MULTIPLY CHARGED HEAVY ION SOURCES

Fumio Fukuzawa

Department of Nuclear Engineering, Kyoto University

Abstract

Formation processes of multiply charged heavy ions in the electron-atom collisions are reviewed and recent developement of various ion sources are briefly summarized.

1. Introduction

Multiply charged heavy ion sources are necessary to construct economically heavy ion accelerators such as a cyclotron and a linear accelerator. Requirements on the modern heavy ion sources are; production of all atomic species, high intensity, good emittance and lon lifetime. For application to atomic spectroscopy of highly charged ions, extraction of ions as a beam is not necessarily required.

Recent progress in heavy ion sources can be seen in the papers reported at two Gatlinburg Conferences on heavy ion sources1,2). Excellent review given by D.J.Clark3) is also frequently referred for the present paper.

2. Formation of Multiply Charged Ions

2.1 Ionization Processes

There are two different processes for the formation of multiply charged ions by electron-atom impacts; single collision ionization and multiple collision ionization.

In the single collision, only one impact can cause highly charged ions. The cross sections of the simultaneous ejection of many electrons are very small, and main process for the production of multiply charged ions in the single collision is the production of the inner shell vacancy followed by successive Auger or shake off processes. The times required for these processes to complete are about 10^{-15} sec.

In the multiple collision, only one electron is removed by one impact and multiply charged ions are formed through step by step ionization. Ejections of more than one electrons in one impact do not change the overall features of the charge state distribution, but may have important contribution in determination of the population of extremely high charge state.

In the heavy ion sources, single collision ionization and multiple collision ionization occur simultaneously. Although determination of the relative contribution of each process is difficult, there is some general argument4). In the ion source with high energy electrons and low current density, only single collision process is to be considered for explaning high charge state. While, that with low energy electrons and high current density, multiple ones may be dominant.

2.1 Charge Fraction Ratio in the Plasma

Charge state distribution of ions in the ion source is determined by the balance between production and destruction rates. Expressions for charge fractions are different according as what processes are taken as production and destruction processes.

In the "corona model"[5], as representative, collisional ionization ($A^{z+} + e \rightarrow A^{(z+1)+} + 2e$) and radiative recombination ($A^{(z+1)+} + e \rightarrow A^{z+} + h\nu$) are considered to be balanced,

$$n_e N_z S_z = n_e N_{z+1} \alpha_{z+1}$$

$$N_z/N_{z+1} = \alpha_{z+1}/S_z \tag{1}$$

where N_z, N_{z+1} : ion density of charge state z+, (z+1)+

n_e : electron density

S_z : collisional ionization coefficient for z+ → (z+1)+

α_{z+1} : radiative recombination coefficient for (z+1)+ → z+.

S and α are functions of electron temperature T_e and ionization potential χ_z. By using suitable expressions for S and α, one obtains

$$N_z/N_{z+1} = 7.87\times10^{-9}\chi_z{}^2(\chi_z/kT_e)^{3/4}\exp(\chi_z/kT_e), \tag{2}$$

where ionization potential χ_z is in eV and electron temperature T_e is in °K. This model is valis in an electron density domain [6]

$$n_e < 3\times10^{13}\chi_z{}^3(kT_e)^{1/2} \tag{3}$$

where kT_e and χ_z are in eV. This means that the corona model is applicable to all practical ion sources including laser plasma type.

In deriving above expressions, it is assumed that changes in the population densities caused by variations in the electron temperature or density take place very slowly in comparison with the intrinsic rate of relaxation of the atomic processes (steady state corona model). The intrinsic relaxation time τ can be obtained approximately from the growth equations in the neighbourhood of steady state, that is,

$$dN_z/dt = n_e N_{z-1} S_{z-1} - n_e N_z \alpha_z \tag{4}$$

$$N_{z-1} + N_z = \text{constant}. \tag{5}$$

Solving these eqs., one obtains the following relation,

$$n_e\tau = 1/(S_{z-1} + \alpha_z). \tag{6}$$

In considering the steady state values one may put $\alpha_z \simeq 10^{-12}\mathrm{cm^2 sec^{-1}}$ and $S_{z-1} \simeq \alpha_z$, and obtains the relaxation time τ to an order of magnitude,

$$\tau \simeq 10^{12}/n_e \ (\mathrm{sec}). \tag{7}$$

For most ion sources, ion confinement times are shorter or about the same as the values of τ, so that it is necessary to use a time-dependent corona model and to solve set of differential equations.

From eqs. (2) and (7), it is clear that electron temperature kT_e and $n_e\tau_i$ (τ_i : ion confinement time) are good measures chracterizing the abilities of production of multiply charged ions. In Fig. 1 are shown the operating ranges of several type of heavy ion sources [3].

2.3 Stripping of Projectiles

In the formation of multiply charged ions in the plasma, only relatibe motion between electron and atom (ion) is concerned. It is possible to use the reverse process for production of multiply charged ions, that is, high velocity projectile ions passing through electron cloud at rest.

It seems in the first that if the projectile velocity is same as the electron velocity in the plasma case the charge state distribution of the projectile ions after passing through electron cloud is same as that in the corresponding plasma ion source. In Fig. 2 are shoen the average charge calculated with corona model and projectile data using T_e(eV) = 363 E/A (MeV/nuc) 6). Comparison should be made between corona model and gas target data Q_g, because solid target data may contains complex phenomena such as density effect, excitation pile up and surface effect.

Very good agreement can be obtained if the corona model calculation is made with four times lower temperature. Therefore, the relation between electron temperature and corresponding projectile energy should be

$$T_e(\text{eV}) = 90\ \text{E/A (MeV/nuc)}. \tag{8}$$

This lowering of temperature is due to the fact that the corona model charge distribution is largely determined by the high energy tail of the Maxwellian.

For fast projectile, the time spent in the charge changing foil is so short that equilibrium charge state distribution cannot be attained. For example, 10 MeV/A projectile spents 10^{-12} sec in the foil of 10 mg/cm^2 thick. While, electron density in the foil of $n_e = 10^{22}$ cm^{-3} leads to $\tau = 10^{-10}$ sec. Therefore projectile ions should be in non-equilibrium charge state distribution.

3. Various Ion Sources for Production of Multiply Charged Ions

Characteristics of multiply ion production in some typical ion sources are compared in Table I 3).

3.1 PIG

PIG type are standard and most widely used heavy ion sources for many accelerators. Plasma characteristics are; arc voltage of 300-2000 volts and arc current of 1-20 amps, dc or pulsed operation. When solid materials are used for heavy ions, either oven is connected to the anode or the block is placed tangentially in the bore of anode.

3.2 Duoplasmatron

This type of source for high beam current can be used also for the production of multiply charged ions. Charge state is lower than that of PIG, but excellent in emittance and lifetime characteristics. UNILAC prefers a duoplasmatron than a PIG for light ions.

3.3 ECR (Electron Cyclotron Resonance)

Most advanced ion sources of this type are MAFIOS and TRIPLEMAFIOS at Grenoble. Output current and charge state from MAFIOS is similar to those of PIG. In TRIPLEMAFIOS, average charge increases about two times, but at 100 timee lower intensity. These sources work well more than one day without maintenance. Direction of developement of ECR sources is to use superconducting coil to reduce present megawatt power and to make the source more compact.

3.4 EBIS (Electron Beam Ion Source)

EBIS is expected to produce very highly charged ions with sufficient intensity, and is veveloped at Dubna, Orsay, Frankfurt, Texas A&M, Kiessen and Nagoya University. This source is hopeful for synchrotron injector. Fully stripped ions are produced now up to Ne. Without large accelerator, EBIS has been used for charge exchange collision experiment on highly charged ions. Technical problems on EBIS are; high precission in construction, superconducting solenoid, good vacuum (10^{-10} Torr).

3.5 Laser

Laser plasma also produces very highly charged ions, but repetition rate is too small to use for accelerator ion source. This source is very useful for atomic spectroscopy of highly charged ions in the same way as vacuum spark and exploding wire.

3.6 Tokamak, Electron Ring Accelerator, Linear Electron Beams

These machine do not aim the production of multiply charged ions, but can produce them effeciently because of large $n\tau$ values.

3.7 Stripping of Fast Projectiles

As mentioned in 2.3, foil or gas stripping of fast projectiles can produce highly charged ions.

Expected charge states from various ion sources stated above are summarized in Fig.3.

In Figs. 4-8, are shown some of the multiply charged ion sources developed in Japan. The hot cathode PIG source with a sputtering electrode (Fig. 4) and that with oven (Fig. 5) are developed for the IPCR cyclotron and linac. The hot cathode PIG source for N and Ne ions (Fing. 6) was installed in the INS SF cyclotron. A compact ECR source (Fing. 7) is developed for Cockcroft-Walton Accelerator at Nagoya University. The EBIS (Fig. 8) is build also at Nagoya University for study of atomic processes.

References

1. International Conference on Multiply-Charged Ion Sources and Accelerating Systems, IEEE Trans. Nucl. Sci. NS-19 No2 (1972)
2. International Conference on Heavy Ion Sources, IEEE Trans. Nucl. Sci. NS-23 No2 (1976)
3. D.J.Clark, IEEE Trans. Nucl. Sci. NS-24 No3 1064(1977)
4. A.Septier, article in ref.1 p22
5. R.W.P.McWhirter, Plasma Diagnostic Techniques (Acad Press) Chap 5 (1965)
6. D.J.Nagel, Beam Foil Spectroscopy, vol 2 p961. ed, I.Sellin andD.Pegg, (Plenum Press) (1976)

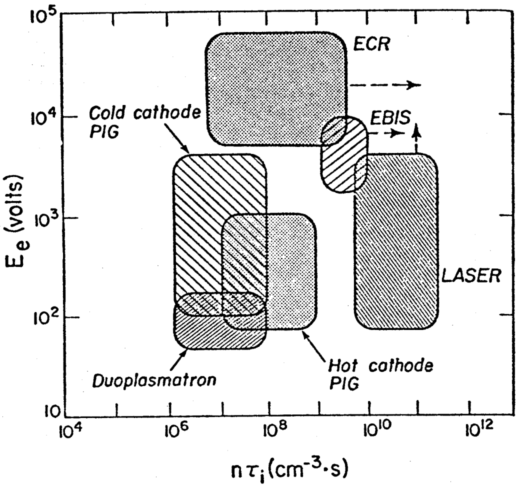

Fig. 1. Plasma parameters.
(D.J.Clark, ref. 3)

SOURCE	$\bar{q}$* NEON	XENON	PEAK OUTPUT ALL q's PART/SEC	DUTY FACTOR
PIG	2	4	10^{15}-10^{17}	.02-1.0
DUOPLASMATRON	1	3	10^{15}-10^{17}	.03-1
ECR—1 STAGE	2	4	10^{16}	.3-1.0
3 STAGES	5	8	10^{14}	.3-1.0
EBIS	8-9	24	a.10^{10}-10^{11} b.10^{13}-10^{14}	10^{-4}

*$\bar{q}$ weighted by part/sec.
a. Average output over long times, assuming 10 pulses/sec.
b. Output during 100 μsec, 10^9-10^{10} part/pulse.

Table I. Ions and intensities.
(D.J.Clark, ref. 3)

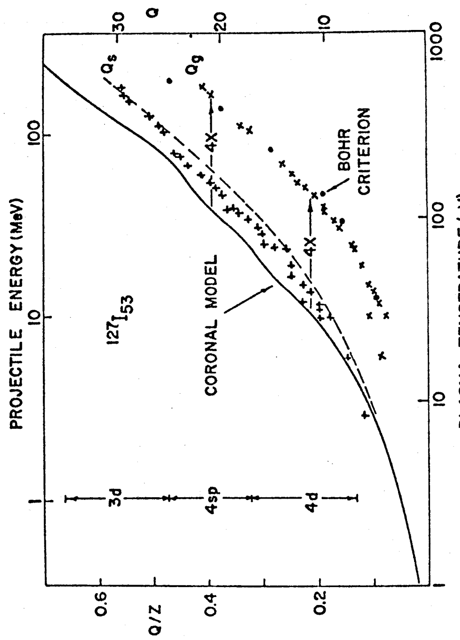

Fig. 2. Average charge states for iodine.
(D.J.Nagel, ref. 6)

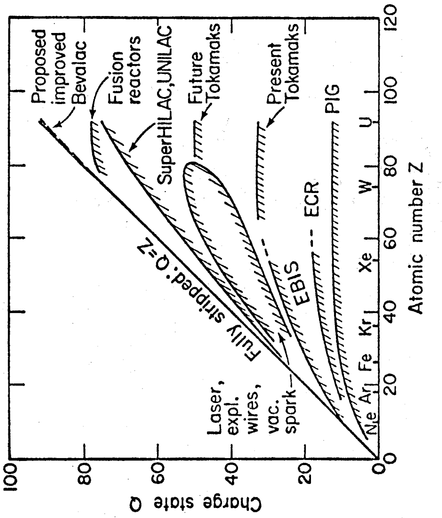

Fig. 3. Charge states available from ion sources.
(D.J.Clark, ref. 3)

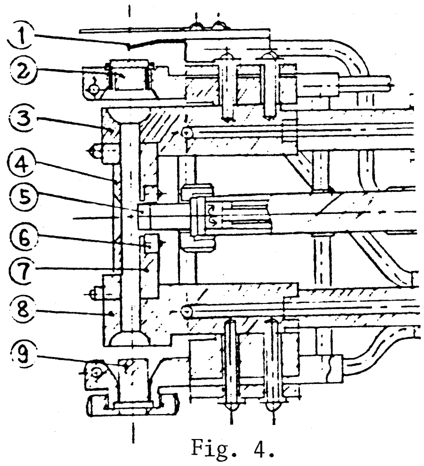

Fig. 4.

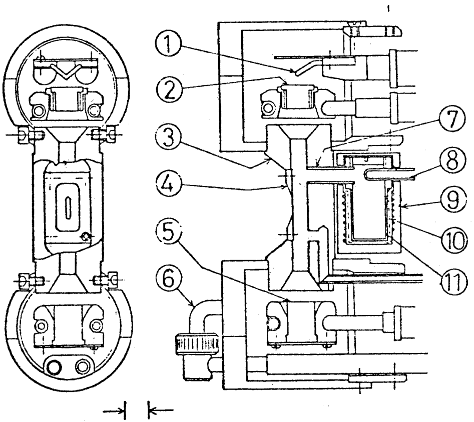

Fig. 5.

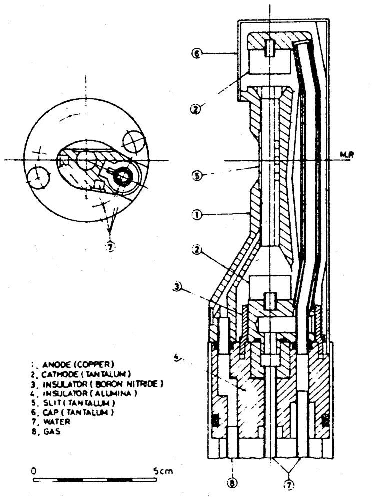

Fig. 6.

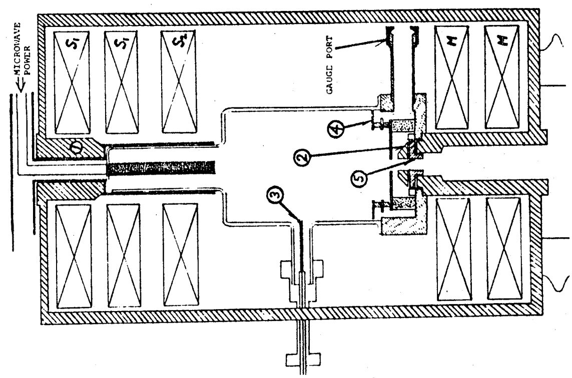

Fig. 7.

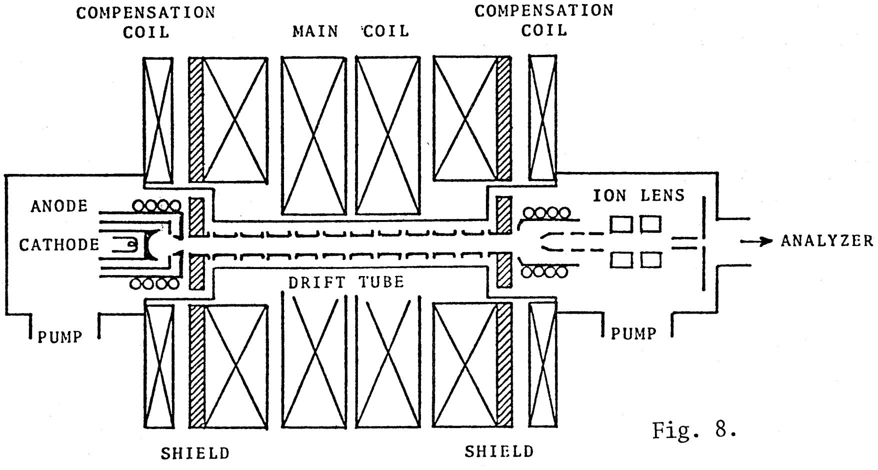

Fig. 8.