An Analysis of Fast Sputtering Studies for Ion Confinement Time

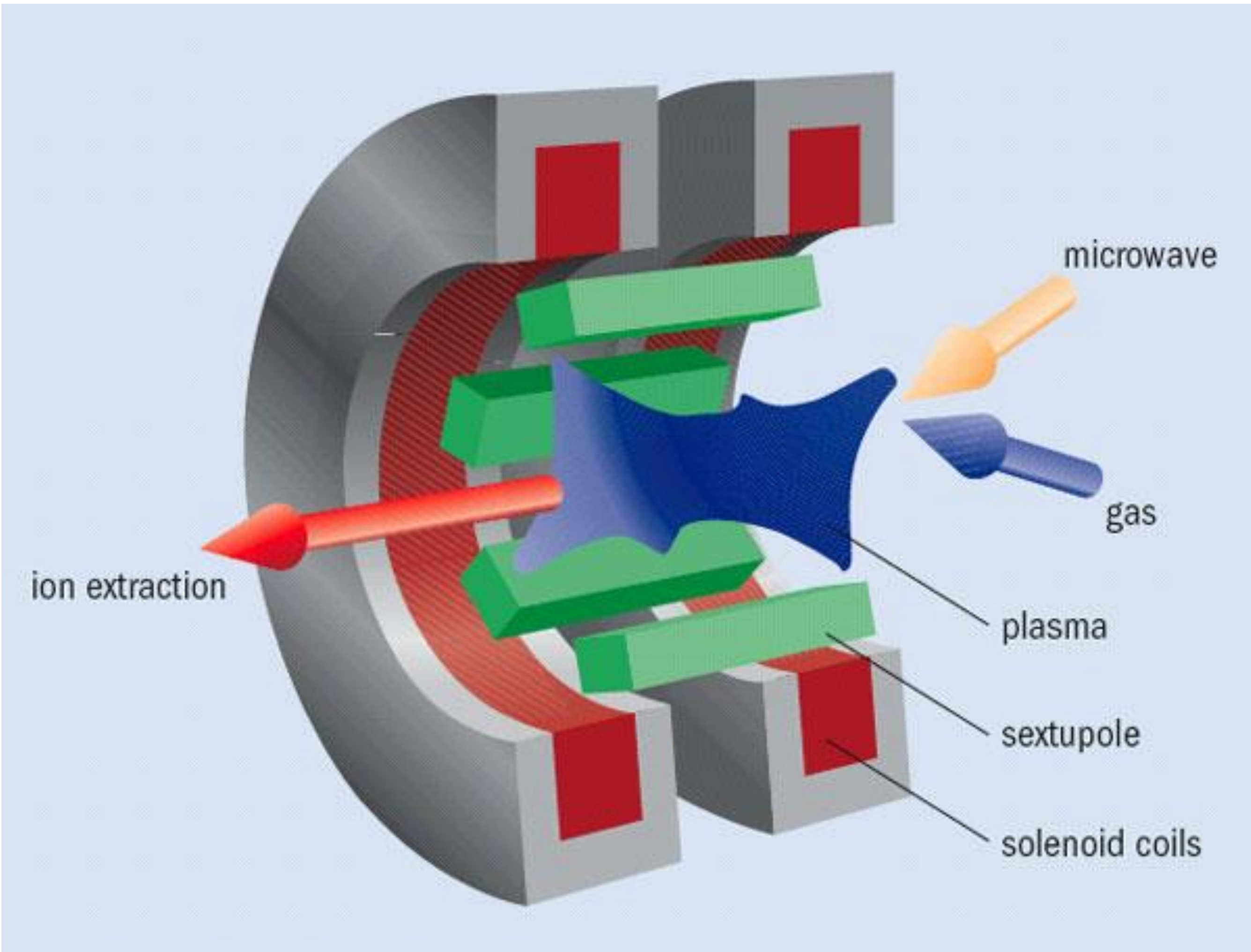
D. Neben*, G. Machicoane, G. Parsey, A. Pham, J. Stetson, and J. Verboncoeur

*neben@nscl.msu.edu

TUPRC032

Abstract

Existing heavy ion facilities such as the National Superconducting Cyclotron Laboratory at Michigan State University rely on Electron Cyclotron Resonance (ECR) ion sources as injectors of highly charged ion beams. Long ion confinement times are necessary to produce dense populations of highly charged ions due to the steadily decreasing ionization cross sections with increasing charge state. To further understand ion extraction and confinement we are using a fast sputtering technique first developed at Argonne National Laboratory (ANL) [1] to introduce a small amount of uranium metal into the plasma at a well-defined time. We present an analytical solution to the coupled ion density rate equations for using a piecewise constant neutral density to interpret the fast sputtering method.



Cartoon drawing of an ECR Ion Source (ECRIS).
D. Leitner, CERN Courier, May 2005

$$\frac{dn_i}{dt} = Sources - Sinks = \alpha_i n_{i-1} + \beta_i n_{i+1} - \gamma_i n_i \quad (1)$$

Rate equation in density for a single ion charge state n_i. Reaction rates γ , α , $and\ \beta$ are assumed to be constant at any given time. Taking a time derivative and substituting equations of the above form for $dn_{i\pm1}/dt$ we find

$$\frac{d^2 n_i}{dt^2} + \gamma_i \frac{dn_i}{dt} = (\beta_{i-1}\alpha_i + \beta_i \alpha_{i+1}) n_i \quad (2)$$

By neglecting all terms of order $n_{i\pm2}$ or higher. This equation may be solved with an exponential function into

$$n_i = c_1 e^{-t/\tau_{i-}} + c_2 e^{-t/\tau_{i+}} + c_3 \quad (3)$$

with

$$\frac{1}{\tau_{i\pm}} = \frac{\gamma_i \pm \sqrt{\gamma_i^2 + 4(\beta_{i-1}\alpha_i + \beta_i \alpha_{i+1})}}{2} \quad (4)$$

as characteristic time constants. We may write the ion beam current extracted from the ion source as

$$I_i(t) = \frac{eQ\kappa V\, n_i(t)}{\tau_i} \quad (5)$$

with the beam line transmission κ, emission volume V charge state Q, and electron charge e, and ion confinement time τ_i [2]. By fitting our decay curves with exponential functions we may state that

$$\tau_+ = \tau_{im} \quad (6)$$

with τ_{im} the measured decay constant. We then solve for the decay rate in terms of the experimentally measured value

$$\gamma_i = \frac{1 - \tau_{im}^2(\beta_{i-1}\alpha_i + \beta_i \alpha_{i+1})}{\tau_{im}} \quad . \quad (7)$$

We are studying ion confinement time in an ECR ion source by introducing a small amount of metal into a gaseous plasma using sputtering and measuring the loss rates of the metal in the extracted beam current.

We assume that the Electron Energy Distribution Function (EEDF) and electron temperature are fixed by the steady state gaseous plasma. In addition we imagine the metal neutral density to be turned off and on instantaneously between two constant values.

We consider only stepwise ionization, charge exchange, and electron recombination reactions.

The reaction rates γ , α , $and\ \beta$ are

$$\gamma_i = n_e < \sigma\nu >_{i\to i+1} + n_0(t) < \sigma_{cx}\nu >_{i\to i-1} + n_e < \sigma_r \nu >_{i\to i-1} - \frac{1}{\tau_i} \ , \quad (8)$$

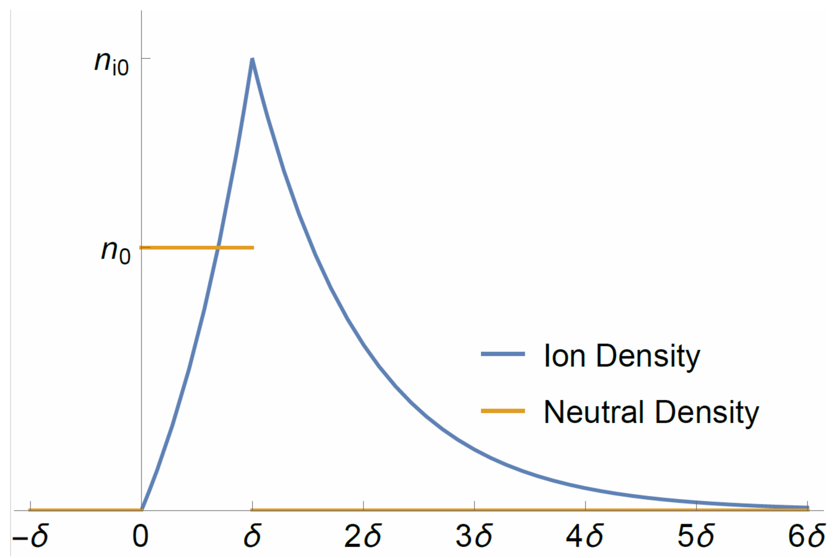
$$\alpha_i = n_e < \sigma\nu >_{i-1\to i} \text{ , and} \quad (9)$$

$$\beta_i = +n_e < \sigma_r\nu >_{i+1\to i} + n_0(t) < \sigma_{cx}\nu >_{i+1\to i} \quad (10)$$

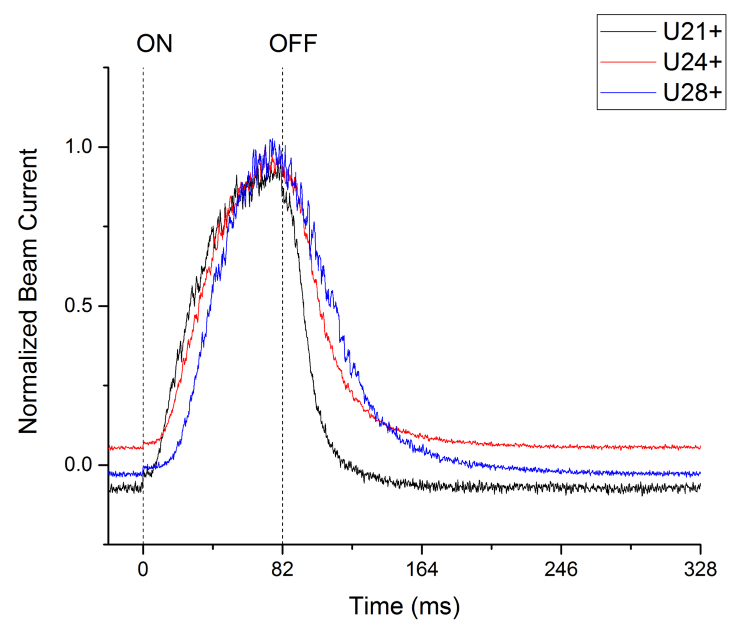
Are substituted into Eq. 7 and solved for ion confinement time into

$$\tau_i = \tau_{im}[1 - \tau_{im}^2 n_e^2(< \sigma_r\nu >_{i\to i-1} < \sigma\nu >_{i-1\to i} + < \sigma_r\nu >_{i+1\to i} < \sigma\nu >_{i\to i+1}) - n_e\tau_{im} < \sigma\nu >_{i\to i+1} - n_e\tau_{im} < \sigma_r\nu >_{i\to i-1}]^{-1} \ . \quad (11)$$

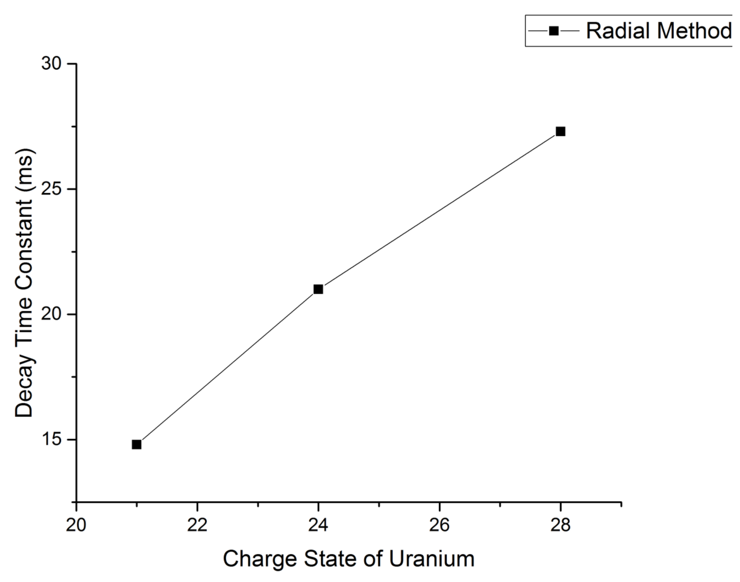
We find if by disregarding all plasma reactions, than $\tau_{im} = \tau_i$, and therefore $\boldsymbol{\tau_{im}}$ ***represents a lower bound for ion confinement in the plasma.***



Ion density equation shown graphically, δ is the pulse width, n_0 is the neutral density, and n_{i0} is the final ion density at the end of the sputter event.



Beam current normalized to the steady state using a radial sputter probe on ARTEMIS. The pulse began at time zero and was applied for 82 ms. Some ion source parameters are tabulated below.



Decay constants from fitting beam current waveforms of uranium (τ_{im}) 18 ms after the high voltage was grounded to 50 ms before the next pulse begins. The beam current waveforms fit well a simple exponential decay function in this region.

	Radial Method
Injection pressure	9.5e-8 mbar
Extraction pressure	7.6e-8 mbar
Total extracted current	1.61 mA
Microwave power	150 W
Sputter Voltage	-700 V

Table of ion source parameters for the Advanced Room TEMperature Ion Source (ARTEMIS) at the NSCL while conducting the fast uranium sputtering experiment.

Summary

We demonstrate that the coupled ion density rate equation may be expanded about the i^{th} charge state and an exponential function satisfies the resulting second order differential equation. In doing so we have assumed the ionization and recombination rates are constant, the neutral density obeys a simple piecewise constant form, and ion densities beyond $n_{i\pm1}$ are zero. Applying this model to beam current decay curves measured from a fast sputtering method represent a lower bound for the ion confinement time of the sampled charge state.

REFERENCES:

[1] R. Vondrasek, *et. Al.*, *Rev. Sci. Instrum.* **73**, 548-551 (2002)
[2] G. Douysset, *et. Al.*, *Phys. Rev. E* **61**, 3015-3022 (2000)

ACKNOWLEDGEMENTS:

This work was supported by Michigan State University and the National Science Foundation: NSF Award Number PHY-1415462

The NSCL is funded in part by Michigan State University and the National Science Foundation.