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A Microwave Resonance Diagnostic for Measuring Characteristics of Pulsed Ion Beams

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ABSTRACT

This paper describes an experiment to characterize ions generated by a pulsed vacuum arc by using a microwave resonant cavity (MRC) as a transient diagnostic. Specific information is desired on the various species which can drift into the beam during repetitive operations of arc plasma generation. The arc source reference voltage is elevated above ground (~200V), which results in a separation of ion species in the beam due to the acceleration experienced by the ions. The cylindrical MRC used in this study has a resonant frequency of ~2.8 GHz when excited by a continuous RF source in the TM_{01} mode of operation. When the neutralized ion beam propagates through the MRC located downstream from the arc source, the resonant frequency of the MRC is shifted by the local disturbance in electric field inside the cavity due to the presence of the electron space charge in the beam. Coupled with the time-of-flight separation of various ion masses, the MRC resonance shift provides a temporally resolved measurement of beam species and density downstream from the vacuum ion source without the use of a potentially invasive diagnostic such as charge collector plates within the beam cross-section. This diagnostic technique should prove useful in a variety of pulsed ion beam studies and applications in research and industrial environments.

Index Terms — **Beam Physics, Vacuum Arcs, RF-Plasma Interaction, Accelerator Physics, Microwave Engineering.**

1 INTRODUCTION

Vacuum arc ion sources have been extensively investigated over the past several decades [1], primarily due to the simple nature of implementing such devices as medium energy (20 – 200 eV) ion sources useful in a variety of materials science applications. Of significant importance is the energy distribution [2] and charge state [3] of metal ions in the beam, in which the desired beam quality may depend. While traditional methods of determining various beam quantities involve using time-of-flight measurements [4], it has been suggested recently [5] that interpretations of these measurements can lead to conflicting conclusions based on the ambiguity of average (as opposed to peak) velocity values of beam ions in various charge states. Additional uncertainty arises due to the practice of using charge collecting plates for beam measurement, where effects such as space charge and ion-induced secondary electron emission complicate interpretation. As a result, there is interest in developing techniques which reduce the uncertainties of time-of-flight techniques and do not require beam interruption during measurement.

Therefore, a new beam diagnostic technique is currently being developed based on the combination of *accelerated time-of-flight* and a *microwave resonant cavity*. When analyzing traditional time-of-flight measurements, heavy ion species tend to slowly diffuse into the beam from the vacuum source and are hard to determine accurately due to the combination of reasonable beam parameters (i.e. multiple charge states, ion species, or source energies). To prevent this blurring due to species uncertainty, an accelerating potential is applied to the source ions which shifts the ion velocity distributions to higher energies. This enables better differentiation of individual mass-to-charge ion states by reducing the spread in time during which the ions propagate down the drift tube. For example, ions with source energies of 50 eV with 25 eV energy spread represent a 50% spread of drift time, while the same ions accelerated to 250 eV represent a 10% spread of drift time. In order to reduce the influence of charge collecting plates on the measured beam signal, a microwave cavity operated at resonant TM_{01} mode is used as the in-line detector. When the neutralized ion beam drifts through the microwave cavity, the internal dielectric properties of the cavity are changed due to the presence of the electrons in the neutral beam. This change induces a shift in the resonant frequency of the microwave cavity, which can be detected by fast rise-time microwave electronics as a function of beam electron density without interrupting the beam drift.

2 ACCELERATED TIME-OF-FLIGHT

The experiment consists of a surface flashover arc generated between two titanium wires separated (<1.0 mm) by a graphite track atop a ceramic insulator bridge. A pair of high voltage power supplies applies a differential charging voltage to an intermediate storage capacitor (20 μF) isolated from ground potential. The capacitor is discharged into the ion source assembly via a TTL triggered fast rise-time high power

MOSFET switch (HTS-31-12-B) supplied by Behlke Electronics. A typical differential charging voltage of 1400V is sufficient in generating a dense plasma arc in 4.0 mTorr H_2 atmosphere. An 8.0 cm ion drift tube is electrically connected to the ion source cathode, and can be raised to a potential above ground (typically 100 – 500V) due to the isolation from the surrounding vacuum assembly. The ion drift tube is terminated by a mesh screen which is separated (< 1.0 mm) from a grounded mesh screen, forming an ion acceleration region. The result is that ions: are created by the arc source at a potential above ground, proceed through the ion drift tube at this potential, and are accelerated as they enter the downstream vacuum chamber via the grounded mesh screen.

Upon leaving the ion drift tube, the ions proceed through a beam neutralization region where plasma electrons are captured by the ion space charge [6]. Free electrons are initially produced by thermionic emission of a thoriated tungsten filament, with initial energies provided by a static voltage (-60V) applied to the filament. In this mode roughly 100 mA of DC electron current can be extracted from the filament into the surrounding volume. These electrons undergo collisions with the low pressure (4.0 mTorr) atmosphere in the neutralization region, producing stable quasi-neutral low temperature plasma throughout the volume. When the ions propagate through this quasi-neutral plasma, electrons are captured by the ion space charge producing a quasi-neutral beam. This neutralized beam enters the time-of-flight drift tube (110 cm) with limited space charge induced beam spreading, and is detected by isolated charge collecting plate(s) at the end of the vacuum beam line. A pair of turbo vacuum pumps allows for differential vacuum pumping between the ion neutralization region (4.0 mTorr) and the time-of-flight drift tube (10^{-6} Torr), thereby reducing the probability of beam-atmosphere collisions during the drift time.

For the initial series of accelerated time-of-flight measurements (see Figure 1), a charge collecting plate is used as the detector. When the plate is charged to a static voltage of 50V, electrons from the quasi-neutral beam are primarily measured by the detector. The series of beam measurements consist of 15 averaged time-of-flight responses for various ion acceleration voltages. These measurements are compared to calculated time-of-flight predictions (a.u.) based on uniform ion emission from the source arc (2 – 40 eV) of H^+, C^+, and Ti^+ ion species. For a relatively small ion acceleration voltage (100V), the time-of-flight response for heavy ions (C^+ or Ti^+) still exhibits the temporal blurring due to the large spread in initial ion energies from the arc source. For example, an initial Ti^+ energy of 20 – 40 eV results in a time-of-flight response almost 10 μs wide. Furthermore, we expect C^+ ions due to the presence of graphite in the source arc, yet it is uncertain whether 8 – 20 eV C^+ ions are in the time-of-flight response. In fact, the entire broad spectrum from 20 – 50 μs could be caused by multiple energies or charge states (Ti^{2+}, Ti^{3+}, etc.) of titanium ions if analysis were dependent on this picture alone.

As the ion acceleration voltage is increased to higher values

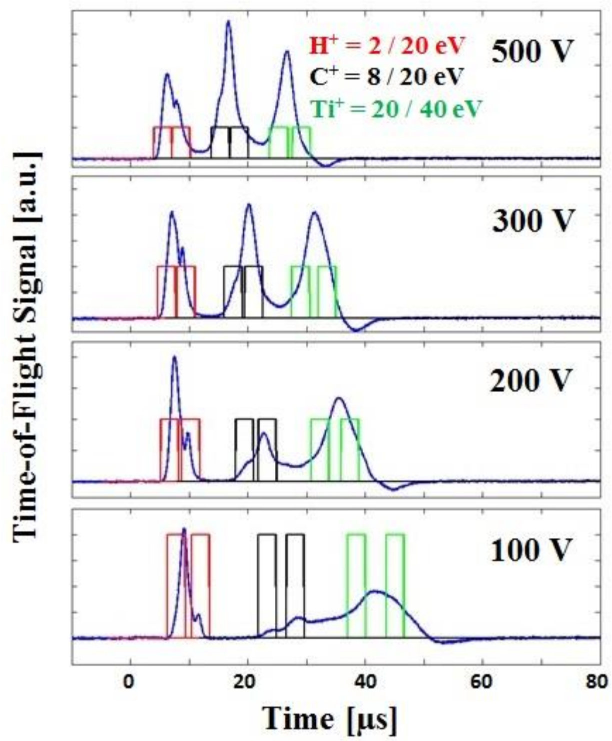

Figure 1. Time-of-flight spectra measured via charge collecting plate as ion acceleration voltage is changed. The response is compared to calculated time-of-flight predictions (a.u.) based on uniform emission of H^+, C^+, and Ti^+ ions from the source arc.

(500V), the spread of initial ion energies from the arc source is a much smaller percentage of the total ion energy in the drift region. As a result temporal spreading is significantly reduced and sharp peaks appear in the time-of-flight response less than 4.0 μs wide. It is therefore much easier to identify ion species using the accelerated time-of-flight technique, however uncertainty still exists due to the method used for measurement (i.e. charge collecting plates).

3 MICROWAVE RESONANT CAVITY

For the second series of experiments, a microwave cavity is used as the detector while the accelerating stage is removed from the ion drift length. The microwave cavity is designed [7] such that the resonant frequency falls in the 2.8 GHz range for TM_{01} mode of excitation, resulting in a cylindrical cavity with 2.54 cm axial length (L) and 4.10 cm radius (a). A hole (b = 0.64 cm) has been removed from both ends of the cylindrical cavity so that the neutralized beam can drift through the cavity volume along the beam axis. Initial testing showed a strong resonance peak at 2.79 GHz with 1.55 MHz bandwidth, corresponding to < 0.5% design deviance and a cavity quality factor of > 1800. As quasi-neutral beam plasma drifts through the cavity volume, the beam electrons cause a change in the dielectric properties of the cavity (due to microwave-plasma interaction) and the resulting cavity resonance is shifted to higher values. The amount of resonance shift can be approximated by [8]:

$$\frac{\delta\omega}{\omega_0} \approx \frac{\mathrm{n_e}\, e^2 \left(\frac{b}{a}\right)^2}{0.54\, m_e\, \varepsilon_0\, \omega^2} \quad (1)$$

where n_e is the electron density in the beam, m_e is the mass of the electron, and ε_0 is the vacuum permittivity. If the cavity is operated at slightly below (0.4 MHz) vacuum resonance, the resulting frequency shift follows the approximately linear portion of the Lorentzian resonance distribution for reasonable plasma densities (10^7 – 10^9 cm^{-3}). The shifted microwave signal is converted to an analog signal via a crystal detector and is measured by a fast rise-time digitizing oscilloscope.

A typical microwave signal recorded due to quasi-neutral beam drift from the ion source is given in Figure 2. The recorded electron density perturbation must be converted to average ion density, which is proportional to the integral of total electrons within each temporal density peak. Lighter ions spend less time drifting through the cavity due to their increased velocity, while heavier ions record a stronger signal due to the increased residence time of co-moving electrons in the cavity. Similarly, ions with higher charge states attract more neutralizing electron space charge and can therefore result in a higher recorded signal. The average ion density from each recorded electron density peak can be estimated by:

$$\langle \mathrm{n_i} \rangle \approx \frac{\mathrm{v_i}}{\mathrm{q_i}} \frac{\int \mathrm{n_e}\, dt}{L} \quad (2)$$

where v_i and q_i are the velocity and charge state of the beam ions. Performing this calculation for the small leading peak (from fast H^+ ions in the beam) results in an estimated H^+ density of 8.7×10^8 cm^{-3}, while the much larger trailing peak (from slow Ti^+ ions in the beam) corresponds to an estimated Ti^+ density of 6.5×10^8 cm^{-3}. Despite the much higher (by a factor of four) Ti^+ signal compared to the H^+ signal, the actual average Ti^+ density is much lower due to the increased residence time of slow moving Ti^+ ions. If neutral beam diffusion from the source can be approximated ($\sim R^2$), the estimated ion source (arc plasma) density is of order 10^{14} cm^{-3}.

4 CONCLUSIONS

Initial experiments using an arc ion source have demonstrated accelerated time-of-flight as a mechanism for reducing temporal uncertainty in time-of-flight measurements of ion beam species. Similarly, the microwave resonant cavity was successful in un-obstructively recording the average ion density in quasi-neutral beams with densities 10^7 – 10^9 cm^{-3}. However, initial attempts to combine the diagnostics were limited due to the reduction of average beam current through the mesh gratings used in the accelerator structure resulting in

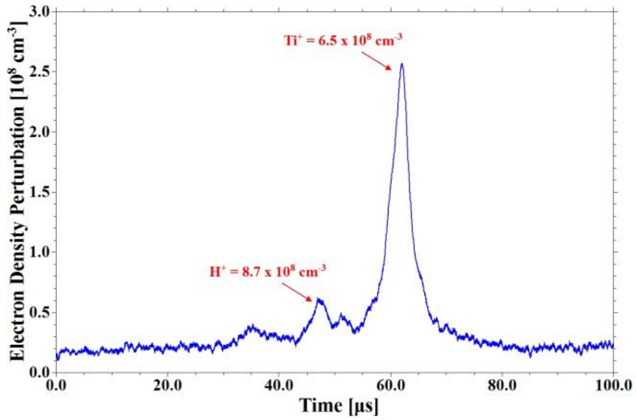

Figure 2. Time-of-flight spectra (in the form of electron density perturbation calculated via Equation 1) recorded using the microwave resonant cavity.

below threshold response of the microwave resonant cavity. Current studies aim to increase the ion densities escaping the accelerator gap by altering the plasma sheath structure along this interface through various improvements to the accelerator design. If successful, accelerated time-of-flight recorded via a microwave resonant cavity should prove useful as a tool for understanding the dynamics of vacuum ion source performance in a variety of industrial environments.

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