RECENT PROGRESS IN HEAVY ION SOURCES*

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Summary

This paper summarizes the progress during the last several years in the technology of sources of high charge state positive heavy ions and negative heavy ions. Subjects covered include recent results in ECR and EBIS source development and comparison of various source types for high charge state heavy ions.

Introduction

The ideal ion source for a modern heavy ion accelerator should provide beams of all atomic species of high intensity, good emittance and long lifetime. The source should be easily accessible for maintenance. For cyclotrons and linear accelerators, which require positive ions from the source, high charge states are desirable because the cyclotron energy is proportional to charge squared, and linac length can be reduced by using ions with higher charge states. For tandem electrostatic accelerators the charge state is -1. (Only a few low intensity ion species have been produced with -2 charge).

Positive Heavy Ion Sources

High charge state ion beams for positive ion accelerators can be produced by electron bombardment of atoms and ions in a plasma or by stripping of fast ions in a foil or gas. Electron bombardment sources were previously reviewed by Vorobev and Pasyuk,[1] Bennett,[2] Eninger,[3] Septier,[4] Winter and Wolf,[5] and Arianer.[6]

For electron bombardment sources the product of the flux density j_e and ion confinement time T_i must be sufficient to produce the desired charge state q. Also the electron energy distribution should include the region of peak ionization cross-section, which occurs at several times the ionization potential. So electron energies should be 10's of eV up to hundreds or several thousand eV. Figure 1, updated from a figure of Winter and Wolf[5] and Clark,[7] shows the operating ranges of several types of heavy ion sources. The sources with higher nT_i produce higher charge states. The principal types of heavy ion sources will be described below. Many examples are described in the two Gatlinburg Conferences on heavy ion sources, References 8 and 7.

PIG Sources

The traditional heavy ion source for cyclotrons and linacs is the PIG (Penning or Philips Ion Gauge). The principles and designs used by various laboratories were reviewed in the last several years by Bennett,[8] Green,[9] Makov[10] and Schulte et al.[11] The first PIG source used in a cyclotron was built by Jones and Zucker[12] at Oak Ridge in 1954 for N^{3+}. Later sources were built by Anderson and Ehlers[13] for the Berkeley and Yale HILACS and by Morosov, Makov and Ioffe[14] for cyclotrons. Many other groups have built PIG sources, mostly for cyclotrons, but most of the designs are similar to those mentioned above.

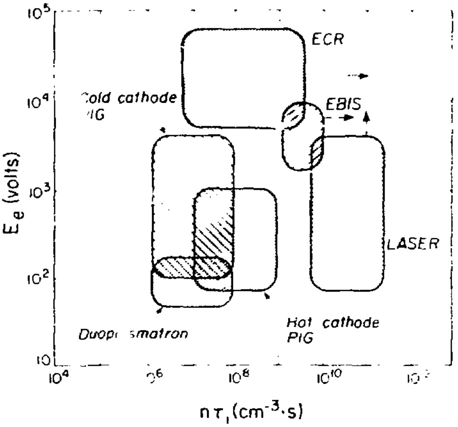

Fig. 1. Plasma parameters of high charge state ion sources. E_e is electron temperature, n is electron density, T_i is ion confinement time.

TABLE I. IONS AND INTENSITIES

SOURCE	$\bar{q}$* NEON	$\bar{q}$* XENON	PEAK OUTPUT ALL q's PART/SEC	DUTY FACTOR	REF.
PIG	2	4	10^{15}-10^{17}	.02-1.0	6
DUOPLASMATRON	1	3	10^{15}-10^{17}	.03-1	20, 21
ECR—1 STAGE	2	4	10^{16}	.3-1.0	24
3 STAGES	5	8	10^{14}	.3-1.0	24
EBIS	8-9	24	a. 10^{10}-10^{11} b. 10^{13}-10^{14}	10^{-4}	25, 26

*$\bar{q}$ 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.

One of the most highly developed PIG sources is that of Pasyuk and Tretyakov at Dubna, shown in Fig. 2.[15] Here we see the arc chamber where the arc is struck between the two cathodes. The filament electron bombardment heating of the upper cathode provides control of the cathode temperature, and thus emission current, giving good control of arc impedance. The electrons are reflected by the cathodes for about 100 traversals. In other PIG source designs, both cathodes may be hot, or both may be cold. If both are cold, the electrons are emitted by secondary emission from ion bombardment of the cathodes. The arc parameters in various sources are 1-20 amps peak and 300-2000 volts, d.c. or pulsed. An extraction electrode is mounted close to the beam slit, with a voltage of 10-100 kV.

Solid materials can be fed into the source by placing them in a cathode, in a block tangent to the bore in the anode (Fig. 2), or by use of an oven. Pasyuk and Tretyakov[15] use an electrode tangent to the arc bore near the extraction slit, biased negative to sputter out the solid feed material with arc ions. Gavin at Lawrence Berkeley Laboratory[16] uses a similar system for the SuperHILAC 2.5 MV source. In addition Gavin found that the output of a very high charge state, Au^{9+}, can be increased by a factor of 3 by using two sputtering electrodes above and below the slit, rather than 1 electrode at the slit.

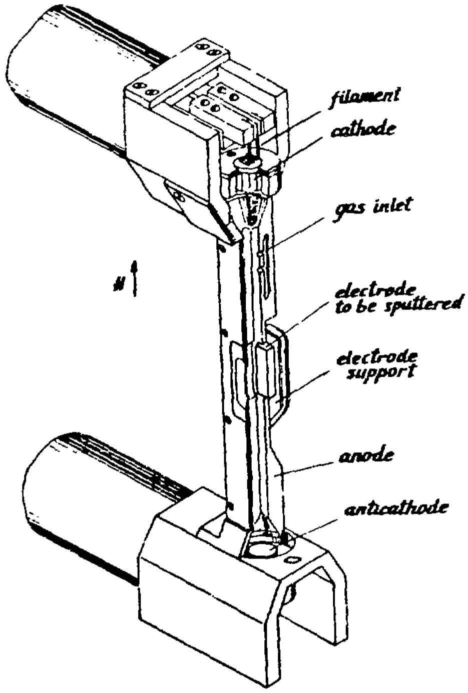

Fig. 2. Internal cyclotron PIG source of Pasyuk and Tretyakov, Dubna.[15]

Hudson et al.[17] found that solid materials can be efficiently fed into the arc of an internal cyclotron source by using sputtering with low charge state heavy ions which reverse in the rf field. A block of the desired material is placed opposite the slit.

The PIG source gives usable beams of charge states up to N^{5+}, Ne^{7+} and Ar^{8+}. Performance is briefly summarized in Table I. It is still the standard source for heavy ion cyclotrons, and for heavy ion linacs, except that the duoplasmatron is used for the lighter ions at the UNILAC at Darmstadt. The lifetime between source changes is a few hours up to a day, at high duty factor operation. Future developments of the PIG source include operational use of mirror magnetic fields as developed by Mallory[16] and investigating possible higher charge state performance in the 40-50 kG fields of future superconducting cyclotron magnets.[18]

Duoplasmatron Sources

The duoplasmatron has been used for heavy ion production by the groups of Von Ardenne[19] and the UNILAC group at Darmstadt. The UNILAC work has been described by Illgen[20] and by Keller and Muller.[21]

The duoplasmatron developed by Keller and Muller for Xe^{6+} is shown in Fig. 3.[21] The cathode-anode voltage is 250 volts, and arc current is 7 amps. Duty factor is 25%. The magnet coil and some steel source components provide an axial magnetic guide field. Keller and Muller found that the output of $Xe^{5+..11+}$ was greatly increased by placing the position of the maximum magnetic field at the anode aperture instead of between anode and intermediate electrode. Also the anode shield is directly water cooled. Reducing the diameter of the intermediate electrode aperture increases the voltage, which gives higher charge states. Extraction is at 20-50 kV. Recently, Richter and Zajec have developed a duoplasmatron with 20 mA of neon (2% Ne^{3+})[22] and 17 mA of xenon.[22] The xenon beam looks like a promising candidate for injection into an rf linac for heavy ion fusion.[23]

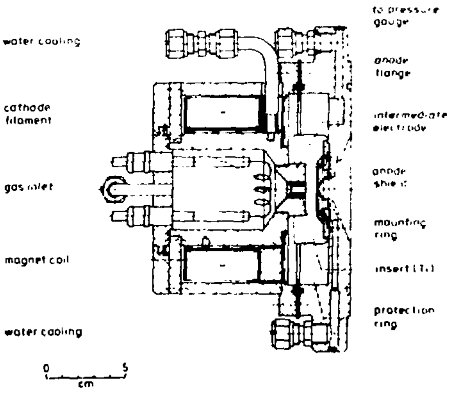

Fig. 3. Duoplasmation source developed at GSI, Darmstadt for Ar^{2+} and Xe^{6+} by Keller and Muller.[21]

[illegible] materials can be fed into the source by use of an oven.

As shown in Table 1, the duoplasmatron has as high intensity as the PIG, but lower average charge state. The emittance and lifetime is better than that of the PIG, and the equal beam shape in the two transverse planes from the duoplasmatron is an advantage for placing the source directly on an accelerator column. The UNILAC heavy ion linac has found that the duoplasmatron is preferred over the PIG for ions lighter than xenon, with their requirement of charge/mass ≥0.046.

Electron Cyclotron Resonance (ECR) Sources

Another type of source which is under development for high charge states is the electron cyclotron resonance source. Here the high energy electrons are produced by feeding in microwave energy at the cyclotron resonance frequency of the electrons in the magnetic field which confines the plasma. The ECR source has been developed at Oak Ridge, Marburg, and Grenoble. The group at Grenoble under R. Geller has made great improvements[24] in the ECR source in the last several years. The work of the other groups is described in other parts of Ref. 7. The latest Grenoble source, called TRIPLEMAFIOS, is shown in Fig. 4. An axial magnetic guide field is provided by coils in a system 3 meters long. Plasma is created by rf power in the first stage. The plasma drifts along the axis through stage 2 where ionization to high charge states takes place at a second rf section. A pressure of 10[illegible] torr in stage 1 is necessary for a dense plasma and differential pumping gives 10[illegible] torr in stage 2 to prevent recombination of the high charge states.

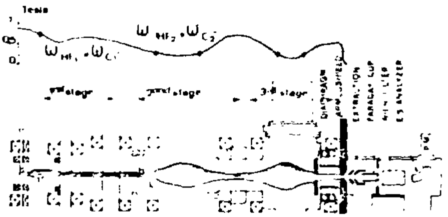

Fig. 4. ECR three-stage source "TRIPLEMAFIOS," Geller.[24]

Table 1 shows two ECR sources. The first is one stage only, referred to as "MAFIOS" by Geller. This gives output currents and charge states similar to those of the PIG. The lifetime is weeks or months. The 3 stage source in Table 1, TRIPLEMAFIOS, shows an average charge state about twice that of the PIG for neon and xenon, but at 100 times lower intensity.

Recent progress at Grenoble[24] includes production of beams of Ar^{8+} at 2×10^{13} part./sec. and Xe^{18+} at 10^{12} part./sec. with TRIPLEMAFIOS, and good emittance. A superconducting coil is proposed to reduce the power from its present megawatt level, and to increase the rf frequency and thus the plasma density. Also experiments have been done on uranium beams. One stage has been used to produce 100 μA total uranium beam, including 50 μA of U^{3+}. Charge states 1-6 were observed. A run with uranium beam lasts at least one day without maintenance.

The ECR source could be used to inject cyclotrons with an external axial or radial injection system, to obtain higher energies.

Electron Beam Ion Sources (EBIS)

The electron beam ion source has been pioneered by Donets at Dubna[25] and also developed at Orsay, Frankfurt, Texas A&M, and Giessen. Work of all these laboratories is summarized in papers at the 1977 Gatlinburg Conference Ref. 27. The principles of operation of the EBIS of Donets are shown in Fig. 5. A superconducting solenoid of 1 meter length confines an electron beam from a gun placed inside the solenoid at one end. The magnetic field keeps the beam collimated to a radius of several millimeters as it drifts down the solenoid axis to the collector at the other end. Gas is ionized and confined electrostatically by the electron beam. A potential well formed by the drift tubes confines the ions longitudinally for typically 10-100 milliseconds, until the desired charge state is reached. Then the potential barrier is lowered at the solenoid exit, providing beam extraction. Beams observed[illegible] include xenon with average charge state of Xe^{24+}, and neon with 10% Ne^{10+}.[26] The performance is summarized in Table 1. Recently the EBIS source of Donets[27] has shown an average charge of Ar^{16+}, with about 20% Ar^{17+}.

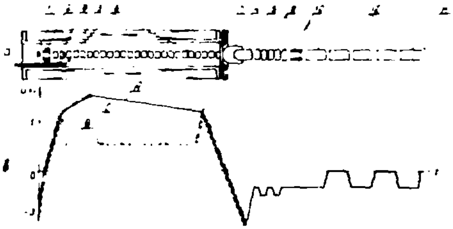

Fig. 5. EBIS source KRION-1 of Donets, Dubna.[25] In upper view, electron beam passes from gun (1,2) through drift tubes (6 to collector (4). Charge States are analyzed by time-of-flight system (9,10,11,12). In lower view, potential distribution along axis is that of (B) during injection, (C) during ionization and (A) for extraction.

At Orsay[27] SILFEC II EBIS is designed with an external electron gun of 100-800 A/cm^2, injection and extraction solenoids, and a liquid helium cryopanel. Its goal is to produce fully stripped ions up to Ca^{20+} in the CW mode for a synchrocyclotron. Electron beam tests are about to begin. The CRYEBIS with superconducting solenoid is expected to begin beam tests later in 1977.

The group of Becker and Klein at Frankfurt[28] are developing TOFEBIS with continuous extraction, and a containment EBIS with cold bore superconducting solenoid for the UNILAC linac at Darmstadt. The EBIS source at the Texas A&M Cyclotron Institute has recently come into preliminary operation[29] with extracted ion beam of 10^9 charges pulse and a vacuum of 10^{-9} torr. Charge distribution measurements are planned for the near future.

The EBIS source requires high technology in construction, with a superconducting solenoid preferred, and vacuums of 10^{-10} torr required for high charge states. Table I shows that the EBIS has the highest average charge states of the sources listed. The output current averaged over long times is orders of magnitude less than for the other sources, but the unique high charge states would make possible significantly higher energies from cyclotrons than with the other sources. Also the pulsed nature of the source, and fully stripped ions (up to neon presently), make it a good match to those synchrotron injectors which are designed for ions of charge/mass = 1/2 [illegible].

Multiple Aperture Sources

High currents of low charge state ions are produced by the multi-aperture sources developed for space propulsion and for injection of multi-ampere beams of hydrogen into thermonuclear fusion reactors. A summary of ion sources for ion propulsion of space systems is given by Stuhlinger[30]. The ions used are Cs, Hg or colloid particles. The types of sources include contact ionization sources for Cs, electron bombardment sources for Cs and Hg, rf ionization source for Hg and a hollow needle spray nozzle for colloidal particles. Accel-decel extraction systems are used. The beam is neutralized just after extraction. Many sources have been designed, with diameters of 5 to 150 cm, beam dc currents of 0.3 to 25 amperes, and beam energies of 1-6 keV.

A multiple aperture source designed for high intensity hydrogen beams, was run at Lawrence Berkeley Laboratory with xenon gas by Mobley[32] in a short test to determine its suitability for the heavy ion fusion program. He used a 7 x 35 cm² area source with [illegible] slots, and obtained 9 amps of peak current at 30 kV extraction in 10 msec pulses. The beam is neutralized just after the source. The conference proceedings, Ref. 31, describes other possible heavy ion sources for heavy ion fusion, to produce 100 mA beams of mass 200, charge 1, for injection into an rf linac and sources for 20 amps with mass [illegible], charge [illegible], for injection into an induction linac.

Laser, Vacuum Spark and Exploding Wire Sources

Several types of sources produce high charge state ions by dumping large pulses of energy into a small spot in short time periods. They are the laser, the vacuum spark and the exploding wire. These sources are being used for studies such as spectroscopy of high charge state ions, usually without extraction of the ions to form a beam.

Laser sources were reviewed by Peacock.[33] Power densities up to 5×10^{14} w/cm² for about a nanosecond produced charge states of Mg^{11+}, Ti^{20+}, Fe^{23+}, and W[illegible]. In a summary paper[34] Nagel estimates that electron temperatures in plasmas produced by present lasers are about 1 keV, and that increases to the 10 keV range are expected with development of higher power lasers in the laser fusion program. In fact, KMS Fusion, Inc. has reported[35] power densities of 5×10^{17} w/cm² on DT-filled glass microshells. Silicon and oxygen ions coming off have an exponential energy distribution, with a calculated average energy of 3 keV/nucleon, assuming they are fully stripped. Other recent laser work is reported in other abstracts in Ref. 35.

The extraction of beams from laser-produced plasma was reviewed by Tonon.[36] The ion energies corresponded to about 1 keV of acceleration in the plasma, with energy proportional to charge state. Energy spread was about 2 %. The repetition rate, and thus duty factor, is small for present lasers.

The other types of pulsed sources are the vacuum spark and the exploding wire. The vacuum spark system at NRL[37] discharges a 14 kV [illegible] a 6 mm gap [illegible] kA peak current. Charge states such as Ti[illegible] and Fe[illegible] are [illegible] spectroscopically. NRL [illegible] [illegible] supply provides [illegible] to a wire [illegible] cm long and [illegible] m diameter. The charge states [illegible] Cu[illegible] and Au[illegible]. [illegible] made of [illegible] drifting out of a laser plasma at MIT[illegible] [illegible] electron [illegible].

Magnetic Fusion Plasma Source

Other sources of high charge state ions [illegible] the dense plasma in magnetic confinement thermonuclear devices, such as Tokamaks. But no method of beam extraction of a good quality beam has been proposed. This type of plasma was proposed and partially developed by Daugherty, et al. in the HIPAC[41] mirror magnet device. Here 1 keV electrons ionize and trap high charge state ions. U[illegible] was predicted after several seconds of ionization time, but development work stopped on this device.

Electron Ring Accelerator

In the first stage of an electron ring accelerator, a high intensity ring of electrons revolves in a confining magnetic field, and is capable of ionizing the residual gas to high charge states. The ERA was reviewed by Peterson[42] and Laslett.[43] In a study at Lawrence Berkeley Laboratory[44] it was estimated that Xe^{50+} would be the mean charge state after one second in a high vacuum electron ring of 4×10^{12} electrons, taking into account charge exchange with background H_2 at 10^{-9} torr. Ions have been formed and accelerated by groups at JINR, U.S.S.R. and Garching, West Germany.

Linear Electron Beams

These were reviewed by Graybill,[4] Yonas[46] and Olson et al.[47,48] In these experiments electron beams of 10 kA to 1 MA of energies 0.1 10 MeV and pulse lengths of 10 100 nsec are used. In the early experiments the beam passed through a guide tube filled with gas at 0.1 torr pressure. Graybill[4] reported the formation and acceleration of [illegible] ions pulse of $N^{4+...6+}$ and $Ar^{6+...12+}$ to energies of 10-20 MeV. Other versions of electron beam systems[4] under study or test include electron beams in vacuum, in plasma, and in diodes. Experiments are described at this Conference by Olson et al. at the Sandia Laboratories on the Ionization Front Accelerator, in which ions are accelerated by a controlled, moving potential well of an intense electron beam. The ions are produced by laser photoionization of cesium gas. The development of electron beams for ionization and acceleration of ions is still in its early stages.

Stripping of Fast Ions

High charge state ions are produced by electron bombardment. In the sources of ions discussed in the previous sections the ions were moving slowly at around thermal velocities, and the electrons were moving at much higher velocities. Since it is the relative velocity of the electrons and ions which

Alternatively, the high charge states can also be produced by passing accelerated ions through a stripping foil or gas cell where the electrons have very low velocities. An analysis by Nagel[34] shows that a MeV/nucleon ion has the same average charge state after a gas stripper as an ion in a plasma at [illegible] keV temperature, assuming the coronal model for the plasma. A comparison of some plasma sources and stripping of accelerators is given in Fig. 6. We see that the accelerators produce very high charge states. They have the desirable characteristic of producing a separated beam of one charge state which are useful for atomic spectroscopy, and the disadvantage of having high velocity, so [illegible] studies cannot be done at low energies. The proposed improved Bevalac will open up a new [illegible] to fully stripped ions of all masses.

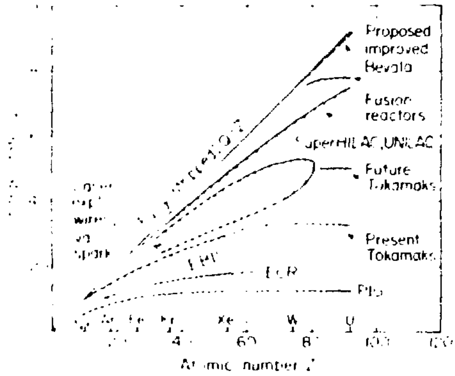

Fig. 6. Charge states available from ion sources, Tokamaks and other plasmas, and stripping of accelerator beams.[34,35]

Negative Heavy Ion Sources

Negative heavy ion sources are used mostly for injection into tandem electrostatic accelerators. This field was reviewed by Dawton,[49] Purser[50] and Middleton.[51] Negative ions normally have a charge of minus one charge, but a few ions such as oxygen, fluorine and chlorine have been observed with a charge of -2, with intensities of about a nanoamp.

Negative heavy ions have been produced by several methods:[51] charge exchange using incident or recoil ions, direct extraction, and by special sources such as the triplasmatron and the duodehcatron. The most important recent advance in negative heavy ion sources has been the development of sputter sources using cesium for bombardment or as surface coating. In the earliest source of this type built by the group of Hortig,[52] the negative ions were sputtered by krypton from a wheel coated with cesium vapor. A later sputter source is the radial extracted PIG, called SPIGS and described by Smith.[53] Here the negative ions are sputtered out of the cathodes into the plasma. A source with similar geometry is the Aarhus ANIS[54] source in which the sputtering material is a concave spherical electrode placed opposite the extraction hole. Cesium is again necessary for high sputtering yield. ANIS produces up to 30 μA of Cu⁻ and 80 μA of Au⁻.

One of the most successful of the sputtering sources is the UNIS source of Middleton.[55] He modified the Hortig system into an axial design shown in Fig. 7. In this source a cesium beam from a tungsten surface ionizer is accelerated to 20-30 keV. It strikes a hollow cone of the feed material, sputtering off negative ions which go through the hole in the cone and are accelerated. A wheel of 18 cones of different material can rotate any one into position to the axis quickly. Gases can be fed in near the cone for those ions not available from solids. The output includes a few μA of Li⁻ and B⁻, and [illegible] μA of C⁻, O⁻, F⁻, Si⁻, S⁻ and Cl⁻. All beams in the periodic table are expected to be available from this source, with the likely exception of He, Ar and Kr. A very similar source was built by Purser at Rochester. The mechanism of cesium negative ion production is not fully understood, but is believed to be partly due to lowering of the work function of the sputter surface.[51]

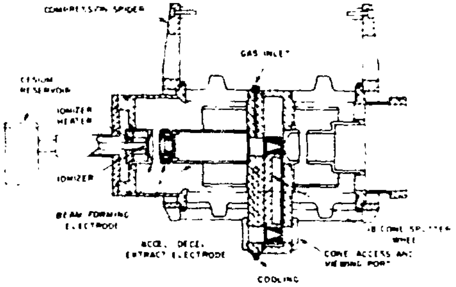

Fig. 7. Negative heavy ion source of Middleton[55] using Cs sputtering of cone material.

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