Extraction and transport of ion beams from an ECR ion source

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Chapter 1

INTRODUCTION

1.1 General introduction

The invention of the ECR ion source [1] in the end of the 1970's and it's subsequent continuous development based on new RF and magnet technology has been an essential step for research programmes utilizing secondary radioactive ions in various accelerator laboratories around the world such as the TRIμP program at KVI [2], the FAIR program at GSI [3], the Radioactive Ion Beam Factory at RIKEN [4], the Facility for Rare Isotope Beams (FRIB) at NSCL [5] and the SPIRAL2 project at GANIL [6], which require primary beams of highly charged ions of all elements up to uranium. Also atomic physics research depends on ECR ion sources when studying the interaction of highly charged ions with atoms, ions and surfaces. In addition to physics research, ECR ion sources are also used in industrial applications such as ion beam etching, implantation and ion beam sputtering deposition, etc.

Generally an intense multiply-charged ion beam is extracted from an ECR ion source, transported in a low-energy beamline and injected into one or a series of accelerators for acceleration to high energies. Cyclotrons are often equipped with an ECR ion source. As in a circular accelerator, such as a cyclotron or synchrotron, the maximum energy is proportional to the square of the charge-state (q^2), the use of higher charge-state ions can reduce the accelerator size and thus the facility costs. This gives a strong motivation to use an ECR ion source, which is capable of producing intense beams of high charge state ions. Furthermore, there are no cathode or filaments in the ion source and stable beams can be produced for long periods (days - months).

Over the last three decades, the performance of ECR ion sources in terms of charge state and current has been greatly improved by using ever higher microwave frequencies for ECR heating of the plasma and corresponding higher magnetic fields. This allows better plasma confinement and higher plasma density, resulting in a higher beam intensity and shift of the charge state distribution towards higher charge states [7–10]. However at the same time the higher magnetic fields and higher beam intensities result in a larger emittance. This is mainly due to angular momentum conservation in the axial magnetic field at the extraction region [11–13] and influence of the space-charge forces when the extraction current exceeds several milliamperes [14]. In addition to this ion beams extracted from an ECR ion source are not rotationally symmetric because of the magnetic-field geometry of the ion source [1]. Therefore, detailed understanding of the ion beam formation, extraction and transport of the intense ion beams is one of the key elements to meet the ever-increasing demands on the quality and intensity of highly charged ion beams and is equally important as ECR ion source improvement itself. The objective of this thesis is to improve the understanding of the physics of ion beam formation, extraction and transport including higher-order effects and correlations. We have applied our simulation tools to study and improve the overall efficiency and quality of the low energy beam transport system of the AGOR cyclotron.

The superconducting cyclotron (AGOR) at KVI is used for the acceleration of light and heavy ions [15]. The Advanced Electron Cyclotron Resonance (AECR) ion source [16] coupled to AGOR produces a variety of ion beams required by the experimental program at the AGOR facility. Present development work is mainly focused on increasing the beam intensities of the ECR ion source injector and optimizing the beam transport and injection into AGOR driven by the requirements of the experiments. At present the transmission of the beam from the ECR source analyzing system up to the cyclotron is at most 50 % due to an insufficient understanding of and control over the properties of the injected beams.

In order to achieve a high transport and injection efficiency in the low-energy beamline it is important to know the initial properties of the ion beam extracted from the ECR ion source and to prevent effective emittance growth during transport due to ion-optical aberrations and space-charge effects. Because of the large emittance of the ion beams extracted from the ECR ion source, the low energy beam transport (LEBT) is more critical than the high energy beam transport of the extracted beam. In general an ECR ion source possess a large beam size and divergence. Therefore, strong higher order effects (aberrations) cannot be avoided and have to be compensated to avoid a large increase of the acceptance of the ion optical system required for high transmission. A computational study has been undertaken to understand the processes that lead to a blow up of the effective emittance and to improve the ion beam transmission efficiency in an economical way. This study concentrates on the full three dimensional (3D) simulation of ion beam extraction and transport from an ECR ion source. The results of this thesis have been validated by measurements of the beam properties including its full 4D phase-space distribution.

1.2 Thesis outline

This thesis is organized as follows: Some aspects of ion beam transport along with the simulation tools used in this thesis are discussed in chapter 2. Chapter 3 briefly describes the physics involved in the production of multiply charged ion beams in an ECR ion source. In addition to this the computer code used for modeling of the ECR ion source is described. Chapter 4 describes the KVI-AECR ion source together with the low energy beamline diagnostic tools used in this study.

In order to make a clean comparison with beam profile and emittance measurements, particularly in the beamline section before the bending magnets, we have first studied the essentially mono-component He^{+} beam. He^{+} formation and the simulation of ion extraction and transport including space-charge are discussed in chapter 5. The results of the calculations are compared with measurements of the beam profiles and emittances. The simulation of multiple charge state neon beam formation and its extraction including space-charge are discussed in chapter 6. In addition to this the transport of a Ne^{6+} beam through the LEBT system up to the matching section is discussed. In chapter 7 a study to decrease the beam losses and improve the ion-optical properties of the analyzing magnet is discussed. In chapter 8 we discuss the application of our simulation approach to the formation, extraction and transport of Ar^{7+} and He^{+} beams from the CAPRICE ECR ion source and EIS test bench installed at GSI, Darmstadt, while in the last chapter some general conclusions on the design of ion optical systems for the transport of large emittance low energy ion beams are given and perspectives for further work are sketched.