# Integrated Modeling Toolset for ECR Charge Breeder Ion Sources *

## – MCBC, GEM, IonEx

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*Tel: (858) 455-6655, Fax (858) 450-9741 www.far-tech.com*

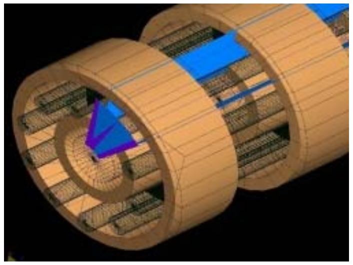
# FAR –TECH, Inc.

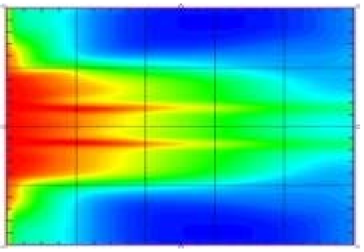
The name FAR stands for Fusion and Accelerator Research

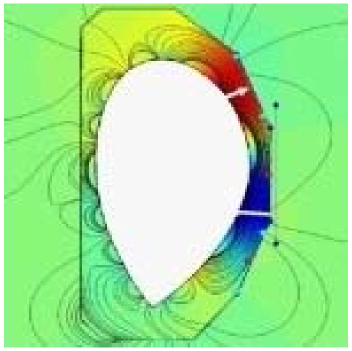
Founded in 1994, located in San Diego, CA

- Core staff: 12 PhD physicists/engineers + 1 admin

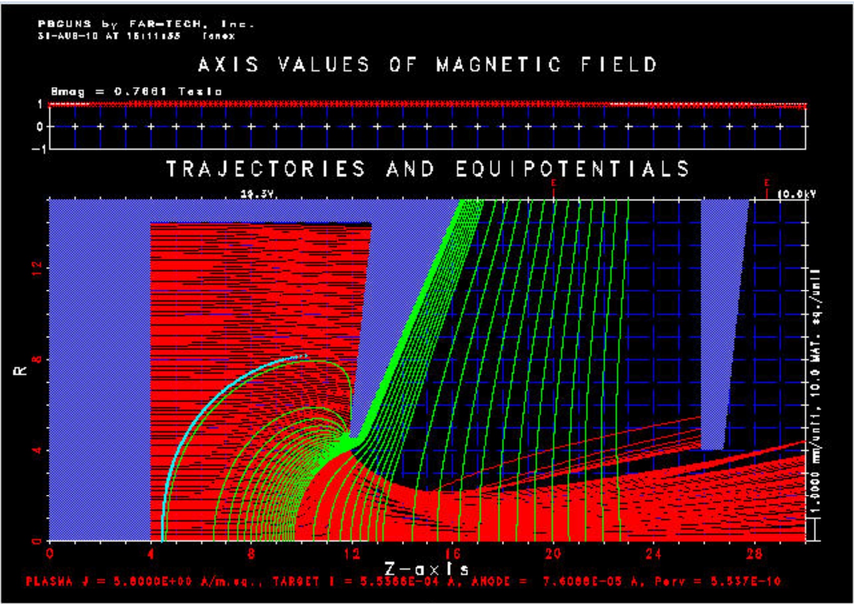
- Core technology: electromagnetism (hardware and software)
  - Accelerator technology ( custom orders received/delivere
    - RF sources
    - RF structure/components
    - System integration
    - Modeling and simulation
  - Plasma science and technology

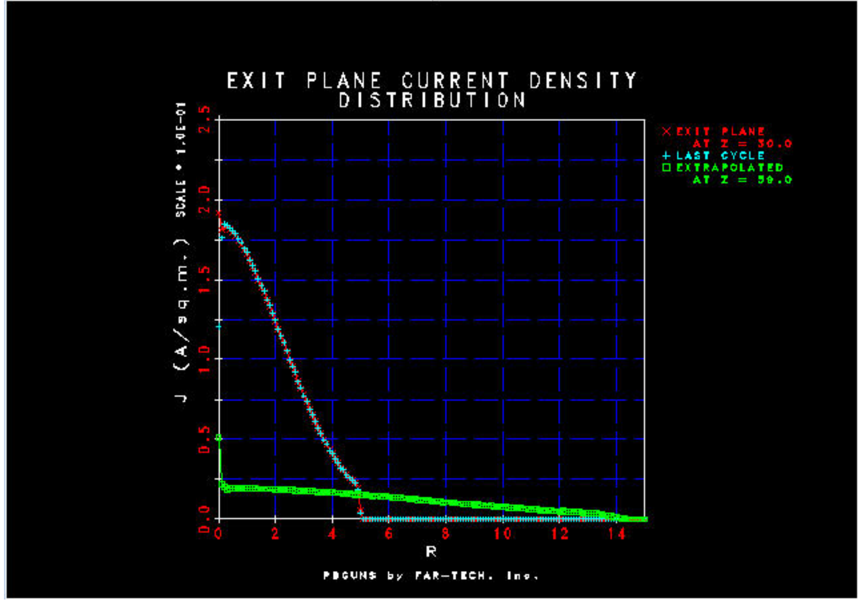


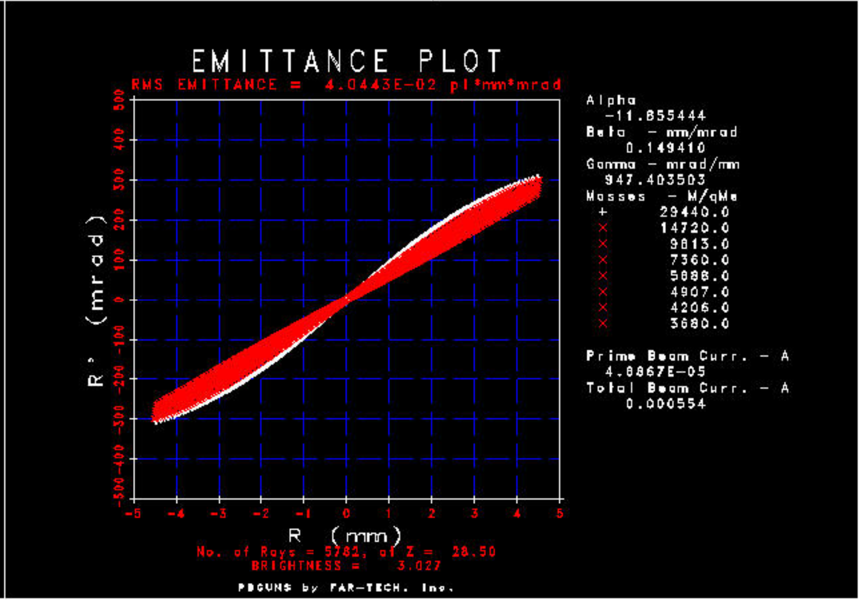




# PBGUNS: (Particle Beam gun simulation) code
# Ion trajectories, J(r) and emittance





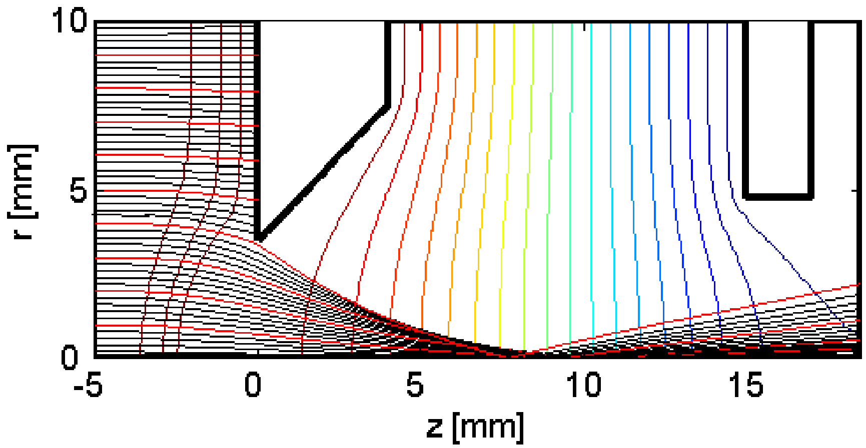


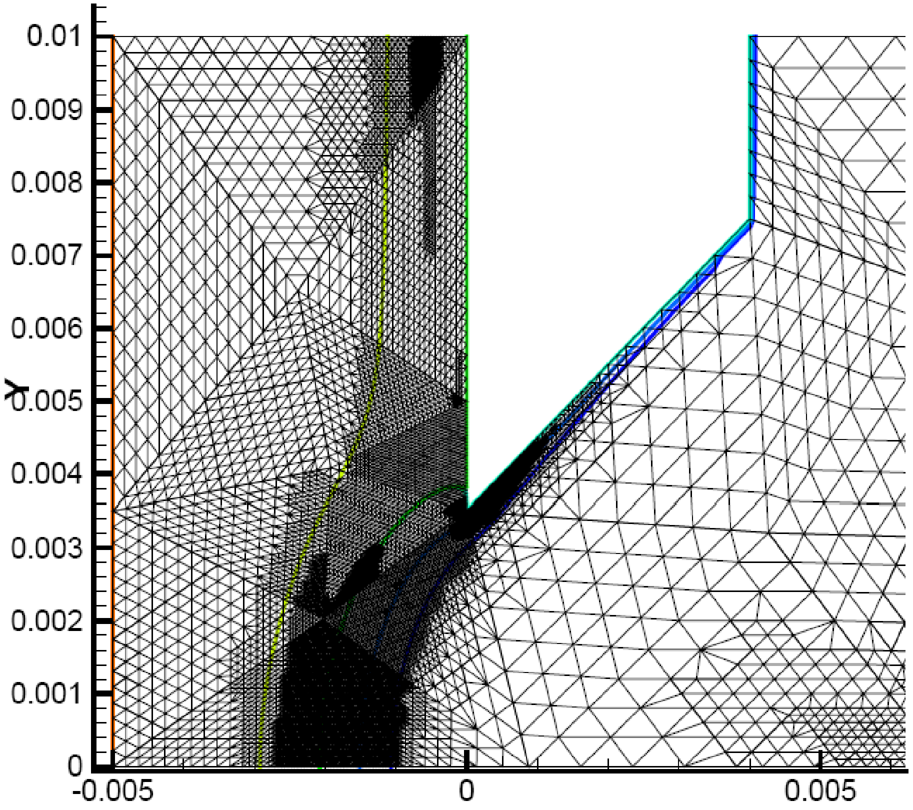
# FAR-TECH has Meshless computing technology

Adaptive computation – multi scale problem

Easy to handle complex geometry

Petascale computing





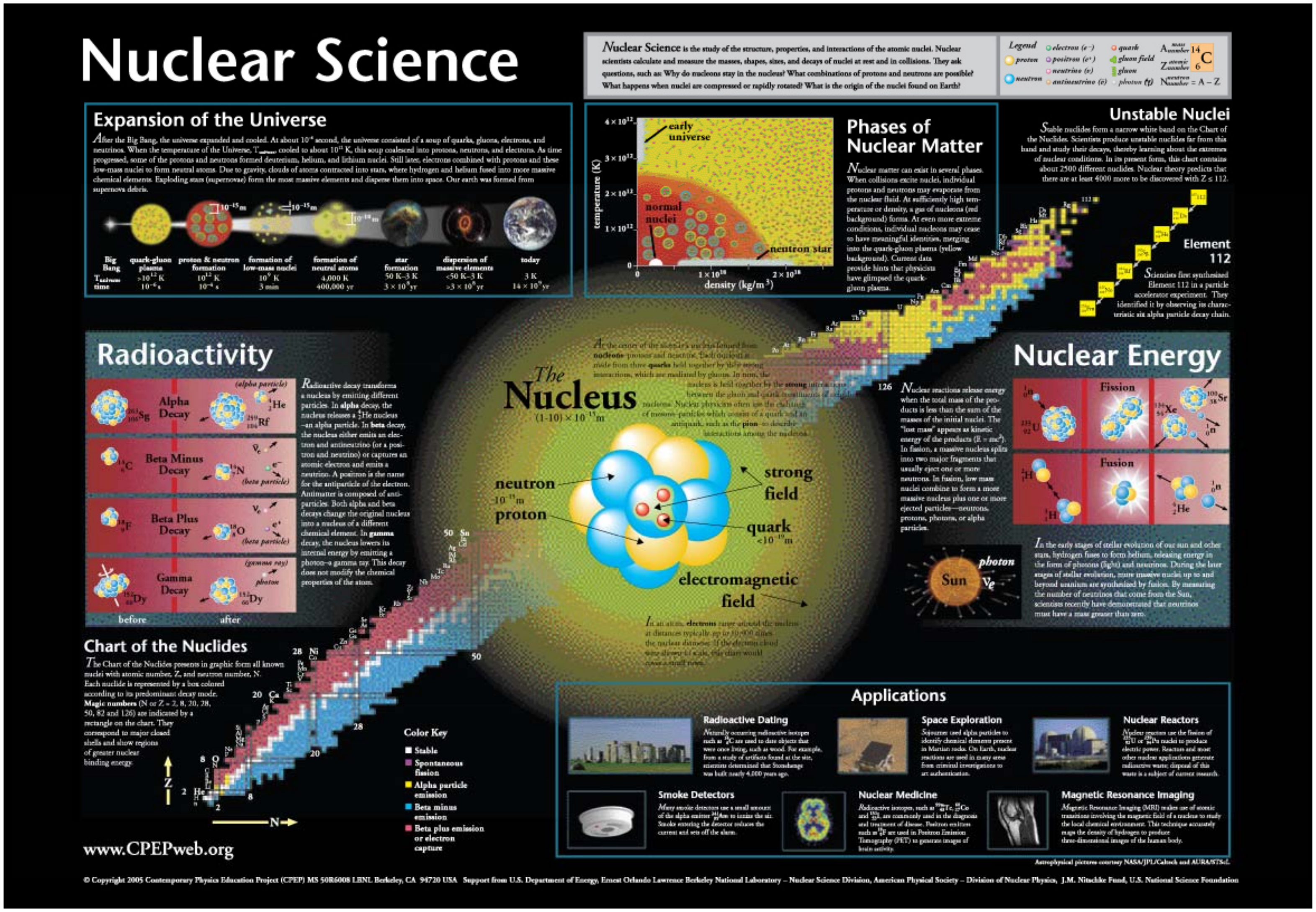
# Integrated Modeling Toolset for ECR Charge Breeder Ion Sources

## Contents

- Motivation and Introduction
- Project
    - Goals
    - Status
- Future Plan

# Motivation and Introduction

# High charged ion beams, in particular Rare Isotope Beams (RIBs), are needed for Nuclear Physics studies and have industrial applications



## Nuclear Science

**Nuclear Science** is the study of the structure, properties, and interactions of the atomic nuclei. Nuclear scientists calculate and measure the masses, shapes, sizes, and decays of nuclei at rest and in collisions. They ask questions, such as: Why do nucleons stay in the nucleus? What combinations of protons and neutrons are possible? What happens when nuclei are compressed or rapidly rotated? What is the origin of the nuclei found on Earth?

Legend
- proton
- neutron
- electron ($e^-$)
- positron ($e^+$)
- neutrino ($\nu$)
- antineutrino ($\bar{\nu}$)
- quark
- gluon field
- gluon
- photon ($\gamma$)

A mass number, Z atomic number: $^{14}_{6}\mathrm{C}$

N neutron number = A – Z

### Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about $10^{-6}$ second, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. When the temperature of the Universe, $T_{universe}$, cooled to about $10^{12}$ K, this soup coalesced into protons, neutrons, and electrons. As time progressed, some of the protons and neutrons formed deuterium, helium, and lithium nuclei. Still later, electrons combined with protons and these low-mass nuclei to form neutral atoms. Due to gravity, clouds of atoms contracted into stars, where hydrogen and helium fused into more massive chemical elements. Exploding stars (supernovae) form the most massive elements and disperse them into space. Our earth was formed from supernova debris.

| Big Bang | quark-gluon plasma | proton & neutron formation | formation of low-mass nuclei | formation of neutral atoms | star formation | dispersion of massive elements | today |
|---|---|---|---|---|---|---|---|
| $T_{universe}$ | $>10^{12}$ K | $10^{12}$ K | $10^{9}$ K | 4,000 K | 50 K–3 K | <50 K–3 K | 3 K |
| time | $10^{-6}$ s | $10^{-4}$ s | 3 min | 400,000 yr | $3 \times 10^{8}$ yr | $>3 \times 10^{8}$ yr | $14 \times 10^{9}$ yr |

### Phases of Nuclear Matter

Nuclear matter can exist in several phases. When collisions excite nuclei, individual protons and neutrons may evaporate from the nuclear fluid. At sufficiently high temperature or density, a gas of nucleons (red background) forms. At even more extreme conditions, individual nucleons may cease to have meaningful identities, merging into the quark-gluon plasma (yellow background). Current data provide hints that physicists have glimpsed the quark-gluon plasma.

### Unstable Nuclei

Stable nuclides form a narrow white band on the Chart of the Nuclides. Scientists produce unstable nuclides far from this band and study their decays, thereby learning about the extremes of nuclear conditions. In its present form, this chart contains about 2500 different nuclides. Nuclear theory predicts that there are at least 4000 more to be discovered with Z ≤ 112.

### Element 112

Scientists first synthesized Element 112 in a particle accelerator experiment. They identified it by observing its characteristic six alpha particle decay chain.

### Radioactivity

Radioactive decay transforms a nucleus by emitting different particles. In **alpha** decay, the nucleus releases a $^{4}_{2}$He nucleus—an alpha particle. In **beta** decay, the nucleus either emits an electron and antineutrino (or a positron and neutrino) or captures an atomic electron and emits a neutrino. A positron is the name for the antiparticle of the electron. Antimatter is composed of antiparticles. Both alpha and beta decays change the original nucleus into a nucleus of a different chemical element. In **gamma** decay, the nucleus lowers its internal energy by emitting a photon—a gamma ray. This decay does not modify the chemical properties of the atom.

### The Nucleus

(1-10) × $10^{-15}$m

At the center of the atom, the nucleus is formed from **nucleons**—protons and neutrons. Each nucleon is made from three **quarks** held together by their strong interactions, which are mediated by gluons. In turn, the nucleus is held together by the **strong** interactions between the gluon and quark constituents of neighboring nucleons. Nuclear physicists often use the exchange of mesons—particles which consist of a quark and an antiquark, such as the **pion**—to describe interactions among the nucleons.

In an atom, **electrons** range around the nucleus at distances typically up to 10,000 times the nuclear diameter. If the electron cloud were drawn to scale, this chart would cover a small town.

### Chart of the Nuclides

The Chart of the Nuclides presents in graphic form all known nuclei with atomic number, Z, and neutron number, N. Each nuclide is represented by a box colored according to its predominant decay mode. **Magic numbers** (N or Z = 2, 8, 20, 28, 50, 82 and 126) are indicated by a rectangle on the chart. They correspond to major closed shells and show regions of greater nuclear binding energy.

Color Key
- Stable
- Spontaneous fission
- Alpha particle emission
- Beta minus emission
- Beta plus emission or electron capture

### Nuclear Energy

Nuclear reactions release energy when the total mass of the products is less than the sum of the masses of the initial nuclei. The "lost mass" appears as kinetic energy of the products ($E = mc^2$). In fission, a massive nucleus splits into two major fragments that usually eject one or more neutrons. In fusion, low mass nuclei combine to form a more massive nucleus plus one or more ejected particles—neutrons, protons, photons, or alpha particles.

In the early stages of stellar evolution of our sun and other stars, hydrogen fuses to form helium, releasing energy in the form of photons (light) and neutrinos. During the later stages of stellar evolution, more massive nuclei up to and beyond uranium are synthesized by fusion. By measuring the number of neutrinos that come from the Sun, scientists recently have demonstrated that neutrinos must have a mass greater than zero.

### Applications

**Radioactive Dating**

Naturally occurring radioactive isotopes such as $^{14}_{6}$C are used to date objects that were once living, such as wood. For example, from a study of artifacts found at the site, scientists determined that Stonehenge was built nearly 4,000 years ago.

**Space Exploration**

Sojourner used alpha particles to identify chemical elements present in Martian rocks. On Earth, nuclear reactions are used in many areas from criminal investigations to art authentication.

**Nuclear Reactors**

Nuclear reactors use the fission of $^{235}_{92}$U or $^{239}_{94}$Pu nuclei to produce electric power. Reactors and most other nuclear applications generate radioactive waste; disposal of this waste is a subject of current research.

**Smoke Detectors**

Many smoke detectors use a small amount of the alpha emitter $^{241}_{95}$Am to ionize the air. Smoke entering the detector reduces the current and sets off the alarm.

**Nuclear Medicine**

Radioactive isotopes, such as $^{99m}_{43}$Tc, $^{60}_{27}$Co and $^{131}_{53}$I, are commonly used in the diagnosis and treatment of disease. Positron emitters such as $^{18}_{9}$F are used in Positron Emission Tomography (PET) to generate images of brain activity.

**Magnetic Resonance Imaging**

Magnetic Resonance Imaging (MRI) makes use of atomic transitions involving the magnetic field of a nucleus to study the local chemical environment. This technique accurately maps the density of hydrogen to produce three-dimensional images of the human body.

Astrophysical pictures courtesy NASA/JPL/Caltech and AURA/STScI.

www.CPEPweb.org

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Taken from www.CPEPweb.org

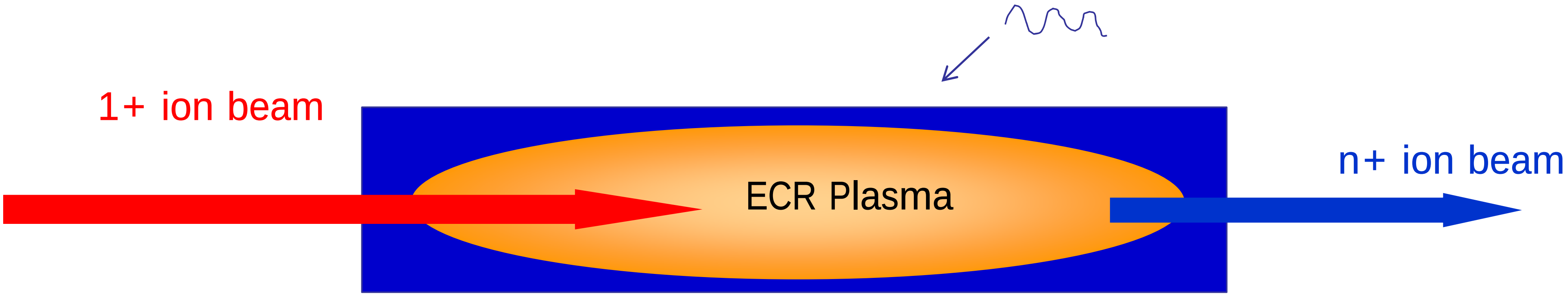
# Rare Isotope beam (RIB) facilities in US and worldwide

- **US RIB Nuclear Physics facilities, such as**
  - Facility for Rare Isotope Beams (**FRIB**) at Michigan State University
  - ATLAS CAlifornium Rare Isotope Breeder Upgrade (**CARIBU**) at Argonne
  - Cyclotron Institute at Texas A&M
  - Holifield Radioactive Ion Beam Facility (**HRIBF**) at ORNL

- **Worldwide RIB Nuclear Physics facilities, such as**

  - **SPIRAL2** (GANIL, France)
  - **ISOLDE** (CERN)
  - **Triumph** (Canada)
  - **KEK** (Japan)
  - …

# An efficient way to produce high charge RIBs is by Electron-Cyclotron-Resonance (ECR) Charge-Breeder (CB) .



- 1+ beam is injected and trapped in a mirror confined plasma
- The plasma is produced/sustained through ECR heating with microwave power
- Trapped ions are bred to high charge state through electron impact ionization
- Highly charged ions are extracted and selected by desired charge/mass ratio

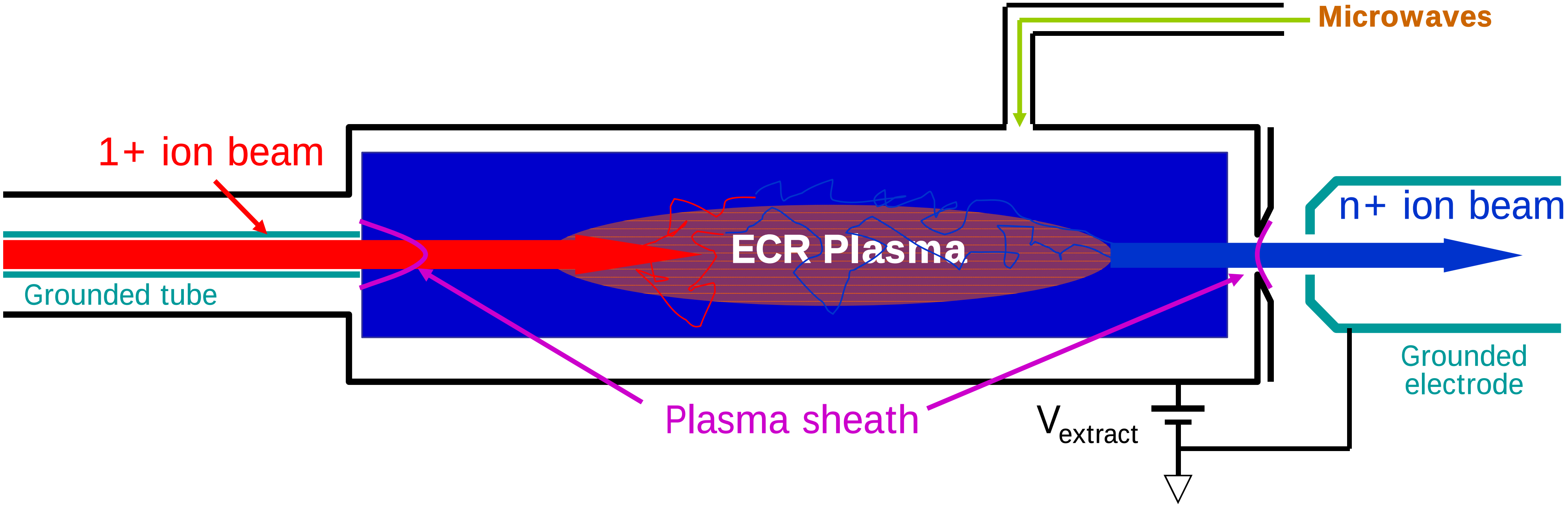
**RIBs and next generation ECRIS are expensive.**

**Modeling can minimize trial and error optimization experimental and design costs.**

***The Project Goal was to develop***

***a charge breeder simulation toolset***

# ECR CB is complex and Modeling is difficult



- ECR CB modeling must integrate ion injection, ionization, and extraction.
- ECR Plasma modeling involves multiple physical processes
- Many ion charge states must be followed
- Extraction region involves multiple spatial scales; must resolve plasma meniscus.

# FAR-TECH's modeling strategy

- **Full particle based (particle-in-cell) modeling is not practical**
  - $10^{11}$ time steps for accurate simulation of ECR heating to steady state
  - Total number of floating point operations

    $= N_{step} \times N_{flop} \times N_p = 10^{11} \times 10^3 \times 10^9 = \mathbf{10^{23}}$
  - Even with petaflops, total time for 1 run requires

    $10^{23}/10^{15} = 10^8$ s = **3.2 years**

- **Instead, plasma is modeled with much faster continuum method**
  - Bounce-averaged Fokker-Planck for electrons
  - Fluid model for ions
  - Time step can be larger than PIC by$10^6$

- **Use particles only for incoming and outgoing beams**

- **Adaptive meshfree computation to resolve multi-scale spatial problem with plasma sheath (meniscus) << 1 mm << device length of 30 cm**

# Modeling is still challenging!

- Multiple species (e.g. 18 charge states for Ar, 37 for Rb)
- Ionization, charge-exchange cross sections not well known
- Coulomb collisions play crucial role
  - Long range force
  - Determine electron confinement time
- Strong gradients within plasma
  - Electron “temperature” ranges from 10 to 10,000 eV
  - Electron density ranges from $10^{14}$ to $10^{18}$ $m^{-3}$

# ECR Charge Breeder is modeled in three modules, each representing distinctive physical process.

**MCBC** **GEM** **IonEx**

**Monte Carlo Beam Code**

**Beam injection and slowing down into an ECR plasma**

# ECR Charge Breeder is modeled in three modules, each representing distinctive physical process.

## MCBC

**Monte Carlo Beam Code**

Beam injection and slowing down into an ECR plasma

## GEM

**Generalized ECRIS Modeling**

- Models ECR heated plasma confined in a magnetic mirror machine
- Calculates charge state distribution and profiles of plasma ions and injected ions

## IonEx

**Ion extraction**

Extraction of an ion beam from an ECRIS

# Each code includes considerable physics and computational techniques (See our publication for details).
# Next, we simply present an example.

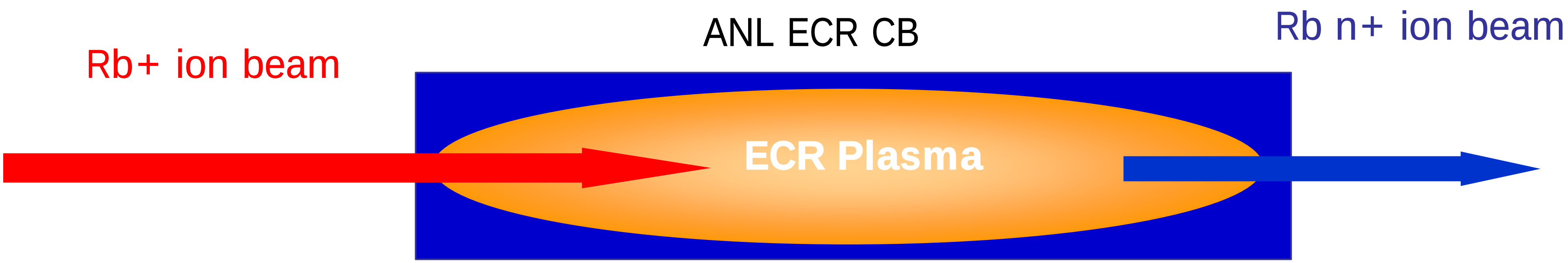
Publication list:

- Jin-Soo Kim, Liangji Zhao, Brian Cluggish, Sergei Galkin, Liz Grubert, “Integrated Modeling of ECR Ion Source and Charge Breeders with GEM, MCBC, and IonEx,” Rev. Sci. Instrum. 81, 02A905 (2010)
- S. A. Galkin, J. E. Grubert, B. P. Cluggish, N. Barov, J. S. Kim, “IonEx – A Meshfree Ion Extraction Code based on PICOP,” Review of Scientific Instruments, Vol. 81, Issue 2, 02B705 (2010).
- L. Zhao, B. Cluggish, J. S. Kim, R. Pardo, and R. Vondrasek, “Simulation of charge breeding of rubidium using Monte Carlo charge breeding code and generalized ECRIS model,” Rev. Sci. Instrum. 81, 02A304 (2010)
- B. P. Cluggish, L. Zhao, and J. S. Kim, “Simulation of Parameter Scaling in ECR Ion Source Plasmas using the GEM code,” Rev. Sci. Instrum. 81, 02A301 (2010)
- B. P. Cluggish, L. Zhao, and J. S. Kim, “Modeling of the Stability of Electron Cyclotron Resonance Ion Source Plasmas,” submitted to Nucl. Inst. Method.
- S. A. Galkin, J. E. Grubert, B. P. Cluggish, J. S. Kim, S. Yu Medvedev, “3D Hybrid Meshless Adaptive Algorithm and Code for Ion Extraction Problem ”, ICOPS Meeting, May 31 - June 5 2009, San Diego, Ca
- L. Zhao, J. S. Kim, and B. Cluggish, “Validation and Application of GEM (General ECRIS Modeling)”, Proc. of the 23rd Particle Accelerator Conference, Vancouver, Canada, 2009.
- L. Grubert, N. Barov, B. Cluggish, S. Galkin, and J.S. Kim, “Graphical Front-End and Object-Oriented Design for IonEx, an Ion Extraction Modeling Code”, Proc. of the 23rd Particle Accelerator Conference, Vancouver, Canada, 2009.
- J.S. Kim, L. Zhao, B. P. Cluggish, I. N. Bogatu, S. Galkin, and L. Grubert, “Status of FAR-TECH’s Electron-Cyclotron-Resonance Charge-Breeder Simulation Toolset: MCBC GEM and IonEx”, Proc. of the 18th annual workshop on ECR Ion Sources, Chicago, IL USA, pp. 156-159, (2008).
- S. A. Galkin, B. P. Cluggish, J. S. Kim, S. Yu. Medvedev “Advanced PICOP Algorithm with Adaptive Meshless Field Solver”, Published in the IEEE PPPS/ICOP 2007 Conf. proc., (2007) pp. 1445-1448.
- B. P. Cluggish, S. A. Galkin, and J. S. Kim, “Modeling Ion Extraction from an ECR Ion Source,” Proceeding of the 2007 Particle Accelerator Conference, Albuquerque, NM, June 25-29, 2007
- J. S. Kim, I. N. Bogatu, B. P. Cluggish, S. A. Galkin, L. Zhao, R. C. Pardo, and V. Tangri, “Status of FAR-TECH's ECR Ion Source Optimization Modeling,” Proceeding of the 2007 Particle Accelerator Conference, Albuquerque, NM, June 25-29, 2007

# ECR CB Example

## Using MCBC, GEM and IonEx

for ANL ECRCB for Rb+ beam into oxygen plasma



ANL ECR CB

Rb+ ion beam

ECR Plasma

Rb n+ ion beam

| | | | |
|---|---|---|---|
| **Device Length** | **29 cm** | **rf Frequency** | **10.44 GHz** |
| **Device Radius** | **4 cm** | **rf Power** | **70 W** |
| $B_{injection}/B_{min}$ | **1.16T / 0.27T = 4.3** | **Plasma Ions** | **oxygen** |
| $B_{extraction}/B_{min}$ | **0.83T /0.27T = 3.1** | **Gas Pressure** | **0.12 micro-torr** |

**Acknowledgement: R. Pardo, R. Vondrasek (ANL)**

# STEP 1

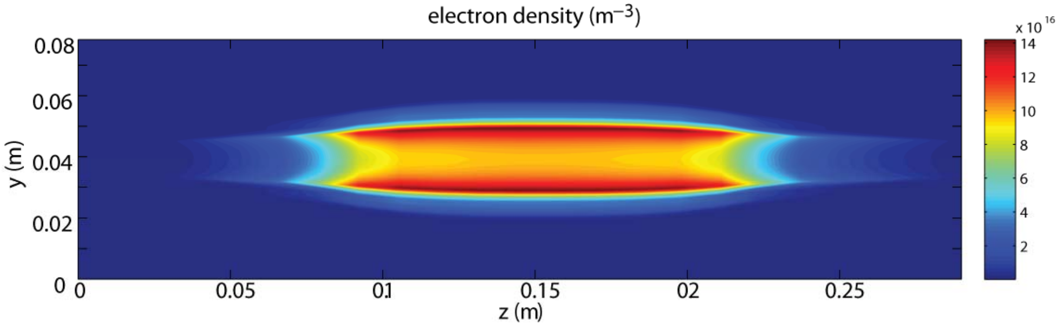
## GEM

### Generalized ECRIS Modeling

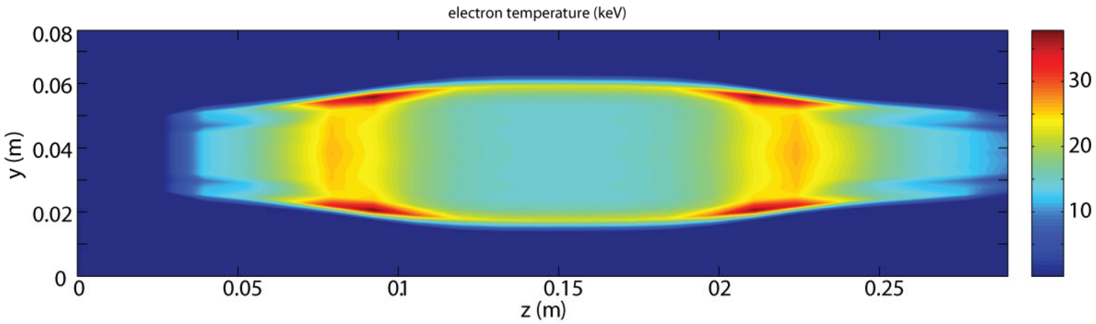
**Obtain a steady state of background plasma with GEM**

# GEM 2D (r,z) simulation

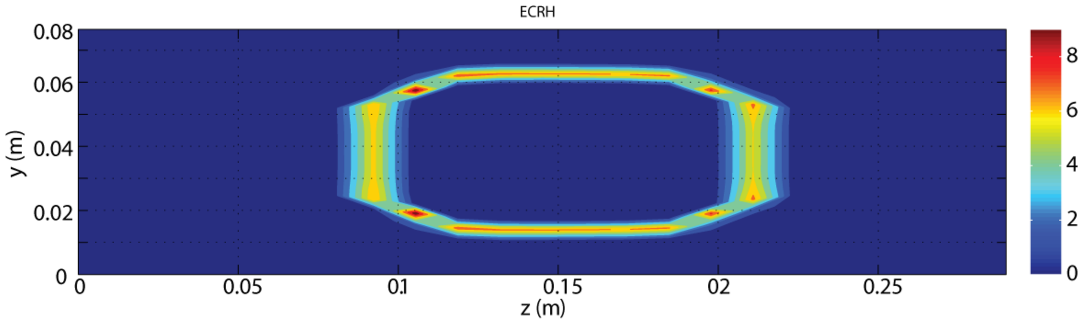
## Steady state background oxygen plasma shows hollow electron density and temperature profiles, due to hollow Electron Cyclotron Resonance (ECR) region



$n_e$



$T_e$



**ECR region where electrons are heated by microwave**

# STEP 2

# MCBC

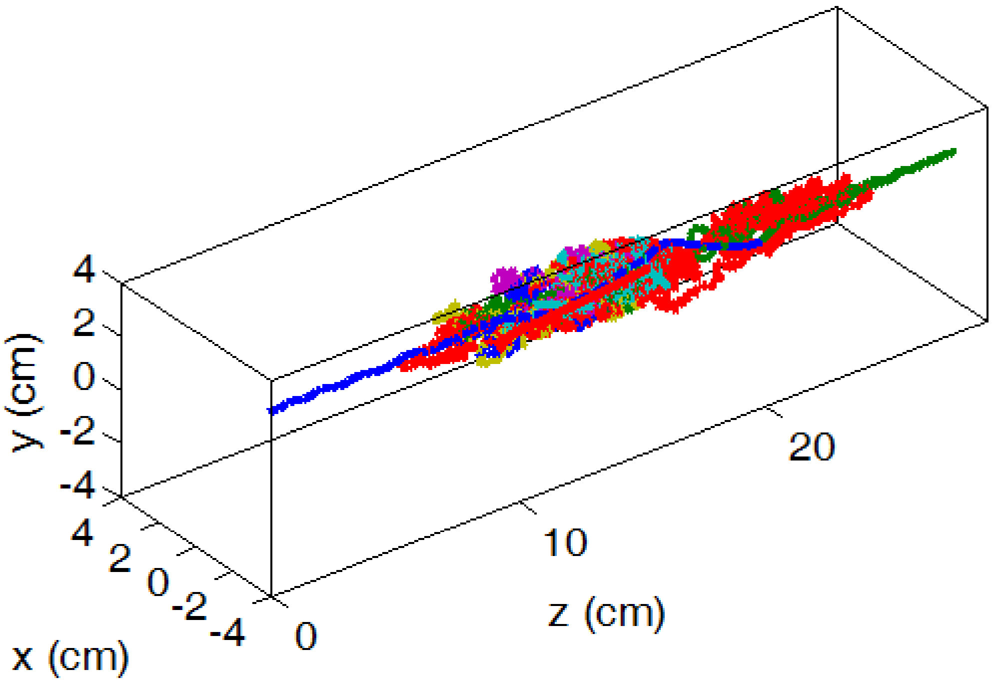
## Monte Carlo Beam Code

**MCBC tacks beam ions in plasma.**

# Movie shows single Rb+ beam ion trajectory simulated by MCBC. As the ion traverses in the plasma longer, it becomes more highly charged (color coded) by electron impact.

## Rb+1 beam

mcbc_big.avi

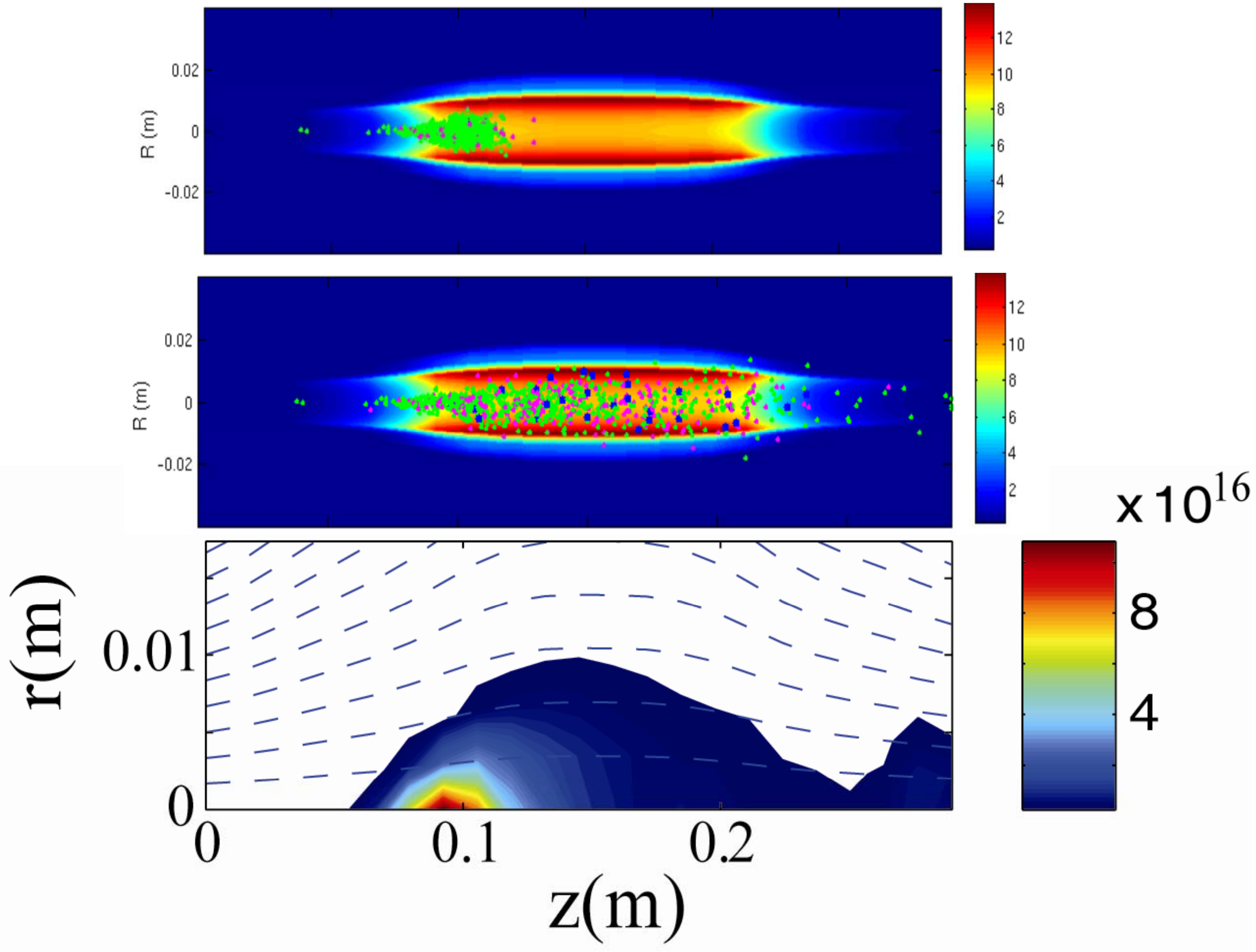


**Tracking all the injected beam ions until extraction is computationally expensive**

**Instead, we compute MCBC until injected ions are pass through, lost to walls or slowed-down to thermal speed of the background plasma ion ("captured").**

**Then utilize the captured profiles as input source profiles for GEM.**

snapshot.avi



**captured $Rb^{2+}$ profile**

# STEP 3

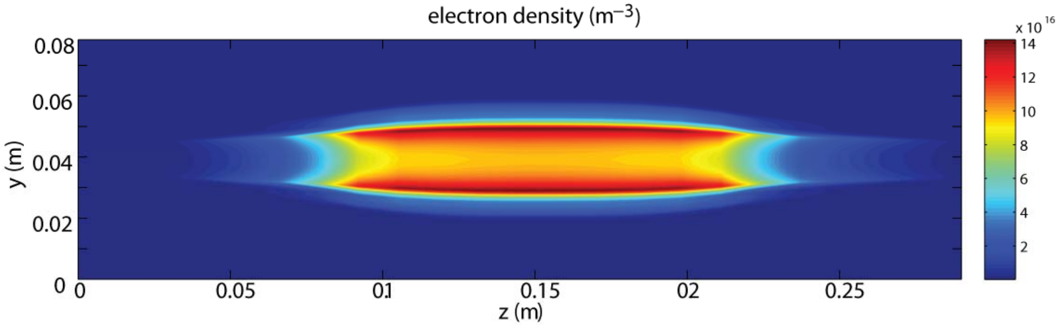
# GEM

## Generalized ECRIS Modeling

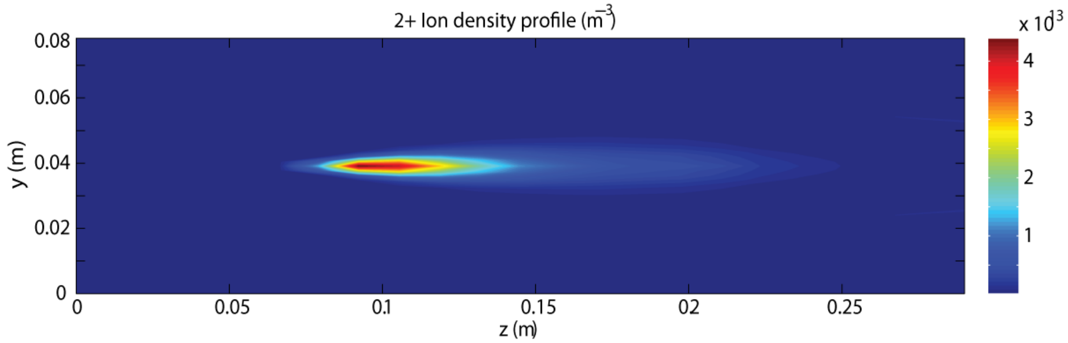
Repeat Step 1, including ion sources from the captured Rb+1, +2, +3, … to GEM

# Steady state profiles of electron density and Rb ions

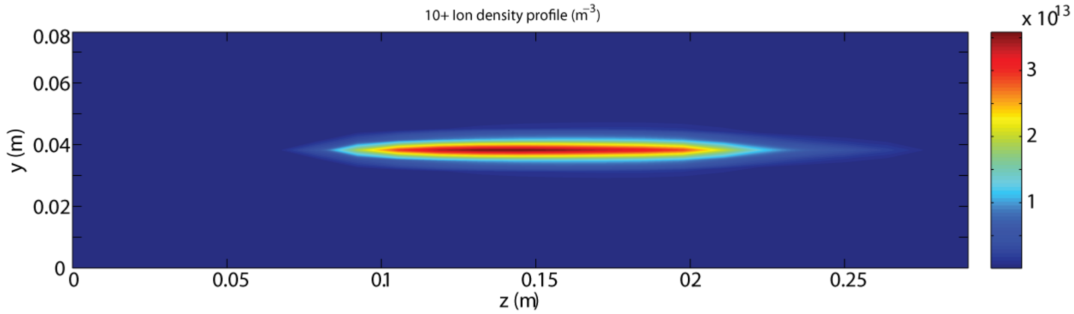
**plasma electron density profile (ne)**



**Rb+2 Profile**



**Rb+10**

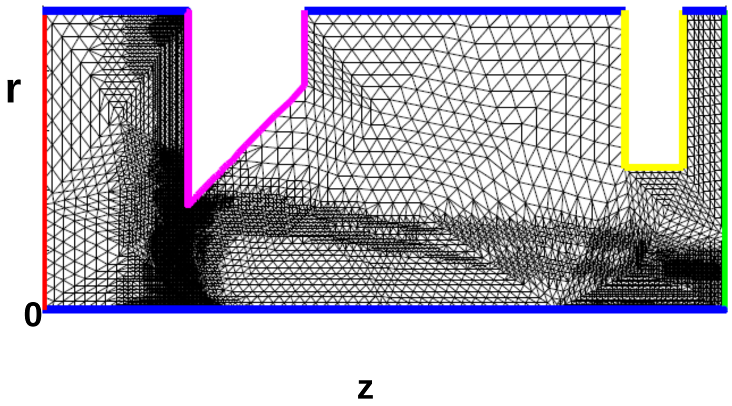


## STEP 4

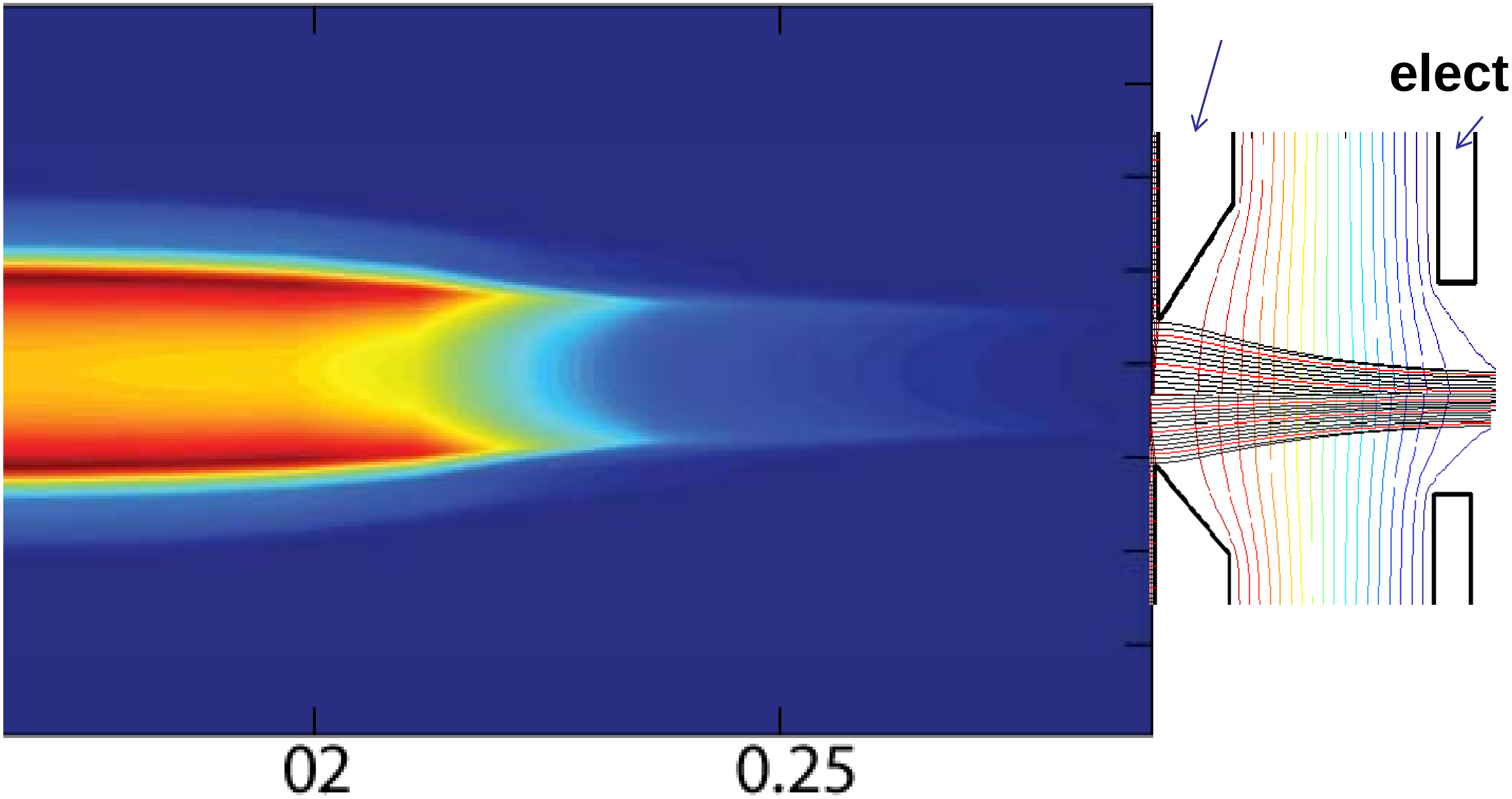
# IonEx

## Ion Extraction Modeling Code

## Adaptive meshfree code



# GEM 2D (r,z) simulated steady state profiles of $n_e$(r), $T_e$ (r), J(r) at extraction are the inputs to IonEx



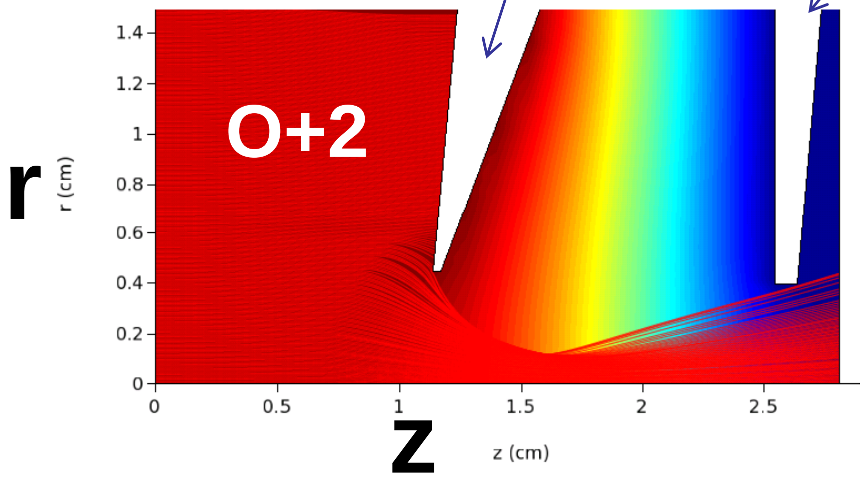
**Plasma wall**

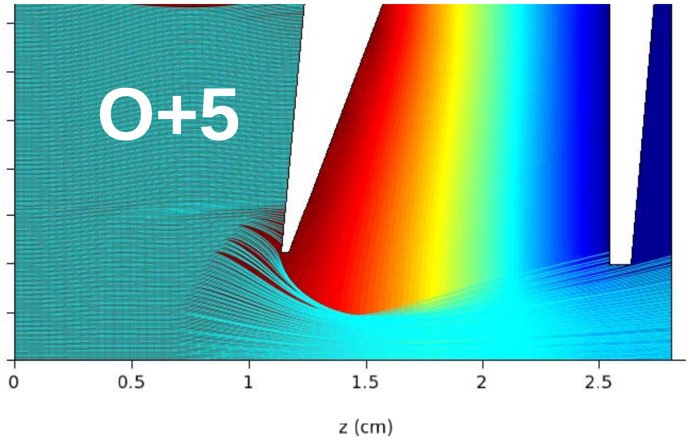
**electrode**

# IonEx simulation

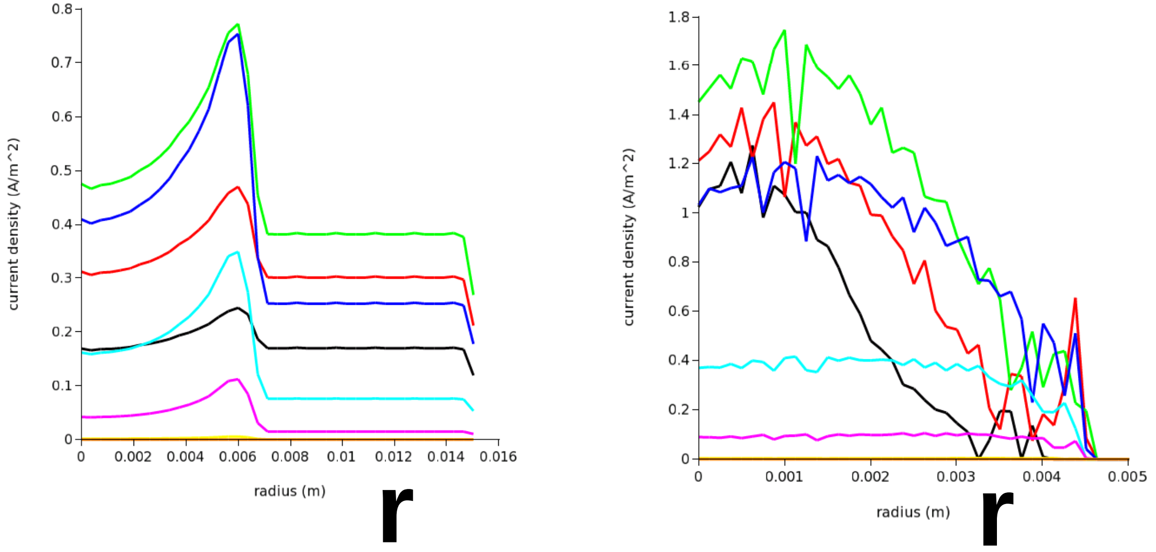
**Plasma wall**

**electrode**

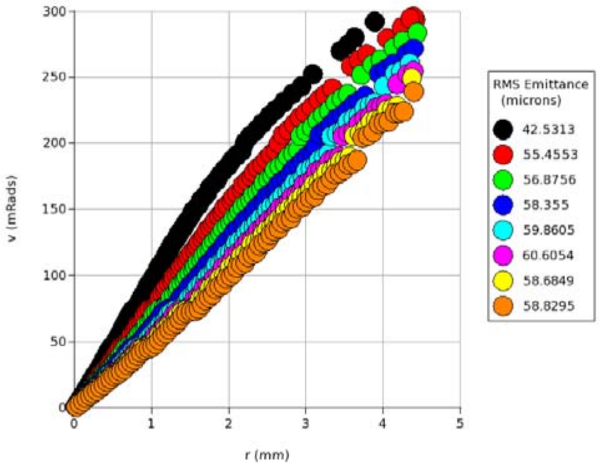




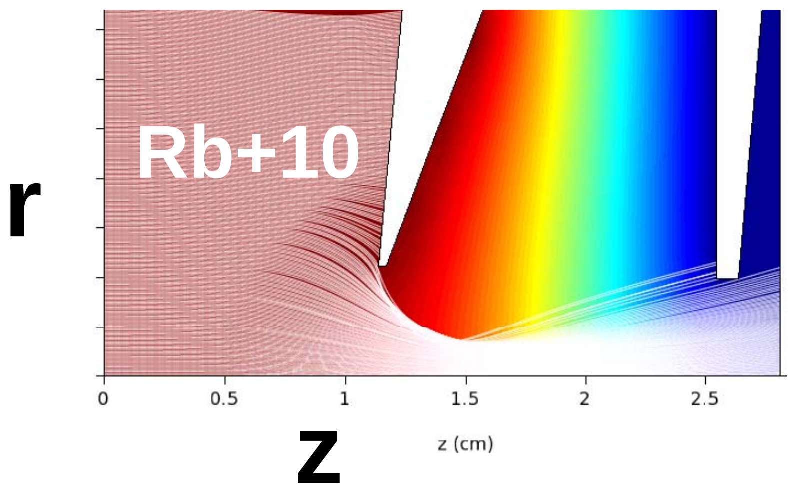
**J(r) for all oxygen ions (+1 thru +8) at z=0 and 2.8 cm**

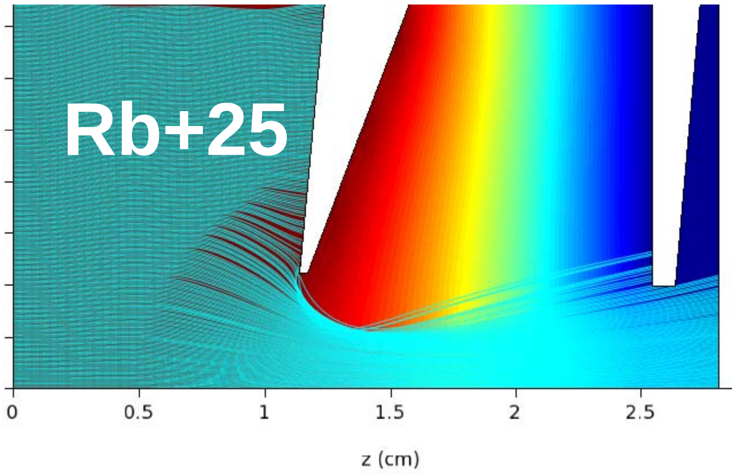


Emittance at z = 2.8 cm

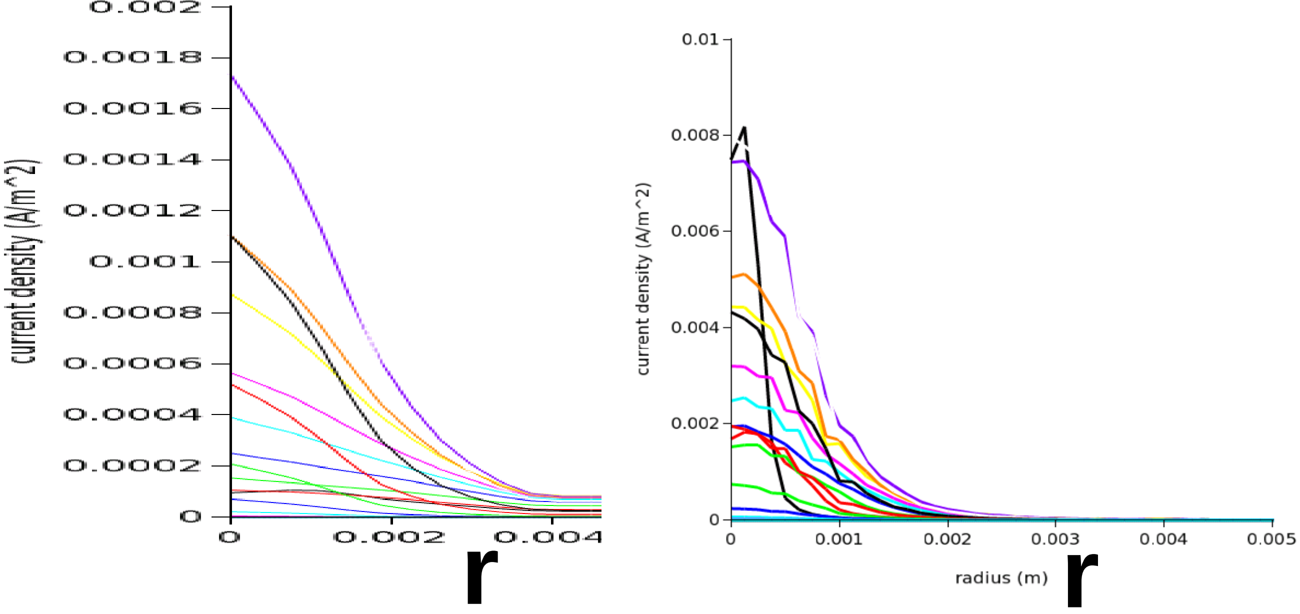


# IonEx Simulations:

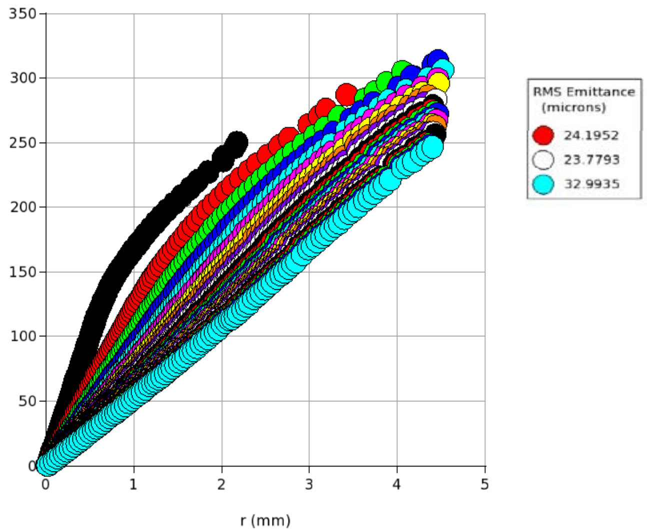




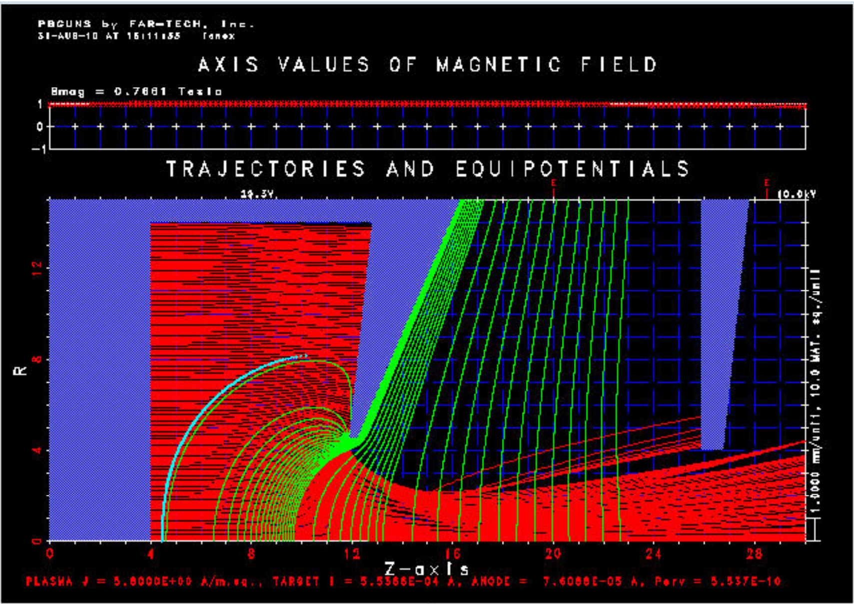
## J(r) for all Rb ions (+1 thru +25) at z=0 and 2.8 cm

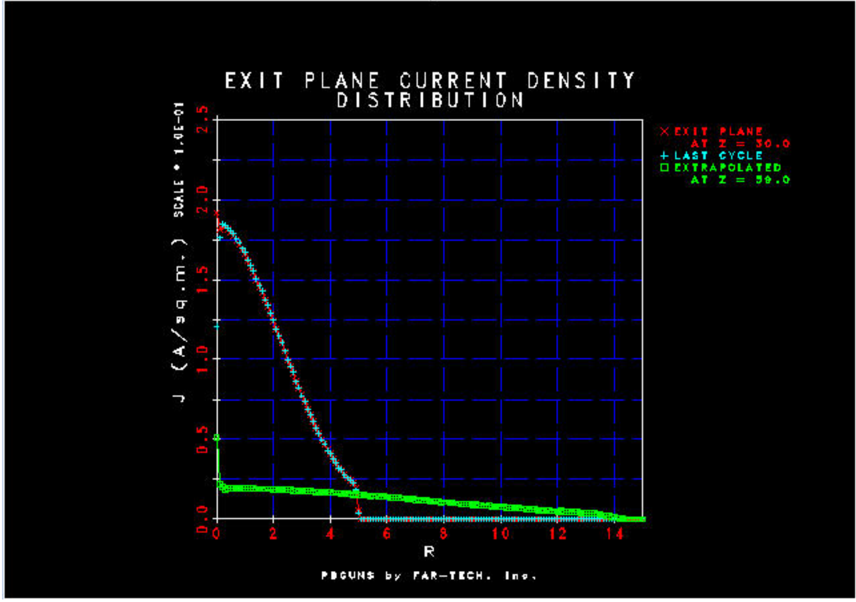


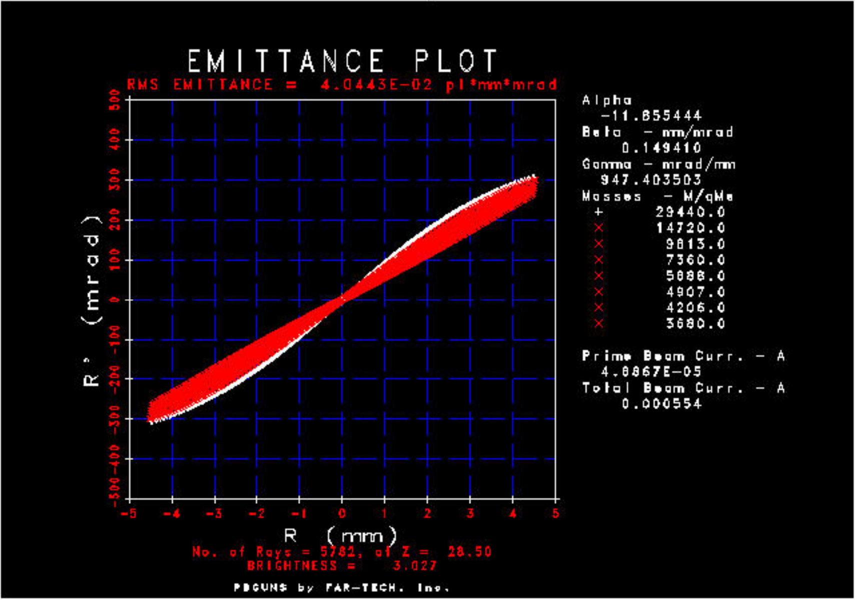
## Emittance at z = 2.8 cm



# IonEx benchmarked with PBGUNS: Trajectories, J(r) and emittance







# Summary

## End-to-End Integration of ECR Charge Breeder Modeling underway

FAR-TECH's Suite of Codes for ECR Charge Breeder Modeling

| MCBC | GEM | IonEx |
|---|---|---|
| Full 3d3v<br>Atomic data<br>Coulomb collisions | 2d2v<br>Fluid Ions<br>Fokker-Plank Electrons (bounce averaged)<br>Coulomb collisions<br>Atomic collisions | Adaptive meshfree<br>Multi-species |

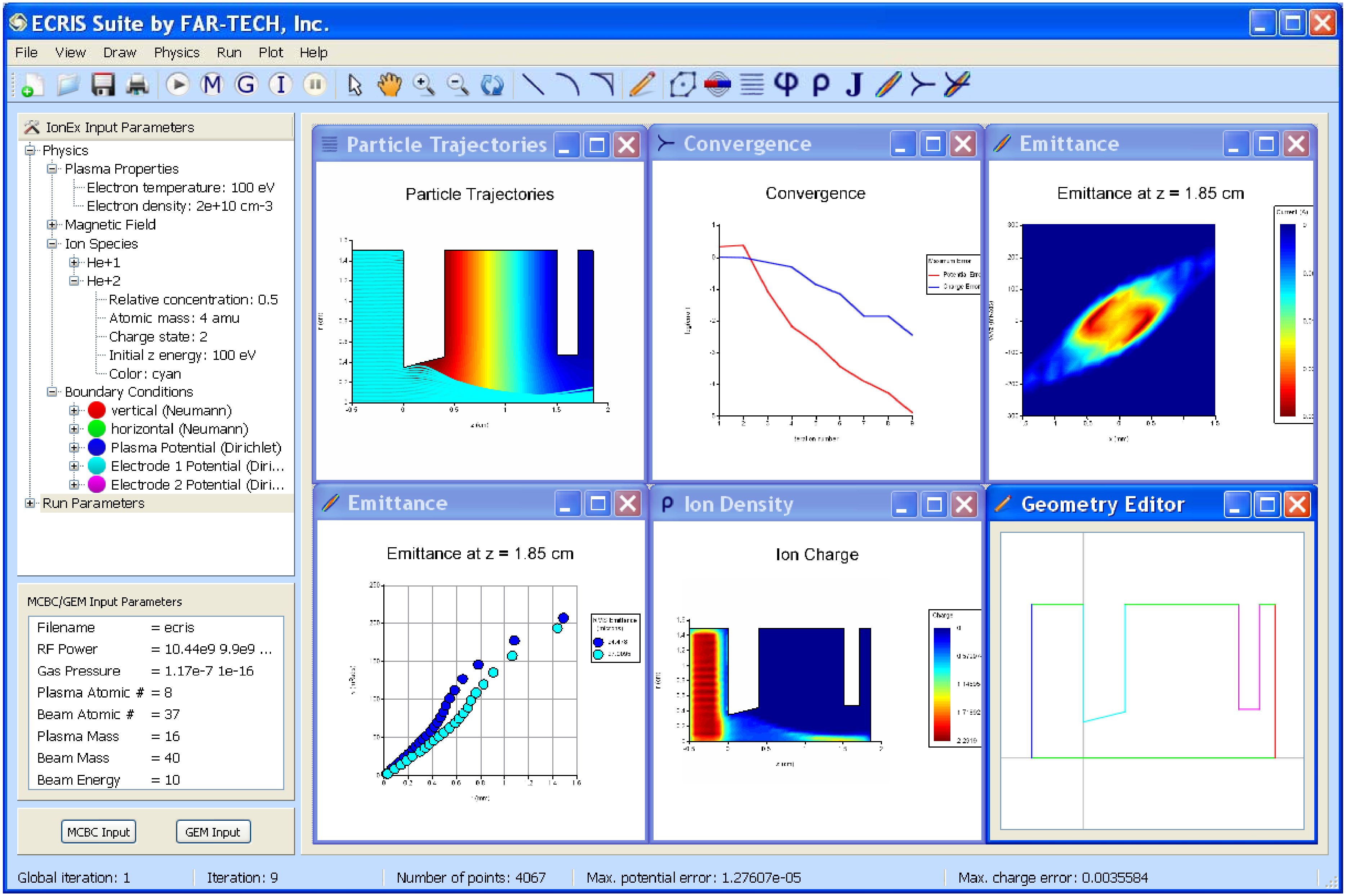
# FAR-TECH's ECRCB modeling toolset begins to provide guidance on ECRCB / ECRIS

- It has provided better understanding of ECRIS plasma and ECRCB through plasma physics and computation.
  – one of the few modeling efforts in the world

- It is the first ECRCB simulation toolset that models from injection to extraction in an integrated manner.

- Integrated modeling provides parameter dependence.
  - Optimum injected beam energy for target charge states

# GUI controls the integration of MCBC, GEM, and IonEx.



IonEx Input Parameters

- Physics
  - Plasma Properties
    - Electron temperature: 100 eV
    - Electron density: 2e+10 cm-3
  - Magnetic Field
  - Ion Species
    - He+1
    - He+2
      - Relative concentration: 0.5
      - Atomic mass: 4 amu
      - Charge state: 2
      - Initial z energy: 100 eV
      - Color: cyan
  - Boundary Conditions
    - 🔴 vertical (Neumann)
    - 🟢 horizontal (Neumann)
    - 🔵 Plasma Potential (Dirichlet)
    - ● Electrode 1 Potential (Diri...
    - 🟣 Electrode 2 Potential (Diri...
- Run Parameters

MCBC/GEM Input Parameters

Filename = ecris
RF Power = 10.44e9 9.9e9 ...
Gas Pressure = 1.17e-7 1e-16
Plasma Atomic # = 8
Beam Atomic # = 37
Plasma Mass = 16
Beam Mass = 40
Beam Energy = 10

Global iteration: 1
Iteration: 9
Number of points: 4067
Max. potential error: 1.27607e-05
Max. charge error: 0.0035584

# Future plan

- The Phase II project ended in Aug 2010.

- Distribution of full executables is still far away.
  - It is best for us to run our codes due to complexity and difficulty of the problem

- Technical support to RIB and ECRIS laboratories is feasible.

- Still much to improve to support ECR CB in an efficient manner! We have plans for improving our models / codes
  - physics model to include 3D mirror fields
  - more robust computational algorithms

# Thanks

# for

# Listening and Support