

Injector Simulations

Daniel Winklehner

Simulation of Beam and Plasma Systems
D. Bruhwiler, R. Lehe, S. Lund, J.-L. Vay, D. Winklehner
 USPAS, Old Dominion U., Hampton, VA, Jan 2018




The opulent buffet of ion sources

<ul style="list-style-type: none"> • Bayard-Alpert type ion source • Electron Bombardment ion source • Hollow Cathode ion source • Reflex Discharge Multicusp source • Cold- & Hot-Cathode PIG • Electron Cyclotron Resonance ion source (ECR) • Electron Beam Ion Source (EBIS) • Surface Contact ion source • Cryogenic Anode ion source • Metal Vapor Vacuum Arc ion source (MEVVA) • Sputtering-type negative ion source • Plasma Surface Conversion negative ion source • Electron Heated Vaporization ion source • Hollow Cathode von Ardenne ion source • Forrester Porus Plate ion source • Multipole Confinement ion source • EHD-driven Liquid ion source • Surface Ionization ion source • Charge Exchange ion source • Inverse Magnetron ion source 	<ul style="list-style-type: none"> • Microwave ion source • XUV-driven ion source • Arc Plasma ion source • Capillary Arc ion source • Von Ardenne ion source • Capillaritron ion source • Canal Ray ion source • Pulsed Spark ion source • Field Emission ion source • Atomic Beam ion source • Field Ionization ion source • Arc Discharge ion source • Multifilament ion source • RF plasma ion source • Freeman ion source • Liquid Metal ion source • Beam Plasma ion source • Magnetron ion source • Resonance laser ion source 	<ul style="list-style-type: none"> • Nier ion source • Bernas ion source • Nielsen ion source • Wilson ion source • Recoil ion source • Zinn ion source • Plasmatron • Duoplasmatron • Duopigatron • Laser ion source • Penning ion source • Monocusp ion source • Bucket ion source • Metal ion source • Multicusp ion source • Kaufman ion source • Flashover ion source • Calutron ion source • CHORDIS • FEBIAD ion source
---	--	--

Daniel Winklehner, MIT
USPAS, Jan 2018, Hampton, VA
2

Come to USPAS @ MSU, E. Lansing, MI

- One week course on Ion Sources
- At MSU in East Lansing, MI
- June 11 - 15, 2018
- Taught by:
 - Guillaume Machicoane (MSU)
 - Alain Lapierre (MSU)
 - Daniel Winklehner (MIT)
- With help from:
 - Damon Todd (UC Berkeley)
 - Daniela Leitner (LBNL)



Daniel Winklehner, MIT
USPAS, Jan 2018, Hampton, VA
3

Acknowledgements

Slide credits go to:

- Taneli Kalvas
- Martin Stockli
- Daniela Leitner
- Damon Todd

Thank you!



Daniel Winklehner, MIT
USPAS, Jan 2018, Hampton, VA
4

Outline

- Morning:
 - Overview of ion sources
 - How extraction can be simulated in select cases
 - Sorted from "Easy" to "Hard" (very subjectively)
- Afternoon Lab I:
 - IBSimu crash course
 - Simulations of plasma ion sources using IBSimu
 - "Simple" plasma extraction + Adding B-field + Negative ions
- Afternoon Lab II:
 - Select challenges with low energy beam transport (LEBT)
 - Multiple species + space charge compensation
 - Warp simulations

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 5

Overview I (FRIB)

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 6

So simple...or not?

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

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 7

Overview II

- In Ion Source/LEBT $v \ll c$ and J is large
- Space charge plays a major role
- Beam generated B-field is negligible.
- Several ion species
- Beam line elements often not well separated (no drift spaces in between).
- Complex electrostatic electrode shapes used.
- Nonlinear effects are significant!
- *Traditional N^{th} order transfer matrix optics cannot be used (well) close to ion sources. More fundamental methods are needed. PIC!*

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 8

Easy: Define Beam from Parameters

- Either injected or emitted
- Beam distribution can be
 - Uniform,
 - Flattop,
 - Gaussian,
 - Maxwellian
 - Mix (Transverse – Longitudinal)
- Described by
 - Sigma matrix
 - Twiss parameters (rms)
 - Envelope parameters
- Often from measurement or well known injectors

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 9

Medium: Ion source has fixed emitter

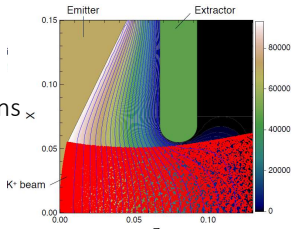
- The beam is emitted from a solid surface that is predefined
- Transverse and time patterns can vary
 - E.g. determined by the laser shape, intensity in case of photoinjector
- Examples:
 - Hot plate source (see Jean-Luc's warp example)
 - Photoinjector
 - (Some) Electron Guns
- Some sort of extraction system (guidance, shaping) necessary.

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 10

Medium cont'd

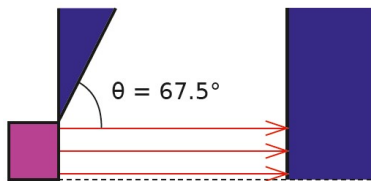
- Parameters:
 - Time structure
 - Transverse shape (often uniform or Gaussian)
 - Temperature
- Space Charge limited

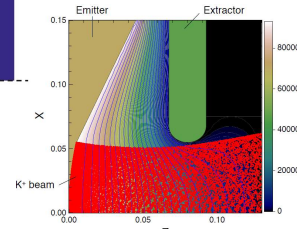
$$I = 1.67 \cdot 10^{-3} A \left(\frac{Q}{mc^2} \right)^{1/2} \frac{V_0^{3/2}}{d^2}$$
- Used for both electrons and ions ×
- Typically singly charged



Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 11

Medium cont'd

- Electrons: Pierce Angle
 
- Typically not so for ions ×



Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 12

Getting to the Harder Ones: Photoinjector

Master Oscillator
RF Drive
Mode-Locked Laser
Half Cell
Photocathode
One or more Full Cells
e⁻

8-96 8204A1

Daniel Winklehner, MIT
USPAS, Jan 2018, Hampton, VA
13

Hard: Emitter is plasma!

Cavity
Transition Waveguide
Plasma Chamber
Plasma Electrode
RF Window
Permanent Magnet Ring
Iron

Container for plasma
Energy in to ionize gas
Gas in
Plasma
Extraction electrodes
Beam out
Electron filter

Flat-Field ECR
Multicusp
ECRIS

Daniel Winklehner, MIT
USPAS, Jan 2018, Hampton, VA
14

Example 1: Filament-Driven Multicusp

Extraction System
SmCo Magnets
He Gas
Gas Inlet
Filament Feedthroughs
E-Beam

Faraday Cup

- MIST-1 @ MIT
- Designed for H₂⁺

Daniel Winklehner, MIT
USPAS, Jan 2018, Hampton, VA
15

A bit of plasma physics

- Plasma is quasi-neutral $n_e = \sum_{j=1}^Z q_j n_q$
- Degree of ionization $\eta_i = \frac{\sum_{j=1}^Z q_j n_q}{n_{atoms} + \sum_{j=1}^Z q_j n_q}$

Ionization Potential (eV)
Atomic Number, Z

Daniel Winklehner, MIT
USPAS, Jan 2018, Hampton, VA
16

A bit of plasma physics

$E = \frac{n_e e \delta x_i}{\epsilon_0}$ Field created between the two charge separated regions
 $W_{pot} = \int_0^{\delta x} e E_x dx = \frac{e^2 n_e (\delta x)^2}{2\epsilon_0}$ $W_{pot} = \frac{1}{2} k_B T_e$ The temperature describes the mobility of the plasma particles
 $\frac{1}{2} k_B T_e = \frac{e^2 n_e (\delta x)^2}{2\epsilon_0} \rightarrow \delta x = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}} = \lambda_D$ Debye Length = screening distance
 $\lambda_D = 743 \sqrt{\frac{T_e}{n_e}}$ mm to 0.01 mm

The Debye lengths defines the sphere in which the electric fields have an influence. Outside this sphere the electric charges are shielded!

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 17

Estimate Emittance from Plasma

Numerous algorithms exist for defining the ellipse from beam data. Often a minimum area ellipse containing some fraction of the beam is wanted (e.g. $\epsilon_{90\%}$). Unfortunately this is difficult to produce in a robust way.

A well-defined way for producing the ellipse is the rms emittance:

$$\epsilon_{rms} = \sqrt{\langle x'^2 \rangle \langle x^2 \rangle - \langle x x' \rangle^2},$$

and similarly the Twiss parameters where

$$\alpha = -\frac{\langle x x' \rangle}{\epsilon}, \quad \langle x^2 \rangle = \frac{\iint x^2 I(x, x') dx dx'}{\iint I(x, x') dx dx'}$$

$$\beta = \frac{\langle x^2 \rangle}{\epsilon}, \quad \langle x'^2 \rangle = \frac{\iint x'^2 I(x, x') dx dx'}{\iint I(x, x') dx dx'}$$

$$\gamma = \frac{\langle x'^2 \rangle}{\epsilon}, \quad \langle x x' \rangle = \frac{\iint x x' I(x, x') dx dx'}{\iint I(x, x') dx dx'}$$

Assuming $\langle x \rangle = 0$ and $\langle x' \rangle = 0$.

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 18

Estimate Emittance from Plasma

Assume circular extraction hole and Gaussian transverse ion distribution

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

The rms emittance can be integrated using the definition and normalized

$$\epsilon_{rms,n} = \frac{1}{2} \sqrt{\frac{kT}{m}} \frac{r}{c}.$$

Similarly for a slit-beam extraction

$$\epsilon_{rms,n} = \frac{1}{2} \sqrt{\frac{kT}{3m}} \frac{w}{c}.$$

Larger aperture \Rightarrow more beam, weaker quality

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 19

Plasma Boundary

Ions are extracted from a plasma ion source

1. Full space charge compensation ($\rho_- = \rho_+$) in the plasma
2. No compensation in extracted beam (single polarity)

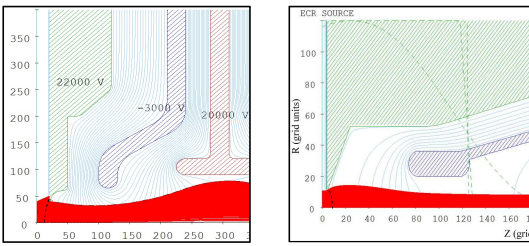
The boundary is often thought as a sharp surface known as the *plasma meniscus* dividing the two regions.

- Works as a thought model.
- In reality compensation drops going from plasma to beam in a transition layer with thickness $\sim \lambda_D \Rightarrow$ plasma sheath.
- E-field in extraction rises smoothly from zero.

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 20

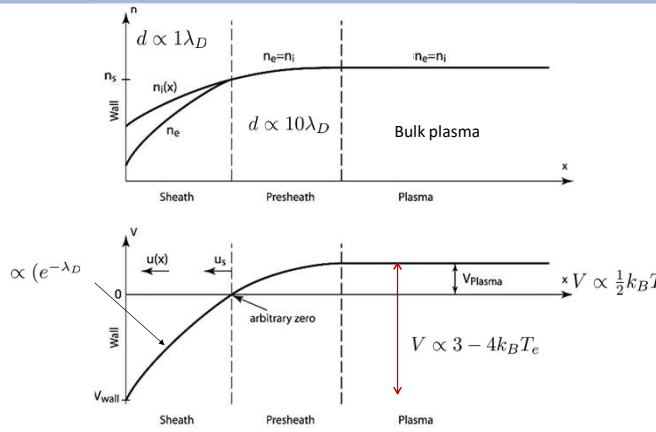
Plasma "Meniscus"

- Misleading: Ions are coming out on their own. Extraction system guides and accelerates, but doesn't really "pull".
- Plasma density vs external electric field → Forms Plasma Meniscus
- Plasma Meniscus can be convex, flat, or concave



Daniel Winklehner, MIT
USPAS, Jan 2018, Hampton, VA
21

Plasma Sheath



Daniel Winklehner, MIT
USPAS, Jan 2018, Hampton, VA
22

Calculate the plasma potential

- Maxwellian electrons: $f(\vec{v}_e) = n_e \left(\frac{m_e}{2\pi kT_e} \right)^{3/2} \cdot e^{-\frac{m_e(v_{e,x}^2 + v_{e,y}^2 + v_{e,z}^2)}{2kT_e}}$
- Flux in z-dir. $\Gamma_e = \int_{-\infty}^{\infty} dv_{e,x} \int_{-\infty}^{\infty} dv_{e,y} \int_0^{\infty} dv_{e,z} f(\vec{v}_e) \cdot v_{e,z}$
- With $\bar{v}_e = \sqrt{\frac{8kT_e}{\pi m_e}}$ → $\Gamma_e = \frac{1}{4} \cdot n_e \cdot \bar{v}_e \cdot e^{\frac{e(\Phi_w - \Phi_p)}{kT_e}}$
 $j^- = e \cdot \frac{1}{4} \cdot n_e \cdot \bar{v}_e \cdot e^{\frac{e(\Phi_w - \Phi_p)}{kT_e}}$
- Bohm Criterion: $c_s = \sqrt{\frac{k(T_i + T_e)}{m_i}}$ → $j^+ = e \cdot \sum_{j=1}^N q_j n_{i,j} \sqrt{\frac{k(T_{i,j} + T_e)}{m_{i,j}}}$

Daniel Winklehner, MIT
USPAS, Jan 2018, Hampton, VA
23

Plasma Potential

- Plasma Potential (5-10 V for typical ion sources):

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

- Now we know at what potential the ions start wrt. source wall ... what else?

Daniel Winklehner, MIT
USPAS, Jan 2018, Hampton, VA
24

Plasma Potential

- Plasma Potential (5-10 V for typical ion sources):

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

- Now we know at what potential the ions start wrt. source wall ... what else?

$$j^+ = e \cdot \sum_{j=1}^N q_j n_{i,j} \sqrt{\frac{k(T_{i,j} + T_e)}{m_{i,j}}} \rightarrow \text{Current depends on mass}$$

$$I = j^+ A_{\text{meniscus}}$$

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 25

Compare with Child Langmuir

Ion beam propagation may also be limited by space charge. The 1D Child-Langmuir law gives the maximum current density for the special case where the beam is starting with $v_0 = 0$ (not plasma).

$$J = \frac{4}{9} \epsilon_0 \sqrt{\frac{2q}{m}} \frac{V^{3/2}}{d^2}$$

The graph plots Current density (mA/cm²) on the y-axis (0 to 100) against Acceleration voltage (kV) on the x-axis (0 to 50). A solid red curve represents the Child-Langmuir limit. Three dashed curves represent different plasma densities: 'high plasma density' (top dashed), 'medium plasma density' (middle dashed), and 'low plasma density' (bottom dashed). All curves start at the origin and increase with voltage, with the Child-Langmuir limit being the highest.

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 26

1D Extraction Model

Groundbreaking work by S. A. Self, *Exact Solution of the Collisionless Plasma-Sheath Equation*, Fluids **6**, 1762 (1963) and J. H. Whealton, *Optics of single-stage accelerated ion beams extracted from a plasma*, Rev. Sci. Instrum. **48**, 829 (1977):

$$\frac{d^2 U}{dx^2} = -\frac{\rho}{\epsilon_0} = -\frac{\rho_n + \rho_e(U)}{\epsilon_0}$$

- Model has been used very successfully for describing positive ion extraction systems since.
- Assumptions: no ion collisions, no ion generation, electron density only a function of potential (no magnetic field).
- Take the model with a semiempirical approach and use it as a tool proving to yourself that it works for your case — don't take it for granted.

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 27

Positive Ion Extraction from Plasma

Modelling of positive ion extraction

- Ray-traced positive ions entering sheath with initial velocity
- Nonlinear space charge term (analytic in Poisson's equation):

$$\rho_e = \rho_{e0} \exp\left(\frac{U - U_p}{kT_e/e}\right)$$

The left diagram shows a potential well U(x) starting at a high value in the 'bulk plasma' region, dropping to a minimum U_p at the sheath edge, and then rising again. 'thermal electrons' are shown as a red shaded region near the minimum, and 'positive ions' are shown as red dots moving away from the minimum. The right diagram is a ray-trace plot showing the trajectories of positive ions in the x-U plane, with x on the horizontal axis and U on the vertical axis. The trajectories are shown as red lines, with a blue shaded region representing the bulk plasma and a green shaded region representing the sheath.

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 28

Algorithm

```

    graph LR
      A[Solve ∇²φ=0] --> B[Calculate trajectories using E and B]
      B --> C[Deposit ρ and under-relax]
      C --> D[Solve ∇²φ=-ρ/ε₀]
      D --> E{Converged?}
      E -- Yes Done --> Exit[ ]
      E -- No --> B
  
```

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

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 29

Codes

- Codes (Raytracing/PIC + Plasma model):
 - IGUN (RZ) <http://www.egan-igun.com/>
 - IBSimu (RZ, 3D, 2D) <http://ibsimu.sourceforge.net/>
 - Warp (RZ, 3D, 2D) <http://warp.lbl.gov/>
 - Kobra-INP (RZ, 3D)
 -

Complications:

- Multiple ion species
- Added magnetic fields (see next):
 - Solenoid
 - Sextupole
- Negative ions/electrons
- 3D advisable!

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 30

One Comment about 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!)

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 31

Challenge: Negative Ions

Labels in diagram:

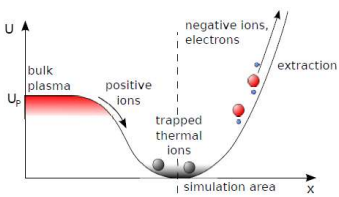
- Magnetic filter field for volume H₂ production formed by electric magnets
- Permanent magnet dipole-antidipole electron dump integrated in puller electrode
- 16 pole NdFeB-42 multicusp and back plate cusp
- 78 mm diameter
- 1.5 mm Ta filament with 70-80 A heating current and up to 8 A arc current at 100-120 V
- 2 mm diameter plasma electrode aperture
- S5430 plasma electrode insert for separating the magnetic fields

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 32

Negative Ions

Modelling of negative ion extraction

- Ray-traced negative ions and electrons
- Analytic thermal and fast positive charges
- Magnetic field suppression for electrons inside plasma

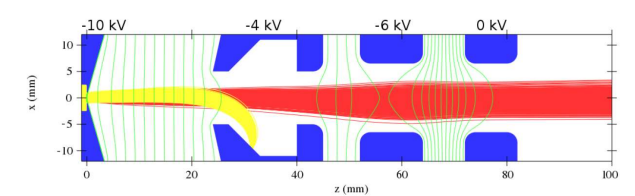
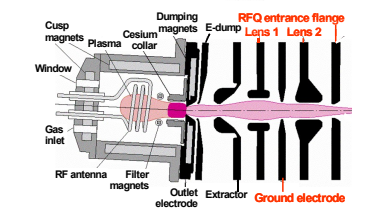


$$\rho_{th} = \rho_{th0} \exp\left(\frac{-eU}{kT_i}\right)$$

$$\rho_f = \rho_{f0} \left(1 + \operatorname{erf}\left(\frac{eU}{E_i}\right)\right)$$

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 33

Challenge: Negative Ions

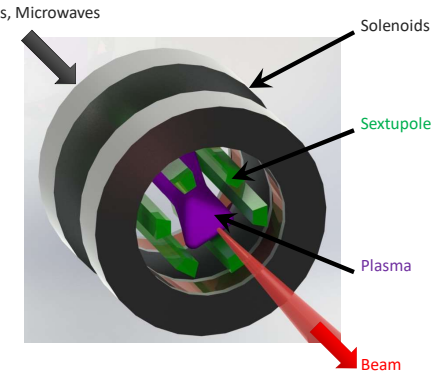



Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 34

Example 2 Electron Cyclotron Resonance

- 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, ~eV in sheath
 - T_i : ~eV
 - n_e : $10^9 - 10^{12} / \text{cm}^3$
 - t_i : ~ms



Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 35

If a circular beam starts from a solenoidal magnetic field (ECR) particles receive a azimuthal thrust of

$$v_\theta = r_0 \frac{qB}{2m},$$

when exiting the magnetic field. Far from solenoid the motion is cylindrically symmetric and

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

The emittance of the beam is

$$\epsilon_{rms} = \frac{1}{4} r_0 r' = \frac{qBr_0^2}{8mv_z}$$

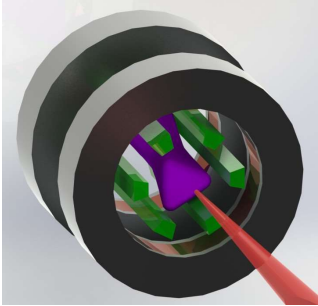
and normalized

$$\epsilon_{rms,n} = \frac{qBr_0^2}{8mc}$$

Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 36

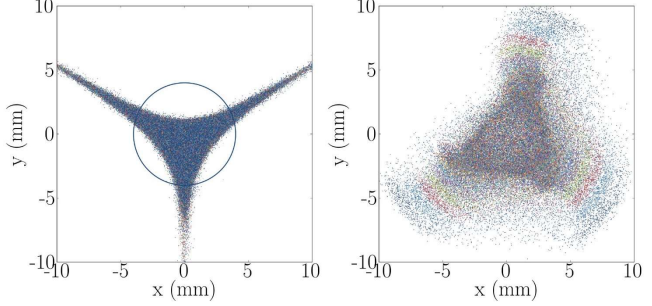
Sextupole

- Adds shape to plasma
- Guides electrons and ions
- Very distorted beams!
- 3D necessary!
- Examples: SuSI, VENUS on next slides



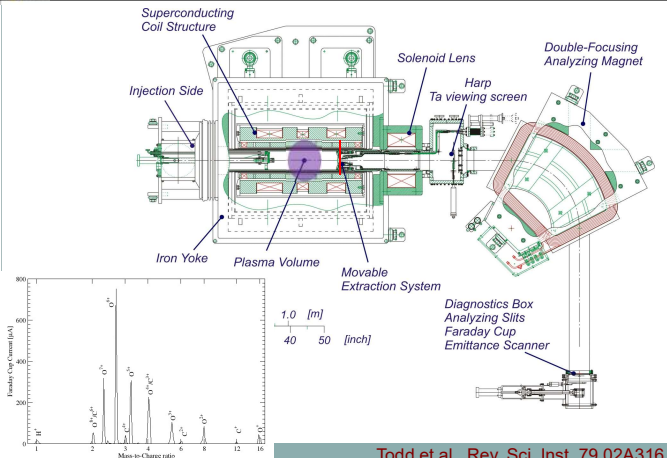
Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 37

Extracted A^{8+}



Daniel Winklehner, MIT USPAS, Jan 2018, Hampton, VA 38

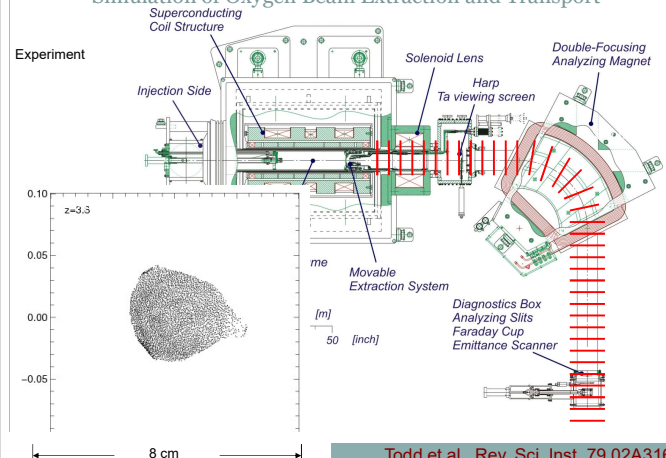
How does the model compare with experiments?



The diagram shows the VENUS experimental setup with components labeled: Superconducting Coil Structure, Injection Side, Iron Yoke, Plasma Volume, Movable Extraction System, Solenoid Lens, Harp, Ta viewing screen, Double-Focusing Analyzing Magnet, Diagnostics Box, Analyzing Slits, Faraday Cup, and Emittance Scanner. A spectrum plot shows Energy (keV) vs. Mass-to-Charge ratio with peaks for various ions.

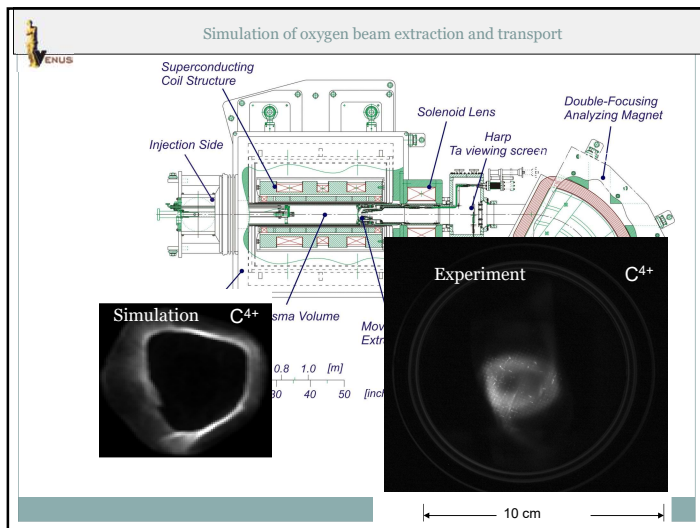
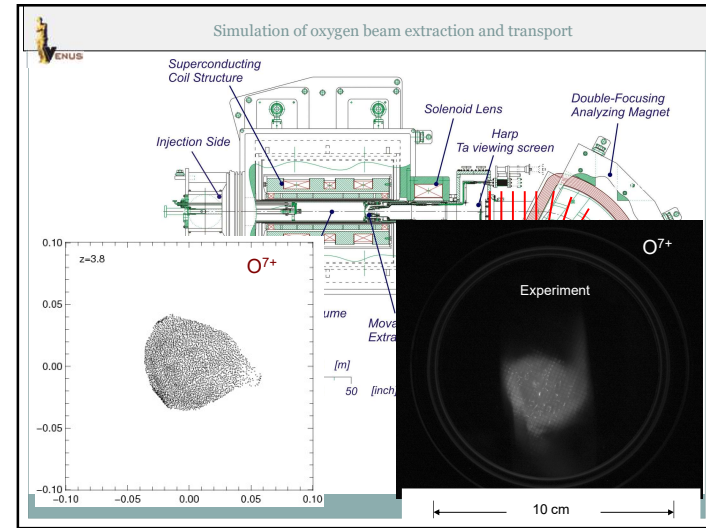
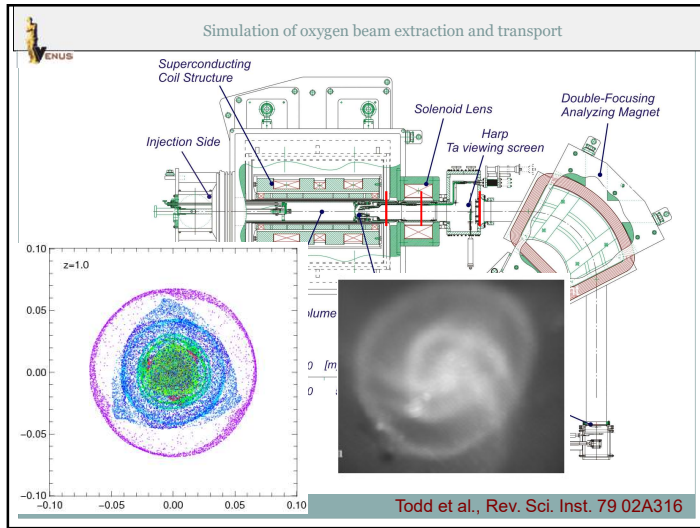
Todd et al., Rev. Sci. Inst. 79 02A316

Simulation of Oxygen Beam Extraction and Transport



The diagram shows the VENUS experimental setup with a simulation overlaid. The simulation shows a beam of oxygen ions being extracted and transported through the system. A scatter plot shows the beam distribution in the x-y plane, with a scale of 8 cm. The simulation parameters are $z=3.5$ and me .

Todd et al., Rev. Sci. Inst. 79 02A316



Before Lunch: A quick test

- So I know that IBSimu + GUI is working on lab computers, let's download the first example and give it a try...
- Download from: https://people.nslc.msu.edu/~lund/uspas/sbp_2018/lec_inj/
- Files: plasmacy1.cpp & Makefile

To compile:

```
>> make
```

To run:

```
>> ./plasmacy1
```

Daniel Winklehner, MIT
USPAS, Jan 2018, Hampton, VA
44