The HIPAC ion source; recent theory and experiments*

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Presented by J. D. Daugherty

ABSTRACT

The HIPAC Ion Source is a novel device intended to produce very highly stripped heavy ions. The achievement of this objective would permit the acceleration of heavy ions in relatively modest cyclotrons. This ion source is presently conceived as a toroidal vacuum chamber of about 20 cm major radius and 3 cm minor radius. An azimuthal magnetic field contains a cloud of $\approx$ 10 keV electrons having a density of $10^{11}/\text{cm}^3$. This cloud forms a toroidal electrostatic potential well which will trap and contain ions as long as the electron cloud remains stable. The 10 keV kinetic energy of the electrons results in an electron impact ionisation flux of $\sim 10^6$ W/cm^2. The effective electron beam power of the source is several hundred megawatts but is wholly reactive. Recent theoretical work has produced estimates of the ion source emittance of $\sim$ 100 mm mrad (MeV/nucleon)$^{1/2}$.

Recent experiments have achieved electron cloud containment times of 5 ms, which were limited solely by vacuum conditions. Electron densities of $7 \times 10^9/\text{cm}^3$ have previously been achieved in a 10 cm minor radius experiment, which should scale directly to $\sim 2 \times 10^{10}/\text{cm}^3$ in a 3 cm device. Our current research is directed to extending containment times to the range of ion source interest (0·1 to 4 s), to increasing the electron density and to demonstration of stripping and extraction of heavy ions. The current status of this research and the prospects for the HIPAC Ion Source are reviewed.

1. INTRODUCTION

Since the cost and size of a heavy ion cyclotron decrease strongly as the stripping state of the ions to be accelerated is increased, there currently exists considerable interest in new, highly stripped ion source concepts. These sources include novel electron beam concepts[1-3] and laser sources[4] as well as the proposed use of a conventional accelerator, typically a large Van De Graaff, together with

* Supported by Contracts AEC (AT (30-1) -3863) and AFOSR F44620-69-C-0095

foil(s) as the cyclotron source. In this paper we wish to describe the present theoretical and experimental status of the HIPAC Ion Source, an electron beam ionisation device. The concept of the HIPAC Ion Source and some of its properties have been described elsewhere.[1,5] For clarity we shall briefly review its basic properties here.

The HIPAC Ion Source is conceived as a small toroidal vacuum chamber such as shown in Fig. 1. The physical size and some of the relevant parameters are listed[5] in Table 1. The fundamental feature of this device is that we propose to contain in it a cloud of essentially unneutralised electrons

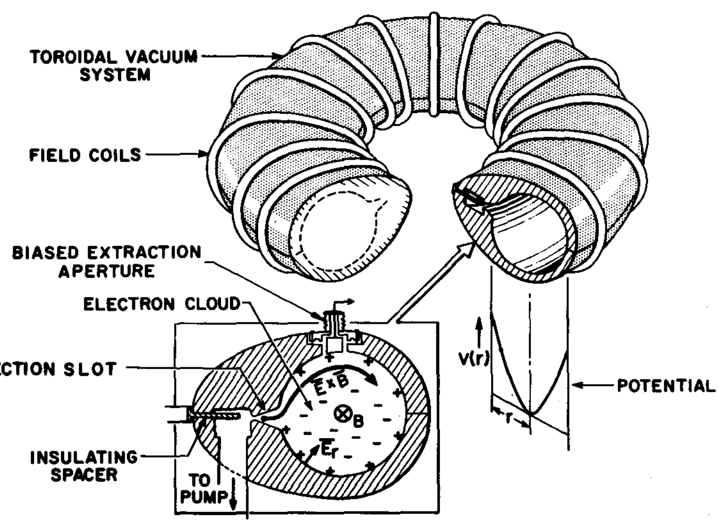

Fig. 1. Conceptual configuration for a HIPAC Source of highly stripped heavy ions

by means of an azimuthally symmetric magnetic field. The equilibrium for this electron cloud is dynamic rather than static, as the cloud rotates about (approximately) the centre of the toroidal minor cross-section. This rotation corresponds to electron kinetic energies of ~ 10 keV. The motion arises from the adiabatic ($\underset{\sim}{E} \times \underset{\sim}{B}/B^2$) motion of the electrons under the combined influence of the space charge electric field and the magnetic field. The electrons are thus sufficiently energetic to highly strip any atom, for example U^{60+}.

The principal problem with electron beam stripping of atoms to high ionisation states is that as Z_{eff} increases the ionisation cross-sections become very small. Thus the residence time for an ion within the electron beam must be made very large, as shown, for example, in Fig. 2, for a 10^6 W/cm^2, 10 keV beam. This long residence time is accomplished automatically in the HIPAC Ion Source by the negative potential well created by the unneutralised electron cloud. Since this cloud is toroidal, this potential well forms an ion trap which nowhere intersects a material surface. Ion residence time is therefore limited solely by electron cloud containment. We discuss the status of this critical area in Section 3.

We should also point out that the HIPAC source is a pulsed source; the repetition frequency is of the order of the inverse of the ionisation time, Fig. 2. The extraction time may be nearly as long as the ionisation time or much

Table 1. NOMINAL PARAMETERS OF A HIPAC ION SOURCE

Minor radius	3 cm	Electron gyro frequency	13 GHz	
Major radius	20 cm	Electron plasma frequency	2·9 GHz	
Volume	3·6 × 10^3 cm^3	Electron circulating frequency	320 MHz	
Surface area	2·4 × 10^3 cm^2	Circulating power	100 MVAR	
		$q = \omega_p^2/\omega_c^2$	5 × 10^{-2}	
Electron density	10^{11} cm^{-3}	Ion density	$10^{10}/Z_{eff}$ cm^{-3}	
Total electrons	3·6 × 10^{14} or 60μ coul.	Total ions	3·6 × $10^{13}/Z_{eff}$	
Peak electric field	270 kV/cm	Ion oscillation frequency	24 MHz	
Potential well depth	400 kV			
Magnetic field	0·45 Wb/m^2	Base vacuum	~5 × 10^{-10} torr	
Drift speed	6 × 10^9 cm/s = 0·2 c	Outgassing	~10^{-11} torr litre/cm^2 s	
Electron drift energy	10 keV			
Magnetic field energy in the torus	300 J		U^{60+}	U^{40+}
Electric field energy	6 J	Stripping time	4 s	0·4 s
Total drift energy	0·3 J	Mean particle rate (~5 states)	1·6 × 10^{11}	2·5 × 10^{12}
Magnet current	450 kA turns			
Magnet power	100 kW			
Magnet weight	100 kg			

This nominal design makes use of the experimentally supported semi-empirical scaling laws discussed in Section 3, and of the calculated ion stripping times shown in Fig. 2.

shorter depending[5] upon the desired duty cycle, and emittance. While it seems probable to us that any other electron impact ionisation scheme will also result in a pulsed source, it is also clear that multiplexing of several sources can produce a nearly continuous beam if this is essential.

Another consideration when attempting electron impact ionisation is the total power required. For yields comparable to those quoted in Table 1, a beam power of the order of 100 MW is required. In the HIPAC source, this beam power arises from the cloud rotation and so is entirely reactive. We therefore characterise the device described in Table 1 as possessing a power 100 MVAR. The actual operating power requirements are determined by magnet copper losses and have been estimated in Table 1 at only 100 kW.

We plan to extract highly stripped ions from the HIPAC source by using grids to lower the electrostatic potential well over a small surface, thus forming

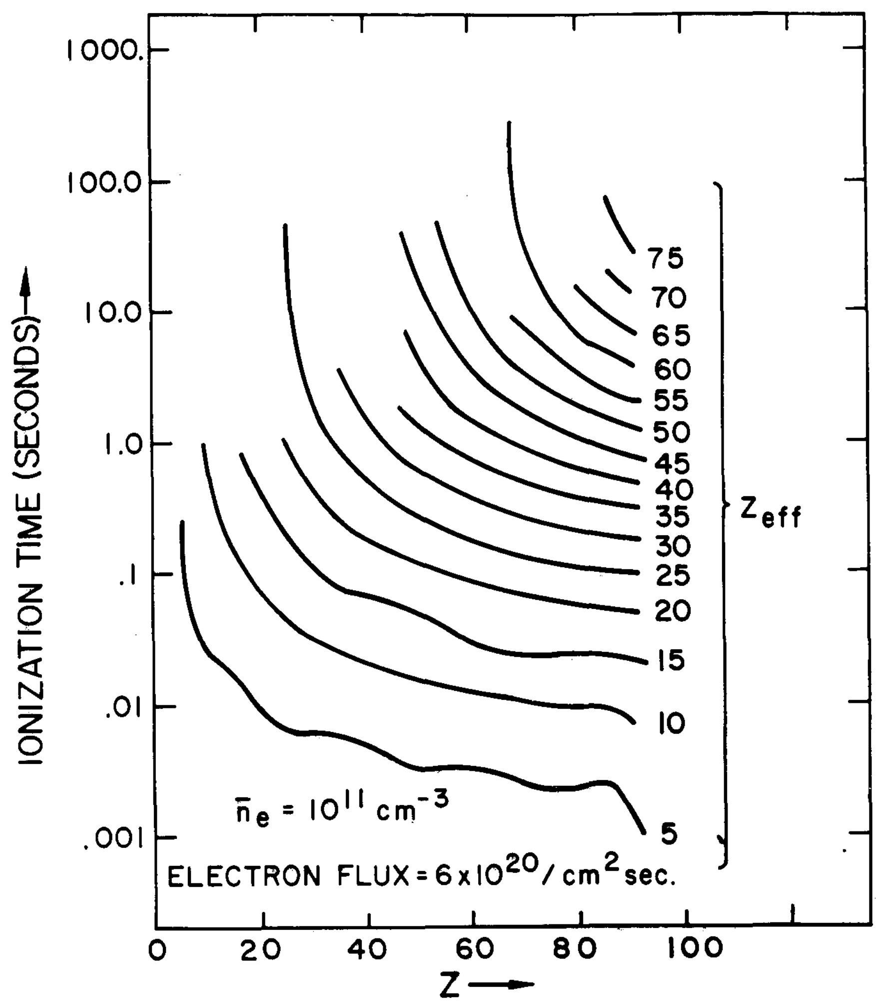

Fig. 2. Calculated electron impact ionisation times vs Z. The parameter Z_{eff} is the number of electrons stripped from the atom. Note that the assumed electron beam carries a current density of 100 A/cm² at 10 kV corresponding to a power density of 1 MW/cm²

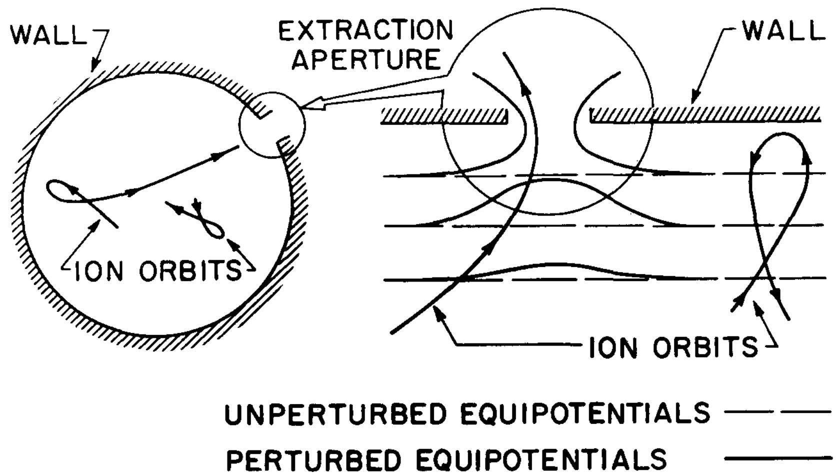

Fig. 3. Conceptual equipotential configuration and particle trajectories near the extraction aperture of a HIPAC Ion Source. The unperturbed equipotentials arise from the space charge of the electron cloud. The indicated perturbation of these potentials is produced by a suitable arrangement of biased electrodes and/or grids

a 'pass' through which the ions having sufficient total energy can escape. The electric field configuration for this scheme is shown in Fig. 3. Most of the particles which have sufficient energy will find the 'pass' and rapidly escape. The energy of those remaining trapped will be raised by reducing the magnetic field and thus causing the loss of a few electrons. This lowers the electrostatic well depth—effectively raising the energy of the trapped ions with respect to the wall. This extraction process may be continuous or pulsed as desired and is continued until almost all of the stripped ions have been extracted. For completeness in this brief review, we repeat[5] Fig. 4 which estimates the ion yields we anticipate from the HIPAC Ion Source.

The emittance of the beam extracted from the HIPAC Ion Source is becoming easier to estimate. We have previously estimated,[5] for a beam of U^{40+}, an emittance of ~ 300 mm mrad $(\mathrm{MeV/nucleon})^{1/2}$ based upon what we thought were reasonably conservative assumptions. While we have not yet obtained the experimental preconditions necessary for actually studying beam emittance, we shall report in Section 2 the results of recent theoretical studies further refining the above estimate.

2. THEORETICAL EXTRACTION STUDIES

As mentioned in the introduction, we have previously estimated that the emittance of the HIPAC Ion Source for U^{40+} would be expected to be <300 mm mrad $(\mathrm{MeV/nucleon})^{1/2}$, based upon what we felt was a conservative assumption as to the value of the random velocity component perpendicular to the extraction aperture. We took the speed to be ~ 5 keV/nucleon; i.e. ~ 10^8 cm/s.

In what follows we shall review our efforts to refine this estimate by summarising (1) the results of acceptance calculations for a convenient extraction aperture and electric field configuration, (2) the results of analytically estimated bounds on the phase space occupied by the stripped ions as the result of ionisation and toroidal ion orbit distortion, (3) the results of computer studies exemplifying the conservatism in the analytically estimated bounds, and (4) the results of ion-ion coulomb scattering. The net result is that it appears that emittances of the order of $\leqslant 100$ mm mrad $(\mathrm{MeV/nucleon})^{1/2}$ are likely to be achieved.

2.1. *Extraction aperture acceptance*

Fig. 5 shows the equipotentials for an electric field configuration which we have studied. The zero equipotential is an ideally thin plane HIPAC wall; one of the neighbouring equipotentials of course being the choice for the wall of a practical

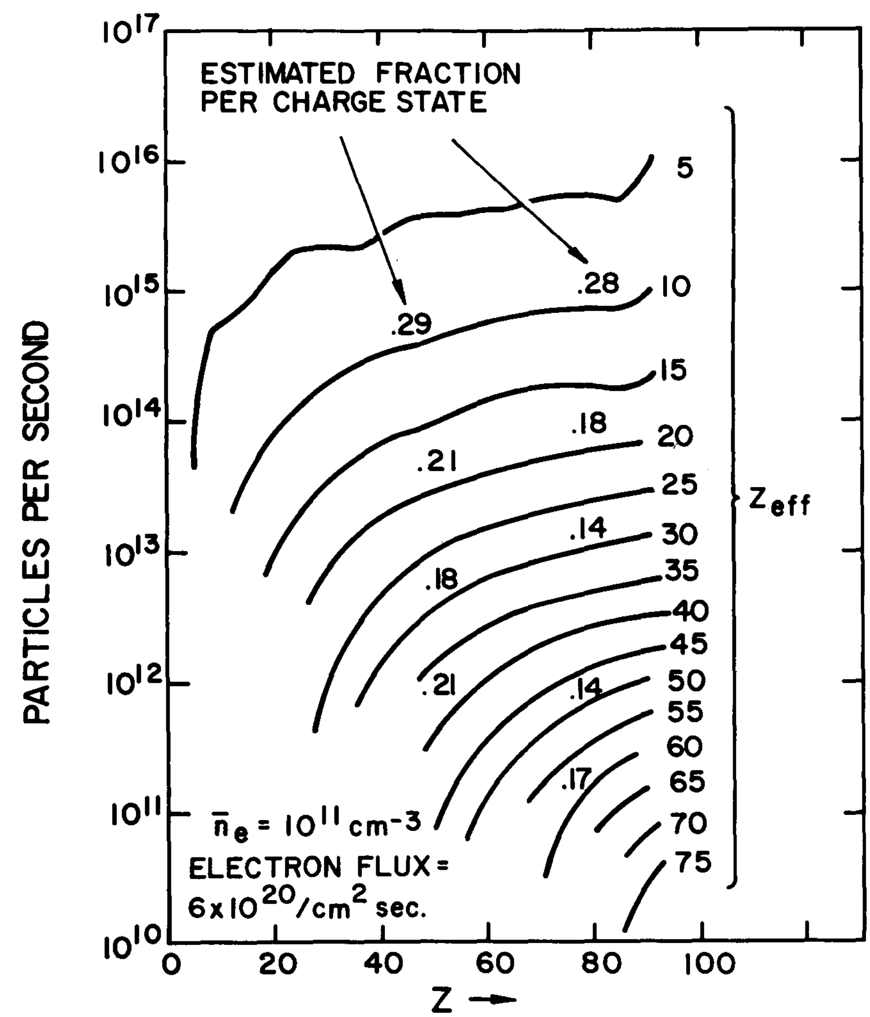

Fig. 4. Estimated average ion currents from a HIPAC Ion Source for atoms of all elements stripped to any level Z_{eff}

device. The internal field E_o arises from the unneutralised electron space charge in the device; for a torus of minor radius a and electron density n_o, $E_o = n_o ea/2\epsilon_o \approx 270$ kV/cm from Table 1. The external field, αE_o, is visualised as being applied via a biased plane grid a convenient distance from the surface of the HIPAC. Practical values for α might be expected to be 0·25 or less (70 kV/cm or less).

The acceptance of this configuration has been studied using the parameter space (x_o, $\dot{x}_o$, y_o, U) where y_o is the maximum value of y that the particular trapped particle can attain if it has energy U; i.e. at $y = y_o$, $\dot{y}_o = 0$. The particle is

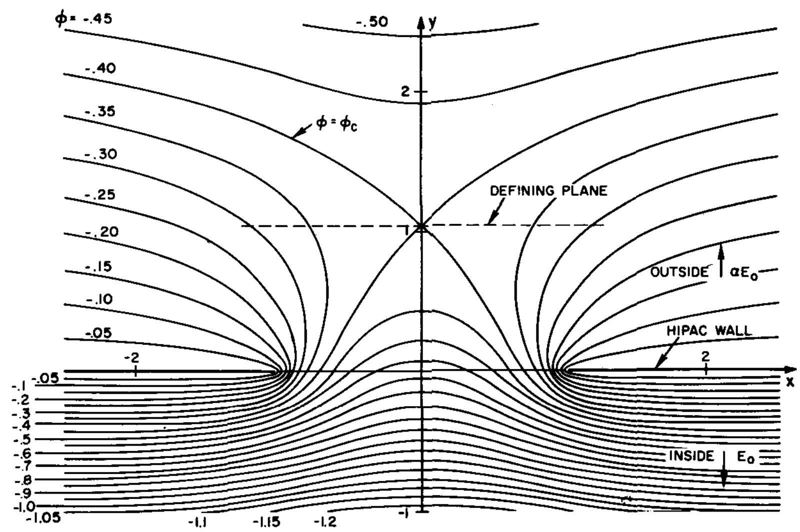

Fig. 5. Two dimensional equipotentials in the vicinity of the extraction aperture. Note the null point in the electric field, caused by the opposition of the HIPAC electric field and the extraction electric field. Ions having energies allowing them to reach equipotentials between the null point and the HIPAC wall can be extracted through the aperture

also labelled by the position x_o and the tangential velocity $\dot{x}_o$. Clearly, what we are envisaging is a small extraction hole in the side of the HIPAC source, the scale size, b, of the hole being sufficiently small—say $b \sim 0{\cdot}1$ cm or so—that curvature effects are negligible. Thus y corresponds to the radius r, $\dot{x}_o$ to $(r\dot{\Theta})_o$ at the peak of the orbit, x_o to the displacement $(r\Theta)_o$ from the axis of the extraction aperture.

Studies of this aperture show that the maximum emittance of the extracted beam is the acceptance of the aperture; the maximum accepted $\dot{x}_o$ is of the order of

$$\dot{x}_o \sim \sqrt{\frac{Z}{A}\frac{eE_ob}{m_H}}\,;\quad m_H = \text{proton mass} \qquad (2.1)$$

$$\sim 1{\cdot}65\sqrt{\frac{Z}{A}} \times 10^8 \text{ cm/s; for Table 1 and } b = 0{\cdot}1 \qquad (2.2)$$

Thus a very small hole, 0·2 cm in diam., biased as indicated, will accept tangential velocities corresponding to energies of the order of 5 keV/nucleon (depending on the Z/A).

We have obtained an approximate formula for the acceptance of this configuration. Thus

$$\text{Acceptance} \approx \pi \sqrt{\frac{Z}{A} \frac{eE_o b}{m_H}}\, b \left(\frac{1+\alpha}{\alpha^{1/4}}\right) \left(1 - \frac{U}{Ze\phi_c}\right) \tag{2.3}$$

where U is the energy of the particle $[U = Ze\phi(y_o) + 1/2\, Am_H \dot{x}_o^{\,2}]$ and $\phi_c = -\sqrt{\alpha E_o b}$ is the critical value of potential separating equipotentials that connect to the outside of the torus from those which do not (Fig. 5). Naturally when $U \leqslant -Ze\phi_c$, the particle does not have sufficient energy to 'cross the pass' and so the acceptance vanishes!

With E_o from Table 1, $b \approx 0{\cdot}1$ and a practical value of ~ 2 for $(1+\alpha)/\alpha^{1/4}$ we obtain

$$\text{Acceptance} \approx 240\pi \sqrt{\frac{Z}{A}}\, (1 - U/Ze\phi_c) \text{ mm mrad (MeV/nucleon)}^{1/2} \tag{2.4}$$

and

$$Ze\phi_c \approx -11\,000\,(Ze) \text{ volts} \tag{2.5}$$

which represents the maximum spread in energy of the extracted particles.

At extraction $U \leqslant 0$, otherwise the ion would have found the wall of the device before it was extracted. For U^{40+}, $Z/A \approx 1/6$, and so for U^{40+}

$$\text{Acceptance} < 300 \text{ mm mrad (MeV/nucleon)}^{1/2} \tag{2.6}$$

This estimated emittance is an upper bound since it assumes that few of the particles are extracted at energies near $-Ze\phi_c$; extraction near $-Ze\phi_c$ is a distinct possibility which we will not attempt to cover here. Also it assumes that $\dot{x}_o$ is as large as can be accepted as given by Eqn (2.1). We have obtained estimates of the limits of $\dot{x}_o$ which can be expected from various perturbations. These estimates were obtained analytically as well as by computer experiment as reviewed below.

2.2. *Tangential velocity estimates–analytic*

In this section we shall see that the HIPAC Ion Source seems to want to produce particles whose orbits are cusping, a very favourable circumstance for small emittances! To begin, consider the case of an infinite circular cylindrincal HIPAC source having a parabolic potential $n_o er^2/4\epsilon_o$ of well depth–$n_o ea^2/4\epsilon_o$. Angular momentum is conserved because of symmetry. We may write the total energy as

$$U = \frac{1}{2} m_I \,[\dot{r}^2 + (r\dot{\Theta})^2] + \frac{Zn_o e^2 r^2}{4\epsilon_o} \tag{2.7}$$

and the angular momentum

$$P_\Theta = m_I \left(r^2 \dot{\Theta} + \frac{Z}{A} \frac{\omega_{CH}}{2} r^2\right); \omega_{CH} = eB/m_H \tag{2.8}$$

As a result of numerous ionisations, it follows that

$$U = (n_o e^2/4\epsilon_o) \sum_1^Z r_i^2$$

and

$$P_\Theta = (m_I \omega_{CH}/2A) \sum_1^Z r_i^2 .$$

The initial neutral atom we have taken to be at rest with no significant error. With these values for U and P it follows that at

$$r^2 = \sum_1^Z r_i^2/Z = r^2_{\max}, \qquad \dot{r} = r\dot{\Theta} \equiv 0;$$

the particle cusps!

This ideal situation would produce a very bright beam. Hence, our purpose has been to estimate the effect perturbations are likely to have. We have considered the effects of (1) a perturbation in the potential well, $V = n_o er^2/4\epsilon_o + V_1(r, \Theta)$ where $V_1(r, \Theta)$ is small, (2) $\omega_{CH} \rightarrow \omega_{CH}(1 - r\cos\Theta/R)$ due to the fact that the magnetic field is toroidal (we assume a/R is small as for the device in Table 1), and (3) perturbations due to the decreasing magnetic field during extraction. Our estimates consider the effect of cyclic perturbations occurring as the ion orbit rotates in the potential well (ion orbits are approximately ellipses rotating at the Larmor frequency $(Z/A)(\omega_{CH}/2)$.

We find perturbations proportional to $(Z/A)(\omega_{CH}\, a)$ due to the extraction process, $(Z/A)(\omega_{CH}\, a)(a/R)$ due to the nonuniform magnetic field, $(Z/A)(\omega_{CH}\, a)(a/R)^2$ due to ionisation in a nonuniform potential and $(a/R)^2 (E_o/B_o)$ due to azimuthal asymmetry of the potential well. Since $E_o/B_o \gg (\omega_{CH}\, a)$ the dominant perturbation for our proposed device is a cyclic one, due to the angular asymmetry of the electrostatic potential well. A conservative estimate yields

$$\Delta(r\dot{\Theta})_{\text{max perturbation}} < 0{\cdot}17\, (a/R)^2 (E_o/B_o) \qquad (2.9)$$

$$< 2{\cdot}8 \times 10^7 \text{ cm/s; for the device of Table 1.} \qquad (2.10)$$

This speed estimate is three times less than our previous assumption of 5 keV/nucleon and so would improve the emittance. Happily, our computer experiments indicate even this estimate is too conservative!

2.3. *Tangential velocity estimates–computer*

We have used a digital computer to solve Poisson's equation in a circular torus. Fig. 6 shows the distorted equipotentials calculated for a radius ratio of $a/R \approx 0{\cdot}4$. Using the appropriate equipotentials for $a/R \approx 1/6$ to suit the device of Table 1, we investigated the perturbations of $\Delta(r\dot{\Theta})$ due to the periodic orbit rotation and due to ionisations. Fig. 7 shows results obtained for several different ionisation histories. The variation for widely differing ionisation histories is small as one would expect from the estimates quoted above.

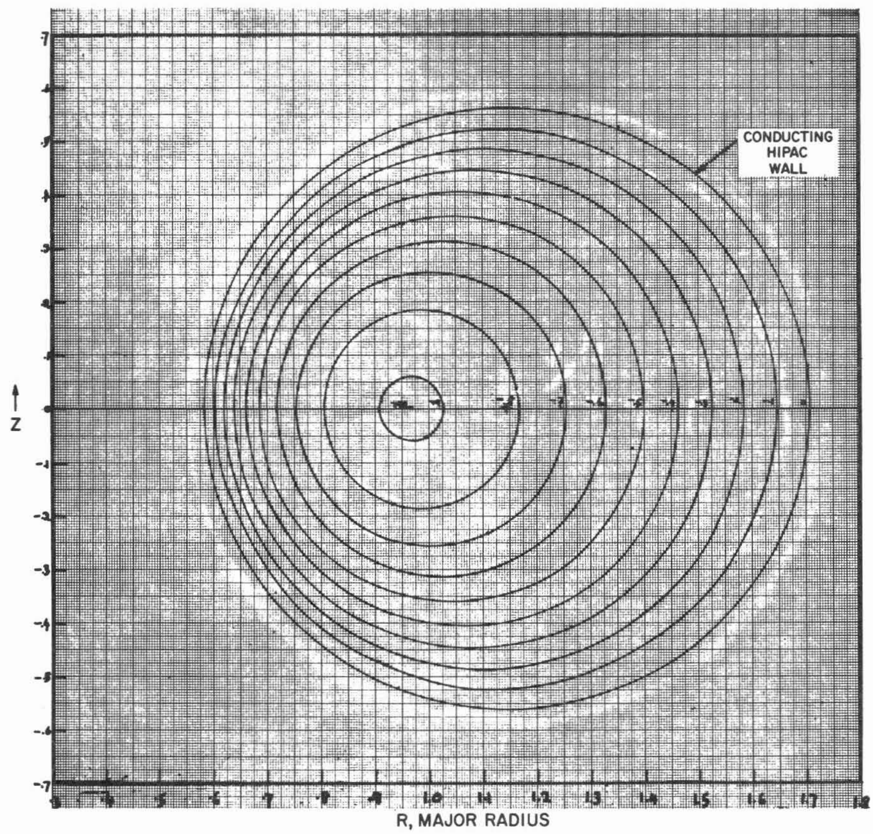

Fig. 6. Equipotentials for a toroidal HIPAC having a radius ratio of $\approx 0{\cdot}4$.

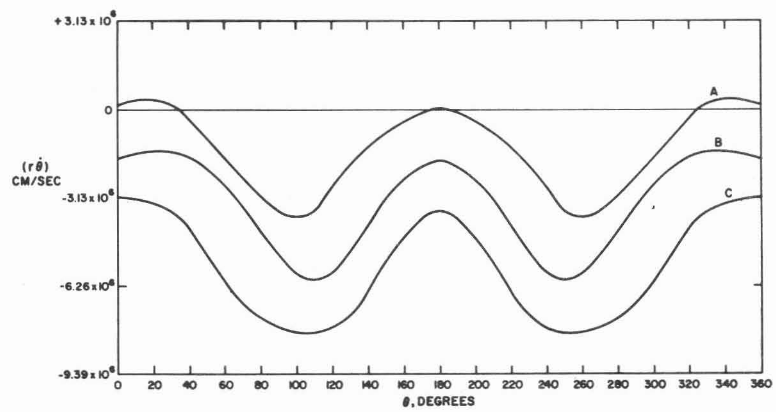

Fig. 7. Calculated values of $r\dot{\Theta}$ as a function of angle Θ for a HIPAC of radius ratio $\approx 0{\cdot}15$ as in Table 1. The curves all correspond to a U^{70+} ion but for different ionisation histories; (A) ionisation midway down the well, (B) near the bottom, and (C) nearly random. Notice that the differing histories cause a change in average deviation somewhat smaller than the cyclic variation in $(r\dot{\Theta})$

Rather, as expected, the more predominant effect is a cyclic perturbation, once each orbit, which is identifiable as due to the asymmetric electric forces.

Investigating these cyclic perturbations we have found the following semi-empirical formula which indicates both the dominant scaling of the phenomena and the magnitude. It appears that

$$\Delta(r\dot{\Theta}) < 0{\cdot}06\,(a/R)^2\,(E_o/B_o) \tag{2.11}$$

which is consistent in form with the analytic estimates given above for the dominant effect. The coefficient 0·06 is three times smaller than the bounding estimate obtained analytically. From Eqn (2.11) it appears that for the device of Table 1, $\Delta(r\dot{\Theta}) = \dot{x}_o$ is

$$\dot{x}_o < 10^7 \text{ cm/s} \tag{2.12}$$

or about 10 times less than assumed previously. If Eqn (2.12) were the only limit, it follows that much smaller emittances than previously estimated should be attainable.

2.4 *Ion-ion Coulomb scattering*

In the foregoing sections we have been concerned with extraction for velocity components perpendicular to the magnetic field. No mention was made of the velocities parallel to the magnetic field. In this regard, the only mechanism studied so far has been ion-ion coulomb scattering. This process, of course, can affect the emittance on both axes perpendicular to the extraction aperture. For ion-ion scattering, we find that the resultant energy/nucleon scales as $(Zn)\,(Z)\,(Z/A)^{3/2}\,\tau_{\text{ionisation}}$. We estimate for 10% neutralisation ($Zn = 0{\cdot}1\,n_o$) in the device of Table 1 that $\dot{x}_o < 3 \times 10^7$ cm/s for U^{40+}. This speed is larger than that in Eqn (2.12) but a factor of three smaller than we had previously assumed. Thus we should now expect emittances of <100 mm mrad $(\text{MeV/nucleon})^{1/2}$ in either perpendicular direction.

3. EXPERIMENTAL RESULTS

As yet no experiments have been conducted in which high stripping states could have been observed. However, a continuing program of experiments conducted with two different toroidal devices, the Mark I and Mark II, has produced $n_e\tau$ products of $5 \times 10^6/\text{cm}^3$ s. The program has produced sufficiently detailed understanding of the basic physics of injection and containment to justify the estimation of the parameters in Table 1. The early work on injection and containment, together with the present status of our experimental results, is summarised below.

3.1. *Electron cloud generation*

The electron cloud is produced by a technique which we term 'inductive charge injection'.[6] In this method, we utilise the flow of magnetic flux into the torus which occurs during the induction of the containing magnetic field. This flow of magnetic flux tubes traps electrons and convects them into the device in a manner which is now well understood.[7] Using a 10 cm minor radius device similar to Fig. 1, semi-empirical scaling laws governing the process have been developed. Briefly, these are:

$$\bar{n}_e \approx \frac{2\bar{B}}{\mu_o\, cea}\,\frac{2eV_{\rm fil}}{mc^2} \qquad \ldots(3.1)$$

$$\bar{B} \approx \frac{2{\cdot}5mV_{\rm fil}{}^{1/2}}{ehw} \qquad \ldots(3.2)$$

where $\bar{n}_e$ and $\bar{B}$ are the average electron density and magnetic field strength, $V_{\rm fil}$ is the bias voltage applied to the electron emitting filament, h is the separation between the filament and the anode, and w is the filament diameter. The data presented on Fig. 8 was taken to verify the dependence of $\bar{n}_e \propto V_{\rm fil}/h^{1/2}$ as predicted by combining Eqns (3.1) and (3.2). The correlation is clearly quite good. The dimension a is the minor radius of the torus (i.e. the radius of the cross-section). While this parameter has not been varied experimentally, the physics underlying Eqn (3.1) supports our belief in the indicated dependence of $\bar{n}_e$ on a. The parameters of Table 1 are based on Eqns. (3.1) and (3.2), using electrically and mechanically reasonable values for $V_{\rm fil}$, h, and w.

Further experiments, in particular a 3 cm minor radius mock-up of the

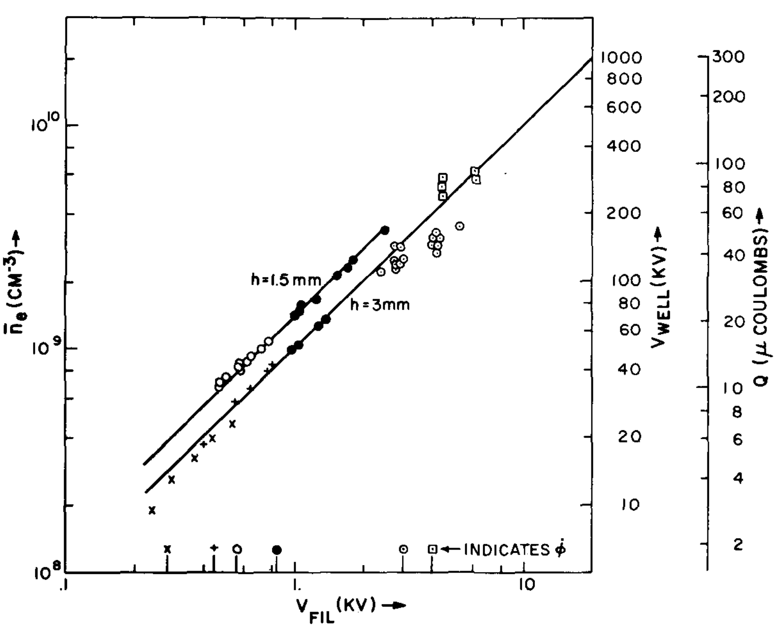

Fig. 8. Experimental results from a torus similar to the one sketched in Fig. 1, having a minor radius of 10 cm. The dependence of $\bar{n}_e$ *on* V_{fil} *and* $h^{1/2}$ *is apparent.* $\dot{\Phi}$ *is the induced e.m.f.* $\dot{\Phi} = d/dt\,(\pi a^2 \bar{B})$. *The directly measured quantity*[7] *is the total charge* Q; $\bar{n}_e$ *and* V_{well} *are inferred.*

device in Table 1, are planned to complete the verification of these scaling laws. A recent experiment using a value of V_{fil} higher than the values quoted earlier,[7] gave an electron density of 7×10^9 cm.$^{-3}$, as shown in Fig. 8.

3.2 *Electron cloud containment*

Experiments[7] with the Mark I device ($p > 4 \times 10^{-7}$ torr) have shown that the electron cloud possesses an equilibrium[8] and can be contained for times several thousand times longer than any of the oscillation periods characteristic of pure electron clouds.[9,10] An instability associated with the interaction of the ions and the diocotron modes of the electron cloud has been predicted[11] and observed.[7] This instability is avoidable if the total charge of the positive ions contained in the electron cloud is limited to the order of 10% of the total charge of the electron cloud. Thus a limit is placed on the experimental vacuum levels to

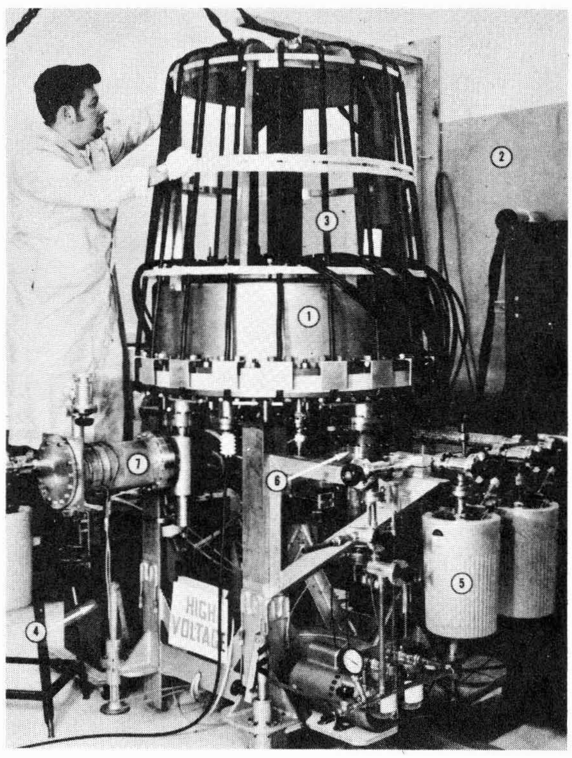

Fig. 9. Mark II torus with the 'd.c.' coil mounted. The picture shows (1) the vacuum chamber, which also serves the function of a single turn magnetic field coil used for injecting the electrons. This coil is powered by a low inductance capacitor bank located inside (2). The 20 turn 'd.c.' coil (3) produces the containing magnetic field and can be powered either from capacitors or a d.c. battery bank. (4) is the filament pulse generator. Also shown are various components of the vacuum system, such as (5) roughing pumps, (6) ion getter pump and (7) manifold for extra pumps connected during bakeout. The combination of two coils as shown permits the combination of a long lasting confinement field with a rapidly rising injection field. For details of this scheme see the HIPAC paper.[6] Also we should note that the scale size of this device was intended to mock-up the HIPAC which requires large potentials and so large scale. The ion source of Table 1 would be considerably smaller

$N_o \leqslant 0{\cdot}1\ n_o/Z_{eff}$, where Z_{eff} is the charge state to which the particular ion will be stripped in the desired containment time. Recent experiments at much higher vacuum levels ($p < 10^{-8}$ torr) using the Mark II device have further verified our earlier interpretation[7] of this ion instability.

For the sake of experimental simplicity, all of our earliest experiments used pulsed magnetic fields driven by capacitor bank discharges and had decay times of a few milliseconds. The achievement of millisecond containment times therefore awaited the provision of longer lasting magnetic fields. A quasi-d.c. field coil has been developed which is shown attached to the Mark II device in Fig. 9. Theoretical and experimental tests on the alignment of this coil show it to be critical but of a practical magnitude. For example, it was found that the axes of the coil and torus must be aligned to the order of 0·1°.

With such alignment, the injection process is not affected and longer term containment has been achieved. The electrical configuration of the ring-down-up injection scheme using this coil was proposed earlier[6] and will not be discussed here. However, we have achieved 5 ms containment of an $\sim 10^9/cm^3$ density cloud which represents a factor of improvement of 100 over our Mark I results.[7]

The present value of containment time is governed by the ionisation of neutral hydrogen desorbed from the stainless steel walls of the device, the desorption being caused by electron bombardment during the injection process. The electron bombardment of the chamber walls occurs because our present electrode configuration is < 25% efficient in converting filament emission into injected current. Measurements indicate that from 0·05 to 0·1 hydrogen atoms are desorbed per electron lost to the walls. Considering that the electron cloud can stably contain ≈ 0·1 H^+ per electron,[11] an improvement in injection current efficiency to > 50% will eliminate this problem. Alternatively, 50% reduction in the adsorbed H_2 should decrease the desorption probably by 50%. Modifications intended to accomplish these objectives are underway.

4. CONCLUSIONS AND DISCUSSION

The HIPAC Ion Source, as discussed in more detail elsewhere,[1,5] presents possible means for achieving large fluxes of highly stripped heavy ions, say U^{40+} or even U^{60+}. We have briefly reviewed its concept and have summarised the status of the current theoretical and experimental effort. In this paper we have:

(a) summarised results of theoretical work which show that the emittance of the HIPAC Ion Source could have an emittance of < 100 mm mrad (MeV/nucleon)$^{1/2}$ because of a tendency of the ion orbits to remain organised during the ionisation process;

(b) summarised the experimental status; densities of $\sim 7 \times 10^9/cm^3$ have now been obtained as well as containment times of 5 ms, a factor of 100 improvement over the experiments in reference 7; we have achieved $n_e \tau \sim 5 \times 10^6$ s/cm^3 (as compared to, say, $n_e \tau$ of 2×10^9 required for Xe^{13+} or 4×10^{10} for U^{40+}); the present limit on containment time is associated with wall desorption of hydrogen during electron injection, a problem for which possible corrective measures are being taken.

The emittances, beam intensities, and in particular the quite high charge state of ions from the HIPAC Ion Source make it potentially an extremely attractive source for a rather modest heavy ion cyclotron. While its development is by no means a certainty, we presently know of no fundamental or technical problem which should prevent success.

DISCUSSION

Speaker addressed: J. D. Daugherty (Avco Everett)

Question by J. R. J. Bennett (RHEL): have you attempted to look at any heavy ions coming out of the device?
Answer: No. We have not yet obtained the necessary conditions, i.e. $n_e\tau$ large enough to look for multiply stripped ions. When we overcome the electron impact desorption problem we expect to be in a suitable range.

Question by M. Reiser (Maryland): What is the repetition rate for extracting heavily stripped ions (say U^{40+}) from your device?
Answer: The repetition rate is approximately the inverse of the ionisation time since the extraction time will be some fraction of it. Assuming that we obtain $n_e \approx 10^{11}$ (as for Fig. 2) then the rate for U^{40+} would be about 2 per second.

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