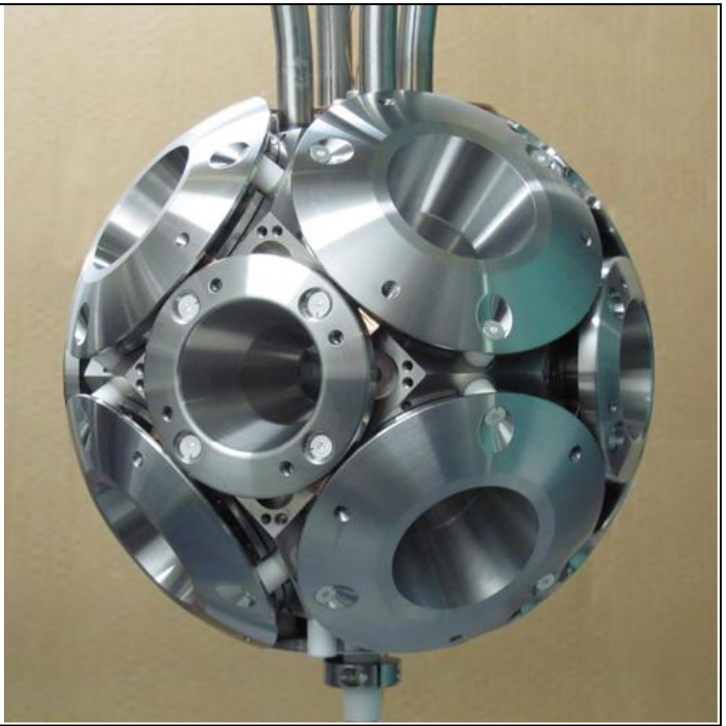
The Multipole Ion-beam eXperiment

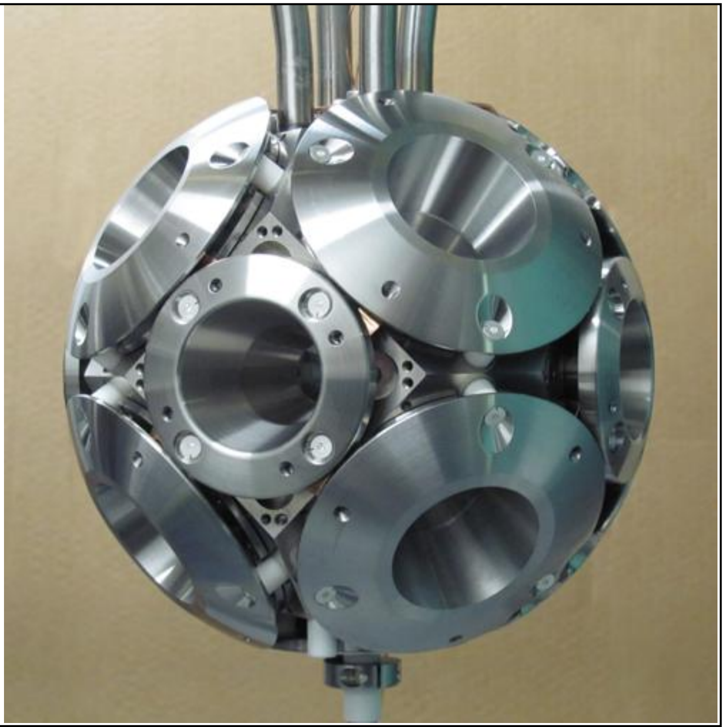


Alexander Klein
www.beamfusion.org

13th US-Japan IEC workshop, Sydney 2011

Outline:

1. What is MIX, why build it?
2. IEC Fusion: predictions
3. Some modeling results
4. MIX as constructed
5. Results & Conclusions

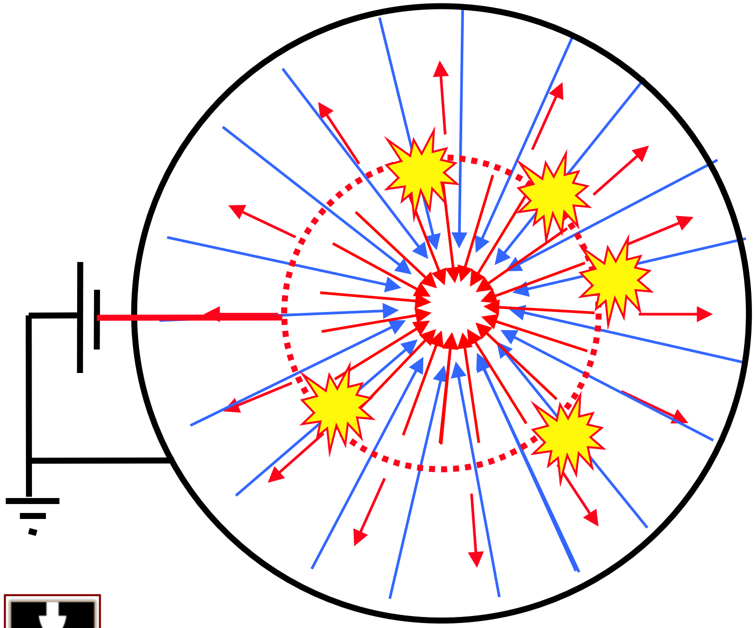


IEC status quo

- IEC fusion for power generation: a path long ago abandoned
- Fusors suffer from fundamental (physics) limitations

however:

- **Practical implementation** of the concept has been what **has been limiting the performance** of these devices

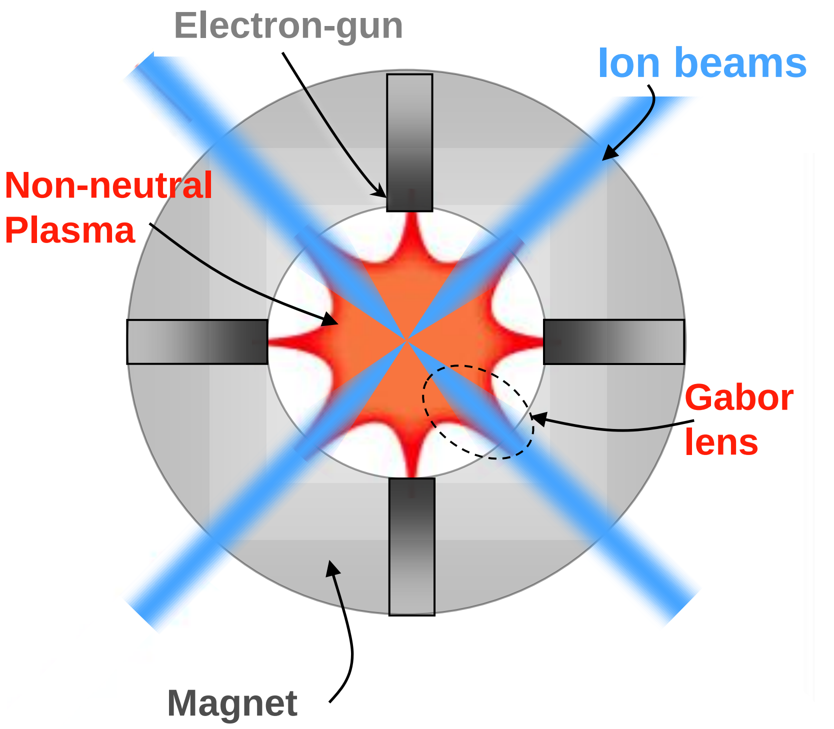


1. Single/simple grids: bad ion optics
2. Ion impact on grid wires limits power
3. High pressure prevents ion recirculation
4. Electron losses = large power drain
5. Severe space charge limitations
   ➔ low power densities

MIX = attempt to do better

MIX: IEC with multipole magnetic electron confinement

- Ions accelerated into negatively charged polyhedral electromagnet, which replaces wire grid
- Optics: Ions recirculate, build up intense trapped beams
- Electrons injected into confining B-field w/ biased emitters
- Electrons create non-neutral plasma in core
- Space charge profiles used to focus ions (Gabor lensing)
- Drive "Hirsch currents", virtual electrodes?



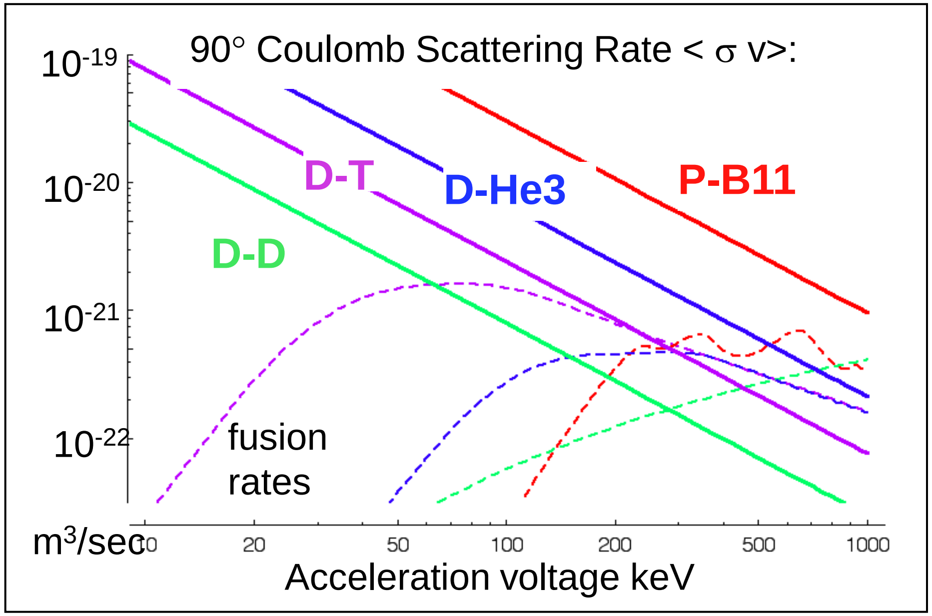
Basic MIX concept

Maximizing efficiency and power

Goals of Experiment:

1. Demonstrating Q = 1
2. 1 kW fusion power level (DT)

Calculations predicted this might be achievable



Energy balance determined by:

1. Fusion
2. Magnetic cusp confinement (electron streaming loss)
3. Coulomb scattering (ion loss)
4. Ion thermalization rate(s)
5. Electron thermalization rate
6. Bremsstrahlung
7. Engineering efficiencies
8. Instabilities?

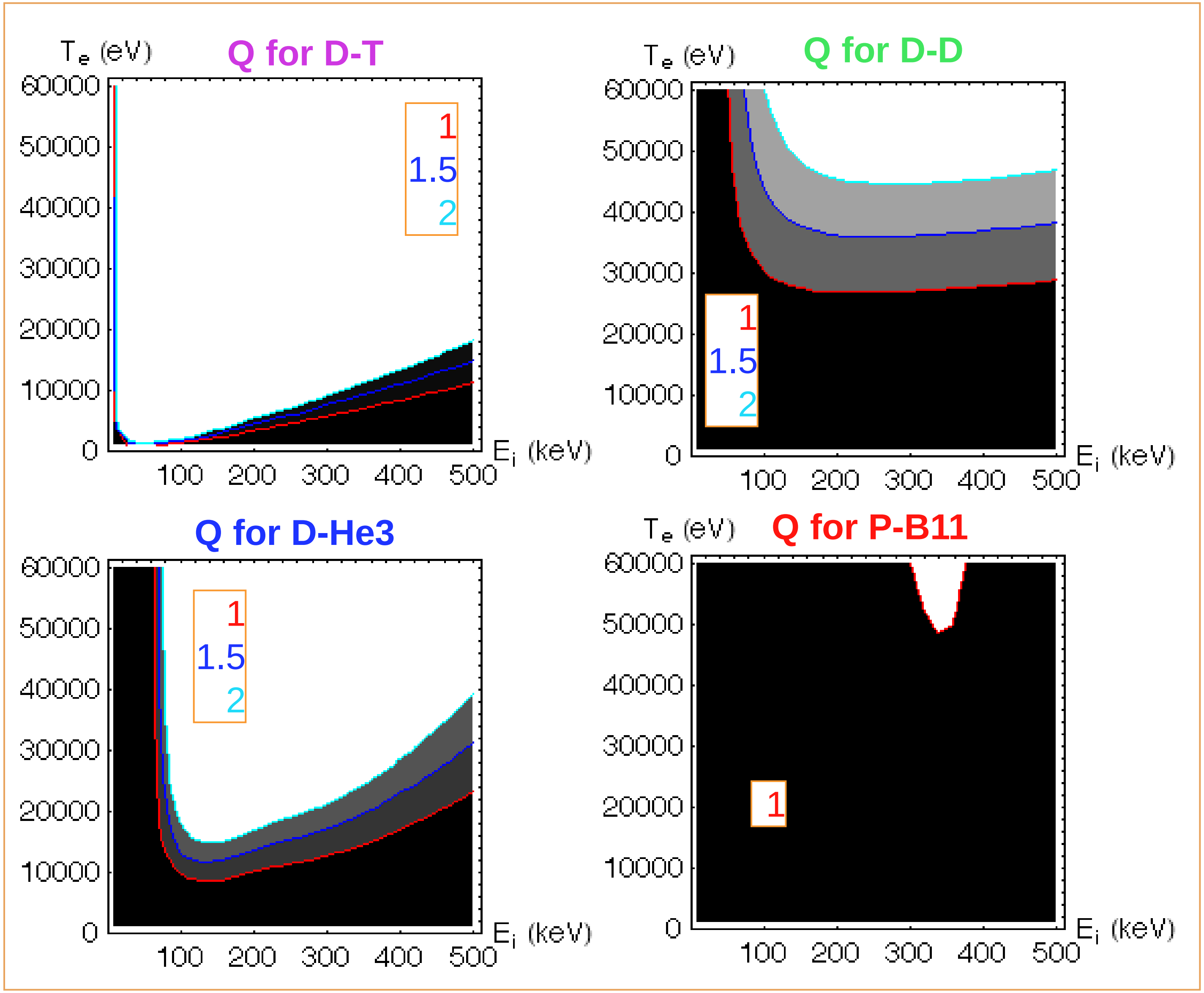
Parameter space for break-even fusion

Fundamental Q limitations as a result of binary collision processes

Included:
- fusion
- i-e energy transfer
- bremsstrahlung
- ion-ion scattering

Not included:
- parasitic electron losses

➔ attracted VC investors who then funded the project



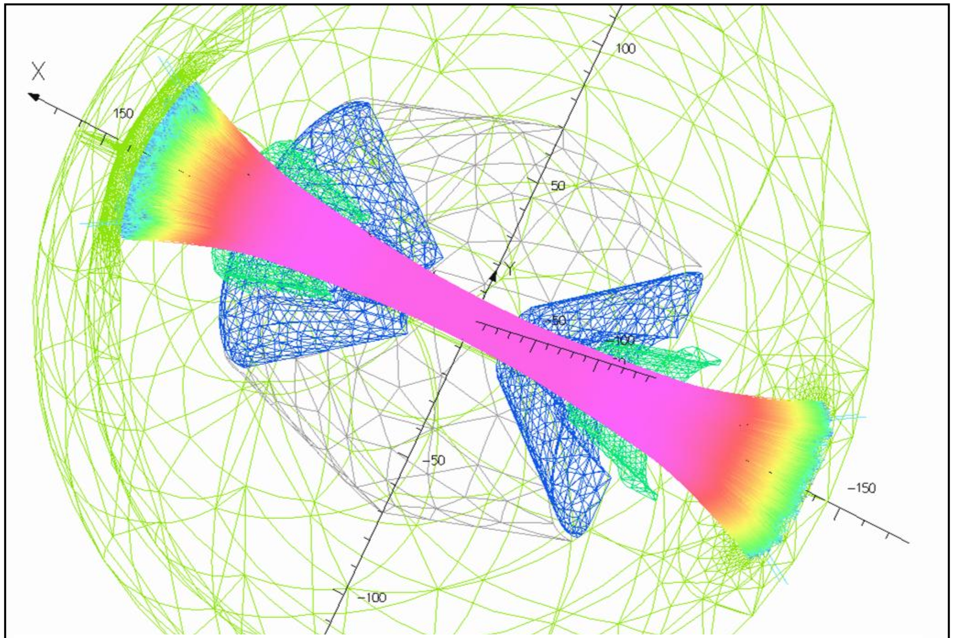
1st step: Modeling

A modest modeling campaign was undertaken to

a) test some basic assumptions

b) guide the design of the cathode-magnet and other hardware. Tools included:

- LSP (3D PIC/fluid hybrid code)
- 32-core Linux Cluster
- Opera & SCALA (3D E/M & FEM & beam codes)
- CPO (charged particle optics)
- Analytical Methods, some new
- GA to find optimal geometries



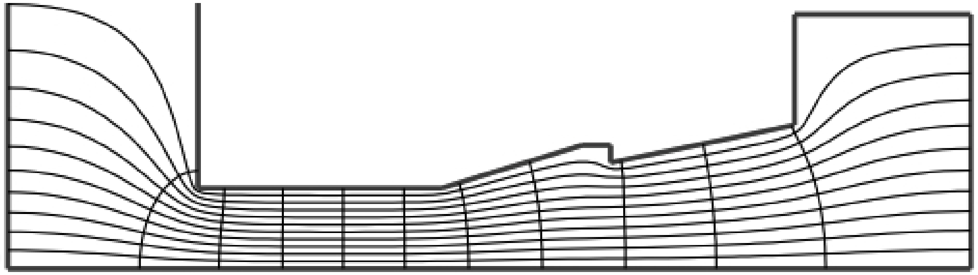
OPERA output: steady state, high current (10 A) trapped ion beam in MIX geometry with 100 kV potential. No electrons, no B-field. Colors indicate ion velocity.

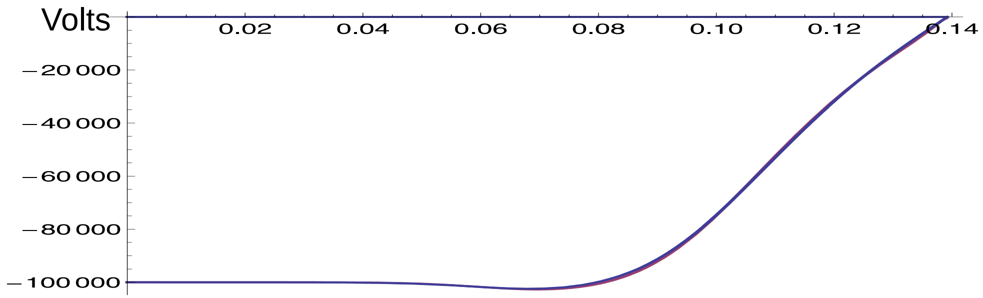
Analytical Modeling

New method* of conformal mapping to approximate ion trap potentials with analytic expressions, allows instant stability analysis

Conformal map resulting from MIX electrode geometry, generates analytical model of electric fields

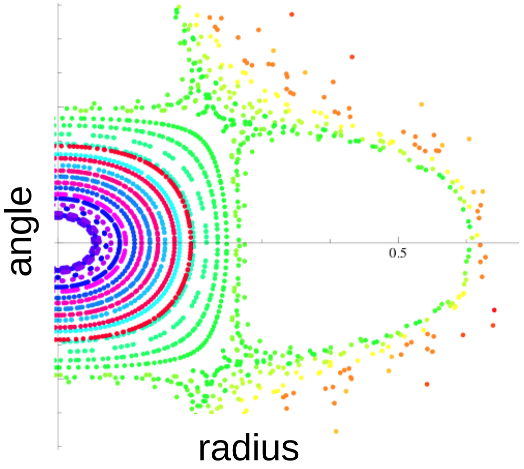
On-axis potential profile: analytical and numerical solution diff. <0.1%

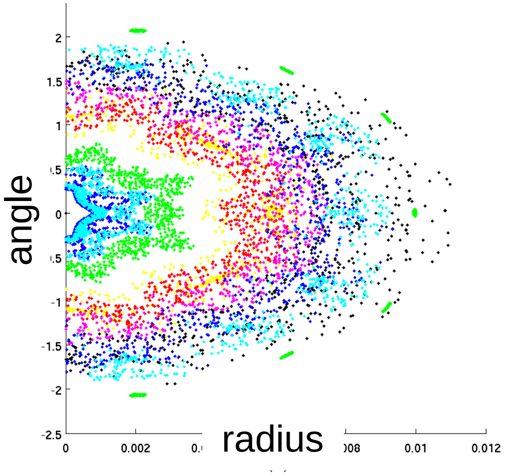




Ultra-simple models: very good tool for insight into physical systems that take very long time to analyze numerically

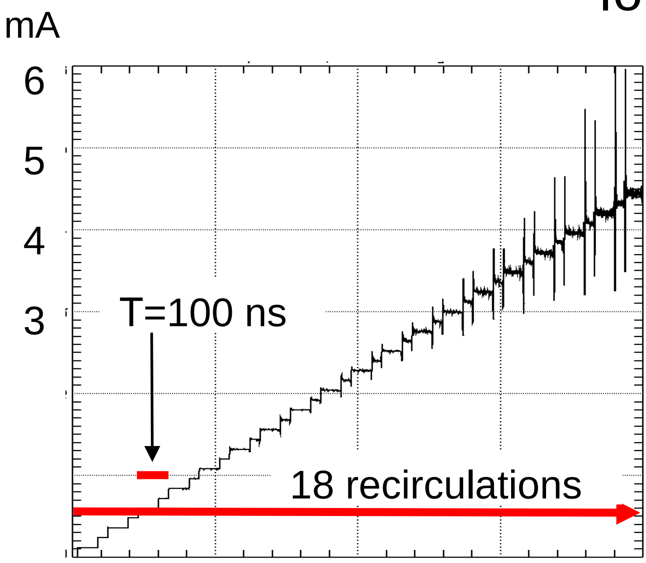
Ion phase space plots: Toy model vs. PIC code results, essential features captured



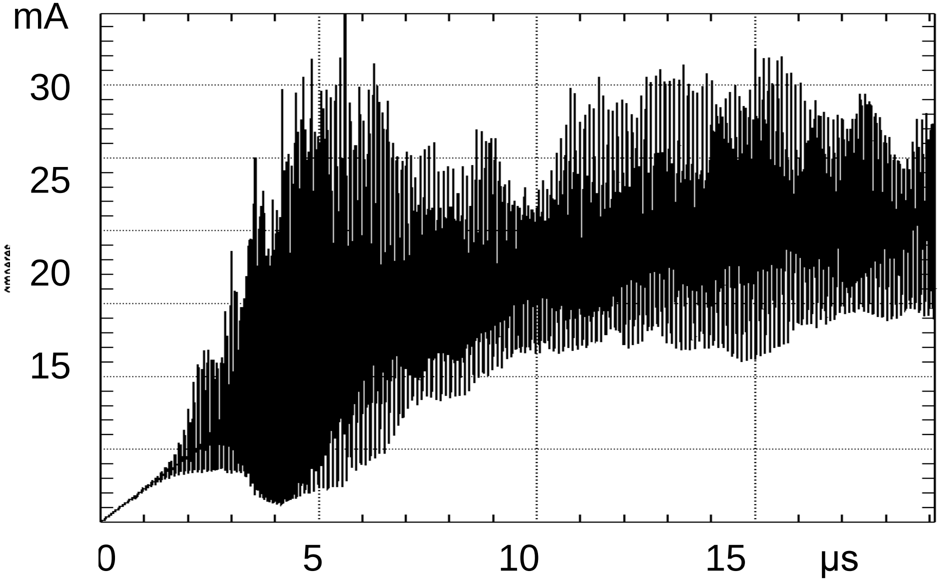


* *A. Valette, Phys. Rev. ST Accel. Beams 13, 114001 (2010)*

Ion dynamics

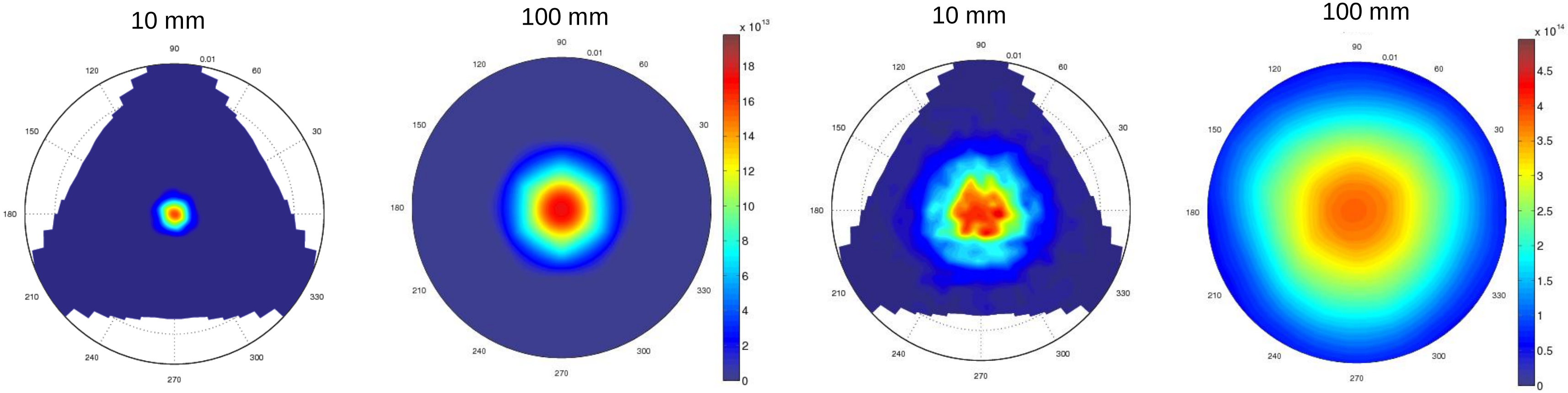


Ion Current through a plane - bunching



Beam density vs time, near and far from core

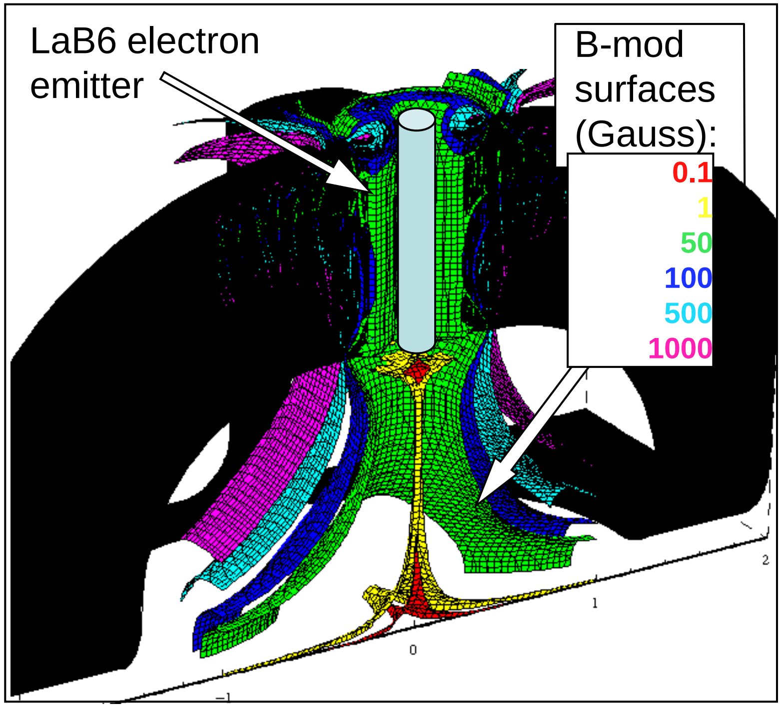
early: 500 ns (5 recirculations) — late: 19 μs (190 recirculations)



Electrons in MIX

- Original plan: Octahedral geometry, electrons injected via point cusps
- T_e set by emitter bias relative to magnet: $T_e = {}^{2}/_{3}\Delta\phi$
- Electrons heated by ion beams are recollected at emitters : $\Delta T_e \ll 1$

➡ **Control of n_e & T_e**



Octo-MIX core cutaway: point cusps for e- injection

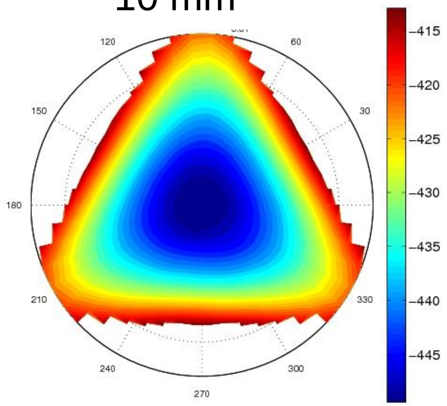
BUT:

- Simulations revealed injection of electrons along point cusps not possible (no field lines to core)
- Changed design to higher order multipole (TC) and inject along mirror axes.

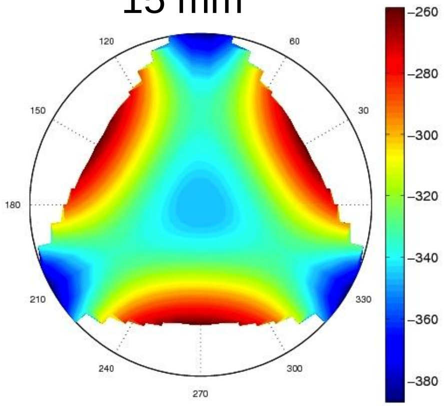
Electron dynamics

Cross sections of potential (largely due to electron space charge) at increasing distances from the core along the ion beam axis:

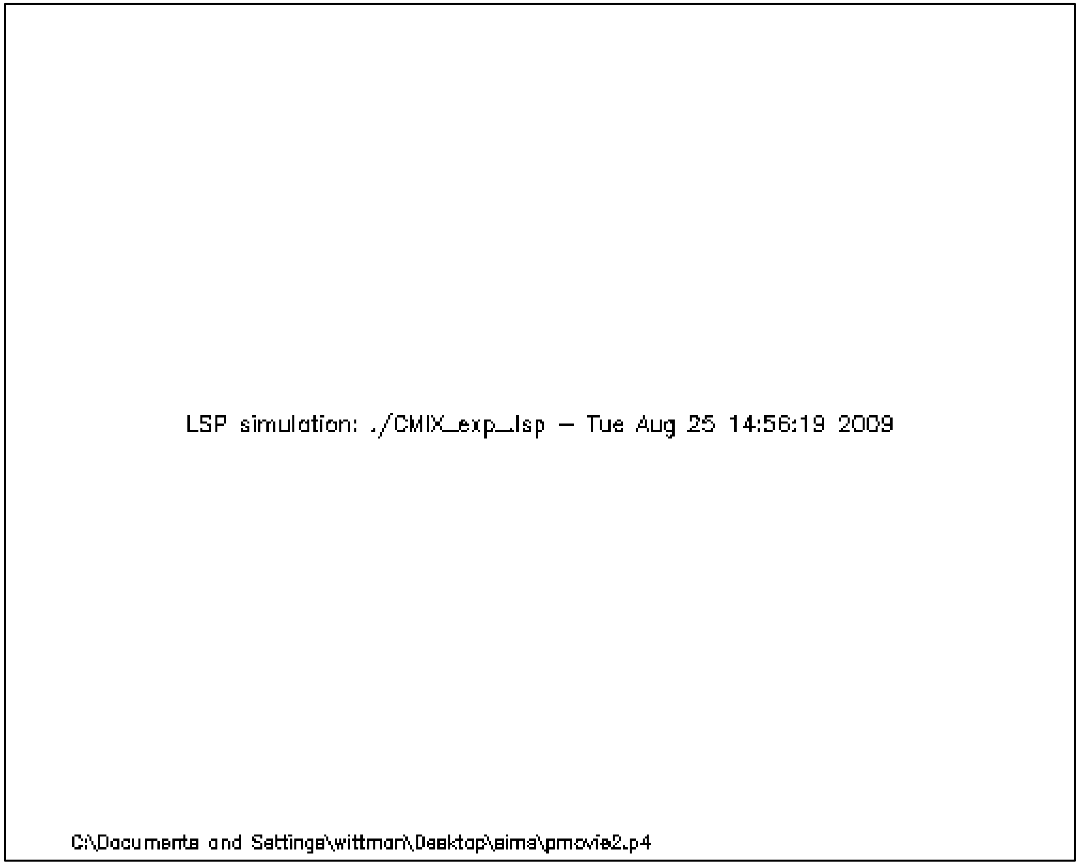
10 mm



15 mm



Modeling electron injection into MIX field

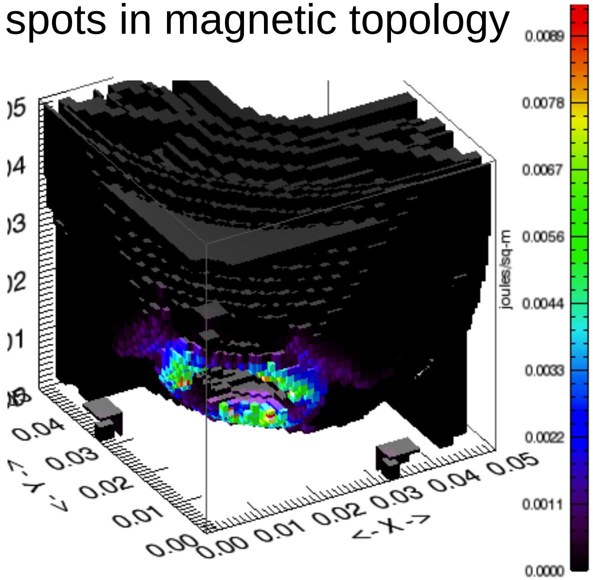


LSP simulation: ./CMIX_exp_lsp – Tue Aug 25 14:56:19 2009

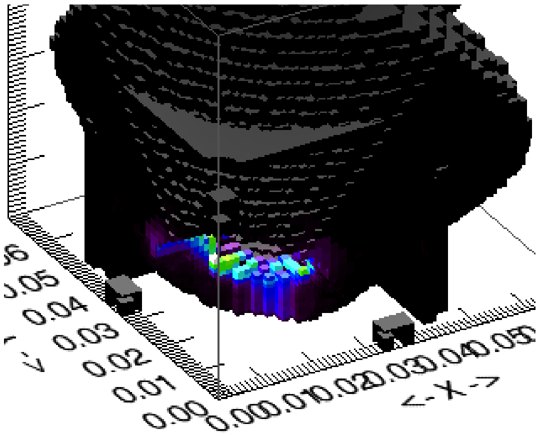
C:\Documents and Settings\wittman\Desktop\sims\pmovie2.p4

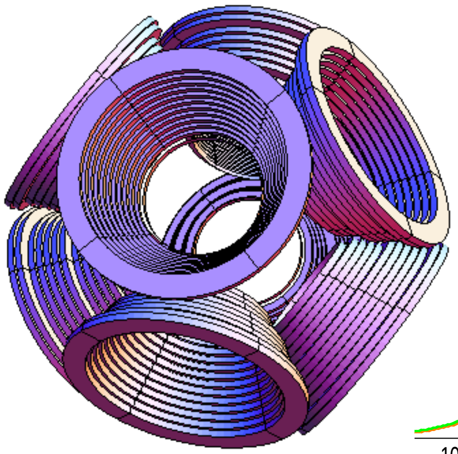
Detailed design questions

Electron energy deposition shows weak spots in magnetic topology

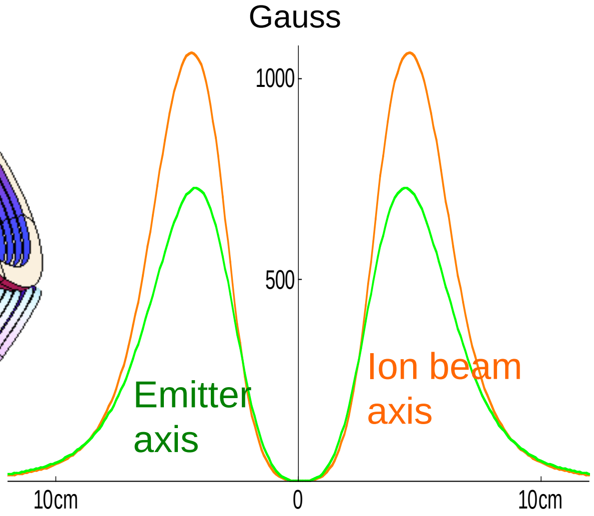


Ion beam energy deposition picture (erosion and heat risks)



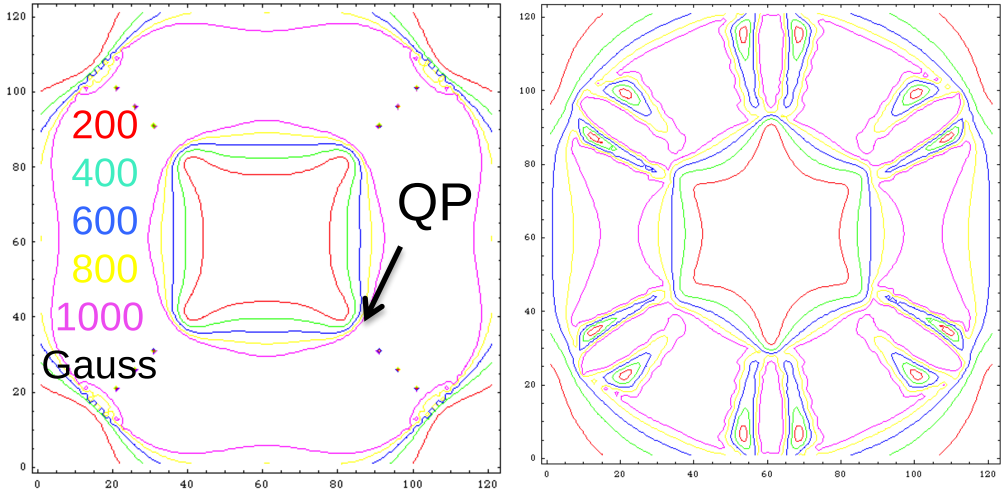


Truncated Cube: 8 cones

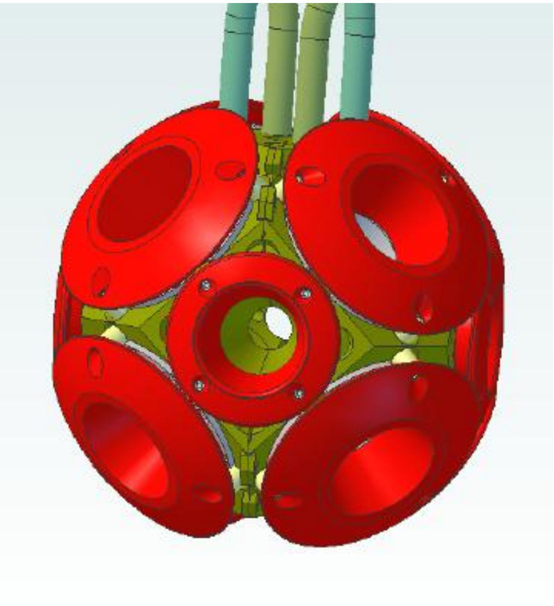


magnetic field strength

B-mod surfaces (2 cross sections)

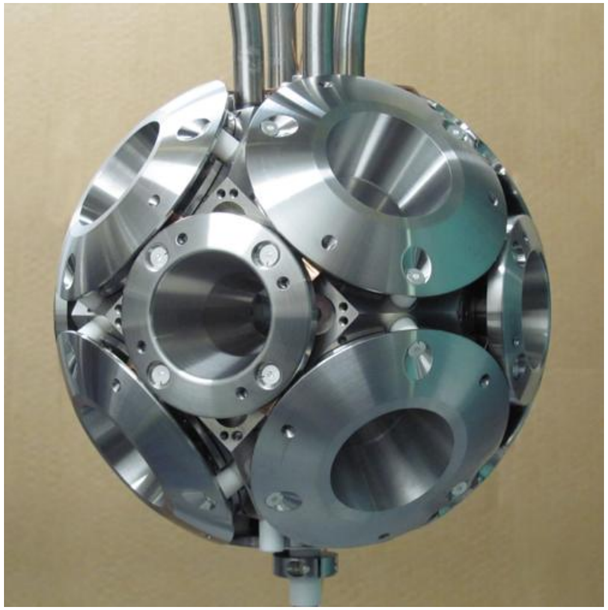


Final magnet design and construction



MIX magnet design

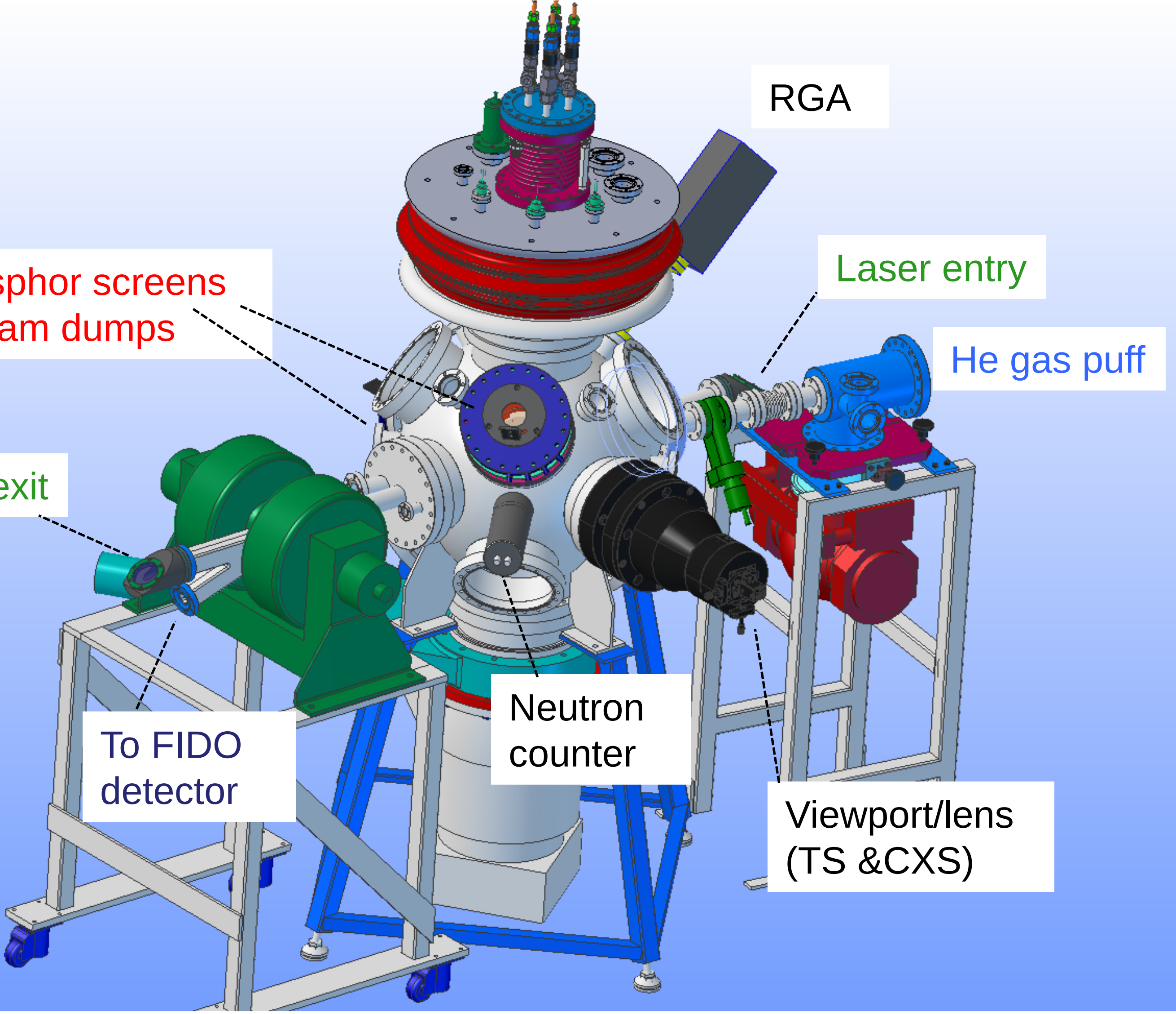
constructed by
Buckley Systems,
(New Zealand)



MIX magnet

- Constructed from two solid hemispheres, each containing 4 o-ring sealed seats for conical coils
- 14 magnetic mirrors: 8 for ion beams, and 6 for diagnostics/electron gun
- 1 kGauss at max power at strongest point on axis of mirror field
- Takes up tp 6 kW (160 A, 38 V) Ohmic power
- High pressure deionized water cooling, insulating up to 150 kV
- Includes e-repellers, many holes and feedthroughs

MIX diagnostics layout



RGA

Laser entry

He gas puff

Phosphor screens & beam dumps

Laser exit

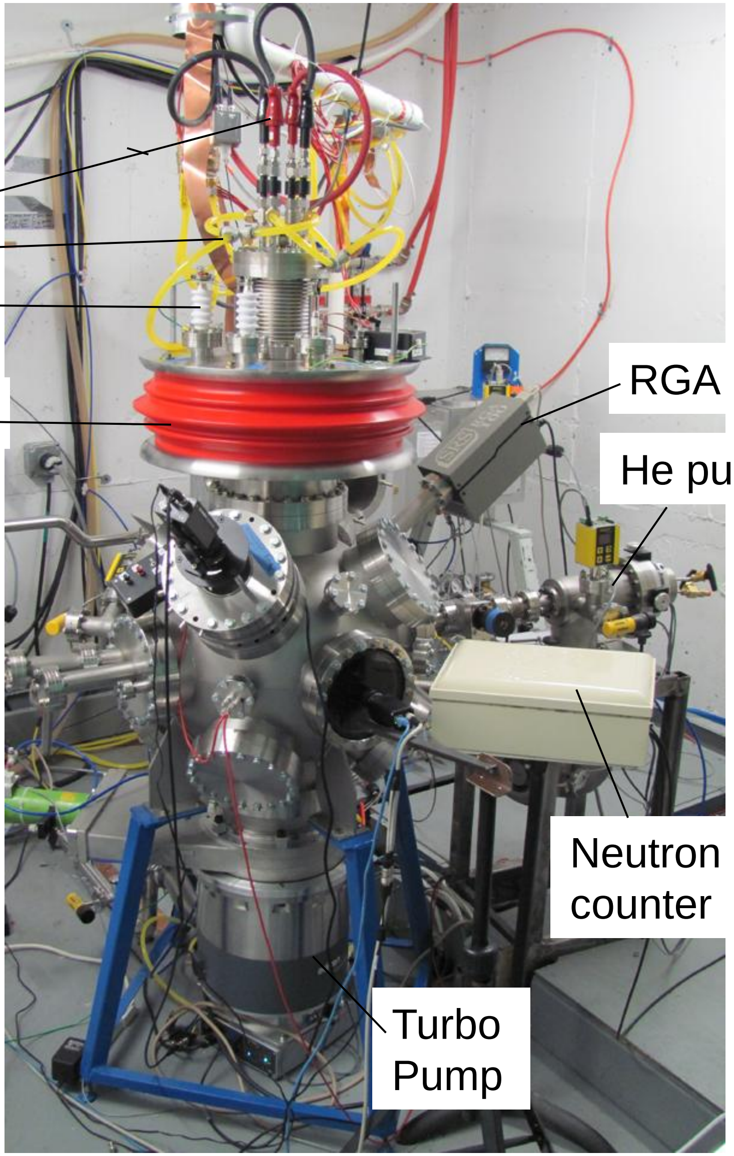
To FIDO detector

Neutron counter

Viewport/lens (TS &CXS)

MIX designed and built in 12 months

Magnet retracts with all electrical connections



Included construction of concrete radiation shield, DAQ system, diagnostics, ion sources,…

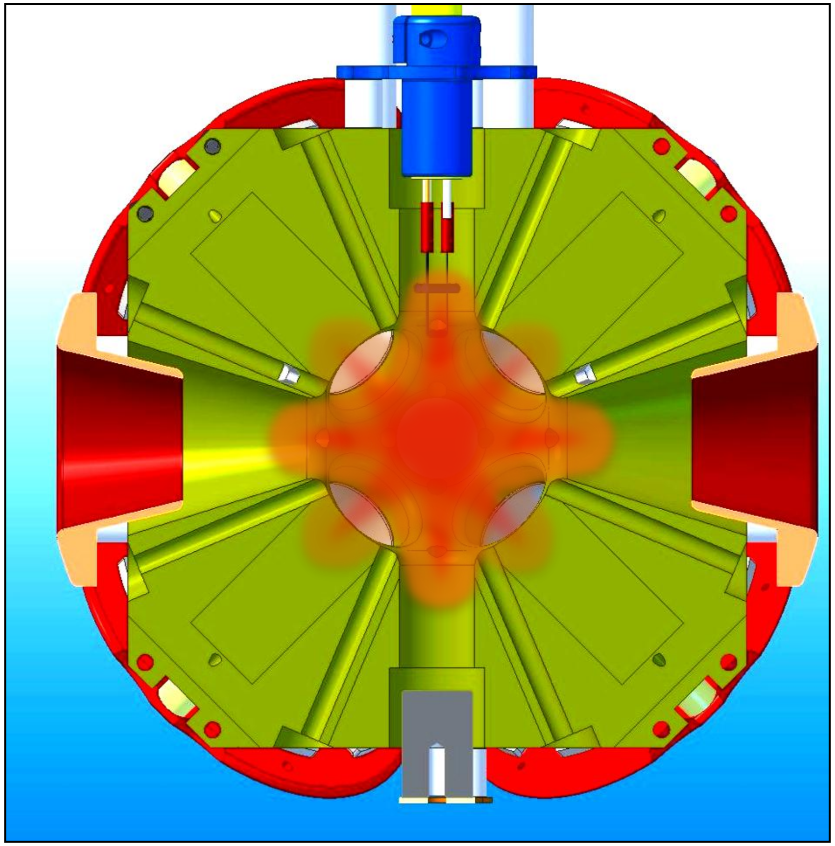
see MIX poster

Results

MIX performance far from goals

Electron Confinement

- Electron injection into magnetic field: Ran small tantalum disk emitter and larger filament emitter, biased up to 1 kV negatively from magnet



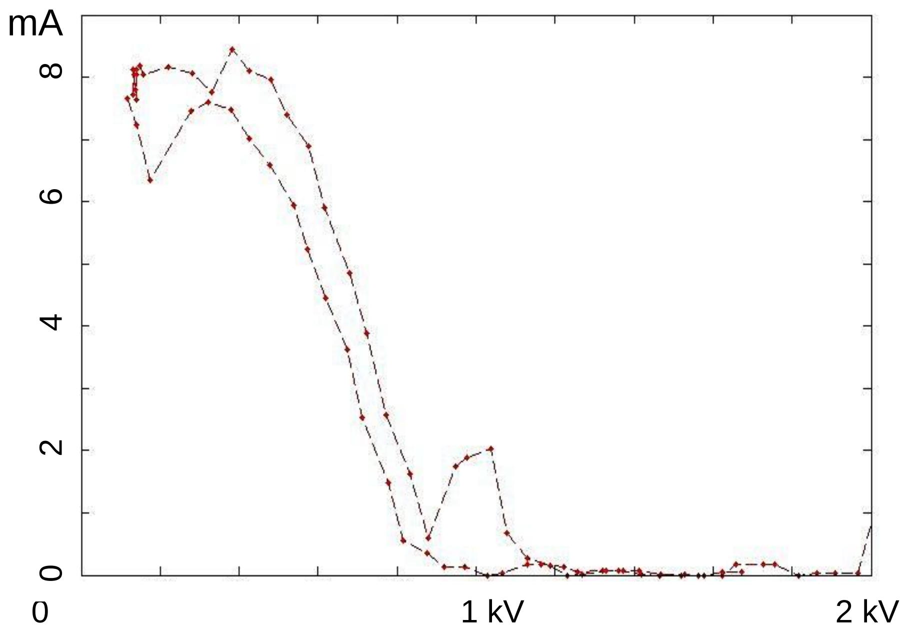
- Ran both emission limited and space charge limited injection modes for full range of magnetic field
- **No surprises:** currents and losses as expected from LSP simulations (in absence of ion beams, neutral plasma)

Electron data – repellers off

- Without repellers, about 40% of injected electrons stream through cusps to ground when B-field “on”.
- Used 80 kV difference to chamber walls to get full effect of electrostatic leakage.
- Current to magnet reduced with higher B, looks like B^2 scaling for weak B, then linear (since negative potential well forms and also grows with B, driving losses)
- But streaming losses get worse with higher B (better confinement ➔ higher density & greater potential well pushing electrons out)
- Total emission magnitude and currents measured consistent with LSP simulations involving emitters of comparable size

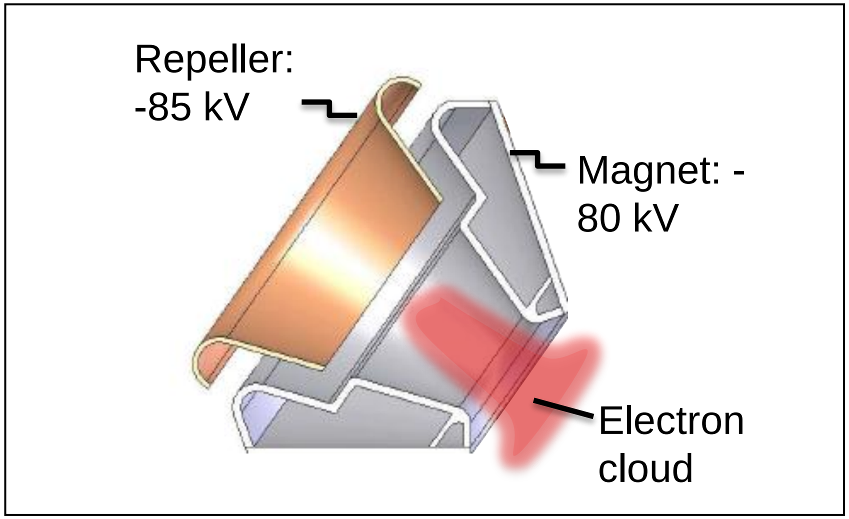
Electron data – repellers on

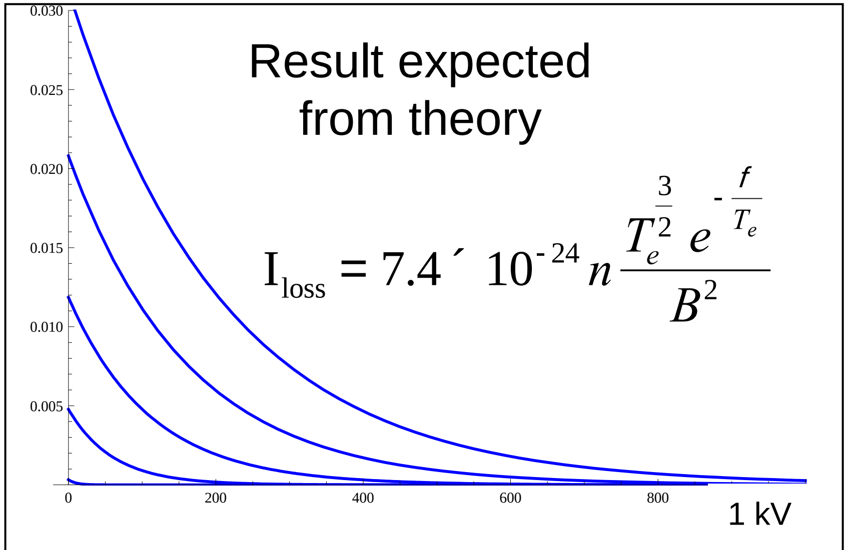
Repellers totally effective in suppressing streaming losses with potential ~ 2x emitter potential



Electron streaming loss current data

(emitter bias at ~500V, HV at 80 kV, sweep repeller to 5 kV. Magnet at 800 G)



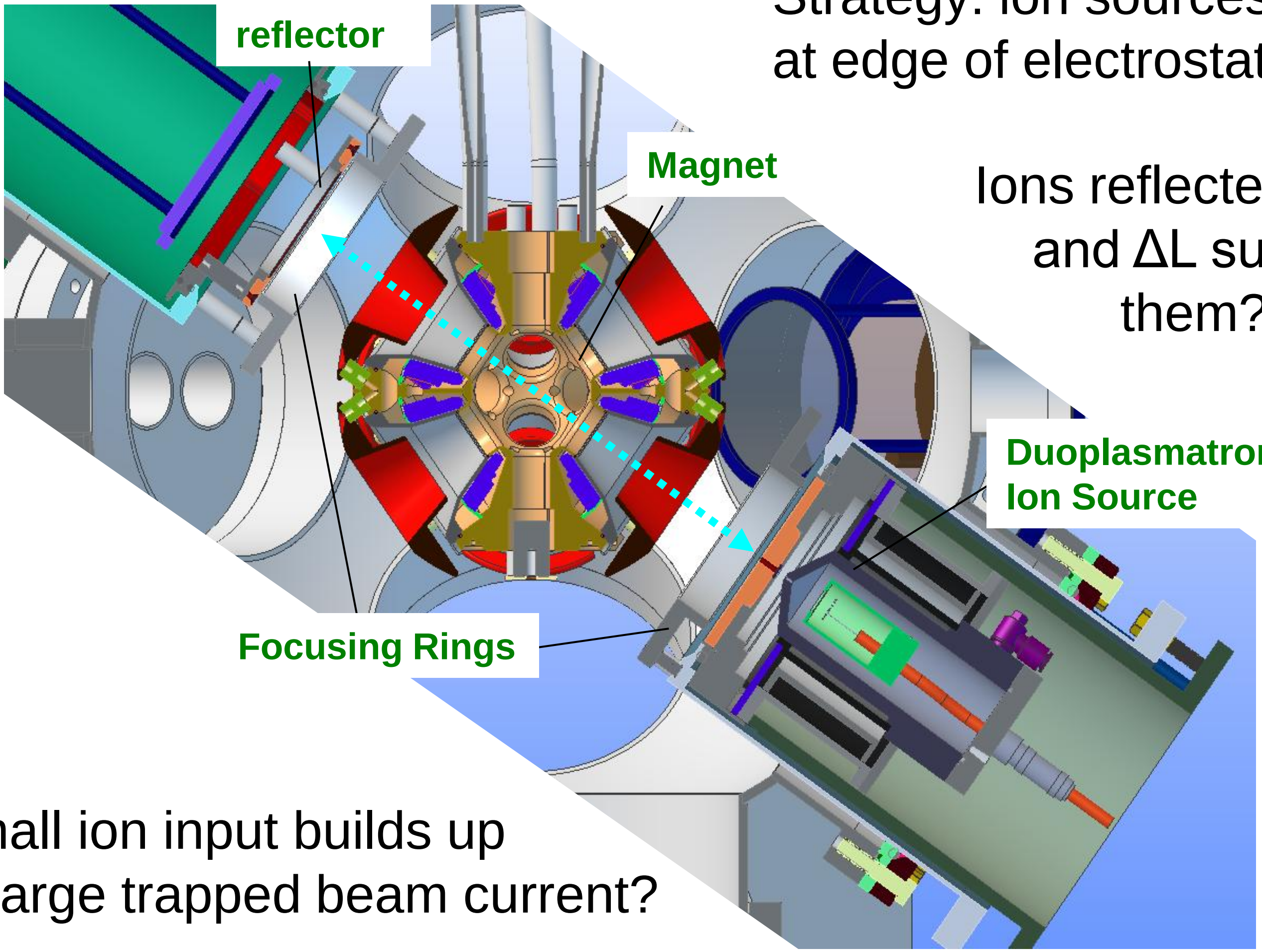


Result expected from theory

$$I_{loss} = 7.4 \times 10^{-24} n \frac{T_e^{\frac{3}{2}} e^{-\frac{f}{T_e}}}{B^2}$$

Ion beam results

Strategy: ion sources creating ions at edge of electrostatic trap

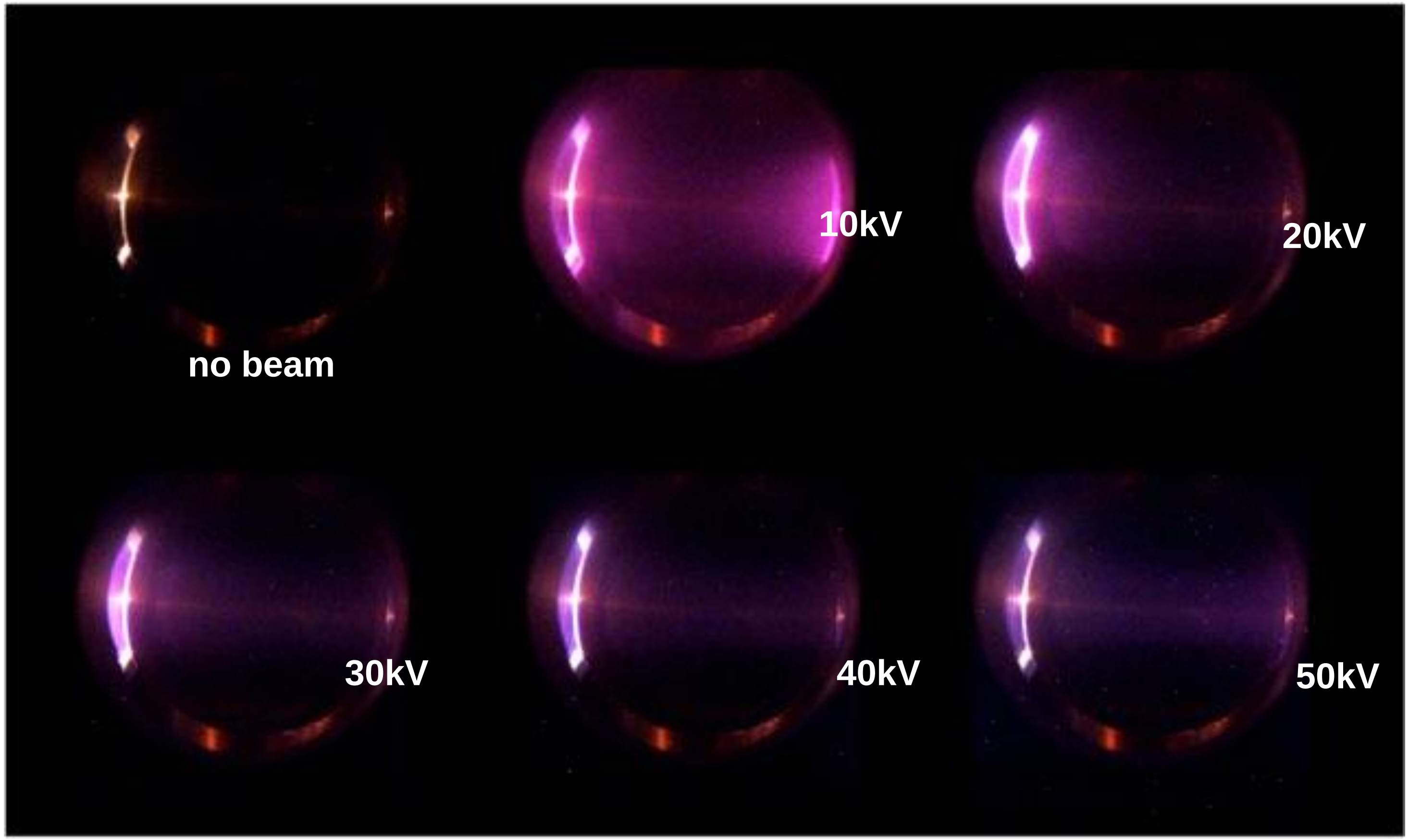


Ions reflected, then: small ΔE and ΔL sufficient to trap them?

Small ion input builds up to large trapped beam current?

Ion beam results

Unfortunately, diagnostics indicate stored ion beam never larger than a few mA recirculating

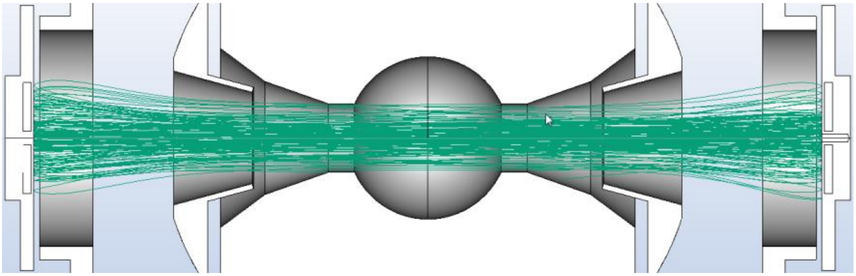


Source located on right, view through core. Beam diverges and impacts magnet apertures

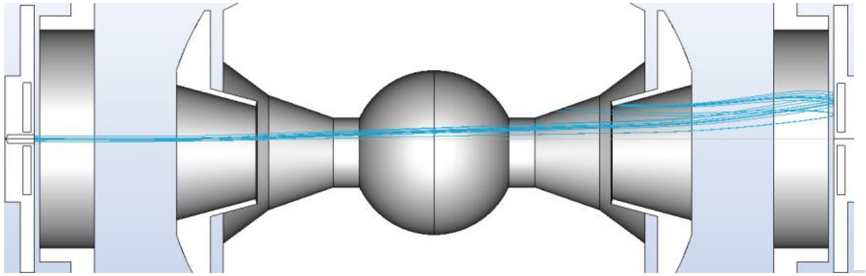
Alignment of ion beam optical system suspected

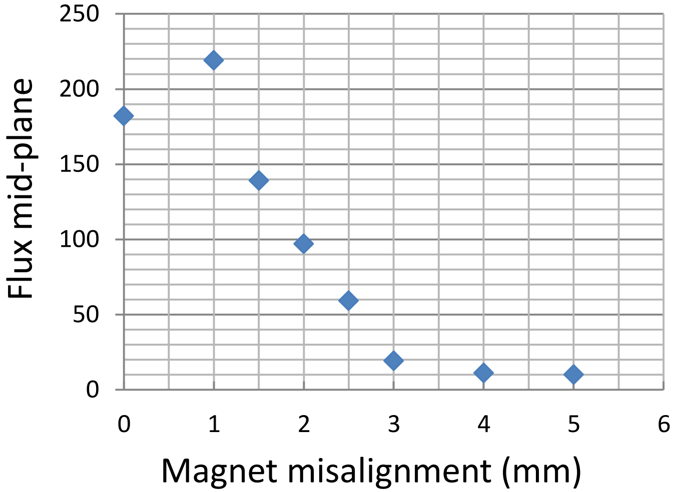
Modeling misalignments:

Perfect alignment



Small offset

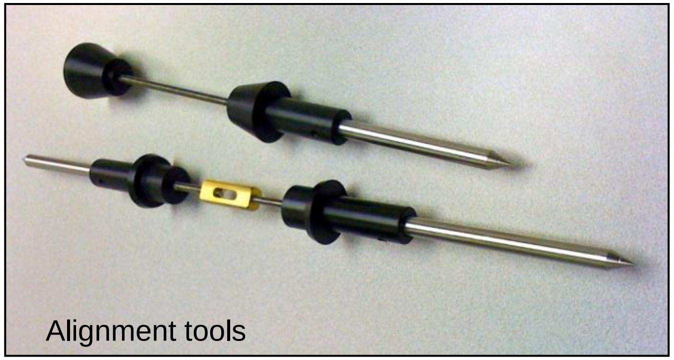




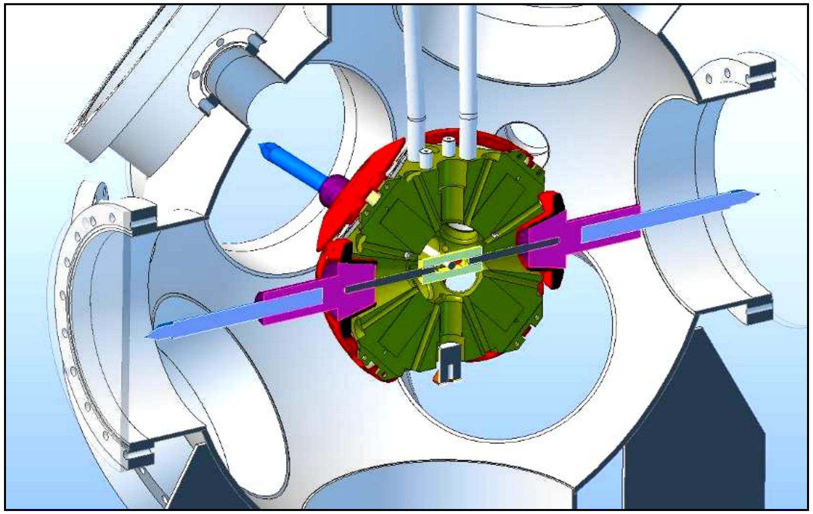
- Small misalignments ➔ all the ions are lost after single reflection
- Very small misalignment ➔ ions lost after a few reflections

Alignment of ion beam optical system

- Built several alignment tools
- Found electrodes had been substantially imperfect
- Aligned electrodes as best as we could to well within requirements



Alignment tools



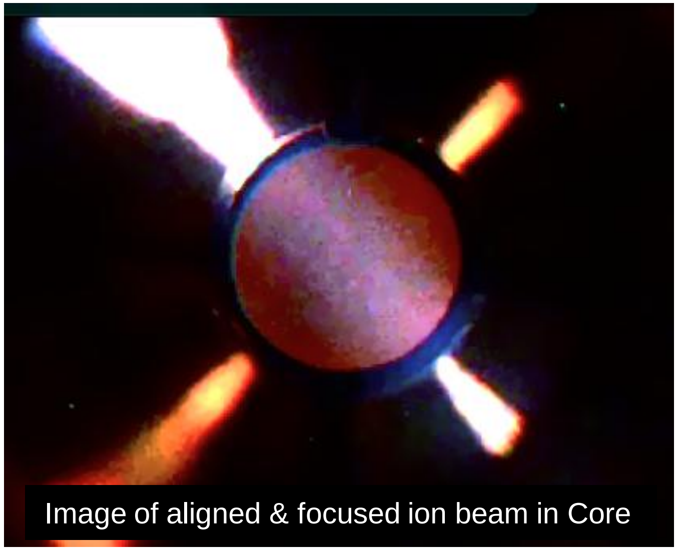
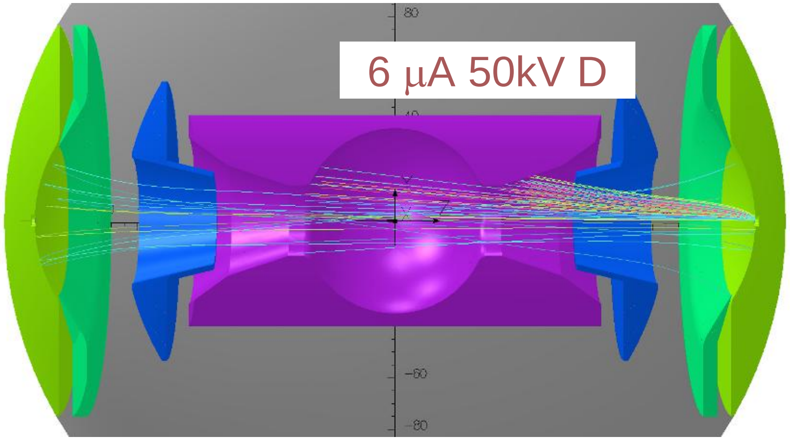


Image of aligned & focused ion beam in Core

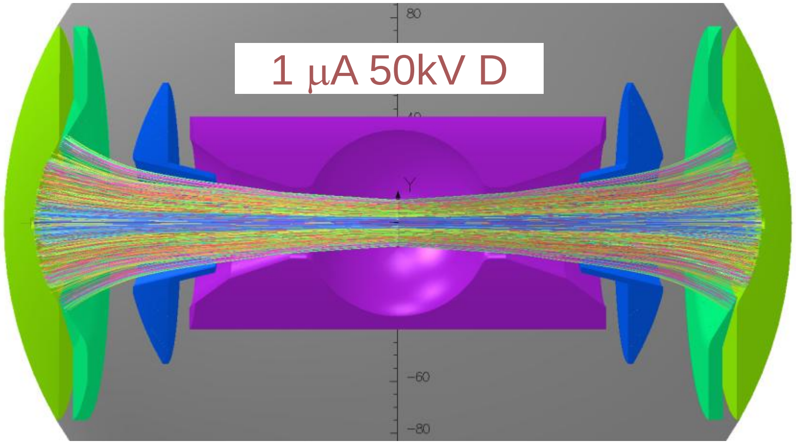
➔ Alignment critical, MIX design not the best in this regard

Challenge: matching source to the trap

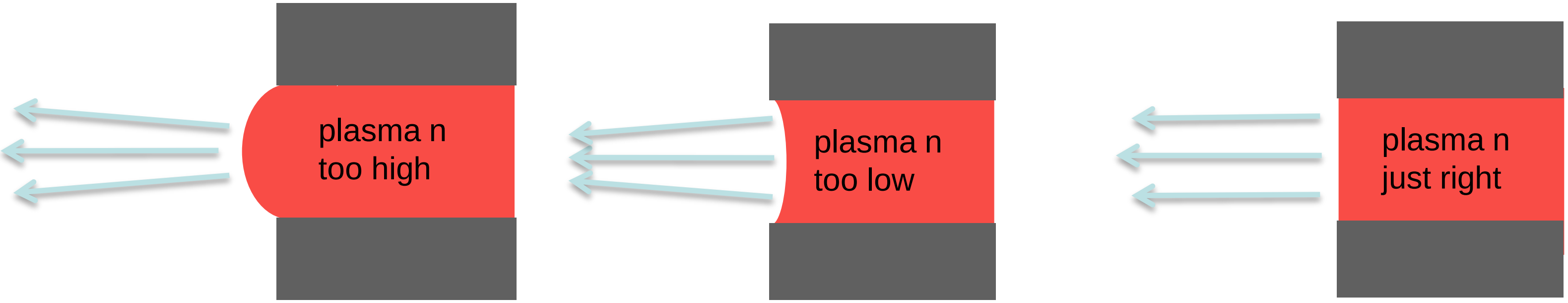
- Example: Duoplasmatron: “nice” beam only with properly matched extraction. Typically, strong extraction field required for converging, focused beam.
- IEC Problem: high density ion source plasma bulges out of source and causes majority of ions to be out of acceptable phase space. Trap cannot fill, or, as trap begins to fill, the extraction field is changed ➔ mismatch



No useful trapping. Beam strike on one pass



Trapping. Beam collected on low-V skirt.


plasma n too high

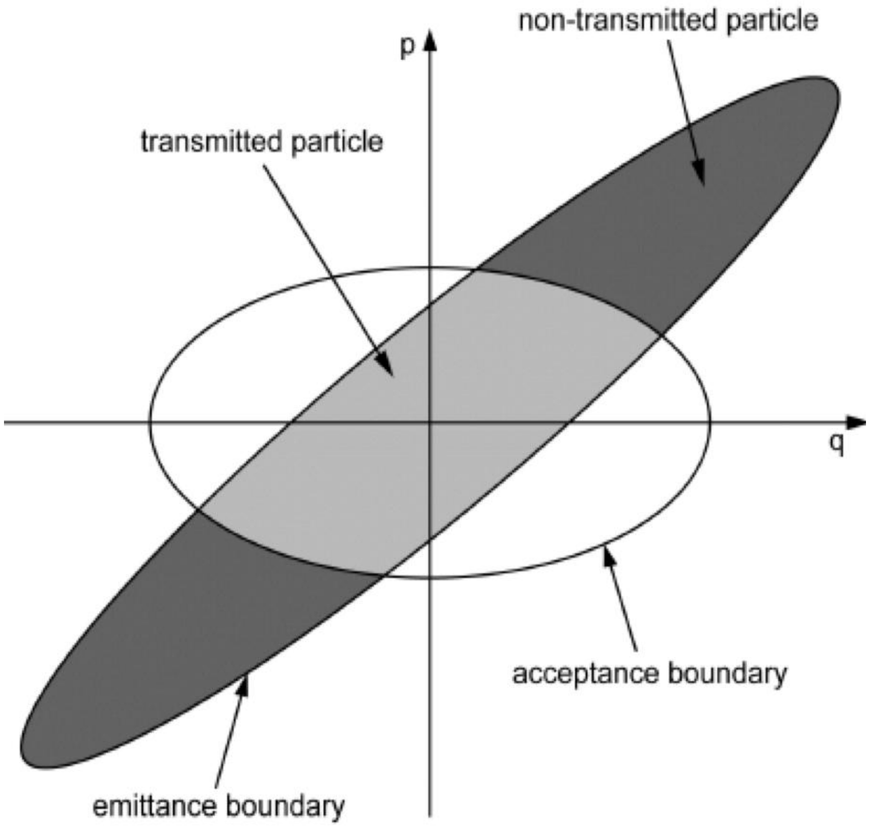
plasma n too low

plasma n just right

The first problem with ion sources

Introduction of ions into a recirculating electrostatic trap ***from the edge of trapping phase space*** turned out to be vexingly difficult, both in simulations and in the lab

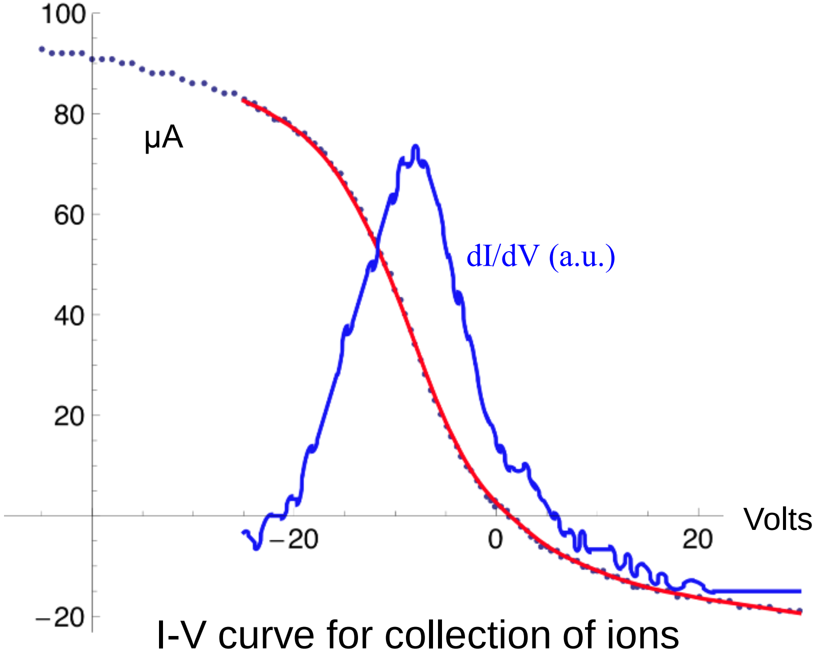
1. Need scattering and violation of Liouville Theorem to get into trapped phase space
2. Expect only 10% of “perfect” ions to survive a succession of a few infinitesimally small scattering events (statistics: “random walk near a cliff” problem)



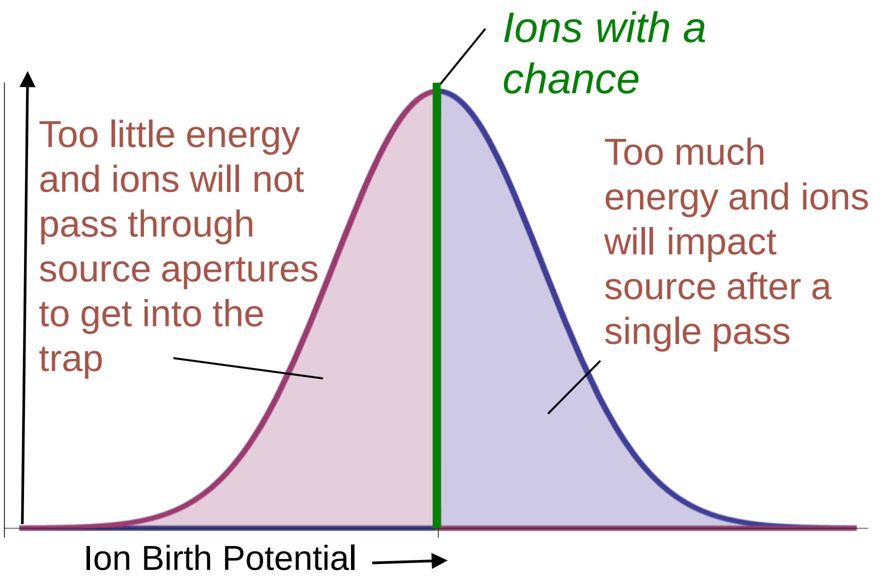
The second problem with ion sources

Only tiny injection current possible, no matter what the ion source

0-E ions = very small portion of incident ions from any ion source due to finite temperature of source plasma



I-V curve for collection of ions directly out of duoplasmatron

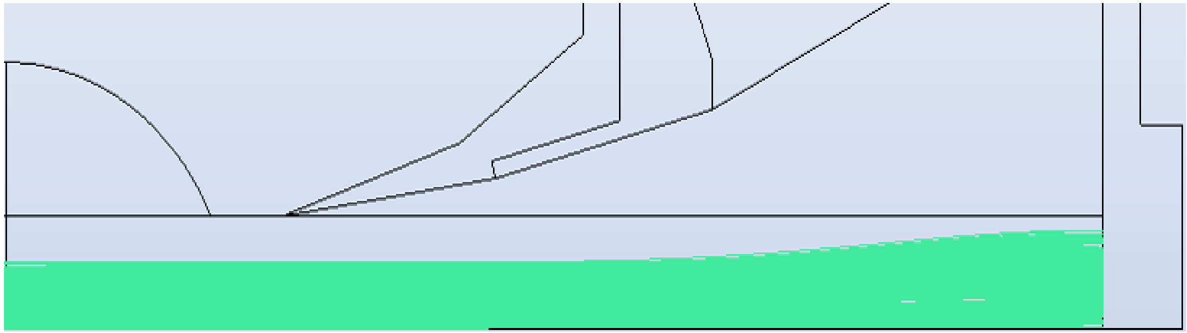


Ion energy distribution function for any ion source

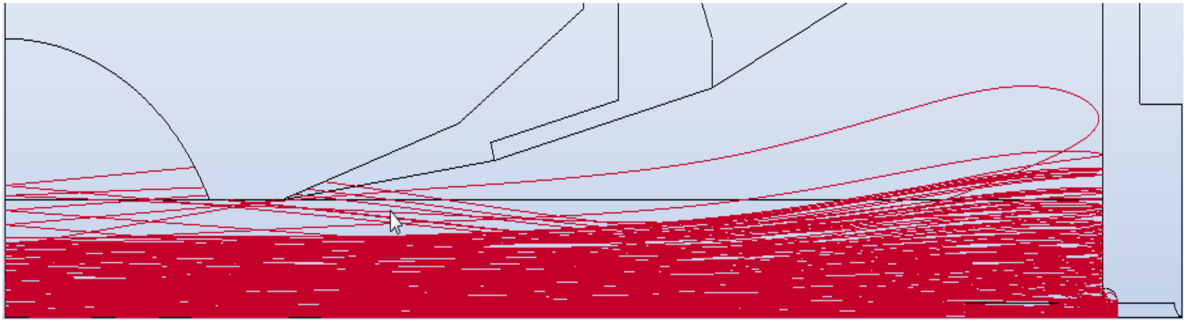
Desirable for IEC: extremely low temperature ion source, but this causes other problems (space charge at turning points)

The third problem with ion sources

- Ion sources invariably involve apertures from which ions are sourced
- Returning ions scatter off the plasma plume (or concave depression) at the source



Simple model, no aperture: All ions reach 50 passes, focused beam

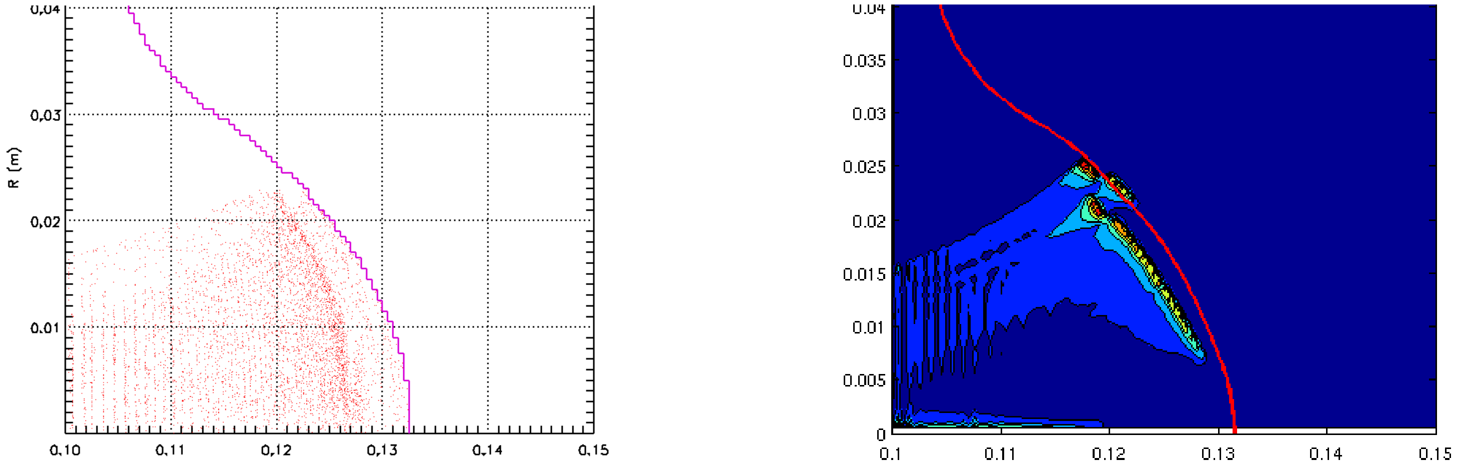


Simple model, aperture with rounded cup (best we could achieve): only 10 % of ions are trapped after 20 passes

Fundamental problem with ion sources

Very thin ion turning region near a real, solid surface: **mission impossible**

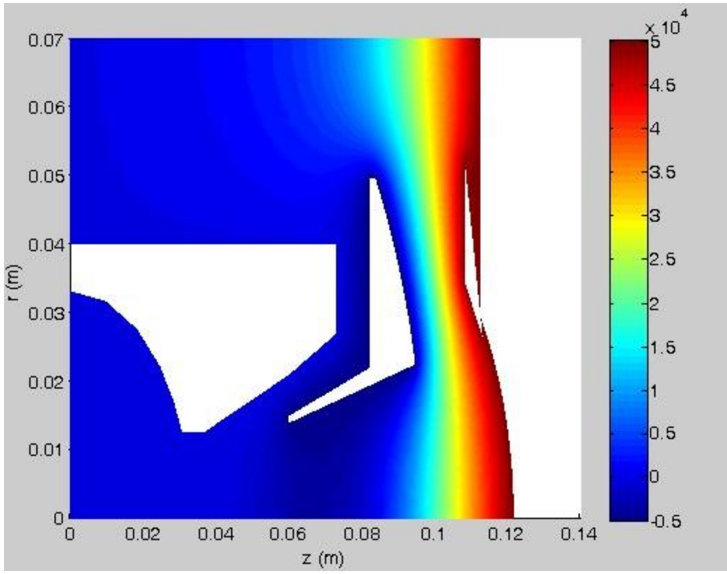
- ions passing and turning very near to solid reflecting surfaces extremely susceptible to tiny imperfections in the electrostatic surfaces
- Ions effectively scattering off irregularities. Because ion velocity tends to 0, the scattering cross-section blows up
- This scattering, in addition to very strong ion-ion scattering in the turning region, prevents stored beam magnitudes from approaching even a small fraction of the Child-Langmuir limit

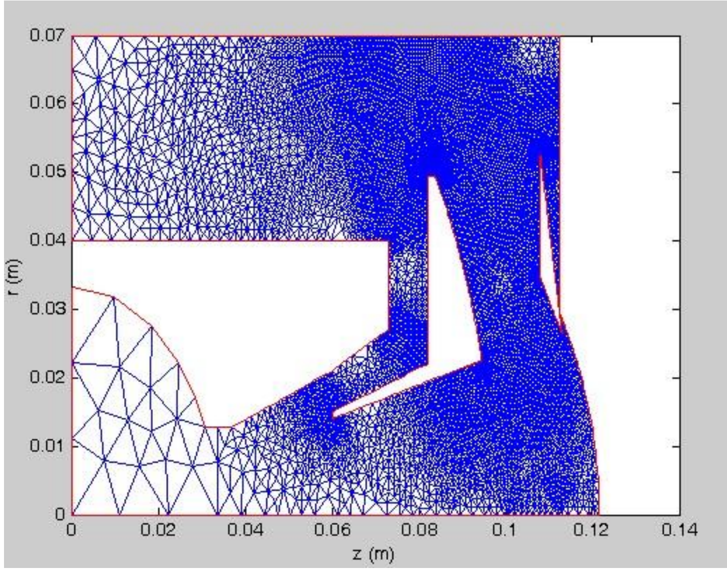


LSP simulation showing tendency for ions to form virtual anode near turning surface and space charge blow up

Fundamental problem with ion sources

- Importing ultra-precise field into PIC code



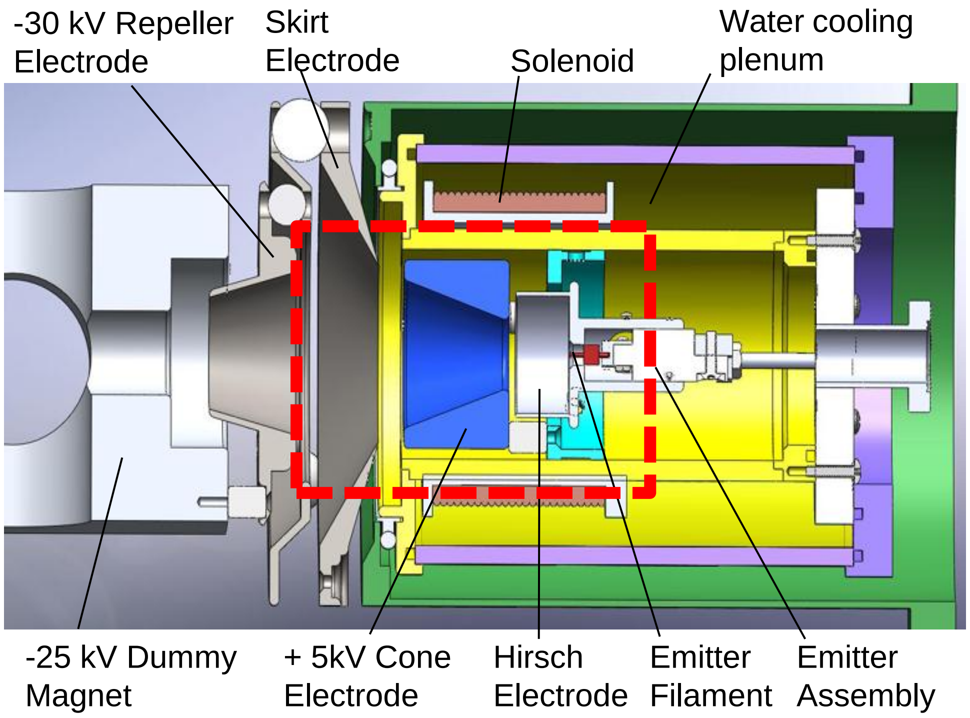


PIC code attempts to simulate ion dynamics with ion orbits passing very near solid surfaces always resulted in stored currents < 2 mA, no matter how precisely the surface was defined (improvement with finer and finer grid cell size, other tricks, but to no avail)

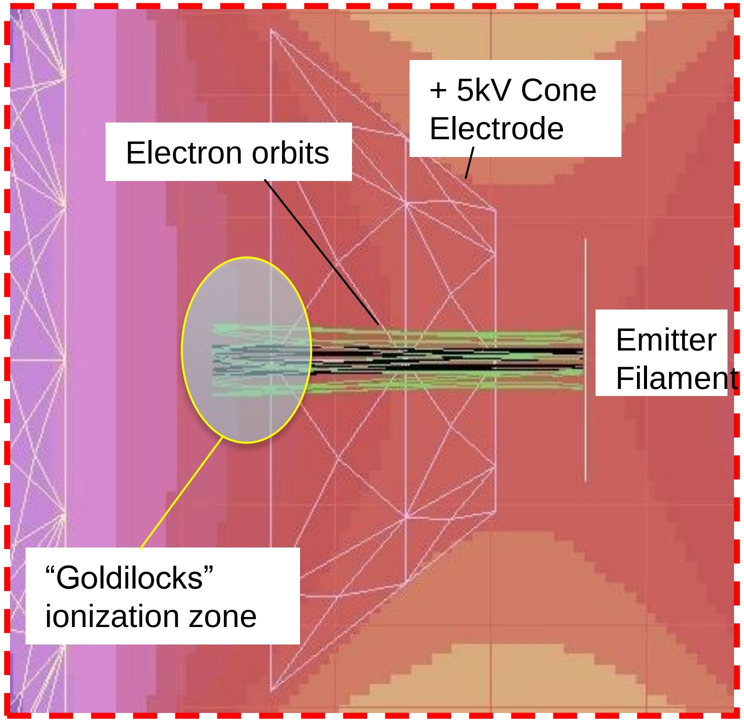
➔ there is a fundamental problem with ions turning at thin surface near solid electrode

Ion Source integrated into beam

Ideal ion source delivers ions from negative birth potential inside trapped phase space –built our own ion source which ionizes in the trap



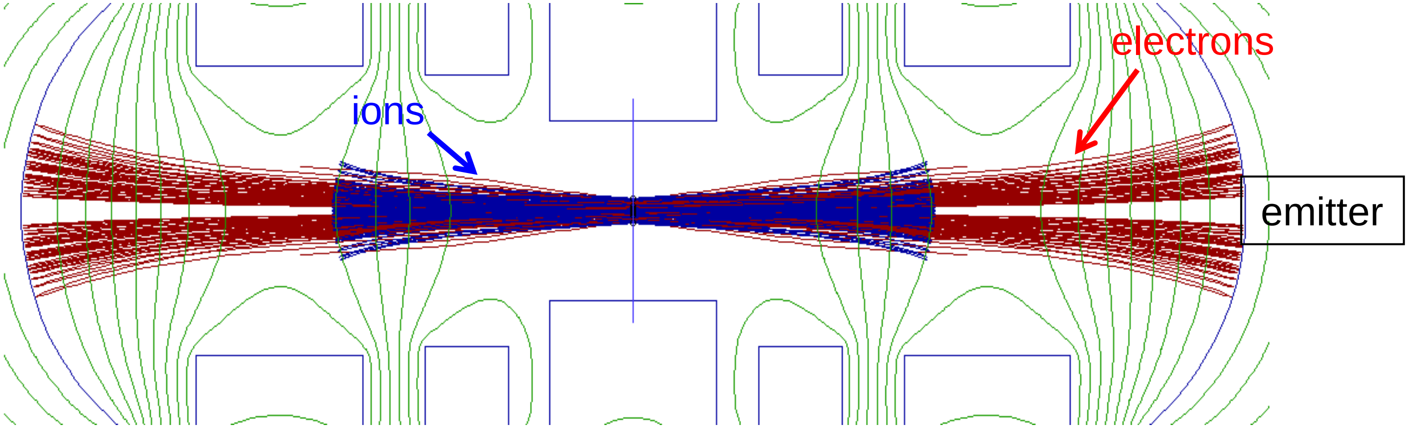
Schematic of FPIG Source



CPO simulation of FPG ion source electrons: contours of equipotentials

But in the process discovered a new approach to IEC

Ion source invention led to MARBLE



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*

Presentation about MARBLE to follow after questions