Improved ECR Extraction and Transport Simulations Using Experimentally Measured Plasma Sputtering

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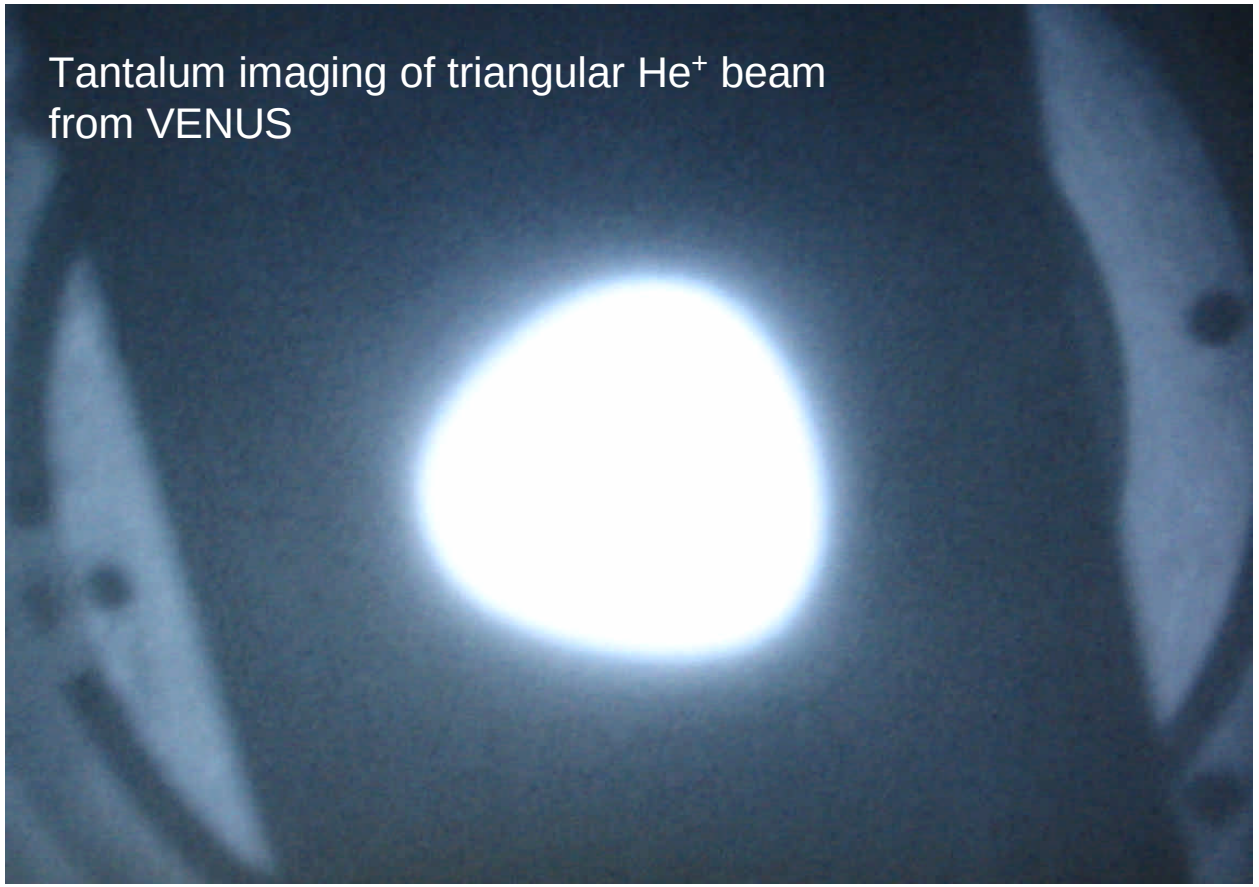
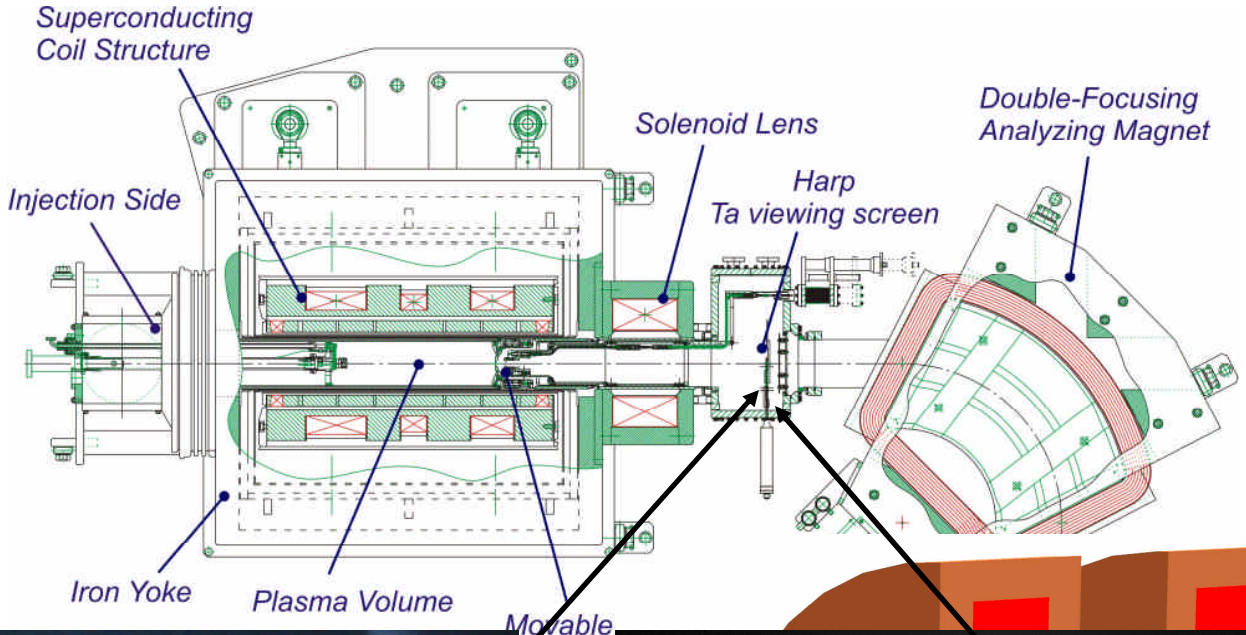
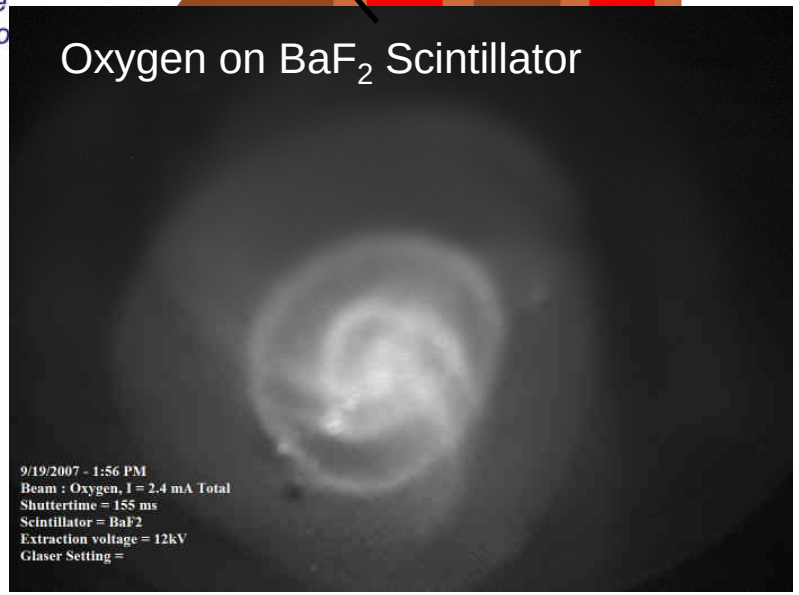
Outline



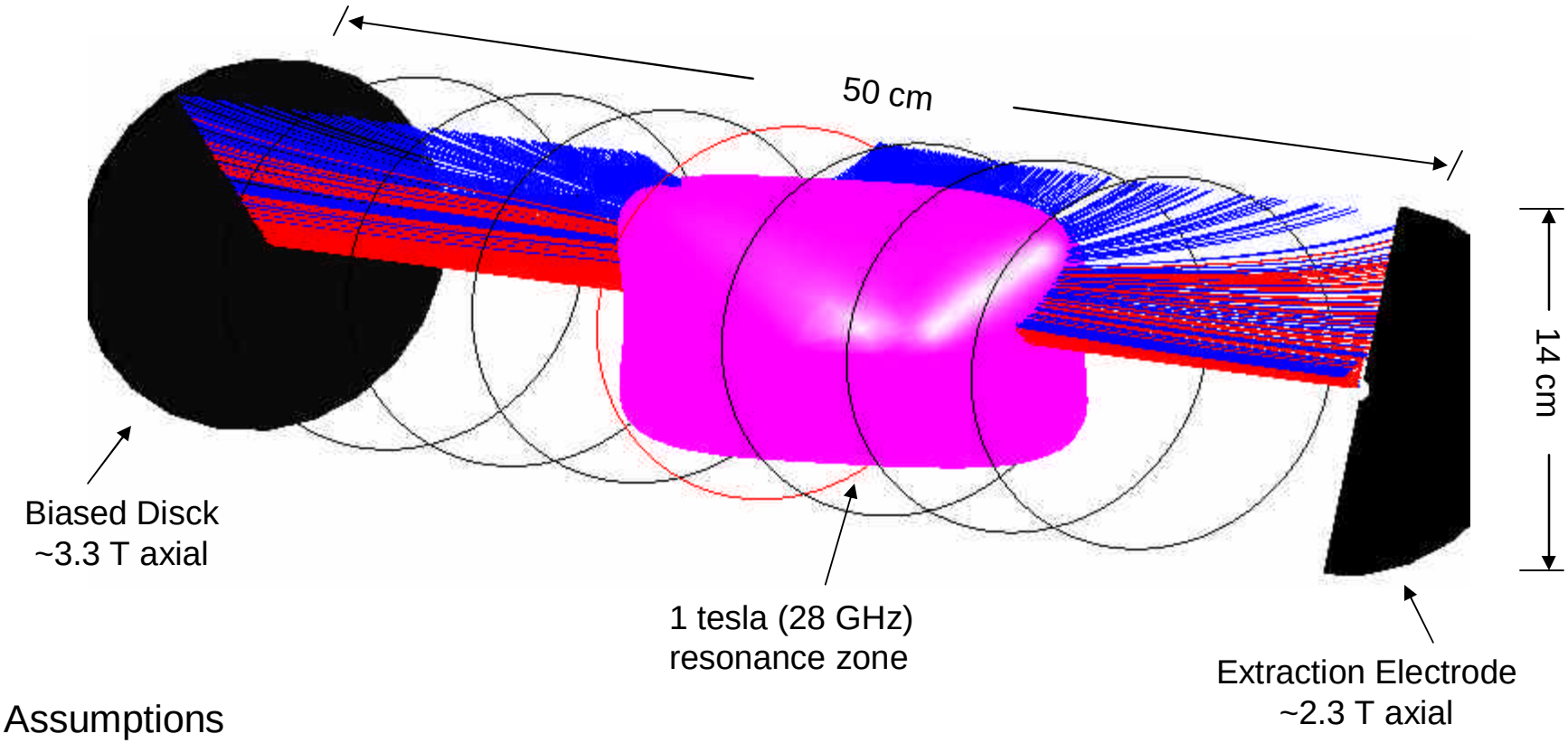
1. Why triangular beams from the VENUS ion source?
2. How to generate triangular distributions for simulation (in VENUS and other sources)
3. Results of extraction and transport simulations compared with experiment for oxygen and bismuth

Where do triangular beams come from?





Source field line analysis



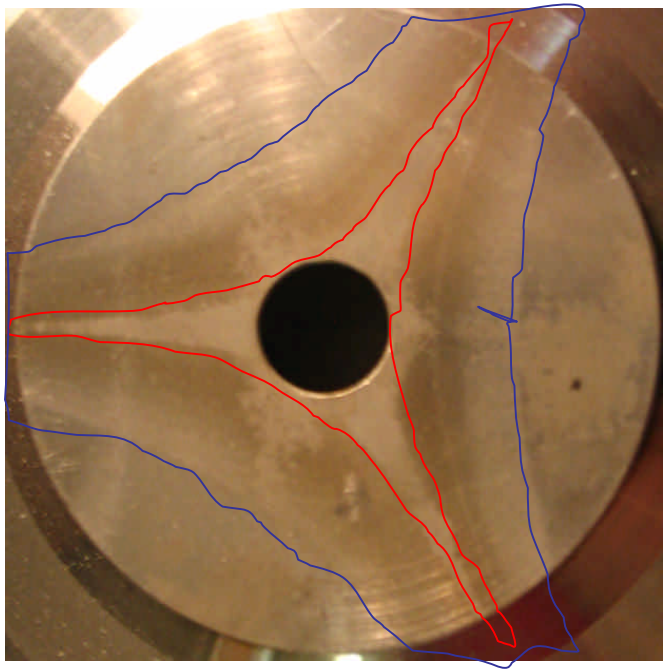
Assumptions

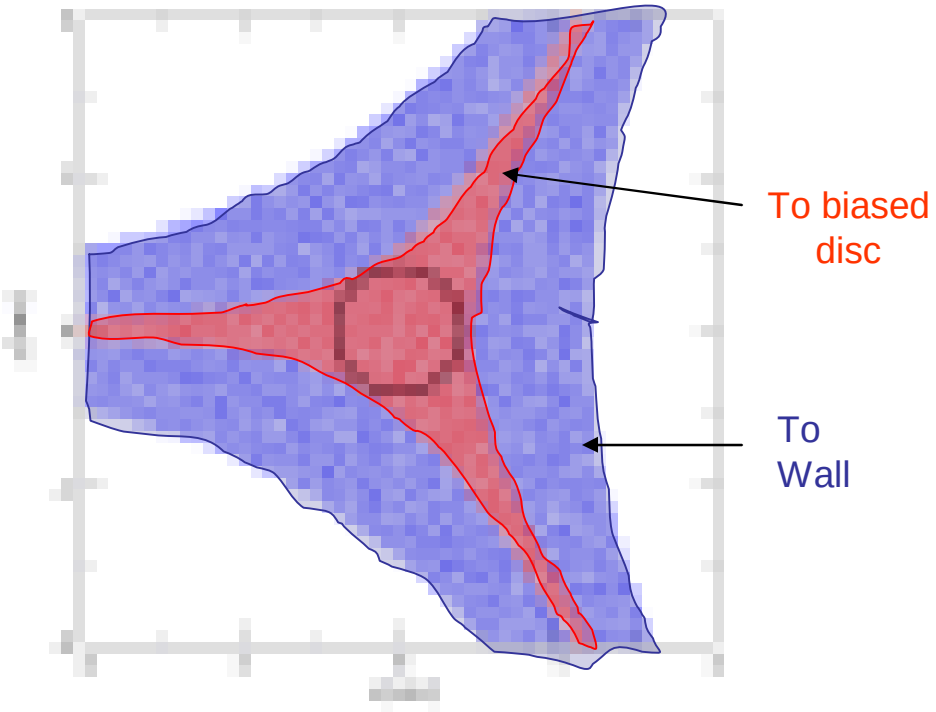
- Ions primarily follow field lines
- Electrons heated only on field lines with resonance zone crossing

∴ get initial conditions from field lines which intersect resonance surface

Plotted field lines → **Red**: Field line terminates on axial ends of source
Blue: Field line terminates on a wall

Field line distribution at extraction electrode



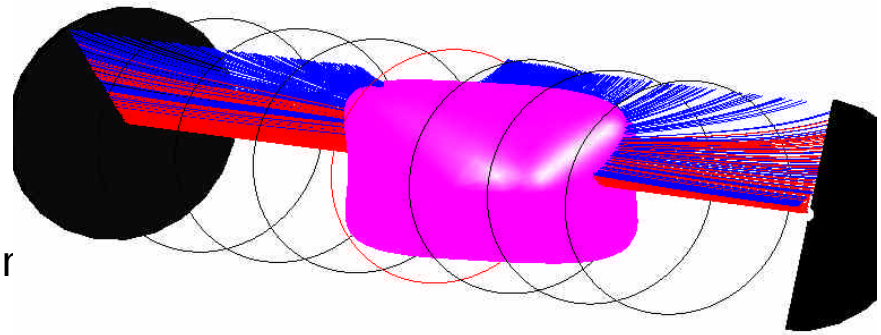


Plasma markings on the original VENUS extraction electrode, replaced in early 2005.

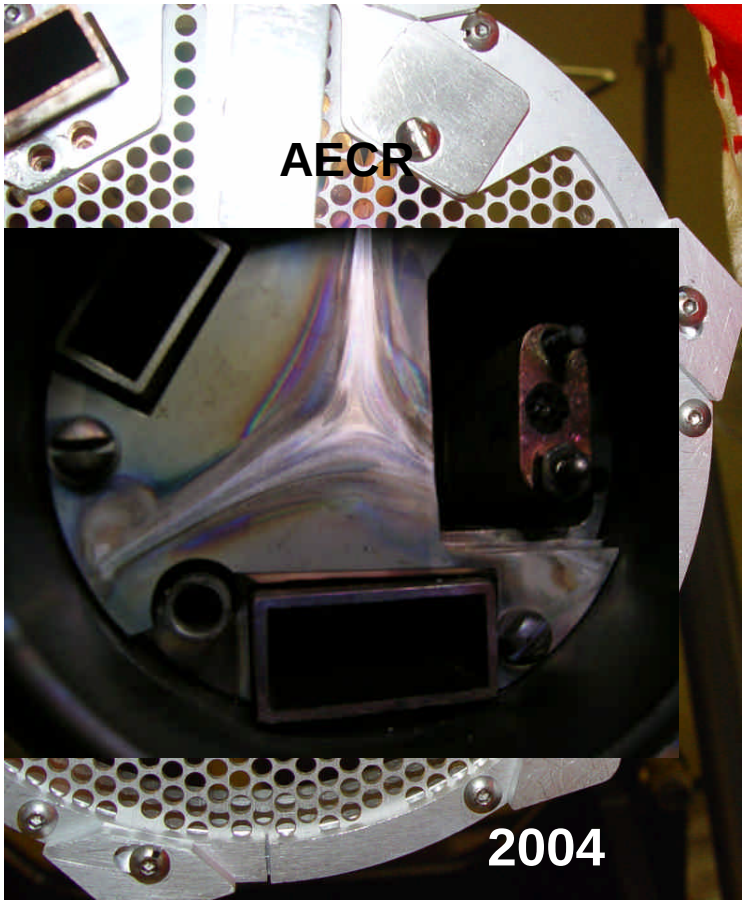
Source aperture has 4 mm radius

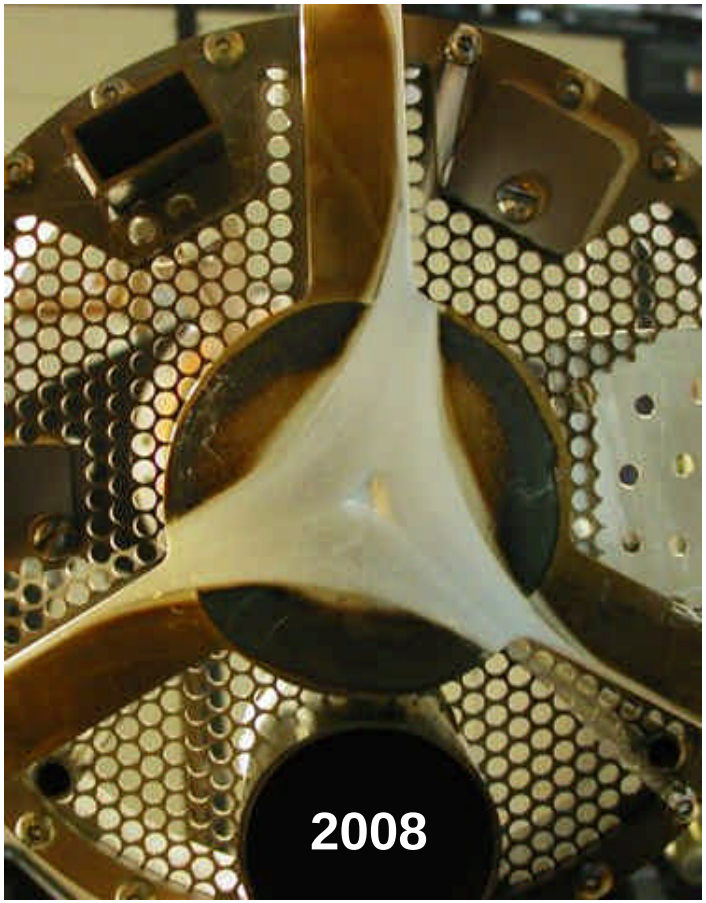
- Triangular structure is larger than the
- Neither ion tracking nor field line tracir

Terminal points of field line tracing through VENUS source fields



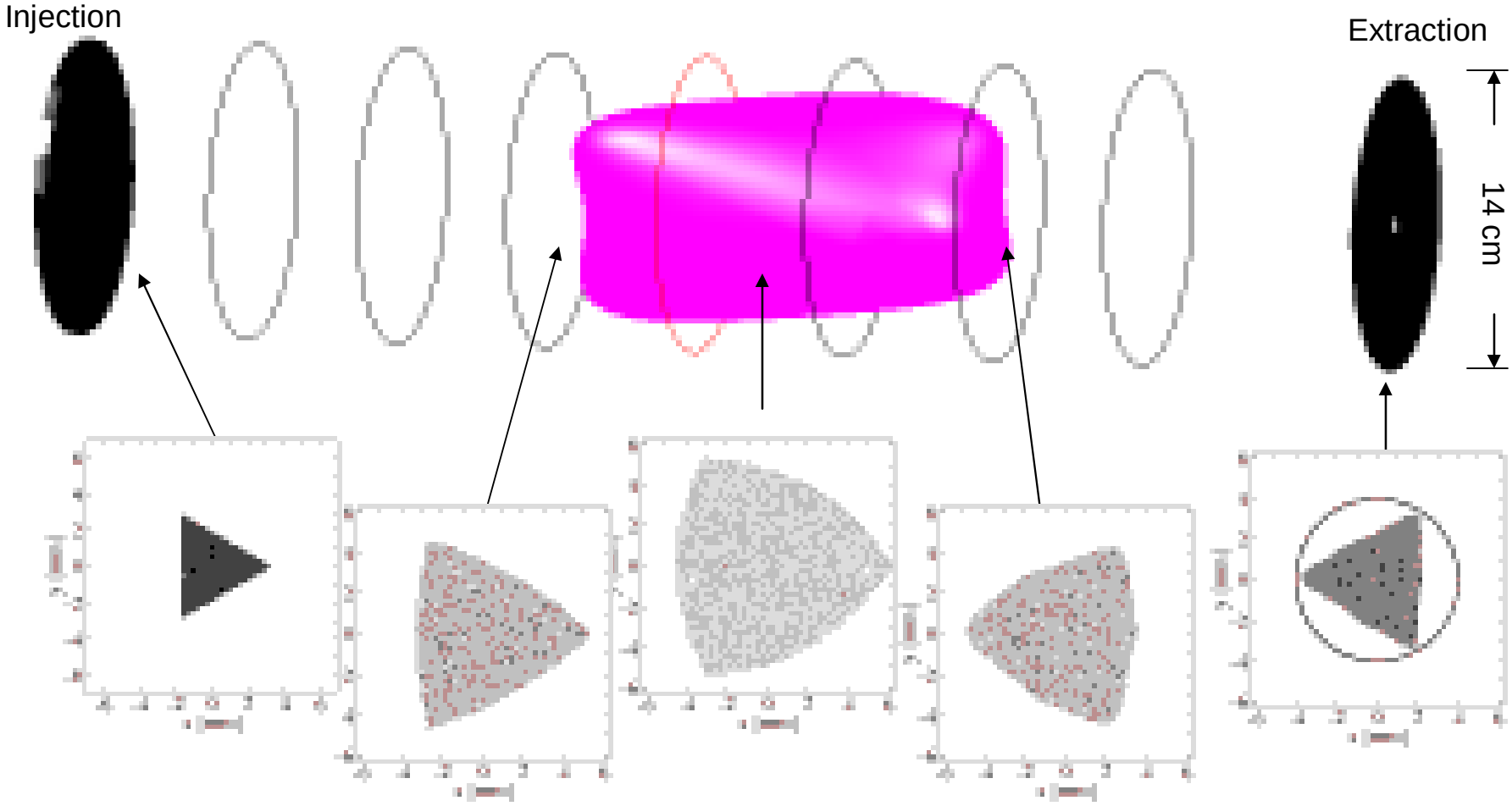
Plasma marks on biased disk





- Biased disk is normally operated between -50 and -100 volts relative to source chamber
- Plasma markings on biased disc similar to extraction electrode, but there is also a 0.5 mm deep, 5 mm tall inner triangle
- Inner triangle has what appears to be constant depth and sharp edges
- Believe that this inner triangle is due to sputtering by ions accelerated into biased disc
- Triangle defines edges of a very different population of ions within the source

Trace field lines from triangle through VENUS

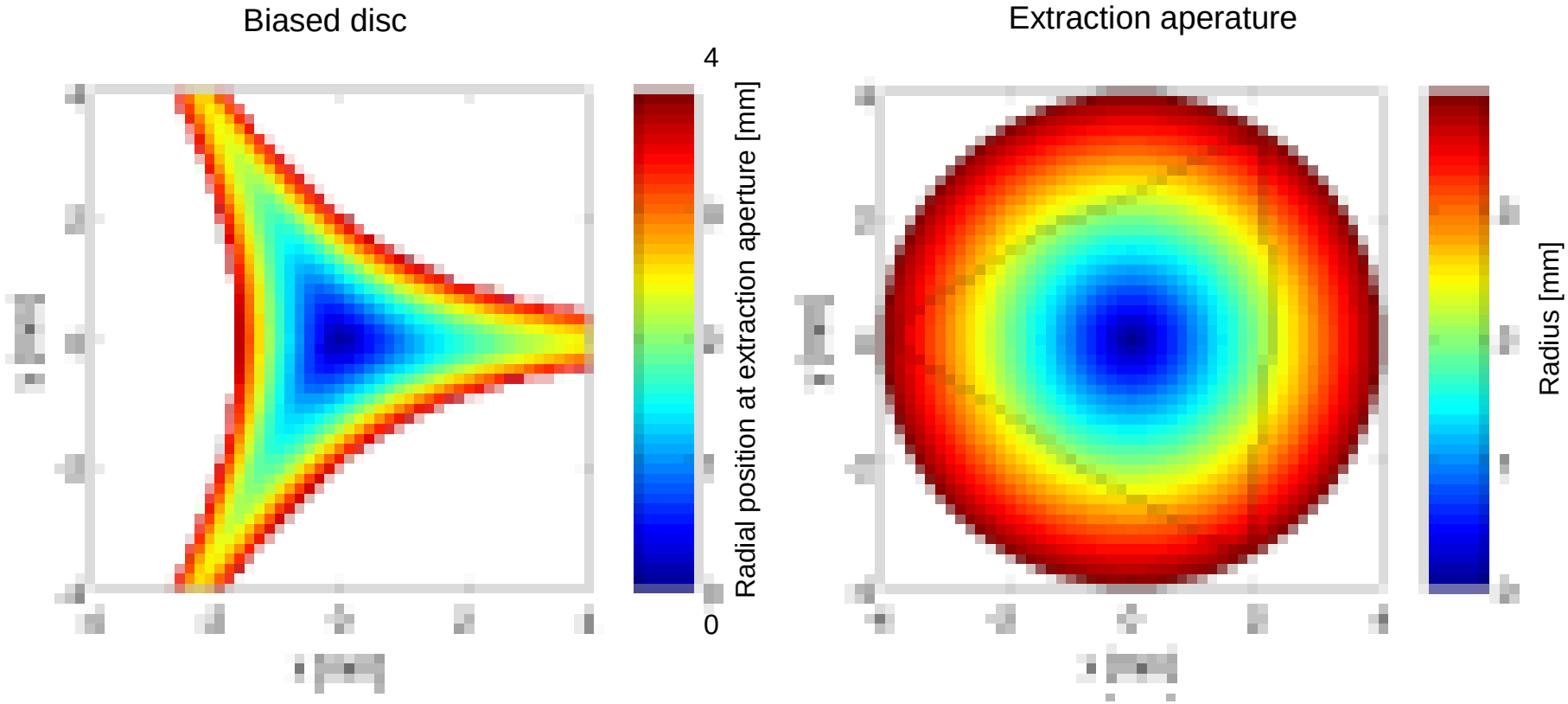


Extraction argument: enhanced population responsible for sputtering is also leaving through the extraction aperture

Why is this distribution there???

Where does the sputtered triangle come from?

Mapping of field lines from the extraction aperture to biased disk.

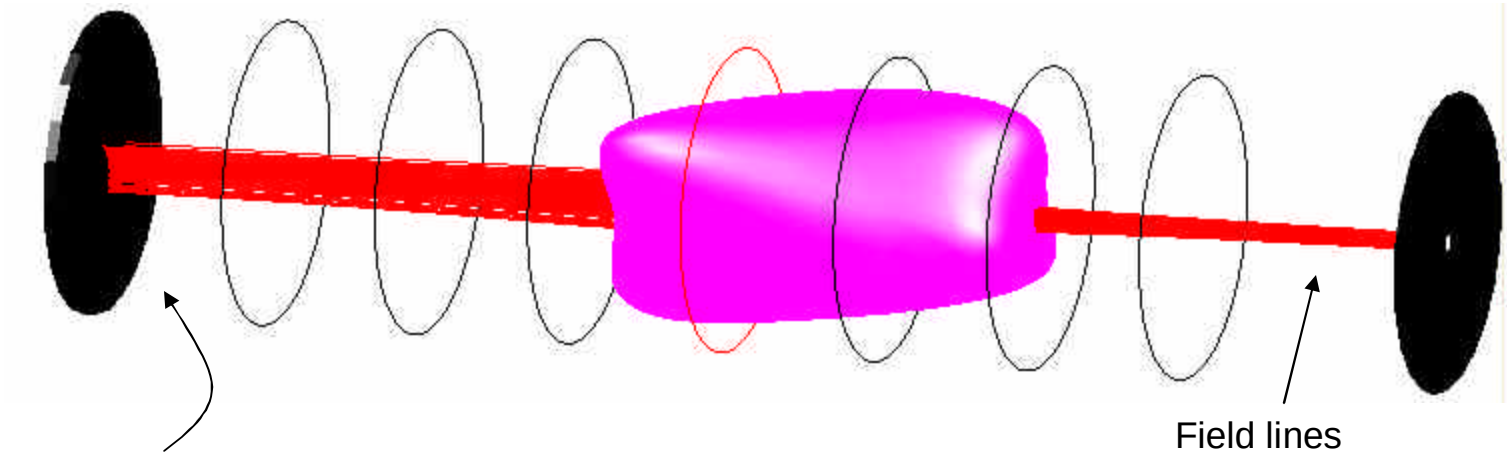


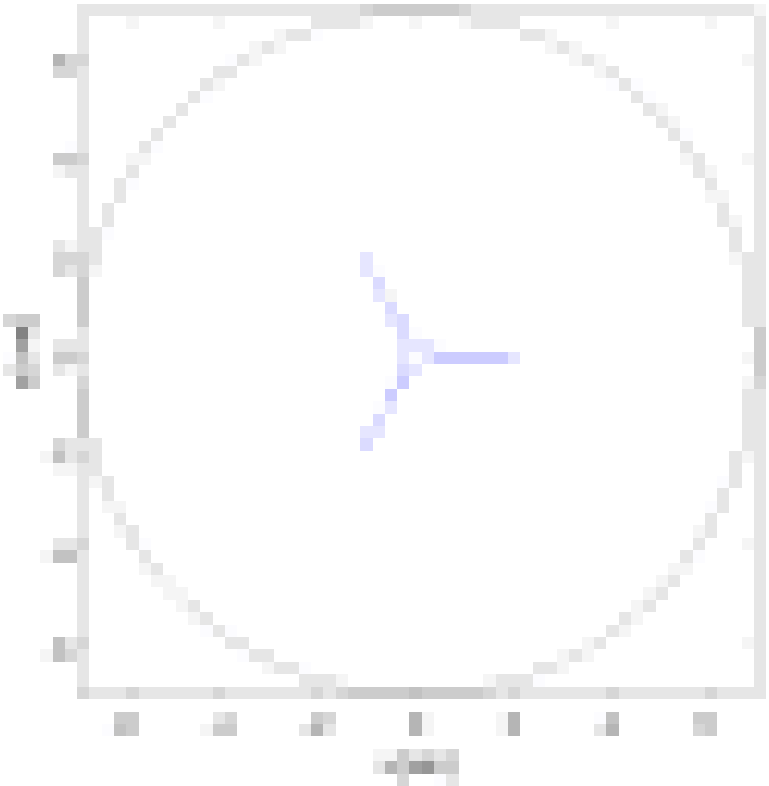
Overlay measured triangle on biased disk

Sputtering argument:

- Electrons from biased disk not sufficiently heated in reasonance zone crossings will reach extraction plane
- Those striking extraction electrode are lost, those passing through aperture may be reflected
- Reflected electrons have at least two extra resonance zone crossings and would be expected to be confined more efficiently
- Losses of arms on biased disk results in triangular distribution at aperture

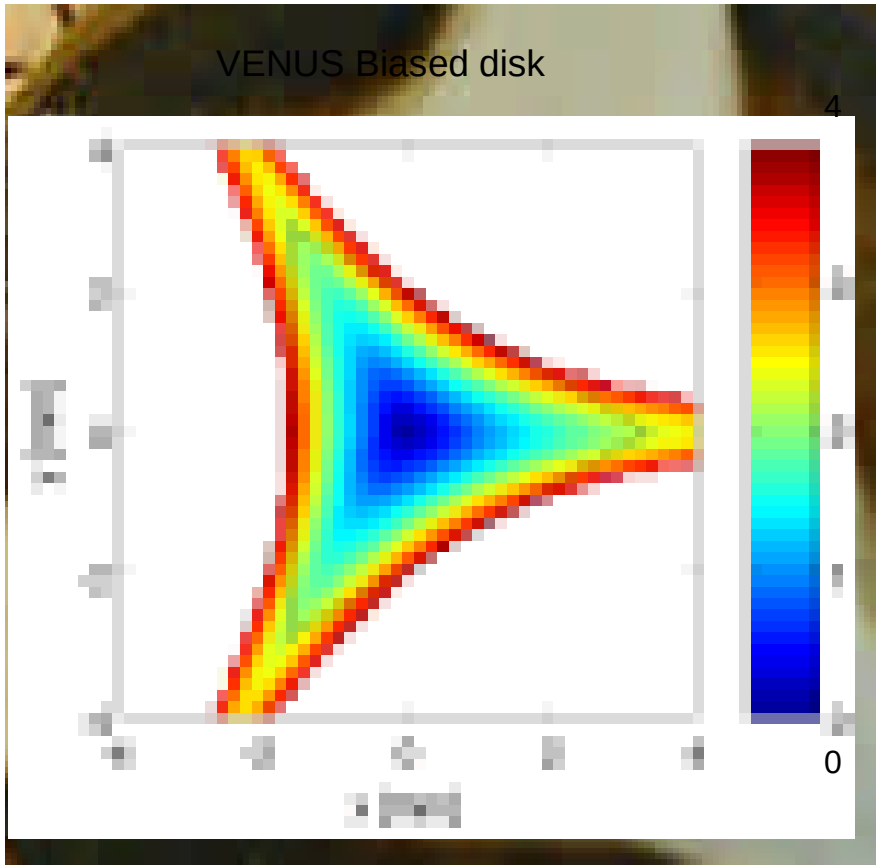
Argument for triangular beam, continued…

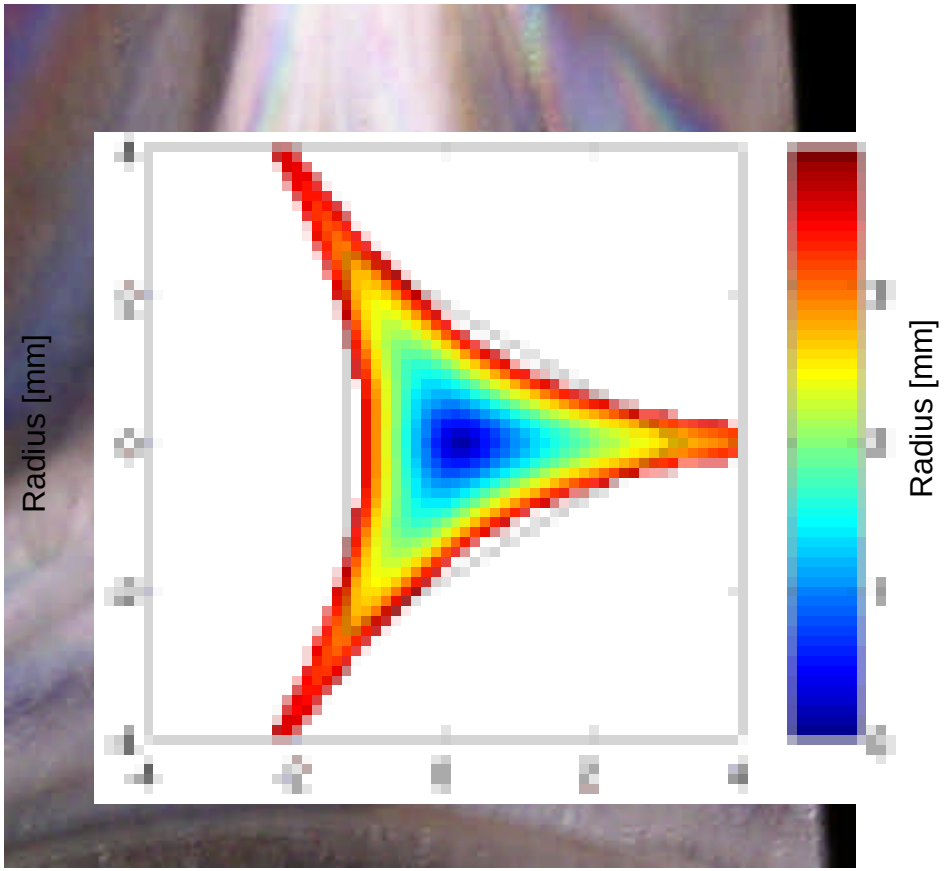




- Small scatterings on arms move particles to field lines which result in losses to the extraction electrode
- Small scatterings near center have greater likelihood of survival

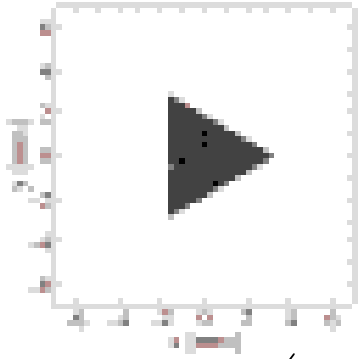
AECR exhibits similar effect





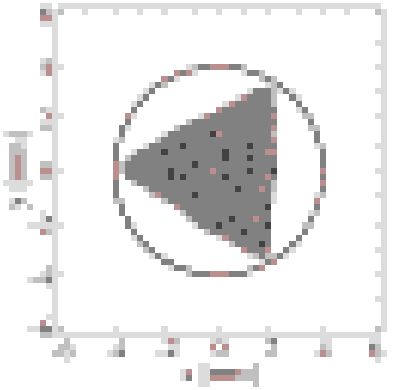
- Aperture can be used to predict size of biased disk sputter mark
- Assume sputter mark directly related to the extracted ion distribution…use it to define initial conditions

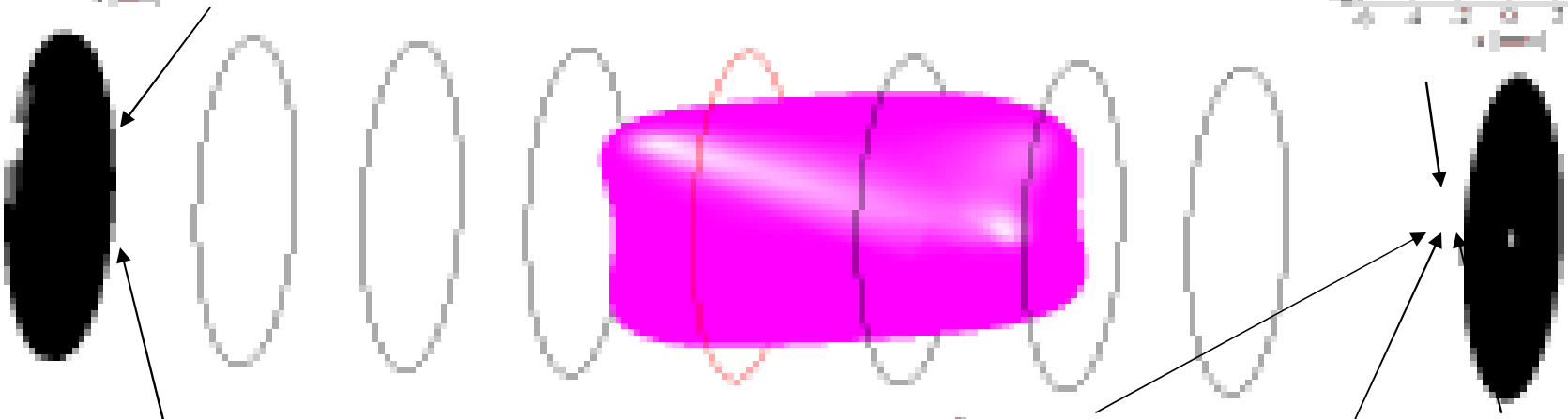
Extraction distribution from biased disk mark

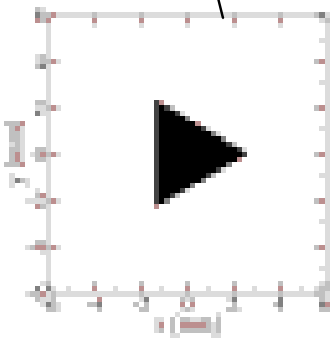


Initial conditions using zero temperature

- Constant distribution at biased disk
- Follow field lines to aperture

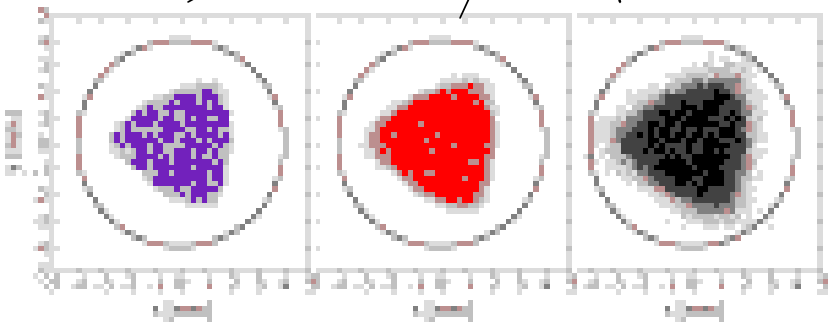






Initial conditions using
non-zero temperature

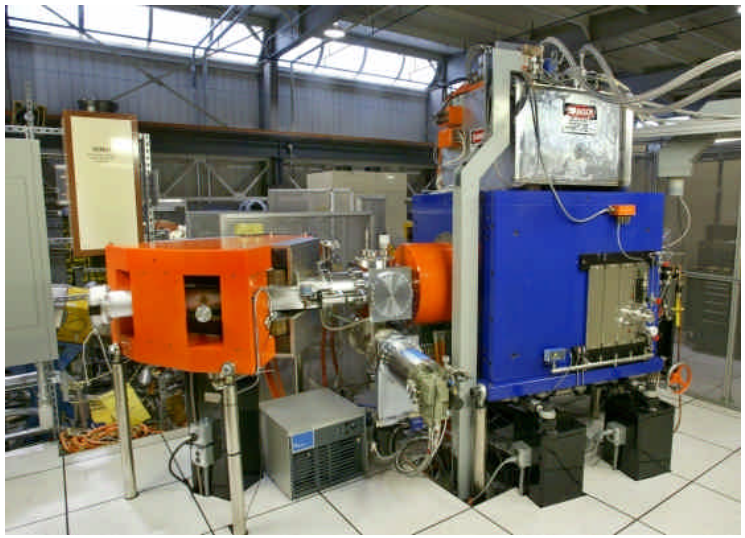
- Constant distribution at biased disk
- Boltzmann energy distribution
- Track ions to aperture

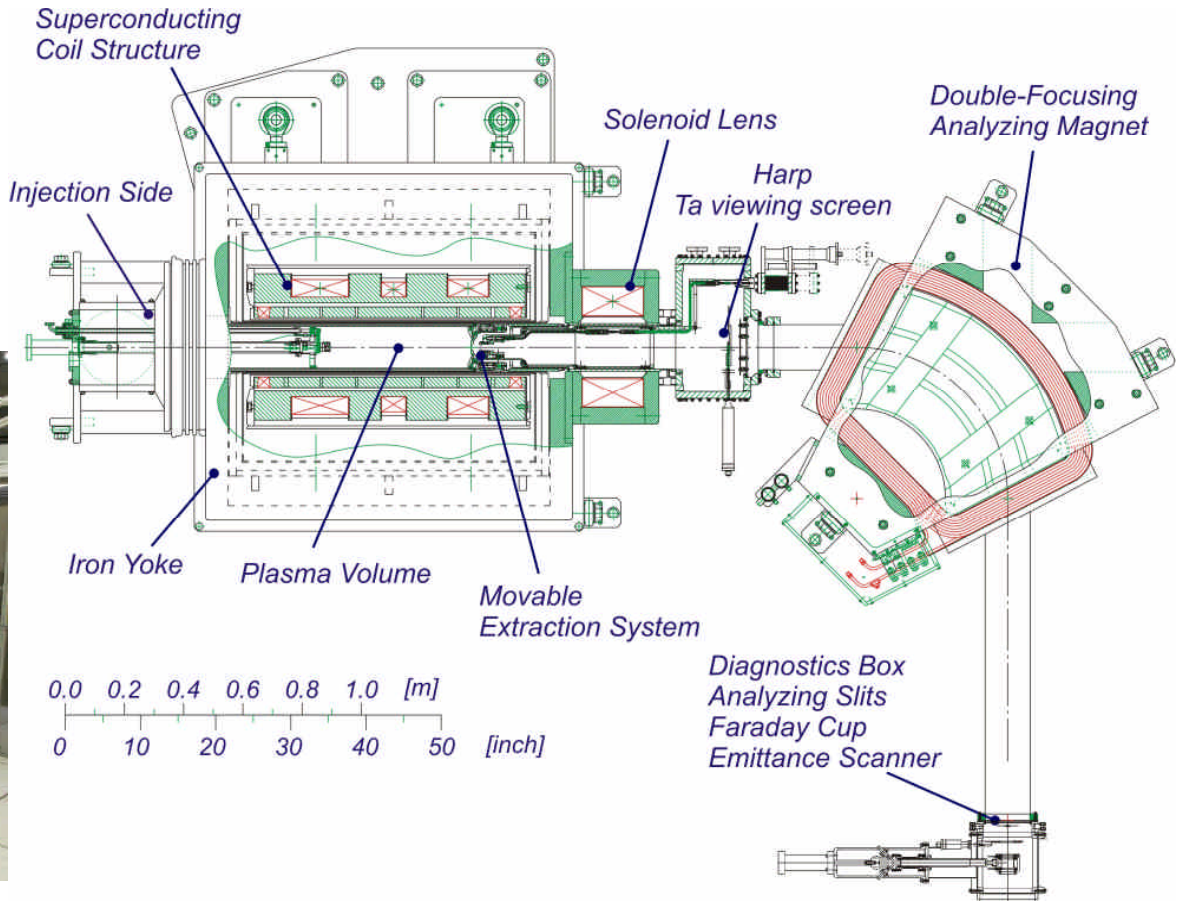


M/Q=2.0 M/Q=4.0 M/Q=16.0

Initial conditions need only be generated once for a given field

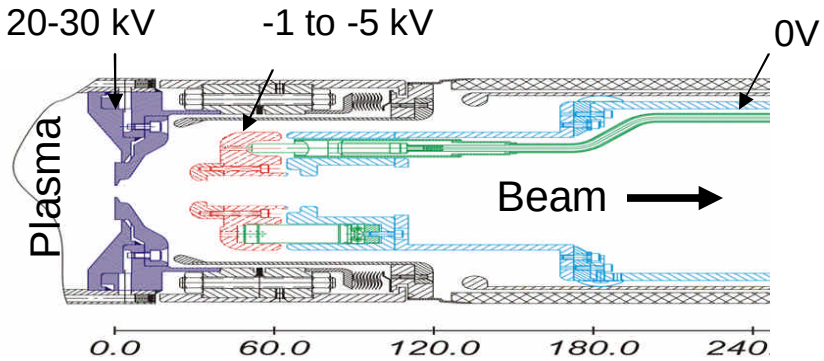
VENUS simulations

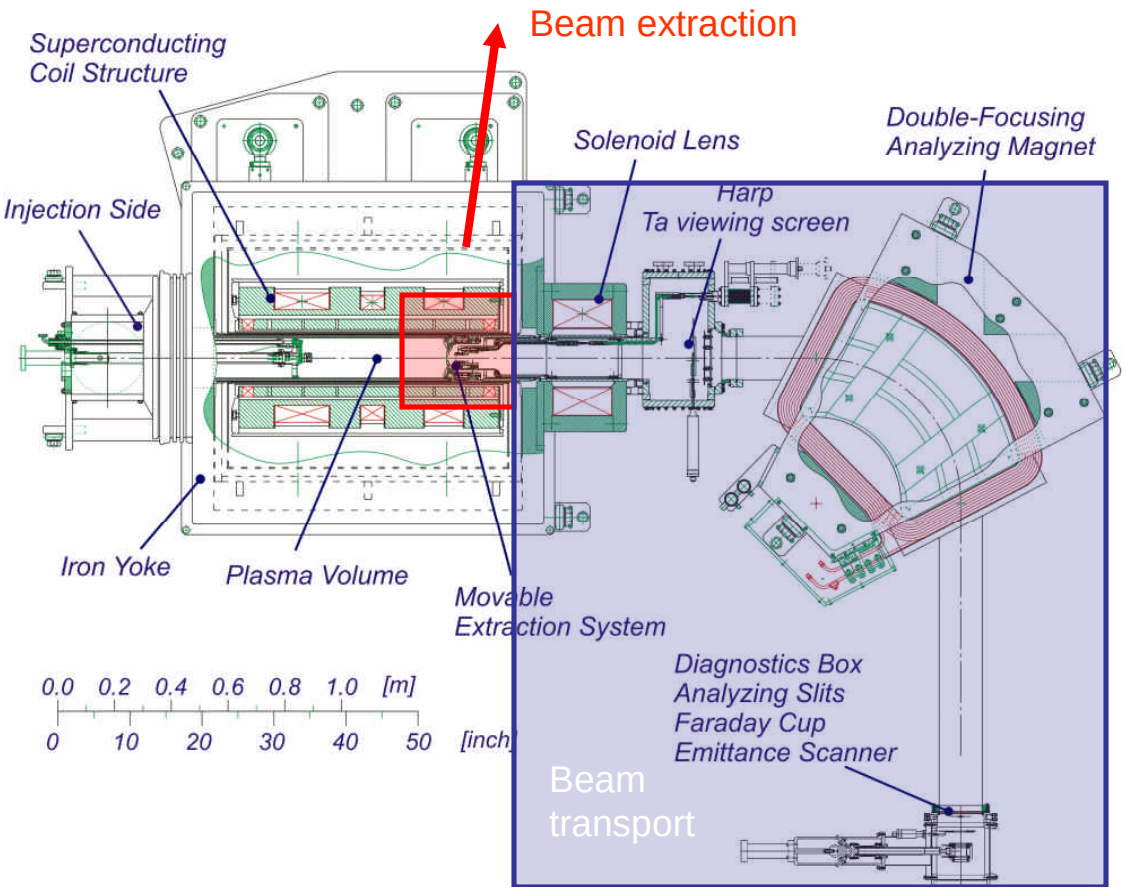




For ion beam analysis the only optical elements used are a solenoid lens and analyzing dipole

VENUS simulation approach: simulate two separate sections in Warp





Simulation of extraction section:

Warp has both 2D (r-z) and 3D PIC plasma extraction model capabilities

Ions tracked in simulation, electrons modeled as Boltzmann density distribution (Self model)

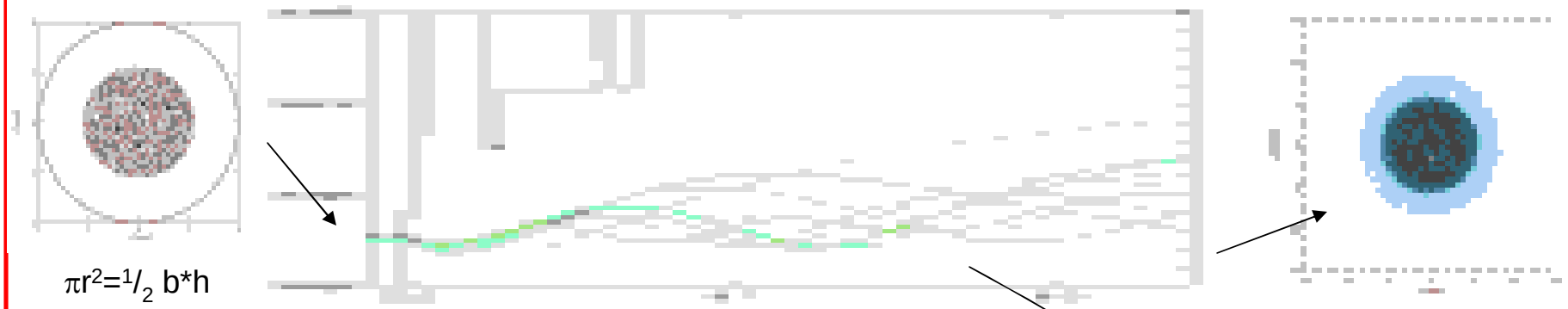
Simulation of transport section

Warp 2D transverse (x,y) solver used

Solenoid lens read in as r-z mesh, full 3D field for dipole

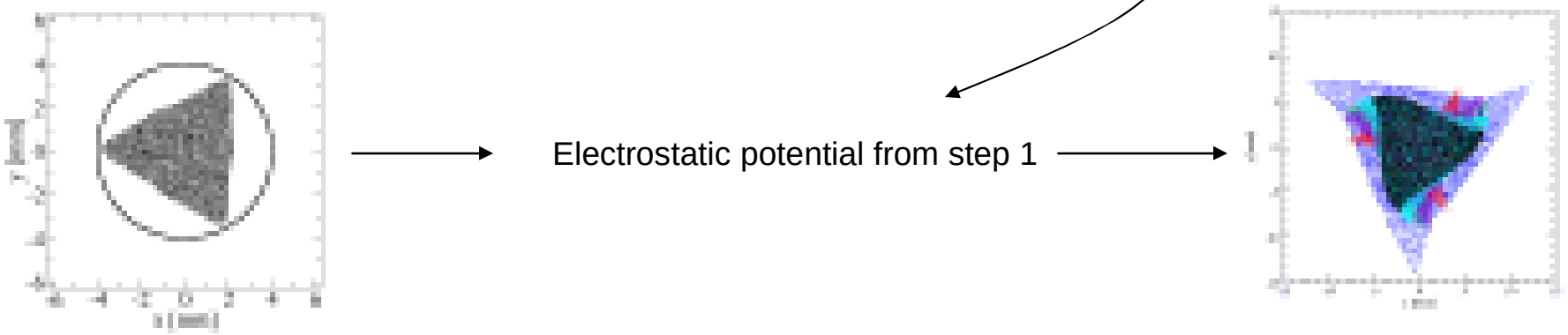
Three-step extraction and transport simulation approach for VENUS

Step 1: Simulate extraction of cylindrically symmetric, multi-species beam



$\pi r^2 = {}^1/_2\ b*h$

Step 2: Track triangular distribution through solved potential of Step 1



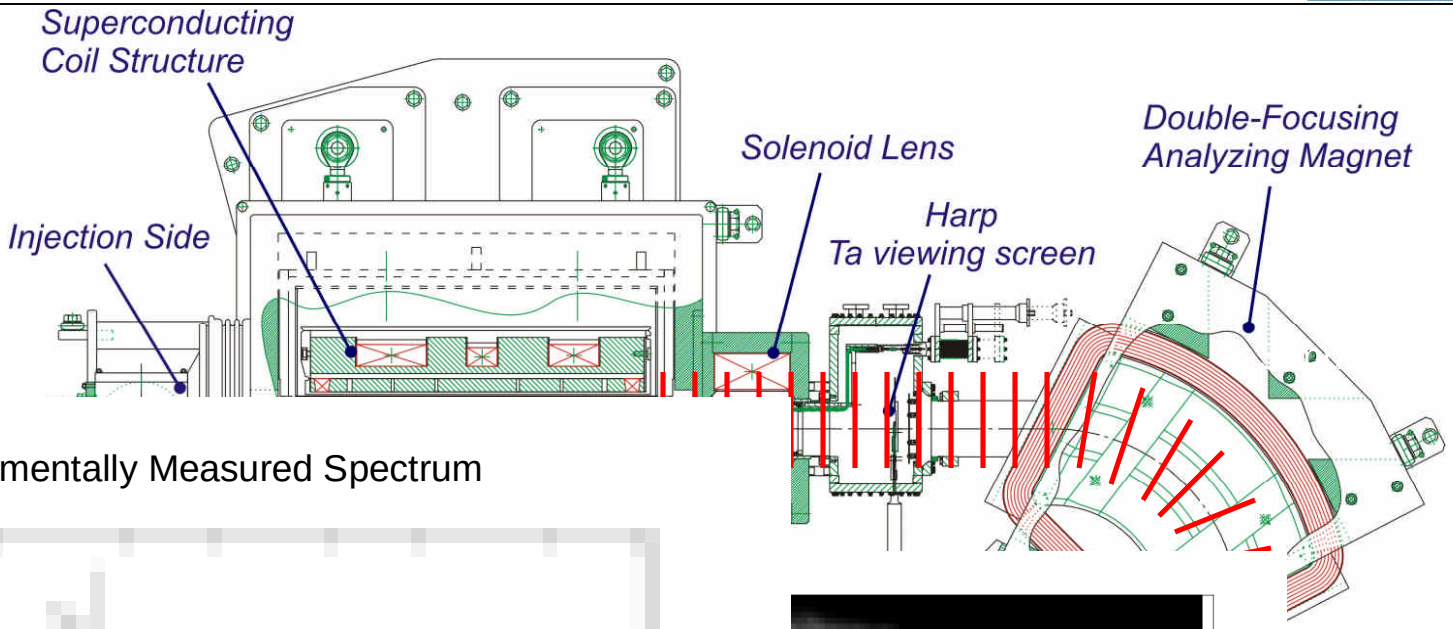
Electrostatic potential from step 1

(has been benchmarked against 3D model)

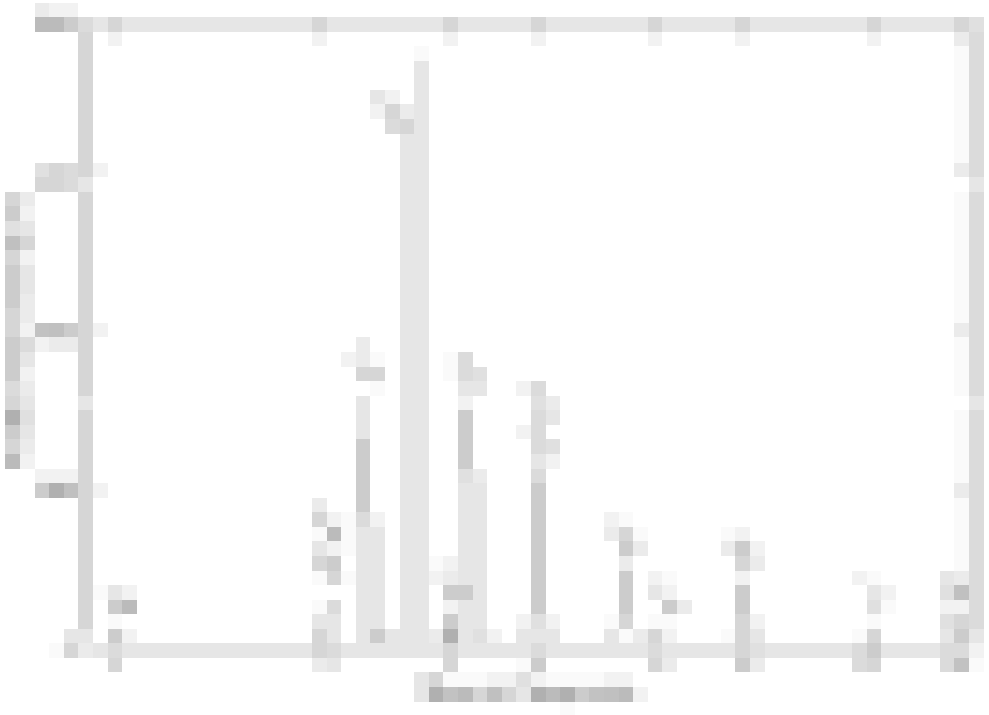
Step 3: Simulation of transport of resulting beam from Step 2 through remainder of system

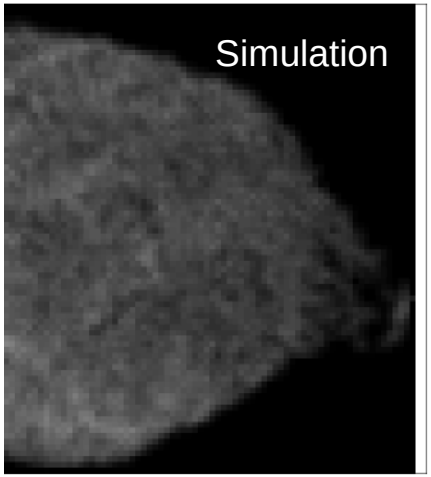
Simulation of Oxygen Beam Extraction and Transport

Experiment

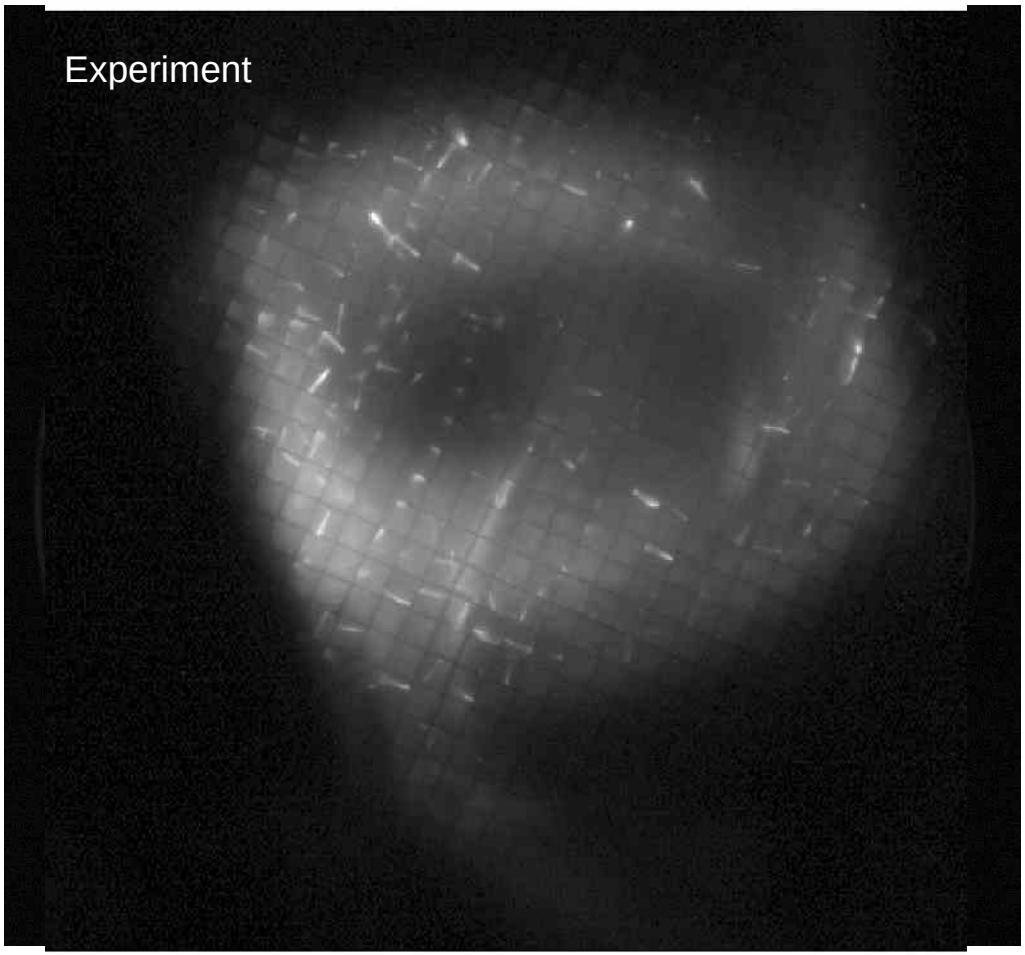


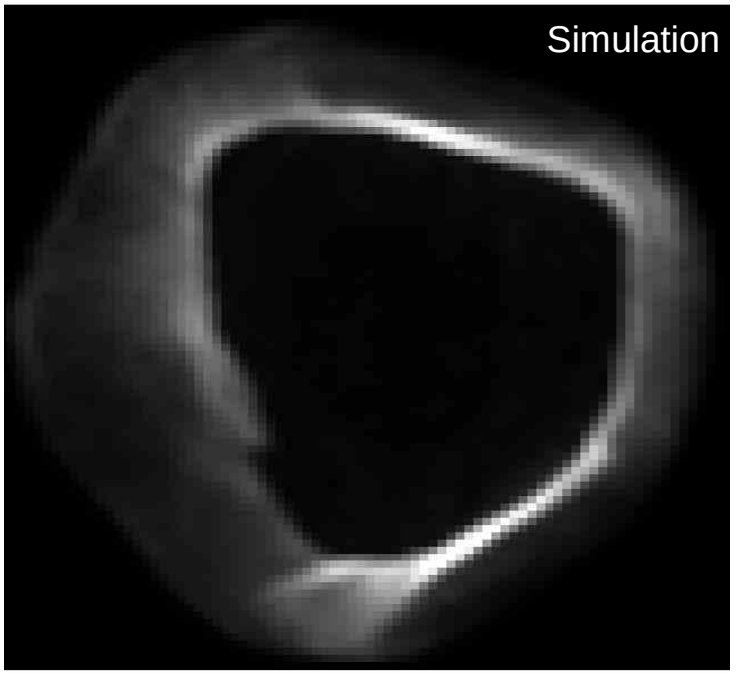
Experimentally Measured Spectrum



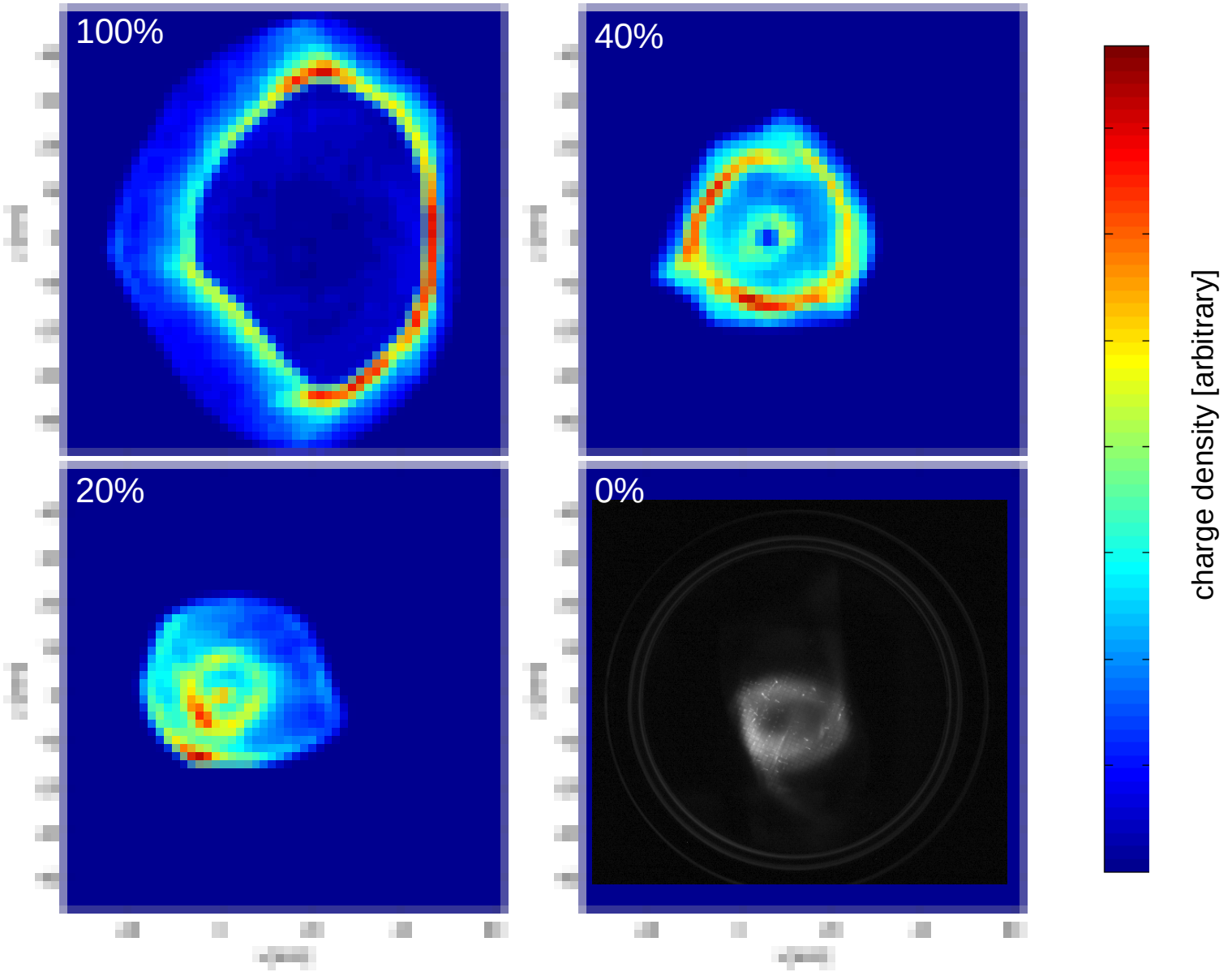


Comparison of C^{4+} beam shape

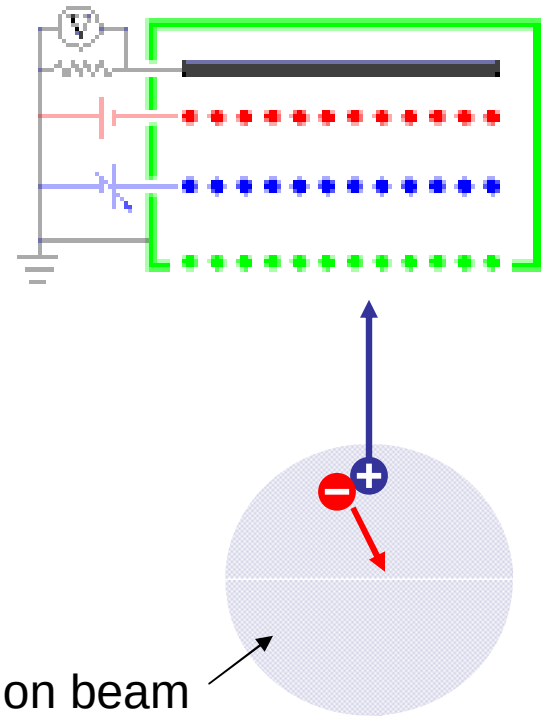


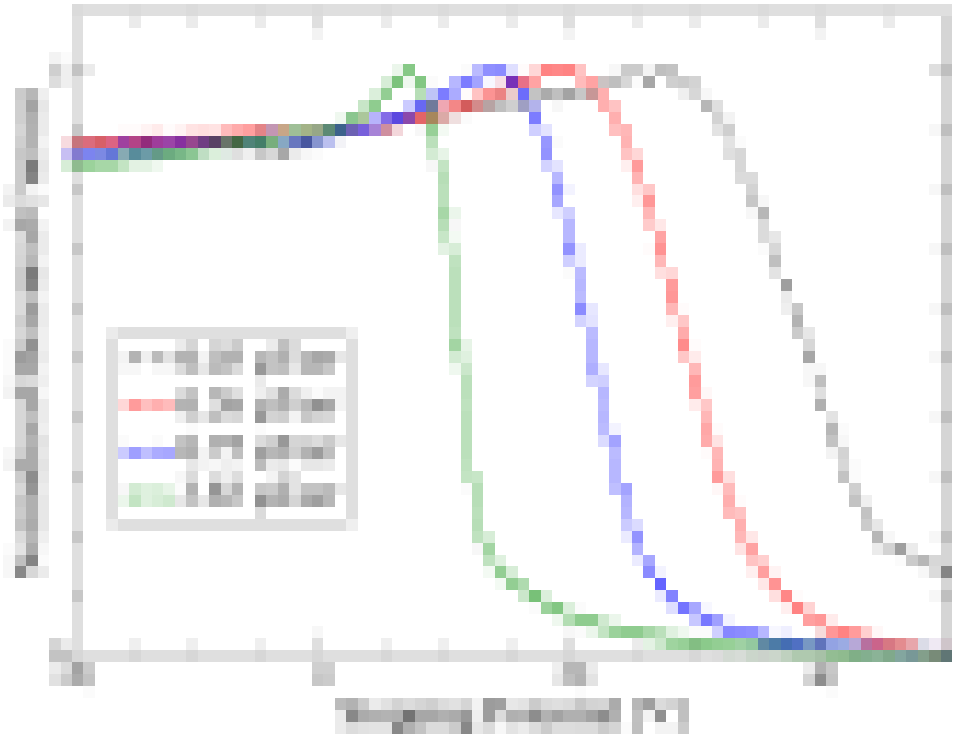


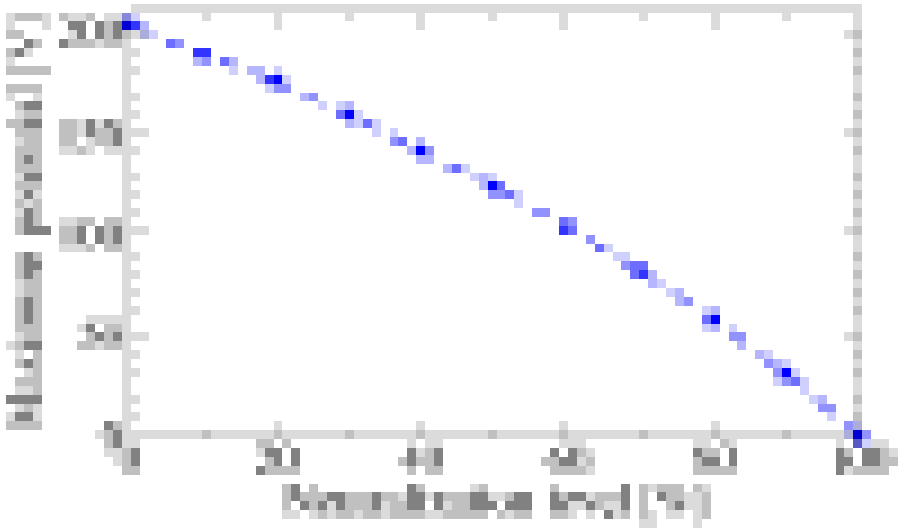
Change in C^{4+} beam with reduced space charge along beam line



Space charge screening along beam line

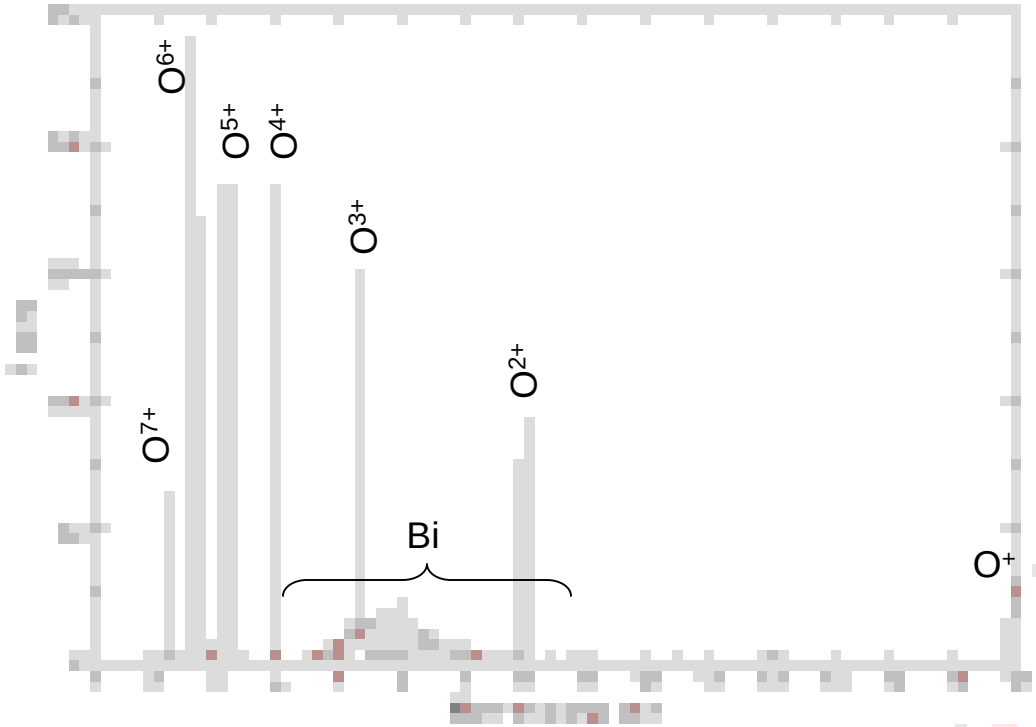


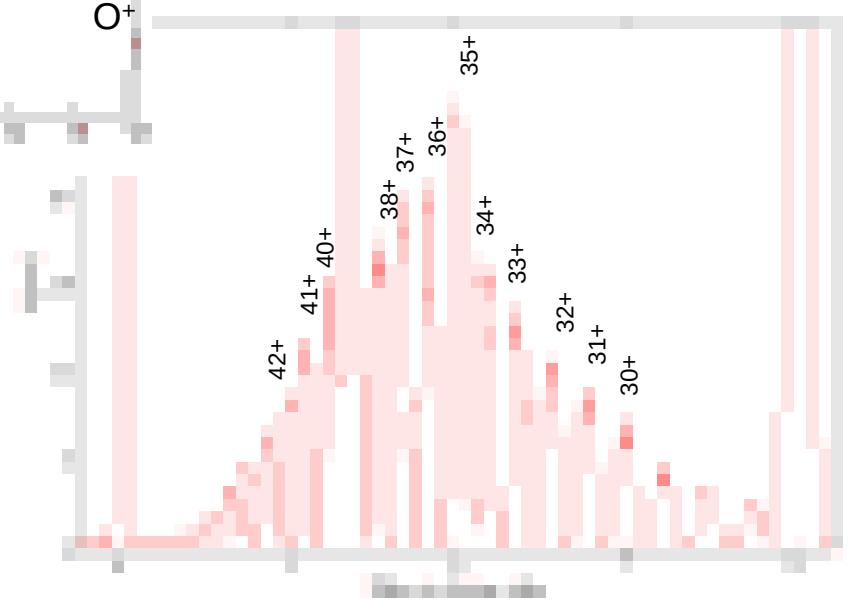




Ion beam ionizes background gas
- Positive ions ejected from beam
- Electrons can be confined by beam potent
- Confined electrons reduce effective potent
- Ion energy related to beam potential

Bismuth simulation





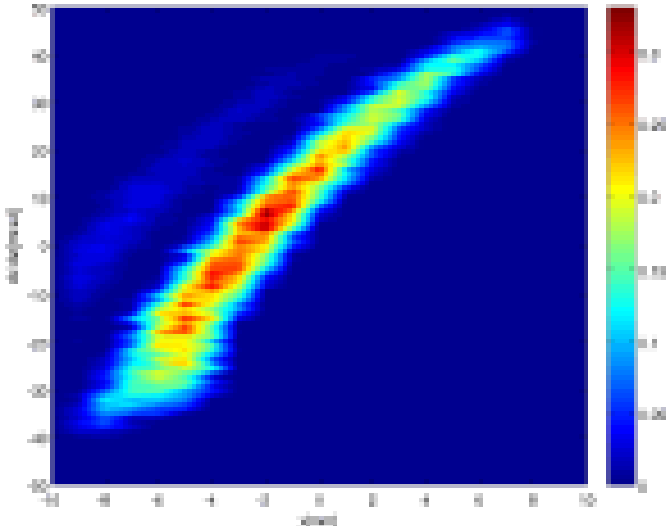
- Simulate 28 ion species
- Linearly scale current to make up for difference between drain current and spectrum (diff ~ 25%)

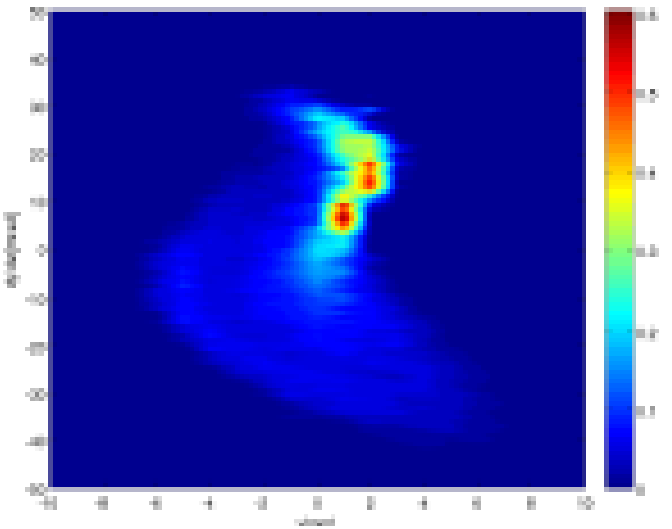
Bi^{35+} phase space

Horizontal

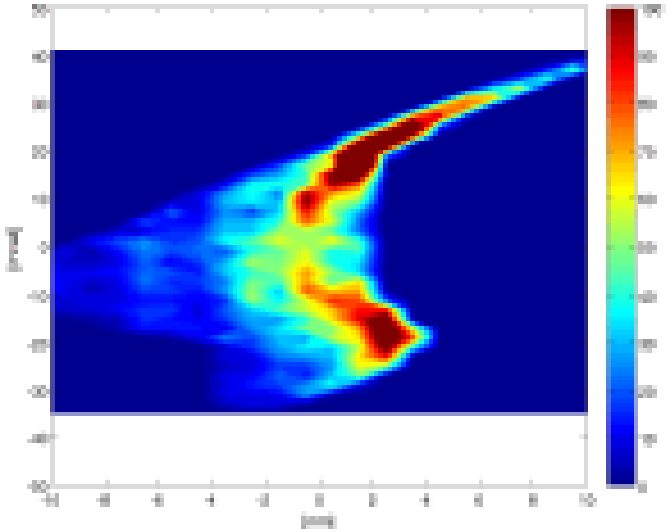
Vertical

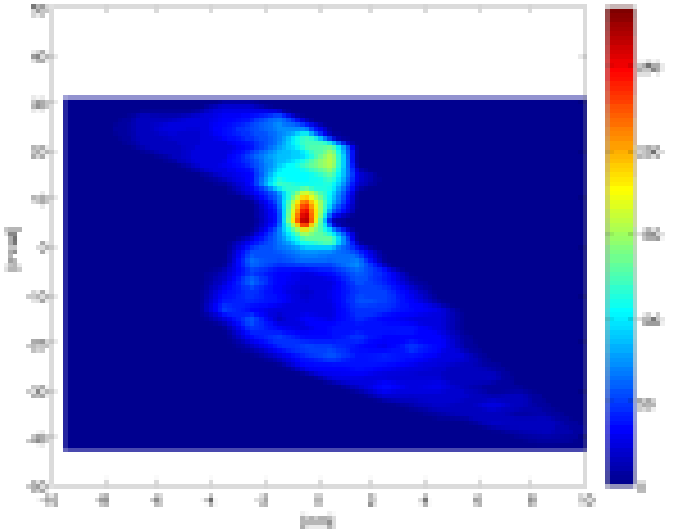
Experiment





Simulation



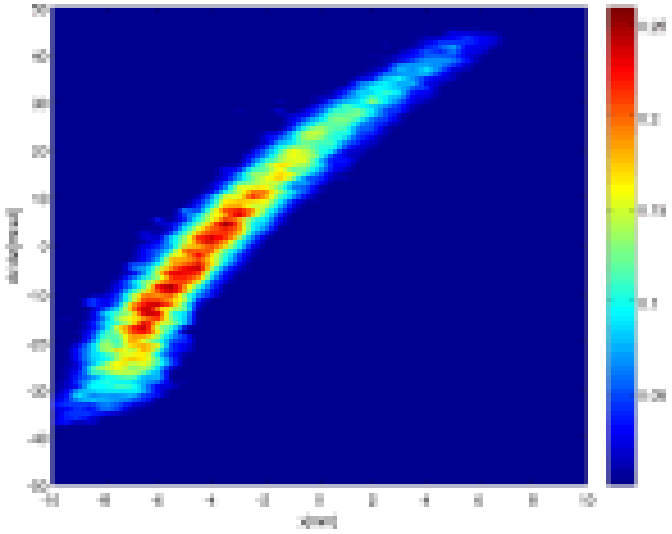


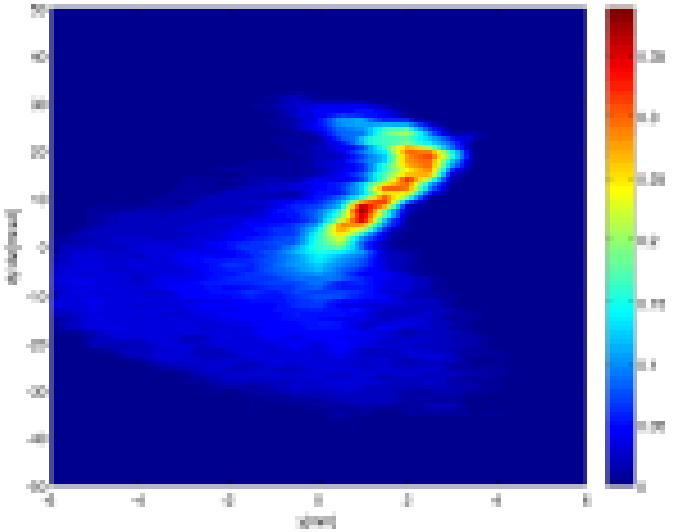
Bi^{37+} phase space

Horizontal

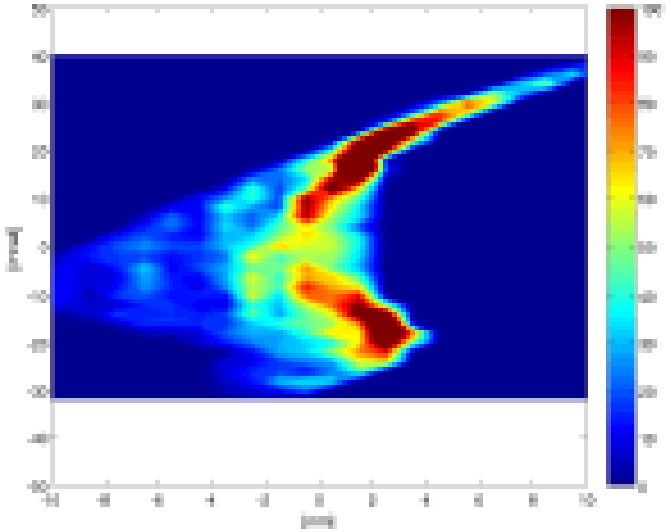
Vertical

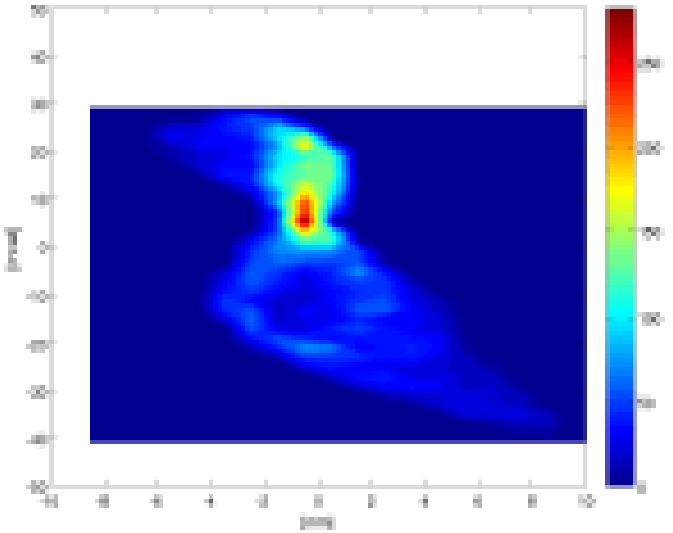
Experiment



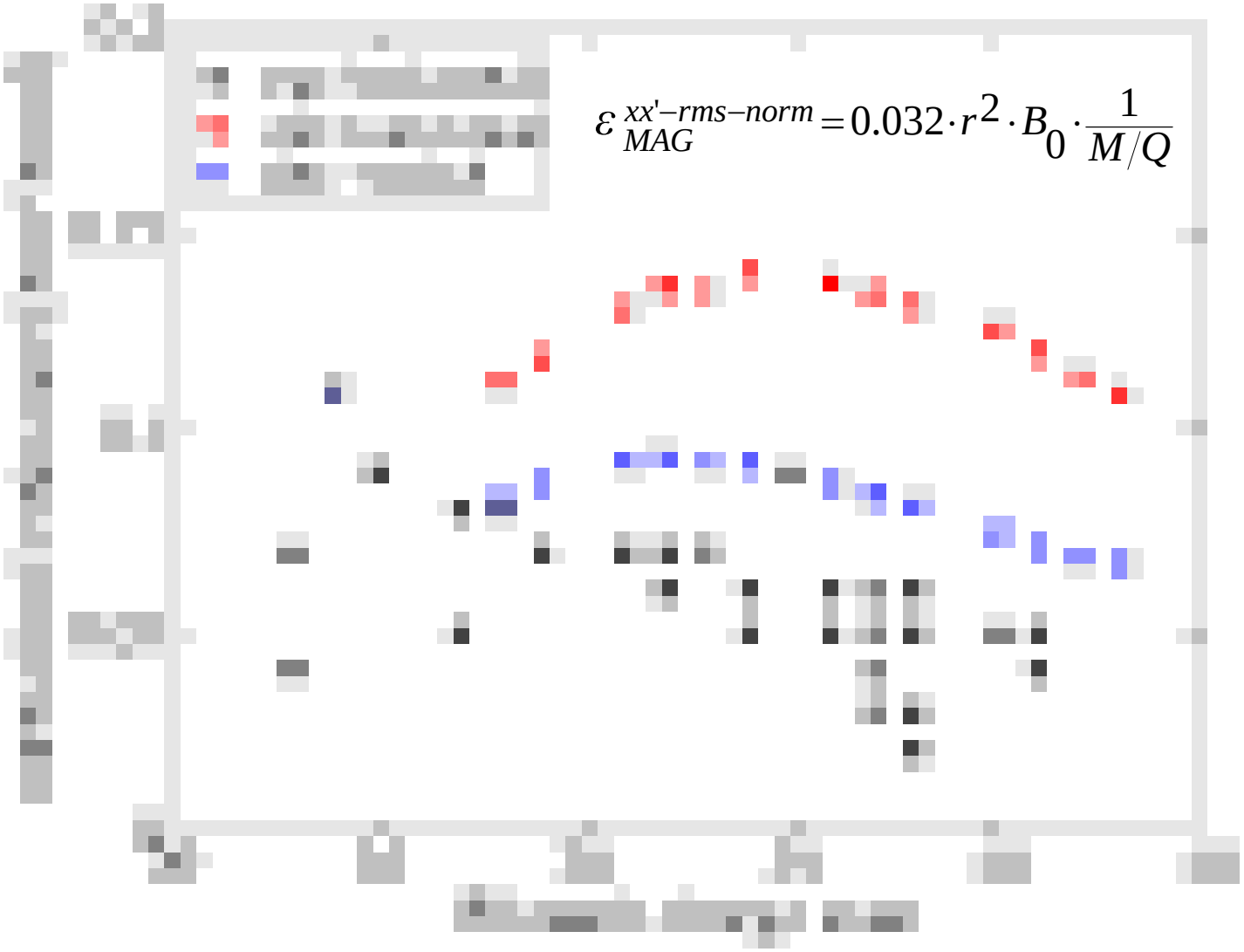


Simulation





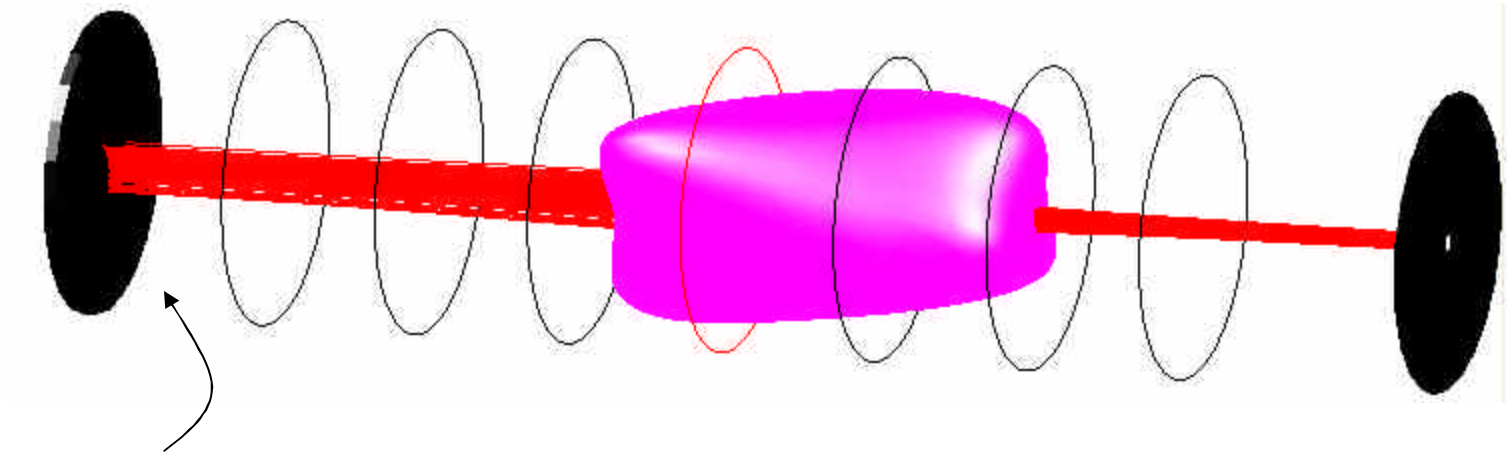
Bismuth emittance analysis

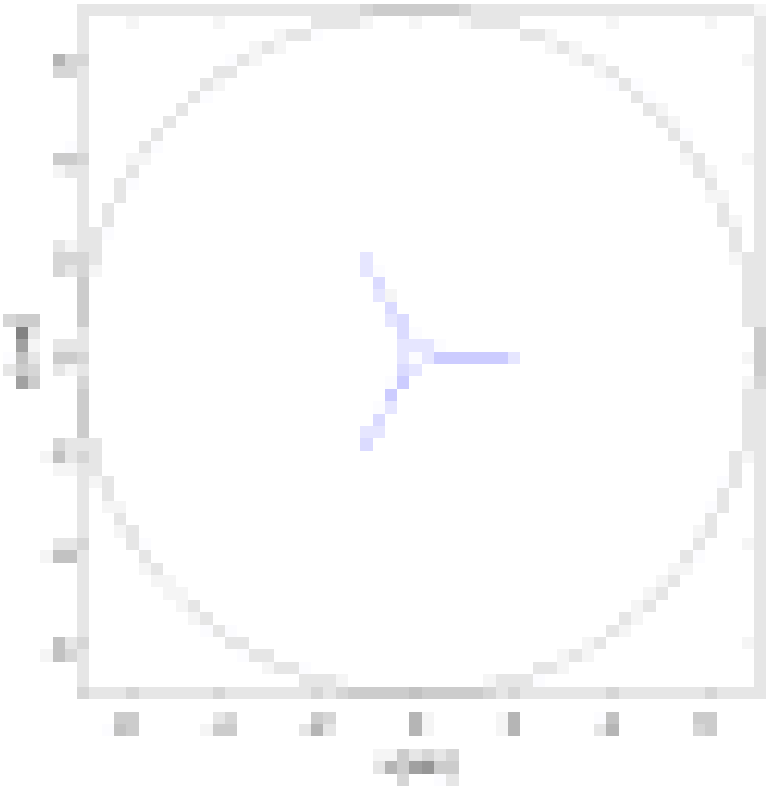


Conclusions

- Developed a predictive method to establish initial conditions for simulations based on experimentally measured sputter marks and aperture geometry
- Simulations using these initial conditions have well-reproduced both configuration and phase space measurements for oxygen and bismuth.
- Simulations show that beam hollowing only appears with nonzero space charge along the transport system---in agreement with the measurement of nonneutralized beams using retarding potential analyzer
- Features such as beam hollowing and the decrease of emittance with increased charge state have been exhibited using constant density distributions at extraction
- What keeps this from being fully predictive: Need ion beam distributions. Need to know level of neutralization.

Field lines that terminate inside 4mm-radius aperture

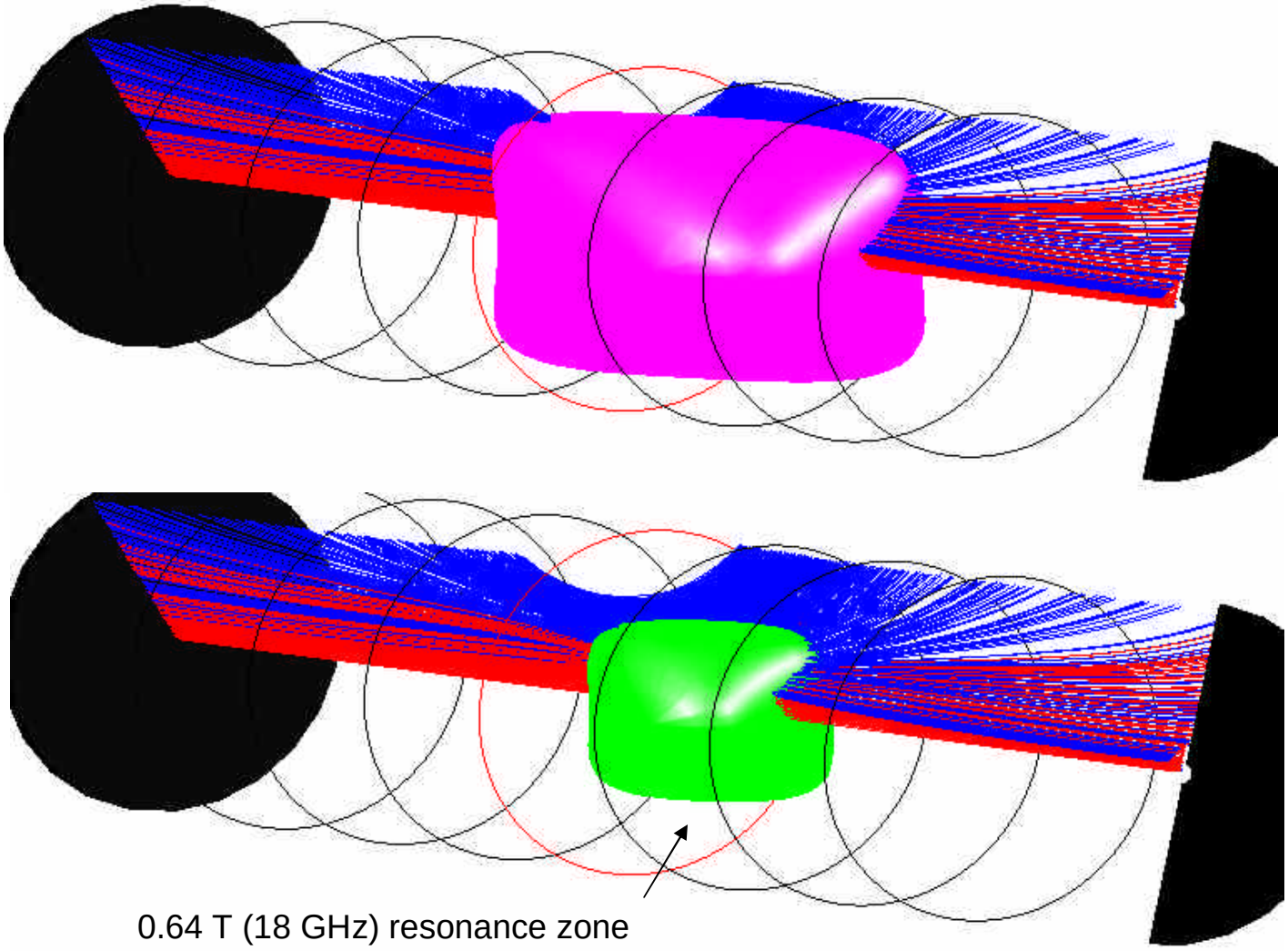




- Every field line passing through the 4mm-radius aperture terminates on the biased disk
- Electrons heated on the plasma edges must undergo radial transport to close to the axis to ionize --- same for ions
- If plasma edge heating is a key mechanism for the production of ions, it is very difficult to argue how a triangular extracted distribution is created in VENUS

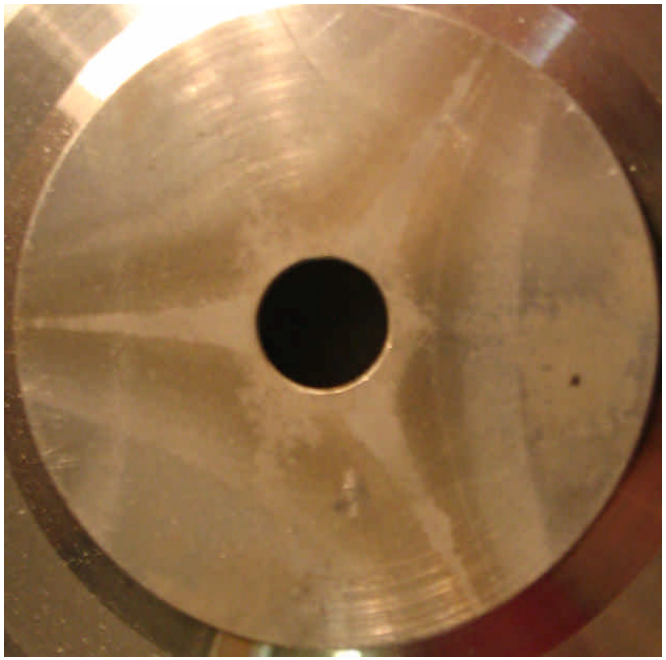
- Neither ion tracking nor field line tracing produce triangular distribution at aperture

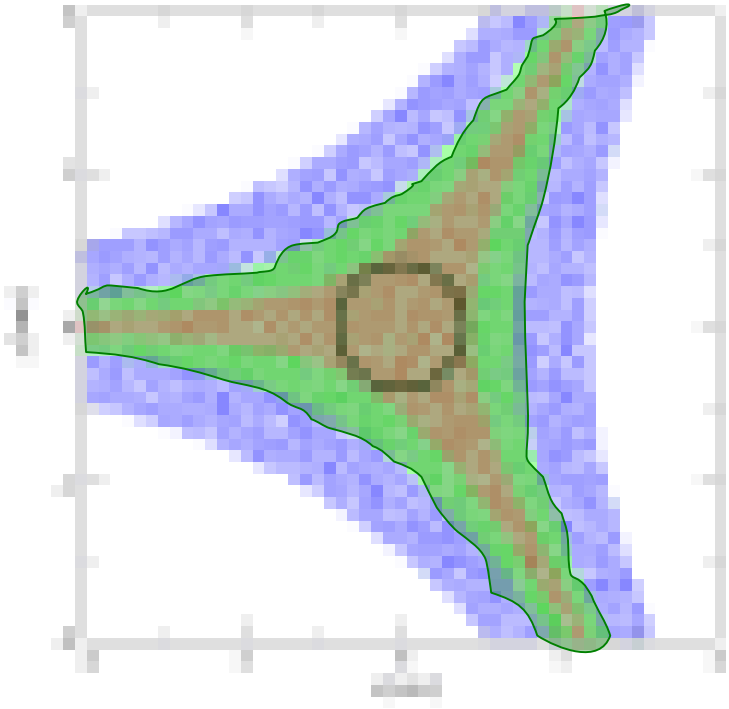
Field lines through 18 GHz Resonance Zone



- All field lines that terminate on the ends of the plasma pass through both resonance zones
- Only some of the field lines that terminate through the wall pass through the 18 GHz (0.64 tesla) zone

Extraction elecrode



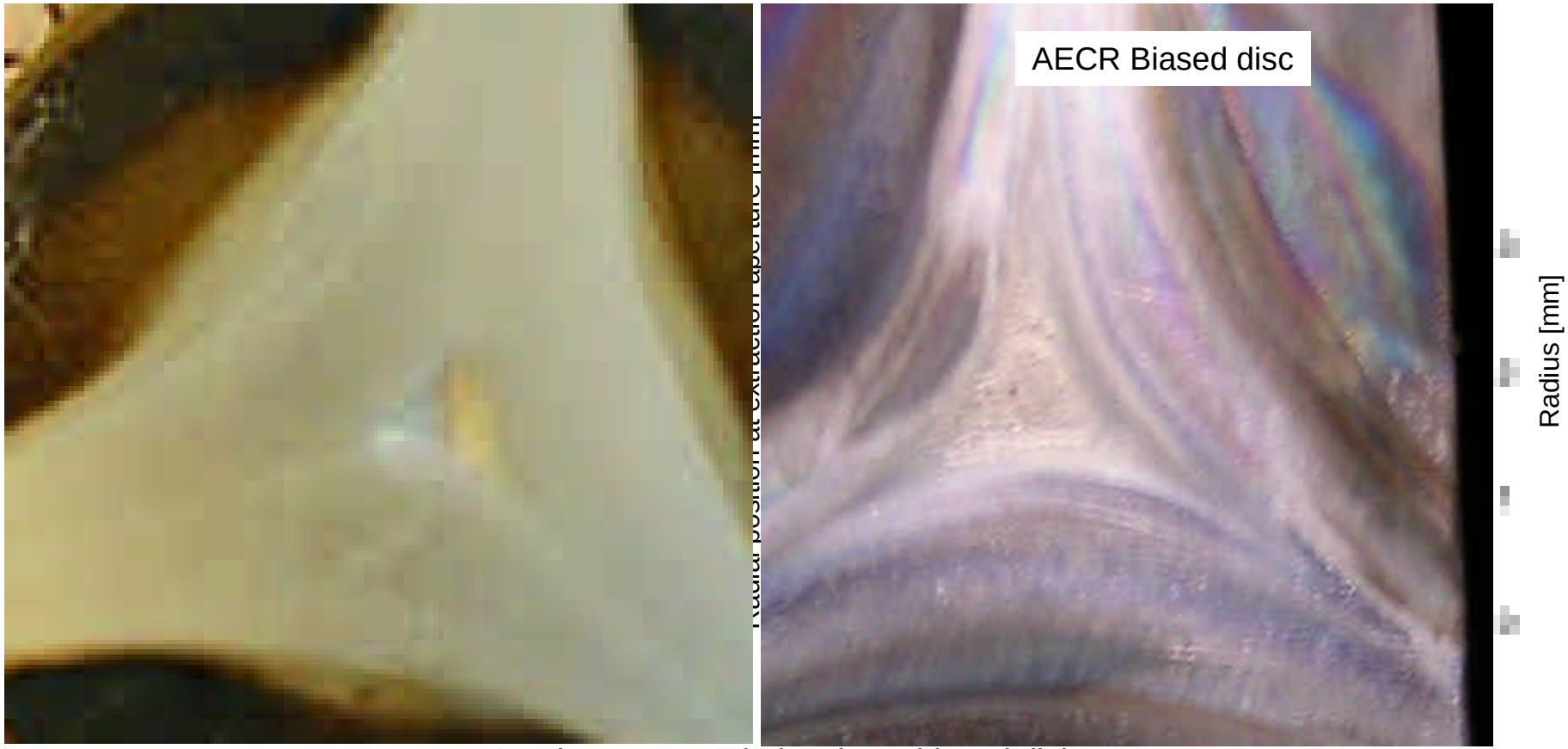


- Red points pass through both resonance zones
- Blue points strike wall but pass through 28 GHz resonance zone
- Green points also strike wall, but pass through both the 18 and 28 GHz resonance zones

Triangular structure larger than aperture. Analysis of distribution of field lines within aperture gives constant density distribution

Where does the sputtered triangle come from?

Mapping of field lines from the extraction aperture to biased disk.



Overlay measured triangle on biased disk

Sputtering argument:

- Electrons from biased disk not sufficiently heated in reasonance zone crossings will reach extraction plane
- Those striking extraction electrode are lost, those passing through aperture may be reflected
- Reflected electrons have at least two extra resonance zone crossings and would be expected to be confined more efficiently