HIGH-TRANSMISSION OPERATION OF THE NSCL ACCELERATORS*

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Abstract

Image-based beam line tuning techniques and a 2-D emittance scanner, along with hardware modifications have allowed, with similar ion source outputs, beam intensity increases from the K1200 of about 400% over the period 2003-2006. Net efficiencies from charge-analyzed beam at the start of the K500 injection line to extracted beam from the K1200 can be as high as 20% depending on the ion utilized (factoring out the unavoidable loss due to the charge stripping foil in the K1200). Methodologies and examples are discussed.

INTRODUCTION

The National Superconducting Cyclotron Laboratory (NSCL) consists of two cyclotrons, the K500 and K1200 [1], which accelerate beams provided by one of two ECR ion sources. While direct injection into the K1200 remains possible, that mode is no longer used since coupled operation provides beam energies and intensities much more suitable for nuclear science experiments with exotic nuclei.

The modifications to couple the K500 to the K1200 were completed in 2001. Beam is injected axially into the K500 from one of two ion sources in use since that time. The newer and primary source, ARTEMIS-A (Advanced Room Temperature Ion Source), is a modified version of the Berkeley AECR-U and operates at a frequency of 14.5 GHz. (A duplicate of this source, ARTEMIS-B, has been constructed and installed on a test stand and is used for development purposes.) A second, 6.4 GHz superconducting ion source (SCECRIS) is available as well and is often used to provide gas-feed beams while ARTEMIS-A is being set up for a following experiment. The extraction voltage is 20 – 25 kV.

Beam from the K500 is injected mid-plane into the K1200 via a 200-800 μgm/cm^2 carbon stripper foil located at a radius of about 32 cm. This is not a problem for ions lighter than krypton (with 50% stripping efficiency), but becomes so with heavier ions such as xenon (19%) and uranium (9%). This, together with the normal fall-off in source output with higher charge state puts a premium on good overall transmission from the source Faraday cup to extracted beam from the K1200.

For some beams, the principal limit to final output remains source intensity. However, for beams produced with sufficient current, losses begin to limit overall output to about 800 W for continuous operation. The radiation shielding in the area of the secondary-beam production target should allow up to 4 kW, so there is room further increases in beam intensities.

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EXPERIENCE

A continuing program of beam development has resulted in increased net efficiencies as shown in Table 1. This, together with improvements in source output have resulted in beam current values for experiment to be increased by up to a factor of 10 over this period.

Table 1: Analyzed source beam output (in pnA) and the resulting beam intensity extracted from the K1200. The net efficiency normalized to source output has increased by about a factor of four from 2003 to 2006.

	~2003 SOURCE OUT → K1200 OUT	~2006 SOURCE OUT → K1200 OUT	GAIN
^{40}Ar	2280 → 58	1920 → 222	4.5
^{48}Ca	1275 → 32	1400 → 160	4.6
^{76}Ge	690 → 17	725 → 63	3.5
^{78}Kr	2640 → 22	2760 → 79	3.4

Table 2: Segment-by-segment beam transmission efficiencies for selected beams are shown. The corresponding K1200 overall extraction efficiency is also indicated together with the percentage of beam passed after collimation through the deflector.

	^{40}Ar	^{48}Ca	^{76}Ge	^{78}Kr
Final (MeV/u)	140	140	130	150
Beam Power (W)	790	890	630	550
Injection Line	68%	100%	94%	94%
Through K500	34%	37%	32%	30%
Coupling Line	97%	92%	83%	84%
Through K1200	56%	63%	69%	53%
Net	**13%**	**22%**	**17%**	**13%**
K1200 EXTR.	71%	85%	88%	76%
DEFL. EFF.	91%	92%	97%	89%

Some present day transmission efficiencies are shown in Table 2. The beams shown are best-case examples that were provided for experiment.

K500 Injection Line

Much development work has gone into the matching of the ion source output into and through the K500. The injection line layout is shown in Figure 1. Simply increasing analyzed beam output does not automatically result in more beam from the K500. Optimizing source parameters and focusing elements in the initial part of the beam line on current extracted from the K500 often results in less source output measured after the analysis magnet. BaF_2 coated viewing plates in the beam lines allow the beam to be imaged directly. This shows that the beam, even when seen directly from the source with no intervening focusing elements, is highly structured, a fact that is much less apparent on wire-scanner devices [2] [3]. The addition of a grid followed by a drift in front of a viewer shows the beam to have complex correlations as well; see Figure 2. The emittance of highly correlated beams is not easily improved by a slit cut. Use of a grid to tune for a de-correlated beam condition at the location of a slit shows promise as a technique in controlling emittance and beam tails without disproportional losses in brightness, and is being explored.

An Allison-type emittance scanner allows for measurement of the horizontal and vertical phase space in two dimensions. The intrinsic source emittance is much larger than the K500 acceptance, ~190 vs. ~75 pi*mm*mrad, and varies strongly with how the source is tuned and how the first focusing lenses are set. As a consequence, the performance of both cyclotrons is very sensitive to the source and injection line tunes.

Initially, both sources utilized solenoids as the lens elements in the beam line. However, it was noted that under conditions where a significant fraction of the unanalyzed beam had a higher charge-to-mass ratio than the desired beam, the analyzed beam had poor qualities (See Figure 3). As a consequence, these solenoids were replaced with electrostatic lenses. The transmission from the source to the first Faraday cup is reduced from about 75% to about 45%, but the loss is primarily of beam that was not extractable, while the low-emittance components are preserved.

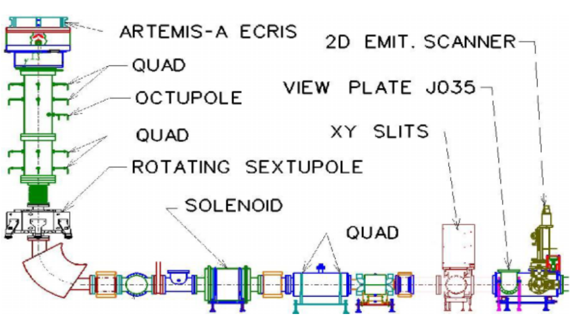

Figure 1: Injection beam line layout. The distance from ARTEMIS-A to the analysis magnet is about 2.2 m. The line continues horizontally, then bends upward for injection into the K500.

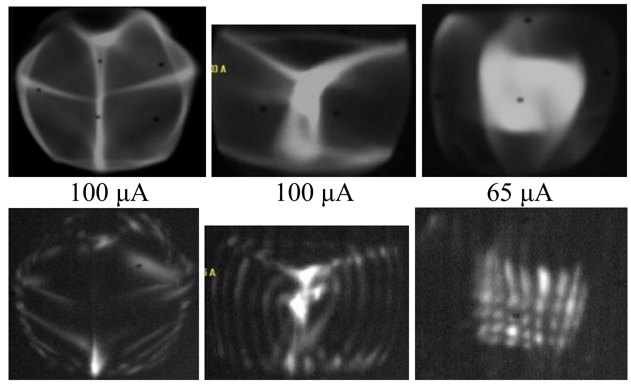

Figure 2: Images of $^{40}Ar^{7+}$ beam from Artemis-B using electrostatic lenses. At top are images of undisturbed beam. At bottom, a blocking grid of 1.5 mm holes located 4 mm apart, is inserted 79 cm upstream of the image. The source tune remains the same; all differences between the image pairs results from changing the settings of the electrostatic doublets before the analysis magnet.

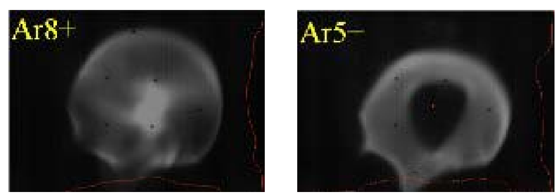

Figure 3: Images of argon beam taken after the analysis magnet with a solenoid being used as the first focusing element. The 8+ beam is normal. The 5+ beam however is degraded by the space-charge of higher charge states being focused inside of the 5+ beam column.[4]

K500

Beam transmission, for good tunes from a Faraday cup ~2m before the spiral inflector to the first cup after extraction, is 30-40%. Only a first harmonic buncher is used and it is located too far from the inflector to achieve a good time focus, at currents giving significant space-charge forces. Normal bunching gain is 3-4. Installation of a 2^{nd} harmonic should improve the gain by 10-15%.

Injection is complicated by the large axial fringe field ranging from ~0.04 T at the beginning of the “up” part of the beam line to ~4 T near the cyclotron mid-plane. Two solenoids are installed in this section to allow for focusing and for rotational matching of asymmetric beams. This matching is particularly required as the final bend in the beam line from horizontal to vertical is accomplished by a cylindrical electrostatic bender having strong y-focusing and no x-focusing. This will be replaced in the near future with a spherical bender.

Normal capture into accelerated beam is 10-15% without bunching, 40-60% with. Before “fine-tuning” one expects extraction efficiencies of about 2/3 without bunching and 3/4 with bunching on. Extraction efficiencies better than this are critically dependent on the injection line tune. Beam “tails” are easily introduced and not easily remedied as shown in Figure 4:

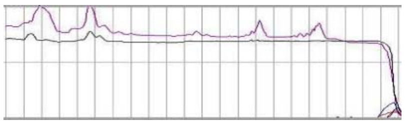

Figure 4: Two K500 radial probe traces of a ^{112}Sn beam, intensity vs. radius from 12 cm to extraction radius of ~68 cm. The topmost shows evidence of large tails, the bottom, less so. The difference between the two comes from small changes of the injection line tune.

Two, radially-adjustable, 1mm thick pins can be inserted into the beam at small radius to be used as phase slits where the turn separation is, in principal, sufficient to allow a phase cut to be made. In practice, they are seldom used as the experimental program rarely requests a short pulse length and gains in extraction efficiency are marginal.

However, a small C-shaped collimator installed originally to protect the magnetic extraction channels from vertical beam excursions, has proven very useful. Since the beam crosses the $\nu_r = 2\ \nu_z$ coupling resonance near full radius, off-center beam is scraped off over several orbits. Tuning to minimize the beam lost on this slit forces good centering and tends to decouple the effects of the centering and extraction field bumps. The losses that cannot be tuned away are generally of beam that would otherwise hit the deflector. The K500 deflectors are not water-cooled and are limited to about 150 W of total heating.

Coupling Line

Relatively little work has been done with the beam line coupling the K500 to the K1200. The K500 beam is already highly filtered with an emittance not hugely greater than the acceptance of the K1200. Losses are minimal unless slits are used to trim the beam. Injection efficiencies into the K1200 are normally 60 – 80%. However, higher injection efficiency tend to result in lower K1200 extraction efficiency, which indicates that better matching and trimming of beam tails will be needed in the future.

Injection efficiency goes down as the beam damages the stripper foil. Foil lifetime is generally lower than expected. For present intensities, lifetimes are acceptable for the lighter beams. However, for the very heavy beams they are unacceptably short, especially considering that future intensities are expected to be higher with a new ECR ion source coming online in 2009. Other options for different foil materials and mounting schemes are being investigated.

K1200

First-time injection of a new beam tends to be difficult, but once the settings are established, it becomes relatively easy considering the spot on the foil must be located to within a couple of millimeters with the right impact angle, and the last beam viewers are a considerable distance upstream. The lack of radial phase probes in both cyclotrons is a significant handicap in the K1200. Setting the main magnet field is quite easy in the K500 where the beam starting phase (without bunching) is clearly defined. However, the K1200 starting phase can be varied at will with a phase shifter. Beam can be accelerated and extracted with +/- 25 degree deviations from the ideal starting phase; the starting phase error can be compensated for by tilting the phase curve with a different main field setting. Mapping with the phase history on multiple points with different values of starting phase with the Smith-Garren method will give a reasonable value but is very time consuming.

The K1200 also has a vertical beam collimator near full radius at the $\nu_r = 2\ \nu_z$ coupling resonance. The tuning benefits are the same as for the K500, but its importance is magnified by the much higher beam powers involved. The deflectors are water-cooled up to about 1 kW, but since much of the heating is localized in areas where the cooling is mostly by radiation, beam losses must be kept under 200 – 300 W. As shown in Table 1, the collimator considerably increases transmission though the deflector.

CONCLUSIONS

Improvement of transmission efficiencies has resulted in significant gains of beam currents available for experiment. Further increases of current will come only through careful control of the 4-D emittance space and with precise cutting of beam tails. The injection line performance is the key element of this process.

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