ECR Ion Sources and Applications with Heavy-Ion Linacs*

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Abstract

The electron cyclotron resonance(ECR) ion source has been developed in the last few years into a reliable source of high charge-state heavy ions. The availability of heavy ions with relatively large charge-to-mass ratios (0.1 - 0.5) has made it possible to contemplate essentially new classes of heavy-ion linear accelerators. In this talk, I shall review the state-of-the-art in ECR source performance and describe some of the implications this performance level has for heavy-ion linear accelerator design. The present linear accelerator projects using ECR ion sources will be noted and the performance requirements of the ECR source for these projects will be reviewed.

Introduction

In the past twenty years, the research efforts in the field of nuclear and atomic physics have moved strongly into experimental programs which require the use of 'heavy ions' - beams of particles heavier than helium. More recently the high energy physics community has begun to emphasize research with heavy ions. Industrial uses of heavy ions are also increasing dramatically, driven by fields such as semiconductor implantation, metallurgical surface treatments (tribology), and medical applications. This switch in the particle mix emphasis required from ion sources has placed before the ion source development community a difficult challenge to develop ion sources with sufficient reliability, beam current, and charge state performance to make delivery of heavy-ion beams economically feasible.

The first application of the electron cyclotron resonance principal was in a H^+ ion source by Geller in 1968(1). The first heavy-ion, high charge-state electron cyclotron resonance ion source (ECRIS) was Geller's MAFIOS in 1972(2). By 1974 SUPERMAFIOS(3) demonstrated most of the features which are identifiable in most modern ECRIS. Those features include a 'minimum B' magnetic field for good plasma confinement, two identifiable plasma regions ('stages'), and a multimode RF cavity. Although the performance of SUPERMAFIOS was good the electrical power consumed exceeded 3MW. Over the next 16 years, ECRIS source performance for high charge-state heavy-ions has continued to improve, the power for the source has decreased, the physical source size has become smaller, and the experience and reliability of the sources for essentially any element has significantly increased.

The first application of ECR ion sources in accelerator-based research was their use at cyclotrons. This application allowed cyclotrons for heavy ions to replace their PIG ion sources, and dramatically increase the energies available for an existing cyclotron due to the availability of large currents of high charge-state heavy ions from the ECRIS.

The applications of ECR ion sources with linacs quickly followed. The first actual use was the acceleration in the CERN linacs of oxygen and sulphur beams with further acceleration in the CERN synchrotrons. The first stand-alone heavy-ion linac project relying on an ECRIS was the Argonne Positive-Ion Injector(4). The high charge-to-mass ratio available from an ECRIS, combined with super-conducting technology, allowed the design of a new class of low-velocity linac using independently-phased resonant cavities even in low-velocity region of the linac(5,6). This proposal was followed quickly by the GSI low -intensity injector project(7) and the most recent plans for an ECR-linac injector, the ALPI(8) project.

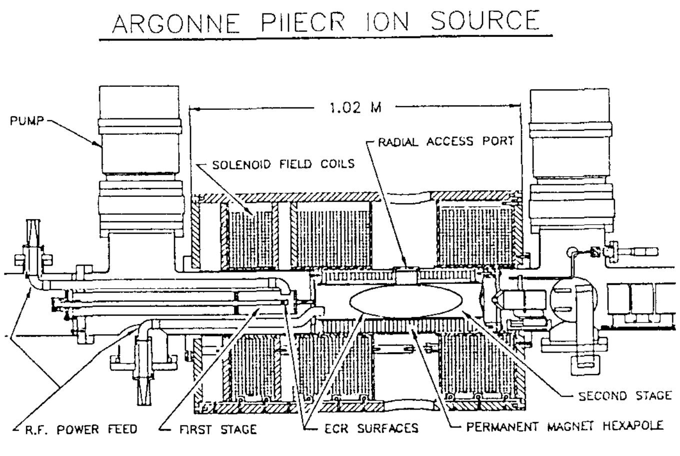

Fig. 1. The major components of the Argonne 10 GHz ECR ion source.

Each of these projects has a goal of accelerating virtually any stable isotope. The design of a linac must assume an initial injection velocity and a minimum charge-to-mass ratio (q/A) for the ion species to be accelerated. In 1985 the first of these projects, the ATLAS PII, chose a $q/A \approx 20/238$ for uranium as a reasonably safe design choice. In 1988 the GSI injector design team felt that a uranium $q/A \approx 28/238$

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should be a good choice. Finally the ALPI ECRIS design at Legnaro expects to achieve a $q/A \approx 32/238$ for uranium. Of course each increase in the reliably achievable charge-to-mass ratio has a significant impact on the cost-performance ratio for such projects. For these projects, the planned beam currents are a few microamps. No significant difficulties with space charge in the linac injection region are expected.

The Present ECR Ion Source

The major features of a high-charge state ECR ion source are shown in Figure 1. An ion begins its journey through the source by introduction of gas into a small 'igniter' region - the first stage. This region usually contains a 'line' region across which the cyclotron resonance condition for electrons exists at the frequency of RF microwave power in use (2.5 - 18 GHz, up to now). Such a condition provides an efficient coupling of power from the microwave source to the electrons. These relatively low-energy electrons provide an initial ionization of the injected gas at high total pressure ($<10^{-4}$ Torr). This low charge-state, high-density plasma diffuses into the larger main region of the source - the 'second stage'. In this stage, a mirror magnetic field configuration is generated by electromagnetic solenoid coils. The magnetic field is shaped into an increasing-field geometry in all directions ('minimum-B') by a hexapolar field usually produced by a permanent magnet configuration. This minimum-B field configuration provides improved magnetic confinement of the hot electrons and produces an ellipsoidal surface on which the ECR resonance condition exists. These two effects allow the electron temperature and density to increase significantly ($T_e \approx 10$ keV, $n_e \approx 10^{12}$ cm^{-3}). The hot electrons further strip the ions, which are confined in an electrostatic trap created by the electrons, to high charge states. Finally the plasma is sampled by the extractor electrode and the ions are extracted from the plasma region.

The the high charge states are reached by sequential ionization. The cross-section for single electron ionization is much larger than any two-electron processes. The charge state of ions from an ECR plasma is a result of the competition between stripping and recombination cross-sections, the confinement time of electrons and ions, and the electron energy distribution temperature. In addition plasma-wall interactions and the elemental distribution of the plasma play an important role in the performance of the ECRIS.

The level of performance of ECR ion sources has increased dramatically over the past decade. The best performance of ECR ion sources for a few selected ion species and charge states is shown in Figure 2 as a function of time. Not only has the maximum ion current increased markedly, but the peak in the ion charge-state distribution available from ECR sources has also continued to increase. Source performance considered 'state-of-the-art' five years ago is now just 'average'. These improvements are the result of new sources incorporating known scaling factors and of improvements in the operating regime of existing sources to better utilize the competing processes mentioned above. The beam currents which are now being reported by new sources with operating frequencies of 14 GHz and greater are within a factor of 2-10 of the beam currents of low charge-state species available from other types of ion source(9).

The ions in an ECRIS plasma are weakly coupled to the RF power. This feature allows the ions to remain unheated by the RF power. The energy spread of ions from the source appears to be dominated by the source plasma potential, voltage stability of the extraction power supply, and energy coupling to the ions from electron-ion scattering. The result is ions which have an energy spread corresponding to an equivalent voltage variation of 7-15 ev(10). At the Argonne PII-ECR source, the energy spread of a beam of $^{11}B^{+3}$ was measured to be 7 volts using doppler-broadened line shapes by laser techniques. Such small energy spreads for high charge-state ions make it possible to deliver beams through linacs with a longitudinal phase-space volume of unprecedented small value. Measurements of the longitudinal emittance of beams from the new Argonne Positive Ion Injector for ATLAS indicate the system emittance is less than one third the corresponding emittance from the tandem injector. This allows the on-target energy spread and time spread to be very small, opening new possibilities in the design of experiments: a capability being used extensively at ATLAS.

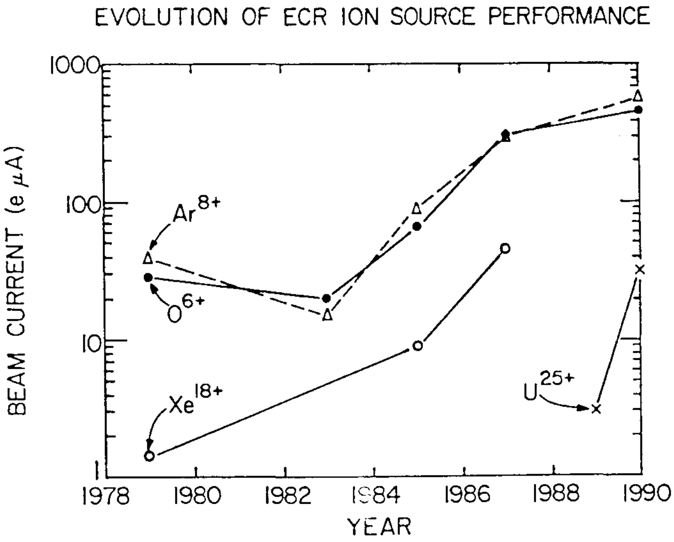

Fig. 2. Evolution of the reported maximum beam currents available from ECR ion sources. The dramatic increase in beam currents in the last decade shows no indication of stopping. (Data from Ref. #3, 17, 25, 27, 28, 29, 30).

The transverse emittance of ECR ion sources has been measured by a number of laboratories(11,12,13). The overall result is that the normalized emittance $\gamma\beta\epsilon$=0.1-0.2π mm-mr at approximately the 80% intensity contour. Such a value is significantly higher than the transverse emittance of other high quality heavy-ion sources such as negative-ion cesium sputter sources(14) which is generally 0.02-0.06π mm-mr, but when compared to the typical transverse emittance after stripping in a tandem accelerator terminal of ~0.09π mm-mr for A$\simeq$58, the ECRIS transverse emittance is similar. For extremely heavy ions, this comparison favors ECRIS beams as multiple scattering in stripper foils dominates the transverse emittance for tandem accelerators.

The measured values agree qualitatively with the assumption that the transverse emittance is dominated by the angular momentum conservation required for particles formed in a magnetic field. This model predicts that the transverse normalized emittance from an ECRIS will be

$$\gamma\beta\epsilon \ \alpha \ (q/A)r^2B,$$

where q, A are the charge and mass of the ion of interest, r is the radius of the effective emitting surface, and B is the magnetic field at the effective emitting surface. A surprising result of this effect is that one expects the transverse emittance to decrease for heavier beams because the ratio (q/A) will be smaller for those beams than for lighter ions. Another surprise is that the actual measured emittances of beams from ECRIS's are smaller than would be expected from simple calculations with this model. Such an effect may imply that high charge state ions are emitted from a region smaller than that defined by the radius of the extraction hole.

The angular momentum model for emittance also predicts that the transverse emittance from high frequency sources will be greater than that from lower frequency sources. No data at present shows this effect. But it will be interesting to see if this feature is observed in the next generation of high frequency sources.

Since the ECRIS evolved from a plasma physics background the first operation of these devices was with gaseous materials. When using gases, an ECRIS demonstrates essentially infinite lifetime; that is the lifetime is limited only by the reliability of external components. But the desirable properties of beams from these sources soon caused demand for beams of heavy ions which could only be produces by using materials in solid form. These sources have demonstrated their ability to use solid material as primary feed material for a number of years. A variety of methods have been employed such as external electrically-heated ovens, plasma heated 'boats', the insertion of the desired material directly into the plasma region for evaporation by direct plasma heating, and the use of gaseous compounds for normally solid materials(15,16,17). An example spectrum for uranium ions from the Argonne ECRIS is shown in Figure 3.

Generally the solid material is injected directly into the 'second stage' in all these approaches. The source performance for these types of materials varies much more than for gases, but in general the performance in terms of beam currents and average charge states is somewhat lower compared to that for nearby elements which are gases. The overall operation of the source is maintained by a continued feeding of a gas such as oxygen or nitrogen which forms the dominate component of the plasma and the material of interest is only a small 'contaminating' portion of the total plasma. One of the negative aspects of using a solid is that the performance of the source may degrade with time, especially with regard to the production of the highest charge states. This effect appears to be related to the wall-plasma interaction noted above. Operating the source with SiH_4 and O_2 will generally recoat the source walls with a beneficial coating which is assumed to be SiO_2 and the source performance is restored.

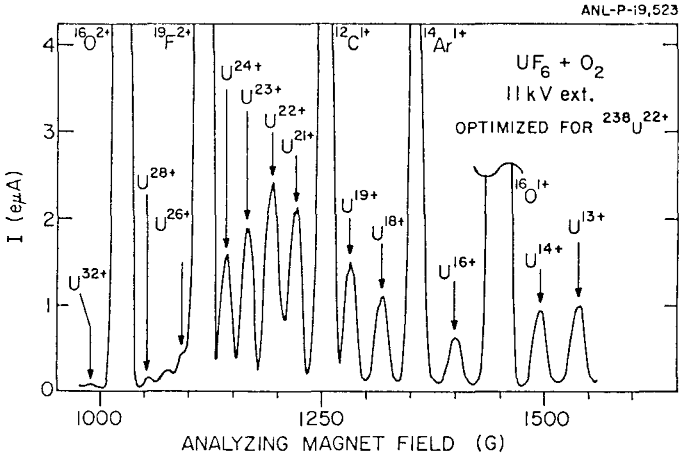

Fig. 3. Example of the charge state distribution for the Argonne ECR ion source for uranium.

The amount of material consumed in an ion source is an extremely important parameter with regard to the use of isotopically enriched material, special experimental applications such as accelerator mass spectrometry, and the long-term reliability of the source for solid material operation. The material consumption for the primary plasma gas can be quite high (tens of mg/h) and strongly depends on the details of the source design as well as operating mode. Material consumption can generally be minimized by feeding material into the 'second stage' region where the total gas flow is lowest. Under these conditions usage rates of approximately 1 mg/h for most materials can be obtained. At Argonne we have achieved usage rates of approximately 0.2 mg/h for krypton. A long run with natural molybdenum consumed the material at a surprising 0.04 mg/h rate while producing approximately 1 electrical microamp of $^{92}Mo^{16+}$ from natural abundance material. This result corresponds to an ionization efficiency of 0.38% for that isotope into the 16+ charge state. Such efficiency for high charge-state production is quite respectable. The value quoted above is similar to typical operating efficiencies for negative-ion cesium sputter sources(18).

A number of ECR sources have been built for low charge-state high-efficiency applications(19,20,21). These sources have demonstrated total ionization efficiencies for 1+, 2+, and 3+ ions in material as heavy as neon with efficiencies ranging from 15% to over 50%. Such high efficiencies make a variety of accelerator applications appealing including the acceleration of radioactive beams(20,21). Literally a whole new world of applications may be in the offing for accelerator physics with performances of this class.

The Future for ECR Ion Sources

The technology of ECR ion sources continues to progress as graphically demonstrated in Figure 1. Some of the progress follows scaling guidelines which are derivable from reasonable plasma physics models of the ECRIS operating regime. These scaling assumptions have been described by Geller(22). The most important results from these considerations is the prediction that the peak in the charge-state distribution should increase rather slowly following a logarithmic relation with frequency:

$$<q> \propto \log(\omega^{3.5}),$$

where ω is the RF power frequency. A second relationship predicts that the beam current for a particular charge should be expected to scale as:

$$I_q \propto \omega^2/A.$$

Both of these relationships have been experimentally supported in comparisons between sources operating over a frequency range of 6.4 to 16.6 GHz. It is these two relationships which are driving the construction of the next generation of high frequency ECR ion sources. The frequency dependence will be tested much further during the next five years as the 30 GHz superconducting ECR ion source project at Michigan State University(23) comes into operation at varying frequencies, culminating in 30 GHz operation later.

Following the predictions of these simple relations given above is made difficult because of the costs involved. Those costs derive from the high cost of high frequency RF power in the regime above 14 GHz, the increased RF power expected to be required in these regimes, and the added costs of the magnetic fields which must scale linearly with the increasing RF frequency in order to maintain confinement and the ECR resonance condition. Therefore, for many application, lower frequency ECRIS applications will continue to deliver the best cost/benefit ratio.

The simple scaling laws outlined above are not the only effects making important contributions to ECR ion source performance. In the last five years, a number of empirical results have changed the performance of existing sources and revised the way new sources are being designed. One of the first surprises was that the average charge state of one plasma species could be improved by introducing a second, lighter gas into the plasma. This gas mixing role is still not well understood, but may be due to energy transfer by elastic scattering of ions between the two species. An effect which may be similar has been observed in ion traps(24).

A second performance improvement came in the redesign of the compact source CAPRICE by Jacquot(25) in Grenoble. In this case, the average charge state did not change significantly from other 10GHz sources, but the total ion current increased by nearly a factor of 10 from the original design. Again exactly what causes the improvement is not fully understood, but may have to do with plasma wall interactions, secondary electrons streaming from an iron electrode, and the detailed shape of the magnetic field in the extraction region.

A third important area effecting ECRIS performance is the plasma wall interactions. The importance of this interaction has long been known. Even the earliest tests of solids in ECRIS's reported 'poisoning' of the source after these tests and minimizing the material usage was known to be beneficial. The first reported improvement in source performance by wall treatment came from the 6.4 GHz Berkeley ECRIS where Lyneis(26) clearly demonstrated improved performance from his source was correlated with previous use of SIH_4 and O_2. Lyneis has surmised that the formation of a SiO_2 layer on the wall provides a source of cold electrons because of the high secondary electron yield of SiO_2. This effect has been demonstrated at other laboratories and recoating the walls of the Argonne ECRIS after long solid material runs is a normal procedure.

Effects of the types described above are much more difficult to predict and understand. It is these types of developments that still keep the 'black magic' in ion source development and give hope of continued improvement for these sources without extreme financial expenditures.

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