OPERATIONAL CHALLENGES OF HERA'S SUPERCONDUCTING PROTON MACHINE

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Abstract

Compared to its luminosity energy of 920 GeV HERA's superconducting proton machine has a rather low injection energy of 40 GeV. During the cycling procedure of the superconducting magnets eddy currents are induced in the superconducting cables. These persistent currents decay over hours during injection and ramp. The magnetic field components driven by these persistent currents are detrimental to the beam and therefore have to be measured and compensated. In this paper the methods are described to adjust the beam energy, the betatron tunes and the chromaticity both during injection and on the ramp.

1. HERA

HERA, the 'Hadron Electron Ring Accelerator' at DESY, is an electron proton collider for high energy physics. Two rings are placed in one tunnel of 6.3 km circumference. The superconducting proton ring has an injection energy of 40 GeV and a flat top energy of 920 GeV. Typically 100 mA are stored in 180 bunches. In the electron ring (12 – 27.5 GeV) typically 50 mA of either electrons or positrons are stored in 189 bunches with a typical spin polarization of 60%.

In the four straight sections of the HERA ring four experiments are making use of the HERA beams: Both H1 and ZEUS use colliding beams to probe the structure of the proton. Hermes uses the polarized electron beam and a polarized internal gas target to investigate the spin structure function of the proton. HERA-B uses a thin wire target in the halo of the stored proton beam to look for CP-violation.

2. HERA'S SUPERCONDUCTING PROTON MACHINE

Between the injection energy of HERA's proton machine and the flat top energy there is a factor of 23 in energy, and accordingly a factor of 23 in current density in the cables of the main dipoles and quadrupoles. This results in a low current density at injection, which gives much room for persistent currents in the superconducting cables. At 40 GeV the field contribution of the persistent currents to the dipole field is 5×10^{-3}. The persistent currents have decay times of the order of a few hours.

Figure 1 shows the proton energy and beam current from the end of a luminosity run to the beginning of the next run. On the horizontal axis the time is given in hours. It can be seen that it takes approximately 35 minutes to fill the proton machine. After injection energy has been reached, a few low current test injections a needed to adjust parameters like beam energy, betatron tunes, chromaticity and injection orbit. Afterwards HERA is filled with three consecutive fills of the preaccelerator PETRA. Then it takes another 25 minutes to ramp up the beam energy. During injection the field components resulting from the persistent currents are constantly changing. At the beginning of the energy ramp persistent currents are induced again.

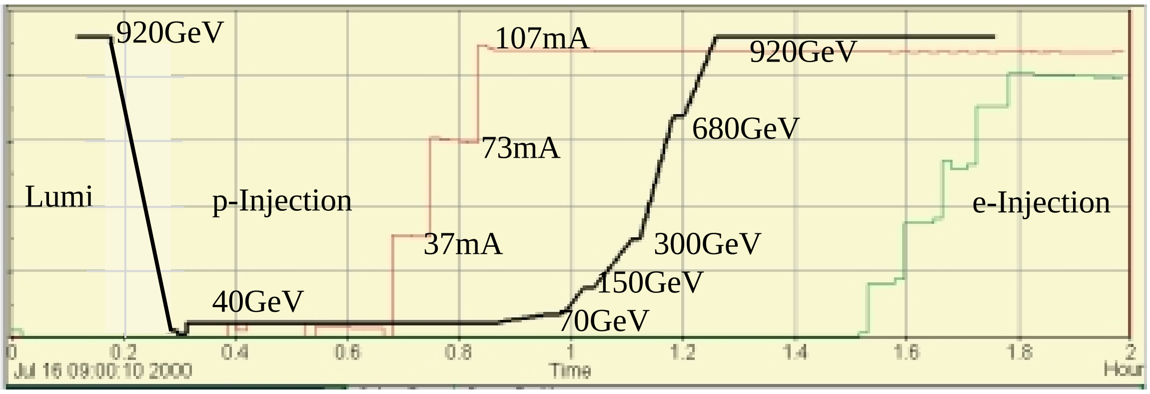

Fig. 1: Data from the HERA archive, showing a refill of the machine from beam dump to luminosity in 2 hours

3. PERSISTENT CURRENTS

Due to the low current density at injection energy there is much room for persistent currents in the cables of the main dipole and quadrupole magnets. Every change in the current driven by the magnet power supply induces magnetic fields in the cables, which then do induce electric eddy currents in the cables. Figure 2 shows a sketch of a strand of superconducting cable with the main current IMAIN, the main magnetic field B and the induced persistent currents I_{PC}.

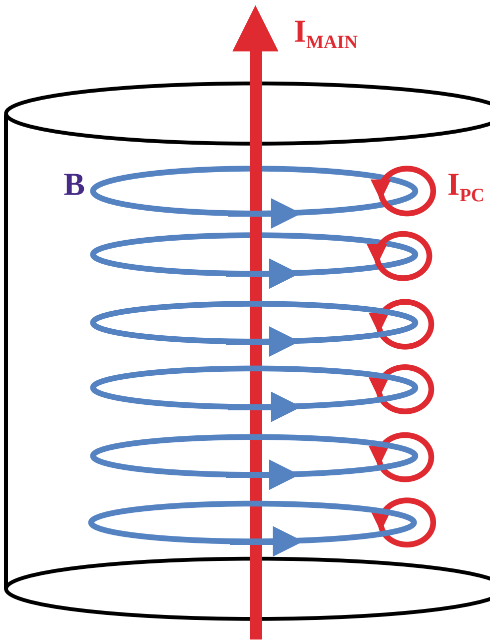

Fig. 2: Sketch of the electric and magnetic fields inside the superconducting cable

As the cable is superconducting, these eddy currents (or persistent currents) decay slowly with typical decay times on the order of hours. Therefore the corresponding magnetic fields (counteracting the main field) decay on the same time scale. For eddy currents perpendicular to the main current the resistance of the superconducting cable is higher than for the main current, as the cable is made up of thousands of small strands. Figure 3 shows a photograph of the cable.

Fig. 3: HERA’s superconducting cable is made up of 24 wires, 1230 filaments each, with a diameter of 14 microns

The field components driven by the persistent currents are mainly dipole and sextupole fields. The contribution of the persistent currents to the dipole field at 40 GeV is 5×10^{-3}, the contribution of the persistent currents to the chromaticity at 40 GeV ($\zeta_{x,PC} = -275$) is about 5 times that of the natural chromaticity ($\zeta_x = -44$) [1].

At the beginning of the proton energy ramp, persistent currents are induced again, leading to nonlinear changes of some field components on the ramp. At higher energies, as the current density in the cable rises, the persistent currents become smaller, until there is no more room for persistent currents in the cables.

4. DIPOLE AND SEXTUPOLE CORRECTION DURING INJECTION AND RAMP

Two HERA dipole magnets (one from each production series) are installed outside the ring, but powered in series with the ring dipoles. In these reference magnets a set of hall probes, NMR probes and rotating coils are used to measure the dipole and sextupole fields during injection and on the first part of the ramp. From 150 GeV on the sextupole component in the dipole magnets becomes so small compared to the main dipole field that the measurement is no longer needed.

From the measured field components corrections are calculated and applied to the horizontal corrector coils and the sextupole magnets in the ring.

5. ADJUSTING THE INJECTION ENERGY

The contribution of the persistent current driven dipole field to the main dipole field at injection energy is of the order of 5×10^{-3} (i.e. 10Γ). Depending on the history of the magnet cycle and the time between the magnet cycle and the injection, the uncorrected dipole field differs from injection to injection. Therefore after each magnet cycle a low current test injection is used to measure the energy of the injected beam relative to the stored beam. If the energy of the injected beam differs from the energy given by the dipole field, the injected bunches will perform synchrotron oscillations around their nominal bunch position. The amplitude of the synchrotron oscillation is measured with a fast beam current monitor and a fast oscilloscope. If the oscilloscope is triggered with the theoretical bunch position, the difference in time between a bunch signal taken a quarter synchrotron oscillation after injection and a signal of the stored bunch is a measure of the energy difference between injected beam and the energy given by the dipole field. With a known calibration factor the dipole field can be adjusted to the energy of the injected bunches. The smallest possible steps in dipole current correspond to relative energy changes of 10^{-4}. In order to avoid hysteresis effects and additional persistent currents in the main dipole magnets, the integral field of all horizontal corrector magnets is used instead with a minimum step size corresponding to a relative energy change of 4×10^{-6}.

For each proton injection the beam energy is adjusted in three steps: First the sum of the field from the reference magnets plus the field from the horizontal correctors is adjusted to the last known good value. Then a test beam with low current is injected; the energy is measured and corrected. Then, as the persistent currents in the reference magnet decay, the horizontal correctors are automatically adjusted to compensate for the changes in dipole field as long as the beam is at injection energy.

6. BETATRON TUNES

As there are no major quadrupole components in the fields driven by the persistent currents, there is no online tune correction at injection. Before beam is injected, the betatron tune quadrupoles are set on the last known good value. After a low current test injection the tunes are adjusted manually. When the beam energy is ramped up, there is a threefold ‘tune controller’: The currents of the tune quadrupoles are changed linearly from file to file (for 40 GeV, 70 GeV, 150 GeV, 300 GeV, 680 GeV and 920 GeV there are files containing all magnet currents for stable operation at these energies). Deviations from the linear behavior are recorded on typical ramps and applied on the following ramps. Last but not least the operator controls the tunes manually.

7. CHROMATICITY

As the sextupole components driven by the persistent current decay during injection, there is an online chromaticity correction using the field data from the reference magnets. First, before injecting beam, the two families of sextupoles are set on the last known good values. After injection of a low current test beam, the chromaticity is adjusted to +3 +/–1 by an automated procedure (change of the rf frequency, measurement of the tune deviation). Then the online sextupole correction keeps the chromaticity constant during injection. When the beam energy is ramped up, persistent currents and therefore sextupole components are reinduced. On the ramp there is a fourfold ‘chromaticity controller’: The currents in the sextupole magnets are changed linearly from file to file. From 40 GeV to 150 GeV the online correction compensates for the nonlinear field changes measured in the reference magnets. From 150 GeV on deviations from the linear behavior are recorded on typical ramps and applied on the following ramps. Last but not least the operator controls the chromaticity manually by looking at the betatron tune spectra. A flat tune peak is a sign for a chromaticity well above +3, which may course bad beam lifetime. A very sharp peak is an indication for low chromaticity approaching zero. Here the chromaticity should be increased immediately to avoid beam instabilities.

8. ACKNOWLEDGEMENT

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References

[1] B. Holzer, C. Montag: ‘Reproducibility and Predictability of Persistent Current Effects in the HERA Proton Storage Ring’, Proceedings of the 7th European Particle Accelerator Conference EPAC 2000, Vienna, June 2000, and further references therein.