high resolution turn-by-turn data, turn-by-turn optics measurement techniques are starting to compete with orbit response measurements. A campaign is currently ongoing at several 3rd generation light sources to compare the two methods. Nevertheless, the turn-by-turn techniques do not yet have the sensitivity to measure β-beating at below the 1% level.

Beam Instrumentation Challenges for Improved Optics Measurements in Synchrotrons

There are three main challenges to improving our understanding of the machine optics functions using turn-by-turn techniques.

Firstly, the excitation needs to be reduced in order to limit emittance growth in hadron machines and avoid non-linearities due to strong sextupoles in next generation synchrotron light sources making use of multi-bend achromats. This implies improving the turn-by-turn resolution of the BPM systems, in order to obtain the same signal to noise performance for smaller excitation levels. It should be noted that the BPM resolution in itself is not currently limiting the measurement of the β-function, as the excitation is adapted accordingly.

Secondly, optics measurements would benefit from a much better BPM linearity in the range of the excitation and in the overall calibration from BPM to BPM. Light sources are currently at the 1-2% level, the LHC at the 3-4% level. Improving this to below the 1%level would allow the use of the oscillation amplitude as well as the phase for β-function reconstruction.

Thirdly, all machines would benefit from a better BPM design to lower the coupling impedance these BPMs present to the beam. This is a serious issue for synchrotron light sources where the machines becomes more sensitive to collective effects as lower beam emittances are achieved, with the BPMs accounting for a significant fraction of the total impedance budget. In addition, the short range, high frequency wakes induced by the BPMs can result in beam induced heating. Many studies are already underway to address this issue (see e.g. [10]).

OPTICS MEASUREMENT & OPTIMISATION IN LINACS AND TRANPORT LINES

Optics Measurement in Linacs and Transport Lines

In single pass structures such as linacs and transport lines, it is important to match the beam line optics to the incoming beam. Two procedures are frequently used: multi-wire (or multi-screen) emittance measurements and quadrupole scans. Both methods are based on wire scanners or screen monitors measuring the transverse beam size. The beam size (x) at a location s can be expressed in terms of the optical α and β functions and the emittance at an upstream location s_0 as

$$\langle x^2(s)\rangle = R_{11}^2\beta(s_0)\epsilon - 2R_{12}R_{11}\alpha(s_0)\epsilon + R_{12}^2\gamma(s_0)\epsilon \qquad (2)$$

with R being the transfer matrix between s_0 and s. In a quadrupole scan, the transfer matrix elements R11 and R12 are varied, by changing the strength of a quadrupole between s_0 and s. Beam-size measurements for at least 3 different quadrupole settings are required in order to solve for the three independent unknown parameters: ε, $\beta(s_0)$ and $\alpha(s_0)$. The fourth parameter, $\gamma(s_0)$ is not free, but determined by $\gamma = (1+\alpha^2)/\beta$. A multi-wire (or multi-screen) emittance measurement is very similar. Here, the quadrupole gradients stay constant, but the R matrices between s_0 and the various beam size measurement devices are different. Again, at least 3 measurements are required. This procedure also provides an absolute measure of the emittance

If a beam is injected into a ring or linac with a mismatch, the beam will filament until its distribution approaches a shape that is matched to the optics of the ring or linac lattice. This filamentation causes the beam emittance to increase. Knowledge of α and β allow quadrupole magnet settings to be adjusted so as to match the optical

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functions to the injected beam and minimize any emittance increase.

Figure 3 shows an example of how this technique can be further improved through the use of tomographical techniques to fully reconstruct the initial phase space density distribution of the beam. Things get more complicated when space charge effects are present, as the measured profiles can no longer be tracked back to the initial profile using linear transformations. Instead, the measurements act as input to simulation codes which attempt to reconstruct the initial distribution based on the optical functions and the measured final profiles, taking into account these space charge effects [11].

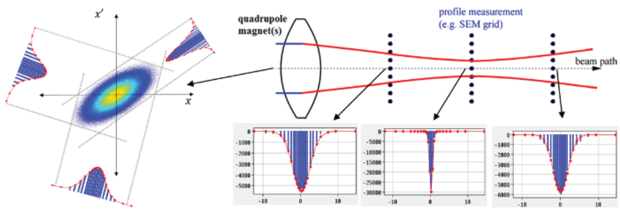

Figure 3: Using tomography to reconstruct the initial phase space distribution in a linac or transport line.

Optimisation of Linacs

For next generation linear colliders the challenge lies in aligning all the thousands of components in the accelerator sufficiently well to limit emittance growth, in particular the BPMs and quadrupoles. Chromatic dilution, the emittance increase due to misaligned quadrupoles, scales with the square root of the number of quadrupoles (and associated BPMs). This means that with the sheer number of quadrupoles in these machines, typically several thousand, even alignment at the 10µm level can lead to significant increase in the emittance.

Beam-based alignment techniques, in particular dispersion free steering, are therefore foreseen to reduce this alignment error to the tens of nm level [12]. This relies on the fact that a beam travelling through the centre of a quadrupole will follow the same path regardless of its energy, while an-off momentum beam travelling with an offset through a quadrupole will undergo a deflection depending on its energy. By measuring and correcting the trajectories of beams of different energy it is therefore possible to thread the beam through the centre of all quadrupoles, limiting the overall emittance increase. This was recently demonstrated at the FACET facility at SLAC [13].

An efficient way of performing dispersion free steering is to introduce an energy chirp on the bunch train passing through the linac. If the BPM system has enough temporal resolution it is then possible to obtain trajectory information for different energies during the passage of a single bunch train.

Beam Instrumentation Challenges for Optics Measurements in Linacs and Transport Lines

The main challenge for optics measurements in linacs is to provide on-line emittance measurements. While slit and grid techniques and 3 wire-grids or screens can be used for setting-up with low intensity beams, non-invasive techniques are required for emittance measurements on high intensity, high power machines. For H^- linacs, laser based systems have successfully been developed to fulfil this role, with the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (USA) using this method on their production beams [14] and Linac4 at CERN having tested a similar system during its commissioning phases [15]. The principle is similar to slit and grid emittance measurements, but where the slit is replace by a thin laser beam that strips one electron from the H^- ions to produce a slice of neutral H^0 atoms. The remaining H^- ions in the main beam are deflected using a dipole magnet, leaving the neutral H^0 atoms to drift to a detector. The resulting profile gives the angular distribution of the particles in the original slice. By scanning the laser through the beam in both horizontal and vertical planes a full 4D reconstruction of the emittance can be obtained.

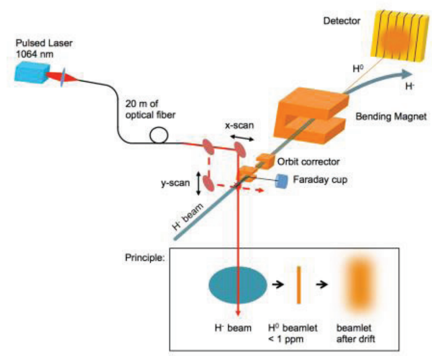

Figure 4: The laser emittance meter at CERN's Linac4.

While this technique provides a non-invasive method for emittance determination in H^- linacs, a viable system for proton linacs still needs to be developed. Ionisation profile monitors have been studied as a possibility, but suffer from space charge effects with high intensity beams, while luminescence monitors are limited by the low light yield for the operational vacuum pressures used in such accelerators.

For next generation linear colliders the challenge lies in providing high resolution BPMs with good temporal resolution for single shot dispersion free steering measurements. CLIC, for example, will have over 4000 BPMs specified to have a position resolution of 50nm, combined with 50ns temporal resolution. To quantify the success of such systems in limiting emittance growth, single shot beam size measurements of sub-micron sized beams will also be required, another of the challenges facing the beam instrumentalists developing systems for such machines.

BEAM DYNAMICS STUDIES USING BETATRON TUNE SPECTRA

Betatron tune measurements are useful for a variety of accelerator physics applications. The tune shift with quadrupole strength gives the local beta function, the tune shift with RF modulation the chromaticity, the tune shift with

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beam current the transverse impedance and the tune shift with amplitude the strength of non-linear fields. Comprehending these tune spectra is also important for the optimisation of beam lifetime, limiting emittance growth, and reducing beam losses through the understanding of instabilities, space charge effects, beam-beam interactions etc.

A normal tune spectrum consists of several components. As the measurement is usually taken using a single BPM in the ring, the main components are revolution lines generated by the periodicity of the circulating beam. These are usually either filtered out by the front-end electronics or simply not displayed in the spectrum reported in the control room. The tune from coherent betatron motion in the plane of excitation is displayed in fractional tune units, from 0 to 0.5 (or 0.5 to 1) of the revolution frequency. If coupling is present a second peak at the tune frequency corresponding to the other plane will also be visible. An example of the beam response to single kick excitation and the corresponding frequency spectrum is shown in Fig. 5.

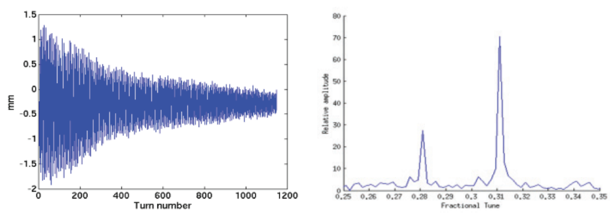

Figure 5: BPM response to a beam exited with a kick (left). Frequency spectrum in the presence of coupling (right).

In the presence of synchrotron motion the interplay between longitudinal motion and transverse betatron motion of an ensemble of particles leads to an amplitude modulation of the centroid of the particle bunch, as measured by a BPM, which depends on chromaticity. This manifests itself as sidebands that appear on either side of the main tune peak in the spectrum (Fig. 6). The distance of these sidebands from the tune can be modified by impedance and space charge effects (Fig. 7) and hence provides important information for optimising machine performance [16].

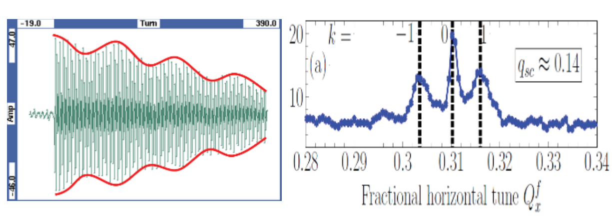

Figure 6: Amplitude modulation of the BPM response in the presence of synchrotron motion and chromaticity (left). Frequency spectrum (right).

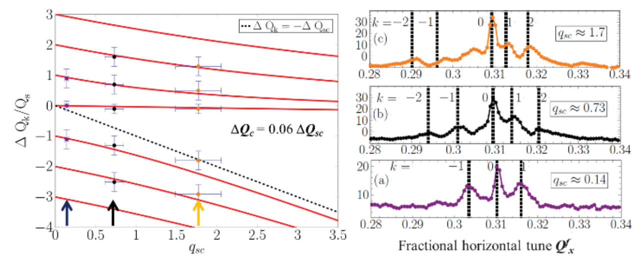

Figure 7: Simulated and measured synchrotron sideband separation for various space charge regimes at the GSI SIS18 (left). Corresponding tune spectra (right).

Tune spectra are also one of the main tools to study transverse instabilities caused by impedance, space charge, electron cloud, beam-beam, etc. Understanding the origin of such instabilities is important to find an appropriate cure which usually involves an interplay between the machine chromaticity, higher order magnetic fields and active transverse damping. Here, the challenge for instrumentation lies in detecting the instability at an early enough stage and then capturing its evolution in as much detail as possible.

The initial detection typically relies on highly sensitive transverse diagnostics, such as the recently developed Base Band Tune (BBQ) system installed at several hadron accelerators worldwide [17]. This permits a signal to be generated at the onset of an instability which subsequently triggers other systems capable of bunch-by-bunch or even intra-bunch measurements for categorising the instability.

Much work is currently ongoing to provide instrumentation for intra-bunch diagnostics on sub-nanosecond bunches [18], where the direct sampling techniques used to date are limited by the dynamic range of high frequency digitizers, the quality of broadband difference hybrids, the relatively short acquisition lengths possible and the large data volumes generated.

The future detectors for such systems will be required to have a wide bandwidth response from MHz to over 10 GHz, in order to resolve the complicated intra-bunch motion that can arise with such instabilities. One technique that is currently being investigated for such measurements involves replacing a standard electro-magnetic pick-up with an electro-optical pick-up (Fig. 8 and [19]). With such an approach the electro-magnetic field of the bunch is used to rotate the polarisation state of a laser traversing a birefringent crystal placed close to the beam. By comparing the variation of the resulting polarisation as a function of time from two crystals on opposite sides of the beam, the position variation along the bunch can be reconstructed. The advantage of such a technique is that bandwidth limiting coaxial cables are replaced by optical fibres, greatly enhancing the overall bandwidth of the system.

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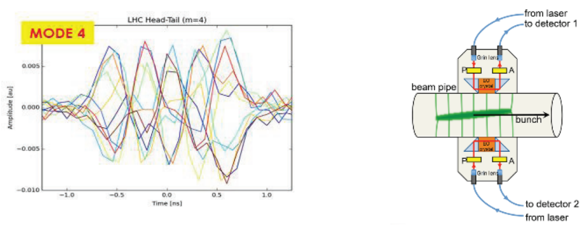

Figure 8: A mode 4 head-tail instability captured on a single bunch in the LHC using direct sampling (left). Schematic representation of an electro-optical BPM (right).

UNDERSTANDING THE BEAM HALO

For high energy or high power accelerators too much beam in the halo can lead to damage of accelerator components, either due to instantaneous beam loss or through long term irradiation. Beam halo control is therefore essential and is best achieved by tuning the machine to avoid populating the tails of the bunch distribution. The beam diagnostic challenges here lie in developing non-invasive techniques with a high enough dynamic range to resolve a beam halo a factor 10^{-5} lower in intensity than that in the beam core.

Synchrotron light sources, FELs and high energy hadron accelerators, such as the LHC, can all use synchrotron light to provide a non-invasive, transverse image of the beam distribution. To be able to measure the beam halo, however, requires an imaging system that eliminates the diffraction fringes created by the intense light from the beam core as is passes through the aperture of the first optical element. These fringes can have an intensity as high as 10^{-2} of the peak intensity and would mask any halo at the 10^{-5} level. To reduce this effect a coronagraph, developed by Lyot in 1936 for solar astronomy, can be used. Such a technique has already been demonstrated at the KEK Photon Factory to achieve a 6×10^{-7} ratio for background to peak intensity [20], and is now being actively studied as a possibility for halo diagnostics for the High Luminosity LHC upgrade.

SUMMARY

Beam dynamics studies are extremely important to push the performance of existing machines, to understand beam stability issues that arise during operation and to study new accelerator physics possibilities for future accelerators. This can only be achieved through partnership with beam instrumentalists striving to enhance the beam diagnostics available for such studies. This results in a better understanding of our machines and pushes the accelerator physicist to develop enhanced correction algorithms and simulation tools.

The main beam instrumentation challenges for the future include the design of high resolution, extremely linear, turn-by-turn BPM systems; non-invasive beam size measurements; high bandwidth detectors for intra-bunch transverse diagnostics; high bandwidth readout systems with on-the-fly data processing and reduction; high dynamic range beam halo diagnostics.

Much of this seminar is based on an excellent workshop "Beam Dynamics meets Diagnostics" held in 2015 as part of the EuCARD2 programme [21].

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