Operating Experience of an ECR Ion Source on a High Voltage Platform

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Abstract

The ATLAS PII-ECR ion source is the first ECR ion source to be designed for operation on a high voltage platform. The source system is required to provide beams of heavy ions with a velocity of $0.01c$ for subsequent acceleration by the superconducting ATLAS Positive Ion Injector linac. The ability of the system to provide high charge state ions with velocities up to $.01c$ is possibly unique in the world today and as such has generated significant interest in the atomic physics community. A beamline for atomic physics has been installed and is now in use. The source began operation in October, 1987. The source capabilities and operating experience to date will be discussed. Other ECR-accelerator combinations will be compared to the ATLAS system.

Introduction

The development of the high charge state electron cyclotron resonance (ECR) ion source (1) during the past 20 years has had a major impact on the heavy ion accelerator physics community and the research programs which make use of energetic heavy ions. It can be argued that the ECR ion source has given cyclotron-based heavy ion programs their flexibility, versatility, and practicality. It is also the high charge state heavy ions from an ECR ion source which has made relativistic heavy ion physics a reality today (2).

These same high charge state heavy ions, which ECR ion sources provide in quantities measured in particle microamps and tens of microamps, have allowed a number of new classes of linear accelerator devices to be designed and

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construction projects initiated. These projects make use of the high charge state of the ions to significantly reduce the total accelerating voltage required for a particular final energy. Also, because the acceleration process is so rapid, the transverse and longitudinal optics of the system become more elegant and simpler compared to the techniques required in the past when low charge-to-mass (q/m) ratio ions were the only type available.

The ECR ion source has a number of properties in addition to the production of large currents of high charge state heavy ion which make it an attractive device for heavy-ion accelerator facilities. The device has extremely high reliability because it has no electrodes and is in no way self destructive, especially when used with gas feed material. The source is extremely versatile, beams from solids as well as gases can be obtained. Essentially any ion species can be obtained from such a source with varying degrees of ease. The beam properties of the sources are also quite attractive. The power delivered into the source does not couple directly into the ions and as a result the ions are relatively cold. This fact results in good transverse emittance ($\gamma\beta\epsilon \approx 0.2 \pi \text{ mm-mr}$) as well as low energy spread ($dE \approx 5q \text{ ev}$). Such properties allows the overall accelerator system to deliver beams of high quality.

In this paper, I shall briefly describe three very interesting 'linear' acceleration device concepts which make use of the high charge state ECR ion source and then discuss our experience with the Argonne PII-ECR source system. Each of these types has properties which make it appealing when considered for certain applications. The devices I will describe are low velocity accelerators. Most of the difficulties in heavy ion acceleration are experienced in the early stages of the acceleration process. Acceleration to higher energy can be accomplished in a conventional scheme if the acceleration process is well behaved up to approximately 1 MeV/A.

Low Velocity Linear Acceleration Designs

The first of these new linear accelerator device concepts, the Argonne PII-ECR superconducting linac (3,4,5), is now under construction and is expected to have first test beams in early 1989. This project combines the high charge state, intense beams from an ECR ion source mounted on a high voltage platform with the high accelerating voltages possible from superconducting resonator technology and individual, independently phased resonator cavities to produce an accelerator concept with a unique combination of properties. The high voltage platform, capable of 350 kV, is necessary in order to provide beams with velocities of $0.01c$ which match the first resonator's forward field velocity component. The superconducting resonators and the high voltage preaccelerator produce a system which operates in the continuous wave mode. Beam quality is expected to be excellent, possibly better than that presently obtained from the tandem injector to ATLAS. The beam quality expected is due to: the linac design which separates the accelerating field region from the magnetic focusing region, the large acceleration boost in the early stages of acceleration from the large ($\gtrsim 4$ MV/m) accelerating field, the high charge state of the ions from the ECR source, and the beam quality from the ECR source.

A second design concept combining an RFQ and interdigital linac with an ECR is in the final design stages. This concept is being developed at the GSI (6) to be used as a second injector into the existing GSI Alvarez linac in support of the low energy heavy ion program at the laboratory. The most exciting aspect of this project is the goal of achieving RFQ operation with a 50% duty factor. Most RFQ's today are pulsed devices with duty factors of the order of 1%. The benefits of this approach include allowing the ion source to remain at ground potential and the ability to accelerate space charge limited beams efficiently in the RFQ. The interdigital linac which will follow the RFQ has properties well matched to the RFQ. It has an extremely high shunt impedance and is expected

to achieve 10 MV total acceleration potential with only 100 kW of RF power. The most important limitation to this concept is that the system is a fixed velocity profile accelerator. Because of this the linac does not make good use of its voltage capabilities for ions whose (q/m) differs significantly from the design value.

Finally, the ECR ion source in an all electrostatic environment can significantly extend the energy regime in which electrostatic devices can be cost competitive. The Argonne PII-ECR has demonstrated the practicality of this approach and recent source development work by Sortais (7) has demonstrated the feasibility of all permanent magnet ECR ion sources. These sources are capable of high charge state performance comparable to conventional sources for the same frequency regime, but remain limited in maximum RF frequency to no more than 14 GHz due to the maximum fields achievable with current permanent magnet technology. The RF power for the source could be provided by either an antenna system or the use of an insulating waveguide - possibly the machine accelerating tube. With such a design it is possible that no power would be required in the terminal for the source. There are many applications where moderate charge states, high currents, and good efficiency are the goals, such as ion implantation and commercial irradiation. Such an electrostatic system may be a good solution to these goals. The benefits of such a system are complete DC operation which maximizes total source beam current performance, relative simplicity of operation, and possibly lower cost per dosage unit. For voltages less than 0.5 MV, an open air platform such as used for the Argonne PII-ECR will be the most cost effective approach. But even higher voltages using a standard electrostatic pressurized tank design may be economically attractive as well for voltages up to 2-4 MV. Such a system is not an active project but should be considered.

The Argonne PII-ECR Ion Source and High Voltage Platform

The design goal of the Argonne PII-ECR ion source was to develop a source with the good charge state and current characteristics of the large ECR sources presently operating. The additional important features of ECR sources important for our application are good transverse emittance, low total energy spread, production of ions from solid materials, and low consumption rates. The power requirements of the source system also must be held to a minimum because the source is operated on a high voltage platform. A cross section of the PII-ECR ion source is shown in Figure 1 and Table I gives major source parameters.

An RF frequency of 10 GHz was selected for the Argonne PII-ECR. This choice was a compromise between the best high charge state performance, power requirements, and perceived operational reliability.

The source is completely enclosed by an iron return yoke to minimize the power requirements of the solenoid coils. The coils design parameters listed in Table I allow the necessary magnetic field to be produced with a total coil power of 35 kilowatts. The large inner diameter (ID) of the coils was necessary in order to gain radial access into the second stage for solid material operation. The coil ID affects the axial field shape in such a way as to require a larger axial separation between elements as the ID is increased, if a given mirror ratio is to be maintained. By using iron field shaping plates between the coils surrounding the first stage, it was possible to reduce the overall source size that would otherwise have been required.

The second stage hexapole magnet design is a twelve pole design and is the first source design to employ Nd-Fe-B alloy material. This design allows the diameter of the second stage vacuum chamber to be sufficiently large to allow four radial access ports for use in solid feed material operation. The hexapole field at the chamber was expected to be 4.1 kG.

The Argonne PII-ECR ion source has been operating for ten months. Since first beam was extracted (8), the source operation has evolved to a point which is comparable to other large ECR ion sources. Figure 2 shows the configuration of the source and charge state analysis system on the platform.

During this period the source has been operated with a variety of gases, solid material tests have begun using both oven and solid feed methods, and a total of nearly three months of beam time has been provided to an atomic physics program which makes use of the relatively high beam energies possible from the source as a result of the location of the source on a 350 kV high voltage platform. The demand for high voltage operation by the atomic physics program has revealed the most serious problem in our system to be the reliability of the high voltage transformers which provide power to the source system.

Present Source Performance

The source performance, at present, when delivering beams from gases is presented in Table II. These results were obtained using gas mixing with either oxygen or helium as the support gas. Total RF power never exceeded 850 watts for any operation. The consumption of gas varied from a low of 1.2 mg/hr for Krypton to 9 mg/hr for one operating mode with Argon.

Solid feed material for source operation has also been initiated. The first solid feed tests were performed with a 2 mm diameter nickel wire fed by a manual linear insertion device. Helium support gas was used in these tests. The best performance for this method is shown in Table III. The operation of the source for production runs will require the use of a stepping motor to position the wire on a continuous basis. To maintain source operation the wire feed had to be advanced approximately every five minutes a distance of 0.2 mm. It appears that a stepping motor controlled on time or current as read by the analyzing magnet entrance slits may provide acceptably stable beams. Also a

different wire trajectory may reduce the sensitivity to position that was observed in these tests. The nickle consumption measured during these tests was 1.1 mg/hour.

A trial with a 2 mm diameter copper wire has also been conducted. The results of that short test are also given in Table III. The operation of the source was more stable with copper than with nickel but the beam current achieved in this test was significantly less than observed with nickel.

A medium temperature (600 C) oven has been constructed for use with materials with the appropriate volatility. The oven is quite simple and small. It is designed to mount on a water cooled radial port flange which is thermally isolated from the oven by thin-wall stainless steel. The total power consumption for this oven is about 150 watts. The oven must heat the sample material sufficiently to achieve a partial pressure of approximately 10^{-4} to 10^{-3} Torr. The results of a run with cesium sample material and nitrogen support gas is shown in Table III and a charge state spectrum for cesium is shown in Figure 3.

High Voltage Platform Performance

The PII-ECR ion source a high voltage platform is designed for operating voltages up to 350 kV. This feature is necessary in order to properly match the velocity of heavy ions from the source to the acceptance of resonators in the PII superconducting linac. In addition to the source, the equipment required on the platform are: all power supplies and associated electronics, the RF klystron transmitter, and a beam transport and analysis system.

Charge state selection on the platform is necessary in order to reduce the total beam current accelerated from the few milliamps extracted from the source to the current due to only the species of interest. This is accomplished with a 90 degree analyzing magnet with mass resolution of $\Delta m/m \sim 100$. The only other active focusing element is an electrostatic einzel lens which forms the entrance

waist for the analyzing magnet. After magnetic analysis, a four harmonic buncher begins the process of bunching necessary for injection of the beam into the PII linac.

The high charge state of ions from the source and the ion energies delivered off the high voltage platform provide a unique set of beams for atomic physics studies and has generated significant interest for use of the system for atomic physics. During the development phase of the source and the construction of the PII linac, a temporary beamline for atomic physics use was installed. A total of about four months of beam time has been provided to the atomic physics program at Argonne since the source began to operate. Of that time about two months of operation at high voltages has occurred.

A variety of measurements (9,10) have been made of energy spread from ECR ion sources which indicate that these sources should be able to provide beams which will compete well with the beam quality from electrostatic accelerator systems. In fact the stability of the preacceleration high voltage will be important in determining the overall beam quality of the preaccelerator.

While providing beam to the atomic physics program, the voltage stability of the high voltage platform has been measured when biased to 100 kV. The voltage was found to have a four volt, 60 hertz ripple due to capacitive coupling from the high voltage transformers and a slow (few hertz), less than one volt oscillation from the high voltage power supply. The total voltage stability was found to be less than 5×10^{-5} from all sources. This value is better than our design goal of 1×10^{-4} . The largest component of this stability can be removed with active feedback as is presently accomplished on a similar system used on our tandem electrostatic accelerator. This will be attempted when beam bunching tests begin in November, 1988.

The power consumed by the source coils, the R.F. transmitter, and the beam analyzing magnet is removed by a deionized water cooling system. The pipes to the platform are standard polyvinyl chloride (PVC) water pipe. The

platform voltage, V_p , is defined at ground potential, $V_p/2$, and V_p by inserting stainless steel pipe unions securely attached to the required voltage. This technique is sufficient to insure that charge is properly added and removed from the flowing water to avoid excessive voltages in the system. The piping path makes one complete revolution around the platform and achieves a total resistance of 3300 megohms. The resistivity of the water is 18 megohm-cm and is continuously monitored. The thermal capacity of the system is approximately 90 kilowatt.

The use of the system at high voltages by the atomic program has provided us with an early test of our high voltage platform components which have been valuable in the system development. Most of the system design features have been shown to operate at or above their design goals. These include the fiber optics control highway, the deionized (resistivity = 10 megohm-cm) water cooling system, and the high voltage power supply. But operation at high voltage has uncovered a major problem with the high voltage isolation power transformers purchased for the system.

Power requirements for the source and beamline components total approximately 70 kilowatts in normal operation. This is provided by a 350 kV isolation power transformer with a total capacity of 140 kilowatts. The current drain through the isolation transformer has been measured to be 200 micro-amps at 350 kV. The units provided have failed twice while operating at approximately 280 kV. The second failure occurred after nearly one month of continuous operation at voltages between 250 and 320 kV. The failure mode is a high resistance short between the primary and secondary windings. The repaired units have been installed and tests indicate adequate performance.

Conclusion

The high charge state ECR ion source has significantly altered the design of heavy ion accelerator systems. New linear accelerator concepts which incorporate the high charge state heavy ions from these sources as integral assumptions in the accelerator design are just now coming into existence. The expected performance of these new machines imply a new dimension in heavy ion accelerator performance. This research was supported by the U.S. Department of Energy, Nuclear Physics Division, under contract W-31-109-ENG-38.

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Table I

Parameters of the Argonne PII-ECR Ion Source

Magnetic Field

Peak on Axis Field	4.75	kG
Solenoid Magnetic Power	35	kW
Maximum Solenoid Current	500	amps
Typical Solenoid Current	390	amps
Mirror Ratio	1.60	
Length of Second Stage Mirror	47	cm
Hexapole Material	Nd-Fe-B	
Number of Poles	12	
Hexapole field at chamber	3.5	kG

RF System

Frequency	10.25	GHz
RF Power	2.5	kW
Independent Control	Both stages	

Dimensions

Solenoid Inner Diameter	21.6	cm
Solenoid Outer Diameter	64.8	cm
Hexapole Inner Diameter	12.0	cm
Hexapole Length	49.5	cm
Vacuum Chamber Inner Diameter	10.8	cm
Extraction Aperture	6	mm
Puller Aperture	13	mm
First Stage Aperture	1.2	cm

Table II

PII-ECR Ion Source Beam Currents for Gases
(electrical micro-amps)

Q	^{16}O	^{20}Ne	^{40}Ar	^{84}Kr	^{129}Xe
4	-	23			
5	60	-			
6	60	18			
7	4	6	40		
8	-	5	60		
9		0.1	30		
10			-		
11			2.5	10	
12			1	-	
13				12	
14				-	5
15				8	4
16				-	-
17				4	2.5
18				-	1.5
19				2	-
20				0.8	1.0
21				-	0.4
22				-	-
23				0.2	0.3
24					-
25					0.2
26					0.2

Table III

PII-ECR Ion Source Beam Currents for Solids
(electrical micro-amps)

Q	^{58}Ni	^{63}Cu	^{133}Cs
7	30		12
8	30		14
9	20		15
10	10	2.5	10
11	4	3.3	10
12	0.5	-	10
13		1.2	10
14			10
15			10
16			6
17			6
18			5
20			3
21			2
22			1.3
23			0.7
24			.25
25			.15
30			.025

Figure Captions

Figure 1. A cross sectional view of the Argonne PII-ECR ion source.

Figure 2. Plan view of the high voltage platform for the Argonne PII-ECR ion source.

Figure 3. Charge state distribution spectrum for ^{137}Cs . Note the vertical scale change at 880 gauss.

ARGONNE POSITIVE ION INJECTOR

ECR ION SOURCE

Figure 1

Figure 2

Figure 3