R&D Effort at NSCL with the Off-line ECR Ion Source ARTEMIS-B*

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Abstract This paper reviews recent experimental work done with the off line source ARTEMIS-B at the NSCL. This source was built during the year 2005 and provides opportunities for off line development that can benefit the Coupled Cyclotron Facility (CCF) operation while minimizing the time taken away from the nuclear experimental program. The Artemis-B setup includes many beam diagnostics and a detailed description of the emittance scanner (Allison) and emittance measurement method is presented. A first beam dynamics study indicates that the analysis magnet has strong field aberrations and that the beam size in the dipole must be small in order to avoid significant beam brightness degradation. A second study compares beam brightness for different focusing systems between the ECR ion source and the analyzing magnet. Two electrostatic devices: a quadrupole triplet and a double quadrupole doublet have been tested successively and compared to a magnetic focusing solenoid. The experimental results tend to indicate a better beam brightness at smaller emittance for the electrostatic devices, although emittances measured for each focusing element were for a large part dependant on the tuning procedure developed to minimize the effects of the analyzing magnet.

Key words ECR Ion source, emittance, electrostatic focusing, solenoid

1 Introduction

A new room temperature ECR ion source was built and commissioned in 2005 at the NSCL. This source, named ARTEMIS-B, is a copy of the source ARTEMIS in operation for injection into the K500 cyclotron since 2001. The main motivation for this project was to have the possibility to test and optimize new hardware and optics without disrupting coupled cyclotron operations. Additionally, the limited acceptance window of the K500 cyclotron (~100πmm·mrad) along with the very limited power losses that can be tolerated on the K500 deflectors have pushed strongly toward improving the beam brightness coming out of the ion source and limit its degradation while going through the injection beam line. The charge states of the ion beams injected in the K500 are relatively low (O^{3+}, Ar^{7+}, Kr^{14+}, Ca^{8+} $\cdots$) and determined mostly by the injection into the K1200 where the ion beam goes through a thin stripping foil ($Q_2/Q_1 \geqslant 2.43$). ARTEMIS-B is based on the AECR-U design and a detailed presentation can be found[1]. It is operated with a 14.5GHz klystron with a maximum power of 2kW although such power is essentially never used for the low charge state beams mentioned above. The source construction was completed by the middle of 2005 and commissioning took place during the Fall of 2005. An R&D program aimed at improving beam brightness by comparing different initial focusing system started

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shortly thereafter.

2 Artemis-B set up

2.1 Artemis-B beam line

By design, the ARTEMIS-B beam line was built to closely match the one used after ARTEMIS. However, some differences exist as ARTEMIS-B beam line is used to test various hardware and is also equipped with more beam diagnostics. The vertical section between the ECR source and the analyzing magnet is about 2m long and includes a focusing system. The analyzing magnet provides a 90-degree bend and is identical to the one in the CCF injection beamline. After the analyzing magnet, various beam diagnostics including a faraday cup (FC), two beam viewers (BV) and an Allison–type emittance scanner (ES) are available. Other beam diagnostics such as a pepper-pot system are currently under development. Beam imaging is done using plates coated with potassium bromide or barium fluoride. In the horizontal line, steering magnets (SM), beam collimators (AP) and a solenoid were also installed to provide basic beam transport capability. Three 500l/s turbopumps keep the beamline vacuum in the mid 10-8 Torr range. The complete Artemis B setup is illustrated in Fig. 1.

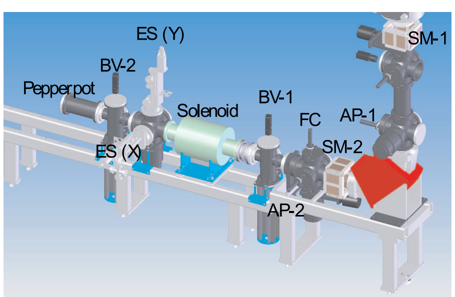

Fig. 1. Artemis-B set-up.

2.2 Description of the emittance scanner

The emittance measurement system is an Allison type emittance scanner. A beamlet is first selected through a slit S_1 (0.5mm×60mm). It then goes through a region with a transverse electric field created by two plates biased with opposite polarity. For any given voltage V_p applied to the plates only a fraction of the initial beamlet will reach a second slit S_2, identical to S_1, with a corresponding beam divergence angle given by

$$x' = -\frac{1}{4}\frac{D}{g}\frac{V_p}{V_{ECR}} \ .$$

Where D and g are the plate's length and gap respectively, and V_{ECR} is the extraction voltage from the ion source. The ion current reaching the second slit is then collected in a faraday cup (10mm×70mm). The faraday cup is equipped with a suppressor biased typically at −200V. Deflector plates voltages are then swept to collect the current coming from all initial angles included in the beamlet defined by the slit S_1. This operation is repeated by mechanically moving the emittance scanner throughout the entire ion beam with a user-defined step size. The maximum angle the scanner can accommodate is defined by the relation $x'_{max} = 2g/D = +/-300$mrad well beyond the divergence of the present beam, which is generally less than +/−50mrad. Given the parameters defined above, the intrinsic resolution in position is defined by the first slit opening S_1=0.5mm and the one in angle by $x'_{int} = s/D = +/-6.7$mrad.

2.3 Emittance measurements

Through the use of two Allison scanners placed perpendicular to one another, each transverse phase space can be measured independently. Step size in position and angle are defined through a Labview interface. The steps used in the acquisition were typically of 2mm in position and 2mrad in angle. One known drawback in the Allison emittance system is the long time needed to acquire emittance data. Typically, a complete scan including both directions takes between 20 to 30 minutes corresponding to roughly 2000 points. Recent development has helped to reduce this time by a factor two.

Before proceeding to the emittance measurement, the beam position and size are checked on the beam viewer located before the emittance scanner and focusing may be adjusted to insure that the emittance scanner will measure the entire ion beam. Additionally, the total current collected during the measurement is always compared with the current read in the preceding faraday cup. In most cases, both values are found to be within 10%. Typically, the current measured with the faraday cup of the emittance box amount to hundreds of nanoamperes for the core of the ion beam. This current is amplified and converted into a 0 to −10V signal and accumulated into the stepper motor memory. Once complete, the data file is sent through the network to the Labview program and saved on a server. The data is then processed in Matlab where 2D plots of the phase space distributions are generated and the rms emittance and associated rms twiss parameters are calculated. Usually, at 5% threshold with respect to the peak current recorded during the measurement is applied and is sufficient to remove most of the noise. Finally, a plot representing the brightness is generated by calculating the fraction of the total beam included within various ellipse areas ($\pi\varepsilon$).

3 Analyzing magnet study

As mentioned above, the analyzing magnets used by both ARTEMIS and ARTEMIS-B are very similar. Initially, tuning was done to optimize transmission and resulted in a beam that was fairly large at the entrance of the analyzing magnet. Emittance measurements then showed significantly distorted phase spaces in both transverse planes. This observation motivated a beam study to quantify the field aberrations in the analyzing magnet. To do so, the ion beam was moved in both transverse directions using a set of magnetic steerers located about 1 meter before the analyzing magnet. The beam centroid displacement and angle at the entrance of the analyzing magnet was then calculated and the position of the beam centroid on the first beam viewer located after the analyzing magnet was measured and is reproduced below (Fig. 2).

The displacement along the bending plane shows a strong non linear dependence and indicates significant magnetic field aberration in the analyzing magnet. Beam dynamics simulations reproduce the experimental results when a sextupole component is added to the field[2]. As a consequence, tuning procedures were developed to minimize the beam size inside the analyzing magnet thus reducing the impact of the field aberrations on the beam emittance. A 25mm aperture placed just before the analyzing magnet was found to be the best compromise in order to optimize transmission without significant beam quality degradation.

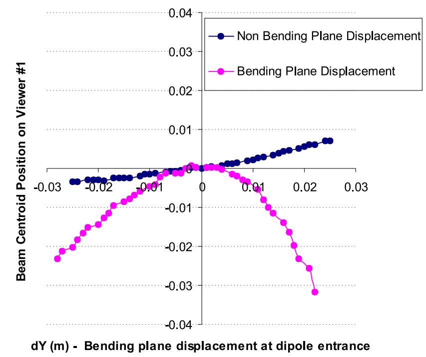

Fig. 2. Beam centroid position at the first beam viewer as a function of the beam position at the entrance of the analyzing magnet. For simplicity only the dependence with the initial displacement along the bending plane is represented.

4 Electrostatic focusing study

Two electrostatic devices were used as a focusing system and tested in ARTEMIS-B. The motivation and the design for both electrostatic systems are detailed in Ref. [2]. In order to compare these devices, we chose a beam of Ar^{7+} extracted at 20kV and kept the drain current close to 1.5mA without using support gas. The microwave power was also fairly low around 150 to 200W, typical of the power level used with ARTEMIS for cyclotron operation.

The first device tested was a Large Bore quadrupole Triplet (LBT) similar to the one already used under the SC-ECR but with a larger aperture. Although, using 25mm apertures directly before the analyzing magnet were later found to be optimum in our configuration, the LBT was tuned with a 15mm aperture. Optimum transmission was obtained with a set of asymmetric voltages between the first a third quadrupole. Emittances measurements were taken and phase plots are represented below (Fig. 3). About 70% of the beam is within 50π·mm·mrad and 90% within 100π·mm·mrad for a total current of about

43eμA.

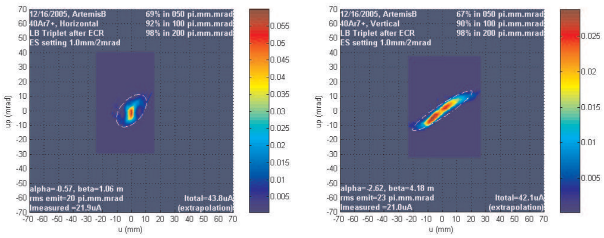

Fig. 3. Phase space distribution for Ar^{7+}20kV obtained with the Large Bore Triplet (LBT).

After a few weeks of testing, the LBT device did exhibit beam marks on the second quadrupole, which indicates a relatively large envelope at this level. This impacts transmission and beam brightness because of the significant field aberrations experienced by the beam in the second quadrupole[2]. It is also in agreement with the distortions in the vertical phase space shown in Fig. 3. An improved focusing system consisting of a Double Quadruple Doublet (DD) was designed at NSCL and fabricated by an outside vendor. In this design, the quadrupoles are longer where the beam envelopes are the largest in order to reduce the effect of the field aberrations as explained in[3]. Also, an octupole is installed after the first doublet of the DD to actively compensate for the aberrations of the second quadrupole. The DD device offers additional tuning parameters compared to the LBT device, which provides more flexibility to optimize transmission and beam size through the analyzing magnet. Phase space plots obtained with the DD focusing system are shown in Fig. 4. The distribution between each transverse plane appears to be more balanced than with the LBT. With the same source condition the current included within 100π·mm·mrad is now higher and reached up to 65eμA.

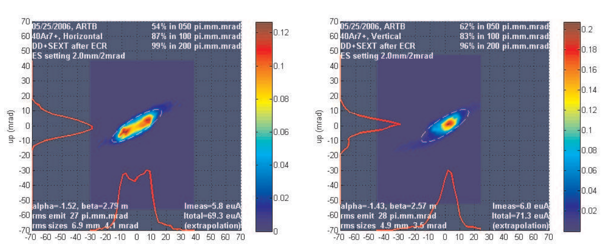

Fig. 4. Measured phase space distributions of Ar^{7+}beam with the (DD) focusing system.

5 Electrostatic focusing vs. magnetic focusing

Finally, a magnetic solenoid was used as a focusing element and its performance compared to the electrostatic devices described above. This solenoid had been previously used with ARTEMIS and was positioned similarly about 40cm from the source. The beam brightness for the solenoid, the LBT and the DD are summarized in Fig. 5. The double doublet, when tuned with a 25mm aperture before the analyzing magnet, exhibits the best beam brightness with up to 65eμA within 100π·mm·mrad (Curve 1). The solenoid shows a lower brightness compare to the DD (2) and has a significant proportion of beam beyond 100π·mm·mrad. The LBT device seems to have an advantage over the solenoid only at small emittance although in this case the aperture used before the analyzing magnet was smaller (15mm) (3). Finally, the two lower curves show a net degradation of the beam brightness for the solenoid case and the DD case when tuned with a large aperture (50mm) before the analyzing magnet (4&5). In the case of the solenoid, this also corresponds to the optimum transmission to the faraday cup (70 to 80%). With the magnetic solenoid, focusing depends on the M/Q ratio and higher charge state (or more generally lower M/Q) could potentially contribute to emittance growth by space charge effect. But in the present condition, no support gas was used and the drain current was relatively modest (1.5mA). Ar^{8+} intensity reached slightly over 100eμA

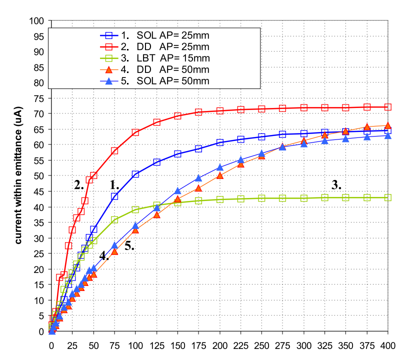

Fig. 5. Brightness comparison for different focusing systems and different aperture sizes before the analysis magnet.

and considering the power level, charge states beyond Ar^{8+} were extremely weak. Preliminary experiments with much larger drain current and support gas would tend to confirm the space charge contribution when a solenoid magnet is used to focus the multi-ion species beam from an ECR, but more work is needed to quantify such an effect.

6 Conclusion

The work performed on ARTEMIS-B with the Allison emittance scanner was important to quantify the effect of the field aberrations in the analyzing magnet on the beam brightness and also to study and define optimum tuning procedures for different electrostatic focusing devices prior to their installation in the production beam lines. Both electrostatic elements have now been transferred and used to inject ion beams extracted from ARTEMIS into the K500. In both cases overall CCF operation showed improved performance and matched the expectations from the measurements made on ARTEMIS-B[2]. In the near future, an einzel lens will be tested with the LBT. The einzel lens will help both to increase the transmission and reduce aberrations by limiting the beam envelope inside the LBT and allowing more flexibility to adjust the beam size in the analyzing magnet. To further improve the beam brightness the analysis magnets will be modified or replaced in the near future.

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