Ultra-low emittance beams from ion traps for high precision collisions

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Objectives of Proposed Research

The recent development of laser-cooled ion traps allows production of ion bunches down to the minimum emittance allowed by the uncertainty principle ($\varepsilon_{norm,rms}=\hbar/(2mc)$ for a single ion). Facilities have extracted a few ions from such a trap to form nanobeams [1]. This project proposes to go further by applying strong out-of-equilibrium focusing, as in a collider interaction point, to the extracted ultra-low emittance beam. The formation of dense foci in this scenario depends on experimental precision rather than power/energy/size, so a major thrust of this research is to test feedback and automatic aberration correction systems for forming this focal point. An ultra-low emittance ion source at Brookhaven National Laboratory (BNL) would also allow injection into the Relativistic Heavy Ion Collider or Electron-Ion Collider hadron accelerator chain, e.g., to precisely measure sources of emittance growth.

In the future, foci approaching the density of white dwarf matter (degenerate matter) can be formed if this approach were extrapolated to 10 MeV energies, and pieces of neutron matter at tens of GeV. The ability to collide multiple nuclei at once, rather than pairwise as in present colliders, opens an alternate path to making neutron-rich superheavy nuclei that may be comparatively stable. This collision environment also allows study of stellar nucleosynthesis paths such as the r-process that only happen at high densities.

Technical Approach

The first core piece of apparatus needed is the Doppler laser-cooled ion trap, shown in Figure 1. It is a fairly compact piece of equipment that has been built elsewhere [1,2] but this proposed project will involve frequently modifying the trap, so the time and expenditure to build one at BNL merits the cost.

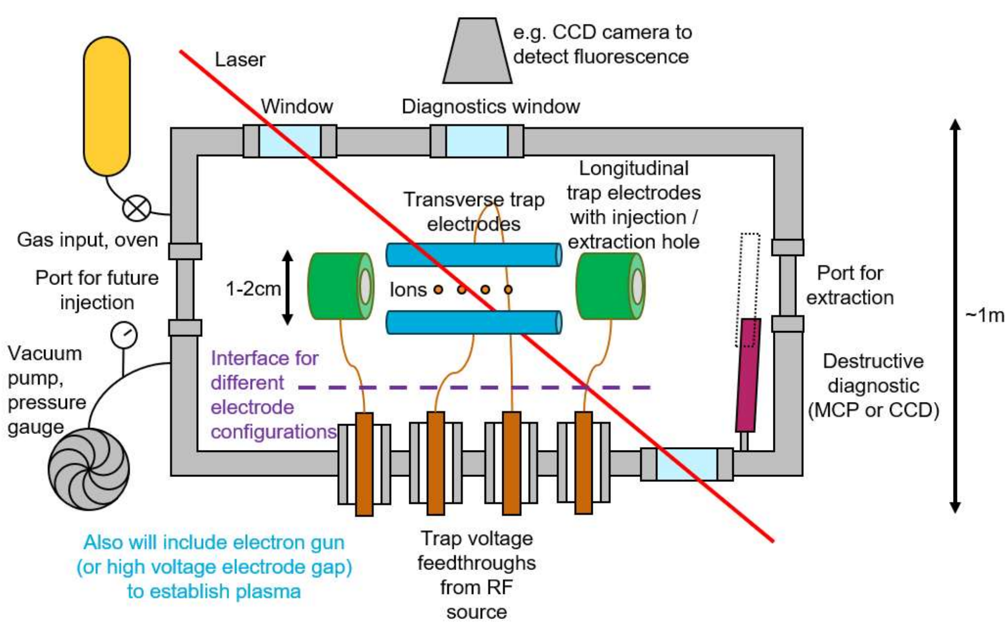

Figure 1. Schematic of a laser-cooled ion trap (Paul trap configuration).

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. Stephen Brooks is an expert in both practical construction of accelerator equipment [3] and simulation, with a strong mathematical background that has already been useful in initial optics simulations that optimize the dense focus.

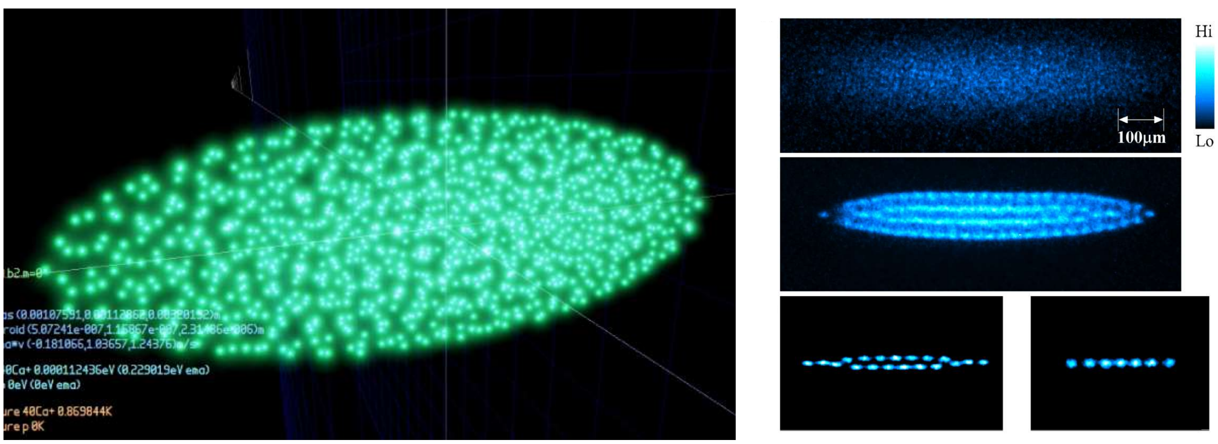

Figure 2. Left: space charge simulation of 1000 Ca^{+} ions in an electrostatic trap. Right: experimental results from fluorescence diagnostic of an ion trap at the University of Hiroshima [1].

The next stage of the experiment is to construct a beamline (Figure 3) and perform the following tasks:

- Cool the ion bunch into an ultra-low emittance Coulomb crystal.
- Lower the longitudinal electrode potential to extract the bunch.
- Fine-tune the bunch velocity distribution with a sequence of configurable electrostatic multipoles.
- Take bunches **out of equilibrium** to make a dense collision point.

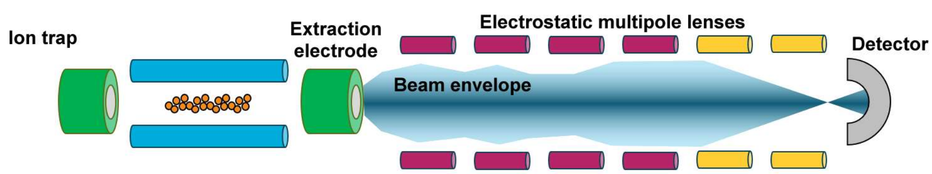

Figure 3. Schematic of beamline, configurable electrostatic multipoles are shown in purple.

Simulations of the velocity fine-tuning with multipoles have shown that multiple orders of optical aberrations may be corrected to approach a true point focus. Experimentally, this requires getting information about aberration at the beam focus using a detector such as a CCD or multi-channel plate and then feeding that back to the optics system.

You could ask: why do this in a complicated way in order to collide just a few ions? The answer lies in the fact that the emittance is nearly zero, so focal size is limited by another effect than in normal colliders:

Coulomb repulsion, or the de Broglie wavelength in the case of lighter ions. This produces a **far** smaller and denser focus, particularly as energy is increased and the number of ions (N) is comparatively few.

In its own rest-frame, the bunch may be modelled as an imploding sphere of charge. If the outermost ions start with inward kinetic energy E_{in} relative to the bunch center rest frame, the minimum radius is

$$r_{min} = x^* = (1/4\pi\varepsilon_0)Nq^2/E_{in}$$

against Coulomb repulsion, where q is the ion charge. At this point, the density of the sphere is given by

$$\rho = M/V = Nm/((4/3)\pi r_{min}^3) = (1/4\pi\varepsilon_0)^3/((4/3)\pi)\ (m/q^6)\ (E_{in}^3/N^2)$$

where m is the ion mass and M and V are the total bunch mass and volume. Densities from this formula are given in Table 1, where the first row may be achievable in this early career award project. One goal will be to measure the beginning of the steep E_k^3 scaling of density with bunch kinetic energy (E_k).

Table 1. Parameter sets for Coulomb-repulsion-limited ion bunch foci. Z=q/e is ion charge number.

Ion Species	Ion population	E_k/Z	E_{in}/Z	$r_{min} = x^*$	ρ/ρ_{water}	Min. normalised emittance (m)
$^{40}Ca^+$	**20000**	**100 kV**	**1 kV**	**28.8 nm**	**0.0133 (dense gas)**	**6.67e-12**
$^{40}Ca^+$	20000	1 MV	10 kV	2.88 nm	13.3 (~Hg)	2.11e-12
$^{40}Ca^+$	20000	10 MV	100 kV	0.288 nm	13300 (white dwarf)	6.67e-13
$^{40}Ca^{20+}$	23700	83 GV	6.8 GV	0.1 pm	3.75e14 (nuclear density)	4.56e-13
$^3H^+$	120	2 GV	27 MV	6.39 fm	5.46e14	8.91e-16

Table 1 assumes the bunch is focussed with a 100 mrad opening angle and a $\delta p/p$=10% momentum spread chirp, leading to an implosion energy of about 1% of the mean forward kinetic energy. The rightmost column keeps track of the maximum 1-plane source emittance $\varepsilon \leq \beta\gamma x^* x'^*$ required to make the focus (note that 1e-13 is readily achievable [1]). By row 3, the ions are starting to penetrate each others' electron shells, so charge shielding is reduced and line 4 uses Ca^{20+}.

Lines 4 and 5 extrapolate to possible future facilities at high energy. Line 4 makes a droplet of neutron matter, using state-of-the-art 0.1 pm alignment such as used for stabilizing the LIGO mirrors [4]. Line 5 performs multi-way fusion from tritium to make a neutron-rich superheavy element (requiring 16 times better alignment) at slightly lower energy. The formula for r_{min} ensures the Coulomb barrier is overcome.

Project Plan and Approximate Schedule

This proposal funds part of the Principal Investigator's salary, a student, and ~$1M of hardware over five years. The rough schedule is as follows. Year 1: Produce, trap, and measure ions. Year 2: add laser and cool ions. Year 3: extract ions from the trap. Year 4 and 5: accelerate and focus ions, optimize the focus.

Conclusion

This is a new way of producing charged particle collisions with near-zero entropy and temperature, the "ideal experiment" where particles' initial positions are known potentially down to the quantum limit. It paves the way to creating unprecedentedly dense material such as neutron matter, as well as superheavy elements and r-process studies. This would support the Nuclear Physics priority areas of understanding limits of nuclear existence in nature and understanding how heavy nuclei are created via stellar nucleosynthesis. The main technical challenge in this line of experiments is precision rather than power.

References

[1] "Controlled Extraction of Ultracold Ions…", K. Izawa et al., J. Phys. Soc. Jpn., Vol. 79, No. 12 (2010)
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[3] "Permanent magnets for [CBETA]", S. Brooks et al., Phys. Rev. Accel. Beams 23, 112401 (2020)
[4] "Advanced LIGO", LIGO-P1400177-v5, arXiv:1411.4547, Tables 6,7 (2014).