BEAM BRIGHTNESS BOOSTER WITH IONIZATION COOLING

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Abstract

The brightness and intensity of a circulating proton beam can be increased up to the space charge limit by means of charge exchange injection or by electron cooling but cannot be increased above that limit. Significantly higher brightness can be produced by means of charge exchange injection with space charge compensation [1]. The brightness of the space charge compensated beam is limited at low level by development of the electron-proton (e-p) instability. Fortunately, e-p instability can be self-stabilized at a high beam density. By development of surface plasma sources (SPS) with cesiation and RFQ, H^- beam injectors were prepared with intensity ~0.1 A. We discuss possibilities for production of a "superintense" circulating beam with intensity and brightness far above the space charge limit. A beam brightness booster (BBB) for significant increase of accumulated beam brightness is discussed. Ionization cooling can be used for suppression of the beam brightness dilution. The superintense beam production can be simplified by development of a nonlinear nearly integrable focusing system with broad spread of betatron tunes and the broadband feedback system for e-p instability suppression [2].

INTRODUCTION

Charge Exchange Injection (CEI) was developed for increasing the circulating beam intensity and brightness above injected beam parameters by multiturn injection of beam into the same transverse phase space areas [3-5]. At that time the intensity of H^- beam from plasma source was below 5 mA with normalized emittance ~1 π mm mrad. The intensity of H^- beam from charge exchange sources was up to 15 mA, but the brightness B of this H^- beam was ~100 times less than the brightness of a primary proton beam because only 2% of the proton beam was converted into the H^- ions. In this situation the increase of the circulating beam brightness up to 100 times was necessary for reaching of the brightness of primary proton beam which can be used for one or several turn injection. The intensity and brightness of H^- ion beams were increased by orders of magnitude by adding a trace of cesium into gas discharges (cesiation effect) [6]. After development of surface plasma source (SPS) with cesiation, the H^- beam intensity was increased up to 0.1 A with emittance ~0.2 π mm mrad [7,8], so the brightness of injected beam approached the space charge limit of real accelerators such as the Fermilab Booster [9]. With such beam the further increase of circulating beam brightness is impossible, but CEI is routinely used to increase the circulating beam intensity by many orders of magnitude by injection into different parts of the transverse phase space (painting in the transverse phase space) [5, 9, 10]. Further increase of circulating beam brightness is possible by using multiturn CEI with space charge compensation by particles with opposite charge (electrons or negative ions) [1, 11, 12]

Unfortunately, such possibility is complicated by strong transverse two-beam instability driven by beam interaction with accumulated compensating particles in the circulating beam.

The strong instability with fast loss of a bunched beam was discovered at 1965 in a small scale proton storage ring (PSR) during development of charge exchange injection and was stabilized by feedback [3, 4, 5, 12, 13]. This instability was explained in [4] as an inverse variant of the strong transverse instability of circulating electron beam caused by the interaction with compensating ions (beam- ion instability) predicted in 1965 by B. Chirikov [14]. An analogue of this instability, electron-proton (e-p) instability with very low threshold was observed experimentally at the same time during accumulation of a coasting beam [1, 5, 11-13]. The e-p instability of coasting beam was in good agreement with theory [14, 15].

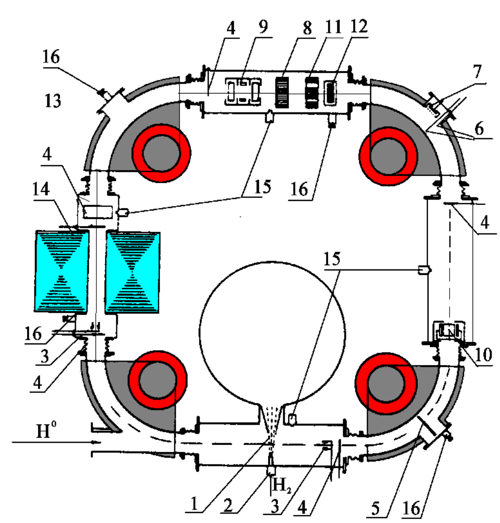

Figure 1: Schematic of storage ring with diagnostics and control. 1-stripping gas target; 2-gas pulser; 3-Faraday Cup; 4-Quartz screen; 5, 6-moving targets; 7-ion collectors; 8-current monitor; 9-Beam Position Monitor; 10-Quadrupole pick ups; 11-magnetic BPM; 12-beam loss monitor; 13-detector of secondary particle density; 14-inductor core; 15-gas pulses; 16-gas leaks.

Superintense circulating beam with intensity far above the space charge limit was produced in BINP in a simple race track ring [5,12,13,16] shown in Fig. 1.

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H^0 beam with current up to 8 mA, energy 1 MeV, produced by stripping of H^- beam, is injected by CEI with electron stripping in the supersonic hydrogen jet into race track with a bending radius 42 cm, magnetic field 3.5 kG, index n=0.2-0.7, straight sections 106 cm, aperture 4x6 cm^2, revolution frequency 1.86 MHz. An inductive core was used for compensation of the ionization energy loss of ~200 eV per turn, which produces some effects of an ionization cooling [3].

A superintense proton beam with intensity ~1 A corresponding to the calculated vertical betatron tune shift ΔQ=0.85x6 =5.1 with Q=0.85 was accumulated with e-p instability self-stabilization by fast accumulation of high circulating beam current and accumulation of plasma from residual gas ionization.

This self- stabilization of the transverse e-p instability in the PSR was explained by increasing the beam density and increasing the rate of secondary particle generation above a threshold level with fast decrease of the unstable wavelength λ below the transverse beam size *a.* (i.e. the sum of beam density n_b and ion density n_i is above a threshold level):

$$(n_b + n_i) > \beta^2 / 2\pi r_e a^2 \; ; \; (r_e = e^2/mc^2).$$

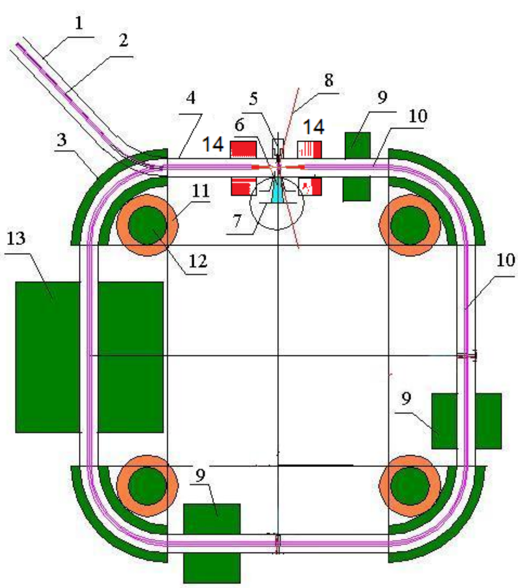

Figure 2: Schematic of BBB of circulating proton beam with thin targets accompanied by enhanced ionization cooling. 1- beam line for transportation of injecting H- beam; 2- injecting beam of H-; 3-bending magnets; 4- vacuum chamber of storage ring; 5- generator of supersonic jet- stripping, reaction target; 6- supersonic jet, stripping-reaction target; 7- pump-recirculate of target jet; 8- cone of resonant gamma rays; 9, 13- iron core for inductor for compensation of beam energy loss in first target; 10-circulating proton beam; 11- magnetic coil; 12- yoke of bending magnet; 14- magnetic lenses for beam focusing to the target.

In high current proton rings it is possible to reach this "Island of stability" by fast, concentrated charge exchange injection without painting and enhanced generation of secondary plasma as it was demonstrated in the small scale PSR at the BINP [5, 12, 13, 16]. The beam brightness loss through proton scattering and ionization loss straggling can be compensated by improved ionization cooling with beam focusing to the target by lenses (14) as shown in Fig. 2. As a prototype of magnetic system it is possible to use a round beam collier VEPP 2000 from BINP with a stron focusing of beams into the colliding point by strong solenoids [17].

The broad betatron tune and corresponding Landau damping are important for increasing the threshold of e-p instability [14,15]. This inference is supported by the increase of instability threshold with increase of bunching RF voltage, increasing of separatrix size and energy spread. With high RF voltage only the central (coherent) part of the beam is unstable and lost.

With a broad betatron tune spread it is possible to produce stable space charge compensated ion and electron beams because e-p instability (electron cloud effect, ion instability) should be suppressed by Landau damping [13, 14, 15].

We hope that production of superintense beam can be easier in BBB with a stable close to integrable nonlinear focusing lattice proposed in [2].

A possible design of such a storage ring is shown in Fig. 3. In design of the storage ring with nonlinear focusing it is good to have possibility for high brightness beam accumulation by charge exchange injection. For energy up to 10 MeV it is possible to use a supersonic gas jet as a stripping target as was done in the small scale proton storage ring in BINP [3-5]. An RFQ and small linac can be used as injector with H^- beam ~100 mA, 2-10 MeV.

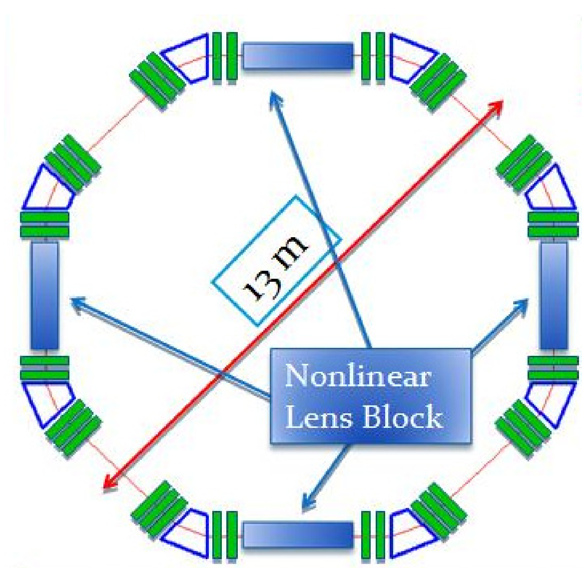

Figure 3: Schematic of storage ring with a nonlinear close to integrable focusing system from [2].

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Some other methods of space charge compensation were discussed in [9, 18].

A circulating proton beam ~10 or 100 A can be accumulated. Such a beam can be used for realization of resonance reaction induced by circulating ions in a thin internal target.

The plasma accumulation during accumulation of superintense beam was discussed in [11].

A comprehensive review of e-p instability in different accelerators and storage rings was presented in [19]. Theoretical estimation of self-stabilization is presented in [20]. Practical application of space charge neutralization in advanced ion implanters is considered in [21].

With the barrier bucket acceleration, tried at the AGS in the collaboration between KEK and BNL [21], it is possible to accelerate a long uniform bunch of ions without loss of space charge neutralization. Acceleration of compensating electrons should be suppressed by magnetic field as in [12, 16].

CONCLUSION

BBB with space charge neutralized superintense ion beams with intensity far above the space charge limit can be useful in an induction Linac with recirculation and for inertial fusion, neutron, antiproton, and muon generators, resonant reaction with internal targets, high power density physics, FFAG accelerators, and inductive synchrotrons.

It is very attractive to repeat an accumulation of superintense ion beam with modern high current injectors. High current density beam should be stable without secondary ions.

The barrier bucket acceleration [22] can be used for acceleration of the long uniform bunch of ions without loss of space charge neutralization.

Now from RFQ it is possible to have H- beam with current ~100 mA and Energy ~2-3 MeV.

This can be enough for accumulation of about 1 kA of circulating proton beam in a small storage ring with R~1m.

As a first step it is possible to conduct realistic simulations of superintense beam accumulation with enhanced ionization cooling. Simulation of the self stabilization of the e-p instability can become a basis for new advanced accelerators and storage rings with intensity far above the space charge limit (by many orders of magnitude). This opens the way for new applications of accelerator technology in high energy density physics and technology. With a high injection current and with nonlinear focusing it is possible to have e-p instability self stabilization without the high density secondary plasma.

The important tasks are the development of a physical model of electron multiplication, including ion generation, slow ion dynamics, ion/electron secondary emission, and gas desorption by ion and electron impact.

An important aspect of this work is the estimation of parameters and scales for physical processes, leading to the development of a mathematical model. It is necessary to verify the proposed physical model. The system of Vlasov equations is nonlinear, requiring the use of numerical methods to solve them. As the first step it is appropriate to perform 1D and 2D simulations and compare the results of simulation with available experimental data and published results of simulations based on other codes [1-5,11-21].

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