Diagnostics for e-p Instability Observation and Damping

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Electron Ion Collider under development in Jefferson Lab. and in BNL

- Ion beam performances can be affected by Electron Cloud (EC)
- Possibility of EC accumulation and Electron-Proton (EP) instability development need be considered
- Cooperation with Cornell University (CesrTA) will be used for experimental verification computer codes used for prediction and development of instability prevention
MEIC Design Choice

• A great opportunity at JLab
  – Electron beam: 12 GeV CEBAF delivers a high repetition (up to 1.5 GHz) high polarized CW beam, can be used as a full energy injector
  – Proton/ion beam: a new green-field ion complex, can be specially designed to match ion beams to the electron beam

→ We should be able to duplicate the great success of e+e- colliders in the EIC!

• MEIC colliding ion beams
  – High bunch repetition rate, up to 1.5 GHz → 115 times higher
  – Small proton bunch charge, a few of $10^9$, → 57 times smaller
  – Short bunch length, down to 1 cm, → 5 times smaller
  – Small linear charge density → 7 times smaller
  – Small beta-star, same to bunch length → 25 times smaller

Bottom line: ELIC

vs.

eRHIC

High repetition rate
Small bunch charge
Short bunch length
Small $\beta^*$
EIC: Forming the High-Intensity Ion Beam

http://casa.jlab.org/meic/

Stacking/accumulation process
- Multi-turn (~20) pulse injection from SRF linac into the prebooster
- Damping/cooling of injected beam
- Accumulation of 1 A coasted beam at space charge limited emittance
- Fill prebooster / large booster, then accelerate
- Switch to collider ring for booster, RF bunching & staged cooling
- E-p instability suppression

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<tr>
<th>Energy (GeV/c)</th>
<th>Cooling</th>
<th>Process</th>
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<tr>
<td>Source/SRF linac</td>
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<td>Full stripping</td>
</tr>
<tr>
<td>Prebooster/Accumulator-Ring</td>
<td>3</td>
<td>DC electron</td>
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<tr>
<td>Low energy ring (booster)</td>
<td>12</td>
<td>Electron</td>
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<tr>
<td>Medium energy ring</td>
<td>60</td>
<td>Electron</td>
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Stacking proton beam in ACR

<p>| | | |</p>
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<tbody>
<tr>
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<tr>
<td>Stacked ion current</td>
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<td>Norm. emit. after stacking</td>
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Abstract

• Development of Charge exchange injection and Observation of e-p instability in small scale PSR are considered. Damping of e-p instability of bunched beam by feedback, stabilization of e-p instability by clearing electrodes and self stabilization of e-p instability of coasting beam will be discussed.

• Diagnostics for observation and identification of instabilities driving by interaction with secondary plasma in small scale PSR are considered.

• Accumulation of circulating proton beam with intensity above space charge limit will be presented. Further development of this phenomena for superintense beam production will be discussed.
Superintense Circulating Beam

Superintense beam- circulating beam with intensity far above a space charge limit (with recalculated tune shift $\Delta Q>1$)

For uniform beam:

$$\Delta Q = -\frac{Nrp}{\pi \beta^2 \gamma^3 Q_a(a+b)} = \frac{Nrp}{4\pi \epsilon_n \beta \gamma^2};$$

$$N = \Delta Q \frac{\pi \beta^2 \gamma^3 Q_a(a+b)}{rp_{\text{Ref}}} = \frac{\Delta Q 4\pi \epsilon_n \beta \gamma^2}{rp};$$

For accelerators is typical $\Delta Q \sim 0.1-0.5 < 1$. 
E-p Instability was observed in INP at 1965 and was damped by feedback. Self-stabilization of e-p instability was observed in 1971. Circulating 100% space charge compensated proton beam with intensity, greater than the space charge limit (tune shift \( \Delta Q > 5 \)) was accumulated in 1971-73.


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 $\lambda$ 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):

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

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.
e-p instability: historical remarks and references

Small scale Proton Storage Rings

Diagnostics

Observations

Damping of e-p instability

Production of a stable space charge compensated super-intense circulating beam

Applications
History of e-p Instability Observation

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

From F. Zimmermann report
First project of proton/antiproton collider VAPP, in the Novosibirsk INP (BINP), 1960

- 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 by Lithium Lenses.

- 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. \textit{Induction Linac, Inertial Fusion, Neutron Generators}. 

\textit{Induction Linac, Inertial Fusion, Neutron Generators}. 
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.IPMI
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 Hojvat 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. 1990's ESS and JHF 4-5 MW sources
14. 2008 SNS 1-3 MW sources
History of Surface Plasma Sources Development (J.Peters)

BDD, G.Budker, G.Dimov, V.Dudnikov

Charge-Exchange Injection

INP Novosibirsk, 1965, bunched beam

**Coherent betatron oscillations & beam loss**
with bunched proton beam; **threshold ~1-1.5x10^{10},**
circumference 2.5 m, **stabilized by feedback**
(G. Budker, G. Dimov, V. Dudnikov, 1965;
V. Dudnikov, PhD.) from F. Zimmermann report

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**Other INP PSR 1967:**

- coasting beam instability;
- fast accumulation of secondary plasma is essential for stabilization;
- 1.8x10^{12} in 6 m

V. Dudnikov, PAC2001, PAC2005
INP PSR for bunched beam accumulation by charge exchange injection (ionization loss~200eV)

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

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.
General view of INP PSR with charge exchange injection, 1965

1. Magnet
2. Vacuum chamber
3. Beam line
5. First stripping target
6. Second stripping target
Residual gas ionization beam current & profile monitors (ICM, IPM), 1965

1 - reflection plate; 2 - suppression grid; 3 - collector plate; 4 - shielding grid; 5 - collector strips.

Faraday Cup

1μs/step
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 signal, and beam intensity vs vertical aperture

\[ a : N_m = 2 \cdot 10^{11}, \quad b : N_m = (2 \div 20) \cdot 10^{14}; \quad 1 - \alpha_z = 6; \quad 2 - \alpha_z = 0.12 \]

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

IPM signal, electron collection in B field

Step 9 mm.

V. Dudnikov, 1965,
Modern IPM (DESY)

Vacuum 10-9 mbar
1 - 60 - 210 Bunches \( \Rightarrow \) \(<\) 0.1 - 160 mA
7.5 - 40 - 820 GeV/c
beam width \(<\) 1 mm, length 30 - 3 cm
Fermilab IPM

- Mark-II details

RF Shield Over MCP

Secondary Screen Grid

J. Zagel
Signal and Timing

- Typical Amplified Strip Signal
- Relative to Beam Sync Clock (Captured in Recycler)

J. Zagel
CERN Luminescence Profile Monitor

- It works with $\text{N}_2$ injection
- 1 light channel is going to a PM for gas-luminescence studies (decay time etc.)
- 2 channels are used for profile measurements:
  - The H channel is in air: it showed high background with LHC beam, due to beam losses
  - The V channel is in vacuum
- The MCP has a pre-programmed variable gain over cycle (it showed some problems to log on timing events)
Proton beam accumulation for different injection current (0.1-0.5 mA), accumulated beam 300mA

- Injected beam
- Circulating beam, Low injection current
- Start saturation
- Strong saturation
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) (& damping by FB system)

1 - pick up electrode signal; 2 - beam loss monitor; 3 - beam intensity; 4 - Rad. BPM; 5 - radial pick ups; 6 - pick up signal Uref=1.4kV; 7 - pick up signal Uref=2.6; 8 - pick up signal Uref=4.2kV; 9 - beam intensity below threshold for instab; 10 - beam intensity above threshold for instability, no field feedback stabilization; 11 - beam intensity above threshold for transverse instability, field feedback stabilization ON.
Transverse instability of bunched beam with a high RF voltage

1-ring pickup, peak 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
Ron Martin, Realization of charge exchange injection in ZGS and in IPNS

3. 1968-70  Ron Martin, ANL ; 50 MeV injection at ZGS;  
**History of the ZGS 500 MeV Booster;**  
http://www.ipd.anl.gov/anlpubs/2006/05/56304.pdf

4. 1972 Jim Simpson, ANL ; 50-200 MeV, 30 Hz booster

5. 1975-76 Ron Martin et al, ANL ; 6 10¹² ppp

6. 1977 Rauchas et al, ANL ; IPNS 50-500 MeV, 30 Hz

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IPNS ANL transverse instability

Intensity and centroid of a slice with width of 5 degrees of rf phase at 212 degrees in the bunch tail for 3.2 ms before extraction. It can be seen that strong oscillations appear before bunch loss occurs. In the figure, \( t = 0 \) refers to approximately 11 ms in the cycle.

The vertical centroid oscillations, case 1, measured at 13.72 ms for 50 consecutive turns. The blue line indicates that the front edge of the oscillation region locates at the intensity peak.
Models of two-stream instability

- The beam induces electron cloud build up 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.

7.  ORBIT, e-p
Koshkarev-Zenkevich Model (1)

Based on earlier work by Budker and Chirikov, the authors made a model of transverse multipole oscillations of two beams. For simplicity they assumed either uniform cross section or a ribbon beam, and considered only forces due to external focusing and the charged particles of the other beam.

For simple dipole oscillations, in which we were mainly interested, they wrote a system of 2 coupled differential equations for the transverse particle displacements of electrons and protons $Z_{e,p}$. They were then averaged over all particles to describe the beam motion:

$$\frac{d^2 Z_e}{dt^2} = -Q_e^2 \Omega^2 (Z_e - Z_p)$$

$$\frac{d^2 \bar{Z}_p}{dt^2} + Q^2 \Omega^2 \bar{Z}_p = -Q_p^2 \Omega^2 (\bar{Z}_p - \bar{Z}_e),$$

where $\Omega$ is the revolution frequency and $Q$ the (vertical) betatron tune due to external focusing. The tunes $Q_{e,p}$ describe the “bounce frequencies” $\omega_{e,p} = \Omega Q_{e,p}$ with which electrons and protons oscillate in the potential well of the other beam.
Simplified centroid model is our working picture for e-p

- Rigid, uniform coasting beam, centroid model of coupled $e$ and $p$ dipole oscillations with linear motion near threshold$^*$

\[
\frac{d^2 y_p}{dt^2} + (\omega^2_p + \omega^2_e) y_p = \omega^2_p y_p, \quad \frac{d^2 y_e}{dt^2} + \omega^2_e y_e = \omega^2_p y_p
\]

\[
\omega^2_p = \frac{2N_p e^2}{\pi b(a+b)R}, \quad \omega^2_e = \left(\frac{f_e m_e}{\gamma m_p(1-f_e)}\right) \omega^2_p, \quad Q_x = \frac{\omega_x}{\omega_0}
\]

- Some Features
  - Unstable modes $(n-Q_\beta)$ close to $Q_\beta$ (ratio of electron bounce frequency to $\omega_0$)
  - Ratio of $e/p$ amplitudes large for unstable motion
  - Threshold condition with Landau damping can explain threshold curves vs buncher voltage assuming $\sim$ constant $f_e \approx 1\%$ and $\Delta Q_e/Q_e \approx 10\%$

\[
\frac{Q^2_p}{Q^2_\beta} \geq \frac{64}{9\pi^2} \cdot \frac{\Delta Q_\beta}{Q_\beta} \cdot \frac{\Delta Q_e}{Q_e}, \quad \Delta Q_\beta = |(n - Q_\beta) \eta - \xi Q_\beta| \cdot \frac{\Delta p}{p} + N.L.
\]

$^*$Kell and Zotter 1971, also Neuffer, Wang, Channell, M Blaskiewicz in last decade

ISIS has much larger $a$ and $b$, and low particle density. Bounce frequency is low. Only low modes of betatron oscillations are unstable. This lead to removing of electrons without beam loss.
Nonlinear Optics as a Path to High-Intensity Circular Machines

S. Nagaitsev, A. Valishev (Fermilab), and V. Danilov (ORNL)
Draft talk for HB2010 Sep 23, 2010

<table>
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<th>e- Energy</th>
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<td>Circumference</td>
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<tr>
<td>Dipole field</td>
<td>0.5 T</td>
</tr>
<tr>
<td>Betatron tunes</td>
<td>( Q_x = Q_y = 3.2 ) (2.4 to 3.6)</td>
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<tr>
<td>Radiation damping time</td>
<td>1-2 s (10^7 turns)</td>
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<tr>
<td>Equilibrium emittance, rms, non-norm</td>
<td>0.06 ( \mu \text{m} )</td>
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**Nonlinear lens block**

<table>
<thead>
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<th>Length</th>
<th>2.5 m</th>
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<tbody>
<tr>
<td>Number of elements</td>
<td>20</td>
</tr>
<tr>
<td>Element length</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Max. gradient</td>
<td>1 T/m</td>
</tr>
<tr>
<td>Pole-to-pole distance (min)</td>
<td>(~ 2 \text{ cm})</td>
</tr>
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</table>
The oscillation tune of the electrons inside the proton beam (bounce frequency, plasma frequency), number of oscillation per turn:

\[
(Q_e \Omega)^2 = 4N_b \, r_e c^2 / a(a+b) L;
\]

\[
(Q_e)^2 = 2N_b \, r_e R / a(a+b) \pi \beta^2
\]

\[
(Q_e)^2 = 2(N_b + N_i) \, r_e R / a(a+b) \pi \beta^2
\]

Wavelength \( \lambda = L/Q_e < a \) self-stabilization.

PSR for beam accumulation with inductive acceleration

- first stripper;
- magnet pole n=0.6;
- hollow copper torus with inductance current;
- main stripper;
- accelerating gap;
- ring pickup;
- BPMs;
- Res.gas IPM;
- vacuum chamber.

FC; quartz screens; Retarding electron and ion collectors/spectrometers.
e-p instability with a low threshold in INP PSR (1967)

1-beam current, $N > 7 \times 10^9 p$
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.
PSR for Superintense Circulating p-Beam Production

1-stripping 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 300 mA is up to 9 time greater than a space charge limit. A Stripping target is a gas jet.
Tune diagram of betatron frequencies of the storage ring:

1-betatron frequency of low intensity beam $\nu_x=1.62; \nu_z=0.85$;

Blue trajectory of operation point with variation of correction current;

Red trajectory of operating point under the influence of the space charge.
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 μs/div.
e-p instability of coasting beam in the INP PSR (1967)
Secondary particles detector:

1 - reflection plate; 2 - collector; 3 - retarding grid; 4 - shielding; 5 - grid; 6 - beam. a - helium ion; b - nitrogen ion; c - electrons.
Mass Spectrum of Ions from the Beam

Integral Signal (bottom), Differential Signal (top)
Ion Detection System for High Vacuum Storage Rings.

Electrode: produce a kick to send ions to collector. Need a voltage supply of ~10kV (the larger, the better), and fast rise time.

Noise filter: using the detector during the abort gap will decrease the noise (no image currents).

electrostatic lens

time of flight mass spectr

Collector: with an MCP we can obtain a large gain (G~10^6)

(to scope)
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
Inductive BPM, INP, 1967, for separation of beam oscillations from electron oscillation.

1-ferrite ring; 2-coils; 3-commutator.
Inductive BPM (DESY)

**Inductive Beam-Position Pickup**

- Circular beampipe of 84 mm diameter aperture.
- 10 mm wide ceramic gap.
- 134 mm diameter NiFe-alloy bandaged toroid transformer with 4 orthogonally arranged single-loops (electrode-coils).
- Normalized sensitivity $\Delta/\Sigma \approx 1.2\%$/mm with a high linearity over the full aperture.
- Typical signal levels range between 10 mV at flat-bottom and several volts at flat-top energy (peak-peak amplitudes, 50 $\Omega$ termination).
- 30 kHz...250 MHz (-3 dB) bandwidth.

**DESY III BPMs**

**Electronics Hardware**

Schematic of the modified analogue BI BPM-electronics.

- A modified BERGOZ BPM-electronics for the new processing:
  - Input frequency range $\approx 3...10$ MHz, to guarantee of any number of bunches in the ring.
  - IF center frequency of 60 MHz, 500 kHz band
  - External LO input, driven from the rf-synchrotron III low-level rf-synthesizer ($\approx 63...70$ MHz).
  - Changes on the internal clock frequency and
  - Two C-size VXI digitizer-boards (VXI-VM2016) with 64 independent 16-bit A/D 512kWord of total memory.
- A PC plug-in delay generator (Stanford DG133) drives the ADC trigger.
- Usual PC-hardware, including a IEEE1394 "Fire the VXI-crates."
Spectrums of coasting beam e-p instability in BINP PSR (magnetic BPM), very similar for LA PSR

Spectrum of signals from vertical beam position monitor.

a) $N = 1.7 \times 10^{10}$ p; b) $N = 1.5 \times 10^{11}$ p.
Spectrums transverse beam instability in LA PSR

Frequency spectra of unstable motion agrees with model

\[ \omega_c = Q_c \Omega_0 = 2\pi f = \sqrt{\frac{2N_{r_s}c^2(1-f_e)}{\pi b(a+b)R}}, \quad f \approx 230 \text{ MHz (6.1}\,\mu\text{C}) \]
Pickup signals and electron current in LA PSR

R.Macek, LANL
Beam accumulation with clearing voltage

- In beginning secondary plasma accumulation suppressed by strong transverse electric field.
- Vertical instability with zero mode oscillation was observed (Herward instability).
Threshold intensity $N$ (left) and growth rate $J$ (right) of instability as function of gas density $n$

a- hydrogen; b- helium; c- air.
Beam accumulation with space charge neutralization

beam accumulation above space charge limit

beam current monitor

vertical BPM, dipole detected

1 ms

cleaning E field ON  cleaning E field OFF
Self-stabilization of e-p instability was observed in 1971. Circulating 100% space charge compensated proton beam with intensity, greater than the space charge limit (tune shift $\Delta Q > 5$) was accumulated in 1971-73.


*e-mail:dvg43@yahoo.com                18 February 2011*
INP PSR for Beam above a Space Charge Limit

Ionization energy loss ~200 eV/turn, compensated by inductance field
Small Scale Proton Storage Ring for Accumulation of Proton Beam with Intensity Greater than Space Charge Limit
Self-stabilization of e-p instability and accumulation of proton beam with intensity above a space charge limit (with high injection current >5.5mA).

Strong instability with low injection current <5.5 mA.

For self-stabilization it is important to have a high injected current density (second threshold) and fast accumulation of secondary plasma.
Proton beam accumulation with intensity greater than space charge limit. Dependence on injection current.

$N_p$ - number of accumulated protons; $I_j$ - injection current; $\Delta Q$ - tune shift.
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 on and off

![Graphs showing beam intensity, dipole oscillation, and quadrupole oscillation with and without plasma generator.]
Space charge neutralized Superintense ion beams with intensity far above space charge limit

Can be useful:
In Inductance Linac with recirculation,
For Inertial Fusion,
For Neutron, Antiproton, Mu meson Generators
For resonant reaction with internal targets
For High Power Density Physics
For FFAG accelerators
For Inductive Synchrotrons

Intensity limit don’t determined
Simulation of electron cloud accumulation and e-p instability development
Model of secondary plasma build up with secondary ion-electron emission as a source of delayed electrons is presented and discussed. This model can be used for explanation of bunched beam instability with electron surviving after gap, for prediction of e-cloud generation in coasting and long bunches beam, and can be important for pressure rise in worm and cold sections of storage rings. A fast desorption by ion of physically adsorbed molecules can explain a “first pulse Instability”. Application of this model for e-p instability selfstabilization and superintense circulating beam accumulation is considered. Importance of secondary plasma for ion beam stabilization in ion implantation will be discussed. Preliminary results of simulation of electron and ion accumulation will be presented.
It is very attractive to repeat an accumulation of Superintense ion beam with modern high current injectors. High current density beam should be stable without secondary ions.

Now from RFQ it is possible to have H- beam with current \(~100\) mA and Energy \(~3\) MeV. This can be enough for accumulation \(~1\) kA of circulating proton beam in a small storage ring with \(R\sim1\) m.
Self-stabilization of e-p instability and accumulation of proton beam with intensity above a space charge limit (with high injection current); instability with low injection current.
Ionization cross sections for H
Fast Ion-beam instability of H- beam in FNAL Linac

BPM signals after preinjector 0.75 MeV 50mA
Transverse instability in FNAL Booster, DC B, Coasting beam. Injection 400MeV, 45 mA.
E-p instability in Fermilab booster

BPM signal

Beam intensity
Secondary electron generation in the FERMILAB booster, normal acceleration

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 V_mcp=\(-200\) V.
- It was observed strong RF signal induced by proton beam with a gap (one long bunch). For intensity of proton beam \(Q_b<4E12\) p electron current to the VIPM plate is low (\(Q_e<0.1\ V\sim 1E-7\ A\)) as corresponded to electron production by residual gas ionization by proton beam.
- For higher proton beam intensity (\(Q_b>4E12p\)) the electron current to the VIPM plate increase significantly up to \(Q_e=15\ V\sim 15\ E-6\ A\) 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 dicserent beam intensity(green, blu).
Instability in Tevatron

e-p instability in tevatron. Change of vacuum for different beam intensity.
Pressure Rise at Injection, 1

- For gold beam 55-bunch injection with bunch intensity of $9 \times 10^7$ (design $1 \times 10^9$), the pressure rise at IR12 reached $1 \times 10^{-5}$ 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.
Cold emission of electrons from electrodes with dielectric films

CATHODE DEPOSITS INDUCE DISCHARGES: cold emission

POSITIVE CHARGE 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-clearing electrodes; Ultra high vacuum.
  - Gaps between bunches.
  - Low SEY coating: TiN, AMORPHOUS CARBON, NEG, AQUADAG COATING, GLASSY CARBON, Grooved Chamber.
  - Transverse magnetic field.
  - Arc resistant material
Conclusion

- Experimental data 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 important to produce this in realistic computer simulations. (ORBIT?)

It is useful to use low energy proton ring for investigation of the e-p instability.
A schematic of a storage ring for resonance reaction production by the interaction of a Superintense circulating ion beam with a thin internal target.

1- beam line for transport of injected H-beam: RFQ, cyclotron or DC accelerator; 2- injected H-beam; 3- bending magnets; 4- vacuum chamber; 5- generator of supersonic jet-stripping, reaction target; 6- supersonic jet, stripping-reaction target; 7- pump-recirculator of target jet; 8- cone of resonant gamma rays; 9- iron core for inductor for compensation of beam energy loss in first target; 10- circulating proton beam; 11- magnetic coil; 12- yoke of bending magnet; 13-16 electron cooling.
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 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;
Electron-Proton ("E-p") Instability

- The E-p instability threshold is extremely difficult to predict \textit{a priori}.
- It depends on numerous factors: chamber surface properties and conditioning history, losses, tunespread, etc.
- The "e-p" threshold is predicted to lie above the 3 MW upgrade intensity [W. Weng et. al., EPAC 2002, p.1070].
- The baseline SNS Ring contains a number of mitigating features:
  - All chambers coated with TiN to reduce SEY
  - Stripped electrons are carefully controlled
  - Solenoid in collimation region
  - Electron collector diagnostics
  - Electron clearing electrode near foil
  - Upgrade will provide injected energy-spread control which gives tunespread control via chromaticity and energy-spread for Landau damping
- Given the large uncertainties inherent in predicting the e-p threshold, we plan to install a wideband feedback system with 400 MHz bandwidth and 1kW power for damping a potential e-p instability.
- Recent successful experimental tests at the LANL Proton Storage Ring show that such instabilities in a long-bunch proton machine can be damped.
Accelerator Physics R&D: E-P Feedback Experiment at the PSR

- We formed a collaboration to carry out an experimental test of active damping of the e-p instability at the LANL PSR:
- We deployed a transverse feedback system designed and built by ORNL/SNS and in two shifts demonstrated for the first time damping of an e-p instability in a long-bunch machine
- In subsequent studies we observed a 15-30% increase in e-p instability threshold with feedback on.
- Continued investigation of e-p feedback will be pursued, as well as simulations to benchmark experimental results.
THANK YOU

For your attention
Instrumentation for observation and damping of e-p instability

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References for first observation of e-p instability

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


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.


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 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.


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.

Advanced space charge neutralization in low energy ion implantation with using negative ion formation

References
[5] V. Dudnikov, Features of space charge compensation by ions and fast beam- ion instability, ICPP-2000, DP1.078, Quebec City, CA.
Beam line with advanced space charge neutralization

- 1-ion source;
- 2-ion beam;
- 3-gas injector;
- 4-magnetic pole;
- 5-ion beam;
- 6-gas injector;
- 7-beam scanner;
- 8-beam damp.
High Current Implanter
Low Energy Beam instability

- Boron ion beam with energy 5 keV on collector after analyzer.
Effect of Space Charge Neutralization with electronegative gas

- $I_b$ - ion beam current
- $p$ - vacuum gauge reading
- $I_{ex}$ - extractor current
- $Q$ - gas flux
- $BF_3, SF_6, CF_4$
Low energy B+ beam after analyzer

Boron ion beam with energy 3 keV, up to 4 mA
Ion beam after analyzer after gas injection

- Boron ion beam 3 keV
- Q of BF3
- 4 ccm
Boron beam mass spectrum, 5 keV

- Mass spectrum for different gas injection
- Q
Damping of beam instability by gas injection

- Boron ion beam 5 keV
- for different flux of BF3 Q, ccm(N2)
THANKS