Production of Heavy Ion Beams with Electron Cyclotron Resonance Ion Sources

Snowmass 21: Contribution *July 9, 2020*

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Introduction

Electron Cyclotron Resonance Ion Sources (ECRISs), a spin off from fusion plasma research in the 1970's, have evolved into powerful and versatile ion sources for the production of intense, highly-charged, heavy ion beams. These flexible sources can produce highly-charge-state ion beams from any elements introduced into the ECRIS plasma. These sources can run in either constant current or pulsed modes. In the latter mode, just after the heating microwaves are turned off the plasma rapidly collapses and produces a doubled beam intensity during a 1 – 2 millisecond pulse called the "afterglow". The next generation of accelerators, such as the Electron Ion Collider (EIC), could be greatly benefited through the utilization of a high-performing ECRIS capable of producing intense highly-charged ions.

An ECRIS utilizes a minimum-B magnetic field configuration with high-strength mirror fields to both confine the plasma and to maintain the plasma by resonantly heating electrons on closed, constant magnetic field surfaces with injected microwave power. The production of highly-charged ion beams requires high plasma electron density n_e, long ion confinement time τ_i, and adequate electron energy. The product of the first two parameters, $n_e\tau_i$, is directly linked to the magnetic field strength B and operating frequency ω of an ECRIS. The relationship between the source performance and these two key parameters $n_e\tau_i$ was recognized and summarized by the inventor of the ECRIS, R. Geller, in his famous scaling law stating that extracted ion current is proportional to the square of the microwave heating frequency, which is also proportional to the square of the field strength at resonance.[1] As ECRISs have been built with increasingly higher magnetic fields and heating frequencies, they have followed this scaling law and are expected to do so with further increases.

Performance of the present ECRISs

VENUS at Lawrence Berkeley National Laboratory, the first 3rd generation ECRIS operating at 28 GHz, and SECRAL-I and SECRAL-II at the Institute of Modern Physics, China, are the world's top-performing ECR ion sources in terms of both beam intensity and charge state.[2-4] Table I lists beam currents, in emA, of a few example beams produced by these ECRISs. If operated in pulse mode, the beam intensities could be increased by roughly a factor of 1.5 – 2.

He^{2+}	11.0	**Ar^{12+}**	1.42	**Kr^{18+}**	1.03	**Bi^{31+}**	0.68
O^{6+}	6.7	**Ar^{16+}**	0.62	**Kr^{23+}**	0.44	**Bi^{34+}**	0.42
O^{7+}	1.9	**Ca^{11+}**	0.85	**Xe^{26+}**	1.10	**U^{33+}**	0.45
K^{9+}	1.0	**Ca^{13+}**	0.37	**Xe^{30+}**	0.37	**U^{36+}**	0.22

Ongoing development of the next generation of ECRIS

To further improve high-current, high-charge-state source performance, the 4th generation of ECRIS is under development and will operate at 45 GHz with proportionally increased magnetic fields.[5, 6] Based on the demonstrated performance increases when moving from 2nd to 3rd generation (14-18 to 28 GHz frequency increase), the 4th generation of ECRIS operating at 45 GHz is expected to produce tens of emA of ion beams from helium to a few emA of uranium ions of mass to charge ratios of 2 to 7. At these beam current levels, intensity enhancement should remain possible and could be realized through pulse-mode operations.

Further enhancement of ECRIS pulsed beam intensity is possible

The typical ECRIS ion extraction efficiency is believed to be 1% - 2%. Based on the plasma volume and the ECRIS extraction efficiency, the total number of helium to uranium ions of mass to charge ratios of 2 to 7 in the 4th generation of ECRIS are expected to be in the range of 10^{13} to 10^{12} (elements of light to heavy) at any given time, or an ion density of a few 10^{10} to ~ 10^9/cm^3. Techniques such as guiding the ions to the extraction region through fast pulsed electric and magnetic fields could be combined with the plasma afterglow to increase the ion extraction efficiency and narrow the beam pulse width from milliseconds down to tens-to-hundreds of microseconds. If successful, this shortened pulse length could the increase beam intensity by another factor of 2-5. These higher intensity beams would benefit future heavy ion accelerators and, in particular, could meet the EIC requirement of a few 10^{11} ions/pulse with the possibility of injecting high charge state uranium ion beams of charge state 35^+ - 45^+ or higher.

Summary

Advancement of ECRIS technology will benefit both existing and future heavy ion accelerators worldwide. With a 4th generation of ECRIS and the possibility of further beam intensity improvements through the optimization of beam pulsing, these sources have great potential in meeting the EIC requirements of injecting highly-charged heavy ions.

References

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