ПЕРЕЗАРЯДНАЯ ИНЖЕКЦИЯ В ИЯФ И В МИРЕ

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Outline

- История разработки перезарядной инжекции в ИЯФ.
- История освоения перезарядной инжекции в мире.
- Обнаружение электрон протонной неусточивости (electron cloud effect).
- Объяснение и подавление e-p неустойчивости.
- Накопление пучка с интенсивностью выше предела по пространственному заряду.

Важнейшие достижения
К числу основных достижений ИЯФ в науке и технике относятся:
В области **физики и технологии ускорителей**:

изобретение и экспериментальная проверка метода перезарядной инжекции, применяемого в настоящее время на всех крупных протонных ускорителях, (1960-1965 гг.);
Открытие эффекта цезирования-значительного повышения эмиссии отрицательных ионов при добавлении в разряд веществ с малым потенциалом ионизации, таких как цезий. Разработка поверхностно плазменных источников отрицательных ионов с цезированием с рекордными характеристиками, используемыми на всех протонных ускорителях.

В области **физики плазмы и термоядерного синтеза**:
разработка поверхностно-плазменных высокоинтенсивных источников отрицательных ионов, получивших широкое распространение во всем мире, (1969-1981 гг.);

Budker Institute of Nuclear Physics SB RAS

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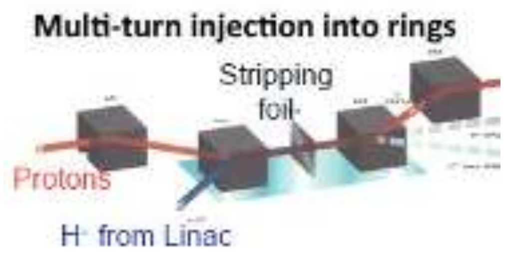
Novosibirsk State University

www.nsu.ru

Charge exchange injection was developed in 1960-1965 in INP, Novosibirsk, Russia

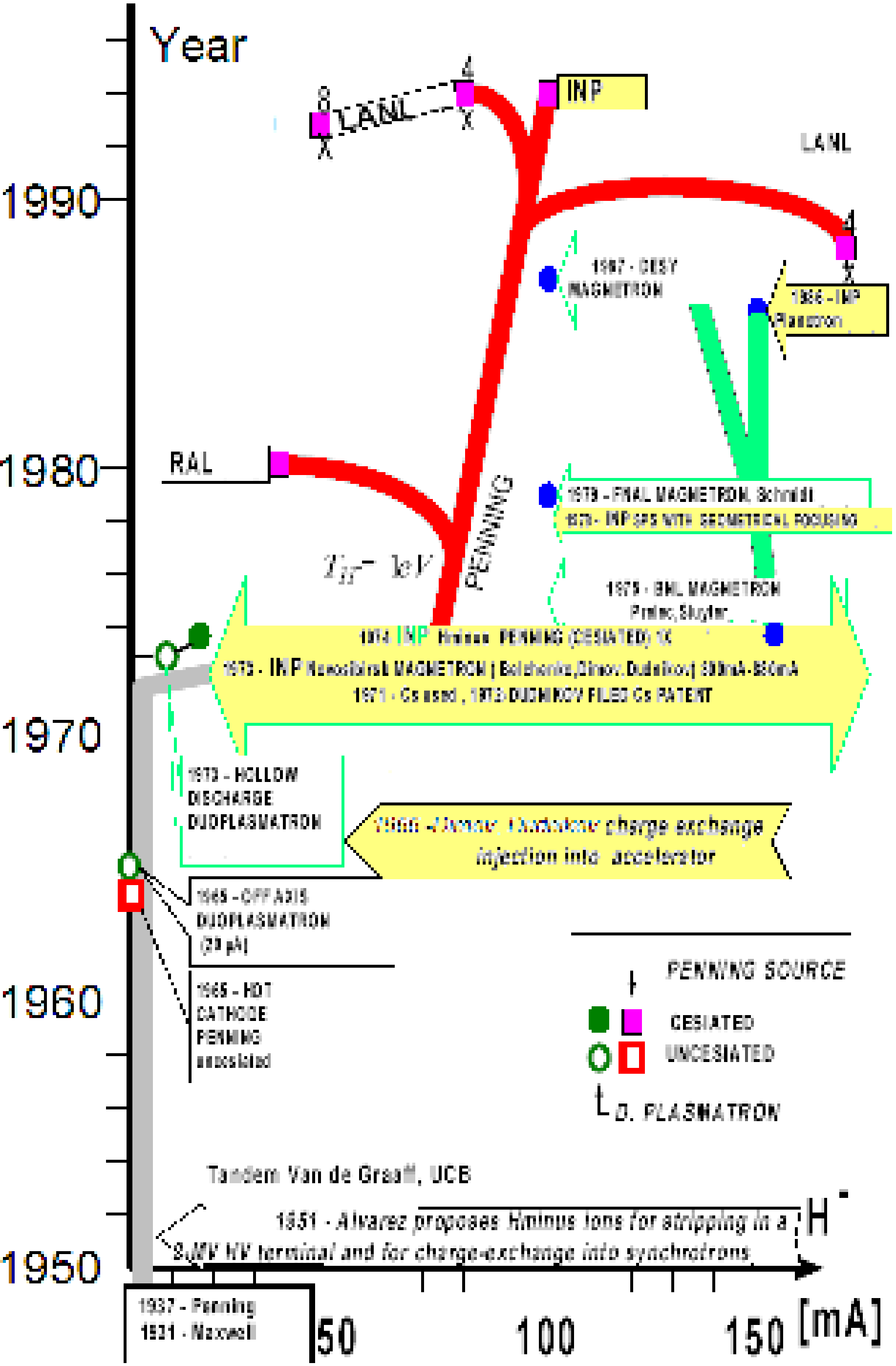
First project of proton/antiproton collider VAPP-4, in the Novosibirsk INP (BINP)

- Development of charge-exchange injection (and negative ion sources) for high brightness proton beam production. First observation and damping of e-p instability.
- Development of Proton/ Antiproton conversion with lithium lens.
- Development of electron cooling for high brightness proton and antiproton beam production.
- Production of space charge neutralized proton beam with intensity above space charge limit. Inductance Linac, Inertial Fusion, Neutron Generators.
- *History of ZGS 500MeV Booster.* *www.ipd.**anl**.gov/**anl**pubs/2006/05/56304.pdf*



- *Martin Reiser, Theory and Design of charged particle beam, second edition.*

History of Surface Plasma Sources Development (J.Peters)



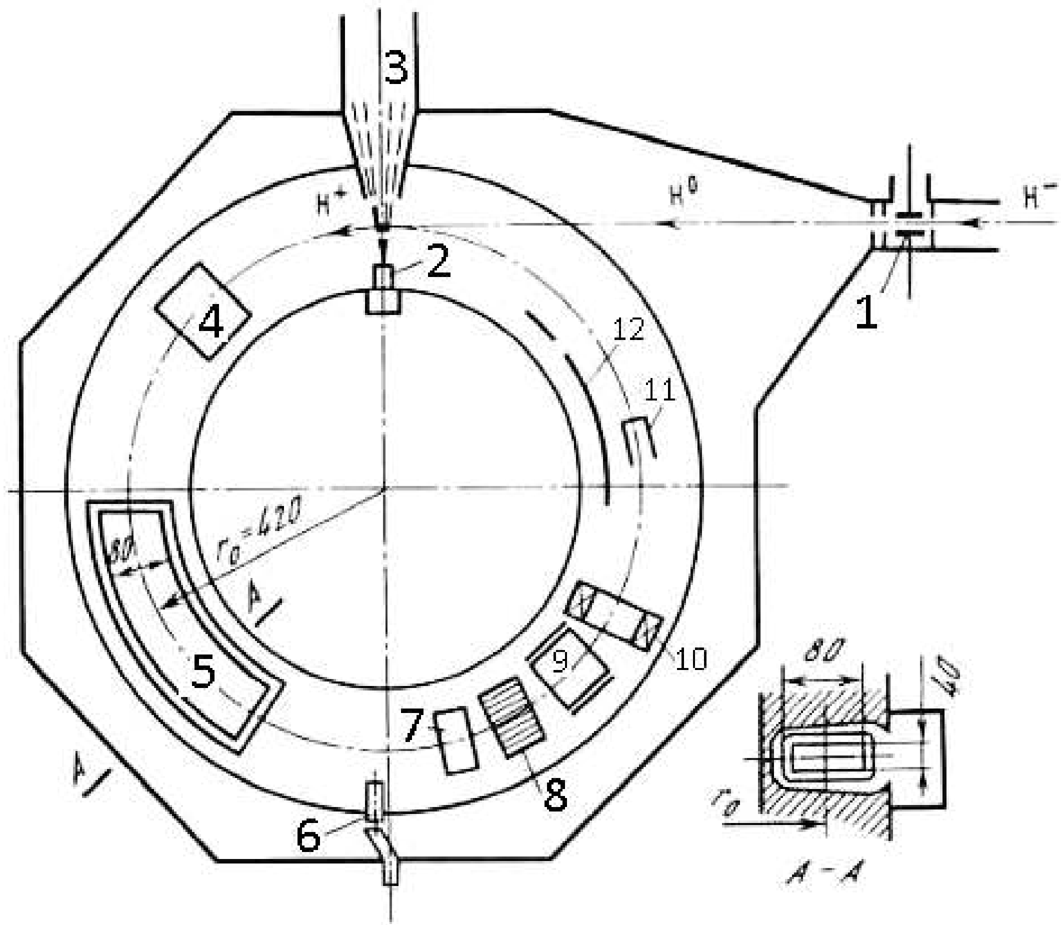
BDD, G.Budker, G.Dimov, V. Dudnikov
Charge-Exchange Injection ,A. E. 22,5 (1966)


History of Charge Exchange Injection

(Rees, ISIS , ICFA Workshop)

1.	1951	Alvarez, LBL (H-) ;
	1956	Moon, Birmingham Un. (H+2)
2.	1962-66	Budker, Dimov, Dudnikov, Novosibirsk ; first achievements; discovery of e-p instability. IPM
3.	1968-70	Ron Martin, ANL ; 50 MeV injection at ZGS
4.	1972	Jim Simpson, ANL ; 50-200 MeV, 30 Hz booster
5.	1975-76	Ron Martin et al, ANL ; 6 10^{12} ppp
6.	1977	Rauchas et al, ANL ; IPNS 50-500 MeV, 30 Hz
7.	1978	Johnson R, et al, FNAL ; 0.2-8 GeV, 15 Hz booster
8.	1982	Barton et al, BNL ; 0.2-29 GeV, AGS
9.	1984	First very high intensity rings ; PSR and ISIS
10.	1980,85,88	IHEP, KEK booster, DESY III (HERA)
11.	1985-90	EHF, AHF and KAON design studies. SSC
12.	1992	AGS 1.2 GeV booster injector
13.	2006	SNS 1.4 MW sources
14.	2016	CERN booster, IFVEE

INP PSR for bunched beam accumulation by charge exchange injection

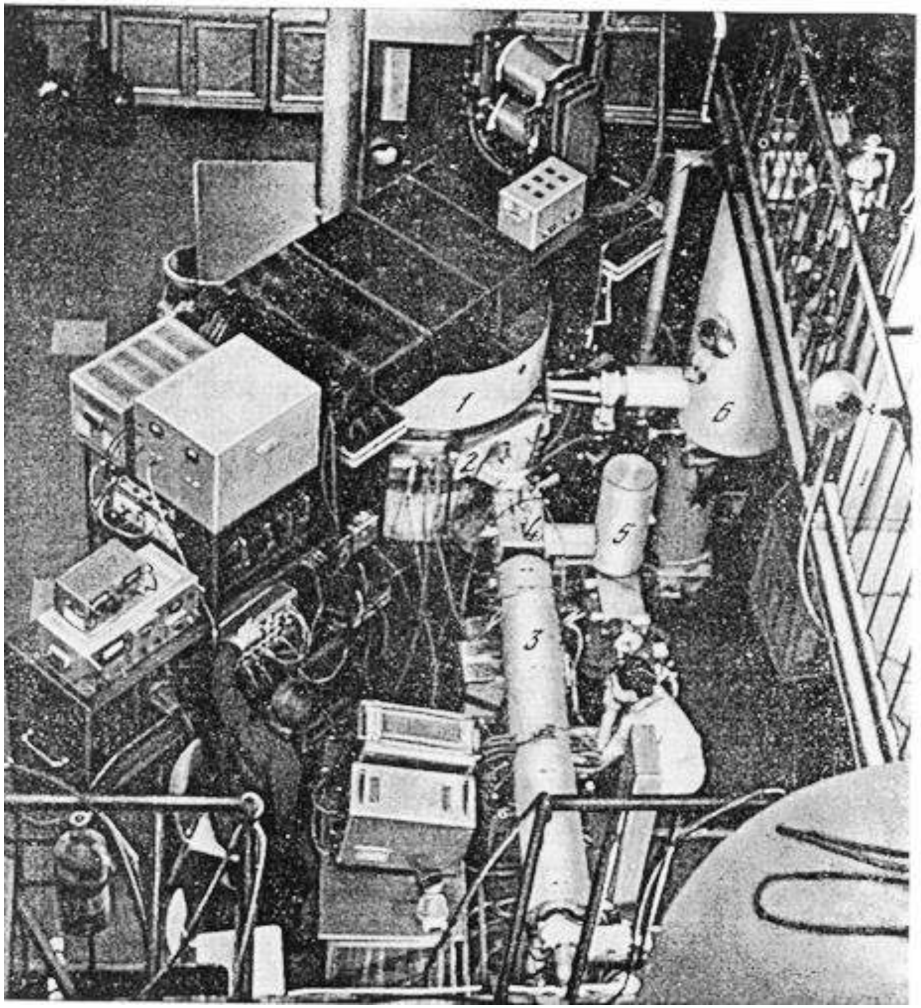


1- Fist stripper; 2-main stripper Pulsed supersonic jet; 3-gas pumping; 4-pickup integral; 5- accelerating drift tube; 6-gas luminescent profile Monitor; 7-Residual gas current monitor;8-residual gas IPM; 9-BPM; 10-transformer Current monitor; 11-FC; 12- deflector for Suppression transverse instability by negative Feedback.

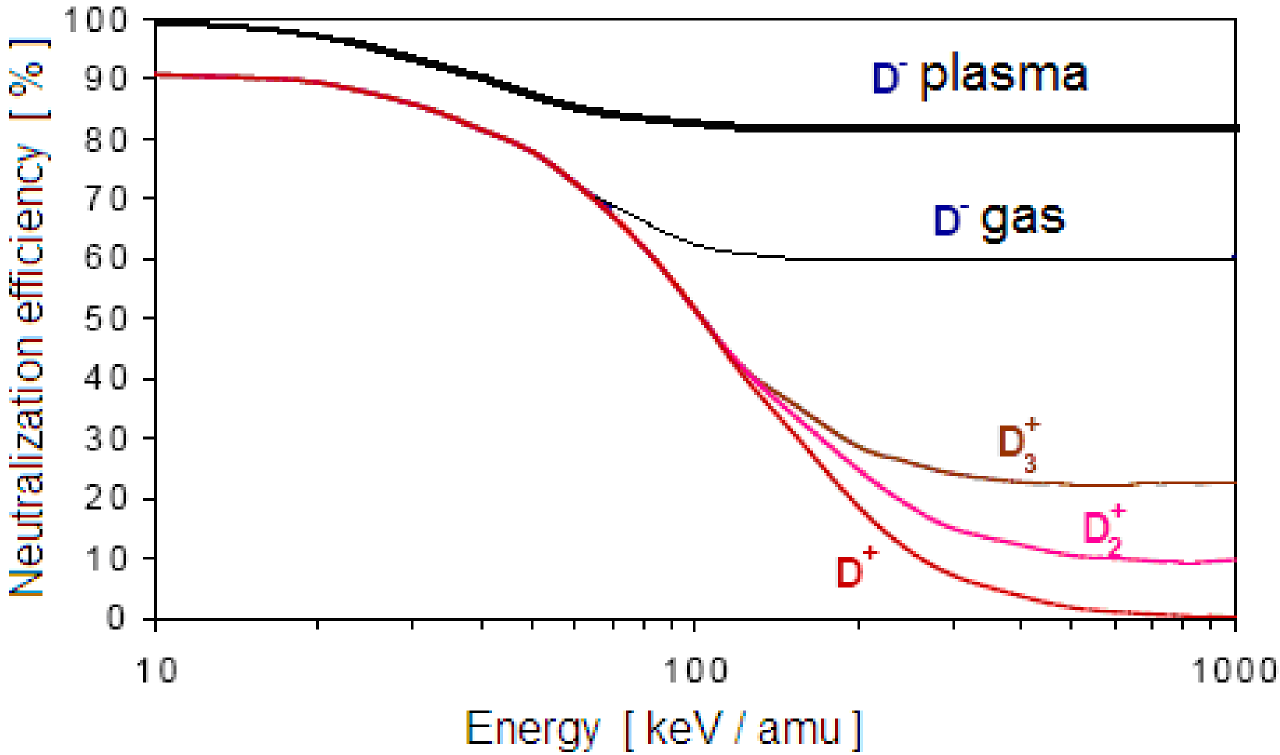
Small Radius- High beam density. Revolution 5.3 MHz. 1MeV, 0.5 mA, 1 ms.

•G. I. Budker, G. I. Dimov, and V. G. Dudnikov. EXPERIMENTS ON PRODUCING INTENSIVE BEAMS BY MEANS OF THE METHOD OF CHARGE-EXCHANGE INJECTION PROTON, Sov. Atomic Energy, 1966.

General view of INP PSR with charge exchange injection, 1965



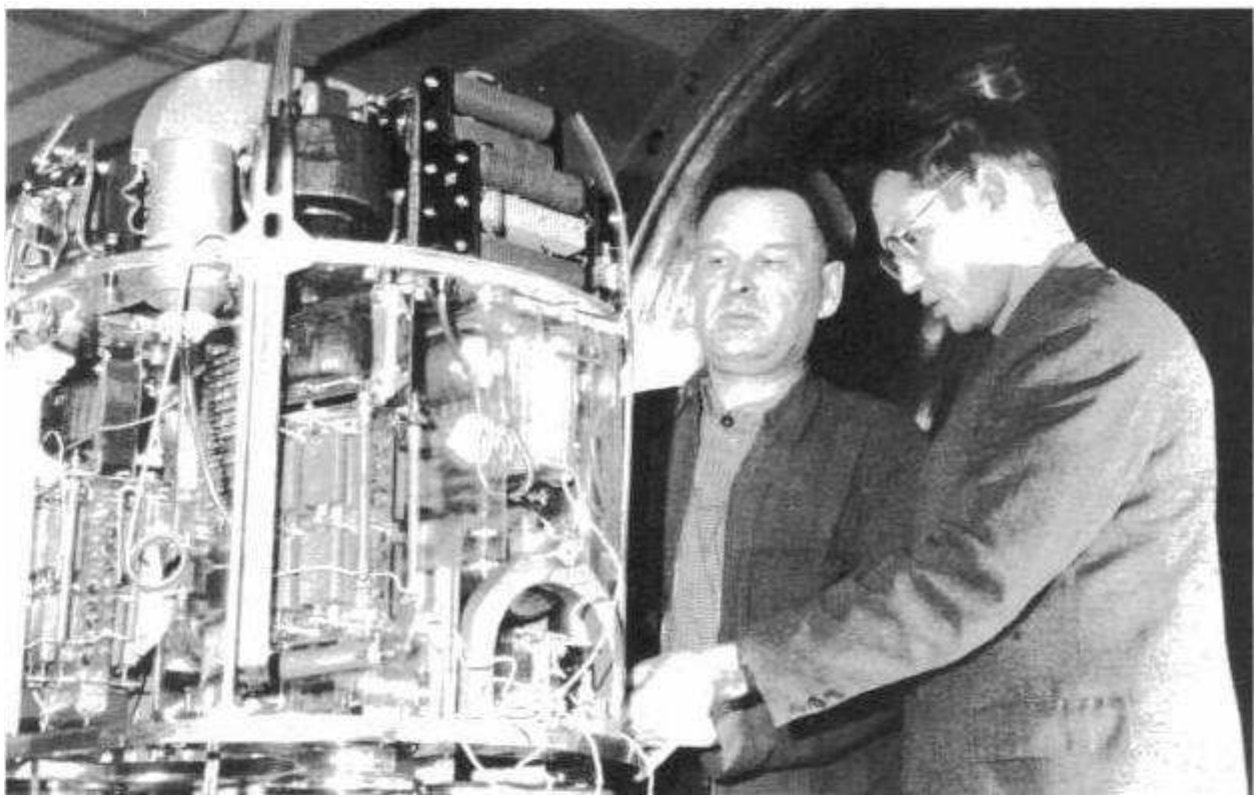
Оптимизация конверсии ионов H- в нейтралы на газовых и плазменных мишенях



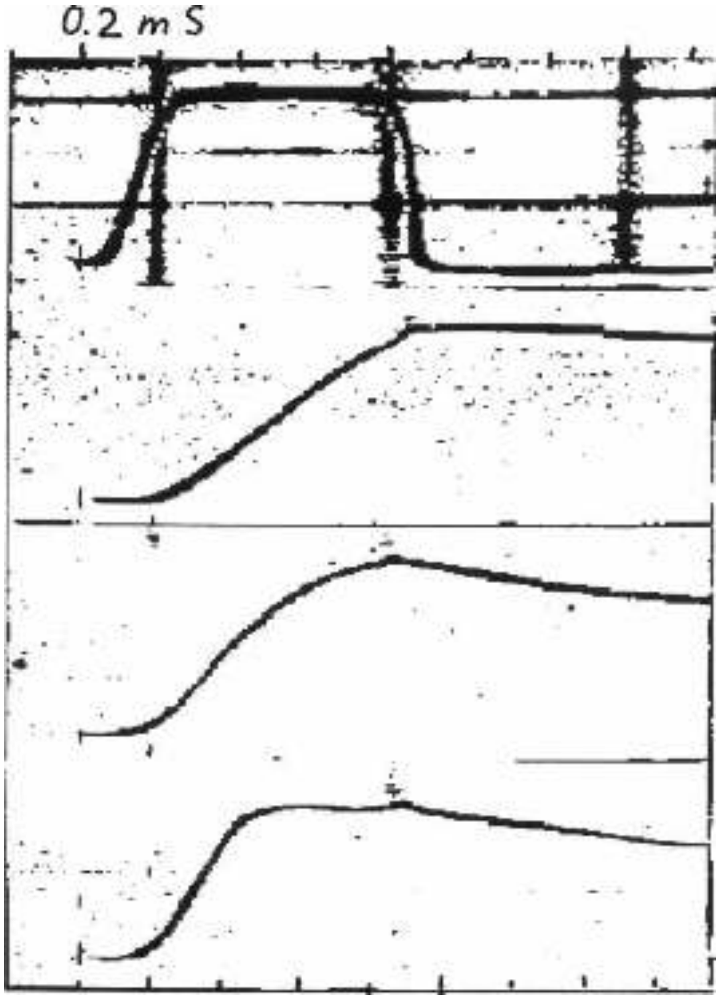
G.I. Dimov and V, G. Dudnikov, CROSS SECTIONS FOR STRIPPING OF-1-MEV NEGATIVE HYDROGEN IONS IN CERTAIN GASES, Zhur. Tekh. Fiz, 36, (1966) 1239; Sov. Phys. -Tech. Phys. 11, 919 (1967).

G.I. Dimov, A.A Ivanov and G.V. Roslyakov, Nucl. Fusion, 15, 551 (1975).

Charge exchange injection was developed (1965) with using of Ehlers type H- source in high voltage terminal of Van de Graf accelerator (1 mA, 1.5 MeV) in high pressure gas tank. Work of Technicien Petr Juravlev was important for SPS success



Proton beam accumulation for different injection current (0.1-0.5 mA)



Injected beam

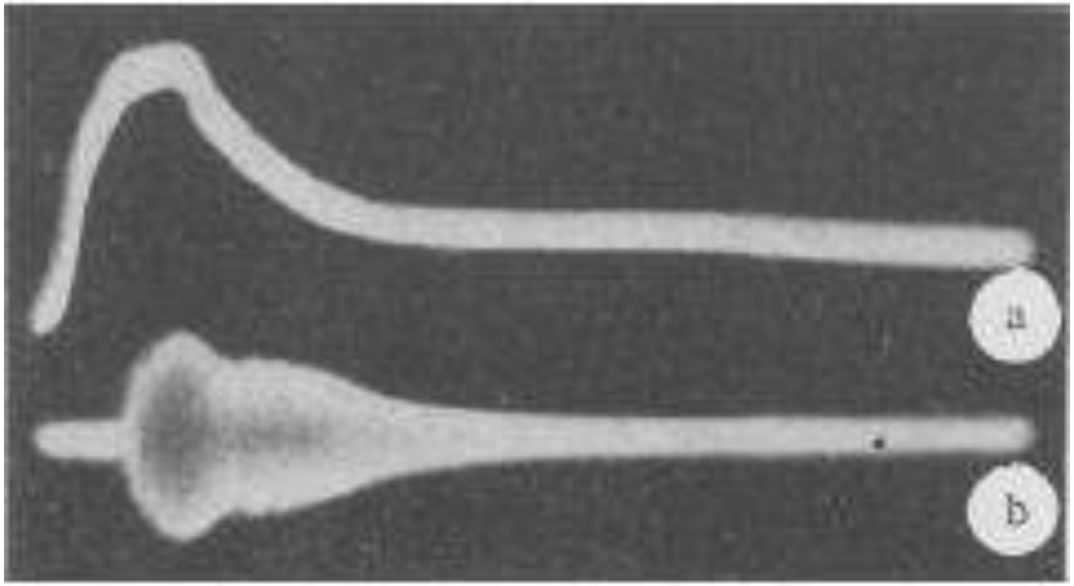
Circulating beam,

Low injection current

Start saturation

Strong saturation

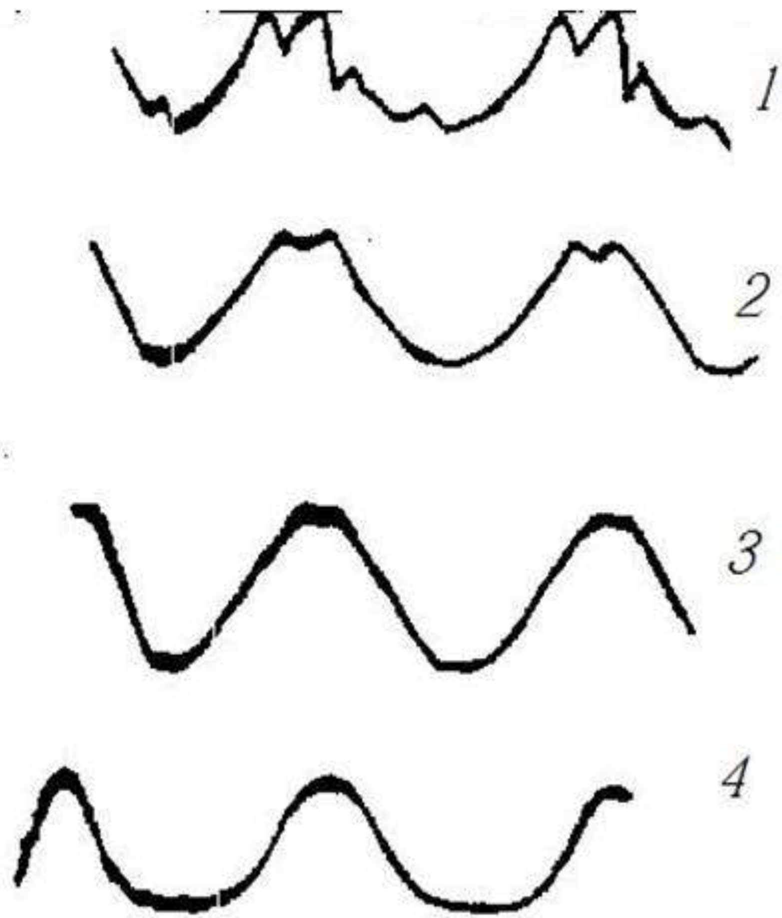
Coherent synchrotron oscillations in INP PSR



Orbital current- (a), and the amplitude of coherent phase oscillations - (b). The scale along the horizontal is 500 μsec/cm.

A certain increase in the proton loss during accumulation process is connected not only with scattering on the jet, but also with the generation of synchrotron oscillations as a result of a reduction in the effective jet thickness along the radius. In order to reduce the effective thickness of the jet and its decay along the radius (as a result of circumvention), the protons were brought to the orbit with a vertical angular deflection of up to 0.135 rad. A capture efficiency of 75-85% was secured in this case. All the subsequent experiments were performed mainly by using a vertical injection angle of 0.1-0.135 rad.

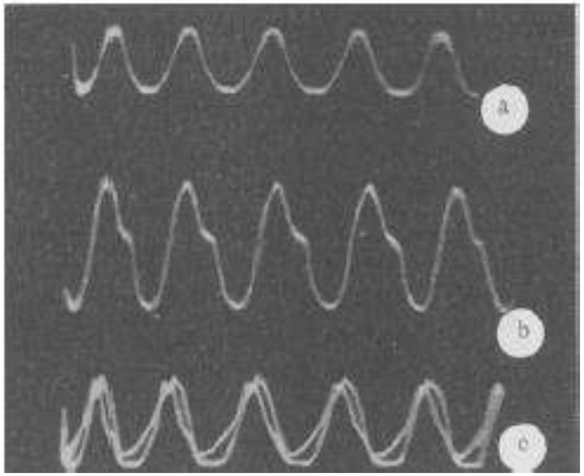
Evolution of bunches profiles in INP PSR



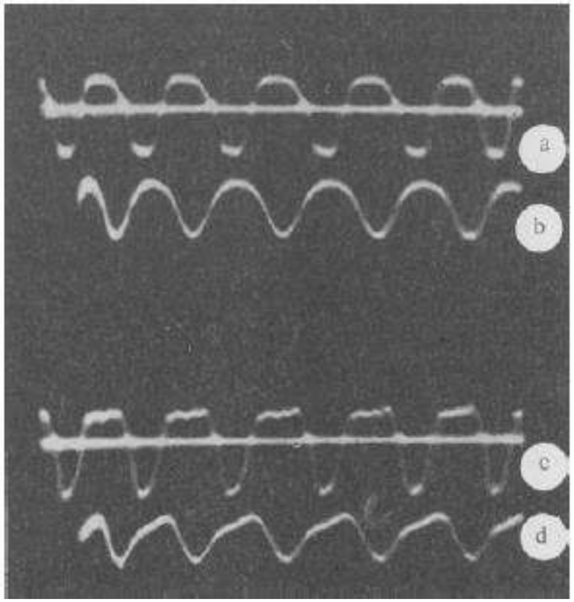
1- 0.05 ms(100 turns);
2- 0.4 ms(1000 turns);
3- 0.8 ms (3000 turns);
4- 2.8 ms, before start

Transverse instability.
Bunches period 188 ns
Coasting beam injection

Beam bunch evolution during accumulation



- Azimuthal proton distribution in bunches,(a) and (b) t = 700 μsec; c) t1 = 800 μsec, t2=1200 μsec.



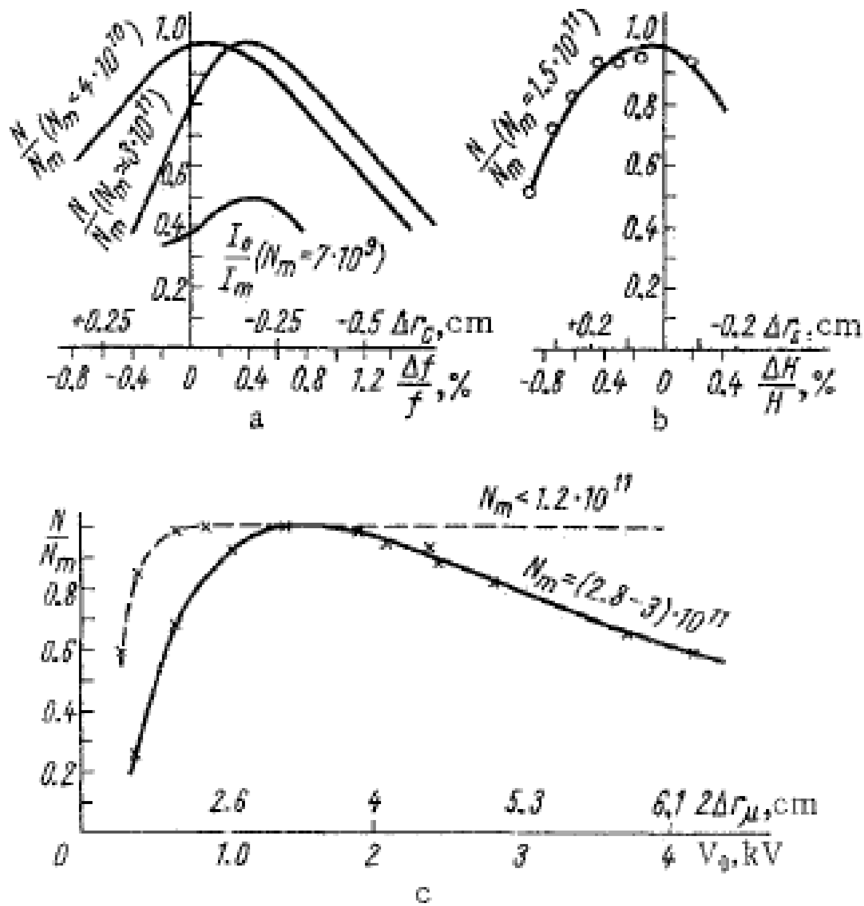
- Azimuthal proton distribution (a) (b)
- and the drift tube voltage (c, d) with the second harmonic of the accelerating field for different ratios of harmonics.

Beam intensity dependence on parameters

Dependence of number of accumulated protons on the frequency of the RF voltage (a),

on the magnetic field (b),

and on the amplitude of the RF voltage for constant injection energy

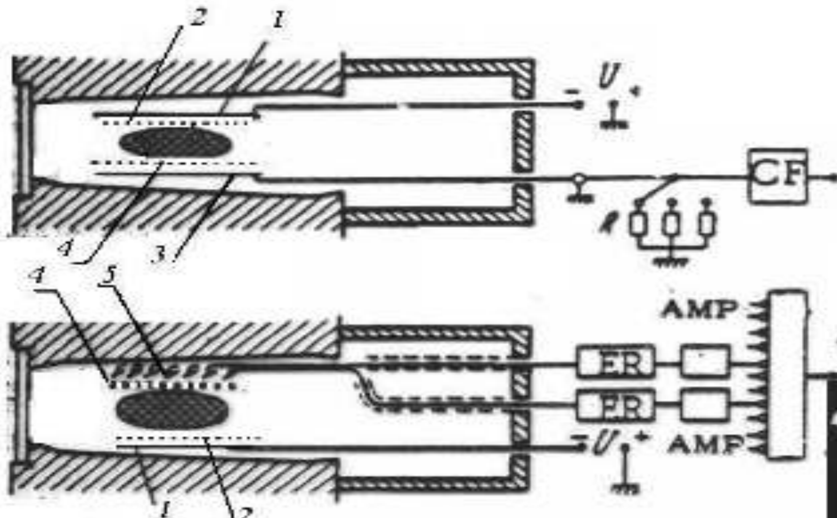


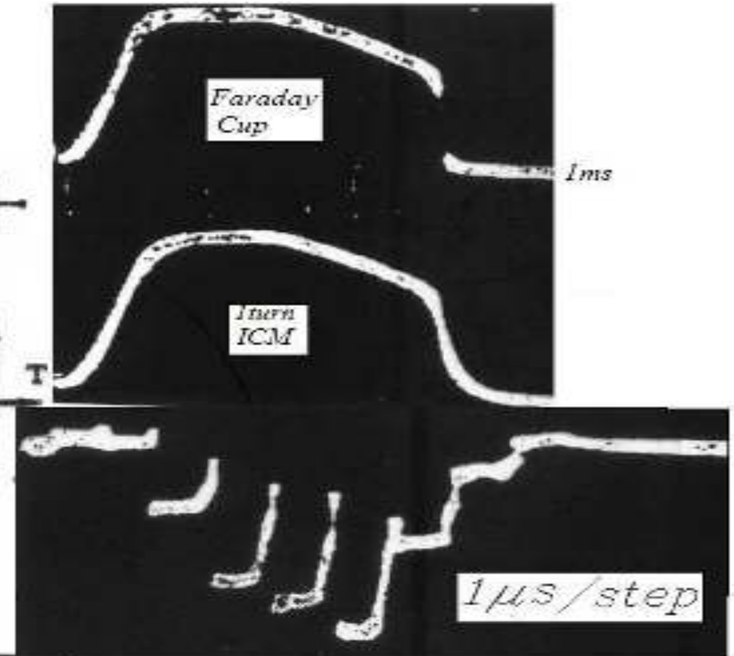
$$\Delta r = r_o[e(V_o+\Delta V)/\pi n(1-n)W]^{1/2}$$

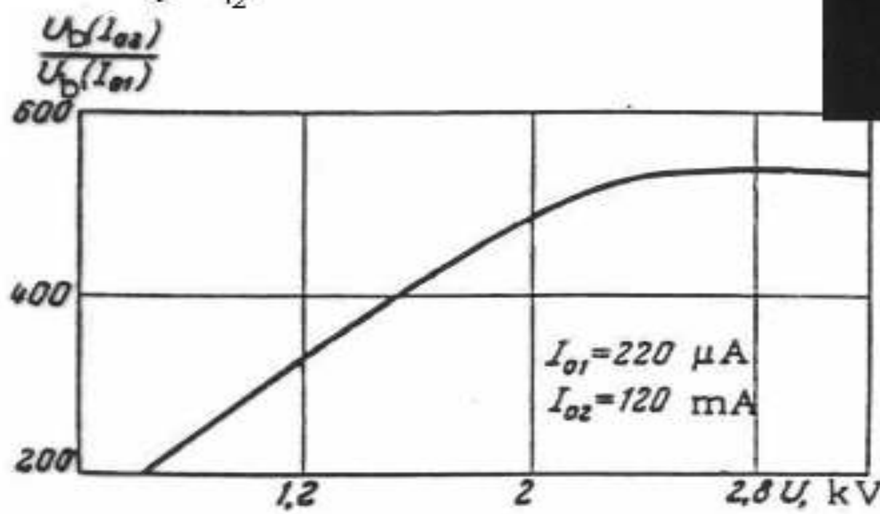
$$\Delta V = f\, eN\, \Delta z / r_o\, \Delta r$$

Intensity limitation by longitudinal space charge effect.
Separatrice Δ r extending by longitudinal RF space charge

Residual gas ionization beam current & profile monitors (ICM,IPM),1965.







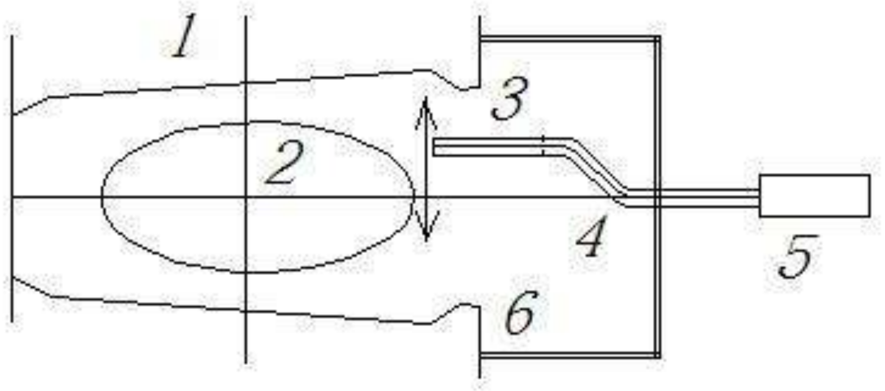
Residual gas IPM.V.Dudnikov,1965.

1-reflection platre;2-suppression grid;

3-collector plate;4-shilding grid;

5 collector strips.

Residual gas luminescent beam profile monitor, INP, 1965



1- magnetic pole;

2- proton beam;

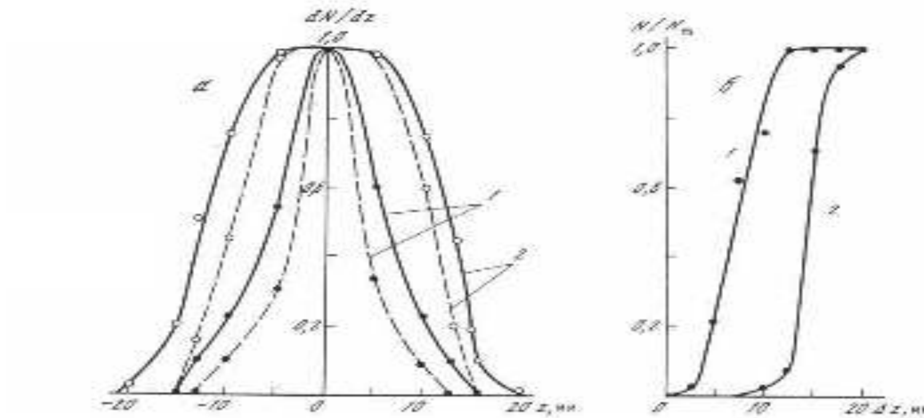
3- moving collimator

4- light guide;

5-photomultiplier;

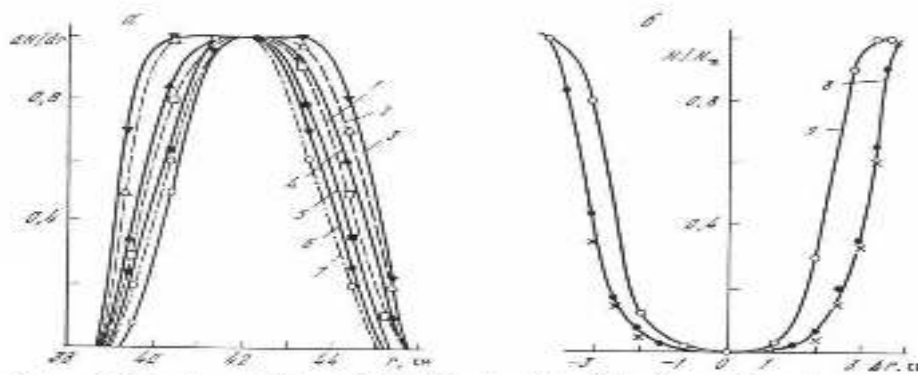
6-vacuum chamber

Beam profiles evolution during accumulation



Residual gas luminescent beam profilometer signa, and beam intensity vs vertical aperture

а) — $N_m = 2\cdot10^{11}$; б — $N_m = (2 \div 20)\cdot10^{10}$; 1 — $\alpha_z = 0$; 2 — $\alpha_z = 0.12$



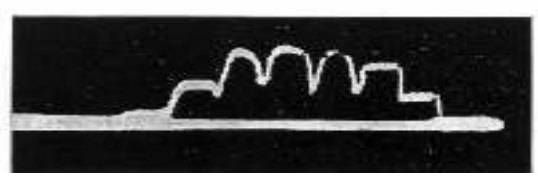
Residual gas ionization beam profile monitor (IPM) signal and beam intensity vs radial aperture

1 — 6: $N_m = 2{,}5\cdot10^{11}$, t = 1600 мкс (1); 900(2); 700(3); 400(4); 200(5); 50(6); 7 — $N_m = 5\cdot10^{11}$, t = 300; 2000 мкс; 8 — $N_m = 3{,}6\cdot10^{11}$; 9 — $5\cdot10^{11}$

IPM signal. electron collection in B field

Step 9mm.

V.Dudnikov, 1965.

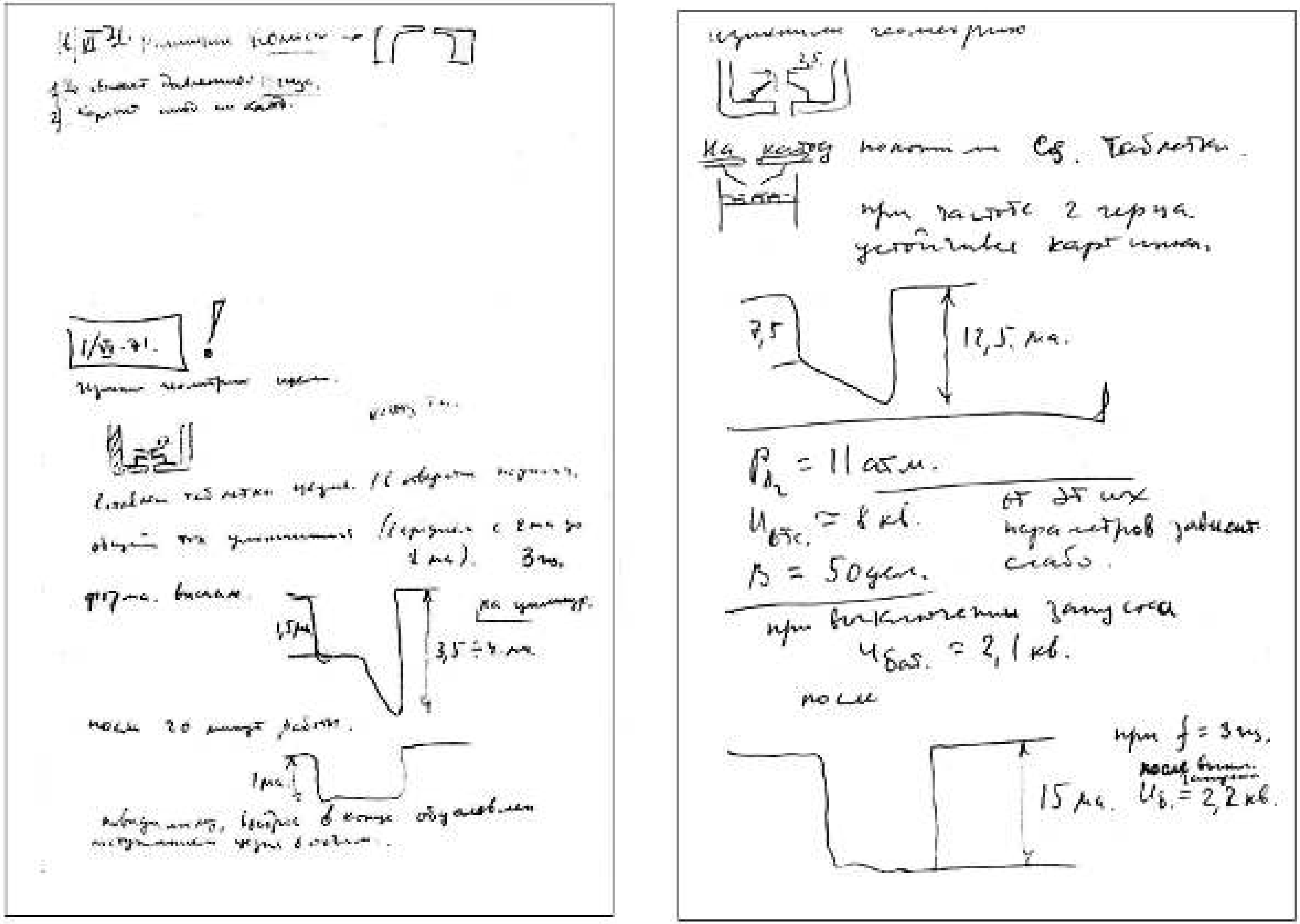


В 70 годы Лаврентьев воевал с Будкером против его политики расширения ИЯФ. Будкер искал источники финансирования. В 1967 Он предложил использовать пучки нейтралов в космосе для инспектирования спутников. Он заключил договор на 2 Мруб с фирмой Королева на разработку источника Н- на 10 мА. Было организовано 3 группы для разработки ионных источников. Группа Рослякова занималась разработкой перезарядных источников. Группа Димова занималась разработкой распылительных источников. Мы с Юрой Бельченко занимались плазменными источниками. К концу срока договора все отчаялись получить нужные параметры и ушли в отпуск. Юра уехал в строй отряд на Колыму строить Билибинскую АЭС и взял с собой нашего лаборанта.

Я продолжал работать один. Мы работали с планотроном, из которого получалось до 5 мА ионов Н-, при токе разряда 100 А, напряжении 600 В.
1 июля 1971 года я закрепил таблетку хромата цезия с 1 мг цезия и включил разряд. Эмиссионная щель была заэкранирована и на коллекторе регистрировался ток ионов 1.5 мА После нескольких минут работы в конце импульса появился выброс тока до 3 мА, После оптимизации подачи газа ток в конце импульса увеличился до 4 мА, но через 20 минут выброс тока исчез и ток на коллектор стал снова 1 мА. Решив, что выброс тока связан с выделением цезия, я поместил несколько таблеток на катод, который грелся сильнее, и закрыл их никелевой сеткой. В этой конфигурации ток на коллектор быстро увеличился до 12 мА а после оптимизации подачи газа и разряда получился прямоугольный импульс 15 мА. Напряжение разряда понизилось с 600 В до 100 В.

По договору с ЦКБ успешно отчитались и заключили новые договора по 5 Мруб на изготовление ППИ для линейного ускорителя мезонной фбрики ИЯИ и для ИВФЭ.(В это время девятиэтажка на -216 квартир стоила 1 Мруб)
Тогда результаты с цезированием признали секретными и публиковать не разрешили. Но в ИЯФ стало наведываться много делегаций из Союза (ЦКБ, НИИЭФА, ИНР, ИФВЭ) и из США. Будкер разрешал показывать ППИ высокопоставленнм визитерам из США как объекты для торгов.
В печати (до наших публикаций) появились публикации в которых говорилось что выход отрицательных ионов можно увеличить добавлением цезия в разряд.

IEEE TRANSACTIONS ON NUCLEAR SCIENCE Volume: NS20 Issue: 3 Pages: 136-141 DOI: 10.1109/TNS.1973.4327065 Published: 1973
”SOME ADVANCES IN NEGATIVE ION TECHNOLOGY”, By Kenneth H. Purser
During the past two decades, the advances which have been made in the techniques of negative ion production have been truly spectacular both in terms of intensity and the available species. For example, while in 1955 negative ions of the hydrogen isotopes were produced at submicroampere intensities, today 22 mA beams of negative hydrogen have been reported [2] and it is rumored *that Dimov and his collaborators at Novosibirsk have seen 200 milliampere* peak pulse intensity during pulsed H- operations. На самом деле к тому времени мы имели пучок ионов H- с током 0.9 А.



Копия страницы из рабочего журнала за 1 июля 1971 года с описанием эволюции интенсивности пучка отрицательных ионов при добавлении цезия в разряд

- **Cesiation effect, a significant enhancement of negative ion emission from gas discharges (from 1.5 mA to 15 mA) with decrease of co-extracted electron current below negative ion current was observed for the first time by location into discharge chamber a compound with one milligram of cesium on July 1, 1971 (7/1/71) in Institute of Nuclear Physics, Novosibirsk, Russia (Now BINP).**

- **This result was not published because was recognised as a "top secret" without permeation for publication. After strong effort of Gennadii Dimov it was permeated only application for patent (Author sertificat): Vadim Dudnikov, "The Method for Negative Ion Production", SU patent, C1.H013/04, No 411542, Appl. 3/10/72.**

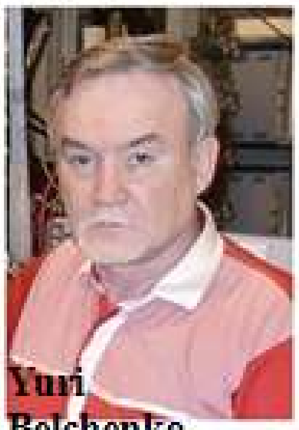
Invention formula:

- *"Method of negative ion production comprising admixture into the discharge a substance with a low ionization potential, such as **cesium**".*
- **There is big difference between "surface production" and "surface plasma production", because without plasma it is possible to have only microAmpers of negative ions as in sputtering type (Middleton) sources.**
- *Further development of SPS was conducted by Belchenko, Dimov, Dudnikov in INP and many teams in many laboratories.*

Cs in Negative Ion Sources

In the early 1970s, (07.01.71) before the Cs physics was understood, V. Dudnikov G. Dimov and Y. Belchenko added Cs to their magnetron source increasing the H^- current to 150 mA for up to 0.5% duty factors.(really up to 0.88A)

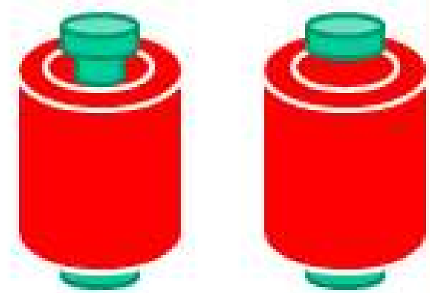
V. Dudnikov, *Russian Patent No. 411542*
http://www.findpatent.ru/patent/41/411542.html
Y. Belchenko, G. Dimov, V. Dudnikov, *Nucl. Fusion, 14, 113 (1974)*



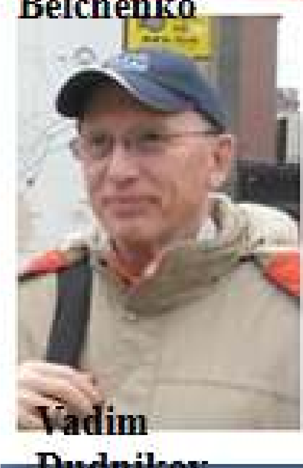
Vadim Dudnikov also developed a Penning H^- source that delivers 150 mA .

With the Siberian "Know How",

- BNL Krsto Prelec et al. developed magnetrons for NBI.
- LANL Paul Allison et al. developed Penning H^- sources.
- LBNL Ehlers and Leung developed Surface Converter H^- sources for LANL.
- FNAL Chuck Schmidt et al. developed the BNL magnetron for accelerators.



magnetron **Penning**



These are Compact Surface Plasma Sources (CSPS)! M. P. Stockli, JAS 2013

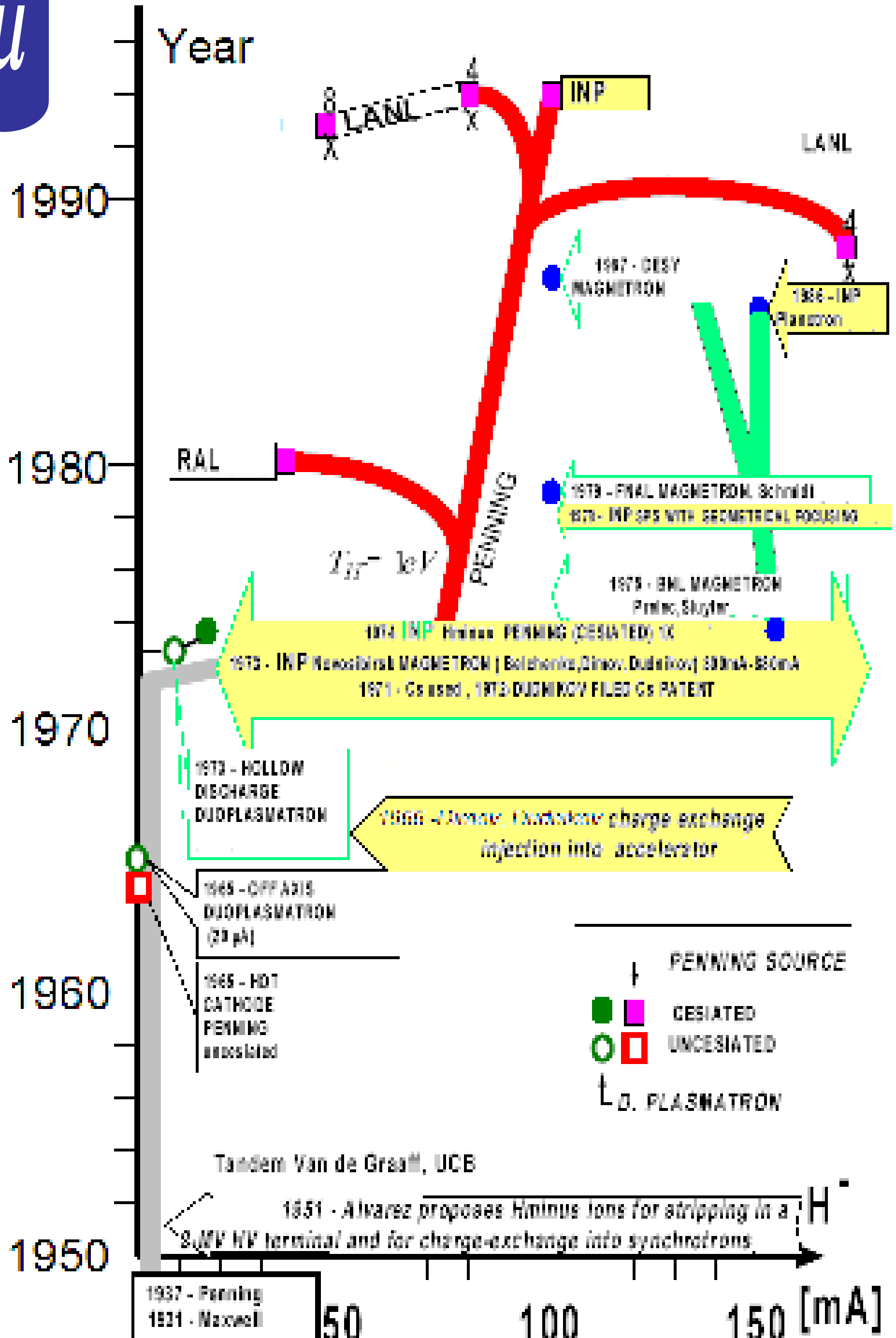
- **First International publication was permeated in 1974 when H- beam current was increased up to 0.9 A :**

BELCHENKO Y.I., DIMOV G.I., DUDNIKOV V.G., “POWEFUL INJECTOR OF NEUTRAL S WITH SURFACE PLASMA SOURCE OF NEGATIVE IONS”, NUCLEAR FUSION   Volume: 14   Issue: 1   Pages: 113-114 , 1974

- **Before this publication it “was ringing, that in Dimov’s Lab. was produced 200 mA of H- by admixture of Cs into the gas discharge”. It was several publications in 1973-74 with statement “intensity of negative ion beams can be increased by injection of cesium into discharge” without any references but successful cesiation was not repeated at this time.**

- Development of high brightness H^- sources was stimulated by first success of high current proton beam accumulation with using a charge-exchange injection [1] and supported by interest of “Star War” [2].
- A recent circumstance was the reason of difficulties and long delay of first publications, but nonofficial communication was relative fast.

- [1] G. Budker, G. Dimov, V. Dudnikov, Sov. Atomic. Energy, 22, 348, 1967; Proc. Int. Symp. on Electron and Positron Storage Ring, France, Sakley,1966, rep. VIII, 6.1 (1966).
- [2] C. Robinson, Aviation Week&Space Tech., p.42, Oct., 1978;
- Rev. Mod. Phys., 59(3), Part II (1987).



History of Surface Plasma Source development

(J.Peters, RSI, v.71, 2000)

Cesiation patent

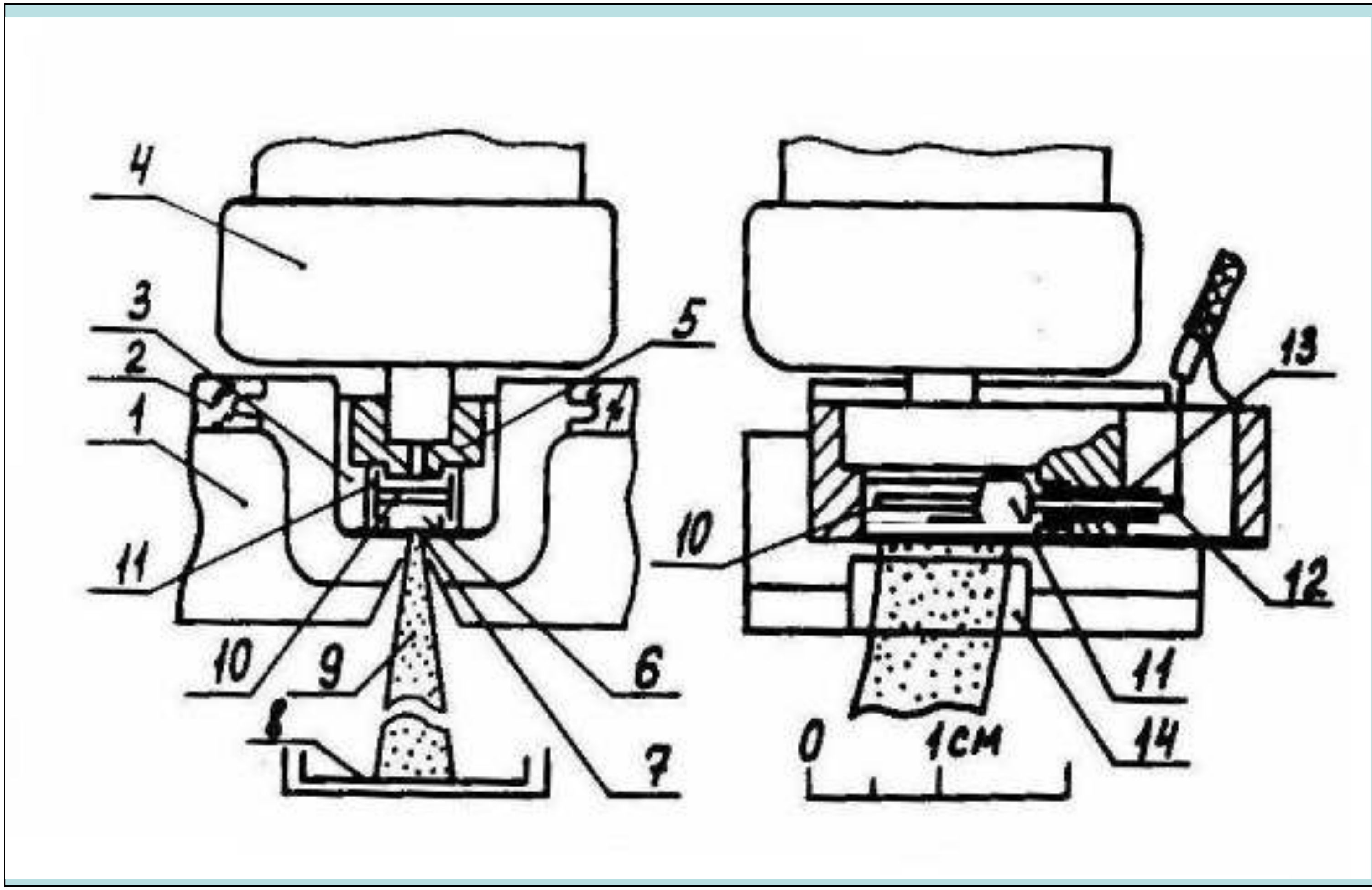
V. Dudnikov. The Method for Negative Ion Production, SU Author Certificate, C1.H013/04, No. 411542, Application filed at 10 Mar., 1972, granted 21 Sept,1973.

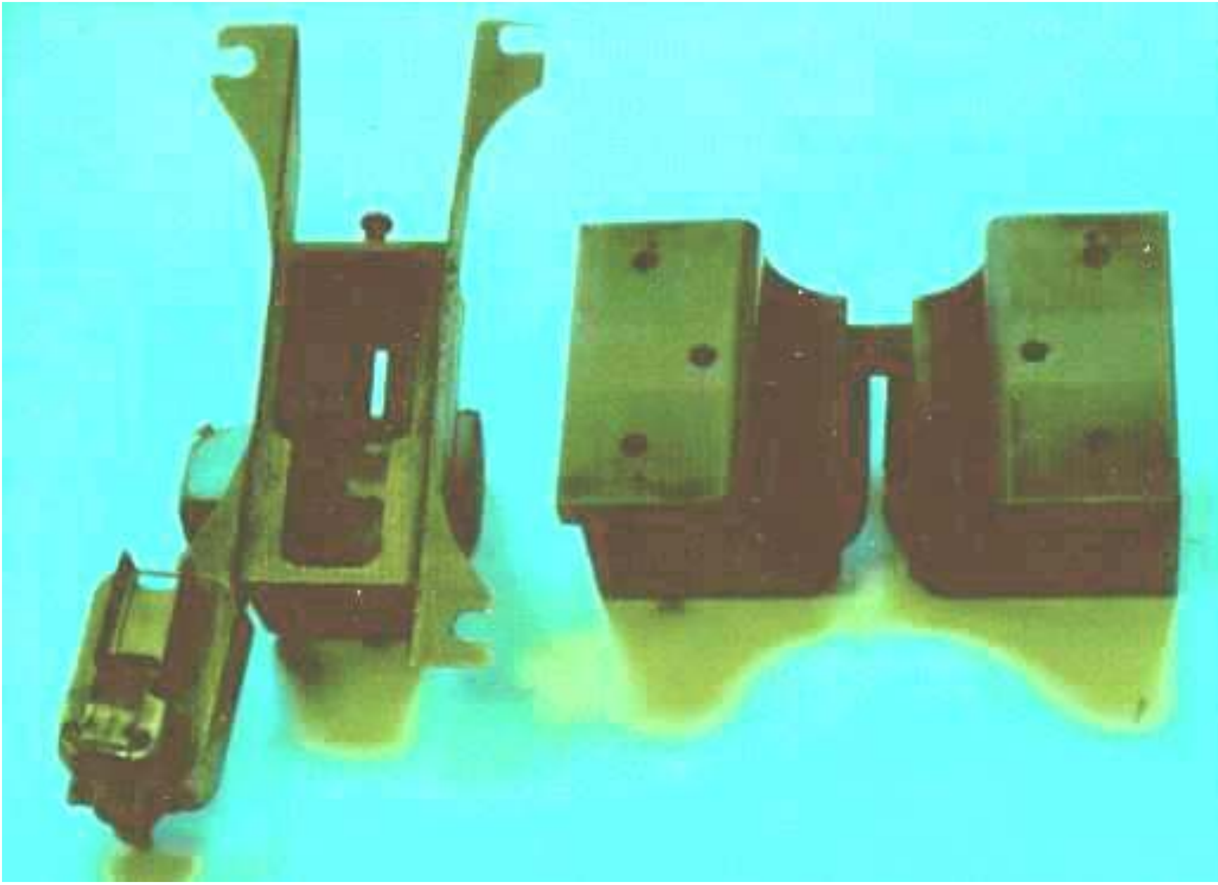
Invention formula:

*"Method of negative ion production comprising admixture into the discharge a substance with a low ionization potential, such as **cesium**".*

First version of Planotron (Plain Magnetron) SPS, INP, 1971,

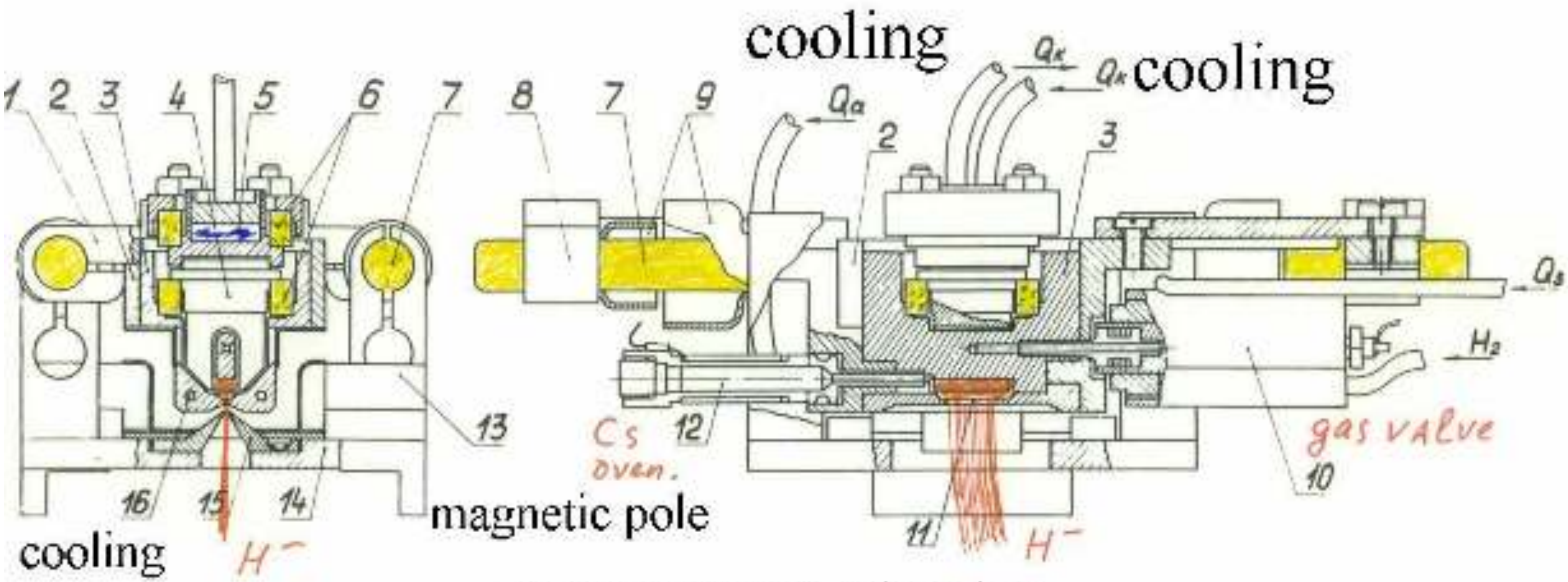
Beam current up to 230 mA, 1.5x10 mm^2, J=1.5 A/cm^2 with Cs





Фотография первого планотрона

Design of SPS with Penning Discharge



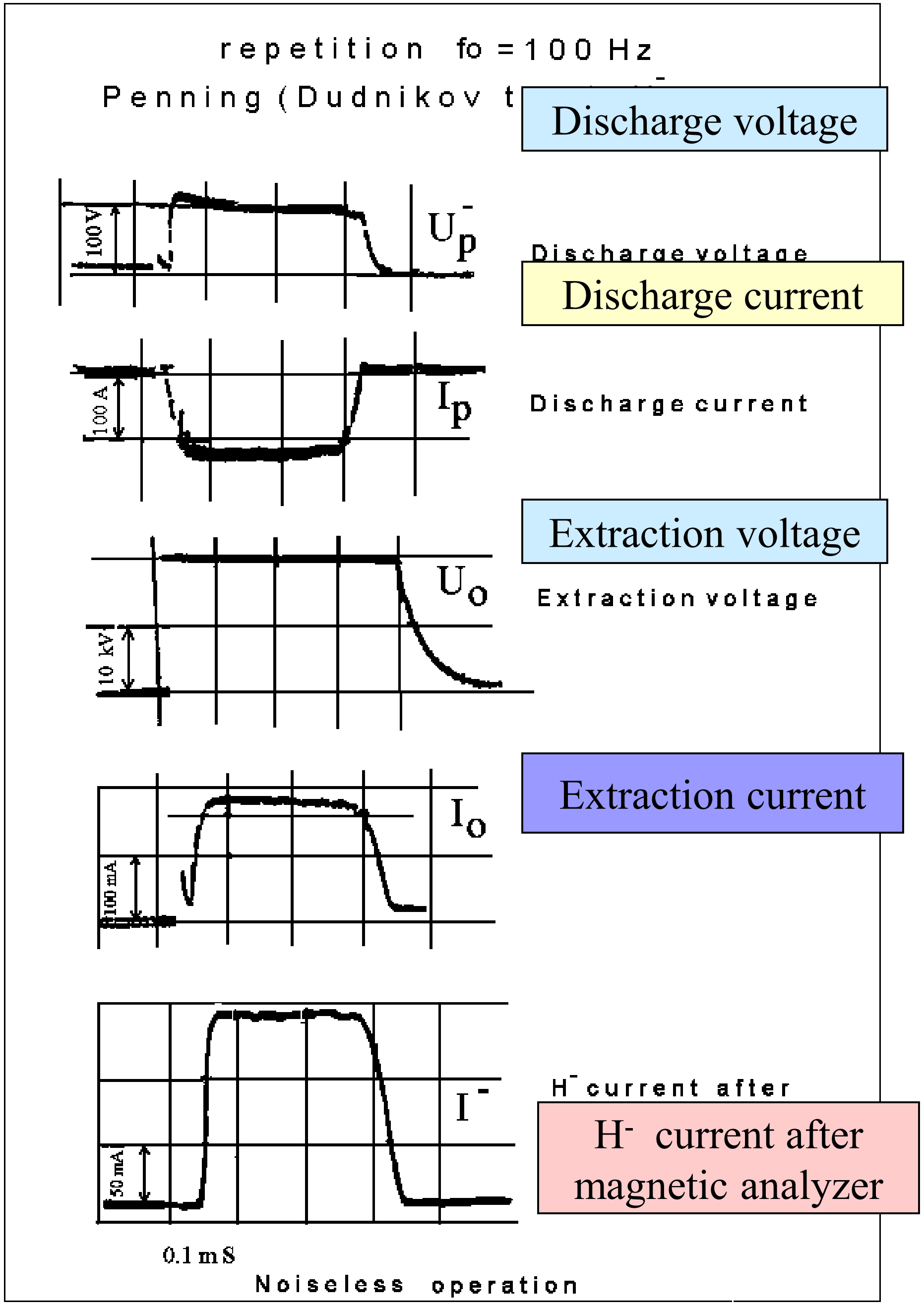
Beam current 0.1 (0.15) A,
Extraction 22 kV
Repetition 100 Hz(teste up to 400Hz)
Puls 0.25 ms
discharge volume 6x3.5x15 mm^3
emission slit 0.5x10mm^2

FIG. 8. Surface-plasma negative ion source with Penning discharge (Dudnikov type ion source). (1) support; (2) gas discharge chamber; (3) anode insert; (4) cathode; (5) cathode cooler; (6) cathode insulator; (7) high-voltage insulator; (8) support; (9) insulator screens; (10) gas valve; (11) emission slit; (12) cesium container; (13) magnetic pole; (14) base plate; (15) extractor; (16) cooling channal.

Rev. Sci. Inst. 61(1) 378(1990) 381

CSPS with Penning discharge

All metal and ceramic. Can be heated to 1000C for activation.



Noiseless operation

100 Hz

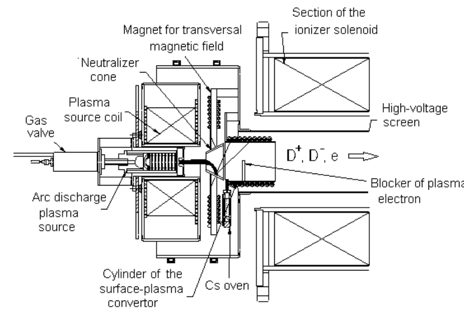
Tested for 300 hs of continuous operation with H- Current>100mA

В 1968 Р. Мартин посетил ИЯФ и ознакомился с разработками по перезарядной инжекции. Он решил, что перезарядная инжекция позволит Аргоннскому синхротрону с нулевым градиентом (ZGS), директором которого он был, конкурировать по интенсивности с Alternation Gradient Synchrotron (AGS,АГС) в Brookhaven National Laboratory (БНЛ).
В 1969 году перезарядная инжекция была успешно опробована на протонном синхротроне ZGS в США на энергию 12 ГэВ при энергии инжекции 50 МэВ. Протоны захватывались на орбиту при перезарядке ионов Н- в мишени из тонкой органической плёнке.
По предложению Р. Мартина была отработана перезарядная инжекция протонов в бустер для синхротрона ZGS.
В 1971 тоду была осуществлена перезарядная инжекция протонов в синхротрон на 200 МеВ – прототип бустера для ZGS [84]. Бустер с 1977 года в течении многих лет служил интенсивным импульсным нейтронным генератором.

R. Martin, Proc. VIII Internat. Conf. on High Energy accel. CERN, p. 540 (1971).
I.D. Simpson, IEEE Trans. Nucl. Sci., NS-20, No3, 198 (1973).
J. Simpson, R. Martin, R. Kustom,**History of the ZGS 500 MeV booste,http://inspirehep.net/record/1322000**

В 1978 году перезарядная инжекция была освоена на бустере Fermi National Accelerator Laboratory (ФНАЛ) при энергии инжекции 200 МэВ.
В 1982 году синхротрон AGS в БНЛ был переведен на перезарядную инжекцию.
В 1984 году перезарядная инжекция была осуществлена в синхротрон ISIS в Ruthrford Appleton Laboratory (РАЛ) в Англии
и на накопителе пртонов в Лос Аламосской Национальной Лаборатории (ЛАНЛ).
В 1980-84 перезарядная инжекция была освоена в Лаборатории физики высоких энергий (КЕК) в Японии,
в Duche Electron Synchrotron (DESY,ДЭЗИ) в Германии.
Перезарядная инжекция используется на накопителе CELSIUS (Упсала, Швеция),
в накопителе COSY (исследовательский центр Юлих, Германия).
Перезарядная инжекция была использована в синхротроне Института экспериментальной и теоретической физики для накопления ионов углерода
В 2006 заработал СНИ в ОРНЛ с перезарядной инжекцие 50 мА, 1 ГэВ Н- в накопитель до 50 А, 50 ГВт.
Сейчас готовится переход на перезарядную инжекцию в бустере Европейского центра Физики высоких энергий (ЦЕРН) в Швейцарии
и в бустере Института физики высоких энергий (ИФВЭ) в Протвино, Россия

Перезарядная инжекция используется для инжекции поляризованных ионов H- в бустер AGS, RHIC d BNL. Использовалась для инжекции поляризованных ионов H- в бустер накопителя Indiana University



Возможно получение поляризованных отрицательных ионов. Для этого по предложению Дудникова струя плотной плазмы конвертируется в отрицательные ионы на цезированном поверхностно-плазменном ионизаторе и затем осуществляется резонансная перезарядка поляризованных атомов на струе отрицательных ионов. Положительные ионы генерируются дуговым разрядом с холодным катодом в диафрагмированном канале и транспортируются магнитным полем на конусную поверхность конвертора, где преобразуются в атомы. Атомы конвертируются в ионы H- на цилиндвоческой цезированной поверхности поверхностно- плазменного конвертора и перезаряжают в отрицательные ионы поляризованные атомы дейтерия. Образовавшиеся поляризованные ионы D- вытягиваются многоапертурной сеточной системой формирования и отделяются поворотным магнитом от неполяризованных ионов H-.

MOTIVATION

- Important feature of SNS at ORNL is very powerful, short (~1 μs) pulse of protons used for neutron pulse generation.
- Outstanding recent achievement is 40 A (40 GW) P beam in the compressing ring (1.4 MW of average power).
- This ~ 10^3 times power compressing is produced by charge exchange injection with using of accelerated H- ion beam.
- Increasing the ion beam current and/or the beam duty factor are normally the most cost-effective solutions for increasing the production rate of accelerator facilities. Advanced H- ion sources are necessary for reliable realization of charge exchange injection.
- Advanced conversion of H- to H+ (stripping) is necessary for reliable operation of charge exchange injection.
- Pulsed beam power can be increased up to 100GW with improved H- ion source, improved H- stripping, suppression of e-p instability.

Transverse instability in the INP PSR, bunched beam (1965)

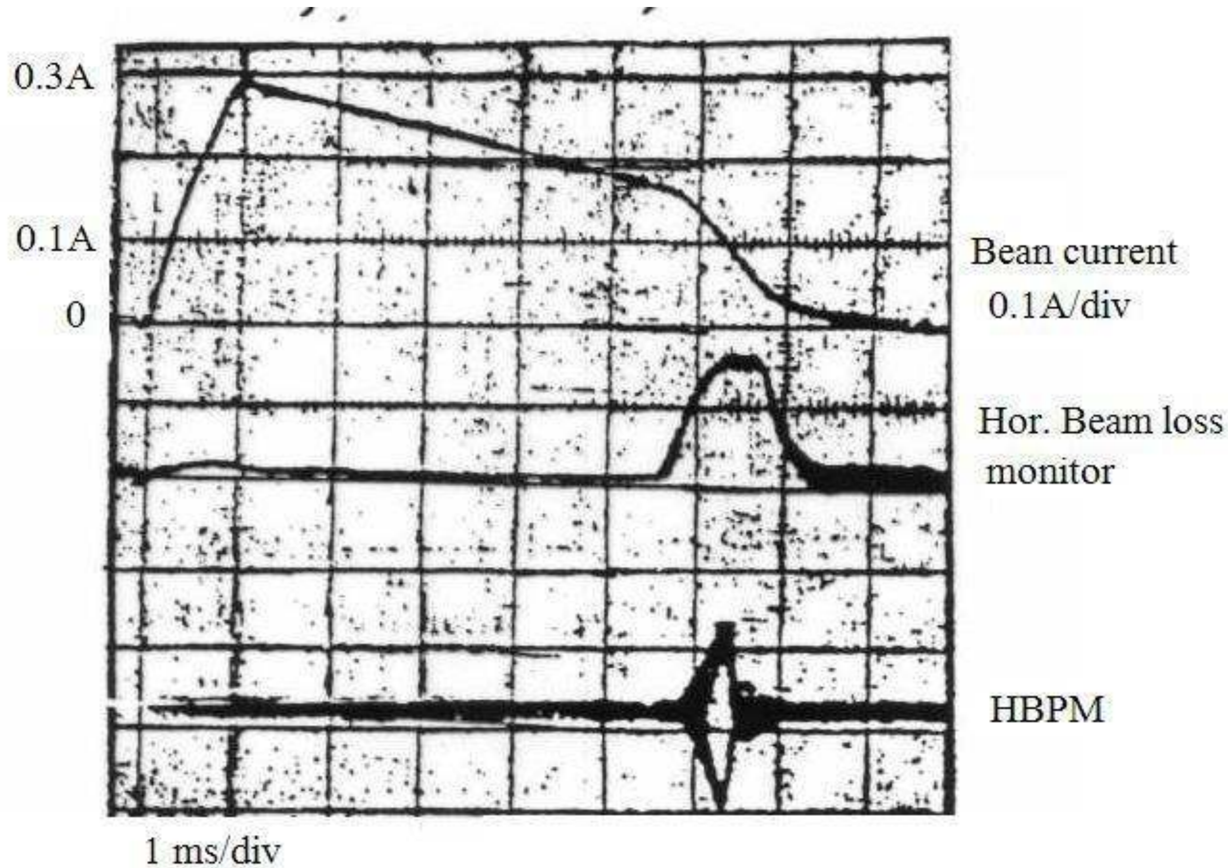
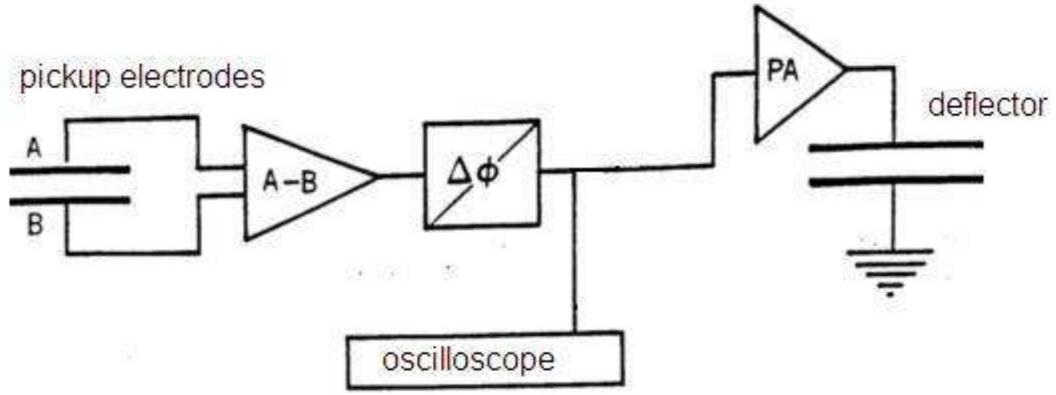
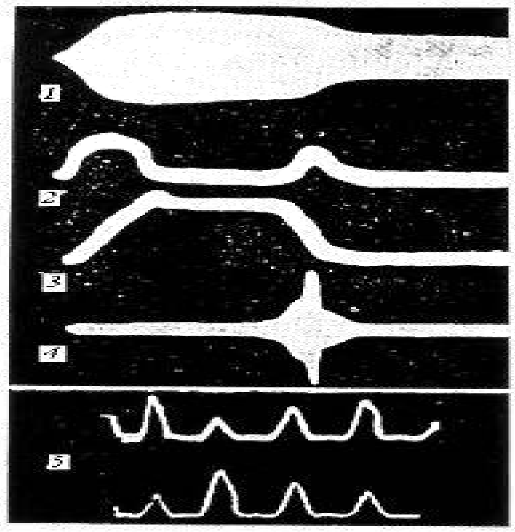
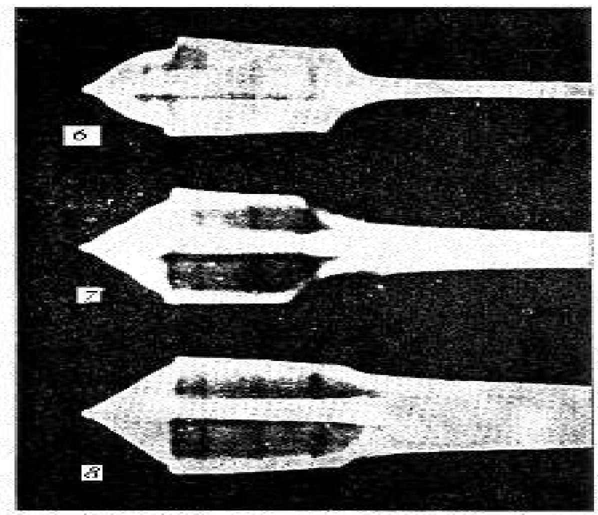


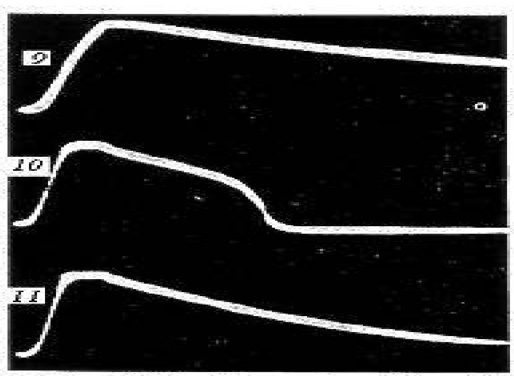
Diagram of feedback system for e-p instability damping (bunched beam)



Transverse instability of bunched beam in INP PSR (1965)



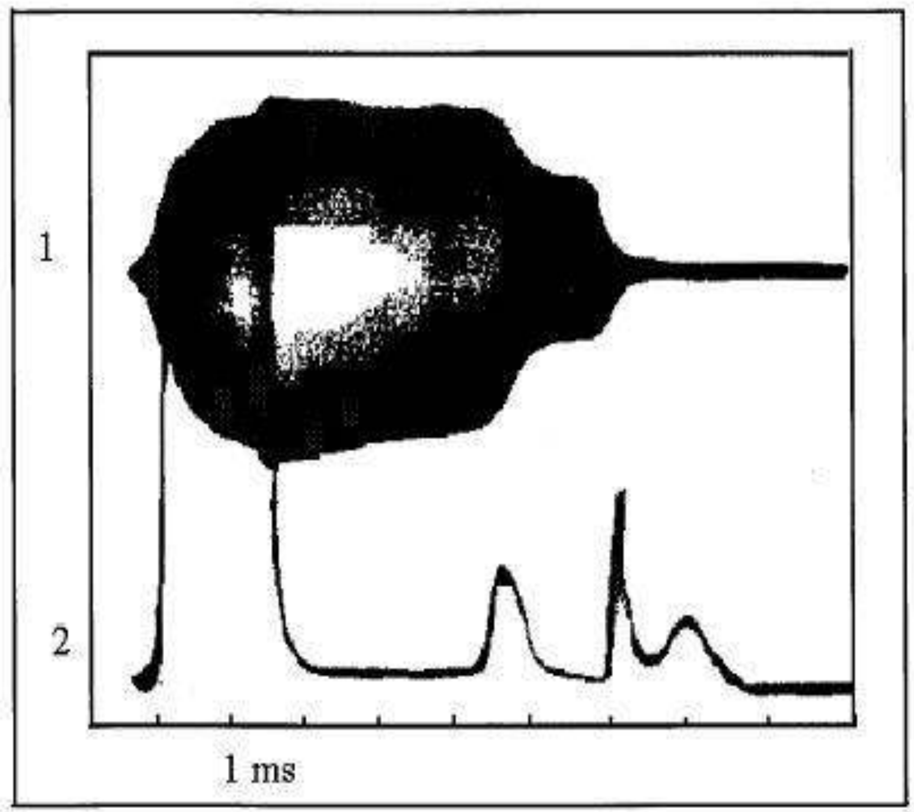




Transverse e-p instability in INP Proton storage ring (PSR), 1965. *bunched beam* *Injection time is 1ms*

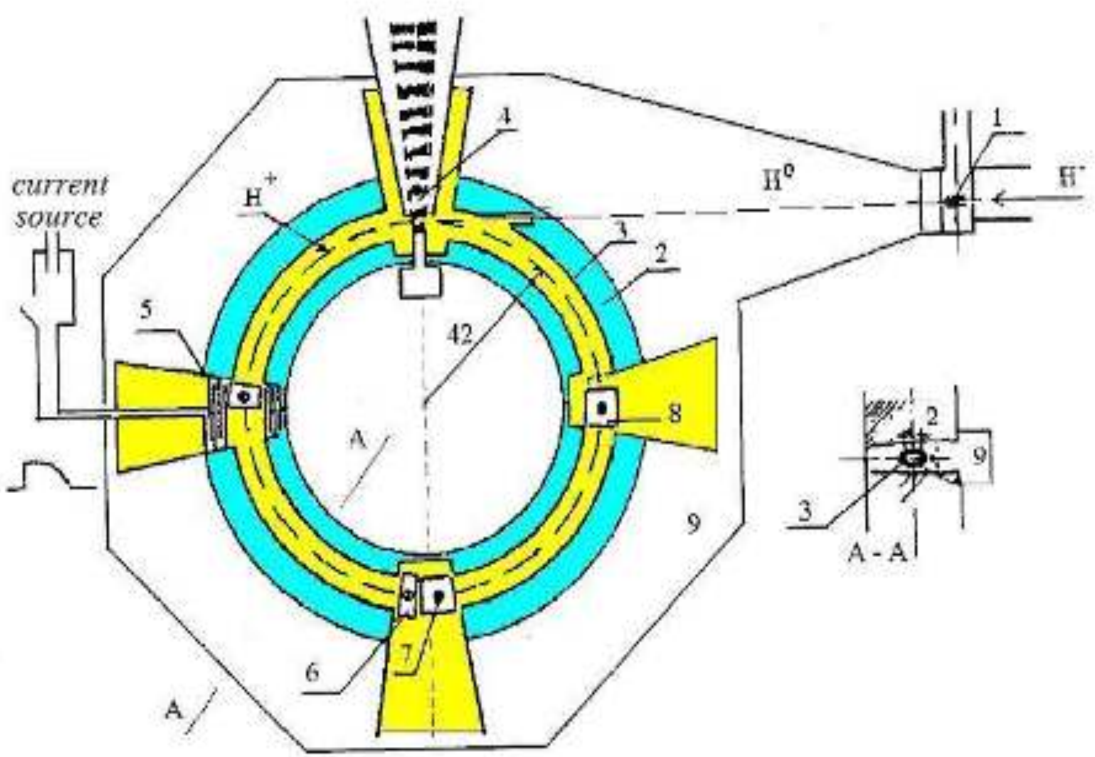
1-pick up electrode signal; 2-beam loss monitor;
3-beam intensity; 4-Rad.BPM; 5-radial pick ups;
6-pick up signal Urf=1.4kV; 7-pick up signal Urf=2.8;
8-pick up signal Urf=4.2kV;
9- beam intensity below threshold for instab;
10-beam intensity above threshold for instability, no fied back stabilization; 11- beam intensity above threshold for transverse instability, fied back stabilization ON.

Transverse instability of bunched beam with a high RF voltage



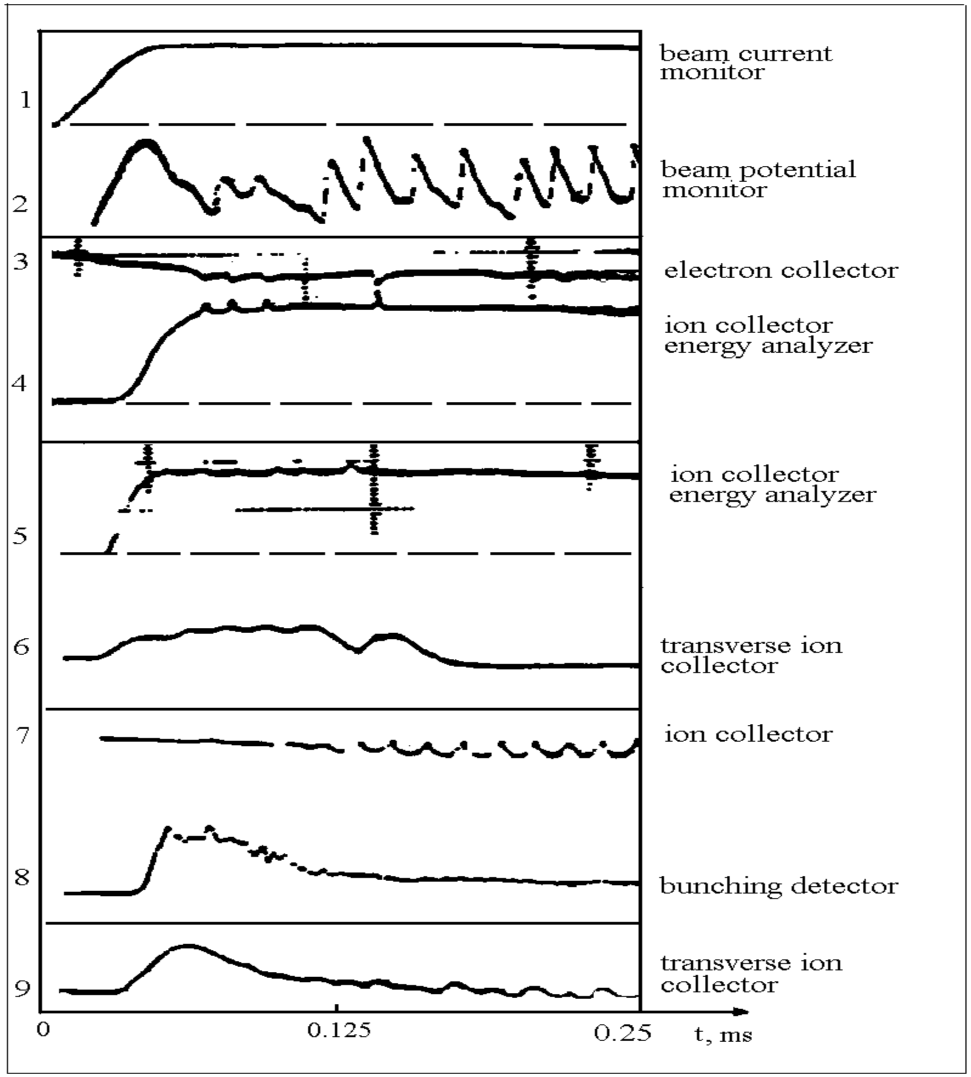
1-ring pickup, peuk bunch intensity ;
2-radial loss monitor.
Beam was deflected after Instability loss.
Two peaks structure of beam after instability loss.
Only central part of the beam was lost

PSR for beam accumulation with inductive acceleration



1-first stripper;
2-magnet pole n=0.6;
3-hollow copper torus with inductance current;
4-main stripper;
5-accelerating gap;
6-ring pickup; 7-BPMs;
8-Res.gas IPM;
9-vacuum chamber.
FC; quartz screens;
Retarding electron and ion collectors/ spectrometers .

e-p instability with a low threshold in INP PSR



1-beam current, N>7e9p

2-beam potential, slow

Accumulation of electrons

10mcs, and fast loss 1mcs.

3-retarding electron collector;

4,5-ion collector, ionizing

Current Monitor;

6,7-ion Collectors Beam

potential monitor;

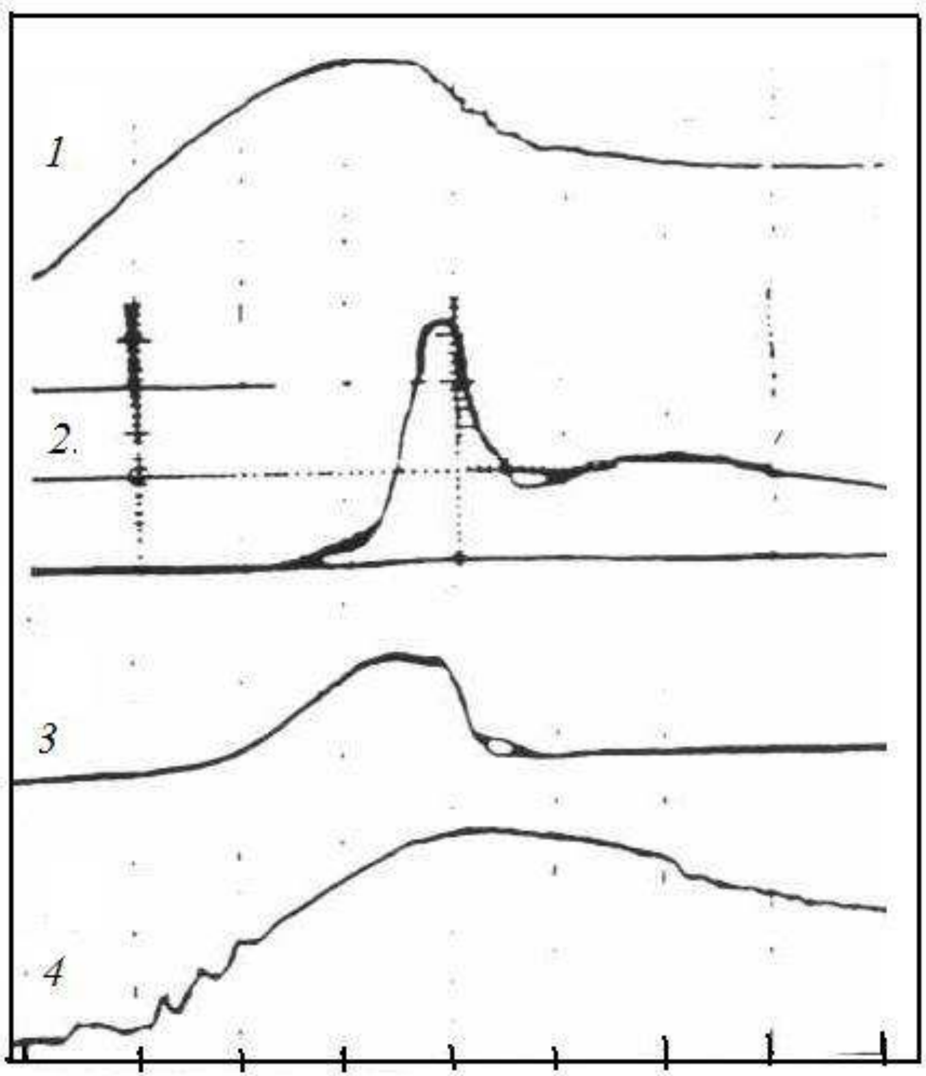
8,9- negative mass Instability.

Injection:

Coasting beam, 1MeV, 0.1mA

R=42 cm.

Instability of coasting beam in AG PSR, 1967



1- beam current monitor;

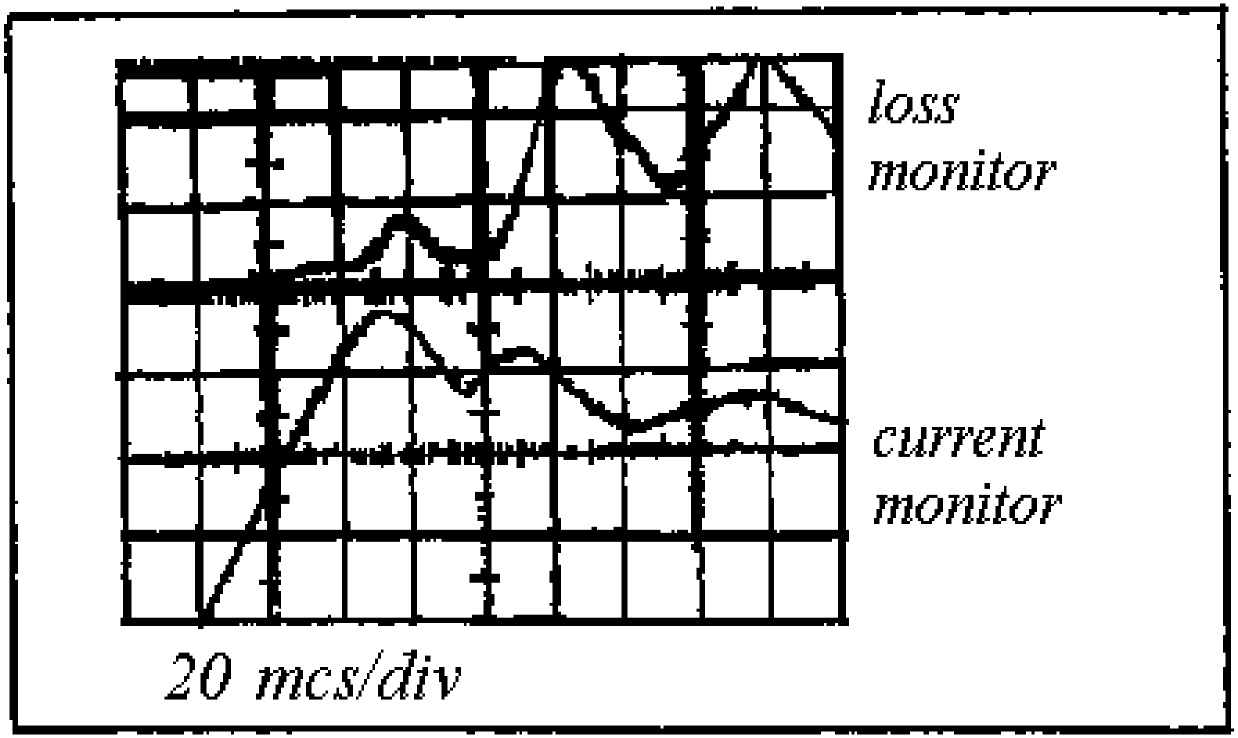
2-vertical proton loss monitor;

3- radial proton loss;

4-detected signal of vertical BPM.

20 mcs/div.

e-p instability of coasting beam in the INP PSR (1967)



. В этих экспериментах впервые наблюдалалась, была исследована, объяснена и подавлена обратной связью электрон-протонная неустойчивость (electron cloud effect), лимитирующая интенсивность пучков в мезонных фабриках и в других больших ускорителях и накопителях. Накопленный пучок живет 1-5 мс затем раскачиваются бетатронные колебания и пучок сбрасывается с орбиты за несколько десятков оборотов. Развитие этой неустойчивости было объяснено на основе теории, развитой Б. Чириковым для объяснения неустойчивости электронного пучка, компенсированного ионами .

Исследование коллективных эффектов в циркулирующих пучках с предельной по пространственному заряду интенсивностью в сочетании с перезарядной инжекцией позволило создать такое «супернеравновесное» образование, как циркулирующий протонный пучок, компенсированный электронным газом, интенсивность которого, почти на порядок больше предела по пространственному заряду.

Б. В. Чириков, “Устойчивость частично компенсированного пучка электронов”, Атомная Энергия, 36, 1239 (1966).

Ю.И. Бельченко, Г.И. Будкер. Г.И. Димов, В.Г. Дудников и др. «Работы по сильнточным протонным пучкам в Новосибирске», Труды Международной конференции по ускорителям, Протвино, 1977; Препринт ИЯФ 77-59, Новосибирск, (1977). http://inspirehep.net/record/127164/files/HEACC77_I_291-298.pdf

M. Reiser, “Theory and Design of Charged Particle Beams”, Wiley-VCH Verlag, second edition, (2009).

Two-stream instability, historical remarks

- Beam instability due to electrons were first observed with coasting proton beam and long proton bunches at the Novosibirsk INP(1965), the CERN ISR(1971), and the Los Alamos PSR(1986).

- Recently two-stream instability was observed in almost all storage rings with high beam intensity.

Two-stream instability

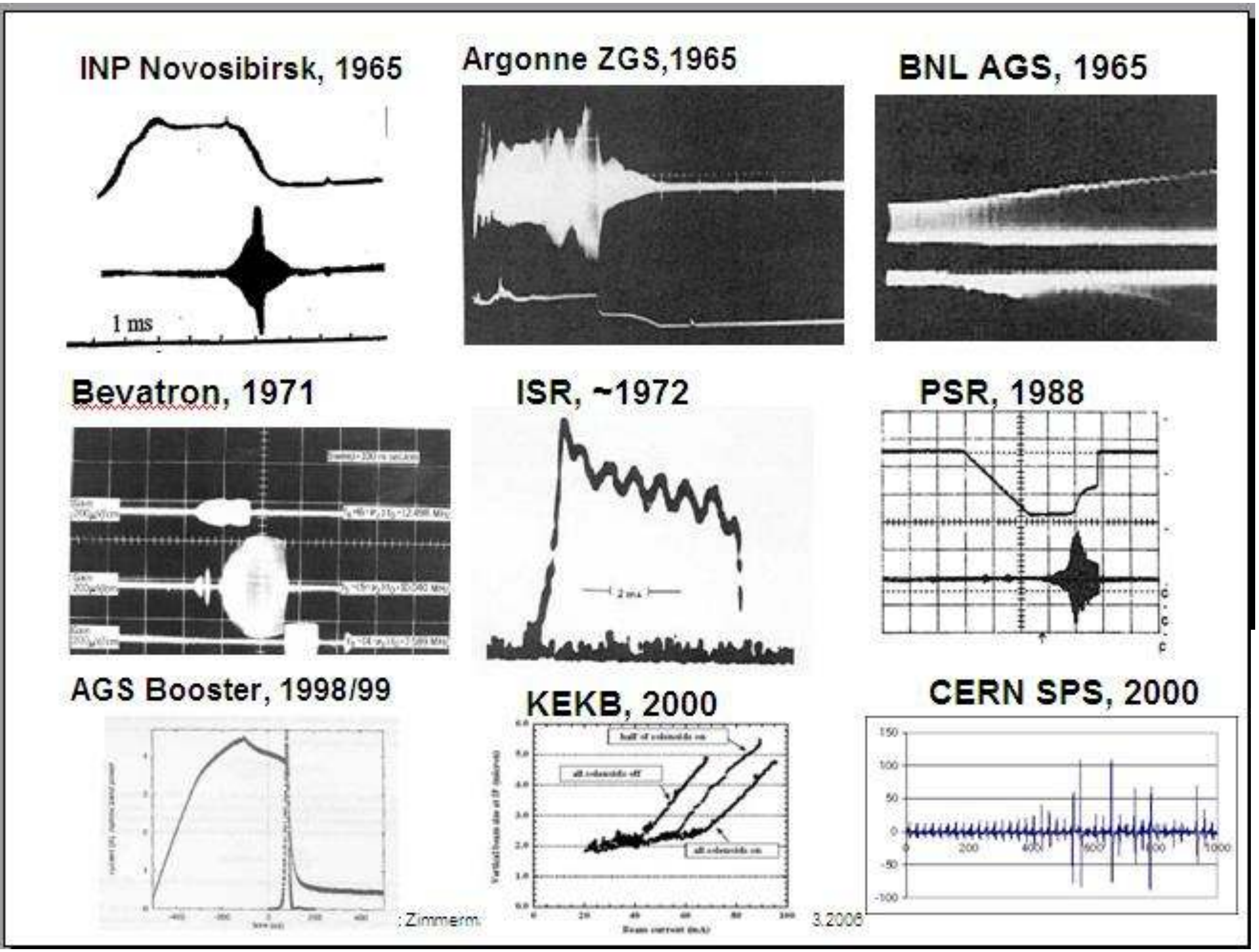
- Beam interaction with elements of accelerator and secondary plasma can be the reason for instabilities, causing limited beam performance.
- Improving of vacuum chamber design and reducing of impedance by orders of magnitude relative with earlier accelerators increases threshold intensity for impedance instability.
- Two-stream effects (beam interaction with a secondary plasma) become a new limitation on the beam intensity and brightness. Electron and Antiproton beams are perturbed by accumulated positive ions. Proton and positron beams may be affected by electrons or negative ions generated by the beam. These secondary particles can induce very fast and strong instabilities. These instabilities become more severe in accelerators and storage rings operating with high current and small bunch spacing

This instability is a problem for heavy ion inertial fusion, but ion beam with higher current density can be more stable.

Instability can be a reason of fast pressure rise include electron stimulated gas desorption, ion desorption, and beam loss/halo scraping. Beam induced pressure rise had limited beam intensity in CERN ISR and LEAR. Currently, it is a limiting factor in RHIC, AGS Booster, and GSI SIS. It is a relevant issue at SPS, LANL PSR, and B-factories. For projects under construction and planning, such as SNS, LHC, LEIR, GSI upgrade, and heavy ion inertial fusion, it is also of concern.

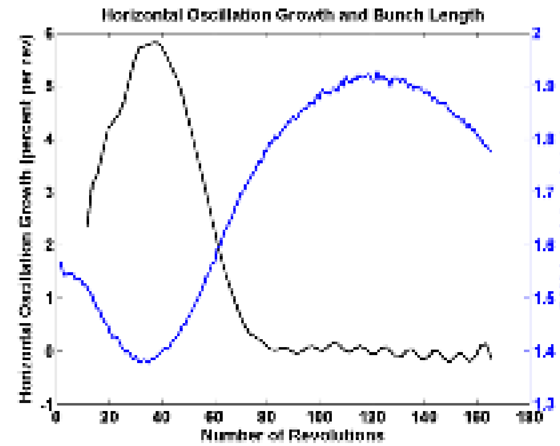
History of e-p instability (e-cloud) observation

Was presented in Cambridge PAC67 but only INP was identified as e-p instability



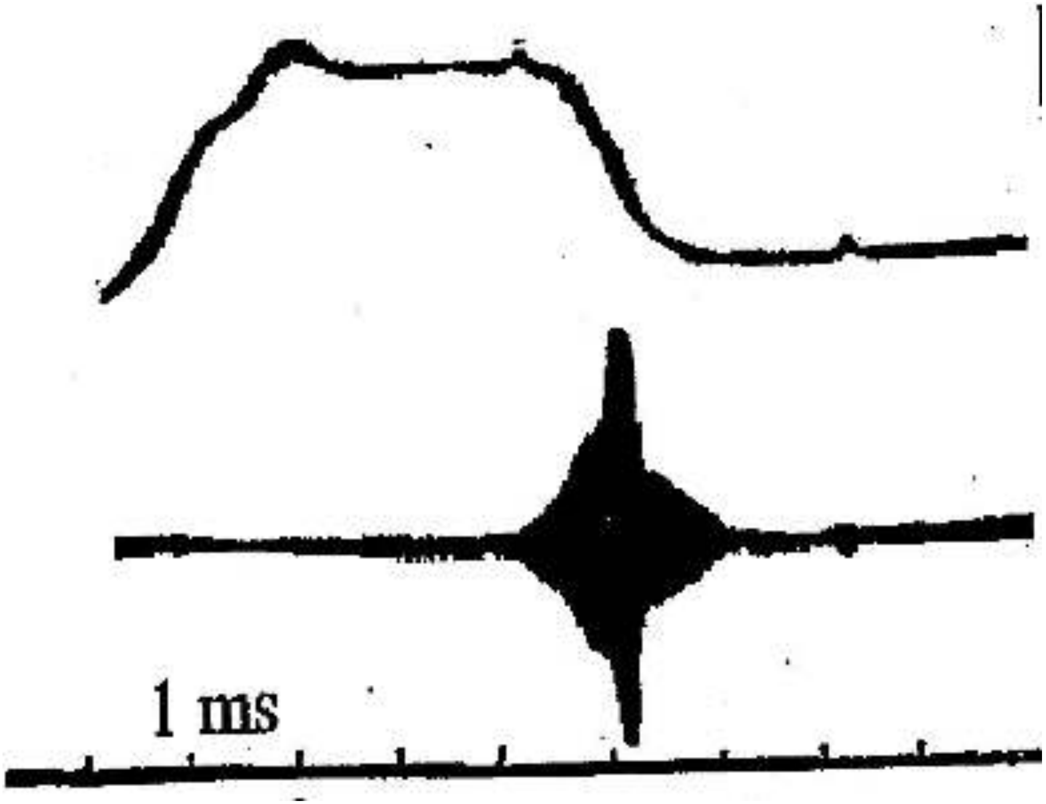
FAST TRANSVERSE INSTABILITY AND ELECTRON CLOUD MEASUREMENTS IN FERMILAB RECYCLER
J. Eldred, et al. 2014.

A new transverse instability is observed that may limit the proton intensity in the Fermilab Recycler.



From F. Zimmermann report

INP Novosibirsk, 1965, bunched beam



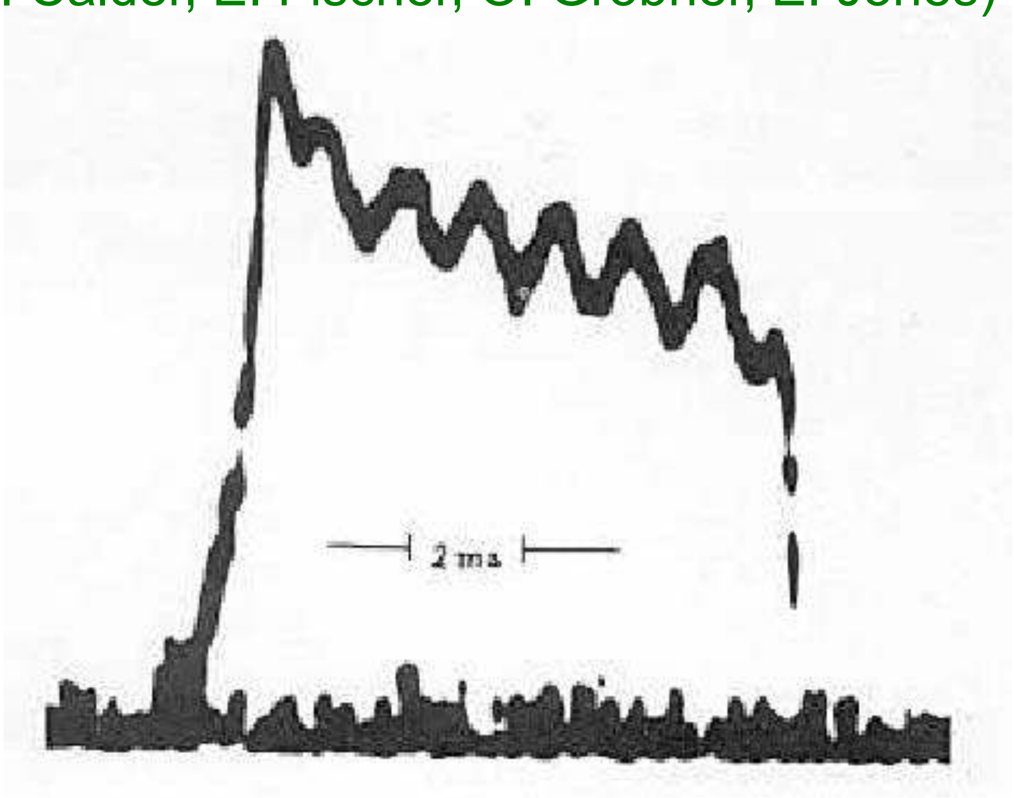
other **INP PSR 1967**:
coasting beam instability suppressed by increasing beam current;
fast accumulation of secondary plasma is essential for stabilization;
$1.8x10^{12}$ in 6 m

'first observation of an e^- driven instability?
coherent betatron oscillations & beam loss with bunched proton beam; **threshold** ~$1\text{-}1.5x10^{10}$, circumference 2.5 m, **stabilized by feedback** (G. Budker, G. Dimov, V. Dudnikov, 1965).

V. Dudnikov, PAC2001

F. Zimmermann

ISR, coasting proton beam, ~1972
(R. Calder, E. Fischer, O. Grobner, E. Jones)



excitation of nonlinear resonances; gradual beam blow up similar to multiple scattering

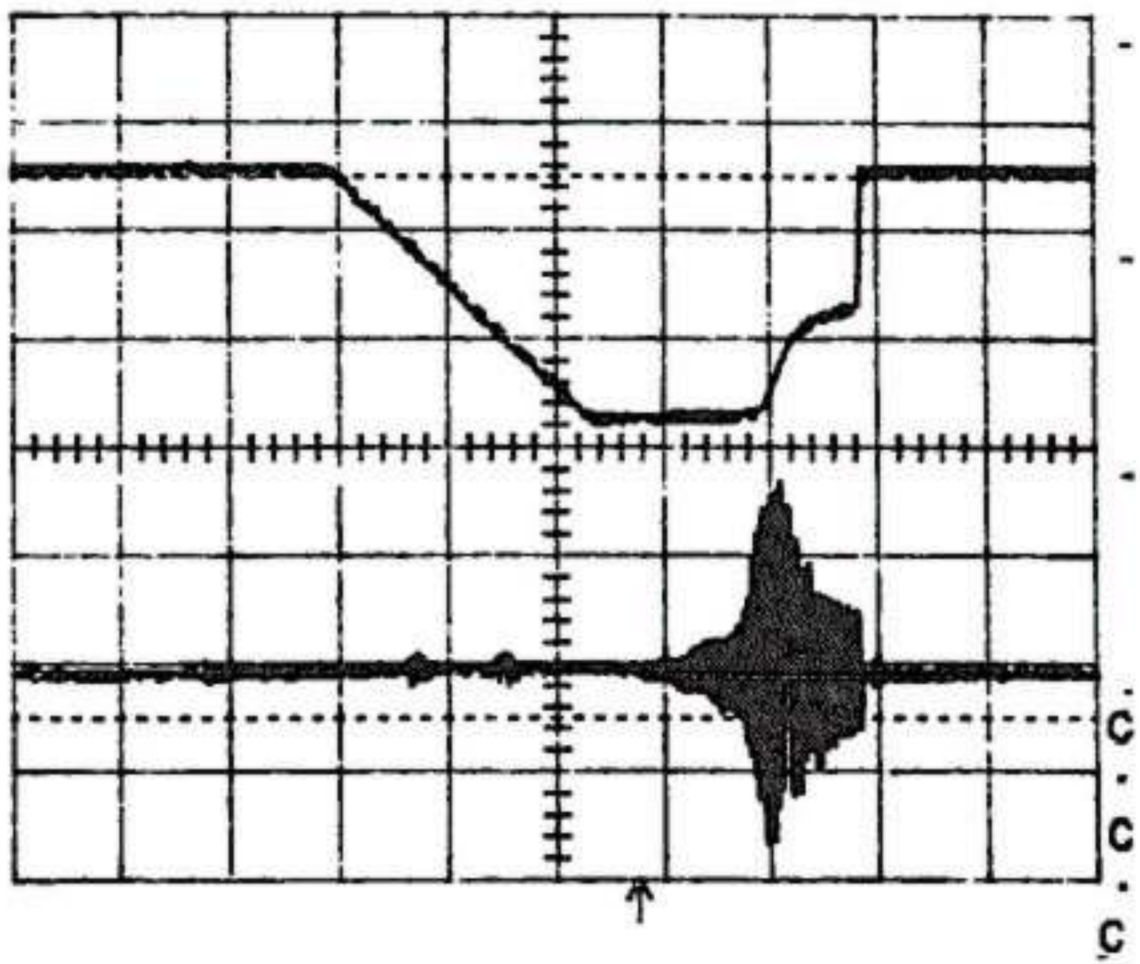
beam induced signal from a pick up showing coupled e-p oscillation; beam current is 12 A and beam energy 26 GeV

2×10^{-11} Torr,
3.5% neutralization,
ΔQ=0.015

extensive system of electrostatic clearing electrodes

PSR instability, 1988

(D. Neuffer et al, R. Macek et al.)

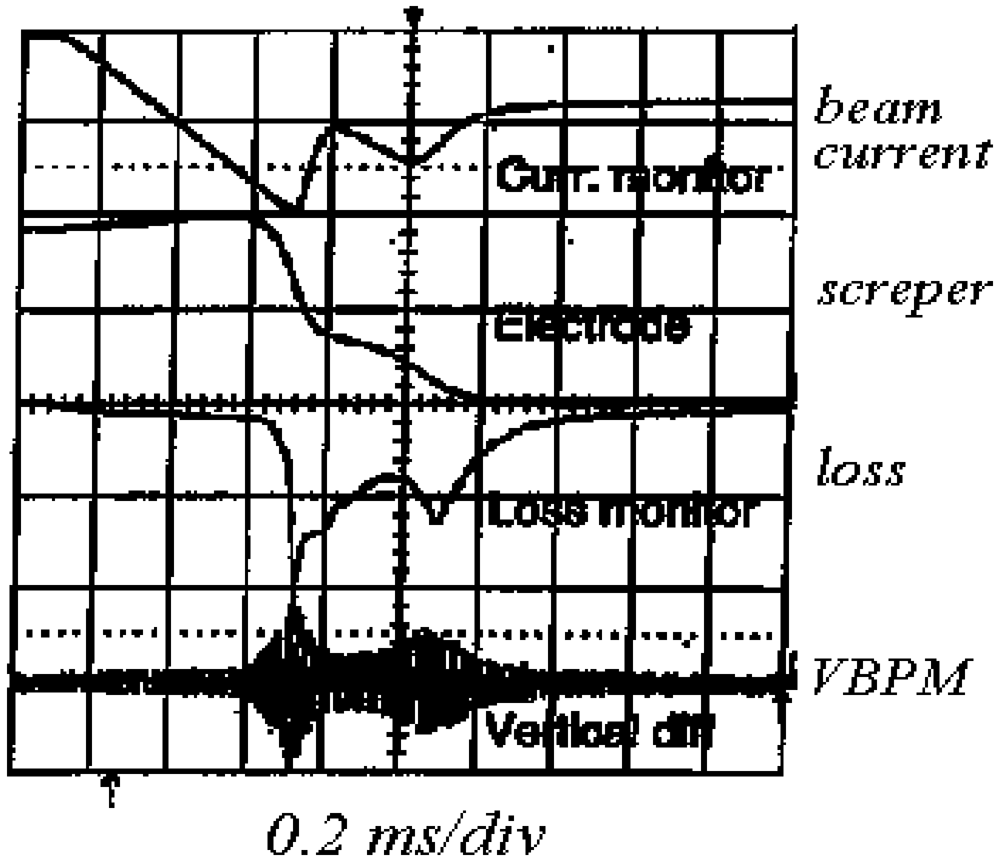


beam current and vertical oscillations;
hor. scale is 200 μs/div.

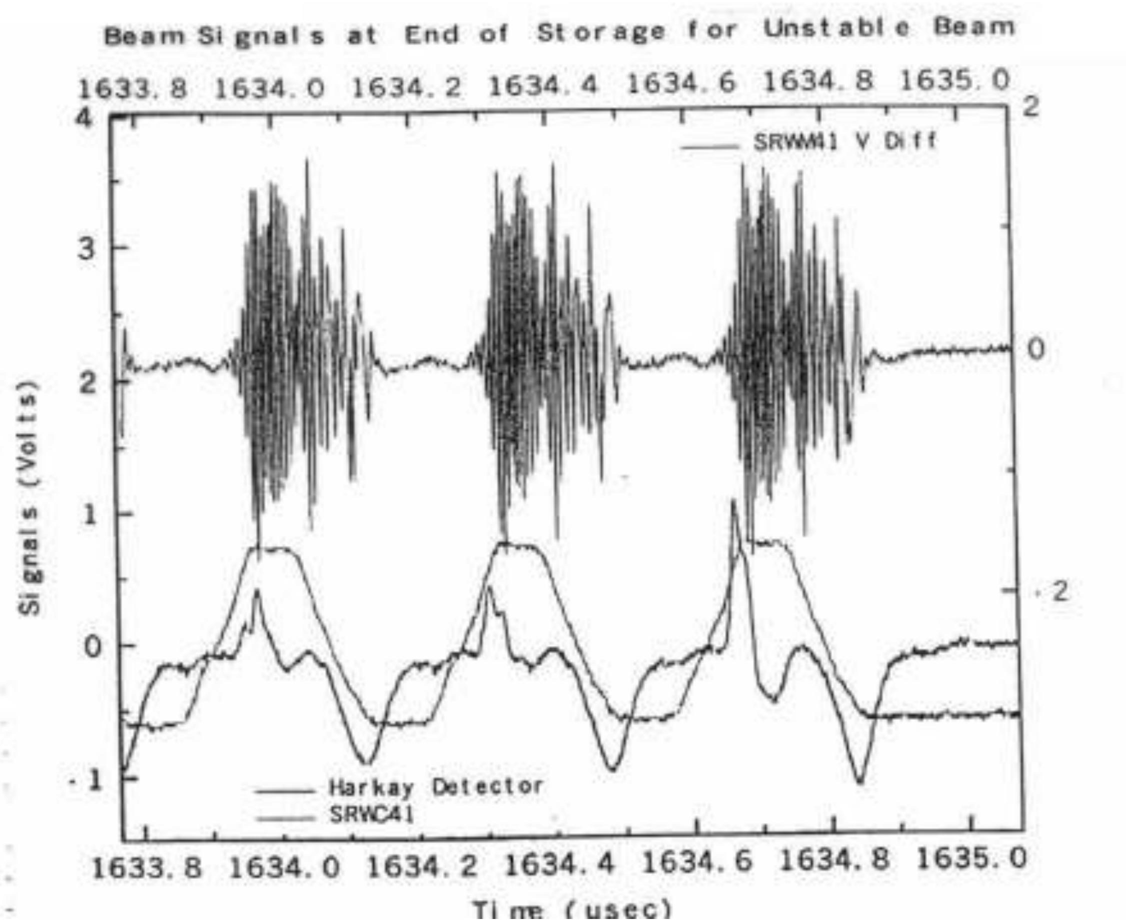
beam loss on time scale of 10-100 μs above threshold bunch charge of 1.5×10^{13}, circumference 90 m,

transverse oscillations at 100 MHz frequency

e-p instability of coasting beam in LA PSR,1986

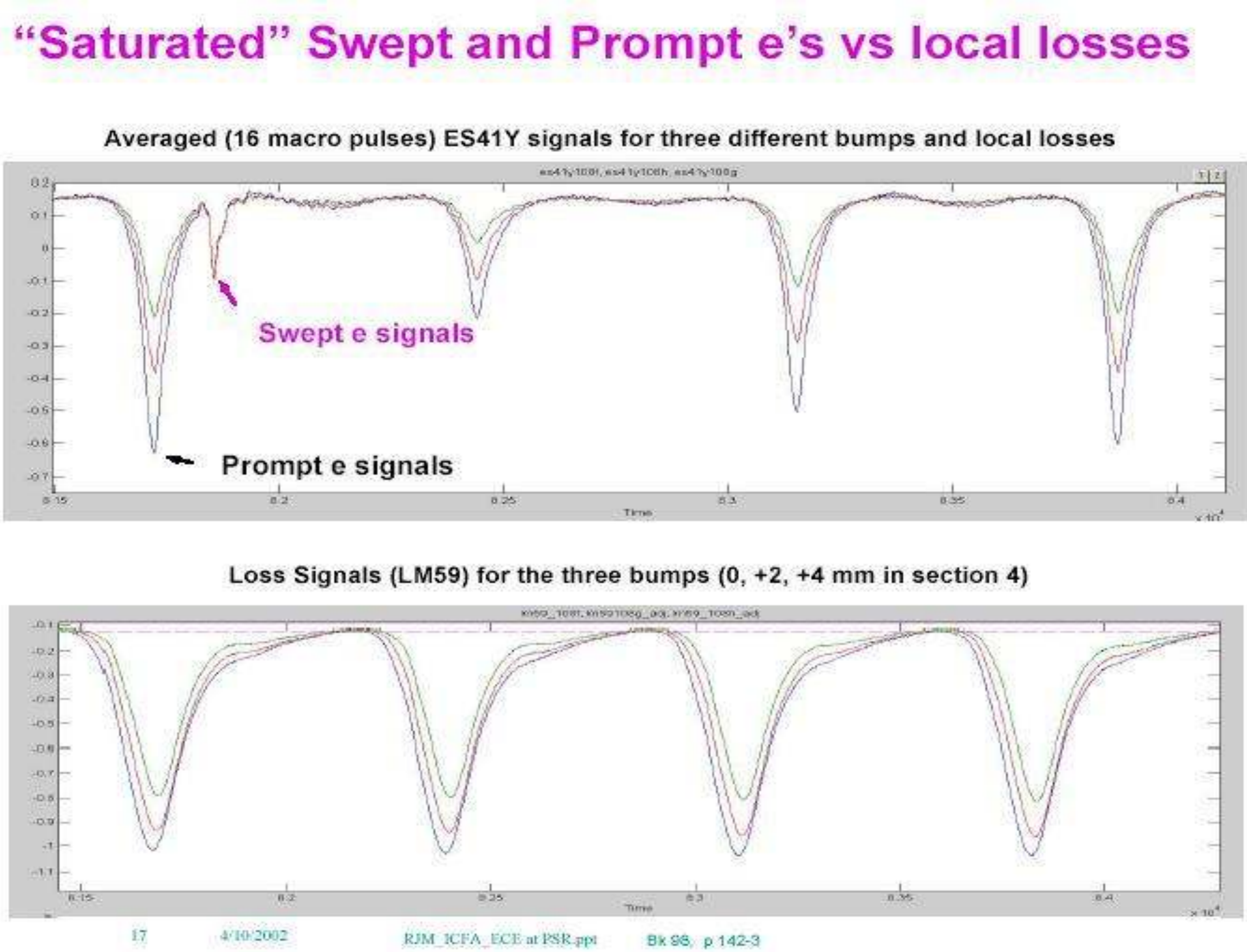


Pickup signals and electron current in LA PSR



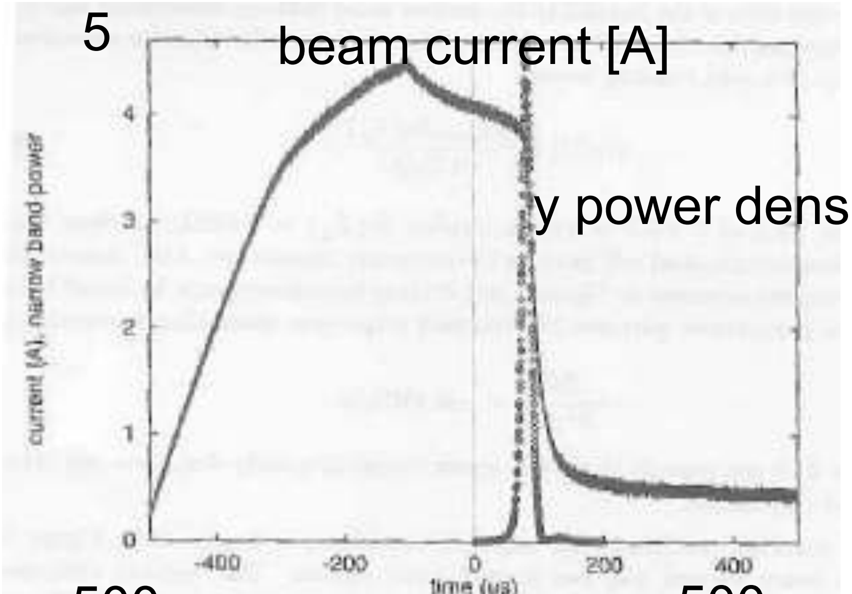
R.Macek, LANL

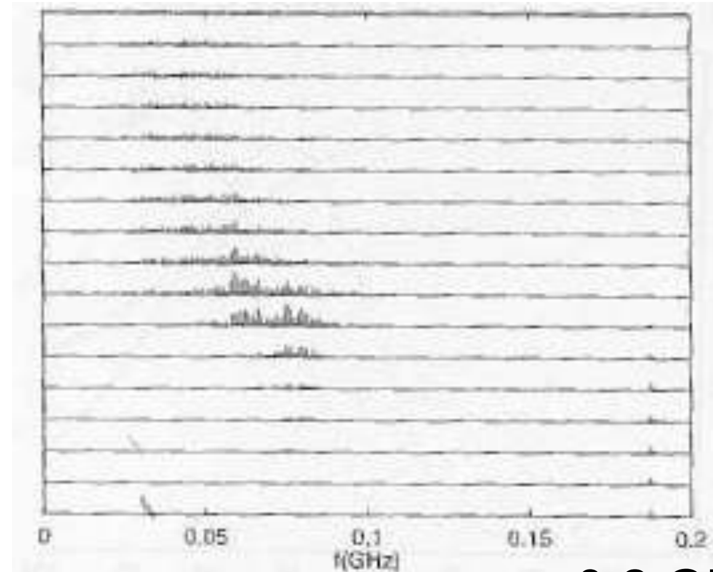
Electron signal and proton loss in LA PSR



R.Macek, LANL

AGS Booster, 1998/99
(M. Blaskiewicz)





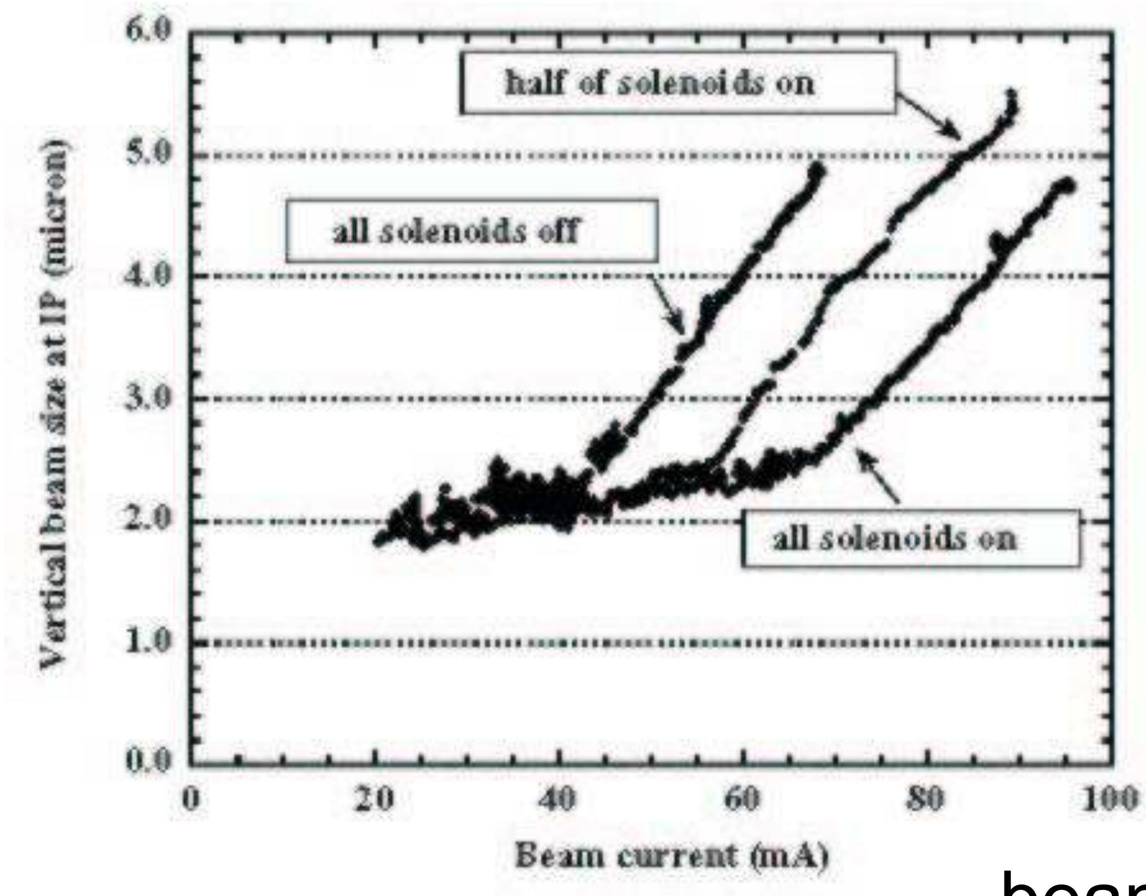
coasting beam
vertical instability
growth time ~3 μs

~100 MHz
downward shift as
instability progresses

KEKB e+ beam blow up, 2000

(H. Fukuma, et al.)

IP spot size



threshold of fast vertical blow up

slow growth below threshold?

beam current

Pulsed SNS US Patent 3,860,828, 1975

United States Patent [19]

Vasiliev et al.

[11] **3,860,828**

[45] **Jan. 14, 1975**

[54] **PULSED NEUTRON SOURCE**

[76] Inventors: **Atlant Anatolievich Vasiliev,** Leningradsky prospekt, 14, kv. 129; **Rakhim Ainudinovich Mescherov,** Peschanaya ulitsa, 15, kv. 20; **Boris Pavlovich Murin,** Baltiiskaya ulitsa, 4, kv. 85, all of Moscow; **Jury Yakovlevich Stavissky,** Sportivnaya ulitsa, 3, kv. 9, Obninsk Kaluzhskoi oblasti, all of U.S.S.R.

[22] Filed: **Aug. 30, 1972**

[21] Appl. No.: **284,968**

[30] **Foreign Application Priority Data**

May 10, 1972 U.S.S.R. 1778710

[52] **U.S. Cl.** **250/501,** 250/502

[51] **Int. Cl.** **G21g 3/04**

[58] **Field of Search** 250/84.5, 501, 502

[56] **References Cited**

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2,902,613	9/1959	Baldwin et al.	250/84.5 X
3,268,730	8/1966	Van De Graaff	250/84.5
3,518,432	6/1970	Uleski	250/84.5

Primary Examiner—Archie R. Borchelt
Attorney, Agent, or Firm—Holman & Stern

[57] **ABSTRACT**

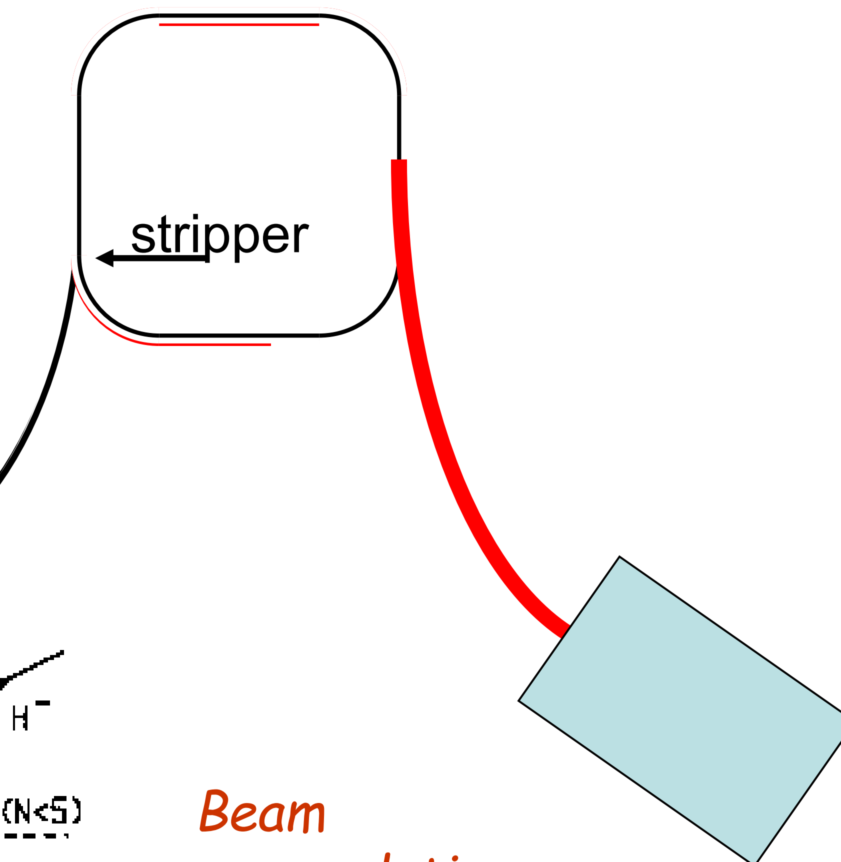
A pulsed neutron source is disclosed comprising a high-current negative hydrogen ion H^- accelerator which shapes and accelerates H^- bunches having a preset duration and repetition interval to the energy of 0.4–1GeV, and a bunching storage ring for proton bunches furnished with a charge-exchange injecting system and with an extraction system for ejecting the proton bunches onto an external neutron-producing target, the bunching storage ring for proton bunches being designed so that the revolution period of proton bunches on the orbit thereof is equal to or is a multiple of the repetition interval of H^- bunches shaped in the accelerator.

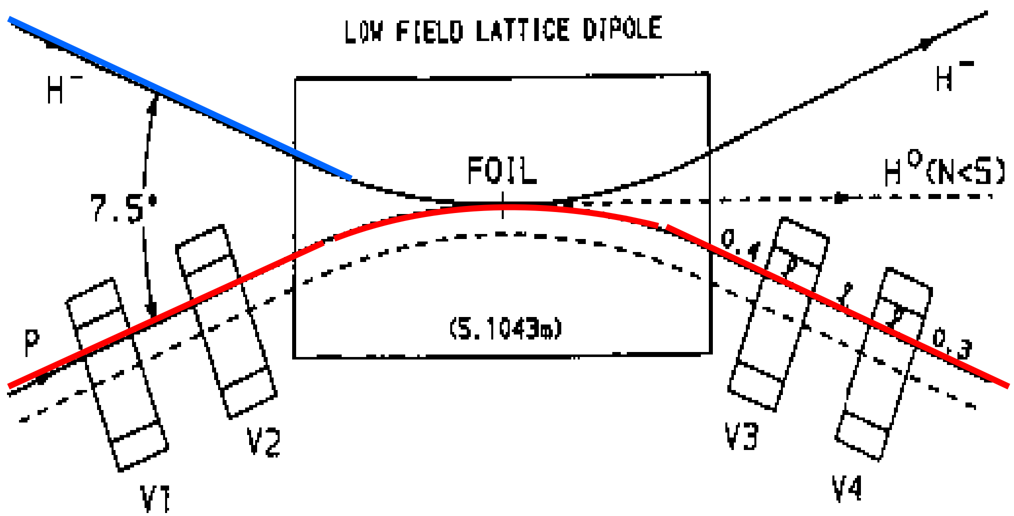
2 Claims, 5 Drawing Figures

The SNS Accumulator Ring

The ring accumulates the ion beam.

- *The stripper foil converts the negative H^{-} ions into protons and merges them with the protons already in the ring!*
- *Accumulating up to 1060 turns brings the ion beam current from tens of mAmps in the LINAC to tens of Amps in the ring before it is dumped onto the target.*





Beam accumulation requires a polarity change. We need negative ions!

References

www.google.com two-stream transverse instability…

For more information see the website for the
8th ICFA Mini Workshop on Two-Stream Instabilities in Particle Accelerators and Storage Rings, Santa Fe, NM Feb 16-18, 2000
http://www.aps.anl.gov/conferences/icfa/two-stream.html

Also see the website for the
International Workshop on Two-Stream Instabilities in Particle Accelerators and Storage Rings, KEK Tsukuba, Japan, Sept 11-14, 2001
http://conference.kek.jp/two-stream/

http://wwwslap.cern.ch/collective/electron-cloud/.

Historical remark

Electron cloud effects (ECEs) were first observed 38 yrs ago in small, medium-energy proton storage rings. These were described as: Vacuum pressure bump instability, beam-induced multipacting, and/or e-p instability:

BINP Proton Storage Ring [G. Budker, G. Dimov, and V. Dudnikov (1966); see also review by V. Dudnikov (2001)] v.dudnikov.ph.D.thesis,1966

CERN Intersecting Storage Ring (ISR) [O. Grobner (1977)]

First observation in a positron ring around 1995: Transverse coupled-bunch instability in e+ ring only and not in e- ring:

KEK Photon Factory (PF) [M. Izawa, Y. Sato, T. Toyomasu (1995) and K. Ohmi, (1995)]

IHEP Beijing e+/e- collider (BEPC): experiments repeated and KEK PF results verified [Z.Y. Guo et al. (1997)]

References for first observation of e-p instability

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- G.I.Dimov, V.G.Dudnikov,V.G.Shamovsky, ” Transverse instability of a proton beam due to coherent interaction with a plasma in a circular accelerator” Soviet Conference on Charge-particle accelerators”,Moscow,1968, translation from Russia, 1 1973 108565 8.
- 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).
- Yu.Belchenko, G.Budker, G.Dimov, V.Dudnikov, et al. X PAC,1977.
- O.Grobner, X PAC,1977.
- E. Colton, D. Nuffer, G. Swain, R.Macek, et al., Particle Accelerators, 23,133 (1988).

Models of two-stream instability

- The beam- induces electron cloud buildup and development of two-stream e-p instability is one of major concern for all projects with high beam intensity and brightness [1,2].
- In the discussing models of e-p instability, transverse beam oscillations is excited by relative coherent oscillation of beam particles (protons, ions, electrons) and compensating particles (electrons,ions) [3,4,5].
- For instability a bounce frequency of electron's oscillation in potential of proton's beam should be close to any mode of betatron frequency of beam in the laboratory frame.

1. http://wwwslap.cern.ch/collective/electron-cloud/.
2. http://conference.kek.jp/two-stream/.
3. G.I.Budker, Sov.Atomic Energy, 5,9,(1956).
4. B.V. Chirikov, Sov.Atomic.Energy,19(3),239,(1965).
5. M.Giovannozzi, E.Metral, G.Metral, G.Rumolo,and F. Zimmerman , Phys.Rev. ST-Accel. Beams,**6**,010101,(2003).

Memo from: Bruno Zotter

www.aps.anl.gov/conferences/icfa/twoo-stream/

- Subject: Summary of my own conclusions of the workshop
- 1) Go on with your plans to coat the most sensitive locations in the PSR (Al stripper chamber, sections with ceramics and with high losses) with Ti nitride - make sure that the deposition technique avoids rapid flaking off;
- 2) If this is not sufficiently successful, install a transverse feedback system based on the wide-band split cylinder pickups - Dudnikov showed an example where a simple feedback seemed to work fine on e-p. If the oscillations are kept sufficiently small by it, there may be no need for high power;

Development of Charge Exchange Injection and Production of Circulating Beam with Intensity Greater than Space Charge Limit

V.Dudnikov. "Production of an intense proton beam in storage ring by a charge- exchange injection method", Novosibirsk, Ph.D.Thesis,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. Observation of the e-p instability of coasting beam in storage ring

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).

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).

G.Dimov, V.Dudnikov, "Determination of circulating proton current and current density distribution (residual gas ionization profile monotor)", Instrum. Experimental Techniques, 5, 15 (1967).

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;.

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.

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).

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).

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).

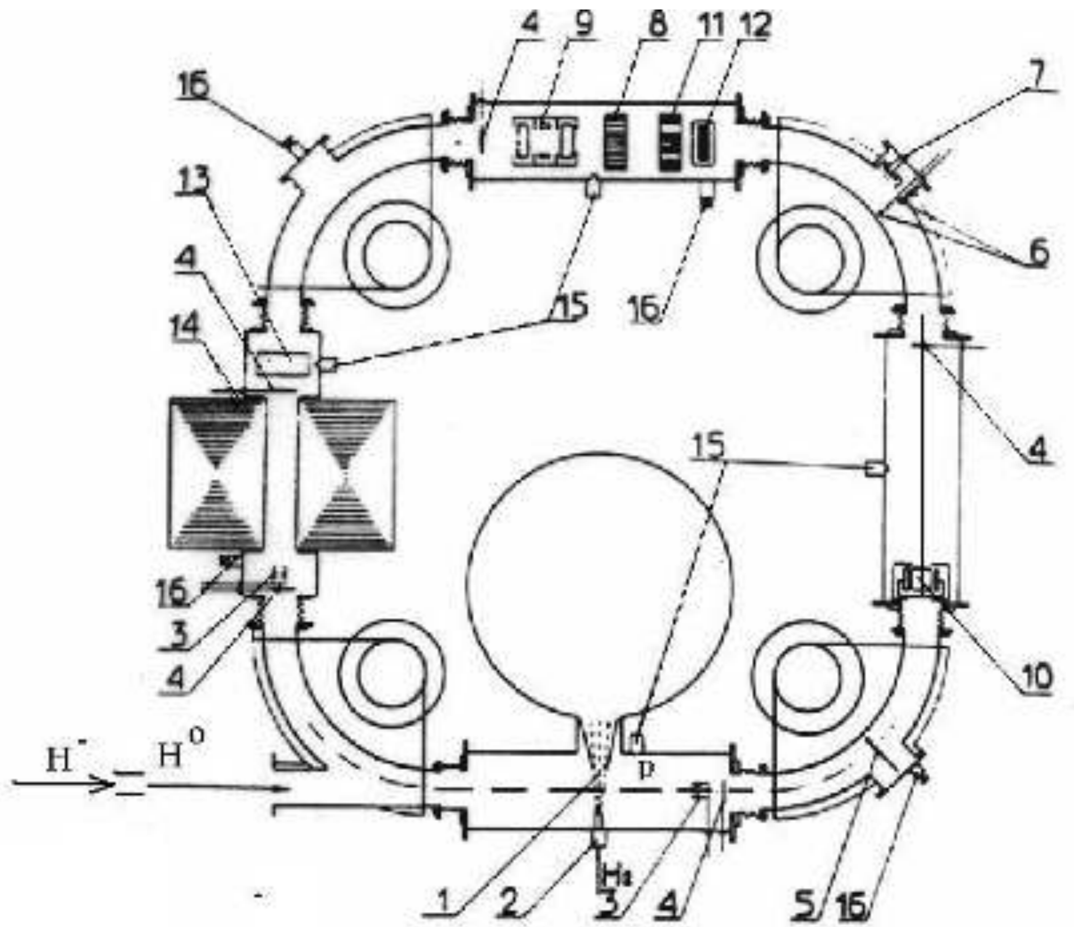
Chupriyanov. "Production of intense compensated proton beam in an accelerating ring", Novosibirsk, INP, 1982.

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). Yu.Belchenko, G.Budker, G.Dimov, V.Dudnikov, et al.X PAC,1977.

PSR for Circulating p-Beam Production



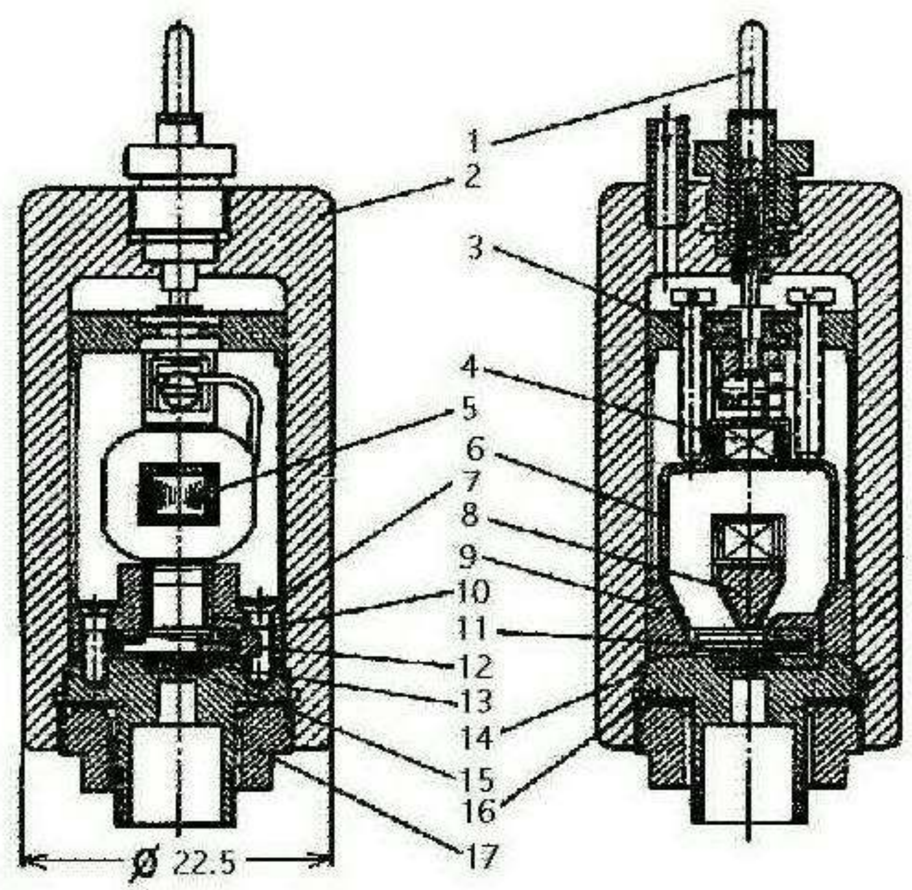
1-striping gas target; 2-gas pulser;3-FC; 4-Q screen; 5,6-moving targets; 7-ion collectors; 8-current monitor; 9-BPM;10-Q pick ups; 11-magnetic BPM; 12-beam loss monitor;13-detector of secondary particles density; 14-inductor core; 15-gas pulsers; 16-gas leaks.

Proton Energy -1 MeV; injection-up to 8 mA; bending radius-42 cm; magnetic field-3.5 kG;index-n=0.2-0.7; St. sections-106 cm;aperture-4x6 cm; revolution-1.86 MHz; circulating current up to 1 A is up to 9 time greater than a space charge limit.

Vacuum control

- Stripping target- high dense supersonic hydrogen jet (density up to e19 mol/cm^3, target e17 mol/cm^2 , ~1ms)
- Vacuum e-5 Torr
- Fast, open ion gauges
- Fast compact gas valves, opening of 0.1 ms.

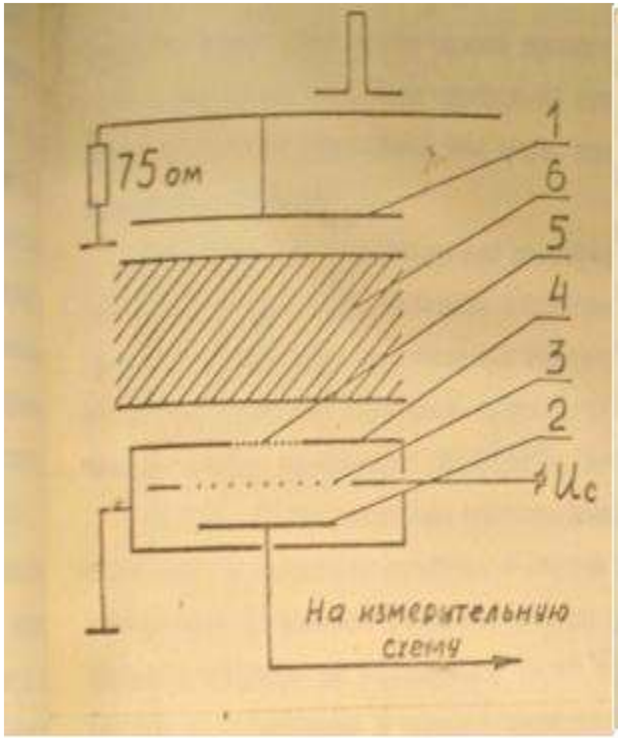
Fast, compact gas valve, 0.1ms, 0.8 kHz

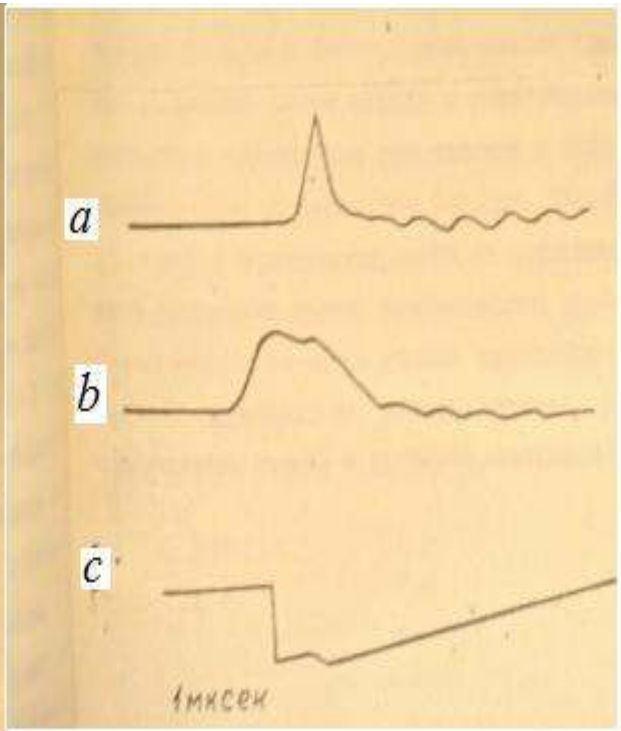


1 -current feedthrough; 2 housing; 3-clamping screw; 4-coil; 5 magnet core; 6-shield; 7-screw; 8-copper insert; 9-yoke; 10-rubber washer-returning springs; 11-ferromagnetic plate-armature; 12-viton stop; 13-viton seal; 14-sealing ring; 15-aperture; 16-base; 17-nut.

Photograph of a fast, compact gas valve

Secondary Particles detector with repeller, INP,1967





Secondary particles detector:

1-reflection plate; 2-collector; 3-retarding grid; 4-shilding;

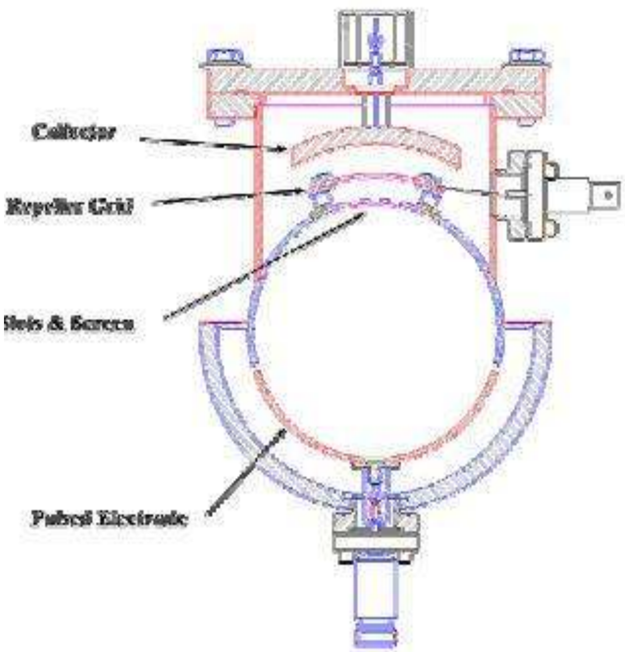
5-grid; 6-beam. a -helium ion;b -nitrogen ion;c -electrons.

ANL Fast collector with repeller

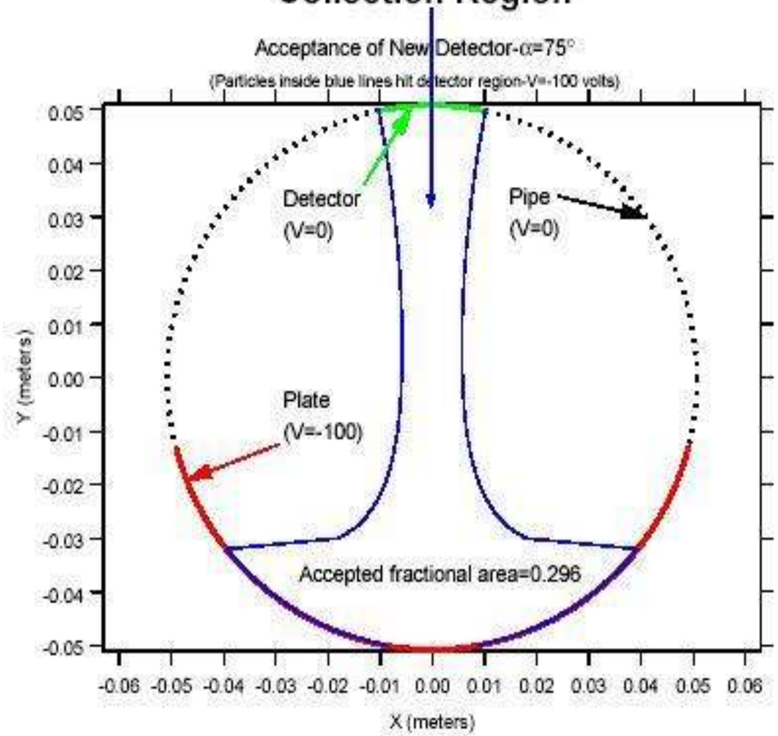
Electron Sweeping diagnostic

- Designed by A. Browman to measure e-cloud surviving passage of the gap
- Short HV (~1kV) pulse is applied to electrode to sweep electrons into RFA

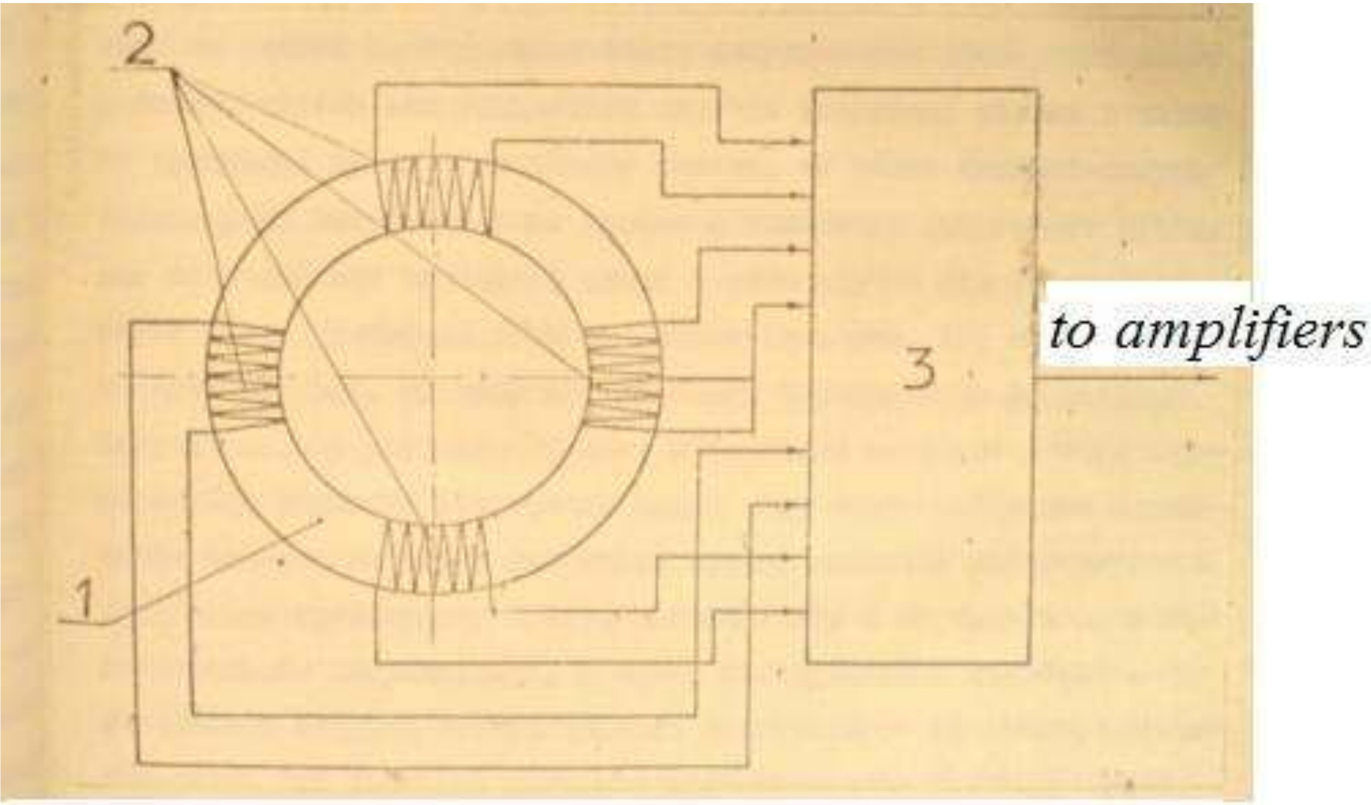
Cross-section



Collection Region

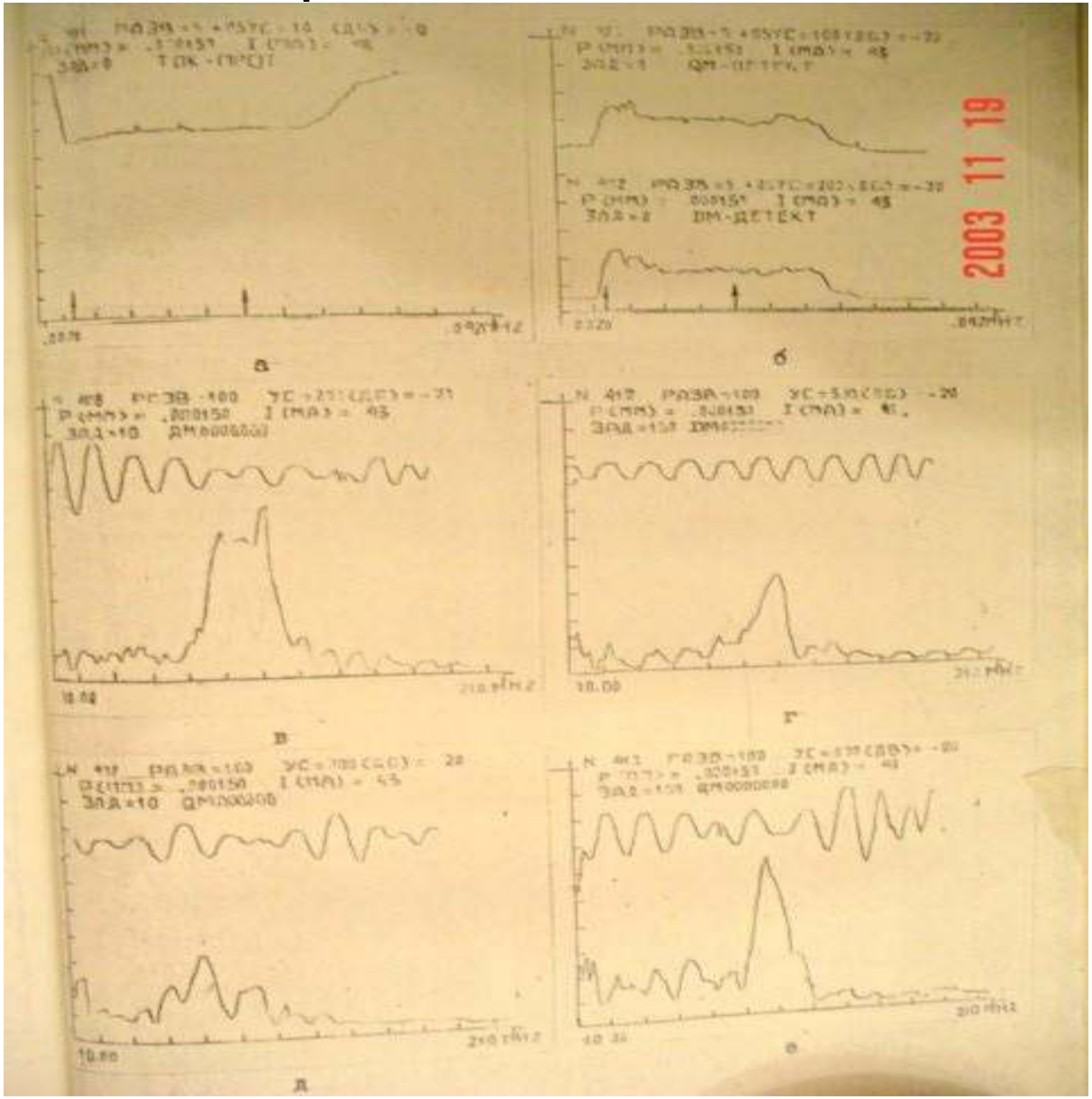


Inductive BPM, INP,1967

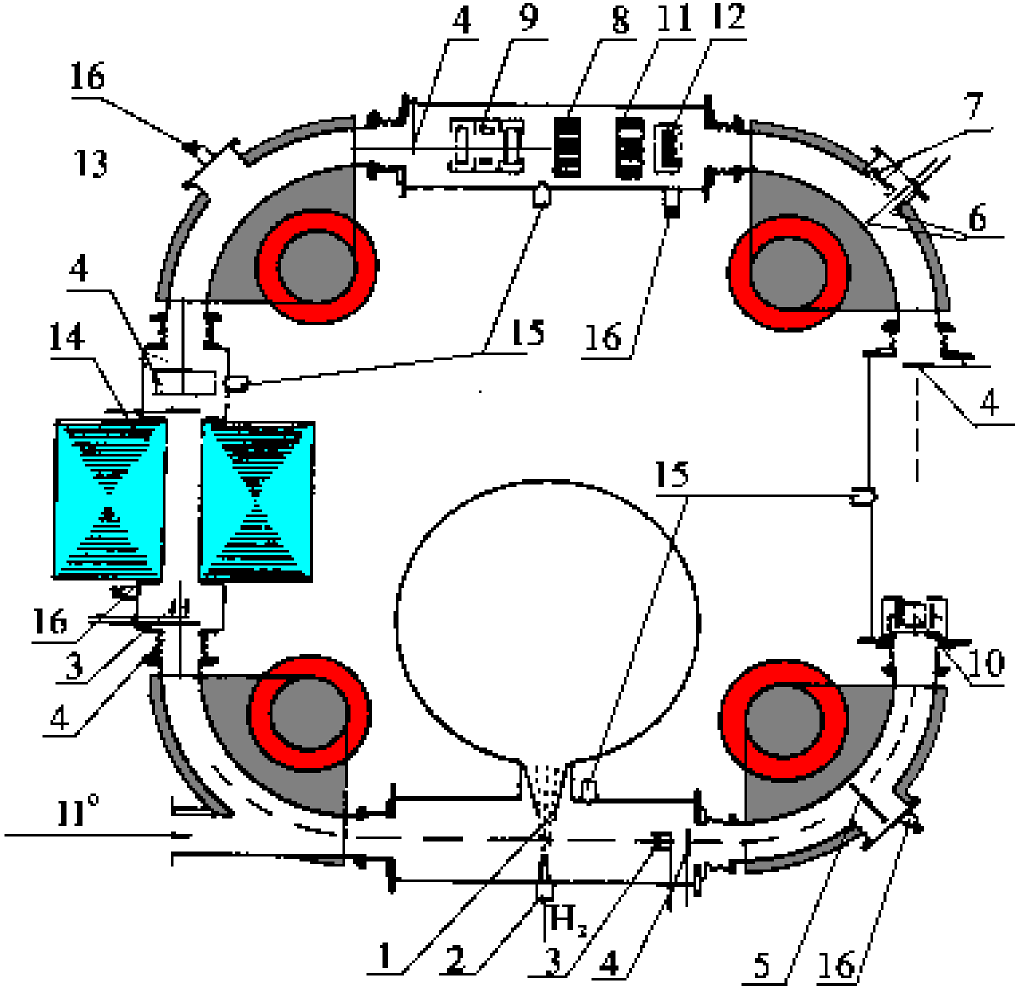


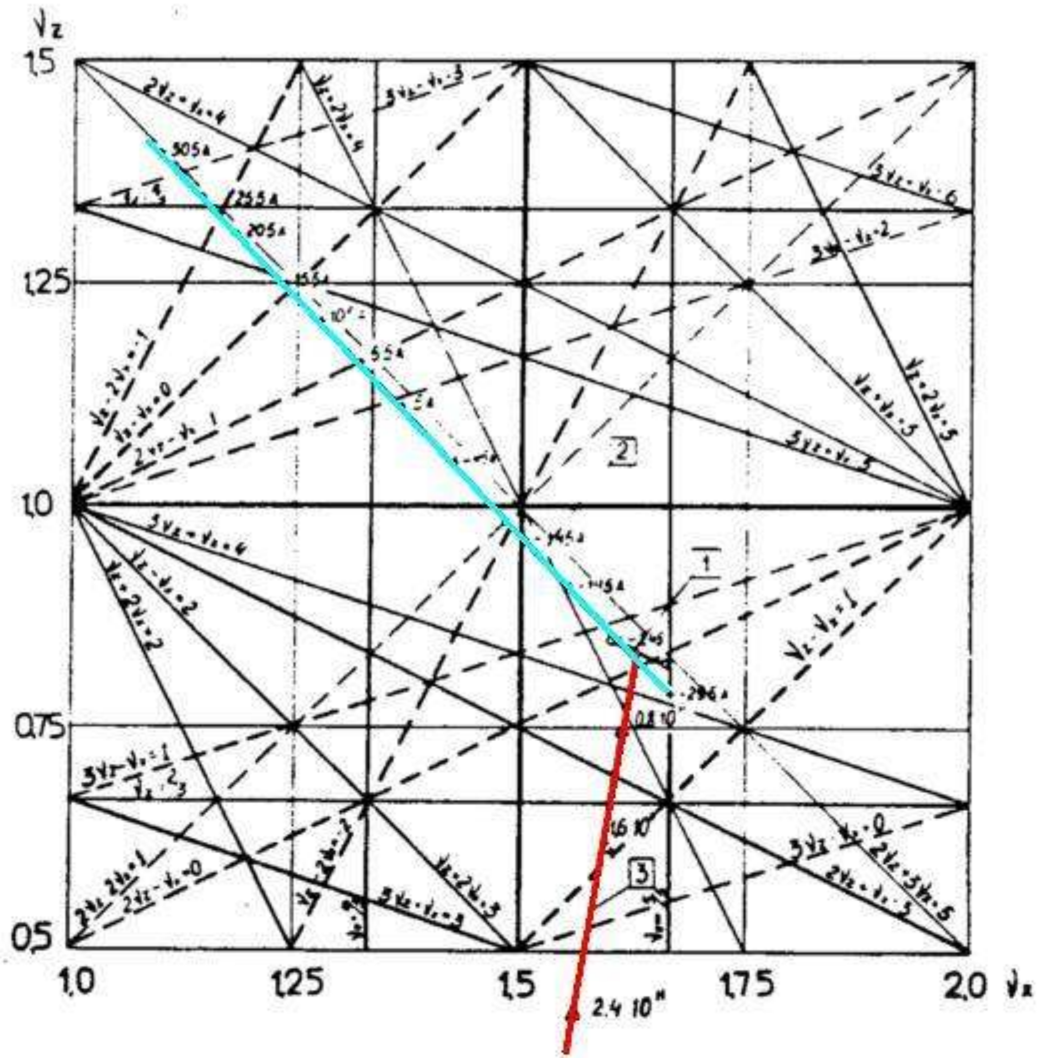
1-ferrite ring; 2-coils; 3-commutator.

Signals and spectrum from inductive BPM



INP PSR for beam above space charge limit





Tune diagram of betatron frequencies of the storage ring:

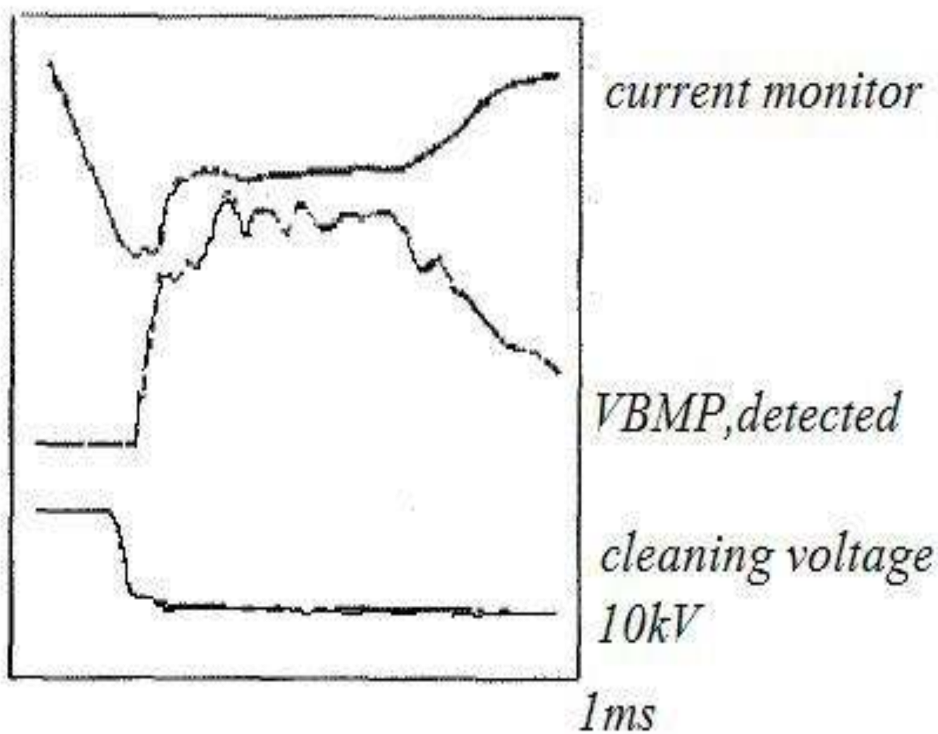
1-betatron frequency of low intensity beam v_x=1.62; v_z=0.85;

Blu-trajectory of operation point with variation of correction current;

Red- trajectory of operating point under the influence of the space charge.

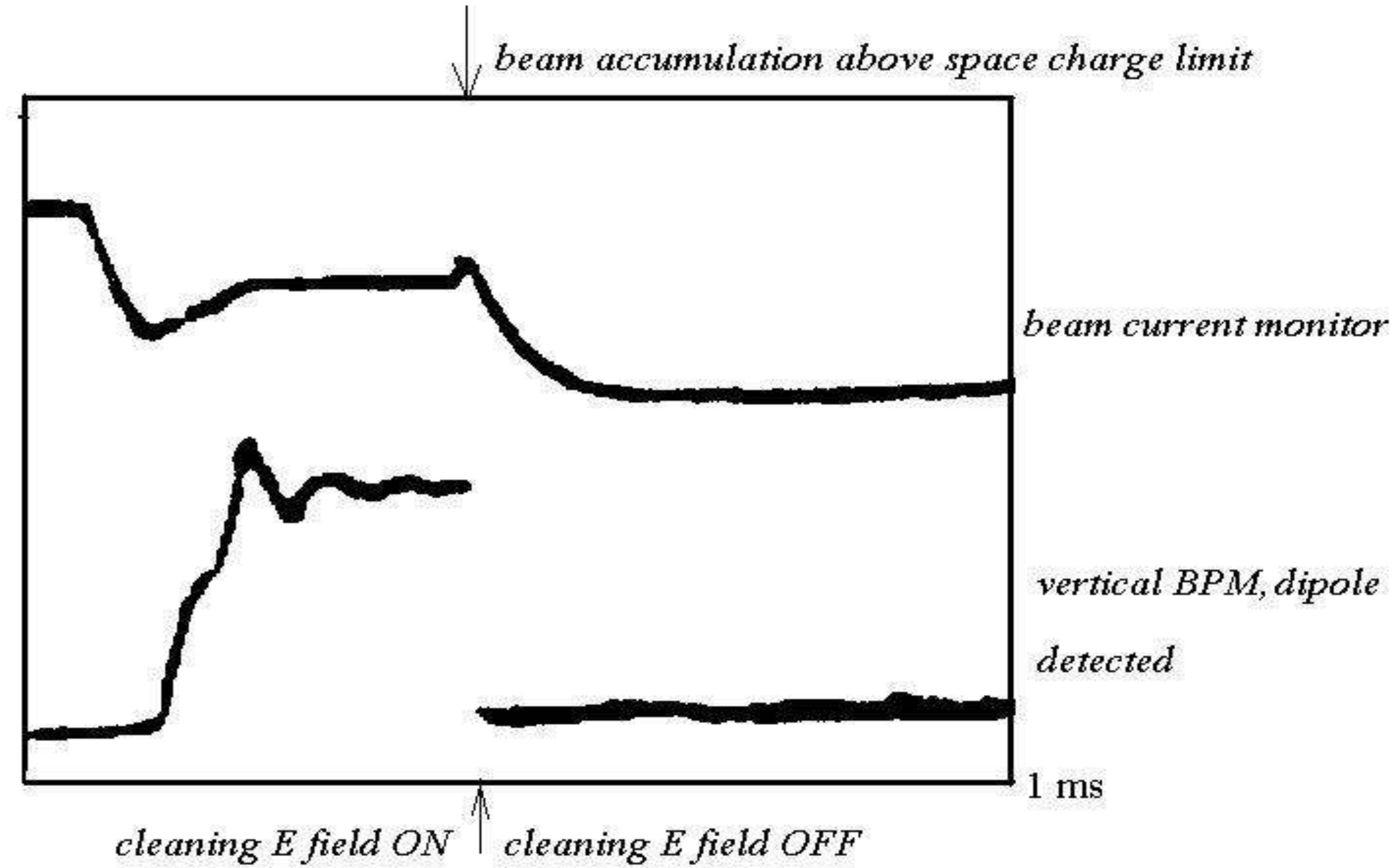
Small Scale Proton Storage Ring for Accumulation of Proton Beam with Intensity Greater than Space Charge Limit

Beam accumulation with clearing voltage

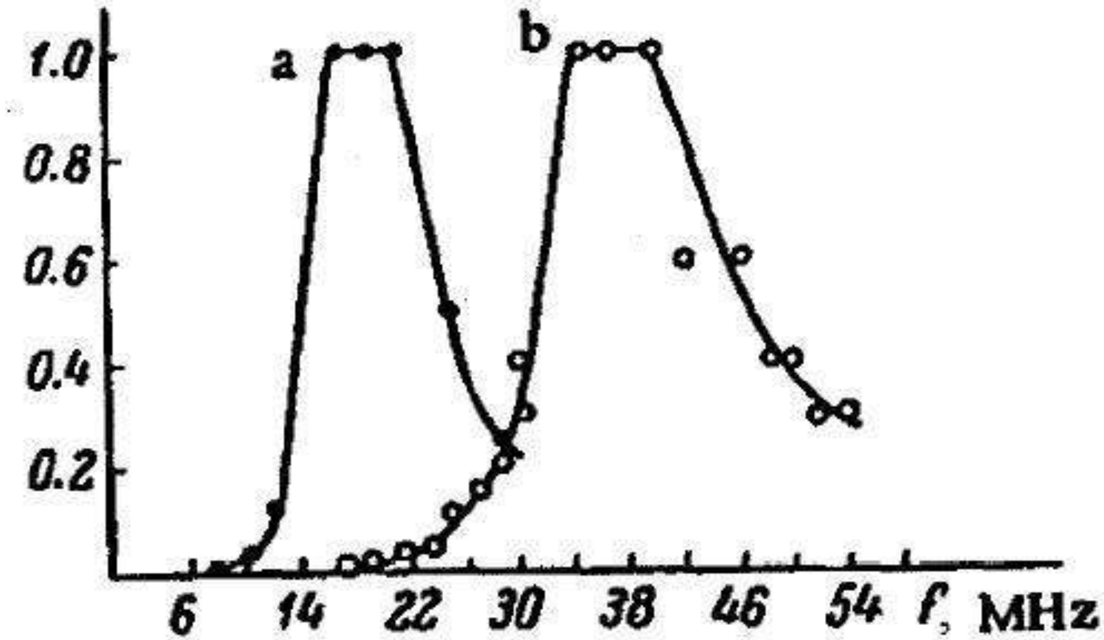


Secondary plasma accumulation suppressed by strong transverse electric field. Vertical instability with zero mode oscillation was observed (Herward instability).

Beam accumulation with space charge neutralization



Spectrums of coasting beam instability in BINP PSR (magnetic BPM)

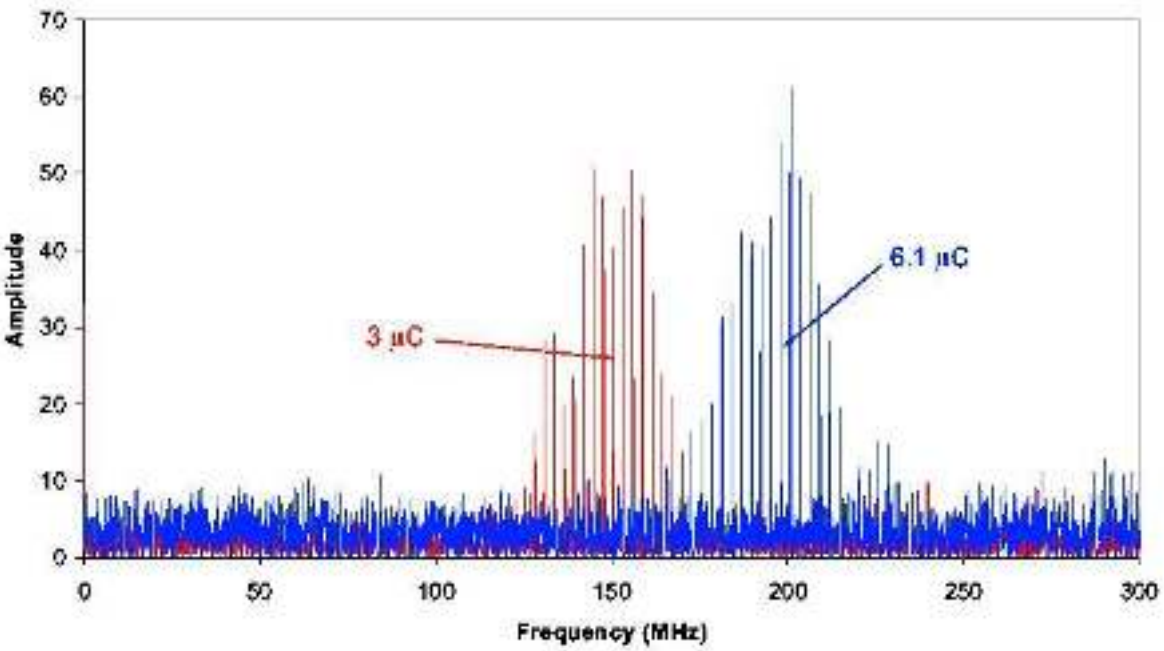


Spectrum of signals from vertical beam position monitor.
a) $N=1.7\ 10^{10}$ p; b) $N= 1.5\ 10^{11}$ p.

Spectrums transverse beam instability in LA PSR

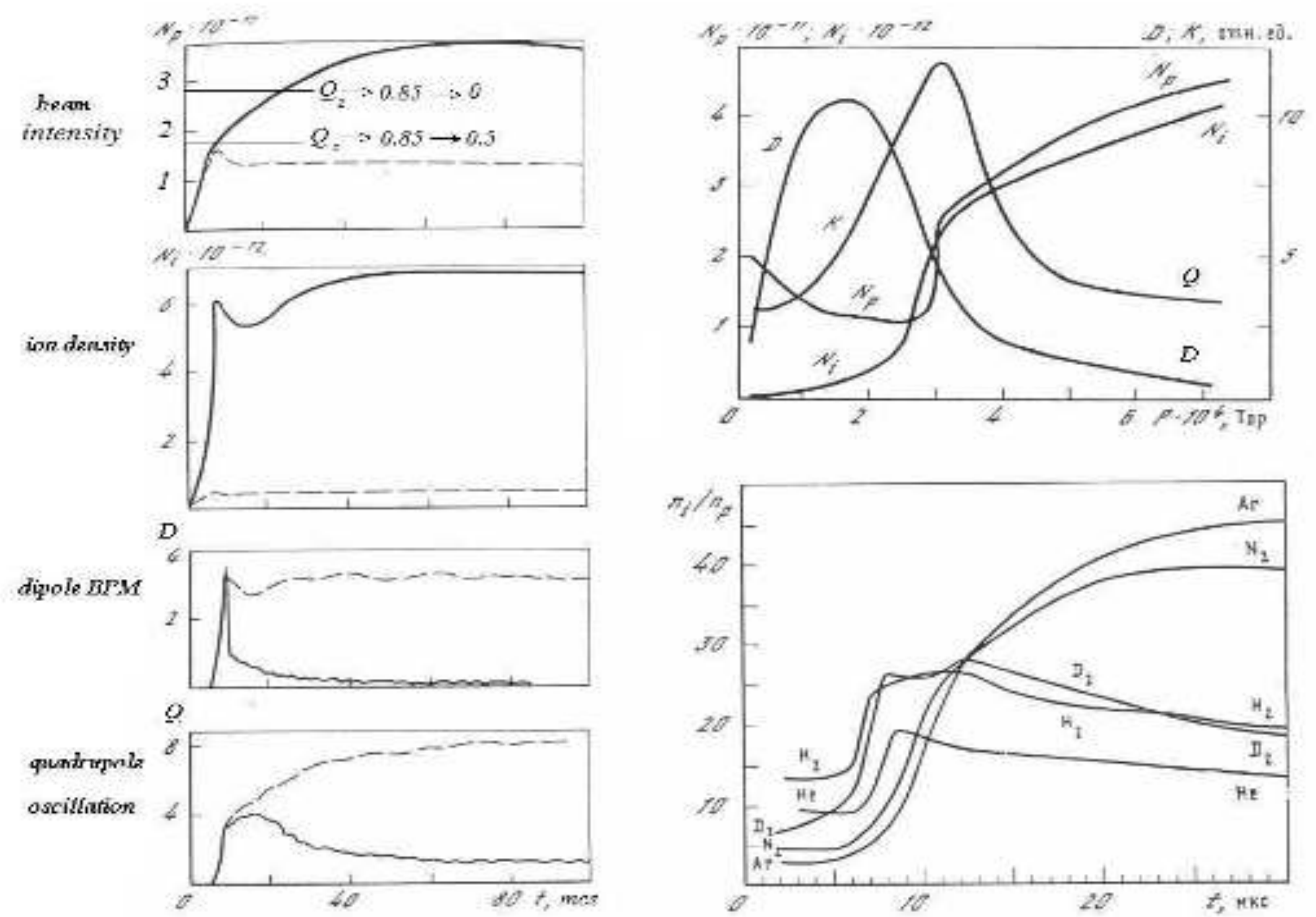
Frequency spectra of unstable motion agrees with model

$$\omega_e = Q_e\Omega_0 = 2\pi f = \sqrt{\frac{2Nr_e c^2(1-f_e)}{\pi b(a+b)R}}, \quad f \approx 230\ \mathrm{MHz}\ (6.1\mu C)$$

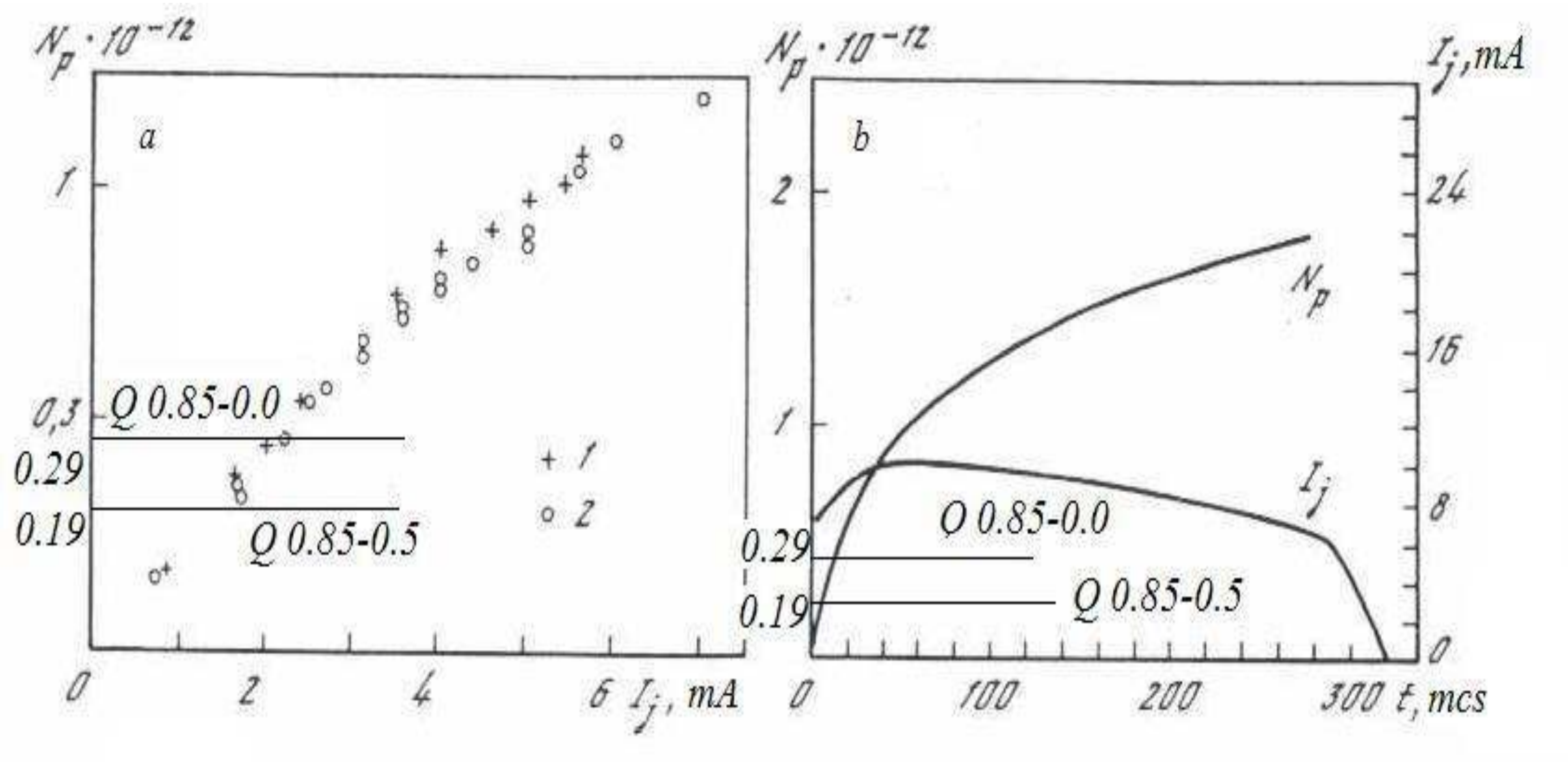


R.Macek, LANL

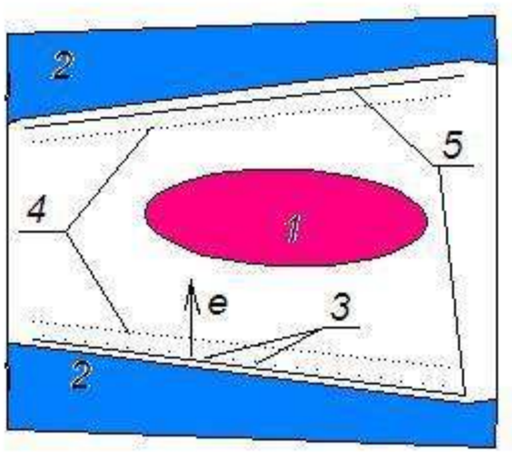
Proton beam accumulation with intensity above space charge limit



Proton beam accumulation with intensity grater than space charge limit. Dependence of injection current.



Plasma generators for space charge compensation



1- circulating proton beam;

2- magnetic poles;

3- filaments, electron sources;

4- grounded fine mesh;

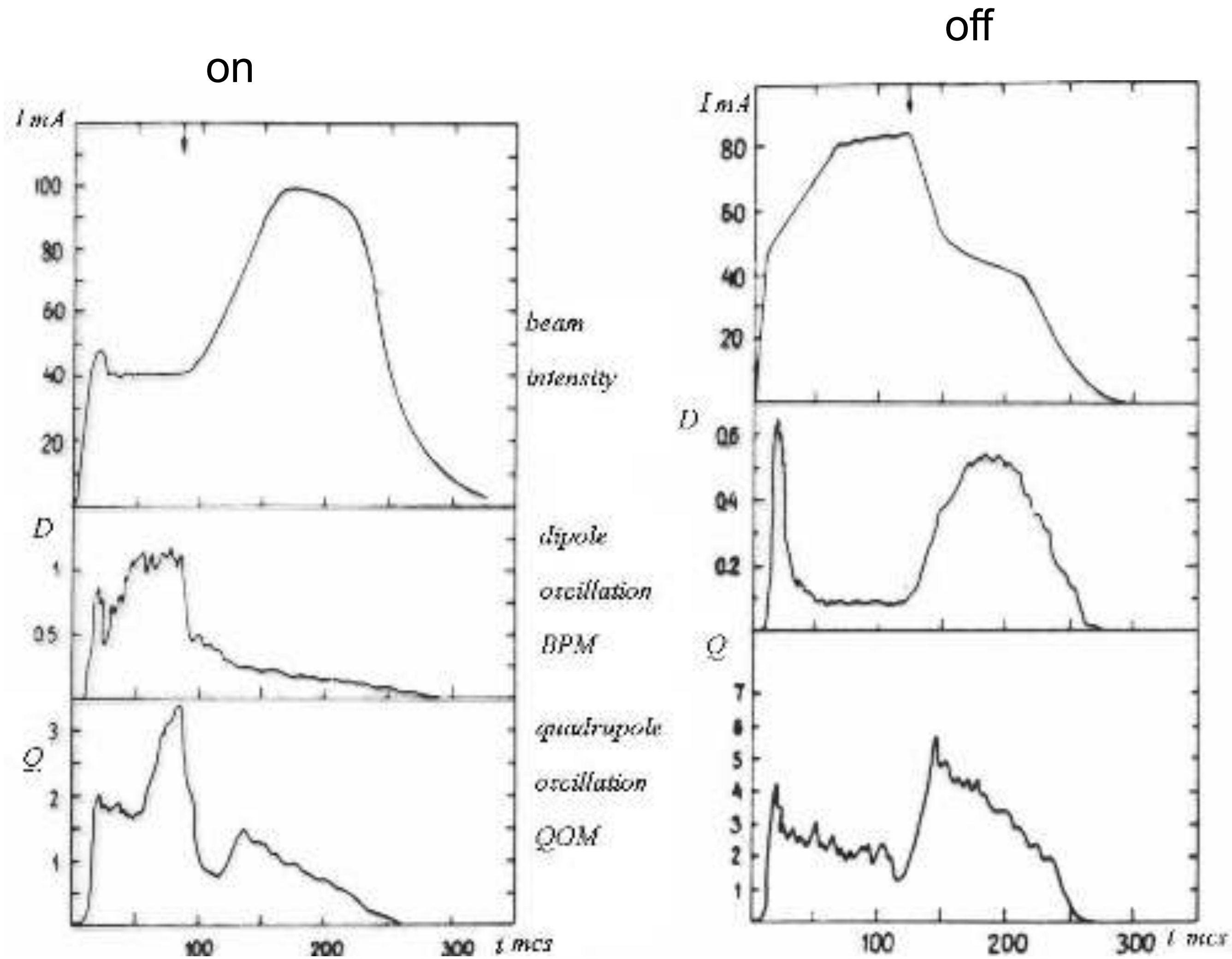
5- secondary emission plate with a negative potential.

Electrons e emitted by filaments 3 are oscillating between negative plates 5 with a high secondary emission for electron multiplication.

A beam density and plasma density must be high enough for selfstabilization of e-p instability (second threshold).

Secondary ion accumulation is important for selfstabilization of e-p instability.

Beam accumulation with a plasma generator



Muons, Inc.

Superintense beam- circulating beam with intensity fare above a space charge limit (with recalculated tune shift ΔQ>1)

For uniform beam

$$\Delta Q = -N r_p R_{ef} / \pi\beta^2\gamma^3 Q a(a+b)$$

$$N = \Delta Q \pi\beta^2\gamma^3 Q a(a+b) / r_p R_{ef}$$

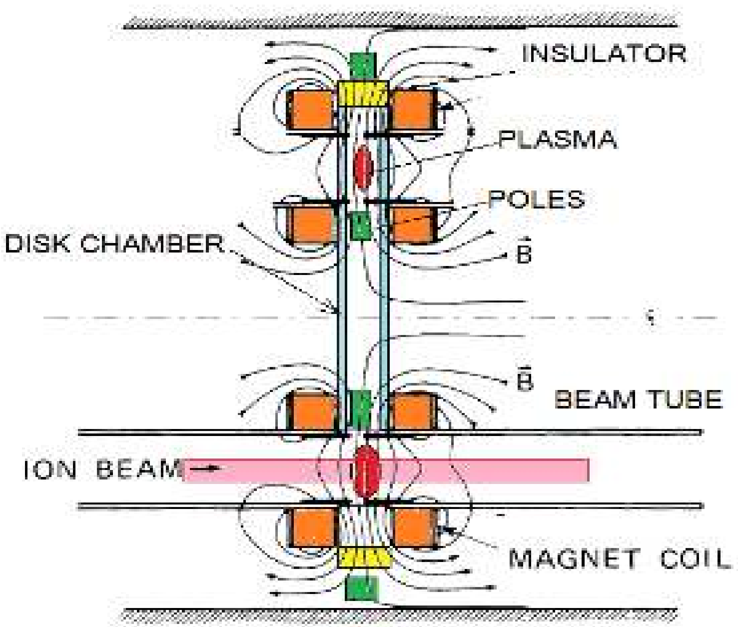
For accelerators is typical $\Delta Q \sim 0.1 - 0.3 < 1$

Transverse e-p instability in the proton SR was self-stabilized by increasing the beam density and increasing the rate of secondary particle generation above a threshold level. This decreases 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):

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

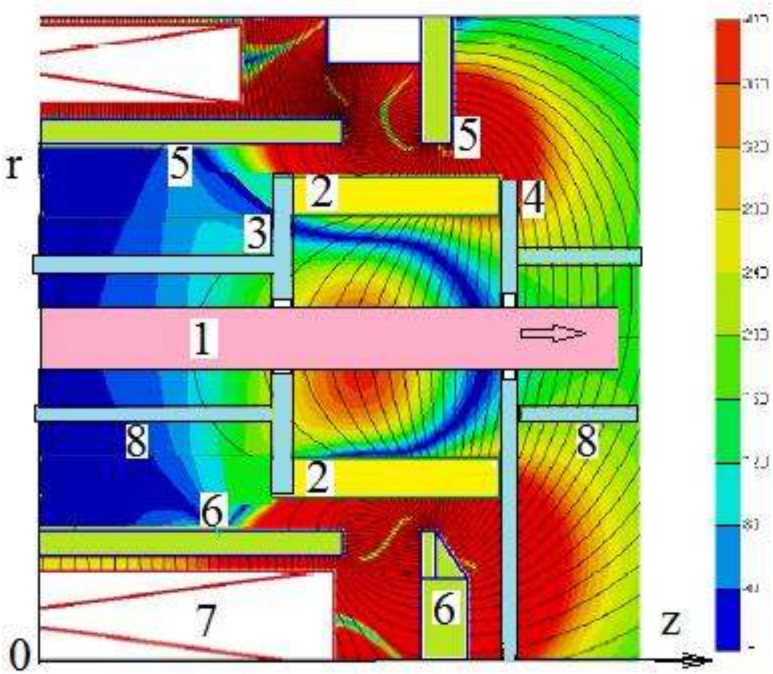
In high current proton rings it is possible to reach this "Island of stability" by fast, concentrated charge exchange injection without painting and enhanced generation of secondary plasma as it was demonstrated in the small scale PSR at the BINP

Acceleration system with ExB electron drift for ion acceleration with a SCC



Electrons are prevented from overloading the induction acceleration system in the BBB by a novel ExB field trap. Ion beam acceleration with a space charge compensation in a gap with a closed cross field drift of electrons (disc chamber).
Radial magnetic field, axial electric field.

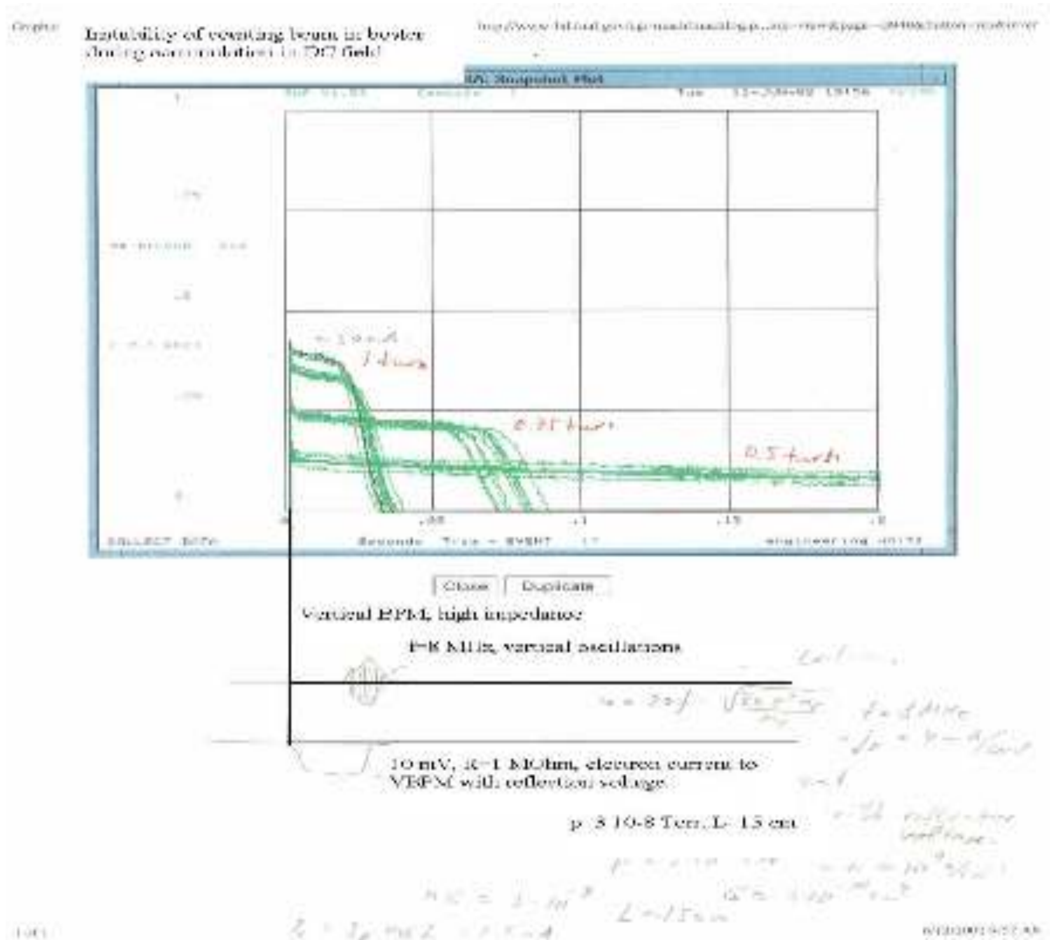
Acceleration gap with a closed electron drift in the crossed ExB fields



1- ion beam; 2-insilators; 3-electrode; 4-second electrode; 5-external magnetic yoke; 6-internal magnetic yoke; 7-magnetic coils; 8-beam pipe;
Color coded magnetic fields distribution.

Z is an axis of cylindrical symmetry

Transverse instability in FNAL Booster, DC B, Coasting beam. Injection 400MeV, 45 mA.



Secondary electron generation in the FERMILAB booster, normal acceleration

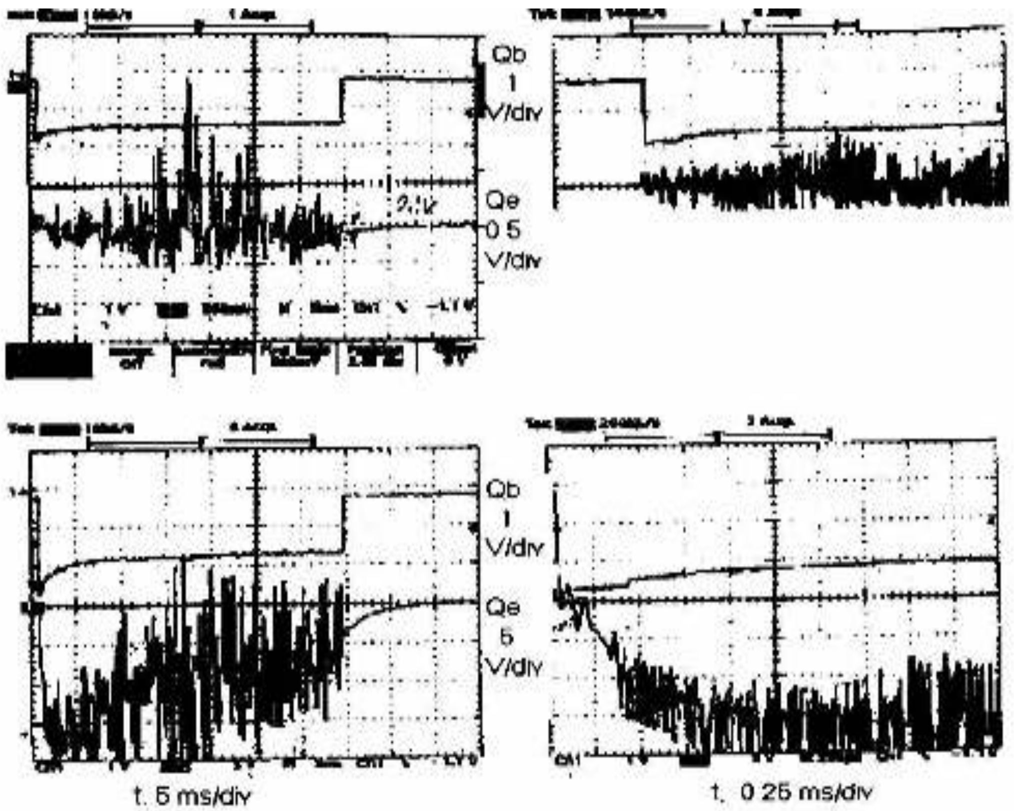
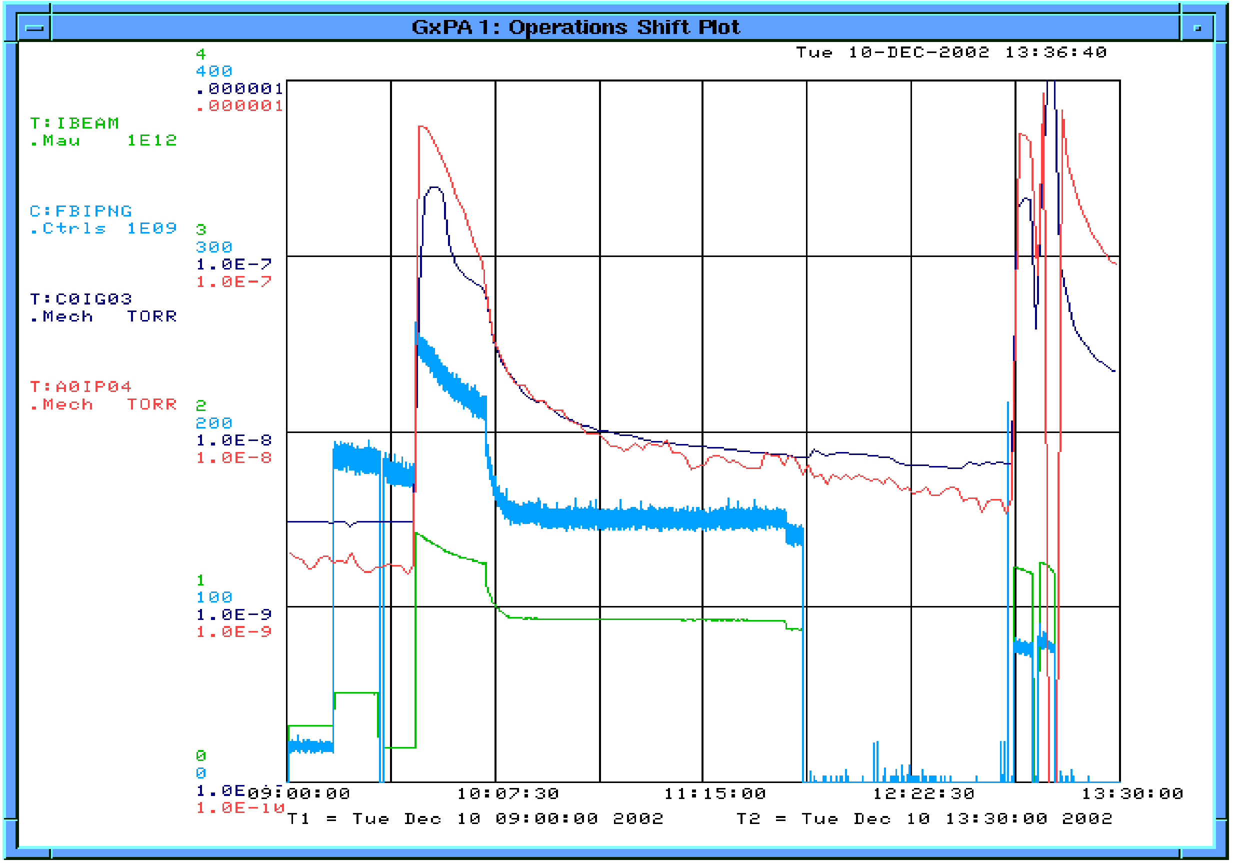


Fig. 1.Secondary electron formation in proton beam of booster
For different proton beam intensity Qb. Calibration 2E12p/V.
1 Channel: Proton beam intensity;
2 Channel: signal from reflecting plate of Ionization profile monitor (IPM). R= 1 Mohm.

Observation of anomaly in secondary electron generation in the FERMILAB Booster

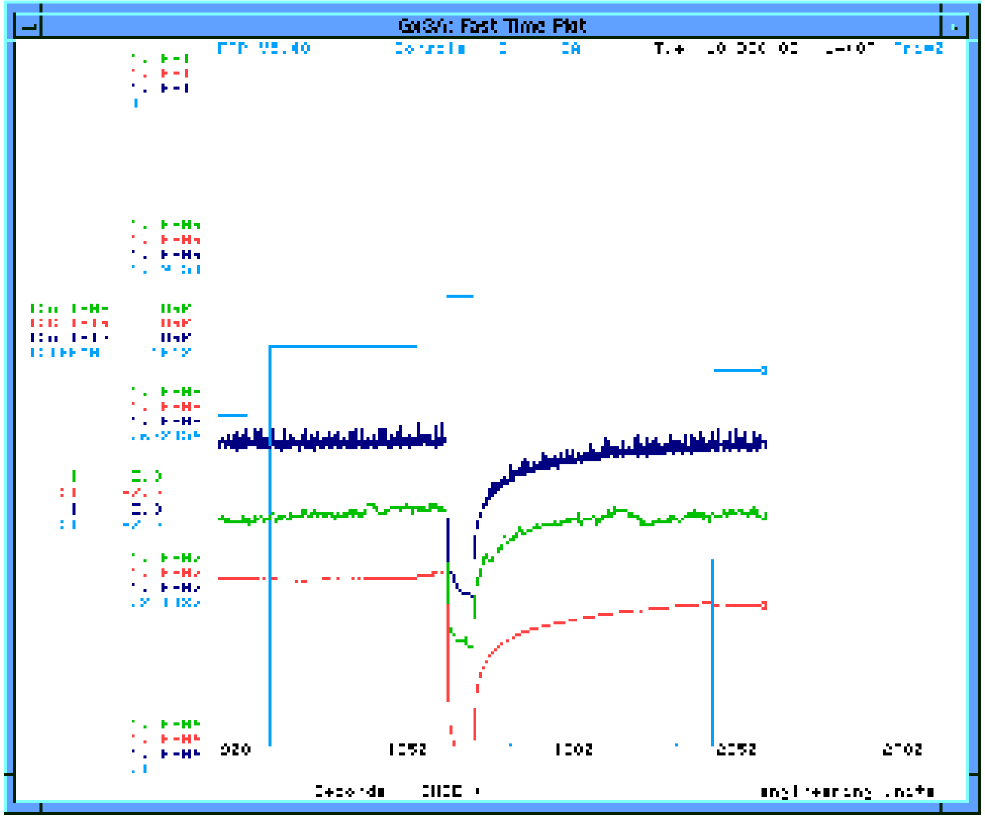
- Observation of secondary particles in the booster proton beam are presented in the Booster E-Log at 04/06/01 .
- Reflecting plate of the Vertical Ionization Profile Monitor (VIPM) was connected to the 1 MOhm input of oscilloscope (Channel 2).
- To channel 1 is connected a signal of proton beam Charge monitor Qb, with calibration of 2 E12 p/V.
- Oscilloscope tracks of the proton beam intensity Qb (uper track) and current of secondary particles (electrons) Qe (bottom track) are shown in Fig. 1 in time scale 5 ms/div (left) and 0.25 ms/ div (right).
- The voltage on MCP plate is Vmcp=-200 V.
- It was observed strong RF signal induced by proton beam with a gap (one long bunch). For intensity of proton beam Qb< 4E12 p electron current to the VIPM plate is low (Qe< 0.1 V~ 1E-7 A) as corresponded to electron production by residual gas ionization by proton beam.
- For higher proton beam intensity (Qb> 4E12p) the electron current to the VIPM plate increase significantly up to Qe=15 V~ 15 E-6 A as shown in the bottom oscillogramms. This current is much greater of electron current produced by simple residual gas ionization. This observation present an evidence of formation of high density of secondary particles in high intense proton beam in the booster, as in Los Alamos PSR and other high intense rings.
- Intense formation of secondary particles is important for the beam behavior and should be taken into account in the computer simulation.

Instability in the Tevatron



electron cloud instability in Tevatron, FNAL.
Change of vacuum and beam loss for diccerent beam intensity(green, blu).

Instability in Tevatron



e-p instability in tevatron. Change of vacuum for different beam intensity.

Instability in RHIC, from PAC03

BROOKHAVEN
NATIONAL LABORATORY

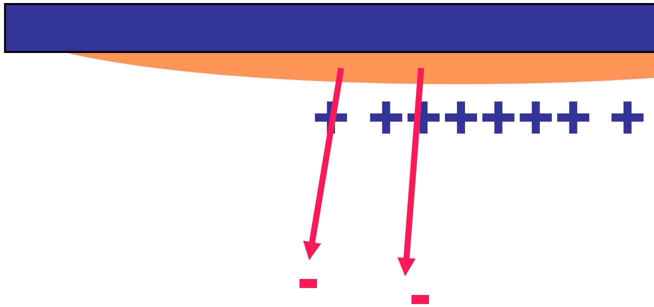
Pressure Rise at Injection, I

- For gold beam 55-bunch injection with bunch intensity of 0.9e9 (design 1e9), the pressure rise at IR12 reached 1e-5 Torr, valve closed, and beam dumped.
- Pressure rise is very sensitive to bunch spacing, for 110-bunch fill, bunch spacing reduced from 216 ns to 108 ns, the pressure rise at single beam straight sections was much higher than 55-bunch mode.

DEPOSITS

Cold emission of electrons from electrodes with dielectric films

CATHODE DEPOSITS INDUCE DISCHARGES: cold emission



POSITIVE IONS ACCUMULATION CREATES HIGH DIPOLE FIELD, INDUCING ELECTRON EXTRACTION (MALTER EFFECT) or sparks

Instrumentation for observation and damping of e-p instability

- 1. Observation of plasma (electrons) generation and correlation with an instability development. Any insulated clearing electrodes could be used for detection of sufficient increase of the electron density. More sophisticated diagnostics (from ANL) is used for this application in the LANL PSR. These electrodes in different location could be used for observation of distribution of the electron generation.
- 2. For determination an importance compensating particles it is possible to use a controlled triggering a surface breakdown by high voltage pulse on the beam pipe wall or initiation **unipolar arc**. Any high voltage feedthrough could be used for triggering of controlled discharge. Could this break down initiate an instability?
- 3. For suppression of plasma production could be used an improving of surface properties around the proton beam. Cleaning of the surface from a dust and insulating films for decrease a probability of the arc discharge triggering. Deposition of the films with a low secondary emission as TiN, NEG. Transparent mesh near the wall could be used for decrease an efficient secondary electron emission and suppression of the multipactor discharge. Biased electrodes could be used for suppressing of the multipactor discharge, as in a high voltage RF cavity.
- 4. Diagnostics of the circulating beam oscillation by fast (magnetic) beam position monitors (**BPM).**
- 5. Local beam loss monitor with fast time resolution. Fast scintillator, pin diodes.
- 6. Transverse beam instability is sensitive to the RF voltage. Increase of the RF voltage is increase a delay time for instability development and smaller part of the beam is involved in the unstable oscillation development.
- 7. Instability sensitive to sextuple and octupole component of magnetic field, chromaticity (Landau Damping), …

Electron generation and suppression

- Gas ionization by beam and by secondary electrons.
- Photoemission excited by SR.
- Secondary emission, RF multipactor,ion-electron emiss.
- Cold emission; Malter effect; Unipolar arc discharge (explosion emission). Artificial triggering of arc.
- Suppression:
- 1-clearind electrodes; Ultra high vacuum.
- Gaps between bunches.
- Low SEY coating: TiN, NEG.
- Transverse magnetic field.
- Arc resistant material

Conclusion

- Experimental dates from small scale rings can be used for verification of computer simulation.
- Stabilization of space charge compensated proton beam with a high intensity has been observed.
- It is useful to use low energy proton ring for investigation e-p instability.