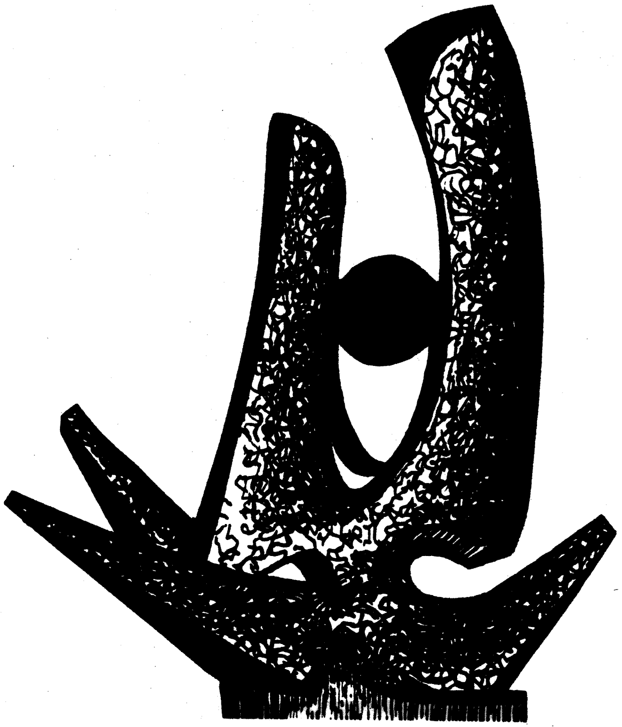
# MICHIGAN STATE UNIVERSITY

## CYCLOTRON LABORATORY

# ANALOGUE RADIOACTIVE ION BEAM ACCELERATION STUDIES AT NSCL

M.L. MALLORY



AUGUST 1985

MSUCL-539

MSUCL-539
August 1985

# ANALOGUE RADIOACTIVE ION BEAM ACCELERATION STUDIES AT NSCL*

M.L. MALLORY
National Superconducting Cyclotron Laboratory
Michigan State University
East Lansing, MI 48824

## Abstract

Acceleration studies are in progress at the NSCL for producing analogue radioactive ion beams from the K500 cyclotron. These analogue radioactive ion beams (i.e., same m/q as the stable accelerated beam) may allow an early start at MSU on an experimental program with radioactive ions. In addition, their brighteness are expected to be several magnitudes larger than an externally cyclotron produced radioactive ion beam. In the following sections, this program is described.

## Introduction

A study of producing exotic beams at the NSCL[1] with an external target and beam analysis system (fragmentation separator) was reported at the past workshop in Washington, D.C. It was concluded that additional work in this area at MSU would have to wait upon the completion of the K800 and other various projects, hence, many years before experiments.

Fig. 1 is a plot of the neutron counts of a detector located near the exit port of the K500 cyclotron. This detector was initially used to locate the resonance of accelerated beams, but today is used only to monitor the neutron rate within the cyclotron's vault. In Fig. 1, the count rate versus the resonance for a $^6Li^{2+}$ beam is shown. This neutron spectrum appears to be different than what is normally obtained for other beams, in that the spectrum is distorted on the low frequency side of the resonance. Possible explanations for this neutron spectrum could be the acceleration of an analogue beam,[2] where analogue beams are ion species that have approximately the same m/q. The resonance frequency diagram for analogue beams, assuming the magnetic central field of $^6Li^{2+}$ is shown in Fig. 2 and indicates that all analogue beams are shifted far from the normally accepted acceleration region of $^6Li^{2+}$.

Recently at MSU we have detected the radioactivation of the cyclotron central region,[3] and have explained this by the stripping of the accelerated ion beam with the background gas pressure in the acceleration vacuum chamber (Fig. 3). It was then natural to ask the question, "Is it possible to make an analogue beam from $^6Li^{2+}$ in some kind of nuclear breakup[4] and would it continue to be accelerated?" Indeed, for $^6Li^{2+}$ such an analogue does exist. It is $^3H^{1+}$ and it is located in the right resonance position to continue being accelerated when $^6Li^{2+}$ is phase shifted below its resonance frequency. Estimates of the expected neutron intensity from this acceleration process are lower than what is detected. However, large uncertainties exist in the ion beam path length for the off resonance beam (i.e., effective target thickness), in the fragmentation cross section for $^6Li^{2+}$ on $N_2$ (the background target gas) and in our

---

*Supported by the National Science Foundation under Grant No. PHY-83-12245.

neutron counter detection efficiency. The important thing is that this neutron problem led to the realization that it may be possible to deliberately produce analogue radioactive ion beams in the normal acceleration process of the K500.

## Analogue Radioactive Beams

Table I lists some of the possible fragmentation analogue beams. The first requirement is that these beams have approximately the same m/q as the stable primary beams. Secondly, it is assumed that the electrons will be totally stripped from the fragmentation ions. The possible ion species then fall into families of charge to mass ratios. For instance, for the family of 2-1, the primary ion particle is twice the mass of the fragmentation ion. The table also includes the type of ion source needed to produce the primary beam. Pig is the conventional cold cathode internal source in use at the K500 cyclotron.[5] ECR is the electron cyclotron resonance ion source,[6] now under construction at MSU. The lifetimes of the fragmentation ions are listed. Several fragmentation beams are stable and may be useful in initially developing the acceleration process. There are six "easily made" radioactive ion beams.

Fig. 4 is the K500 cyclotron operating region diagram. The energy per nucleon versus cyclotron central magnetic field is shown. Three lines for m/q of 3,4, and 5 are plotted and indicate that for rf first harmonic operation, energies from 20 to 55 MeV/u are possible for m/q=3, 12 to 35 MeV/u for m/q=4 and 9 to 20 MeV/u for m/q=5.

## Phase History Studies

The first acceleration studies are computing the necessary magnetic fields for simultaneous resonance acceleration of a stable and radioactive beam. This condition is best illustrated by the sine phase history plot as shown in Fig. 5, where the stable beam is $^6Li^{2+}$, and the radioactive beam is $^3H^{1+}$. Curve A is the resonance sine phase history for $^6Li^{2+}$ versus radius and indicates that this beam was successfully accelerated to the extraction radius. For a phase value of ±1, the beam will be 90° out of phase with the rf. Curve B is the phase history obtained for $^6Li^{2+}$, with the rf frequency shifted by .011 $MH_z$ and indicates that the particles fall out of phase with the rf at 14 inches. Assuming a target was located at point C, the phase history curve for $^3H^{1+}$ has been plotted and it crosses zero and then falls out of phase at 21 inches.

The K500 operates with fixed orbit geometry and has ~530 turns for full energy gain particles. Classical calculations show that $^3H^{1+}$ will have appropriately 100 turns before falling out of phase with $^6Li^{2+}$. Therefore, if point C was located less than 100 turns from the extraction radius, no adjustment in the trim coil field would be needed. In our cyclotron, this option put a very small size limit on the target width. In a separated sector cyclotron, the turn spacing may easily allow a target near the extraction radius. Phase curve D is a theoretical curve where the average magnetic field is adjusted for the mass difference between the beams, ~80 gauss for the $^6Li^{2+}$ to $^3H^{1+}$ case, after the breakup at the target. Fig. 6 is the magnetic field contribution of the K500 odd numbered trim coils[8] at 300 Amps. It is apparent that 80 gauss corrections are easily within their capability. Fig. 6 also indicates that approximately 1" radial travel of the accelerated beam is needed in the acceleration process before the phase history would be changed by an adjacent trim coil. In Fig. 7, the turn number versus radius for a full energy gain particle is shown and it is concluded that locating the target before 20" radius in the K500 allows the trim coils to correct for the mass difference. Table II lists the particle radius at 15 MeV/u,[8] where it is assumed that the cross section for fragmentation has reached its peak, for the maximum energy particles of the possible radioactive beams. The conclusion from the table and curve is that it will be possible to fit the theoretical sine phase curve. Modification to the MSU magnetic field fitting code are in progress to confirm this.

## Target Considerations

Fig. 7 is a picture of a new current probe for the K500 cyclotron that is under construction. The probe is designed to reach into 14" radius of the cyclotron and has a vacuum lock. Modifying the probe for mounting a target will be a straight forward job. The target is assumed to be a self-supporting slab of carbon and will be cooled by thermal radiation. The target thickness[9] and width are yet to be determined. Fig. 8 is the turn separation of the beam as a function of radius where the maximum beam energy gain is assumed. A target width of 0.09" would be used for the 55 MeV/u $^3H^{1+}$ if inserted at 14" radius.

Based on cyclotron emittance measurements, it is assumed that the angular acceptance of the radioactive beam into the acceleration phase space will be $\pm.5^\circ$ in the particle orbit forward direction in both axial and radial dimension. The energy spread acceptance of the cyclotron has to be calculated, but is expected to be large, since the target will be located at a radius where the beam stable phase space area is large.

Locating the target in the K500 extraction system has also been considered. Question of isotropically pure beams is a concern, where it is assumed that the major background is the unstripped primary analogue beam.

## Advantage of Cyclotron Radioactive Ion Beam

Producing these ion beams within the acceleration region of the K500 cyclotron will result in the extraction of an isotropically pure radioactive beam. This production location allows these beams to be utilized in any existing experimental station, thereby using the maximum experimental capability of the laboratory. Initially the cyclotron and beam transport system can be tuned with the primary ion beam, before inserting the target and making the trim coil adjustments. The internal target allows the primary beam intensity to be raised to the ion source limit, which is several magnitudes above the present beam power limit of the extraction system. It is, therefore, expected that the brightness of these beams will be as large as any other proposed method of production.[10]Finally, utilizing the cyclotron allows these radioactive ion beams to be produced early in our program without a fragmentation separator.

## Summary

Calculations and experiments are planned for the near future to validate the feasibility of using the internal beam of the K500 cyclotron in the production of analogue radioactive ion beams.

---

1. L.H. Harwood, J.A. Nolen, Jr., and A.D. Panagioutou, Workshop on Phase II Apparatus, Michigan State University MSUCL 411 (Dec., 1982).
2. E.D. Hudson, M.L. Mallory, and S.W. Mosko, IEEE Nucl. Sci. NS-18, No. 3,113(1971).
3. M.L. Mallory, T. Antaya, F. Marti, and P. Miller, Nucl. Instr. & Meth. in Physics Research 222,431(1984).

4. C.M. Castaneda, H.A. Smith, Jr., P.P. Singh, and H. Karwowski, Physical Review C, Vol. 21, No. 1,179(1980).
5. T.A. Antaya, J.A. Kuchar, M.L. Mallory, P.S. Miller, and J. Riedel. Proc. Tenth International Conf. on Cyclotrons and Their Applications, IEEE New York (April, 1984) 126.
6. D.J. Clark, Y. Jongen, C.M. Lyneis, Proc. Tenth International Conf. on Cyclotrons and Their Applications IEEE New York (April, 1984) 133.
7. T. Bellomo and F. Resmini, MSUCP-31 (June, 1980).
8. A.J. Cole, LBL-19724 (April, 1985).
9. Isao Tanihata, Hyperfine Interactions 21,251(1985).
10. J.M. Nitschke, LBL-17935 (June, 1984).

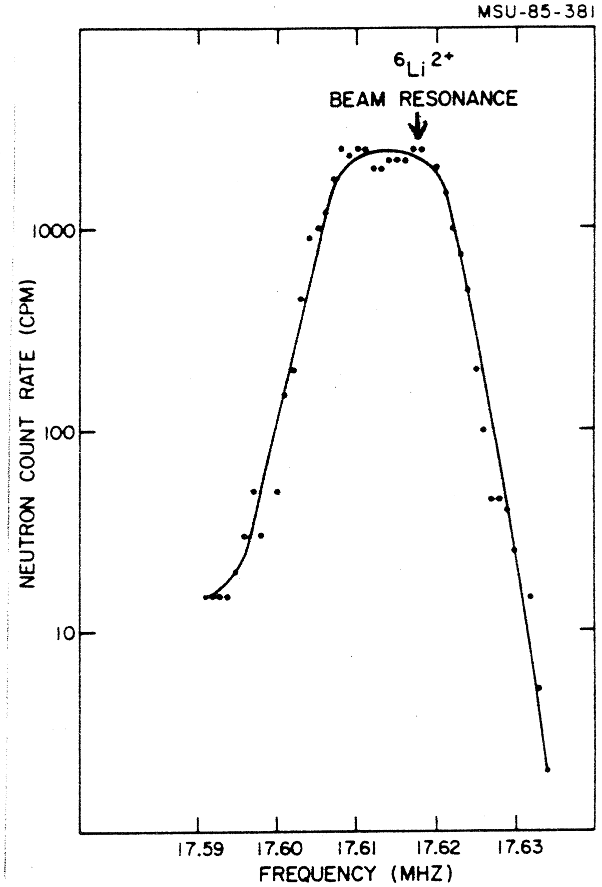


Fig. 1. The neutron count rate of a detector located near the extraction port of the K500 cyclotron versus the rf frequency. The neutron spectrum appears to be distorted on the lower frequency side of the beam resonance point, indicated by the arrow. The frequency scan was done over the range covered by the tuning capacitor. Measurements outside of this range would have required the adjustment of the rf stem short position.

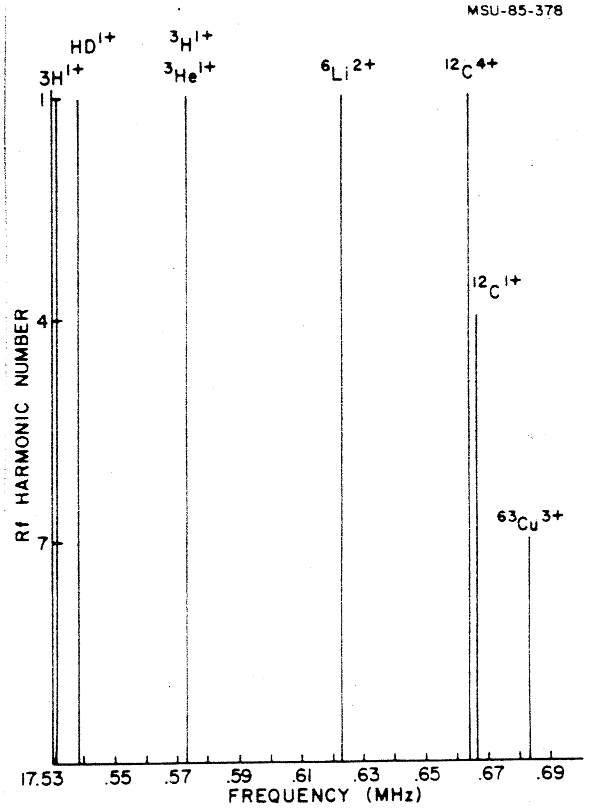


Fig. 2. The resonance frequency for various beams near the $^{6}\mathrm{Li}^{2+}$ beam is shown, where the central magnetic field of $^{6}\mathrm{Li}^{2+}$ was used in the resonance calculations. The height of each beam indicates its harmonic number, with one being the tallest. All beams are shifted far from the lithium resonance. The $^{12}\mathrm{C}^{4+}$ and $^{12}\mathrm{C}^{1+}$ is an example of two beams that would be accelerated together for many turns in the K500 before separation.

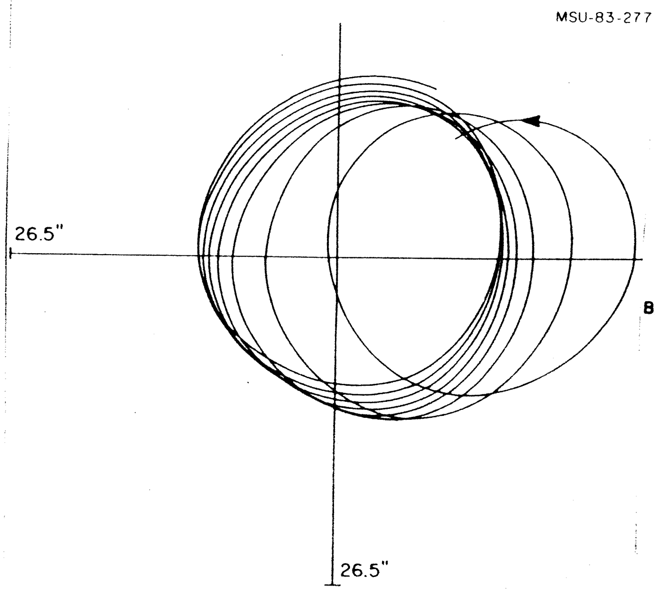


Fig. 3 The orbit of a $^{12}C^{4}+$ beam stripping to charge state 5+ and track by computing is shown hitting the center region of the cyclotron before hitting the edge at 26.5 inch. This beam then activated the cyclotron central region. This phenomena of change to the primary beam led to the idea of analogue radioactive ion beams.

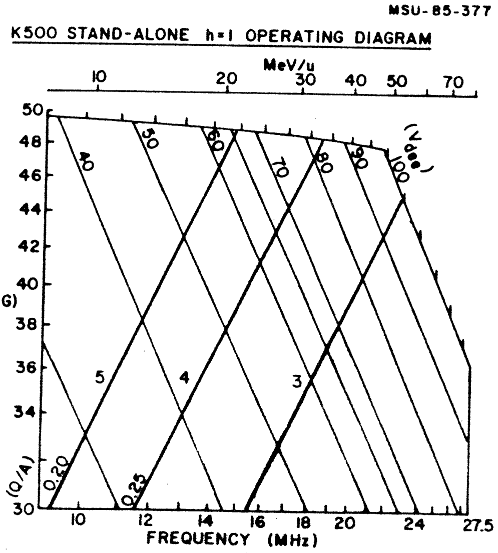


Fig. 4 The operating diagram of the K500 magnet is shown. The energy per nucleon versus the central magnetic field are plotted for various m/q ions. The m/q ions of 5,4,3 are labled. Energies greater than 50 MeV/u can be obtained for the radioactive ion beams.

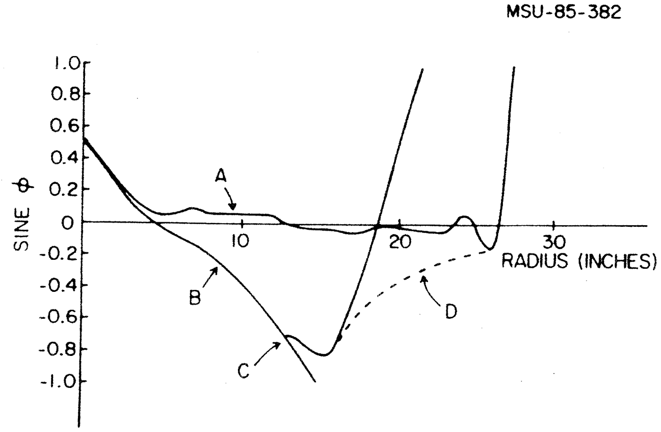


Fig. 5 The sine phase versus radius is shown for various beam condition. Curve A is for a $^{6}Li^{2}+$ accelerator to its extraction radius. Curve B is for a resonance shifted beam of Li and point C is the location of a target to produce a $^{3}H^{1}+$ beam, which then falls out of phase.

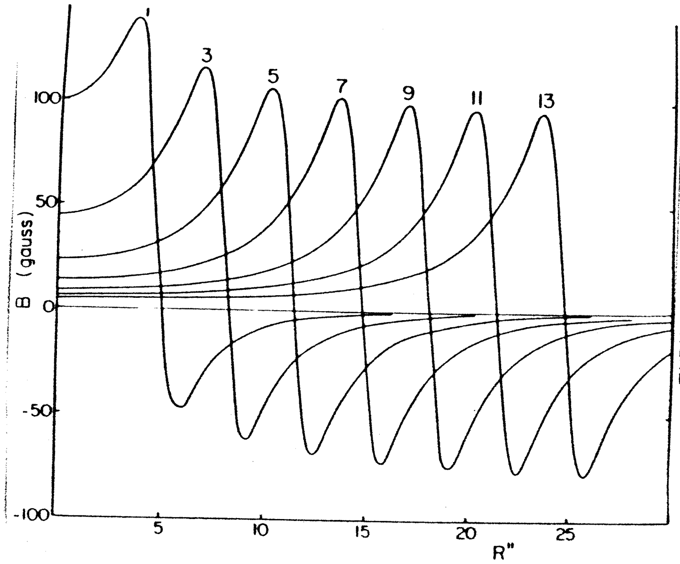


Fig. 6 The magnetic field contribution of the odd number trim coils are shown for a current of 300 amps. The half-peak height of the field is 3" wide and the amplitude is approximately 100 gauss. It is then apparent that the trim coils are capable of correcting the phase difference between the primary and fragmentation beam.

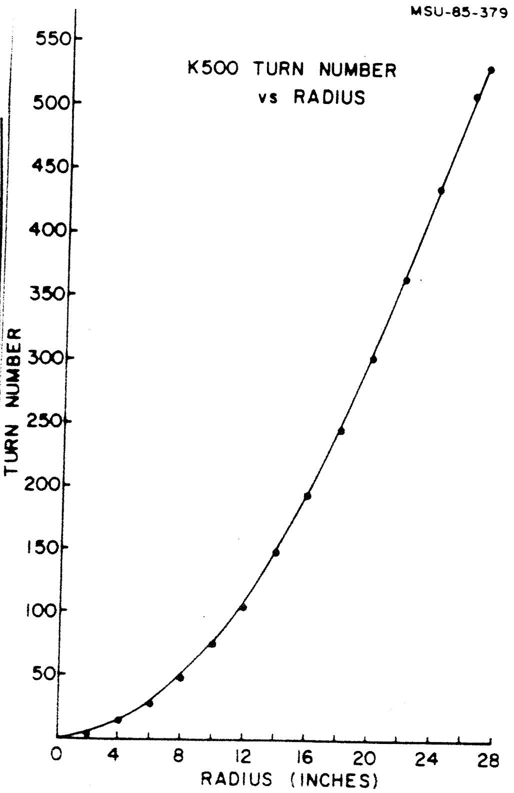


Fig. 7 The turn number versus radius for a 55.5 MeV/u $^{6}\text{Li}^{2+}$ beam is shown. At 15 MeV/u (~14") the ions would only need 50 full energy gain turns to reach 16" and hence come under the influence of the magnetic field of the next trim coil.

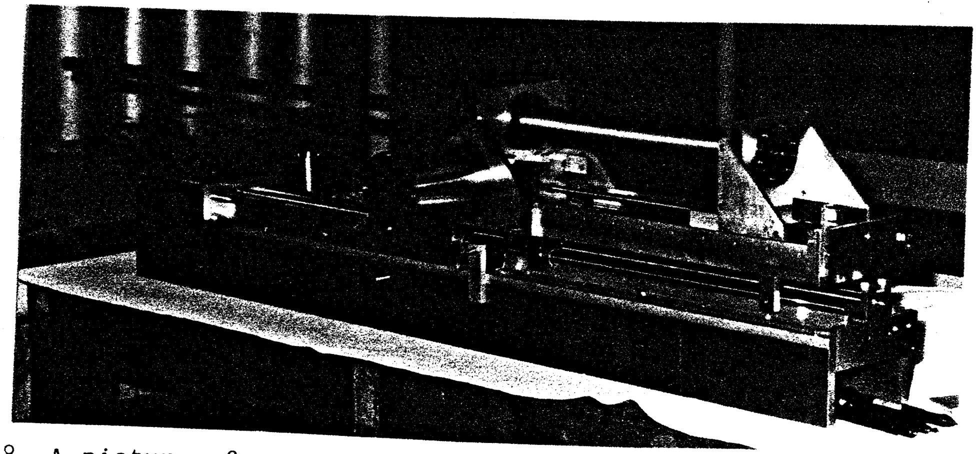


Fig. 8 A picture of a current probe that travels to 14" and has a vacuum lock is shown. Modification of this probe to contain a target would be a straight forward job.

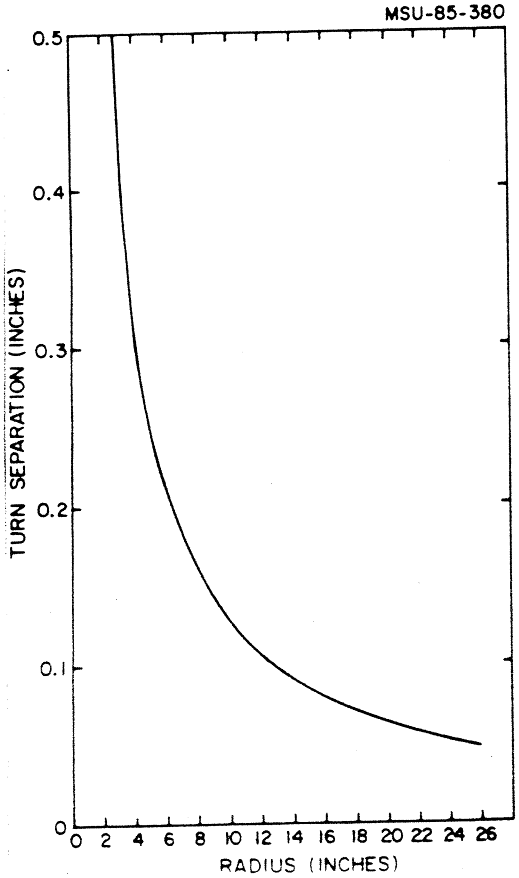


Fig. 9 The turn separation of a $^{6}Li^{2+}$ beam versus radius is shown. For a target located at 14", a turn separation of 0.090 inches is achieved. Studies of using the inner harmonic coils on the primary beam may increase this separation.

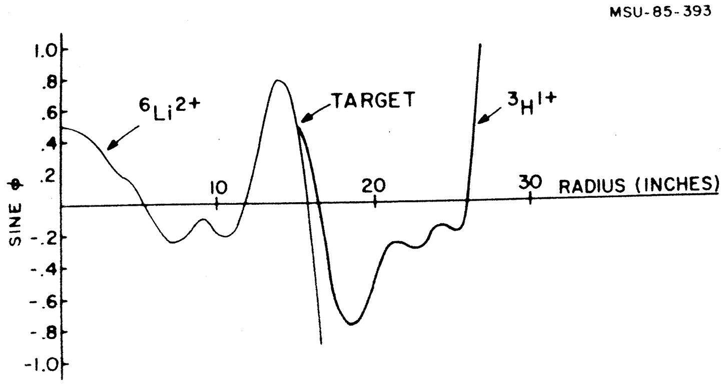


Fig. 10. The computed sine phase curve for $^6Li^2+$ going to $^3H^1+$ and final energy of 30 MeV/u is shown and confirms the capability of adjusting the K500 trim coils to match the mass difference between the two beams that occur at the target location. The starting phase at the target yields an energy gain of ~90% to the tritrons, thereby easily clearing the target on the next particle orbit.

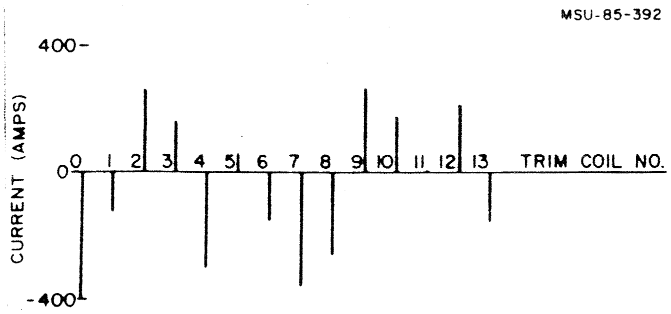


Fig. 11. The trim coil current settings for the phase curve of Fig. 10 is shown. The trim coil appear capable of adjusting the magnet field for a $\Delta\frac{(m)}{(q)}$ of 1 part in 500.

Table I

Analysis Fragmentation Ions From the K500 Cyclotrons

| Family | Primary Beam | Fragment Beam | Ion Source | Lifetime |
|---|---|---|---|---|
| 2-1 | $^{4}He^{2+}$ | $^{2}H^{1+}$ | Pig | Stable |
| | $^{6}Li^{2+}$ | $^{3}H^{1+}$ | Pig | 12.3 yrs |
| | $^{12}C^{4+}$ | $^{6}He^{2+}$ | Pig | 802 ms |
| | $^{16}O^{6+}$ | $^{8}Li^{3+}$ | Pig | 850 ms |
| | $^{18}O^{6+}$ | $^{9}Li^{3+}$ | Pig | 175 ms |
| 3-1 | $^{18}O^{8+}$ | $^{9}Be^{4+}$ | ECR | Stable |
| | $^{20}Ne^{10+}$ | $^{10}B^{5+}$ | ECR | Stable |
| | $^{22}N^{10+}$ | $^{11}B^{5+}$ | ECR | Stable |
| | $^{9}Be^{3+}$ | $^{3}H^{1+}$ | Pig | 12.3 yrs. |
| | $^{18}O^{6+}$ | $^{6}He^{2+}$ | Pig | 802 ms |
| | $^{27}Al^{9+}$ | $^{9}Li^{3+}$ | ECR | 175 ms |
| | $^{36}S^{12+}$ | $^{12}Be^{4+}$ | ECR | 11.4 ms |
| | $^{45}Sc^{15+}$ | $^{15}B^{5+}$ | ECR | 10. ms |
| | $^{54}Fe^{18+}$ | $^{18}C^{6+}$ | ECR | Not detected |
| | $^{63}Cu^{21+}$ | $^{21}N^{7+}$ | ECR | Not detected |
| 4-1 | $^{32}S^{8+}$ | $^{8}He^{2+}$ | ECR | 122 ms |
| | $^{48}Ti^{12+}$ | $^{12}Li^{3+}$ | ECR | not detected |
| 5-1 | $^{50}Ti^{10+}$ | $^{10}He^{2+}$ | ECR | not detected |

Table I. The list of analogue beams is presented above. The fragment beam is assumed to be totally stripped in the reactions. Six radioactive beams and several stable particle beams are exact analogue fragments.

Table II

| Beam | Max. Energy MeV/u | Radius at 15 MeV/u (inches) |
|---|---|---|
| $^{6}Li^{2+} \rightarrow {}^{3}He^{1+}$ | 55.5 | 13.7 |
| $^{12}C^{4+} \rightarrow {}^{6}He^{2+}$ | 55.5 | 13.7 |
| $^{16}O^{6+} \rightarrow {}^{8}Li^{3+}$ | 10.3 | 12.2 |
| $^{18}O^{6+} \rightarrow {}^{9}Li^{3+}$ | 55.5 | 13.7 |
| $^{32}S^{8+} \rightarrow {}^{8}He^{2+}$ | 31.5 | 18.2 |

Table II. The maximum energy of the five analogue radioactive beams are given and the radius in the K500 that the beams achieve at 15 MeV/u is computed.