THE STATUS OF HERA

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Abstract:

The preaccelerator chains are operational delivering 13 GeV electron (positron) and 40 GeV proton beams to the HERA rings. The electron ring has achieved 27.5 GeV at 5% of the design intensity and with a beam lifetime of several hours. The first octant of the proton ring was cooled down last summer, the quench protection was successfully tested and the optics was checked using a 7 GeV positron beam.

The HERA proton ring was completed in early November 1990 and it has been at cryogenic temperatures since mid December. The steady state condition at 4.4 K could easily be established and the measured cryogenic heat load of the ring is below the predicted value. Commissioning with beams started end of March with a 7 GeV positron beam and continued through April with the injection of single 40 GeV proton bunches. A stored beam was obtained just a few days after the first injection. Presently the lifetime is 30 min for single low intensity proton bunches at 40 GeV.

I. INTRODUCTION

The electron proton colliding beam facility HERA has two distinct features: it is the first electron-proton collider ever and it has been built in an international collaboration. Institutions in Canada, CSFR, France, Israel, Italy, The Netherlands, PR of China, Poland, United Kingdom and the USA have contributed either in kind or by delegating skilled manpower to the project. A picture of the two accelerators is shown in Fig. 1. The parameters of the collider and further details can be found in [1-4].

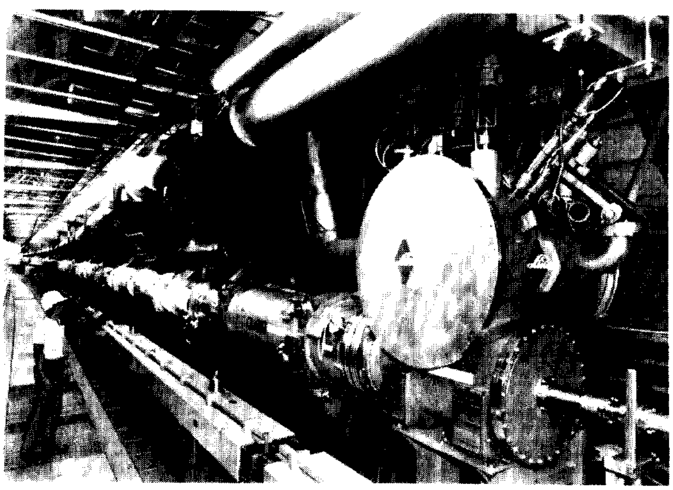

Fig. 1 - A view of the two rings at the end of a quadrant. The helium transferline and a feedbox are also shown.

II. PREACCELERATORS

The electron (positron) and the proton injection chains have been described elsewhere [3]. The expected 6 min filling time of the electron ring is dominated by the 2 min cycle time of PETRA. Using a new longitudinal and transverse feedback system, the threshold for multibunch instabilities in PETRA has recently been raised from 2.6 mA to the design current of 60 mA [5].

The 50 MeV linear accelerator for negatively charged hydrogen ions is in routine operation and delivers a 6 mA beam with a normalized 95% emittance of 3.3 πmm mrad horizontally, 5.7 πmm mrad vertically, and a momentum spread of $\pm$ 0.1%.

The negatively charged hydrogen ions are stripped upon their injection into DESY III. After a multiturn injection, protons are captured into 11 buckets, spaced 28.8 m apart as in HERA, accelerated to 7.5 GeV, and transferred to PETRA II. The design intensity of 1.1·E12 protons can be injected and accumulated in DESY III with high efficiency, however, only 50% reach 7.5 GeV. The main loss occurs at flat bottom and is associated with space-charge blow up, field non-linearities and inefficiencies in the rf capture of the coasting beam. A transverse instability is also observed in the early part of the cycle. Associated with the early beam loss is a reduction in emittance. During acceleration the normalized transverse emittance grows by roughly a factor of 3. The longitudinal emittance at 7 GeV is 0.16eVs in rough agreement with the prediction.

The maximum number of 70 bunches at 10% of the design intensity has been accumulated in PETRA II and accelerated to the final energy of 40 GeV. The lifetime was 1 hr at 7.5 GeV and increased to more than 10 hrs at 40 GeV. The cycle time of 5 min is limited by the tune shift caused by eddy currents in the thick aluminium vacuum chamber. The tune shift is measured in real time using a fast Q-measuring system [6]. It is compensated by varying the current in two distributed quadrupole circuits.

III. THE ELECTRON RING

While the first run of the electron ring in August 1988 was mainly used to inject and store a beam, a second run in September 1989 focussed on the performance of the ring. The results are summarized below:
- The injection efficiency into HERA at 7 GeV and 13 GeV was 93%.
- The electron beam was ramped to 27.5 GeV without loss.
- The beam lifetime was 5 hrs at low current and high energy.

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- The maximum single bunch current was 2.49 mA, nearly a factor of 10 above the design value.
- The maximum current in a multibunch mode was 2.87 mA or 5% of the design value. The main limitations were low accumulation rate, poor lifetime at high currents, but also horizontal instabilities.
- The measured luminosity optics was in good agreement with the predicted values.
- The vertical dispersion after orbit correction was 15 cm, corresponding to a 5% vertical coupling.
- The dynamical aperture was 9 π mm mrad, corresponding to 11.9 standard deviations at 35 GeV.

During the present six weeks' shutdown several new components will be installed in parallel to the effort needed to restore the integrity of the electron ring.

To reach the design current of 56 mA a longitudinal and transverse damping system [5] similar to the tested PETRA system will be installed.

The conventional rf system will be augmented by a set of 16 four-cell 500 MHz superconducting cavities [7], assembled pairwise into 8 cryostats. These cavities have been industrially produced from high purity niobium (RRR=300). At the design current of 58 mA the gradient is limited to 1.7 MV/m due to the 100 kW power rating of the high power couplers. The cavities reach 3 MV/m at $Q = 3 \cdot E9$. At higher gradients, Q drops below $1 \cdot E9$ due to the presence of niobium-hydrogen compounds resulting from hydrogen dissolved in bulk niobium.

A picture of the first four cryostats installed in the HERA tunnel is shown in Fig. 2. These cryostats have been cooled down to the operating temperature of 4.2 K. Three more will be installed in May leaving the last one to search for remedies against the HNb_x problem. This system together with the conventional rf system is able to accelerate and store a beam up to the design energy of 30 GeV.

The transverse polarization of the circulating electron beam will be determined [8] by measuring the azimuthal asymmetry of a back-scattered polarized laser light. The components are ready for installation.

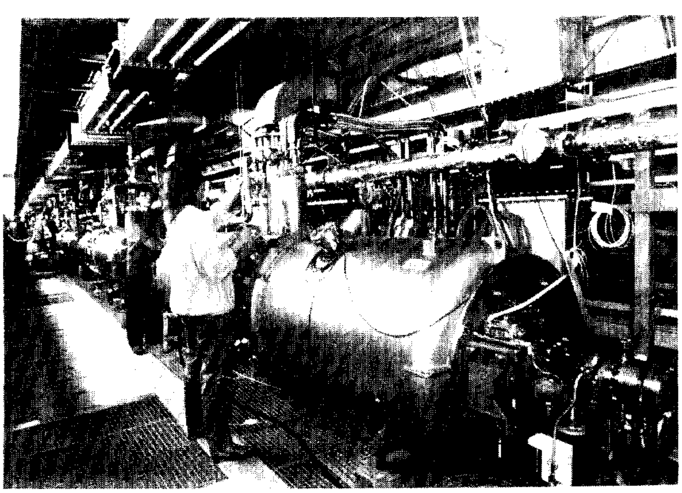

Fig. 2 - The first 4 cryostats installed in the HERA tunnel.

IV. THE HERA PROTON RING

The installation [9] of the proton ring components (including the helium distribution system) was completed by November 1990, roughly 6 1/2 year after authorization and in accordance with the original time schedule.The cryogenic system and the superconducting magnets are the most challenging components of HERA. I will first describe the status and the performance of these components and then discuss the results obtained during the first commissioning run.

IV.1 The Refrigeration System

The central refrigerator is located on the DESY site. It is subdivided into three identical plants each providing 6.6 kW isothermally at 4.3 K, 20.4 g liquid helium per second and 20 kW at 40 K to 80 K.

The cryogenic plant is very reliable, each of the three coldboxes has run for about 12000 hrs. Liquid helium and 40 K helium gas are supplied by a fourfold transferline to precoolers and feedboxes which are installed at the ends of each octant. The same transferline is used to return helium gas of 4.6 K and of 80 K to the refrigerator. In the case of a quench the warm gas from the quenched magnets is fed through a safety valve to a ring line which returns the gas to the storage vessels at a pressure up to 20 bar. A detailed description of the cryogenic system and its performance can be found elsewhere [10]. Here we only summarize the main results.

Of the 15 tons of helium stored in the magnets and in the transferlines some 5 tons have been consumed last year, mainly because of the testing of the superconducting magnets and of the helium distribution system.

The north half ring was cooled to the operating temperature of 4.4 K by mid October, the south half ring by mid December. The cooldown time of 140 hrs was determined by the condition that mechanical stresses caused by the temperature gradient within a magnet should be limited to 100 MPa - a factor of two below the critical values. All octants can be cooled down in parallel. A typical cooldown profile is shown in Fig. 3.

During Christmas the He plant was shut down and the magnet temperature rose from 4.4 K to 150 K. The proton ring has been kept at 4.4 K since the middle of January. Instabilities or pressure oscillations have not been observed during more than 3000 hours of operation of the complete ring.

Semiconductor temperature sensors are installed in the single-phase helium volume of each dipole, allowing to monitor the temperature with a precision of 0.02 K [11]. A first measurement of the heat load, using these monitors at a known mass flow, yielded a heat leak of 5.1 kW at 4.4 K and 28.5 kW at the shield level for the whole ring, including transferlines and feedboxes. These values com-

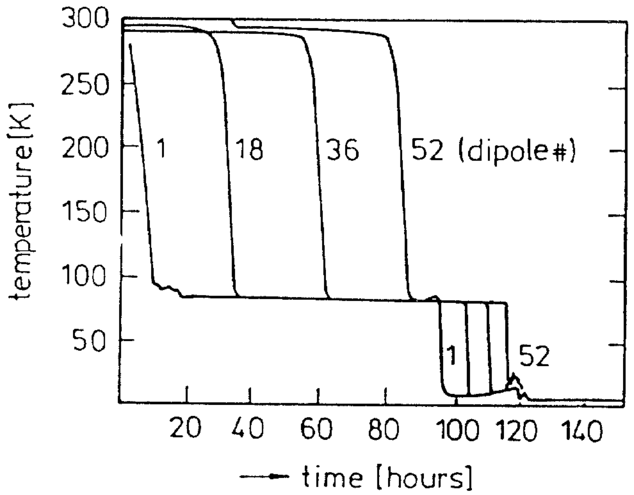

Fig. 3 - Cooldown profile of a HERA octant.

pare favourably to the proposal values. The heat leak of the magnets alone is 3.6 kW at 4.4 K and 19.6 kW at the shield level, in excellent agreement with heat leak measurements on single magnets.

At a current of 5020 A an additional heat load of 21 W at 4.4 K per octant was observed. Ramping the magnets at the nominal rate of 10 A/s led to a heat load of 80 W per octant at 4.4 K.

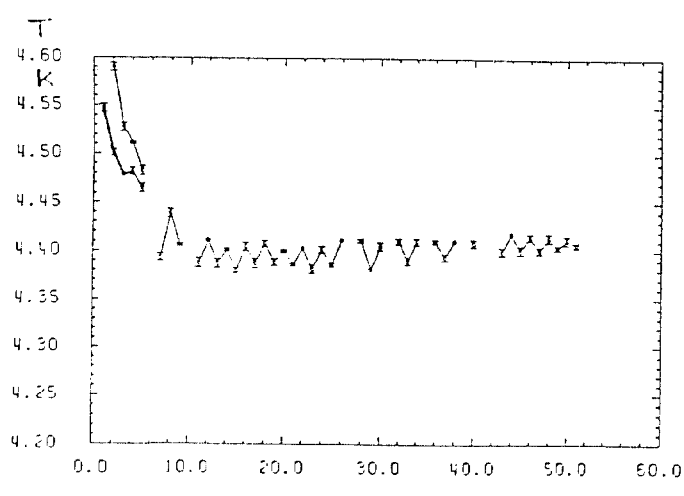

Fig. 4 - The temperature distribution measured in the dipoles along an octant. The re-cooling of the one-phase flow by heat exchange with the two-phase flow is clearly seen. The heat leak at the end of the octant is caused by the current leads.

IV. 2 The Superconducting Magnets

A total of 1819 superconducting magnets and correction coils has been installed in the HERA proton ring. In the arcs the superconducting magnets are arranged in 104 cells with an ordering shown in Fig. 5.

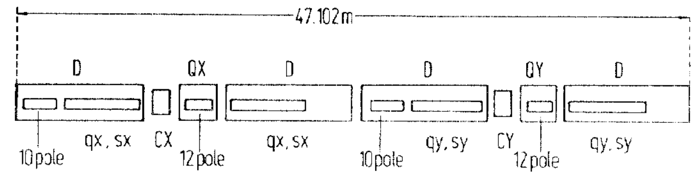

Fig. 5 - A unit cell of the proton ring. D: main dipole; QX, QY: main quadrupoles, qx,qy: quadrupole correction coils, sx, sy: sextupole correction coils, CX, CY: correction dipoles. In addition, there are 10-pole and 12-pole correction coils.

The design [12,13] and the performance [3,14] of the magnets have been reported elsewhere. Here we just summarize the main results. The industrial production of superconducting magnets was a success. During series production, DESY received an average of 8 dipoles and 6 quadrupoles per week, exceeding the contractual rates. Out of 449 dipoles and 246 quadrupoles, only 5 magnets were rejected, four of which had shortened windings and one a bad spot in the superconductor.

All magnets were tested [15] at liquid helium temperature and the results can be summarized as follows: Nearly 93% of the magnets reached the critical current at the first or second excitation. Adjusted to an operating temperature of 4.4 K the average quench current was (6900 ± 130) A for the dipoles and (7840 ±160) A for the quadrupoles. Only magnets with a quench current above 6600 A were installed in HERA. The field quality of both the dipole and the quadrupole magnets is better than specified. The field integrals of the dipole magnets produced in Italy and Germany differ systematically by 0.19%. Among the dipoles from one vendor the rms variation is 0.05%. The integrated quadrupole gradient has an rms spread of 0.085%.

The direction of the dipole field varies along the magnet by (0.5 ± 1.6) mrad. The dipole magnets are installed such that on the average the protons have no vertical deflection. The field direction of the quadrupoles with respect to gravity is (1.5 ± 1.1) mrad. The position of the quadrupole axis at 4.7 K agrees horizontally to (0.02 ± 0.36) mm and vertically to (-0.38 ± 0.32) mm with the positions as determined by the manufacturers at room temperature. The data from the magnetic measurements were used for the alignment in the tunnel.

At the low injection field of HERA the persistent current multipoles [14,15] are large. However, they vary little from magnet to magnet and are compensated by the multipole coils which are wound directly on the dipole and quadrupole beam pipes.

Caused by flux creep in the superconductor and other effects, the magnetization current decays with a nearly logarithmic time dependence. This drift is also compensated using the correction coils.

In order to determine the required strength of the correction elements at injection and during acceleration, the dipole and sextupole fields will be measured continuously in cold "reference magnets", powered in series with the ring magnets.

IV. 3 Commissioning of the Proton Ring

During last summer the first octant was cooled down and operated at liquid helium temperature for several months. A 7 GeV positron beam was injected and passed through the 632 m long octant without the use of steering coils. To minimize the effects of the persistent-current sextupole the magnets were - prior to injection - cycled in temperature from 4.4 K to 20 K and back to 4.4 K and then excited to a predetermined maximum before setting the current corresponding to a 7 GeV beam. This procedure reduced the sextupole field in the dipoles by almost two orders of magnitude. The positron beam was used to calibrate the beam position monitors and to measure the optical parameters of the octant which were found to be in agreement with the predictions.

After a careful test of the quench protection system the magnets were powered to 6000 A which corresponds to a proton energy of 980 GeV. Induced quenches in single magnets at currents up to 5600 A and a current decay time of 18 s (300 A/s) did not cause the quench to propagate. The magnets could be ramped at the nominal rate of 10 A/s and be powered at 5027 A without a spontaneous quench. Finally, all magnets in the octant were quenched simultaneously at 6000 A. No helium was lost and operation continued after 6 hours.

The first test run with the completed proton ring started on March 4th and continued through April. The first three weeks in March were used to activate the interlock system and complete the first commissioning of the 400 power supplies needed to run HERA. In parallel a 40 GeV proton beam was extracted from PETRA and transferred to the injection septum magnet of HERA. In the last week of March a 7 GeV positron beam was injected into HERA and used to adjust the timing of the beam position monitors. The magnets were temperature- and current-cycled to erase any persistent-current sextupoles. The horizontal correction dipoles were used to compensate for the different bending strengths of the two groups of dipoles. After commissioning of the complex synchronization system between PETRA and HERA the beam was threaded around the HERA ring and several turns could be obtained using a few correctors only.

An image of the injected beam and the overlap of five turns on a screen positioned at the septum magnet is shown in Fig. 6.

A coasting beam was obtained after orbit correction. Turning on the 52 MHz rf system resulted in a stored beam with a lifetime of 30 s. The commissioning was greatly eased by the excellent performance of the beam position monitors [16]. The tune measurement system [6] and the beam profile monitors [17] worked immediately. Fig. 7 shows a measured beam profile.

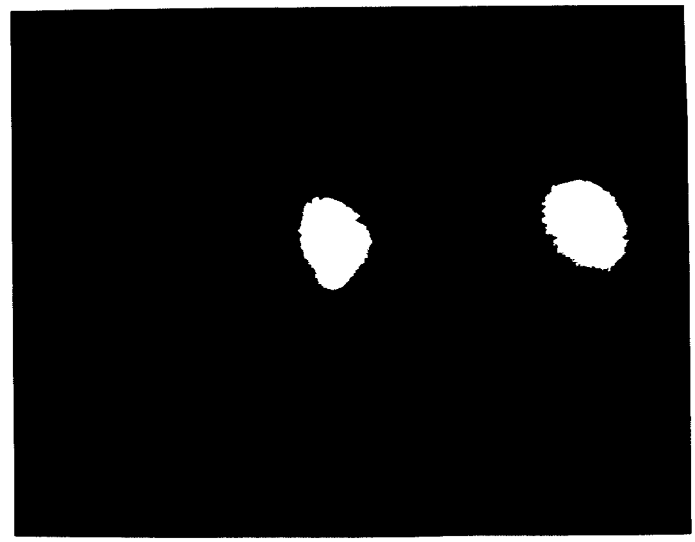

Fig. 6 - Images of the injected beam (right spot) and of 5 successive turns (left spot) on a screen close to the septum magnet. The distance between the spots is 3 cm.

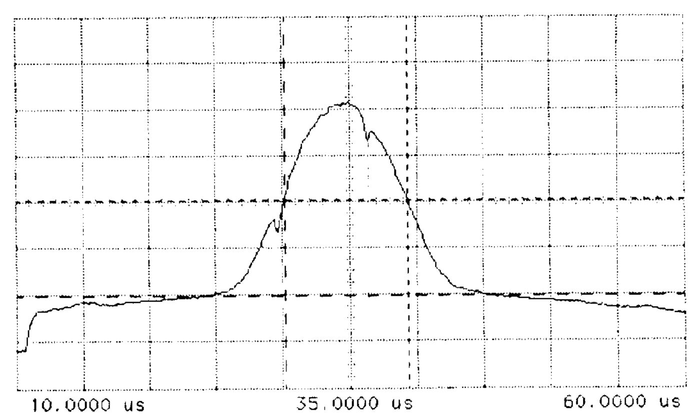

Fig. 7 - Beam profile measured with the residual gas monitor. Full width at half height is 13.8 mm.

The experience gained in the first run can be summarized as follows:
- Linac III and DESY III worked reliably during the whole period. The reliability of PETRA II as a 40 GeV proton accelerator must be improved.
- The complex timing and triggering system linking PETRA and HERA worked well in the single bunch mode. The multibunch mode was not yet available.
- The cryogenic system was very reliable. Some minor problems resulting from the process control computer have been corrected.
- The beam vacuum in the cold arcs was better than E-11 mbar. In the warm straight section East, which had been

baked out in situ at 250^{o}C, the vacuum was a few E-11. In the remaining three straight sections the vacuum was a few E-8, leading to an average pressure of some E-9.

- The injection and the beam abort system worked reliably.
- After some initial problems the 400 power supplies including the control system were reliable and reproducible.
- The proton 52 MHz rf system worked reliably. The 208 MHz system could not be tested in the time available.

Preliminary information was also obtained on the performance of the accelerator. Only single bunches were injected and the number of protons was kept between E8 and E10 per bunch to avoid accidental quenches.

- The transfer efficiency of a single proton bunch between PETRA and HERA was as high as 90%.
- The measured injection optics is in agreement with predictions.
- The pathlength difference between electrons and protons agrees with the expectation to within 3 mm.
- The beam intensity at injection decays nearly exponentially with a time constant of at least 30 min (see Fig. 8). Beam-gas multiple scattering is one possible explanation of this behaviour. There is a hint that particles with large amplitudes have a shorter lifetime indicating some influence of non-linear resonances.
- Persistent current effects are not important at present lifetimes and intensities.
- Crossing the 4th order resonance leads to loss of beam.
- Crossing the 5th and 6th order resonance influences the beam lifetime.
- The acceptance of the proton ring was of the order of 1.5 πmm mrad.

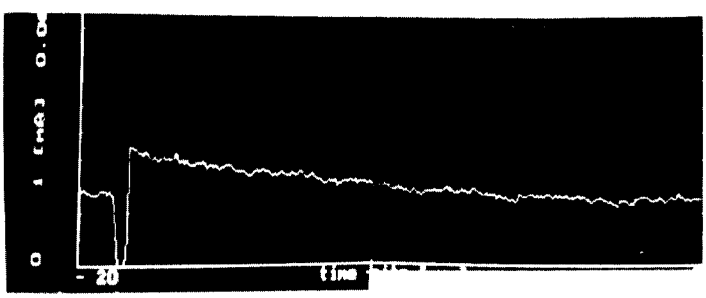

Fig. 8 - Intensity versus time for a bunch of 5 · E9 injected protons. Total time range is 20 min. Visible at the left side are the extraction of the previous bunch and the new injection.

After the 6 weeks' shutdown which started on May 2nd, the commissioning will resume with an electron run. In parallel the quench protection system for the proton magnets will be checked at currents up to 5000 A. Late July the commissioning of the proton ring will continue with the aim of providing luminosity for the H1 and ZEUS experiments towards the end of the year.

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