The

Multiple **A**mbipolar **R**ecirculating **B**eam **L**ine **E**xperiment

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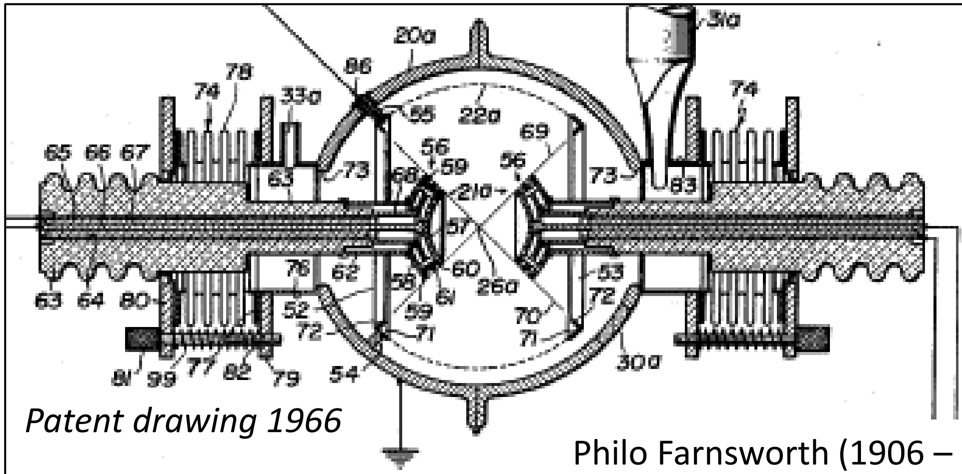
13th US-Japan IEC workshop, Sydney 2011

Outline:

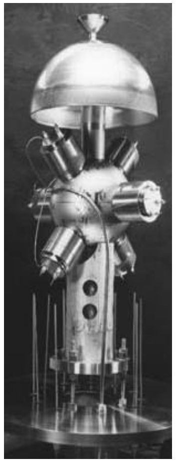
1. Linear electrostatic traps
2. Multiple beam trapping
3. Ambipolar beam trapping
4. Addition of a magnetic field
5. MARBLE-1 prototype
6. Further thoughts and issues

IEC = LEIT

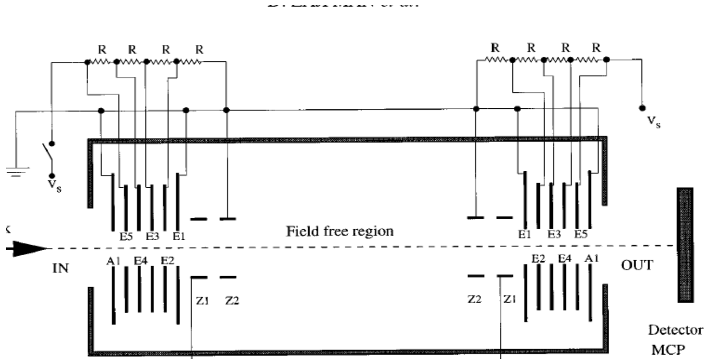


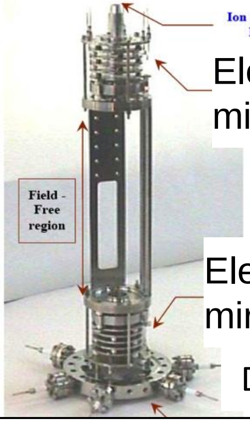
Patent drawing 1966

Philo Farnsworth (1906 – 1971)



1999: Linear Electrostatic Ion Trap at Weizmann Inst (Israel)





Electrostatic mirror

Electrostatic mirror

Daniel Zajfman (1959-)

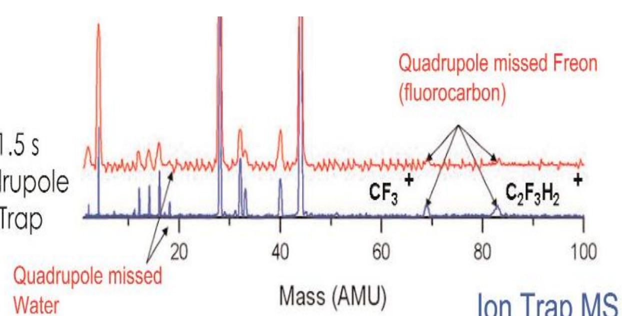
2008: McGuire (student) at MIT makes the connection

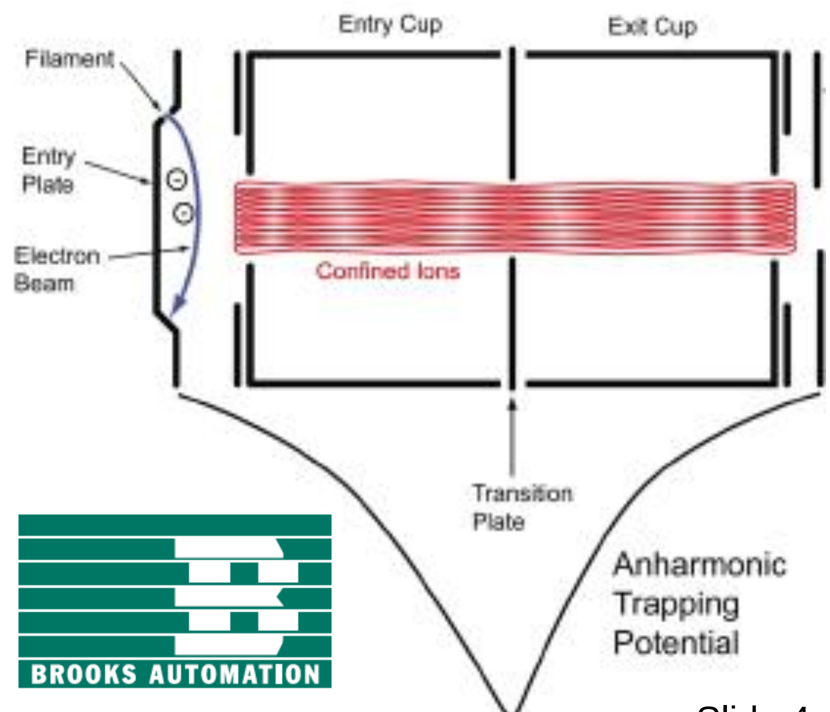
IEC = LEIT

- LEIT community: ions for basic research, with very long confinement times (now > 5 minutes!)
- IEC community: ions for fusion applications, wants high density

2010: Commercial LEIT RGA

Resolution and Gas Detection
obtained in 1.5 s (single Quadrupole scan, 21 Ion Trap scans)

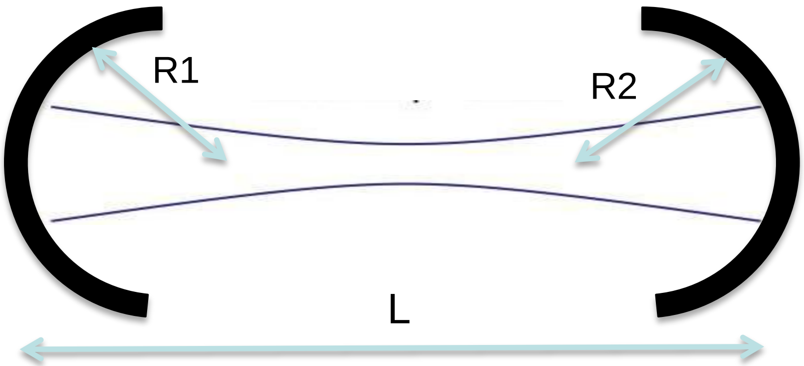




BROOKS AUTOMATION

IEC = LEIT

Confinement of ions is based on optical resonator



$$0 \le \left(1 - \frac{L}{R1}\right)\left(1 - \frac{L}{R2}\right) \le 1$$

Stability criterion in a confocal cavity

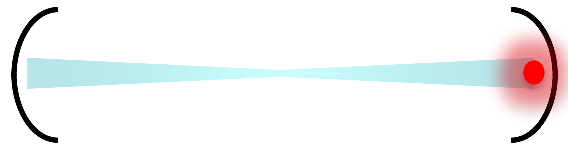
Laser cavity (photons) & electrostatic optical cavity (ions) work on essentially the same principle, **but with 3 major differences**:

1. Photons have no charge ➔ no space charge effects, bosons
2. Photons bounce on real (mechanical) surfaces, but charged particles are reflected at iso-potential surfaces in space
3. The stability of ion orbits is a function of ion energy, because turning-potential and focusing action is different for different ion energies

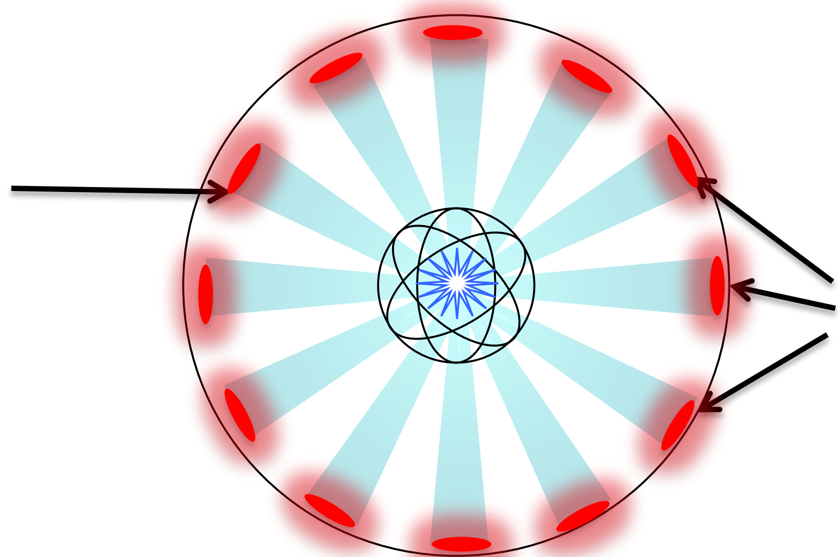
THE issue with IEC: space charge

Electrostatic confinement necessitates Debye lengths > beam dimensions
➔ low densities, low fusion rates

Near turning points for ions, space charge is concentrated (low velocity)
➔ **turning regions set limitations for electrostatic traps**

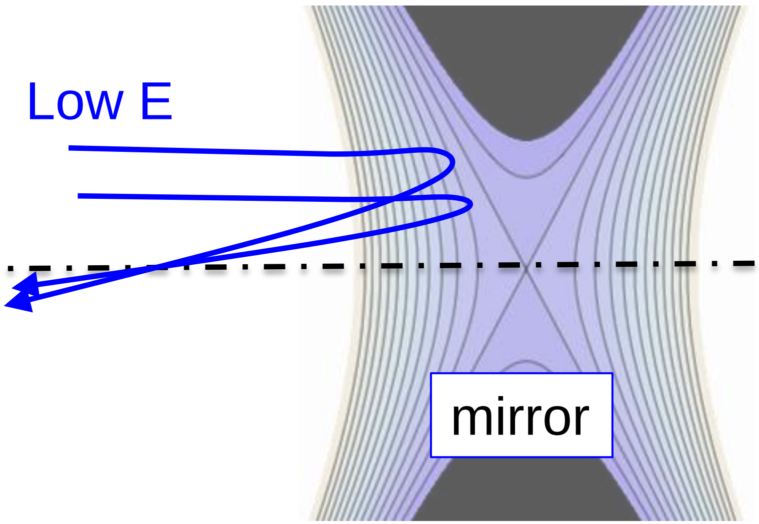


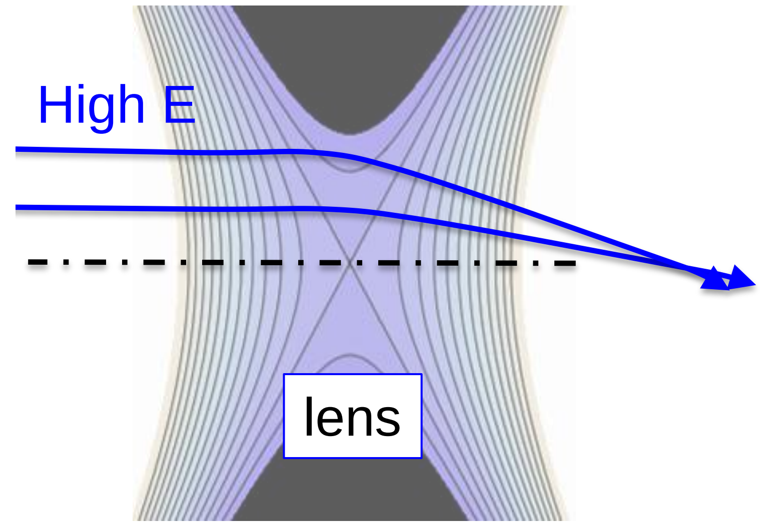
To boost density, increase capacity of turning regions or increase the number of turning regions. IEC community does this by crossing many LEIT beams through a common core



Some electrostatic optics

- Depending on particle beam energy, the electrostatic field due to an electrode can serve either as **mirror or lens**.



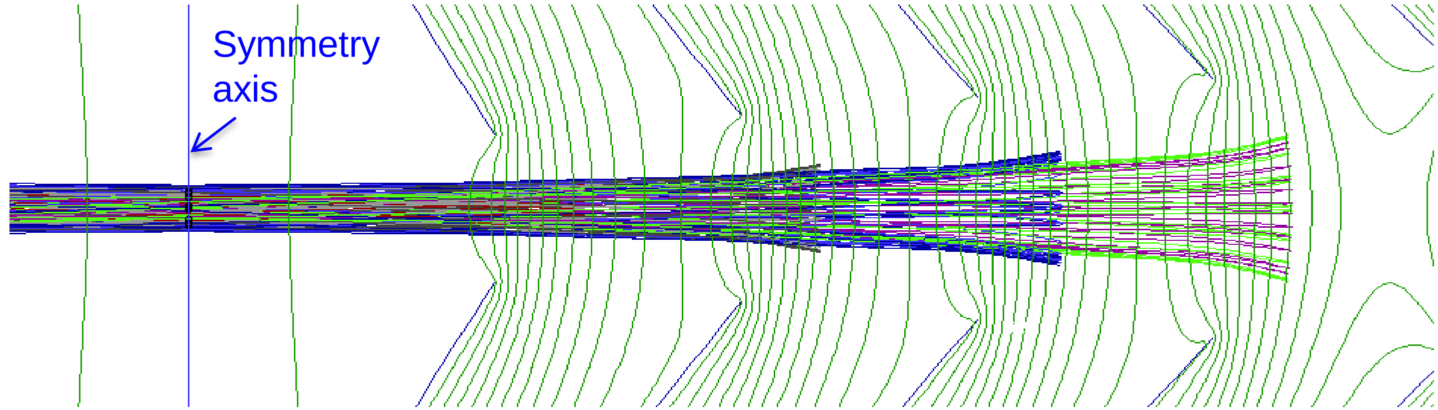


- Charged particle beams: two well known methods for focusing:
  a. Accel-deccel lensing, and b. Alternating gradient (strong) focusing
- Electrostatic ion traps are the equivalent of very long particle beam transmission lines with periodic elements – understanding beams & CP optics very useful

These facts can be exploited to manipulate several *distinct* populations of charged particles in very different ways, using the same electrodes

Multiple beams in one trap

One can arrange simple conical electrodes, with monotonically increasing potentials, and form a series of mirrors/lenses which confine multiple beams on the same axis



CPO simulation of 5 cone-shaped equispaced electrodes (angle: 45°, bias 100-500V in 100V increments.). Shown: 4 stably trapped beams, with four turning surfaces

- Enlarged stable phase space, effectively changing LEIT from 1-D to 2-D
- Each beam is essentially independent of the others, turning regions separated
- This configuration can be used for particle trapping, or for simple "one way" beam generation

Multiple beams in one trap

One can arrange simple conical electrodes, with monotonically increasing potentials, and form a series of mirrors/lenses which confine multiple beams on the same axis

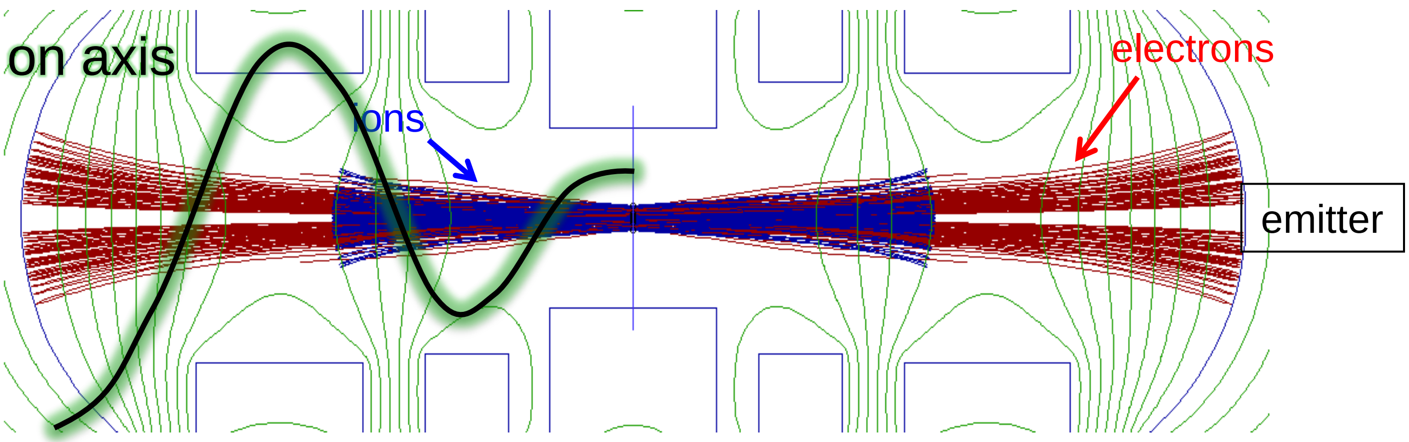
- If trapping, small angle scattered ions (majority) may easily be deflected onto the next lower stage, so **most of the ion energy can be recovered**
- Total beam is not mono-energetic. Can be pulsed to yield temporal compression (simultaneous exit of all particles); if trapping, beams **can be arranged to all have the same period**

Ambipolar beams in one trap

Accel-decel focusing to trap ions also works for electrons

Configuration easily found which contains both energetic ions and electrons on the same axis and in stable orbits

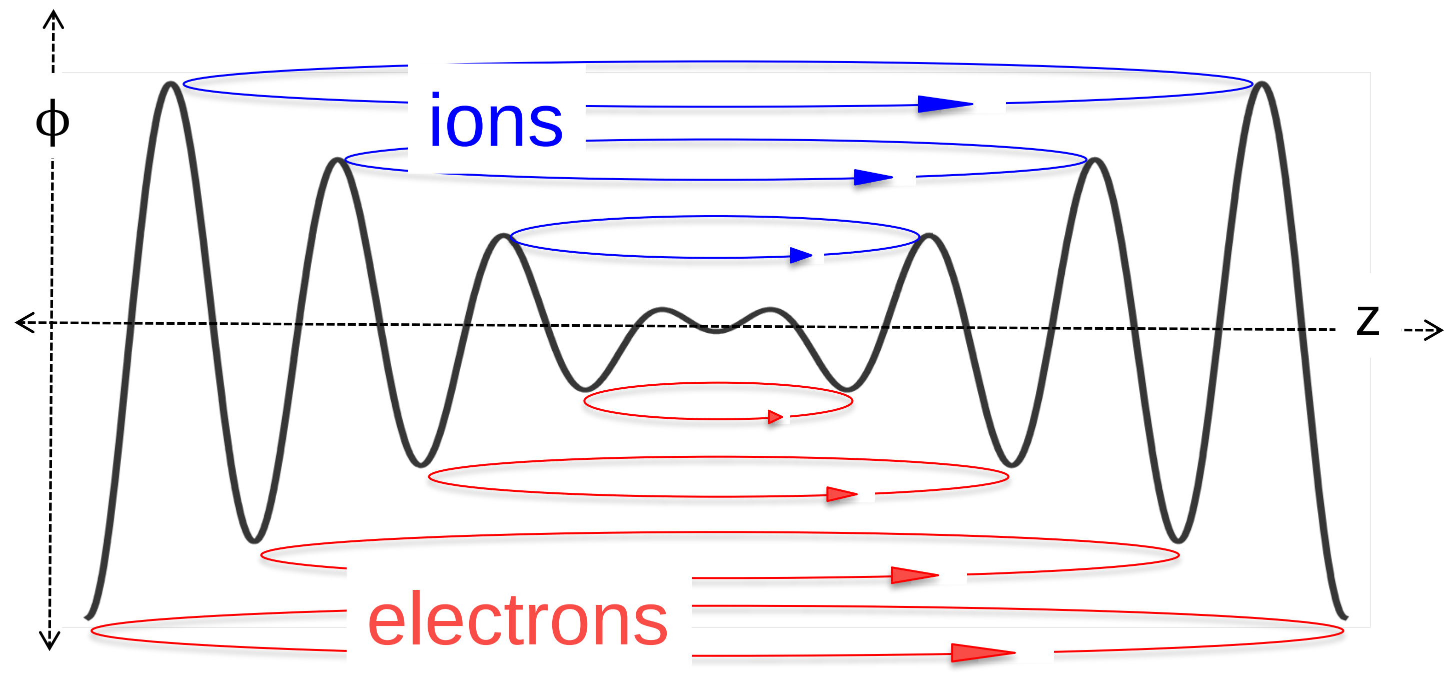
- Electron emitters are extremely simple, can produce large currents with very narrow temperature spread (unlike ion sources)
- Electrons can be used to mitigate effects of ion space charge on beams, Lorentz modeling shows higher trapped ion current reached



*Charged Particle Optics (CPO) simulation of simple cylinders forming electrode configuration containing trapped ion (blue) and electron (red) beams. **Energy of both ion and electron beams in the core is 40 keV.** Green lines are equi-spaced equipotentials*

Multiple ambipolar beams

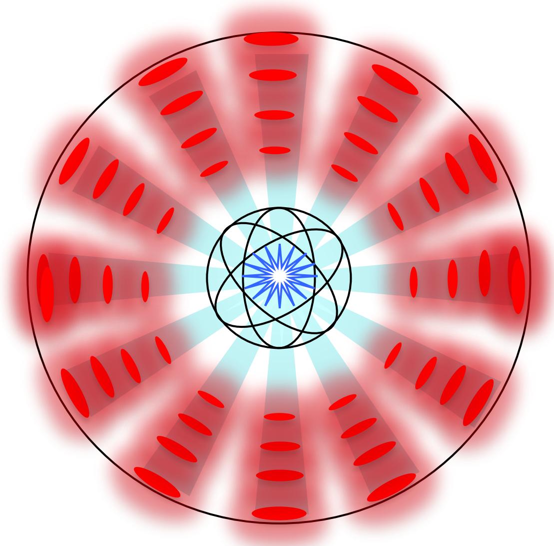
Accel-decel focusing can be extended to multiple beams, with multiple energies, by adding electrodes with alternating polarities and increasing voltage magnitudes



Schematic of potential profile on axis for trapping multiple beams of dual polarities

This arrangement can be achieved with relatively simple electrode geometries. **All particles** in the system **confined purely electrostatically**

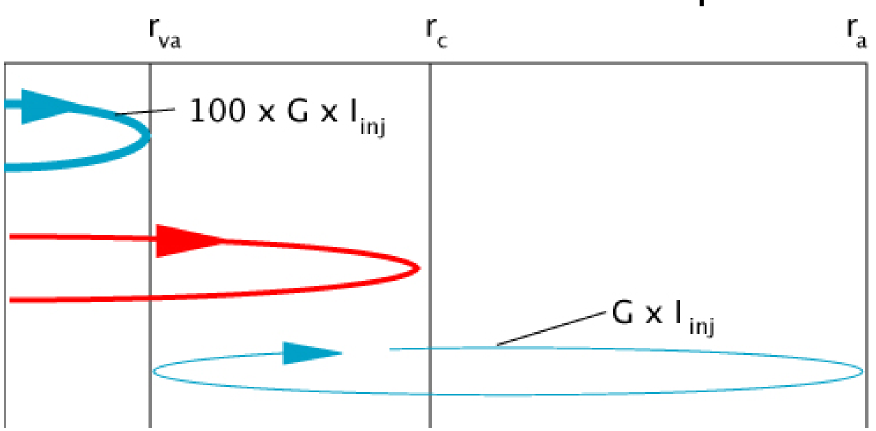
Essential summary



- Went from “1-D” (LEIT) to “2-D” (IEC fusor) to “3-D” type of trap, increasing density limits by several orders of magnitude
- Scattered ions can be collected at low energy on electrodes not too different from ion birth potential
- All ions can be made to have same period

Electron/ion co-recirculating beams reminiscent of Hirsch *:

- To access very high density regime, IEC devices must include electrons to neutralize ion space charge and drive virtual electrodes. In Hirsch’s multiple well hypothesis, virtual cathodes form by “magic”, i.e. spontaneously with spherical beams.
- MARBLE would seem to drive virtual cathodes at chosen locations, with depths controlled by e-emitter voltages…



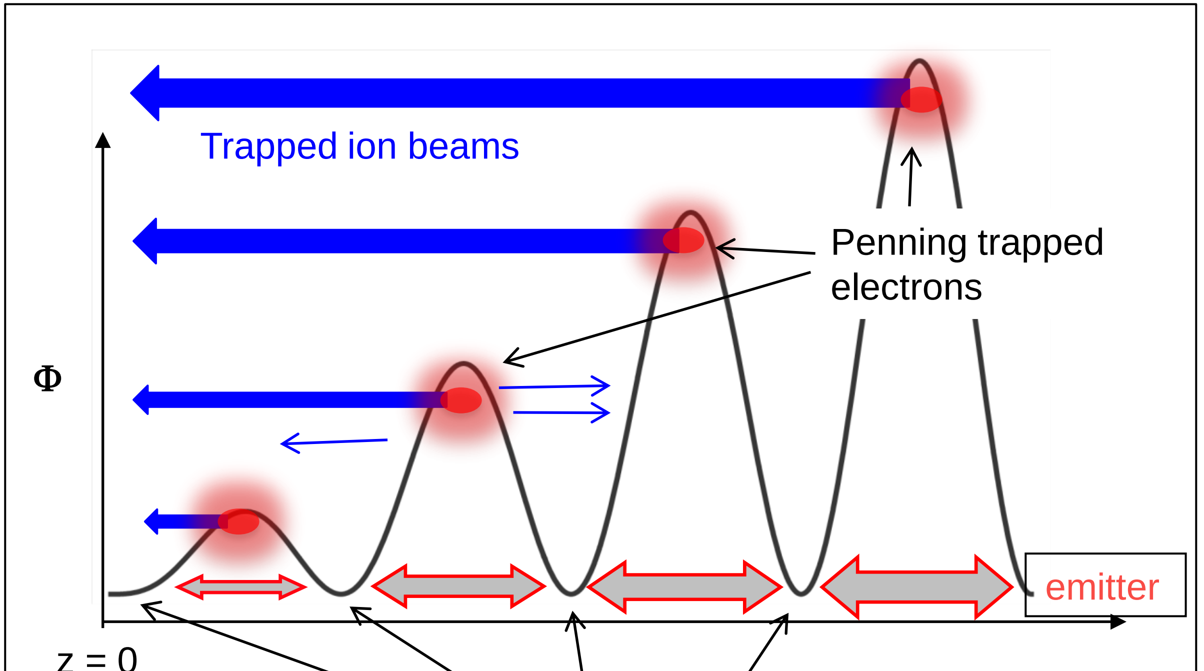
**Hirsch, J. Appl. Phys. 38, pg4522 (1967)*

Some issues

- Electrons tend to scatter & thermalize much faster than ions ➔ intuitively, 'multiple ambipolar beams' is a very delicate state
- Requires 2 polarities of high voltage?
- How to place proper trapped ions into the arrangement (ionization)?

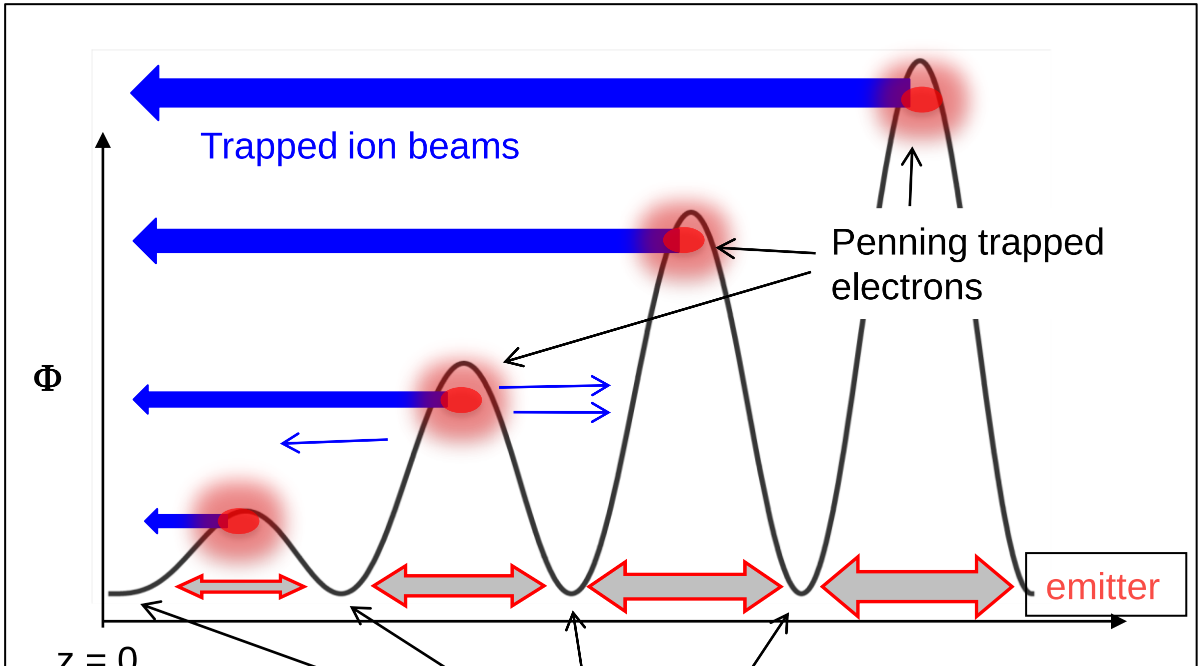
The fix: adding an axial magnetic field

- Now, electrons confined axially by B
- Electrode voltages may be simplified
- Electrons may come from outside of trap
- Top of ϕ hill with an axial B $\equiv$ **Penning Trap** (excellent confinement of cool electrons)



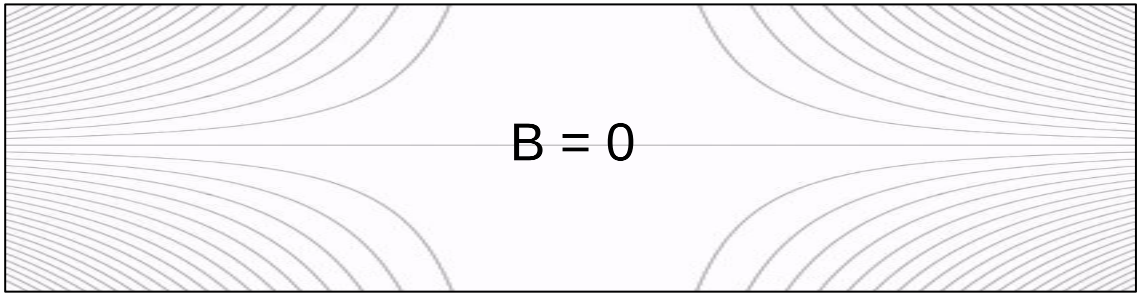
MARBLE

- Adjusting negative electrodes $\rightarrow$ ground potential can create virtual cathodes between ion birth regions. Virtual cathodes fed via single external grounded emitter, electrons constrained radially by B-field
- At potential peaks, electrons ionize low-density background gas. Ions born outside of trapping regions are immediately lost. Those ions born within trapping phase space feed recirculating beams
- Only modest B-fields required (~ 200G) to be effective
- External emitter can be used merely to jump-start ionization, as each ionization event creates a well-confined electron used in further ionizations



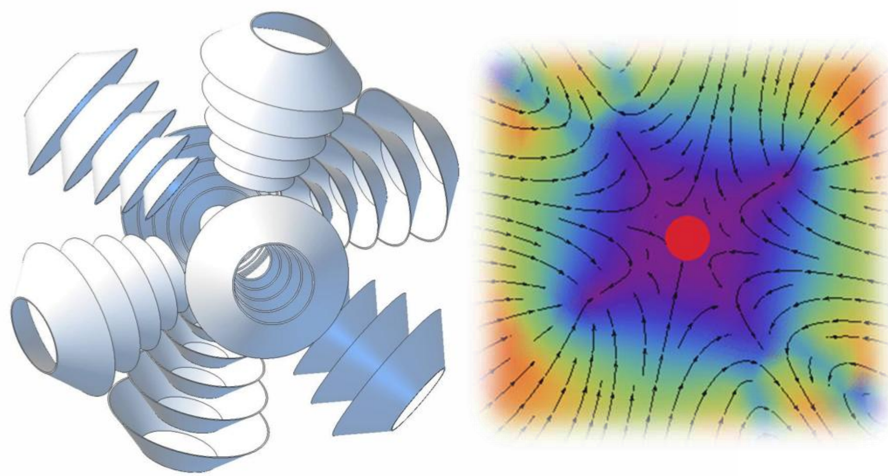
On the magnetic field

- To create axial magnetic fields, have the option for opposing fields on each side of symmetry axis ➔ cusped field (B = 0 at core)



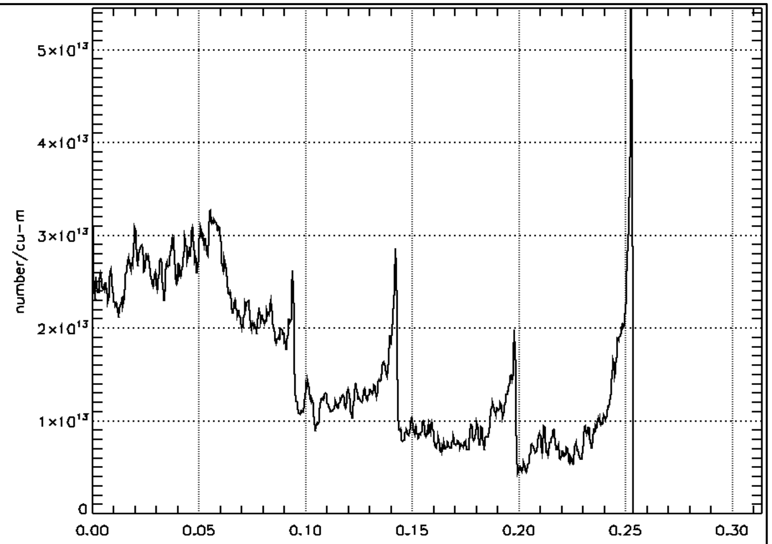
- **Cusped field allow crossing of many linear stages ➔ multi-pole**

- From initial experiments: lower E-fields call for lower B-fields to achive “good” n_e throughout
- ➔ weak B required towards core (lower ϕ)
- ➔ Possibility of simple coils exterior to vacuum system

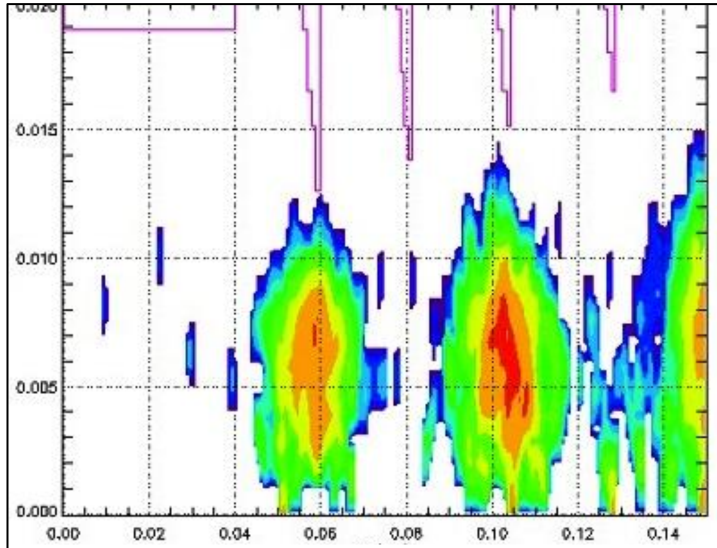


Crossed MARBLEs & multipole field

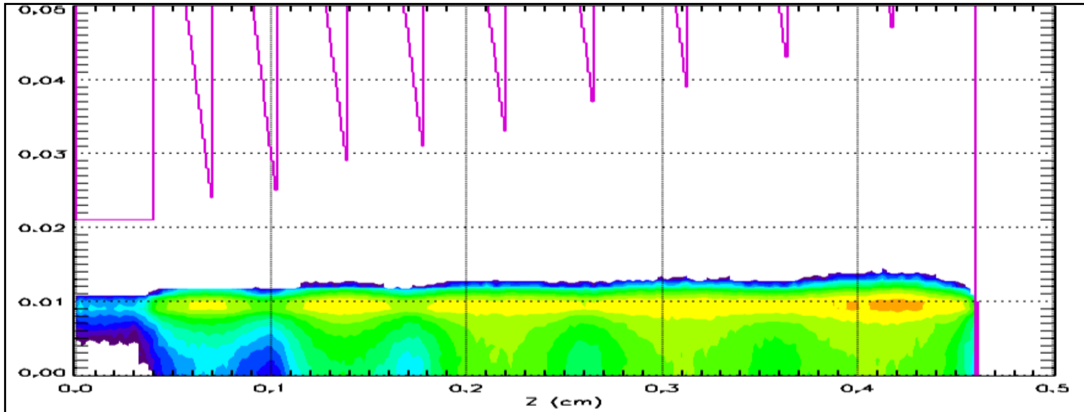
PIC code simulations confirm ideas



Ion-only multi-beam (4) simulation shows space charge dominates at turning points, core density = sum of beams



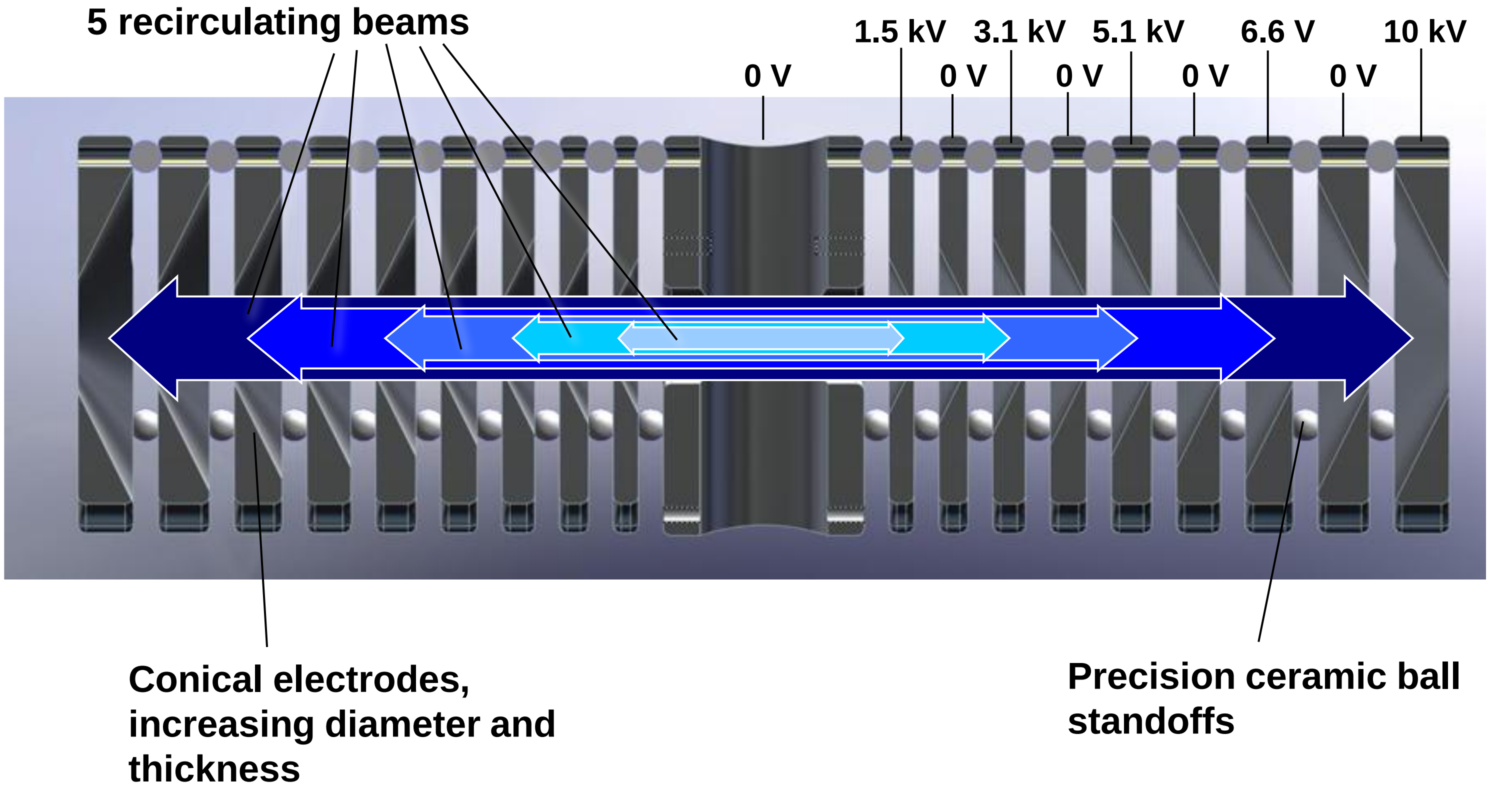
Electron density resulting from ionization in MARBLE shows Penning traps near potential peaks ➔ good ion source



Primary electron density resulting from external emitter in MARBLE, electrons travel all the way to core & are axially constrained by B-field

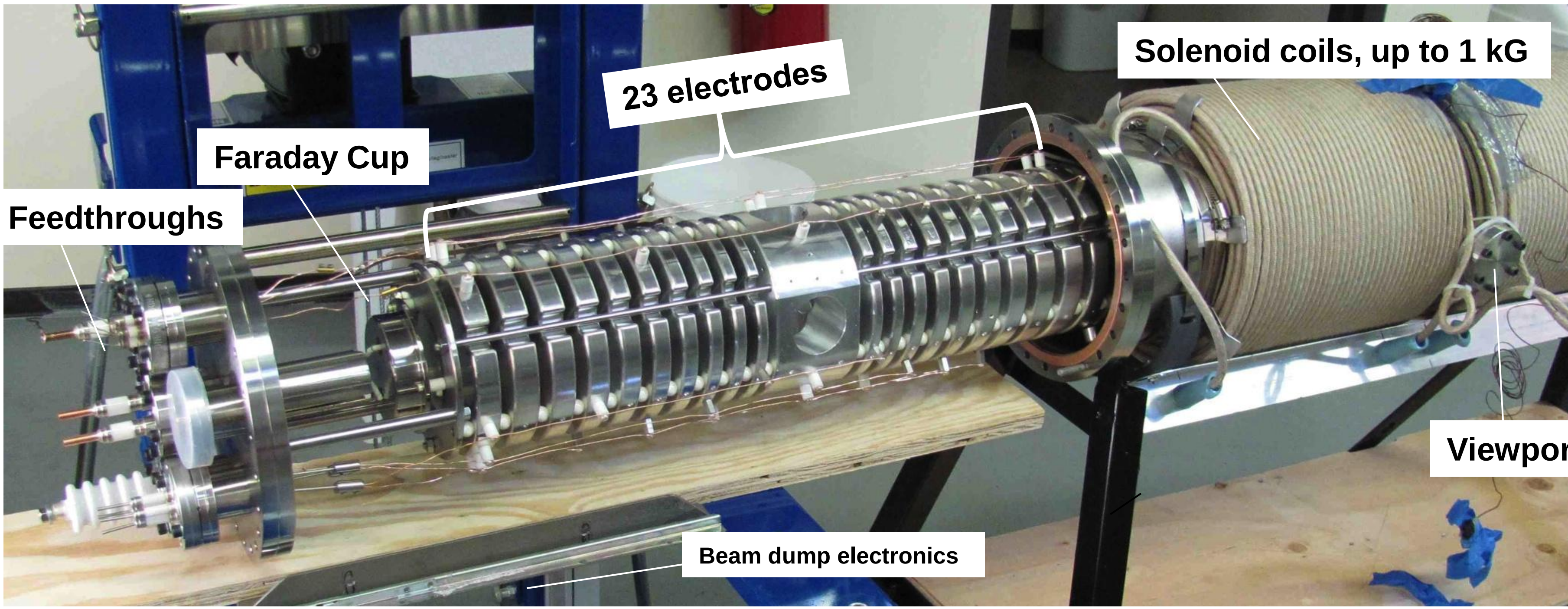
MARBLE Prototype: MARBLE-1

Design of 5-beam experiment based on short modeling campaign which looked for simple electrode shapes, robust ion trapping, versatility:



MARBLE-1

- Versatile basic physics experiment, simple yet very high quality engineering
- Became operational in March, 2011, but project shutdown 2 months later



The entire MARBLE device can be quickly removed/inserted with all wired connections intact

For details on this device, see poster

Preliminary results

- Penning trapping very effective. Ionization is spontaneous, given sufficient B-field, Φs on electrodes, and neutrals (gas)
- If B-field too strong, create plasma which destroys ion trapping optics. Reducing B to ~200 Gauss is adequate to limit this effect. It appears $n_e = n_{Brillouin}$ ➔ **control n_e with B**
- “Electron beam” mode by biasing emitter and Faraday cup at both ends negative, electrons bounce between ends (all other potentials ≥ 0). Under certain conditions, emitter not even required to get into this mode.
- With solenoids forming cusp, nearly all primary electron current (from grounded external emitter) to innermost positive electrode ($B \to 0$), if this electrode is biased > +50V (EBIT) ➔ **low power HV supplies**
- High freq. instability observed when B-field is low (~100 G), freq $\propto$ B & ϕ (diocotron?)
- Beam dump signals (primary diagnostic) can change from strongly negative to strongly positive - secondary electrons present challenge to signal interpretation ➔ measuring inventory of 5 distinct beams not yet done

Status & Plans

- Project terminated and equipment neatly packed up in May 2011 due to exhaustion of funding. (VCs declined further investment)

- MARBLE-1 and all associated equipment (> $1M) re-located to U. of MD (lab of Prof. Ray Sedwick, site of next workshop?)

- Will try to apply for available U.S. grants and see if MARBLE-1 experiment can be reactivated, and research be continued in academic setting

- Eager to collaborate with any & all entities who are interested in MARBLE, who may want to study any aspect of the concept (theoretically or experimentally)

If time permits, 15 minutes of additional material follow

Further thoughts

- Possible applications
- Optimization of MARBLE
- Scaling estimates
- Anticipated problems and challenges

Applications

Whether MARBLE approach can be developed to form basis of a high-performance neutron generator: not yet clear, although I think it has good prospects. However, there might be other applications for the technology.

Consider that the MARBLE:

1. Confines particles that fall into energy bands, and fails to trap particles outside of these bands
2. Allows an inventory of energetic particles to be rapidly switched out, producing very short pulses
3. Need not be a trap at all: one half of the geometry could be omitted entirely to produce a single-pass high-current and high-power particle beam consisting of multiple energies. With the MARBLE approach ("beams within beams"), beams could be produced from a small area footprint, with powers and currents perhaps substantially exceeding what can be done today

Possible applications: *energy analyzers? ion propulsion engines? proton therapy machines? ion implanters?* Interested in your thoughts, please email to alex@beamfusion.org

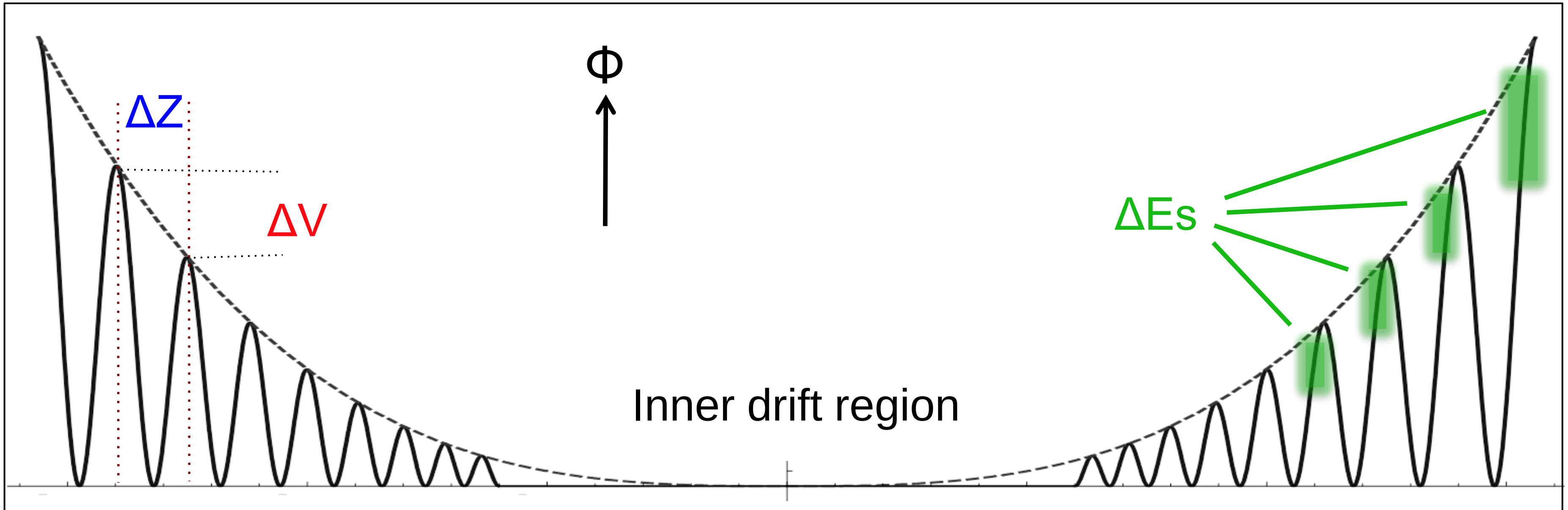
Basic MARBLE Questions

Energy bands, forbidden energies: reminiscent of QM systems. How much of the total phase space is available for trapping, how to maximize?

ΔE: How to maximize width of each stable energy band?

ΔV: What energy ratio between beams is achievable? Smaller ΔV = more beams

ΔZ: How close to pack electrodes? Closer = smaller device, but also higher ‘m’

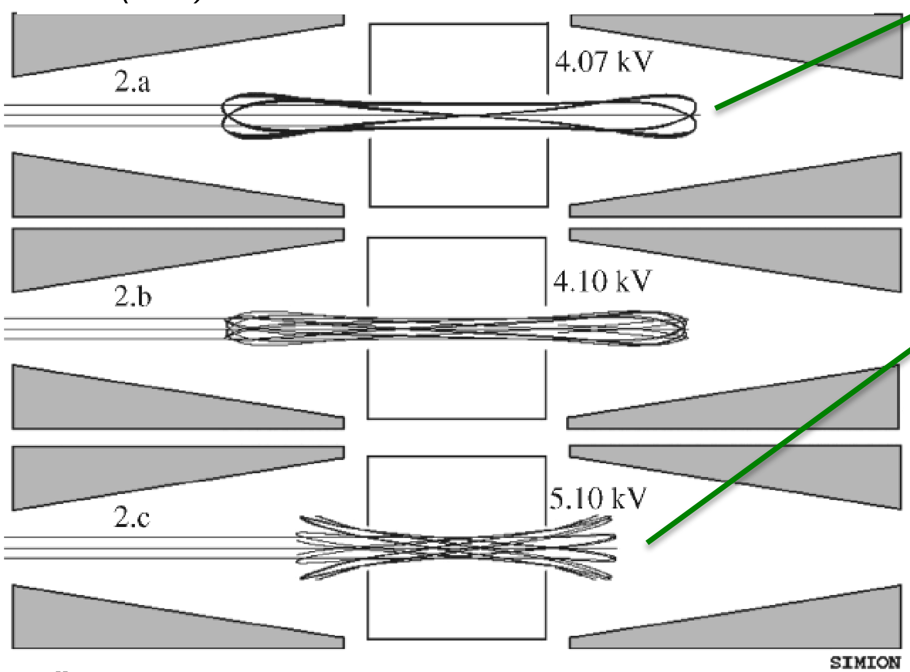


Schematic of potential profile on axis for a 8-stage MARBLE with arbitrary particular parameters

Regarding ΔZ: The “Cone Trap”

- ΔZ related to ΔE: spatial distance between lowest & highest turning Φ for stable particles
- 2 types of turning: “hard” (wall) & “soft” (beach)

from H.T. Schmidt et al., Nucl. Instr. And Meth. In Phys. Res. B 173 (2001) 523-527



“soft” mirrors → loopy turning orbits, “hard” mirrors with large potential gradients → more laminar trajectories

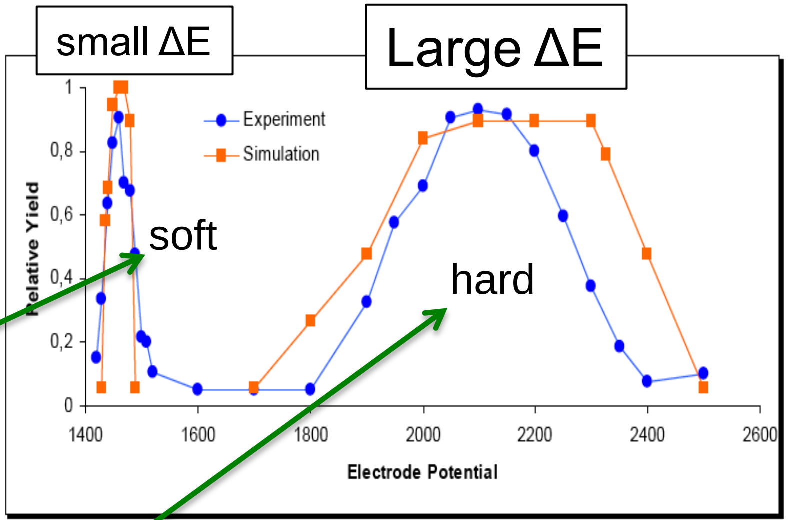


Fig 9. *Measured trapping of 1.4 keV N^+ for different V_{trap} both in simulations and experiment*

Larger ΔZ (lower E-field):

- > electron ionization efficiency but < ion recircs (CX)
- < space charge (spreads turning points), but weak E-field easily distorted by space charge
- Results in larger device size.

Regarding ΔE, Δr

- ΔE: Larger E-trapping range ➔ higher current limits + densities, larger available phase space

- ΔR: Larger beam radial extent while turning, or larger range of allowable angles when crossing core ➔ higher current limits + densities, larger available phase space

Maximizing allowable ΔR and ΔE for trapped particles crossing the core = **minimization of spherical and chromatic aberrations in the ion optical system** via variation of electrode shape parameters.

- Previous work: design of electron microscopes and ion mass spectrometers which use electrostatic reflectors
- Using electrostatic mirrors to correct for aberrations in lenses in electron micro-scopes* forms basis for highest precision instruments today (2.5 nm resolution)
- Results & methods entirely applicable to the MARBLE optimization challenge

**Gertrude Rempfer et al, Journal of Microscopy and Microanalysis, pg 14 (1997)*

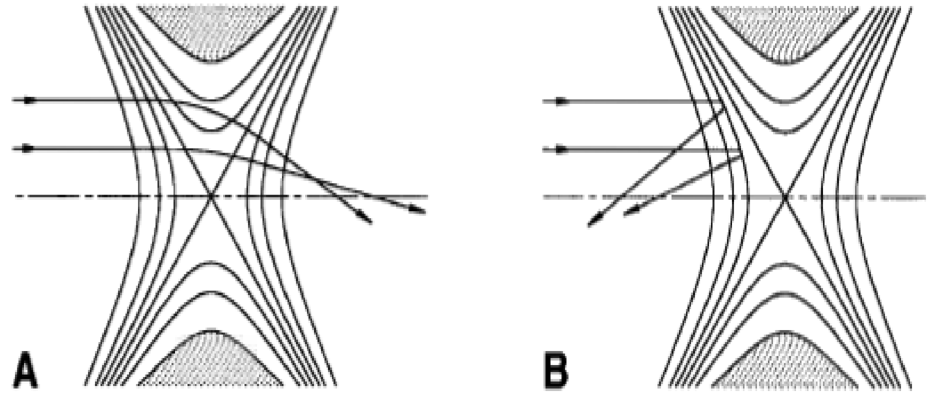
Regarding ΔE, Δr

Fortunately, electrostatic lens & mirror have spherical & chromatic aberration coefficients w/ opposite sign

Spherical aberrations

In lens, outer ray travels farther up the potential hill, takes longer to pass, thus has shorter focal distance than the paraxial ray.

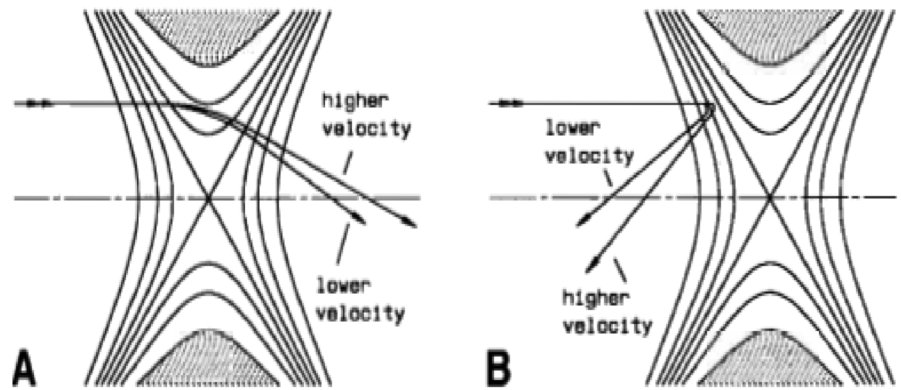
In mirror, the two rays are turned back at same ϕ surface, but distance traveled is shorter for outer ray. With less time for influence of field it has longer focal length



Chromatic aberrations

In lens, faster ray takes less time to get through, thus has longer focal length than slower ray.

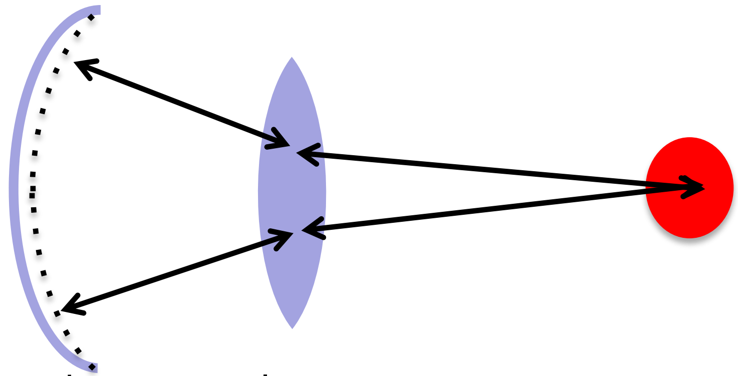
In mirror, higher energy particle penetrates farther, experiences focusing for a longer time. After reflection, higher-velocity ray crosses axis at a shorter distance from the mirror.



Maximizing ΔE, Δr

Analyzing ion-optical system in MARBLE device

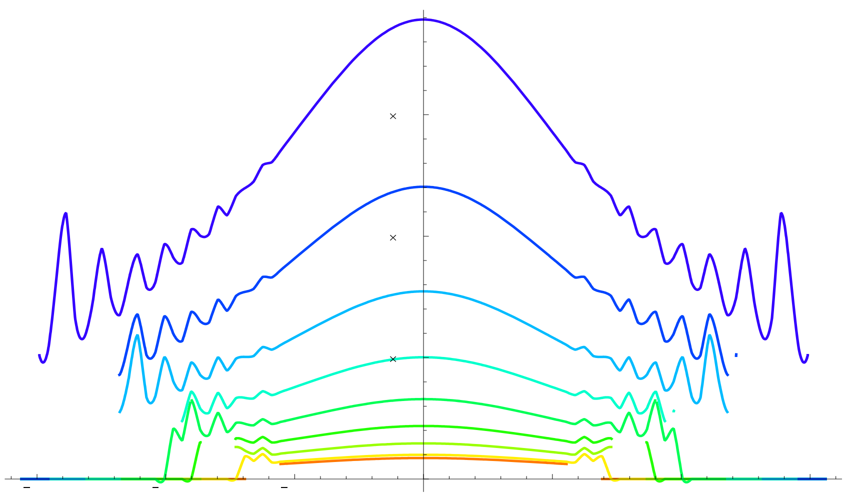
Matching lens to mirror such that 1st order spherical and chromatic aberration coefficients are equal magnitude & opposite sign allows for largest trapping phase space of beam



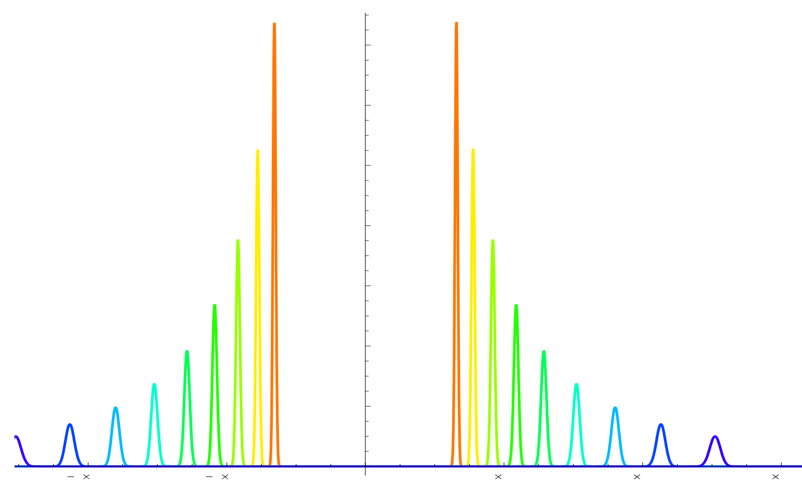
- "Lens" = sum of lenses between reflection & core, for outer beams is effect of several lenses (inner lenses act weakly on outer beams)
- Ions pass through mirror once & lenses twice (in & out) on each pass
- To first order, generic apertures produce hyperbolic equipotentials with known (analytical) optical properties and aberration coefficients
- But: detailed design requires the addition of space charge in the calculations & systematic variation of electrode shapes and potentials

Scaling

- Rough estimates: 1000 A of ion current recirculating through a fist-sized core is possible, without violating Child-Langmuir laws & with device diameter <1 meter. Such a scenario (50 linear 20-stage MARBLEs arranged about common core)produces fusion rates ~ 100 Watts (DT) from beam-beam reactions alone, compared with ~1 mW beam-background from a standard fusor
- Constraints/assumptions: Electrode potentials < 200 kV, 50% solid angle taken up by hardware, plausible Voltage ratios between stages (ΔV > 1.3)



Linear density profiles for MARBLE from assuming 0.5 fraction of CL current, some reasonable geometry



Beam velocity profile in core (z = 0)

Instabilities

- MARBLE is candidate for electrostatic two-stream & magnetostatic Weibel instabilities
- 10 keV energy difference between beams in theory is stable up to ~3 Amperes/beam (deuterium), and 1D simulations in LSP confirm this
- Multiple beams at multiple energies have higher threshold for unstable density when energy difference between beams is higher
- Literature* suggests MARBLE stable up to three magnitudes higher densities than without magnetic field

* Hiromu Momota and George H. Miley, "Neutron Source Based on a Counter-Deuterium Beam Linear IEC", J. of Fusion Energy, 28,191-194

2-stream: *"A deuterium counter-beam column with 30 keV, energy, 3 m in length and 0.5 cm in radius with a deuterium beam density up to 2.9x10^{20}/m^{3} can be stabilized by an external magnetic field stronger than 0.1 Tesla"*
Weibel: *"A deuterium counter-beam column with 30 keV of energy and a density 10^{19}/m^{3} will be stabilized by an applied magnetic field stronger than 0.4 T, independently of the column radius"*

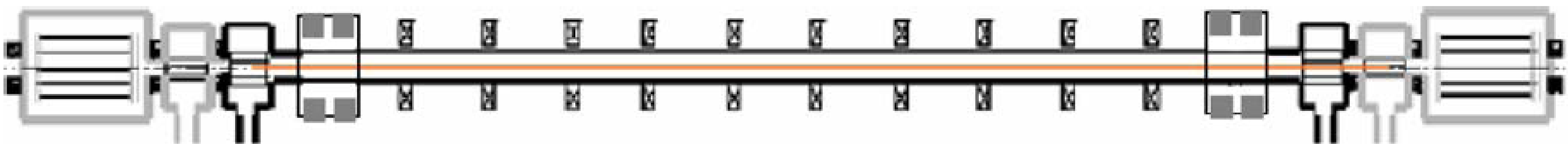


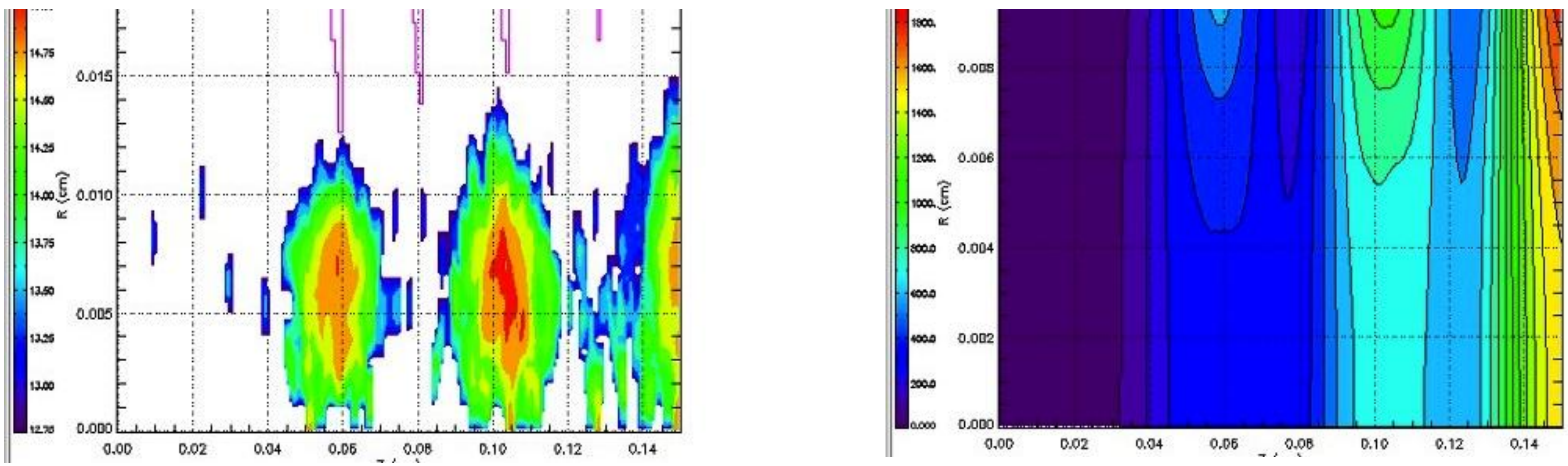
Fig. 1 A conceptual drawing of the neutron generator

Penning electrons problematic

- High n_e distort vacuum ϕ and destroy stability of ion orbits. Very high n_e ➔ plasma, loss of electric fields ➔ no ion confinement

- Reducing magnetic field limits the effect – control n_e with magnetic coils

- **Electrons shift the stability regions** for ions, simply changing the energy and bandwidth for stable ions. Can we understand enough to control ϕ-profile and design electron space charge into the ion optics?



LSP output: left, electron density in steady state with 250 Gauss axial field. Right: Contour plot of potential near axis shows significant distortion of vacuum field ➔increase in concavity for ion turning surfaces (over-focusing).

Thank you