INSTRUMENTS AND METHODS OF INVESTIGATION

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Charge exchange injection into accelerators and storage rings

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Contents

Abstract. The development of charge exchange injection technology at the Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences, mastering charge exchange injection at research centers worldwide, and the experimental observation, explanation, and damping of electron–proton instability (electron cloud effect) are overviewed. Techniques for preparing a circulating proton beam whose intensity is an order of magnitude higher than the space-charge limit are considered. Problems with stripping-foil stability in the process of injection of intense beams and laser ionization of accelerated atoms are also discussed.

Keywords: charge exchange injection, storage ring, RF field, induction acceleration, space charge compensation, e–p instability

1. Introduction

Particles entering the stationary magnetic field of an accelerator from a magnetic field-free domain describe ‘transit’ infinite trajectories, which cross and escape the magnetic field domain. The particles irreversibly captured in the magnetic field of the accelerator trace out along quasiperiodic finite trajectories. Particles that start moving along finite trajectories from an injector, which is located in this trajectory, approach this injector several turns later and become lost if it is not ‘transparent’ enough. To irreversibly transform the transit trajectories to the captured ones and divert the finite trajectories from the nontransparent injector, we must apply nonstationary effects on the particles being captured: alter the magnetic field and expose the particles to additional electric and magnetic fields. These external actions are usually nonselective. While ensuring the irreversible capture of injected particles, they are responsible for the loss of previously captured particles.

Many concrete methods have been developed for capturing accelerated particles into stationary orbits in the guiding magnetic field of accelerators and storage rings: a single-turn injection with an inflector, injection into a growing field, helical accumulation, the phase shift technique, etc. These traditional injection techniques permit bringing the in-orbit particle storage time up to a hundred orbiting periods. In this case, the newly arriving particles are resided in the phase space domain of a system unoccupied by previous particles, so that the accumulated beam brightness (the particle density in the phase space of transverse coordinates and momenta) cannot exceed the injected beam brightness. The existing injection technology makes it possible to fill the accelerator paths practically in accordance with their phase capacity for a low magnetic field strength. However, the brightness of existing proton beams is not high enough to completely fill the paths of high-field accelerators and storage rings with a significantly higher space-charge limit.

The charge exchange method for capturing particles on the accelerator path was discussed by L W Alvarez back in 1951 [1]. At that time, however, the methods for producing negative ion beams were still in their infancy, so that one might have expected only the investigation of orbits in a stationary magnetic field without hoping for the storage of beams with appreciable intensity. More recently, the attractiveness of charge exchange proton injection into accelerators has been independently noted by several authors [2].

A purposeful investigation of the problems arising in charge exchange proton injection into accelerators was commenced at the suggestion of G I Budker [3] at the Institute of Nuclear Physics (INP), SB of the USSR AS (presently Budker INP, SB of the RAS) in 1959 to obtain high-intensity proton beams in connection with the development of the antiproton–proton colliding beams (VAPP-4) program. More recently, this program was implemented at the Fermilab (USA) with the use of INP developments in charge exchange injection, antiproton production, and electron cooling, and with the leading participation of former BINP staff members [4]. Since the point was to accumulate ultimately intense beams, and the record intensity of H^- ion beams obtained by that time amounted to only

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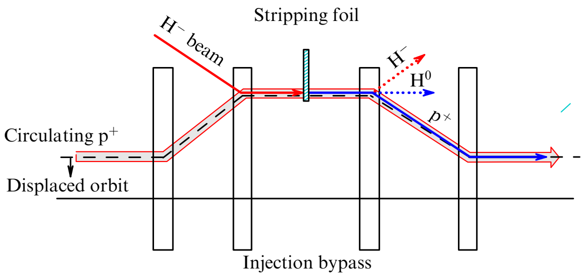

Figure 1. Schematic representation of charge exchange injection [3].

70 μA, developing methods for producing high-intensity beams (on the order of several milliamperes) of hydrogen negative ions was an important part of the program under implementation.

Charge exchange particle injection into accelerators and storage rings is an important application of charge exchange technology [5]. The charge exchange injection is schematically diagrammed in Fig. 1. An equilibrium orbit is displaced by four magnets to form a bump. Negative ions are fed to the orbit tangent and are stripped by a stripping foil, which they pass through in subsequent circulations.

Charge exchange technology makes it possible to realize an injector located in an equilibrium finite trajectory and transparent to irreversibly captured particles. The function of injector is fulfilled by a converting target (a stripping foil), which 'produces' protons. The H^-, H^0, H_2^+, and H_3^+ particles undergoing conversion are accelerated to the required energy and are brought to the target in such a way that the protons (ions) generated therein should move along the desired equilibrium trajectories. On completion of injection, the target may be 'removed' and its influence on the particle motion may thereby be completely eliminated. In this case, it is significant that new portions of particles find themselves in the phase space domains already filled with the captured particles, so that the accumulated beam brightness may exceed the injected beam brightness by orders of magnitude. In doing so, it is possible to obviate the limitations imposed by the conservation of particle phase density due to the Liouville theorem.

2. Investigations of charge exchange injection at the Budker INP, SB RAS

Charge exchange proton injection into the circular path of a storage ring was successfully implemented at the INP, SB of the USSR AS in 1964 [6]. Next, the proton beam intensity accumulated by the charge exchange technique in the path of the storage ring was brought up to the space charge limit [7–9]. The facility of the Budker INP, SB RAS, intended for charge exchange injection research, is schematized in Fig. 2. This small storage ring consists of a permanent cyclotron type magnet with weak focusing, orbit radius $R = 42$ cm, field index $n = 0.6$, vertical betatron oscillation frequency $Q_z = (0.6)^{1/2}$, and radial betatron oscillation frequency $Q_r = (1-0.6)^{1/2}$. Delivered to the charge exchange target in these experiments was a 1-MeV beam of H^0 atoms obtained by conversion of 1-MeV H^- ions on a gas target. The H^--to-H^0 conversion efficiency was high ($\sim$ 50%), as shown in Fig. 3. For a stripping target intended to convert accelerated atoms into protons, advantage was taken of a supersonic hydrogen jet with a density of up to 10^{19} cm^{-3} engaged during

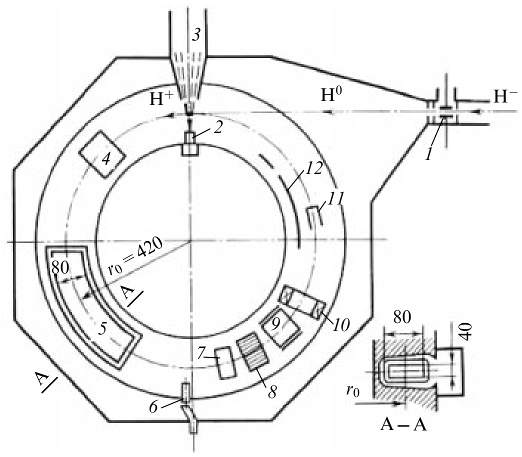

Figure 2. Schematic of the facility for studying charge exchange injection [9]: *1* — first stripping target, *2* — supersonic jet nozzle, *3* — jet receiver, *4* — annular pickup electrode, *5* — drift RF acceleration tube, *6* — collimator of a fluorescence beam profilometer, *7* — ionization beam intensity meter, *8* — ionization profilometer, *9* — beam position pickup monitor, *10* — beam current transformer, *11* — Faraday cup, and *12* — deflector for electron–proton instability suppression. All dimensions are given in mm.

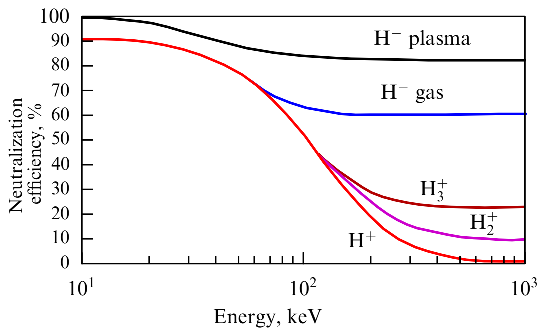

Figure 3. Generalized data about the attainable conversion efficiency of hydrogen ion beams into fast atomic beams for different energies of resultant atoms [9].

injection. The orbit radius was equal to 42 cm, and the aperture measured 4×8 cm^2. Ionization loss was compensated for by a radio-frequency (RF) voltage applied to the drift tube *5*. In these experiments, the ionization of the residual gas and its fluorescence were involved for the first time to measure the current density distribution in the circulating proton beam (ionization profilometer *8* and fluorescence profilometer *6* in Fig. 2), which are now routinely employed in all proton and ion accelerators. The experiments bore out the initial premises. In accumulation with a radio-frequency compensation for ionization loss, the capture efficiency in the course of 2000 turns amounted to 75%, in accordance with the separatrix area; in the injection during 4000 turns, the efficiency lowered by only 20% [10]. In the above experiments, electron–proton instability (electron cloud effect) was observed for the first time and was suppressed by feedback. This instability restricts the beam intensities at meson factories and in other large accelerators and storage rings [11]. The accumulated beam lives for 1.5–5 ms, then betatron oscillations set in, and the beam is dumped in several dozen turns.

Subsequently (in 1967), experiments were carried out to obtain a circulating proton beam with a compensated space charge and ionization loss compensation using an inductive

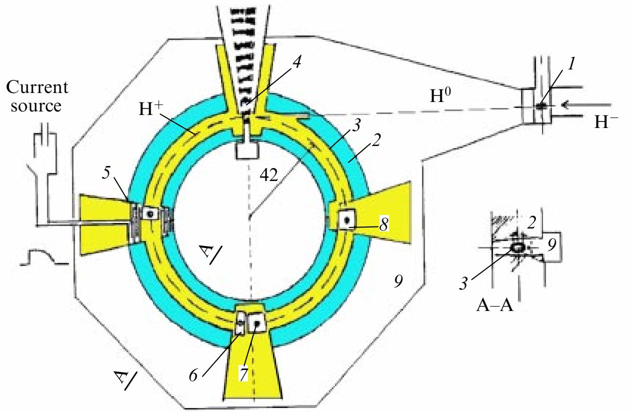

Figure 4. Storage ring with betatron compensation for ionization loss [12]: *1* — first stripping target, *2* — magnet pole, *3* — roll, *4* — second stripping target, *5* — labyrinth, *6* — annular pickup, *7* — ionization current meter, *8* — ionization profilometer, and *9* — vacuum chamber, electron–ion collector.

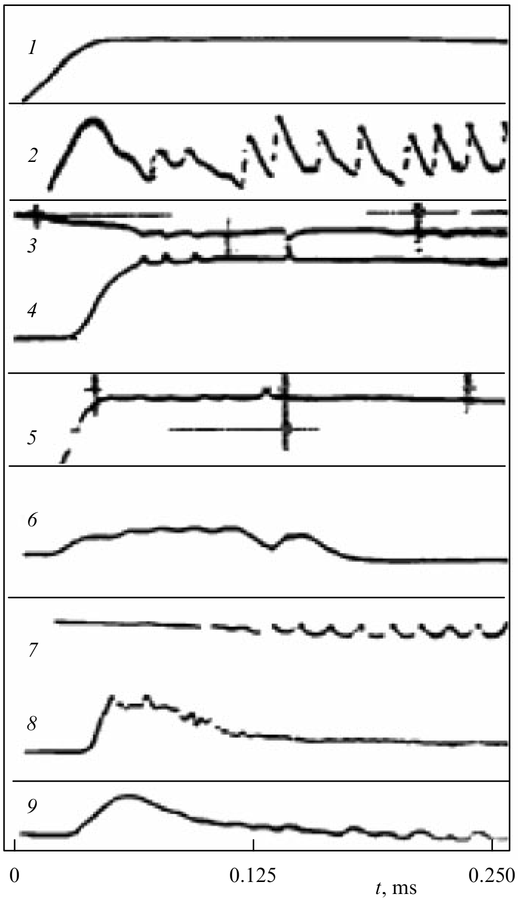

Figure 5. Selected oscillograms characterizing the accumulation of a circulating proton beam in a roll in the quasibetatron mode [12].

electric field. The storage ring with betatron compensation for ionization loss is schematically shown in Fig. 4. A hollow copper 'roll' — hollow toroidal inductor *3* — was placed between the electromagnet poles. A beam of accelerated neutrals was injected into the inductor to be converted into a proton beam on a supersonic hydrogen jet. The induction field was produced by a capacitor bank discharge to a roll cut with a labyrinth, which prevented the penetration of the pulsed magnetic field into the roll. Figure 5 shows a sample

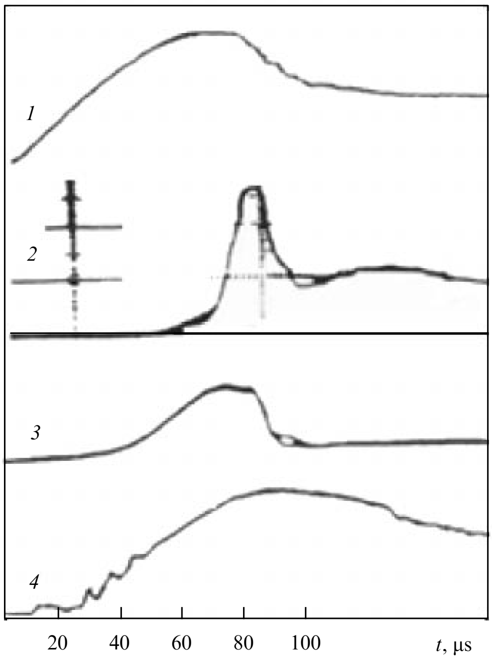

Figure 6. Beam accumulation signals with ionization loss compensation by the induction field [12]: *1* — current meter signal, *2* — signal from the vertical loss probe, *3* — signal from the horizontal loss probe, and *4* — signal of vertical coherent beam oscillations.

of oscillograms which characterize the proton beam accumulation in the roll.

The circulating beam was accumulated up to the equilibrium level *1*. The beam potential, which was measured with a ring pickup, raised and then gradually lowered due to the accumulation of compensating electrons for 10 µs. Next, the potential raised sharply due to ejection of the electrons, and the electron accumulation was repeated (*2*). Grid-screened collectors recorded the ejection of electrons and ions synchronously throughout the orbit (*3*, *4*, *5*, *7*). In the beam bunching, due to the negative mass effect (*8*), electrons did not accumulate and the instability was suppressed (*6*, *9*).

To suppress the negative mass effect, poles with a strong focusing were installed in the electromagnet. The beam accumulation with ionization loss compensation by the induction field was investigated with these poles. The signals of beam accumulation with ionization loss compensation by the induction field are depicted in Fig. 6. The beam current is first accumulated and then saturates (*1*) with an increase in the signal from the horizontal loss probe (*3*). Similarly, the signal from the vertical loss probe also increases (*2*). The vertical beam position probe monitors the growth of vertical betatron oscillations (*4*) up to vertical beam dumping [12]. This instability is related to the oscillation of compensating particles in the potential well of the beam and is nicely described by the instability theory constructed by B V Chirikov [13] for an ion-compensated electron beam. Later on, a more detailed theory of this instability was developed by Koshkarev and Zenkevich [14] and Bosch [15].

The investigation of collective effects in circulating beams with space charge-limited intensity in combination with charge exchange injection made it possible to create such a 'supernonequilibrium' object as a circulating proton beam compensated for by electron gas, and with an intensity nearly an order of magnitude higher than the space charge-limited

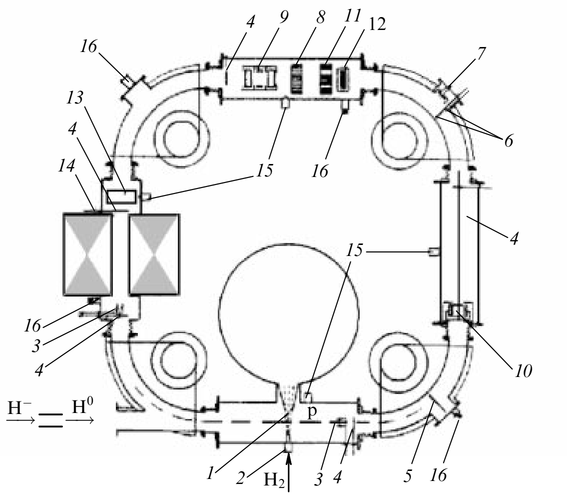

Figure 7. Storage ring for creating a circulating proton beam with an intensity exceeding that of the space charge-limited beam [12]: *1* — supersonic jet as a stripping target, *2* — pulsed jet valve, *3* — beam collector, *4* — quartz screen, *5*, *6* — mobile targets, *7* — ion collector, *8* — Rogowski loop, *9* — beam position pickup monitor, *10* — electrostatic pickup of quadrupole beam oscillations, *11* — electromagnetic sensor of transverse beam oscillations, *12* — vertical beam loss sensor, *13* — meter of secondary charged particles in the beam, *14* — induction core, *15* — pulsed gas puffing, and *16* — stationary gas puffing.

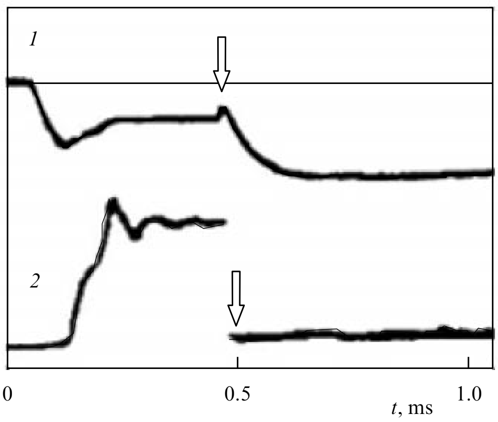

Figure 8. Oscillograms of the first observation of beam accumulation with an intensity exceeding that of the space charge-limited beam [12]: *1* — accumulated beam intensity, *2* — signal from the vertical beam position monitor; the arrow indicates the instant the extraction voltage is turned off.

intensity [16, 17]. The storage ring for obtaining a circulating proton beam with an intensity higher than the space charge-limited one is schematized in Fig. 7. This is a 'racetrack' type magnetic system with a long perimeter of 6 m, radius of the deflecting magnets $R = 42$ cm, rectilinear gaps of 106 cm each, and a continuous proton beam. The beam was also liable to electron–proton instability, with a threshold of 1.2×10^{10} protons, which was suppressed (self-stabilized) by raising the injection current and gas puffing. The existence of a 'stability island' for a high current density was predicted by the theories of Chirikov [13] and Bosch [15].

The oscilloscope traces of the first observation of beam accumulation with an intensity exceeding that of the space charge-limited case are depicted in Fig. 8. The beam was accumulated up to the space charge limit, with an electron suction being turned on throughout the orbit (*1*). Developing in this case becomes the Herward instability related to the proton beam interaction with the ion trace, which does not entail a beam loss (*2*). After turning off the electron suction, these oscillations decayed rapidly (*2*), and the in-orbit beam intensity rose above the space charge limit (*1*) [18] if the injected beam intensity exceeded the critical magnitude. When the injected beam intensity was under the critical magnitude, the intense oscillations developed after de-energizing the suction, and the accumulated beam intensity decreased significantly.

Upon raising the H^--ion beam intensity to 15 mA (the injected atomic current to 8 mA), it became possible to accumulate beams with higher intensity than that of the space charge-limited beam without electron suction. Figure 9 demonstrates the beam accumulation with an intensity higher than the space charge-limited beam intensity. When the injected beam intensity is higher than the critical one (~ 5 mA), the circulating beam accumulates above the space charge-limited beam intensity, many positive ions accumulate in the beam, and dipole and quadrupole oscillations decay rapidly. When the injected beam intensity is lower than the critical one, the circulating beam intensity is limited at a low level (the dashed curves in Fig. 9a), positive ions are not accumulated in the beam, and dipole and quadrupole oscillations remain strong. The oscillation stabilization in this case is due to the wavelength shortening of unstable oscillations to the lateral beam size, when they become surface oscillations and cease affecting the beam volume. It was possible to bring the accumulated beam intensity up to 1 A, which is six times the absolute space charge limit (see Fig. 9), whereby the space charge should nullify the focusing power of the magnetic system, and is 150 times the threshold of electron–proton instability (electron cloud effect). Attempts to obtain a circulating beam with a compensated space charge are now being undertaken at the IOTA facility at the Enrico Fermi Laboratory [19].

The results of investigations into the charge exchange method for proton injection into accelerators are outlined in Refs [20, 21]. The inverse charge exchange of protons to atoms on targets of neutral particles limits the injection time for particle energies lower than 10^6 eV. Only the multiple scattering of the circulating protons is significant at higher collision energies, which limits the injection time at a level of 10^4 turns. By placing the target at the local minimum of the β-function of the focusing system, it is possible to weaken the effect of multiple scattering and even ensure the decay of incoherent betatron oscillations due to ionization energy loss in the target [22]. Such a long admissible duration of the high-efficiency proton capture permits the requirements for the injected beam intensity to be greatly loosened and, which is especially important, the requirements concerning the brightness of injected beams in the charge exchange technique become lower. Results which may only be obtained by traditional injection methods — by injecting proton beams of ultimate admissible intensity and brightness — may be achieved with the use of H^- beams hundreds of times lower in intensity and brightness.

Existing beam particle sources and those under development do not furnish the injection into synchrotrons of sufficiently intense beams polarized in the nuclear spin of the ions. Sources with an intensity of 10^{-3} A have been developed to date. With the application of charge exchange injection, such an intensity would suffice to fill the booster synchrotron to the space charge limit [23].

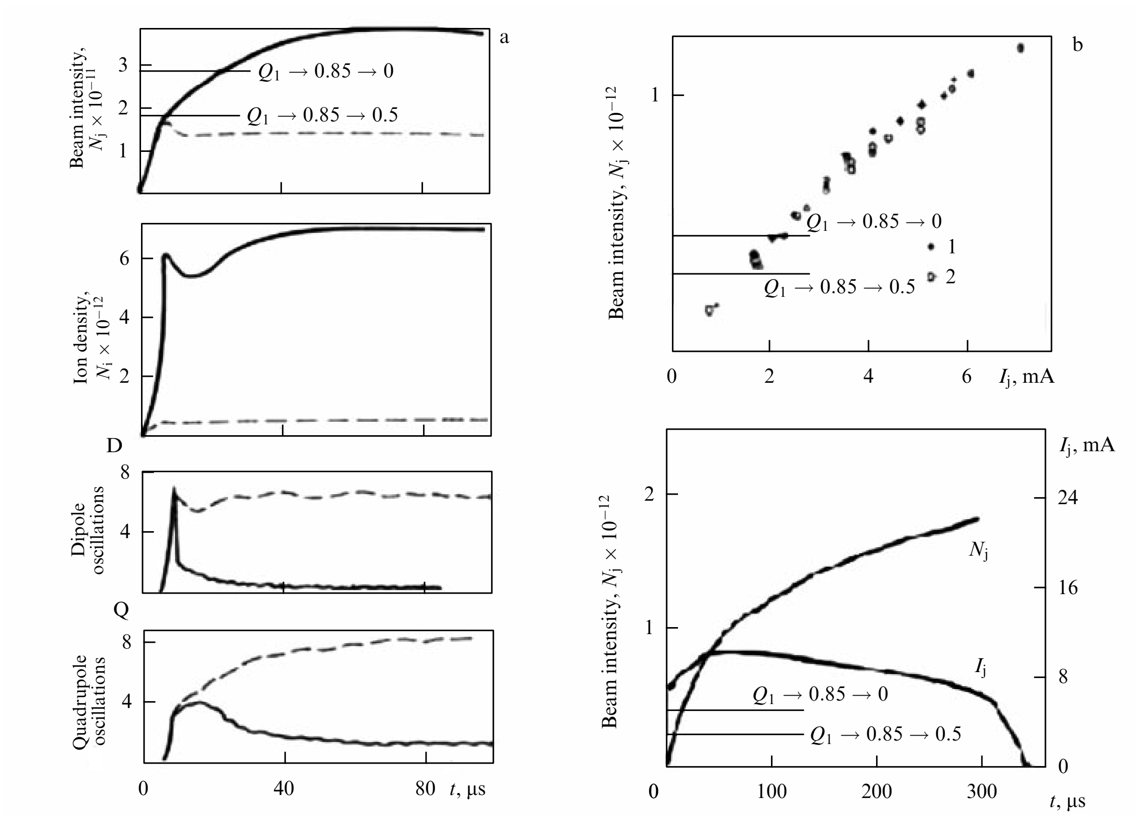

Figure 9. (a) Accumulation of a proton beam with an intensity above the space charge limit; (b) circulating beam intensity in relation to injected beam intensity [16].

Charge exchange injection may also be employed in cyclotrons. The injected particles may be admitted to the cyclotron center in the form of neutral particles and charge-exchanged (stripped) on the target located in the path of first turns. This injection technique was used to inject polarized protons into cyclotrons.

3. Mastering charge exchange injection worldwide

In 1968, R Martin visited the INP (Novosibirsk, Russia) and familiarized himself with developments in charge exchange injection. Martin, then Director of the Argonne Zero Gradient Synchrotron (ZGS), decided that charge exchange injection would permit it to compete in intensity with the Alternating Gradient Synchrotron (AGS) of the Brookhaven National Laboratory (BNL). In 1969, charge exchange injection was successfully tested in the USA on the proton ZGS at an energy of 12 GeV and an injection energy of 50 MeV [24]. The protons were produced and captured into orbit in the charge exchange of H^- ions with a thin organic film target. Under Martin's proposal, the charge exchange injection of protons into the booster for the ZGS was developed [24, 25].

In 1971, charge exchange injection of protons was realized in a 200-MeV synchrotron — a prototype of the booster for the ZGS [25]. Beginning in 1977, the booster fulfilled the function of a high-intensity neutron generator for many years [26]. In 1978, charge exchange injection was mastered on the booster of the Fermi National Accelerator Laboratory (FNAL) for an injection energy of 200 MeV [27]. In 1982, the AGS at the BNL was converted to charge exchange injection [28]. In 1984, charge exchange injection was implemented on the ISIS synchrotron at the Rutherford Appleton Laboratory (RAL) [29] and on the proton accumulator ring at Los Alamos National Laboratory [38]. In 1980–1984, charge exchange injection was implemented at the KEK (High-Energy Center, Japan) [30] and at the Deutsches Electronen Synchrotron (DESY), Germany [31]. Charge exchange injection is employed in the CELSIUS (Uppsala, Sweden) [32] and the COSY (Jülich Research Center, Germany) storage rings [33, 34]. Charge exchange injection was realized in the synchrotron of the Alikhanov Institute of Experimental and Theoretical Physics (Moscow) for the accumulation of carbon ions [35]. Preparations are now under way for the passage to charge exchange injection in the CERN booster (Geneva, Switzerland) [36] and in the booster of the A A Logunov Institute for High Energy Physics (Protvino, Russia) [37].

The pulsed beam intensity in a storage ring was limited by the development of electron–proton instability [38]. In 2006, the Spallation Neutron Source (SNS) (Oak Ridge National Laboratory) [39], a high-intensity neutron source with charge exchange injection, was put into service. In this facility, H^- ions with a current of ~ 40 mA are accelerated in a superconducting linear accelerator up to an energy of 1 GeV and stored for $\sim 10^3$ turns in a compact storage ring with a turn cycle of 1 μs (accumulated current: up to ~ 50 A, and power up to ~ 50 GW).

4. Engineering and physical issues with the implementation of charge exchange injection

The implementation of charge exchange injection will be considered by the example of charge exchange injection into the SNS storage ring. The setup in use is schematized in Fig. 1.

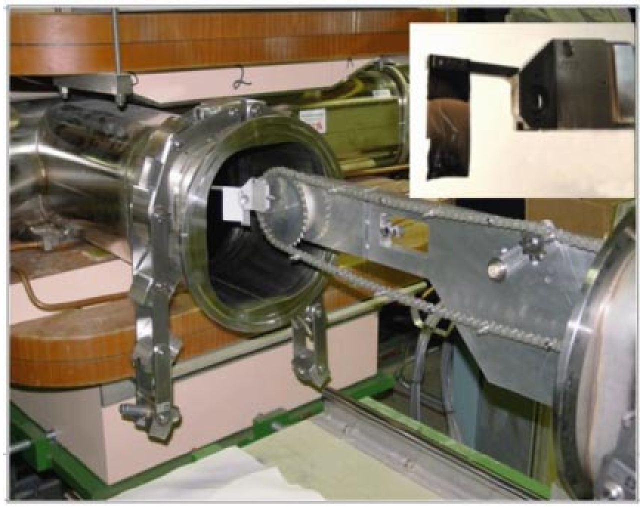

Figure 10. Photograph of the stripping foil on the SNS holder [40].

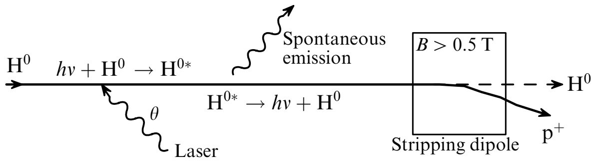

Figure 11. Schematic of the experiment on the ionization of hydrogen atoms with energy 1 GeV by laser radiation for accomplishing laser-assisted charge exchange injection [42].

The stripping foil is embedded in the scattered field of the second magnet with a 0.25 T in strength. Located behind the third magnet is a thick stripping foil, which strips the remaining H^- ions and atoms (including the excited ones) up to protons, which are delivered to the protected beam collector. The stripping foil is attached by one side to a holder. Figure 10 displays a picture of the foil on the holder. The foil of fine-crystalline carbon 12×30 mm^2 in area is 350 μg cm^{-2} in thickness. The foil holder is fastened to a bicycle chain, and the lower end of the foil is exposed to the beam in the displacement of the chain, as shown in Fig. 10. For an H^- ion beam power of 1 MW, the stripped electrons possess a kinetic energy of 0.5 MeV and a power of 3 kW. The electrons spiral around magnetic field lines towards a graphite trap at the lower pole of the second magnet under the foil. The reflected electrons may damage the foil holder. For an average beam power of up to 1.4 MW, the foil withstands a stripping of up to a 5×10^3-C charge (10^5 pulses). This is the intensity practical limit for a carbon foil, because the foil overheats and carbon begins to sublimate. The complicated stability issues of charge exchange foils are discussed by Plum [40].

Laser-assisted ionization of accelerated H^0 atoms to protons was tested in Refs [41, 42]. The experiment is schematized in Fig. 11. The first electron is detached due to Lorentzian ionization in a strong magnetic field. The laser radiation encounters the atomic H^0 beam at an angle θ in the laboratory frame of reference. The frequency of laser radiation ω_0 in the rest frame of the H atoms is related to the laser frequency ω in the laboratory frame as $\omega_0 = \omega\gamma(1 + \beta\cos\theta)$, where θ is the angle between the direction of laser radiation and the direction of atomic motion, $\gamma = 1/(1-\beta^2)^{1/2}$, and $\beta = v/c$. For the excited upper state with $n = 3$ ionized in the magnetic field, one

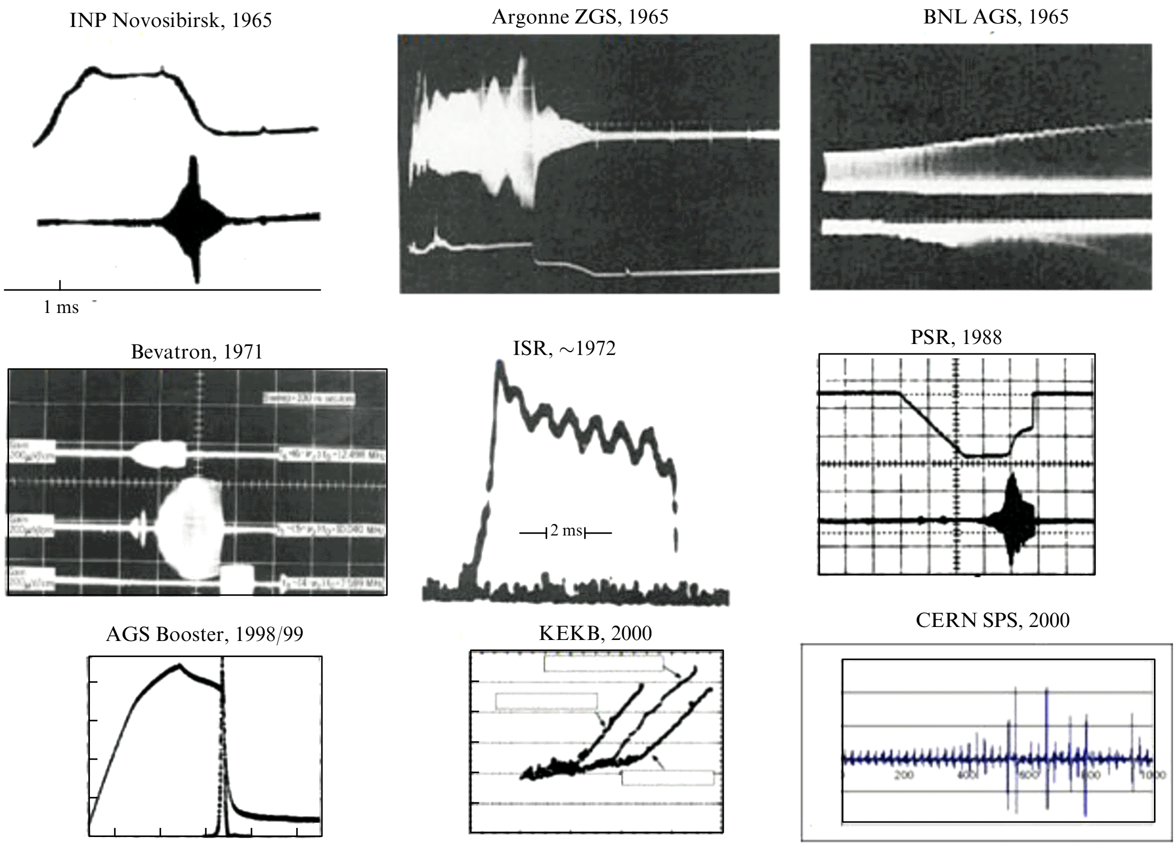

Figure 12. History of the discovery of electron–proton instability worldwide [43].

finds $\omega_0 = 1.84 \times 10^{16}$ Hz and $\lambda_0 = 102.6$ nm. This wavelength corresponds to the third 355-nm harmonic of 1064-nm radiation for an angle $\theta = 1.064$ rad and the atomic beam with energy 1 GeV. The structure of laser radiation is matched to the beam structure from the linac (linear accelerator): 50-ps long pulses arriving at a repetition rate of 402.5 MHz. The atoms of higher energy make up a somewhat smaller angle with the radiation direction and remain at resonance with the radiation. The macropulse duration is equal to 10 µs. The pulsed radiation power is ~ 1 MW. This power is sufficient for the Lorentzian stripping of 90% of excited atoms in the second magnet (see Fig. 11). The next step should involve the use of an optical resonator for accumulating laser radiation and lengthening the period of atom stripping to 1 ms.

The history of the discovery of electron–proton (e–p) instability is diagrammed in Fig. 12 [43]. As is clear now, e–p instability was observed in 1965 on the ZGS at the ANL and on the AGS at the BNL, but it was only at the INP that this observation was correctly interpreted, explained, and suppressed [44]. In 1971, the e–p instability was suppressed in the Bevatron by negative feedback. In the case of proton crossed beams (CERN ISR, Geneva), this instability produced the background for the detector. At the Los Alamos National Laboratory (LANSCE, PSR), this instability has limited the pulsed beam intensity since 1988. Since 2000, e–p instability has limited the beam intensities at B-factories, in high-intensity positron beam storage rings, and in the storage rings for proton and ion beams in the Relativistic Heavy Ion Collider (RHIC) of the BNL and at the Large Hadron Collider (LHC) in Geneva, Switzerland.

Meeting the demands of charge exchange injection required reliable H^- ion sources with a pulsed intensity of up to 100 mA and a high duty factor. This became possible after the researchers in INP, SB of the USSR AS discovered and developed the surface-plasma method for negative ions obtaining [45] and developed the surface-plasma sources with cesiation of high-intensity bright negative-ion beams [46–49].

5. Conclusion

The successful development of charge exchange injection at the Budker INP, SB of the RAS opened the way for the broad application of charge exchange injection technology in all ion accelerators. Without charge exchange injection, the loss of injected beams amounts to $\sim 10\%$, whereas charge exchange injection permits lowering it to 0.02% [50].

The discovery and explanation of electron–proton instability became an important achievement in the physics of high-intensity ion beams. This instability still limits the intensity of the largest accelerators and storage rings.

The implementation of circulating beams with an intensity well above the space charge limit and the development of the RF acceleration system with a space charge compensation [51] gives hope for a significant increase in intensity of cyclic accelerators.

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