Parks and Donnelly.[4] The points obtained by extrapolation to $V_R = 0$ have been matched to the theoretical curve by shifting all the data along the temperature axis. The magnitude of the required shift was 18 mdeg, well within the absolute error in the temperature measurement. The data are in good agreement with the theoretical predictions and demonstrate capture and escape up to at least 1.81°K. This agreement shows that the turbulence is composed of individual, singly quantized vortex lines identical to those produced by rotation except for configuration.

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NEGATIVELY CHARGED OPEN-ENDED PLASMA TO STRIP AND CONFINE HEAVY IONS*

Thomas H. Stix†
Weizmann Institute of Science, Rehovot, Israel
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A negatively charged plasma with energetic magnetic-mirror-confined electrons may provide a suitable environment for long-term ion confinement and for intense multiple ionization of heavy ions. Classical rates for ion loss from the negative potential well are low compared with the comparable ion mirror-loss rates. It is proposed to maintain the plasma by steady electron injection together with cyclotron acceleration for electron trapping and heating.

Considerable current interest is attached to the possibility of producing far-transuranic elements by fusion of heavy nuclei.[1] Ghiorso[2] has discussed the difficulties of heavy-nucleus acceleration. An intricate technique of injection, acceleration, foil stripping, and reacceleration is required to achieve the desired output energy by conventional methods. However, it has been pointed out by Daugherty et al.[3] that a high degree of electron stripping may be obtained by confinement of heavy ions in the electrostatic potential well of an electron plasma and by the exposure of these ions to the energetic electrons of the plasma. The impressive significance of this concept is that the availability of a proper source of prestripped ions would make possible the efficient acceleration of heavy nuclei in conventional cyclotron, synchrotron, and Van de Graaff accelerators.

The calculation by Daugherty et al.[3] indicates that an exposure time corresponding to $n_e\tau \sim 10^{10}$-10^{11} sec cm^{-3} is required to attain 50% removal of electrons for elements in the range $Z = 20$-92. Here n_e designates the density of 13.6-keV electrons and τ is the ion exposure or confinement time. This combination of required density, average electron energy, and ion confinement time represents a performance level beyond current achievements for conventional magnetically confined charge-neutral plasmas. In this Letter we examine the use of an open-ended energetic-electron plasma with electrostatic ion confinement to achieve the superb ion confinement needed for heavy-ion stripping.

As an illustrative example we consider a cylinder of plasma of 1 cm radius centered inside a long metal cylindrical shell of somewhat larger radius and immersed in a conventional static axisymmetric magnetic-mirror field with $B = 3000$ G in the central region. We assume an average electron density of 10^{11} cm^{-3} and an electron temperature of 10 keV. We assume further that the ions in the plasma are ions of uranium, each with net charge $Z = 46$ and with average energy per unit charge of 150 eV ($kT_i = 100Z$ electron volts). Finally we assume that, by means of an electron sheath on the surface of the plasma, the space potential within the plasma is depressed by about 1000 V below the potential of the metal shell. The rms ion Larmor radius is 1.1 cm and the ion containment is thus electrostatic. To estimate the rate of ion leakage over the potential-energy barrier we first note that, for a Maxwellian distribution of energies, the fraction F of ions with kinetic energy greater than E is approximated by the asymptotic expression

$$F = \left(\frac{2}{\pi}\right)^{1/2} \theta^{1/2} \left[1 + \frac{1}{\theta} - \frac{1}{\theta^2} + \cdots\right] \exp\left(-\frac{\theta}{2}\right),$$

where $\theta \equiv 2E/(kT_i)$. Thus, approximately 1 out of 5900 ions in a $100Z$-eV distribution will have an energy exceeding $1000Z$ eV and can escape over the energy barrier. Now a uranium ion with kinetic energy of $1000Z = 46\,000$ eV would normally lose its excess energy by collisions with the thermal ions[4] in about 1.0 msec. A crude detailed-balance argument would then require that the truncated energy distribution be refilled at this same rate. Refilling the tail of the distribution pushes these ions over the energy barrier and the characteristic loss time for a U^{+46} ion selected at random would be $5900 \times 10^{-3} = 6$ sec. This ion loss time is considerably longer than the time required to strip uranium in this plasma down to $Z = 46$.

The rate of ion loss is, however, very sensitive to the ion temperature and we may examine briefly the processes of ion heating and cooling. Ions in the specified plasma come slowly to temperature equilibrium with the electrons. In 6 seconds, for example, the U^{+46} temperature rise due to ion-electron collisions[5] would be 80 eV per unit charge. Additional energy is gained by the ions in the stripping process: At each ionization step the potential energy of the ion is changed by the amount $e\varphi$ (the freed electron acquires $-e\varphi$ in potential energy), thus the total energy acquired by an ion is $e\sum\varphi(\mathbf{r}_j)$ where $\mathbf{r}_j$ is the position at which the jth ionization occurred. However, it will be seen below that the ion-confining potential well tends to have steep sides and a very flat bottom with the consequence here that the potential energy acquired during ion stripping is not large. We estimate that an initially neutral test atom would gain a total amount of energy of order kT_i in this fashion. On the other side of the ledger, ion loss provides a powerful cooling process. For example, with the barrier height equal to 1000 V, the loss of only 18% of ions with an initial temperature of 200 eV per unit charge would drop the temperature of the remaining ions to 100 eV per unit charge.

For illustrative purposes we have chosen a model plasma with a single ion species (U^{+46}). During buildup of the plasma from lower ionization states, the low-energy electrons from the ionization process must be trapped and heated and, if lost, replaced by injection (see below). It is clear that the preceding analysis may be applied to ions of different mass and different charge states, including the interesting case of He^{++}. The important qualitative points for any such plasma are that the ions acquire energy slowly due to ion-electron collisions and due also to the multiple-ionization process which takes place within an electrostatic potential well, and that ion-ion collisions tend rather quickly to randomize the distribution of this energy. Some ions escape over the electrostatic potential barrier but each carries away a significantly above-average amount of energy with the result that the temperature of the remaining ions is lowered and their confinement time in the electrostatic well is correspondingly lengthened.

We turn now to consider the spatial variation of the electron and ion densities and of the electrostatic potential. Taking first a cross section of the model plasma perpendicular to the magnetic field, we write down Poisson's equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\varphi}{\partial r}\right)=4\pi e\left[n_e(r)-Zn_I(0)\exp\left(-\frac{Ze\varphi}{kT_I}\right)\right].$$

We assume symmetry in the azimuthal direction and at this stage neglect the slow axial variation. The electron-density function $n_e(r)$ is determined by the electron injection and loss process; the number of ions can be varied by changing $n_I(0)$. The detailed spatial variations of the ions and of the electric potential are allowed to come to a self-consistent equilibrium. [Extrapolation of the form of the above ion distribution, $n(r,Z)=n(0,Z)\times\exp(-Ze\varphi/kT_I)$, would indicate, incidentally, that the most highly stripped ions lie deepest in the potential well.] The electrons are unable to move radially across the magnetic field and qualitative examination of the Poisson equation above shows Debye shielding of the electrons by the ions, $n_I(r)\lesssim n_e(r)$, from $r=0$ out to the radius r_0, at which the total number of available ions is almost exhausted. The potential variation in this range, $r<r_0$, can be found in an approximate manner by equating the right-hand side of the equation to zero. Then, in a region of a few Debye lengths $[\lambda_{DI}{}^2=kT_I/4\pi Ze^2n_e(r_0)]$ around $r=r_0$, the ion density drops to almost zero. The electrostatic potential outside of r_0 then rises in accordance with the variation of the electron space charge $n_e(r)$, for $r>r_0$.

A similar analysis yields the axial variation. Integration of Poisson's equation over the cross section of the plasma shows E_r at the plasma surface proportional to the net line charge $e(ZN_I-N_e)$. Now we assume that the electron sheath at $r=r_0$ has negligible thickness and that the ratio of r_0 to the wall radius r_w is constant. We designate the constant wall potential by φ_w and neglect small radial variations in order to write the space potential within the plasma simply as $\varphi(z)$. Integration of E_r between r_0 and r_w then gives us the approximate solution to Poisson's equation with axial (z-direction) variation:

$$\frac{\varphi_w-\varphi(z)}{\varphi_w-\varphi(0)}=\frac{N_e(z)-ZN_I(z)}{N_e(0)-ZN_I(0)}.$$

We again let the ions reach a self-consistent equilibrium,

$$N_I(z)=N_I(0)\exp\{-Ze[\varphi(z)-\varphi(0)]/kT_I\},$$

and select a simple model for the mirror-confined electrons:

$$N_e(z)=N_e(0)[\exp H(z)-\exp H(z_m)]\times[\exp H(0)-\exp H(z_m)]^{-1},$$

for $|z|<|z_m|$ and with $H(z)\equiv[e\varphi(z)-\langle\mu\rangle B(z)]/kT_e$, and where the maximum mirror field is designated by $B(z_m)=B(-z_m)$.

Examination of these three equations brings out the qualitative details. With $ZT_e\gg T_I$, the ion Debye length is short compared with the electron Debye length and the ions again perform Debye shielding for the electron distribution; $N_e(z)\approx ZN_I(z)$ and $\varphi(z)\approx\varphi(0)$ as long as $N_e(z)\gtrsim N_e(0)-ZN_I(0)$. Now the difference $N_e(0)-ZN_I(0)$ represents just the line density of net negative charge required to drop the space potential down to $\varphi(0)$. When, at $z=z_0$, the mirror confinement factor in $\exp H(z)$ finally reduces $N_e(z)$ to this required value for net charge, ion shielding is no longer demanded. Further reduction of $N_e(z)$ now at last allows $\varphi(z)$ to rise and drives $N_I(z)$ rapidly toward zero. Axial profiles of potential and density are sketched in Fig. 1.

In the sample plasma described above, $\varphi_w-\varphi(0)=1000$ V is much smaller than $kT_e/e=10\,000$ V so that the electrostatic potential-energy factors in $\exp H(z)$ never deviate far from each other, i.e., the electron-density distribution is almost the same as it would be for a charge-neutral plasma. Such deviation as does appear occurs in the vicinity of the end electron sheath at $z=z_0$. The thickness of this sheath is determined primarily by the requirement that electrons falling out through the end sheath still be confined by mirror forces; that is, that $\langle\mu\rangle[B(z_m)-B(z_0)]\gtrsim e[\varphi_w-\varphi(0)]$.

The question of plasma stability has not been analyzed. An initial candidate for consideration is the short-wavelength diocotron instability[6] of the radial electron sheath. At full electron density the $q\equiv\omega_{pe}{}^2/\omega_{ce}{}^2$ figure for our model plasma is 0.11, at which value the diocotron growth rate is still small. It may be pointed out that the confined ions already occupy their lowest energy configuration and also that a pure electron instability will not be harmful provided the electron-loss rate does not exceed the available feed. Furthermore, the presence of electron-cyclotron–frequency radiation can actually be helpful as will be explained below. Nevertheless $q\sim0.5$ appears to be an experimental upper limit for the density of the energetic electrons in well-confined neutral plasmas.[7]

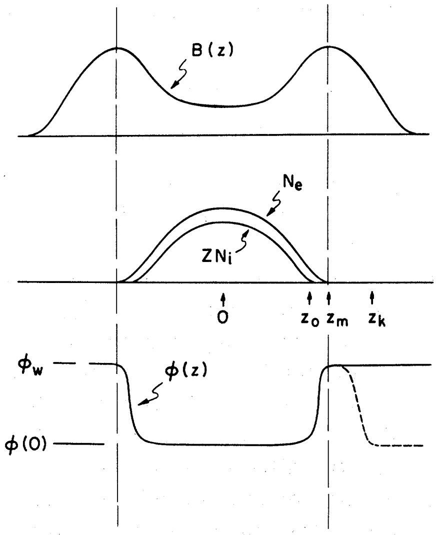

FIG. 1. Magnetic field, electron and ion line density, and electrostatic potential along the axis ($r=0$) of a negatively charged open-ended plasma. The electron density profile is determined by the injection process and by loss through scattering out the ends. The ions, which are relatively cold, form a Debye cloud shielding the electrons. The difference, $N_e - ZN_i$, which is almost constant for $|z| < |z_0|$, essentially represents the unneutralized electrons in the radial sheath located near $r=r_0$. Electrostatic injection from a cathode located at z_k requires the accelerating potential indicated by the broken line. Electrons scattered into the potential maximum between z_0 and z_k, and trapped there, must be removed lest their space charge alter the potential profile and reduce its ion-confining capability. Microwave-produced cyclotron acceleration near $z=0$ traps injected electrons inside $|z_m|$.

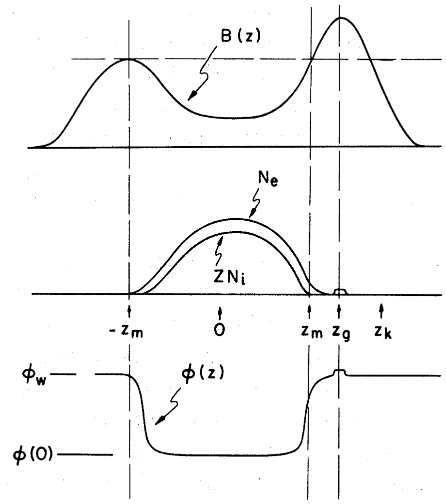

FIG. 2. Axial profiles illustrating magnetostatic injection. The magnetic mirror fields are made unequal; cyclotron-frequency microwave excitation at the field maximum z_g of the stronger mirror increases the magnetic moment of slow electrons emitted from the cathode at z_k and concentrated near z_g by the local increase of wall potential. A few moderate-energy electrons are trapped between the magnetic field maximum at z_g and the electrostatic potential minimum. A second microwave source tuned to cyclotron resonance near $z=0$ traps injected electrons to form the main body of plasma. Most easily trapped are the electrons which reach $z=0$ with $v_\| \simeq 0$; it should prove useful to continuously adjust the electron-gun accelerating potential (Fig. 1) or the B field strength at $-z_m$ (Fig. 1) so that injected electrons just barely fail to reach a detector located to the left of $-z_m$.

Finally, we consider the formation of the plasma. The plausible criterion that $q \lesssim 0.1$ implies unusually careful control[3] over the original admission and re-emission of neutral molecules into the plasma volume. Experiments on the minimum-B geometry Interem device at Oak Ridge National Laboratory,[8] happily, indicate magnetohydrodynamic stability of a hot electron plasma with a reduced density of cold plasma background. The required microwave source power will be best determined by experiment; Dandl et al.[7] consistently obtained hot electron ECRH (electron cyclotron-resonance heated) plasmas with microwave generators in the range 1-50 kW. Unique to the proposed stripped-ion source, however, is the need to maintain the space potential of the mirror-confined hot electron plasma at a negative value which is considerably larger in magnitude than the classical ambipolar potential.[9] Electron injection is therefore demanded and the need to overcome the repulsive negative potential in fact requires injection from an electron gun.

A simple electrostatic gun with a cathode at $z = z_k$ outside one of the mirrors biased at $\varphi(z_k \approx \varphi(0)$ would bring electrons into the central region. However, the scattered electrons would tend to become trapped in, fill up, and thus eliminate the ion-confining potential maximum between the edge of the plasma at $z=z_0$ and the gun at $z=z_k$; see Fig. 1. These undesirably trapped electrons could, however, be ejected, for instance by frequent pulsing of the cathode up to φ_w.

Alternatively, the problem of electron trapping outside of z_0 is almost eliminated with traveling-wave electron acceleration or magnetostatic ($\mu\nabla B$) acceleration. Magnetostatic acceleration has the advantage of supplying electrons which reach $z=0$ already with considerable perpendicular energy. The principles are illustrated in Fig. 2.

With any type of injection the electrons must be trapped inside the mirrors. Microwave excitation[10] applied around $z = 0$ at the local electron frequency can impart additional perpendicular energy to transiting electrons so as to cause them to be mirror confined. From another point of view, the cyclotron acceleration at $z = 0$ and the subsequent collisional scattering cause extensive diffusion of the electron distribution function in velocity space and thus allow the configuration-space density at $z = 0$ to considerably exceed the density of the injected beam.

In summary, Levy and colleagues have calculated that immersion in a plasma of $kT_e = 10$ keV electrons will cause $\gtrsim 50\%$ stripping of the electrons from heavy nuclei (e.g., uranium) in a time $\tau \lesssim 10^{11}/n_e$ sec cm^3. It is proposed to use a negatively charged mirror-confined hot electron plasma for this purpose. A 1000-V negative potential well in the plasma space potential will ensure classical electrostatic confinement of the heavy ions ($kT_i/Z \lesssim 100$ eV) for times considerably longer than τ. Debye shielding by the ions will cause such a three-dimensional potential well to be almost flat bottomed with the more highly stripped ions in the center of the well. Except for thin electron sheaths on its radial and end surfaces, the plasma cloud is essentially charge neutral. It is suggested that the desired plasma can be maintained by steady injection of electrons followed by their cyclotron acceleration and mirror trapping.

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†John Simon Guggenheim Memorial Foundation Fellow, on leave from the Plasma Physics Laboratory, Princeton University, Princeton, N. J.

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