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ION SOURCES FOR CYCLOTRONS

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Abstract.- This paper describes the principles, performance and future prospects of ion sources used for cyclotrons. Sources discussed include the filament, PIG, ECR, and EBIS sources.

1. Introduction.- The cyclotron ion source has the responsibility for producing well collimated intense beams of various charge states of many atomic species, polarized and unpolarized. The source should have high reliability, long lifetime and quick change time. The first sources were "internal sources," designed to fit within the few centimeters of space inside the first orbit of acceleration in the central region. The approximately uniform magnetic field in this region was fortunately a great asset in producing intense ion source arcs.

With the advent of more advanced sources of heavy and polarized ions, a space of 1 m^3 or more was required for the source, so it had to be placed outside the cyclotron as an "external source." Injection systems were developed to transport the beam to the cyclotron center region, either axially or radially. Descriptions of these sources are given in the following pages. Also some of the expected future developments are reviewed, particularly in the area of high charge state sources. Polarized sources are not included, since good recent reviews exist, below.

Previous reviews of ion sources suitable for cyclotrons include a book by Valyi [1] and an article by Green [2]. Reviews of positive ion sources have been given by Bennett [3], Septier [4], Winter and Wolf [5], Arianer [6], Clark [7], Loiseaux [8] and Kutner [9]. Polarized ion sources have been reviewed by Haeberli [10-12] and Parker [13].

2. Production of Ions.- To create singly or multiply charged positive ions we must remove one or more electrons from atoms and ions, which requires energy. This energy can be supplied by a bombarding electron, by a heated surface of high work function, by a very high electric field or by a photon. For cyclotron sources we are most interested in electron bombardment. Negative ion sources depend upon source plasma conditions which promote the attachment of electron to an atom, or upon charge exchange at surfaces or in vapor.

For production of positive ion beams by electron bombardment, electrons of energy greater than the ionization potential bombard the molecules and ions in a plasma. For highest production rate the electron energy should be 2-3 times the ionization potential. The ionization potentials of the elements are shown in Fig. 1. These "total ionization potentials" are the sum of all the ionization potentials between the neutral atom and the charge state shown on the contour lines. This total ionization potential is an indica-

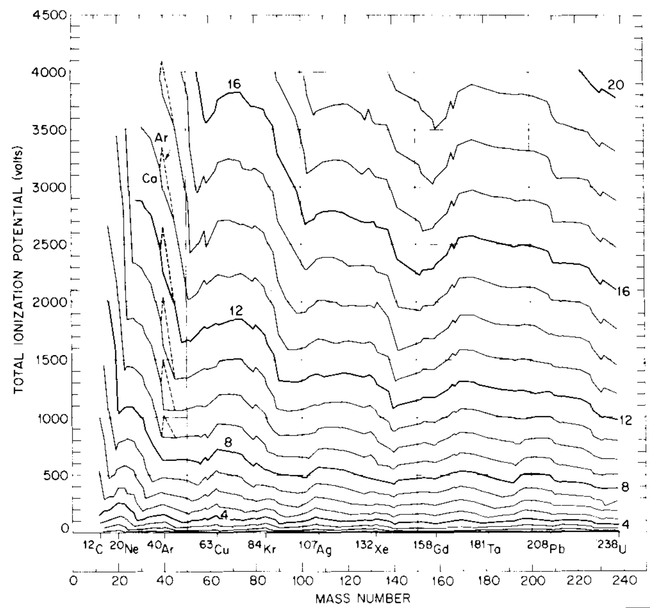

Fig. 1: Total ionization potentials for charge states shown on plots. Data is from Carlson [14]. Figure courtesy of Oak Ridge National Laboratory.

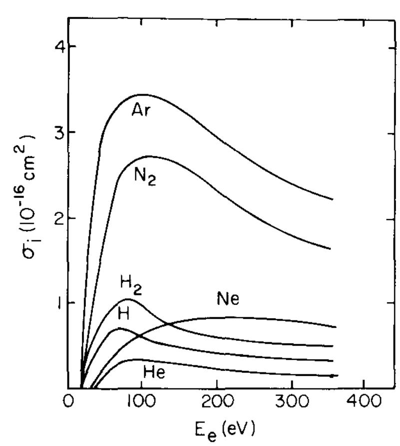

Fig. 2: Electron impact ionization cross-sections for some common gases versus electron energy, from Valyi [1].

tion of the difficulty of producing the ion in a source.

The cross-section for ionization from one charge state to the next is a function of the ionization potential and the electron bombarding energy. The variation of cross-section with energy for ionization from neutral atom or molecule to charge state 1^+ is shown in Fig. 2 for several gases. It starts at zero at the ionization potential, reaches a maximum at an electron energy of about three times the ionization potential, and then falls with increasing electron energy.

To make calculations on the ionization process, it is convenient to fit these ionization cross-sections with an empirical formula. A formula used frequently is that of Lotz [15]:

$$\sigma_{i\rightarrow i+1} = \sum_{j=1}^{N} a_j q_j (E_e V_j)^{-1} \ln (E_e/V_j)$$

for $E_e \gg V_j$, where j is the subshell number, q_j is the number of electrons in the j subshell, N is the number of subshells, E_e is electron energy, V_j is ionization potential of electrons in the j subshell, and a_j is the fitting parameter. The summation is taken over all the remaining subshells of the ion. Lotz showed that this equation provided a good fit to measured cross-sections for low charge states. The time evolution of the charge distribution can be calculated from the cross-sections and the electron beam density. An example for argon is shown in Fig. 3. The ionization factor, $j\tau$, is the total number of electrons/area seen by an ion, where j is charge/(area-time) and τ is the confinement time of the ion in the electron beam. This calculation does not include charge exchange with other ions or molecules, or recombination with electrons. The $j\tau$ required for various charge/mass ratios of all atomic species is plotted in Fig. 4. The right hand scale of Fig. 4 is $n\tau$, where n is the plasma density. $n\tau$ is a figure of merit for confinement frequently used in fusion reactors. However, high charge state ion sources require high electron temperatures and only moderate $n\tau = 10^8$–10^{12} cm^{-3} sec, while fusion reactors need high temperature ions and a very high $n\tau = 10^{14}$ cm^{-3} sec. The operating ranges of several high charge state sources are shown in Fig. 5. The ECR and EBIS advanced sources have higher ranges of E_e and $n\tau$ than the conventional PIG source, and so are better suited to the production of very high charge states.

3. Present Ion Sources.- In the early 1930's the first cyclotrons of Lawrence used a hot filament ion

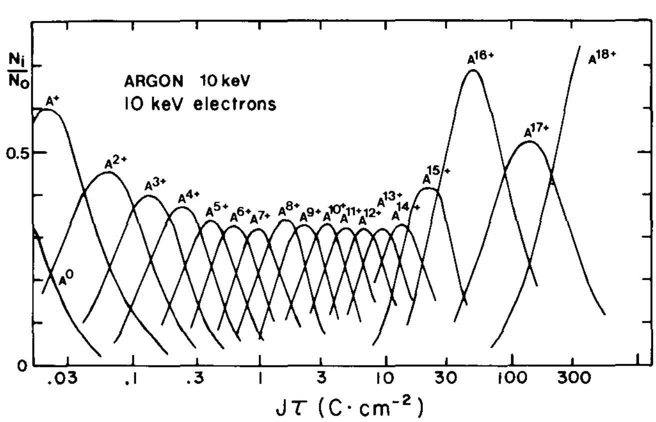

Fig. 3: Charge state fraction for argon plotted versus the ionization factor $J\tau$ for bombardment with 10 keV electrons, from Orsay [16].

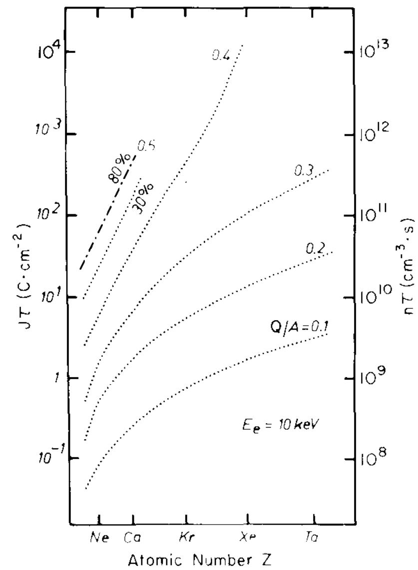

Fig. 4: Charge to mass ratio, Q/A, obtained when atom of number Z is bombarded with 10 keV electrons with ionization factor $J\tau$, from Orsay [16].

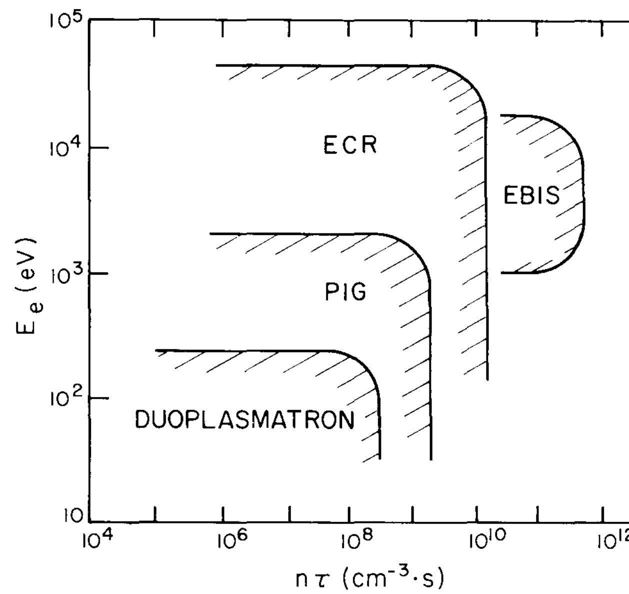

Fig. 5: Operating regions of ion sources used in present accelerators, and advanced high charge state ion sources.

source with a hydrogen gas feed to produce protons in an open arc. The cyclotron magnetic field was very convenient for collimating the arc to localize the source of ions. Later a hood was placed over this arc to confine the region of high gas pressure and reduce loading on the dee system. A reflector was added above the filament to use the arc electrons more than once. A version of this source is shown in Fig. 6. The alumina insulator has later been replaced with boron nitride. Such a source can produce high intensity accelerated cyclotron beams (a few mA) of protons and deuterons and adequate α-particle and $^3He^{2+}$ intensities. A modified version is used in negative ion (H^-, $^2H^-$) cyclotrons.

In the 1950's when heavier ions of high charge state were required, the filament source had to be improved. The filament was replaced by a solid cathode button, the reflector was connected to the cathode and more arc power was provided. The result-

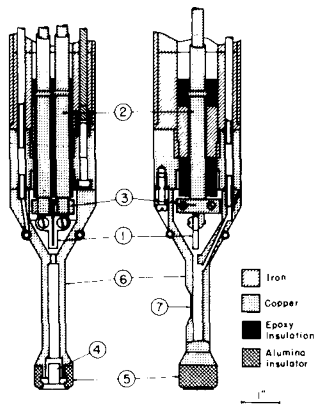

Fig. 6: Hot filament positive ion source for hydrogen and helium ions used at the LBL 88-Inch Cyclotron [17]. 1. Filament, 2. Squirt tubes, 3. Electron shield, 4. Reflector cathode, 5. Alumina insulator, 6. Anode, 7. Ion exit slit.

ing source, shown schematically in Fig. 7, is used by many heavy ion cyclotrons. It is called the PIG source, from Penning Ion Gauge or Philips Ion Gauge. PIG sources were previously reviewed by Bennett [18] and Green [19].

In this simplest version of the PIG the cathodes start cold. An arc is struck by raising the arc voltage to about 3 kV and increasing the gas pressure. Background ionization starts the discharge. The arc current builds up as the cathodes heat to give thermionic emission, and is stabilized by the arc supply current regulator or ballast series resistor. The confinement time is just the drift time of the ion from formation to extraction, on the order of microseconds. Gas can be fed in at the cathode or anode. Arc currents are 1-15 amps for dc sources and higher for pulsed sources. Arc voltages are 300-2000 volts. Source extraction voltage is 10-30 kV dc for external sources, with the anode being biased positive. For internal sources, the anode is usually grounded and 30-100 kV of rf voltage is used for extraction with a feeler or puller extending from the dee. Typical currents and emittance from an external PIG source are shown in Table I. The charge state distribution

Table 1. Some typical beam intensities from several high charge state heavy ion sources.

Ion	Q	PIG $I(s^{-1})$	ECR(Sup.MAF.-B) $I(s^{-1})$	EBIS $I(pulse^{-1})$
N	2+	$1x10^{15}$		
	5+	$1x10^{13}$	$5x10^{13}$	$2x10^{10}$
	7+		$5x10^{12}$	10^{10}
Ar	3+	$2x10^{15}$		
	8+	$4x10^{12}$	$3x10^{13}$	10^{10}
	12+		10^{12}	$8x10^{9}$
	18+			$6x10^{9}$
Xe	3+	$2x10^{14}$		
	10+	$1x10^{12}$	$4x10^{12}$	10^{10}
	26+		$4x10^{10}$	$4x10^{9}$
	44+			$2x10^{9}$
Norm. Emit. ε_n (π mm mrad)		.1-1	.1-1	.1

PIG data for 15 hour average from Bex [21].
ECR data from Geller [37].
The EBIS intensities are calculated as $10^{11}/Q$, and its repetition rate could be $1-10^3$ Hz, depending on confinement time and charge state.

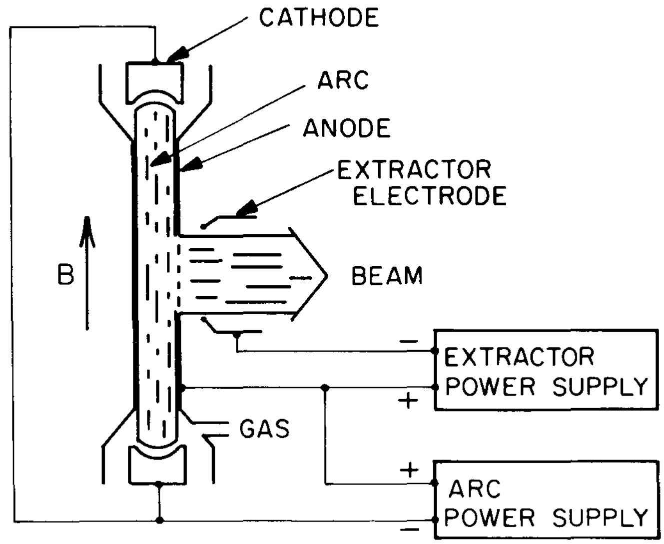

Fig. 7: Schematic diagram of heavy ion PIG source with arc-heated cathodes and side extraction.

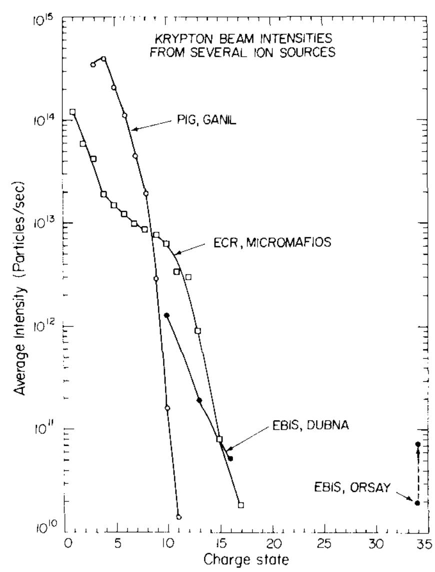

Fig. 8: Comparison of krypton charge state distribution of three heavy ion sources. The GANIL PIG [20] has 25% duty factor and beam averaged over 15 hours. The ECR source is MicroMAFIOS [38]. The Dubna EBIS plot uses KRION-2 data [46] and assumes extraction equal to containment time with immediate repetition (cyclotron mode), ions/pulse = $10^{11}/q$, and peak charge state equal to 1/4 of total beam. The lower Orsay EBIS point uses the data of CryEBIS [48] assuming equal containment and extraction times while the upper point uses the Dubna EBIS assumptions, but with the Orsay shorter containment time of 5 ms.

for krypton is shown in Fig. 8. The PIG is a compact source which fits into the space available in the cyclotron center and greatly extends the range of ions and charge states above that available with a filament source. A disadvantage is the need for cathode replacement and anode cleaning at intervals of a few hours to a day.

Several modifications of this PIG source design are shown in Fig. 9. This GANIL test stand source was developed from previous versions at Dubna and Orsay. One feature of interest is the use of filament heating of one cathode by electron bombardment. The other cathode or "anticathode" is well cooled. This system allows additional control over the arc impedance by adjustment of the bombardment power. Another feature of interest is the insulated electrode half way up the anode, which is adjustable in position. It is biased by an adjustable negative potential which causes sputtering of its atoms into the arc by the arc ions. This serves as an effective feed system for solid materials into the arc. This type of source is typically pulsed at 25% duty factor.

The development of any ion source requires many tests of new geometries and procedures and thus requires months or years of source testing time. This type of development is most efficiently done on a test stand which is independent of the running schedule of an accelerator or of users' groups. A good example of such a test stand is that of GANIL [22]. It includes its own power supplies, magnet, vacuum chamber, and external beam line with focussing and diagnostics. The charge/mass spectrum obtained with this test stand is shown in Fig. 10. Here xenon gas was run in the source. The plot illustrates the value of having sufficient resolution to separate the xenon isotopes, and also to identify possible impurities. The data from an emittance measurement at the GANIL test stand is shown in Fig. 11. The data is taken in 2 minutes with a movable slit and a downstream set of 32 collector strips. A microprocessor controls the data collection and generates the display. An automatic system like this is valuable for source data taking and evaluation.

For an internal source it is difficult to fit a sputtering electrode into the available space, although this has been done by the Dubna group for a classical cyclotron [24]. A system of solid material feed developed by the Oak Ridge ORIC cyclotron group is shown in Fig. 12. It is based on the orbit trajectories of heavy ions in the source-extractor gap. The source is at ground potential and the "accelerating electrode" or extractor is attached to the dee, which has up to 80 kV of rf voltage at 10-20 MHz. The Oak

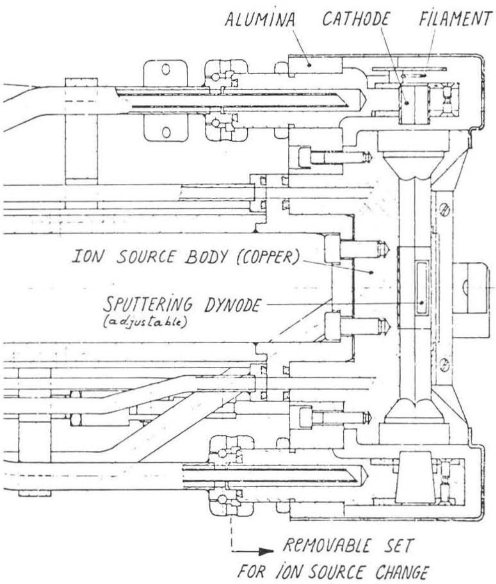

Fig. 9: PIG source used by the GANIL group for test stand development [22]. Source uses indirectly heated upper cathode and adjustable sputtering electrode.

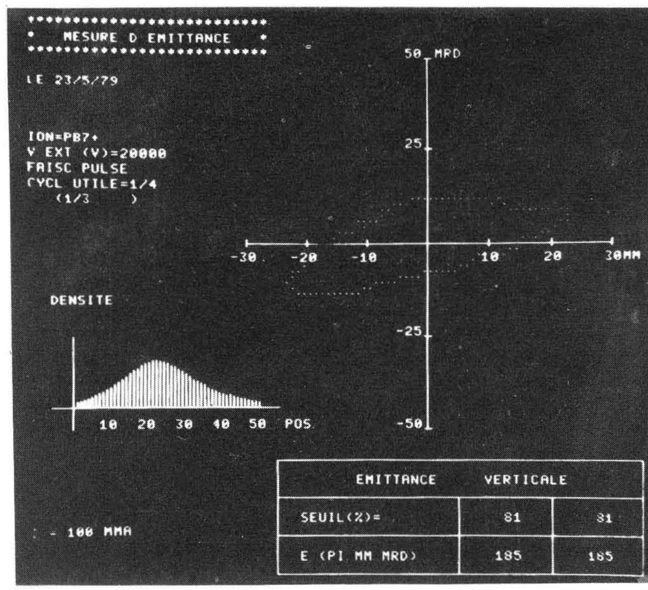

Fig. 11: The computer processed vertical emittance data from the GANIL PIG source test stand [22].

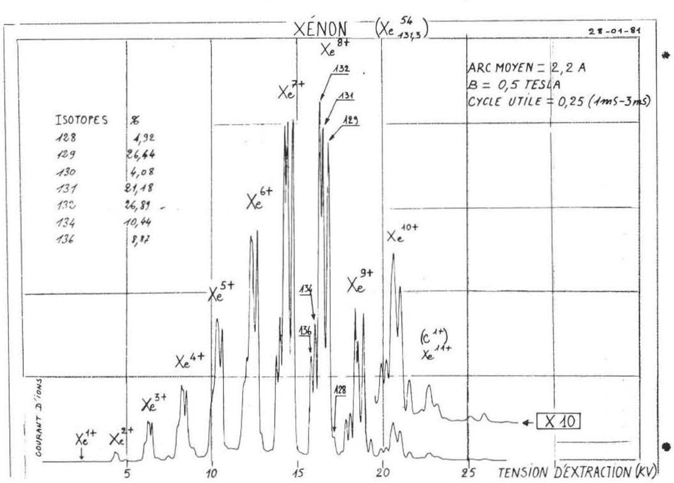

Fig. 10: Xenon spectrum from PIG source test stand at GANIL [23].

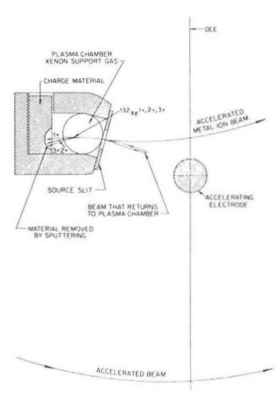

Fig. 12: Internal cyclotron PIG source solid feed system using back bombardment sputtering by decelerated low charge states, developed at the Oak Ridge National Laboratory ORIC Cyclotron [25].

Ridge group noticed an erosion at the back of their anodes in the position shown, and upon orbit analysis found that it was due to low charge state ions such as $Xe^{1+,2+,3+}$ being accelerated part way across the extraction gap, losing phase and accelerating back into the anode slit. They sputter atoms from the anode wall into the arc, where they are ionized and can be extracted and accelerated. This was first observed as a copper beam, coming from anode material. This phenomenon was adapted to a useful solid feed system by inserting blocks of the desired feed material. Other groups have used ovens to evaporate solid materials into the arc, in some cases with an internal source.

The development of PIG sources is continuing in many laboratories to improve intensity, reliability and range of ion species. But improvements are not expected to be large, since intensity is limited by the short confinement time of ions and by the limited electron density available from the cathodes. Lifetime is also limited to close to present values by the sputtering of cathode material onto the anode. Pulsing the arc extends lifetime at the cost of beam duty factor. Other techniques such as rotatable cathodes [25], and dual source shafts for quick exchange through the same port or alternate poles [26] have been used and suggested to improve efficiency.

Several other types of positive ion sources are used for external injection of light ions. For example a duoplasmatron is used by Indiana to produce H^+, $^2H^+$, $^3He^+$ and $^4He^+$ beams [26]. The measured normalized emittance is .4π mm-mrad for 100 μA dc at 500 keV. A high intensity application of an external proton source is at the new SIN injector where a cusped field single aperture source with four-electrode extraction will be used [28]. It is designed for a 30 mA dc beam of protons at 40 keV, and will be placed in a 860 kV terminal. Testing and development of the source is in progress.

The source of Li^+ at Indiana uses a beta-euchryptite button [27]. It gives 40 μA with a normalized emittance of .8π mm-mrad. The beam is converted to 10% Li^{2+} and 1% Li^{3+} in a high molecular weight vapor after dc acceleration to 600 keV.

Sources of negative protons or deuterons are used in several cyclotrons, either internally or externally. Some groups use the filament type of cyclotron source, Fig. 6, which was developed for H^- production by Ehlers [29]. At TRIUMF a Cyclotron Corporation source of this type was put into operation and further developed. It produces 2mA of H^- at 12 keV with a normalized emittance of .32π mm-mrad. The source is placed in a 300 kV terminal for injection into the cyclotron. At Milan development of this type of source has produced 45 μA of H^- accelerated to 45 MeV from an internal source, implying over 100 μA accelerated in the first turns after the source [30]. The Cyclotron Corporation has further developed this type of source over the past several years to give 600 μA at 15 cm radius [31]. When the beam is optimized at full radius, the currents are up to 300 μA at 15 cm and 250 μA maximum at the full 50 cm radius where the energy is 42 MeV. This is a factor of 2 more current at full energy than was obtained with the older external source and axial injection system into a 15 MeV cyclotron [32]. Although the external source had better pumping at the source, the system was space charge limited at 100 μA in the 15 kV injection line.

The Manitoba cyclotron uses an external duoplasmatron for H^- axial injection [33]. An improvement of cyclotron external beam quality has been observed due to the change from an internal to an external source.

An interesting fast pulsing system [34] is used by the Colorado cyclotron group on a light ion source such as that of Fig. 6. They use a wire loop gating electrode at the source exit slit, which is biased positive to suppress beam and pulsed negative a few hundred volts to transmit one rf pulse. The pulse rate can thus be reduced by 1/2 to 1/30. Unfortunately this system works only for hydrogen arcs, and not with higher power helium arcs. The observation that the average current falls much more slowly than the division factor, has led to studies of rf penetration into source arcs reported at this conference.

4. Advanced High Charge State Sources.- For heavy ion cyclotrons there is a large premium upon producing high charge states with the ion source, since energy is proportional to charge state squared. For other positive ion accelerators such as linacs or synchrotrons there is also a significant advantage. So a number of ion source groups throughout the world have worked on the problem of high charge state ion sources. These have included the HIPAC magnetic toroid device [35] where 10 keV electrons would ionize and trap ions up to U^{60+} in several seconds. Work on this device has terminated. Another system was the electron ring accelerator(ERA) where fast electrons were injected into and trapped in a cyclotron-like magnetic field. A study at Lawrence Berkeley Laboratory [36] estimated that Xe^{50+} would be the mean charge state in a high vacuum ring of 4 x 10^{12} electrons after one second, but this proposal was not funded. In the plasma of magnetic fusion machines such as Tokamaks, very high charge state ions have been seen as impurities, but a method of extraction is needed and the plasma volume is much larger than necessary for an ion source. In this section we will discuss advanced sources which are being developed for present accelerators, and some which may have potential for the future.

The Electron Cyclotron Resonance (ECR) source uses microwave power to accelerate electrons at their cyclotron resonance frequency, ω_{ce}, in a magnetic field, B, where ω_{ce} = Be/m, and electron charge/mass is e/m. At a field of 3.5 kG, the microwave frequency is 10 GHz for example. This type of source has reached its highest development in Geller's group at the CEN lab at Grenoble. The layout of Geller's large high charge state source, Super MAFIOS-B [37], is shown in Fig. 13. The operation of the source is as follows. Plasma of the desired species is produced

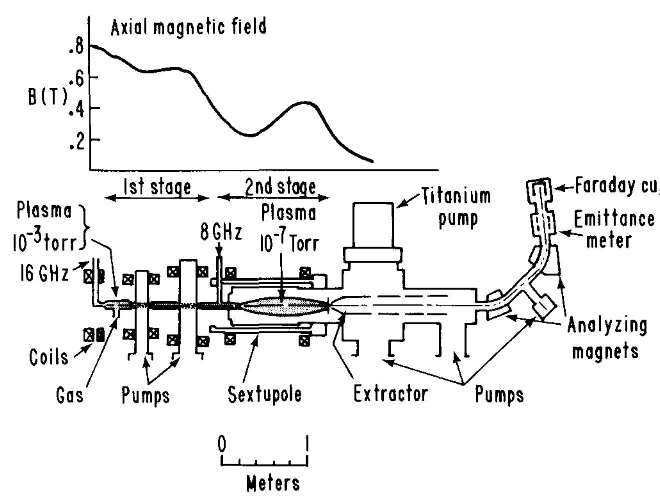

Fig. 13: The SuperMAFIOS-B ECR source of Geller at Grenoble. Before it was shut down, this large plasma machine demonstrated high charge state production with its two ionization stages [37].

in the small first stage by feeding in gas and microwave power. The pressure in this first stage is 10^{-3} torr, a typical value for many ion sources. The charge state at this point is approximately the same as in a PIG source: 2^+-3^+ for mass 10-20. An axial magnetic field of 6 kG guides the plasma to the second stage. Here the stripping to high charge states is done by the energetic electrons of up to 20 keV created by a second microwave resonance. The background pressure in this second stage must be low to prevent charge exchange by the high charge state ions that are created: 10^{-7} torr in SuperMAFIOS-B. For a long confinement time of the ions against plasma instabilities, a sextupole magnetic field is superimposed on the basic mirror configuration of the second stage, in a minimum B configuration. The ion confinement time in the second stage is estimated as 10-15 ms. The measured plasma density of 3×10^{11} cm^{-3}, gives $n\tau = 4 \times 10^9 cm^{-3}$ sec. The beam is extracted from the source at 10-20 kV. Selected high charge state beam currents extracted are shown in Table 1. The charge state distribution is broader than that of a PIG. The emittances are a reasonable match to accelerator injection systems. A key design feature in the system is the two stages with pumping in between. The first stage generates the plasma while the second high vacuum stage produces the high charge states. The duty factor can be 100%, and lifetime is 1000's of hours, since there are no sputtered cathodes to replace.

The disadvantage of this device was its large power consumption of 3 MW, and it has been shut down for that reason. But it pointed the way to the design of ECR sources with higher charge states than those of the PIG. The clear direction to follow is the duplication of this source with superconducting coils to reduce the power consumption. This path is being followed by some laboratories, but the next version of the two stage ECR source to operate was the compact version called MicroMAFIOS [38].

The MicroMAFIOS is shown in Fig. 14. It was built as a cooperative project of CEN Grenoble, and the cyclotron labs at Louvain and Karlsruhe. It is now operating in Grenoble. It uses several simplifications to save cost. It is compact in size, uses small bore room temperature solenoid magnets, samarium cobalt permanent magnets for the hexapole, and 10 GHz for both microwave frequencies. The total power is about 100 kW, with 2 kw of UHF power. Duty factor is 100%. Extraction voltage is up to 8 kV and will be increased to 20 kV in the future. It was expected that the charge states might be considerably lower than for SuperMAFIOS-B due to the smaller size, but fortunately the performance approaches that of the larger source.

The output of the MicroMAFIOS has been analyzed with a magnet. A sample spectrum of ^{18}O obtained with this magnet is shown in Fig. 15. The use of ^{18}O permits the separation of $^{18}O^{8+}$ from H_2^+. The resolution of the analyzing magnet shows all the charge states of ^{18}O, separated from the impurities.

The charge state distribution of MicroMAFIOS is shown in Fig. 8. Several cyclotron laboratories are planning to purchase MicroMAFIOS sources, including Grenoble and Groningen. Geller has also tried a simpler version called MiniMAFIOS which uses one cavity and one UHF generator. Its start-up is a little more difficult, but its best performance approaches that of MicroMAFIOS.

The cyclotron laboratory at Karlsruhe is building a source called HISKA [39], Fig. 16, which uses superconducting and room temperature solenoid coils, together with a samarium cobalt permanent magnet hexapole. While awaiting the full scale source, a small 2-stage source, p-Hiska, similar to MicroMAFIOS has been built [40], and is producing 25 nA of N^{7+} and 80 nA of $^7Li^{3+}$. The N^{7+} has been successfully injected and accelerated in the cyclotron. The cyclotron laboratory at Louvain is building an ECR source with superconducting solenoid and hexapole coils, called ECREVIS [41], Fig. 17. Tests of a 1/3 scale superconducting model are also planned. The Julich cyclotron plans a similar source. Work is also underway at GSI, Darmstadt to develop an ECR source for high current and medium charge state: 100 μA of U^{10+} for injection into the UNILAC.

The confinement of ions in the ECR source is not completely understood theoretically. There are several models discussed by Geller [37], Jongen [42] and West [43] for the diffusion of heavy ions and the potential well in the plasma. The plasma density should increase as the square of the microwave frequency (and magnetic field). Whether the average charge state will also increase is still a matter of

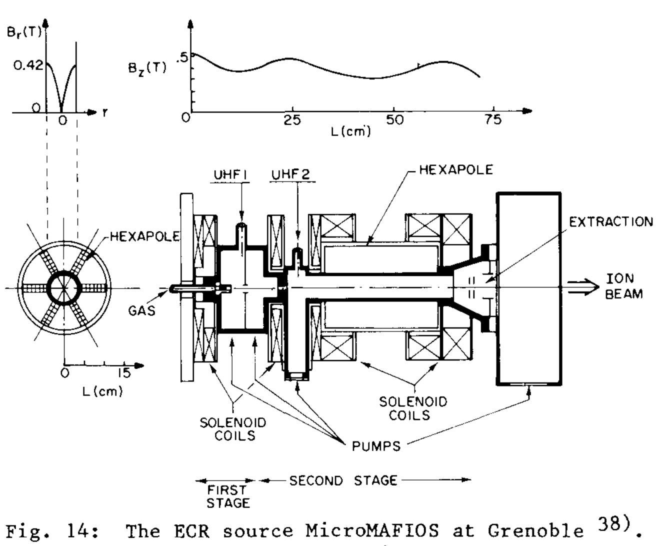

Fig. 14: The ECR source MicroMAFIOS at Grenoble [38]. This compact two-stage source gives almost the same performance as SuperMAFIOS-B.

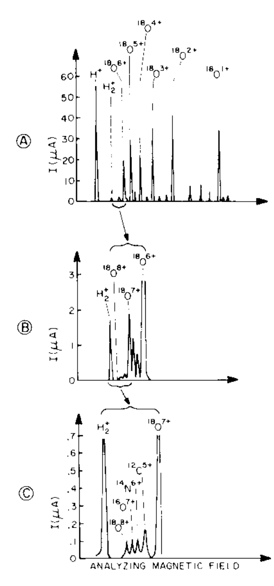

Fig. 15: Ion spectra obtained with an analyzing magnet on MicroMAFIOS [38].

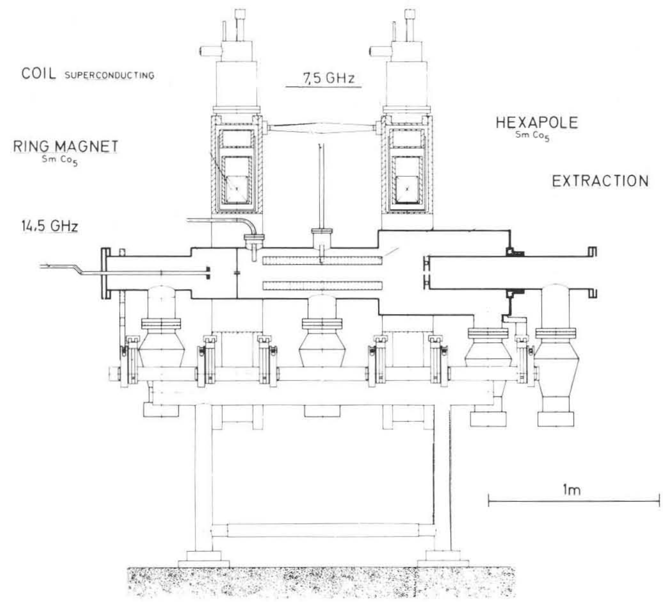

Fig. 16: The Karlsruhe ECR source HISKA which uses superconducting solenoid coils and permanent magnet hexapole [40].

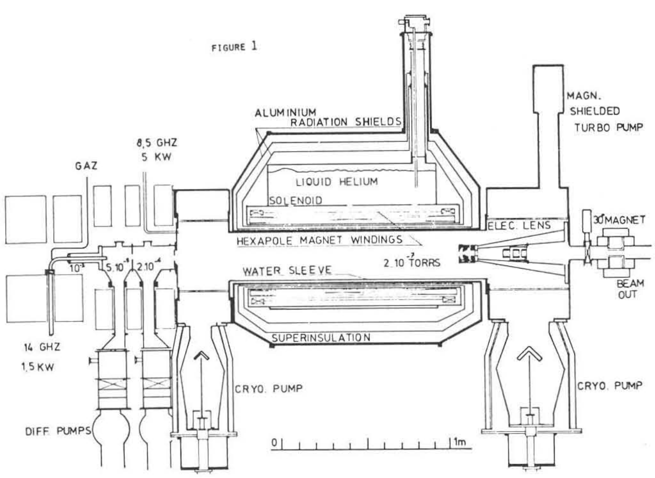

Fig. 17: The Louvain ECR source ECREVIS with super-conducting solenoid and hexapole coils.

debate, and awaits the results of the higher frequency sources.

Another advanced source being developed by several laboratories is the Electron Beam Ion Source (EBIS). Recent progress was summarized by Becker et al. [44]. The concept of the EBIS to produce high charge states was pioneered by Donets in Dubna starting in 1967, with the first experimental results on EBIS reported in 1969. A history of the Dubna EBIS development is given by Donets [45]. The principle of the EBIS is illustrated in Fig. 18. An electron gun launches a small diameter (1 mm) electron beam down the axis of a magnetic solenoid about 1 m long. The beam stops on the electron collector. The potential along the axis is defined by a number of hollow cylindrical drift tubes, and stepwise ionization begins. The ions are contained radially in the electrostatic potential well of the electron beam, and axially by positive potential barriers on the end drift tubes as shown in the potential distribution. During a short "injection" period, the desired number

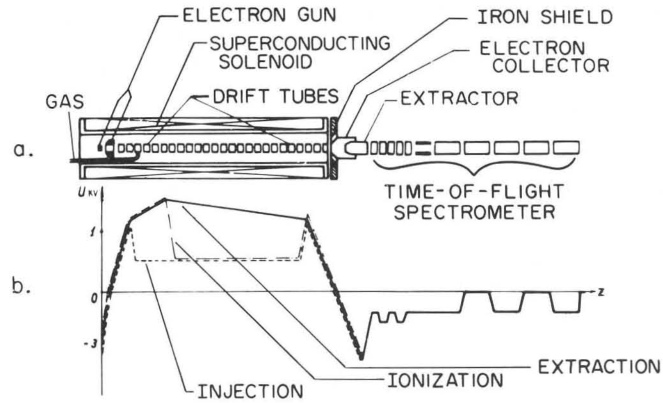

Fig. 18: Schematic drawing of KRION ion source of the EBIS type, developed at Dubna. Electron gun is inside solenoid magnet.

of ions is accumulated in the well. Then the potential distribution is switched to the "ionization" mode, in which the first barrier is moved downstream to prevent additional low charge state ions from entering the potential well. The ions reach progressively higher charge states as the containment continues. When the average charge state has reached the desired value, the potential distribution is switched to the "extraction" mode. This applies a ramp voltage on the drift tubes, accelerating the ions out of the source into the extractor, time-of-flight modulator and transport system. The system thus uses a batch type process in which the intensity is determined by the number of ions per pulse and the number of pulses per second. For cyclotron injection we need maximum ions/pulse and minimum containment time to give maximum repetition rate. The maximum number of ions per pulse is the number to just neutralize the electron space charge. For typical source parameters of a 10 keV, 1 A electron beam and 1 m length, the number of ions is $10^{11}/q$ where q is the average charge state. The time-of-flight ion spectrum from the Dubna KRION-2 [46] EBIS is shown in Fig. 19. We can see Ar^{18+} clearly at 2000 ms = 2s containment time. In other measurements Kr^{34+} and Xe^{48+} were obtained with $j\tau$ = 3 x 10^{21} cm^{-2}, and electron energy of 18 keV. The ionization is step-by-step and the

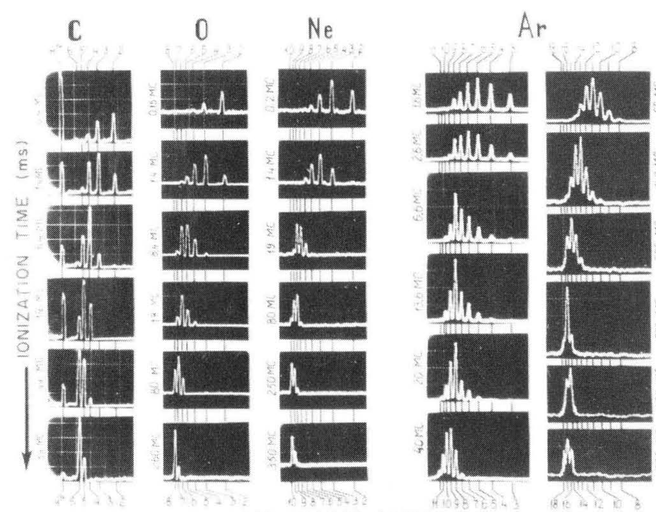

Fig. 19: Experimental data obtained with KRION-2 source at Dubna. Charge distributions from time-of-flight analyzer are shown for several ionization times for each element.

$j\tau$ values agree fairly well with calculations similar to those used for Fig. 4. The average krypton beam of KRION-2 with fast repetition rate is shown in Fig. 8. The older KRION-1 source is used to inject the Dubna synchrotron.

The construction of a successful high charge state EBIS requires a precisely straight magnetic axis, good alignment of the electron gun with the axis, a high vacuum (10^{-10} torr) and a gas pulsing system. A number of EBIS projects have had difficulty with reliable production of high charge state beams, because one or more of the above requirements were not met. The production of beams from solid material feed systems appears feasible with a vaporization system or by ion injection through the cathode.

Another EBIS design is the CRYEBIS built by Orsay [47] as an injector for the Saturne-II synchrotron at Saclay. It is shown schematically in Fig. 20. The special features of this source include an external electron gun, and modes of operation for heavy ions and polarized ions. The external gun is used to compress the electron beam electrostatically and then magnetically as it enters the solenoid magnet, to create a high electron beam density, j, in the ionization region. The electron gun is shown in Fig. 21. A high magnetic field is used to obtain high compression for heavy ions using the Dubna gas injection system.

A surprising result from CRYEBIS was reported by the Orsay group in 1979 [48]. The production of high charge states such as Kr^{34+} and Xe^{44+} occurred in the very short confinement time of 5 ms. This time was much shorter than expected from the compressed electron beam. From the calculated $j\tau$ values (Fig. 4), j values of up to 10^5 A cm^{-2} are deduced. This supercompression of the electron beam might be explained by space charge compensation by the positive ions created, since calculations of electron beam trajectories were made without neutralization. Such a short confinement time would allow fast pulsing of the source at 100 Hz, which would then provide good intensities for injection into cyclotrons or an accumulator ring for a synchrotron. Such performance

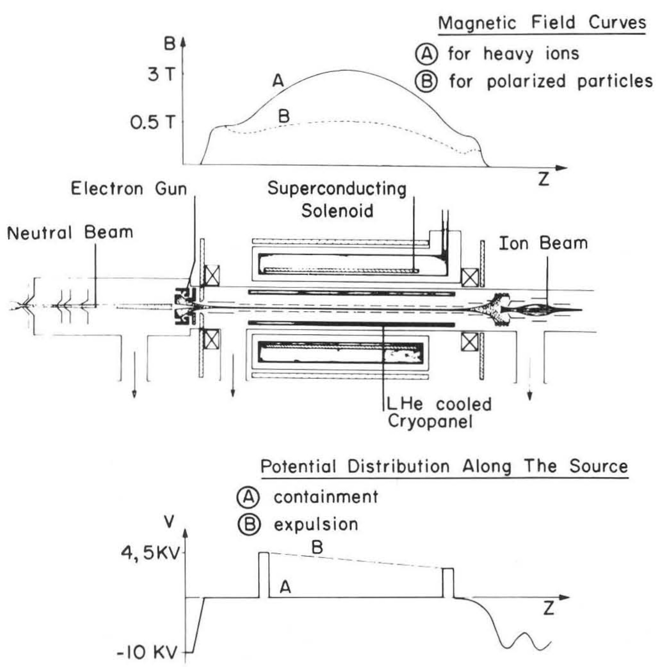

Fig. 20: The EBIS source developed at Orsay, named CRYEBIS.

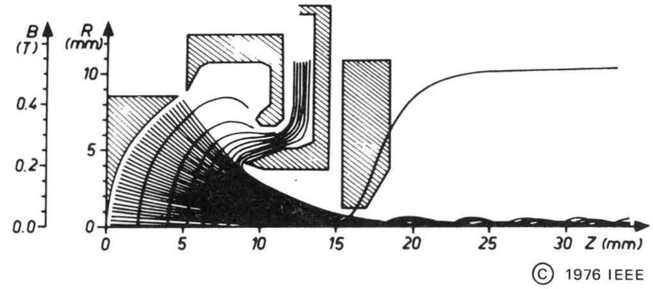

Fig. 21: The external electron gun for the Orsay CRYEBIS source [47].

is shown in Fig. 8. Unfortunately, there has been difficulty repeating these unusual results after CRYEBIS was moved. The alignment requirements would be extremely stringent for this super-compressed electron beam of .01 mm diameter.

A number of other groups are using or developing EBIS sources [44]. The Frankfurt group has recently measured charge state distributions [49] from their EBIS, which uses a cold bore superconducting 5T magnet, and is designed to study EBIS techniques and physics. Giessen uses a dc EBIS for atomic physics. Nagoya is building a superconducting EBIS called CRYONICE, similar to the Dubna KRION. At Berkeley a test bench EBIS with normal conducting coils is being used to understand EBIS design and to reproduce the Orsay compression results for cyclotron application. Cornell is testing a room temperature EBIS with an external gun and distributed sputter ion pumping to be used for atomic physics [50]. A recent summary of EBIS physics was written by Vella [51].

The EBIS source has the advantage of higher charge states than the PIG or ECR, but with the typical long confinement times of the usual source such as that of Dubna the average intensities in the cyclotron mode are only competitive for the very high charge states and low intensities (Fig. 8). If the Orsay high compression results could be repeated, the intensities could be several orders of magnitude higher. It is hoped that one of the EBIS groups can accomplish this task.

There are some other prospects for high charge state sources which are further in the future [7]. These utilize lasers, plasma focus, sparks, and exploding wires. Although some of these sources produce very high charge states (Au^{51+} for exploding wire), they have short pulses and low repetition rates, and so have low average intensities.

The laser source was reviewed by Tonon [52], who indicates that we need a power density of about 10^{13} W/cm^2 to get ions such as Kr^{20+}. Recently the University of Arkansas [53] has used a .3 J laser with 10^{11} W/cm^2, 50 Hz rate, to form a plasma plume and extract ions at 15 kV. Ions up to C^{5+} and Al^{7+} have been observed. Duty factor may be stretched by a long drift distance and emittance improved by a programmed extractor voltage [54].

A plasma focus device has been used by Rhee [55] to produce fully stripped ions up to argon (Fig. 22). In this system gas is fed continuously into a gap which is pulsed at 300 kV. Ions are identified with a Thomson spectrometer and emulsions. They are found to have 550 keV/Z of energy. The charge state identification will be rechecked. Duty factor is low at present in this source.

Collective ion acceleration can produce ion pulses at several MeV/nucleon with partially stripped ions. Such an accelerator can be considered as both an ion source and a preaccelerator. This field was reviewed by Reiser [56]. Remaining problems to be

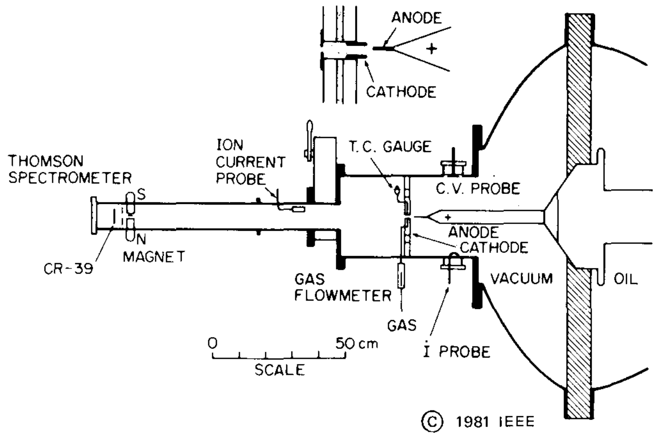

Fig. 22: The plasma focus high charge state source of Maryland [55].

solved are selection of ions with proper energy spread and emittance, and increasing the repetition rate.

5. Summary.- We have discussed many cyclotron sources, low and high charge state, positive and negative. We compared the charge state distributions of 3 high charge state sources in Fig. 8. Two stage accelerator systems such as GANIL, MSU, and SuperHILAC utilize the high output of 10^{13}-10^{14}/sec of the PIG source at low charge states in the first stage. The beam is then stripped and accelerated at 3-4 times the charge, in the second stage at a loss of perhaps only a factor of 5 in intensity. So the first stage plus stripping gives many orders of magnitude more intensity at the high charge state than the source alone. The ECR source extends the range of both single and two stage accelerator systems.

There are many new developments ahead. In high charge state sources we expect the new generation of ECR sources to provide higher energy heavy ions and to improve our understanding of the source scaling and physics. For the EBIS source we expect several groups to contribute to improved performance and to the understanding of high compression operation.

6. Acknowledgements.- The author wishes to thank all those who contributed information to this paper, either in written or oral form.

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" DISCUSSION "

F. RESMINI : In the ECR source, how firmly established is the f^2 dependence of the electron density in the second stage and which kind of developments could be expected ?

D.J. CLARK : The proportionality of electron density and cut off frequency squared is well established in plasma physics. So higher ion currents should be available with the higher microwave frequency ECR sources, providing sufficient power is available. The open questions are the dependence of power on frequency : where it lies between f^2 and f^4 and whether there is an increase of average charge state with frequency as Geller has suggested.