RF FIELD EFFECTS ON THE CYCLOTRON ARC SOURCE

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Abstract. - By exploiting recent developments in plasma physics a program to diagnose changes in source properties during ion beam extraction has been initiated to improve source efficiency. A small cyclotron with a conventional hooded arc provides radiation from excited species (H_β and the 4685 Å line of HeII) which is spectrally analyzed and detected by a high-frequency photomultiplier. The intensity of the radiation is sensitive to changes in the electron and ion densities, and enables an analysis of the effect of the RF field on the plasma properties of the source. We have evidence that coupling of the RF extraction field to normal modes of the plasma - the Electrostatic Ion Cyclotron waves - occurs, permitting RF field penetration to the entire plasma column and large beam extraction.

1. Introduction.- A study has been initiated of the process through which the RF field extracts ions from a typical cyclotron source, with a view to increasing beam current and upgrading source performance. The impetus for this work stems from observations that, when beam extraction was repetitively suppressed over a number of RF cycles, the average beam current remained nearly constant, instead of decreasing. This result suggests that if the interaction between the RF field and plasma were understood, ion sources could be operated to yield higher instantaneous beam currents.

Measurements of the inter-relationship between ion density in the source, extracted beam current, RF power, magnetic field, and discharge parameters such as arc current and pressure are reported. Optical diagnostics to infer changes in ion density without perturbing the arc properties are the principal tool. Such methods are rapidly developing in plasma physics; an early measurement of RF modulation of Balmer lines was performed by S. M. Hamberger$^{1)}$ in 1963, and used to infer the effect of the RF field on the discharge electron density.

2. Instrumentation.- The ion source test facility is a miniature cyclotron, comprised of a magnet, vacuum chamber, a single dee, and a hooded-arc source. A Faraday cup near the source collects beam current. The vacuum chamber has ports and windows oriented so that the source can be viewed optically with low f-number lenses. Magnetic field strength ranges up to 9 KG, and an RF source capable of 10 KV peak-peak at about 3 MHz excites the dee. RF extraction only is used. Fig. 1 shows the plan of the device.

Optical radiation from the source, or a region within it, can be spectrally resolved, and is detected by a fast photomultiplier. Real-time instrumentation: heterodyne detector, boxcar averager or phase-lock amplifier, are used to process the light signal.

Tests have been carried out with H and He discharges. In H discharges the optical signal stems from neutral atoms, not the extracted species, whereas in He, we use the line emission from the ion itself. Thus in H, changes in emission intensity, I, are due to changes in the electron density and temperature primarily. The RF field modulates these electron properties, which via collisions modulate I, as shown by Hamberger$^{1)}$ under equivalent conditions. Assuming the discharge to be neutral overall, we can expect the ion number density to differ very little from the electron density. Thus under conditions when the electron temperature is relatively un-influenced by the RF field, the changes in I in H discharges can be expected to be roughly linearily related to the changes in H^+ density.

This assumption is consistent with measurements of I versus discharge current, J, shown in Fig. 2. This shows the integrated intensity in the Balmer H line at 4861 Å to be linear in J. In gas discharges at our conditions, J is known to be linear in the electron density n_e. We expect changes in I at this line to be a linear indication of changes in H^+ density.

Note that the linear I vs n_e relation implies that electrons in the discharge are energetic enough to dissociate the H_2 molecule and excite the atom in a single collision. This requires that the electron acquires in the discharge an energy of order 10-100 V, which is the net voltage across the discharge. Thus, electrons undergo on the average only one collision during their transit from cathode to anode. We conclude that the principal effect of the RF field on electrons in H discharges will be to modulate n_e, and not the electron temperature T_e. This, again, allows us to consider that changes in I reflect linearily changes in the H^+ ion density, rather than some convolution of density and temperature.

The situation is more complicated in He discharges. Depending upon filament current, the I vs. J relationship at the 4686 Å line of He^+, shown in Fig. 2, varies from linear to quadratic. The linear relation implies that electrons are sufficiently energetic to ionize and excite the atom in a single collision. The quadratic dependence indicates that the electron energy is much lower; here I is taken to be proportional to the product $n_e \cdot n_i$ of electron and ion density, since in one collision the average electron ionizes the atom, and a second collision with this target is necessary to excite it. Assuming neutrality, it turns out therefore that $I \propto n_i^2$.

The simplest method to detect changes in source properties induced by the RF field is to modulate the field strength at a convenient low frequency, and observe the corresponding changes in I. Note that if the only effect of the field were to sinusoidally modulate the density of electrons (in H) or ions (in He^+), viewing the effect over many RF periods would show no net change in intensity I. Thus, changes in I must be interpreted as being due to 1) changes in the average electron and ion density of the source, caused by the RF field, and/or 2) a non-linear modulation in the instantaneous density, responsible for a non-zero-average density change.

3. Experimental results. - Fig. 3 shows a typical result obtained in H. The intensity, I, of the Balmer line is seen to be 180° out of phase with the RF field strength, i.e., when the RF is on, the emission is reduced. For normal cyclotron operation, $\omega=\omega_{ci}$, the ion cyclotron frequency ω_{ci} is below the lowest eigen-frequency of the discharge plasma, so the plasma screens the applied electric field from the bulk. Only a thin sheath of the order of the Debye length is directly affected. Ion flow from the discharge center towards the edge is increased by the RF field; the bulk ion density decreases slightly as indicated by our observations.

An essential question is whether the field-induced changes in discharge density described above occur during a single RF cycle? This requires measurement of the time-dependence of I with a period short in comparison with the RF period. In a heterodyne scheme the photomultiplier signal is fed to a crystal and mixed with a reference (local oscillator) signal at a frequency ω_{LO} displaced from the RF frequency ω. The difference frequency $(\omega_{LO}-\omega)$ is filtered and amplified in a narrow-band device, and fed to a phase-sensitive detector and to a boxcar integrator. Both the detector and integrator are referenced (triggered) by an independent signal at the same difference frequency $(\omega_{LO}-\omega)$, obtained by mixing the RF field with the local oscillator signal in a separate mixer-filter circuit. Here the phase-sensitive detector and boxcar integrator extract the component of I coherent with the RF frequency.

The results shown in Fig. 4 confirm that the light signal, I, has an appreciable component synchronous with the RF field. It is delayed in phase, and also has a non-sinusoidal shape. These results qualitatively indicate that the RF-induced ion beam extraction "loads" the discharge ion density during a single cycle. The phase shift and response form give diagnostic information about the details of the process. However, details require wider bandwidth amplifiers than are used now.

4. Interpretation. - The preceding results suggest that only a small sheath region surrounding the bulk of the discharge is capable of supporting the applied field. What conditions permit the field to penetrate further into the plasma, by allowing it to couple of a normal mode? Recent studies$^{2)}$ of magnetized plasmas in the presence of applied RF fields in the vicinity of the ion cyclotron frequency and its harmonics, where normal modes with appreciable electric field components normal to the static magnetic field can be excited, show evidence for particle (ion) transport across the field. This has been unequivocally confirmed in isotope-separation experiments,$^{3)}$ as well as in current diffusion tests using optical tagging of individual ion groups. We have therefore carried out measurements of RF field penetration into the source region, using the previous optical technique, under conditions where such normal modes can occur.

In the conventional cyclotron geometry, these conditions are incompatible with efficient operation, because these modes all occur at frequencies in excess of ω_{ci}, the condition for optimum particle acceleration. Conditions for optimum field penetration into the source are expected to occur at a magnetic field not optimized for acceleration. At a later stage we will attempt to reconcile the two sets of conditions.

A plasma mode appropriate for our purposes is the electrostatic ion-cyclotron waves (EICW), the simplest of which has the dispersion:

$$\omega^2 = \omega_{ci}^2 + k^2 c_s^2 \qquad (1)$$

where ω is the wave frequency, k the propagation wave number, and c_s the "ion sound speed," roughly given by:

$$c_s^2 = \frac{k_B T_e}{m_i}$$

Here k_B is the Boltzmann constant, T_e the electron temperature and m_i the ion mass. For the excitation of this mode, the product of wavenumber and plasma diameter, kd, has to be >1. In our case d of order 2 mm requires k of order 5 cm^{-1}. For H^+ masses and T_e of order 10 eV, as in our discharges, the product kc_s required is therefore of order 10^7 sec^{-1}. For our frequencies f=3 MHz, i.e. $\omega \approx 2\times10^7$, eq. (1) can be satisfied only for $\omega_{ci} \approx \omega/2$. RF frequencies suited for acceleration cannot excite EICW modes.

Ohnuma et al.$^{4)}$ have shown that $\omega \approx 2\omega_{ci}$ EICW can be generated and are strongly absorbed by the plasma. Fig. 5 illustrates some similar results. At low RF fields a resonance appears in the optical modulation of the He^+ 4686 Å line at magnetic fields of 4.7 KG where $\omega/\omega_{ci} \approx 1.7$.

As RF intensities increase, the resonance is enhanced, but becomes superposed on an overall magnetic-field-independent increase in modulation. The overall increase in modulation may be interpreted as due to electron heating by the RF field in the sheath, a well-known process leading to strong excitation as well as enhanced ionization. At even higher magnetic fields, $\omega/\omega_{ci}<1$, a complicated pattern of modulation is observed when the RF field is sufficiently high. A sharp increase in modulation is observed followed by abrupt saturation near 10 KV at $\omega/\omega_{ci}=0.7$. Under such conditions RF fields are known to cause second-harmonic as well as sub-harmonic excitation, so that the normal linear dispersion relations are no longer operative. Measurements of extracted beam from a hydrogen plasma show significant enhancement near $\omega/\omega_{ci} \approx 2$. Fig. 6 is an example of these results. For a fixed RF frequency, higher extracted beam occurs when the magnetic field is tuned to the vicinity of the second harmonic. Also note that as RF power is increased, the extracted beam at $\omega/\omega_{ci} \approx 2$ grows at a much greater rate than near the fundamental. This strong scaling could be very important, considering that cyclotrons usually operate at much higher RF voltages than are used here. These results support our belief that typical ion source luminosities can be enhanced.

Means to reconcile the conditions for optimum source luminosity and acceleration represent the goal for our further investigation.

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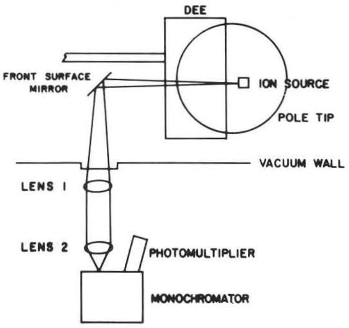

Fig. 1 : Miniature cyclotron optical system (not to scale)

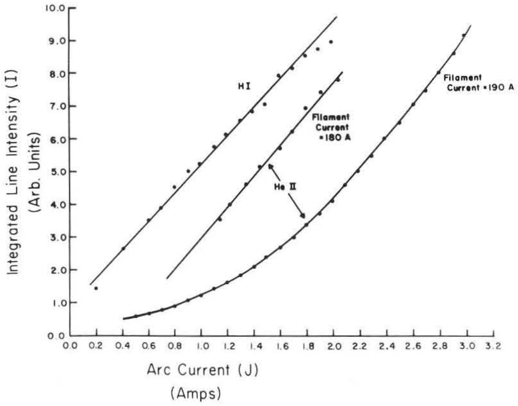

Fig. 2 : Source arc optical emission at 4861 Å for hydrogen and 4686 Å for helium versus arc current. Note the difference between curves for HeII different average electron energy.

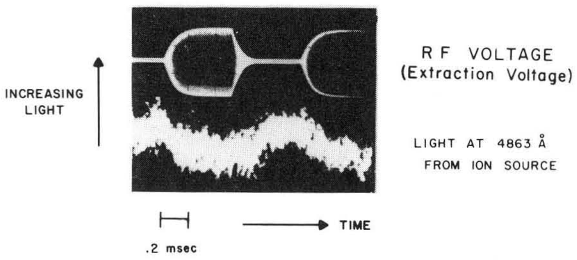

Fig. 3 : Light emission and corresponding RF voltage at $\omega \approx \omega_{ci}$ in hydrogen plasma, where ω_{ci} is ion cyclotron resonance frequency. Change in light results from the time average nonlinear effect of the R.F. field.

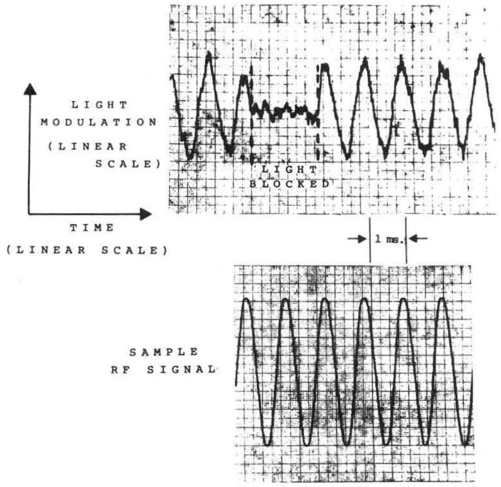

Fig. 4 : Heterodyned RF coherent intensity modulation of ion source.

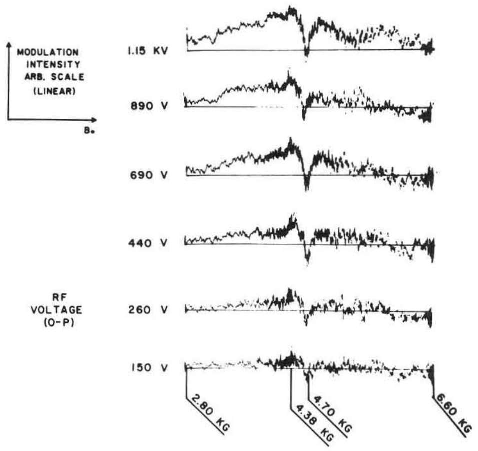

Fig. 5 : HeII (4683 Å) intensity modulation vs. magnetic field. Dip occurs at $\omega/w_{ci} \approx 1.7$.

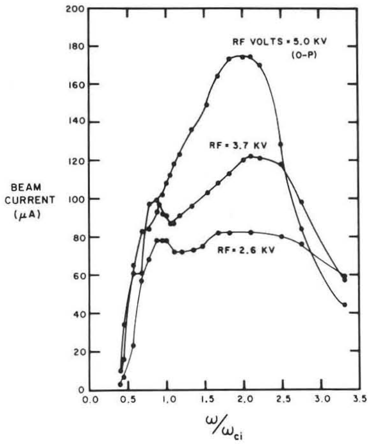

Fig. 6 : Hydrogen source emission current versus ω/ω_{ci} for fixed RF frequency and varied magnetic field. A normal cyclotron operates at $\omega/\omega_{ci} = 1$