PLANNED EXPERIMENTS ON THE PRINCETON ADVANCED TEST STAND*

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Abstract

The Princeton Advanced Test Stand (PATS) is currently being developed as a compact experimental facility for studying the physics of beam-plasma interaction and volume plasma sources for use on the Neutralized Drift Compression Experiment (NDCX). PATS consists of a six-foot-long vacuum chamber with numerous ports for diagnostic access and a pulsed capacitor bank and switching network capable of generating 100 keV ion beams. This results in a flexible system for performing experiments on beam neutralization by volume plasma relevant to NDCX-I/II. Planned experiments include studying beam propagation through a tenuous plasma ($n_p < n_b$). This regime is relevant to final stages of neutralized drift compression when the beam density begins to exceed the plasma density. The experiment will investigate charge neutralization efficiency, effects of plasma presence on beam emittance, and collective instabilities.

INTRODUCTION

In a Heavy Ion Fusion (HIF) driver, an ion beam pulse has to be compressed after the acceleration stage in order to achieve the required power density. To compress high-perveance ion beams with kV transverse self-potentials, a volume plasma can be introduced in the beam path to neutralize the beam space charge. This approach is studied on NDCX-I at Lawrence Berkeley National Laboratory (LBNL). The NDCX-I beamline consists of a 0.35MeV K^+ source, a 4-solenoid transport channel to give the beam a converging trajectory, and an induction gap where a time-dependent electric field slows down the head of the beam and accelerates the tail to impart longitudinal compression. After the induction gap, the beam encounters a plasma-filled drift region. The plasma neutralizes the beam space charge, so the beam can focus on target ballistically. Previous experiments on NDCX-I [1] have achieved 50-fold longitudinal compression and transverse compression to a 1 mm radius on target.

The physics of an ion beam propagating through a plasma is determined by the plasma density n_p, beam density n_b, radius r_b, kinetic energy E_b, and plasma electron temperature T_e. The effect space charge on the beam is characterized by dimensionless perveance Q:

$$Q = \frac{2\pi e^2 Z^2 n_b r_b^2}{\gamma^3 M_i V_b^2} \quad (1)$$

where e is the electron charge, Z is the charge state of the beam ions, M_i is the beam ion mass, V_b is the ion velocity, and γ is the relativistic factor. Conditions for good charge and current neutralization have been derived analytically [2]. It was found that good charge neutralization requires for the beam pulse duration τ_b to be much longer than the plasma period:

$$\tau_b \omega_{pe} \gg 1 \quad (2)$$

where ω_{pe} is the electron plasma frequency. For good current neutralization it was shown that the beam radius should be greater than the plasma electron skin depth ($r_b \gg \delta_p = c/\omega_{pe}$).

The effect of an axial magnetic field has been considered [3], and it was shown that a qualitative change occurs in the neutralization dynamics magnetic field strength satisfies the condition:

$$\omega_{ce} \gg \beta \omega_{pe} \quad (3)$$

where ω_{ce} is the electron cyclotron frequency and $\beta = V_b/c$ is the relativistic factor. including the appearance of a collective focusing force. These effects are relevant to NDCX due to the fringe fields of the 8 Tesla final focus solenoid present inside the plasma-filled drift channel.

Other important effects include plasma mode generation and beam emittance growth, which degrade focusing. Experimental studies of various aspects of beam-plasma interaction are important to NDCX-I/II and future neutralized drift facilities. Since analytical results depend on dimensionless parameters such as n_b/n_p, it is possible to scale parameters on a small experiment to study physics relevant to large HIF facilities such as NDCX-I/II. Currently such a facility, called the Princeton Advanced Test Stand (PATS) is being developed at PPPL.

THE PRINCETON ADVANCED TEST STAND

The Princeton Advanced Test Stand (PATS) is based on the apparatus that was the STS-100 test stand (Fig. 1). STS-100 previously operated at LBNL where it was used for ion source development. It consists of a multicusp RF ion source mounted on a large vacuum chamber, and a 100 nF capacitor bank capable of being charged to 100 kV for driving the beam current. The capacitor bank is switched on and off by two triggered spark gaps. The spark gaps are triggered by 50 kV and 100 kV Maxwell trigger generators which allow sub-ns timing of the beam extraction. The 13.56 MHz multicusp RF ion source is driven by a 20 kW compact oscillator and has been used with different gases (Ar, H, He, O_2) to produce current densities of up to 50 mA/cm^2.

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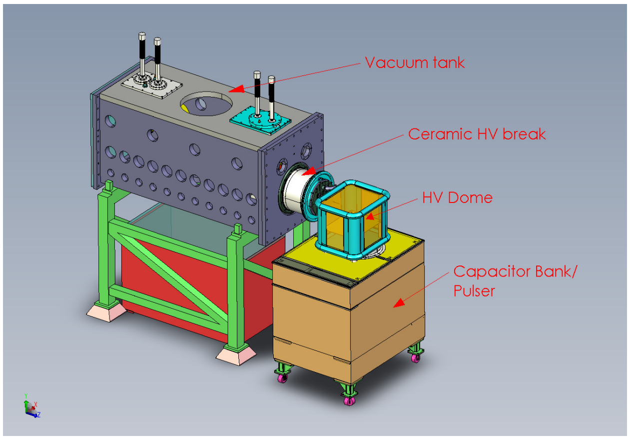

Figure 1: A drawing of the PATS configuration, showing the capacitor bank, HV dome and the large ($6' \times 2.5' \times 2.5'$) main chamber with numerous ports.

STS-100 is being rebuilt into a platform for studying the neutralization of an ion beam by a volume plasma in support of the NDCX-I project at LBNL. Neutralizing plasma on PATS will be produced by ferroelectric plasma sources (FEPS) [4] that are developed at PPPL for use on NDCX. Thus, the research on PATS will also provide opportunities for improving FEPS performance, with immediate benefits to NDCX. While the capabilities of PATS will be different than NDCX-I, it is still possible to study relevant beam physics by investigating the parametric relationships that define the processes of charge and current neutralization. Furthermore, in some cases it will be possible to operate with beam-plasma dimensionless parameters that match those on NDCX, or even heavy ion fusion driver configurations.

It is evident that PATS is a flexible platform for performing a wide range of experiments that will be of interest to the NDCX effort. The PATS beamline will involve an ion beam passing through a FEPS source. Diagnostics before and after the plasma source will measure its effect on the beam, such as the extent of emittance growth for specific beam and plasma parameters. In order to carry out such experiments in a well-controlled manner, the beam parameters (n_b, r_b, E_b) must be controlled independently. This capacity will be developed on PATS by adding two elements to the beamline: extraction optics with variable gap spacing, and a compact Electrostatic Quadrupole Lattice (ESQ).

Electrode with Variable Gap Spacing

The ion current that can pass through a diode gap d with an applied voltage V is given by the Child-Langmuir law:

$$j_{CL} = \frac{4\epsilon_0}{9}\sqrt{\frac{2Ze}{M_i}}\frac{V^{3/2}}{d^2} \tag{4}$$

where ϵ_0 is the electric constant. A system of extraction electrodes will be built, where d is variable in order to control the current independently of the accelerating potential. Correspondingly, changing d will control the beam perveance Q and particle density n_b. Thus, it will be possible to produce beams with a wide range of perveances but with the same beam velocity. For instance, with V=100 kV, changing d from 5 cm to 10 cm will change j_{CL} from 11 mA/cm^2 to 2 mA/cm^2. A set of attainable parameters is shown in Table 1.

Table 1: Beam parameters attainable with the tunable extraction gap.

	β	r_b [cm]	I_b [mA]	Q	n_b [cm^{-3}]
K+	2.3×10^{-3}	0.14	9	1.2×10^{-3}	1.3×10^{10}
K+	2.3×10^{-3}	0.14	2	2.6×10^{-4}	2.9×10^{9}
K+	2.3×10^{-3}	1	9	1.2×10^{-3}	2.6×10^{8}
H+	1.5×10^{-2}	0.14	40	8.2×10^{-4}	9.3×10^{9}

ESQ Lattice

A compact 6-element ESQ lattice with an aperture radius of 5 cm based on the design presented in [4] will be built. ESQ focusing is effective for slow heavy ion beams ($\beta < 1.67 \times 10^{-2}$) and they are relatively simple to design and construct. The purpose of the ESQ lattice is to focus the beam to some desired radius and convergence angle at the FEPS entrance (Fig. 2). Altogether, varying the gap spacing d will control the beam perveance, while the ESQ lattice will shape the beam envelope. This combination gives the control and flexibility needed for the parametric studies planned on PATS. For instance, for studying the effect of n_b/n_p on charge neutralization, it will be possible to vary n_b while keeping r_b constant at the FEPS entrance.

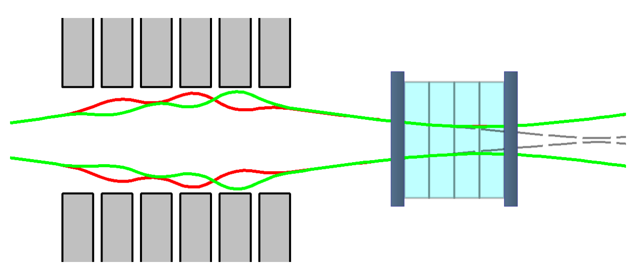

Figure 2: Envelope solution for PATS ESQ lattice, with $Q = 0.5 \times 10^{-3}$, $\epsilon = 160$ mm mrad for producing a convergent beam. After the lattice the beam passes through a FEPS element, where it is neutralized ($Q \to 0$, dashed line). Downstream of the FEPS, the neutralized spot size is 1.3 mm, and the unneutralized spot size is 3.5 mm.

OVERVIEW OF PLANNED EXPERIMENTS

Charge Neutralization

Good charge neutralization is predicted for $\tau_b\omega_{pe} \gg 1$ and is independent of the beam density, meaning that the beam space charge can be effectively neutralized even with a tenuous plasma ($n_p \sim n_b$). Understanding the tenuous plasma regime is important for future HIF facilities that will produce beam pulses of increasing density that will begin to approach the plasma density produced by available plasma sources.

This experiment will study how the effectiveness of charge neutralization depends on n_b/n_p. A robust method for assessing if a beam is well-neutralized involves launching a converging beam into a FEPS element and measuring the beam spot size some distance downstream of the plasma source. In the absence of plasma, a beam with a reasonably high perveance ($Q \sim 5 \times 10^{-4}$) will expand strongly after reaching its waist point, so the effectiveness of neutralization can be assessed by comparing the spot sizes of the beam with and without the plasma.

By varying the source extraction gap and the ESQ lattice elements, to produce convergent beams of varying n_b but constant radius at the FEPS entrance. Reaching a regime where $n_p \sim n_b$ require operating with high beam perveance which is restricted by the ESQ lattice. The maximum n_b attainable on PATS is about 10^{10} cm^{-3}, which corresponds to a 9mA 100kV Ar+ beam with $Q = 1.2 \times 10^{-3}$ focused to a 3mm diameter spot. Therefore the available parameter range is from $n_p \gg Zn_b$ to $n_p \sim Zn_b$.

Effects of Axial Magnetic Field

It was shown that an axial magnetic field has a qualitative effect on beam dynamics inside a plasma if the field strength satisfies $\omega_{ce} \gg \beta_b\omega_{pe}$. For a 100 kV Ar$^+$ beam with $\beta_b = 2.3 \times 10^{-3}$ and $n_p = 10^{11}$ cm^{-3} this minimum field strength is about 2 Gauss. In order to study this effect on PATS it will be necessary to operate with higher β_b, which is possible by producing an H$^+$ beam in the multicusp RF source.

For a 100 keV H$^+$ beam and $n_p = 10^{11}$ cm^{-3}, the minimum magnetic field strength given by condition (3) is 15 Gauss. The radial inward force due to the collective focusing effect is given by [5]:

$$F_r = Z_b^2 m_e V_b^2 \frac{1}{n_e}\frac{dn_b}{dr} \quad (5)$$

This force is due to a collective response of the magnetized plasma electrons, and its magnitude does not depend on the strength of the applied magnetic field. For a FEPS plasma with $T_e \sim 3$ eV the electron Larmor radius is 1.2 mm for $B_0 = 50$ Gauss.

An order-of-magnitude estimate shows that collective focusing can be observed for the beam and plasma parameters attainable on PATS. The magnitude of the collective focusing force F_r can be compared to the radial force F_E due to the self-electric field of the beam, where $F_E = e^2 n_b r_b/2\epsilon_0$, and $F_r \simeq Z_b^2 m_e V_b^2 n_b/n_p(1/r_b)$ assuming that $n_e \sim n_p$ and $dn_b/dr \sim n_b/r_b$. Thus,

$$\frac{F_r}{F_E} = \frac{2\epsilon_0 m_e V_b^2}{n_p e^2 r_b^2} \quad (6)$$

For a 100 kV H$^+$ beam with $r_b = 0.25$ cm and $n_p = 10^{10}$ cm^{-3}, $F_r/F_E \sim 0.19$. Thus the collective focusing force will be comparable to the electrostatic self-force, so this effect can be observed experimentally on PATS. This will require operating with a high-perveance ($Q \sim 6 \times 10^{-4}$) H$^+$ beam, as well as developing a method for producing a FEPS discharge in a solenoidal magnetic field. The experiment will measure the effect of the collective focusing and its dependence on the strength of the axial magnetic field and on the beam and plasma parameters.

CONCLUSIONS

The Princeton Advanced Test Stand is an experimental platform under development at PPPL as a flexible platform for studying the physics of neutralized drift compression relevant to NDCX-I/II. The ion beam parameters (n_b, r_b, E_b) on PATS will be controlled independently, making it attractive for parametric studies of beam neutralization. It is planned to study charge neutralization and emittance growth for varying n_b/n_p, with a particular interest in the tenuous plasma regime ($n_b \sim n_p$). Other experiments will investigate neutralization in an applied axial magnetic field, such as the proposed collective focusing effect.

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