ON THE CHARGE EXCHANGE INJECTION OF PROTONS INTO RING ACCELERATORS

G. I. Budker, G. I. Dimov

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

(Presented by G. I. Dimov)

The problem of intensity is important in any accelerator, but it becomes the main problem in an accelerator with opposing beams. An air-core accelerator with such opposing proton beams has been developed at the Institute of Nuclear Physics of the Siberian Branch, Academy of Sciences USSR. In it the particles accelerating in opposite directions along two slightly eccentric orbits collide during the process of acceleration. Since the accelerated particles are not deflected here, the efficacy of such a setup is very sensitive to the initial current value.

In connection with this, work is done at the Institute on multi-turn injection of negative ions or hydrogen atoms into the accelerator, splitting them at a target along the orbit, and capturing the protons into the accelerator path by means of charge exchange. The purpose of this work is to dispense with the deflecting system during injection of the maximum current as determined by the space charge in the beam.

A schematic diagram of the experimental setup is shown in Figure 1. Particles are injected here from the 1.5 MeV Van de Graaff generator into the ring accumulator. The orbit inside the accumulator has a radius $R = 42$ cm, half the width of the ring chamber cross section is $\Delta R = 0.1\ R$. The charge exchange target, M, along the orbit must be sufficiently "transparent" to circulating protons and must be quickly enough removed from the chamber after completed injection. The charge exchange target, M, consists of a gas jet flowing out of a deLaval nozzle. A hydrogen jet is found to be most "transparent" to protons, however, a less divergent jet can be formed more easily with a monoatomic gas. The gas jet flows across the vacuum chamber and then through a diaphragm into a vacuum reservoir. We were able to obtain a gas jet in vacuum with a 0.1 radian divergence and a 10 cm length. With a diaphragm 3 cm in diameter at the reservoir, less than 1 percent of the gas from the deLaval nozzle remained in the working region. It is further planned to use a nitrogen pump as a reservoir for receiving the hydrogen jet. The gas jet is turned on only for the duration of the injection and this is done by an electrodynamic valve. The shortest duration of a jet obtained by us was about 30 μsec. The width of the trailing edge of the gas density pulse in the jet is determined basically by the length of the deLaval nozzle.

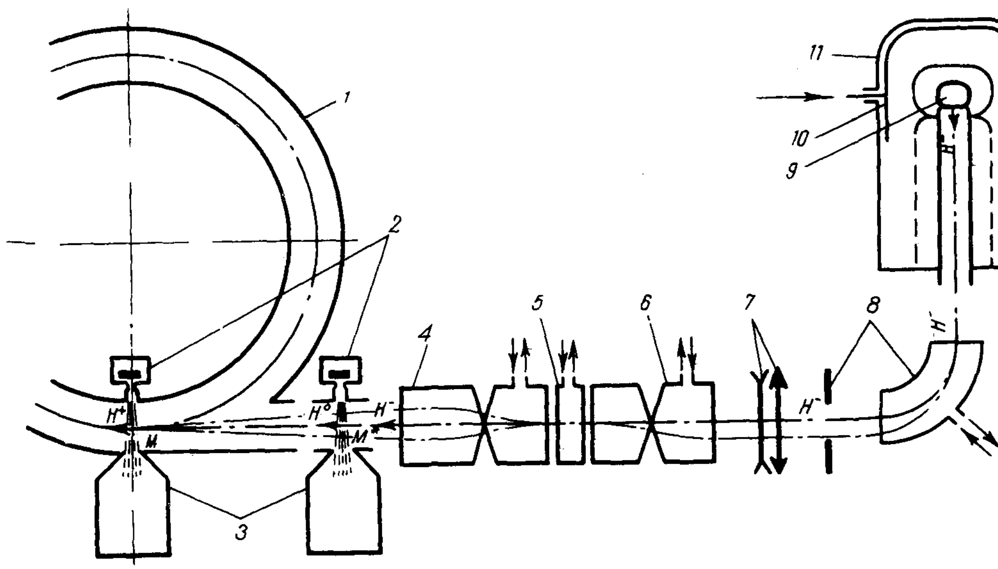

Figure 1. Schematic diagram of the experimental setup.

1 -- Ring accumulator; 2 -- gas nozzle with valves; 3 -- gas reservoirs; correctors: of angles (4), of the crossover point (5), of the bias (6); 7 -- quadrupole lens; 8 -- magnetic analyzer; 9 -- source of H^-; 10 -- liner; 11 -- Van de Graaff generator. M and M* -- charge exchange targets.

The negative hydrogen ions in the electrostatic accelerator become discharged into hydrogen atoms at the target M* which is located immediately before the entrance to the accumulator. This target is also in the form of a gas jet. The transfer of charge is not mandatory, but it facilitates the supply of particles to the target located along the orbit and their recharging into protons -- although there is some loss of particles at the M* target. The coordinates and angles of beam guidance are adjusted independently by corrective magnets placed in front of target M*.

The Van de Graaff generator can produce ion beams with a pulse current up to several tens of milliamperes and up to 10^{14} particles per pulse. The small voltage drop in the generator during a current pulse is compensated by the electrostatic method. A high-frequency source of negative ions will be used for the first experiments and later on a pulsed-arc ion source with charge exchange at the hydrogen target will be installed. In this source the protons are drawn directly from the plasma flowing out of the discharge chamber to the grid-shaped electrode. A tube with hydrogen for charge exchange is placed immediately behind that grid. The hydrogen is introduced into the arc chamber and into the charge exchange chamber in pulses by means of electromagnetic valves. While the proton beam passes through the charge exchange target, the positive charge should be compensated by delta-electrons. According to our calculations, the relaxation time for the beam is approximately 1 μsec. A proton current of about 1 A and 100 μsec duration can be produced at the present time.

Highly efficient multi-turn proton injection is possible primarily because at energies above 1 MeV [1, 2] the charge exchange from atoms to protons predominates very strongly over the charge exchange in the reverse sense. While the circulating protons pass through the charge exchange target along the orbit, there is not only a reverse charge exchange taking place but also some scattering and loss of energy. The latter two lead to a partial loss of protons along the walls of the accelerating chamber. This limits the effective number of injection turns.

The mean energy loss [3] can be compensated either by a suitable acceleration of particles or by reducing the magnetic field during the time of injection. The proton loss depends on the parameters and operating conditions of the accumulator or the accelerator.

The basic proton loss is determined by the degree of multiple elastic scattering and by the fluctuation of ionization losses. The latter not only step up betatron oscillations (radial) but also cause the particles to spread over the orbits of the betatron mode and step up synchrotron oscillations in the resonance mode.

The coefficient of capture into the betatron mode is

$$\eta_B \sim \frac{k_{eff}}{k}\left(1 - e^{\frac{-k}{k_{eff}}}\right)\left(1 - e^{-\sigma_{01}\delta}\right),$$

where k is the number of injection turns, $k_{eff} = \frac{\alpha}{\sigma_n \delta}$, with σ_n the resultant cross section of the proton loss in the chamber, δ the target thickness, atoms/cm^2 and α the target by-pass ratio.

As δ increases, the capture coefficient η becomes larger, but the effective number of injection turns k_{eff} decreases. It is reasonable to assume that $\delta \sim (2\text{--}3)\sigma_{01}^{-1}$. The effective number of injection turns is approximately proportional to the injection energy, but inversely proportional to the accelerator chamber aperture squared, and inversely proportional to the square of the number of betatron oscillations per turn.

The coefficient of capture into the resonant mode at zero equilibrium phase is

$$\eta_C \sim \frac{2}{\pi}\left(1 - e^{-\sigma_{01}\delta}\right) \times$$

$$\times \int_{1-\rho}^{1} \frac{1 - e^{-p^2(u)\frac{k}{k_{eff}}}}{p^2(u)\frac{k}{k_{eff}}\sqrt{\varrho^2 - (1-u)^2}}\, du,$$

where

$$\varrho = \frac{\Delta r}{\Delta R}; \quad p^2(u) = \frac{\mu_x}{u^2} + \frac{\mu_y}{\varrho^2(u-1+\varrho)^2} + \mu_z;$$

$$\mu_x = \frac{\sigma_i + \sigma_e}{2\sigma_n}; \quad \mu_y = \frac{\sigma_i}{2\sigma_n}; \quad \mu_z = 1 - (\mu_x + \mu_y);$$

Δr is half the radial width of the separatrix; σ_i is the cross section of proton loss due to fluctuations of the ionization energy loss; σ_e is the cross section of proton loss due to multiple elastic scattering.

The coefficient of capture into the resonant mode is shown in Figure 2 as a function of the number of injection turns for a weakly focusing accelerator with a hydrogen target; the dependence of this coefficient on the radial dimension of the separatrix is shown in Figure 3. The maximum value of this coefficient occurs at $\varrho < 1$ [$\varrho > 1$ in the original text]. At $\varrho < \varrho\ (\eta_{max})$ the particle loss due to stepping up of synchrotron oscillations predominates.

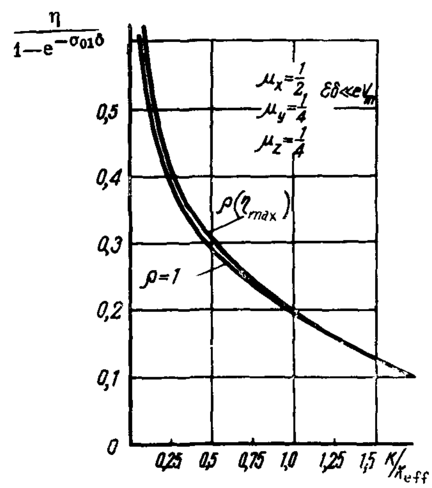

Figure 2

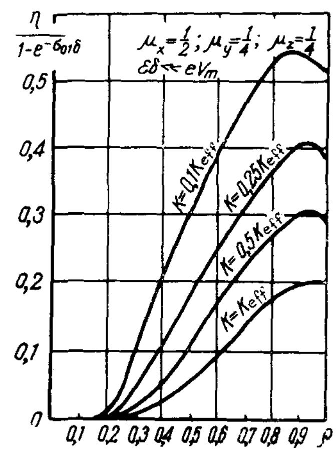

Figure 3

The betatron oscillations are damped out by ionization losses. When the aperture of the ring chamber is relatively large, then the rms amplitude of betatron oscillations referred to the orbit radius squared is limited by the order of magnitude of the electron/proton mass ratio. At the same time the basic loss of particles is determined by their spread over the orbits or by the stepping up of synchrotron oscillations, single scattering and reverse charge exchange.

If the target thickness varies along the radius, additional damping may take place while radial betatron and synchrotron oscillations are stepped up. However, the sum of the damping coefficients remains unchanged. In order to avoid stepping up the radial oscillations, it is necessary to limit the effective radial gradient of the target thickness.

In the experimental setup with a hydrogen target $\delta =$ $= 4 \cdot 10^{17}$; $\langle x_m^2 \rangle \sim \frac{1}{6} \Delta R^2$; $\langle z_m^2 \rangle \sim \frac{1}{12} \Delta R^2$; $k_{eff} \sim 10^5$. At $k = 10^4$ (injection time about 1.5 msec) the coefficients of capture are $\eta_B \sim 0.88$ (damping taken into account) and $\eta_C \sim 0.37$ (damping not taken into account).

The circulating protons heat up the get jet. The gas temperature during the movement across the chamber must not increase by more than approximately 10^{-3} eV lest the jet be disrupted. The heating up of the target may limit the number of protons that can be stored in the chamber.

At a particle energy of several MeV $\sigma_{1-1} < \sigma_{10} \ll \sigma_{01} < \sigma_{-10}$, the cross section $\sigma_{-11} < \sigma_{-10}$, but there are no reasonably accurate data available for σ_{-11} at an energy of the order of one MeV. If it is assumed that $\sigma_{-11} \ll \sigma_{-10}$, then the relative output of neutral particles at the optimum thickness of target M* is

$$\Phi_0 = \left(\frac{\sigma_{01}}{\sigma_{-10}}\right)^{\frac{\sigma_{01}}{\sigma_{-10}-\sigma_{01}}}.$$

$\Phi_0 \sim 0.67$ in a hydrogen target at an ion energy of several MeV.

Figure 4 shows one variant of a scheme by which particles are injected into an air-core weakly focusing accelerator with opposing beams. Admission into the magnetic field zone is difficult in an air-core accelerator. Therefore, the particles are introduced along one of the straight-line sections where the orbits of opposing protons intersect. An entrance magnet is placed at one such section, it produces a sign-reversing magnetic field as shown in Figure 4. This field must be symmetrical with respect to its transverse center plane, it must be constant in the radial direction and its mean value along the orbit must be equal to zero. The introduction of an entrance magnet into the straight-line section does not seem to have any effect on the betatron oscillations of the protons circulating in the accelerator orbits. The entrance magnet makes it possible to introduce atom beams into the

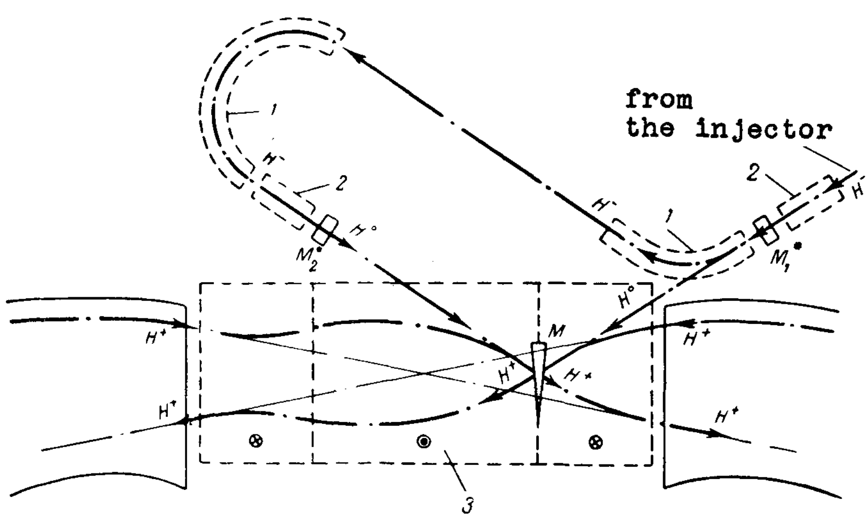

Figure 4. Straight-line section of the accelerator with opposing beams.

1 -- Rotary magnet; 2 -- corrector; 3 -- entrance magnet. M -- Common charge exchange target; M_1^* -- bisecting neutralizing target; M_2^* -- neutralizing target for the second beam.

accelerator at a large angle to the orbits. The particle beam from the injector is split into two in the M_1^* target. The thickness of this target is chosen on the basis of the charge exchange condition of half of the negative hydrogen ions. In this particular variant $W = 2$ MeV, $z = 1$, $\delta = 6 \cdot 10^7$, $R = 200$ cm, $\Delta R = 0.02$, $k_{eff} \sim 10^4$; at $k \sim 10^3$ (injection time about 1 msec) the coefficient of capture into the synchrotron mode is $\eta_C = 0.47$.

The charge exchange method of injection into ring accelerators was proposed by one of the authors of this report in 1959 and the feasibility of such injection was also demonstrated in a later work [4].

BIBLIOGRAPHY

1. Barnett, C. F., Reynolds, H. K. Physics Review, Vol 109, 355 (1958).
2. Allison, S. K. Review of Modern Physics, Vol 30, 1137 (1958).
3. Whaling, W. Handbuch der Physik, Vol 34, 193 (1958).
4. Heinz Voigt. Patent, Federal German Republic, No 1090349 (1961).