



# Condition for Production of Circulating Proton Beam with Intensity Greater than Space Charge Limit

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**Abstract.** Transverse e-p instability in proton rings could be damped by increasing the beam density and the rate of secondary particles production above the threshold level, with the corresponding decrease of unstable wavelength  $\lambda$  below the transverse beam size  $h$  (increase of beam density  $n_b$  and ion density  $n_i$  above the threshold level:  $n_b + n_i > \beta^2 / (r_e h^2)$ , where  $r_e = e^2/mc^2$ ). Such "island of stability" can be reached by a fast charge-exchange injection without painting and enhanced generation of secondary plasma, which was demonstrated in a small scale Proton Storage Ring (PSR) at the Institute of Nuclear Physics, Novosibirsk, Russia [1]. With successful damping of e-p instability, the intensity of circulating proton beam, with a space charge neutralization was increased up to 6 times above a space charge limit. Corresponding tune shift without space charge neutralization should be up to  $\Delta\nu=0.85 \times 6$  (in the ring with  $\nu=0.85$ ). In this paper, we review experimental observations of transverse instability of proton beams in various rings. We also discuss methods which can be used to damp the instability. Such experimental data could be useful for verification of computer simulation tools developed for the studies of the space charge and instabilities in realistic conditions [4,5].

## INTRODUCTION

Limitation of beam intensity as a result of space-charge force is in general accepted as a "natural" limit for the high-intensity rings. Such a limit is often a design goal of the projects in physics and technology. However, in some cases this limit could be overcome by means of the space-charge neutralization (compensation) with the particles of an opposite charge. The importance of transverse beam instability driven by the interaction with the plasma-compensating particles was considered in the first proposals of the high intensity beam production of the stabilized relativistic beam [6]. In the analysis of the stability of a partially compensated electron beam by Chirikov [7], it was shown that the threshold intensity and the level of compensation for the instability of a coasting circulating beam can be lower than the conventional space-charge limit. In this model of the electron-ion instability, low energy compensating particles (electrons or

ions) are trapped within the space-charge potential of the circulating beam. As a result, coupled transverse oscillations of the beam and trapped particles are developed with transformation of beam energy into the energy of oscillation, leading to a beam loss. Starting with the first projects of electron-positron colliders, the clearing electrodes were used to remove the secondary particles along all the orbits, to prevent beam degradation caused by the compensating particles. With a very good vacuum, this was sufficient to avoid such an instability.

## EXPERIMENTAL OBSERVATION OF E-P INSTABILITIES

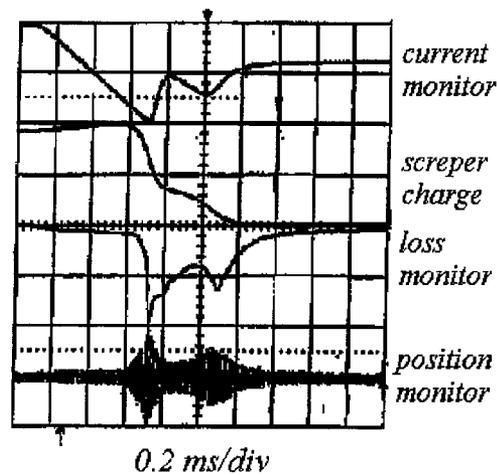
For the first time, transverse instability of bunched proton beam driven by the compensating particles was observed in 1965 in a small scale Proton Storage Ring (PSR) in INP, Novosibirsk, Russia, used for the development of the charge-exchange

injection [2,3]. In this small PSR with a circumference  $L=2.5$  m, the 800-turn charge-exchange injection of 1 MeV  $H^-$  was used to achieve the linear proton density  $\rho \sim 2.5 \cdot 10^9$  p/cm and the volume density  $n \sim 10^8$  cm<sup>-3</sup> with the corresponding beam potential of 1kV. This instability was accompanied by a fast loss of bunched beam. It was stabilized with a simple negative feed-back using the pickup electrode, the resonance amplifier and the deflection electrode. In 1967, in another small PSR, the instability of a coasting proton beam with a very low threshold was also observed. It was attributed to accumulation of the compensating electrons [1,8]. The behavior of this instability was in good agreement with Chirikov's analysis [7]. This instability was damped by increasing the bounce frequency of electrons in the proton beam with increase of the positive-ion density [1,9]. Recently, these results were summarized in [10,11].

Observation of transverse instabilities in the AGS and ZGS were presented at the Cambridge Accelerator Conference (1967), along with [8], but only last was identified, as the e-p instability. The instability of the coasting proton beam with accumulation of electrons were also observed in the Bevatron and CERN ISR in 1971. In the Bevatron, this instability was damped by a feedback and by beam bunching, and in the ISR by improving vacuum from  $10^{-10}$  Torr to  $10^{-11}$  Torr with additional installation of the clearing electrodes. A similar instability with accumulation of positive ions in an electron and antiproton beams was observed in synchrotron radiation source ALADDIN and in antiproton accumulators (AA) at CERN and Fermilab[12]. The instability in AA was damped by using sophisticated methods of ion repulsion with shaking of the beam in addition to the vacuum improvement and clearing by electric field. Theoretical analysis of the instability of the dipole and quadruple oscillations was developed in 1972 by

Koshkarev and Zenkevich [13] which was further extended in later publications.

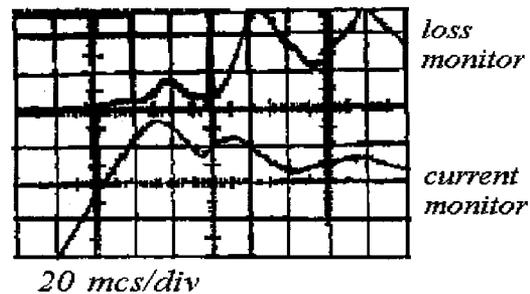
New attention to the e-p instability was attracted after the observation in the LANSCE PSR of strong transverse instability with the loss of both bunched and unbunched beam [14]. This unpredicted and "mysterious" instability limited the pulsed intensity of the spallation neutron source to the level below its design goal for many years. After many studies, a good understanding of coasting beam instability and good agreement with the theoretical models were reached, but instability of the bunched beam does not have



yet a complete understanding.

**FIGURE 1.** Oscilloscope of coasting beam instability in the LANSCE PSR (LANL).

Typical development of e-p instability for coasting beam in the LANSCE PSR is shown in Fig.1



**FIGURE 2.** Coasting beam instability in the INP PSR (Novosibirsk, Russia).

It is absolutely identical to the corresponding picture from the INP PSR shown in Fig.2.

Development of the instability for bunched beams is also very similar in INP PSR (1965) and in LANCE PSR [10,11].

Various aspects of the e-p instability in different accelerators and storage rings and further development in understanding and damping of the instability were discussed in recent workshops [15-17]. Transverse instability of coasting beam was observed in BNL and Fermilab Booster with a DC field. With an increase of beam density, the bounce frequency of the secondary-particle oscillations is increased and strong oscillations may develop during a single pass of a bunch or train of bunches through the portion of secondary particles accumulated during only one pass of the bunch or bunch-train. A possibility of "Fast beam-ion instability" was discussed in Reference [18]. This type of instability was observed in the ALS with increased density of He gas [19]. Such "Fast beam-ion instability" was, in fact, observed in 1975 in a low energy negative ion beam after the ion source [1] and after FNAL 0.75 MeV preaccelerator [20]. The space-charge compensation with ions exhibit essential differences in comparison with the electron compensation. The resulting instability has some features related to the mass difference and the ability to keep coherence.

### DAMPING OF E-P INSTABILITY

For low beam density, an electron bounce frequency

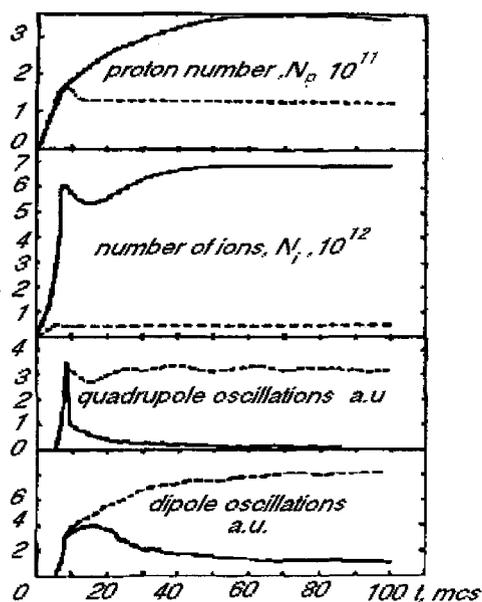
$\omega^2 = 4c^2 r_e n_i$  is comparable with a revolution frequency and bounce oscillation coupled with the low modes of betatron oscillations. For low modes, the magnitude of electron oscillations is larger than the one of beam oscillations. As a result, electrons are removed from the beam by a very small oscillations of protons. This mechanism is

used to remove ions from the antiproton beam.

Strong instability requires high beam density and significant source of secondary particles. Suppression of secondary particles production is a "traditional" method for the e-p instability cure. The typical guideline is: improve vacuum, use a gap for electron removal, use clearing electrodes, suppress secondary emission. A feedback system could be also very effective to damp the instability. Progress in suppressing of the e-p instability in LANL PSR was discussed in reports by R. Macek [15-17,21]. The need for higher beam intensity at PSR and in future high-intensity proton drivers motivated a multi-lab collaboration (LANL, ANL, FNAL, LBNL, BNL, ORNL, PPPL) to undertake research for better understanding of causes, dynamics and cures of the e-p instability. Important characteristics of the electron cloud were recently measured with ANL electron analyzers and various collection electrodes [22]. Suppression of electron production with TiN coatings confirmed the importance of secondary emission processes in generating the electron cloud. New tests of potential controls included dual harmonic RF, damping by higher order multipoles, damping by X,Y coupling and use of inductive inserts to compensate the longitudinal space-charge forces. Use of a skew quadrupole, heated inductive inserts and higher RF voltage has enabled the PSR to accumulate stable beam intensity up to 9.7 mC ( $6 \cdot 10^{13}$  p/p), which is a significant increase (60%) over the previous maximum of 6 mC. This beam was stable with a high rate of secondary electron production.

Efficient damping of the e-p instability by increasing the beam current density and the rate of the secondary-plasma density was demonstrated in a small scale PSR at INP, Novosibirsk, in 1976 [1,9]. This process of the proton accumulation by charge-exchange injection is shown in Fig. 3.

With injected current below 2 mA and low gas density, a fast excitation of the dipole and quadrupole coherent oscillations was observed. The proton accumulation saturated by a beam loss at the level of  $N_p = 1.2 \cdot 10^{11}$ , as shown by dotted lines. By increasing the injected current and gas density above the threshold level, the accumulation dynamic changed dramatically, as shown by solid lines. The number of circulating protons was increased during all injection period with the limitation coming only from the injected current, with the oscillations being quickly damped.



**FIGURE 3.** Accumulation of circulating protons in the INP PSR before critical intensity (dotted lines) and above critical intensity (solid lines) with damping of instabilities and overcoming a space charge limit.

The density of secondary ions and electrons in the beam was increased dramatically. Such an increase of positive ion density up to  $n = 3-4 \cdot 10^8 \text{ cm}^{-3}$  moved the bounce frequency of electron oscillation out of the bend of instability. Nonlinearity of the fast accumulation of the secondary plasma is important for e-p stabilization. With 1 MeV H<sup>+</sup> injection current of 5 mA up to  $1.8 \cdot 10^{12}$

protons were accumulated in the PSR with circumference of 6m. This intensity corresponds to a tune shift (without compensation) of  $\Delta\nu = 0.85 \times 6$  in the PSR with  $\nu = 0.85$ . Such an increase of beam and ion density above the second threshold (corresponding to the damping of the instability) could be used for the production of extremely bright ion beams with the increase of brightness by a non-Liouville's charge-exchange injection and for acceleration of the high current ion beams in recirculators with an inductance linacs. It looks like the space-charge compensation of the bunched beam is also possible.

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