Studies of Charged Particle Beam Dynamics on the Paul Trap Simulator Experiment (PTSX)

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In collaboration with

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What is a Charged Particle Beam?

A collection of particles of same charge species all traveling in the nearly same direction with the nearly same speed.

Snapshot of beam in time \((t)\) and space \((z)\)

= Distribution of particles in phase space \((x, x')\)

Emittance

~ Effective phase space area occupied by particles

When mutual interaction becomes significant, a charged particle beam behaves like a nonneutral plasma.
Why Charged Particle Beam?

Industry
- Ion implantation
- Treatment of foodstuff
- Sterilization of medical devices
- Beam lithography

Medicine
- Radio Isotope Production
- Radiotherapy
- Precision surgery
- Medical Diagnostic

Basic Sciences
- High energy and nuclear physics
- Neutron production for biological and material research
- Generation of coherent radiation

Energy
- Nuclear waste transmutation
- Heavy ion fusion
Modern Accelerators for Charged Particle Beams

High current and intensity are required for various advanced applications

Self-field effects are important

Intense beams

Need to accelerate intense beam for a long distance (~ 1 km)
How to Focus Intense Beams?

Periodic focusing quadrupole magnetic field

= Alternating Gradient (AG) transport system = FODO lattice
An Intense Beam is a Nonneutral Plasma in the Beam Frame

\[ s \ (\text{space}) \rightarrow t \ (\text{time}) \]

Intense Beam Propagating in Periodic Focusing Quadrupole Magnetic Field

Nonneutral Plasma Trapped in Time Varying Quadrupole Electric Field

\[ H_{\perp}(x, y, x', y', s) = \frac{1}{2}(x'^2 + y'^2) + \frac{1}{2}\kappa_q(s)(x^2 - y^2) + \psi(x, y, s) \]

Self-field potential

\[ H_{\perp}(x, y, \dot{x}, \dot{y}, t) = \frac{1}{2}m_b(x^2 + \dot{y}^2) + \frac{1}{2}m_b\kappa_q(t)(x^2 - y^2) + e_b\phi^s(x, y, t) \]

Self-field potential
How Paul Trap Works?

Radial direction

- At time $t_1$, the radial direction shows a potential difference with rf voltage.
- At time $t_2$, the radial direction shows a different configuration with rf voltage.

Axial direction

- Time average shows a continuous rf voltage.

Diagram descriptions:
- Radial direction diagrams illustrate the potential variations in time.
- Axial direction diagrams depict the overall axial movement.
Paul Trap Simulator Experiment (PTSX)

Apparatus

- Pressure \(10^{-10} \sim 10^{-8}\) Torr
- Trap Time \(1 \sim 100\) ms
- Density \(10^5 \sim 10^6\) cm\(^{-3}\)
- End Electrodes (DC) \(36 \sim 150\) V
- Central Electrodes (AC) \(f < 100\) kHz, \(V_{0\text{max}} < 400\) V
Smooth Focusing Frequency, Vacuum Phase Advance, and Normalized Intensity Parameter Characterize the System

The smooth trajectory’s phase advance during 1 applied focusing period to avoid instabilities.

\[
\sigma_v^f = \frac{\omega_s}{f} < \sigma_{v_{\text{max}}}
\]

Normalized intensity parameter to confine the space-charge.

\[
s \equiv \frac{\omega_p^2}{2\omega_q^2} < 1
\]

\(s \sim 0.2\) for Spallation Neutron Source.
Cesium Ion Source Has Been Used for the Initial Phase of PTSX

Aluminosilicate cesium source

Pierce electrode

Acceleration/Deceleration grid

~ 10 A ~ 1000 °C ~ 0.1 eV

67.5° opening angle

85% transparent electroformed copper mesh

Good enough for low energy beam

Contact ionization of cesium at hot porous tungsten

Triode system having possibility to change the extraction field strength without changing the beam energy

1.25 in
Many Interesting Results Have Been Obtained by a Faraday Cup Charge Collector

Because of low beam energy, there is no secondary electron emission.

Radial scan along the potential null of the quadrupole field.

Low level charge measurement (~1 fC)

\[
\text{R}_b, \text{Nb}
\]

\[
m\frac{\omega R}{3} = 2kT + \frac{Nq^2}{4\pi\varepsilon_0}
\]

emittance
PTSX Has Simulated Several Important Scientific Issues in Accelerator Community

1. Beam Mismatch
2. Transverse Compression
3. Random Noise Effect


1. Beam Mismatch

When initial injected beam radius is not equal to the final equilibrium radius in the focusing channel, there are oscillations in beam envelope.
2. Transverse Compression

Application of present-generation accelerators require transverse compression of charge bunch to a small spot.

What about radial profiles?

How slow is slow?
3. Random Noise Effect

In real accelerators, there are always unavoidable errors on components.

<table>
<thead>
<tr>
<th>Components</th>
<th>Limit on error</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEBT</td>
<td>1.732 %</td>
</tr>
<tr>
<td>DTL</td>
<td>0.5 %</td>
</tr>
<tr>
<td>CCDTL &amp; CCL</td>
<td>0.25 %</td>
</tr>
</tbody>
</table>

![Graph 1: Average on-axis charge (pC) vs. Duration of noise (msec)](image1)

![Graph 2: Amplitude of uniform noise vs. Duration of noise (msec)](image2)
More Advanced Diagnostic?

Can we do that in the PTSX too?

Maybe, by using the Laser-Induced Fluorescence (LIF) diagnostic

Optical Detection of a Single Barium Ion in a Paul Trap

Dehmelt, Toscheck et al.
Barium Ion’s Atomic Structure is Amenable to LIF

- Barium ions are **heavy enough** (137 amu) to be confined in the PTSX
- Barium ions are produced primarily in the ground state ($6^2S_{1/2}$), but **some in the metastable states** ($5^2D_{3/2}$, $5^2D_{5/2}$)
- Because PTSX does not utilize external magnetic field, there is **no Zeeman split**
- Because time average electric field vanishes in the PTSX, there is **no first order Stark effect**
### Possible LIF Schemes for Barium Ion

**Plan A:**
Nova Photonics’ Dye laser with DCM

**Plan B:**
WVU’s Dye laser

**Plan C:**
Nova Photonics’ Dye laser with C102

<table>
<thead>
<tr>
<th>Plan</th>
<th>Scheme</th>
<th>Wavelengths</th>
<th>A_{23}</th>
<th>Quantum efficiency</th>
<th>Filter efficiency</th>
<th>Stray light</th>
<th>Dye</th>
<th>Laser power</th>
<th>Density of initial state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan B</td>
<td>6^2S_{1/2}</td>
<td>493.4077 nm</td>
<td>33.2 \times 10^6 s^{-1}</td>
<td>&gt; 40%</td>
<td>&gt; 50%</td>
<td>Small</td>
<td>C102 (unstable)</td>
<td>&lt; 450 mW</td>
<td>10^{5} \sim 10^{6} cm^{-3}</td>
</tr>
<tr>
<td>Plan B</td>
<td>5^2D_{3/2}</td>
<td>649.6898 nm</td>
<td>95.5 \times 10^6 s^{-1}</td>
<td>&lt; 15%</td>
<td>~ 45%</td>
<td>Small</td>
<td>DCM (stable)</td>
<td>&lt; 800 mW</td>
<td>&lt; 0.8 % \times 10^{5} \sim 10^{6} cm^{-3}</td>
</tr>
</tbody>
</table>
New Compact Barium Ion Source Has Been Developed

- Currents about 100 ~ 200 nA are required to fill up the PTSX
- Ionizer (Pt mesh) will be maintained near 1000 °C
- Reservoir (Ta tube) will be maintained above 400 °C, so that barium oxide can decompose
- Length of the tube is determined so that heat conduction and radiation processes sustain proper temperature distribution along the tube

Stainless steel can reduces visible radiation from the hot source and prevents neutral barium from contaminating electrodes

Radius of the source is determined so that beam can be RMS-matched to external focusing field for nominal operating condition of PTSX
Schematic Diagram of LIF Diagnostic Setup

Custom-made Reentrant Flange

(Aquadag Coated)
Laser Injection System

- Coherent 899-21 ring dye laser used for MSE-LIF diagnostic
  - Optically pumped by an argon ion laser
  - Dye: Exciton DCM dye for 649.6898 nm transition
  - Laser linewidth: ~ 2 GHz ~ 0.0025 nm for broadband operation using a three plate birefringent filter (mode-hopping?)
  - Laser power: ~ up to 1000 mW for broadband operation

Assembly of the optical fiber, line generator, beam shutter, and x-y translation stage, which is enclosed by a light-tight aluminum box

A line generator, which uses a Powell lens, transforms the collimated laser beam into a line with a uniform output intensity
Collection Optics

Aquadag coating

Only 1” OD viewport
(to minimize distortion in quadrupole field)

Bandpass filter

500 nm
70%

40 nm

Lens Requirements

f < 11 mm , FOV ~ 41° , MOD < 135 mm

Overall efficiency of collection optics
~ 5.4 %

PULNiX TM-1010 high resolution camera
1” (9.1 mm x 9.2 mm) CCD imager
1008 x 1018 resolution
Up to 10 sec integration time
FS9901 inverting image intensifier
Initial Background Light Measurements

- A glowing red-hot ion source can be a source of background light

(a) $I = 0$ A  
(b) $I = 10.5$ A  
(c) $I = 14$ A  

- Scattered laser light from windows and electrodes can be a source of background light

W/O Laser  
W/ Laser
Conclusions

- A laser-induced fluorescence diagnostic system has been developed for the nondestructive measurement of the transverse ion density profile in the PTSX device.

- The accompanying barium ion source has been developed with the goal of maximizing the metastable ion fraction and minimizing the visible radiation.

- Since the density of the metastable ions is very low, technical issues such as suppressing background light and data acquisition with long integration times must be resolved to obtain meaningful data for the study of beam mismatch and halo particle production.

- Initial experiments will begin in January, 2007.
I like to thank my colleagues