Some Features of Transverse Instabilities in Small Scale Storage Rings

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**ICFA Mini- Workshop on Two- Stream Instabilities in Particle Accelerators and
Storage Ring, Santa Fe, NM February 16-18, 2000**

Review of experiments in 4 versions of proton storage rings at the Budker Institute of Nuclear Physics (BINP), Novosibirsk
(1958- 1985)

- Historical remarks
- Storage rings
- Diagnostics
- Charge Exchange Injection
- Transverse instability of a bunched beam. Damping of instability
- Transverse instability of a unbunched beam. Damping of instability
- Circulating proton beam with intensity above space charge limit
- Discussion
- Conclusion

INP Accelerator activities had its start from the development of a relativistic Self- Stabilized Electron beam (Bennet- Budker RSSE beam)

- Transverse instability 'snake' in space charge compensated beams could be the limit for the RSSE beam production
- Theory
- G. Budker. "Relativistic Self- Stabilized electron beam", Doctor thesis, 1958 ; Soviet Atomic Energy 5, 9 (1956)
- B. Chirikov. " The stability of a partly compensated electron beam", Soviet Atomic Energy, 19, 239 (1965)
- Experiments: Spiral Betatrons, Plasma Betatrons
- Unlimited electron beam current in TOKAMACs

- For the first proton-antiproton collider project and pulsed neutron sources have been developed:

1. charge-exchange injection (H^- stripping)
2. electron cooling
3. high intense, high brightness negative ion sources (Surface Plasma Sources)

Theses , Institute of Nuclear Physics, Novosibirsk.

V.Dudnikov. "Production of an intense proton beam in storage ring by a charge- exchange injection method", Novosibirsk, INP, 1966.
Development of a Charge- Exchange Injection; Accumulation of proton beam up to space charge limit; Observation and damping of synchrotron oscillation; Observation and damping of the coherent transverse instability of the bunched beam.

1. G. Budker, G. Dimov, V. Dudnikov, "Experiments on production of intense proton beam by charge exchange injection method" in Proceedings of International Symposium on Electron and Positron Storage Ring, France,Sakley,1966, rep. VIII, 6.1 (1966).
2. G. Budker, G. Dimov, V. Dudnikov, "Experimental investigation of the intense proton beam accumulation in storage ring by charge- exchange injection method", Soviet Atomic Energy, 22, 384 (1967).
3. G.Dimov, V.Dudnikov, "Determination of the current and current density distribution in a proton beam (residual gas ionization profile monotor)", Instrum. Experimental Techniques, 3, 18 (1969).

G.Dimov. "Charge- exchange injection of protons into accelerators and storage rings", Novosibirsk, INP, 1968.
Development of a Charge- Exchange Injection; Accumulation of a proton beam up to the space charge limit; Observation and damping of synchrotron oscillations; Observation and damping of the coherent transverse instability of the bunched beam; observation of the e-p instability of coasting beam in storage ring.

V.Shamovsky. "Investigation of the Interaction of the circulating proton beam with a residual gas", Novosibirsk, INP, 1972.
Observation of transverse e-p coherent instability of the coasting beam in the storage ring, Observation of a transverse Herward's instability, Damping of instabilities, Accumulation of a proton beam with a space charge limit.

1. G. Dimov, V. Dudnikov, V. Shamovsky, "Transverse instability of the proton beam induced by coherent interaction with plasma in cyclic accelerators", Trudy Vsesousnogo soveschaniya po uskoritelyam, Moskva, 1968, v. 2, 258 (1969).
2. G. Dimov, V. Dudnikov, V. Shamovsky, "Investigation of the secondary charged particles influence on the proton beam dynamic in betatron mode ", Soviet Atomic Energy, 29,353 (1969).
3. G.Budker, G.Dimov, V. Dudnikov, V. Shamovsky, "Experiments on electron compensation of proton beam in ring accelerator", Proc.VI Intern. Conf. On High energy accelerators, 1967, MIT & HU,A-104, CEAL-2000, (1967).

V. Chupriyanov. “Production of intense compensated proton beam in an accelerating ring”, Novosibirsk, INP, 1982.

Observation and damping transverse coherent e-p instability of coasting proton beam and production of the proton beam with an intensity up to 9.2 time above a space charge limit.

G.Dimov, V. Chupriyanov, “Compensated proton beam production in an accelerating ring at a current above the space charge limit”, Particle accelerators, 14, 155- 184 (1984).

G.Budker, G. Dimov, V. Dudnikov et al. Development of the intense proton beam at the Novosibirsk, Proc. X Internat. Conf. Particle Accelerators, Protvino, 1977, v.2,p. 287 , 1978.

NON-LIOUVILLEAN INJECTION

$H_2^+ \overrightarrow{\text{gas}} H^+$	Moon (Birmingham, 1956)
$H^- \overrightarrow{\text{gas}} H^+$	Budker, Dimov (Novisibirsk, 1968) 1966 Dudnikov
$H^- \overrightarrow{\text{foil}} H^+$	Martin (ANL, 1970-76)
100 × Brightness	ZGS
Stability	ZGS BST (IPNS)
	KEK BST
	FNAL BST
	AGS (BNL)
	PSR (LANL) (field stripping)
	ISIS (Rutherford)
$HI^+ \overrightarrow{\text{laser}} I^+$	Martin, Arnold (1976) HIF
$Bi^+ \longrightarrow Bi^{2+}$	Rubbia (1989) HIF Main Ring
$Ba^+ \longrightarrow Ba^{2+}$	Hofmann (1990) HIF Compressor Rings

Extraction $H^- \overrightarrow{\text{foil}} H^+$ TRIUMPF (Vancouver)

Proposed for ACCTEK Proton Theraphy,
Proton Radiography and Computed Tomography

AIP 253

2. The second point is illustrated by examining the effect of the longitudinal transverse coupling in a linac, arising from the $(x^2+y^2)z$ term in the Hamiltonian. If the transport channel is matched for the synchronous particle, a nonsynchronous particle will lead to an elliptical distortion of the "matched circle" in the transverse phase space, where the magnitude of the elliptical distortion is proportional to the magnitude of the initial longitudinal oscillation, and where its orientation depends on the initial phase of the longitudinal oscillation. A projection will therefore occupy a greater phase space area, even though the original 6-D volume is not changed. This suggests that it may ultimately be possible to reduce emittance growth in the projections by introducing the appropriate initial 6-D phase space correlations. Of course this may turn out to be very difficult to implement, but it is one further indication that some emittance growth is <u>not</u> inevitable.

Finally, I wish to add that my interactions with Martin Reiser here at UMCP and away from home at Los Alamos, where we have spent time together, have been a pleasure. Happy birthday, Martin.

<u>R.L. MARTIN</u>: *History of Non-Liouvillian Injection and Its Connection to the Initiation of the U.S. Program in Heavy Ion Fusion*

The first suggestion that I am aware of the possibility of non-Liouvillean injection was by Moon from Birmingham in 1956. It was published in the Proceedings of the First International Accelerator Conference held in CERN that year. He suggested the molecular dissociation of H_2^+ to give protons. I am not aware that it was ever tried experimentally.

I visited Novosibirsk in late 1968 and saw a laboratory experiment by G. Dimov on charge exchange injection of H$^-$ ions. He injected 1.5 Mev H$^-$ ions into a small storage ring ($\sim$ 2 m in diameter) in a two stage process ($H^- \rightarrow H^0 \rightarrow H^+$) by gas stripping. Although he only accumulated a few3$\times 10^{10}$ protons this was impressive because it was at the space charge limit of the ring at 1.5 MeV and required many turns of injection. It was therefore clearly non-Liouvillean. Even more impressive to me was that Dimov had developed an H$^-$ source of 16 mA output. (Dudnikov, for whom a source type is named today, was part of Dimov's group.) This was far superior to any other H$^-$ source in the world at that time, and the current was adequate to make charge exchange injection practical on an operating physics machine at high intensity.

I therefore began a program on H$^-$ charge exchange at Argonne where the ZGS injector was a 50 MeV Alvarez Linac. At 50 MeV one could make plastic foils thin enough (2000 Å) and that the complication of gas stripping could be avoided. Major questions were:

1) would lifetime of foils be long enough to make the operation acceptable
2) how much gain in brightness was achievable
3) could one reach high intensities (5 - 10 $\times 10^{12}$ protons/pulse).

Some features of transverse instability of circulating proton beam

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Abstract

Accumulation of the particles with an opposite charge is a powerful source of instability of circulating and direct beams. Transverse instability of a coasting circulating proton beam with admixture of electrons was investigated very well both in theory and in experiments. Deep understanding of this instability has permitted to accumulate a circulating proton beam with intensity up to 9.5 time above of the space charge limit, and was limited only by injection current. However, transverse instability of the bunched beam in storage ring observed many years ago [1,2] does not have an acceptable explanation until present. From first observations [1,2] the explanation of this instability was connected with accumulation of secondary particles in the beam. Not all features of instability could be related to the interaction of the beam with electrons.

Some evidences may have an interpretation that the accumulation of negative ions in a proton beam could be the reason for the beam loss in the proton storage ring (PSR), as it was proposed in [1,2,3]. Strong oscillation of coasting proton beam has developed during beam injection in resonance interaction of the beam with accumulating electrons. This phenomenon is well investigated. Strong oscillation of the bunched proton beam has started with a long delay time (T~ 1-3 ms) after accumulation above threshold intensity. This delay time is an important feature of the transverse instability of bunched beam in the storage ring (PSR). An intensity of accumulated bunched beam could be up to 30 times higher than the threshold intensity for this instability. An increase of intensity decreases the delay time, but does not eliminate this delay time. The reason for this delay time could be explained as a time for negative ion formation. An injection of the DC beam with RF voltage in bunching cavity creates a circulating beam with protons between bunches, but does not develop instability. Strong excitation of compensating electron oscillations creates a big signal in the position monitors, but corresponding dipole-??????? dipole oscillation of proton beam should be smaller than electron oscillations, because the mass of electrons is very small. Resonant oscillation of heavy ions with a low mode number maybe not too big, but correspondent oscillation of proton beam is much bigger. Electrons accumulation and oscillations have created condition for negative ion formation in the volume and on the walls of beam chamber with any delay after electron accumulation. An observation of the instability damping in Los-Alamos PSR by shaking of the proton beam in low mode frequency f(3- ν), while corresponding H- resonance frequency in proton beam potential could be an evidence for killing role of negative ion in the PSR. For the reason that proton beam has a very high positive potential a vacuum break down (multipactor) or unipolar arc could be a powerful source of electrons and negative ions. For separation of proton beam oscillation from the electron and negative ion oscillation it is necessary to clean a pick- up electrode from the electrons or use a

magnetic (loop) pickups. Negative feedback could be used for stabilization of low mode oscillations. Dipole or quadruple "shaking" in low modes and laser beam electron detachment from the negative ions could be used for negative ion removing and damping of the killing instability. Material with a low secondary emission of electrons and negative ions (as Mo, TiN,...) could be useful for suppression of negative ion formation. Admixture of a heavy electronegative gases as CF4, SiF4, SF6,.. could be used to decrease the frequency of ion oscillation and increase the threshold of instability.
Direct detection of electrons, positive and negative ions in the beam after repulsing by high voltage pulse could be useful diagnostics for identification of the reason of instability as in production of proton beam with intensity above the space charge limit [14].

Who is killer of a bunched proton beam in PSR?

The answer to this detective question is under investigation from 1966, when a strong instability of the betatron oscillations of the bunched proton beam in the storage ring was observed by V. Dudnikov during development of Charge exchange injection.
This phenomena has been described in Ph. D thesis of V. Dudnikov " Production of intense proton beam in storage ring by charge- exchange injection method", Institute of Nuclear Physics, Novosibirsk, 1966 [1], , and published in [2,3,4].
Strong instability of the unbunched, coasting proton beam in a small (R=42 cm) storage ring has been observed by V. Dudnikov and explained in reports [5,6]. Last phenomena behavior was in good agreement with theory of instability of the partly space charge compensated beam in cyclic accelerators, developed by B. Chirikov [7]. Interaction of the circulating proton beam with electrons, accumulated in the space charge of proton beam was the reason of instability and observed oscillations and loss of beam. Strong instability of the bunched and unbunched proton beam in the Los Alamos proton storage (PSR) ring was observed in 1986 [9] and many reports with investigation of these instabilities have been presented at many conferences and workshops[10].
In the bunched beam electron should escape from the orbit during passing the gap between bunches. In publications [2,3,4,8] it was suggested that accumulation of the negative ions could be the reason of the big transverse oscillations of circulating protons and loss. Space charge compensation by heavy particle is very different from compensation by electrons, because heavy particles could accumulate from space charge not only big energy, but also big moment and can induce a big displacement of the beam. The same instabilities of antiproton beam induced by accumulation of positive ions have been investigated in ref. 11. Removing of compensating ions and stabilization of instability by a resonant shaking of antiproton beam were developed.
Now it is possible to present some arguments for conformation of this proposal. In [12] there is the following remark : " We attempted to shake the PSR with a pulser tunable to frequency bands from 0.5 to 100 MHz. While no effects were observed at high frequencies (electron resonance), excitation at lowest frequency sidebands (proton

resonance) slightly improved stability and Fig 13 demonstrates the damping of proton beam instability by beam shaking at the frequency of f(3- ν)". This phenomenon could be an argument for participation of negative ion in the killing of the circulating proton beam, as positive ion in antiproton beam instability.

Space charge compensation by heavy particles is very different from the space charge compensation by electrons, because heavy particle can keep coherence much stronger then electrons. Fast beam- ion instability is very strong and fast in negative ion beam compensated by positive ion and in positive ion beam compensated by negative ion. This instability can have strong development in distance L= 0.1-1 m for ions with energy 10 keV and in L=5-10 m for ions with energy 1 MeV. [19].

A precision dipole and quadruple "shaking" proton beam in resonant with negative ions could be used for negative ion removing as positive ion removing from the antiproton beam in ref. [11] and laser beam destruction of negative ions could be used for negative ion removing as in [13]. Using of the surface with a low secondary emission of electrons and negative ions could be useful for suppression of the negative ion formation. For this it is useful to have a surface with low concentration of electronegative admixtures, such as Mo, TiN.

Admixture of the heavy electronegative gases as CF4, SiF4, SF6,... could be used for testing and decrease the frequency of ion oscillations and increase the threshold intensity for instability development.

Direct diagnostics of electron, positive and negative ion density in the beam could be useful for the identification of the reasons of instability, as in [14].

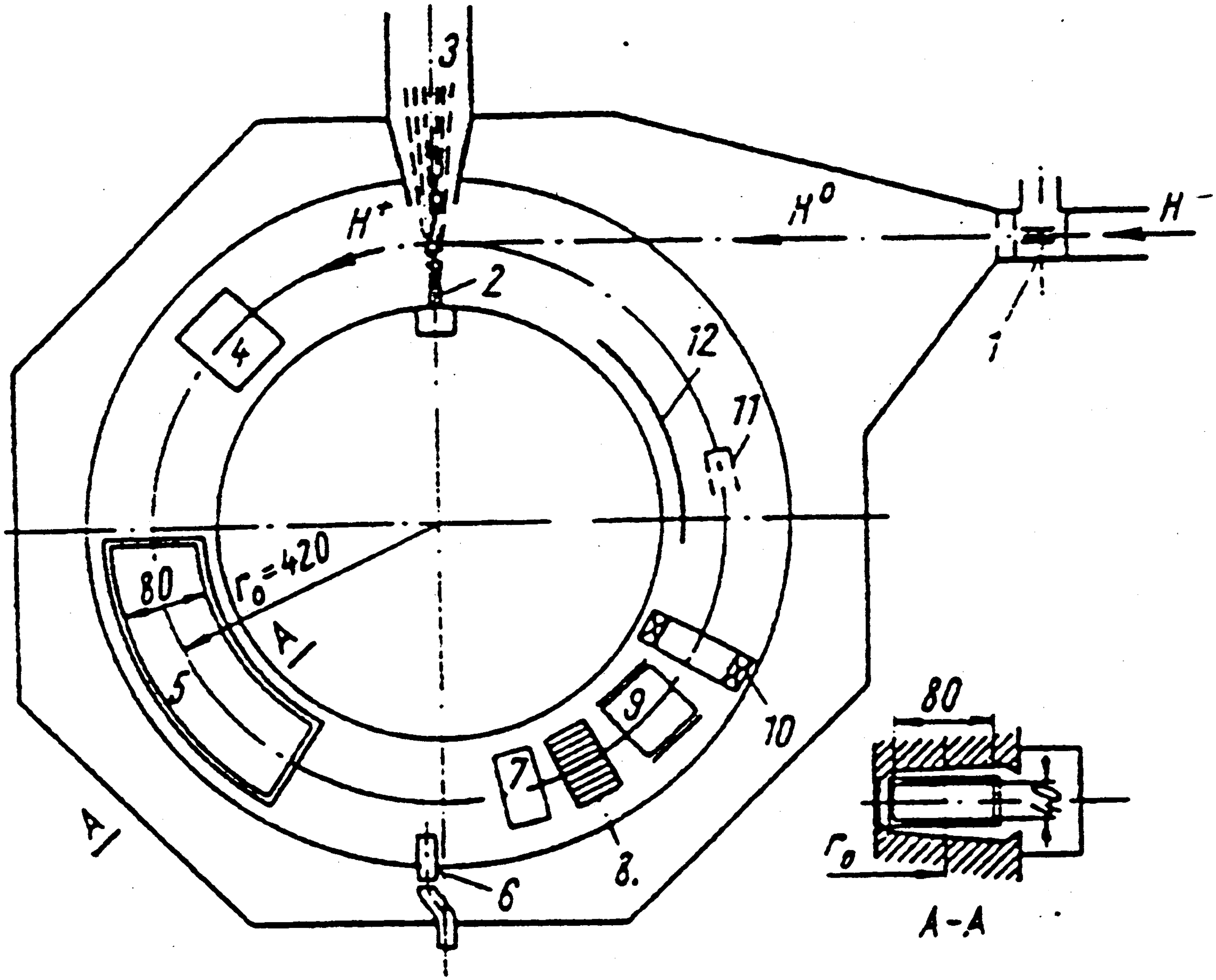
Suppression of e-p instability in the coasting proton beam and accumulation of the proton beam with an intensity up to 9 time above the space charge limit has been discussed in [14-18].

References:

1. V. Dudnikov ,Ph. D thesis “Production of intense proton beam in storage ring by charge- exchange injection method”, Institute of Nuclear Physics, Novosibirsk, 1966
2. G. Budker, G. Dimov, V. Dudnikov, “Experiments on production of intense proton beam by charge exchange injection method” in Proceedings of International Symposium on electron and Positron Storage Ring, France,Sakley,1966, rep. VIII, 6.1 (1966)
3. G. Budker, G. Dimov, V. Dudnikov, Experimental investigation of the intense proton beam accumulation in storage ring by charge- exchange injection method”, Soviet Atomic Energy, 22, 384 (1967).
4. G. Dimov, V. Dudnikov, V. Shamovsky,” Transverse instability of the proton beam induced by coherent interaction with plasma in cyclic accelerators”, Trudy Vsesousnogo soveschaniya po uskoritelyam, Moskva, 1968, v. 2,p.258(1969).
5. G. Dimov, V. Dudnikov, V. Shamovsky,” Investigation of the secondary charged particles influence on the proton beam dynamic in betatron mode ”, Soviet Atomic Energy, 29,353 (1969).
6. G.Budker, G.Dimov, V. Dudnikov, V. Shamovsky, Experiments on electron compensation of proton beam in ring accelerator, Proceedings of the sixth Internat. Conf. On High energy accelerators, 1967, MIT & HU,A-104, CEAL-2000, 1967.
7. B.Chirikov,” The stability of partly compensated electron beam”, Soviet Atomic Energy, 19, 239 (1965).
8. V. Dudnikov, A. Shabalin, Transverse instability of proton beam in storage ring induced by negative ion, HIPAC’92, v.2,1025, Hamburg, 1993.
9. E. Colton, D. Nuffer, G. Swain, et al., Transverse collective instability in the PSR, Particle Accelerators, 23,133 (1988).
10. Proceedings of the Santa Fe Workshop on electron Effect, 1997, LA-UR-98-1601.
11. J. Marriner, Yu. Orlov, et.al., Particle Accelerators, 30, 13 (1990).
12. D. Nuffer, E. Colton, D. Fitzgerald, et al., Observation f a fast transverse instability in the PSR, Nucl. Instrum. Methods A321, 1 (1992).
13. D. Bolshukhin, D. Meyer, U. Wolters, K. Wiessemann, Negative hydrogen ions and evidence for a potential dip in an electron cyclotron resonance for highly charged ions, Rev. Sci. Instrum, 69 (2), 1197 (1998).
14. G.Dimov, V. Chupriyanov, Compensated proton beam production in an accelerating ring at a current above the space charge limit, Particle accelerators, 14, 155-84 (1984).
15. G.Budker, G.Dimov, V.Dudnikov, et al., Development of the intense proton beam at the Novosibirsk, Proc.X Internat. Conf. Particle Accelerators, Protvino, 1977,v.2,p.287, 1978.
16. V.G. Dudnikov, Experiments with High Intensity Proton Beams at Novosibirsk, Proc. of the Workshop on Accelerators for Future Spallation Neutron Sources, 1993, Santa Fe, NM. LA-UR-93-1356, Vol.II B, p.973-992(1993).
17. V.G. Dudnikov, Proton Storage Ring with Intensity Greater Space Chage Limit, Proc. of the Workshop on Muon Colliders, 1993, LANL, Los Alamos, NM.(1993).

18. V.Dudnikov, J.Whealton, Experience with e-p Instability in Russia, Proc. Santa Fe Workshop on Electron Effects, LA-UR-98-1601, p. 253-270, 1997.

19. V.Dudnikov, G.Derevyankin, The Art of high brightness ion beam production, Production and neutralization of negative ions and beams, Sixth Interna. Symp.,BNL, 1992,AIP N 287, p.239. 1994.


3
H^+
H^0
H^-
2
1
4
12
11
$r_0 = 420$
80
A
5
A
9
10
7
8.
6
A
80
r_0
A - A

Proton Storage Ring for Charge- Exchange Injection Development (1964-1968)

*Accumulation of circulating proton beam up to space charge limit 0.3 A

*Development of diagnostics (Residual gas ionization (and luminescent) profile monitor, …

*Observation and damping coherent synchrotron oscillations (1965)

*Observation and damping coherent betatron oscillations of bunched beam (1965)

H^- energy W^-=1 MeV, Pulsed electrostatic accelerator

H^- Current I^- = 1mA-5 mA, Proton Current I^+=0.5 -2 mA. Ehlers type source

Radius R= 42 cm, T= 0.2 µs, Aperture 2ΔR x 2Δz= 8x4 cm^2

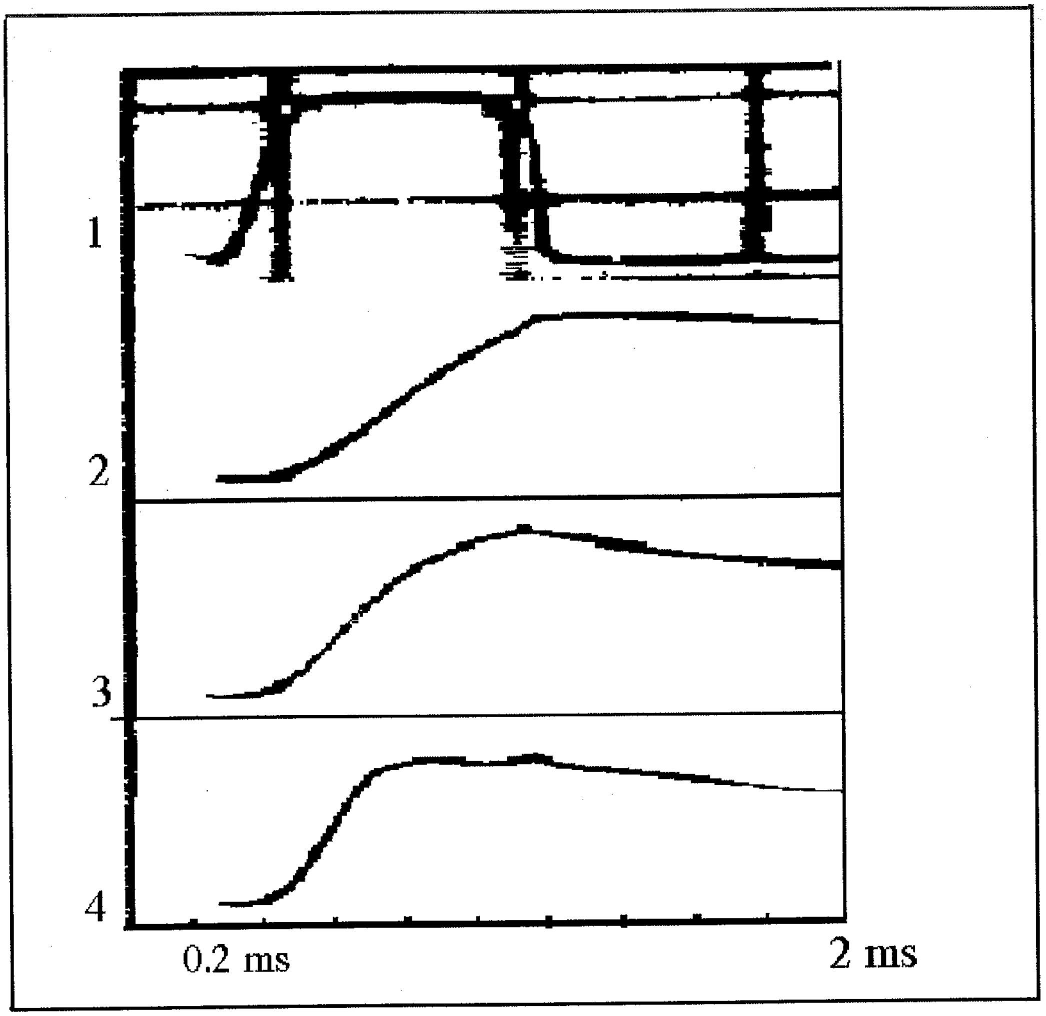
n=-RdB/BdR= 0.6; ν_r= 0.633; ν_z= 0.775; B= 3 kGauss

Schematic view of storage ring:

1- first stripping target for conversion $H^- \rightarrow H^0$. Pulsed CO_2 gas in tube.
2- main stripping target for conversion $H^0 \rightarrow p$. Pulsed Supersonic Hydrogen jet, 1 ms; M~ 12; Energy loss 200 eV/ turn.
3- gas receiving cone and pumping.
4- ring inductance electrode (electrostatic Pick- Up). Linear charge density detection. Beam intensity monitor. Synchrotron oscillation detection.
5- accelerating drift tube; RF generator f= 5 MHz.
6- collimator with PM for vertical profile detection by gas luminescent.
7- residual gas ionization beam current monitor with reflector plate.
8- residual gas ionization radial beam profile monitor; 9 strips + 9amplifire+ multiplexor.
9- horizontal and vertical position monitors- electrostatic Pick-Ups (~30 MHz).
10- magnetic toroid current monitor.
11- Faraday cup for detection first turn intensity.
12- deflector for suppressing coherent instability

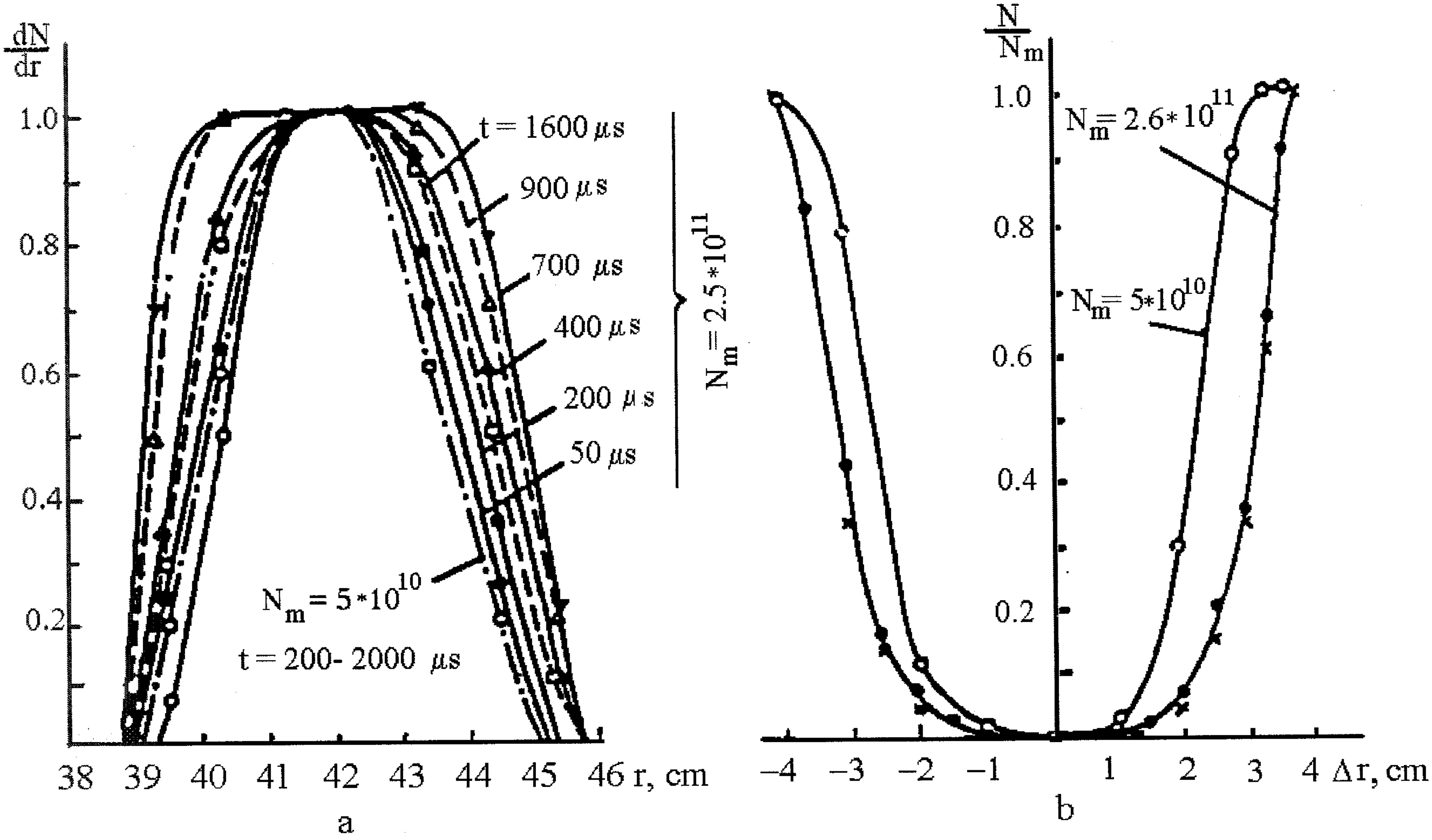
Quartz screens for beam positioning in first turn.

Radial and vertical beam loss monitors.

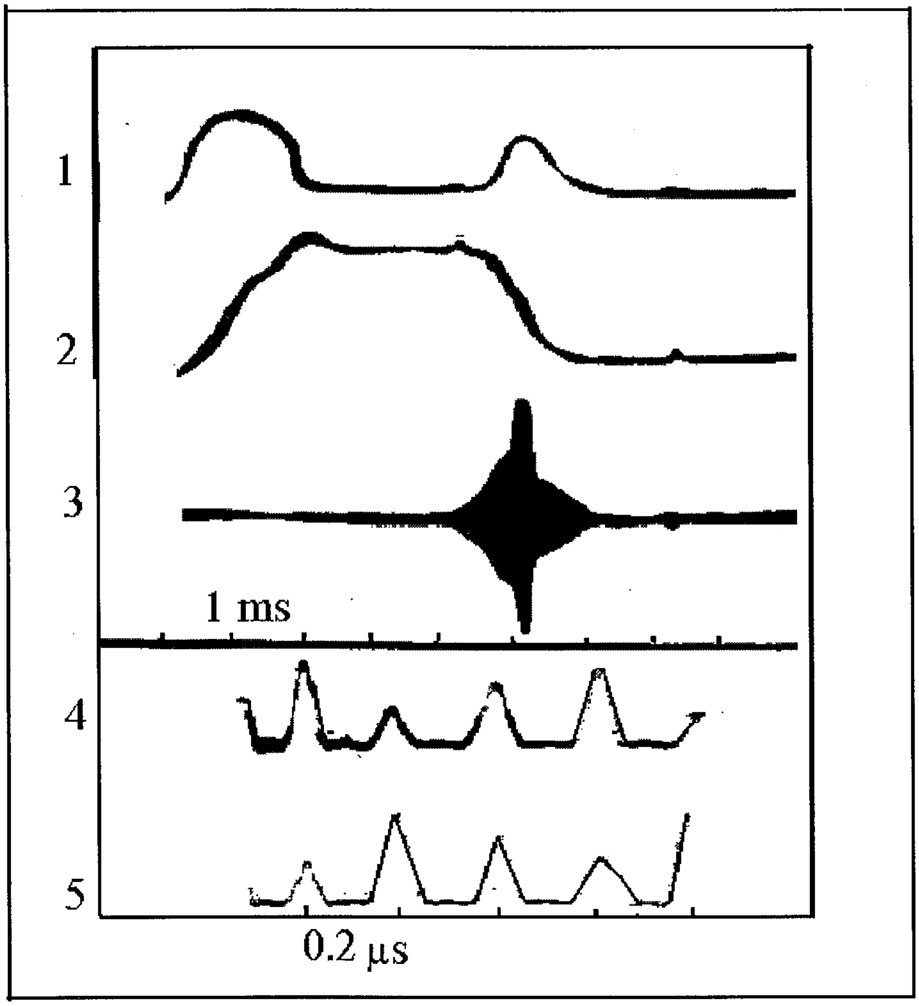


Accumulation of a circulating proton beam by Charge- Exchange Injection method with compensation of the ionization loss by RF field. Bunched beam.

1 - proton current after stripper target in the end of the first turn.
2 - linear accumulation with the low injection current (up to N= $3 \cdot 10^{10}$ p).
3 - small nonlinearity with a high intensity.
4 - saturation of accumulated beam (space limitation by longitudinal electric field N= $3 \cdot 10^{11}$ p.



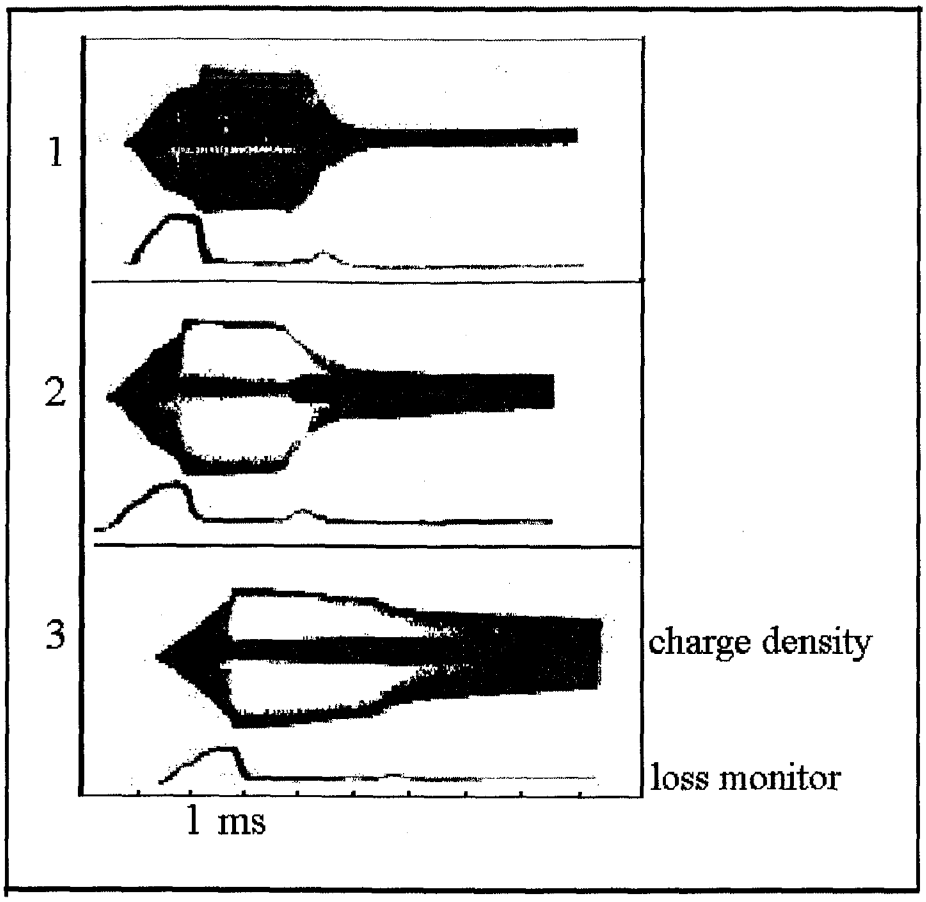
Radial distribution of the proton current density at various instants of time (a) and dependence of the intencity of proton beam on radial aperture.
Evolution of proton density distribution has been determined by the residual gas ionization beam profile monotor.



Development of coherent betatron oscillation (BINP 1966). Bunched beam.

1 - proton current from the radial beam loss monitor - movable target.
2 - proton beam intensity from ionization current monitor.
3 - differential signal from the radial position monitor with selective amplifier on the frequency $f_r = f_0(1 - \nu_r)$.
4 - 5- signal from separate electrodes of radial position monitor.

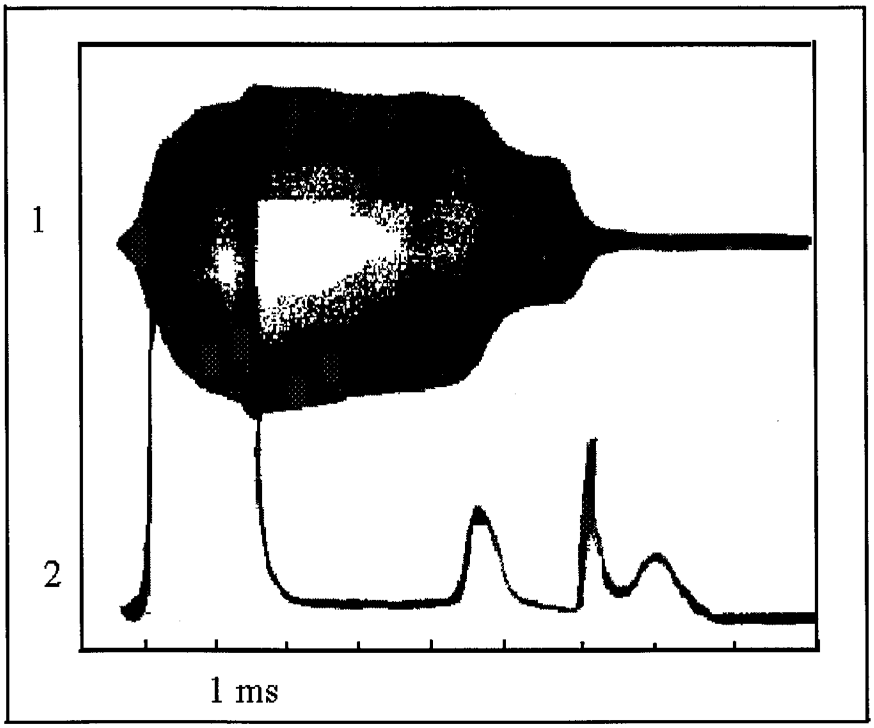
Threshold intensity $N_t = 1 - 1.5 \cdot 10^{10}$ p.
INP PSR (1966). This instability is very similar to instability of bunched beam observed at LANL PSR (1986).



Development of transverse coherent instability for different RF voltage. Signal from ring Pick-Up and signal from radial beam loss monitor.

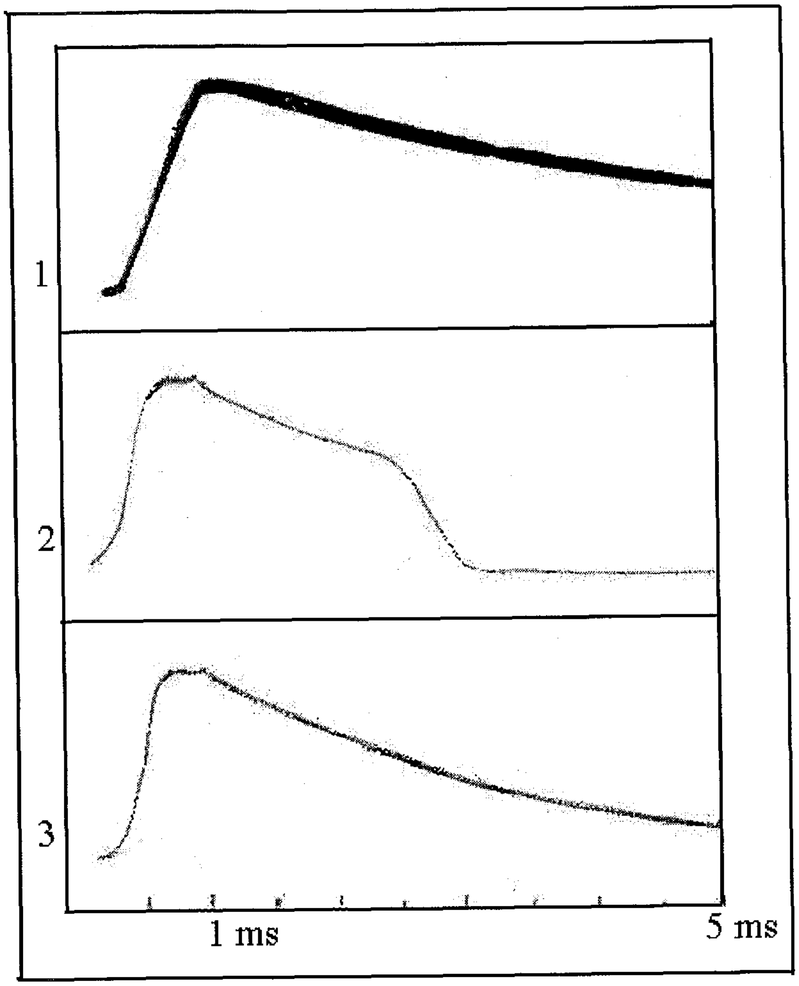
1 - U = 1.4 kV;
2 - U = 2.8 kV;
3 - U = 4.2 kV.

For higher RF voltage increase a threshold intensity and drop beam loss.



Development of coherent instability for high RF voltage and beam structure after beam loss. Beam was deflected by kicker to the beam loss monitor after self stabilization of coherent instability.

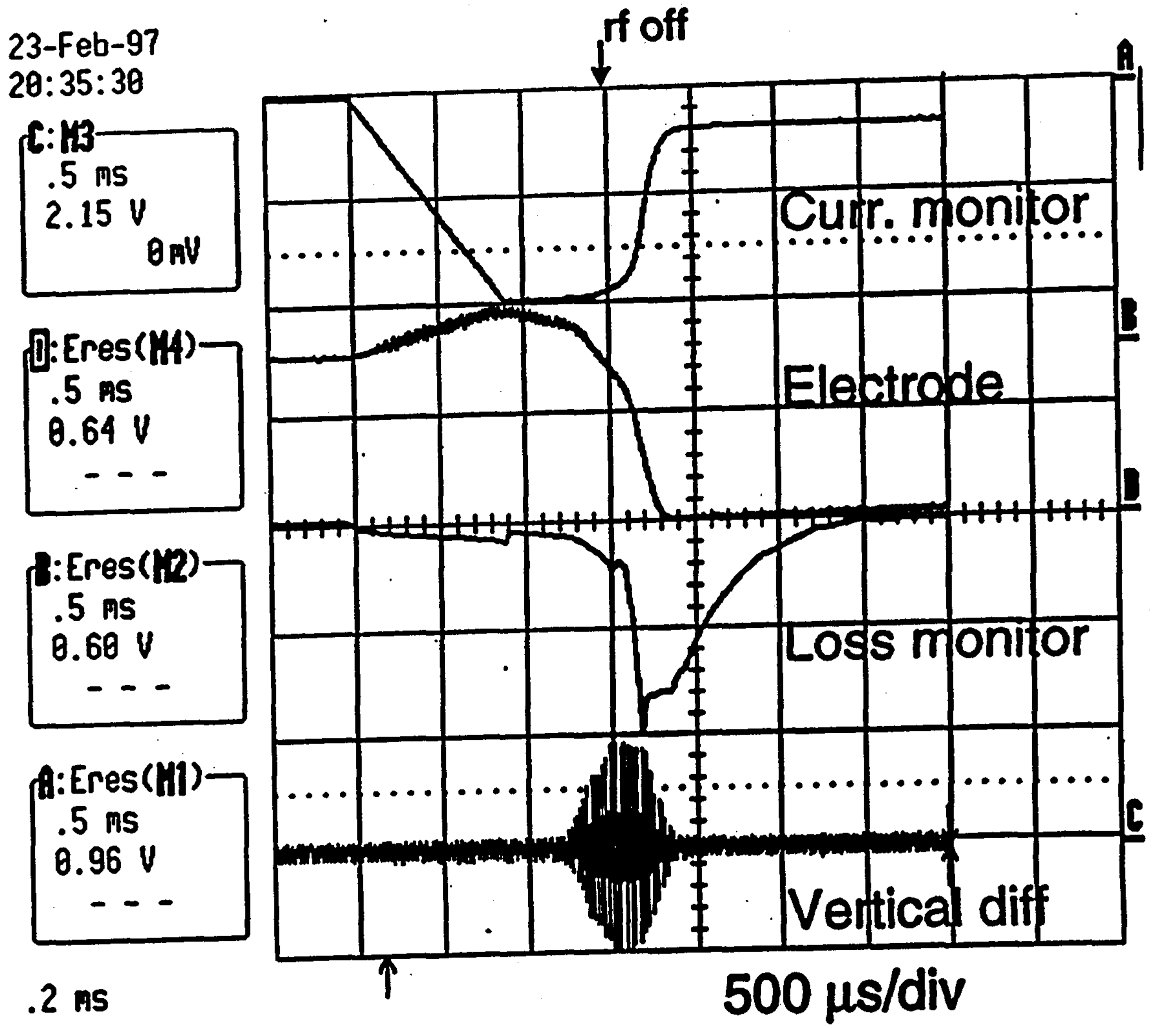
1 - signal from ring Pick-Up (beam intensity).
2 - signal from radial beam loss monitor. Two peaks structure of beam after instability. Only central part of the bunch has been lost during instability.



Suppression of coherent bunched beam instability by negative feed back. Oscillogram of beam intensity versus time. Signals from current monitor.

1 - low intensity beam, below threshold for instability.
2 - high intense beam without stabilization. Loss of beam.
3 - high intense beam with close stabilizing loop. Stable beam.

Bunched beam instability signals



3.0 µC
925 µs injection
250 ns PW
6 kV rf

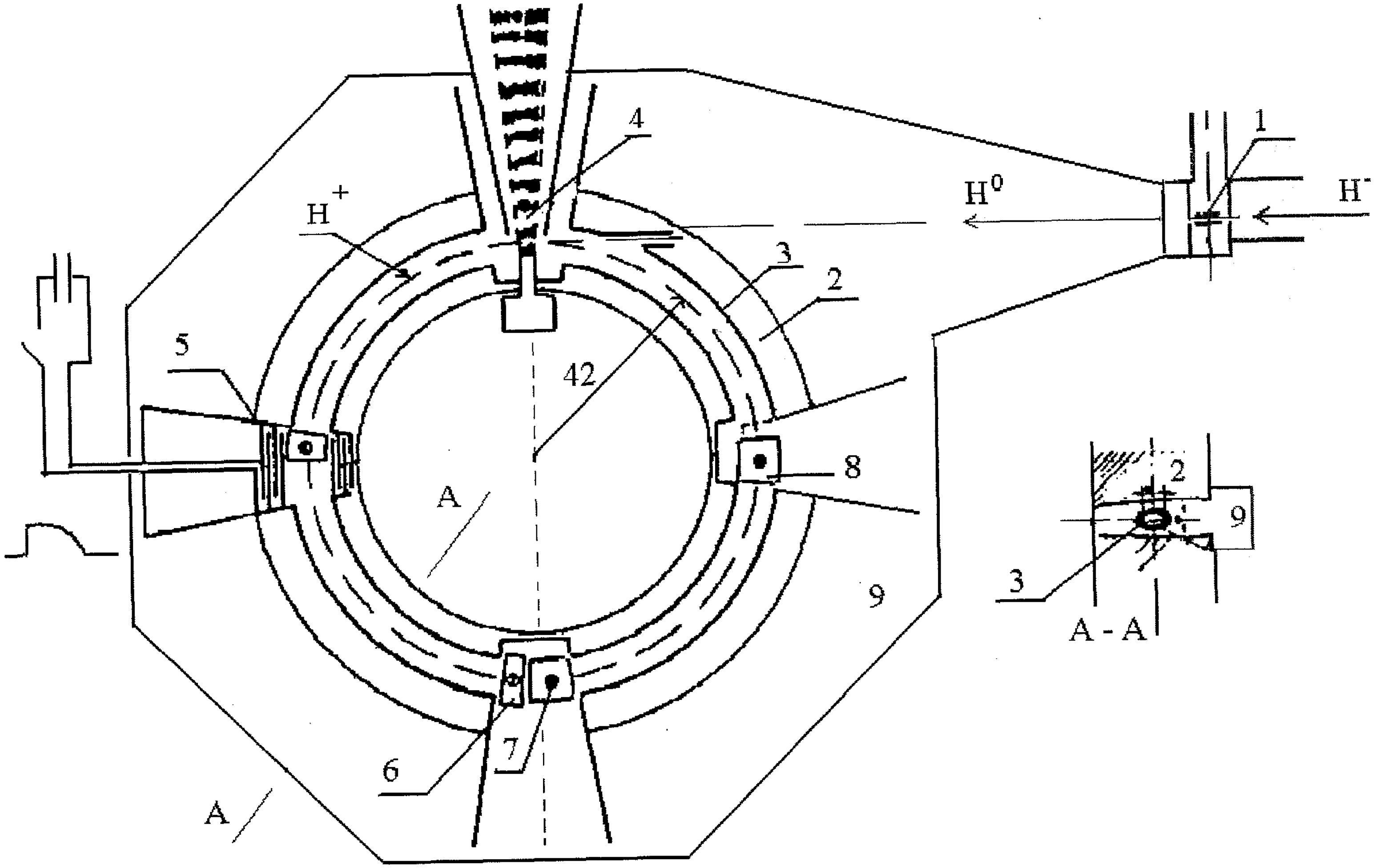
LANSCE
Los Alamos Neutron Science Center

Features of the bunched beam instability:

1. In storage ring with the perimeter 2 πR= 2.5 m , f_0 =5 MHz, instability of radial betatron oscillations have a threshold intensity N_t=1-1.5·10^{10} protons, but up to N_m=3·10^{11} p could be accumulated and stored during T=1.5 ms without instability. A pick proton density n_m for these different intensities should be not too much different (n_m ~10^8 cm^{-3}). Threshold intensity is higher for higher RF voltage.
2. Transverse bunch motion has betatron frequency f_r=$f_0(1-\nu_r)$.
3. Instability has a long delay time after accumulation T_d = 3-4 ms for the threshold intensity and decreases to T_d =1.5 ms for N =4-30·10^{10} p. (Accumulation- injection time T_i =1 ms).
4. A time of instability development up to the loss of beam (T =0.2 ms),is much shorter of the delay time but corresponded a long time resonant interaction (10^3 turns). .
5. During the accumulation time circulating beam has an intense unbunched component (up to 10-20%) and good condition for accumulation of electrons, but has no e-p instability. Just before instability start a beam has a well bunched structure with a big gap.
6. Delay time decreases from T_d =1.5 ms to T_d = 1ms with an increase of a residual gas pressure from p=8·10^{-6} Torr to 6·10^{-5} Torr without change of N_t.
7. With a high RF voltage only a small central part of the bunch participates in oscillation. After loss of this part, the circulating beam is stable with intensity much higher than the threshold. Beam injection with increased synchrotron oscillation could produce a stable beam.
8. Coherent instability of synchrotron oscillations and NMI suppresses a transverse instability. Second harmonic of RF voltage has a low influence on a transverse instability.
9. Transverse instability has been suppressed by a simple feedback system with a resonant amplifier between a pick up and a kicker in first mode of betatron oscillation.

10. Discussed features correspondent to a transverse instability, induced by interaction of beam with a compensating particles.
    But the threshold proton density is much higher than what is necessary for a low mode e-p instability. This compensating particles should have a long lifetime in the bunched beam and have a long accumulating time, corresponding to the instability delay time 5 ms. Accumulation of negative ions could be a reason of instability. Secondary emission from the wall, multipactor or unipolar arc could be a source of the secondary electrons and negative ions.
11. Local cleaning of the beam from compensating particles by a strong electric field have a week influence on instability behavior.
12. We don't see high frequency electron oscillations in the bunched beam operation because we haven't used high frequency sensors. It is could be and should be high frequency coherent oscillation of electrons in the potential of proton bunch, but it could have only week influence to the low mode oscillation of a proton bunch.
13. Almost all the properties of the observed transverse instability of bunched proton beam in the INP storage ring (1966) are similar to the observed in the bunched beam of the LANL PSR (1986).
14. All properties of the transverse instability of the coasting beam investigated in the INP race-track storage ring (ring 4) are similar to the observed in the coasting beam of the LANL PSR and have a good agreement with a theory of e- p instability.
15. The instability of coasting beam has been suppressed by increase of secondary ion density and proton beam intensity up to 9.5 time above space charge limit has been reached.
16. Local density of particles in the beam is a main parameter, determined properties of possible instability of the partly compensated circulating beam.
17. Strong focusing of negative ions by the electric field of a proton bunch with defocusing by space charge can keep negative ions in the beam. Resonance of betatron oscillation with a dipole or quadruple oscillation of negative ions could be a reason of low mode instability. Modulation of betatron frequency by negative ion can excite a parametric instability of radial or vertical oscillations.

18. A precision dipole and quadruple “shaking” proton beam in resonant with negative ions oscillations could be used for negative ion removing as positive ion removing from antiproton beam.



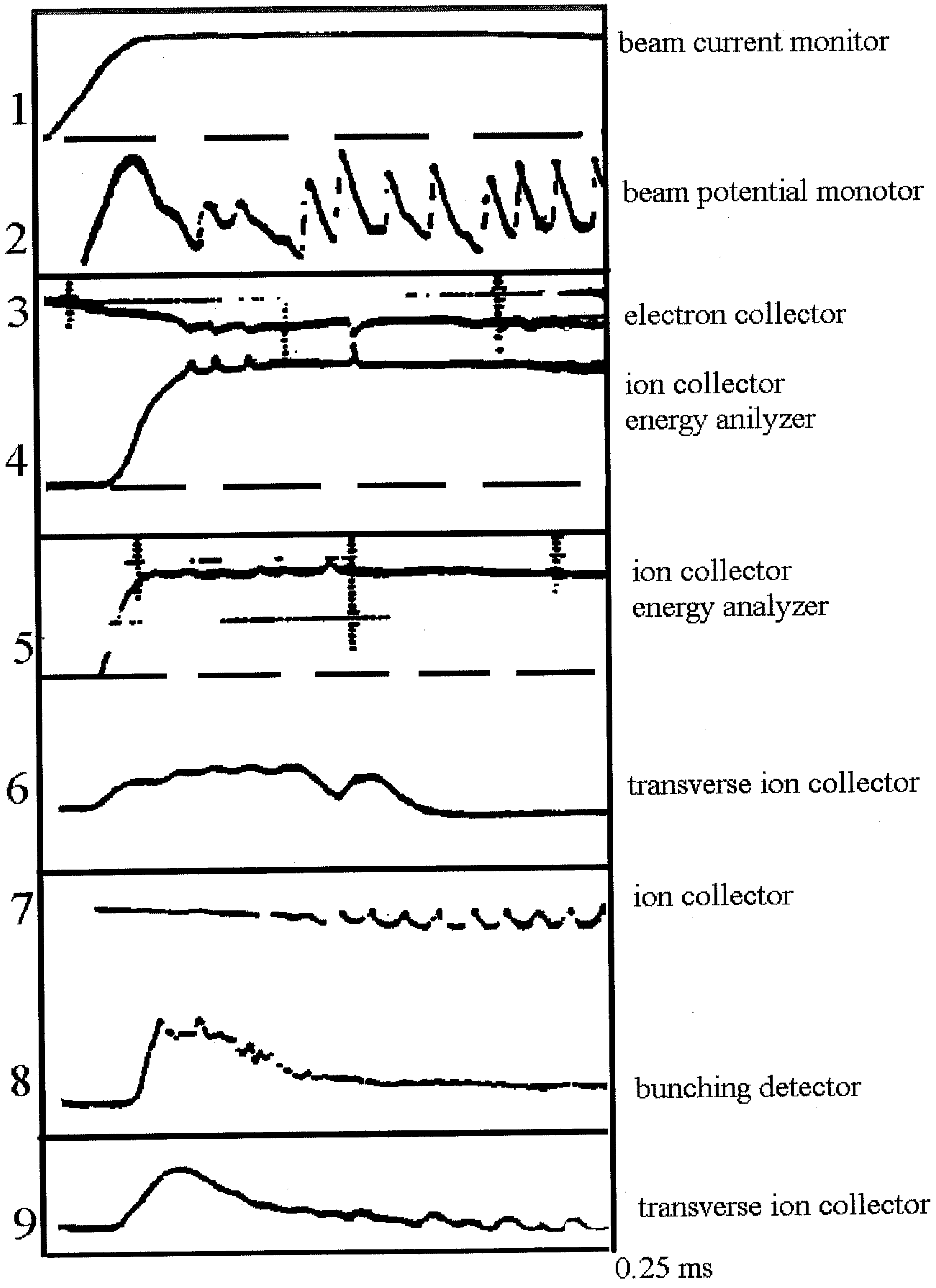
A layout of the experimental setup

Proton Storage Ring 2 for accumulation of circulating beam with a betatron field in toroid.

*Accumulation of a circulating proton beam is limited by the Negative Mass Instability $N_m=1.5 \cdot 10^{11}$ p.
*Observation of Negative Mass Instability (NMI).
*Observation of coherent betatron oscillations of coasting beam (1967), identification as e-p two stream instability.
*Beam bunching by NMI remove electrons and stop low modes of e-p instability.

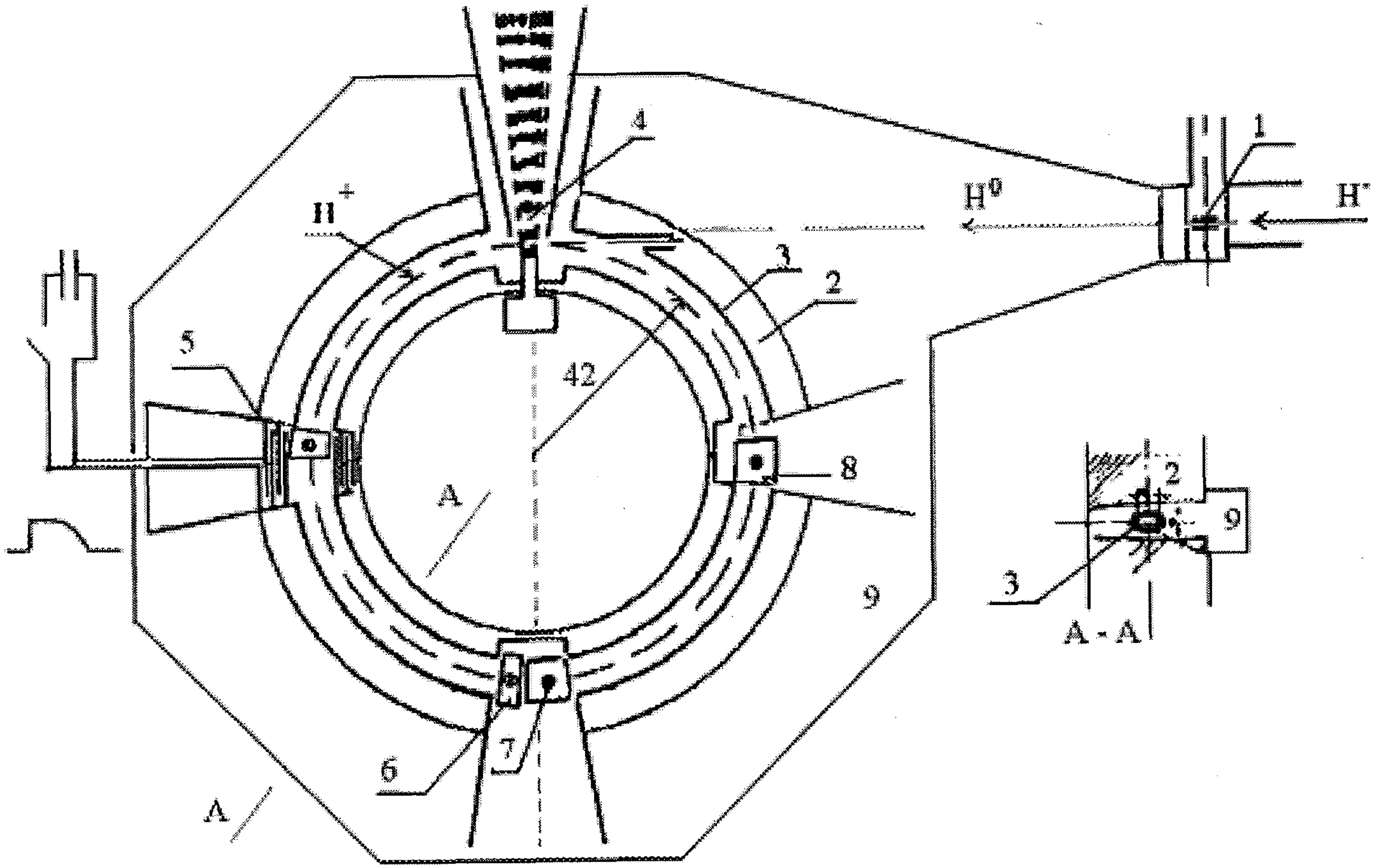
H^- energy $W^- = 1\text{-}1.5$ MeV, Pulsed electrostatic accelerator
H^- Current $I^- = 1$mA, Proton Current $I^+ = 0.3$ mA, T_i=0.5 ms. Ehlers type source.
Radius R= 42 cm, T= 0.2 μs, Aperture $2\,\Delta R \times 2\,\Delta z = 4 \times 3$ cm.
$n = -RdB/BdR = 0.6$; $\nu_r = 0.633$; $\nu_z = 0.775$; B= 3 kGauss.

Schematic view of storage ring 2:
1- first stripping target for conversion $H^- \rightarrow H^0$. Pulsed CO_2 gas in tube.
2- magnetic pole, weak focusing.
3- copper toroid with a gap for accelerating field production.
4- main stripping target for conversion $H^0 \rightarrow p$. Pulsed Supersonic Hydrogen jet, 1 ms; M ~ 12; Energy loss 200 eV/ turn. Density up to $n = 10^{19} cm^{-3}$.
5- accelerating gap of toroid with a labyrinth shielding $\int E\, dl \cdot T = 200V \times 0.2$ ms.
6- ring inductance electrode (electrostatic Pick- Up). Pick linear charge density and potential detection. Beam intensity monitor.
7- horizontal and vertical position monitors- electrostatic Pick-Ups (~30 MHz).
8- residual gas ionization beam current monitor with reflector plate and residual gas ionization radial beam profile monitor; 9 strips+ 9 amplifier+ multiplexor.
9- vacuum chamber.
Faraday cup for detection first turn intensity.
Quartz screens for beam positioning in first turn.
Radial and vertical beam loss monitors.
Mesh shielded collectors for electrons and ions energy analyzing.


1
beam current monitor
2
beam potential monotor
3
electron collector
ion collector
energy anilyzer
4
ion collector
energy analyzer
5
6
transverse ion collector
7
ion collector
8
bunching detector
9
transverse ion collector
0.25 ms

Development of transverse e-p instability in coasting proton beam in week focusing storage ring (relaxation of electron's accumulation)

1- current monitor ($N > 7 \cdot 10^9$p, $\Delta W/W > 1.5 \cdot 10^{-4}$).
2- beam potential (linear charge density) monitor. Slow drop of potential (10 µs), fast jump (1 µs)- slow accumulation of electrons, fast remove by development of the low modes of e-p instability.
3- electron collector (along magnetic field).
4- ion collector (along magnetic field- ionizing current monitor).
5- ion collector (along magnetic field- ionizing current monitor).
6- ion collector (transverse magnetic field- beam potential monitor).
7- ion collector (transverse magnetic field- beam potential monitor).
8- a signal of a linear density monitor with a NMI.
9- a signal of a beam potential monitor with a NMI.



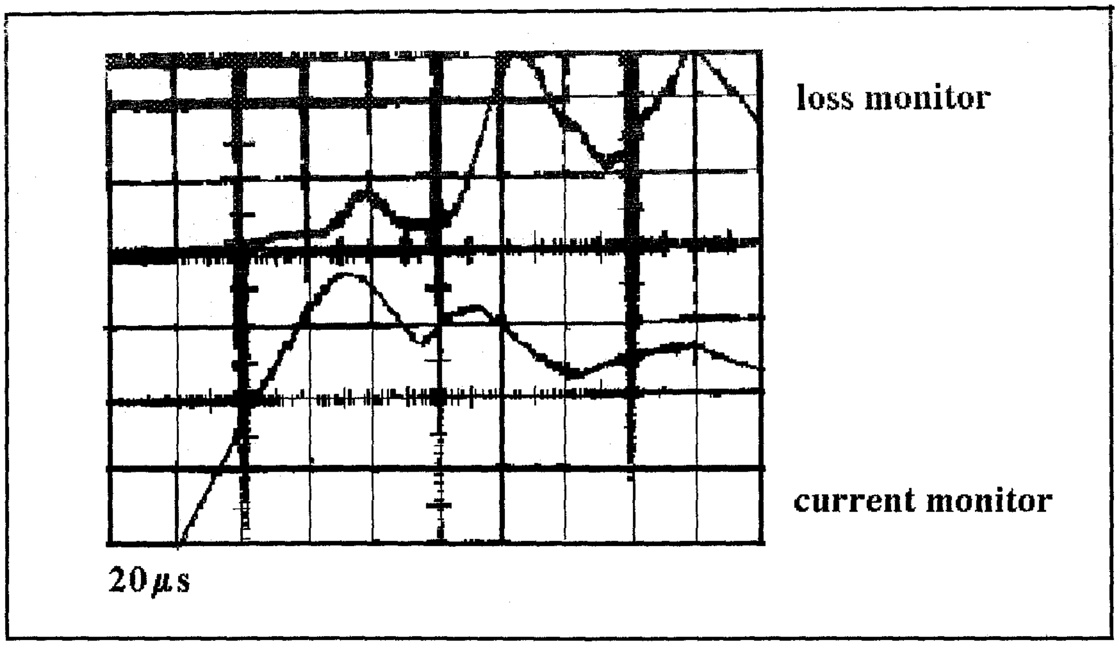
A layout of the experimental setup

Proton Storage Ring 3 for accumulation of a circulating beam with a betatron field in toroid and strong focusing magnetic field .
*Accumulation of a circulating proton beam without Negative mass instability.
*Observation and investigation of a strong coherent betatron oscillations of coasting beam (1967), identification as e-p two stream instability.

H^- energy W^-=1-1.5 MeV, Pulsed electrostatic accelerator
H^- Current I^- = 1mA, Proton Current I^+= 0.3 mA, T_i= 0.5 ms. Ehlers type source.
Radius R= 42 cm, T= 0.2 μs, Aperture $2\Delta R \times 2\Delta z = 4 \times 3$ cm^2.
4 F&D sectors, $\alpha = 0.7$; ν_r= 1.15; ν_z= 0.76; B= 3 kGauss.

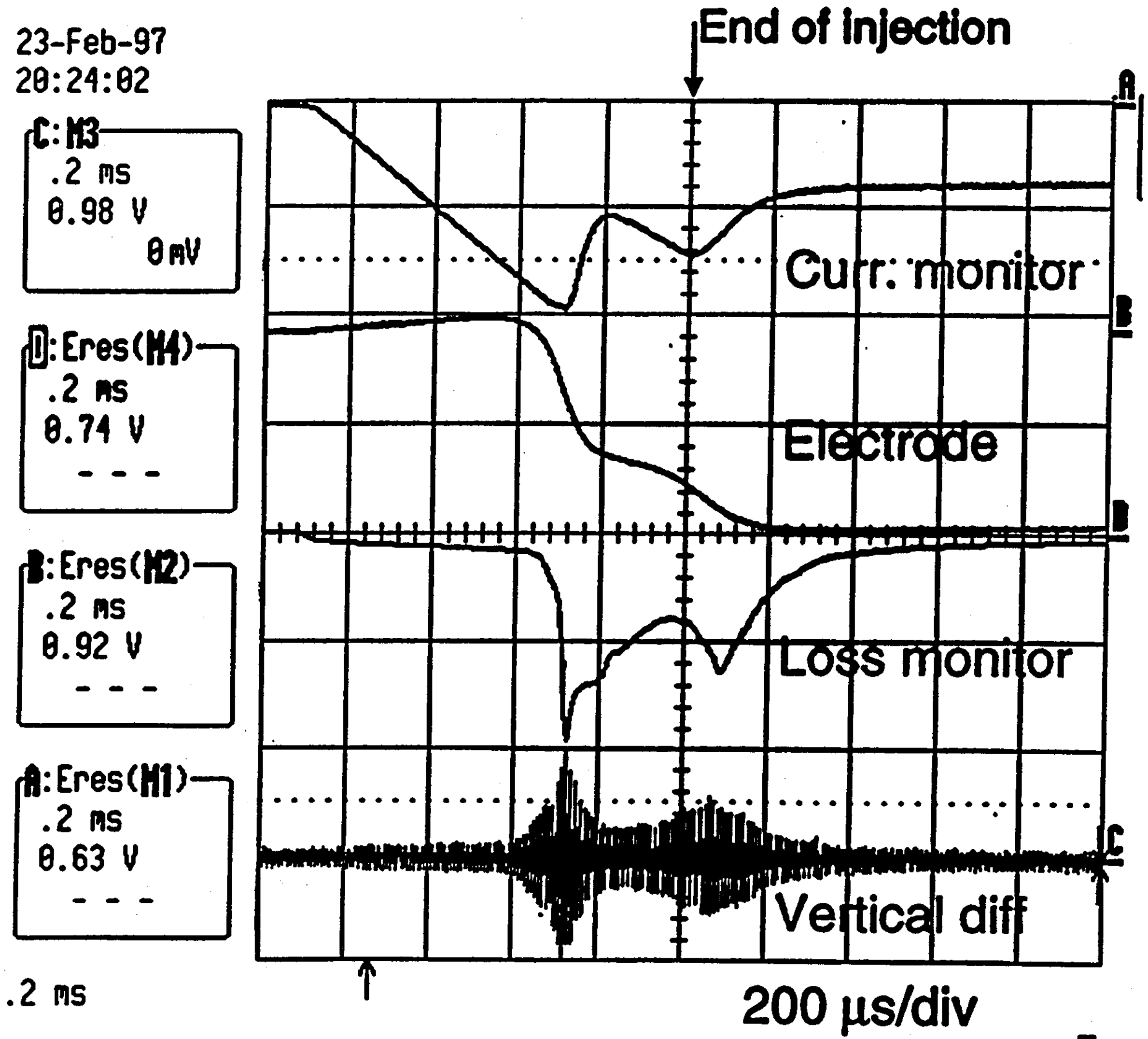
Schematic view of storage ring 3:

1- first stripping target for conversion $H^- \rightarrow H^0$. Pulsed CO_2 gas in tube.
2- magnetic poles, strong focusing.
3- copper toroid with a gap for accelerating field production.
4- main stripping target for conversion $H^0 \rightarrow p$. Pulsed Supersonic Hydrogen jet, 1 ms; M~ 12; Energy loss 200 eV/ turn.
5- accelerating gap of toroid with a labyrinth shielding $\int E\, dl \cdot T$=200Vx0.2 ms.
6- ring inductance electrode (electrostatic Pick- Up). Pick linear charge and potential detection. Beam intensity monitor.
7- horizontal and vertical position monitors- electrostatic Pick-Ups (~30 MHz).
8- residual gas ionization beam current monitor with reflector plate and residual gas ionization radial beam profile monitor; 9 strips + 9 amplifiers + multiplexer.
9- vacuum chamber.
Faraday cup for detection first turn intensity.
Quartz screens for beam positioning in first turn.
Radial and vertical beam loss monitors.
Mesh shielded collectors for electrons and ions energy analyzing.

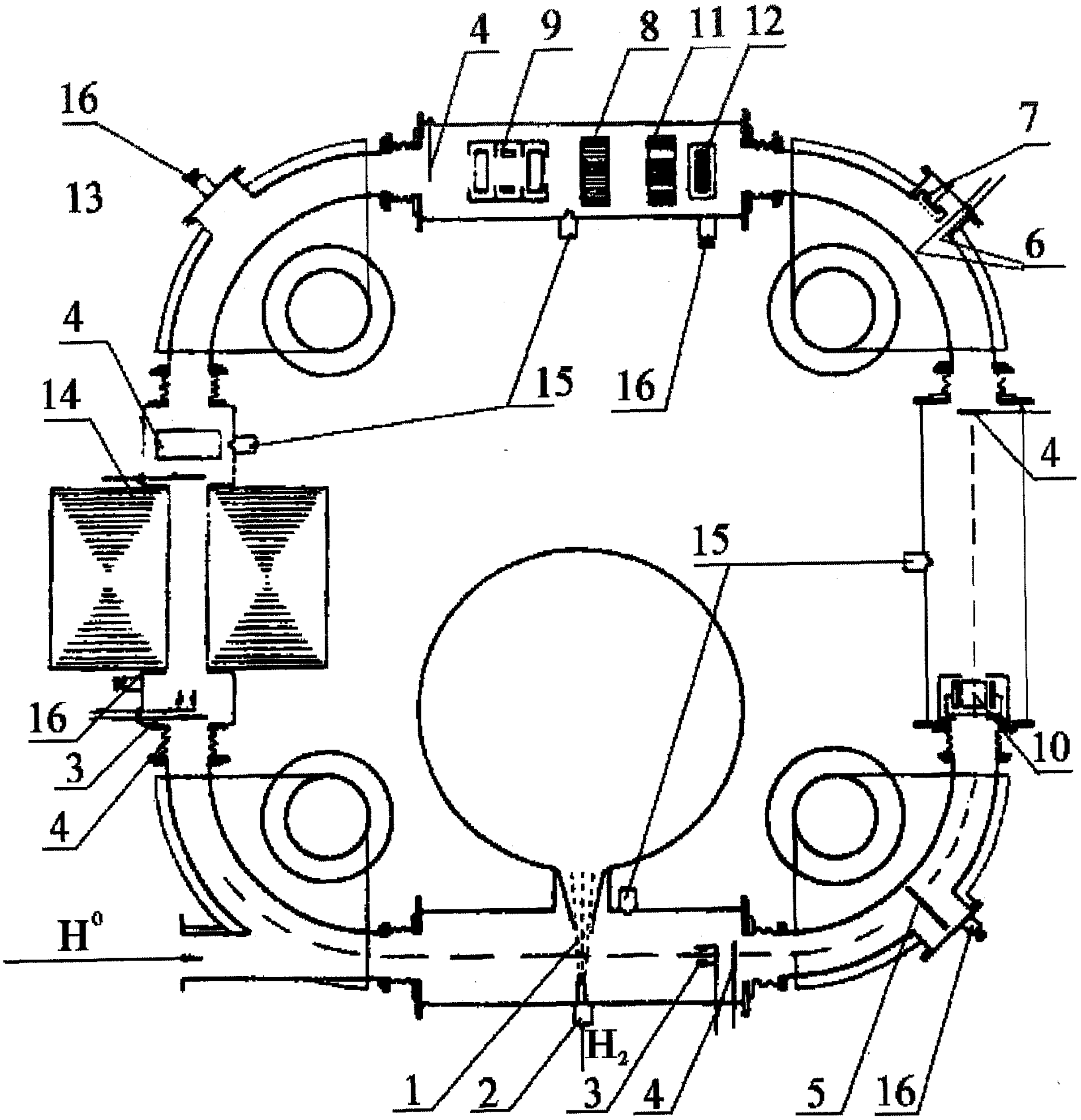


e-p instability of coasting proton beam with a betatron compensation of ionization loss, INP PSR (1967).
This instability is identical to observed in LANL PSR (1986).

Coasting beam instability signals



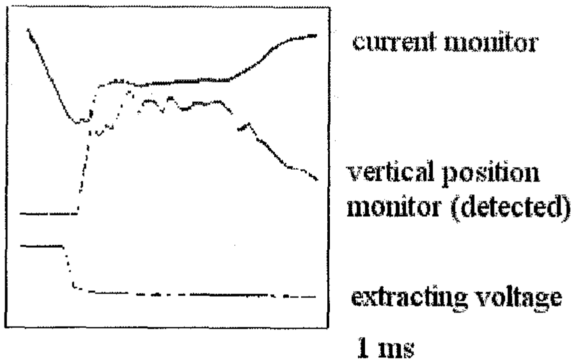
3.0-µC injected
(2.0 µC before instab.)
925 µs injection
250 ns PW
rf off


4
9
8
11
12
16
7
13
6
4
14
15
16
4
15
16
3
10
4
H^0
H_2
1
2
3
4
5
16

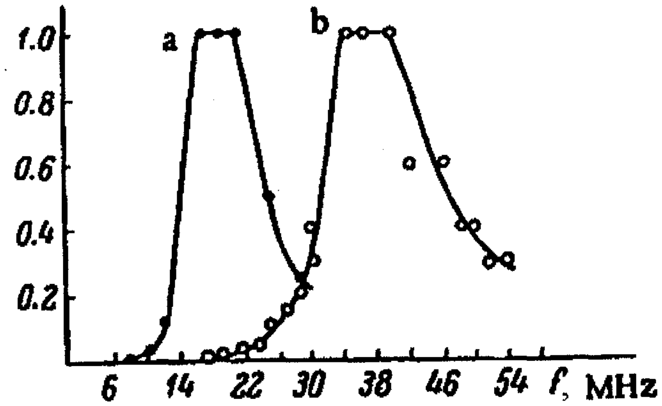
Racetrack Storage Ring (ring 4) for accumulation circulating proton beam with intensity above space charge limit (1968- 1985).
Investigation and Control of e-p instability.
Space charge compensated proton beam with the intensity $1.8 \cdot 10^{11}$ p up to 9.5 time higher, than shifting $\nu_z \rightarrow 0.5$ and 6 time higher than shift $\nu_z \rightarrow 0$.

- Proton (H^-) energy W= 1 MeV.
- Injection current I up to 8 mA . Pulse T up to 0.3 ms. Charge- exchange arc discharge ion source in high voltage terminal.
- B= 3.5 kGauss; n= 0.2- 0.7 varied by corrector current.
- R= 42 cm; Straight section L= 106 cm; Aperture 6x4 cm^2.
- Revolution frequency f=1.86 MHz. Betatron compensation of energy loss. Suppression negative mass instability.

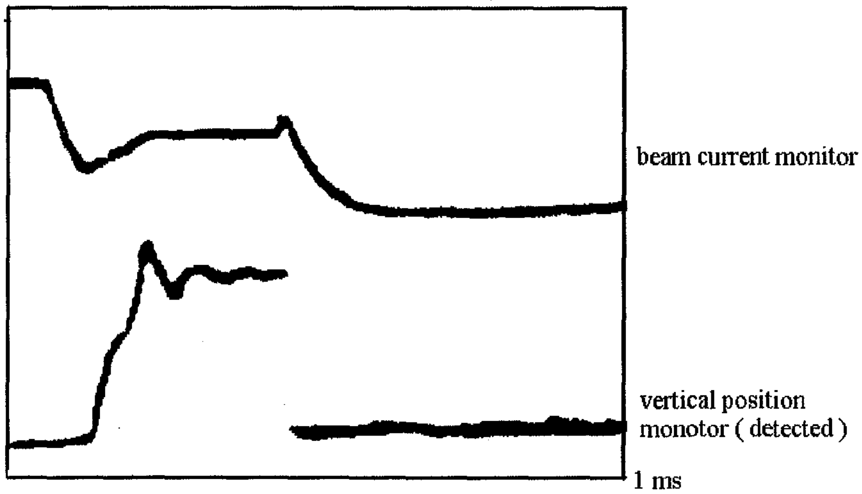
Schematic view of storage ring.
1- Striping target- hydrogen gas jet.
2- pulsed gas valve with Laval nozzle.
3- Faraday cups for first turn monitoring.
4- quartz screens for beam position monitoring.
5- 6- movable loss monitors.
7- slow ion collector- analyzer- beam potential monitor.
8- current transformer- beam intensity monitor.
9- H&V beam position monitors- electrostatic Pick-Ups up to 200 MHz.
10- electrostatic monitor of quadruple beam oscillations.
11- magneto inductance beam position monitor up to 150 MHz.
12- fast vertical beam loss monitor.
13- TOF for detection of secondary ions and electrons density in the beam. 15 kV, 0.1 μs pulser for remove ion and electrons from the beam + collector.
14- betatron core for proton energy loss compensation. 350V x 0.5 ms.
15- pulsed gas valves.
16- gas microleak.
clearing electrodes along all orbit up to 2 kV. Fast switches of ~ 1 μs.
electron sources for plasma production.



Accumulation of proton beam with the intensity up to space charge limit in the rastrack (ring 4) with removing of compensating particle by electric field. After electric field switch of observed fast development coherent e-p instability and drop of intensity.



Spectrum of signals from vertical beam position monitor.
a) N=1.7 10^{10} p; b) N= 1.5 10^{11} p.



Accumulation of proton beam with intensity above space charge limit after voltage switch off.

TABLE III

Threshold pressures and densities

Gas	H_2	D_2	H_e	N_2	Ar
Threshold pressure, Torr	$2.6 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	$5 \cdot 10^{-3}$	$3.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-4}$
Threshold density, cm^{-3}	$9.2 \cdot 10^{13}$	$6.0 \cdot 10^{13}$	$17.7 \cdot 10^{13}$	$1.1 \cdot 10^{13}$	$7.8 \cdot 10^{12}$

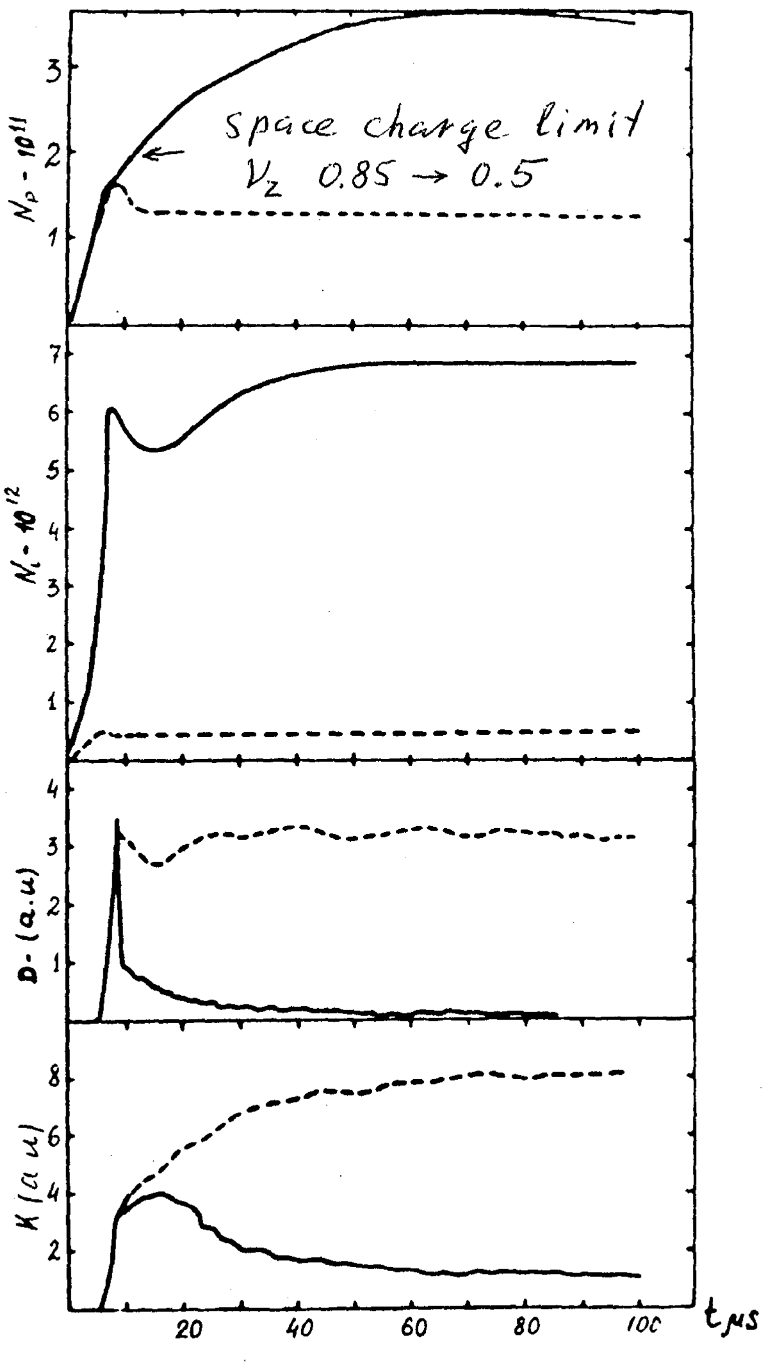


FIGURE 4 The process of proton collection in the compensated beam with hydrogen pressures of $1.4 \cdot 10^{-3}$ Torr (dotted curves) and $3.6 \cdot 10^{-3}$ Torr (solid curves). The current of proton injection is 5.5 mA (when the first turn is completed). N_p is the number of protons in the beam: N_i is the number of secondary ions in the beam: D is the amplitude of rf signals from electrostatic vertical-position electrodes per unit orbital proton current; K is the same for quadrupole electrodes.

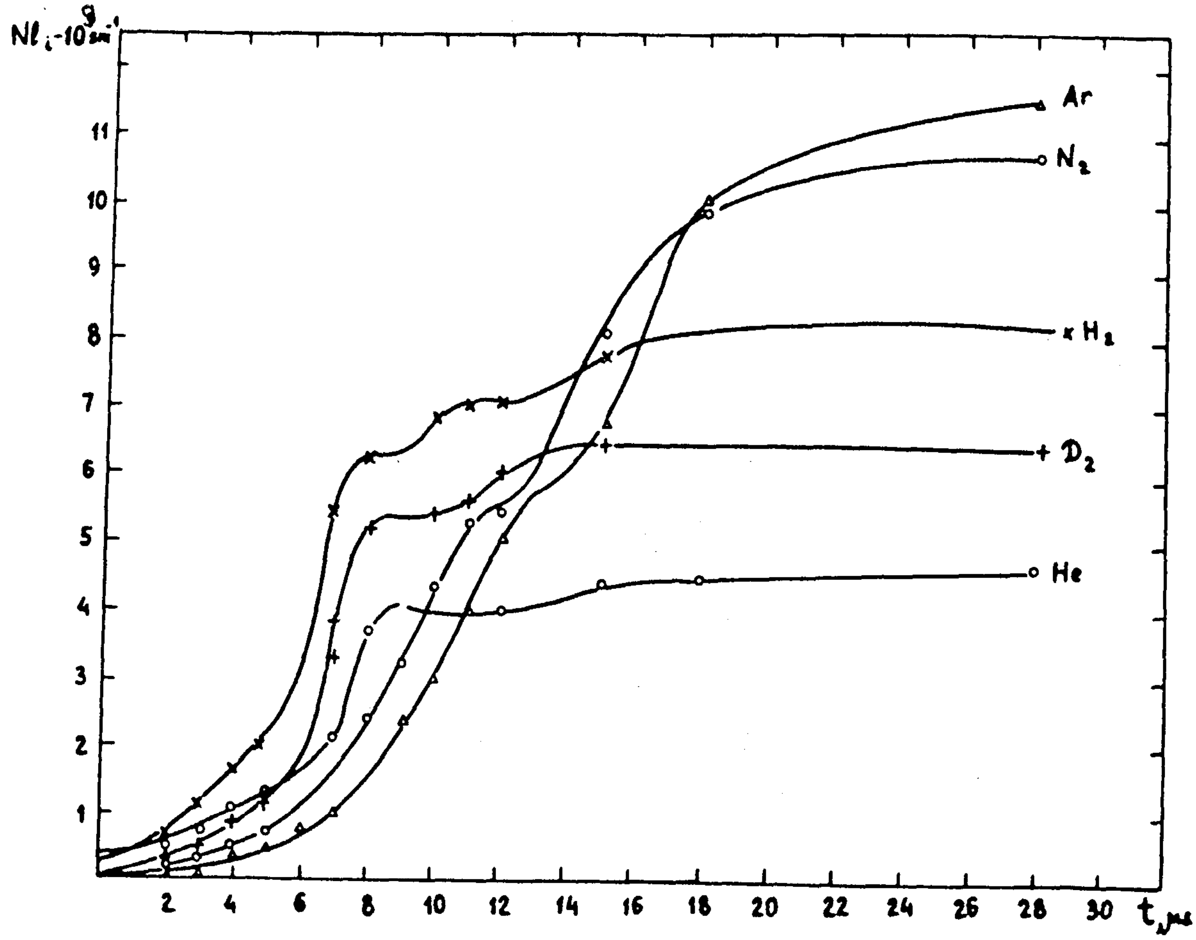


FIGURE 5 Time dependence on linear density of secondary ions at after-threshold pressures on different gases.

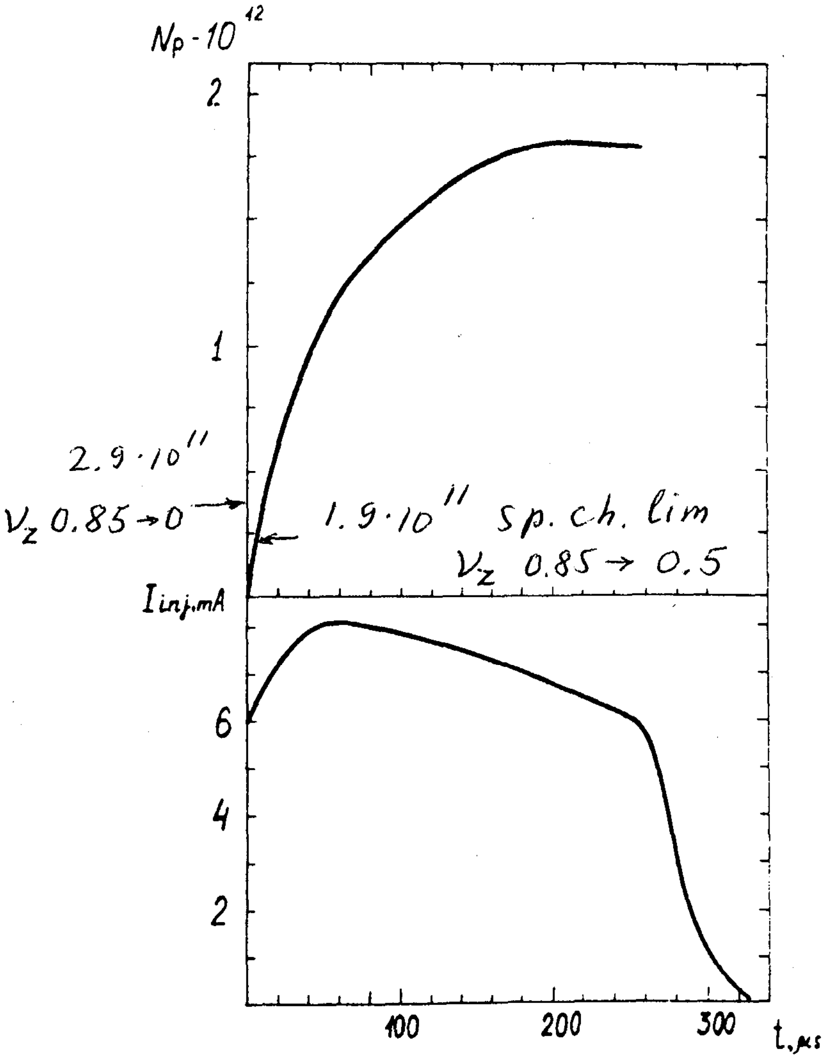


FIGURE 10 Oscillograms of stored protons in betatron mode (a) and the injection current (at the end of the first turn) (b) using pulsed pumping of hydrogen.

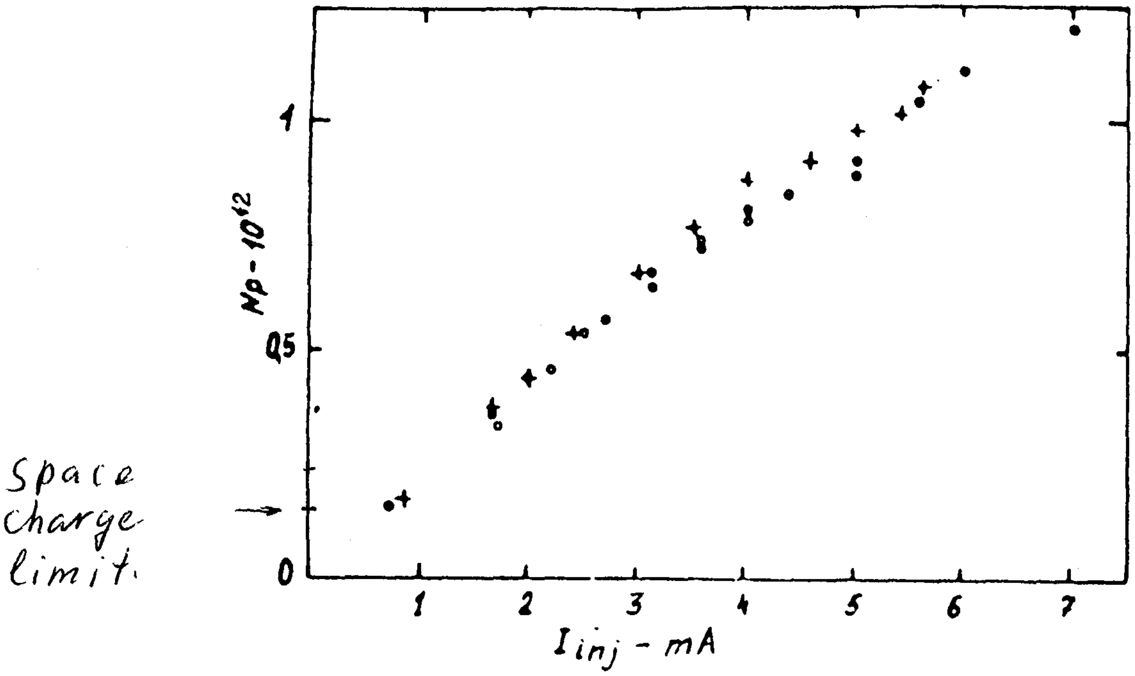


FIGURE 9 Number of stored protons as a function of injection current in the quasibetatron mode when filling with deuterium (+) and hydrogen (O).

Conclusion

1. Transverse instability of coasting proton beam, observed in the INP PSR (1967) is identical to transverse instability observed in the LANL PSR (1986) and have a good agreement with theory of coherent e-p instability in rings (Chirikov (1965), Koshkarev and Zenkevich (1972)).
2. Transverse instability of a bunched proton beam observed in the INP PSR (1965) is very similar to instability observed in the LANL PSR (1986) and have no complete understanding up to now.
3. Linear charge density λ and volume density n of the beam particles, determined a bounce frequency of compensating particles in the beam are a main parameter determined a properties of transverse coherent instability. In PSR of INP and LANL was reached a highest value of these parameters $\lambda > 2 \cdot 10^{11}$ p/m, and $n > 10^8$ p/cm^3, and instability of a bunched beam have been observed. In other accelerators and storage rings was observed only instability of coasting beam.
4. Experimental data from small scale storage rings could be useful for testing and development of the simulating codes.
5. For oscillation with a low mode number an amplitude of electrons oscillation Y_e is $M/m = 1836$ time larger of amplitude of proton oscillation Y_p ,and excitation of this oscillation is remove electrons from the beam. Development of the beam oscillations up to loss could be excited by high modes of oscillation or oscillation of heavy compensating particles.
6. Instability of bunched beam have a long delay time after accumulation above a threshold level. Fast accumulation and extraction could be used for elimination of the transverse instability. Injection with a large synchrotron oscillations could be used for enhance a beam stability.
7. Suppression of the bunched beam instability by simple feed back with a selective amplifier could be successful, as in small scale storage ring.
8. Increase of the threshold for transverse instability of bunched beam with increasing of the RF voltage could be improved by injection with increased synchrotron oscillation.