White Paper for *Frontiers of Plasma Science Panel*

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Oral	X
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Either Oral or Poster	
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Title:	Nonneutral Plasmas and the Physics of Intense Charged Particle Beams
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**(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)**

- ***Describe the research frontier and importance of the scientific challenge.***

The field of single-component, nonneutral plasmas has a lengthy history of computer simulations, theory and experiments working together to advance the understanding of plasma physics in many broad and diverse areas. In these plasmas, the inherent large space-charge forces lead to a wide range of self-organization phenomena. For example, research has been carried out on: wave-particle interactions [1]; rotational pumping [2]; long range $\boldsymbol{E}\times\boldsymbol{B}$ drift collisions [3]; asymmetry-induced and resonant particle transport [4,5]; the effect of separatrices on transport and mode damping [6]; 2D inviscid fluid dynamics and vortex dynamics [7]; Coulomb crystals [8]; autoresonant excitation and control of nonlinear oscillators [9]; screening enhancement of nuclear reaction rates [10]; the physics of toroidal confinement [11], including stellarator configurations [12]; pair plasmas [13]; and the manipulation of antimatter plasmas [14], to mention a few examples.

Charged-particle beams are bounded nonneutral plasma systems in which the particles are moving together in the laboratory frame of reference [15]. In many cases, the self-electric and self-magnetic field effects of the charge bunch can be neglected and the dynamics of charged-particle beams can be treated as

a collection of non-interacting particles moving through a transport system. However, the research frontier lies in developing an improved understanding of the dynamics of intense charged-particle beams where the self-field effects are important and the dynamics become nonlinear. Key scientific questions include:

How can intense charged-particle beams be transported over long distances while maintaining high brightness and low emittance?

What are the mechanisms of emittance growth and halo particle production, and can they be controlled or mitigated?

Can nonlinear transport systems be developed to manipulate or control the phase space of charged-particle beams?

Intense beam dynamics is a cross-cutting topic in plasma science that is an excellent example of the synergy between pure and applied research that impacts areas such as: the physics of nonneutral plasmas, the manipulation of antimatter for probes of the Standard Model [16], accelerator-driven high energy density laboratory plasmas [17], ion-driven inertial fusion energy [18], the intensity frontier in high energy physics [19], and accelerator development for nuclear physics applications.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

While, in principle, these key scientific questions could be addressed in large accelerator facilities or with advanced numerical simulations, in practice those approaches are not straightforward. Large accelerator facilities lack the flexibility to carry out these studies without disrupting users, and even modern simulation methods and computational resources may not fully capture the relevant physics. Therefore, the approach to advancing the frontier is to carry out experiments in small, nimble laboratory experiments with sufficient diagnostics and with the support of numerical simulations. Research tools include linear Paul traps that are used to simulate the transverse dynamics of intense beams, the University of Maryland Electron Ring (UMER), and Malmberg-Penning traps containing positrons that are used to create low-energy positron beams. Note that in each of these cases, extensive use is made of codes, such as the WARP particle-in-cell code, to compare experimental results with and to aid in extending experimental results to infer quantities that are inherently difficult to measure.

The Paul Trap Simulator Experiment (PTSX) at the Princeton Plasma Physics Laboratory is a compact laboratory experiment that places the physicist in the beam's frame of reference since the temporally-periodic quadrupole electric fields of a linear Paul trap are the Lorentz transformations of the spatially-periodic quadrupole magnetic fields of an alternating-gradient transport system [20]. Moreover, the self-electric field of the charge bunch in a linear Paul trap is the analog of the combined self-electric and self-magnetic fields of a charge bunch in a transport system. Varying the amount of charge injected into the trap allows studies to be carried out with equivalent beams that are moderately intense. Precise computer control of the applied voltage waveform to the Paul trap walls over thousands of lattice periods enables PTSX to study long distance propagation of intense beams in linear transport systems, or multi-turn transport in ring systems. For example voltage waveform manipulation has been used to study: beam compression [21]; and the effects of injection mismatch, random noise, and coherent periodic perturbations on emittance growth and halo particle production [22].

The UMER facility is a scaled model of a high intensity ring that injects electron bunches with space charge intensities ranging from weak to strong [23]. The charge bunches are confined transversely by alternating quadrupole magnetic fields generated by electromagnets fabricated from flexible circuit board

materials. Successful multi-turn operation has enabled experiments to be carried out on emittance growth and halo particle production from injection mismatch and long-distance propagation. The effects of space charge on longitudinal dynamics have been studied, including de-bunching and induction focusing, the creation of soliton wave trains [24], and streaming instabilities when the charge bunch expands longitudinally to fill the circumference of the ring [25].

Future work using PTSX would benefit from improved ion source capabilities and applied voltage waveform systems in order to reach the regime of strong space charge. Additional diagnostic capabilities, such as time-resolved laser-induced fluorescence, would allow the physics of halo particle generation and mitigation to be studied in greater detail. Upgrading the PTSX electrodes by subdividing the four electrodes into many more would enable the study of rotating field configurations where the x and y transverse emittances are coupled, and the study of higher-order multipole fields for both understanding the excitation of collective beam modes and for understanding how to use nonlinear fields for the stable transport of intense beams.

Future work using UMER would benefit from the installation of an extraction section that would enable detailed measurements of the 6D phase space of the beam. Improved diagnostics, such as capacitive beam position monitors or beam current monitors, are important for measuring the beam orbit and higher-order beam moments for characterization and control of the UMER beam. This characterization and control, in turn, is important for studies of nonlinear lattices designed to transport intense beams.

Malmberg-Penning traps, such as those used by Surko *et al.*, are used to create high-quality positron beams [26]. Trapped positrons are accumulated, compressed, and cooled to create high-density single-component plasmas that serve as reservoirs for low-emittance positron beam extraction [27]. In contrast to the efforts of experiments such as PTSX and UMER that place a strong emphasis on minimizing beam degradation during transport, these experiments are focused on the initial creation of a high-quality beam. Important results have included understanding how to use apertures and grids in high-permeability foils to extract positron beams from the strong magnetic field within the Malmberg-Penning trap into regions of field-free space with minimal emittance growth [28]. Future work would include the continued development of multi-cell traps that are designed to increase the overall number of positrons that can be stored in a trap.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

The study of nonneutral plasmas and the physics of intense charged particle beams strongly impacts the field of plasma science because these are systems where the strong self-fields lead to complex nonlinear dynamics when considered together with the external fields that provide the dynamically stable confinement. An improved understanding of the physics leading to self-organization in these systems will benefit plasma science in general. This research has a strong impact on accelerator science since the stable transport of intense beams is one of the most important issues facing modern accelerators. In many cases, beam losses are a key factor in design trade-offs and therefore a cost driver in large machines. Intense beam dynamics play important roles in machines such as an electron-ion collider (EIC) and accelerator-driven sub-critical reactor systems (ADS). In nuclear physics, electron beam quality is of utmost importance. Accelerators have broad societal benefits including their use in medical treatments, the production of medical isotopes, spallation neutron sources for materials and biological research, and high-energy particle physics. The continued development of the generation of high-quality positron beams is important for research on pair plasmas, and on antihydrogen formation, which, in turn, enables precision tests of the charge/parity/time-reversal (CPT) symmetry of the Standard Model.

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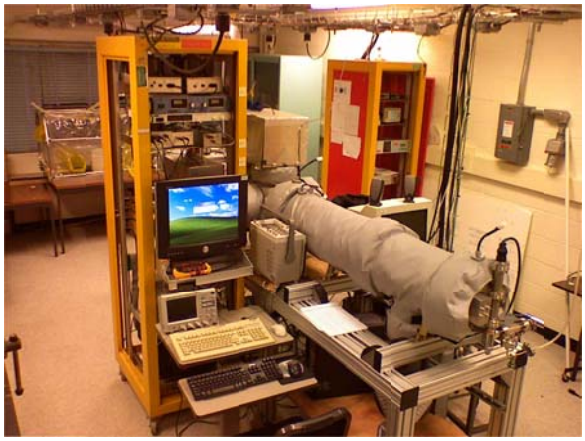

Figure 1. The Paul Trap Simulator Experiment (PTSX) is a compact laboratory Paul trap that is used to study the transverse dynamics of intense charged-particle beams.

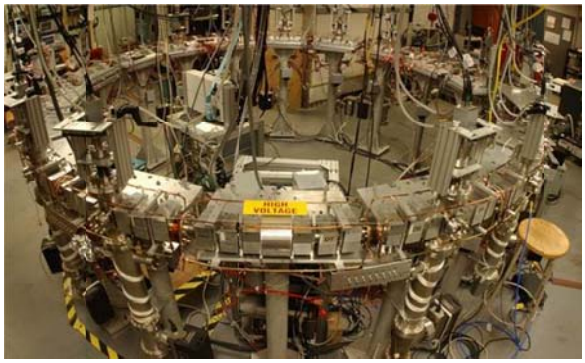

Figure 2. The Univeristy of Maryland Electron Ring (UMER) is a scaled model of a high intensity ring that studies intense beam dynamics.

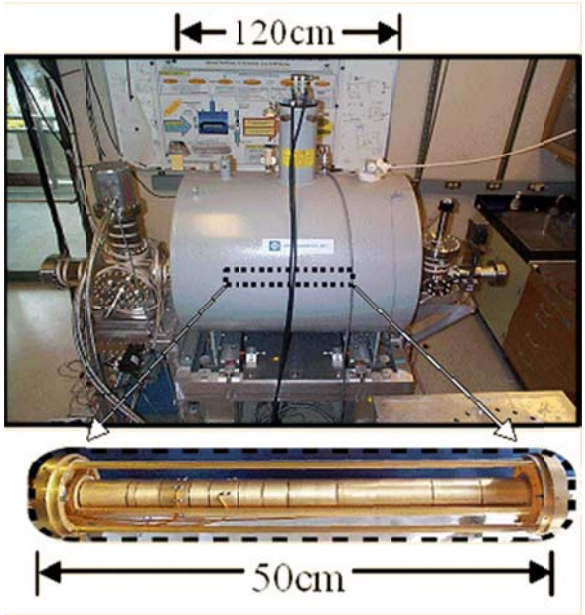

Figure 3. The U. C. San Diego Malmber-Penning trap used for positron trapping and beam extraction.