Supported by Office of Science

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

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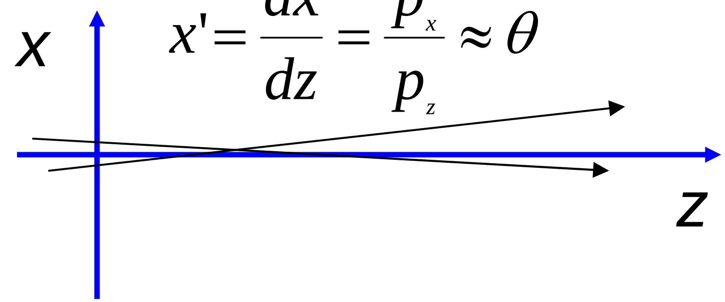
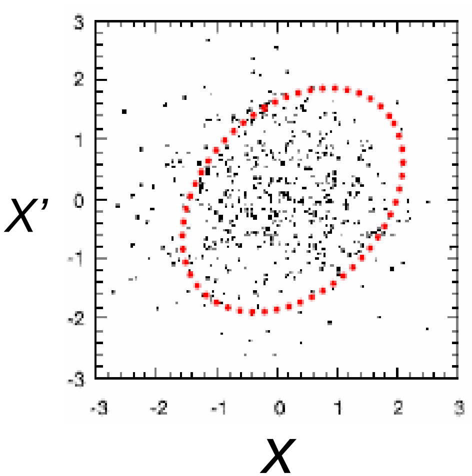
What is a Charged Particle Beam?

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

$$x' = \frac{dx}{dz} = \frac{p_x}{p_z} \approx \theta$$



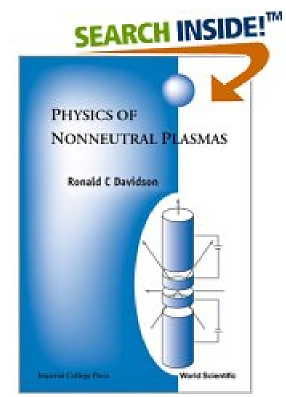


Snapshot of beam in time (*t*) and space (*z*)

= 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?

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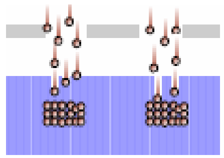
Charged Particle Beam

Industry



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

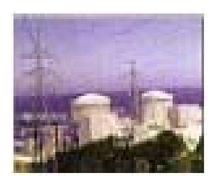
Medicine

- 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

Spallation Neutron Source

Heavy Ion Fusion

Linac Coherent Light Source

High current and intensity are required for various advanced applications

↓

Self-field effects are important

↓

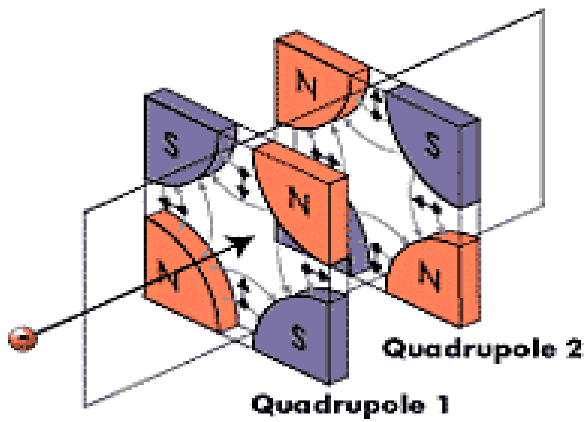
Intense beams

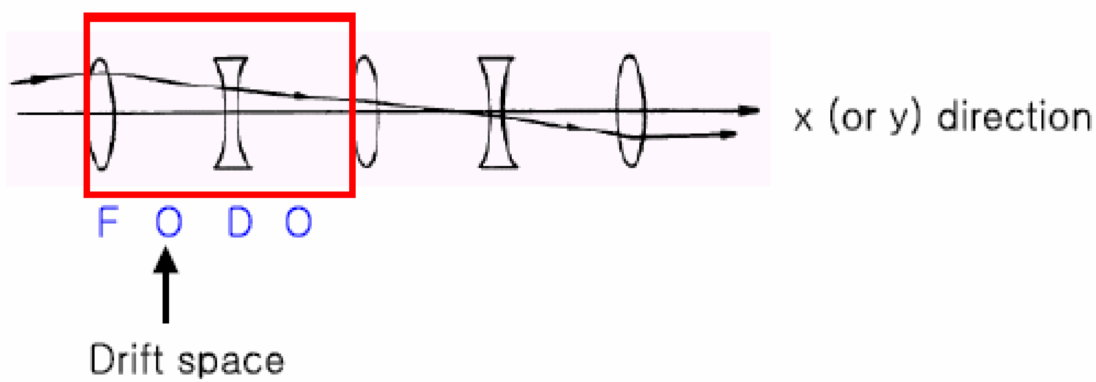
Need to accelerate intense beam for a long distance (~ 1 km)

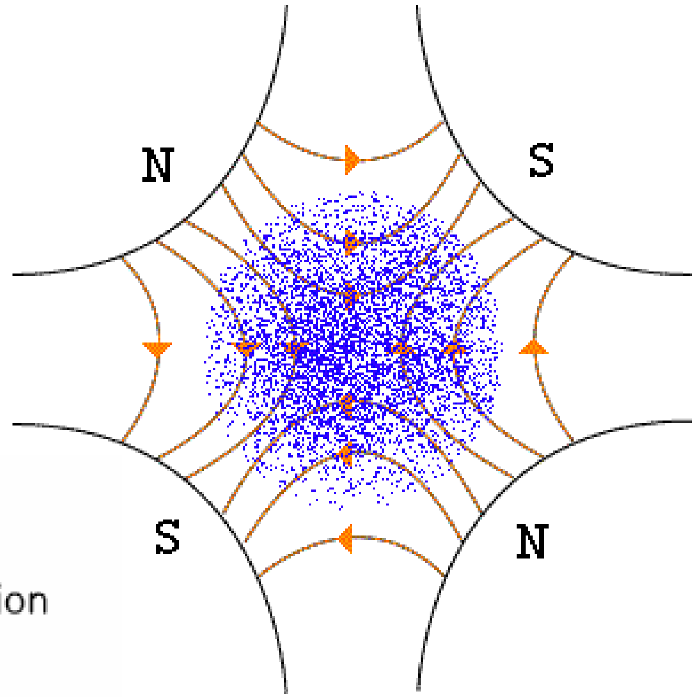
How to Focus Intense Beams ?

Periodic focusing quadrupole magnetic field

= Alternating Gradient (AG) transport system = FODO lattice



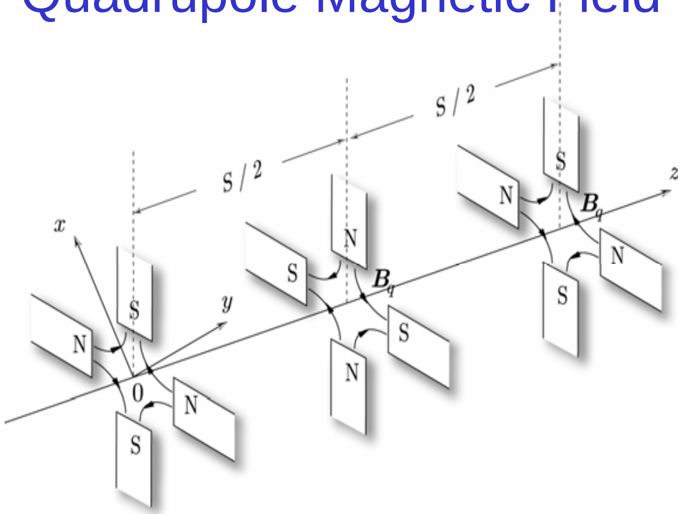




An Intense Beam is a Nonneutral Plasma in the Beam Frame

$$s \ \text{(space)} \rightarrow t \ \text{(time)}$$

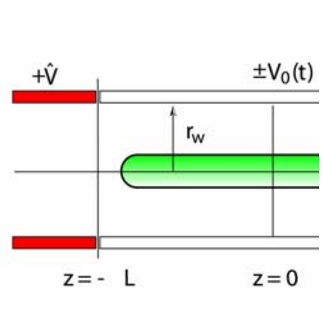
Intense Beam Propagating in Periodic Focusing Quadrupole Magnetic Field

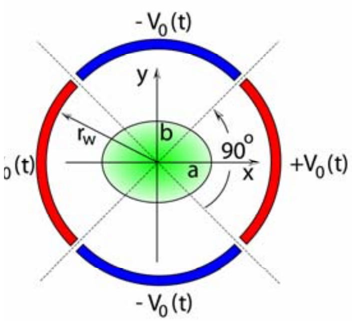


$$H_{\perp}(x, y, x', y', s)$$
$$= \frac{1}{2}(x'^2 + y'^2) + \frac{1}{2}\kappa_q(s)(x^2 - y^2) + \underline{\psi(x, y, s)}$$

Self-field potential

Nonneutral Plasma Trapped in Time Varying Quadrupole Electric Field



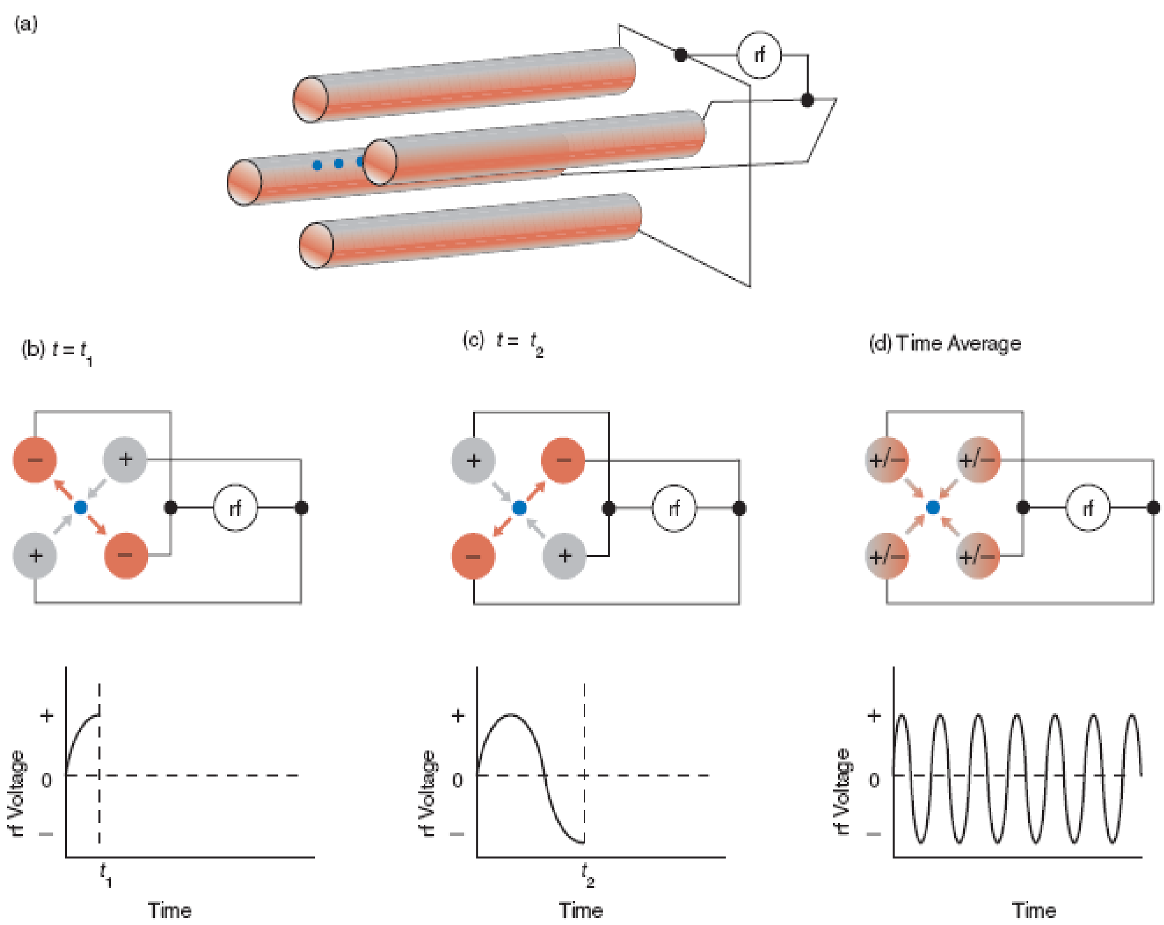


$$H_{\perp}(x, y, \dot{x}, \dot{y}, t)$$
$$= \frac{1}{2}m_b(\dot{x}^2 + \dot{y}^2) + \frac{1}{2}m_b\kappa_q(t)(x^2 - y^2) + \underline{e_b\phi^s(x, y, t)}$$

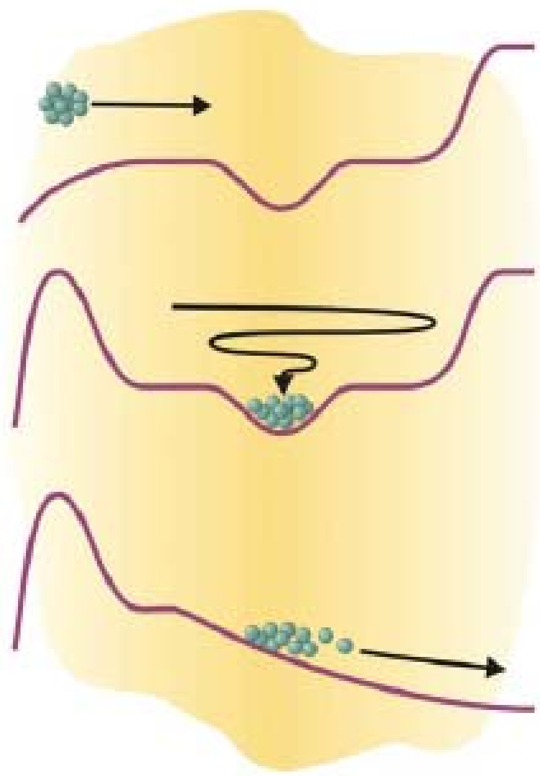
Self-field potential

How Paul Trap Works?

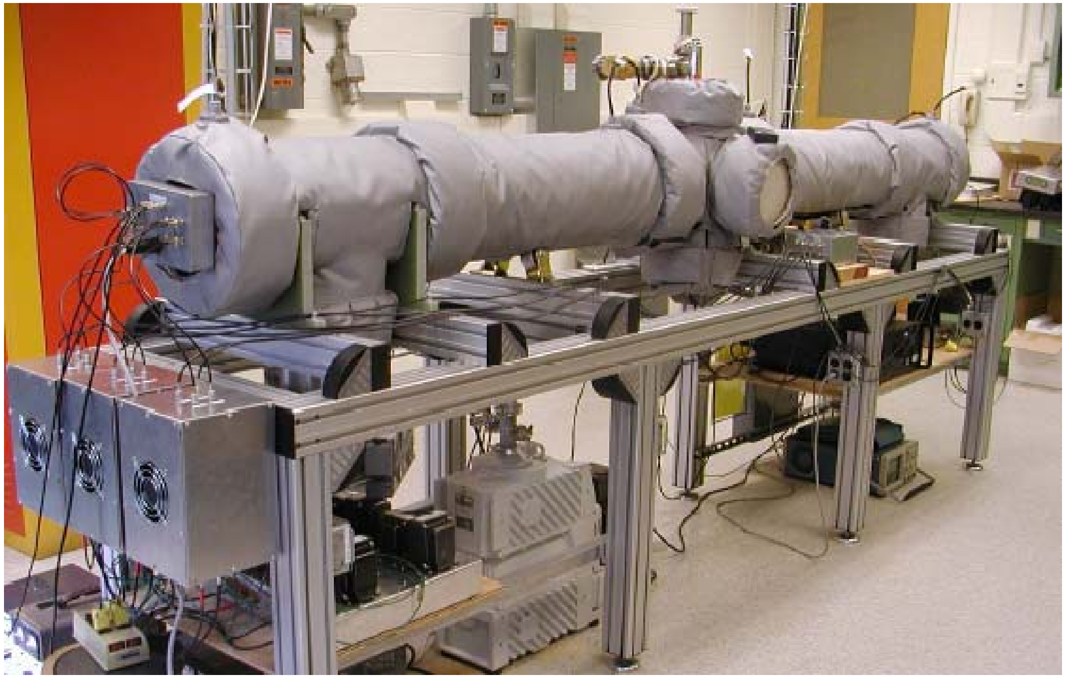
Radial direction



Axial direction



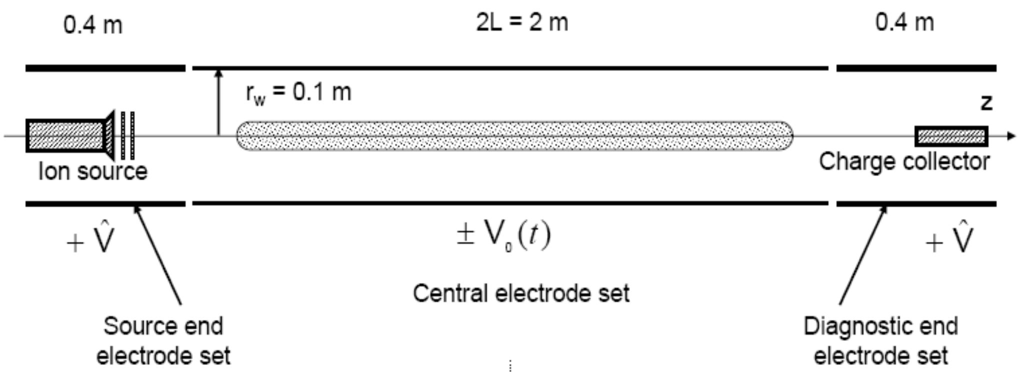
Paul Trap Simulator Experiment (PTSX) Apparatus



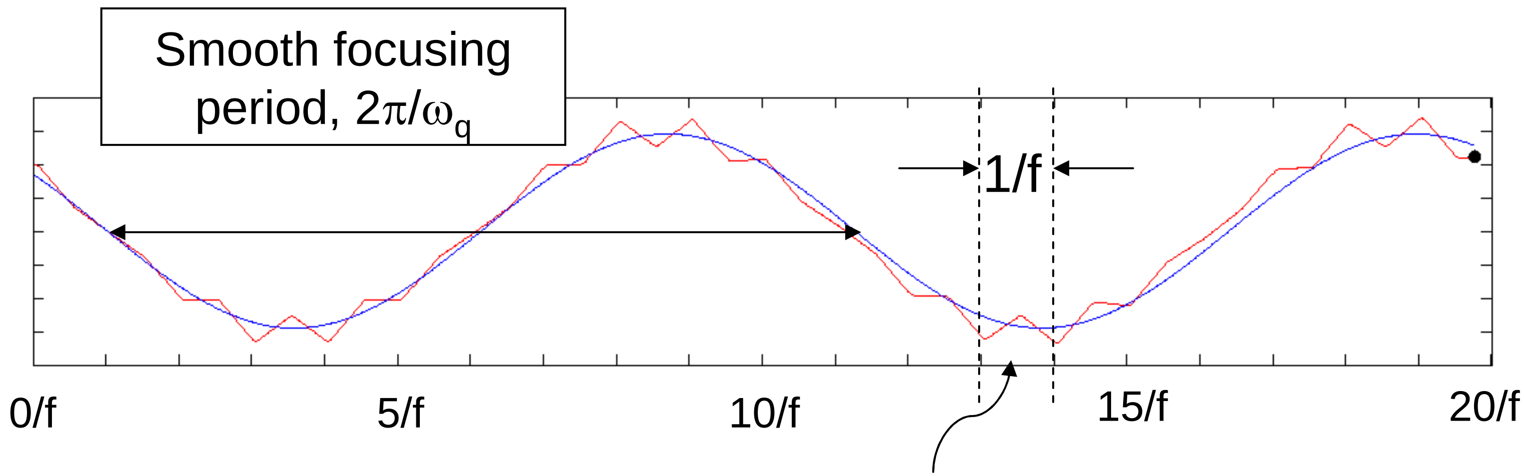
- Pressure $10^{-10} \sim 10^{-8}$ Torr
- Trap Time 1~100 ms
- Density $10^5 \sim 10^6$ cm^{-3}
- End Electrodes (DC)

  36 ~ 150 V
- Central Electrodes (AC)

  f < 100 kHz , V_{0max} < 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 $\sigma_v^{sf} = \frac{\omega_q}{f} < \sigma_{v\max}$ to avoid instabilities.

Normalized intensity parameter $s \equiv \frac{\omega_p^2}{2\omega_q^2} < 1$ to confine the space-charge.

s ~ 0.2 for Spallation Neutron Source.

Cesium Ion Source Has Been Used for the Initial Phase of PTSX

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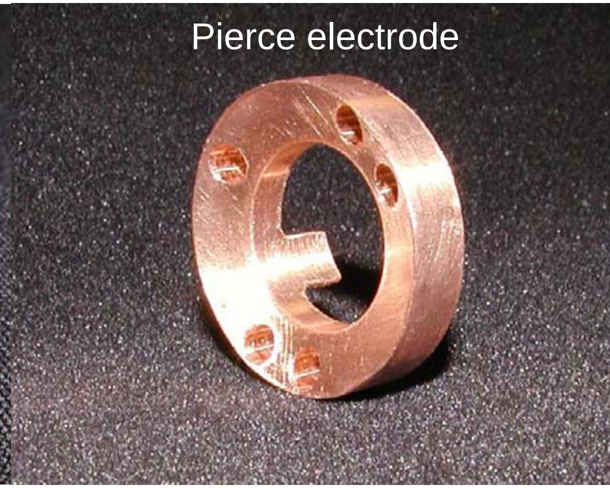


~ 10 A ~ 1000 ^{o}C ~ 0.1 eV

67.5^{o} opening angle

85% transparent electroformed copper mesh

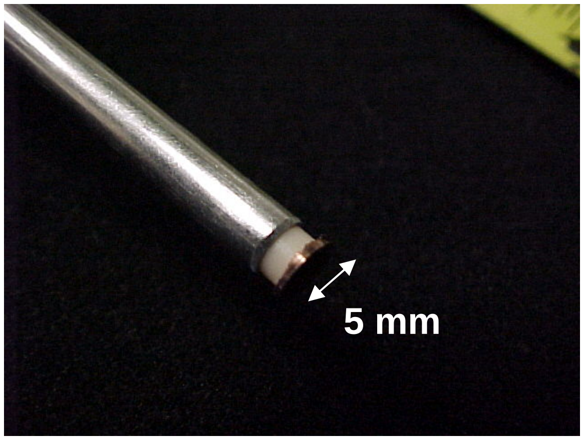
Good enough for low energy beam

Contact ionization of cesium at hot porous tungsten

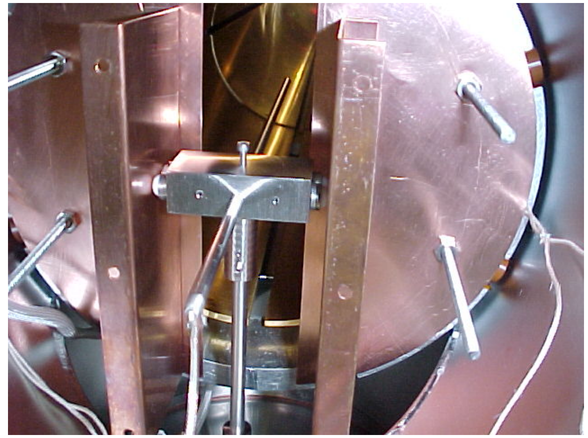
1.25 in

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

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

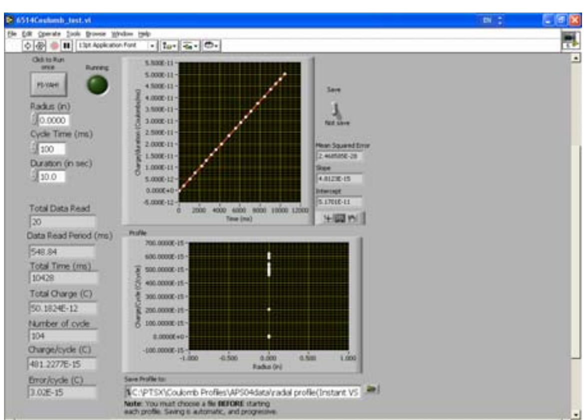


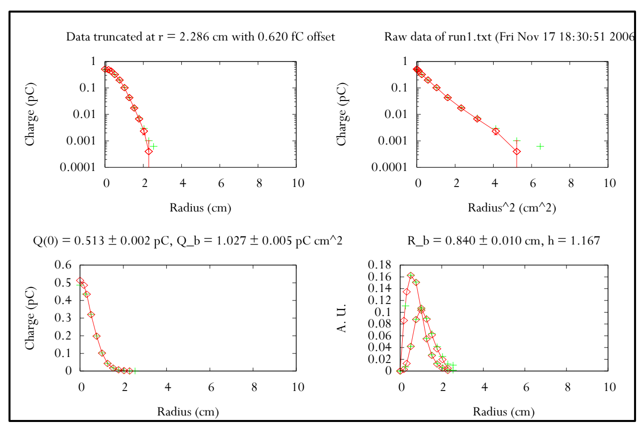
Because of low beam energy, there is no secondary electron emission



Radial scan along the potential null of the quadrupole field

Low level charge measurement (~1 fC)





Rb, Nb

$$m\omega_q^2 R_b^2 = 2kT + \frac{N_b q^2}{4\pi\varepsilon_o}$$

T

emittance

PTSX Has Simulated Several Important Scientific Issues in Accelerator Community

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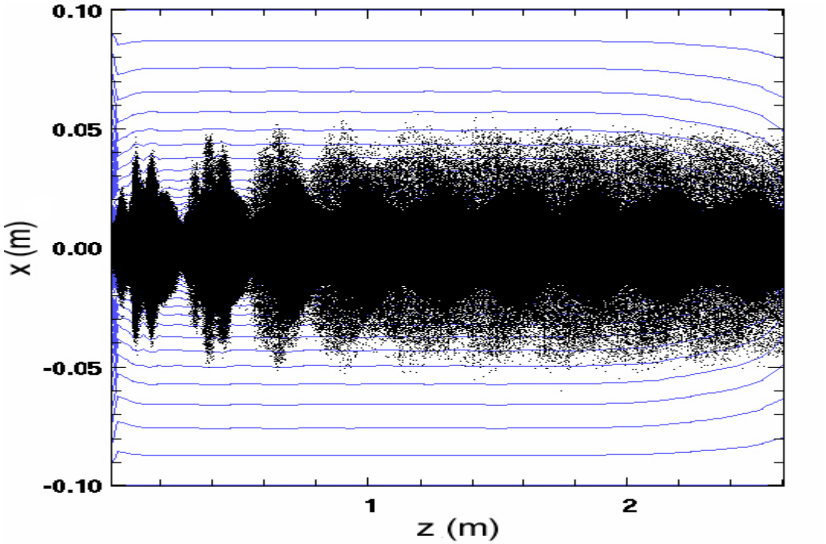
1. **Beam Mismatch**
2. **Transverse Compression**
3. **Random Noise Effect**

Conditions for minimization of halo particle production during transverse compression of intense ion charge bunches in the Paul trap simulator experiment (PTSX), E. P. Gilson and M. Chung et. al. Nuclear Instruments and Methods in Physics Research A, submitted (2006).

Experimental Simulations of Beam Propagation Over Large Distances in a Compact Linear Paul Trap, E. P. Gilson, and M. Chung et. al. Physics of Plasmas 13, 056705 (2006).

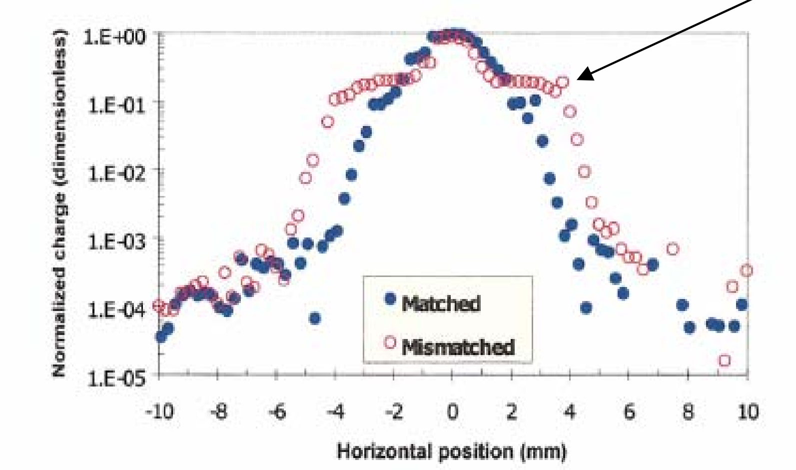
1. Beam Mismatch

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

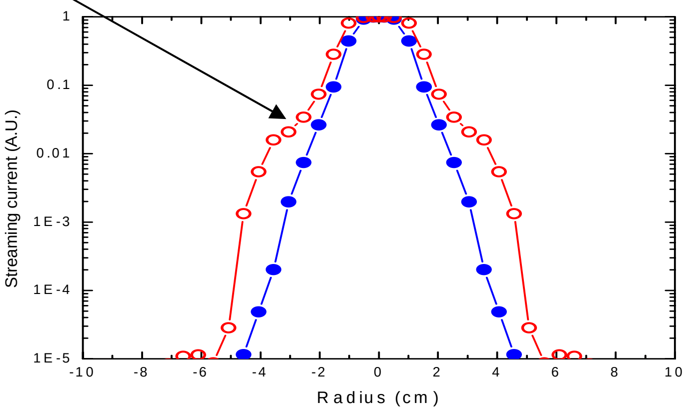


shoulder

In the real accelerator

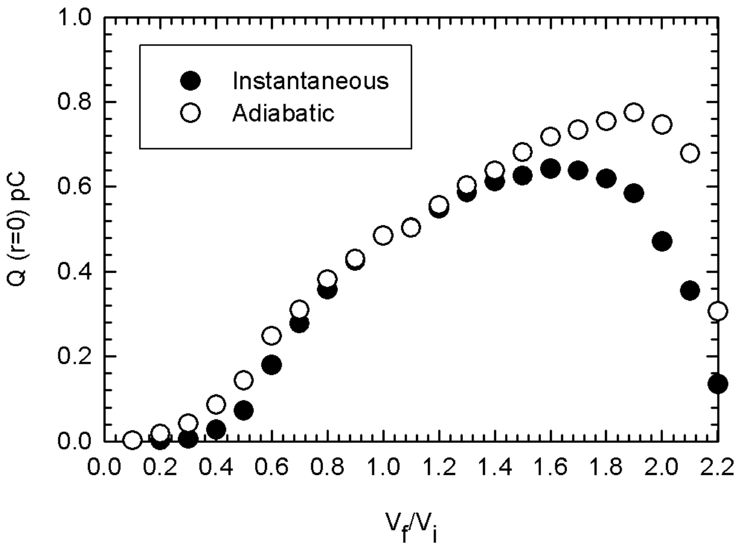


In the PTSX

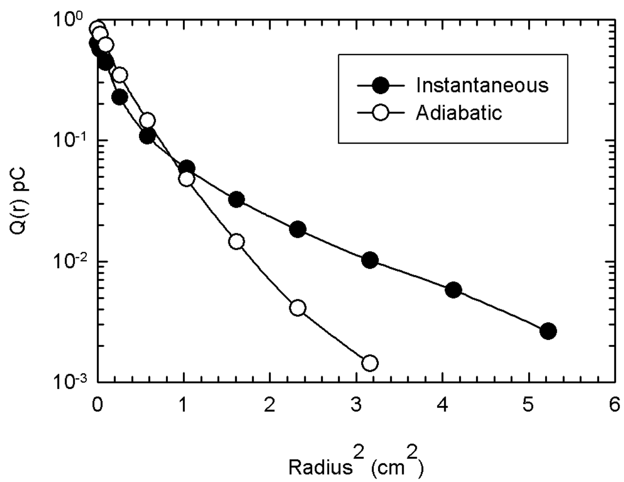


2. Transverse Compression

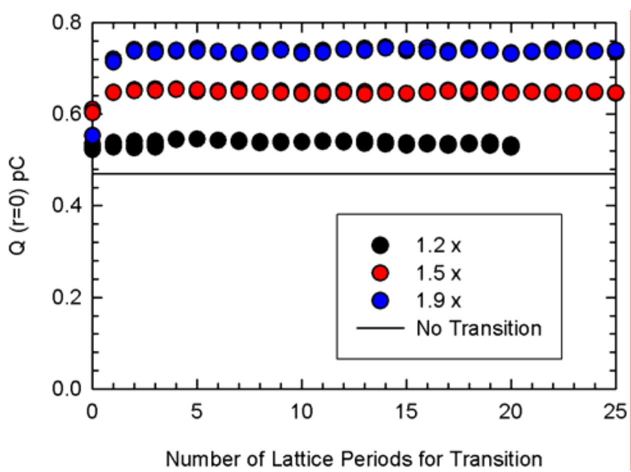
Application of present-generation accelerators require transverse compression of charge bunch to a small spot



What about radial profiles ?



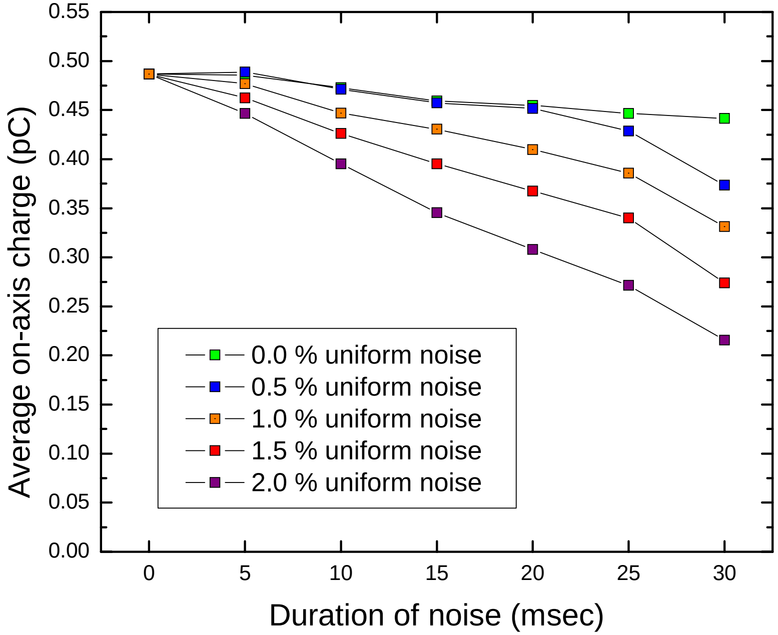
How slow is slow ?

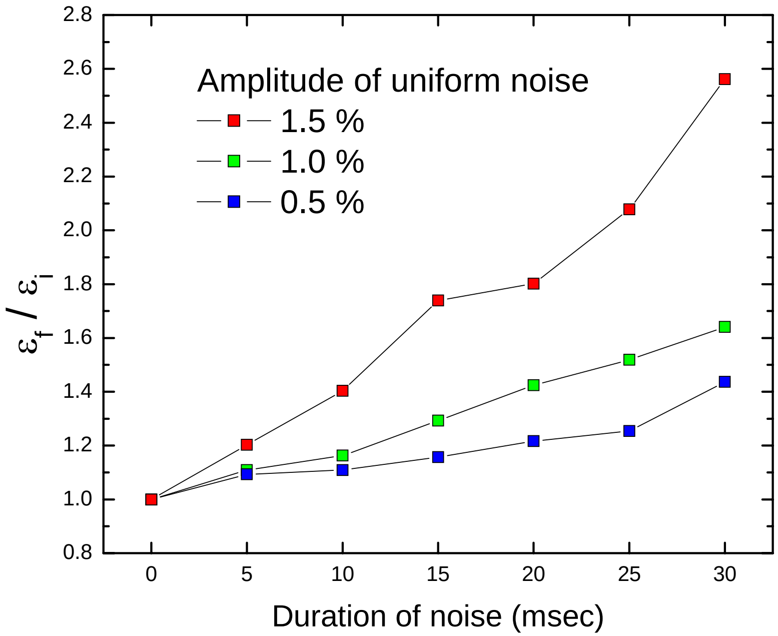


3. Random Noise Effect

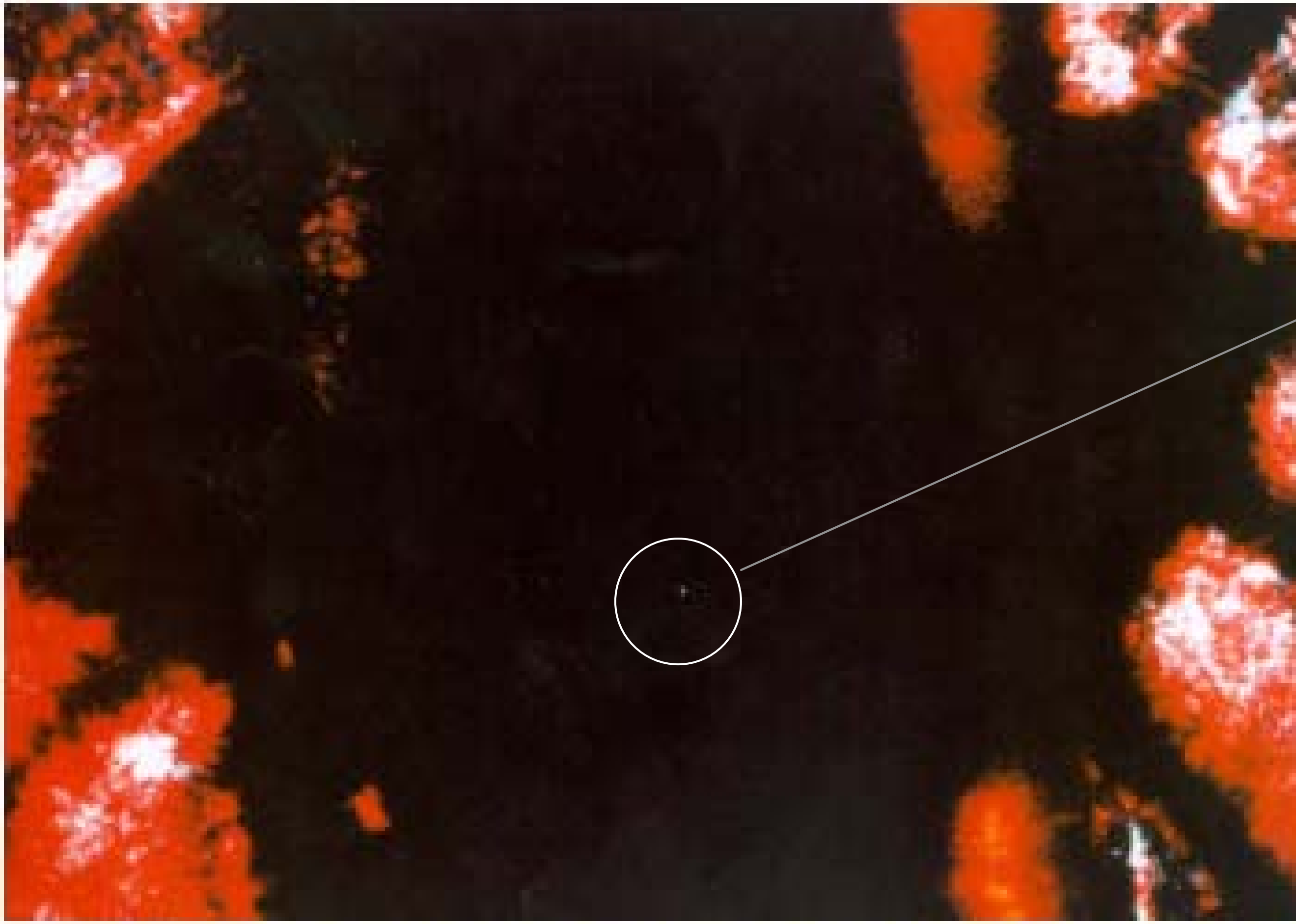
In real accelerators, there are always unavoidable errors on components.

Components	Limit on error
MEBT	1.732 %
DTL	0.5 %
CCDTL & CCL	0.25 %





More Advanced Diagnostic ?

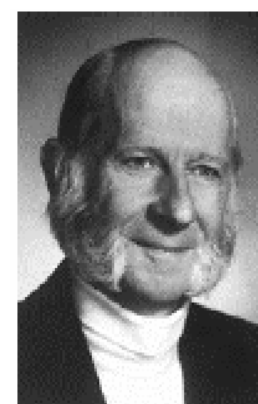


Optical Detection of a Single Barium Ion in a Paul Trap

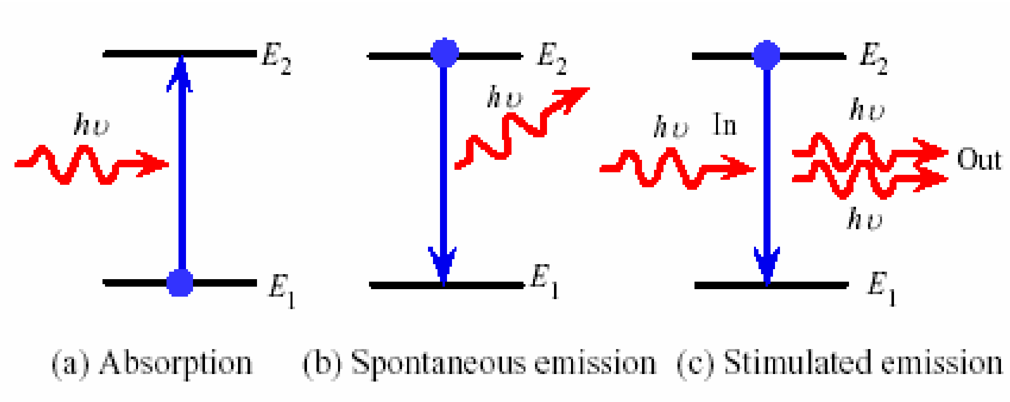
Dehmelt, Toscheck et al.

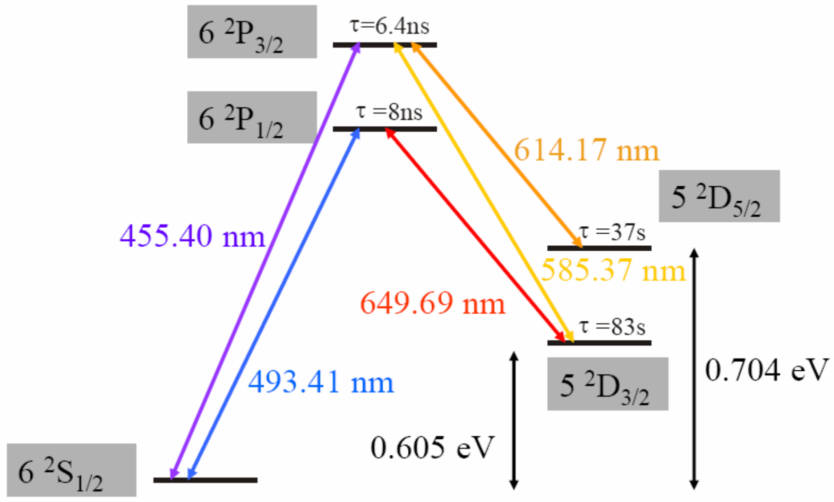
Can we do that in the PTSX too ?

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



Barium Ion's Atomic Structure is Amenable to LIF



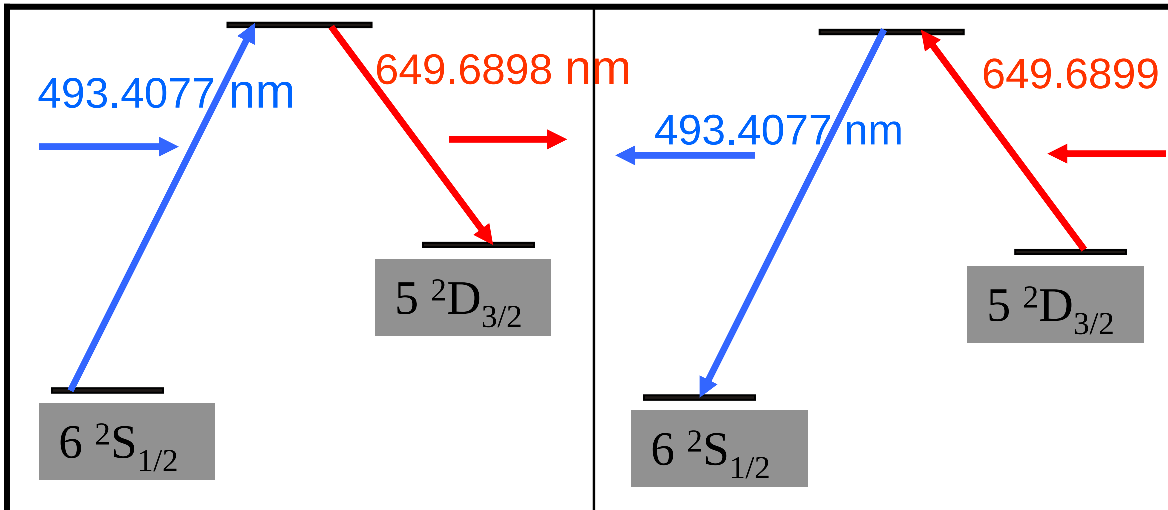


- Barium ions are heavy enough (137 amu) to be confined in the PTSX
- Barium ions are produced primarily in the ground state (6 $^2S_{1/2}$), but some in the metastable states (5 $^2D_{3/2}$, 5 $^2D_{5/2}$)
- Because PTSX does not utilize external magnetic field, there is no Zeeman split
- Because time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

Possible LIF Schemes for Barium Ion

Plan B:

WVU's Dye laser



A_{23}= 33.2 x 10^6 s^{-1}	A_{23}= 95.5 x 10^6 s^{-1}
Quantum efficiency > 40%	Quantum efficiency < 15%
Filter efficiency > 50%	Filter efficiency ~ 45%
Small stray light	Small stray light
Dye : C102 (unstable)	Dye : DCM (stable)
Laser power < 450 mW	Laser power < 800 mW
Density of initial state :	Density of initial state :
10^5 ~10^6 cm^{-3}	< 0.8 % x 10^5 ~10^6 cm^{-3}

Plan A:

Nova Photonics' Dye laser

with DCM

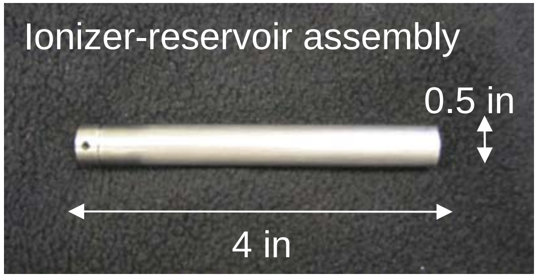
Plan C:

Nova Photonics' Dye laser

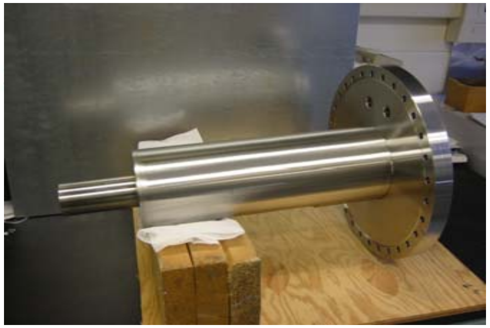
with C102

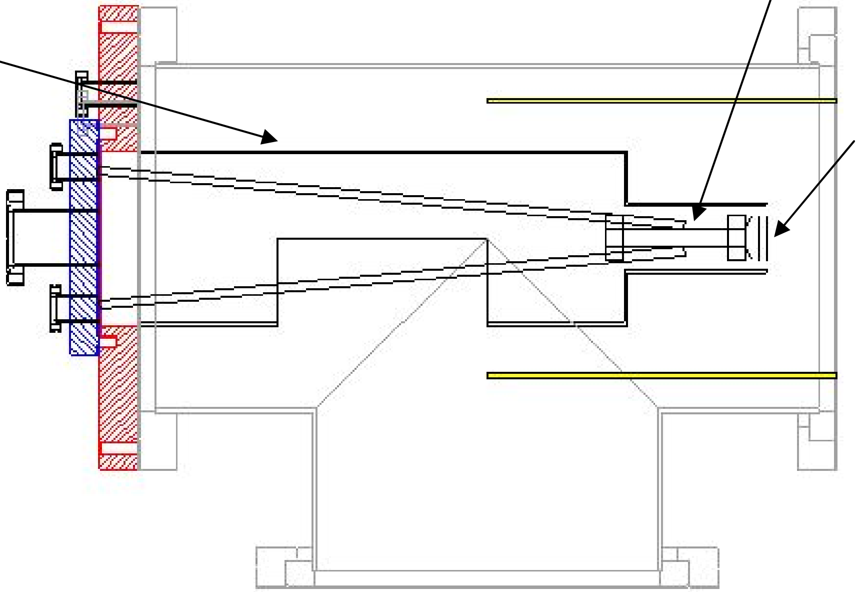
New Compact Barium Ion Source Has Been Developed

- Currents about 100 ~ 200 nA are required to fill up the PTSX
- Ionizer (Pt mesh) will be maintained near 1000 ^oC
- Reservoir (Ta tube) will be maintained above 400 ^oC, 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



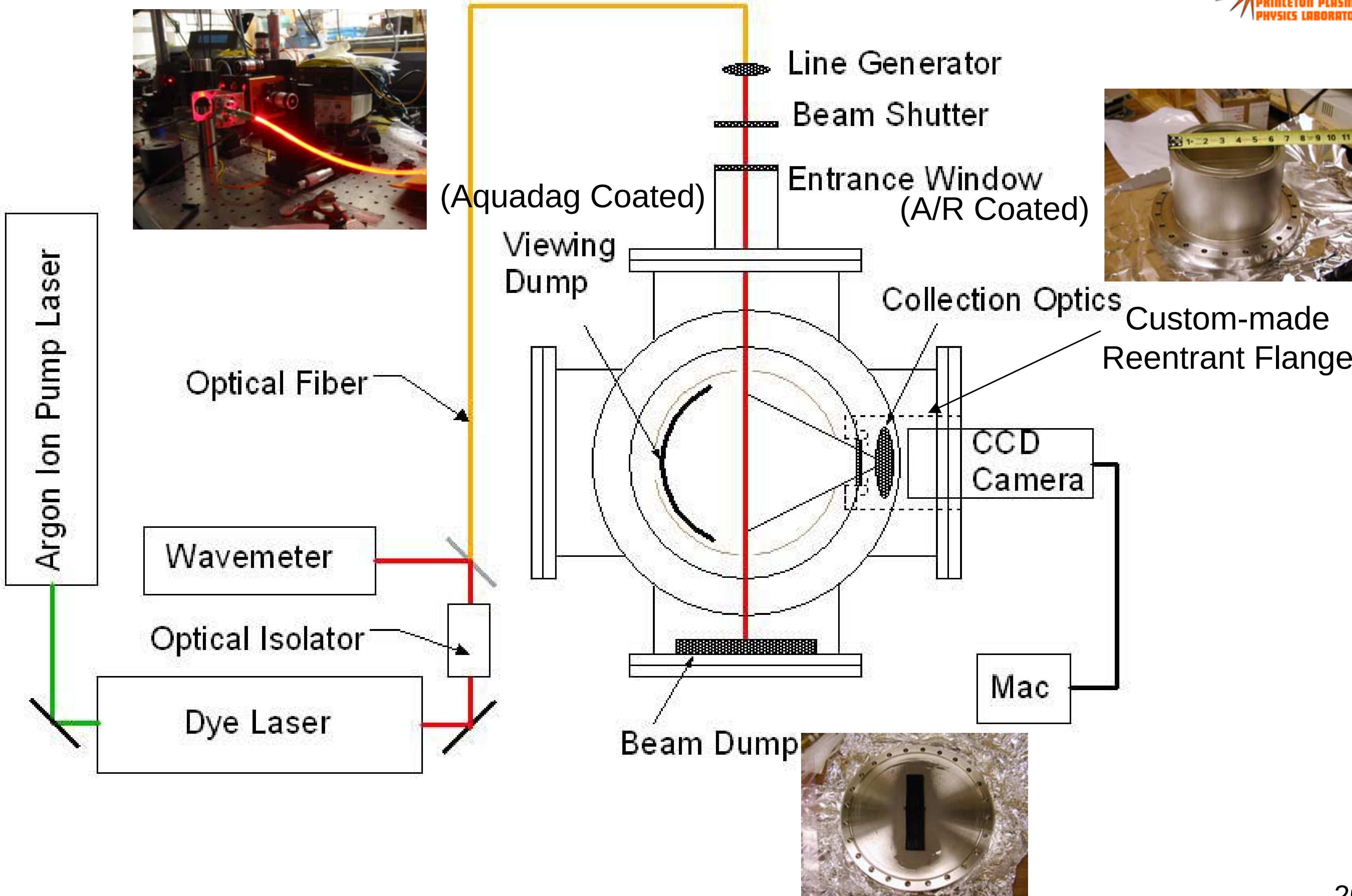
Stainless steel can reduces visible radiation from the hot source and prevents neutral barium from contaminating electrodes





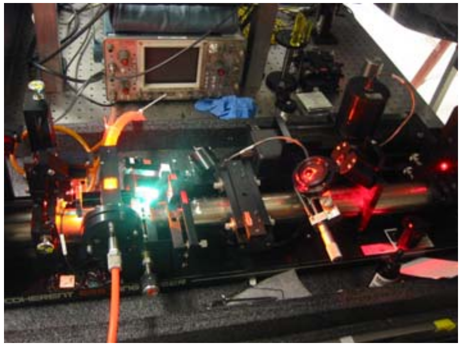
Radius of the source is determined so that beam can be RMS-matched to external focusing field for nominal operating condition of PTSX

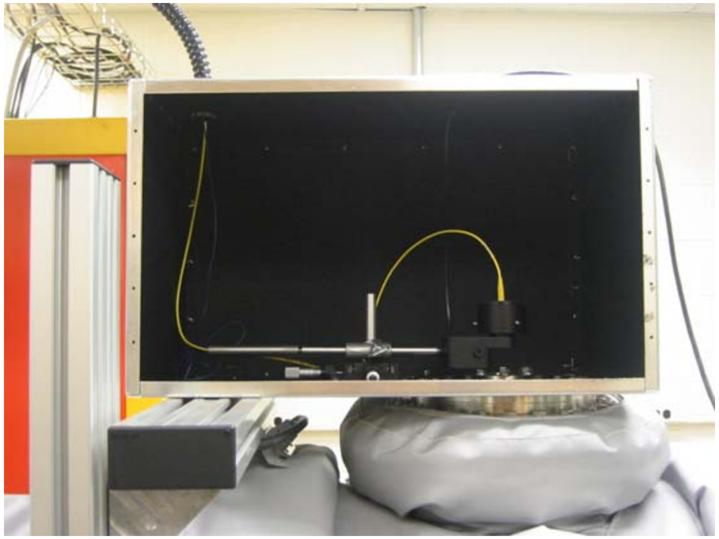
Schematic Diagram of LIF Diagnostic Setup



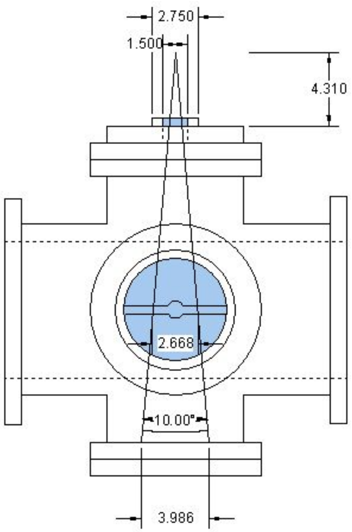
Laser Injection System

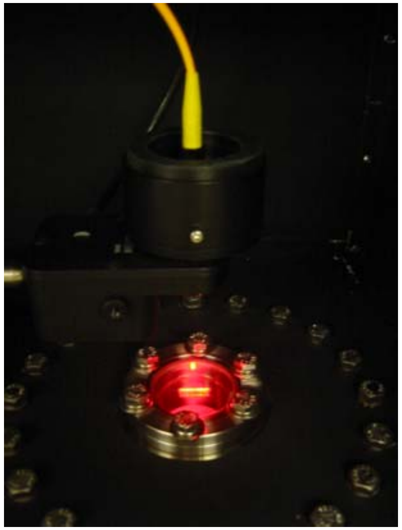
- Coherent 899-21 ring dye laser used for MSE-LIF diagnostic
  - – Optically pumped by an argon ion laser
  - – Dye : Exciton DCM dye for 649.6898 nm transition
  - – Laser linewidth : ~ 2 GHz ~ 0.0025 nm for broadband operation using a three plate birefringent filter (mode-hopping ?)
  - – Laser power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





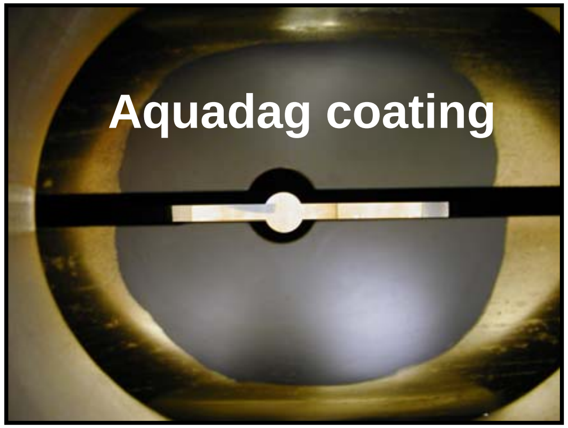
Assembly of the optical fiber, line generator, beam shutter, and x-y translation stage, which is enclosed by a light-tight aluminum box



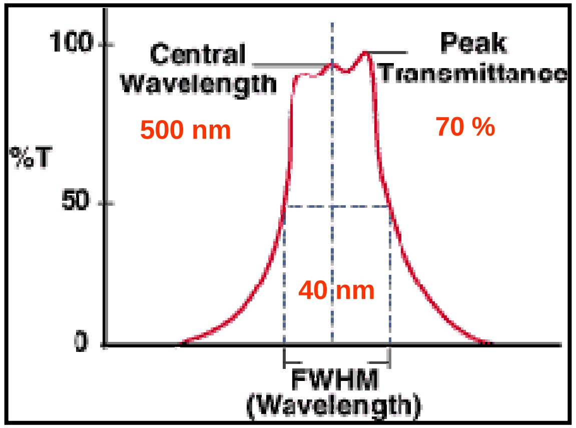


A line generator, which uses a Powell lens, transforms the collimated laser beam into a line with a uniform output intensity

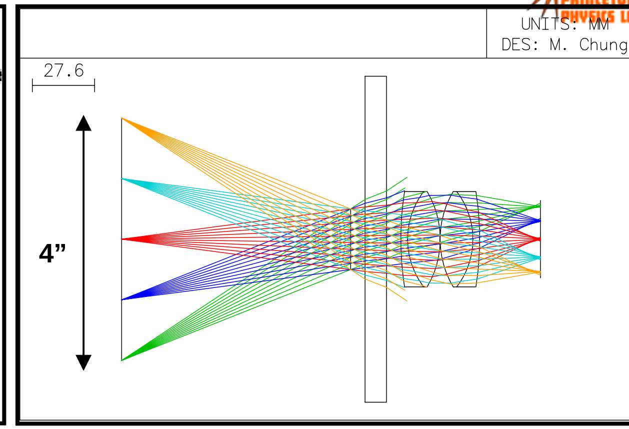
Collection Optics



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



Bandpass filter



Lens Requirements

f < 11 mm , FOV ~ 41^{o} , MOD < 135 mm

Overall efficiency of

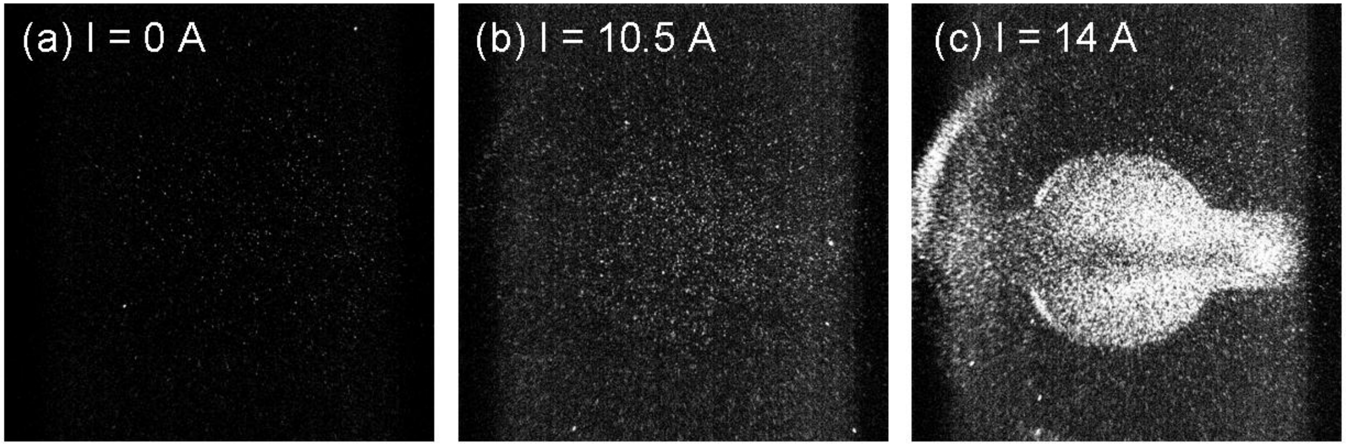
collection optics

~ 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

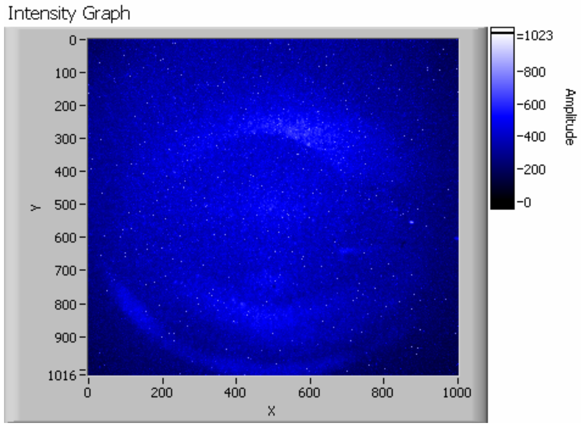
Initial Background Light Measurements

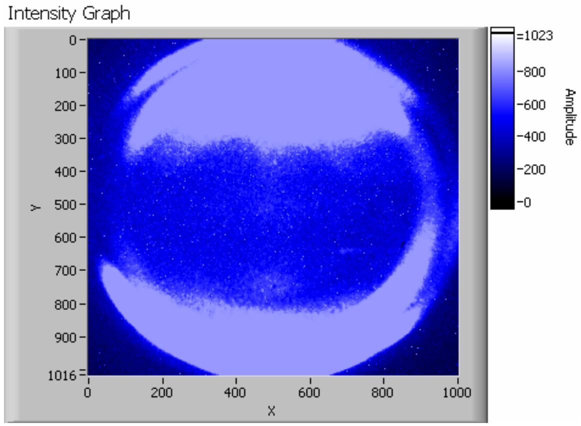
•A glowing red-hot ion source can be a source of background light



•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