# BEAM BRIGHTNESS BOOSTER WITH SELF-STABILIZATION OF ELECTRON-PROTON INSTABILITY

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*Abstract*

The brightness and intensity of a circulating proton beam now can be increased up to space charge limit by means of charge exchange injection or by an electron cooling but cannot be increased above this limit. Significantly higher brightness can be produced by means of the charge exchange injection with the 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. Discovery of "cesiation effect" significantly increases the negative ion emission from gas discharges, and surface-plasma sources for intense high brightness negative ion beams production were developed. These developments prepared a possibility for production of stable "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. The superintense beam production can be simplified by developing of nonlinear nearly integrable focusing system with broad spread of betatron tune and the broadband feedback system for e-p instability suppression [2].

## INTRODUCTION

Charge Exchange Injection (CEI) was developed for increase of a circulating beam intensity and brightness above injected beam parameters by multiturn injection of beam into the same transverse phase space areas (Non **Liuvillian** injection) [3-5]. At that time 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 then the brightness of a primary proton beam because only 2% of 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. Intensity and brightness of $H^-$ ion beams were increased in orders of magnitude by admixture into gas discharges trace of cesium (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 ~1 π mm mrad [7,8] the brightness of injecting beam become close to the space charge limit of real accelerator such as the Fermilab booster [9]. With such beam it is impossible the further increase of circulating beam brightness, but CEI is routinely used for increase the circulating beam intensity for many orders by injection in 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 of 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 driving by beam interaction with accumulated compensating particle in the circulating beam.

The strong instability with fast loss of a bunched beam was discovered at 1965 in small scale proton storage ring (PSR) during development of charge exchange injection and was stabilized by feed back [3, 4, 5, 12, 13].

This instability was explained in [4] as an inversed variant of the strong transverse instability of circulating electron beam caused by the interaction with compensated ions (beam- ion instability) predicted at 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 a good agreement with theory [14, 15].

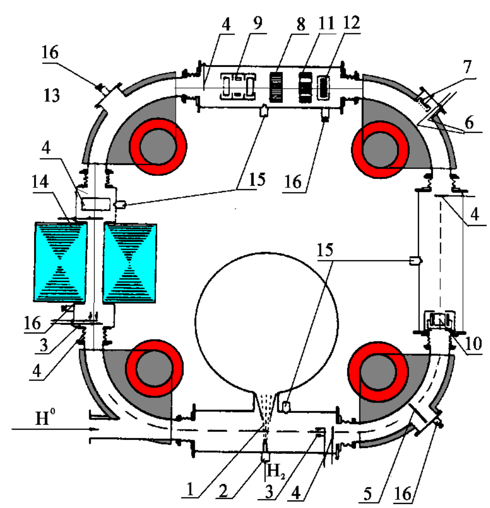


Figure 1: Schematic of storage ring with diagnostics and control. 1-striping gas target; 2-gas pulser; 3-Faraday Cup; 4-Quartz screen; 5, 6-moving targets; 7-ion collectors; 8-current monitor; 9-Beam Position Monitor; 10-Quadrupol pick ups; 11-magnetic BPM; 12-beam loss monitor; 13-detector of secondary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

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

$H^0$ 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 is -1.86 MHz. An inductive core was used for compensation of the ionization energy loss ~200 eV per turn, which produce some effects of an ionization cooling.

Superintense proton beam with intensity ~1 A corresponding to 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 if high circulated 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 $n_i$ are above a threshold level):

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

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

With a broad betatrone 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 more easy in BBB with a stable close to integrable nonlinear focusing proposed in [2].

Possible design of such storage ring is shown in Fig. 2. 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 10 MeV it is possible to use a supersonic gas jet as a stripping target as was in the small scale proton storage ring in BINP [3-5]. RFQ and small linac can be used as injector with $H^-$ beam ~100 mA, 10 MeV. A circulating proton beam ~10 or 100 A can be accumulated. Such beam can be used for realization of resonance reaction induced by circulating ions in thin internal target as shown in Fig. 3.

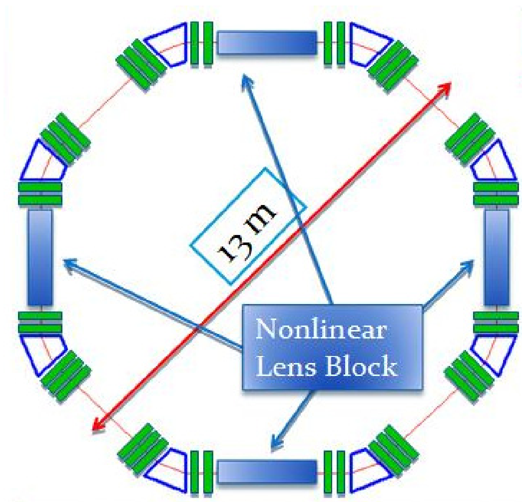


Figure 2: Schematic of storage ring with a nonlinear close to integrable focusing system from [16].

Electron cooling can be used for scattering and energy spread compensation. Some other methods of space charge compensation was discussed in [9, 17].

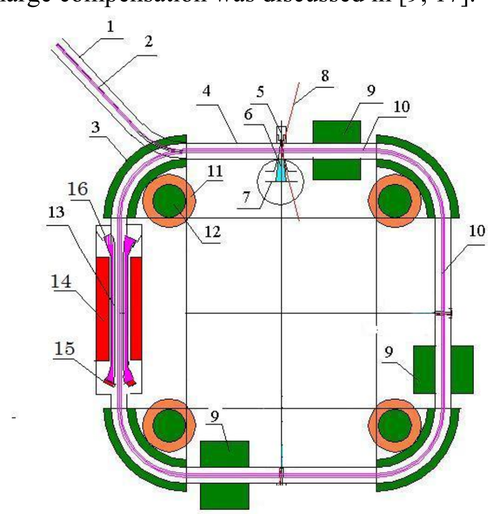

Figure 3: Schematic of resonance reaction production in interaction of circulating proton beam with thin targets accompanied by electron cooling. 1- beam line for transportation of injecting H- beam; 2- injecting beam of H-; 3-bending magnets; 4-vacuum chamber of storage ring; 5- generator of supersonic jet- stripping, reaction target; 6- suprsonic jet, stripping-reaction target; 7- pump-recirculator of target jet; 8- cone of resonant gamma rays; 9- 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; 13-cylindrical hollow electron beam; 14- solenoid of electron cooling system; 15- cathode of electron cooling beam; 16- collector of electron beam.

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

Comprehensive review of e-p instability in different accelerators and storage rings was presented in [18]. Theoretical estimation of self-stabilization is presented in [19]. A practical using of the space charge neutralization in an advanced ion implanters is considered in [20].

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 ion without loss of space charge neutralization. Acceleration of compensating electrons should be suppressed by magnetic field as in [12,16].

## CONCLUSION

BBB with the space charge neutralized Superintense ion beams with intensity fare above space charge limit can be useful for:

In Inductance Linac with recirculation,

For Inertial Fusion,

For Neutron, Antiproton, Mu meson Generators

For resonant reaction with internal targets

For High Power Density Physics

For FFAG accelerators,

For Inductive Synchrotrons.

Intensity limit don't determined.

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

The barrier bucket acceleration 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 ~3 MeV.

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

As first step it is possible to conduct realistic simulation of superintense beam accumulation. Simulation of the self stabilization of the e-p instability can become a basis for new advanced accelerators and storage rings with intensity greatly 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 it is proper to perform 1D and 2D simulations and compare the results of simulation with appropriate experimental data and published results of simulations based on other codes [1-5,11-20].

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