INTENSE BEAM OPERATION OF THE NSCL/MSU CYCLOTRONS*

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Abstract

Intense heavy-ion beam acceleration by superconducting compact cyclotrons presents significant challenges since surfaces impacted by lost beam are subject to high thermal loads and consequent damage. High transmission efficiencies allow 0.7 – 1.0 kW beams to be routinely delivered for experiment at the NSCL, with minimal negative impact on reliability. Net beam transmission measured from just before the K500 to extracted beam from the K1200 is often about 30% and usually above 20% depending on the ion used (factoring out the unavoidable loss due to the charge stripping foil in the K1200). Results, techniques and examples are discussed.

INTRODUCTION

The National Superconducting Cyclotron Laboratory (NSCL) consists of two coupled cyclotrons, the K500 and K1200 [1], which accelerate ion beams produced by an ECR-type ion source (ECRIS). For the majority of running time, the machines are used as “drivers”, impacting the beam onto a target at the object of the A1900 particle separator to produce fragments which are then purified and sent downstream as a rare ion beam (RIB) suitable for nuclear science experiments with exotic nuclei.

Presently, two ECRIS’s are available for axial injection into the K500. Besides providing a measure of redundancy in the event of a failure of one source, being able to alternate between two sources is a significant benefit to operations overall in that the next beam can be prepared while the present experiment is running. This is particularly important when the ions come from a solid rather than gaseous material, which may require venting the source, special hardware, cleaning the plasma chamber, or long periods of conditioning. The older source, called ARTEMIS-A (Advanced Room Temperature Ion Source), is a modified version of the Berkeley AECR-U operating at a frequency of 14.5 GHz. (A duplicate, ARTEMIS-B, located on an independent test stand is used for development purposes.) A new, 3rd generation, ECRIS named SUSI (SUperconducting Source for Ions), presently operates at 14 or 18 GHz [2], [3]. Both sources run with extraction potentials ranging from 18 – 27 kV depending on the K500 injection requirements.

Beams in the range of 8 – 15 MeV/u from the K500 are injected mid-plane into the K1200 through a 200 - 800 μgm/cm^2 stripper foil (usually amorphous carbon) located at a radius of about 32 cm. Transport dynamics require the ratio of beam charge going into the foil to the charge coming out to be between 2.3 and 2.7.

In the evolution of the NSCL to a provider of RIB’s almost exclusively, the emphasis has shifted from “maximum energy” to “maximum intensity”. Development toward producing higher-power beams continues, but must remain consistent with an active experimental physics program which requires reliability, consistency, and the avoidance of unscheduled downtime that may result from running at high power.

PRESENT LIMITS

A list of most of the NSCL beams, together with their present estimated intensity limits and the reason for those limits, is provided in Tables 1, 2 and 3 below. These intensity restrictions fall into the general categories of power-limited, source-limited, and stripper foil-limited. Several additional NSCL-run beams are not listed because they have not yet been developed to their full potential, due either to being only recently introduced (^{82}Se, for example) or due to limited user demand. About half of the NSCL running time uses five beams (^{48}Ca, ^{40}Ar, ^{78}Kr, ^{76}Ge, and ^{86}Kr) of the 22 ion species available, so consequently, these beams are the most thoroughly developed. The values given in theses tables are generally not the peak recorded intensities, nor are they what is guaranteed to experimenters for planning purposes (those are made available on the NSCL website), but are values considered reasonably achievable and maintainable for some hours. However, days-long RIB production using beam powers greater than that presently run will require additional machine protection features than are presently available in order to limit damage in the event of beam position excursions. It will also require active feedback from non-intercepting probes to precisely monitor and maintain the high extraction efficiency obtained in the initial tune throughout the duration of the high-power run.

Table 1: Beams presently limited by ECRIS output.

Ion	Mev/u	pnA	Watts
58-Ni	160	40	370
64-Ni	140	15	134
76-Zr	120	3	37
112-Sn	120	10	120
118-Sn	120	3	38
124-Sn	120	3	44

Refractory-metal beams are an area of experimental interest, but are difficult to produce in the ion source because of the high temperatures required. Continued

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SUSI and associated oven development is expected to rapidly raise the existing output of the present beams and to make other ion species available at useable intensities in the future.

Table 2: Beams presently limited by power issues.

Ion	MeV/u	pnA	Watts
16-O	150	500	1200
18-O	120	500	1080
22-Ne	150	220	726
24-Mg	170	200	816
36-Ar	150	150	810
40-Ar	140	200	1120
48-Ca	140	140	941
78-Kr	150	100	1170
86-Kr	140	70	843
124-Xe	140	25	434

For most of the beams shown in Table 2, the limiting factor is beam loss on the K1200 deflector. While the K500 deflectors are not as well-cooled, no heat-related problems have been noted up to double the chosen loss-limit of 100 W, nor have there been any beam-related failures. The K1200 deflectors are water-cooled, with a planned loss-limit of 1000 W, but there have been failures well below that level, so losses much greater than 200 W are avoided. Deflector limits in practice however, are not only determined by the value of the power lost, but also by the energy density created by beam hitting the (tungsten) septum. Oxygen, with a range of 4.1 mm, causes less material damage at a given beam power than xenon which has a range of 0.7 mm at the NSCL energies. An additional source of K1200 deflector heating can be the large-angle impact of injected beam that is not charge-stripped from its starting value. (This factor is a problem for some beams and not others, depending on the details of the injection dynamics.)

Separate from other considerations, the subset of medium-heavy beams capable of ~1 kW power, presently argon, calcium, and krypton, are also restricted by potential damage to the A1900 production target during the course of an experiment. Experience has shown that sustained, full-power exposure over the course of an experiment can damage these targets (usually beryllium) within the 1 mm diameter beam impact region, causing an unacceptable reduction in both the resolution of and transmission through the A1900 separator. This effect occurs even when the overall heating of the target material is significantly less than its 500 W cooling limit. Replacement of the present fixed target with a rotating version is planned and should greatly curtail this problem.

The uranium, lead, and bismuth beams share both low stripping efficiency characteristics and short ranges in materials. A thinner foil absorbs less energy, but may be far away from the equilibrium thickness required for best stripping efficiency. A thicker foil may give better stripping efficiency, but absorb more power and increase beam emittance. Such conditions make optimization of these heavy beams difficult.

Table 3: Beams presently limited by stripping-foil issues.

Ion	MeV/u	pnA	Watts
208-Pb	85	2	36
209-Bi	80	2	34
238-U	80	0.3	6
238-U	45	0.1	1

In the case of the 80 MeV/u uranium beam, an injected beam of 7.7 MeV/u $^{238}U^{30+}$ at a current of 20 pnA, will noticeably degrade the foil in about 15 seconds and make it totally unusable after a few minutes. Even reducing this incoming beam intensity by ½ or more will only extend the foil lifetime to at most to 3 or 4 hours. It is not clear that there is a solution to the foil lifetime problem for the heaviest ions within the constraints of the present machines. A detailed discussion of stripper-foil performance is presented in this conference [4].

Improvements in High-Intensity since 2006/07

The trend toward higher transmission efficiencies through the cyclotrons has continued. A comparison of four selected beams normalized to the same output power is given in Table 4 and Table 5.

Transmissions for the K1200 are given with the unavoidable losses due to the stripping efficiency of the foil factored out; this allows comparison of machine tune quality across the range of 22 different ions presently used at NSCL. The efficiency of stripping into the desired charge state for acceleration are experimentally-determined results from measurements taken on a test setup in the K500 to K1200 coupling beam line. Each ion type used for acceleration is tested for stripping ratios at the required energy with the particular foil thicknesses and, in some cases, materials used. The selection of foil thickness to be used is made based on these measurements as well. A sample of such results is given in Table 6.

Most remarkable in this comparison has been the improvement in the K500 total transmission (measured in the injection beam line ~ 2 m upstream of the K500 inflector and on the first Faraday cup in the K500 - K1200 coupling beam line). Presently, the expectation of this value for normal tunes is 40-50%.

The transmission efficiency of beam through the K1200 has also improved over this period, with the effect of improving the net transmission through both machines by about a factor of two and generally reducing losses on the deflectors at comparable intensities.

Table 4: High-power beam transmissions and related deflector losses in 2006/2007. Unacceptably high deflector losses are indicated by red shading.

2006/2007	^{16}O	^{48}Ca	^{78}Kr	^{124}Xe
Final E (MeV/u)	150	140	150	140
Beam Power (W)	1500	1000	1000	400
K500 out / K500 in	**21%**	**37%**	**15%**	**28%**
K500 Deflector Loss (W)	113	78	180	79
K1200 out / K1200 in	**34%**	**63%**	**49%**	**53%**
K1200 Deflector Loss (W)	484	111	380	110
K1200 out / K500 in	**6%**	**22%**	**6%**	**14%**

Table 5: High-power beam transmissions and related deflector losses in 2009/2010.

2009/2010	^{16}O	^{48}Ca	^{78}Kr	^{124}Xe
Final E (MeV/u)	150	140	150	140
Beam Power (W)	1500	1000	1000	400
K500 out / K500 in	**50%**	**51%**	**36%**	**43%**
K500 Deflector Loss (W)	106	37	68	36
K1200 out / K1200 in	**66%**	**66%**	**61%**	**57%**
K1200 Deflector Loss (W)	290	140	112	88
K1200 out / K500 in	**20%**	**33%**	**30%**	**25%**

Table 6: Stripping efficiencies into the desired charge state for K1200 acceleration using a 600 μgm/cm^2 thick amorphous carbon foil.

	^{16}O	^{48}Ca	^{78}Kr	^{124}Xe	^{238}U
Charge In, Out	3+ 8+	8+ 20−	14+ 34+	19− 45−	30− 69−
Efficiency	95%	69%	53%	26%	9%

HARDWARE MODIFICATIONS 2007-2010

A number of hardware changes contributed to increased beam powers over this period including, (1) installation of a beam chopper, (2) adding a second harmonic to the K500 buncher, (3) repair of a polarity error with one pair of K500 centering bump coils, (4) the replacement of an older 6.4 GHz ECRIS with SUSI, and (5) replacement of a cylindrical-type electrostatic bender under the K500 with one of a spherical-electrode design.

A 2-plate electrostatic beam chopper was installed on the K500 injection beam line in January of 2008. While not directly a performance enhancement, it greatly enhances exploration of high beam intensities by reducing the likelihood of thermal damage during optimization of the machine tune, but still allows evaluation of machine performance at high burst intensity. Previous to this time, control of the injected beam intensity was entirely done with attenuator grids and/or slits, giving results that were often not scalable to the full-intensity tune.

Second-harmonic capability was added to the buncher in August of 2008, with immediate improvements observed in accelerated beam intensities in rough agreement with expectations (a gain over DC of a factor of 5 assuming 40 degrees of phase acceptance) [5]. This compares to a gain of about 3 for first harmonic bunching alone.

In April 2009, a long-standing wiring error in the K500 resulting in a reversed polarity on one of the three inner trim coil sets used to generate an adjustable field bump for beam centering was discovered and remedied. This repair resulted in better extraction and lower losses for a given beam intensity, as well as less "scatter" in parameter settings from run-to-run.

First beam through the cyclotrons from SUSI occurred in October 2009. The development and injection of beams from this source is in its early stages and is hence yet to be fully optimized. Initial results are however encouraging (showing improved final beam powers with krypton and oxygen beams, to date) and SUSI is already in reliable rotation with ARTEMIS as a producer of beams used in the NSCL experimental program.

The last 90 degree bend of the injection line is upwards onto the center axis of the K500. Until recently, this was accomplished with a cylindrical-plate electrostatic bender, which has strong vertical focusing and no horizontal focusing, making it difficult (or impossible) to pass a symmetrical beam to the K500 for injection. This bender was replaced by a spherical-electrode bender in April 2009. The requirement for a large electrode gap of 64 mm and a small bending radius of 200 mm, plus the restriction of fitting into the existing small vacuum chamber, demanded a rather unique design in order to keep aberrations at a minimum and to get the bent beam simultaneously on-axis and with the proper 90 degree angle. The general configuration of this device is shown in Fig. 1.

The overall better matching possibilities provided by this double-focusing design have allowed transmissions through the K500 with injected beam emittances of 10π mm×mrad (rms) achieved before this change, to be achieved with double that emittance afterwards..

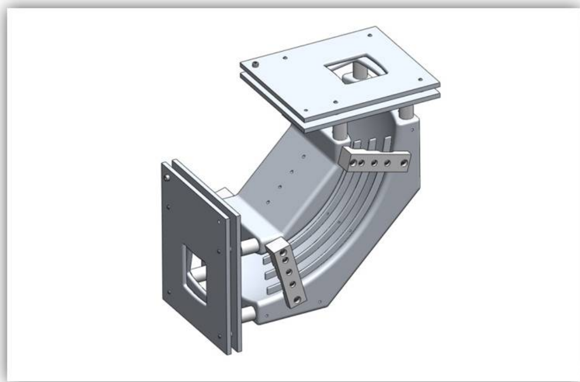

Figure 1: The electrode configuration of the high-acceptance, low aberration, spherical bender is shown. The entrance and exit aperture plates can be biased and aid in precise shaping of the electric field at the ends of the main electrodes. Since sides of the main electrodes come as close as 10 mm to the grounded vacuum chamber, the pair of 3 "arc" electrodes are provided to act as a voltage-divider for straightening the field on both sides. The bend radius and main electrode gap are 200 mm and 64 mm, respectively.

DEFLECTORS

A measure of beam loss on the extraction deflectors of heavy-ion superconducting compact cyclotrons is unavoidable. The turn separation of the outer orbits in the K500 is about 1.3 mm center-to-center and half that in the K1200, even when not taking into account the "arc" created by sine-wave acceleration over a significant phase width. The detrimental effects of such loss are compounded by the short penetration depth of heavy ions in materials. For the NSCL beams of significant power, their ranges in tungsten (the chosen septum material) vary from 0.03 to 0.08 mm in the K500 and from 0.7 to 4.1 mm in the K1200, depending on the ion being accelerated and its energy. These losses, the high power density per watt created upon beam impact, and the high electric fields required (up to 75 kV/cm in the K500 and 115 kV/cm in the K500) conspire to make reliable deflector operation a difficult challenge. Some specific engineering considerations to meet these challenges are described in Ref. [6]. Additionally, experience has led to a procedure whereby all new or repaired deflector assemblies are conditioned for several days to run at high voltage without sparking or significant current draw. This is done in a vacuum chamber kept in a magnetic field provided by a retired bending dipole permanently installed in an x-ray shielded area. After conditioning, the deflectors are kept in a sealed container until use. This minimizes the time from their mounting in the cyclotron until they are fully ready to run, and guarantees that a serviceable spare is immediately available in case of a failure.

A further requirement of successful deflector function is the continuous introduction of oxygen during intense beam operation. Stress on the deflector appears either as an increase in the spark rate or an increase in the drawn current (over minutes or hours) which eventually results in the power supply no longer being able to generate the high voltage required. Small amounts of oxygen gas fed along the high-voltage connections directly into the deflector housing seem to mitigate these effect. For K1200, the normal flow rate is about 0.2 standard cubic centimeters per minute (sccm). (The K500 deflectors generally require flow rates under the 0.1 sccm limit of the present mass-flow controllers, so their flow is pulsed on and off at about once per minute).

For difficult K1200 cases, the flow rates may be raised significantly up to 2 sccm, until the deflector responds and the current draw drops, whereupon the flow can be reduced to a more-normal value. It's desired to keep the flow rates as low as possible because the increased pressure in the vacuum chamber causes increased attenuation of the accelerated beam, however for flows under 1 sccm and for all but the heaviest ion species, this effect is minimal.

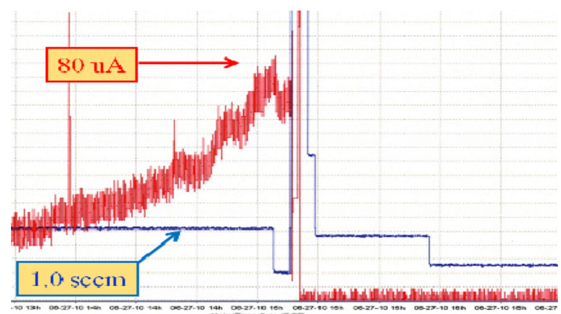

Figure 2: Oxygen gas-flow rate in sccm (blue) and K1200 deflector power supply current in µA (red) as a function of time are shown. Normal operation is interrupted by a rise of the drain current to a level (here ~80 µA) where full voltage cannot be maintained. A "high-pressure gas treatment" is applied as described above, dropping the drain current to low levels and allowing normal operation to resume after a 20 minute interruption. The total period shown is 3 hours.

For severe cases, when the K1200 deflector has essentially failed and is unable to maintain voltage, another technique, called a "high-pressure gas treatment", is used. First beam is stopped upstream, and the RF is shut off. Then, with the deflector still set for the desired voltage, the mass-flow controller is opened to deliver its maximum flow of about 12 sccm. This raises the chamber vacuum from its base value of around 2 µTorr to about 50 µTorr. The current normally will drop quickly. If this doesn't work, then a manual bypass valve is opened to increase the flow even further, inducing a high-current, low-voltage corona discharge in the deflector. After period of discharge for as long as 30 minutes, the deflector will then usually return (upon reducing the gas flow) to the desired low-current, high-voltage state and normal operation can be resumed. An example of this process is given in Fig. 2 above.

Why this process works and why oxygen seems to be effective is not clear, but it may be similar to oxygen plasma cleaning techniques becoming common in industry.

To achieve reliable operation, the K500 deflector loss limits are set to about 100 W and the K1200 at 200 – 300 W, conditional on housing temperatures remaining under 110 degrees C. (Limits on the xenon beams tend to be considerably lower.) Design engineering, pre-conditioning, oxygen gas flow, and loss-limit restriction taken together have made interruptions of beam delivery caused by deflector failure, rare events.

OTHER CONSIDERATIONS

A well-established requirement for good performance from the NSCL cyclotrons is a beam of low emittance and minimal "tails" injected into the K500. The intrinsic emittance of an ECRIS beam is about 200π mm×mrad, while best K500 performance is achieved with beams less than 20π mm×mrad.

Besides the clear relationship between injected transverse phase space and maximally-separated turns for good extraction efficiency, there is a strong cross-coupling across the injected transverse phase ellipse to the phase spread of the bunched beam as it passes though the spiral inflector. While it is possible to pass a 100π mm×mrad beam from the axial injection path into the K500 cyclotron midplane for acceleration, particles on one side of the transverse phase ellipse can be shifted into a phase 40 degrees different than particles located on another side [7]. A reduction in the injected emittance minimizes this effect. K500 performance continues to improve as emittance is reduced to levels that become difficult to measure with the available instrumentation (2 – 5π mm×mrad).

A system of collimation techniques for ARTEMIS-A and its associated beam line achieves this and still allows up to about 30% of the ECRIS beam intensity to pass through. A thorough discussion of these techniques is given in Ref. [8]. Once established, the quadrupole settings are quite consistent between different ion species and scale well by rigidity. The collimation scheme for SUSI is quite different and still being optimized. A discussion of those techniques is given elsewhere during this conference [9].

Reproducible and stable ECRIS tunes are important in both the initial setup of high-power beams for RIB production and keeping that intensity at high levels for the duration of the experiment. The high sensitivity of the K500 to any shift in beam position or any increase in injected emittance puts increased stability constraints on source operation. A general and effective technique to aid stable running, made possible by the availability of two sources, is that the one to be used for the next scheduled beam is run for at least 24 hours beforehand at the output required for that experiment.

Still, source changes affecting cyclotron beam output do occur over the course of a run and can be difficult to detect as they do not always involve clear changes in the source output current or in other easily-measurable parameters. Quickly isolating source issues from a myriad of potential other reasons for a reduction in cyclotron output can be a difficult task. To solve this problem and potentially aid as a tool for source optimization and physical understanding of sources in general, a new tool is being explored.

Using a signal take directly (except for a resistor to drop the voltage created by the ~ 25 kV beam potential and a low-pass filter to eliminate spurious < 1 MHz noise from various unrelated devices), one can see with an oscilloscope that the beam produced by the ECRIS is not pure DC but contains AC components ranging from near zero to around 10% for tunes that otherwise appear reasonably stable. For the most part, the AC components also have defined characteristic frequencies which can be analyzed real-time via the scope's FFT function (if available). Varying normal source parameters such as microwave power or feed gas flow may either smoothly change the characteristic frequencies seen, or they may remain rather unaffected over a wide range, only to flip suddenly into a new mode frequency with tiny further changes. The output beam intensity may or may not change between mode transitions.

An example of sudden transitions is shown in Fig. 3 where the source, in this case ARTEMIS, exhibited three distinctly different oscillation modes over the small range of 305 to 315 W in microwave power, with the settings of all other devices remaining unaltered.

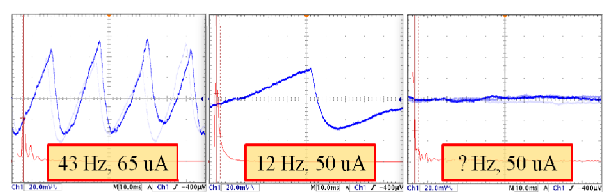

Figure 3: A beam of $^{40}Ar^{7+}$ at a 24.43 kV extraction potential is shown on an FFT oscilloscope for microwave powers of 305, 310, and 315 W. The AC coupled signal is shown as the upper trace in blue, with the AC component of the DC signal being 2.7%, 1.9%, and < 0.1%, respectively.

To date, only one attempt to correlate various source modes with K500 performance has been made, but it proved interesting in an unexpected way. After a day of tuning different-mode beams through the K500, the source was left in a chaotic frequency, low-noise mode, similar to that shown on the right in Fig. 3 above, for the overnight hours. By morning, with the exact same device settings as before, and with similar source output current, the K500 output was down by about 50%. The source had drifted into a distinctly different mode with 75 Hz oscillations. Very slight changes to the gas flow and microwave power restored the original condition and simultaneously restored the original tune quality. With tweaking of the injection line steering and focusing, both conditions gave good results from the K500, but each mode required a somewhat different beam line tune to transmit properly into the cyclotron. It is suspected that source mode changes may be responsible for some otherwise-unexplained needs to "peak up" the machine tune over several-day running periods. Monitoring the state of the source using this technique (which, if the signal comes from a wire put into the injected beam path, can be easily done without beam interruption) is expected to reduce the need for such retunes.

Investigation of these effects is continuing, but some very preliminary observations are as follows: (1) The sensitivity to source parameters is greater for the heavier ions, (2) The modes vary between different charge states of the same ion (with source parameters kept constant), (3) For a given ion and charge, there seem to be a set of modes < 100 Hz, a set of modes >1 kHz, and a range of "quiet chaos" in between, and (4) Mode shifts may occur at or near peak source output. (This last point, in particular, is in line with operational experience where the operators often shift the source tune away from peak intensity, most often using a change in gas flow, to achieve best long-term stability.)

Low-emittance injection, in addition to its intrinsic benefits, helps make evident other effects that were hidden before. An example is the influence of a steering effect of the leads powering the innermost trim coil (TC01) of the K500 became evident. Unlike the other trim coil leads which are fed in through the caps, the TC01 leads run along the injection beam path near the machine center. It was found empirically that by setting this coil to zero and roughly compensating with TC02, that the centering bump magnitude could be reduced. Upon this discovery, the predicted trim coil settings were recalculated with TC01 forced to zero. In terms of trim coil settings, this feedback loop of hand-tuning improvements, determining what those settings represent in terms of a radius vs. phase history, then using that history to guide a new calculation, has proven quite productive. Ideally, one would also measure the resulting phase history, but the long-standing absence of a functional phase probe makes that impossible at present. A certain degree of confidence in the predictions is warranted however, because, to date, every such feedback cycle has worked; the predicted new values of trim and main coil settings based on the calculated phase history of an empirically-determined trim coil set seem to give identical results as far as the beam is concerned.

Through a similar process, it was discovered that increasing the phase error at injection right to the edge of vertical focusing limits, resulted in consistently better extraction efficiency when compared to smaller offsets. By injecting well off-phase, then bringing the beam back to zero phase at a larger radius, the energy gain per turn increases over the region, and is believed to result in a phase compression effect along the lines described in Ref. [10].

THE FUTURE

In principle, further gains in beam intensities can be achieved. (The progression would be along the path of increased beam collimation at critical points and compensating with increased source output that is anticipated with SUSI.) However, the "easy" gains have already been made, considering the limitations inherent in the design of the present machines. In addition, the planned retirement of the cyclotrons and their replacement by a much higher intensity heavy-ion linac driver means that the cost/benefit of any major future cyclotron improvements must be carefully considered.

CONCLUSIONS

After a series of upgrades to hardware and improvements in tuning techniques, the NSCL coupled cyclotrons are reliably producing heavy-ion beams at powers up to 1 kW. Improvements with the intention of increasing present power limits will continue, but progress is likely to be incremental.

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REFERENCES

[1] F. Marti, P. Miller, D. Poe, M. Steiner, J. Stetson, and X.Y. Wu, in Cyclotrons and their Applications, AIP Conf. Proc. 600 (2001) p. 64.

[2] P. Závodszky, *et.al.* in Rev. Sci. Instrum. 79, Issue 2 (2008) 02A30.

[3] G. Machicoane, D. Cole, and P. Závodszky, in Proc. of ECRIS08 (JACoW), Chicago, USA, (2009) p. 14.

[4] F. Marti, S. Hitchcock, P. Miller, J. Stetson, J. Yurkon, *this conference*.

[5] F. Marti and A. Gavalya, in Proc. of the 11th Intl. Cyclotron Conf., Tokyo, Japan, (1987) p. 484.

[6] A. Alfredson, F. Marti, P. Miller, D. Poe, and G. Stork, AIP Conf. Proc 600 (2001) p. 133.

[7] F. Marti, J. Griffin, and V. Taivassalo, IEEE Trans. On Nucl. Sci., Vol. NS-32, No. 5 (1985) p. 2450.

[8] J. Stetson, in Proc. of ECRIS08 (JACoW), Chicago, USA, (2009) p. 208.

[9] G. Machicoane, D. Cole, M. Doleans, T. Ropponen, J. Stetson, L. Sun, X. Wu, *this conference*.

[10] A. Chabert, G. Gendreau, P. Lapostolle, and P. Yvon, in IEEE Trans. of Nucl. Sci., Vol. NS-28, No. 3, (1981).