Argonne NATIONAL LABORATORY

Electron and ion beam dynamics in the CARIBU EBIS charge breeder

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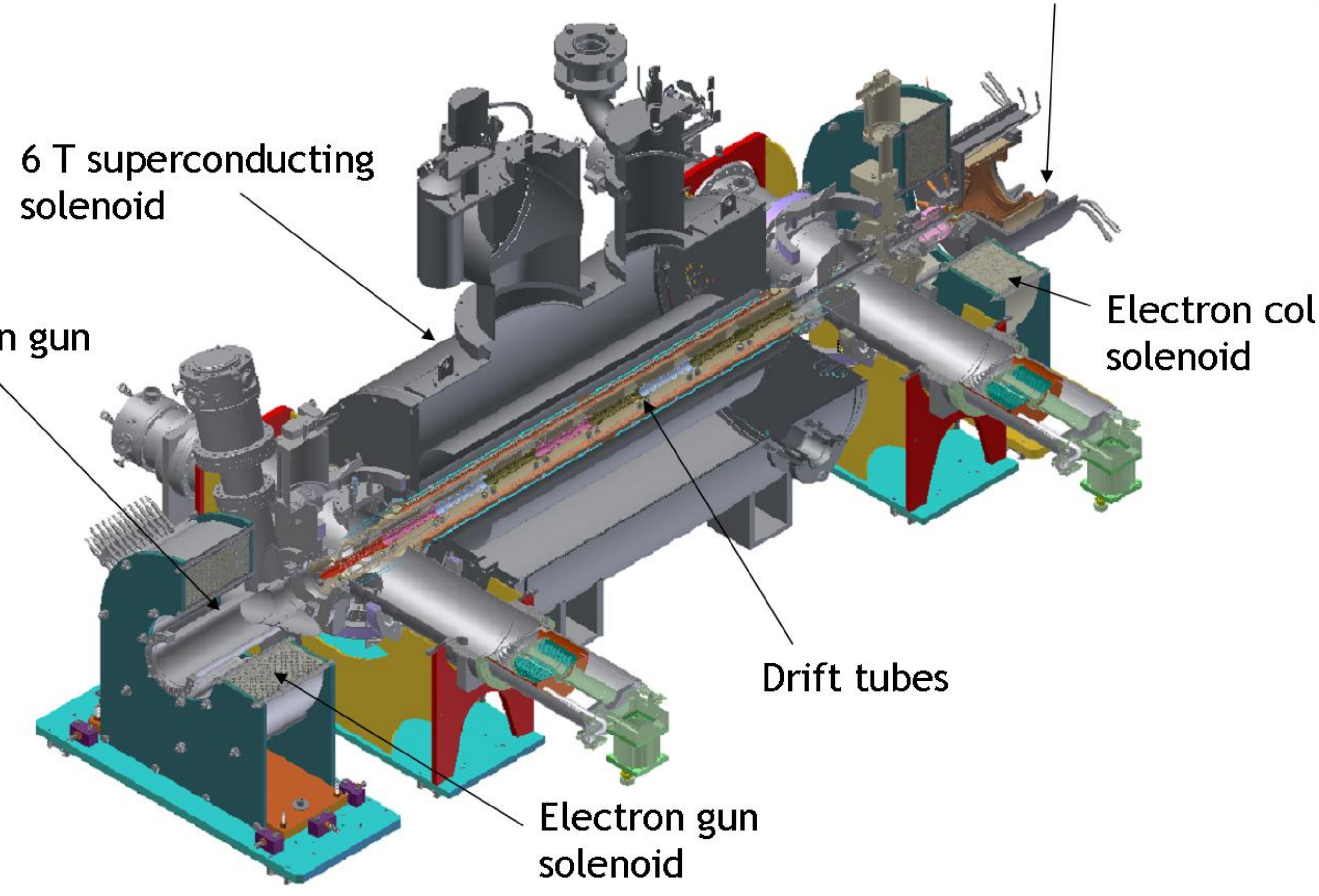
Outline

- CARIBU EBIS charge breeder
- Goals of beam dynamics studies
- Simulation software
- Simulation results
  - Electron beam
  - Electron beam – ion beam interactions
- Summary

CARIBU EBIS charge breeder

- Layout



CARIBU EBIS charge breeder

- Design parameters

Parameter	Electron gun	
	High current	Low current
Maximum current	2 A	0.2 A
Nominal trap solenoid magnetic field	6 T	
Trap length	700 mm	
Trap current density	500 A/cm^2	
Electron beam energy (gun/trap)	10/4–5 keV	7.7/1.2–2 keV
Cathode diameter	4 mm	1.6 mm
Drift tube diameters	20 mm	

Goals

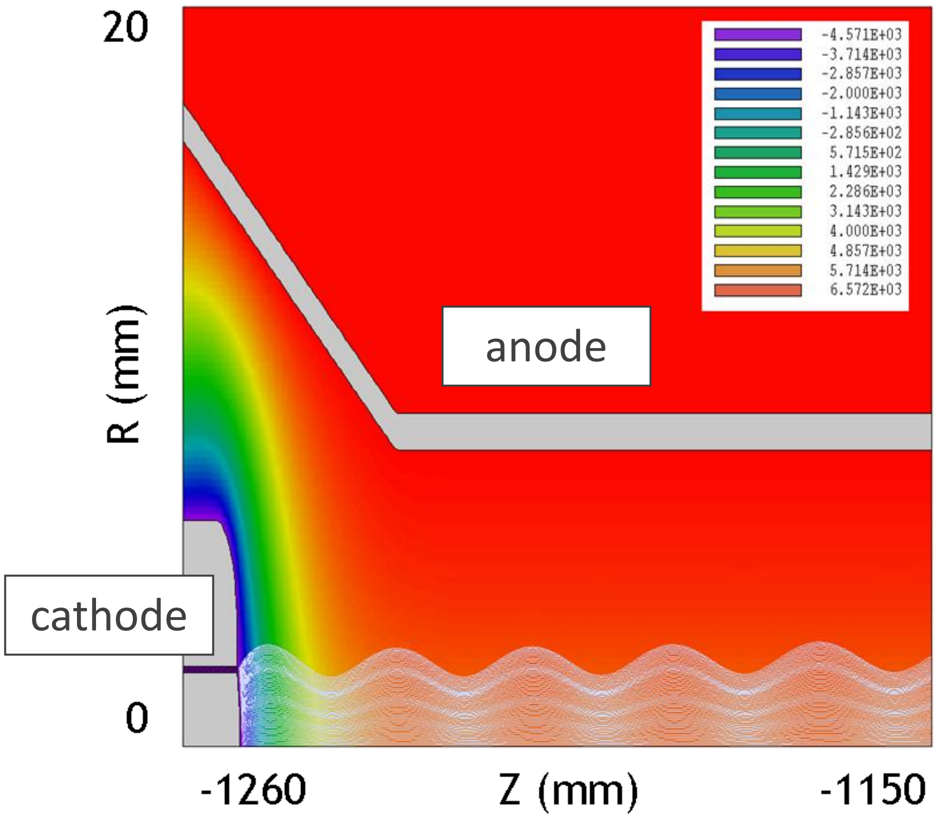
- Electron beam simulations
  - Determine the magnetic field at the cathode surface needed to avoid reflections
  - Ensure the design objectives (I=2 A, J>500 A/cm^2) can be met
  - Establish design parameters for the collector
  - Establish an electric field for ion injection and extraction simulations
- Electron beam – ion beam interactions
  - Establish the acceptance for injected ions
  - Establish ion beam parameters for the extracted beam

Simulation Software

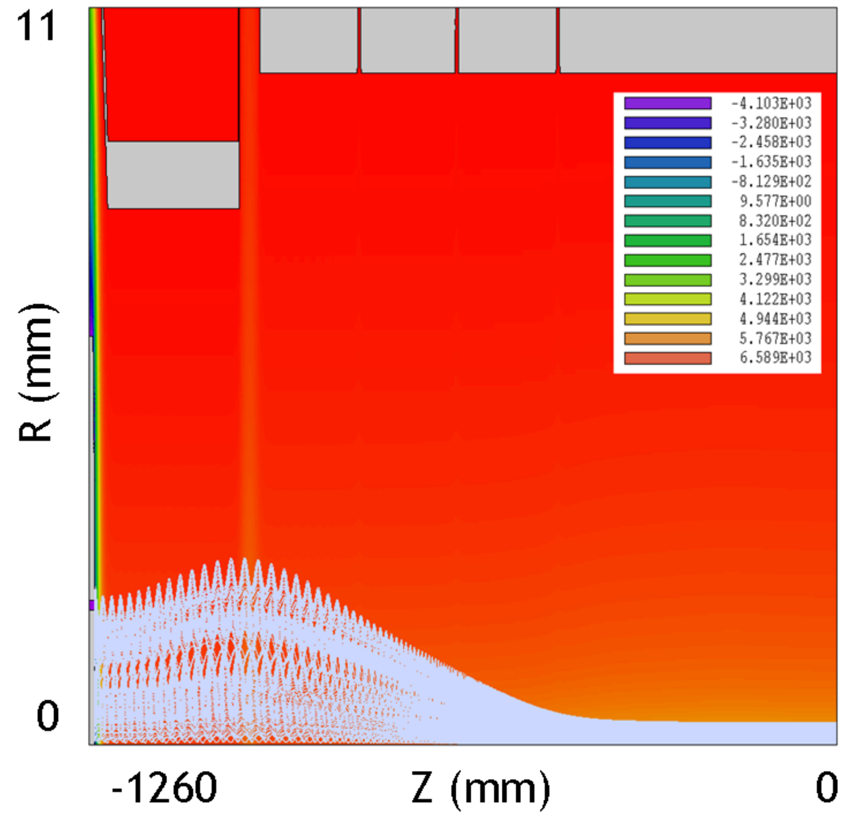
- TriComp
  - Calculates 2-d planar or axisymmetric electrostatic and magneto static fields from actual component cross sections
  - Numerically solves the Poisson equation for charged particles moving in the static fields
  - Accounts for the space charge of the electron beam
- Longitudinal symmetry of the EBIS allowed simulations to be separated into two regions
  - Gun-to-trap
  - Trap-to-collector

Gun-to-trap simulations

- The specifics of the gun design were established by the manufacturers at the Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia



Gun simulation



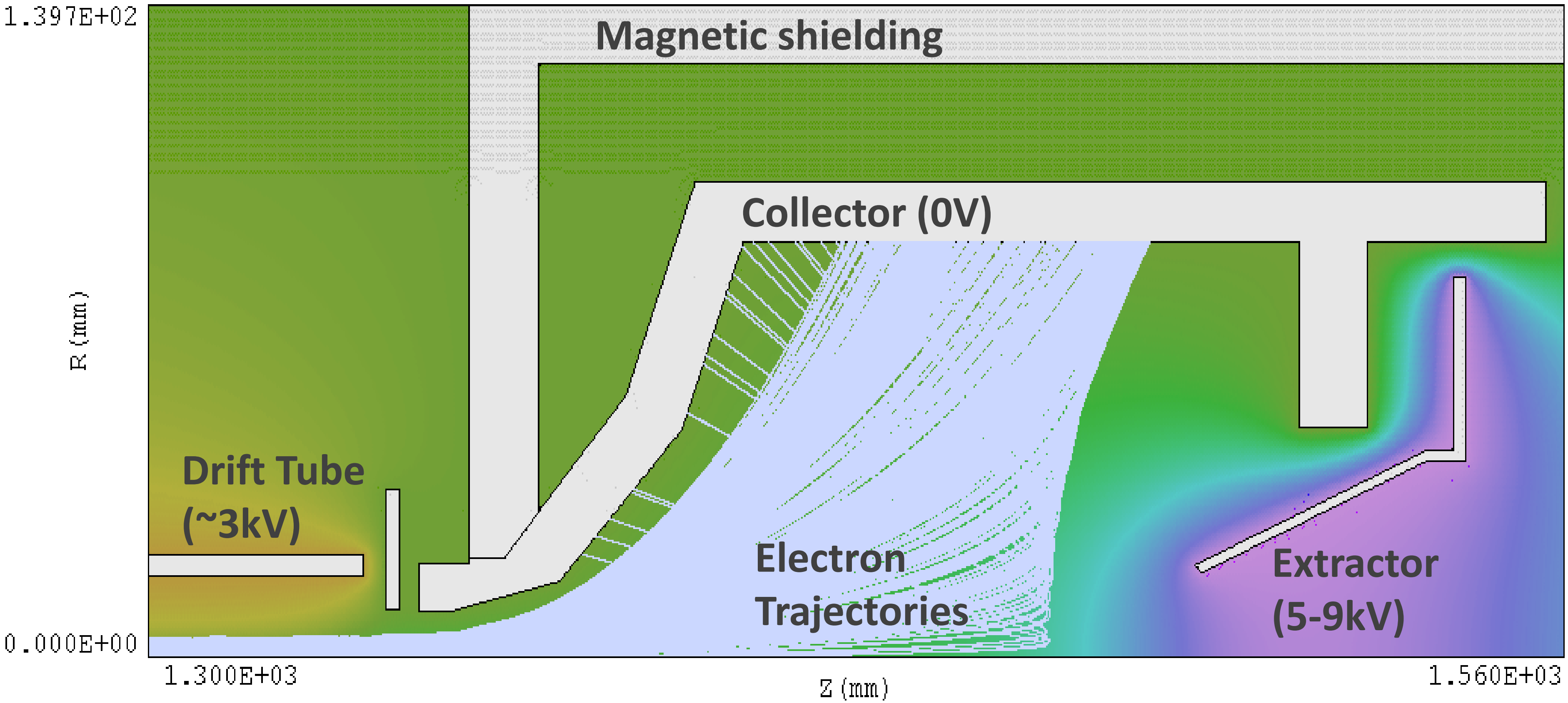
Gun to trap simulation

Gun-to-trap simulations

- Minimum cathode surface magnetic field, B_c, required
  - 0.15 T
- Contribution from 6 T main solenoid
  - 0.03 T
- Maximum electron gun coil performance
  - 0.16 T
- Beam parameters within the trap for high current electron gun and B_c=0.15 T
  - $r_{e,t}$ = 0.316 mm
  - J = 636 A/cm^2

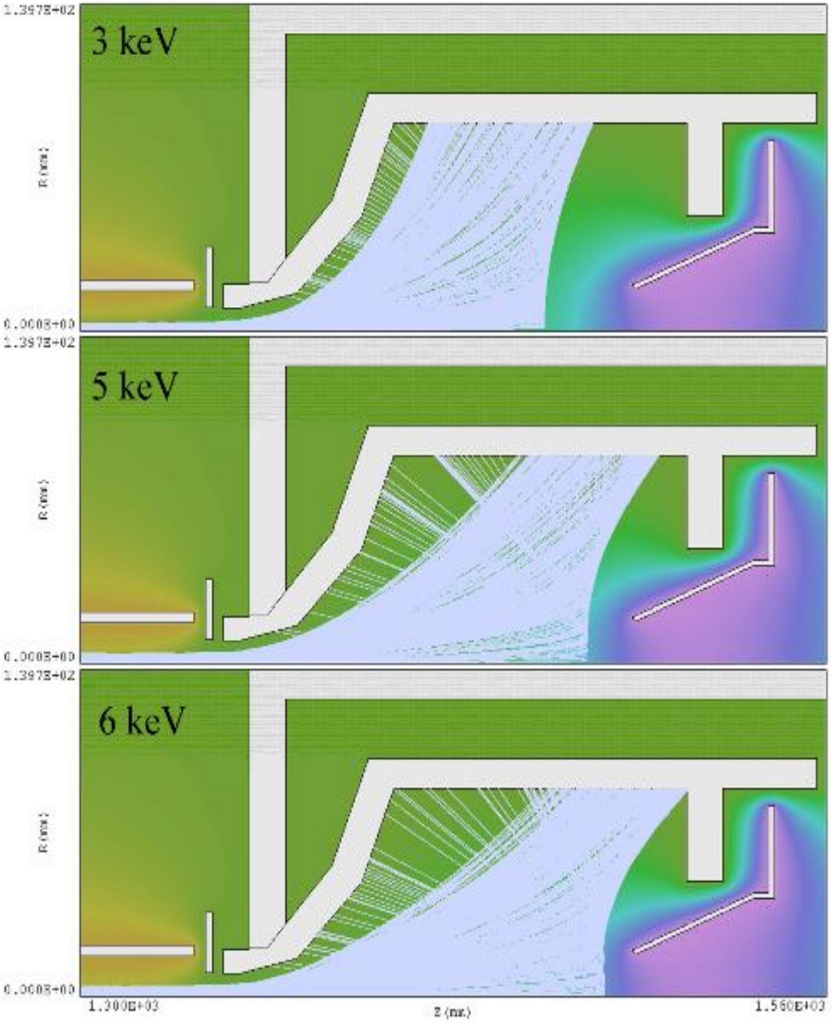
Trap-to-collector simulations

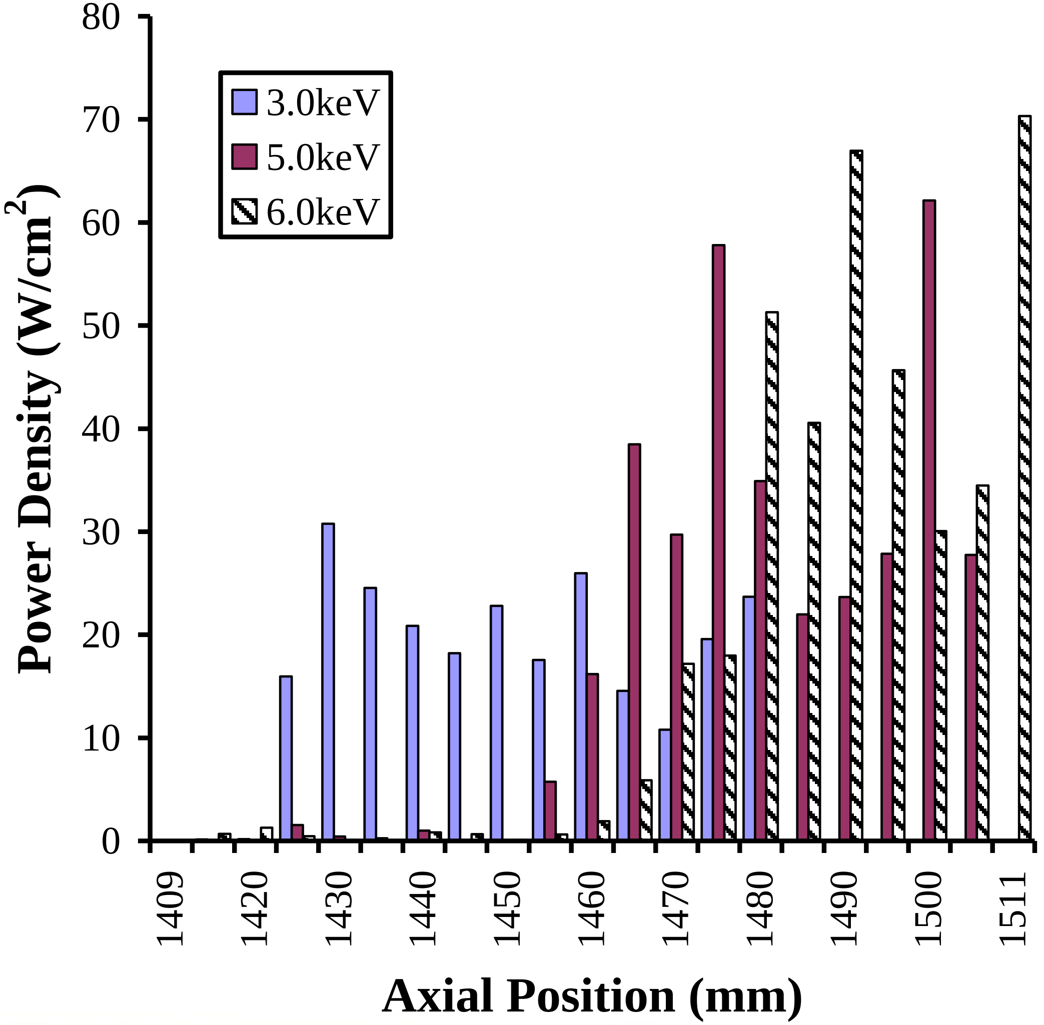
- Simulation result showing electron trajectories, EBIS components, and electric potential distribution



Electron Distributions in the Collector

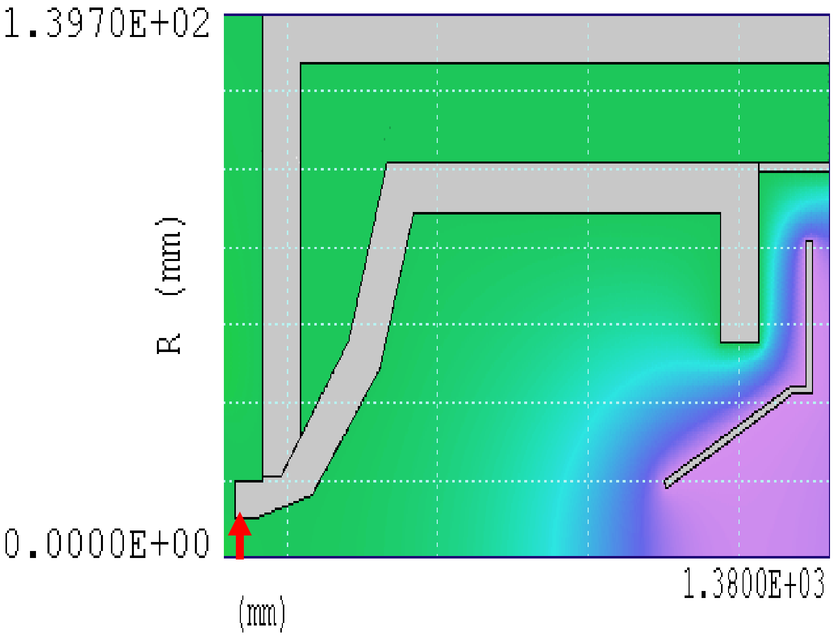
- For constant extractor potential, -9kV



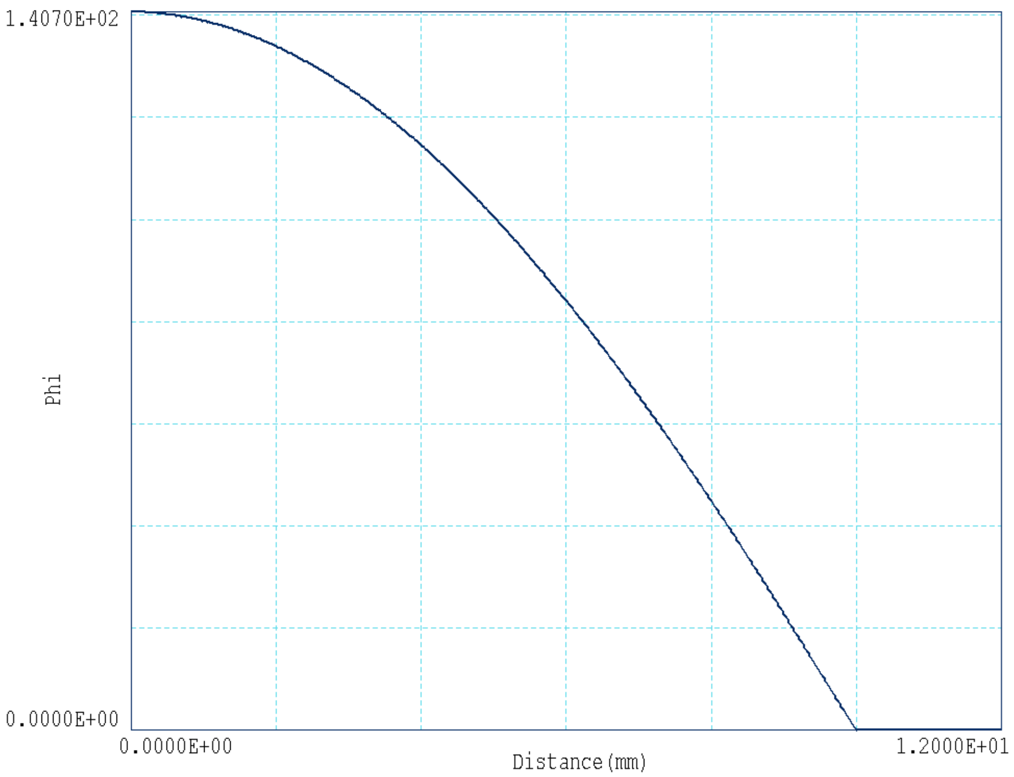


Electric Field Solutions

- Solutions to electron trajectory simulations resulted in electric fields which accounted for the electron beam space charge



w/o electrons



Potential, radially from axis to entrance of collector

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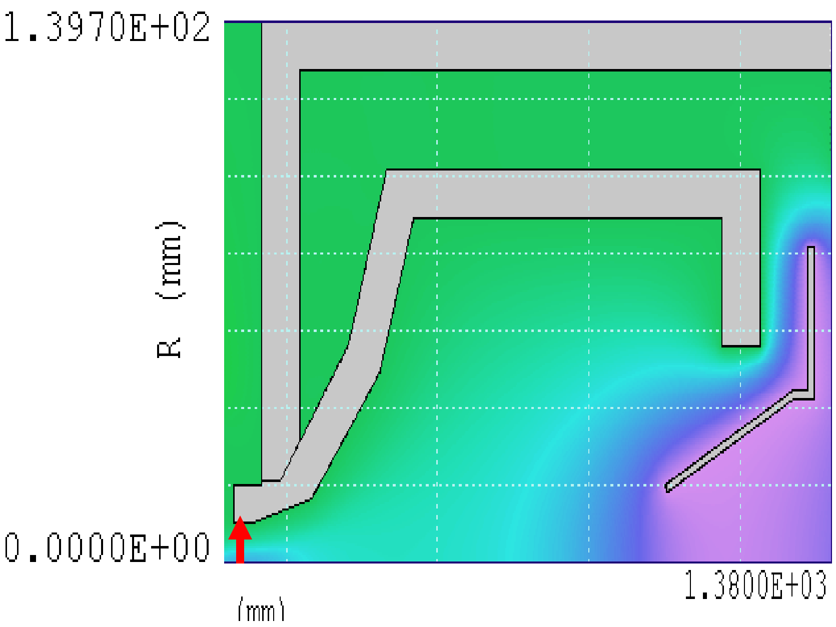
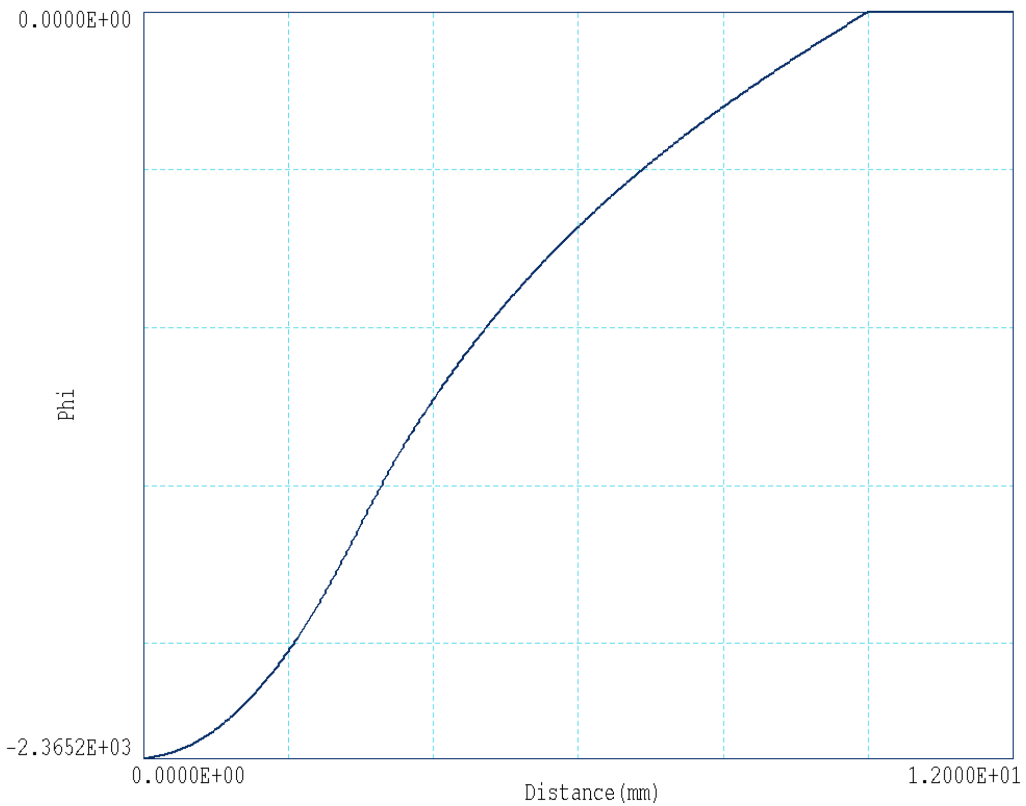


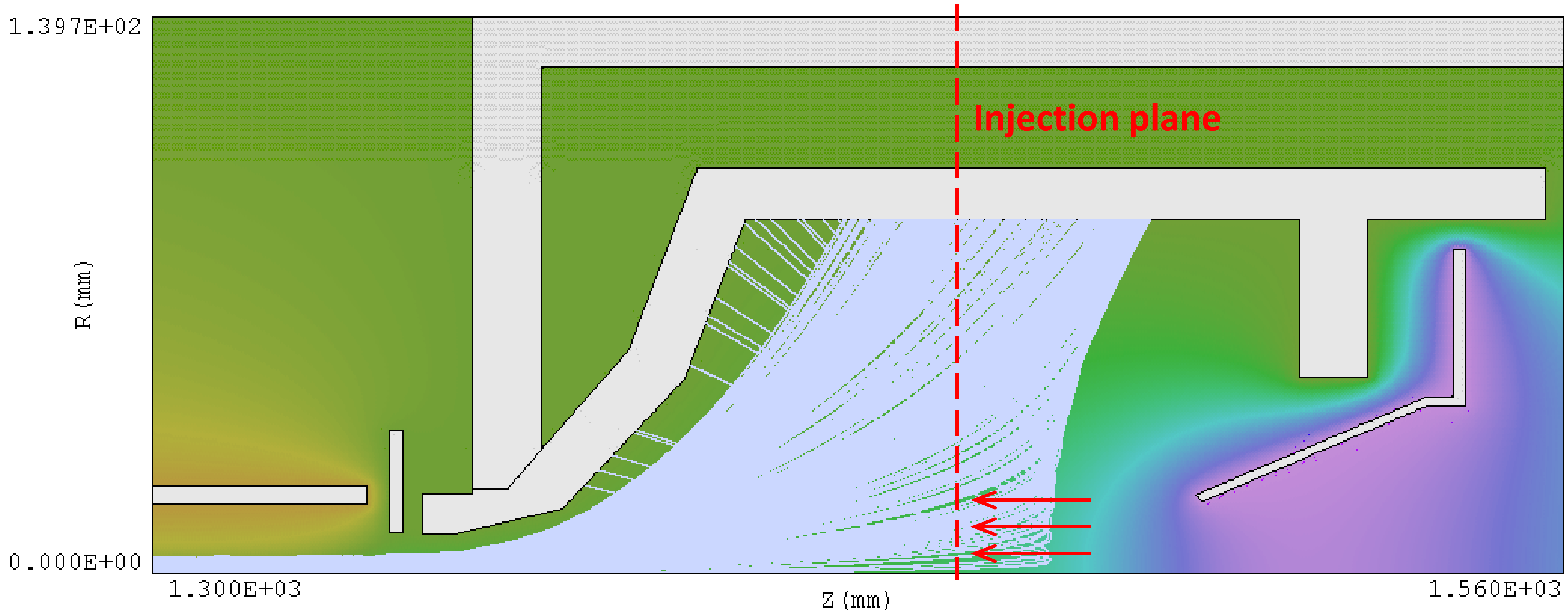
w/ electrons



Potential, radially from axis to entrance of collector

Ion Optics in the EBIS

- Acceptance was determined by injecting ions into the EBIS fields from a plane within the collector

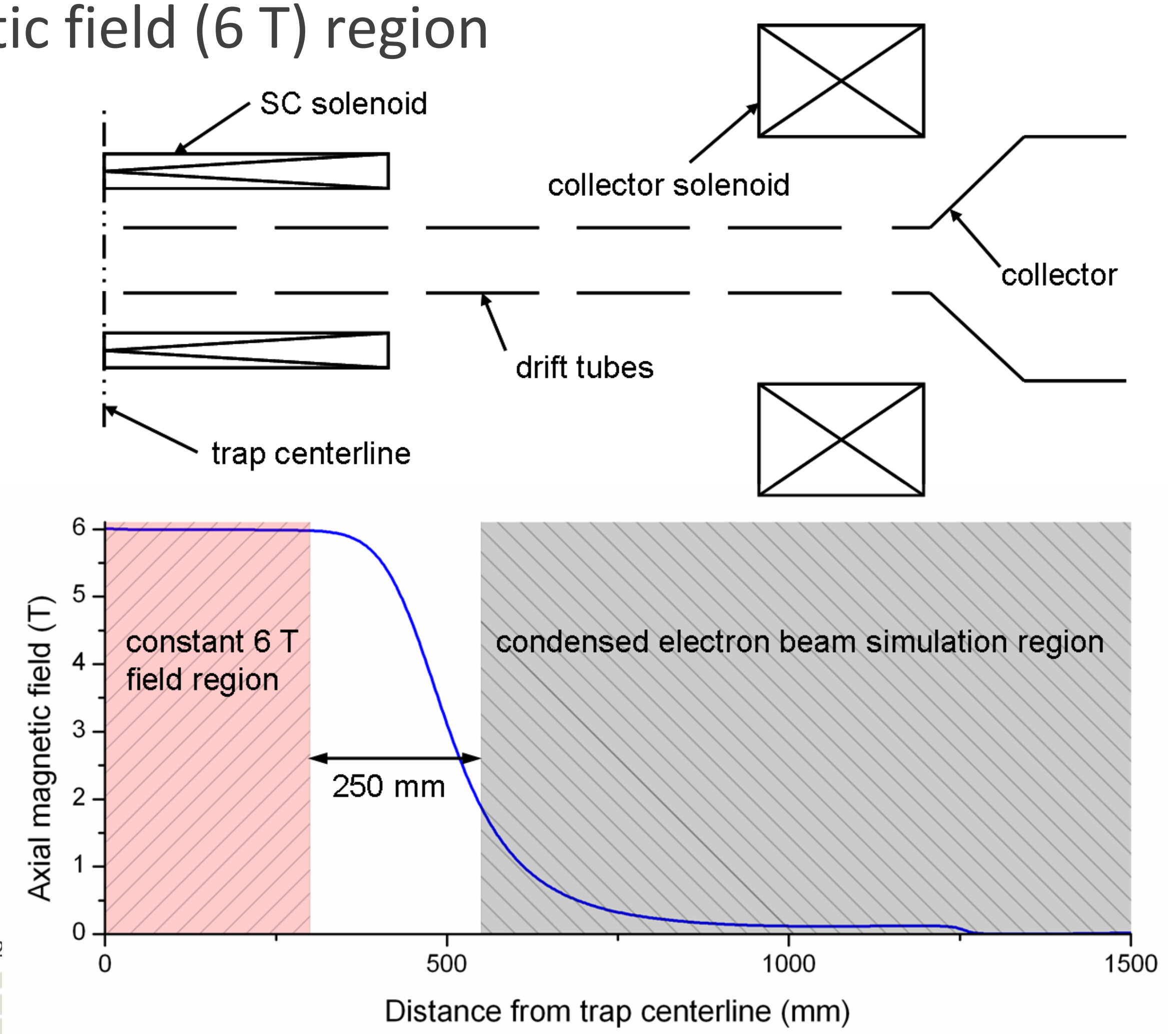


Acceptance

- Tracking the injected ions all the way to the center of the trap came at a price
  - Mesh elements for the field regions >~2 T needed to be 5-10x smaller to accurately represent the electron beam electric field
  - Time steps between consecutive trajectory calculations needed to be 10-100x shorter to correctly track the ions
- These type of simulations were possible and a few were performed as a baseline . . .
- But at ~1.5 hrs per run a more efficient method was used for the bulk of the calculations

Acceptance

- Instead of tracking to the trap center, the injection simulations were stopped 250 mm from the maximum magnetic field (6 T) region



Acceptance Criterion

- Ion beam radius = e-beam radius in trap; $r_{i,t} = r_{e,t}$
- $r_{i,s}$ – the ion beam radius at the end of the simulation which corresponds to $r_{i,t} = r_{e,t}$

$$\varepsilon_{i,t} = \varepsilon_{i,s}$$

$$\varepsilon = 2r\left(\frac{k_B T_\perp}{mc^2}\right)^{1/2}$$

$$r_{i,s} = r_{i,t}\sqrt{\frac{T_{\perp t}}{T_{\perp s}}}$$

$$\frac{T_{\perp t}}{T_{\perp s}} = \frac{\Delta U_{i,t}}{\Delta U_{i,s}}$$

ΔU_i – potential well within the radius of the ion beam

*Adapted from work by A. Pikin

Acceptance Criterion

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$$r_{\mathrm{i,s}} = r_{\mathrm{i,t}}\sqrt{\frac{T_{\perp\mathrm{t}}}{T_{\perp\mathrm{s}}}}$$

$$\frac{T_{\perp\mathrm{t}}}{T_{\perp\mathrm{s}}} = \frac{\Delta U_{\mathrm{i,t}}}{\Delta U_{\mathrm{i,s}}}$$

$$\Delta U = \frac{I}{4\pi\varepsilon_0 v_{\mathrm{e}}}\left(\frac{r_{\mathrm{i}}}{r_{\mathrm{e}}}\right)^2$$

ΔU – assuming $r_{\mathrm{i}} \le r_{\mathrm{e}}$ and uniform e-beam current density

$$\frac{\Delta U_{\mathrm{i,t}}}{\Delta U_{\mathrm{i,s}}} = \frac{v_{\mathrm{e,s}}}{v_{\mathrm{e,t}}}\left(\frac{r_{\mathrm{e,s}}}{r_{\mathrm{i,s}}}\right)^2$$

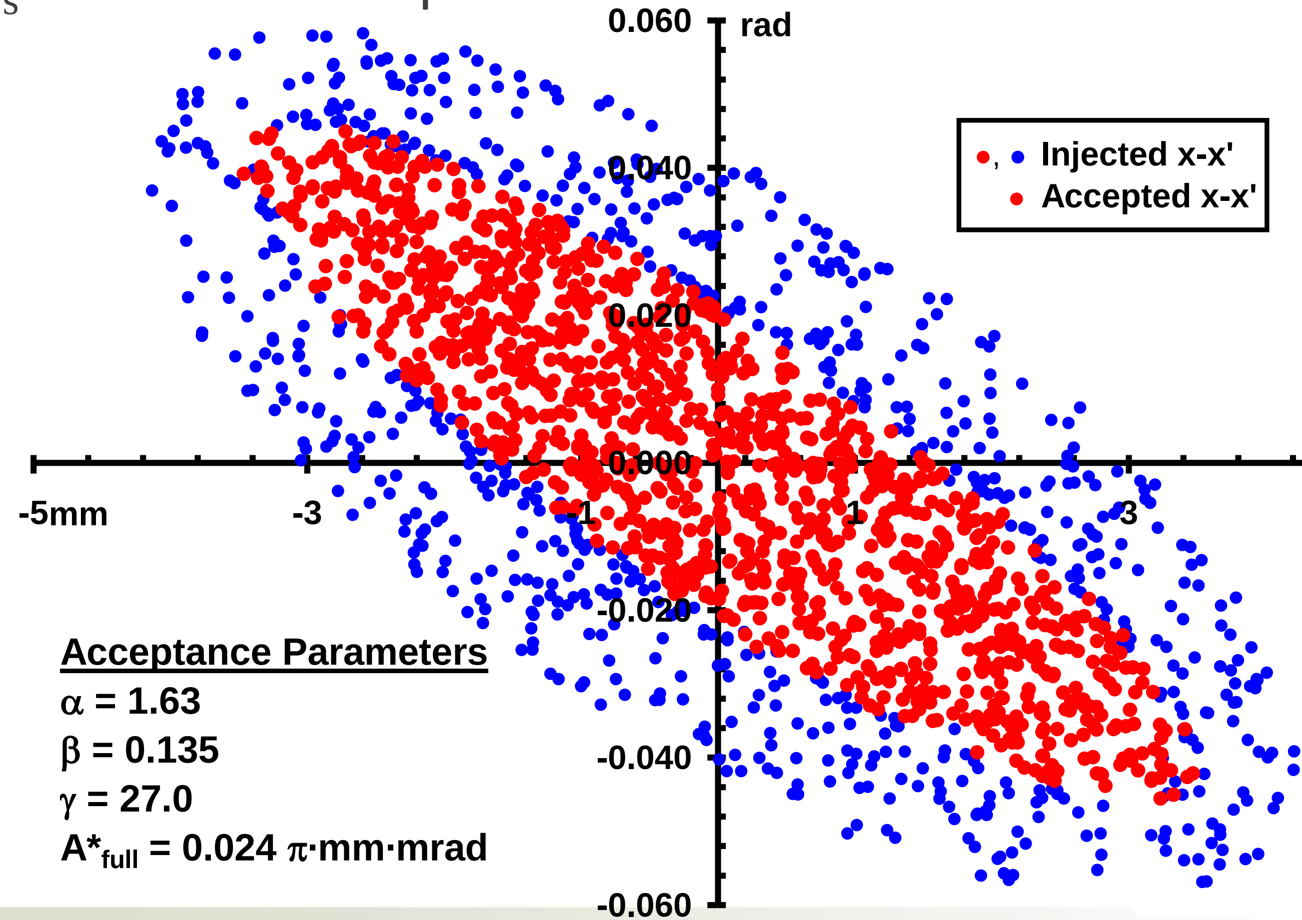
$$r_{\mathrm{i,s}} = \left[r_{\mathrm{e,t}} r_{\mathrm{e,s}}\left(\frac{v_{\mathrm{e,s}}}{v_{\mathrm{e,t}}}\right)^{1/2}\right]^{1/2}$$

- Cutoff radius, $r_{\mathrm{i,s}}$, outside the trap could be calculated given electron beam parameters

*Adapted from work by A. Pikin

Acceptance

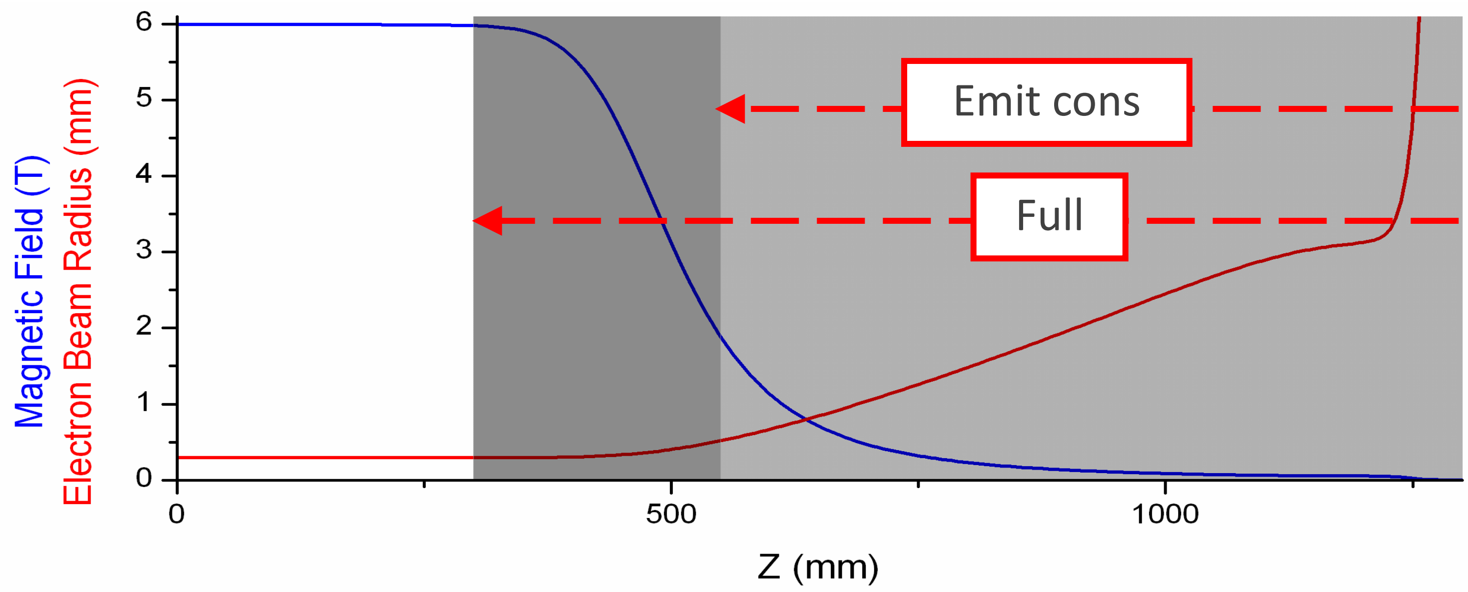
- Ion radii at the end for the injection simulations were compared to the $r_{i,s}$
- If $r_i \leq r_{i,s}$ ions were accepted



Acceptance Comparison

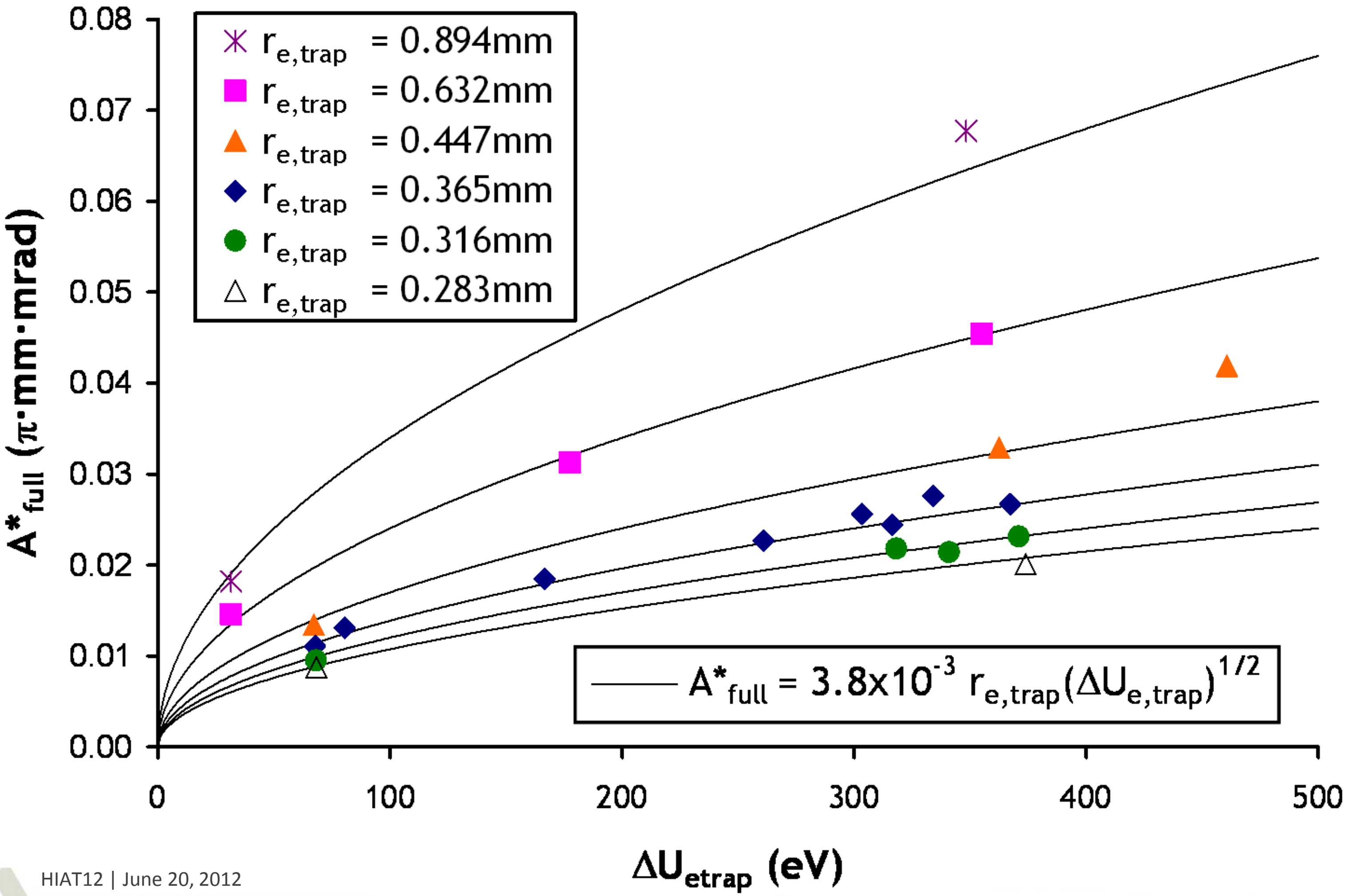
- Comparing the results from the emittance conservation method (B_{max}=2 T) and the full tracking method (B_{max}=6 T)

$r_{e,t}$ (mm)	I_e (A)	B_t (T)	A^*_{full} (π·mm·mrad)	
			emit cons	full
0.316	2	6	0.0233	0.0222
0.283	2	6	0.0201	0.0201



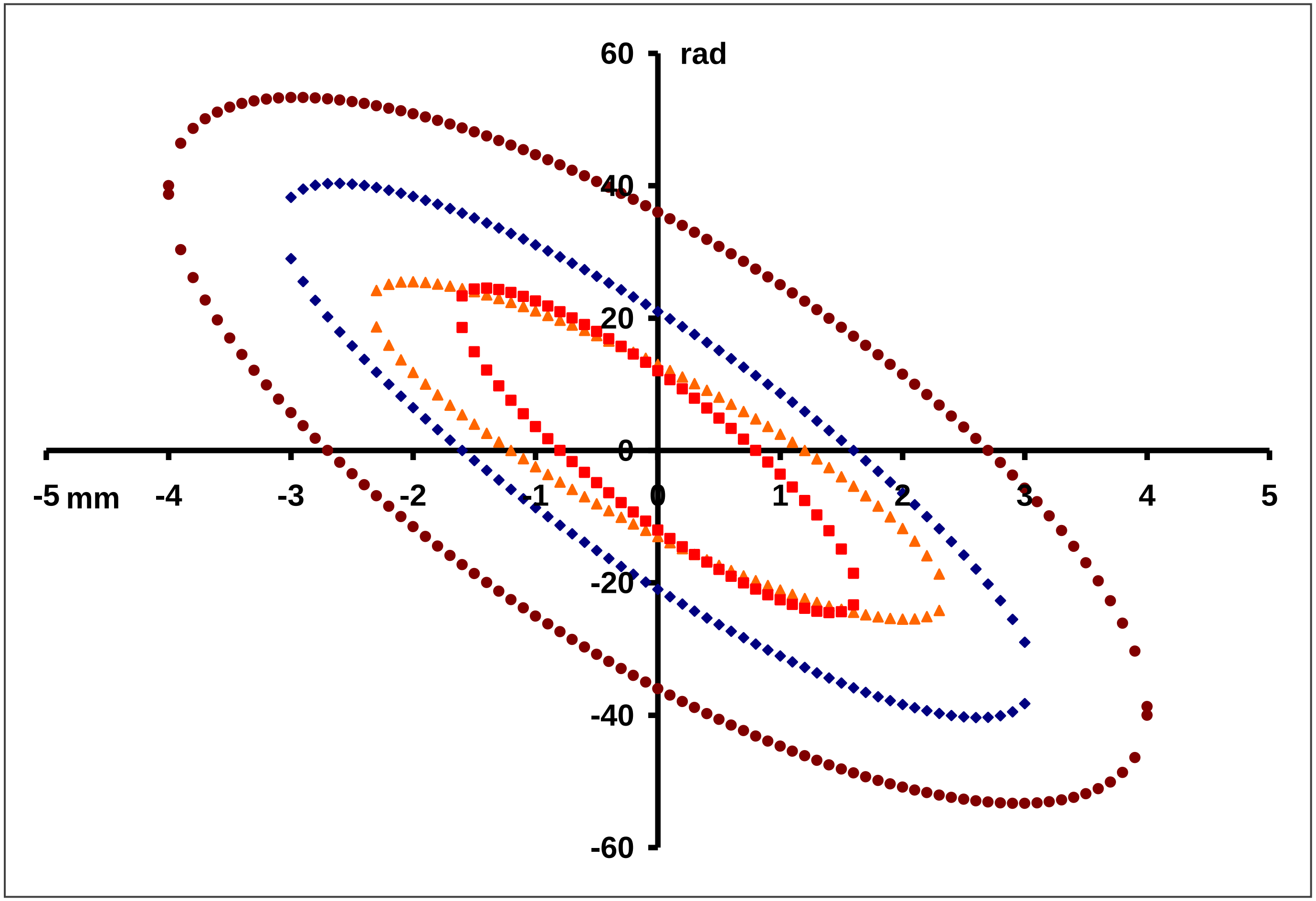
Acceptance

- Acceptance was calculated for wide range of conditions



Acceptance

- The calculated phase space volume can be used for beam matching from the ion beam transport line



Extraction

- Determining the extracted beam emittance
- Analytically
  - Magnetic contribution

$$\varepsilon_m^* = \frac{2\pi eqBr^2}{4mc} \cdot 10^6 \left[\pi \cdot mm \cdot mrad\right]$$

  - Electric contribution

$$\varepsilon_e^* = 2r\left(\frac{k_B T_\perp}{mc^2}\right)^{1/2} \cdot 10^6 \left[\pi \cdot mm \cdot mrad\right]$$

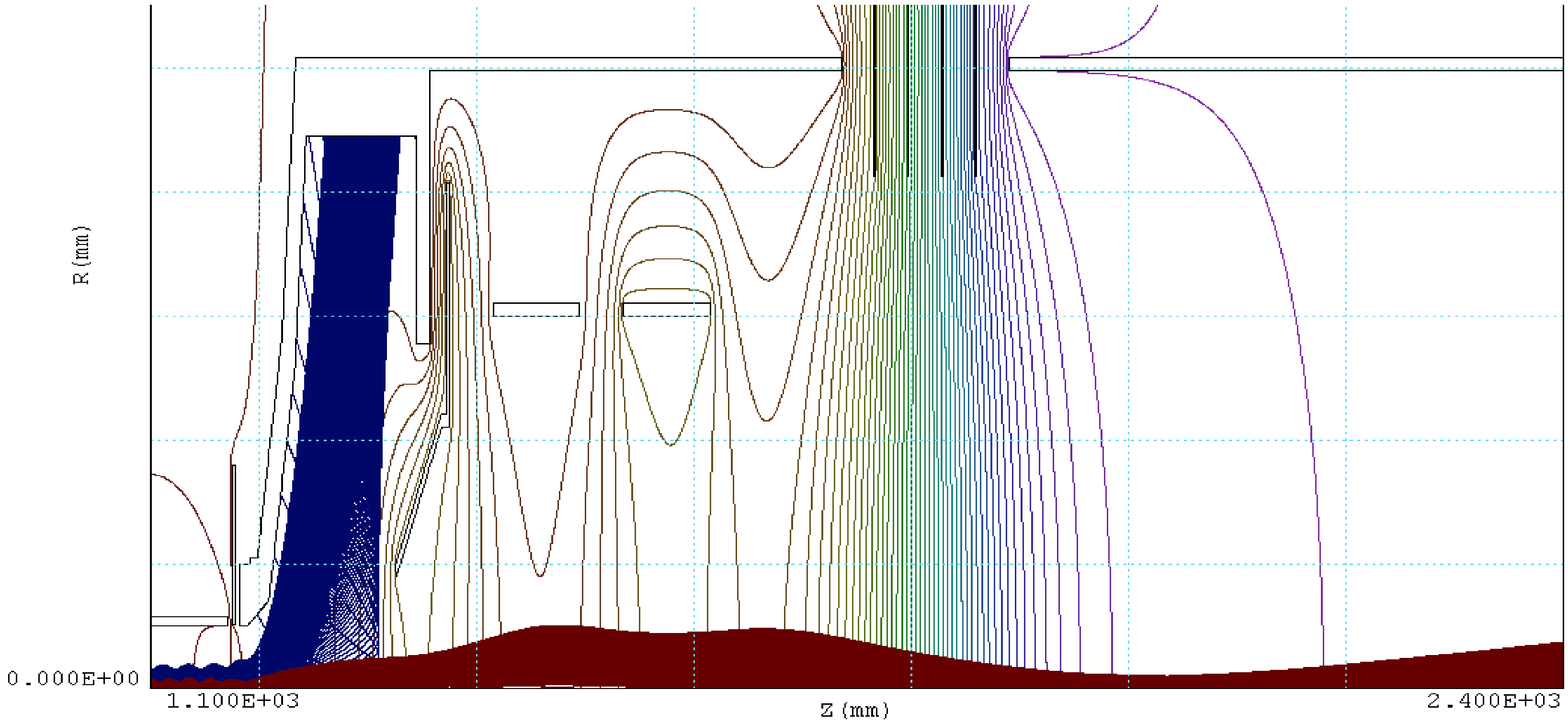
  - Upper limit for the extracted beam emittance for $^{133}Cs^{+20}$

$$\varepsilon_{tot}^* \approx 0.2 \left[\pi \cdot mm \cdot mrad\right]$$

- BNL results from Test EBIS
  - 0.8-1.0 π·mm·mrad for 1-3 mA of Au^{32+}

Extraction

- Emittance conservation method but assuming $r_{i,t} = 1.5 * r_{e,t}$
- Ion beam radius can be calculated along electron beam
- Ion beam transported within electric field of electron beam simulation solution



Summary

- Required magnetic field at the cathode surface is 0.15 T, within operating range of gun coil
- The electron beam can be adequately transported to achieve the design goals ($I=2$ A, $J>500$ A/cm^2)
- The electron beam power can be safely dumped within the collector
- The acceptance of the EBIS has been determined for a wide range of operating parameters
- Acceptance and extraction simulations facilitate beam matching for the transport lines