# SOME FEATURES OF TRANSVERSE INSTABILITY OF PARTLY COMPENSATED PROTON BEAMS

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*Abstract*

Suppression of generation and accumulation of secondary particles is a traditional method for suppression the transverse electron-proton instability: improve the vacuum, use a gap in beam for electron removing, use cleaning electrodes, suppressing secondary emission. But opposite solution is also possible. Transverse e-p instability in proton rings can be damped by increasing beam density and the rate of secondary particles generation above a threshold level, with decrease of the unstable wavelength below a transverse beam size. In high current Proton Storage Rings (PSR) such as, the LANSCE PSR it is possible to reach this island of stability by multiturn, concentrated charge exchange injection without painting and by enhanced generation of secondary plasma. This possibility was demonstrated in smaller scale PSR at the INP, Novosibirsk [1]. Damping of the e-p instability allowed to accumulate a coasting, space charge compensated, circulating proton beam with intensity, corresponding to the Laslett tune shift of $\Delta\nu=5$ in the ring with original tune of $\nu=0.85$. In the other PSR transverse instability of bunched beam was damped by a simple feed back [2,3]. In this article we discuss experimental observations of transverse instability of proton beams in different accelerators and storage rings and consider methods to damp the instability. The presented experimental dates could be useful for verification of computer simulation tools developed for investigation of space charge effects and beam instabilities in realistic conditions [4,5].

## 1 EXPERIMENTAL OBSERVATION OF E-P INSTABILITIES

Beam intensity and performance limitation due to repulsing space charge forces is generally accepted as a "natural" limit and reaching of this limit is often set as a design goal of accelerator projects. Sometimes this limit could be overpassed with use of space charge neutralization (compensation) by opposite charged particles. Development of the industrial scale electromagnetic isotope separation for the "Manhattan Project" is an example of very successful development of the space charge neutralization (SCN) of heavy ion beam. Beam intensity had been increased from microampers to hundreds of milliamps. At present this SCN is a basis for ion implantation in the semiconductor industry. But SCN is very delicate and nonequilibrium process and development of strong instabilities can destroy the neutralization and beam propagation. Admixture of compensating particles can drive the beam instability with low threshold intensity, far below the space charge limit. Circulating beams in the accelerators and storage rings are more sensitive to any influences, than beams in finite transportation. The increase of the beam intensity and brightness is increase a nonequilibrium, and instability development due to compensating particles can start in any part of an accelerator complex from an ion source to a booster. Special cures should be used to avoid the instability. The importance of the transverse beam instability driven by interaction with a plasma compensating particles has been considered in the first proposals of the high intense beam production as the "stabilized relativistic beam" [6]. In the analysis of stability of partly compensated electron beam by Chirikov [7], it has been shown that the threshold intensity and level of compensation for instability of coasting circulating beam are low. In this model of the electron-ion instability, the low energy compensating particles (electrons or ions) are trapped within the space- charge potential of the circulating beam. Coupled transverse oscillations of the beam and the trapped particles are developing with a transformation of the energy of beam to the oscillation energy, leading to the beam loss. To prevent beam degradation caused by compensating particles in electron- positron colliders used clearing electrodes. They remove secondary particles along all orbits, and with a sufficiently deep vacuum this was enough for avoiding an instability.

Transverse instability in the bunched proton beam, driven by compensating particles has been observed by author at 1965 in small scale storage ring used for development of charge exchange injection [2,3]. In that small PSR with

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circumference L=2.5 m employed 800 turns charge exchange injection of 1 MeV $H^-$ were reached a linear proton density $\lambda$~*2.5* $10^9$ *p/cm*, a volume density *n* ~$10^8$ $cm^{-3}$ and corresponding beam potential relative the chamber wall U~1kV. Instability causing fast loss of bunched beam had been stabilized by simple negative feedback system with pick up electrode, resonance amplifier and deflection electrode. In 1967 in other small PSR instability in coasting proton beam with a low threshold, connected with an accumulation of the compensating electrons was observes [1,8]. The behavior of that instability was in good agreement with a Chirikov s analysis [7]. This instability has been damped by increase of the bounce frequency of electrons in the proton beam by increasing of ion charge density. A stable circulating proton beam with completely compensated space charge and with intensity, corresponding a tune shift of $\Delta\nu$=0.85x6 in the ring with $\nu$=0.85 (up to 9 time above a space charge limit) was accumulated [1,8]. These results were discussed in [10,11].
Transverse instabilities in the AGS and in the ZGS has been reported at the Cambridge Accelerator Conference 1967 along with [8] but only recent was identified at that time as electron-proton instability. Instability of the coasting proton beam with accumulation of electrons has been observed in the Bevatron and in the CERN ISR in 1971. In the Bevatron the instability was damped by feedback system and by beam bunching, and in the ISR by improving a vacuum from $10^{-10}$ Torr to $10^{-11}$ Torr and by increasing the number of clearing electrodes. Similar instability with accumulation of positive ions in negative charged electron and antiproton beams, has been observed in the synchrotron radiation source ALADDIN and in the CERN and Fermilab Antiproton Accumulators (AA) [12]. Instability in AA was dumped by using a sophisticated methods of ion repulsing as beam shaking in supplement to vacuum improving and clearing by electric field.
Further theoretical analysis of instability of dipole and quadruple oscillation has been developed in 1972 by Koshkarev and Zenkevich [13] and has been extended in

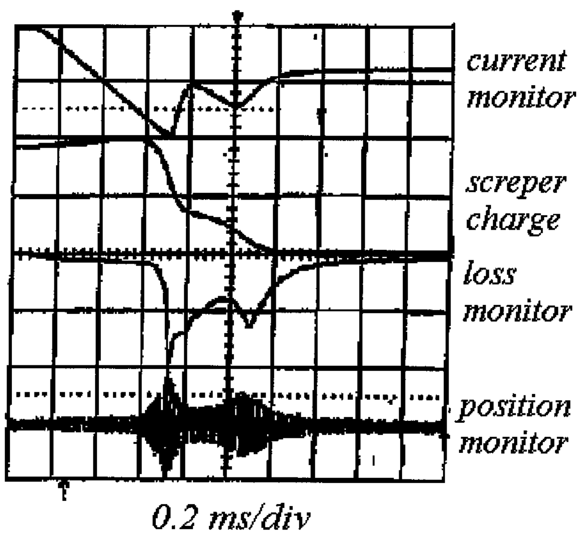


Figure 1: Oscillograms of coasting beam instability in the LANSCE PSR

other publications.
New attention to the e-p instability was attracted after observation in the LANSE proton storage ring (PSR) a strong transverse instability with loss of bunched and unbunched beam [14]. That unpredicted and mysterious instability during 20 years limited the peak intensity of the spallation neutron source at the level, below design the goal. Some acceptable understanding of coasting beam instability and any agreement with theoretical models was reached after extensive investigation, but the instability of the bunched beam had not acceptable understanding.

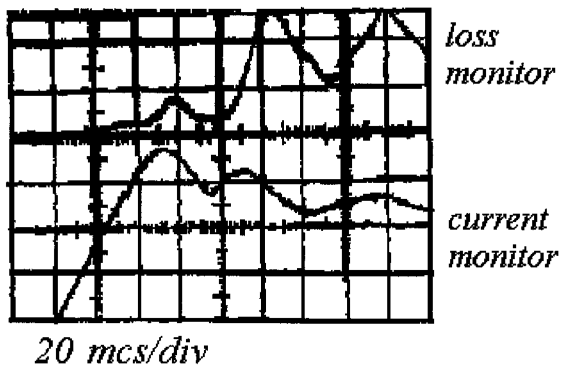


Figure 2: Coasting beam instability in the INP PSR.

Typical development of an e-p instability in coasting beam of the LANSCE PSR is shown in Fig.1. It is absolutely identical to the corresponding picture from the INP PSR in Fig.2. Different aspects of the e-p instability in different accelerators and storage rings and further development for understanding and damping of the instability has been considered in many Workshops [15-17]. Transverse instability of coasting beam was observed at the BNL Booster and in Fermilab Booster with a DC field.
With an increase of beam density the bounce frequency of secondary particles oscillations growsand significant development of oscillation could be reached during one pass of bunch or train of bunches through the portion of secondary particles accumulated during only one pass of the bunch or bunch train. The attention to this possibility of "Fast beam- ion instability" has been attracted in paper [18]. Such type of instability has been observed in the ALS with an increased He gas density [19]. This " Fast beam- ion instability" has been observed before in low energy negative ion beam after ion source in 1975 [1] and, also in beamline of FNAL 0.75 MeV preaccelerator [20]. Space charge compensation by ions exhibit essential differences in comparison with compensation by electrons and corresponding instabilities have some features connected with mass difference and the ability to keep coherence.

## 2 DAMPING OF E-P INSTABILITY

For low ion beam density the electron bounce frequency $\omega^2 = 4c^2 r_e n_i$ is comparable with a revolution frequency and the electron oscillation are coupled with lower modes of the beam betatron oscillations. For the lower modes, the magnitude of electron oscillations is greater many times the beam oscillations amplitude and electrons removed the beam by very small oscillations of protons. This mechanism used for ions removal from antiproton beams. For a stronger instability is needed to have higher beam density and stronger source of secondary particles. Suppression of generation and accumulation of secondary particles is a traditional method for the e-p instability suppression: improve the vacuum, use a gap for electron removing, use leaning electrodes, suppressing secondary emission. A feedback system could be efficient in the instability damping.

Progress in suppressing of the e-p instability in LA PSR was discussed in reports of R. Macek, presented in [15-17,21]. The need for higher beam intensity at PSR and for future high-intensity, proton drivers has motivated a multi-lab collaboration (LANL, ANL, FNAL, LBNL, BNL, ORNL, PPPL) to undertake research for better understanding of causes, dynamics and cures for e-p instability. Important characteristics of the electron cloud were recently measured with ANL electron analyzers and various collection electrodes [22]. Suppression of secondary electron generation by TiN coatings has 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 the use of inductive inserts to compensate 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 $10^{13}$ 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.



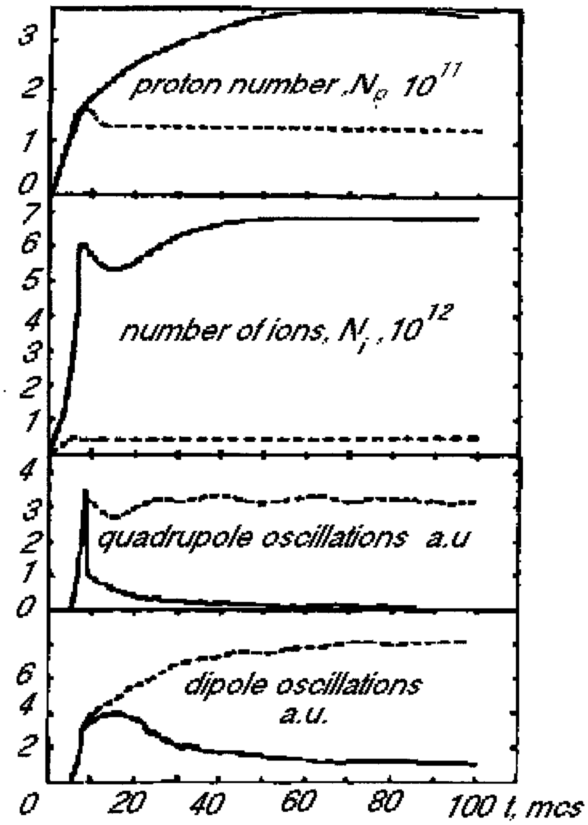


Figure 3: Accumulation of circulating protons in the INP PSR before critical intensity (dotted lines) and above a critical intensity (solid lines) with damping of instabilities and overcoming a space charge limit.

Efficient damping of the e-p instability by increasing beam current density and increase rate of secondary plasma generation has been demonstrated in small scale PSR at INP, Novosibirsk, in 1976 [1,8]. The process of the proton accumulation by charge- exchange injection is shown in Fig.3. Fast excitation of dipole and quadrupole coherent oscillations, and saturation of proton accumulation is by loss on the level of $N_p = 1.2\ 10^{11}$ observed with injected current below 2 mA and low gas density as shown by dotted lines. With increase injection current and the gas density above a threshold level, the accumulation dynamics was changed dramatically, as shown by solid lines. A number of circulating proton increase during the all injection time and was limited only by injected current. Oscillations are damped after a short, fast growing. The densities of secondary ion and electron in the beam were increased dramatically. This increase of positive ion density up to $n = 3\text{-}4\ 10^8\ cm^{-3}$ have shift the bounce frequency of electron oscillation out of the instability bend. Nonlinear, anomalous fast accumulation of secondary plasma is important for the e-p instability stabilization. With injection current of 5 mA, 1 MeV $H^-$ up to 1.8 $10^{12}$ protons were accumulated in the 6 m PSR. Such intensity correspond to tune shift of $\Delta\nu=0.85x6$ in the PSR with original tune of $\nu=0.85$. This increase of beam and ion density above a second threshold for e-p instability could be used for production of extremely bright ion beams with increase a brightness by non-Liouvillean charge exchange injection and for acceleration of high current ion beams in recirculators with an inductance linacs. It looks that the space charge compensation of the bunched beams is also possible.

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