USPAS - Fundamentals of Ion Sources
6. Ion Extraction

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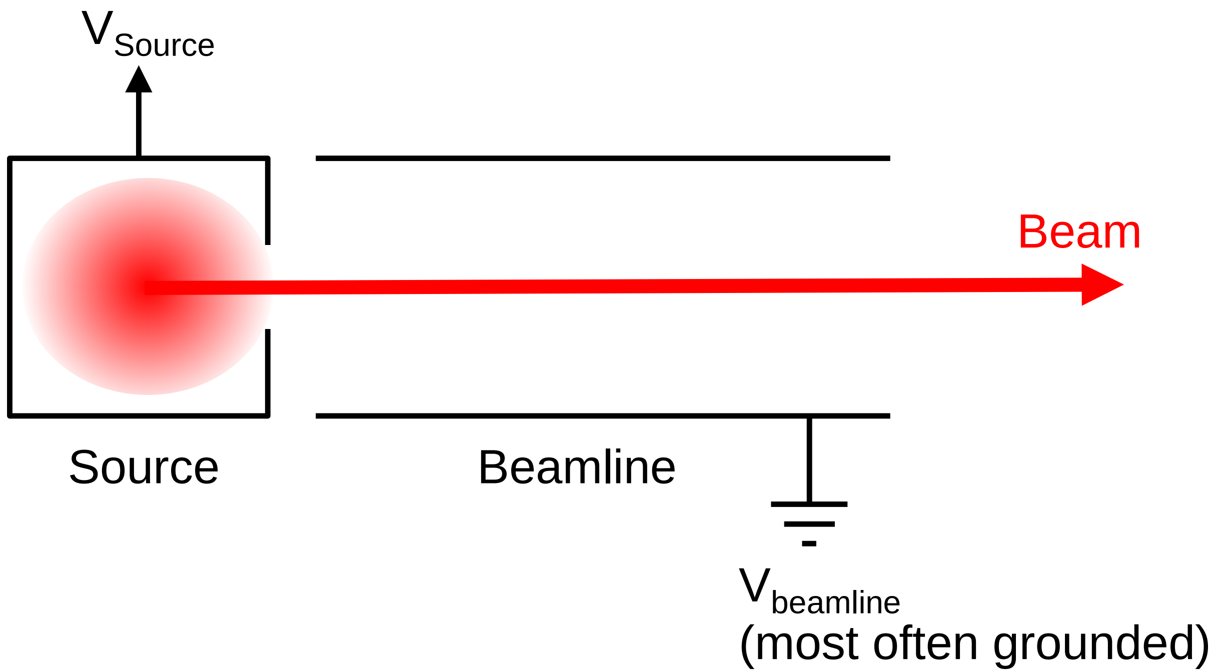
Introduction

In simple terms: $\mathrm{E_{kin}} = q(V_{Source} - V_{Beamline})$



Unfortunately…Not so simple.

Strict beam requirements:

- Current
- Emittance
- Species

Extracting from a plasma (typically):

- What happens inside the source?
- What happens at the boundary?
- What happens after initial acceleration?

Outline

Start with a few approximations, look at general principles.

Then we will look at this mostly from the Simulation side:

- Review the theory that we need to model the processes at the plasma boundary.
- How do Computer Codes implement this?
- What codes are available?
- A quick IGUN example to demonstrate.

Many theory slides adapted from T. Kalvas – CERN Accelerator School.

Thermal Emittance Estimate

Using
$$\epsilon_{rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2} \qquad [mm\text{-}mrad]$$
$$\langle x^2\rangle = \frac{\iiiint x^2 f(x,y,x',y')dxdydx'dy'}{\iiiint f(x,y,x',y')dxdydx'dy'}$$ etc.

With a (somewhat) realistic distribution like a Gaussian

Extracted from a circular hole

$$I(x,x') = \frac{2}{\pi r^2}\sqrt{r^2 - x^2}\sqrt{\frac{m}{2\pi kT}}e^{\frac{-m(x'v_z)^2}{2kT}}$$

One can make an estimate for the normalized rms emittance:

$$\epsilon_{rms,norm.} = \frac{1}{2}\sqrt{\frac{kT}{m}}\frac{r}{c}$$
with T the ion temperature and r the aperture radius.

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Magnetic Emittance Growth

- In many ion sources a strong solenoidal field is present at the extraction aperture. Thus the particles receive an azimuthal thrust upon exiting the source:

$$v_\theta = \frac{qBr_0}{2m}$$

- The emittance can be calculated outside of the influence of the magnet when the azimuthal motion has been completely changed into radial motion:

$$r' = \frac{v_r}{v_z} = \frac{v_\theta}{v_z} = \frac{qBr_0}{2mv_z}$$

- Thus: $\epsilon_{rms} = \frac{1}{4} r_0 r' = \frac{qBr_0}{8mv_z}$ and $\epsilon_{rms,norm.} = \frac{qBr_0}{8mc}$

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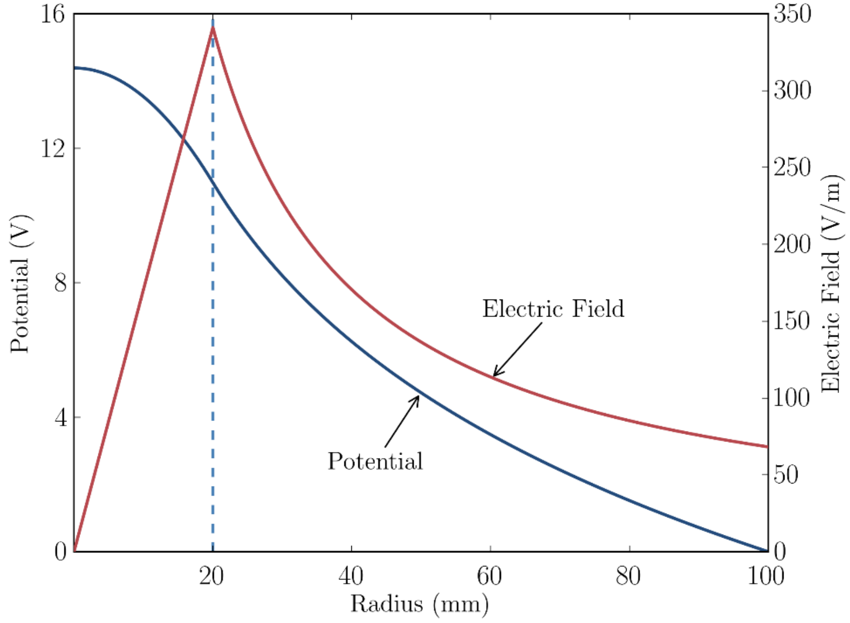
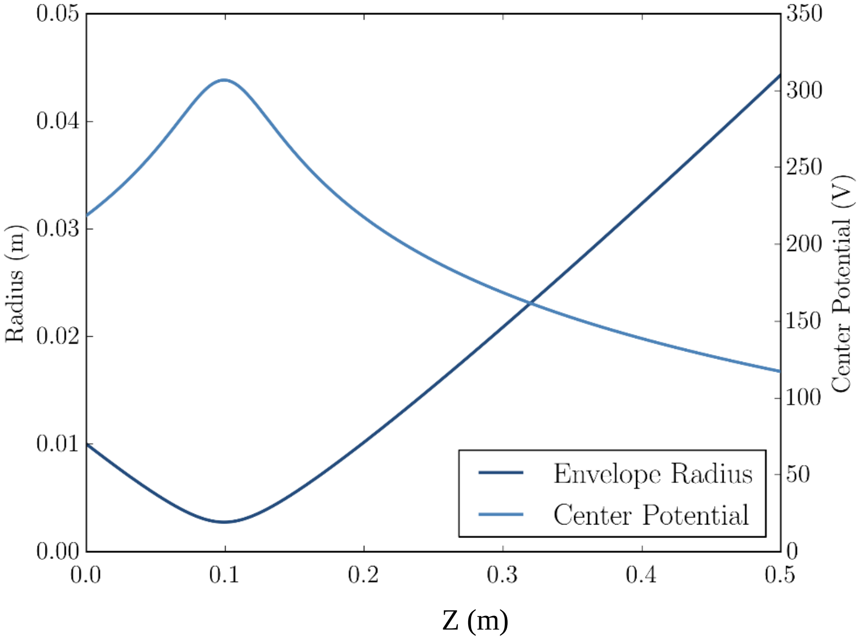
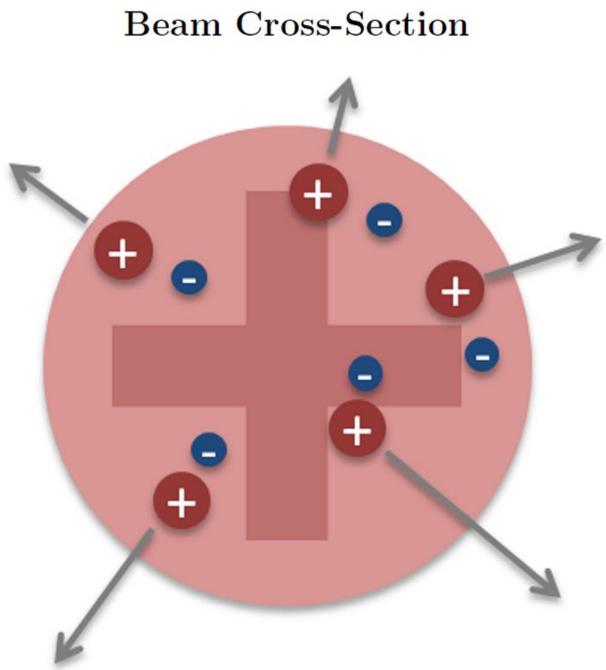
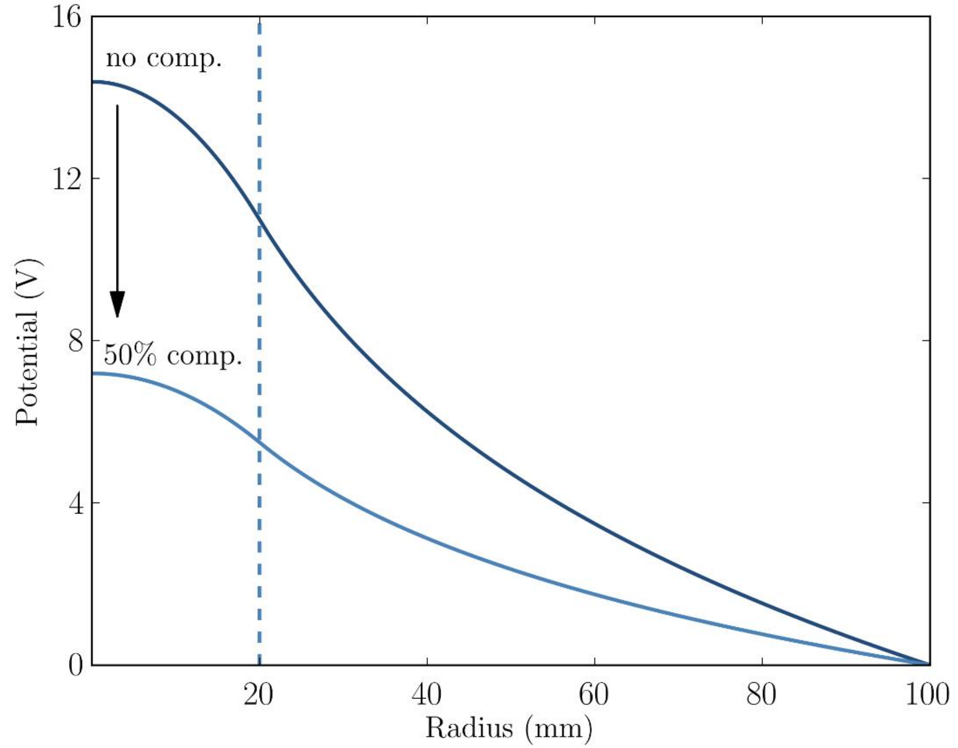
Space Charge





Space Charge Compensation





Space Charge and Space Charge Compensation will be discussed Thursday

Two Limits to Maximum Current:

From Poisson's Equation we get the *Child-Langmuir Law*:

$$\mathrm{I} = 1.67 \cdot 10^{-3} \mathrm{A} \left(\frac{Q}{mc^2} \right)^{1/2} \frac{V_0^{3/2}}{d^2}$$

From plasma physics we get available Ions:

$$\mathrm{I} = \frac{1}{4} \mathrm{A} q n \bar{v} \quad \text{with} \quad \bar{v} = \sqrt{\frac{8kT}{\pi m_i}} \quad \text{or} \quad j_s = n_i q \cdot \left(\frac{kT_i}{m_i} \right)^{1/2}$$

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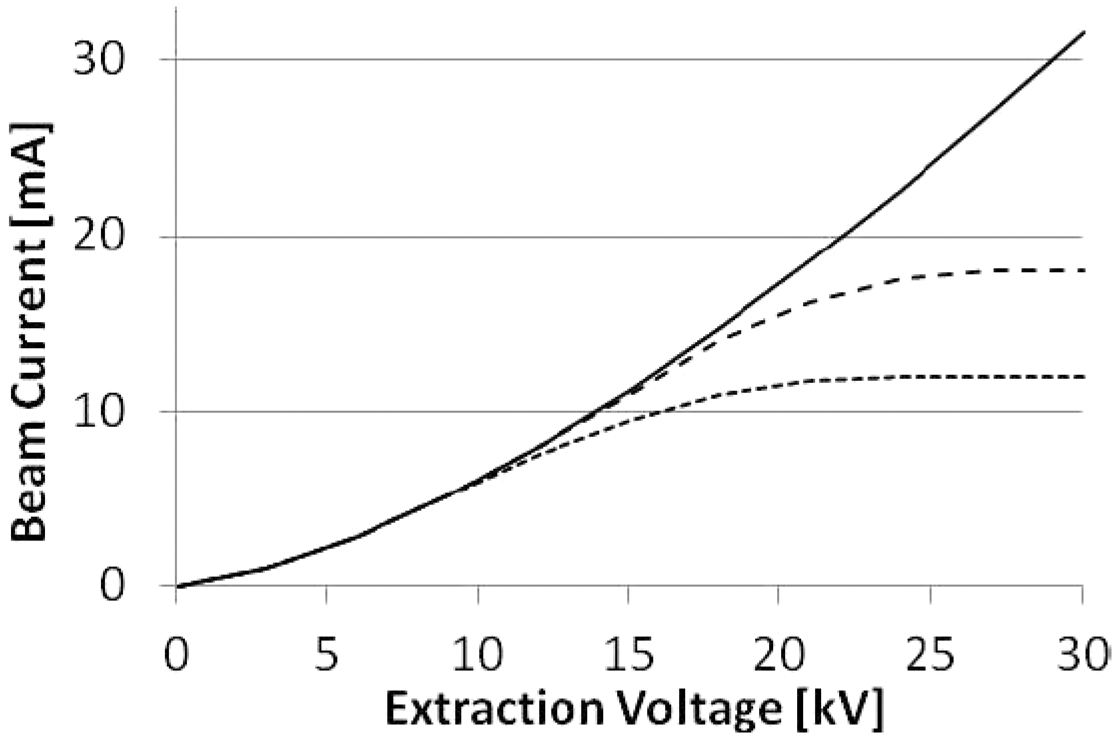
Child-Langmuir vs Plasma Limit

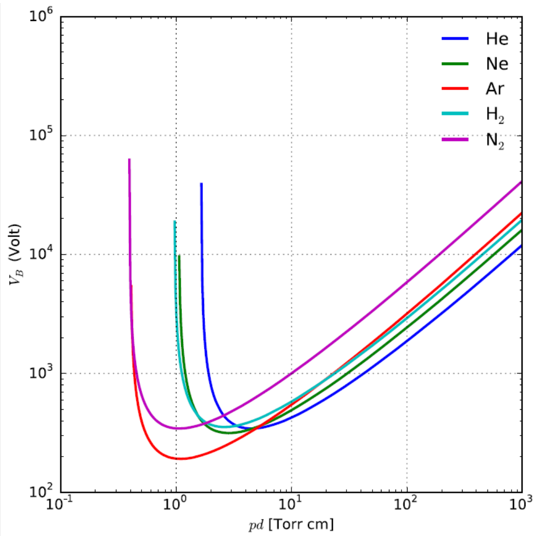


Maximum Voltage (Minimum Distance)

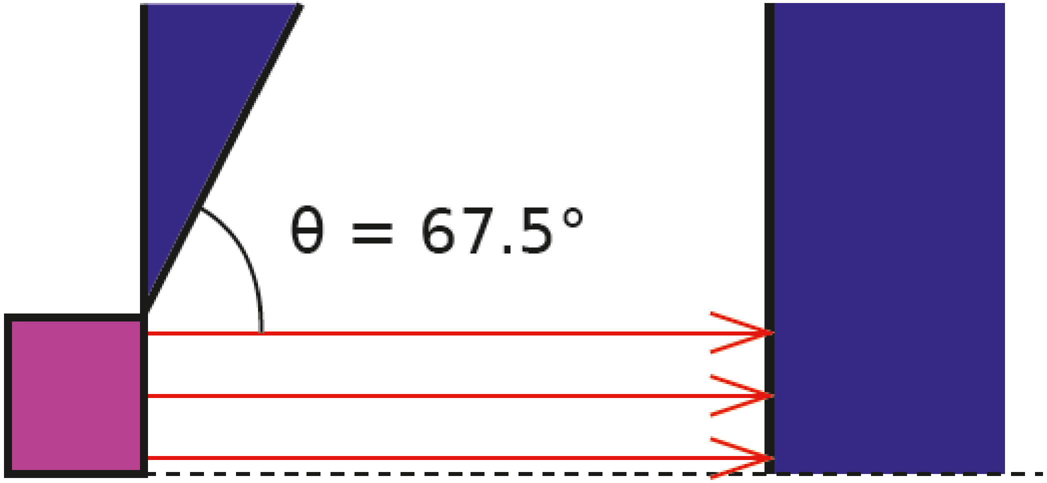
Empirical Formula:

$$d = 0.014 \cdot V^{3/2} \left[\mathrm{mm/kV^{3/2}}\right]$$

Also depends somewhat on pressure (remember Paschen curve)



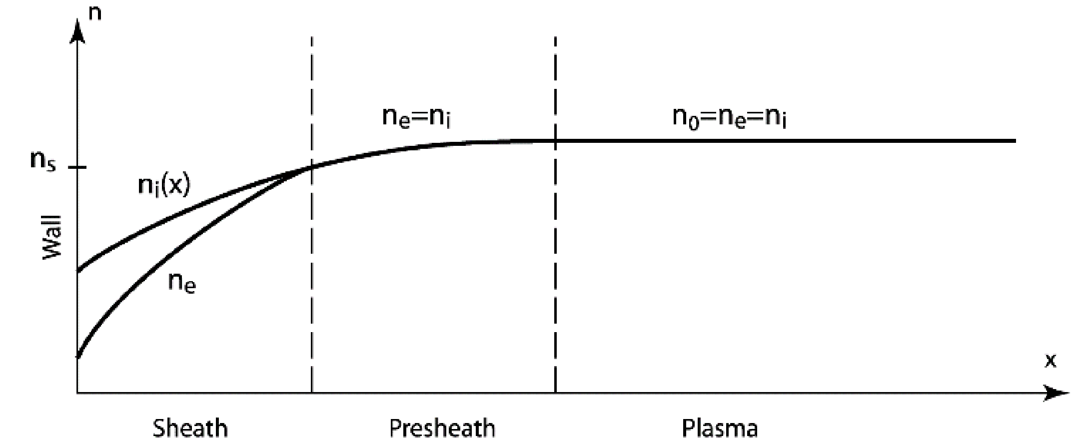
Pierce Angle for Electrons

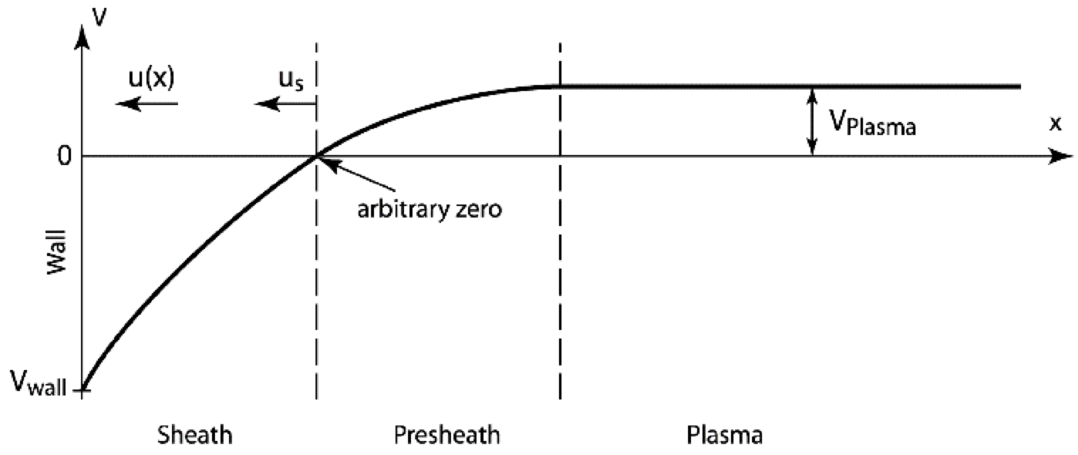


Unfortunately, the same does not generally exist for ions…

Recap from Morning Session: Plasma Sheath

- Positive potential
- Ignore Pre-Sheath (except for Bohm criterion).





Plasma Potential

From a simple sheath model, we can derive the plasma potential

Electron current density = ion current density to the wall (multiple ion species):

$$\Phi_p = \Phi_w + \frac{kT_e}{e}\left[\ln \sum_{j=1}^{k} q_j n_{i,j} - \ln\left(\sum_{j=1}^{k} q_j n_{i,j}\sqrt{2\pi \frac{m_e}{m_{i,j}}\left(1 + \frac{T_{i,j}}{T_e}\right)}\right)\right]$$

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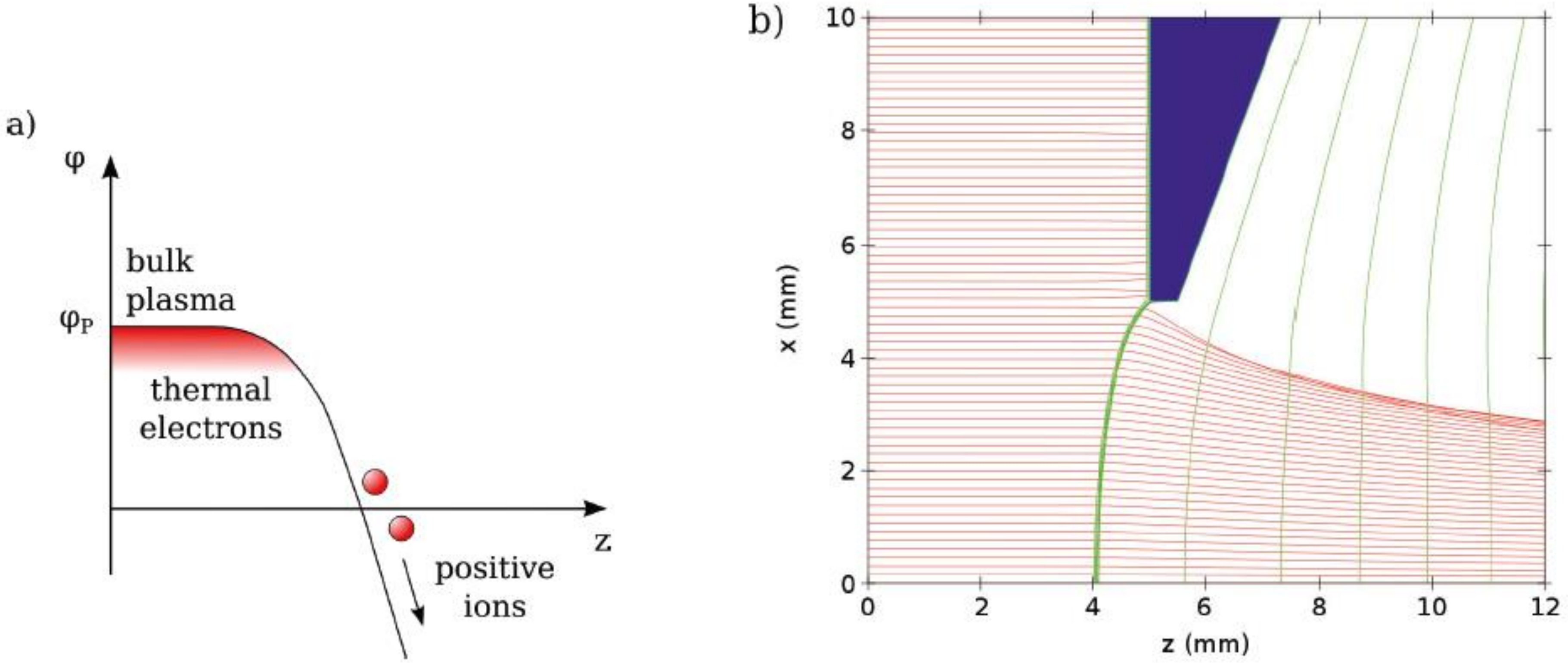
Ion Extraction – The Problem to Solve

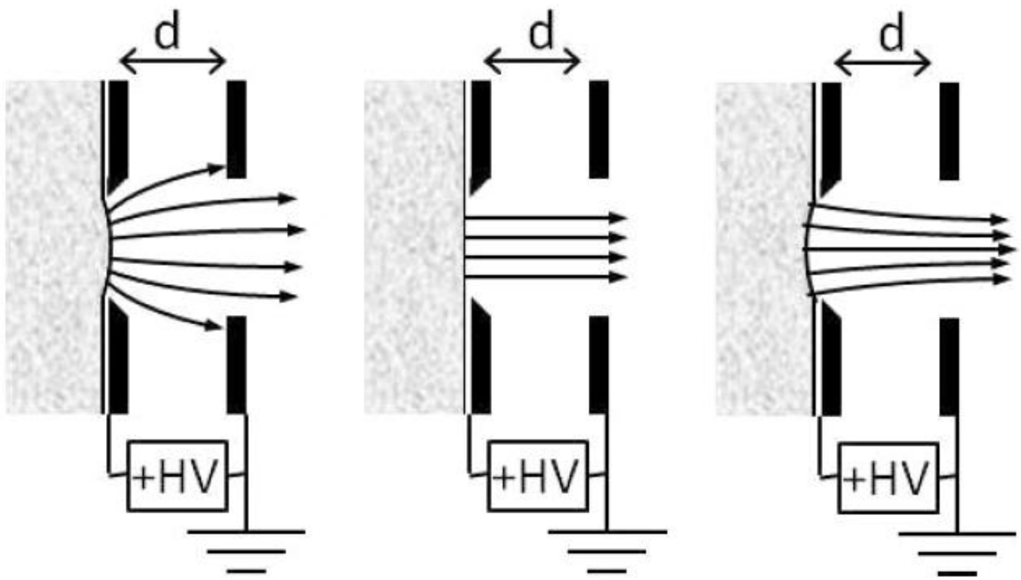
Quasi-Neutral Plasma – Boundary – Non-neutral beam plasma. Plus: Acceleration, Magnetic Fields, …

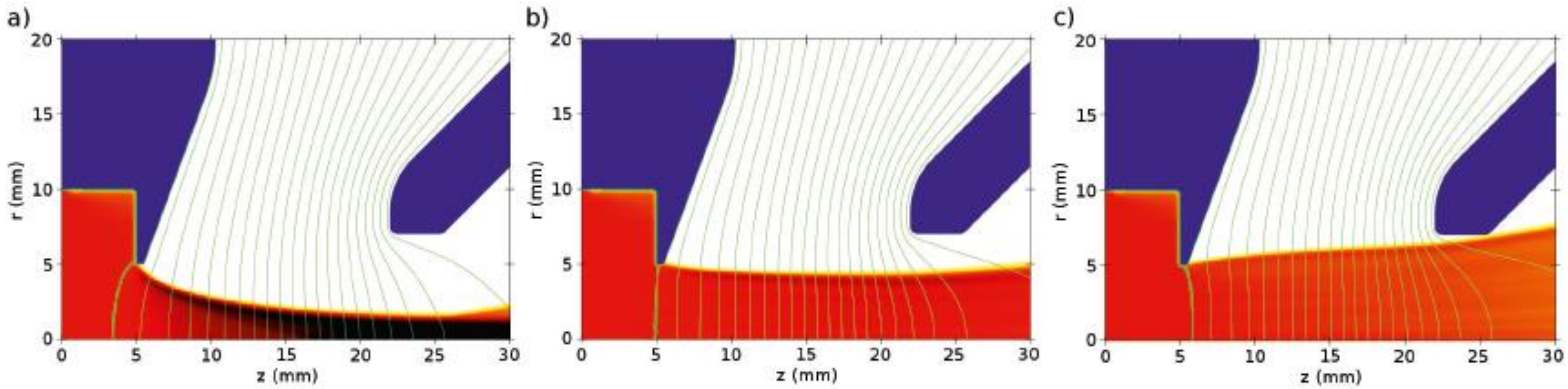
Ultimately: Only possible numerically…raytracing codes, relaxation process.

Positive Ion Extraction

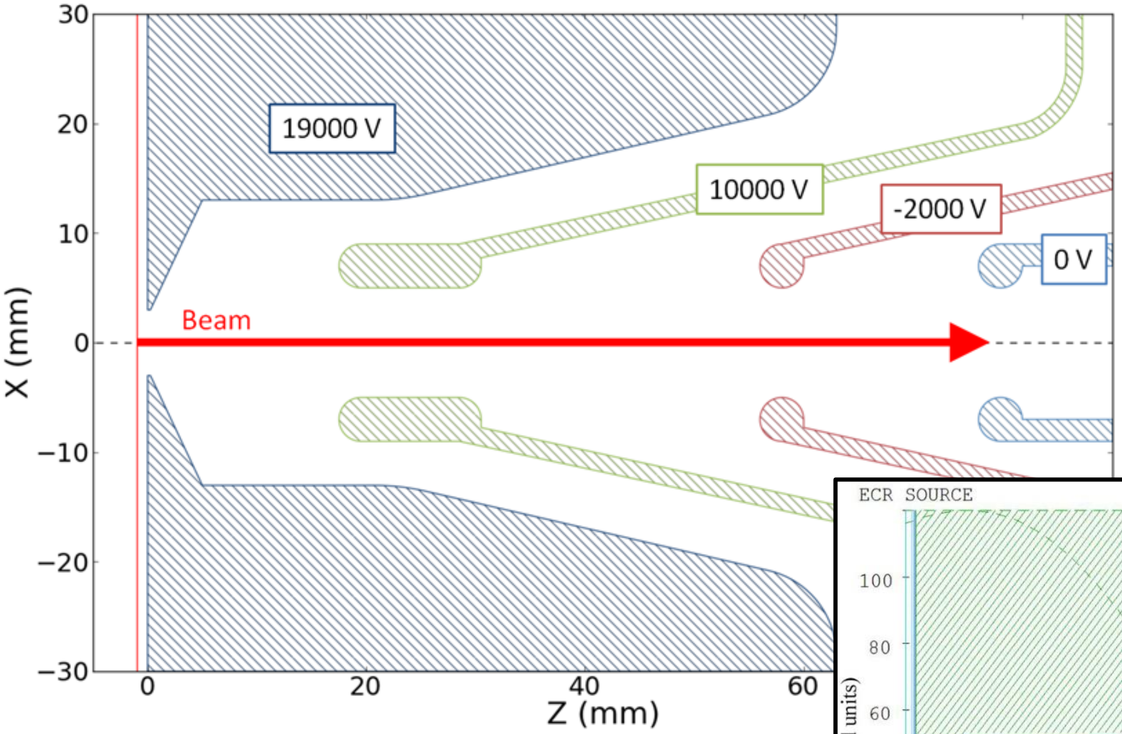


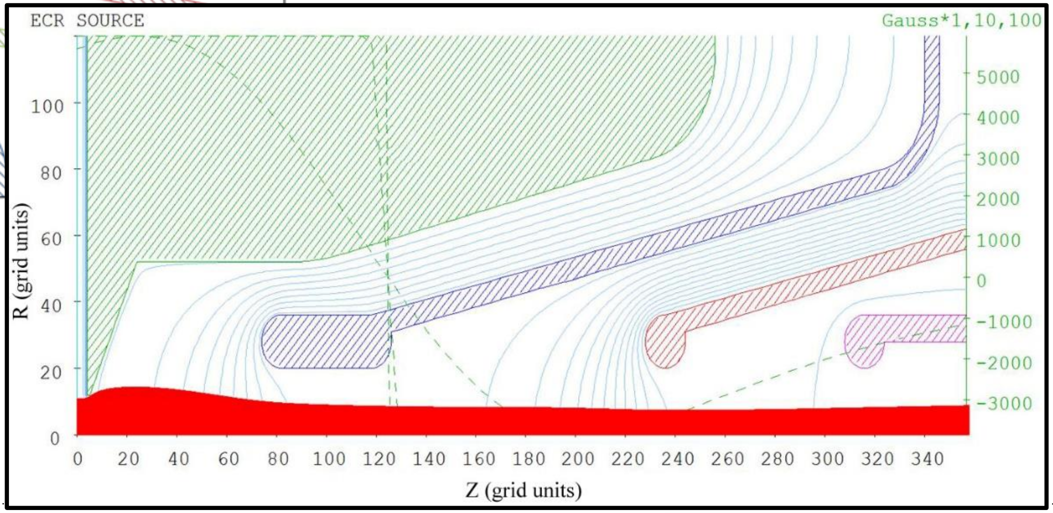
“Plasma Meniscus”





Typical Extraction System





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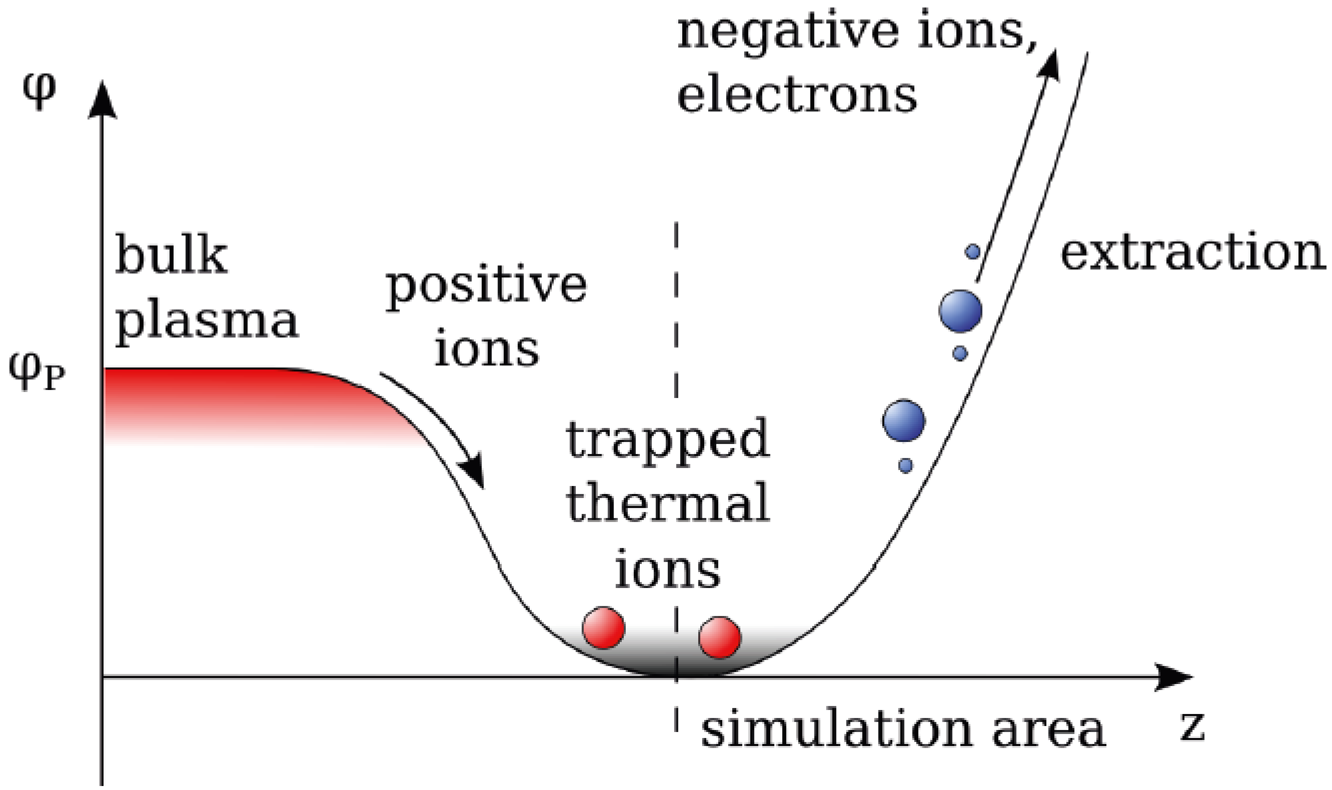
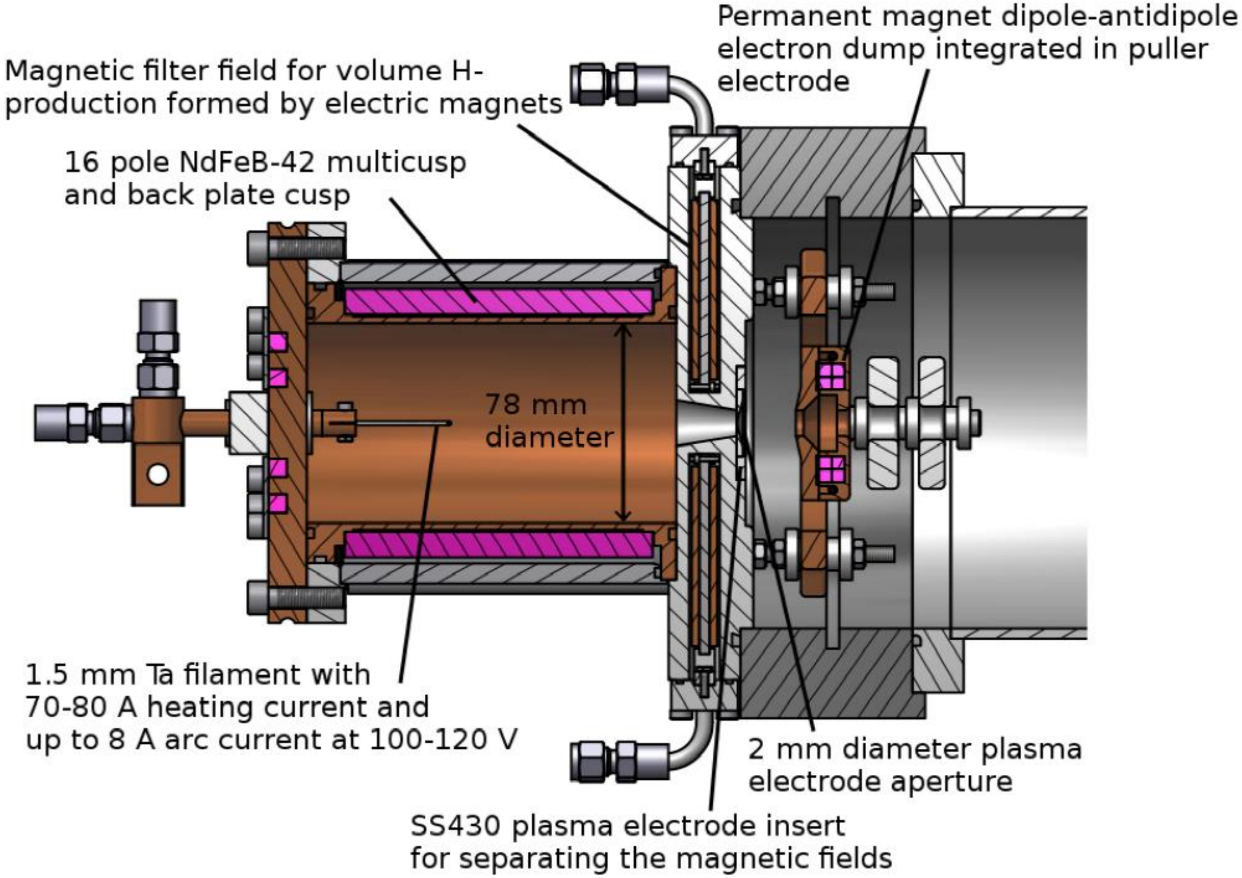
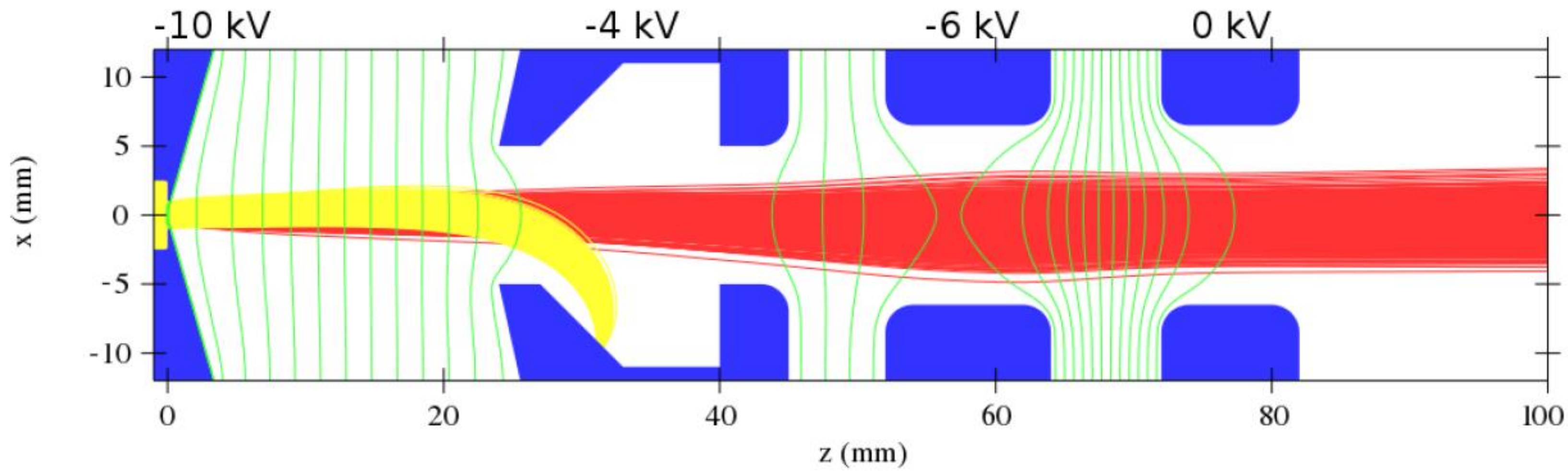
Negative Ion Extraction

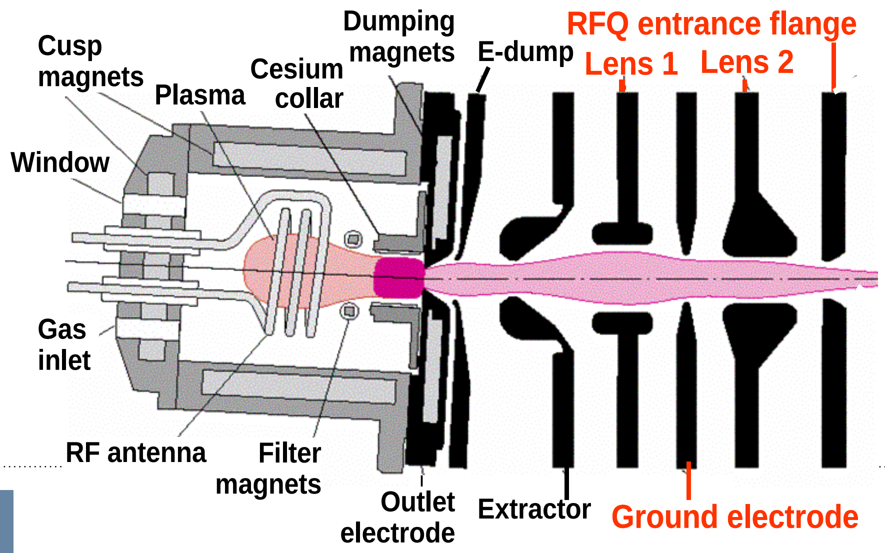


Problem with negative ions: Co-extracted electrons



Problem with negative ions: Co-extracted electrons



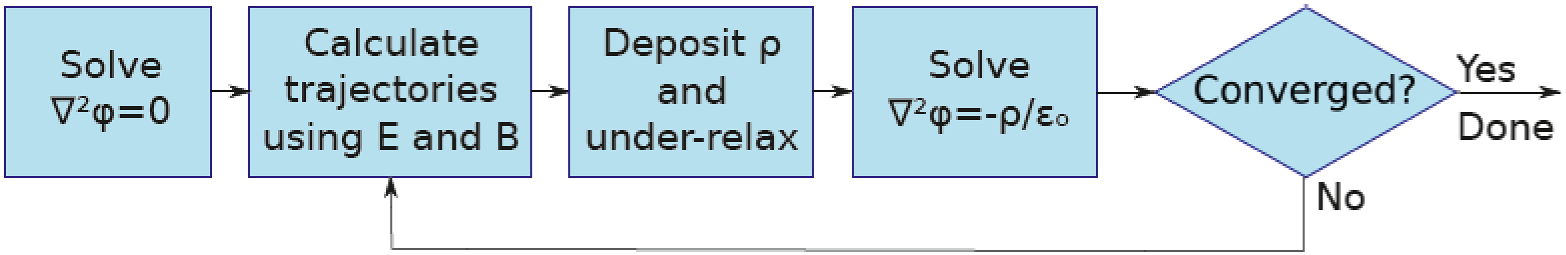


More on H- sources and
Extraction from them tomorrow
In multicusp lecture

RZ vs 3D

- Advantages of RZ:
  - Speed
  - Resolution
  - Well-established codes (IGUN, PBGuns)
- Disadvantage:
  - Throwing away part of the information
  - Can include skew velocity (Necessary for B-fields!)

How is it done in Computer Programs?



- Relaxation Process
- Maxwellian Electrons included in non-linear Poisson solver.

Electric Potential and Field

Finite Difference Method

Poisson Equation: $$\nabla^2\phi = \frac{\mathrm{d}^2\phi}{\mathrm{d}x^2} + \frac{\mathrm{d}^2\phi}{\mathrm{d}y^2} + \frac{\mathrm{d}^2\phi}{\mathrm{d}z^2} = -\frac{\rho}{\epsilon_0}$$

Discretized:

$$\frac{\phi_{i-1,j,k} + \phi_{i+1,j,k} + \phi_{i,j-1,k} + \phi_{i,j+1,k} + \phi_{i,j,k-1} + \phi_{i,j,k+1} - 6\phi_{i,j,k}}{h^2} = -\frac{\rho_{i,j,k}}{\epsilon_0}$$

Boundary Conditions:

Dirichlet $\phi_{i,j,k} = \phi_{\text{const.}}$

Neumann $$\frac{-3\phi_{i,j,k} + 4\phi_{i+1,j,k} - \phi_{i+2,j,k}}{2h} = \left(\frac{\mathrm{d}\phi}{\mathrm{d}x}\right)_{\text{const.}}$$

Software Overview

- IGUN: *R. Becker, W.B.Herrmannsfeldt*.
  http://www.egun-igun.com/
- KOBRA-INP: *P. Spädtke, GSI*
  [INP, Junkerstr. 99, 65205 Wiesbaden, Germany]
- WARP: *D. Grote, LBNL/LLNL*
  http://warp.lbl.gov/
- IBSimu: *T. Kalvas, University of Jyväskylä.*
  http://ibsimu.sourceforge.net/
- Other commercial codes that can do ion extraction or particles dynamics. (SimION, PBGuns, VectorFields SCALA,…)

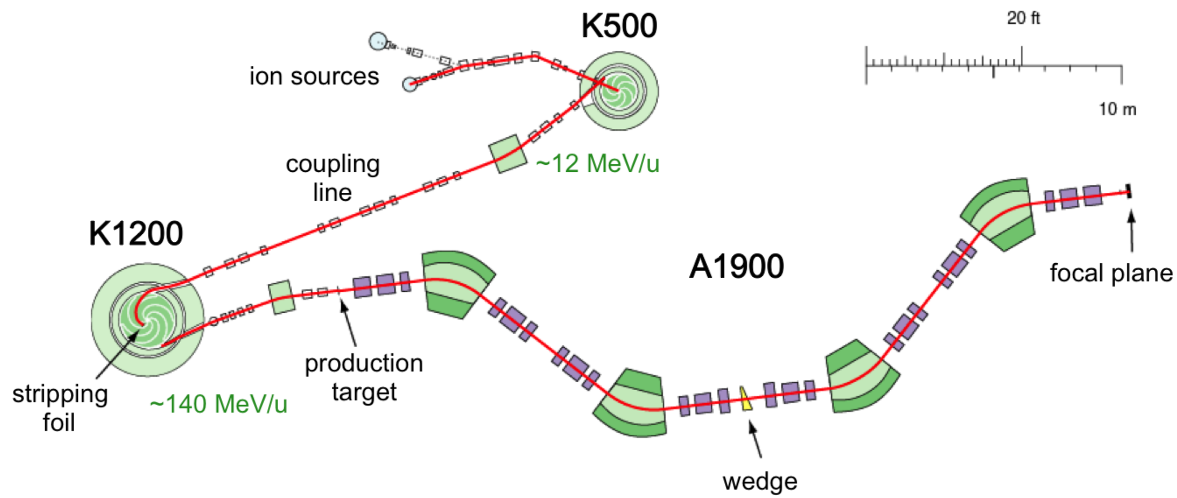
One Simple IGUN Example…

…So you can do the HW later :)

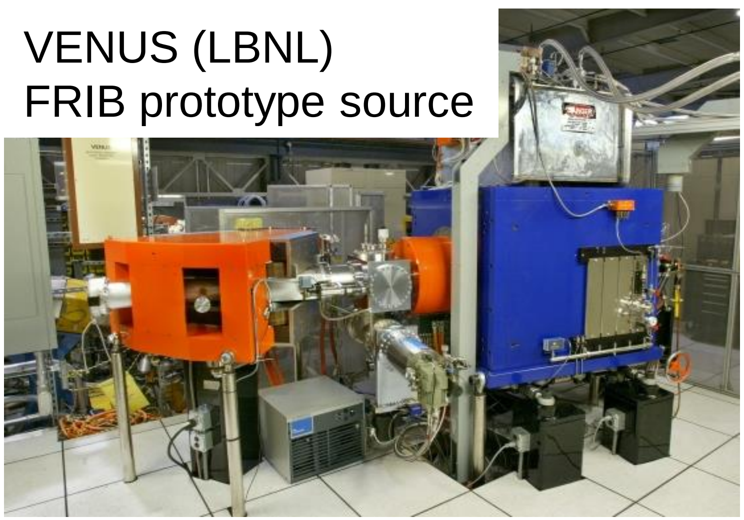
…And a few caveats.

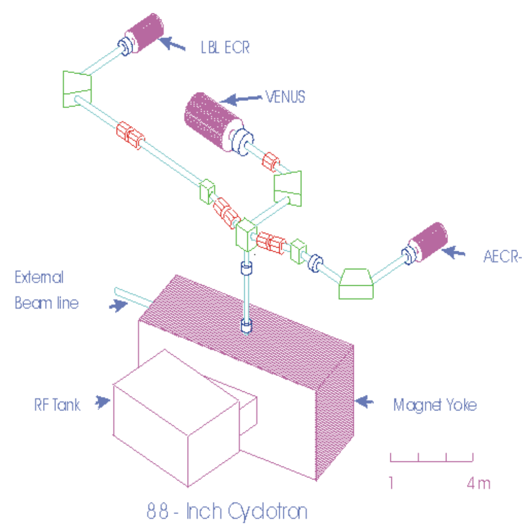
ECRIS as Sources for Heavy Ion Accelerators

SuSI at CCF



VENUS (LBNL)
FRIB prototype source





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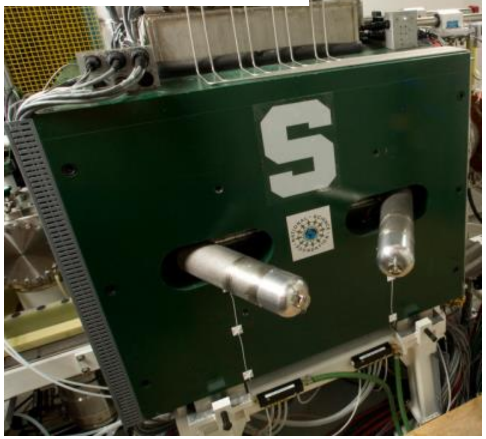

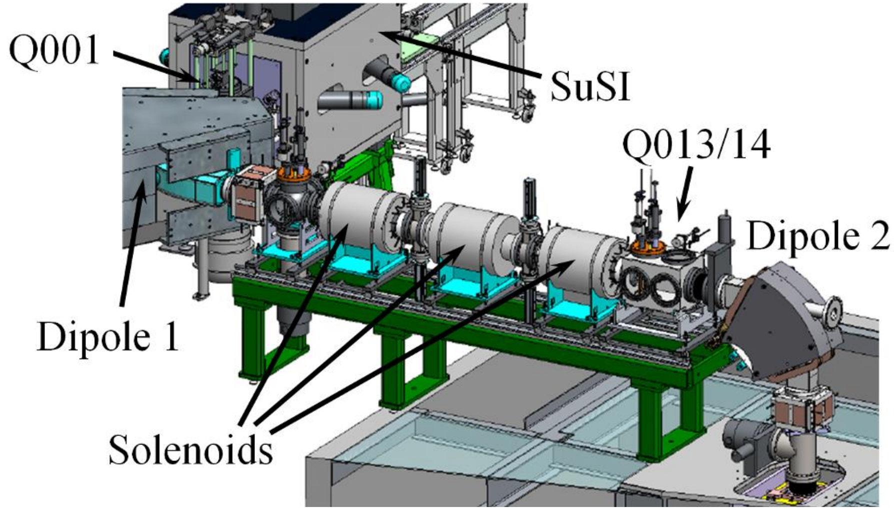

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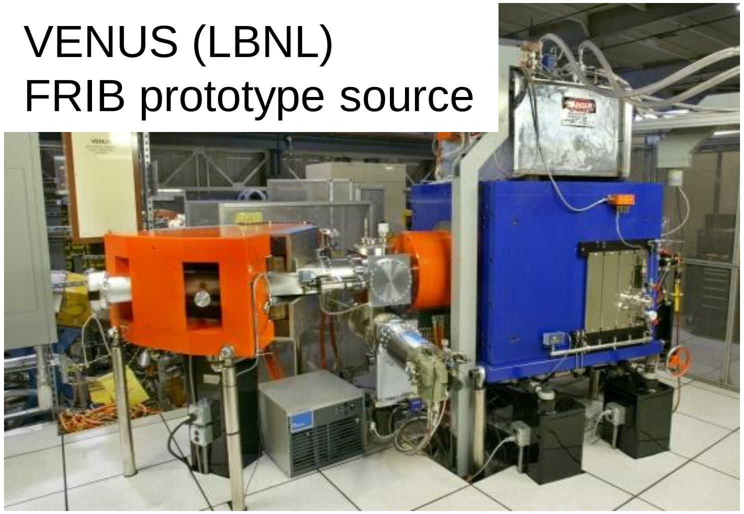
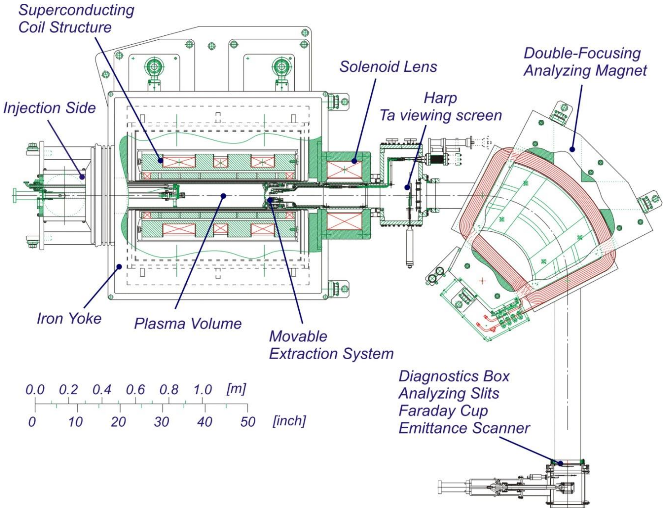
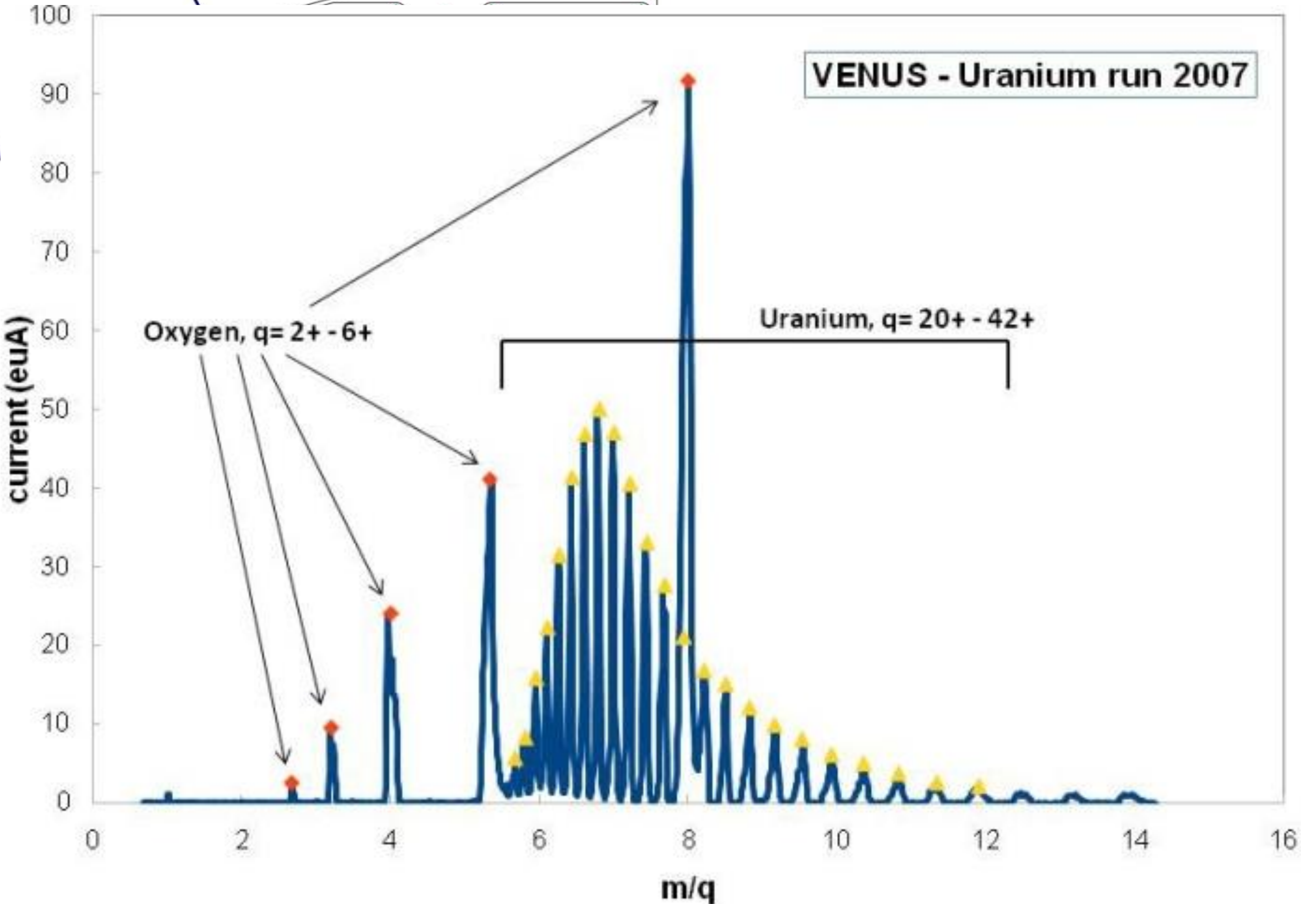




VENUS – Charge State Distribution

Superconducting
Coil Structure



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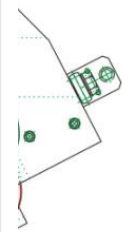
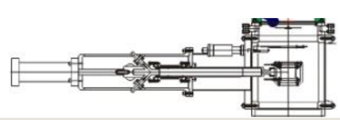


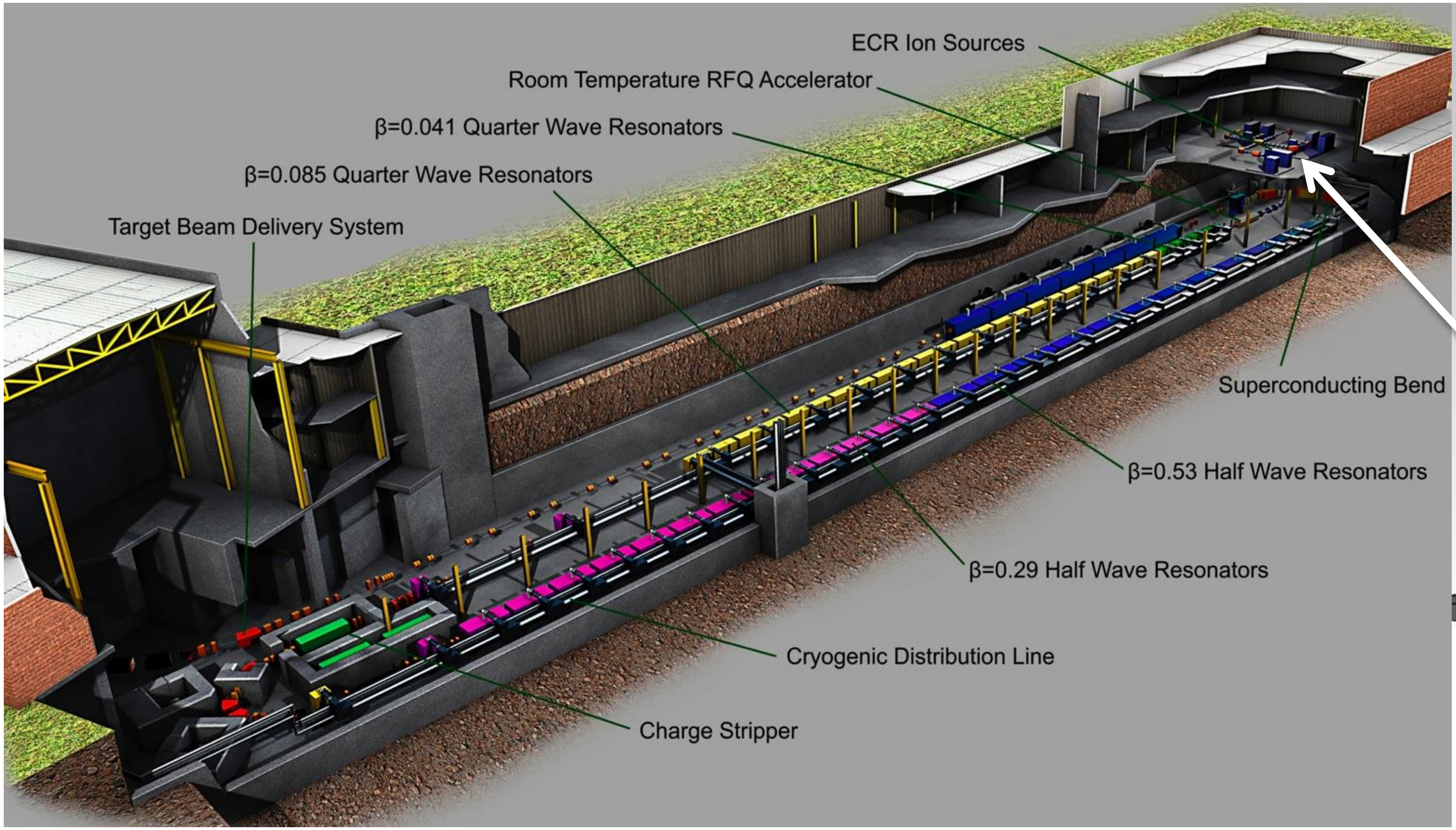
$$B\rho = \frac{p}{q}$$

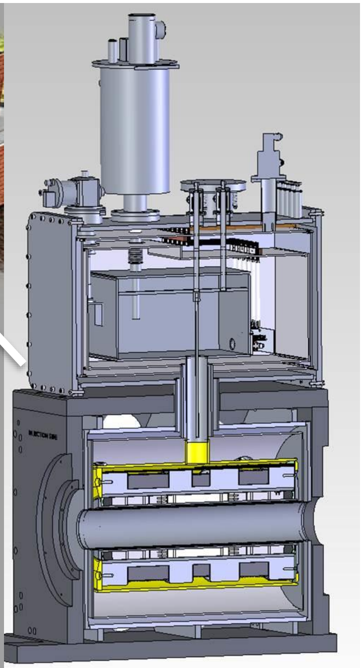
$$B\rho = \sqrt{\frac{m}{q}} \cdot \sqrt{\frac{2\Phi}{e}}$$



Facility for Rare Isotope Beams (FRIB)

Calls for a total of 480 eμA of Uranium 28+/29+ (2 charge states)



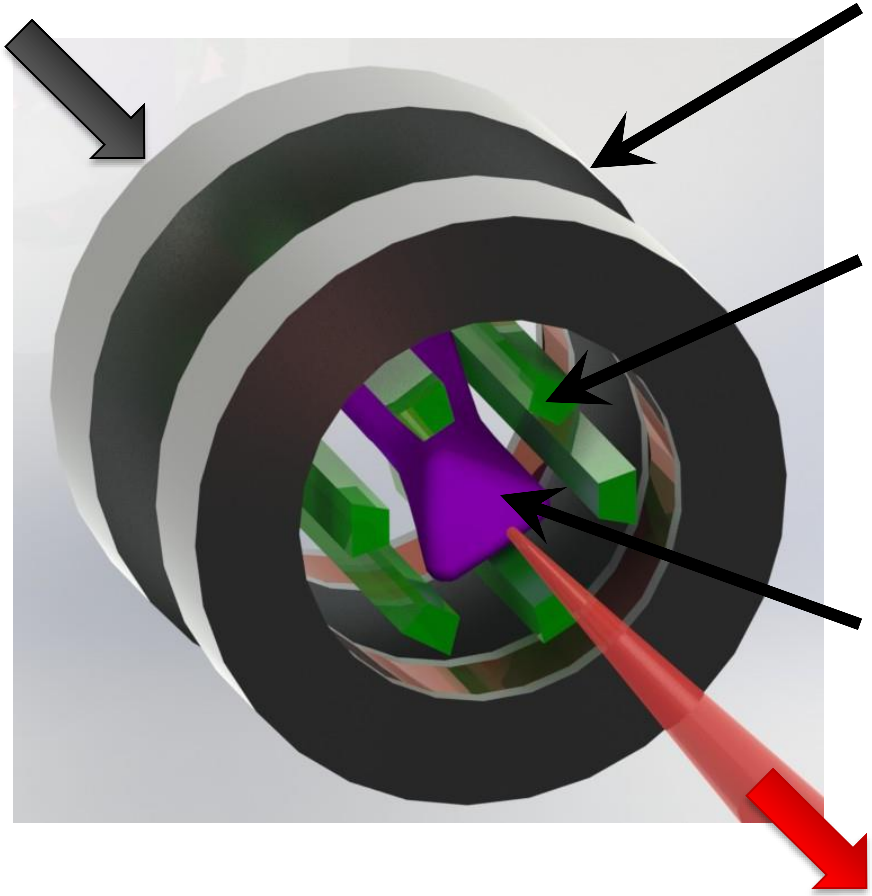


28 GHz ECRIS
(VENUS like)
Under design

U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

Courtesy of D.Leitner

Intermezzo: ECRIS – Principle



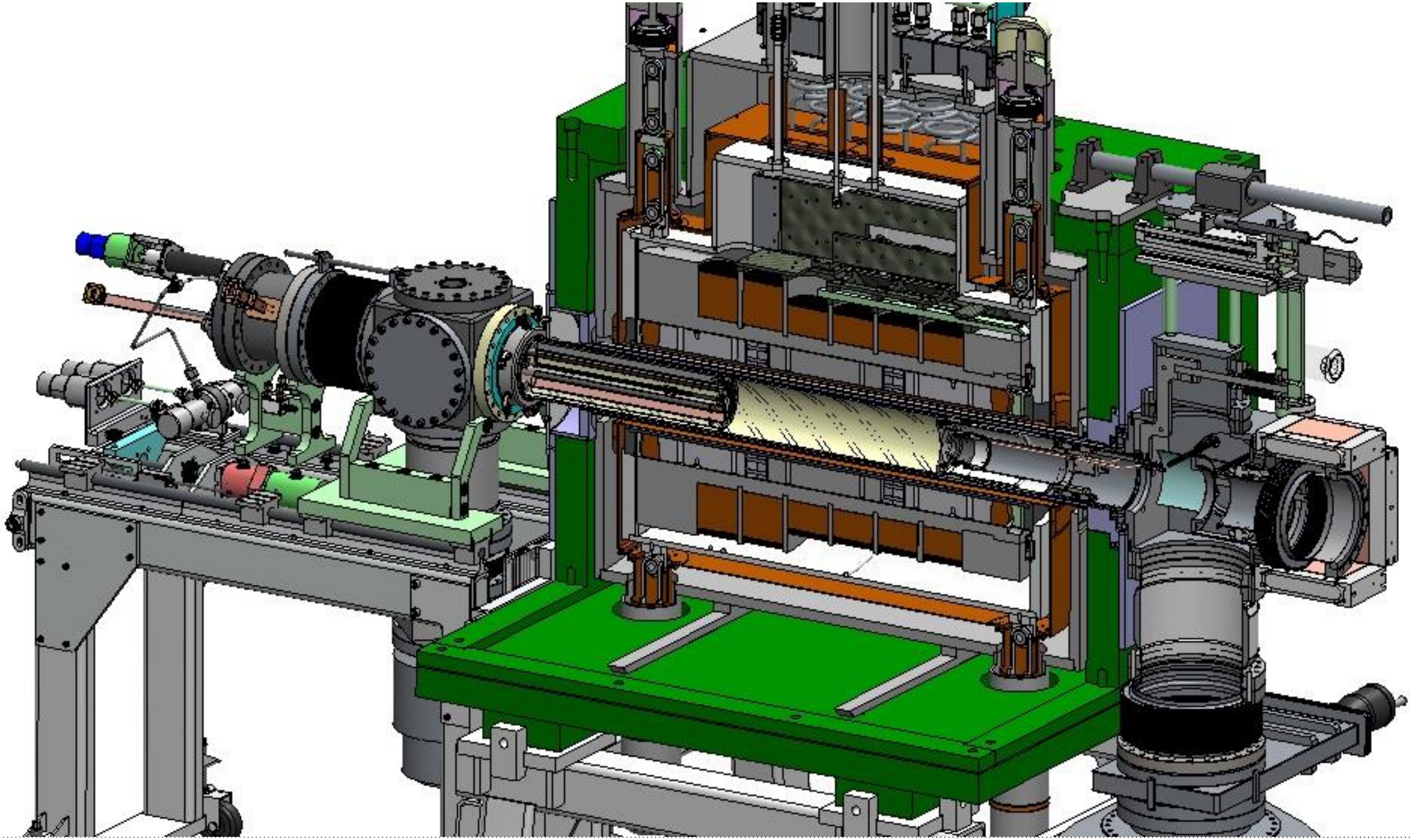
ECR – Condition:

$$\omega_{ecr} = \frac{e \cdot B}{m_e}$$

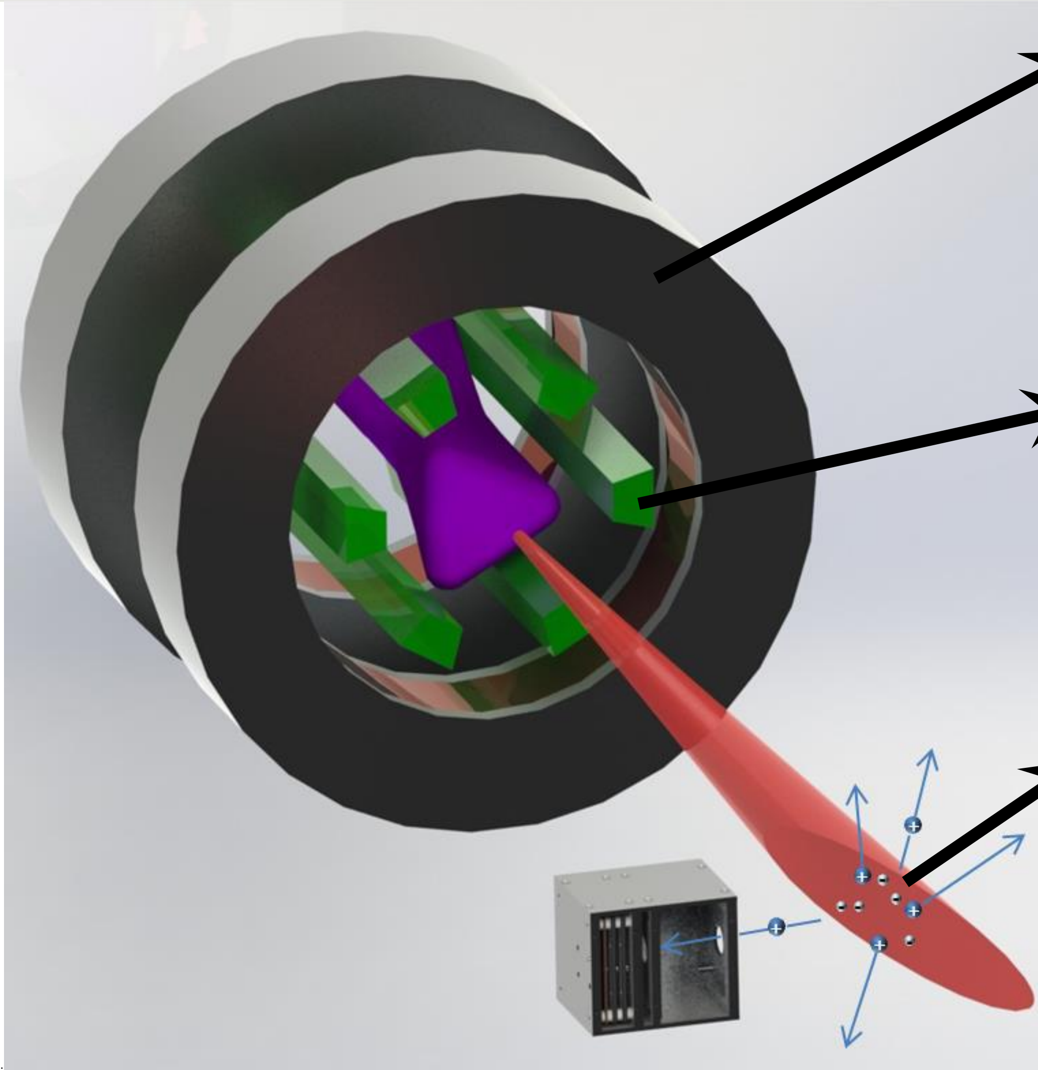
Typical parameters (VENUS):

- Microwaves: 28 GHz
- B_{ecr}: 1 T
- B_{max}: 2.2 T (extraction)
- T_e: ~eV to MeV in resonance zone

SI – Cross-Sectional View



ECRIS Simulations – What is so special?

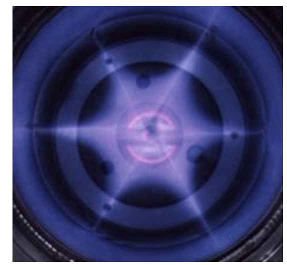


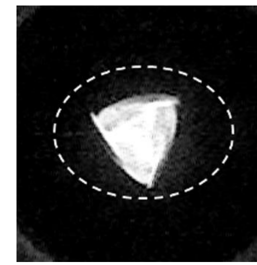
- Solenoids → Emittance Growth

$$\epsilon^{th}_{n-rms} = 0.016 \cdot r\sqrt{\frac{k_B T_i}{A}}$$

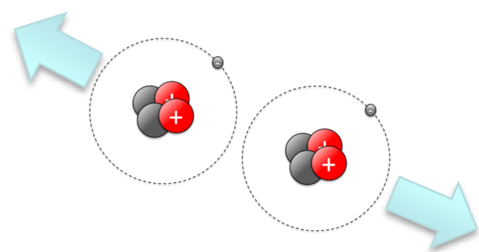
$$\epsilon^{mag}_{n-rms} = 0.032 \cdot r^2 B_0 \frac{1}{A/q}$$

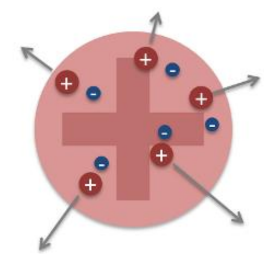
- Sextupole → Triangular beam





- Space Charge (Compensation)

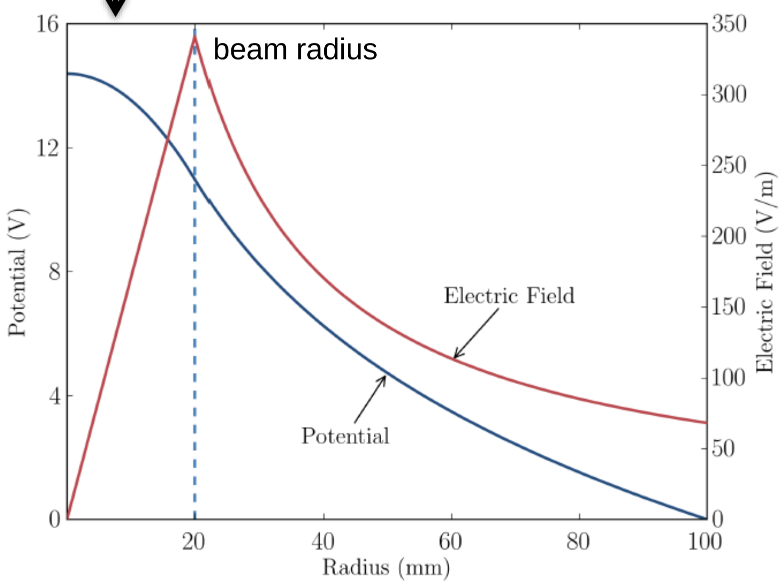


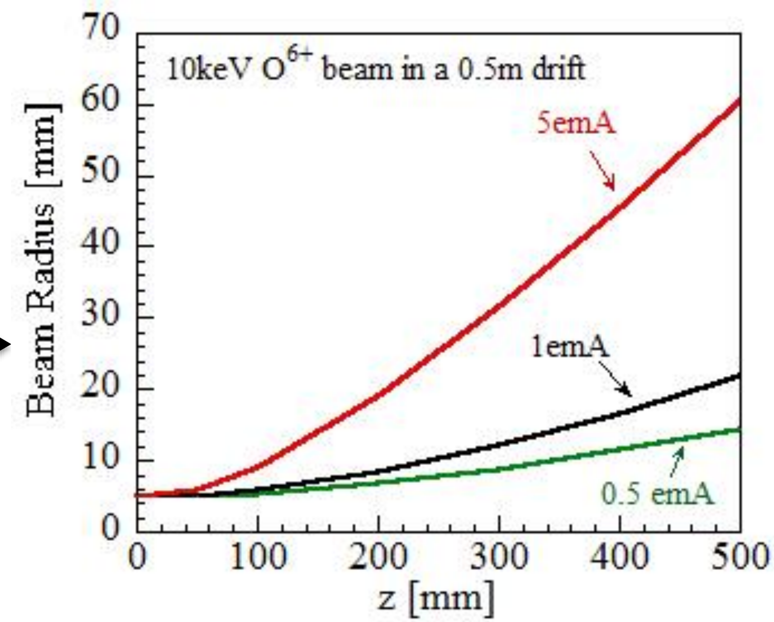


Space Charge

- Space charge potential of a uniform and round beam with beam radius r_b in a grounded beam pipe r_p:

$$\phi(r) = \begin{cases} \Delta\phi \left(1 + 2\ln\frac{r_p}{r_b} - \frac{r^2}{r_b^2}\right) & \text{for } r \le r_b \\ \Delta\phi \; 2\ln\frac{r_p}{r} & \text{for } r_b \le r \le r_p \end{cases} \qquad \Delta\phi = \frac{I}{4\pi\epsilon_0 v_b}$$





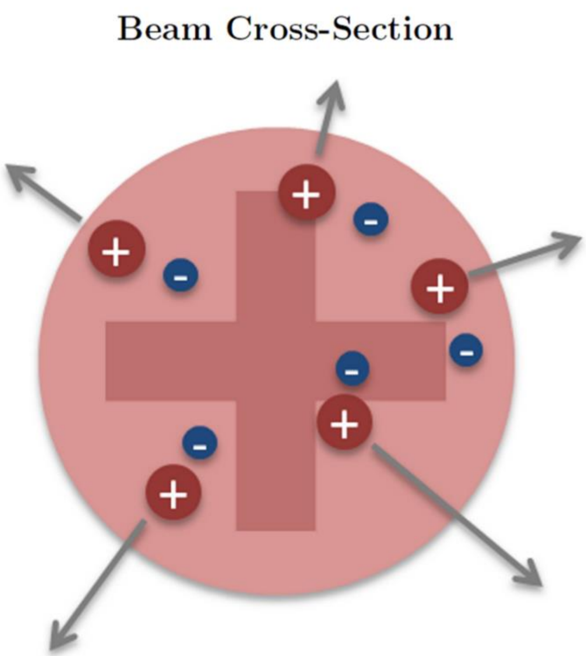
- Acts defocusing on the beam → need to counteract with beam optics elements

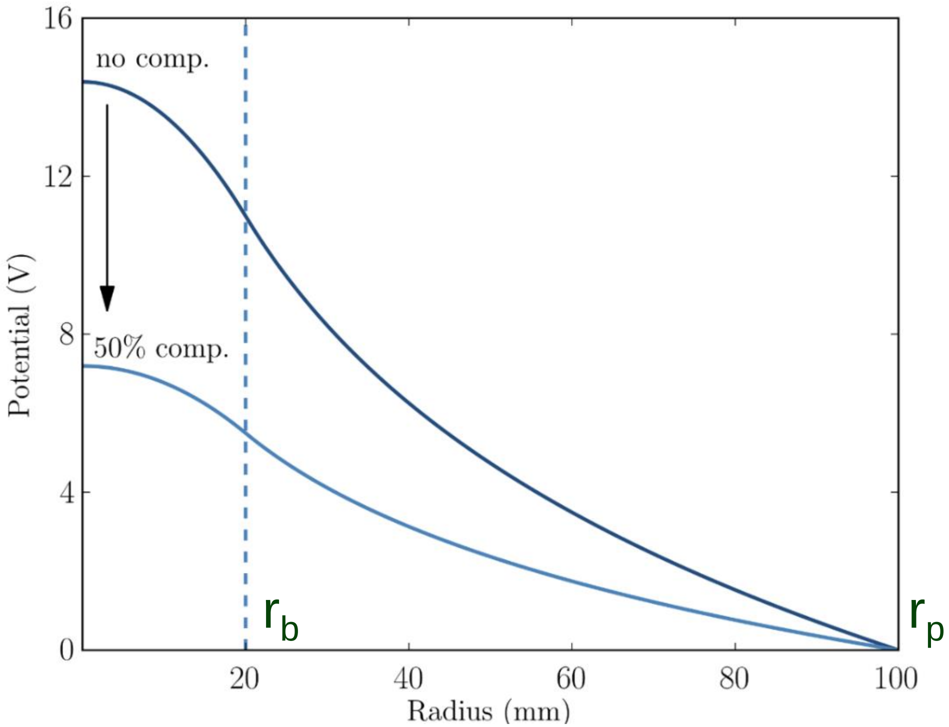
Space Charge Compensation (Neutralization)

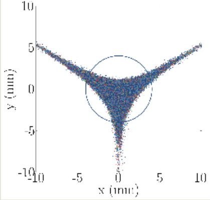
- Beam interacts with residual gas

$$\sigma_e = \sigma_{ionization}$$
$$\sigma_i = \sigma_{charge-exchange} + \sigma_{ionization}$$

$$\Delta\phi = \frac{I \cdot (1 - f_e)}{4\pi\epsilon_0 v_b}$$

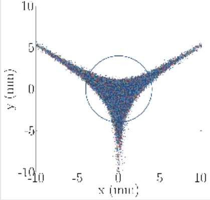






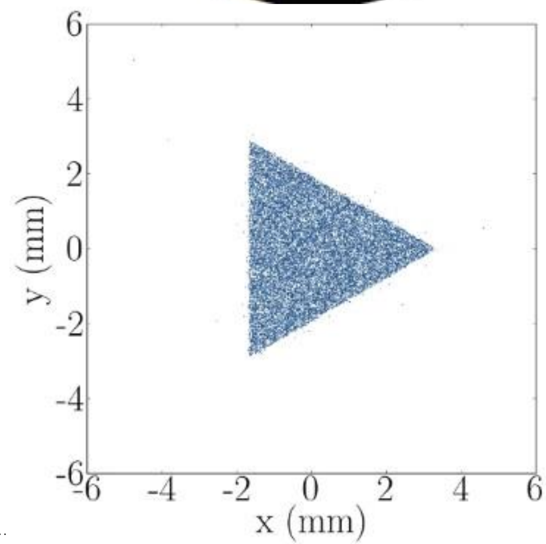
WARP - Introduction

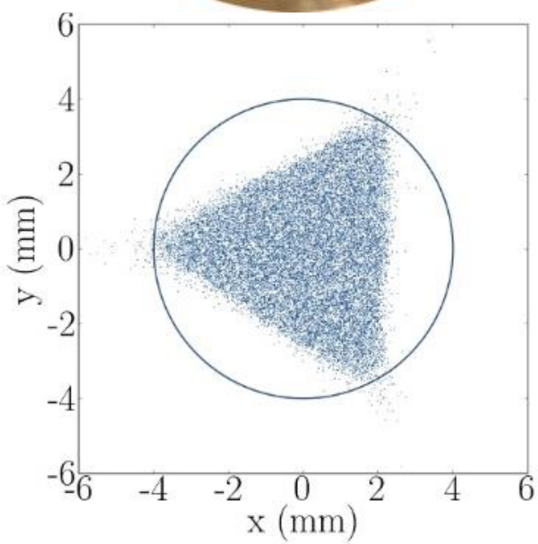
- Particle In Cell code (PIC) – Fortran code with Python interface
- Fieldsolver and particle pusher separated, both have:
  - 3D mode
  - 2D modes: RZ, XY slice
- Fields (lattice elements) can be loaded in the following ways:
  - Hard-edged multipole elements
  - Axially varying multipole elements
  - Gridded elements (3D field maps)
  - Electrostatic elements can be solved with SOR Poisson solver from electrode geometry and voltages
- Space charge calculated self-consistently on a mesh
- WARP comes with a 2D and 3D plasma extraction model

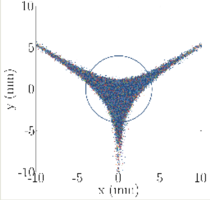


Simulations - Initial Conditions

- Semi-empirical by using plasma markings inside the source as template for particle distribution.
- Generate 3D field map with Lorentz-em or Opera3D
- Import into WARP
- Assume: no collisions during final pass of particles.
- Track particles from injection side to extraction aperture (XY mode, small step size).
- Save particle distributions for next step.

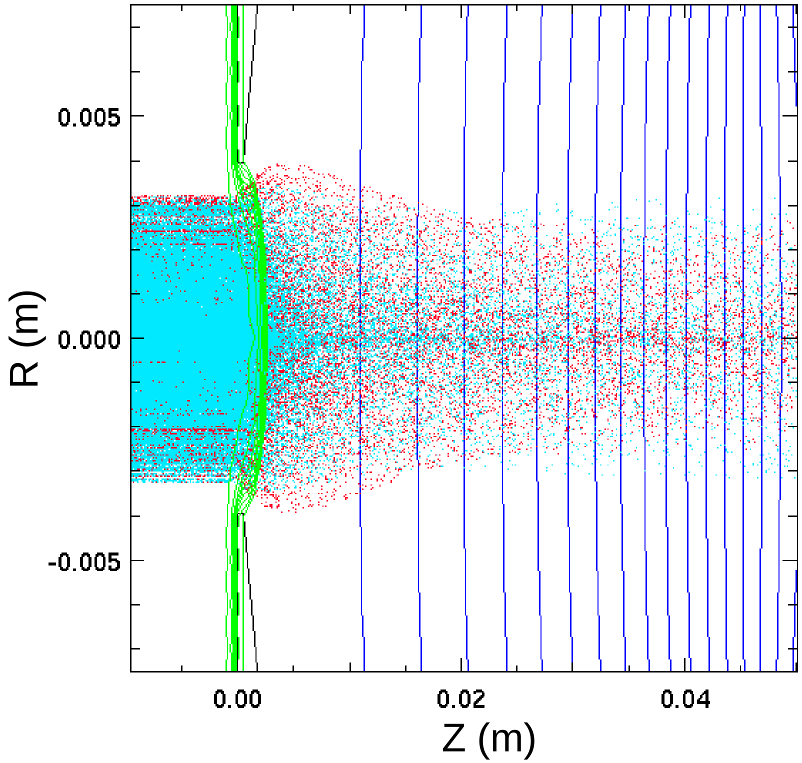






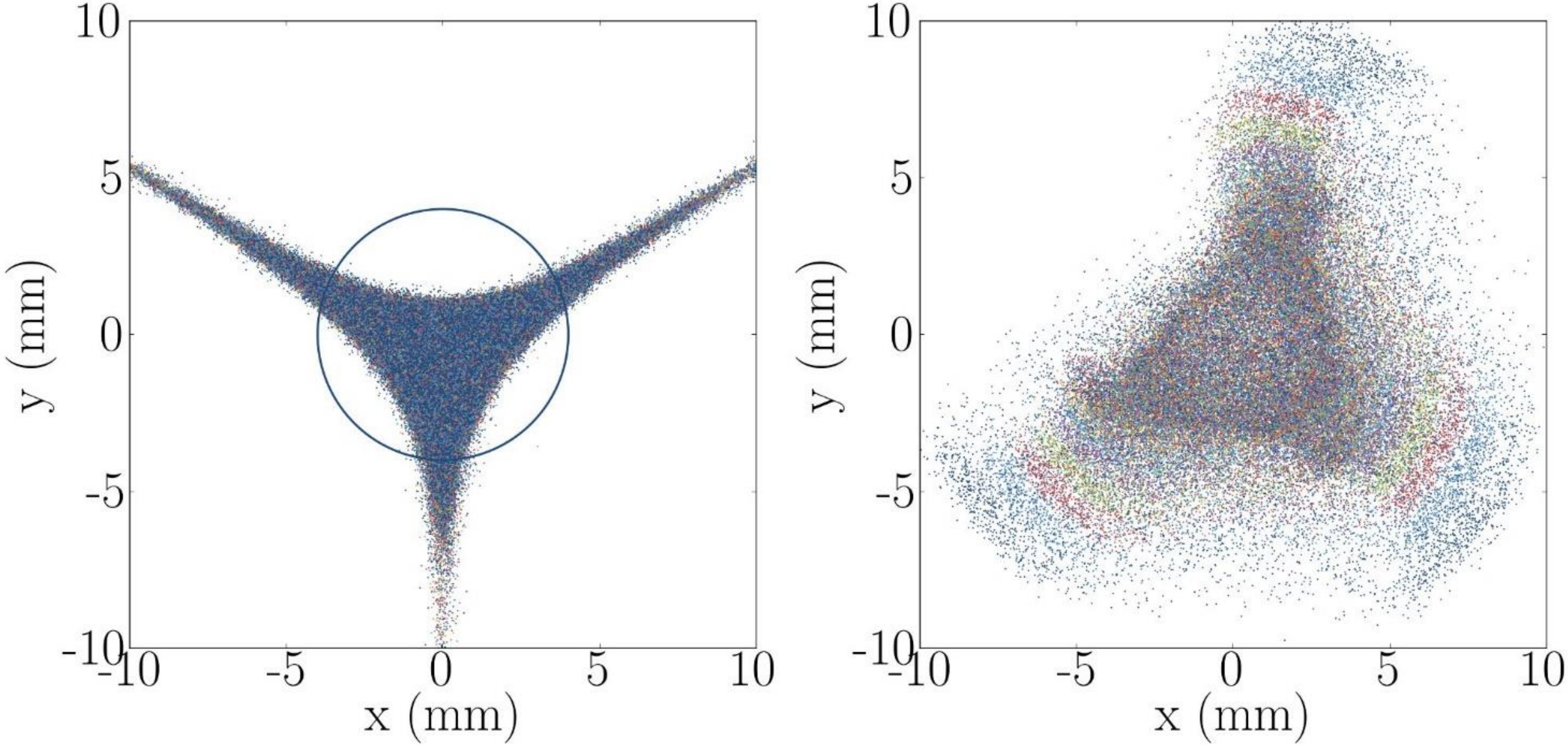
2D+ Extraction Model

- WARP has 2D and 3D plasma extraction model - Relaxation Process:
  - Start ions from plasma potential (V_{source} + ~20 V)
  - Track through applied fields (phi)
  - Save particle charge density on mesh (rho)
  - Solve Poisson equation (rho + phi)
  - Add electrons with Boltzmann distribution
  - Repeat with solution as applied fields
- 3D simulations: Need high resolution, take very long, instead:
- 2D+ method (D. Todd):
  - Do relaxation process in RZ mode using same currents, species, etc.
  - Save field solution and use as applied field in final 3D run with triangle distribution



D.S. Todd *et al.*, *Simulation and beam line experiments for the superconducting electron cyclotron resonance ion source VENUS*, AIP, p. 02A316, 2008

Extracted Ar^{8+}



Quick Note about Homeworks

- Homeworks are due the next morning, solutions will be available when you hand in the homework.
- Simulation Homeworks (except 6a today) will be graded "on-the-fly" by us.
- At least one of us will be present in either the classroom or the computer room from 4:00 PM to 6:00 PM and after dinner until ~10:00 PM.
- I would like to get feedback on the homeworks. When you hand them in, please fill out the (anonymous) list with difficulty and time spent.
- Difficulty in mJackson :) → Analysis on Friday.