Nonneutral Plasmas and the Physics of Intense Charged Particle Beams

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The Research Frontier

The research frontier in nonneutral plasmas and the physics of intense charged-particle beams 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.

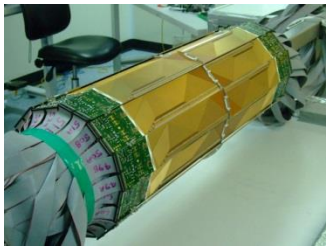
Nonneutral plasmas are plasmas without overall charge neutrality. There are numerous types of confinement systems including: Penning-Malmberg traps, Paul traps, storage rings.

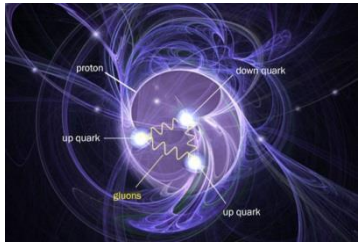
Charged particle beams are single-component plasmas in which the relative motion between particles in the charge bunch is small compared to the average motion of the charge bunch in the laboratory frame.

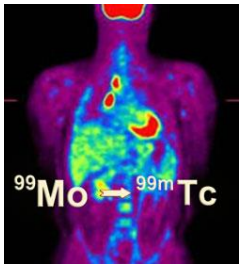
Broad Impact and Societal Benefit

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
- nonlinear dynamics
- high-quality positron beams for research on pair plasmas, and for antihydrogen formation
- accelerator-driven high energy density laboratory plasmas
- ion-driven inertial fusion energy
- the intensity frontier in high energy physics
- accelerator development for nuclear physics applications
- electron-ion colliders (EIC)
- accelerator-driven sub-critical reactor systems (ADS)
- accelerators for medical treatments
- medical isotopes production
- spallation neutron sources for materials and biological research
- waste transmutation







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Key Scientific Questions

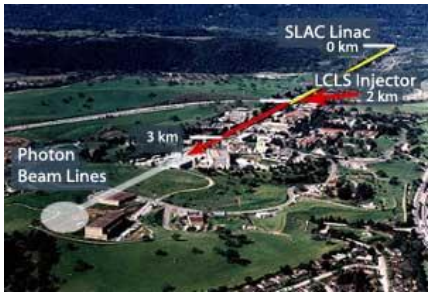
- How can intense charged-particle beams be transported over long distances while maintaining high brightness and low emittance?
- What are the mechanisms of emittance growth and halo particle production, and can they be controlled or mitigated?
- Can nonlinear transport systems be developed to manipulate or control the phase space of charged-particle beams?
- How can heavy ion beams be compressed to the high intensities required to create high energy density matter and fusion?

In principle, these questions could be addressed in large accelerator facilities or with advanced numerical simulations. However, 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, flexible laboratory facilities with sufficient diagnostics and in conjunction with theory and numerical simulations.

Long Distance Propagation

Stable long distance beam propagation is critical for beam applications.



Charged-particle beams are commonly transported over large distances through periodic lattices of quadrupole magnets. These lattices provide transverse beam confinement while the charge bunch is being accelerated to high-energy, or being held in a storage ring.

For single, non-interacting particles, dynamic stability produces orbits that remain bounded as long as parametric instabilities are avoided. For intense beams, particles interact through the self electric field forces and ***j*** x ***B*** forces, resulting in nonlinear equations of motion.

Chaotic particle orbits or excitation of collective modes can lead to emittance growth – an increase in the transverse phase space volume occupied by the particle distribution – and particle loss.

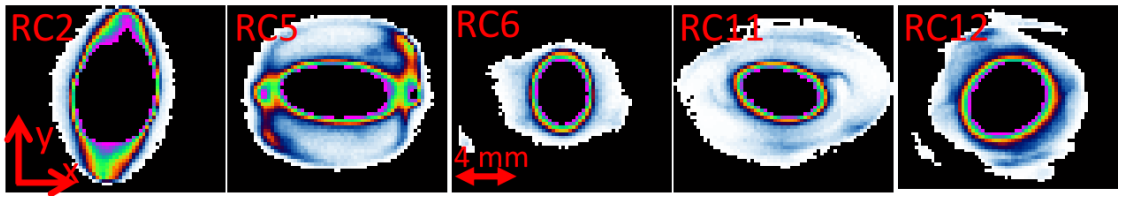
Emittance Growth and Halo Particles

Emittance growth and halo particles – particles at large radius, outside the central core of the charge bunch – degrade beam quality and limit ultimate beam performance parameters.

It is important to understand mechanisms for emittance growth and halo particle generation, with an emphasis on mitigation techniques.

These effects can occur in various parts of the system and have various sources, including:

- particle source physics
- injection mismatch
- envelope mismatch
- collective mode excitation
- chaotic particle orbits
- coherent lattice errors
- random lattice noise



UMER

In many cases, beam losses from emittance growth and halo particle generation are a key factor in design trade-offs and therefore a cost driver in large machines.

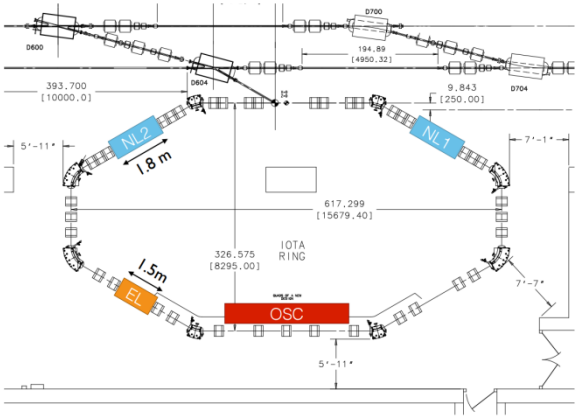
Nonlinear Transport Systems

While quadrupole lattice elements create forces that depend linearly on radius, higher-order multipole elements produce nonlinear confining fields. Hexapole lattice elements are used for correcting for chromatic effects. These fields also couple the *x* and *y* particle motions, leading to complex phase space dynamics.

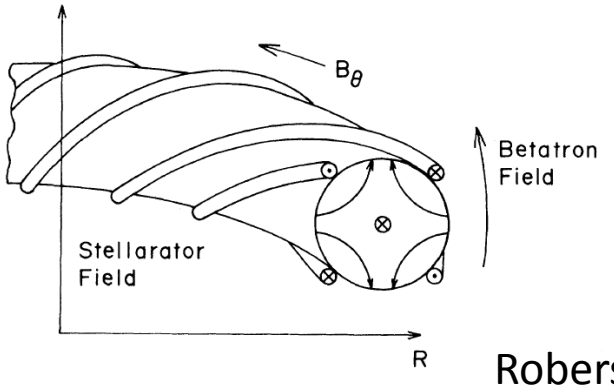
What are the transport properties of periodic lattices built using higher-order multipole elements?

Can lattices with nonlinear elements be used to transport intense beams by creating near-integrable systems?

Does coupling the *x* and *y* dynamics, e.g. in rotating lattices, allow emittance growth to be mitigated?



IOTA



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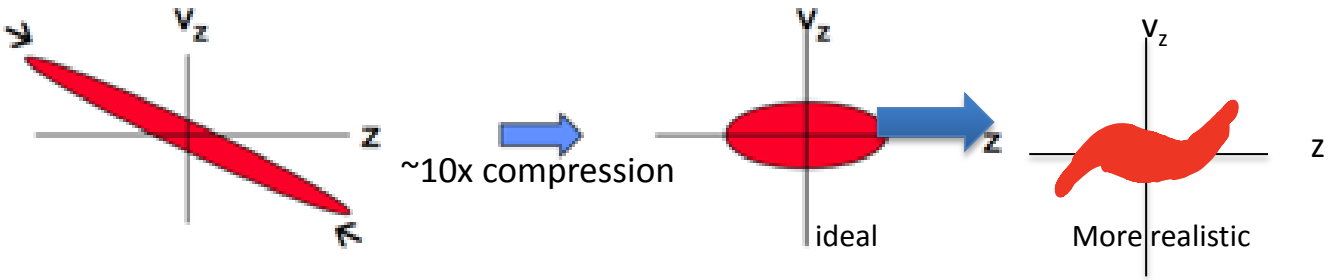
Beam Compression

How effectively can beam compression, in both the longitudinal and transverse directions, be achieved in order to increase beam current without particle loss or emittance growth?

Longitudinal compression can be achieved with ramped accelerating voltages.

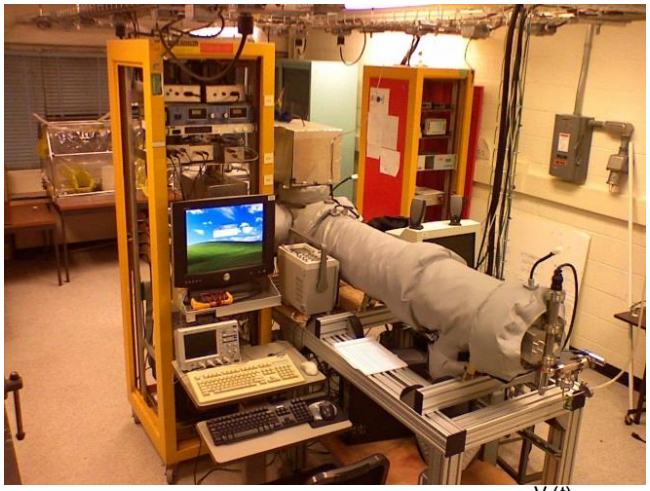


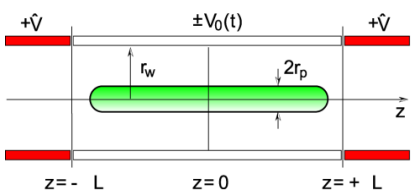
Transverse compression can be achieved with solenoidal lenses, plasma lenses, or with collective focusing effects.

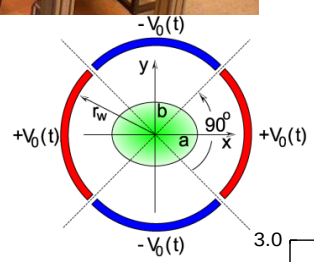
Beam/plasma interactions: good.
Background plasmas maybe used as a sources of charge-neutralizing electrons for ion beams in order to overcome space-charge forces and reach small ultimate spot size.

Beam/plasma interactions: bad.
How important are two-stream and electron cloud instabilities?

Paul Trap Simulator Experiment



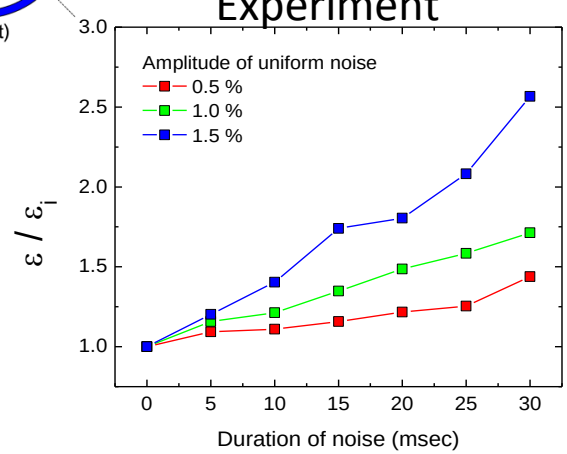




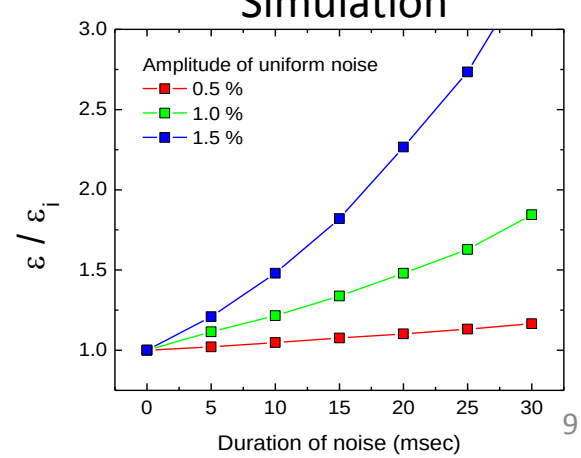
A compact laboratory experiment that places the physicist in the beam's frame of reference since the temporally-periodic quadrupole electric fields of a linear Paul trap are the Lorentz transformations of the spatially-periodic quadrupole magnetic fields of an alternating-gradient transport system.

Research has included: beam compression; and the effects of injection mismatch, random noise, and coherent periodic perturbations on emittance growth and halo particle production.

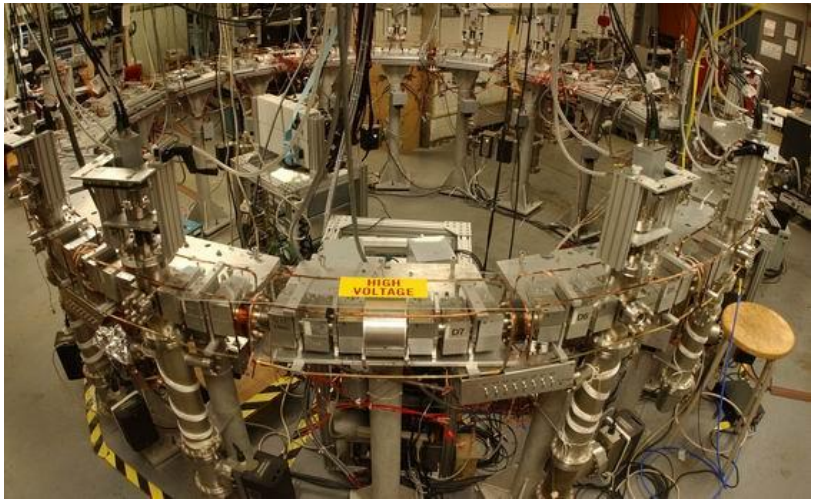
Experiment



Simulation



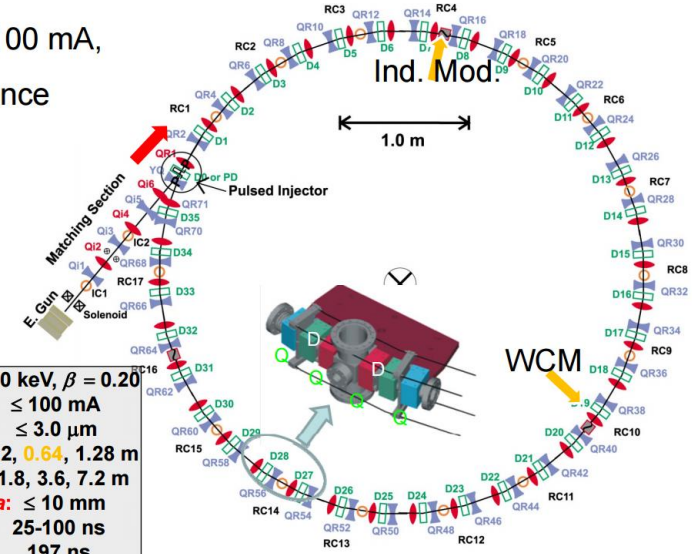
University of Maryland Electron Ring



10 keV e-, 0.5-100 mA,

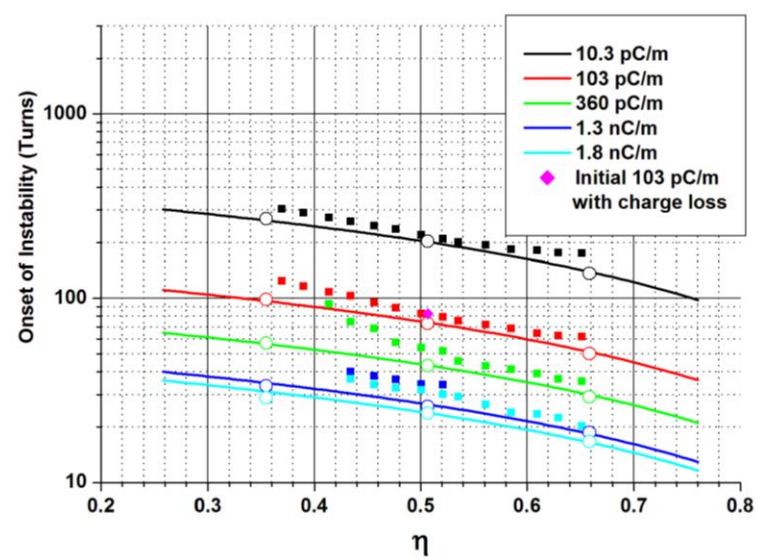
0.3-3 μm emittance

~10^{10} particles

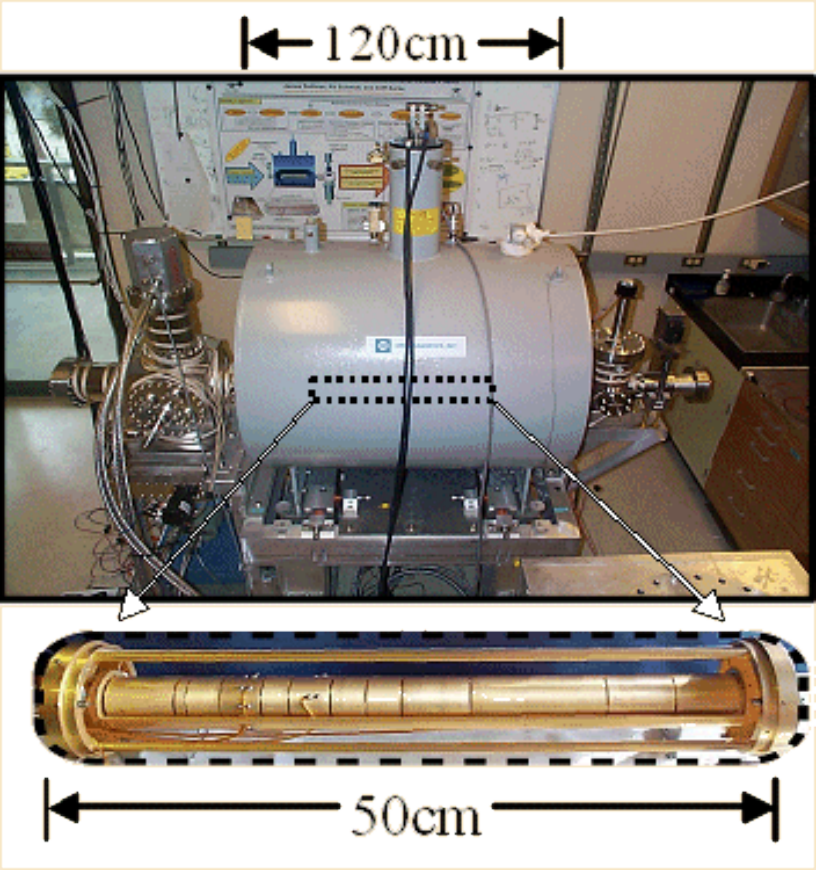


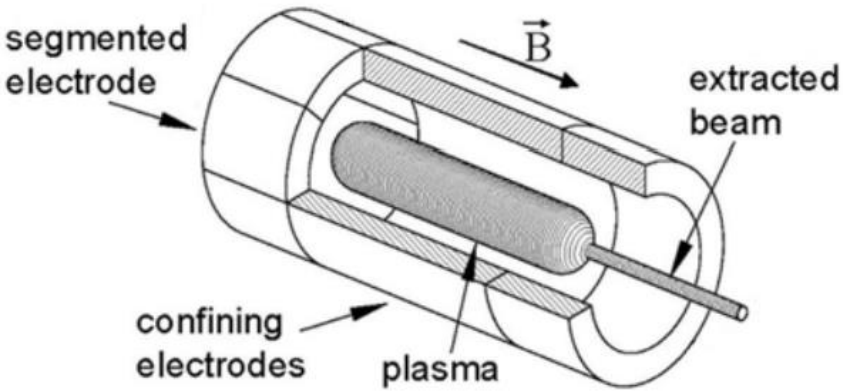
Energy:	≤ 10 keV, $\beta = 0.20$
Current, I:	≤ 100 mA
Emittance*, ε:	≤ 3.0 μm
Lattice period, S:	0.32, 0.64, 1.28 m
Zero-current λ_0:	≈ 1.8, 3.6, 7.2 m
Av. beam radius, a:	≤ 10 mm
Pulse length:	25-100 ns
Lap time:	197 ns

A scaled model of a high intensity ring that injects electron bunches over a wide range of space charge intensities. Multi-turn operation has enabled experiments to be carried out on emittance growth and halo particle production from injection mismatch and long-distance propagation. Longitudinal dynamics have been studied, including de-bunching and induction focusing, the creation of soliton wave trains, and streaming instabilities.



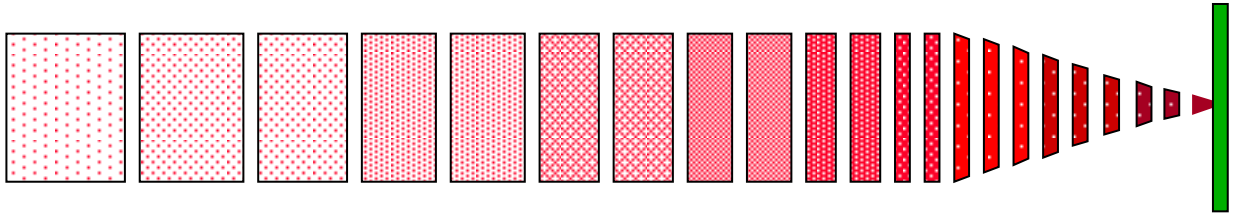
UCSD High Field Trap





Trapped positrons are accumulated, compressed, and cooled to create plasmas that serve as reservoirs for low-emittance positron beam extraction. 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.

Neutralized Drift Compression Experiment

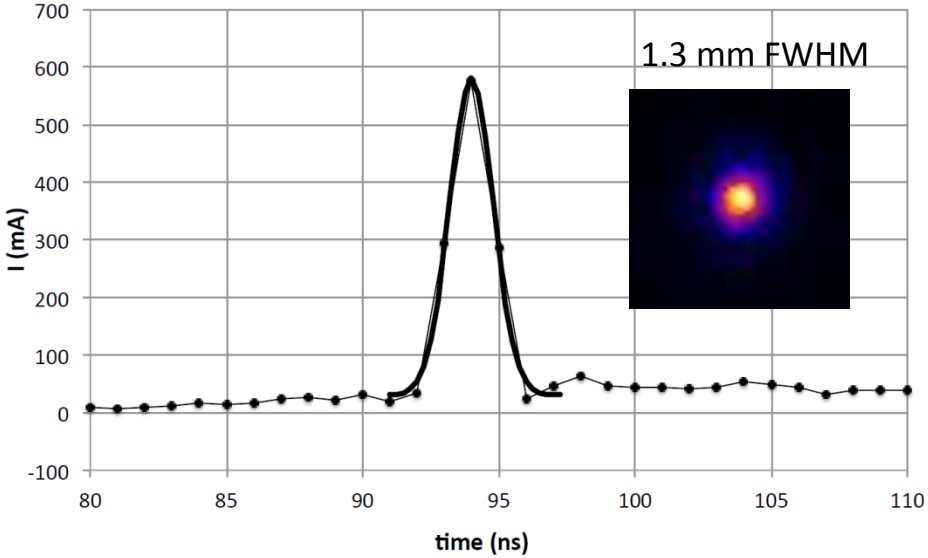


Linac custom waveforms for rapid beam compression

Neutralized drift compression and final focus

Target

An induction accelerator with shaped waveforms to longitudinally compress lithium or helium ion beams as they are accelerated to 1.2 MeV. The beams pass through a plasma with space-charge-neutralizing electrons and are then radially focused by a strong solenoid located before the target plane.



Experiments have demonstrated the ability to transport intense charged-particle beams through a solenoidal focusing lattice while undergoing extensive phase space manipulations and passage through a neutralizing plasma.

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Summary

The Frontier: developing an improved understanding of the dynamics of intense charged-particle beams where the self-field effects are important and the dynamics become nonlinear.

The Approach: Therefore, the approach to advancing the frontier is to carry out experiments in small, flexible laboratory facilities with sufficient diagnostics and in conjunction with theory and numerical simulations.

The Impact: strong impact on plasma physics and beam physics, as well as a strong societal impact.

Resources such as the Paul Trap Simulator Experiment (PTSX), the University of Maryland Electron Ring (UMER), the UCSD High Field Trap, and the Neutralized Drift Compression Experiment (NDCX-II) can be used to carry out high-impact research at the frontier.