PERFORMANCE OF THE K1200 CYCLOTRON AT MSU

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ABSTRACT

The current performance of the K1200 cyclotron, the primary accelerator in the National Superconducting Cyclotron Laboratory, is reported and results of development projects are summarized.

1. RELIABILITY

The initial reliability of the cyclotron system, as evidenced by statistics of equipment breakdown, was not acceptable. Breakdowns occurred in many different systems. Improvements of deflectors, rf power supply and rf voltage holding are outlined below. Efforts to improve reliability of the overall facility were successful and are continuing.

Running statistics are shown in Figures 1 and 2.

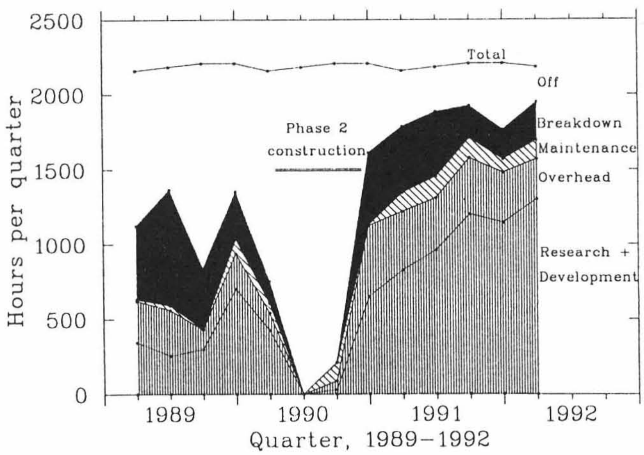

Fig. 1. K1200 operating time distribution.

Displayed in Fig. 1 is the distribution of the total time in each 3 month period among the following categories: operation (total of research, development and overhead), breakdown, maintenance and scheduled down time. In Figure 2 the reliability ratio, operation time divided by operation plus breakdown time, is plotted for the same period, 1989 to the present. From February to September 1990 the K1200 was shut down for construction of the A1200 fragment separator and completion of the Phase 2 beam lines.

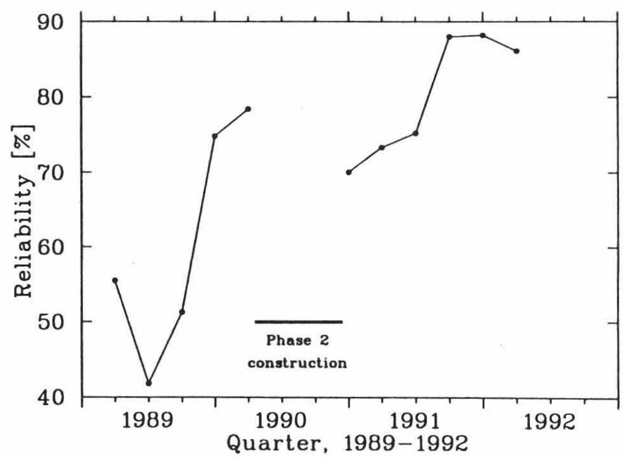

Fig. 2. Reliability, measured as the ratio of operating time to time scheduled for operation.

1.1. Deflectors

The voltage that electrostatic deflector E1 will sustain with beam present has increased from 45 kV on 7 mm gap in 1988[1)] to 60 kV on 6 mm gap at present. The second deflector, E2, being shorter and having no hinges, operates reliably up to 80 kV (6 mm). Advances in voltage holding performance have resulted from the following developments[2)] :

- ceramic glass/ metal vacuum feedthrough with internal cable and current limiting resistor
- suppression of electron emission current by an insulating coating on the cathode

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- ceramic glass insulator material and terminations which resist arcing breakdown
- conditioning procedures that avoid large dark currents and sparks, which are detrimental to electrodes
- stainless steel anode plates, which seem to remain cleaner and smoother than tungsten or molybdenum plates during operation

In anticipation of increased beam current, a water cooled section of E1 with copper anodes has been installed. Performance with low beam power (<5 W) has been similar to the standard deflector.

1.2. Rf transmitter anode power supplies

The anode power supply consists of a power distribution section, with crowbar unit and controls, and a separate power transformer and rectifier. Due to its high reliability the 400 kW transformer and rectifier from the K500 cyclotron has been used for approximately 95% of the operating time of the K1200 in 1991 and the first half of 1992.

The large (1200 kW) transformer is required to run beam energies above a threshold that depends on the charge/mass of the ion and is in the range 80 to 140 MeV/u. The 1200 kW subsystem has experienced failures in the transformer, filter choke and rectifiers. The major cause of these failures has been transient current and voltage swings associated with triggering the crowbar circuit. The large magnetic forces resulting from the short circuit current during a crowbar event exceeded the capabilities of the windings in the original transformers and the filter choke. The transformer, choke and rectifier have been redesigned and new units ordered. Besides being more rugged, the new rectifier and choke will be more accessible for maintenance, as they are not immersed in oil. The modifications will be finished in summer 1992.

1.3. Reduced dee voltage

The dee voltage in the K1200 is set for each beam in such a way that the design ray follows the same path through the cyclotron central region for all beams. The voltage requirements thus depend on the charge to mass ratio and the final velocity. The central region was designed originally for a maximum dee voltage of 200 kV. The cyclotron was operated with this central region until March 1991. During this period we discovered that the resonators would spark across the dee stem support insulators on the atmosphere side when the voltage at the insulator reached 80 kV. Due to the variation of the voltage at the insulator with frequency, this effect restricted the range of charge/mass for energies between 30 and 100 MeV/nucleon. Therefore, a new central region was designed and installed which allows a dee voltage reduction of 20%. This change has eliminated the problem at the cost of a small increase in phase slip. The absolute value of $\sin(\phi)$ remains less than 0.50. The required input power to the rf amplifiers at maximum energy (200 MeV/u) is reduced to 920 kW by this modification.

2. IMPROVEMENTS IN HIGH ENERGY BEAM LINE TUNING

A systematic program to improve beam line tuning was begun and partially implemented in 1991 with goals of reducing tuning time, increasing reproducibility, and improving the beam on target. Tuning is complicated by the use of inherently large emittance secondary beams and the desire to make clean, low cross section measurements at very forward angles.

Key to this effort is the use of TRANSPORT code predictions for each set-up. Initial attempts to do so gave poor correspondence between predicted and measured beam envelopes. All beam transport lines were physically measured, dimensioned in the CAD layout drawings, and the TRANSPORT input decks altered to reflect the corrected distances. Inter-element distances and effective lengths of the super- conducting quad doublets were revised to reflect the dimensions of the magnets in their cold state. Current calibrations were checked and higher resolution DACs were fitted to quads and bending magnets. With these changes, correspondence was improved significantly and is now of sufficient quality to allow reasonably accurate pre-run estimates of the actual beam envelope and magnet settings.

Development and testing of a complete set of predicted values for beam line magnets on each of the five vaults was begun and partially completed. Beams are assumed to be of three general types: primary (x and y emittance of 3 π mm-mr),[3] medium acceptance (30 π mm-mr) and high acceptance (x=50 π mm-mr, y=80 π mm-mr).

Operational experience has been important in determining the choice of optical conditions to be fitted by TRANSPORT. Primary beam experiments with the 4π array in the N2 vault indicated that the 5 cm dipole gaps impose significant restrictions on desireable optical solutions. When predictions gave a vertical beam height of more than about 2 cm in this gap, runs using such predictions had substantially increased noise due to particles hitting the target frame (presumably from halo scattering from the pole faces) as compared to optical solutions giving a smaller beam height in the dipole.

Additionally it was noted that while the spot size and shape at the object point for the beam transport system remains relatively constant for different beams and energies, the primary beam emittance, hence divergence, could vary by a factor of 2 or more.

These two considerations, together with desire to transmit high-emittance secondary beams with maximum efficiency, led to abandoning the technique of point-to-point transfer of the beam from the A1200 to target with multiple foci, in favor of no intermediate imaging and reduced divergences until the final spot on target.

Rules for generating beam line optics have been developed. This program has already resulted in performance improvements that meet its three general goals.

3. ENERGY RANGE

The maximum energy per nucleon of ions from the K1200 cyclotron was envisioned to vary with mass number as shown by the curve in Fig. 3. The points plotted on the graph show examples of beams obtained. The energy goal for mass 208 has been exceeded (mass 238); that for mass 129 has been reached. Progress toward the goals for lighter ions can be seen from the graph.

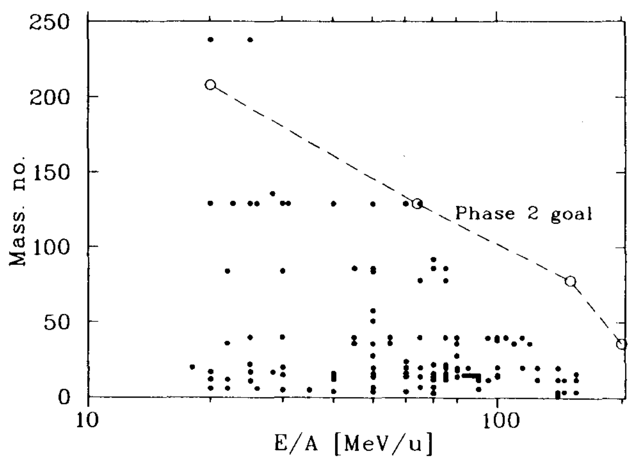

Fig. 3. Mass number vs. beam energy: actual performance (solid points) and goal (open circles).

4. ENERGY AND ION VARIABILITY

For schedule planning purposes the time allowed for changing beams is 8 hours. Many experiments are scheduled to run 2 or 3 different beams (ion-energy combinations). In the year Jan.-Dec. 1991 a total of 72 beams were produced by the K1200 for experiments and development. There were 134 beam changes made in the year, i.e. an average of 1 change every 2.1 days, during the 6877 hr. that the cyclotron was scheduled for operation. In this same period 31 nuclear science experiments were performed. Not included in the energy change figures are so-called cocktail beams which have become increasingly in demand for calibration of detector energy response. For example, the following series of ions, all with charge/mass approximately 0.2, were run in a 6 hour period: $^{129}Xe^{26+}$, $^{84}Kr^{17+}$, $^{65}Cu^{13+}$, $^{55}Mn^{11+}$, $^{50}Cr^{10+}$, and $^{15}N^{3+}$. The frequency was shifted by the small amount corresponding to the difference in charge/mass to select the ion to be accelerated, but all magnet currents remained constant.

Table 1 contains examples of energies and intensities obtained for some respresentative ions produced by the ECR ion sources and accelerated.[4] Molecular beams are a useful option. Compared to atomic ions in the K1200, molecular ions containing hydrogen and helium allow lower energy helium and deuterium beams than otherwise available, and they allow acceleration of protons. In addition, the (H- He)$^+$ ion has been used to excite and study forces produced by electron wake distributions in a target.

Table 2 lists a few secondary beams produced in the A1200 separator and used for physics experiments. Primary beam intensity is in the range 10-50 pnA.

Table 1. Examples of beams extracted from the K1200.

Ion	E/A [MeV/u]	Intensity [part. nA]	Source feed
$^{11}B^{2+}$	25	15	solid
$^{51}V^{13+}$	50	1	"
$^{58}Ni^{15+}$	70	2.4	"
$^{92}Mo^{25+}$	70	0.024	"
$^{238}U^{39+}$	25	0.0004	"
$^{6}Li^{2+}$	90	25	oven
$^{40}Ca^{11+}$	55	3.2	"
$^{12}C^{6+}$	155	0.1	gas
$^{18}O^{6+}$	80	53	"
$^{20}Ne^{9+}$	125	0.27	"
$^{20}Ne^{10+}$	140	0.008	"
$^{28}Si^{8+}$	50	5	"
$^{78}Kr^{22+}$	75	0.30	"
$^{129}Xe^{31+}$	65	0.0005	"
Molecular ions:			
(D-H)$^+$	70	25	gas
(H-He)$^+$	35	6	"
(D-He)$^+$	26	1.5	"

Table 2. Examples of radioactive beams.

Ion	E/A	Intensity p/s/pnA	accept. mode	primary beam
^{11}Li	64	50	high	^{18}O, 80 MeV/u
	35	20	"	"
^{20}Mg	65	0.35	high	^{36}Ar, 80 MeV/u
^{40}Cl	55	200000	med.	^{40}Ar, 80 MeV/u

5. TIME STRUCTURE

The cyclotron central region accepts injected beam in a time interval of 40 degrees.[5] The time distribution of the beam is cut by the loss of beam on the deflector septum and possibly by other contraints placed by the extraction process. The time structure of the external beam has several peaks distributed over a portion of the acceptance interval (see Fig. 4a).

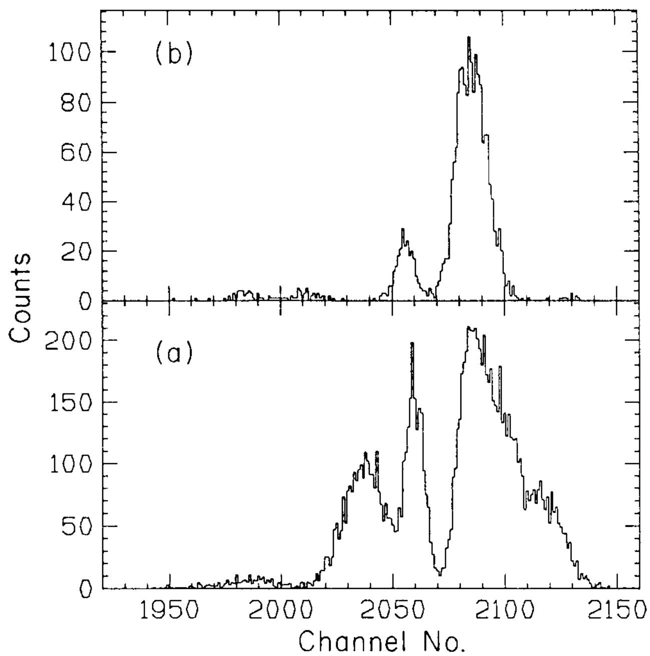

Fig. 4. (a) Time of flight spectrum obtained from a solid state detector in the focal plane of the A1200 separator detecting the primary beam, 60 MeV/u 24 Mg 7+. The stop signal for the time converter is derived from the dee voltage. The rf period is 61.7 ns, and 1 ns corresponds to 40.8 channels. The base width of the distribution is 3.1 ns (18 degrees). (b) As above except phase slits are inserted into the beam. The primary peak centered at channel 2085 has a full width at half maximum of 0.44 ns (2.6 degrees). The beam intensity is reduced X 0.25 by the phase slits.

The phase slit system narrows this time distribution. It is similar to the one used in the K500 cyclotron[6)7)] . Two independently movable pins are inserted into the beam at a radius near 7 inches. The time spectrum in Fig. 4b is an example of the results. The performance of the phase slits is being studied and the operator interface is being developed for routine beam diagnostic use.[8)]

6. BEAM DIAGNOSTICS

A probe shaft with a thin scintillator mounted on the tip and viewed by a miniature TV camera 10 cm from the scintillator is used to display the internal beam spot as a function of position in the median plane.[9)] This probe enables the operator to directly see effects of parameter adjustments on the radial and axial betatron oscillations. It is therefore useful for detecting and correcting centering errors, especially with beams which are sensitive to centering because they remain near a resonance for a long time during acceleration.

A computer program is used to automatically center the beam. This program controls the TV probe drive, a frame grabber to digitize the picture of the beam spot and the centering coil power supplies. It measures the horizontal size of the beam spot as a function of radius and determines the betatron oscillation amplitude. Repeating this for different centering coil currents, it finds settings that minimize this amplitude. The search takes approximately 15 minutes.

A second hill probe was built in access port A5, and is presently used to measure current.

7. CONCLUSIONS

The K1200 cyclotron with the ECR ion source has met the energy goals for Xe and heavier ions. Improvements to the deflectors and the rf system are being made to increase the energy for light ions. The reliability has remained consistently good in the past year. A great variety of ions and energies is available and transitions between different beams occur rapidly. The laboratory produces many secondary beams by projectile fragmentation.

8. REFERENCES

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