Chromaticity Measurements in the HERA Proton Storage Ring

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Abstract

An important consideration for operation of the HERA proton storage ring is compensation of sextupole magnetic field contributions generated by persistent currents in the superconducting dipole magnets. We present measurements of the chromaticity at injection energy and during acceleration and compare them with predictions based on measurements of the sextupole fields.

INTRODUCTION

In the HERA proton ring, protons are injected at 40 GeV and accelerated to 820 GeV, with corresponding magnetic fields in the superconducting main dipole magnets of 0.23 and 4.68 Tesla. At the low injection field, persistent current effects in the superconducting cable make significant and magnet history dependent contributions to the multipole content. The most important is the sextupole field, which gives a contribution to the chromaticities much larger than the natural chromaticity of the machine, so that careful correction is essential. A further complication is the time dependence of the persistent currents, which results in a gradual decay of the sextupole field as the machine sits at 40 GeV, and then a sudden jump at the beginning of the acceleration.

Our knowledge of these effects is based on laboratory measurements on the HERA dipoles, and on measurements on the HERA reference magnets, two standard dipoles (one Italian and one German) which are connected in series with the ring magnets and have been equipped with NMR probes and measurement coils [1,2]. We here present direct measurements of the chromaticities using stored protons in HERA, and compare them to predictions from the magnetic field measurements.

APPARATUS

The chromaticity measurements use the Personal Computer based tune measurement system built for the HERA proton ring [3]. Betatron oscillations of the proton bunches are excited by a quick frequency sweep applied to a kicker, and the tune signals are processed by fast Fourier transforms and displayed on the PC monitor. The repetition rate is variable up to 8 Hz and the frequency spectra can be written to disk for later analysis.

For the chromaticity measurements a connection was created which permits control from the PC of the frequency applied to the proton RF cavities. The PC sends a command for a frequency change to the NORD 120 computer controlling a module which adds small offsets to the RF frequency. The change is installed by a frequency ramp with steps of 0.025 Hz at about 500 steps/second (the RF frequency during injection is 52 MHz). The low ramp rate is determined by the requirement that the frequency change be adiabatic with respect to the 20 Hz synchrotron frequency in HERA at 40 GeV.

The dipole fields in the reference magnets are measured during stationary conditions by NMR probes and during the ramp by coils and integrators and a system of Hall probes. The sextupole fields are measured by rotating coils and lock-in amplifier detectors, with measurements available at a rate of 2 Hz. During operation of HERA, field measurements are made continuously, stored to hard disk on the VAX computer which manages the system, and periodically archived so that the complete history of the magnet cycles is available.

CHROMATICITY CONTRIBUTIONS

We use chromaticity defined in terms of the betatron tune and beam momentum as $\xi = dQ/(dP/P)$. The natural chromaticies contributed by the quadrupoles in the design injection optics for HERA are $\xi_h = -44.1$ and $\xi_v = -47.0$. The predicted contributions from the sextupole fields in the dipole magnets at 40 GeV are $\xi_h = -275.3$ and $\xi_v = +242.0$ [4]. This corresponds to sextupole field components at 2.5 cm radius in the dipoles of about 7.5 Gauss from the persistent currents and about 0.8 Gauss from geometric effects.

The chromaticities are corrected to approximately zero by sextupole coils wound onto the beampipes inside the HERA dipole magnets and powered in two families. During the turn-on of the HERA proton ring we installed correction currents based on predictions from laboratory measurements of the dipoles, and measured chromaticities of about 10 units, indicating that the machine properties agreed well with the predictions.

TIME DEPENDENCE AT 40 GEV

The expected time required for injecting the design fill of 200 proton bunches into HERA is 20 to 30 minutes, so we are sensitive to the persistent current decay effects in this time interval. Laboratory measurements show a decay which is roughly logarithmic in time and which depends on the maximum excitation field in the previous cycle. Our standard cycle during this operating period was: inject, ramp to 480 GeV (2.9 Tesla), at the end of the fill cycle down to 0.05 T, up to 1.0 T, back down to 0.05 T, and up to the injection field of 0.23 T. The additional loop to 1.0 T was expected, on the basis of the laboratory measurements, to decrease the time dependent effects.

We therefore performed measurements over a period of about 30 minutes, starting 2 minutes after the magnets had reached the 0.23 T injection field. The chromaticity was measured by changing the frequency of the proton RF and measuring the betatron tune shift due to the resulting offset in the average beam momentum. The RF was varied ±25 Hz, and the horizontal and vertical betatron tunes were measured 20 times and averaged at 12.5 Hz intervals. The measurement cycle was performed once per minute. The chromaticities were then calculated assuming the design value for the transition energy of 27.4 GeV. The results are shown in Fig. 1.

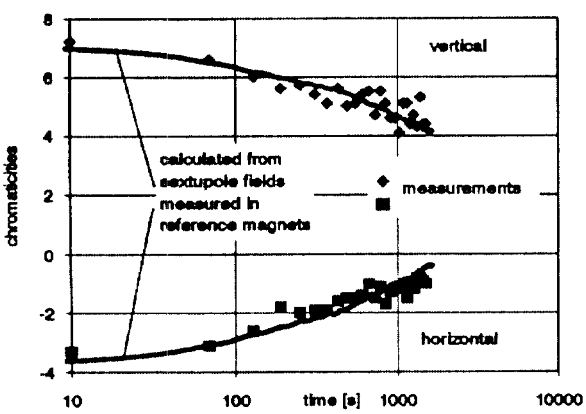

Fig. 1 Chromaticities during a 30 minute wait period at the 40 GeV injection energy; comparison of the measured values (symbols) with the changes predicted from the reference magnets.

Fig. 1 shows in addition the change in the chromaticities expected from the sextupole field measurements for this same magnet cycle, as recovered from the archive tape. These changes are calculated using the sensitivities of the chromaticities to the sextupole content of the dipoles calculated for the HERA design optics, and the values are set equal to the beam derived values at the beginning of the measurement period. A problem with the comparison is that we know the start time of our measurements only to within about 30 seconds of the timing of the magnet measurements. The agreement of the two methods indicates that the errors in both methods are not larger than 1 unit of chromaticity. The total change is about 4 units; we expect that this will double when the HERA dipoles are excited to the design value of 4.68 T [1].

Ramp Measurements Between 40 and 70 GeV

Because the typical chromaticity measurement using the above system takes 5-10 seconds, it is not an appropriate technique for observing the rapid changes at the start of the acceleration cycle. To measure chromaticities during the ramp we therefore performed several ramp cycles, each with different offsets of the RF frequency from the nominal value. During the ramp the RF frequency is controlled by a look-up table driven by the dipole field change measured in the reference magnet; a hardware module permits adding a fixed frequency offset to the look-up table values, resulting in a momentum offset of the beam during the ramp. By making measurements with 3-4 different offset values we were also able to check the consistency of the measurements.

Data were taken for ramps between 40 and 70 GeV, spaced by the standard 1000 amp cycle. The ramp rate was 0.28 GeV/sec, with 16 second parabolic turn-on and turn-off intervals, resulting in a total time of 130 seconds. Tunes were measured at 2 Hz and written to disk. The tune measurements contained random scatter, due in part to the large width of the tune peaks caused by the large chromaticities (±30) midway in the ramp; the plots shown in fig. 2 were produced by averaging and smoothing the data. From consistency checks using different combinations of data samples we estimate an uncertainty of ±3 units for the measurements. Two important sources of systematic error are first, that the start time of the tune measurements with respect to the ramp may have varied by several seconds, and second, that the time at 40 GeV before the start of the ramp was not held constant.

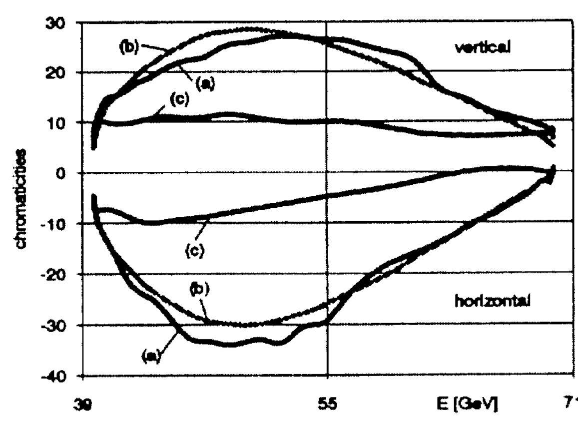

Fig. 2 Chromaticities during acceleration from 40 to 70 GeV. The lines are (a) measured chromaticity , (b) change in chromaticity derived from the reference magnet measurements, and (c) measured chromaticity after compensation.

The reference magnet data for these ramp cycles were again used with the design optics to predict changes in chromaticity. In figure 2 these predictions have been set equal to the measured values at the start of the acceleration cycle. The agreement is consistent with the estimated error of the measurement.

The large chromaticity values observed midway in the ramp deserve an explanation. During the ramp all elements in the ring, including the correction sextupoles, are driven linearly between start and end files for the magnet currents which have been adjusted for reasonable tune and chromaticity values. The deviations from a linear dependence vs energy of the chromaticity result from the sextupole contribution of the persistent currents, which is not proportional to the magnet excitation current.

Fig. 2 also shows a measurement of chromaticity during the ramp after the values measured above were used to program the correction sextupoles to remove the observed non-linear dependence. The corrections were installed in a look-up table in the PC, which sent correction pulses to the magnet controllers during the ramp.

IMPLICATIONS FOR OPERATION OF HERA

Our measurements establish that the sextupole field measurements in the reference magnets can be used to predict changes in the machine chromaticity. A system is now being built which will feed the measurements from the sextupole coils back into currents in the correction sextupoles and thus compensate the persistent current effects both at 40 GeV and during acceleration.

For reasons of beam dynamics it is desirable for the chromaticity to be slightly positive (perhaps 4 ± 2 units). During the next period of operation, by controlling more carefully the time at 40 GeV and the timing of the tune measurements, we should be able to test whether the reference magnet system gives control of the chromaticity at this level. It will also be important to make measurements at higher ramp rates to test for ramp rate dependent effects (the design rate is 1.3 GeV/sec)

ACKNOWLEDGEMENTS

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