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

- *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*
- *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*
- *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*

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)

Acknowledgements

Slide credits go to:
- Taneli Kalvas
- Martin Stockli
- Daniela Leitner
- Damon Todd

Thank you!

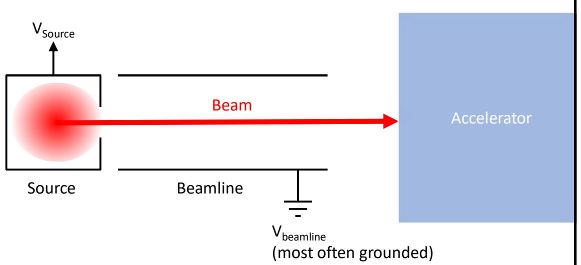
Outline

- 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

Overview I (FRIB)

So simple…or not?

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



Overview II

- In Ion Source/LEBT v ≪ 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!*

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

Medium: Ion source has fixed emitter

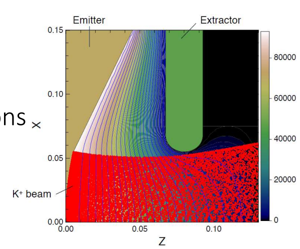
- The beam is emitted from a solid surface that is predefined
- Transverse and time patterns can vary
  - E.g. determined by the laser shape, intensity in case of photoinjector
- Examples:
  - Hot plate source (see Jean-Luc's warp example)
  - Photoinjector
  - (Some) Electron Guns
- Some sort of extraction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

Medium cont'd

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

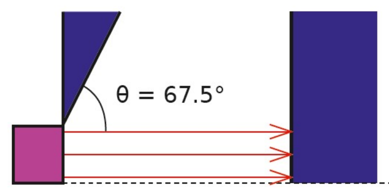
$$I = 1.67 \cdot 10^{-3}\mathrm{A}\left(\frac{Q}{mc^2}\right)^{1/2}\frac{V_0^{3/2}}{d^2}$$

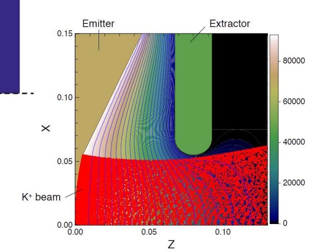
- Used for both electrons and ions
- Typically singly charged



Medium cont'd

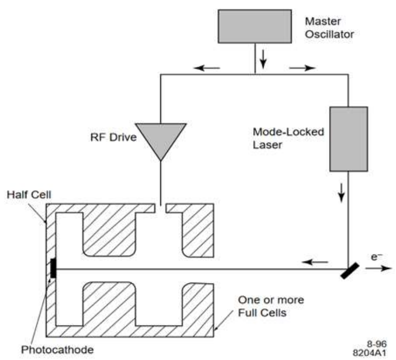
- Electrons: Pierce Angle



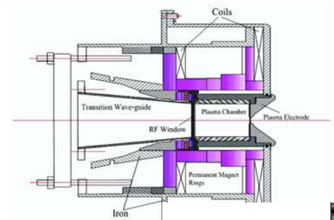


- Typically not so for ions

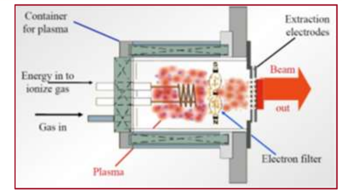
Getting to the Harder Ones: Photoinjector



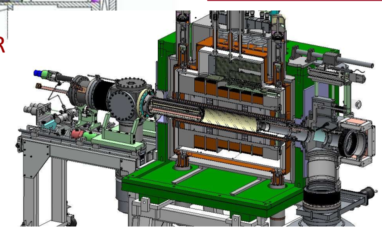
Hard: Emitter is plasma!



Flat-Field ECR

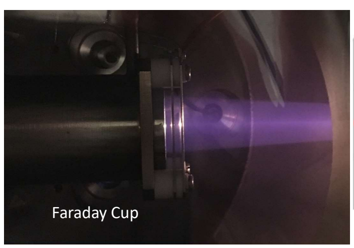


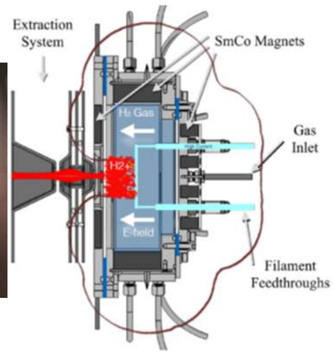
Multicusp



ECRIS

Example 1: Filament-Driven Multicusp

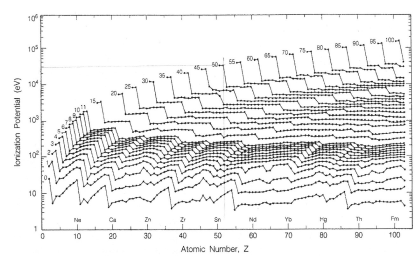




- MIST-1 @ MIT
- Designed for H_2^+

A bit of plasma physics

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



A bit of plasma physics

$$E = \frac{n_e e \delta x_i}{\epsilon_0}$$

Field created between the two charge separated regions

$$W_{pot} = \int_0^{\delta x} eE_x dx = \frac{e^2 n_e (\delta x)^2}{2\epsilon_0} \quad W_{pot} = \frac{1}{2} k_B T_e$$

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!

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:

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

and similarly the Twiss parameters

$$\alpha = -\frac{\langle xx' \rangle}{\epsilon}, \quad \beta = \frac{\langle x^2 \rangle}{\epsilon}, \quad \gamma = \frac{\langle x'^2 \rangle}{\epsilon},$$

where

$$\langle x^2 \rangle = \frac{\iint x^2 I(x,x') \mathrm{d}x \mathrm{d}x'}{\iint I(x,x') \mathrm{d}x \mathrm{d}x'}, \quad \langle x'^2 \rangle = \frac{\iint x'^2 I(x,x') \mathrm{d}x \mathrm{d}x'}{\iint I(x,x') \mathrm{d}x \mathrm{d}x'}, \quad \langle xx' \rangle = \frac{\iint xx' I(x,x') \mathrm{d}x \mathrm{d}x'}{\iint I(x,x') \mathrm{d}x \mathrm{d}x'}.$$

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

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

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

Similarly for a slit-beam extraction

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

Larger aperture $\Rightarrow$ more beam, weaker quality

Plasma Boundary

Ions are extracted from a plasma ion source

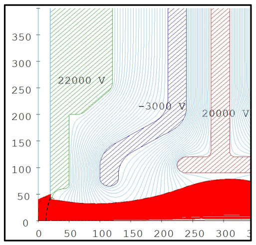
1. Full space charge compensation ($\rho_- = \rho_+$) in the plasma
2. No compensation in extracted beam (single polarity)

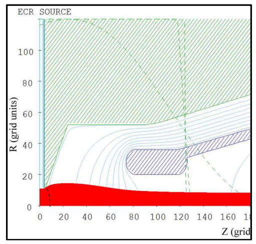
The boundary is often thought as a sharp surface known as the *plasma meniscus* dividing the two regions.

- 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.

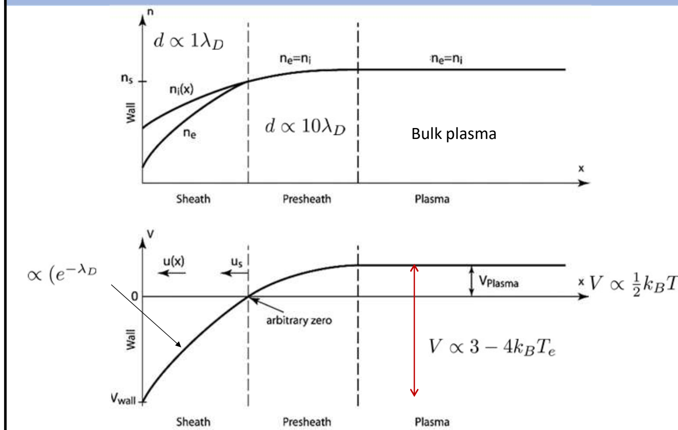
Plasma "Meniscus"

- 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





Plasma Sheath



Calculate the plasma potential

- Maxwellian electrons: $f(\vec{v}_e) = n_e \left(\frac{m_e}{2\pi k T_e}\right)^{3/2} \cdot e^{-\frac{m_e(v_{e,x}^2+v_{e,y}^2+v_{e,z}^2)}{2kT_e}}$
- 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:

$C_s = \sqrt{\frac{k(T_i+T_e)}{m_i}}$ → $j^+ = e \cdot \sum_{j=1}^{N} q_j n_{i,j} \sqrt{\frac{k(T_{i,j}+T_e)}{m_{i,j}}}$

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?

Plasma Potential

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

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

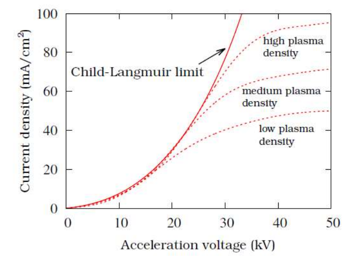
→ Current depends on mass

$I = j^+ A_{meniscus},$

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).

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



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):

$$\frac{d^2U}{dx^2} = -\frac{\rho}{\epsilon_0} = -\frac{\rho_{\rm rt}+\rho_{\rm e}(U)}{\epsilon_0}$$

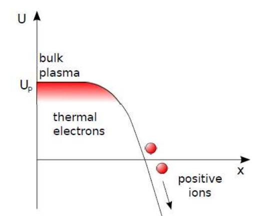
- Model has been used very successfully for describing positive ion extraction systems since.
- Assumptions: no ion collisions, no ion generation, electron density only a function of potential (no magnetic field).
- Take the model with a semiempirical approach and use it as a tool proving to yourself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

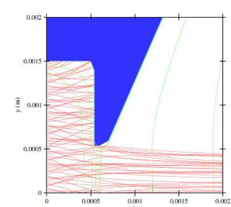
Positive Ion Extraction from Plasma

Modelling of positive ion extraction

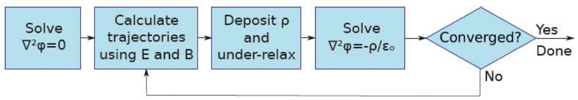
- Ray-traced positive ions entering sheath with initial velocity
- Nonlinear space charge term (analytic in Poisson's equation):

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





Algorithm



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

Codes

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

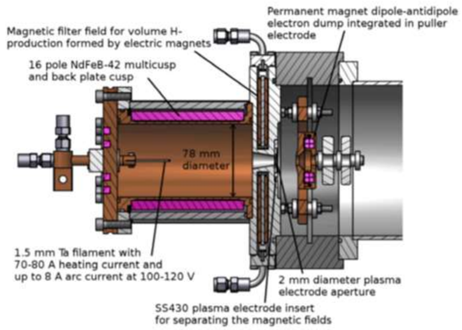
Complications:

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

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!)

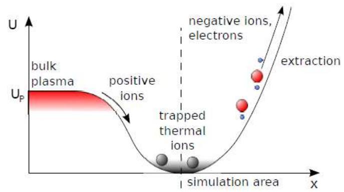
Challenge: Negative Ions



Negative Ions

Modelling of negative ion extraction

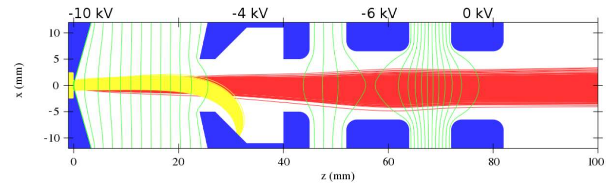
- Ray-traced negative ions and electrons
- Analytic thermal and fast positive charges
- Magnetic field suppression for electrons inside plasma

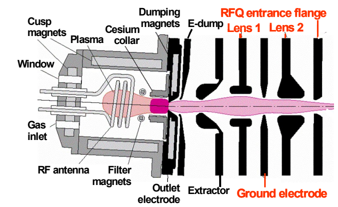


$$\rho_{\rm th} = \rho_{\rm th0} \exp\left(\frac{-eU}{kT_i}\right)$$

$$\rho_{\rm f} = \rho_{\rm f0}\left(1 + \mathrm{erf}\left(\frac{eU}{E_i}\right)\right)$$

Challenge: Negative Ions



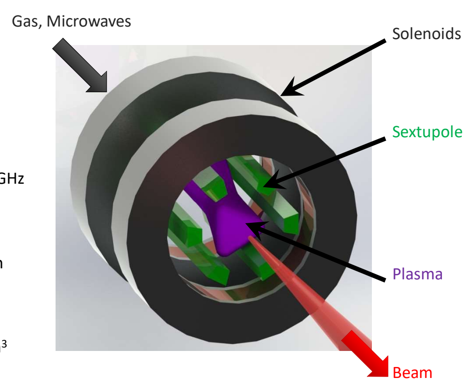


Example 2 Electron Cyclotron Resonance

- 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} /cm^3
  - t_i: ~ms



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

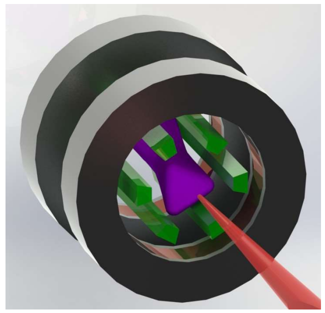
$$\epsilon_{\rm rms} = \frac{1}{4} r_0 r' = \frac{qBr_0^2}{8mv_z}$$

and normalized

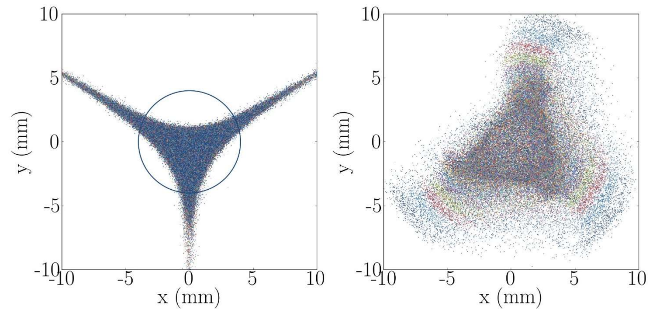
$$\epsilon_{\rm rms,n} = \frac{qBr_0^2}{8mc}$$

Sextupole

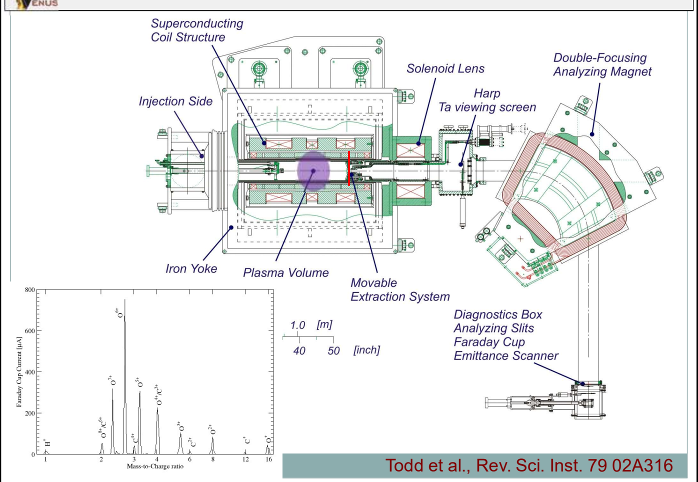
- Adds shape to plasma
- Guides electrons and ions
- Very distorted beams!
- 3D necessary!
- Examples: SuSI, VENUS on next slides



Extracted A^{8+}

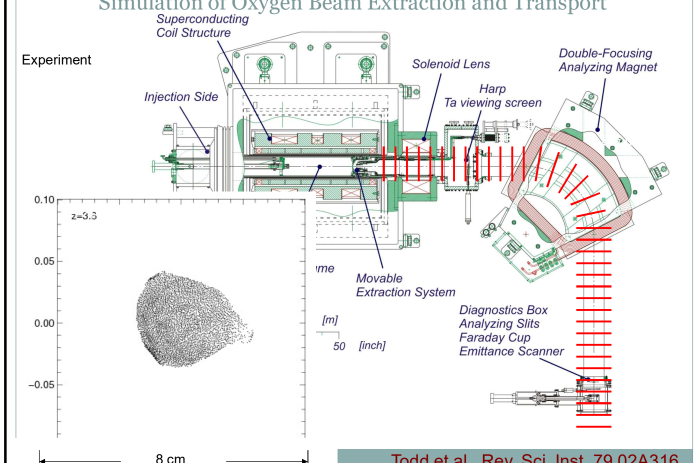


How does the model compare with experiments?



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

Simulation of Oxygen Beam Extraction and Transport



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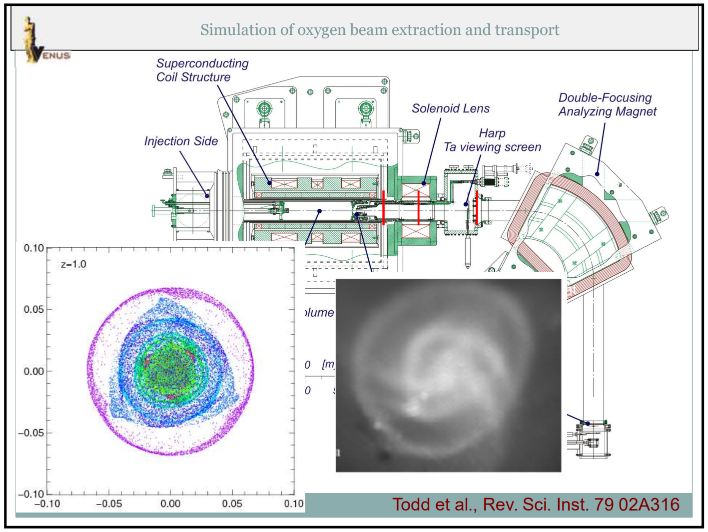

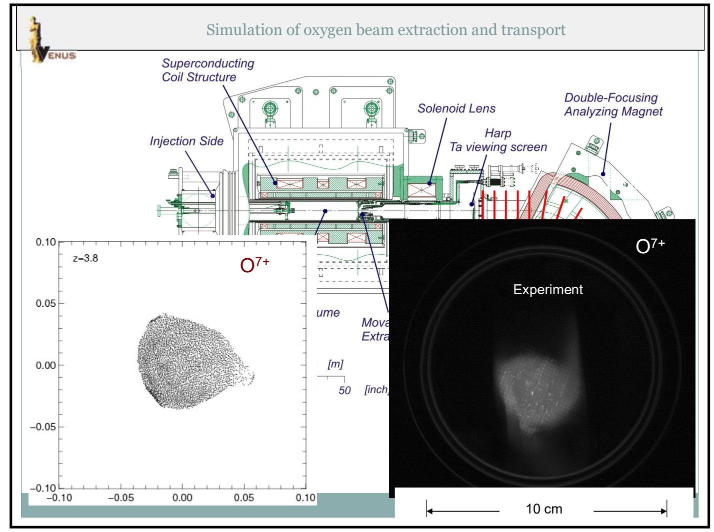

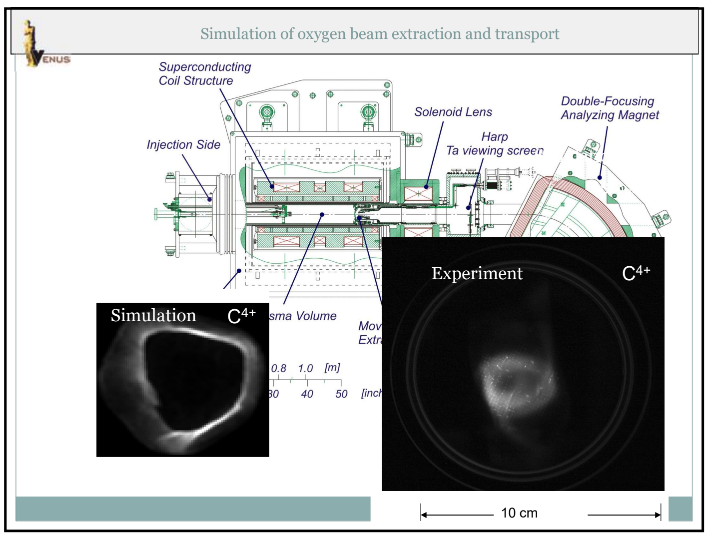

Before Lunch: A quick test

- 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.nscl.msu.edu/~lund/uspas/sbp_2018/lec_inj/
- Files: `plasmacyl.cpp` & `Makefile`

To compile:

```
>> make
```

To run:

```
>> ./plasmacyl
```

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