LINEAR OPTICS CORRECTION IN THE CEBAF ACCELERATOR*

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Abstract

During commissioning of the CEBAF accelerator, correcting dispersion, momentum compaction and betatron beam envelopes was essential for robust operation. To speed the diagnostic process we developed a method which allows one to track and correct the machine optics on-line. The method is based on measuring the propagation of 30 Hz modulated betatron oscillations. The beam optics of the accelerator was altered to decrease lattice sensitivity at critical points and to simplify control of the betatron function match. The calculation of the Courant-Snyder invariant from signals of each pair of beam position monitors was used for a correction of the betatron functions. The experience of optics correction and the study of long and short term machine reproducibility obtained during 1996 and early 1997 are also discussed. With minor modifications this method can also be used for on-line optics measurement and correction in circular accelerators.

1 INTRODUCTION

The CEBAF accelerator[1,2] is a five pass CW recirculator with beam power up to 800 kW. It consists of a 45 MeV injector, two superconducting (SC) linacs of 400 MeV ener-gy gain, and nine arcs which connect the linacs for beam recirculation for total beam energy of 4.045 GeV. Logically the machine is separated into the following regions: injec-tor, north and south linacs, nine 180^0 bend recirculation arcs with associated entrance and exit matching regions, and the spreader and recombiner regions at the ends of each linac which separate particles of different energies or merge them for reinjection into the succeeding linac. After acceleration to the desired energy, the beam can be split and directed to three experimental halls for nuclear physics experiments. The path traversed to full energy is more than 6 km in length, over which the beam is focused by about 700 quadrupoles. Each quadrupole is independently powered, which creates many possibilities for machine optics but also complicates the machine tuning and operation.

During machine commissioning in early 1995, the betatron functions were found to be seriously degraded with beam acceleration and local dispersion correction was not reliably stable over time spans of days. Machine operation was overly sensitive to small energy and steering fluctua-tions. Periodic arc-by-arc dispersion correction allowed ma-chine operation with the full energy CW beam at the end of 1995, but severe betatron mismatch still remained. Initially, corrections were done using measurements of differential orbits generated by DC changes in steering magnet settings. The combination of poor machine reproducibility and limited tuning time made it difficult to accomplish optics diagnostics and correction with existing instrumentation.

2 INSTRUMENTATION FOR OPTICS STUDY

To accelerate the measurements[3], we added an ability for the BPMs to detect beam displacements excited by an AC external perturbation. Because line-synched 60 Hz pulsed beam has been the main mode for machine tuning, we chose the modulation frequency of 30 Hz. This choice automatically suppresses both power line electromagnetic interference and the deleterious effects of slow beam drifts. The 30 Hz modulation is generated by a function generator that resides in the machine control center and is phase locked to the beam pulses. The modulation is delivered to one of the modulation devices by computer controlled switches, depending on the type of measurement to be accomplished. Presently, there are two types of modulation used: beam energy modulation performed by changing the accelerating gradient of the superconducting cavities, and transverse beam modulation performed by air core dipole correctors. Both types of the modulation can be applied at the end of the injector at an energy of 45 MeV, and at the beginning of ARC1 at an energy of 445 MeV, providing optics measurements of the entire machine. Beam energy modulation is achieved by switching the modulating voltage to an analog input of the gradient feedback loop of the eight RF control modules. The modulation voltage is adjusted for a relative energy change of about $(1\div2)\cdot10^{-3}$. The eight se-lectable correctors (two vertical and two horizontal in each of the 45 and 445 MeV energy regions) allow for excitation of a betatron motion with different betatron phases. Usually we excite beam motion with an initial amplitude of about 3 mm, which after acceleration by a factor of ten dies down to about 1 mm due to adiabatic damping.

The beam position measurement system includes approximately 500 BPMs distributed across a network of 20 input-output controllers (IOC). Data for the BPM measurements are acquired at a 60 Hz rate and stored in IOC memory for processing. The mean value of the beam

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position and the amplitude of the 30 Hz beam motion are calculated from each 12-sample buffer of successive hardware readings. Because the modulating voltage is locked to the beam pulses, the ADC measurements of the BPM signals are automatically synchronized to the modulation. The synchronization of readings for different IOCs is accomplished by broadcasting a sign bit of the 30 Hz modulation. One of the IOCs, called the master IOC, measures the sign of the 30 Hz signal and sends synchronization messages through the network.

3 ALTERNATE OPTICS

The large scale of the accelerator requires high field accuracy of the magnets. The design specifications for the quadrupoles ($\sim 1 \cdot 10^{-3}$) have not been met in the real machine, and, consequently, that required an intensive study how to tune the accelerator optics to provide high quality beam transport. These matters were complicated by frequent adjustments of the accelerating profile along the linacs and the machine path length, and by overall deficiencies in machine reproducibility.

Adjustment of the accelerating profile is caused by changes of state of the accelerating cavities as they are taken off- or on-line for maintenance reasons. The accelera-ting profile is always non-uniform and changes from day to day. Such changes are accounted for in the focusing of the first-pass beam at the time of accelerating gradient adjust-ment, but the higher passes are subjected to the betatron mismatch. Path length adjustments are necessary to keep higher passes on the crest of the accelerating wave. The desired path length accuracy of about 0.25 mm (~0.5 deg.) results in frequent path length adjustment to track seasonal and weather variations. The large vertical beta-function in the path length correction chicane (dogleg) magnets (located in the spreaders) results in a significant change of the vertical focusing in the course of correction. The largest effect has been found in the first two arcs where the beta-functions deviate from the design values by more than a factor of two over the nominal adjustment span of one path length chicane.

The following requirements have guided the redesign of the optics: decreasing beta-functions at linacs and doglegs, creating a set of orthogonal knobs for global betatron match, and adjusting functions to satisfy the requirements of beam-based feedback systems used for suppressing beam drifts[4]. To satisfy these requirements, the quadrupoles in the spreaders and recombiners were adjusted, changing the machine functions in the spreaders, recombiners, and linacs while leaving them unchanged in the arcs. The vertical beta functions inside the doglegs were decreased by about a factor of three. The largest improvement in the beta functions of the linacs was for the last two passes. In particular, for the fifth pass, the decrease of the beta functions was about 30% for the north linac and more than a factor of two for the south linac.

The orthogonal knobs for optics correction, have been a main feature of the new optics. Eighteen regions, one in each spreader and recombiner, allow one to do a smooth match throughout the entire machine. Each region has four quadrupoles assigned for correction of the beta-function and its derivative, for both the horizontal and vertical planes. To decouple the horizontal and vertical corrections there is a large difference in the horizontal and vertical beta-functions inside these quadrupoles. Because a mismatch of the beam envelope oscillates at twice the betatron frequency, the two quadrupoles of each correction set, horizontal or vertical, are shifted by ($45+n\times 90$) deg. in betatron phase. This orthogonality of their effects results in minimal changes of their gradients to perform a betatron match.

4 PERFORMING OPTICS CORRECTION

Dispersion correction requires a modulation of the beam energy. The horizontal and vertical differential beam positions will be proportional to the horizontal and vertical dispersions. Adjustment of assigned quads allows on-line cancellation of the cumulative dispersion downstream from each dispersive section of the machine for both the horizontal and vertical planes.

Performing the betatron match is more complicated. It is based on the fact that if the machine lattice matches the design lattice the Courant-Snyder invariant remains constant. The general idea is to excite the betatron motion and observe how the invariant changes during beam transport. The changes occur at elements which have incorrect focusing. The perturbation depends both on the focusing error and the betatron phase. Thus measurements with different betatron phases are performed to obtain complete information on the betatron match.

For performing the betatron match, in addition to the differential BPM screens, we built a program which calculates (x, x', y, y') from pairs of adjacent BPMs. Using design beta-function information, this program plots the effective betatron motion amplitude for the entire machine. This amplitude is proportional to the square root of the Courant-Snyder invariant and has an additional beam energy normalization so that the amplitude remains constant with beam acceleration.

As in the case of dispersion correction, the correction of betatron functions is performed arc-by-arc. To match beta-functions of two sequential regions of the machine an operator must adjust four corresponding quadrupoles (two for each plane) assigned for betatron match between these regions so that the normalized amplitudes for all four correctors are unchanged throughout the accelerator.

Figure 1 shows the behavior of normalized amplitudes for a horizontal perturbation after correction of the betatron match. Note that the normalized amplitude does not change significantly in one arc and errors are not accumulated along the machine. Without this tuning the normalized betatron amplitude usually grows by a factor of from three to ten. The occasional large spikes on the curves are associated with BPMs that are not functioning properly.

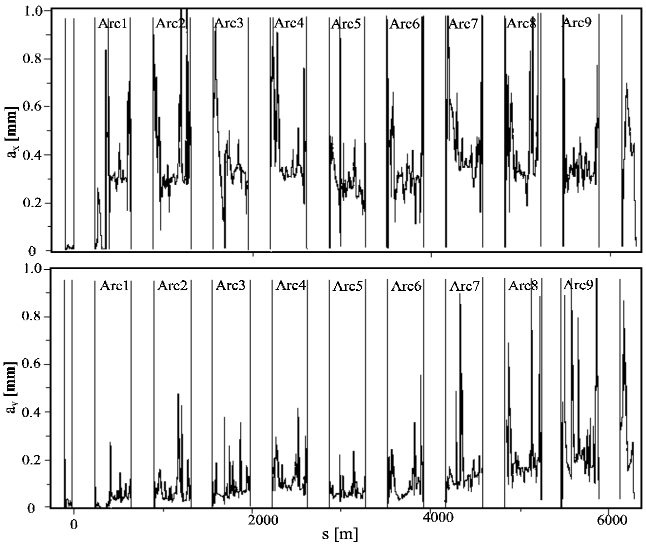

Figure 1. Normalized betatron amplitude for horizontal and vertical beam motion throughout the accelerator in the case of horizontal kick at the beginning of ARC1.

Usually an operator watches screens for horizontal and vertical normalized amplitudes simultaneously and can see an effect of the horizontal-vertical coupling in the process of correcting the betatron functions. This coupling originating from skew-quadrupole fields of the SC-cavity couplers[5] is adjusted during and at the end of the betatron match by skew-quadrupole correctors located near each cryomodule. The effect of the coupling is seen in Figure 1 where the amplitude of the vertical motion is slowly growing along the machine for an initial horizontal perturbation. Although one can still see a residual coupling, its size is significantly reduced compared to the case without corrections.

5 DISCUSSION AND CURRENT STATE

These improvements in instrumentation, software, and procedures provide fast on-line ability to carry out tests of the beam optics and to perform any necessary corrections. The ability to tune the machine quickly has been crucially important in conditions of poor machine reproducibility. After the machine was tuned it has been much easier to study the causes of irreproducibility. As a result one of the first actions taken was zeroing of all machine sextupoles. The sextupoles were installed to perform chromatic correction of the machine functions and, consequently, to increase energy aperture. Unfortunately they make the optics orbit dependent, so that in the real machine a change of vertical orbit in the arcs causes a strong mismatch in both vertical and horizontal dispersions and a decrease of the energy aperture.

The main issue for study over the past year, after correction of a serious problem with the magnet power supplies, was machine reproducibility. This study showed that the major remaining problem occurs during hysteresis cycling of the quadrupoles and correctors. Each of these magnets (about 1600 in number) has its own power supply. The high inductance of the highest-energy quadrupoles (the largest quadrupole family) was not properly considered in the selection of tuning parameters for the power supply regulation circuits. As a result the power supplies are under-damped when used with these magnets, which makes a cur-rent overshot at the cycle end. The IOC-based control used to ramp the magnet setpoints then introduces a timing de-pendence upon network and IOC load. That causes a varia-ble result of hysteresis cycle. A second problem is hard-ware errors in the digital communication path, which causes incorrect setpoints to be written to the power supply a few times per million writes. These points are being corrected.

In spite of the fact that during dispersion and betatron function matching we did not directly monitor the beam sizes, performing the match resulted in a small beam size throughout the machine. Measurement shows that there is practically no emittance growth during beam transport, which yields average rms beam sizes of about 50 μm at full beam energy. Although we already achieved the design quality of the beam transport, we still need to understand better the reasons of the machine optics deviations from the design, such as too large field correction in quads responsible for vertical dispersion correction, and the origin of x-y coupling in spreaders and recombiners.

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