BEAM DIAGNOSTICS IN CIRCULAR MACHINES: REVIEW OF NEW DEVELOPMENTS

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Abstract

Recent developments in beam diagnostic equipment and measurement techniques have been driven by commercial technological advances, better data analysis algorithms, and the need to measure complex beam properties. The need for such developments is due to the increased diversity, beam intensity, and luminosity/brightness requirements of charged particle circular accelerators. In addition, the advent of fast analog-to-digital converters and cheap, powerful microprocessors have fundamentally changed the approach to beam diagnosis, allowing designers to create systems where signal processing is performed locally at each detector.

New beam monitors from a wide variety of circular accelerators are reviewed. A number of interesting or innovative ideas are presented in detail.

Introduction

Reviewing papers submitted to recent accelerator conferences, one notes that the fields of accelerator physics and technology are becoming ever more complex and diverse. From medical accelerators to high energy physics machines, from synchrotron light sources to recirculating linacs, the beam energy, current, and sizes are dramatically different. In addition, the cycle times, revolution and RF frequencies, and geometries of these accelerators can range more than three orders of magnitude.

Modern accelerators are pushing the frontiers of high brightness, luminosity, and spill efficiency. The technological and beam dynamics problems which come with such accelerators must be diagnosed and/or monitored. For instance, the beam orbit in a synchrotron light source or superconducting magnet machine must be closely monitored, else damage to the beam pipe or magnets can occur. The requirements of high beam currents and small longitudinal emittances invite coherent beam instabilities, for which sufficient specialized diagnostic monitors must exist if the instabilities are to be characterized, monitored, and cured.

For the above reasons, beam diagnostic systems must likewise become more diverse, faster, and more intelligent than their ancestors. Thanks to advancements in high speed electronics and realtime microprocessor hardware and software, such systems are now being realized.

Scope

The charge for this paper is to review new developments in beam diagnostics for circular accelerators. Given that only a small fraction of accelerators around the world are even remotely round, instrumentation for any type of machine with more than two passes of beam through the same vacuum chamber is included in the discussion. Therefore, recirculating linacs, microtrons, and cyclotrons are in principle represented. This paper is divided into individual sections, each concentrating on a particular type of existing beam diagnostic. Particularly novel monitors and future ideas are described in more detail. Beam detectors specifically utilized for feedback systems are not reviewed. Therefore, devices like stochastic cooling pickups for cooling systems are not mentioned. On the other hand, beam transfer function measurements are included, since the high sensitivity of available detectors allow nondestructive levels of beam excitations.

Longitudinal Profile and Bunch Length

The longitudinal profile and length of a particle bunch is an important piece of information when diagnosing coherent effects such as bunch lengthening and couple bunch oscillations. In addition, in colliders where the beta function is comparable to the bunch length, measurement of the bunch length is required to accurately calculate luminosity and synchrobetatron resonance widths due to the beam-beam interaction.

In high energy electron machines used for synchrotron light or high energy physics the bunch lengths tend to be on the order of centimeters. Commercially available streak cameras, coupled to optical systems focussed on the synchrotron radiation from the beam, have recently emerged as dedicated, powerful longitudinal profile monitors. They are used to measure potential well distortion [2], beam instabilities [3], bunch lengthening [4], and longitudinal impedance [5]. One of the modifications to the old streak camera design is the implementation of multiple sweeps, or double sweeping, which allows for up to 50 individual traces per frame [6].

For accelerators which have lower RF frequencies and longer bunches (for example, proton, heavy ion, and medical accelerators), bunches with rms lengths of 1 ns and greater can now be observed directly using wideband resistive wall current monitors and digital sampling oscilloscopes [7]. Either the entire profile can be recorded, or a microprocessor linked to the oscilloscope via an IEEE-488 communication port can continuously calculate bunch lengths and intensities. This approach is especially useful in colliding beam accelerators where the individual bunch lengths and intensities are needed for luminosity calculations.

High bandwidth sampling scopes coupled to light detectors with fast pulse response characteristics are also used to measure bunch length in electron storage rings [8]. Bunch lengths as small as 6 cm have been observed using this method. As in the case above, the IEEE-488 communication port of the oscilloscope is connected to a microcomputer to do the actual data acquisition and analysis. Note that all of the above systems use commercial electronics coupled to customized beam detectors or optical systems.

At LEP CdTe photoconductors have been placed behind a Be window and exposed to X-rays emitted inside a dipole magnet [9]. Because of their short carrier lifetime of approximately 10 ps, and the geometry of the detector (composed 16 imbedded matched lines), the autocorrelation of the longitudinal profile (and hence bunch length) of the beam is extracted.

Another new and novel approach to bunch length measurements utilizing synchrotron radiation has been developed for LEP [10]. It consists of a system monomode optical fibers which are designed to act as photon storage rings. The time of flight of single photons are measured to an accuracy of approximately 10 ps. This information is then histogrammed in order to restore the pulse shape.

In fast cycling accelerators the average bunch length of the entire beam can now be measured realtime with a monitor [11,12] which compares the beam current at two multiples of the RF frequency. Assuming that the bunches are Gaussian, the rms bunch length can be calculated using analog components, with a total bandwidth of 10 kHz.

The signal from a longitudinal beam pickup is split into and sent into two bandpass filters at the two RF frequency multipoles. Generally the fundamental RF frequency is used. The other RF frequency harmonic is chosen based on the range of expected bunch lengths. In the case of proton machines the third harmonic is sufficient. For electron machines much higher harmonic numbers may be necessary to get a sufficient difference in harmonic powers between the two channels. The widths of the bandpass filters must be identical, especially in accelerators which have gaps in their bunch spacing distributions. In this way the ratio of the harmonic powers after signal processing each channel is independent of the bunch spacing distribution. In principle the performance of this monitor is insensitive to the frequency response of the beam detector, since amplifiers or attenuators can be used to equalize the two narrow band signals in the limit of zero bunch length.

Beam Position

Since beam position monitoring systems have been perfected over the decades, one may question what could possibly be considered a new development. As it turns out, the requirements of recirculating linacs and microtrons and the wish to perform dynamic aperture studies with accelerator beams are driving not better beam detectors, but better algorithms for interpreting beam position signals.

In the case of the CEBAF recirculating linac, there is a need to know the orbit for the beam through the linac sections as a function of turn number. Since 5 continuous electron beams are traversing the linac sections simultaneously, a novel approach is required. Two potential solutions have emerged. The original idea was to modulate the bunch intensity of an interval of beam less than a circulation time (4.2 μs) at between 1 and 10 MHz [13]. Therefore, the 1.5 GHz bunch spacing acts as the carrier with a 1-10 MHz amplitude modulation superimposed. Beam position monitors sensitive to 1-10 MHz then detect only the fraction of the beam on the desired recirculation orbit.

A similar but potentially more powerful method would be to pseudorandomly vary the bunch intensities [14]. By correlating the beam intensity waveform at the electron gun with the signals from the beam position monitors after an appropriate delay, one can measure beam position as a function of recirculation orbit number. A potential problem with both schemes could come from coupled bunch betatron oscillations due to beam instabilities, power supply ripple, or RF phase noise (if the dispersion is nonzero in the linac sections). If these oscillations have a frequency spectrum which mimics that of the intensity modulation, the beam position data will become noisy or invalid.

In the age of the design and construction of large proton storage rings, such as HERA, UNK, SSC, and LHC, it is imperative to understand dipole magnet multipole tolerances before magnet construction. A host of people doing theoretical calculations and particle tracking computer simulations on these machines need to verify the validity of their results by comparing their prediction of existing accelerators with measurements.

Given that the prediction of long term stability and beam lifetime is based on understanding the nonlinear nature of the coordinate mapping around the arcs, a natural experiment easily reproduced both in calculations and in particle tracking simulations is single particle nonlinear dynamics. All that is required is to track the phase space of a small transverse emittance beam undergoing coherent oscillations for many (on the order of 1 million) turns. Traditional beam position monitor systems with local data processing capabilities typically only had on the order of 1024 turns of buffer memory. Therefore, special beam position data acquisition systems were constructed. Such experiments were done on the Tevatron [15] and the SPS [16]. In the case of the Tevatron, a commercial CAMAC-based 2-channel analog-to-digital converter with on-board memory sufficient for storing a million turns of beam position data was installed. A workstation was used to read the position data and analyze it. The entire system was independent of the existing control system. Even though the interface hardware and beam detectors/processing electronics were reasonably standard, the million turn acquisition capability along with the online analysis power of a workstation were new developments.

When the Tevatron was constructed a powerful beam position monitor system [17] was implemented in order to prevent damage to the superconducting magnets due to beam loss. If the beam strayed too close to the beam pipe wall, it was quickly extracted (aborted). Similarly, present day synchrotron light sources require careful beam position monitoring to prevent damage due to the intense synchrotron radiation flux. In addition, in order to make full use of their small emittance, the beam position and angle around the accelerator must be precisely maintained. Logically, since the synchrotron radiation position and angle is the important quantity, it should be directly measured [18,19]. Split ion chambers, photo-emission detectors, and various graphite and solid state monitors are now generally utilized.

Transverse Profile and Beam Width

Perhaps the most difficult nondestructive beam measurement necessary in a circular accelerator is determining the horizontal and vertical emittances. This is especially the case in proton and ion rings, where there are only a limited number of strategies available so far.

A popular option in high energy physics machines is the flying wire [20] or wire scanner [21]. A thin carbon fiber (with a diameter of approximately 20 μm) traverses the beam at speeds as great as 15 m/s, and the interaction of the beam with the wire is measured. Since the position of the wire is also recorded, the transverse density distribution of the beam is produced.

Three different types of beam-wire interactions are either used or contemplated. If the temperature of the wire during the passage of the beam remains below the threshold for thermionic emission [21], current drawn into the wire due to secondary emission of electrons can be recorded. In accelerators where thermionic emission is a problem, or in a collider where one is interested in measuring the profile of each beam separately, detection of the radiation shower from the beam/wire interaction is implemented [20]. Finally, imaging of the bremsstrahlung [22] or optical [23] radiation from the traversal of the particles through the carbon is yet another means of mapping the density distribution of the beam.

Though the wires are interacting with the beam, their effect in terms of transverse emittance growth or beam current reduction is found to be negligible [20,21]. In fact, a situation arose in the Tevatron at 900 GeV where the microprocessor controlling the wire failed in such a manner that the wire flew every 5.2 seconds [24]. Usually the wire is flown once per hour. The current lifetime of the beam dropped from 25 to 15 hours, which reduces to a fractional particle loss of $\Delta N/N = 36\times10^{-6}$ per fly. The transverse emittance growths of the 20π mmmr beam was 0.002π mmmr per fly.

Though in principle one would like to record each profile, in general only the transverse emittances and fractional momentum spread of the beam are required. Since microprocessors (typically in a VME environment using many commercial components and software applications) are used to control these systems [20,21], it is natural to also have these computers do fits to the recorded beam profiles. Therefore, only a single number per bunch per fly need be transmitted over the control system.

Another method of monitoring the profile of proton and ion beams is to measure the distribution of ions generated by the passage of a beam through the residual gas in the vacuum pipe. Though this technique has been used in many machines in the past [25], technological advancements have recently made these devices much more attractive from sensitivity, flexibility, and radiation damage points of view [25,26]. The fact that they are essentially nondestructive monitors make them especially useful in low energy accelerators [27]. Unfortunately, in superconducting accelerators such as the Tevatron, or in most electron machines, the vacuum pressure is so low that the ion accumulation rates become intolerably small.

A truly nondestructive method of measuring the transverse emittance of a beam is through the observation of its transverse Schottky signals. Stochastic betatron signal acquisition is now rather commonplace in laser [28], electron [28,29,30,31], and stochastic cooling [32,33,34] rings. But a recent development is to place Schottky monitors in a ring as stand alone beam diagnostics to measure transverse and longitudinal emittances. For example, a narrow band cavity has been installed in the Tevatron collider which is designed to independently measure the horizontal and vertical Schottky spectra [35]. The resonant frequency of the cavity is approximately 2 GHz, whereas the revolution and RF frequencies are 47 kHz and 53 MHz. As expected, the coherent portion of the beam spectrum is quite small at 2 GHz. After mixing the spectra down to 24 MHz (independent of the RF frequency, and hence time in the acceleration cycle) and plugging the resultant signals into commercial radio receivers, the emittances can be measured by centering the radio input filters on the betatron lines and monitoring the AGC output voltages. These voltages are then fed into the control system.

At present this transverse Schottky detector is equally sensitive to the proton and antiproton beams. An upgrade [36] is in progress in which a pair of these cavities are spaced 1/4 wavelength apart at 2 GHz. By splitting the signals from each detector and applying 1/4 wavelength delay lines to alternate branches, independent proton and antiproton emittance measurements can be made.

In electron rings synchrotron radiation from a dipole magnet or insertion device can be focussed, sometimes using elaborate optical systems, onto a diverse set of possible of detectors. These systems can be broken down into two basic regimes; optical and x-ray. Because of recent, major advances in technology and considerable cost reductions, CCD arrays are now becoming the standard in optical synchrotron radiation detection [9,37] of transverse beam size.

In many electron accelerators one wishes to maintain a minimum vertical beam height. As a result optical monitors sometimes do not have sufficient angular resolution. A number of dedicated beam profile monitors based on x-rays [38,39,40] have recently been commissioned. In addition to the increased beam height resolution made possible by using x-rays, it was found [41] that the entire two dimensional vertical phase space distribution could be measured. This is because the x-rays are emitted into a small opening angle tangent to the source particle trajectory, making the position of the x-ray at the detector a function of both the source particle's phase space position and angle. Instead of measuring the position projection of phase space, a slanted phase space projection is sensed. The recent use of fluorescent screens and CCD cameras, rather than ungainly arrays of monochrometers and rotating silicon crystals, has increased the usefulness and reliability of this measureme..t technique.

Luminosity

In the past the measurement of luminosity in high energy electron-positron colliders was left to the detector physicists. Typically, a counting rate of a few hertz was adequate for their purposes. Tuning the accelerator to maximize luminosity became a tedious task, where every time a parameter was changed, minutes would pass before a statistically significant sample of counts would be accumulated and converted into a luminosity number.

Since the realization [42] that counting rates of hundreds of hertz per 10^{31} cm^{-2} sec^{-1} are possible by placing the coincidence counters on the far side of the vertically focussing low-β quadrupoles in the horizontal plane, this detector geometry has become the standard [43,44]. The developments here are in designing radiation survivable calorimeters and detector geometries which intercept very small Bhabha scattering angles. Moveable detectors [44] now achieve scattering angles of 2 mr.

Polarization

Equipment for the continuous or systematic measurement of polarization in circular storage rings has recently become more prominent. Polarization of beams is useful both to accelerator physicists and to the users of their machines. In the case of electron machines, the self polarization of the beams due to synchrotron radiation is destroyed by tuning the accelerator onto a depolarizing resonance. Since the spin tune of the accelerator depends directly on the beam energy, the energy of the accelerator can be calibrated [45,46,47]. These polarimeters are composed of a laser which shines light on the beam. The back-scattered gamma rays are detected by a segmented monitor which measures the scattering angle asymmetry indicative of the beam polarization.

At the Indiana University Cyclotron Facility [48] polarized protons are used to test the Siberian Snake concept. A thin carbon target internal to the beam pipe is placed at the fringes of the beam. Large amplitude protons hit the target and scatter. The scattering angle asymmetry is used as a measure of polarization.

Transfer Functions

The measurement of beam properties by exciting the beam with a known deflection signal and observing the resultant effects is a powerful and nondestructive tool given beam detectors of sufficiently high sensitivity. In the longitudinal plane resonant longitudinal pickups or well shielded, broad band resistive wall monitors [7] provide sufficient sensitivity. In the transverse plane resonant detectors [49] tuned to a specific revolution harmonic coupled with low noise electronics [50] fill the above requirement.

Single beam transfer function measurements are typically used to measure the transverse [51] or longitudinal [52] impedances of the ring using unbunched or bunched beam, respectively. Bunched beam transverse transfer function measurements are useful for measuring coupling and chromaticity [53].

Bunched beam transfer function measurements can also be used to probe the properties of the beam-beam interaction [53,54,55]. When one beam is excited, the beam-beam interaction acts as a coupling mechanism which transmits the oscillations to the other beam. By measuring the properties of these normal mode oscillations one can probe the strength and nonlinear nature of the interaction.

At Fermilab a project has been initiated to map the longitudinal and transverse impedance as a function of frequency in the Accumulator, Main Ring , and Tevatron accelerators. In the case of the longitudinal measurements, broad band (6 kHz - 6 GHz) resistive wall monitors [7] are used to sense the current modulation of a unbunched beam induced by a broad band (6 kHz - 6 GHz), high power (200 V max) RF cavity. A Hewlett-Packard HP8753B Network Analyzer is used to do the measurements.

Conclusions

The diversity exhibited in recent beam diagnostic developments closely parallels the increased diversity of new accelerators and the increased demands for current, luminosity, or brightness in existing accelerators. Advances in technology are helping instrumentation designers produce faster, more sensitive, and intelligent beam diagnostic systems.

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