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 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 have become even 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 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.

Because of these reasons, beam diagnostic systems must likewise become more diverse, faster, and more intelligent than their ancestors. Thanks to advancements in high speed electronics and real-time 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 this 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. 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.

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.

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frequency is used. The other RF frequency harmonic is chosen based on the range of expected bunch lengths. In the case of using both, choosing 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 obtain 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 beam intensity of an interval of beam less than a circulation time (4 μs) at 1 MHz [13]. Therefore, the 1.5 GHz bunch spacing rate 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 comes 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 intensity of an arc, a need to know the orbit number reproduced both in calculations and in particle tracking simulations is a 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 24 bits per channel was 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.

In the Tevatron, 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 emittance. 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 is above 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 traversals of the particles through the carbon is 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 0.4% per hour. The transverse emittance growths of the 20 fm mmr beam was 0.002 mmr per fly. In principle one would like to record each profile in general only the transverse emittance 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 these entirely 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 as a result of recent advances [28] in the development of new techniques such as the use of commercial radio receivers, the emittances can be calibrated [32,33,34] rings. But a recent development in this 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 cavities 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 GHz and 52 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 adding 1/4 wavelength delay lines at the branches, independent proton and antiproton emittance measurements can be made.

In electron rings synchrotron radiation from a dipole magnet or insertion device can be focused, 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 pickups using floating electron and 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 uniaxial arrays of monochrometers and rotating silicon crystals, has increased the usefulness and reliability of this measurement 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 $10^{32}$ cm$^{-2}$ sec$^{-1}$ are possible by placing the coincidence counters on the far side of the vertically focussing low-$\beta$ 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 intersect the beam at scattering angles. Moveable detectors [44] now achieve scattering angles of 2 mrad.

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 the 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 range to probe the energy of the accelerator. The scattering angle asymmetry is measured as a use 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, well 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] stability 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 (0 kHz - 6 GHz) resistive wall monitors [7] are used to sense the current modulation of a unbunched beam induced by a broad band (5 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.

References

1. Operated by the Universities Research Association under contract with the U.S. Department of Energy.


26. J.Koster, private Fermilab communication.


