K1200 CYCLOTRON BEAM DEVELOPMENT TECHNIQUES

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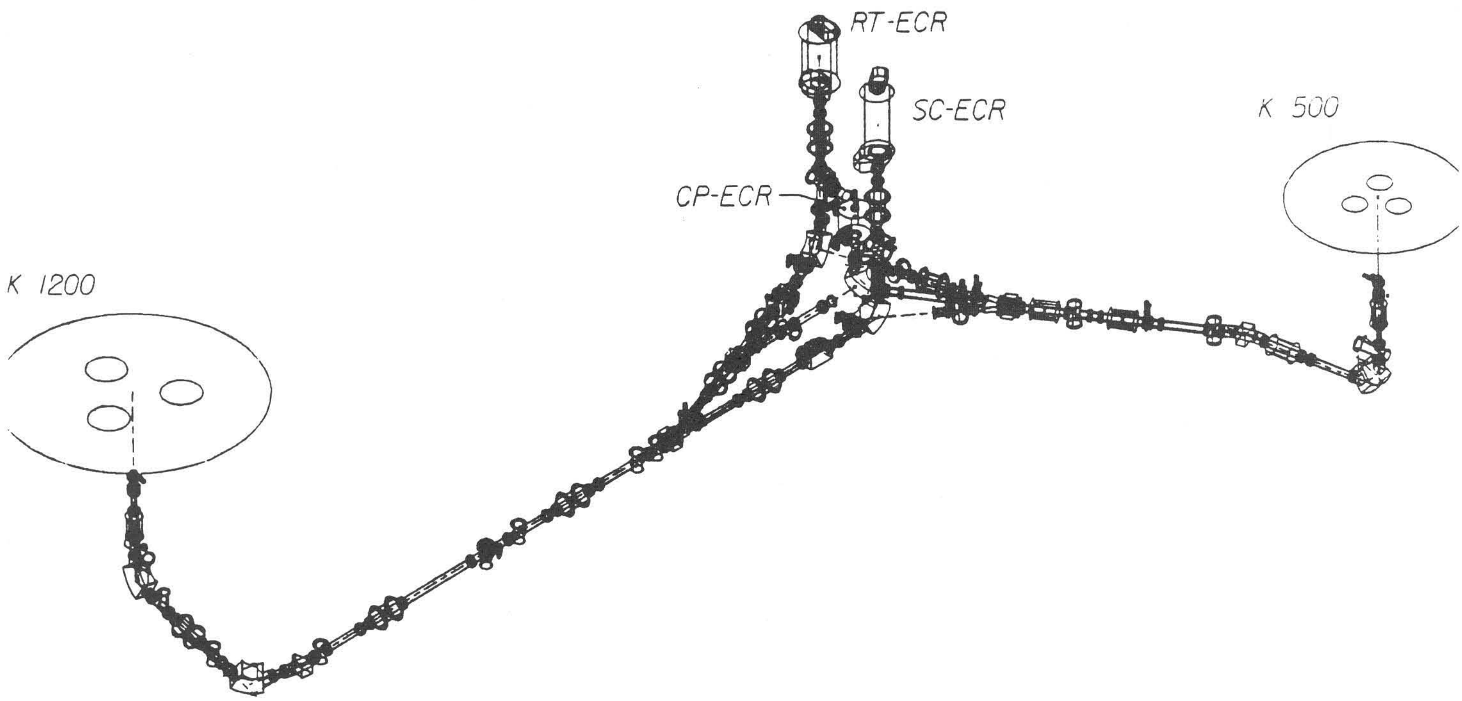

Figure 1. The beam development system at NSCL consists of ECR sources, injections and the superconducting cyclotrons.

1. Introduction

We now accelerate ions from hydrogen to uranium in the K1200 cyclotron at NSCL. There are several classes of problems associated with producing these beams: source tuning, beam transport and injection, and cyclotron tuning. The development of a particular beam can be critical in more than one of these areas. For example, uranium 35–39+ ions are not fully resolved from mixing gases at the ion source, the cyclotron fringe field is high, and an analog beam must be used to tune the cyclotron. Still, uranium beams at 20 and 25 MeV/n using 35+ and 39+ respectively, have been produced. Atomic hydrogen cannot be accelerated directly in the K1200, and H_2^+ ions are only useful for high energy hydrogen beams. For low energy hydrogen beams, HeH+ molecules are produced in an ECR source, injected, and then stripped after acceleration. We also accelerate series of ions simultaneously at fixed q/m ratios: 1/5, 1/4, 1/3, 1/2, using multiple species and/or ion sources.

The full facility for production of heavy ion beams at NSCL is shown in Figure 1. It consists of three ECR ion sources, a switchyard to connect any ion source to either cyclotron, the two superconducting cyclotrons and their main injection lines. In this paper, we will focus on beam development techniques for stand alone operation of the K1200 cyclotron, since that is also the main facility emphasis at the present time.

2. Ion Sources and Switchyard

Ion beams injected into the K1200 cyclotron come from one of three electron resonance sources, as shown in Fig. 1. The RTECR, commissioned in 1985, and operating more than 6000 hours every year since 1986, is the basis for most K1200 cyclotron beams. Recent performance at the RTECR is summarized in Figure 2. This ion source has served both as a production ion source and development platform for new concepts, and is perhaps the most optimized of all ECR source designs. Gaseous ion production is based on a reduced first stage, single microwave feed, high injection magnetic field, SiO_2 coated plasma chamber walls and low operating pressure [1]. Metallic ion production is now based on the super gas mixing technique for highly charged metallic ions [2], but the RTECR can use (and has used) a number of different techniques for metallic ion beams.

The CPECR has two modes of operation. With the oven stage installed , it produces stable beams of alkali metals, particularly $^{6,7}Li^{2+,3+}$ [3]. The key to long stable lithium runs is a heated stainless steel liner in the main stage operating at about 400°C. The heated liner allows for enhanced recirculation of lithium into the main stage plasma. In order to accommodate oven conditioning and operation, the CPECR can be operated at pressures as high as $1 \bullet 10^{-4}$Torr, without microwave vacuum feedthru or extraction insulator failures. At such high pressures, intense beams of low binding energy molecules can be produced in the CPECR, when the oven stage is replaced by a gaseous feed first stage. The most unusual of these molecules is HeH^+, shown in Figure 3, which permits low energy H+ beam production in the K1200 thru post-accelerator stripping of the helium 'anchor weight'.

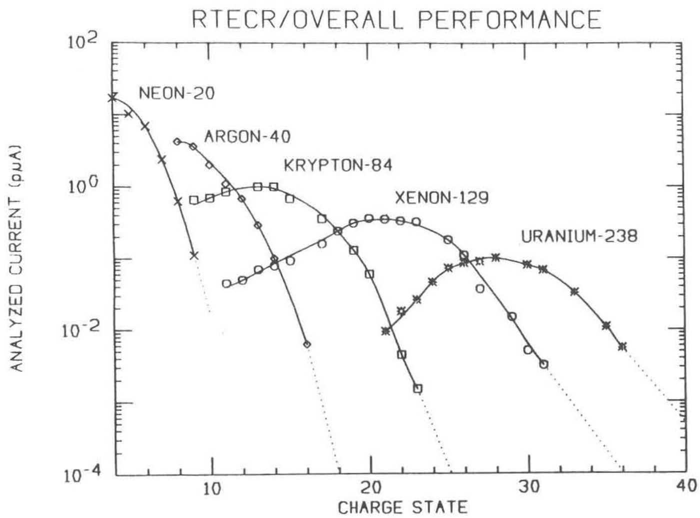

Figure 2. The optimized performance of the RTECR is smooth in Q and Z.

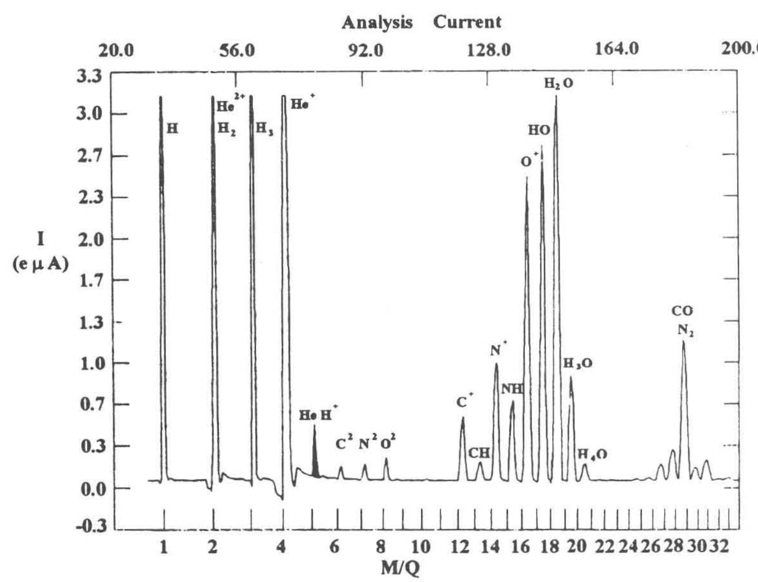

Figure 3. The He+H charge state distribution of the CPECR, showing the presence of the HeH+ molecule, used to produce low energy H beams in the K1200 cyclotron.

The multi-frequency high field SCECR now in development, is the third ECR ion source built at NSCL. The SCECR ion source structures are equivalent to the RTECR, but the magnet field is produced by a full set of superconducting coils [4]. This coil set is not operated in persistent mode, as have previous superconducting ECR designs [5,6,7], so source tuning over a wide dynamic range of magnet settings is possible. The source has available 6.4 and 14.5 GHz microwave feeds. Early experience has shown that 6.4 GHz operation at high magnetic field is equivalent to 14.5 GHz of a nominal magnetic field. Figure 4 shows a comparison of oxygen ion performance of the RTECR and SCECR at 6.4 GHz. We note that the SCECR performance in Fig. 4 comes without use of gas mixing or wall coatings, and requires 1/10 as much microwave power as the RTECR tune.

Each ion source can be connected to either main injection line (K500 or K1200) via a switchyard beamline. Switching is accomplished by breaking a beamline joint and rotating the analysis dipole to the new line. The RTECR and SCECR remain insolated and under vacuum during this process. The CPECR does not have such an insolation gate valve and must be vented. The process takes typically 2-4 hours, and is limited mainly by the need to attain high vacuum ($\leq 10^{-7}$Torr) in the beamline before operating the sources. Controls and interlocks are automatically switched to the new beamline by the PLC.

Since the K500 cyclotron is generally not operated, the full ion source set can be directed to K1200 cyclotron operations and beam development, giving unparalleled capabilities and flexibility.

3. Injection Lines

The K1200 cyclotron injection line is simply a longer version of the K500 injection line. Both were described at the Tokyo Cyclotron Conference [8]. Matching ECR beams to these injection lines has been extensively studied [9]. We find that the emittance is dominated by the fact that the ions originate in a magnetic field, but the beam transport is dominated by space charge forces. Features of this injection design that aid development include the use of solenoid lenses for focusing, the large bore beam pipes (6" ID solenoids, 4" ID dipoles), and the

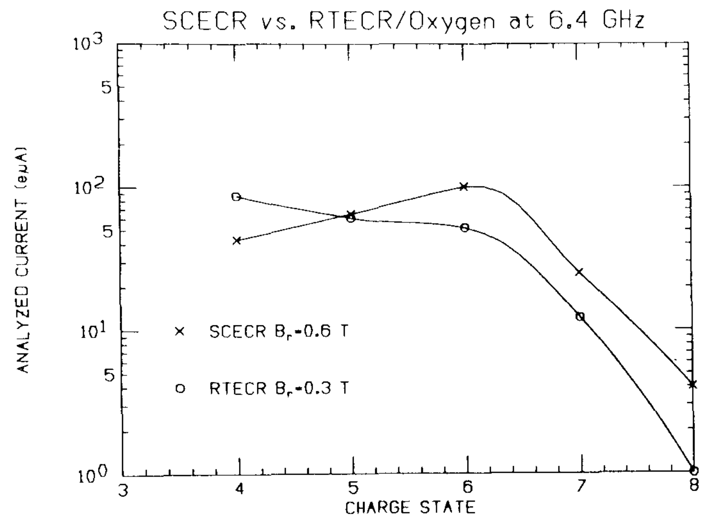

Figure 4. A comparison of the oxygen ion production of the RTECR and SCECR ion sources operated at 6.4 GHz. See text for details.

generally linear response of the system to changes in beam rigidity. However, the source operating voltage is set by injection criteria, so it is not always possible to use the optimum ion source extraction conditions.

The typical transmission from source analyzed beam current to K1200 spiral inflector is 30%. Major losses occur primarily in two areas: the transition from the switchyard to the main injection line, and the vertical beamline under the K1200 cyclotron. The losses associated with the transition from the switchyard to the main injection line occur mainly for the two room temperature ECR sources, and appear to be due to transit path differences and non-linear beam distortions in the short 'merging' dipole. On the axis of the K1200 cyclotron, there is a mis- match between the final beam emittance and the acceptance of the spiral inflector. Just above the last bend, beam profiles are elongated with a central core and high divergence tails. Part of this beam distortion is due to the cyclotron fringe field– the 'cyclotron off' transmission from the RTECR to the K1200 cyclotron axis is about 70% or higher. Space charge is also important, as the distorted beam shape is sensitive to beam current. The lowest injection transmission, about 10%, occurs for high $K_{bending}$ operation with low Q/M ions, and is attributable to both using low velocity ions and high fringe field injection.

4. K1200 Cyclotron Characteristics

The general characteristics of the K1200 cyclotron have been summarized well at this conference [10]. We would also echo the emphasis in that paper on the excellent ion and energy variability of the K1200. Of course, these high energy beams are provided by a *single accelerator*, injected by ECR sources, rather than a set of accelerators. Specifically with regard to beam development, one should also note that there is a very good correspondence between calculated K1200 parameter settings and actual operating settings, both for internal parameters and extraction elements. The main magnet is set by calculations [11], and the resulting operating frequency is accurate to better than a few kilohertz. Therefore analog beam tuning for difficult beams is a very effective technique–both the absolute frequency of the analog and calculated frequency shift to the desired species are dependable. Once tuned, the K1200 cyclotron parameters are found to be stable and reproduceable.

5. REFERENCES

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