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The Constance B Mirror as a Source of Highly Stripped Ions

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ABSTRACT

The potential of the Constance B mirror as a source of highly stripped ions for fundamental atomic physics research is described. The hot electron, cold ion plasma ($n\tau > 2\times10^{11}$ cm^{-3}-s, T_{eh}=400 keV, T_i<20 eV) created by electron cyclotron resonance heating (ECRH) is characterized by a confinement time which is long compared to the ionization time for many high Z ions. Calculations indicate that helium-like argon will be formed in Constance when the neutral pressure is reduced to 10^{-8} torr during the decay of the hot electrons. A 28 GHz upgrade machine in which Xe^{+50} could be produced, is also described.

Introduction

Highly stripped ions have many diverse applications in present day physics research and industrial uses. Accelerators use high Z ion sources to produce highly stripped, high mass ion beams for basic atomic and nuclear physics research. Hydrogen and helium-like ions up to xenon (Z=54) as well as less stripped ions up to uranium are needed in order to perform accurate spectroscopic measurements of the Lamb shift in the VUV and soft x-ray regions. The wavelengths of some of the transitions of high Z states may have applications for the creation of high power lasers in the XUV and x-ray wavelength regions. Highly stripped ions can also be used for deep implantation of dopant ions into semiconductors.

Hot electron mirrors have been recognized as practical sources of highly stripped ions since 1974 [1]. Minimum-B mirrors are widely used as ion sources for cyclotron injection since the endloss currents which are characteristic of mirrors makes them ideal for injection into beamlines. Using electron cyclotron resonance heating (ECRH), hot electron temperatures of hundreds of kilo-electron-volts are easily attained. These temperatures are greater than the ionization potentials of most high charge state heavy elements. The confinement time for heavy ions is longer than the ionization time so that the ions can become very highly stripped in these plasmas. In ECR plasmas the ion temperature is very low (<20 eV), an advantage for precision spectroscopy work.

This report discusses the Constance B plasma from the viewpoint of high Z ion production and presents calculations which indicate the high Z ion potential of the machine. The few experimental results we have in this new area are presented. We also discuss the prospects for an upgraded, high density facility which will be capable of providing even higher charge states.

Constance B Plasma

Hot electron plasmas are made in Constance using several kilowatts of microwave power at the electron cyclotron resonance frequency (ω_{ce}=eB/mc). The microwaves ionize the gas which is puffed into the vacuum chamber, and the electrons then gain predominantly perpendicular energy from the rf electric fields and are rapidly heated to relativistic energies. A typical measured heating rate is 600 keV/sec-kW. Three separate electron components are measured- cold (T_c=100 eV), warm (T_w=2 keV) and hot (T_h=400 keV). The ratio of the hot to cold electron density varies with neutral pressure but is typically on the order of unity when the microwave power is on. The warm electron density is less than one-tenth of the hot density. Typical plasma parameters for a hydrogen plasma are listed in Table 1. These parameters can be substantially varied by changing the gas pressure, the microwave power, and the magnetic field [2].

Figure 1 shows a sample of the usual shot sequence. The magnet is turned on and the gas is puffed in via a piezo-electric valve before the microwave power is injected at t=0 seconds. The cold electron density rises to its steady state value within 50 ms. The hot electron density is approximately constant after the first 100 ms, while the hot electron temperature typically increases during the shot. The hot electron temperature is measured with a NaI detector. The ion temperature is measured to be < 50 eV when no ion heating is used. When

Table 1. Plasma Parameters in Constance B

Hot electron temperature	400 keV
Cold electron temperature	50 eV
Hot electron density	2×10^{11} cm^{-3}
Cold electron density	2×10^{11} cm^{-3}
Ion temperature	< 20 eV
Beta	30 %
Potential	150 V
Plasma volume	8 liters
Plasma radius	10 cm
Neutral pressure	5×10^{-7} torr
Pulse length	2 seconds

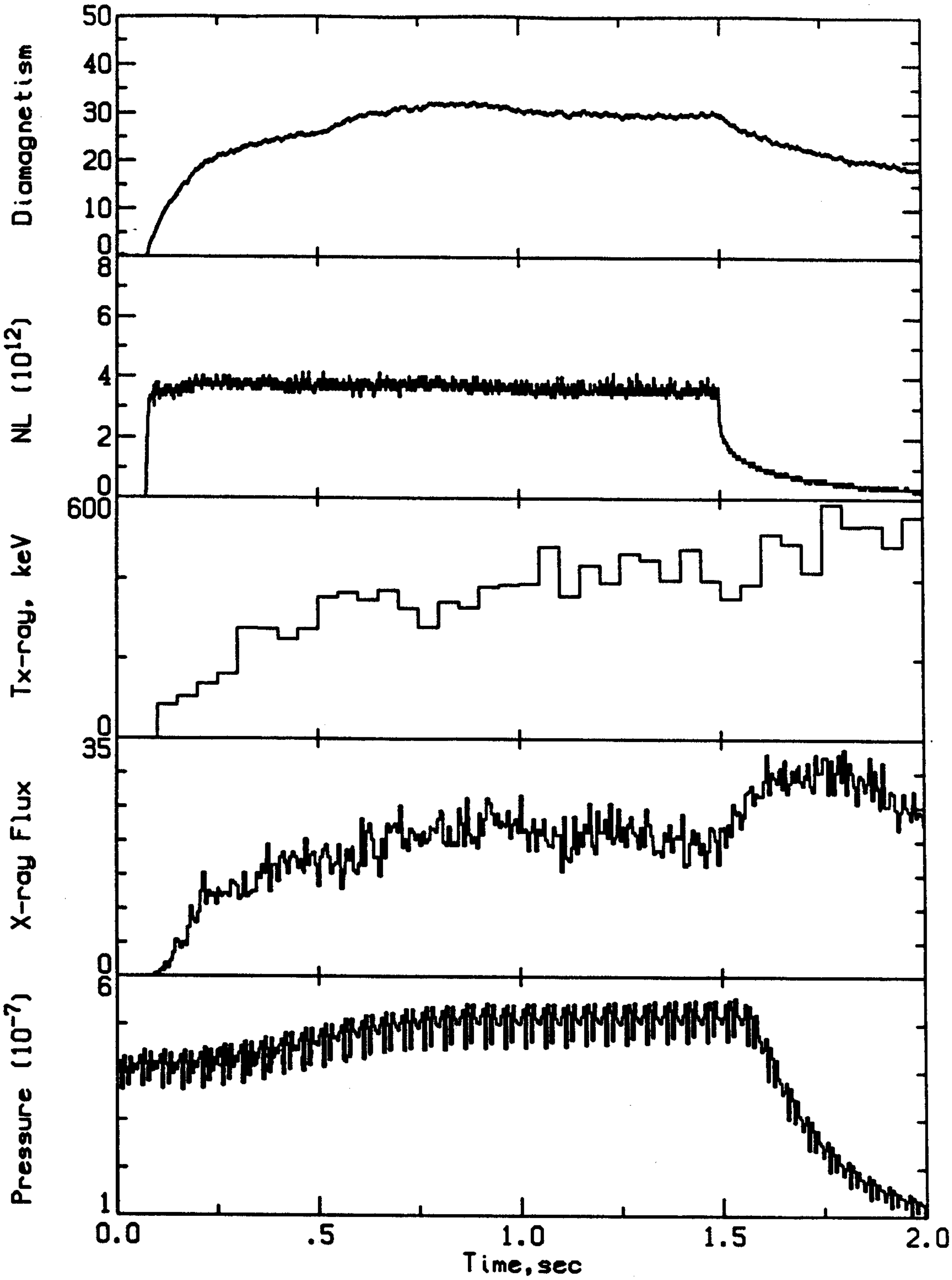

Fig. 1. Diagnostic signals from a plasma shot with 4 kW of ECRH and a midplane magnetic field of 3 kG. The plasma diamagnetism, the electron line density, the x-ray temperature, the x-ray flux, and the edge hydrogen pressure as a function of time are shown. The ECRH is turned off at t=1.5 seconds.

the ECRH is turned off (t=1.5 sec), the plasma character changes markedly.

The afterglow plasma is the mostly hot electron plasma which persists after the ECRH is turned off. The bulk of the cold electron plasma collisionally decays within a few hundred microseconds of rf turn-off. The hot electrons have a much longer decay time (seconds) because of their higher temperature ($\tau \propto T_e^{3/2}$). There are some cold electrons formed by ionization of the background gas by the hot electrons but their number is small (estimated to be <10%) because the ionization cross-section is low at electron temperatures. The ions will necessarily have the same long confinement time which characterizes the hot electrons in order to maintain charge neutrality.

The gas can be shut off when the ECRH is turned off so that the neutral pressure can be lowered in the afterglow. In our present mode of operation (i.e. without a preionization source) the background gas is necessary when the ECRH is on to make the plasma. If the gas pressure is too low (<5×10^{-8} torr) breakdown does not occur and the density will not build up. However low gas pressure is desirable for the production of highly stripped ions because charge exchange losses (which we will see are very important in the next section) are reduced. Thus by turning off the gas a situation is created where we have a pure hot electron plasma in a low neutral pressure - the charge exchange time goes down while the ionization time is unchanged. In hydrogen or oxygen, for example, the pressure can be reduced almost 2 orders of magnitude in a few hundred milliseconds. We would expect the ions to become more and more highly stripped under these conditions.

High Z Ion Generation Physics in the Constance Plasma

Given the plasma conditions described in the previous section, what will be the resultant ion charge state distribution? The atomic processes which determine the charge state distribution which will result are : single and multiple step ionization, single and multiple step charge exchange between a neutral and an ion, radiative recombination, and dielectronic recombination. Plasma processes such as confinement and transport also obviously impact on the charge state distribution.

In our calculations, we assume that ionization occurs via stepwise electron impact ionization, and that single step charge exchange is also dominant over multiple step charge exchange. This is a good assumption for the low density plasmas in question. Figures 2 through 4 show some characteristic times for these processes in helium-like argon, krypton, and xenon as a function of electron density. A hot electron temperature of 100 keV and a cold electron temperature of 100 eV have been assumed. We have chosen the helium-like state since it is of interest for Lamb shift studies. The ionization time is calculated using the cross-section given by Müller [3] for ease of computation, even though it is known to not work very well for elements other than argon. The charge exchange time is found using the prescription by Müller [4] and is shown for a neutral pressure of 10^{-8} torr (the time is inversely proportional to pressure). Radiative recombination is computed using the Bates/McWhirter [5] model, which is found to be low compared to some more recent models, but it is very easy to calculate. The limitations of each of these models are described by West [6]. Given these limitations we feel these calculations can only be accurate to a factor of two or three. The radiative recombination time labelled

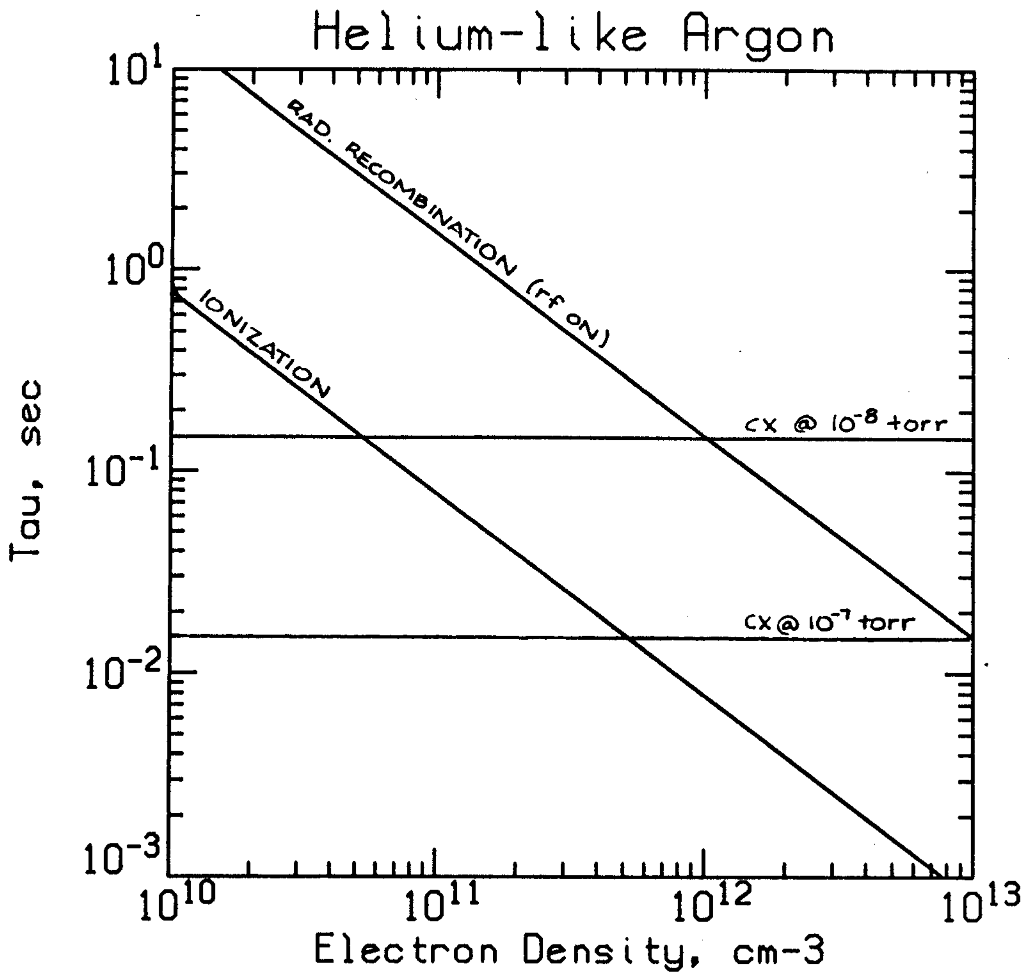

Fig. 2. Calculated ionization, charge exchange and radiative recombination times for helium-like argon as a function of electron density.

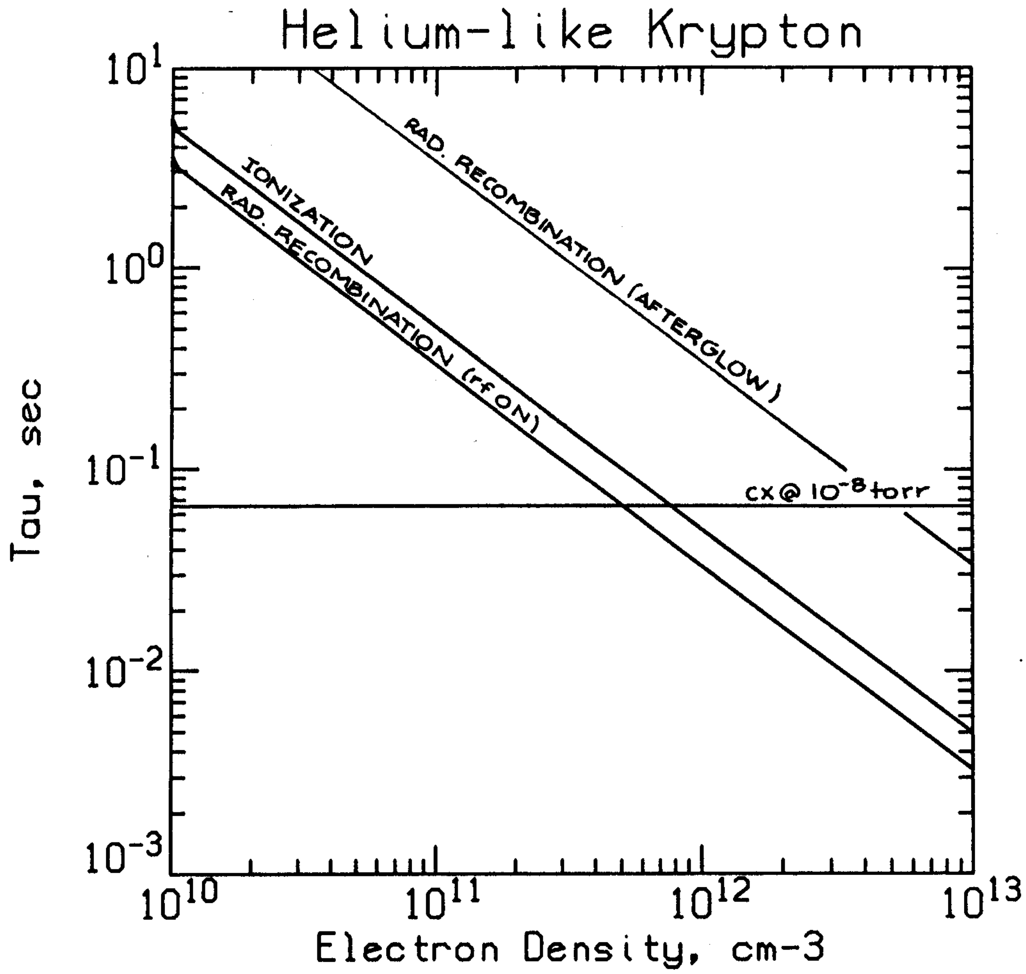

Fig. 3. Calculated ionization, charge exchange and radiative recombination times for helium-like krypton as a function of electron density.

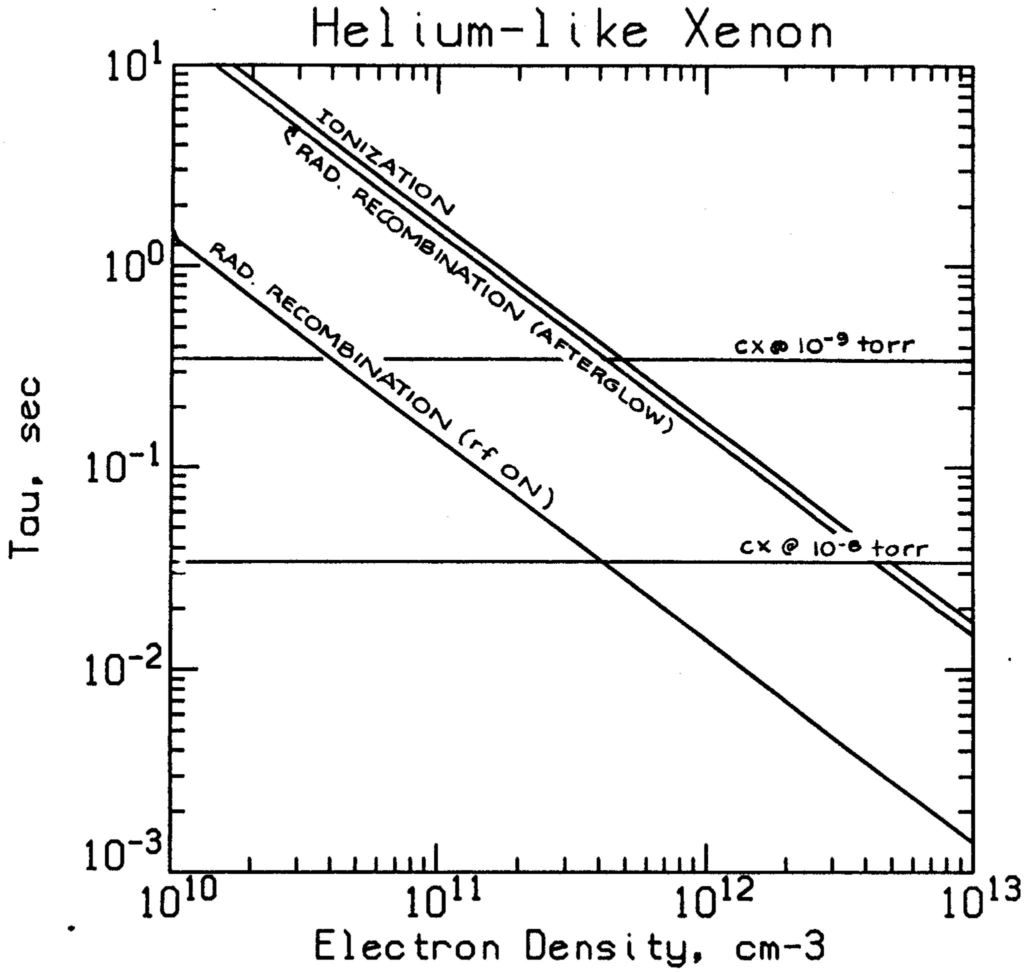

Fig. 4. Calculated ionization, charge exchange and radiative recombination times for helium-like xenon as a function of electron density.

"rf on" is calculated based on a cold electron density which is equal to the hot electron density. The afterglow value is calculated assuming n_c=0.1 n_h.

From these graphs one can see that for argon plasmas with a 10^{11} cm^{-3} density and a background neutral pressure of 10^{-8} torr, the ionization time is longer than the charge exchange time and less than the 1 second confinement time so that we may expect the presence of helium-like argon. The radiative recombination time is much longer than all other times, so that it can be neglected. For helium-like krypton the radiative recombination time is comparable to the ionization time when there are equal densities of hot and cold electrons. In the afterglow the cold electron density is typically reduced by an order of magnitude when the rf is turned off, so that in fact the calculated radiative recombination time is unduly pessimistic. When the cold electron density is reduced by 10, the radiative recombination time increases by a factor of ten and then we would operate in a regime where charge exchange again becomes the limiting process. Then for densities of $2x10^{11}$ cm^{-3}, neutral pressures of 10^{-9} torr are necessary for helium-like krypton. Conversely, if the pressure were constrained to be 10^{-8} torr by the available pumping speeds, then densities of 10^{12} cm^{-3} are necessary.

For helium-like xenon, the requirements become more stringent. Densities near 10^{12} cm^{-3} and neutral pressures less than 10^{-9} torr are necessary in the absence of radiative recombination losses. But even in the afterglow plasma, the radiative recombination rate is higher than the ionization rate. Another critical issue for xenon is the scaling of confinement time with density. The confinement time in hydrogen at 10^{11} cm^{-3} is 1 second, and presumably the confinement time scales at least inversely with density given that it is related to the scattering time. Thus at 10^{12} cm^{-3} the confinement time may be comparable to the ionization time. Clearly the scaling of confinement time with density should be measured. Therefore, as a result of recombination losses and the limit imposed by the hot electron confinement time, it is unlikely that helium-like xenon will be obtained, even in a 10^{12} cm^{-3} density Constance device.

In this analysis, dielectronic recombination losses have not been considered. The dielectronic recombination rate is higher than the radiative recombination rate for partially ionized atoms. For the higher mass ions such as xenon, it is undoubtedly important (especially when the ECRH is on) and should be calculated.

Of course, even though the helium-like states of the very heavy ions (Z>50) are unlikely to be achieved in a Constance plasma because of recombination losses, very high charge states are still possible. We calculate that for xenon, Xe^{+33} is where the radiative recombination time becomes comparable to the ionization time (for equal hot and cold densities). During the afterglow, this occurs for Xe^{+50} (assuming $n_{eth}=n_e/10$).

Time Evolution of the Charge State Distribution

Since the hot electron temperature is measured to rise at a rate of 600 keV/sec-kW, one can see that the hot electron temperature exceeds the ionization potential for very highly stripped states (tens of kV) within the first 100 ms of the shot. The density is also established at its steady state value by this time. Therefore the charge state distribution is established early in the shot. When the ECRH is on, the average charge state of a Z>20 plasma will be determined in most cases by the recombination losses, and will be kept low by the presence of cold plasma component.

When the ECRH is turned off the cold plasma density is greatly reduced, as has been previously mentioned. This diminishes the recombination losses. If the gas pressure can also be decreased when the rf is turned off, then the charge exchange losses can also be reduced. This, coupled with the reduction in the recombination losses will also allow the average charge state to increase with time as the hot electrons decay. This is shown schematically in figure 5. Clearly the afterglow is the preferred operating regime.

The rate at which the pressure can be reduced depends on the gas species; i.e. the pumping speed for that gas. In Constance, pumping is provided by three sources: a turbo-molecular pump, a cryo-pump, and titanium gettering on the vacuum chamber surfaces. The titanium gettering is the largest pump for hydrogen and oxygen because of the large surface area. The pumping speed is on the order of 100,000 l/sec compared to 1000 l/sec for the turbopump and the cryopump. In hydrogen the pressure can be reduced by almost two orders of magnitude (from $2x10^{-6}$ to $5x10^{-8}$ torr) in approximately 400 ms when the gas is turned off due to the tremendous pumping speed for hydrogen. The cryopump pumps heavy gases more effectively than the turbo-molecular pump but the pumping speed is still not high enough to get the pressure back down to the base pressure in less than 5 or 10 seconds.

Therefore in pure heavy gas plasmas such as xenon or krypton it will not be

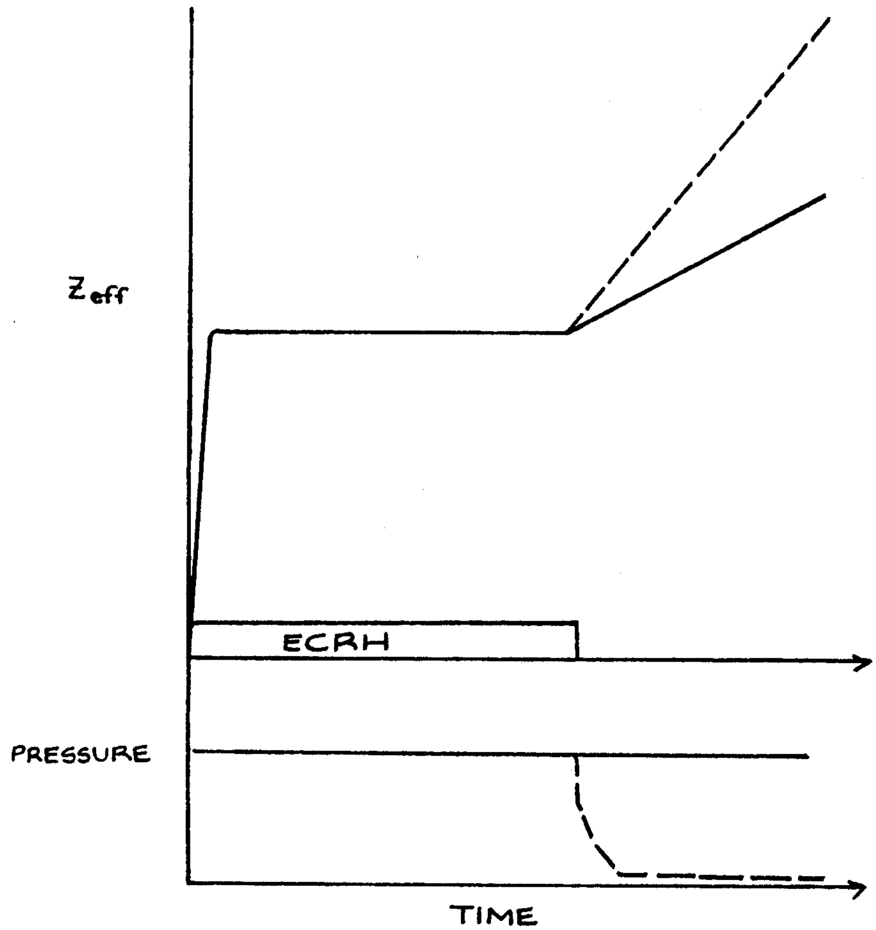

Fig. 5. Schematic representation of the evolution of the average charge state during a plasma shot. The dotted line shows the expected effect of reducing the neutral pressure in the afterglow.

possible to see the orders of magnitude changes in neutral pressure in the afterglow before the hot electrons have decayed. However, there are two ways to get around this situation. The first is to exploit the phenomenon of gas mixing which has been used with great success on ECR ion sources [7]. It has been found that by running their machines in a mixture of a heavy gas (e.g. xenon) and a light gas (e.g. oxygen or nitrogen), the extracted currents at the higher charge states of the heavy gas are enhanced relative to the case of a pure heavy gas. By using a mixture of xenon or krypton with oxygen, for example, the average charge state will be higher than with pure xenon or krypton and in addition the pressure in the afterglow can be reduced by pumping out the light gas. This will reduce the charge exchange losses.

The second method also comes to us via the ECR ion source community. The conventional ECRIS in use today for cyclotrons consists of three stages: a first stage preionizer, a minimum-B mirror confinement stage, and an extraction stage. In the first stage a microwave discharge plasma is created which flows into the second stage. This eliminates the need for high gas pressures for startup in the minimum-B region. The gas feed can be reduced to a very low level in the minumum-B region. A separate microwave source is presently being designed for Constance and we anticipate it will be installed by late summer 1987.

Highly stripped ions of solid elements can also be generated. The solid material can be inserted into the plasma on a probe where it will be vaporized. Another technology available on Constance is to drop small spheres of the desired material into the preformed plasma.

Experimental Results to Date

High resolution x-ray data is not available since we do not have instruments to measure the emission spectra in the appropriate wavelength region. Such measurements are vital to establish the existence of highly stripped ions in Constance. Low resolution soft x-ray measurements using germanium and lithium-drifted silicon detectors have been made. Figure 6 shows the low energy soft x-ray spectrum measured with a Si(Li) detector for a hydrogen plasma. Note the presence of the argon, titanium and copper impurity lines.

Figure 7 shows the soft x-ray spectrum measured in a xenon plasma. One of the interesting features of the xenon spectrum is the enhanced continuum level between the K_β and the K_α peaks, which may be due to recombination. The spectrum does not indicate the presence of helium-like xenon, but we would not expect it to for the operating conditions under which the data was taken.

A time-of-flight analyzer has recently been installed on the machine to measure the q/m components of the plasma endloss current. This is not the same as the charge state distribution of the ions in the plasma, but is related via the confinement physics. Data from the time-of-flight analyser (TOFA) from an unoptimized argon plasma is shown in figure 8 where up to Ar^{+10} is clearly visible along with charge states of carbon, aluminum, and oxygen impurities. Charge states greater than 10 would be in the noise level.

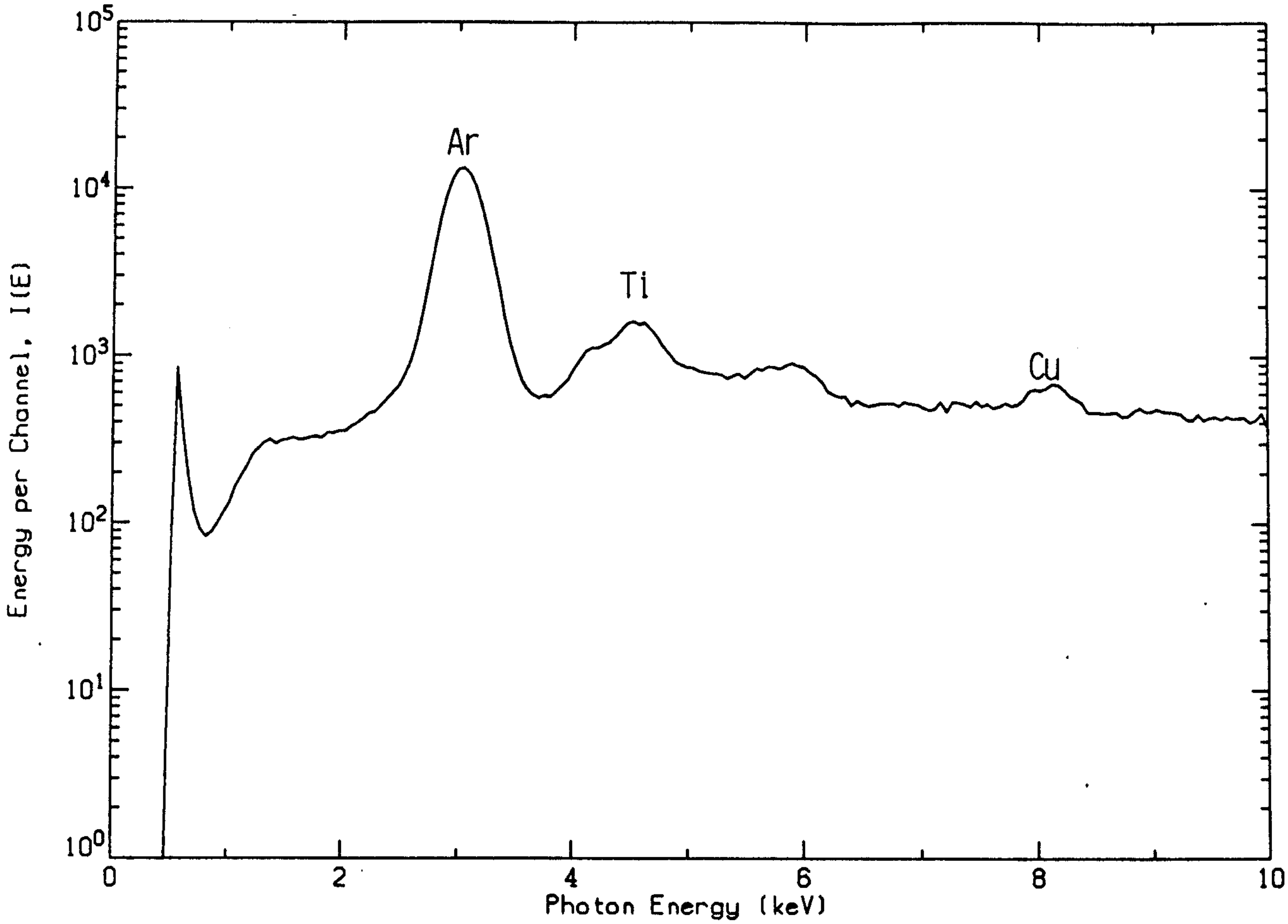

Fig. 6. Soft x-ray spectrum of a hydrogen plasma as measured with a Si(Li) detector.

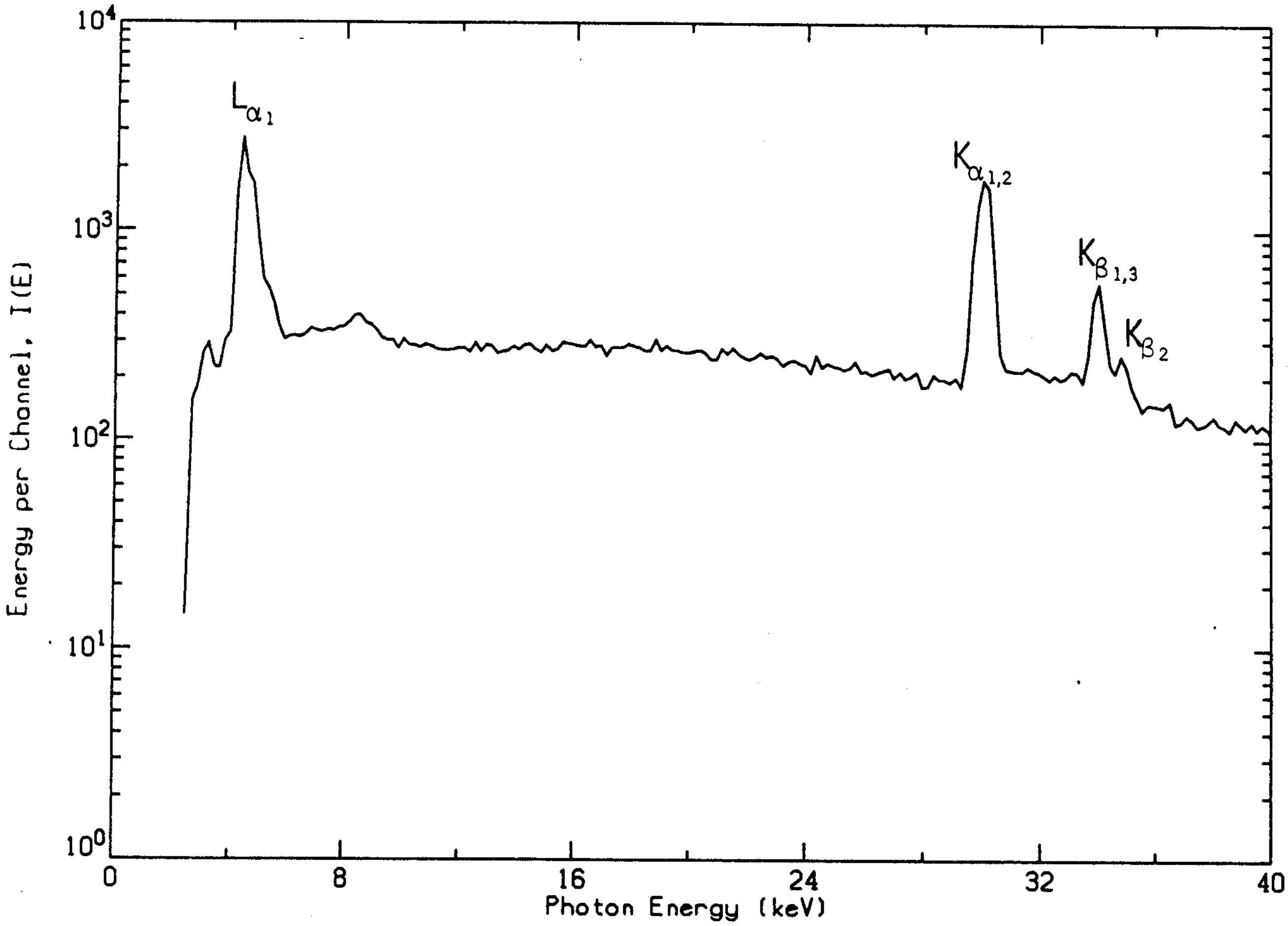

Fig. 7. Soft x-ray spectrum of a xenon plasma measured with a Si(Li) detector. The measured energy resolution of the instrument was 390 eV at 22 keV.

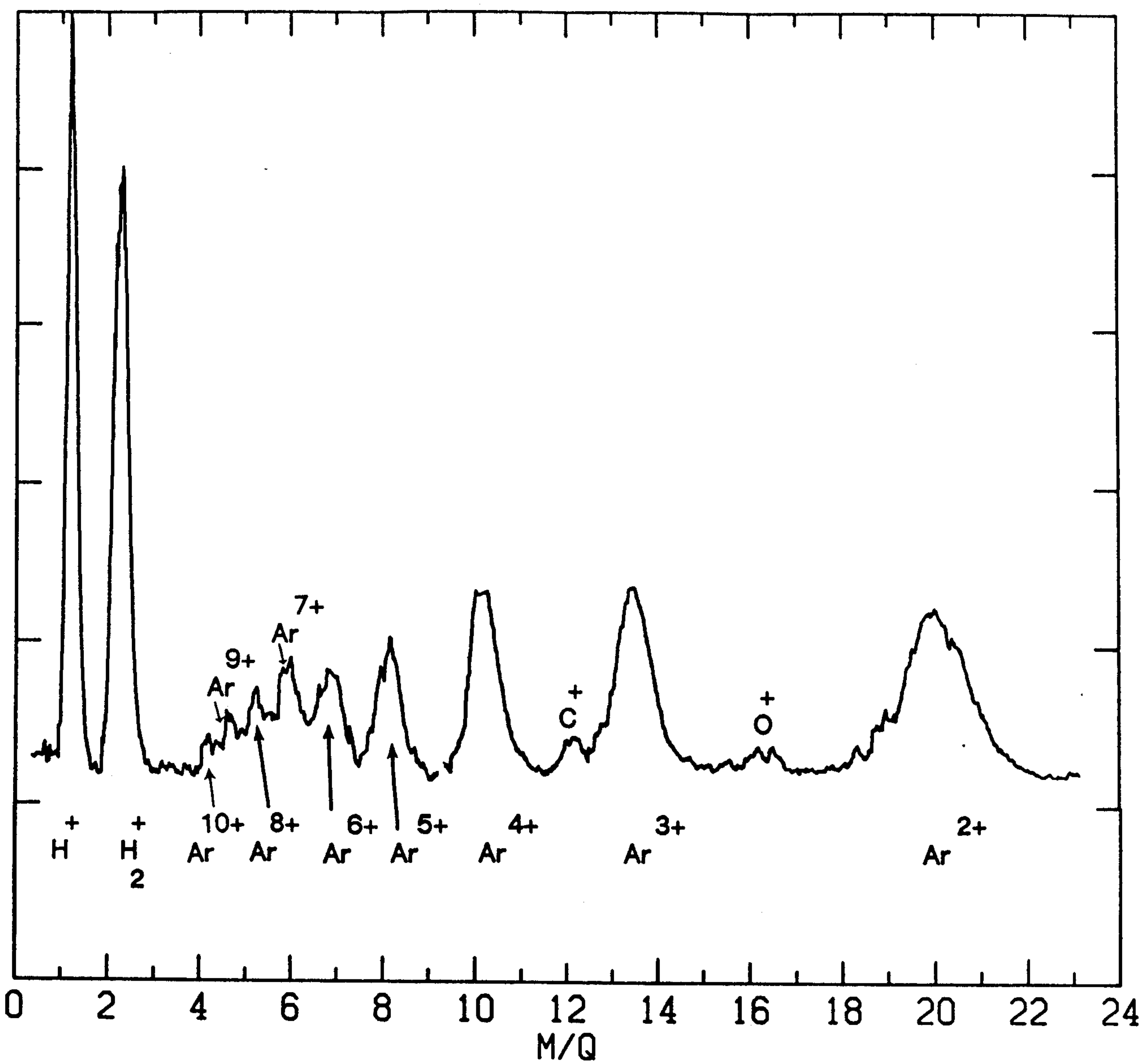

Fig. 8. Time-of-flight analyzer data for an argon plasma.

Count Rate

For measurement of the high Z ion spectra in the VUV or soft x-ray region, a critical issue is the count rate; i.e. can the spectrum be measured with a given instrument? Hokin [8] has estimated the count rate for the xenon K_α line from his HPGe and Si(Li) measurements to be in the vicinity of 5×10^9 counts/steradian/shot. Depending on the details of the instrument, this will or will not be an adequate count rate. The x-ray background from high energy x-rays can be reduced by the use of massive amounts of lead shielding. The shot-to-shot reproducibility on Constance is very good so that adding spectra over many shots is possible in order to enhance the signal strength. The usual shot repetition rate varies from 10-15 shots per hour, depending on the magnetic field and the pulse length.

28 GHz High Density Upgrade

In order to increase the hot electron density to the 10^{12} cm^{-3} range, it is necessary to raise the microwave frequency and the magnetic field. The Constance program is in a unique position with regard to the construction of a high field, high density ECR mirror. Within the next year, it is highly likely that there will be 28 GHz gyrotrons, a higher field quadrupole magnet, and the vacuum chamber which contains the coil available for use. Thus it would be possible to build a 28 GHz machine at an extremely low cost. The cutoff density for 28 GHz is 10^{13} cm^{-3}. One additional advantage of a higher density machine will be that the count rates will be increased so that fewer shots will be necessary to get a spectrum.

Conclusions

From the calculations which have been presented, one can see that in the Constance device highly stripped ions can be produced and will be well-confined. The afterglow plasma provides the optimum conditions for the production of high charge states. The high electron temperatures (hundreds of keV) are much greater than the ionization potentials for even fully stripped xenon (~40 keV). For low Z ions ($Z<20$) charge exchange appears to be the dominant process which limits the higher charge states. For the helium-like state of elements with atomic numbers greater than 20, radiative recombination becomes more important than charge exchange for reasonable neutral pressures, and near $Z=36$, the radiative recombination time can be comparable to the ionization time for the helium-like charge state. The recombination time in the afterglow is comparable to the ionization time for Xe^{+50}. High resolution spectral measurements are needed now to verify the predictions of these calculations.

For studies of the ionization balance in moderately and highly stripped ions, Constance will be well suited due to the extensive diagnostic base available to the machine. The use of the time-of-flight analyzer to measure the charge state distribution of the unconfined ions, and high resolution x-ray spectroscopy to measure the confined ion charge state distribution will allow detailed study of the ionization kinetics. Other relevant parameters, such as electron and ion temperatures and densities, are routinely measured.

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