Nuclear Physics Institute, Siberian Branch of the
USSR Academy of Sciences

Preprint

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Novosibirsk 1965

Translated at CERN by A.T. Sanders
and revised by N. Mouravieff
(Original: Russian)

(CERN Trans. 66-2)

Geneva
February, 1966

Experimental Study of Charge Exchange Injection of Protons into Accelerator and Storage Rings

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This report describes experiments on storing protons in a ring by a charge exchange method, with the set-up illustrated in Fig. 1. A beam of hydrogen atoms or negative ions is injected onto a proton orbit in a magnetic field at a point where the orbit intersects with a hydrogen jet. The particles lose electrons in the jet and are stored on the orbit in the form of protons. Passing repeatedly through the jet, the protons lose energy and scatter. In a constant magnetic field the storage time is limited by the deviation of the circulating protons towards the inside wall of the storage ring because of energy losses in the jet. When the mean energy losses are compensated for, the storage time is limited by the elastic scattering and energy spread of the protons.

In August 1964, charge exchange injection of protons into a storage ring was carried out in the experimental set-up described in a report at the Accelerator Conference at Dubna[1]. High proton trapping efficiency was achieved for quasi-betatron and resonant operation.

The first experiments were carried out in a storage ring with an aperture $2\Delta R \times 2\Delta Z = 8 \times 4$ cm^2 in a weak-focusing magnetic field with a field gradient of 0.6; the orbit radius R = 42 cm. The hydrogen jet directed radially from the inside of the ring is switched on for 300 - 600 μsec by means of an electromagnetic valve. The diameter of the jet in the region of the orbit is about 1 cm. The emission of protons out of the jet onto the orbit increases exponentially up to 100% with increasing density of the jet. Observation of the proton beam on its first turn showed that it diverges when emerging from the hydrogen target, on account of its finite width. It expands to 1.7 cm in radial dimension after a quarter of a radial betatron wavelength, and after half a wavelength it is focused again to the initial transverse dimension of 3 - 4 mm. The vertical dimension of the beam in the first turn is 3 - 4 mm, and in practice it does not change, with only insignificant proton losses. The proton beam in the first turn follows a circular orbit to within ± 2 mm.

In the case of charge exchange injection into a storage device without an accelerating field (quasi-betatron operation) the protons travel in an inward spiral. Proton storage under these operating conditions was observed from the intensity of luminescence of the hydrogen jet, recorded by a photomultiplier, and also by wide-band pick-up electrodes and a target on the inner wall of the ring chamber. For an energy of 1 MeV and an injection time of 20 μsec (100 turns), Fig. 2 shows oscillograms of the negative ion current on the input target, of the proton current from the hydrogen jet, of the intensity of luminescence of the jet and of the proton current on the inside target. The luminescence of the jet and a similar signal from the pick-up electrodes, indicate that for 100 turns, when the beam is injected into the storage ring, the circulating current grows linearly; then for about 150 turns the current remains constant, during which time the radius of the whole injected beam shrinks (which was observed by means of vertical pick-up electrodes), but the beam is not yet lost to the inside wall of the chamber. Then the beam strikes the internal target. The charge striking the internal target is 100 times greater than the charge in the proton beam during the first turn. The amplitude of the signal from the pick-up electrodes during storage is 100 times greater than when a shutter is inserted at the end of the first turn. These measurements are accurate to within about 10%. The signal from the electromultiplier recording the light from the jet increases by a factor of only 40 to 50 during storage, apparently owing to the difference between the transverse current distribution of the stored proton beam and that of the first turn. There is a similar ratio for injection up to 250 turns. Thus for charge exchange injection in quasi-betatron operation, the injection efficiency is near to 100%.

Charge exchange injection of protons was also carried out for resonant (r.f.) operation. Under these operating conditions, the r.f. accelerating field compensates for ionization losses of proton energy. The amplitude of the accelerating voltage was up to 6 kV, with constant frequency. In Fig. 3 is shown an oscillogram of the beam current (signal from the r.f. pick-up electrodes) upon injection for resonant operation. Energy: 1 MeV; injection time: 300 μsec (1500 turns); accelerating voltage: 1.5 kV. In Fig. 5 are shown oscillograms characteristic of trapping into resonant operation. Energy: 1 MeV; injection time: 20 μsec. The first two oscillograms represent the signal from the wide-band pick-up electrodes with and without an r.f. accelerating field. Comparison of the signals shows that the linear density of trapped protons in the centre of the bunch in resonant operation is one-and-a-half times greater than that of the protons stored in quasi-betatron operation. The third oscillogram shows the signal from the r.f. pick-up electrodes, and the fourth the signal from the internal target when protons are being stored in resonant operation. Comparison of the last oscillogram with the signal from the internal target during injection into the quasi-betatron (see Fig. 2) shows that, unlike what occurs when protons are injected in quasi-betatron operation, more or less constant particle losses occur during the injection of protons in resonant operation. The protons go mainly towards the inside wall of the ring (the signal from the external target is many times smaller). Particle losses upon injection in resonant operation are 20 - 25%. In Fig. 5 are shown oscillograms of the beam current of protons stored under resonant operating conditions for 500 - 1000 turns (energy 1 MeV). It can be seen that the current stored in resonant operation increases linearly with time.

The cross-section of proton losses due to scattering on gas in the ring chamber is

$$\sigma = \frac{\pi e^4 Z}{T^2} \left\{ \left(\frac{2\alpha R}{\Delta R}\right)^2 + Z(\lambda + 1)\left[\left(\frac{R}{\nu_x \Delta R}\right)^2 + \left(\frac{R}{\nu_z \Delta Z}\right)^2 \right] \right\}$$

where T is the kinetic energy of the protons; α the momentum compaction factor; ν_x and ν_z the number of betatron oscillations per turn, and λ the Coulomb logarithm.

In this expression the first term corresponds to the spread of the ionization energy losses in gas, the second to elastic scattering. In the hydrogen jet (Z = 1) the proton losses due to the energy spread and to elastic scattering are approximately equal. In the above-mentioned experiments with the hydrogen jet $\sigma = 4.5 \times 10^{-22}$ cm^2/atom. In the last turn, the proton trapping efficiency for betatron operation without taking into account the damping and build-up of the oscillations on the gas, is

$$\Phi = 2 \operatorname{erf} \frac{\sqrt{K_{eff}}}{2K} - 1 \qquad \text{for} \quad \frac{K}{K_{eff}} \gtrsim 1.45$$

and the injection efficiency

$$\eta = \sqrt{\frac{2K}{\pi K_{eff}}} \times e^{-K_{eff}/2K} + 2 \operatorname{erf} \sqrt{\frac{K_{eff}}{2K}} - 2 \frac{K_{eff}}{K} \left(1 - \operatorname{erf} \sqrt{\frac{K_{eff}}{2K}}\right) - 1$$

where K is the number of injected turns

$$K_{eff} = \frac{\xi}{\Pi \sigma} \quad ;$$

here Π is the thickness of the jet in atoms/cm^2, ξ is the by-pass factor of the jet. When $K = K_{eff}$, $\Phi = 0.36$, $\eta = 0.71$.

Any energy losses of the particles circulating in the ring result in damping or build-up of betatron and synchrotron oscillations or the increase of the orbit spread with increments on reverse turns

$$\delta_z = \frac{1}{2} \frac{W}{\beta^2 E} \; ; \qquad \delta_x = \delta_z \left(1 - \alpha \frac{L}{W} \frac{\partial W}{\partial L}\right) \; ;$$

$$\delta_\varphi = \delta_z \left(\beta^2 \frac{E}{W} \frac{\partial W}{\partial E} + \alpha \frac{L}{W} \frac{\partial W}{\partial L}\right) \; ; \qquad \delta_r = 2\delta_\varphi \quad ,$$

where W is the energy loss per turn, E the energy of the particle, β the relative velocity, and L the orbit length.

Ionization losses in the jet are responsible for the following increments

$$\delta_x = \frac{1}{4}\frac{V}{T}\left(1 - \alpha\frac{R}{\Pi}\frac{\partial\Pi}{\partial r}\right); \quad \delta_\varphi = \frac{1}{4}\frac{V}{T}\left(\alpha\frac{R}{\Pi}\frac{\partial\Pi}{\partial r} - 2\right) .$$

For radial positioning of the jet

$$\frac{R}{\Pi}\frac{\partial\Pi}{\partial r} \sim -\frac{2}{M}\frac{R}{a} ,$$

where a is the diameter of the jet in the region of the orbit and M the Mach number. This relation is correct provided that the protons always cross the jet in its diametral plane. In reality, the jet is by-passed, mainly when $r < R$, where the jet has a small diameter (according to our measurements the diameter of the jet on the inside wall of the chamber is very small, about 2 mm, although the cross-section of the jet output nozzle is 6 mm in diameter). As a result, the effective value $(R/\Pi)(\partial\Pi/\partial r)$ may drop to zero. This is confirmed by the fact that according to our measurements the shrinkage velocity of the orbit radius quasi-betatron operation decreases on the inside wall of the chamber.

In our experiments $(2/M)(R/a) \sim 6$. For a target thickness $H = 2 \times 10^{17}$ atoms/cm^2, the energy losses in the jet amount to about 200 eV and the increment in orbit spread δ_r = 1/500 to 1/5000 per turn. The increase in orbit spread because of ionization friction in the jet reduces the effective number of injection turns K_{eff} from 11000 to 1000-7000. In order to increase the effective number of turns, the jet should be positioned axially. In our experimental set-up it was difficult to do this because of the design of the magnet. Since under quasi-betatron operating conditions the injection time was limited by the spiraling of the orbit to a few hundred turns, we could not observe proton losses, since even for $K_{eff} \sim 1000$ with $K = 250$ the losses amounted to only 2%.

For injection for resonant operation, the rated effective number of injection turns falls by a factor of approximately one-and-a-half, and the increase in synchrotron oscillations is twice as small as the increase in the orbit spread. The fact that upon injection in resonant operation proton losses did not noticeably increase up to 1500 turns, shows that the effective value of $(R/\Pi)(\partial\Pi/\partial r)$ is considerably less than 6. Constant particle losses of 20 - 25% upon injection for resonant operation agree fairly well with shrinking of the azimuthal dimension of the separatrix due to energy losses.

In the first experiments the negative hydrogen ion source was provided by a high-frequency ion source with maximum constant current of 21 μA, with a power supply of 400 W. The ion extraction system is without a probe and the extraction voltage goes up to 12 kV. The distinctive feature of the source is the stopping of secondary electrons in the charge exchange channel of the extraction electrode with a voltage of 250 - 300 V.

When the source was installed in the Van de Graaf accelerator, the atomic beam was not separated, which considerably increased the electron charge in the accelerating tube. Accordingly, a beam of negative hydrogen ions of up to 12 mA was obtained from the accelerator (at this power the radiation doses under the accelerator amounted to 30 rad/h).

In the storage device the beam was fed in separate pulses lasting 1 - 300 μsec from a cut-off capacitor installed in the ion duct. With a quadrupole lens, the beam of negative hydrogen ions was focused on the inlet of the storage device, which had a diameter of 3 - 4 mm and an aperture angle of 2×10^{-3}. Here the beam passed through the gas target made in the form of a drift tube of 5 cm length and a diameter of 1 cm, and with diaphragms and differential pumping. The gas was admitted to the drift tube in separate pulses, lasting 1 μsec, by means of an electromagnetic valve. The atomic hydrogen beam from the input target was put into the orbit with an accuracy of ± 1 mm on the transverse position and $\pm 2 \times 10^{-3}$ on the angle, achieved by means of a magnetic corrector. The energy stability was ± 0.2%.

For the purpose of obtaining the maximum output of the atomic beam, charge exchange cross-sections of negative hydrogen ions were measured by mass spectroscopy in various gases (H_2, N_2, C_2H_2, C_3H_3, CO_2, SF_6, $CC\ell_2F_2$)

at an energy of 1 - 1.5 MeV. The maximum output of the atomic beam was found to depend only slightly on the kind of gas and on the energy, and amounted to 50 - 55%. We used for the injector target hydrogen and carbon dioxide with an optimum thickness of 2.5×10^{16} and 3×10^{15} molecules/cm^2, respectively.

An air (tubular) coil was installed in the storage chamber in order to carry out multi-turn charge exchange injection for betatron operation, and to study the possibility of compensating for the space charge of the proton beam with electrons (see Fig. 6). Proton storage takes place inside the coil. Accelerating voltage up to 200 V is fed to the coil from a special generator, in approximately square pulses lasting 500 μsec, which allows storage to take place during 2500 turns. The current through the coil from the generator increases approximately linearly up to 300 kA. Care was taken to shield the coil cavity from the external magnetic accelerating flux.

Proton storage takes place in an axially symmetrical ($\alpha = 2.5$) and an alternating gradient field ($\alpha = 0.8$). The cavity aperture is 4×3 cm^2. Taking into account damping and build-up in the jet, the effective number of injection turns at an energy of 1.5 MeV is 4000. Proton trapping efficiency for betatron operation is about 85%. The maximum current due to space charge limitation is 0.75 A (0.7×10^{12} particles).

For storing large currents, a source of negative hydrogen ions with a current of up to 1.5 mA in pulses lasting 1 μsec was installed in the Van de Graaf accelerator. The source is of the cyclotron type described by Ehlers et al.[2]. Figure 7 gives a diagram of the source. Along the magnetic field (2000 gauss) in the anode channel an arc is ignited (current 4 - 5 A, voltage 300 V) with a tantalum thermo-cathode (power 160 W). The arc serves as a powerful emitter of electrons, which in the neutral gas form negative hydrogen ions. The latter are accelerated across the magnetic field towards the extraction electrode (extraction voltage 5 kV). The electron current onto the extraction electrode is limited by the magnetic field and amounted in our source to 100 mA. The admission of hydrogen is pulsed by means of an electromagnetic valve (duration of pulse 1.5 μsec). The ion current is fairly sensitive to the density of the gas. The optimum thickness of the hydrogen layer between the surface of the arc and the draining electrode is about 10^{15} at/cm^2. The hydrogen flow rate is 5×10^{-3} cm^3 per pulse. In order to lessen the pulsed hydrogen charge in the accelerating tube, the volume of the vacuum chamber of the source was increased to 10 ℓ. The pumping-down time for this chamber is about 0.2 sec. The pulse shape of the ion current is sensitive to the cathode temperature. Figure 8 shows an oscillogram of the ion current pulse when there is slight overheating of the cathode. The breakdowns observed in the ion current were connected with instability of the arc.

The negative ion beam issues in the form of a ribbon with an increased aperture angle in the plane perpendicular to the magnetic field. The phase space area of the beam in this direction is less than the phase space area in the direction parallel to the magnetic field. By means of quadrupole lenses, the beam is focused 10 cm from the inlet into the accelerating tube with a diameter of 4 - 5 mm and aperture angles of 0.07 and 0.15 rad. In focus, the beam is accelerated up to 10 - 12 keV for electronic-optical matching with the accelerating tube. At the outlet of the accelerator at an energy of 1.5 MeV, the transverse phase space area of the beam is about 5×10^{-3} cm rad, which satisfies our requirements.

The negative hydrogen ion source described makes it possible to store about 10^{12} protons (current about 1 A) in the betatron coil cavity.

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REFERENCES

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2) K.W. Ehlers, B.F. Gavin and E.L. Hubbard, Nucl.Instr. and Methods 22, 87 (1963).

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FIGURE CAPTIONS

Fig. 1 :
1. Negative hydrogen ion source
2. Accelerator
3. Entry gas target
4. Hydrogen jet on orbit
5. Storage ring

Fig. 2 : Horizontal: 1 cm = 10 μsec.

Fig. 3 : Horizontal: 1 interval = 500 μsec.

Fig. 4 : Horizontal: 1 cm = 10 μsec.

Fig. 5 : Horizontal: 1 cm = 50 μsec.

Fig. 6 :
1,2. Inside and outside wall of vacuum chamber
3. Magnet pole
4. Betatron air coil
5. Indicator box
6. Entry flow target
7. Hydrogen jet
8. Voltage supply to coil

Fig. 7 :
1. Magnet
2. Vacuum chamber
3. Electromagnetic valve
4. Gas supply
5. Anode
6. Cathode
7. Magnet poles
8. Extraction electrode
9. Electrostatic and magnetic screen
10,11. Quadrupole lenses

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12. Cut-off electrode
13. Accelerating electrode
14. Accelerating tube

<u>Fig. 8</u> : Horizontal: 1 cm = 500 μsec.
Vertical: 1 cm = 500 microamperes.