THE STATUS OF HERA

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Abstract: HERA, the electron proton colliding beam facility now under construction in Hamburg has two distinct features. It is the first electron-proton collider ever and it is being built in an international collaboration modelled after the construction of large experimental facilities. Institutions in Canada, CSR, France, GDR, The Netherlands, Israel, Italy, Peoples' Republic of China, Poland, United Kingdom and the USA are contributing either in kind or by delegating skilled manpower to the project.

The HERA project was authorized in April 1984 and it is now nearing its completion.

Electrons were first injected and stored in the HERA e-ring in August 1988. In a second commissioning run in September 1989 electrons were accelerated to 27.5 GeV and stored with lifetimes of several hours. To reach the nominal energy of 30 GeV a set of 64 superconducting r.f. cavities are under construction and will be installed in HERA before the end of the year.

The central helium refrigeration system has operated extremely reliably for the past three years. The 6.5 km long helium distribution system has been installed and in part commissioned. The industrial production of superconducting magnets is coming to an end with all quadrupoles and correction magnets and some 90 % of the dipole magnets delivered. More than 70 % of the superconducting magnets have been installed in the tunnel and the first octant is now being commissioned at liquid helium temperatures. The first cooldown of the complete proton machine is scheduled for the end of 1990.

Introduction

The main HERA parameters are listed in Table 1.

Table 1: General Parameters

	p-ring	e-ring	units
Nominal energy	820	30	GeV
Polarization time		28	min
Luminosity	1.5×10^{31}		$cm^{-2}s^{-1}$
Space between IR Quad	15		m
Interaction points	4		
Crossing angle	0		mrad
Circumference	6336		
Magnetic field	4.68	0.165	T
Number of particles	2.1	0.8	10^{13}
Number of bunches	210		
Injection energy	40	14	GeV
Filling time	20	15	min
σ_x/σ_y at I.P.	0.29/0.07	0.26/0.02	mm
σ_z at I.P.	110	8.0	mm
Energy loss/turn	6.24×10^{-6}	127	MeV
Circumferential RF voltage	0.2/2.4	260	MV
RF-frequency	52.033/208.13	499.776	MHz
RF-power	1	13.2	MW
Refrigerator	21.0 kW (isothermal at 4.3K) 60 g/s Liq.He 60 kW (40 K - 80 K)		

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The layout and a technical description of the HERA project can be found elsewhere [1-4].

The Electron Ring

The first commissioning run of the electron ring in August 1988 was very successful and a stored beam was obtained only a few days after the ring had been closed. Whereas this run was mainly used to commission various components, a second run, carried out in September 1989, was focussed on the performance of the ring.

The main results can be summarized as follows:

- 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 hours at low currents and high energy.
- The maximum single bunch current was 2.49 mA corresponding to $3.26\cdot10^{11}$ electrons per bunch or 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 current was mainly limited by low accumulation rate and poor lifetime at high currents, but horizontal instabilities were also observed.
- The measured luminosity optics was in good agreement with the predicted values.
- The vertical dispersion after orbit correction was 15 cm, corresponding to 5 % vertical coupling.
- The dynamical aperture in the transversal plane was 9 mm mrad, corresponding to 11.9 standard deviations at 35 GeV.

The status of the e-ring components which have not yet been installed is given below.

The final vacuum system over a distance of ± 50 m adjacent to the interaction point is under construction and will be installed in the autumn of this year.

A longitudinal and transverse damping system modelled after the system [5] successfully tested in PETRA is now being constructed and will be installed in HERA later this year.

The conventional r.f. system will be augmented by a set of superconducting cavities [6]. A prototype, made of two 4 cell 500 MHz cavities installed in a single 4.2 m long cryostat, has been tested at PETRA. Both cavities reached an accelerating gradient of 5 MV/m at $Q = 1.5\cdot10^{9}$. Based on this test an order for sixteen 4 cell cavities assembled pairwise into 8 cryostats has been placed with industry.

The delivery of these cavities, which are made of high purity niobium (RRR = 300), is now underway. The first cavities have reached gradients from 7 to 8.5 MV/m and Q-values of 2 to 3 $\cdot10^{9}$ at low field, compared to the design value of 5 MV/m, respectively $2\cdot10^{9}$. A measurement of the static heat load of the three first cryostats yielded 3 Watt at the 4.2 K level and 70 Watt at the shield level. Cold helium will be provided by the central helium plant and the distribution system is now being installed.

In Fig. 1 the maximum HERA electron energy is plotted versus the beam current for the normal conducting r.f. system alone and with the superconducting system. At high currents the energy is limited by the power rating of the r.f. windows, at lower currents by the assumed gradient of 5 MV/m.

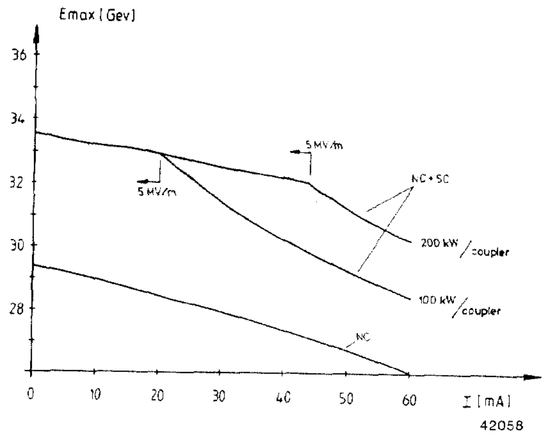

Fig. 1 Maximum electron energy versus stored current for the normal conducting r.f. system alone and augmented by the superconducting system.

A spin rotator [7] has been assembled and is ready for installation in straight section East. However, it is prudent to demonstrate the existence of transverse polarisation before installing the spin rotators.

The Proton Ring

The conventional components of the proton ring have to a large extent been installed and are now being commissioned.

The 123 conventional magnets which guide the protons in the straight sections over an accumulated distance of 1 km have all been installed. The installation and testing of this part of the vacuum system is nearly complete.

The superconducting magnets and the helium production and distribution system are the most challenging components. I will now describe the status and the performance of these components.

The Refrigeration System

The refrigeration plant 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. Liquid helium and 40 K helium gas are supplied by a fourfold transfer line to feed boxes which are installed at the ends of each octant. The same transfer line is used to return helium gas of 4.6 K and of 80 K to the refrigerator.

The performance of the helium plant [8] meets or exceeds the specified values listed above. The plant is rather efficient, 287 Watt of electrical power are required to produce 1 Watt of cooling power at 4.2 K.

The 4-fold transfer line [9] has been installed in the tunnel. It has been operated without any difficulties for several months providing helium to the two experiments installed in Hall South and Hall North, respectively. Preliminary measurements of the heat leak yielded 0.2 Watt/m at 4.6 K and 1 Watt/m at the shield level in rough agreement with the specifications.

The 23 feed boxes needed to provide helium to the ring and to the experiments have been installed. A part of the system has been tested successfully at liquid helium temperatures.

In the case of a quench the quenched magnet is by-passed by a set of cold diodes. The quench is detected [10] by a balanced bridge circuit using the dipole half coils as a part of the bridge. Heaters in the coils of the quenched magnet are fired, the power supply is disconnected from the magnets and the stored energy is dumped in external resistors. The warm gas from the quenched magnets is fed through a safety valve to a ring line which returns the gas to storage vessels at a pressure up to 20 bar.

The Superconducting Magnets

The superconducting magnets [11] in the arcs are arranged in 104 cells and the ordering within one such cell is shown in Fig. 2.

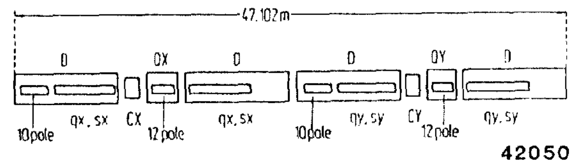

Fig. 2 A unit cell of the HERA proton ring. D - main dipole; QX, QY - main quadrupole; qx, qy - quadrupole correction coils; sx, sy - sextupole correction coils; CX, CY - correction dipoles. In addition there are 10-pole and 12-pole correction coils.

The main dipoles and the quadrupoles are powered in series with the forward current flowing through the dipoles and the return current through the quadrupoles. A small, auxiliary supply in the quadrupole circuit makes it possible to simultaneously change horizontal and vertical betatron tunes.

Status Superconducting Magnets

A total of 416 superconducting dipole magnets [12], 8.824 m long and 6 vertically deflecting dipole magnets 3.356 m long are needed to complete the HERA ring. The nominal field of 4.682 T, corresponding to 820 GeV, is reached at an excitation current of 5027 A.

Three of the 30 preseries magnets went through the accelerator life test which consisted of 30 temperature cycles between 40 K and 300 K, 2000 current excitation cyles and some 100 spontaneous quenches at currents 25 % above the nominal operating current. These magnets were then disassembled and inspected. After the correction of minor faults the series production of collared coils was released in the spring of 1988 and the production of the complete magnet at the end of 1988.

Istituto Nazionale di Fisica Nucleare in Italy contributes half of the dipole magnets to the HERA project and these magnets are being manufactured by a group of Italian firms. The remaining part is being built by German industry.

A total of 392 magnets have been delivered and we expect the series production to be completed by July 1990.

The quadrupole magnets have been developed by CEA, Saclay [13]. A total of 224 magnets with lengths between 1.861 m and 1.514 m are needed. The nominal gradient at 820 GeV is 90.18 T/m. The production of the quadrupoles was divided between a French firm which produced the magnets contributed by France to the HERA project and two German firms. After the successful completion of the accelerator life test the series production of collared coils was released in early 1988 and the production of the complete magnets in mid 1988. The series production was completed in September 1989.

The sextupole/quadrupole correction coils [14] and the superferric dipole magnets have been designed in collaboration between DESY and NIKHEF. These magnets (440 S/Q-coils and 250 dipoles) have been financed by the Netherlands and produced by Dutch companies. All the correction magnets have been produced, tested and accepted. The quench currents exceed the operating current by a factor of 2 to 3. The field quality is also a factor of 3 better than required.

Some 40 superferric quadrupoles have been designed and produced at DESY. The measured quench current exceeds the operating current by a factor of 3.

Magnetic Measurements

After passing the mechanical and electrical acceptance measurements at room temperature the magnets are tested [15] at liquid helium temperature. The turn-around time for the cold measurements is 80 hours per magnet.

So far 328 dipole magnets and 230 quadrupole magnets have passed the cold test. The results are summarized below:

- None of the magnets quenched below the nominal operating current of 5027 A. Each magnet was quenched on the average five times, and 95 % of all magnets reached the short sample critical current on the first or second quench. Due to heat leaks caused by the warm measurement tube inside the cold beam pipe the ambient temperature of the coil during these measurements was 4.75 K leading to an average quench current of (6455 ± 126) A for the dipoles and (7388 ± 144) A for the quadrupoles. Adjusted to an operating temperature of 4.4 K this corresponds to a quench current of (6910±135) A for the dipoles and (7840 ± 150) A for the quadrupoles. Only dipoles with quench currents exceeding 6600 A at 4.4 K will be installed in the ring.
  It has been shown that at least up to currents of 7500 A the dipole quench limit is determined by the critical current of the conductor and not by mechanical forces.
  The field quality of both the dipole and the quadrupole magnet is excellent. The skew and normal multipoles measured in the dipoles at 5000 A are plotted in Fig. 3.

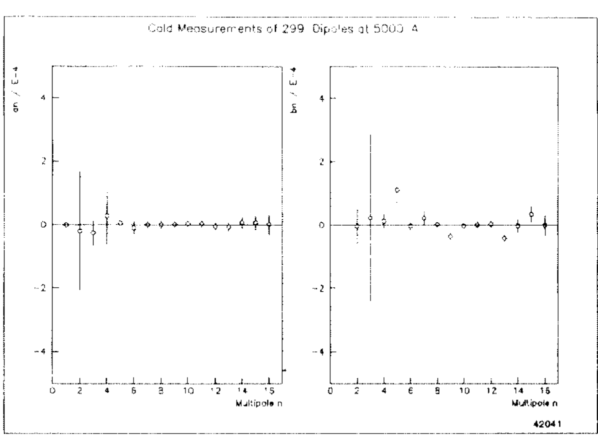

Fig. 3 The average value of the multipole coefficients at full field normalized at 2.5 cm to the dipole field.

The magnetic lengths of the dipole magnets produced in Italy and Germany differ by 0.1%. Among the dipoles from one vendor the length has an rms variation of 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 position of the quadrupole axes 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 are used for the alignment in the tunnel.

Persistent Currents

Persistent magnetization currents are induced in the niobium-titanium filaments whenever the field of a superconducting magnet is changed. These magnetization currents will generate all allowed multipoles with strengths which are proportional to the filament diameter and the critical current density $J_c(T,B)$. The persistent current effects are therefore particularly strong at injection and can be neglected at full field. A complete discussion of these effects for the HERA magnets can be found in Ref. 16.

The skew and normal multipoles measured at the injection field are plotted in Fig. 4. In addition to the dipole also the sextupole and the decapole receive large contributions from the magnetization currents.

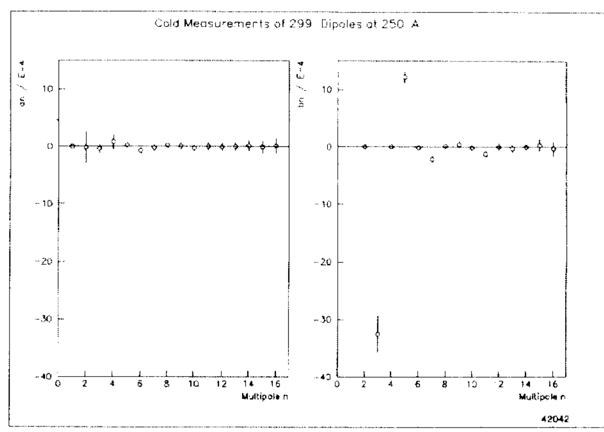

Fig. 4 The average values of the multipole coefficients at injection field normalized at 2.5 cm to the dipole field.

The values of the persistent current multipoles, measured 200 s after reaching the injection energy, are listed below:

Dipole (inside correction coils):

$$b_3 = (31.3 \pm 1.6)\ 10^{-4}$$

$$b_5 = (12.5 \pm 1.2)\ 10^{-4}$$

Quadrupole:

$$b_6 = (20.3 \pm 2.7)\ 10^{-4}$$

Although these multipoles are large they vary little from magnet to magnet and are compensated by a constant excitation current in the multipole coils which are wound directly on the dipole and quadrupole beam pipe (Fig. 2).

Presumably caused by flux creep in the superconductor, the magnetization current decays as shown in Fig. 5 with a nearly logarithmic time dependence.

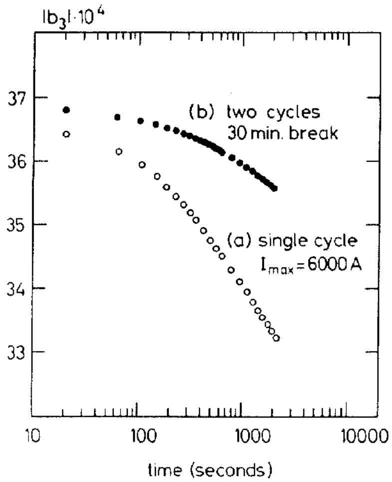

Fig. 5 - Time dependence of the absolute value of the sextupole coefficient at a dipole current of 250 A for the current cycles (a) and (b).

The decay rate of the persistent current multipoles depends strongly on past history and is different for cables made by different manufacturers. In Table 2 the change in the persistent current multipoles between 200 s and 2000 s after reaching the injection field is given for magnets wound with cable produced by ABB and by LMI. Shown are data obtained with two different initial current cycles:

a) coil is quenched using heaters
   0 A - 6000 A
   6000 A - 50 A
   50 A - 250 A

b) 50 A - 5500 A - 50 A
   50 A - 2000 A - 250 A
   30 minute waiting period at 250 A
   250 A - 50 A - 250 A

Table 2
Change in persistent current multipoles between 200 s and 2000 s at 250 A

Multipole		ABB-cable	LMI-cable
n=1	(a)	(0.68±0.18)Gauss	(1.15±0.23)Gauss
	(b)	(0.24±0.08)Gauss	(0.40±0.10)Gauss
n=3	(a)	$(1.77\pm0.49)10^{-4}$	$(3.23\pm0.62)10^{-4}$
	(b)	$(0.80\pm0.18)10^{-4}$	$(1.27\pm0.33)10^{-4}$
n=5	(a)	$(0.73\pm0.16)10^{-4}$	$(1.04\pm0.21)10^{-4}$
	(b)	$(0.21\pm0.06)10^{-4}$	$(0.37\pm0.12)10^{-4}$

Note that by using cycle (b) the decay of the magnetization currents can be reduced by more than a factor 2 if needed. With both cycles the magnetization will approach its old value when an acceleration is resumed after injection.

In order to control the fields at injection and during acceleration the dipole field and the sextupole field will be measured continuously in cold magnets powered in series with the ring magnets. The data will be fed back to the correction magnets. Note that Italian and German built dipole magnets will be installed in different octants and can thus receive different corrections. The measured temperature variations of 0.05 K along an octant cause a totally negligible change in the persistent current multipoles.

Octant Test

An octant is 632 m long and consists of 52 dipole magnets and 27 quadrupole magnets with a total cold mass of 445 tons. An octant, which is the smallest cryogenic unit in the ring, is cooled as follows.

The supercritical helium (4 bar, 4.8 K) is passed through a heat-exchanger and enters the magnet chain at a pressure of 2.4 bar and a temperature of 4.35 K. At the end of the octant, the supercritical helium is expanded through a Joule-Thomsen valve and transformed into two-phase helium with approximately 95% liquid contents. The two-phase helium is returned to the feed box passing through tubes in the magnets which provide heat exchange with the supercritical helium. The heat loads on the individual magnets increase the vapour contents of the two-phase stream. The steady state is reached when the liquid helium level in the pre-cooler remains constant.

The shield is cooled using cold helium gas entering the octant at 14 bar and 40 K and returning to the refrigerator at the end of the octant.

The results [17] of the cryogenic test of the first octant can be summarized as follows:

- The resulting cooldown profile is shown in Fig. 6. The cooldown time was determined by the condition that mechanical stresses caused by temperature gradient within the magnets should be limited to 100 MPa - a factor of two below the critical value. With more experience this cooldown time can be reduced substantially.
- The steady state could be established easily. No instabilities or pressure oscillations were observed during 100 hours of steady state operation. At a flow rate of 40 g/s an average heating power of 200 W was required for the liquid helium level in the feed box to remain constant.
  Strong variations in the mass flow could easily be controlled by measuring the liquid helium level in the pre-cooler and regulated using the input flow valve and the heater.

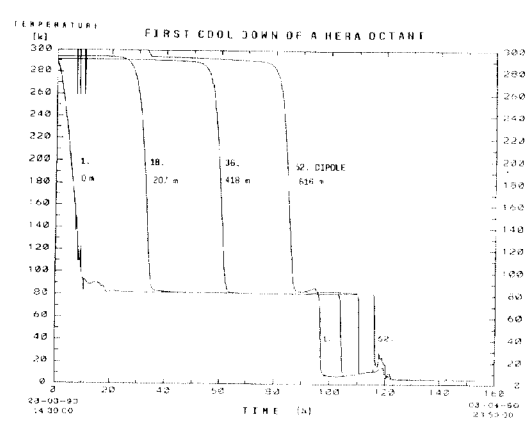

Fig. 6 The cooldown profile

- The steady state magnet temperature profile is pictured in Fig. 7. The total temperature drop of 50 mK is as expected from the two phase pressure drop including the hydrostatic contribution.

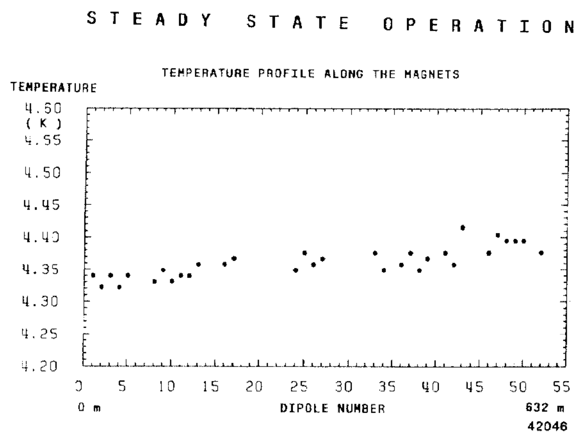

Fig. 7 The steady state temperature profile along the magnet.

- The total heat loads were measured in steady state condition. The total heat load including the feed box and the return box was 495 Watt at 4.4 K and 3017 Watt for the shield cooling. Both numbers are below the values in the proposal.
- The warm-up went smoothly and lasted for about 100 hours.
- Vacuum cold leaks did not develop.

Preaccelerators

A new e^+/e^--injection sequence has in part been implemented and tested.

450 MeV electrons and positrons from Linac II are injected unbunched at a rate of 50 Hz directly into PIA, accumulated into a single 60 mA low emittance bunch and transferred to DESY II with an efficiency of 100 %. In DESY II, with a rate of 12.5 Hz, the bunch is accelerated to 7 GeV and transferred to PETRA in a single cycle on axis injection with an efficiency of 100 %. In PETRA 70 bunches are accumulated, accelerated to 13 GeV and injected off axis into HERA. With this new sequence it will be possible to load the HERA e-ring in 6 min with $7.35 \cdot 10^{12}$ electrons divided into 210 bunches spaced 96 ns apart.

The e^-/e^+ filling time is dominated by the cycle time of PETRA. It is thus important to verify that the design current of 58 mA can be accumulated and accelerated in PETRA.

To that end a new multibunch feedback system [5] has recently been tested.

The longitudinal damper operates at 1 GHz acting on the beam via two cavities which are driven by a klystron of 100 kW maximum output power. The system has a 5 MHz bandwidth corresponding to the bunch spacing of 96 ns. All longitudinal beam modes of 80 bunches could be damped with a damping time of 400 μs. For comparison the Landau damping time is 20 msec.

Together with the improved transverse feedback system tested last year in PETRA, the beam was damped both longitudinally and transversally with an average damping time of 500 μs. The threshold for multibunch instabilities could be raised from 2.6 mA without feedback system to 45 mA with feedback system.

The proton preaccelerator chain is made up of a 50 MeV H^- linear accelerator, the 7.5 GeV DESY III synchrotron and the PETRA ring upgraded to 40 GeV, equipped and instrumented for proton acceleration. The protons never cross transition in the whole injection cycle since 7.5 GeV is below the 9 GeV transition energy in DESY III and above the 6.5 GeV transition energy in PETRA II.

In principle, with 70 bunches in PETRA II it should take 6 min to fill HERA with 210 bunches each filled with 10^{11} protons and spaced 28.7 m apart. The Linac is in routine operation and delivers a 10 mA beam in a normalized transverse emittance of 6 mm mrad and an energy spread of $1\text{-}2 \cdot 10^{-3}$.

The H^--ions are stripped and injected into DESY III. After a multiturn injection, protons are captured into 11 buckets, spaced 28.7 m apart as in HERA, accelerated to 7.5 GeV and transferred to PETRA II. At present, the maximum intensity is $1.7 \cdot 10^{10}$ protons per pulse or 20 % of the design intensity and is apparently limited by non-linearities caused by a magnetic seam in a fraction of the vacuum chambers. These chambers will be replaced during a shut-down in September.

The bending magnets in PETRA II limit the maximum proton energy to 40 GeV. The quadrupoles are rather weakly focussing resulting in large dispersion functions and β-functions of respectively 13 m and 70 m in the arcs.

The ground insulation of the PETRA II dipole coils had been damaged due to synchrotron radiation. The coils have been repaired and tested at 2 KV to ground, or about a factor of 2 above the maximum voltage required for 40 GeV operation.

The commissioning of PETRA II as a proton machine is now under way. Protons have been stored [17] with lifetimes on the order of 20 min at the injection energy. The optics is in agreement with the predictions.

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