MARBLE-1

The Multiple Ambipolar Recirculating Beam Line Experiment

Alexander Klein
www.beamfusion.org

Abstract

MARBLE concept: Conventional ion beam storage devices provide stable containment for only a small volume in phase space (p, E). We have recently discovered that multiple, separate volumes in stable phase space can be effectively realized in a single linear trap with simple arrangements of electrodes. In addition, it is possible to confine both ions and electrons on stable orbits together and at the same time - purely electrostatically. Finally, the addition of an axial magnetic field produces an extraordinary effect: all electrons in the system are constrained to travel axially, regardless of energy. With a single externally located electron source, virtual cathodes are easily established along an ion trap device, such cathodes being located near the (negative) valleys of the free space vacuum potential. At the same time, the (positive) peaks of the vacuum potential are transformed into classical Penning traps, where cold electrons are extremely well confined and may be used to ionize a rarefied population of neutrals (acting as ion sources).

The MARBLE-1 is a linear electrostatic ion-beam trap which is designed to stably contain up to five overlapping (yet largely independent) beam populations. It incorporates an axial magnetic field, electron injection schemes, high vacuum, and other features which are all interfaced with a compact PXI LabView data acquisition and control system. This machine was hastily constructed and started operations only six weeks after conception! Although very simple and relatively inexpensive in design, the quick pump-down and configurability make the MARBLE-1 a very versatile device to explore the physics of the MARBLE concept. This poster describes the experimental apparatus, associated hardware/software and diagnostics systems.

MARBLE Basics

Electrostatic trapping of energetic ions in linear traps is based on an optical cavity principle: electrostatic reflectors and lenses provide a trapped phase space analogous to that found in a laser cavity for photons. However, in electrostatics, very unlike in photonics, reflecting surfaces are not solid material structures, but equipotentials in free space. Such surfaces reflect only particles with a specific kinetic energy – while higher-energy particles can traverse said surface unimpeded, although not unaffected.

It is therefore possible to arrange electrodes which provide the required focusing/reflection action for trapping a multitude of energy-groups of ions, and even for both polarities of charges (+/−), along one common axis. Reflecting surfaces for one group of particles serve as focusing lenses for the others. This kind of arrangement is the essence of MARBLE.

Electrostatic confinement suffers from severe space-charge limitations. To increase trapable ion current, some sort of neutralization is desirable. Additionally, a method for introducing ions into the trap is required, and electron impact ionization is one of the simpler ways to achieve this. Immersing the MARBLE in an axial magnetic field has several dramatic effects:

•Electrons, being of very low mass, are constrained to remain trapped even outside of purely electrostatic stable region in phase space
•Penning-type fields cause a build-up of low energy electrons near preferred ionization region for ions. Their density is expected (and has been observed) to be approximately equal to the local Brillouin density
•Virtual cathodes can intentionally be established near potential minima, similar to the 'Poissors' in Hirsch's conjecture in advanced IEC device [4]
•The field allows for containment of small high density plasma to serve as target for beam particles

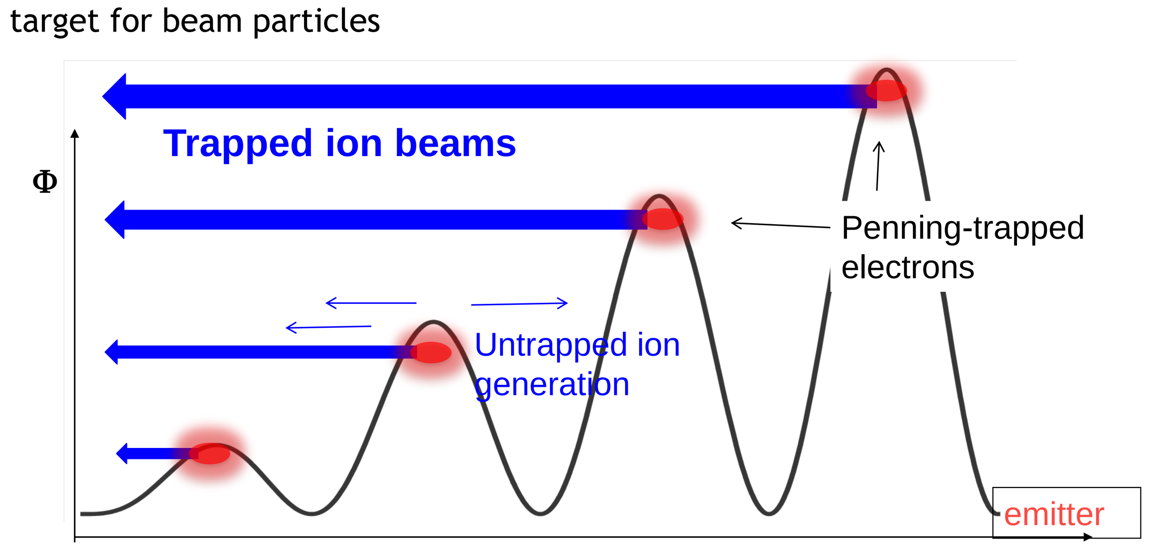


Fig 1: Schematic of potential profile on axis of MARBLE trap containing multi-energetic ion beams. With longitudinal magnetic field: ionization predominantly occurs near peaks of the electrostatic potential. Ions born outside of trapped phase space are accelerated to nearest ground-electrode and lost, while ions born in trapped volume re-circulate and build to sizeable density

Electrode Design and Construction

- A short modeling campaign using LSP & CPO led to quick design of a prototype MARBLE device
- Constraints: requirement of trapping five separate beams, reasonable voltages (< 5 kV), incorporating large trapped energy spreads (more on this later), accommodating large trapped angles for ions for each beam
- Additional requirements: needed to be quickly buildable, using inexpensive parts/materials, simple electrode shapes, good vacuum
- Arrived at design using conical electrodes, which (with particular potentials - ratio of energies between adjacent beams ~ 1.8) yielded trapped energy spreads of ΔE/E ~ 20%
- Conical electrodes incorporate apertures and spacings which increase in proportion to the distance from the core

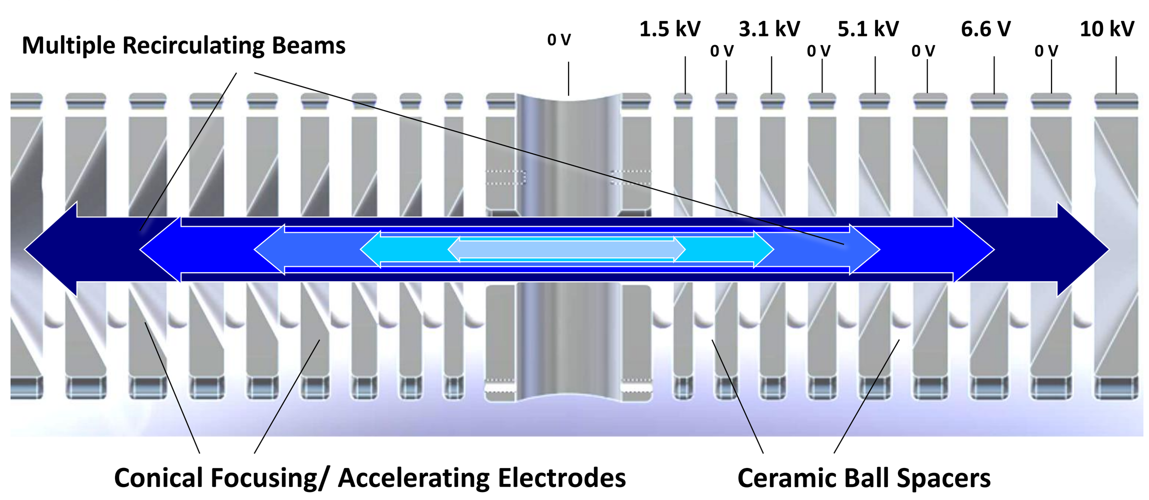


Fig. 2: Five stage MARBLE design, with optimal voltages on electrodes to trap five beams with large energy spread in each beam (~20 % dE/E)

From concept, to design, to construction, to pump-down and first operation took only six weeks to complete! All metal seals resulted in 1x10-9 Torr vacuum within days. Electrode assembly with feedthroughs on rolling track allows for quick removal without disconnecting any electrical

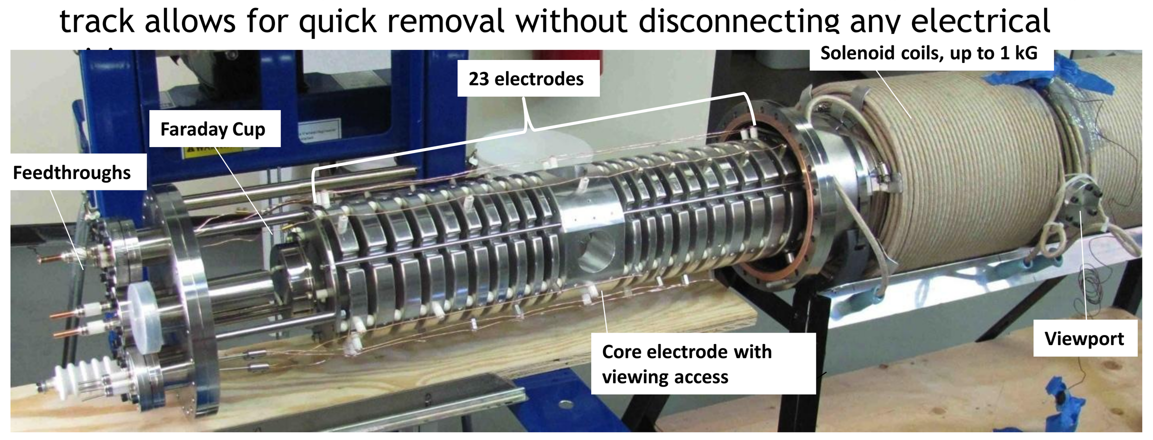


Fig. 3: MARBLE-1, prior to vacuum chamber insertion. Entire assembly slides

MARBLE Magnetic Field

In the MARBLE array, smaller electric fields call for weaker magnetic fields in order to keep neutralization from Penning-trapped plasma below the critical threshold. So, a magnetic field topology in which the strength is reduced towards the center of the trap is sought. A natural way to achieve this is with a cusped geometry, where the coils on either side of the array are wound in opposite sense. The MARBLE-1 can operate with a mirror field or a cusped field by reversing the polarity of one of the coils. **Cusped fields also allow for multiple crossed MARBLE devices to form a quasi-spherical array with min-B magnetic configuration in the core (to trap cool dense plasma as fusion target).**

The coils are driven with up to 6 kW of Ohmic power (2500 Ampere-turns), producing a maximum of 1 kG of axial field in the device. The heat generated in the coils can be used to bake out the vacuum chamber, which has five thermocouples to indicate when T = 250° C (max rating of coils). It takes two hours to get up to temperature, and a few hours of baking yields P ~ $1x10^{-9}$ Torr .

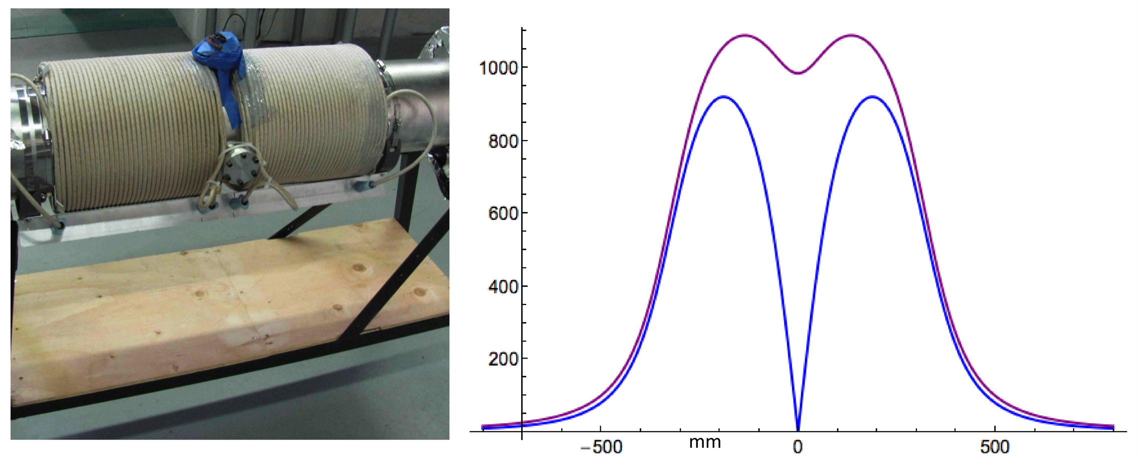


Fig. 4: Left: Magnetic coils, Right: Axial magnetic field (Gauss) for mirror and cusped configuration, maximum coil current

DAQ & Control System, Diagnostics

The MARBLE-1 device is controlled remotely and all data is collected via a compact PXI system, run with LabVIEW. The system consists of two racks, isolated via fiber optic cable (one of them can float to very high voltage if need be) and an 8-core PC. The modules are packed with numerous modules, which include hundreds of channels of analog in/out, oscilloscopes, function generators, video processors,…

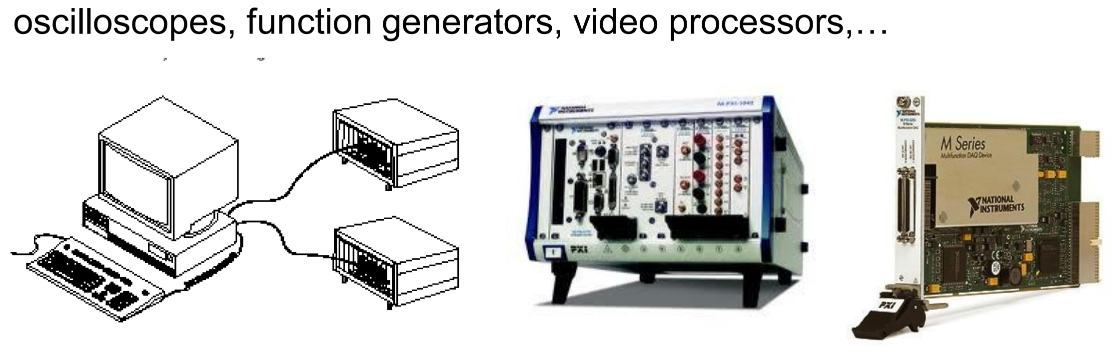
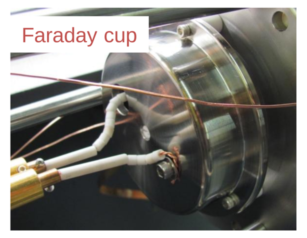
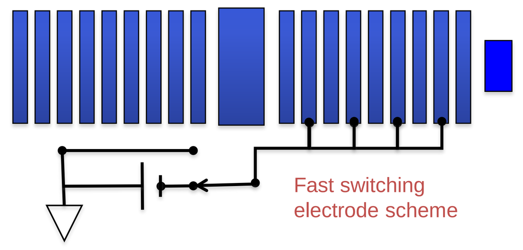


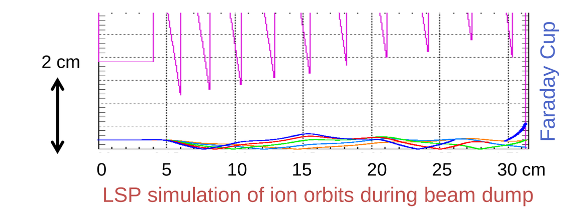
Fig. 5: $100k of modular DAQ fit into two small rack-mounted crates

Diagnostics

1) **Faraday cup** at one end of the MARBLE collects ions and/or electrons during computer controlled fast **beam dump**. The usually grounded electrodes on one side of MARBLE are switched down by up to 6kV in ~10 nsec; ion orbits lead to the Faraday cup for all or some of the trapped beams

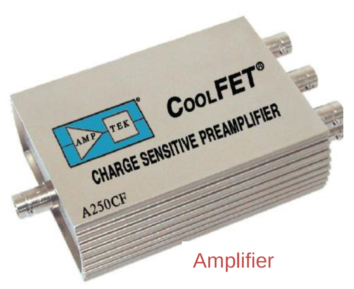


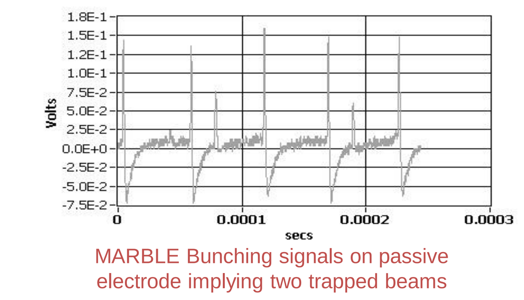




2) **Autoresonance:** An electrode near the core, normally grounded, is wired separately from the others; its potential can be modulated with a programmable function generator. If the frequency of the small driving voltage matches the transit time (or multiples thereof) of one of the beams, **bunching** is induced and a **resonance** forms. The bunches capacitively drive charges on another electrode, which is connected to a cryo-cooled charge sensitive amplifier detected on another electrode. Function generator can do frequency sweep from 0.1 to 1 MHz in one second.

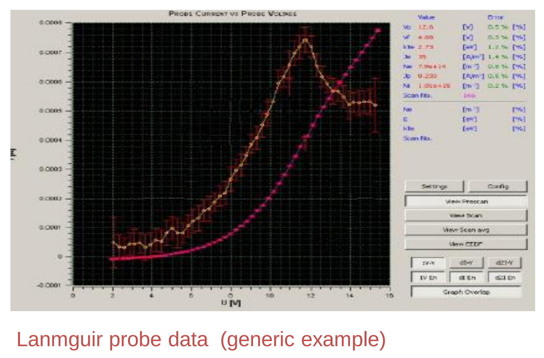
Self-bunching ion beams can be seen spontaneously in certain conditions





3) A **video camera** is aimed through a hole in the center electrode, and with amplification can pick up recombination light from plasma in the core.

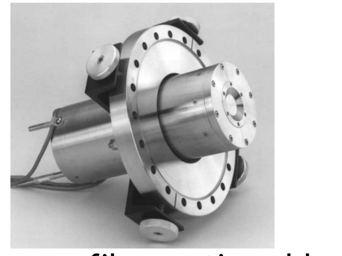
4) **Currents drawn** to each of the energized electrodes (collecting electrons) are carefully measured to estimate ionization rates and Penning-electron densities.



5) A moveable **Langmuir probe** can be inserted along the axis to measure electron densities in each Penning discharge and in between the positive electrodes, where virtual cathodes form). The probe is driven by a smart power supply, and together with a software package forms part of a commercial off the shelf system.

In addition to these implemented diagnostics, equipment exists to pursue more ambitious methods to observe and measure what is happening in the device:

•Fast puff valve (20μs, 10 Hz) installed on differentially pumped vacuum section, skimmer. Opposite side of chamber has fast ion gauge. Can generate high-density super-sonic gas plug for charge exchange spectroscopy.



•Full optics (collection lens, light baffles, filters, mirrors, fiber optic cables, spectrometer,…) for multipoint Thomson Scattering

•Highest throughput imaging spectrometer - accommodates 10 separate fiber optic inputs

•ICCD camera gate-able to 2 ns, 50% quantum efficiency - single photon counting

•Numerous phosphor screens for particle impact imaging

Other hardware

Floatable electron gun constructed from filament + extraction/suppression grid allows for timed and controlled electron injection, primary electrons can give rise to large number of secondaries at Penning locations. At sufficient gas pressure (>2 x 10^{-6} Torr) and magnetic field (> 200 Gauss), discharges in MARBLE-1 are spontaneous and don't require emitter.

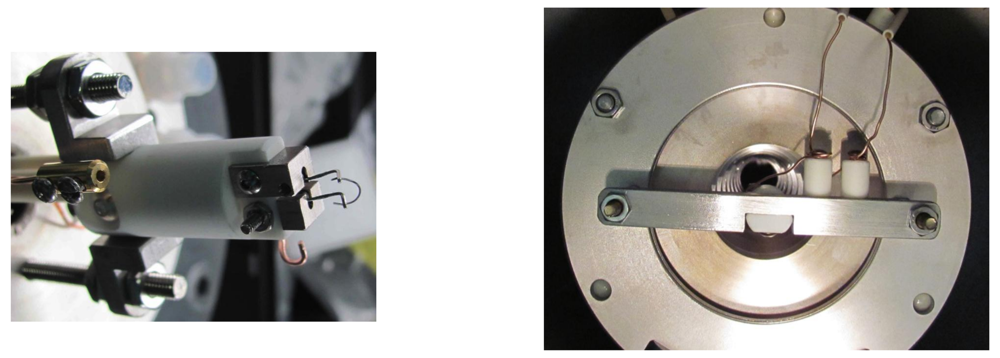


Fig. 6: Left: Electron source, Right: Emitter as mounted into MARBLE-1 device

Vacuum: The small MARBLE chamber is evacuated with a large 2,400 l/s mag-lev turbomolecular pump, which takes up the entire diameter of the chamber and thus ensures low pressures and the purity of background gas. All seals on the chamber are copper (Conflat), partial and total pressures are measured with ion gauges and RGAs.

Gas is introduced via a remote controlled MKS pressure regulator, which can control the pressure in a reservoir from 0.1 to 10 Torr. Manual needle valves regulate the flow from this reservoir to the MARBLE chamber; such a method of gas introduction results in excellent control over a large dynamic range (10^{-9} to $1x10^{-1}$ Torr with D_2).

Some Experimental Findings

The MARBLE-1 device was designed and assembled in less than two months, and was operational for only a few weeks before company funds were exhausted and a complete shutdown was forced by the investors. Nevertheless, in the short lifetime of this project, some encouraging results were obtained:

Preliminary data:

•Penning ionization readily occurs at low pressures, no external electron injection required
•B-field can be used very effectively to control electron density, density near Brillouin limit. Potential is destroyed if too many electrons (Debye length)
•Optimal B-field is approx. 200 Gauss, depending on accelerating voltages
•Bunching signals on inner electrode consistent with multiple ion beam trapping, at expected bounce frequencies and only during expected conditions
•Fast (20 nsec) switching of grounded electrodes on one side of device ➔ dump of all beams into Faraday cup; but quantity of ions is not yet definitive. Complications due to switching time & secondary electrons (from switched electrodes), as demonstrated in PIC code simulations.

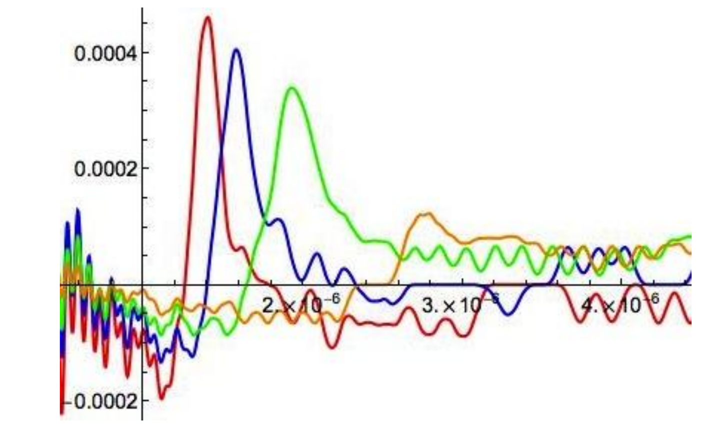


Fig. 7: Derivative of smoothed beam dump signal (current to F-cup) for 3 different trap voltages consistent with trapped ion beam(s)

Next Steps

To maximize beam currents in MARBLE, need much theoretical work:

•Geometry to provide largest volume for stable phase space in each beam. Electrostatic lenses and mirrors have opposite sign for spherical and chromatic aberrations, we can use this to maximize ΔE and ΔP for each beam. Preliminary simulations indicate ΔE/E = 20% is possible
•Instabilities (2-stream) predicted at high current levels (Amps)
•Control of electron profiles and shaping to create large, stable phase space for ions?
•Limits to current densities?

The MARBLE-1 device will be set up at the University of Maryland, in the Lab of Prof. Raymond Sedwick, in the hopes that experiments can soon be restarted.