THE ATOMIC NATURE OF THE ION PRODUCTION LIMIT IN ECR ION SOURCES

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INTRODUCTION

There are now about 45 ECR ion sources in operation for multiply charged positive ions. The majority of these ion sources are used for accelerator injection.[1] There are also about 10-15 ECR sources either under construction or being planned for construction, but the majority of these new ion sources will be used for atomic physics research. Given this emerging atomic research application, in this paper we will consider the ion production limits from the standpoint of atomic physics, by looking in some detail at the operation of the 6.4GHz RTECR.[2]

Positive ions are produced in ECR ion source mainly by successive electron impact ionization, although the importance of single-step multiple ionization processes and auto-ionizing metastable states, particularly for low and intermediate charge ions, is becoming more apparent.[3] Even before the original ECR source prototype Super Mafios-B had been copied, ECR source operating characteristics were being estimated and compared to other types of ion sources, as shown for example in Figure 1.[4] Here the operating limits are specified in terms of ionizing electron energy, and the logarithm of the product of plasma density times the confinement time. Why choose these particular parameters? As we will show, the rate of ionization does scale with $n_e\tau_c$, but the total extracted ion current should scale something like $I \propto n_e/\tau_c$, seemingly a contradiction. Similarly, to avoid recombination losses of highly charged ions, we should have $n_e/n_o >> 1$, where n_o is the un-ionized particle density in the plasma. However, to build up a high plasma density in such gas fed ionizers, one finds experimentally that $n_e \propto n_o$, another contradiction. Furthermore, how high should E_e, the ionizing electron energy, be for the production of multiply- charged ions in ECR sources. Given these considerations, are parametrizations like that in Fig. 1 actually useful?

RTECR OPTIMIZED PERFORMANCE

Several ECR sources have now been operational since the early 1980's–the LBL 6.4GHz ECR [5], the Groningen, Ganil, and SARA 10GHz Minimafios,[6–8] the Oak Ridge 10GHz ECR,[9] the RTECR at NSCL[10], and perhaps some others. Most of these sources have thousands of hours of operation, with many species ionized. For example, the RTECR, turned on in late 1985, has operated about 6000 hours/year since 1986. Is there anything about this performance that would suggest that Fig. 1 scalings are valid?

Figure 2 shows the overall performance of the RTECR for the noble gases through uranium. For clarity, other species are not shown, though they fit smoothly between

these performance curves. (Note that particle microamps are plotted in Fig. 2–because of the high charge of heavier species, such curves are distorted by plotting the intensities in electrical units, so we avoid that). In examination, two trends are observed in Fig. 2. First, the lighter masses have higher absolute intensities. Second, the charge state distributions spread out with increasing Z. It is very difficult to obtain high absolute intensities of highly charged ions of high Z materials, and this is a general result.

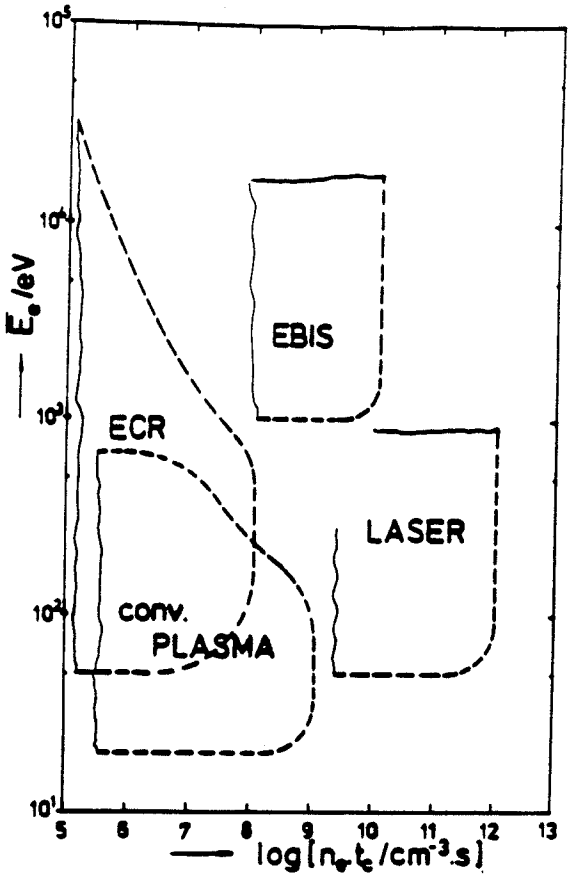

Figure 1. Even before the so called exotic sources (Laser, ECR, EBIS) had widespread application, their performance was rated in the parameters E_e–the ionizing electron temperature, N_e–the effective plasma density, and τ_c–the average ion confinement time. (From Ref. 4)

The performance of the RTECR is highly optimized. For example, for highly charged Uranium, it has the best cw performance, exceeding even the high performance 18GHz minimafios of Grenoble, as shown in Figure 3. The optimized performance of the RTECR is based on many techniques: 2 stages[11], high axial confinement on the 1st stage side[12], gas mixing[13], SiO_2 wall coating[14], super gas mixing for metallic species like the uranium shown[15], and finely optimized ion extraction[16]. Given that these techniques are highly empirical, and all do something different to the plasma, is there any possible general explanation for the overall performance shown in Fig. 2?

Curiously, the answer is yes, and the single parameter of importance seems to be the electron impact ionization energy E_e. To show this, we mark the 1μA level of operation of the RTECR, for several species, including gases and metals, on a plot of successive ionization potential versus Z in Figure 4. On this plot, the 1μA level of performance of the RTECR falls on a nearly straight line with an effective ionization potentials of 1000eV! It is as if one could say that, knowing the ionization potential for some ion, the performance of the RTECR for all other species is predictable. This suggests that we should look in more detail at the ionization mechanism.

SUCCESSIVE ELECTRON IMPACT IONIZATION

In Fig. 4, we are looking at the performance of the RTECR for *highly charged* ions; and in all ECR sources, these are produced by step-wise successive electron impact ionization. A single step in this process would then be

$$X^i + e \rightarrow X^{i+1} + 2e \tag{1}$$

The ionization rate for this step, ignoring all losses, is

$$\nu_{i,i+1}(E_e) = n_e(E_e) v_e(E_e) \sigma_{i,i+1}(E_e) \tag{2}$$

where n_e is the ionizing electron density, v_e the electron velocity, and $\sigma_{i,i+1}$ the cross-section for this ionization step. Now a big problem with estimating this rate is that distribution of electron energies in ECR sources is not well known. However, it appears to be maxwellian[17], so we take a Maxwell-Boltemann distribution for the electron energy E_e. Assuming as well that $n_e(E_e) = n_e$, and setting $\beta \equiv 1/kT_e$, we can write the average rate of ionization as

$$\nu_{i,i+1} = \left(\frac{2}{M_e \pi}\right)^{1/2} n_e \beta^{1/2} \int \sigma_{i,i+1}(E_e) \beta E_e exp(-\beta E_e) dE_e \tag{3}$$

To reduce this further, we take the Müller formulation for the ionization cross sections [18], obtaining finally the reduced ionization rate

$$S_{i,i+1} \equiv \frac{\nu_{i,i+1}}{n_e} = \frac{C\beta^{1/2}}{\phi_i} \int_{\beta\phi_i}^{\infty} \frac{e^{-x}}{x} dx \tag{4}$$

where C=$(1.4 \times 10^{-13})(\frac{2}{M_e \pi})^{1/2}$ is assumed. As an example, the reduced ionization rates for production of argon 1+ - 16+ have been calculated and plotted in Figure 5. For each ion, the ionization rates increase from $E_e = \phi_i$ to a maximum and then gradually decline with increasing energy. Also, since the ionization rates normalized to available plasma density decrease rapidly with increasing charge removed, one could then say that more highly charged ions are more difficult to produce, but how much more difficult?

IONIZATION DIFFICULTY

Instead of looking at ionization rates, as in Eq(3), we can look at the time required for a single ionization step. We expect these step times to be long for highly charged ions, and if they are longer than some characteristic time constant in the plasma, we can say that the production of these ions is truly *difficult.*

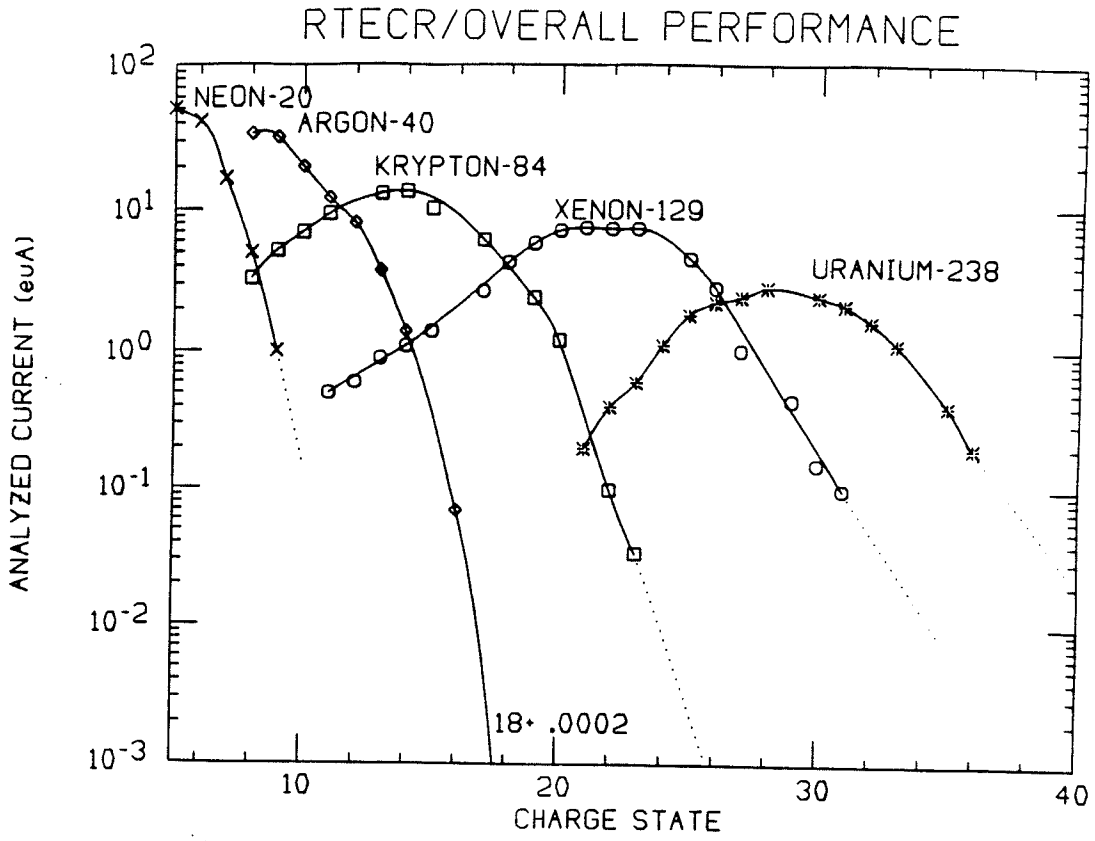

Figure 2. After several years of operation, the RTECR ion source at NSCL shows a smooth dispendence of extracted particle intensities (not electrical!) on the number of electrons removed, over the whole periodic table.

Let

$$\tau_{i,i+1} = \frac{1}{\nu_{i,i+1}} = (n_e(E_e)\sigma_{i,i+1}(E_e)v_e)^{-1} \tag{5}$$

Again assuming $n_e(E_e) = n_e$ and averaging the electron energy E_e over a M-B distribution, yields an average step ionization time

$$\overline{\tau}_{i,i+1} = n_e\,(\xi_{i,i+1}(E_e))^{-1} \tag{6}$$

where we have let

$$\xi_{i,i+1}(E_e) \equiv < \sigma_{i,i+1}(E_e)v_e >_{E_e} \tag{7}$$

$\overline{\tau}_{i,i+1}$ is the average time required for the step-wise ionization of X^{i+} to X^{i+1}. Let τ_c be the average ion lifetime in the plasma. For the step i$\rightarrow$i+1 to be possible, we require at least that

$$\tau_{i,i+1} \leq \tau_c \tag{8}$$

And combining this relation with Eq.(15), we then have

$$n_e \tau_c \geq \xi_{i,i+1}^{-1}(E_e) \tag{9}$$

On the left side of Eq.(8), we have only plasma parameters; on the right, only atomic information parameterized in E_e, the electron impact energy. This is exactly the kind of parametrization we need to explain Fig. 4.

For fully stripped ions, Eq.(8) can be reduced to an analytic expression, as plotted in Figure 6. In order to go from He^{2+} to U^{92+}, the electron energy must increase almost four orders of magnitude, while at the same time $n_e \tau_c$ must increase five orders of magnitude. Also, U^{92+} is seen to be nearly one order of magnitude more difficult than producing U^{90+}!

For optimum conditions for a particular fully stripped ion, we can also ask what charge states would be obtained for partially ionized, higher Z elements, and these are also indicated in Fig. 6. Hence, the observation of a particular fully stripped ion extracted from an ECR source can then be used to predict the performance for other species (at probably similar intensities).

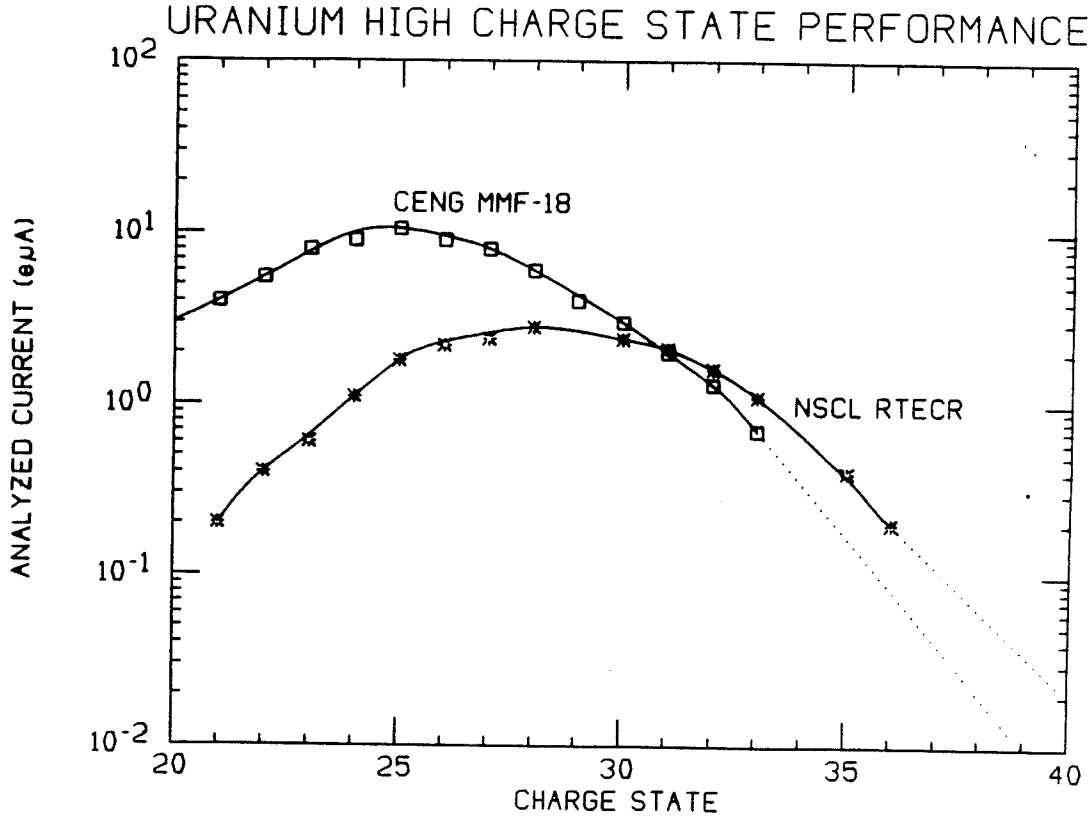

Figure 3. Even more remarkable, the high charge tail of the uranium distribution produced by the 6.4 GHz RTECR is seen to exceed that of the 18 GHz Grenoble ECR [19], an ion source that is presumed to operate at substantially higher ionization rates.

In Table 1, we summarize the performance of the RTECR for ions with extracted intensities equal to those of N^{7+} and Ne^{10+}. Table 1 also includes predictions based on Eq.(8), for ions that would be expected to have production difficulty equal to that of N^{7+} and Ne^{10+}. For the case of N^{7+}, one can see excellent agreement between actual values and theoretical predictions. The implication for the RTECR (and other ECR sources), is that, all the empirical ion production techniques notwithstanding, the ultimate performance depends entirely on atomic limits.

Table 1. A comparison between RTECR actual performance and the ionization difficulty parameterization.

OPTIMUM ION	Ne	Ar	Kr	Xe	U
THEORY-N^{7+}	9	14	20	28	34
RTECR 0.1 pμA	9	14	19	26	28
THEORY-Ne^{10+}	-	16	26	35	47
RTECR 0.01 pμA	-	16	22	29	35

When looking at the Ne^{10+} case in Table 1, one sees a discrepancy between the actual and predicted values that increases with increasing Z. This is to be expected, since we have not included any atomic loss processes, and these losses should be increasingly more important as the number of electrons removed is increased.

FINAL REMARKS

We see evidence for an atomic limit in the ion production in ECR sources. This is good for several reasons. First, knowing what limits ion production will certainly be helpful in improving performance. Second, we have now a formalism for *predicting* the performance of ECR sources for species not yet attempted. As Fig. 4 shows, the RTECR 1μA level is smooth in Z, and this should be the same for other ECR sources. Third, this formulation can be applied to other kinds of ion sources– the Ar^{18+} line in Fig. 6 certainly matches EBIS ion source performance, at least qualitatively. Finally, comparing Fig. 6 and Table 1 with Fig. 1, one can conclude that the early predictions for the scaling of performance of the exotic sources were not too bad! All this makes one hopeful that scientific criteria may yet replace the alchemy at the heart of source development.

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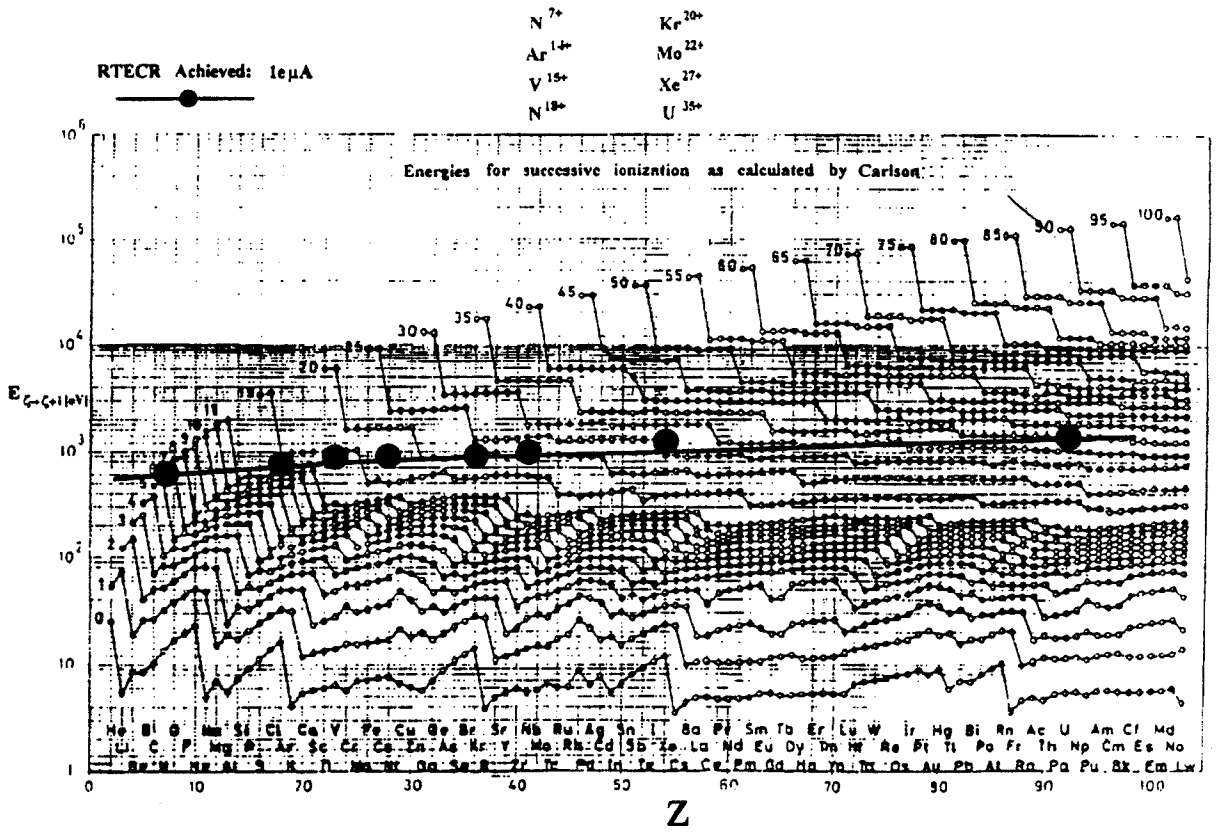

Figure 4. While the performance of the RTECR for metallic or gaseous species is derived from many techniques, it appears to be parameterizable on the basis of one single parameter: successive electron impact energy. The question is–why? (Ionization potential data is taken from Ref. 20.)

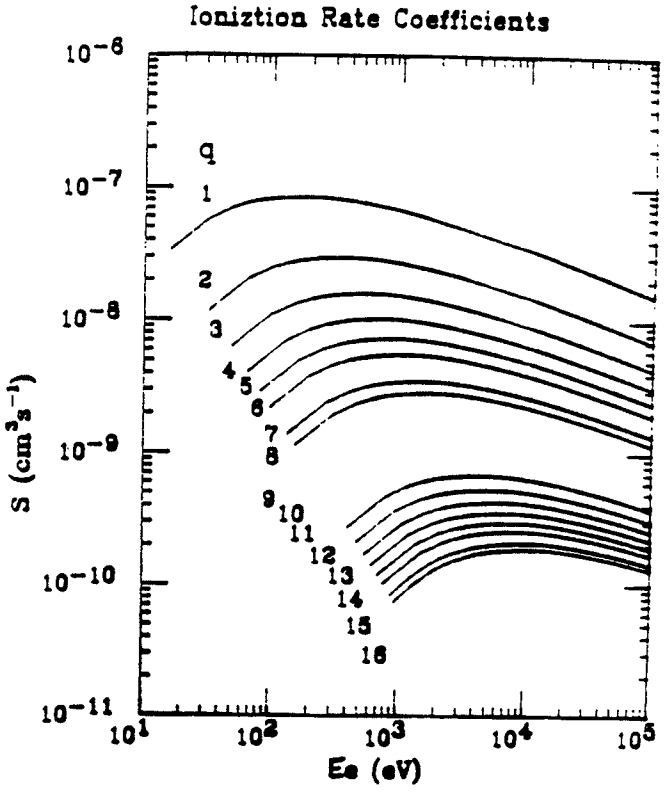

Figure 5. A plot of the reduced ionization rate for argon ion production shows that higher charge states require higher electron energies (no surprise), and yet still have lower production rates. This does not immediately explain the RTECR performance shown in Figures 2 or 4.

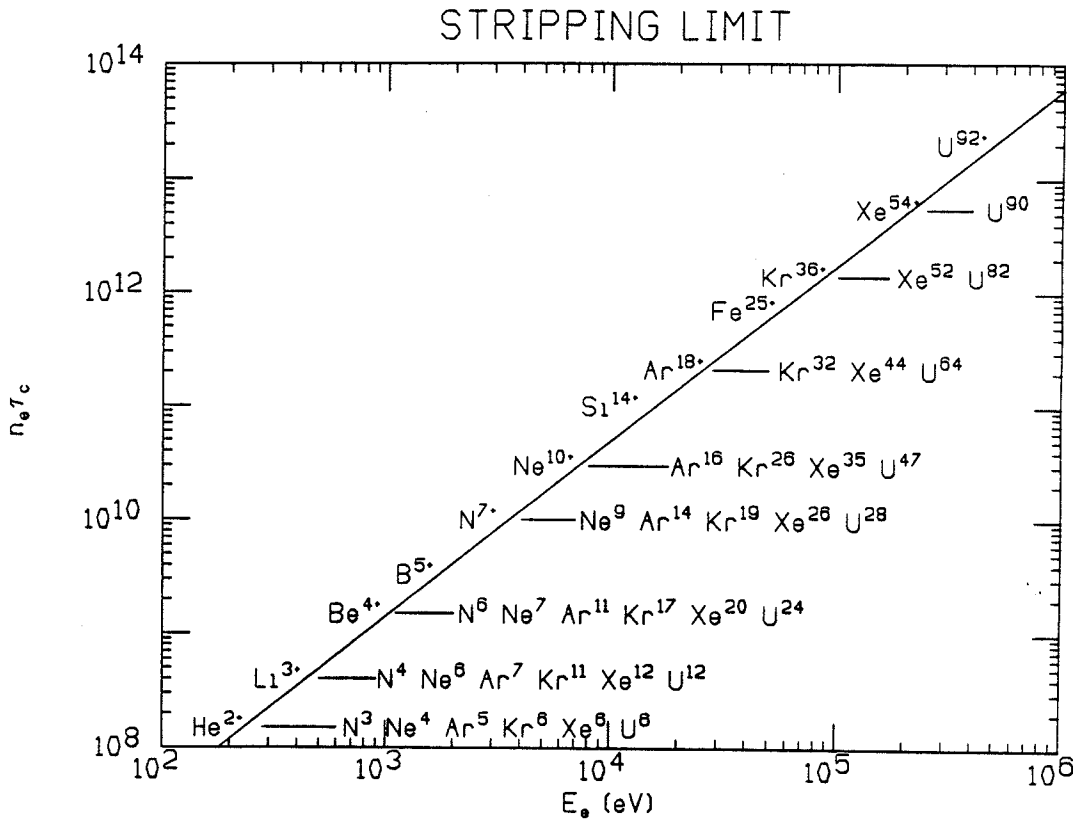

Figure 6. When we plot $n_e\tau_c$ versus E_e for the production of fully stripped ions, we can also derive optimum partially stripped species for the same E_e. This leads one to the concept of 'ionization difficulty', which increases with both $n_e\tau_c$ and E_e, confirming the parameterization of the exotic sources given in Figure 1, and suggesting why the RTECR performance has the dependence shown in Figure 4.