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With almost no exception, all heavy ion accelerator preinjection schemes, for nuclear and high energy physics research, are based on electron stripping by energetic particles. Ionization of heavy ions can be attained by either fast heavy ions moving through stationary particles like in foils, or by bombardment of slow heavy ions by energetic electrons. Laser sources, ECR's, and various plasma discharge devices are limited in the attainment of heavy ions with very high charge by existence of background plasmas, and EBIS devices have not produced these ions in sufficient quantities. To increase the amount of such ions, the electron beam current must increase to a level at which EBIS stability has not been proven. Foils, have a drawback in costly acceleration of low charge state ions to rather high energies and emittance growth. To avoid these shortcomings, we have explored plasmas characterized by high energy electrons and fully ionized ions as candidates for stripping and focusing of low energy heavy energy ions.

I. INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) [1], now under construction at BNL, is expected to become operational early in calendar year 1999. Initially, the RHIC physics program will concentrate on Au+Au collisions with 100 GeV in each beam. However, there is physics justification for eventually colliding uranium beams in RHIC [2]. The existing tandem preinjector is quite adequate and reliable for the Au+Au collision program, but the tandems are not expected to produce sufficient beam currents for uranium ions. There is also a need for high energy heavy ion implanters. Present day high energy ion implanters utilize low charge state ion sources in combination with rf accelerators. It is desirable to have instead an intense, high charge state ion source on a relatively low energy platform to generate high energy ion beams for implantation. A couple of new Mevva based approaches for heavy ion beam injection (e.g., into the Relativistic Heavy Ion Collider [RHIC] at BNL) were explored. Recent results [3], were consistent with a scaling law, which in turn, lead us to believe that a viable preinjector for RHIC might be possible using E-Mevva and/or Z-Mevva, which are enhanced versions of the well-known Metal Vapor Vacuum Arc ion source [4]. Limitations on charge state reached were due to high circuit inductance [3], which in turn hindered the formation of energetic electrons needed for attainment of higher charge states. As indicated by experimental results [3], heavy ions with charge state needed for a RHIC preinjector could be generated in those E-Mevva and Z-Mevva configurations driven by low inductance circuits. However, further considerations indicated that additional modifications are needed to prevent charge state reduction by neutrals and low charge state ions.

With almost no exception, all heavy ion accelerator preinjection schemes, for nuclear and high energy physics research, are based on electron stripping by energetic particles. Stripping of heavy ions by energetic particles can be attained by either fast heavy ions moving through stationary (or slow) particles like in foil stripping, or by bombardment of slow heavy ions by energetic electrons (occurring in most heavy ion sources). To reach a required high ionization state, ions must be bombarded by certain number of energetic particles, having an energy higher than the final state binding energy, for a sufficient time τ. In devices like ECRs and EBISs stepwise ionization by electrons dominates. To achieve very high ion charge states, in these devices, two things are needed: (1) high $J\tau$, which is the product of electron current density and electron-ion interaction time, and (2) high E, which is the effective electron "beam" energy. Donets [5] is credited with illustrating that the maximum charge state achievable for any element can be predicted on a plot of $j\tau$ versus E. Since ionization in ECRs and in EBISs is done by electron whose energies far exceed the binding energies, various formulas (e.g., Lötz's) can be used to compile $J\tau$ plots. In general EBIS devices have had good experimental agreement with $J\tau$ predictions.

Conventional strippers, e.g. foils, have a drawback in requiring acceleration of low charge state ions to rather high energies (not efficient and costly), as well as other problems like emittance growth and cooling. Laser sources, ECR's, and various plasma discharge devices are limited in the attainment of heavy ions with very high charge by existence of background plasmas with low charge state and by neutrals. EBIS devices have produced very high charge state heavy ion in relatively small quantities. To increase the quantity of ions with such charge states, the electron beam current in such an EBIS device must be increase to a level at which EBIS stability has not been examined. Alternative approaches, which were based on proven technologies and physics, were explored.[6] Z-Mevva [3] is one such option, which has been pursued experimentally. Encouraging results suggesting, that substantially higher charge states can be reached in a low inductance Z-Mevva, were obtained. However, further considerations indicate that this approach too might be limited by neutrals and low charge state background ions like other sources based on plasma discharges.

In this note, plasmas characterized by high energy electrons and fully (or highly) ionized ions, are explored as candidates for strippers of heavy low energy ions. Stripping of ions in plasmas is attained by either bombardment of slow heavy ions by energetic electrons, or by fast ions moving through a stationary plasma. We have been pursuing E-Mevva and Z-Mevva approaches. The principle of Z&E-Mevva is the same as for ECR or EBIS, namely stepwise ionization, in which an energetic electron "beam" successively removes bound electrons to reach the desired stage of ionization. Description of these devices, as well as progress in our program, has been described elsewhere [3]. But, since we have foreseen some limitations, we would like to suggest the idea of plasma strippers for low energy heavy ions as a modification to our original approach.

II. SOME PHYSICS ISSUES

For a plasma to be a viable stripper for slow ions, it must contain a sufficient number of fast electrons needed to attain a desired charge state during an ion dwell time. The basic idea of this scheme is to inject slow, low charge state ions into an intense discharge for further stripping and for extraction. However in addition to stripping, charge state reduction due primarily to charge exchange with low charge state ions and neutrals also occurs in most plasma ion sources, a phenomenon this scheme is designed to minimize.

A. Attainable Charge States

In cases where stepwise ionization, by electrons with density n_e and velocity v_e, is the dominant stripping process, the following equation describes the rate of change in the number N_q of ions in a charge state q,

$$dN_q/dt = -N_q n_e \sigma_{q\rightarrow q+1} v_e + N_q n_e \sigma_{q-1\rightarrow q} v_e \qquad (1)$$

where σ is the cross section for ionization of ground state ions. A reasonablely good expression for σ is Lötz's semi-empirical ionization formula [7],

$$\sigma_{q\rightarrow q+1} = 4.5\text{x}10^{14} \Sigma (n_j/EI_j) \ln(E/I_j) \qquad (\text{cm}^2) \qquad (2)$$

where n_j is the number of electrons in subshell j, I_j is the ionization energy of subshell j in eV and E is the electron incident energy in eV. In absence of any other processes, equation 1 can be integrated to yield an expression describing the time evolution of the number N_q of ions in a charge state q as a function of $J\tau$. The "Donets plot" (Fig. 1) is obtained by plotting the minimal E required to reach a charge state versus the $J\tau$ which maximizes the yield of that charge state. Ideally, an EBIS should have results which match Donets plot predictions, however, interactions with residual gas and lack of perfect overlap between trapped ion trajectories and the electron beam reduces EBIS performance. Nevertheless, well designed very clean EBIS devices come very close to those predictions. Furthermore, with ion cooling charge state distributions can exceed predictions but at a cost of lower ion yields, since the EBIS trap capacity (total ion charge yield Q), which is given by [8]

$$Q = 10^{13}\eta I_b L/E^{0.5} \qquad (\text{MKS units}) \qquad (3)$$

is limited. Lighter ions used for cooling reduce the charge yield of the desired ions. In equation 3, η and L are neutralization ratio and length of the EBIS trap. I_b is the electron beam current.

Most operating EBIS device are low intensity and very clean. Their operating cycle begins with trap loading (by ion or gas injection), followed by ionization to desired charge state. It ends with ion extraction, i.e., emptying the trap. Charge exchange and additional plasma formation are negligible in such a trap. In most plasma heavy ion sources like PIGs, Mevvas, ECRs, E-Mevva and Z-Mevva configurations, plasma is generated throughout the cycle. Hence, charge exchange is a very important factor in these devices. Charge exchange of high charge state ions with newly formed plasma ions and background atoms lowers their charge state. To include the effect of charge exchange, in an equation describing the rate of change in the number N_q of ions in a charge state q, an additional term is incorporated in equation 1.

$$dN_q/dt = -N_q n_e \sigma_{q\rightarrow q+1} v_e + N_q n_e \sigma_{q-1\rightarrow q} v_e - \Sigma N_q n_i \sigma_{cq\rightarrow q-1} v_i \qquad (4)$$

where, $\sigma_{cq\rightarrow q-1}$ is the single electron capture cross section by charge exchange with ions in the discharge with charge state less than q. These ions have a variety of charge states, n_i and v_i are density and relative velocity (to ions with charge q) in charge state i<q. For $\sigma_{cq\rightarrow q-1}$ there is a simple semi-empirical formula which describes the dependence of this cross section on q and on v_i [9]

$$\sigma(q,v_i) \propto q^a/v_i^m \qquad (4a)$$

where the parameters a and m are to be determined from either experimental or theoretical work. In studies with MeV projectiles,[9] the value of a was estimated and measured in the range of 2 - 3.7, while m was 3 - 4. Our interest is in a much lower (keV) energy range where the value of a may be even larger than 3.7.[10] Multi-electron capture is rather significant for highly charged ions as it was measured in Kr^{+18} - Ar collisions.[11] A more realistic version of equation 4 would require inclusion of multi-electron capture as well, however only limited data is available. Nevertheless, it is clear from equations 2, 4, and 4a, that in sources with continuous plasma formation, very high charge states can not be attained in large quantities, since the stripping cross section decreases with increase in ionization energy (i.e., charge state), while the electron capture cross section increases with charge state. Plasma formation rates in heavy ion sources (in which plasma is continuously formed) are usually large enough to result in a significant density of low charge state ions, which in turn suppress generation of high charge state ions. In vacuum arcs with currents of a few hundred Amperes, e.g., typical cathode erosion rate is about 30 μg/Coulomb[12] resulting in an ion current which is roughly 10% of the total arc current.[13]

Equations 1 and 4 are based on stepwise ionization of ground state ions. However, charge state formation rates higher by a factor of 2.5 have been observed in Z-pinches.[14] A number of additional contributions may lead to the higher rates, e.g., ionization of excited ions which have a cross section larger than equation 2; and, excitation - autoionization (Auger) processes. In most plasma heavy ion sources like EBISs, ECRs, PIGs, and Mevvas, excited ions decay before collisions leading to ionizations occur. At higher charge states in a typical EBIS, the time interval between successive ionizations is at least a number of milli-seconds, i.e., orders of magnitude longer than the decay time of most excited ions, whereas the whole ionization process in a Z-pinch lasts a microsecond or less. Same arguments can be extended to an E-Mevva with an intense electron beam.

Therefore, equation 4 must be modified for such intense devices to include autoionization, ionization of excited ions and, in the case of a Z-pinch, ionizations due to energetic ions. Including those contributions yields,

$$dN_q/dt = \Sigma^*(-\dot{N}_q n_e \sigma_{q\rightarrow q+1} v_e + \dot{N}_q n_e \sigma_{q-1\rightarrow q} v_e) - N_q n_i \sigma_{iq\rightarrow q+1} v + N_q n_i \sigma_{iq\rightarrow 1\rightarrow q} v - \Sigma N_q n_i \sigma_{cq\rightarrow q-1} v_i(\qquad (5)$$

where Σ^* refers to summation over all ion states (ground and excited) $\dot{N}_q$ is the density of each state; the total ionization cross section by electron impact $\sigma = \sigma^* + \sigma^{s+a}$ in which, σ^* in the ionization cross section of excited ion (for which the is no analytical expression and very little data) and σ^{s+a} is the total impact ionization of ground state ions by electron stripping as well as autoionization [a semi-empirical formula for σ^{s+a} can be found in Burgess and Chidichimo, Mon. Not. R. Astr. Soc. **203**, 1269 (1983)]. Third and fourth terms on RHS of equation 5, contribute only when energetic ions are involved, e.g., in a Z-pinch. These terms account for ionization by background ions a procedure for computing σ_i can be found in McGuire and Richard, Phys. Rev. A **3**, 1374 (1973).

Stripping of excited ions is a dominant process in a stripper, if the time interval between successive ionizations is shorter than the decay time of a typical excited ion. In Z-pinches or in other intense strippers options, which we would like to explore, this condition is met.

B. Ion Propagation

Dynamic friction (slowing down by electrons) is the dominant process affecting trajectories of low energy ions entering an intense fully ionized plasma stripper. Much of the following analysis parallels calculations done for the plasma window.[15] Similarly, a properly oriented plasma stripper can also focus those ions.
Examining plasma effects,[16] the fastest relaxation rate is slowing down of ions by plasma electrons (dynamic friction) given by[16]

$$\nu_s = 1.6 \times 10^{-9} n\lambda q^2 \mu^{-1} T^{-3/2} \quad . \qquad (6)$$

And, the forward velocity slowing down rate is $d\underline{V}_z/dt = -\nu\underline{V}_z$. E in equation 6 is the ion energy, and $\boldsymbol{\lambda}$ is the Coulomb logarithm.

In a beam of charged particles, propagating through a field-free region, there are two forces acting on the particles: space charge forces trying to "blow" the beam up, and a magnetic force pinching the beam[17] (due to the magnetic field generated by the beam current). This magnetic force is a consequence of the Lorentz force, F, given by:

$$F = q\underline{V}x\underline{B} \qquad (7)$$

Where q is the particle charge, V its velocity, and B is the magnetic field. When a beam enters a plasma, space charge forces are neutralized, hence, beam focusing results from the magnetic field. If the plasma carries a current, the resulting magnetic field must be added to Equation 7. In all cases of interest to this subject matter, currents generated in the arcs far exceed the beam currents, so beam self focusing is negligible. Detailed computation of the lensing can be done with the beam envelope equation,[18]

$$\frac{d^2R}{dz^2} + \kappa R - \frac{K}{R} - \frac{\epsilon_\perp^2}{R^3} = 0 \qquad (8)$$

which describes growth in beam radius R as a function of propagation distance z. Beam focusing function is described by κ, $\epsilon_\perp$ is the transverse emittance, and the generalized perveance $K = 2I_b/(\beta\gamma)^3 1.7\times10^4$ (which describes space charge driven radial growth in a beam with a current I_b). However, inside a plasma stripper the space charge term is negligible. Growth in transverse beam energy $T_\perp$ (by lateral scattering) increases emittance[19] as $\epsilon_\perp = 2R(kT_\perp/mc^2)^{0.5}$. Computing the focusing function κ (for substitution into Eq. 8) requires knowledge of the radial current profile of the plasma channel. Evaluating such an expression must be done numerically even for the simplest cases. Hence, solving Eq. 8 rigorously requires a numerical solution which is beyond the scope of this work. Furthermore, in strippers with a large axial magnetic fields, the lensing effect will be greatly diminished.

III. PLASMA STRIPPER OPTIONS

Rather than attempt to extend parameters of existing ion sources to levels at which plasma stability is yet untested, we explore plasma strippers with parameters that have capability for generating the required ion output for RHIC. Only existing technologies and devices, which achieved or exceeded the needed parameters in stable operation are considered. Dense, high current plasmas seem to be good candidates. An additional benefit for intense plasma strippers is a significantly enhanced effective $j\tau$. The following is a description of four intense plasma discharges.

A. Candidate Plasmas

Spark (or Z) channels are plasma channels characterized by large currents (100s of kA), which have been developed to transport (and focus) intense beams of light ions over distances of up to 5 meters.[20] These channels consists of two annular plates (or rings) placed in a vacuum chamber. These plates are biased to serve as anode and cathode of the discharge, their spacing determines the channel length. The vacuum chamber is usually filled to a pressure of as low as a few Torr to as high as 40 Torr with either a light or a heavy gas. After an appropriate bias (10s of kV) is applied to the plates and an appropriate gas fill of the vacuum chamber, a discharge can be initiated with either an exploding wire or a laser pulse. This initial discharge preionizes and heats the gas. After the heated gas expands and rarefies on axis, a four-fold reduction in gas density on axis occurs with a corresponding ten-fold reduction in the breakdown voltage. Once breakdown occurs, the hot expanding channel acts as a piston compressing the gas outside the channel. Choice of an appropriate gas fill determines the channel expansion rate that must accommodate the current rise time (which is in turn determined to a large extent by the circuitry).

A large variety of these channels have been made, and an even larger variety is possible.[21] Pulse lengths of 10s of nsec at a repetition rate of 500 Hz - 1 kHz have been generated, as well as three microsecond long pulses at lower repetition rates. Hundreds of kA of discharge currents have been attained. Channel radii from 1 cm to over 10 cm were reported

Electron beams can be rather effective strippers. E-Mevva is a very good example where an electron beam has been used as a stripper. E-Mevva performance can be enhanced with an improved electron gun. State-of-the-art electron guns can greatly enhance E-Mevva yields. Mega-Ampere electron beams have been generated by diodes. Although most of these diodes operate with pulses that are in the nsec range, some diodes have operated with pulse lengths of up to 2 microseconds. This kind of electron beams in E-Mevva configurations have the potential of yielding very high charge states ions.

A Z-pinch involves a sudden compression of a low-density plasma by means of a large discharge current that can last for a few microseconds. It bears some superficial similarity to a spark channel, but their plasma properties are very different. Its fill pressure is below a milli-Torr. First, a low-density, low-temperature plasma is created by rf or exploding wires. Second, a large voltage is applied to the end plates that drives a very large axial current that compresses the plasma due to an inward acceleration of a surface current shell (just opposite to what occurs in spark channels). Discharge currents of 10 MA over a few centimeters have been reached in a rather expensive system.[22] In a series of experiments with magnetized (axial magnetic field of 1.5 Tesla) Z-pinches, 2 MA were reached for a length of 0.8 meters with a pulse length of 250 microseconds.[23]

Vacuum Sparks are variations on Z-pinches. A vacuum spark (or a pseudospark) is a vacuum arc Z-pinch, i.e., plasma is generated from ablated cathode material. Charge states as high as Mo^{+41} have been observed spectroscopically.[24]

B. Options Evaluated

Equation 4 and the ensuing discussing clearly indicates that, in discharges with continuous formation of neutrals and low charge state ions, very high charge state heavy ions can not be attained in significant quantities. To illustrate this charge exchange limitation, experimental data from figure 1 of reference 9 can be examined rather than perform lengthy calculations. Charge changing cross sections of iodine ions passing through a hydrogen target is plotted in that figure. The cross sections for 5 MeV I^{+7} are: 18.5 Å^2 for electron capture (i.e., charge exchange resulting in I^{+6}), and 0.045 Å^2 for electron loss (i.e., ionization resulting in I^{+8}) respectively. As predicted by equations 2 and 4a, the data proves that the ratio (of over 400) between these processes (cross sections) is rather unfavorable for high charge state formation. Since the I^{+7} energy is much larger than the hydrogen binding energy, the electron loss cross section is equivalent to ionization by free electrons with an equal relative velocity (as would be the case in an ion source). However, in any conceivable (useful) ion source, ion energy spread would not exceed a few KeV. Hence, based on equation 5, the electron capture cross section in an ion source would be much higher than what was measured in reference 7. Furthermore, the data and equation 4a indicate worsening of cross section (charge-exchange/ ionization) ratios with increase in charge state, e.g., the ratio which is (3.54 Å^2)/(3 Å^2) = 1.18 for I^{+2} grows to 400 for I^{+7}.

An obvious limitation for electron beam diodes and for vacuum sparks is constant plasma formation due to a large rate of electrode ablation. To generated high charge state ion beams, with one of these devices, extremely quick extraction, before charge state reduction by charge exchange with neutrals or low charge state ions occurs, is required. Z-pinches and Z-discharges require a working gas. Since Z-pinches can reach 100% ionization, operation in hydrogen could eliminate any adverse charge exchange with the working gas. And to minimize continuous plasma generation, metallic ions must be generated outside the Z-pinch and injected only at the beginning of the discharge.

Stripping of fast (8.6 MeV/nucleon) gold ions in a hydrogen Z-pinch[14] proved to be rather effective. In that case the fast ions contributed to the relative velocity needed for stripping. Ionization of slow ions (KeVs or less) to high charge states in such a stripper has to be done by fast electrons. As a consequence of the large electron density (10^{18} cm^{-3}) in such a plasma, it is obvious from equation 6 that KeV gold ions are stopped in less than one nsec (by dynamic friction). Therefore, the pulse length of the Z-pinch determines the interaction time τ in such a stripper. A 0.5 MA Z-pinch, with a discharge diameter ranging from 1 cm (strong axial field) to 1 mm (let it pinch), has a current density J range of $6.4\text{x}10^5$ A/cm^{-2} to $6.37\text{x}10^7$ A/cm^{-2}. For a 1 μsec discharge, $J\tau$ ranges from 0.63 $Coulomb/cm^{-2}$ to 63.6 $Coulomb/cm^{-2}$. Consulting figure 1, this range of $J\tau$ should yield U^{+19} to U^{+50} as the dominant charge state. Higher charge states are likely, since figure 1 does not include Z-pinch observed enhancements to $J\tau$.

IV. A COUPLE OF POSSIBILITIES

A. Enhanced E-Mevva

E-Mevva yield of higher charge states can be enhanced by raising the intensity of the electron beam in the drift region, and an even more important enhancement contribution is the prevention of "fresh plasma" formation during stripping. In view of the section II discussion, the effect of charge exchange with low charge state ions must be avoided.

A relatively easy way to accomplish this is to make the E-Mevva electron beam pulse much longer than the Mevva pulse. For example, the following timing sequence can be tried: the electron gun is fired for a 10's of μsec. The electron gun triggers a Mevva pulse which lasts about one microsecond, i.e., the electron gun pulse is much longer than the Mevva pulse. Length of electron beam pulse should by slightly longer than the ion confinement (drift) time in the system. If no fresh plasma is generated during most of the electron beam pulse, the an favorable charge exchange (shown in equations 4, 4a, and 5) would be greatly reduced, and electron stripping will be the dominant process.

B. LIZ-MEV

Development of LIZ-MEV, a Low Impedance Z-discharge Metal Vapor ion source has commenced at U.C. Irvine.[25] It is basically a magnetized vacuum spark. Simplicity is a notable feature of LIZ-MEV. However, attainment of extracted very high charge states is most likely limited by continuous plasma formation through out the pulse. Figure 2 shows one of possible improvement of this device, which would retain its simplicity by avoiding any complex timing. A hydrogen Z-pinch is used, as a second stage, to further strip metallic ions emanating form the vacuum spark.

Time sequence of the figure 2 is as follows: first, proper voltages are applied to the electrodes. At the onset, a short (10's of nsec) vacuum spark is fired. Ions and radiation emanating from the vacuum spark trigger the Z-pinch, which lasts for a μsec or longer. Metallic ions enter the Z-pinch during the first 10's of nsec of the Z-pinch pulse. As previous section calculations indicate, metallic ion charge states are raise by electron stripping. These ions are extracted at the end of the Z-pinch pulse.

V. DISCUSSION

Nardi and Zinamon [26] were first to indicate that fully ionized plasmas are much better strippers (than gas cells) due to elimination of the unfavorable charge exchange (with lower charge state ions) process. Their stimulating work, let to the impressive GSI stripping results.[14] However, that work involves very fast heavy ions. A source based on that approach would not offer a tangible advantage over stripping foils, and such a source is impractical for industrial and many scientific applications.

Stripping of stationary heavy ions by fast (or even ions) can be easily accomplished in table top experiments. And, very high charge states heavy ions have been observed spectroscopically.[24] A more difficult task is to prevent neutralization of these ions, and to extract them into a useful beam. An improved E-Mevva, and LIZ-MEV are possible ways to accomplished this task.

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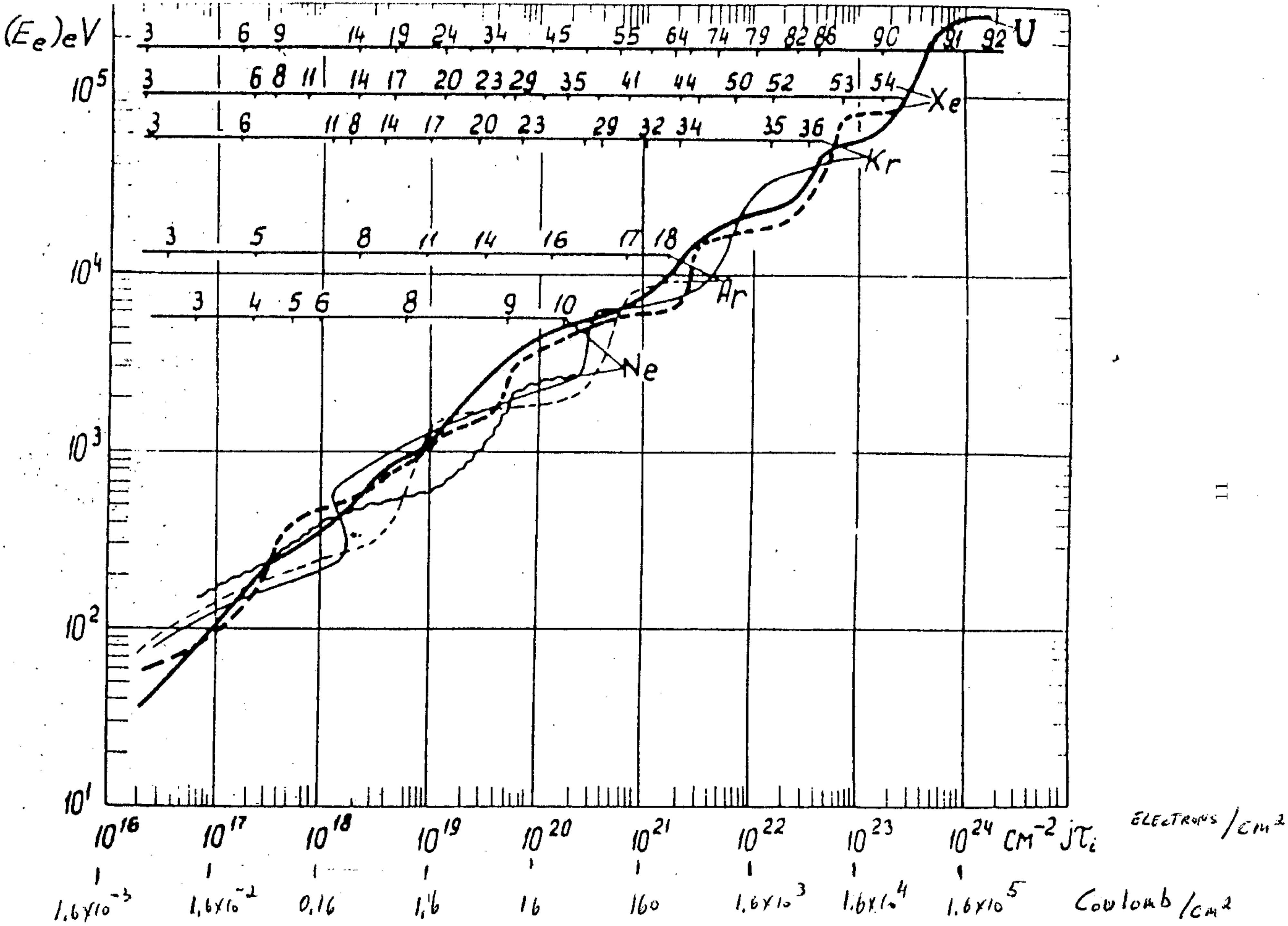

(E_e)eV
10^5
10^4
10^3
10^2
10^1
3 6 9 14 19 24 34 45 55 64 74 79 82 86 90 91 92 U
3 6 8 11 14 17 20 23 29 35 41 44 50 52 53 54 Xe
3 6 11 8 14 17 20 23 29 32 34 35 36 Kr
3 5 8 11 14 16 17 18 Ar
3 4 5 6 8 9 10 Ne
10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21} 10^{22} 10^{23} 10^{24} CM^{-2} $j\tau_i$
ELECTRONS /cm²
1.6×10^{-3} 1.6×10^{-2} 0.16 1.6 16 160 1.6×10^{3} 1.6×10^{4} 1.6×10^{5}
Coulomb /cm²

FIGURE 1

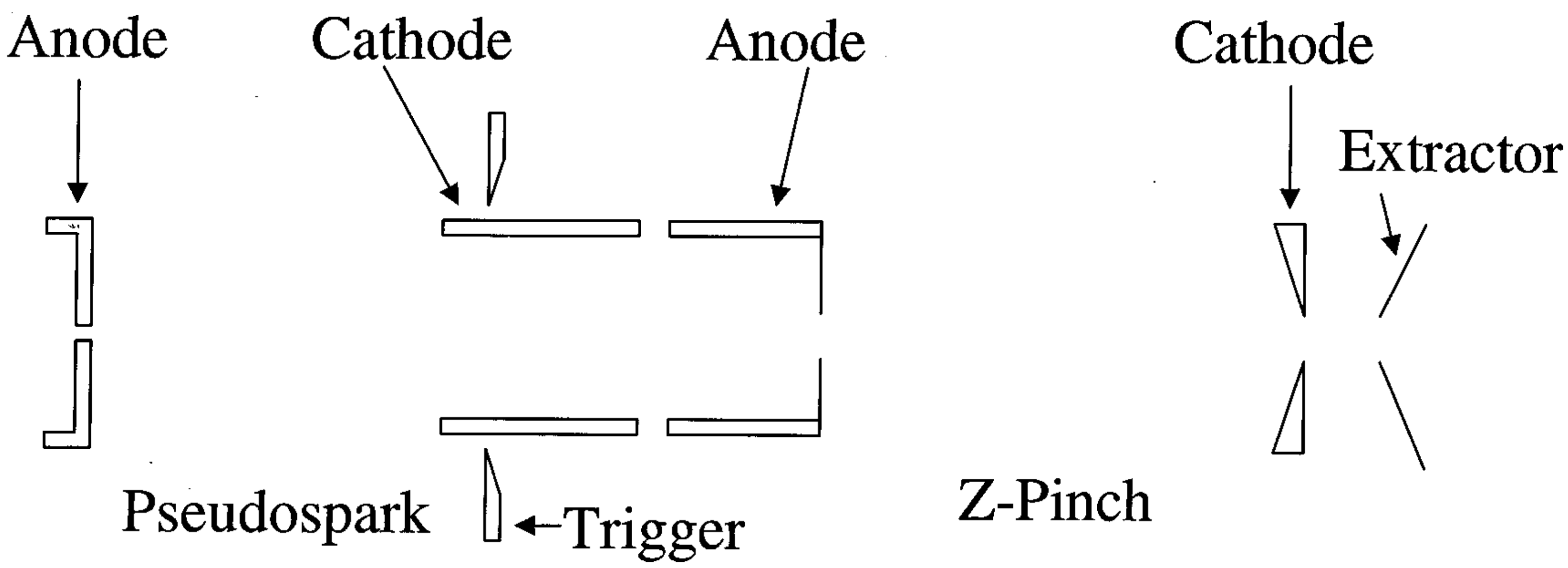
Anode
Cathode
Anode
Cathode
Extractor
Pseudospark
Trigger
Z-Pinch

Figure 2