BROOKHAVEN NATIONAL LABORATORY
PROPOSAL INFORMATION QUESTIONNAIRE
LABORATORY DIRECTED RESEARCH AND DEVELOPMENT PROGRAM

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DEPARTMENT/DIVISION	**AD/NPP**	**DATE**	**3/8/23**
OTHER INVESTIGATORS	**Kevin Brown (co-PI), George Mahler, Dejan Trbojevic**		
TITLE OF PROPOSAL TYPE B	**Ion trap test stand and laser cooling studies of ultra-low emittance bunches for high luminosity**		
PROPOSAL TERM (month/year)	From **10/2023**	Through **09/2025**	

SUMMARY OF PROPOSAL

Description of Project:
Laser-cooled ion traps are used to prepare ions or groups of ions in very low temperature states, exhibiting such phenomena as Coulomb crystallization. In accelerator terminology, this corresponds to a very small emittance. Typical accelerator ion sources [1] produce normalized RMS emittance $\varepsilon_{norm,rms}$ in the 10^{-7}–10^{-6} m range, whereas laser Doppler cooled ion traps [2] produce 10^{-13}–10^{-12} m: a bunch that can potentially be focused a million times smaller. Such an ultra-low emittance source could reduce the current needed in accelerators to produce a given luminosity and reduce the aperture requirements. Investigation of the accelerator applications of laser-cooled ion traps has been sparse so far, with the most advanced group extracting nano-beams for ion implantation [2]. We propose to study the combination of these ultra-low emittance bunches with accelerator techniques, to mature concepts for high density focal points and high-specific-luminosity colliders, among others. The construction of a flexible test stand: a vacuum chamber containing replaceable electrode configurations and a gas source, with windows for lasers, will greatly accelerate BNL's experience and build competencies with these techniques. The initial configuration can be similar to other existing ion traps to verify operation, before reconfiguring the system, for example to allow bunch extraction into a beamline or even the RHIC/EIC accelerator chain. In parallel, accelerator-relevant variations of this concept will be investigated with simulations, such as linear, helical or ring cooling channel designs for increased bunch number or current throughput.

Expected Results:
The experimental campaign will produce the foundational ion trap system that must be constructed in order to extract into accelerator beamlines. Building the ion trap at an accelerator lab rather than a laser or atomic physics lab is an important step to enable interdisciplinary research. Trapped ion dynamics can test non-trivial accelerator beam dynamics principles, even without laser cooling [3].

Theoretical and simulation work will produce publications in the following fields:

- How can ultra-low emittance bunches be transported, focused and harnessed for increased accelerator performance? Can a design with much higher specific luminosity be achieved?
- Novel dense foci can be formed from these low emittances, even approaching the nuclear density if extrapolated to energies of 10s of GeV. This is a pathway to studying new forms of nuclear matter, including neutron-rich environments underlying the r-process in stellar nucleosynthesis.
- Possible optimizations of the laser-cooled trap design to allow higher current throughput, faster cooling rate or different ion species.

PROPOSAL

Introduction, Uniqueness, Motivation

Laser-cooled ion traps have found much use in atomic and optical physics for manipulating the states of individual ions, for instance [5] gives a thorough account of the dynamics of such a trap, cooling of the ions and its use in quantum computing. The IBEX experiment [6] at Rutherford Appleton Laboratory (RAL) uses a non-cooled ion trap to emulate beam bunches under space charge conditions. The S-POD trap at the University of Hiroshima [2] has extracted small populations of cooled from such a trap to form nanobeams as well as accumulating 0.8×10^7 ions in a single cooled trap [7]. Additional cooling techniques [4] have even achieved the quantum positional ground state, which for a $^{40}Ca^{+}$ ion commonly used in laser Doppler cooling is $\varepsilon_{norm,rms}=5.26\times10^{-17}$ m. The uniqueness of the ion trap in this proposal is that it is both at an accelerator lab (like IBEX but not S-POD) and built with the intention of extracting the ion bunches for later use (like S-POD but not IBEX).

Accelerator labs have many reasons to be interested in sources with ultra-low emittance: the source emittance is often the limiting factor when injecting into rings, for example. Circulating currents in rings are very high because only a small fraction of particles interact per turn; this fraction would be increased by using smaller emittances. Linear colliders also require very small emittances and tight focal points.

Application Studies

Part of this proposal will study applications of cold trapped ions through simulation, design and theory:

- In collider accelerators, most particles do not interact each time they pass through the interaction point; for instance, 20 collisions out of bunches of 10^9 hadrons. With ultra-low emittance beams, the limits of high luminosity per particle can be explored, which requires correspondingly small focal sizes and careful magnetic aberration correction. The ultimate limit is the 'single particle collider' where two ions of minimal emittance hit each other at a focus the size of an atomic nucleus, with a collision probability near 100%. Design and simulation studies can explore the region between these two extremes, in which luminosity per watt improves by several orders of magnitude, with the goal of designing a precursor experiment.
- Low emittance beams can be used as probes to better understand space charge phenomena [8], residual gas interactions, intra-beam scattering, and emittance growth during acceleration. Eventually, the bunch source and diagnostics developed here could be used to identify areas in the RHIC/EIC accelerator chain where emittance growth could be reduced.
- Creating dense beams at low energy will improve understanding of crystalline beams (Coulomb crystals), low-energy collisional phenomena and beam cooling techniques. Coulomb crystal phenomena also apply to astromaterial sciences (neutron star atmospheres) [9].

The flexible experimental test stand would also benefit the education of future accelerator scientists, as the platform is ideal for performing student-driven experiments that could lead to a doctoral thesis.

An exciting future application is that with million-times smaller emittances, beam focal points can achieve very high densities, even without a colliding beam (the bunch collides with itself). For instance, N=23700 $^{40}Ca^{20+}$ ions at 83 GeV, with a normalized RMS emittance of 4.56×10^{-13} m or less, will be limited by Coulomb repulsion rather than emittance when focused with a 100 mrad (large!) cone angle. The focal size is only 10^{-13} m and the density 3.75×10^{14} g/cm^3, that is, the nuclear density. So in the future, droplets of neutron star or white dwarf matter could be created in the lab using an accelerator with very high alignment precision that uses a laser-cooled ion trap as its source.

Apparatus

The core piece of apparatus is the laser Doppler cooled ion trap, shown in Figures 1 and 2. It is a compact piece of equipment that has been built elsewhere [2,6] but this proposed project will involve frequent experimental modifications the trap, as well as extraction from the trap potentially into other accelerators, so the unique experimental opportunities of building one at BNL merit the cost.

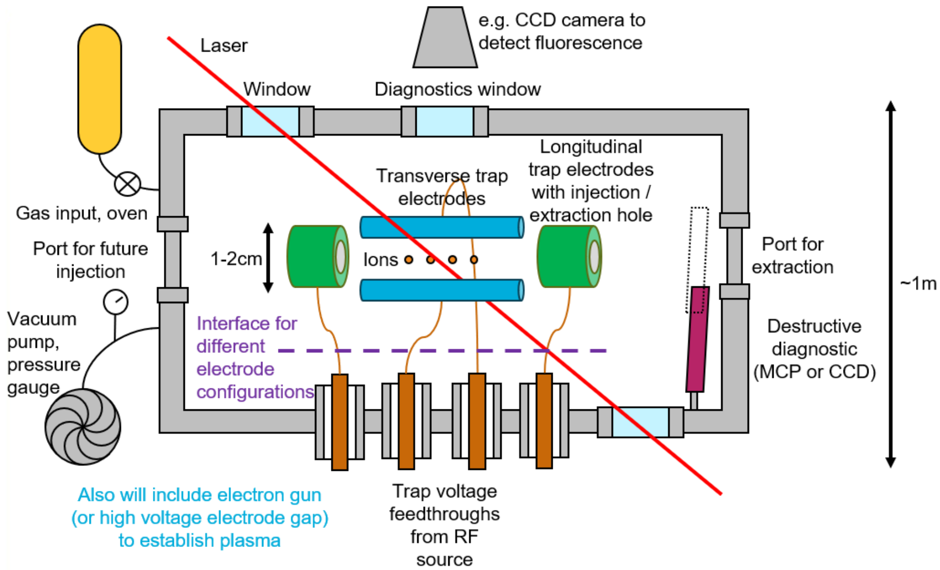

Figure 1. Schematic of a laser-cooled ion trap (Paul trap configuration).

The cooled ion trap itself is a flexible source with variable parameters over wide range:

- Bunch charge can be changed via varying ion gas pressure and trap voltage.
- Bunch size can be controlled via trap voltage and collimation. The directional electrode voltages can also change the shape of the bunch from "cigar" or chain to "pancake" as well as spherical.
- Emittance and temperature can be set to a wide range of values by stopping the cooling process part way.
- Ion species other than the coolable ion (e.g., $^{40}Ca^{+}$) can be cooled by using sympathetic cooling: mixing the desired species in contact with the coolable ion in the trap.
- Trap topology can be changed via the easily exchangeable electrode configuration. This includes a dipole+sextupole configuration with two stable points, for producing two bunches at once that may be separated and used in a collider topology, while still maintaining timing accuracy.

The ion trap construction phase also allows learning from existing skills of the BNL ion source and RF groups, plus other groups who have built similar equipment.

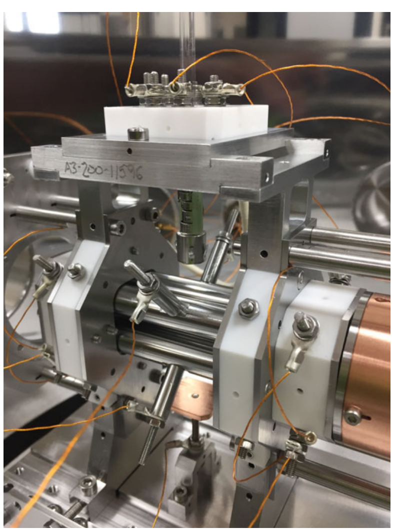

Figure 2 (left). The IBEX Paul trap [6] with vacuum chamber opened. The four rods in the center of the image are the transverse trap electrodes.

Figure 3 shows a simulation of a Coulomb crystal compared to experimental results from the S-POD trap [2]. There are several diagnostics available for ion traps, the simplest being extraction onto a screen (multi-channel plate amplifier and phosphor screen, or CCD) to get a two-dimensional projection of the ion distribution. During laser cooling, the ions will emit photons at the rate they absorb them, and this is how the fluorescence image in Figure 3 was produced. A large angle lens and camera are required to magnify and collect the light efficiently. Further diagnostics include probing the fluorescence signal strength as a function of frequency shift of the laser, which gives a slightly smeared version of the ion velocity distribution in the laser beam axis (this was used in [10]).

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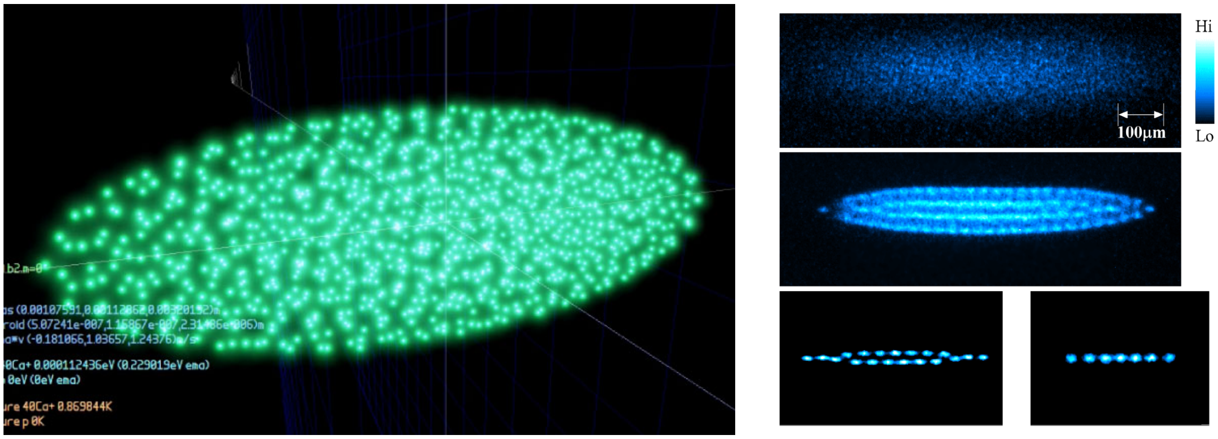

Figure 3. (left) Space charge simulation of 1000 Ca^+ ions in an electrostatic trap. (right) Experimental results from fluorescence diagnostic of an ion trap at the University of Hiroshima [2].

Initial Simulation Results

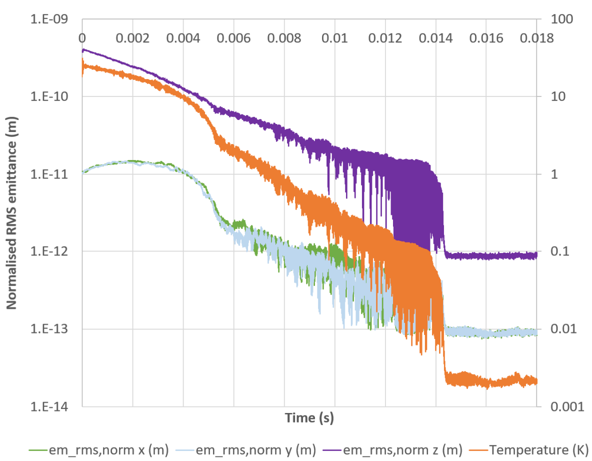

Figure 4 (left). Laser Doppler cooling simulation of 500 $^{40}Ca^+$ ions forming a Coulomb crystal in a trap. Final emittances are just under 10^{-12} m longitudinal and 10^{-13} m transverse, with a final temperature of 2.14 mK.

Figure 4 shows a simulation of the cooling rate in a laser-Dopper cooled trap, taking into account the laser intensity, and photon absorption and emission rates. This includes the heating term from random photon emission.

Figure 5 shows the optimization of 3D focal size tracked in a generalized beamline of multipoles. Many orders of optical aberration are corrected by the optimizer.

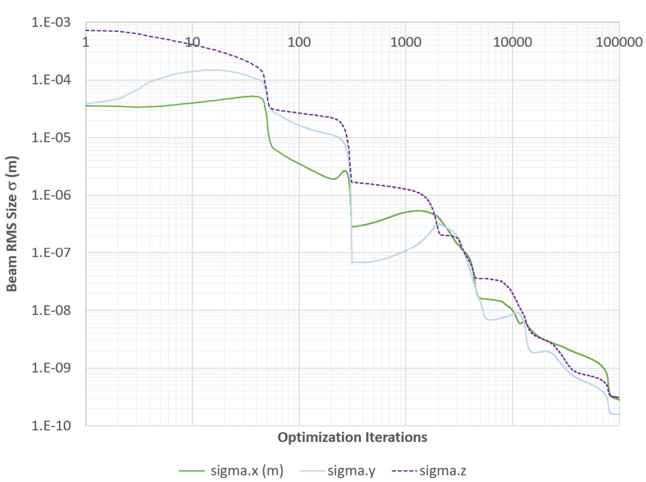

Figure 5 (left). Progressive optimization of focal size for a 500 Ca^+ ion bunch in a simulation of a beamline of configurable electrostatic lenses.

Timeline & Milestones

0-6 months: Simulation and design work, initial assembly and test of vacuum chamber, start purchase of required hardware. **6-12 months**: Ion trap electrodes built and mounted in chamber. Gas injection tested with pressure gauge. Detector sourced and initially tested. **12 months**: Submit publication on simulation and design work including future accelerator applications. **12-24 months**: Ionization and trapping experiments. **24 months**: Publication of first experimental results.

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