ADJUSTMENT AND TEST OF THE 300 MeV EXTRACTION SYSTEM FOR THE NASA 600 MeV SYNCHROCYCLOTRON

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Summary

A regenerative system for extracting 300 MeV protons from the NASA 600 MeV synchrocyclotron at Langley Research Center was installed and tested. This system,[1] which brings the protons out of the accelerator through a 20-foot long channel from a point almost half of the normal exit radius, was designed to have some manual adjustments of the iron components to produce the magnetic field shape necessary for successful extraction. This paper describes the magnetic measurements, orbit calculations and magnetic calculations that were used for adjusting this extraction system, which successfully extracted reduced energy protons with about 20% of the full energy current. Initial adjustments in the location and quantity of iron were made when magnetic measurements were performed using orbit calculations and phase-space plots based on the measured magnetic fields which were systematically altered until the phase-space plots indicated that the peeler-regenerator sections would produce extraction of protons with acceptable energy. During the final adjustments, using radiographic techniques to locate the proton beam in the extraction channel, alterations were made to various sections of the channel permitting it to accept the proton energy and entrance angle produced by the peeler-regenerator sections.

Introduction

For part of the studies contemplated at the NASA Space Radiation Effects Laboratory, protons having energies much less than the 600 MeV available from the synchrocyclotron are required.[2] In order to reduce the energy, it was decided that extraction from a smaller radius would provide a practical means of obtaining lower energy. The problem of bringing the protons out by magnetic shielding becomes increasingly difficult as the radius is decreased. Extraction from less than sixty percent of full radius seemed to be unreasonable.

The basic problems of extraction from so deep within the cyclotron gap were those of compensating the field distortions caused by the channel and adjusting the channel for proper focusing and bending of the beam. Regenerative extraction was itself nothing new and seemed to present no new problems. However, regenerative systems are usually near the edge of the magnet where the reduced field is an aid to extraction.

Description of System

Extraction Theory

As the circulating beam of particles is accelerated in a cyclotron, its radius gradually increases so that the path of the particles is a spiral of small angle. The particles' gain in energy per turn will have its corresponding gain in radius per turn. If the radial gain per turn were great enough to leave a gap between successive turns, a thin wall could be placed in the gap to separate regions with different electrostatic and magnetic forces such that those particles beyond the wall could be steered out of the cyclotron and those inboard of the wall could receive additional acceleration so that they would be extracted on subsequent turns.

Unfortunately, the rate of acceleration in the 600 MeV synchrocyclotron is much too small to give a large enough radial "jump" per turn to use a physical wall of reasonable dimensions. In order to extract an external beam, it is necessary to provide some means, other than normal acceleration, to produce an adequate radial jump. The peeler-regenerator system[3,4] can provide such a jump.

The peeler is a region in which the magnetic field decreases with increasing radius and the regenerator is a region in which the magnetic field increases with increasing radius, with these regions both starting abruptly at some critical radius. As the circulating particles increase in energy and radius they come out to the edge of the peeler where the decrease in field causes a lower bend angle so that as they leave the peeler they have gained an increment of radial momentum which carries them out to a greater radius in the zone between the peeler and regenerator. At the regenerator a higher magnetic field is encountered causing the particles to bend inward giving a decrease in radial momentum. The alternate increasing and decreasing of radial momentum produces an increasing radial oscillation of the particles. If phase stability exists, an adequate localized radial gain per turn may be produced so that many of the particles can jump over a shielding wall into a region of lower magnetic field where they may be steered out of the cyclotron. The portion of the particles that will be lost as they strike the leading edge of the wall depends upon the width of the wall and rate of increase in radius of the particles.

The particles entering the channel have been brought from their earlier radius and radial momentum to new values corresponding to the entrance of the channel. The design problem at this point is to further change the radius and radial momentum, in approximately one-half turn, to values that can be accepted by the external beam transport system.

The radius, radial momentum, vertical position and vertical momentum are coordinates of the particle in phase space. The channel must now transform these phase space coordinates of the particle at the entrance to match the phase space acceptance of the beam transport system. This can be done in a multitude of ways by gradually increasing the radius of curvature of the beam using magnetic shielding, but vertical as well as radial focusing must be maintained.

Design

Based on the peeler-regeneration system, a design was prepared. The design consists of a peeler-regenerator system and an extraction channel. The peeler-regenerator system brings the 300 MeV protons out of their normal orbits, at a radius of 58.69 inches, to the entrance of an extraction channel, at a radius of 63.45 inches. The extraction channel then guides the protons out of the cyclotron. Figure 1 shows the arrangement and also shows the beam path schematically.

Peeler-Regenerator. The protons enter the peeler, when they reach the 58.69-inch radius, where they are subjected to a reduced field for 10°. After leaving the peeler they travel 48.75° in the normal field before coming to a 15°-wide regenerator. The entire magnet pole is considered as four simple wedge-shaped bending magnets having different indices with abrupt transitions and being joined so that all have the same field at a radius of 58.69 inches.

The field index designed for the peeler was 2.28 and for the regenerator -2.383. The field index elsewhere is .033. Using these values, the transfer matrices for each bending magnet were computed using the OPTIK computer code[5] as were the product matrices for small deviations in r, P_r, z and P_z. Several successive paths are shown on Figure 2 where it is seen that both the radius and the radial momentum are increased at the entrance to the peeler on successive turns. The magnitude of jump per turn increases adequately to bridge the inner wall of the extraction channel. The roots of the product transfer matrix indicate vertical stability.

Extraction Channel. The extraction channel shown in Figure 1 consists of a series of bending magnets having lower fields than the cyclotron so that greater radii of curvature is obtained. The entrance radius is 63.45 inches and the entrance angle is 0.0393 radians. The exit of the channel, at the center of the first bending magnet in the beam transport system, is at a radius of 141 inches. The desired angle at this point in 50° but some deviation is allowable here because a bending magnet can provide correction.

After leaving the edge of the magnet pole, the beam traveling through the fringe field received only slight bending. Using a fringe field approximation. a beam position was determined such that the travel of the beam through the fringe field from 104.33 to 141 inches would require no additional magnetic shielding. This shielding channel exit was at 104.33 inches and an angle of $15^{\circ}27'$. The total bend in the channel is $153^{\circ}30'$.

By geometric construction, three successive regions were found to satisfy the desired entrance and exit conditions. These regions have the following radii of curvature and bend angle: 73.2 inches, $50^{\circ}5'44''$; 86.5 inches, $94^{\circ}18'18''$; 170 inches, $9^{\circ}6'$. Other combinations may be possible.

Each region with its characteristic radius of curvature is composed of short straight sections in which a specified magnetic shielding and field gradient is obtained. By alternating the gradients, focusing was accomplished to give reasonable phase space acceptance for the channel in both the horizontal and vertical planes.

Shielding and Compensation

To produce local changes in the magnetic field without the use of additional coils, iron was added to the cyclotron gap. Placing two bars symmetrically above and below the median plane produces an increase in field in the area between the bars. Putting a single bar straddling the median plane causes a decrease in the field adjacent to the bar.

A computer program was used to calculate the changes in magnetic field produced by single bars or by multitudes of bars, from which the amount and location of iron to give the required magnetic configuration was determined. However, it was clear that some adjustments based on measurements would be required.

The reduction in magnetic field of the magnetic channel was obtained by placing bars of magnetic material on either side of the channel. These bars provided shielding from the field, established the horizontal aperture of the channel and h where unequal provided a field gradient. The shielding effect extended outside of the channel. The decrease toward the center of the cyclotron was compensated for by placing additional iron above and below the median plane inboard of the channel.

The peeler required an abrupt decrease in field starting at a radius of 58.69 inches. Since the channel produces a decrease in field which extends farther in than 58.69 inches, some compensation was provided.

The regenerator required a sharp increase in field at 58.69 inches, thus it must be over-compensate for the channel. Since in reality neither the regenerator nor the peeler could give an abrupt change as considered in the conceptual design, the effective edge of the regenerator was made adjustable by the radial positioning of the regenerator.

Figure 3 shows the entire 300 MeV extraction system mounted on a removable platter. This platter is easily extractable from the cyclotron so that other systems can be installed and used. The removal of the platter is also necessary for making adjustments to the channel or related equipment. The entrance is in the far side of the picture and the exit is in the near side.

Magnetic Measurements

Measurements were made to obtain magnetic field data for use in orbit calculations to verify the configuration of the 300 MeV extraction system as installed and for use in making necessary changes in the field configuration in order that the system would function properly.

To match the input acceptance of the extraction channel with the output of the peeler-regenerator extraction system, an optics program was used initially to give a desirable field value. At this stage, the general orbit code[6] developed by Dr. David I. Hopp of VARC was used with the measured field values to determine the output of the peeler-regenerator system.

Initial Measurements

Field measurements were made in the radial mode of operation with a magnet current of 1700 amps. A grid of $R = 1$ inch and $\theta = 5^{\circ}$ was used everywhere, except in the vicinity of the peeler and regenerator, where θ was 1° in some cases. In the extraction channel, measurements were made using a probe moved by hand from section to section; nine measurements being made in each section. These consisted of three radial positions each at the entrance, center and exit of each section.

A set of measurements was made for which orbit calculations were performed to find the highest stable energy that would remain within the cyclotron. The orbit calculations for the first measured field showed the highest stable energy in the cyclotron to be about 250 MeV, which was much too low.

Radial plots of the field through the peeler and regenerator indicated the the regenerator extended too far into the center by two inches and that the field values in the channel in almost every section was too high by about 300 to 400 gauss. The presence of the large channel created a very large distortion in the field.

The first correction was made by simply moving the regenerator two inches radially out from the center, but new measurements and orbit calculations showed the changes in compensation were still required to correct the distortion caused by the channel.

Three approaches to the compensation problem were made. (1) Calculations of orbits based on hypothetical changes in the magnetic field to verify the desirability of the contemplated changes, (2) calculations of changes in field that would result from contemplated changes in size and location of compensation bars and (3) actual changes in size and location of compensating bars followed by verifying measurements in particular sections.

The remaining problem which had to be worked out was the channel itself. The field strength in the channel was too high and was lowered by adding iron to the walls using only the incremental field change to determine the additional iron required.

Orbits for Hypothetical Field

The hypothetical field was obtained from the measured field by arbitrarily assigning new field values in the regions inward of the peeler and regenerator that were equal to the average field for the particular radius. These did not give a zero first harmonic but rather gave values which hopefully could be obtained with reasonable effort.

Orbit calculations on this hypothetical field showed stable orbits up to 306 MeV which was high enough to give a beam which the channel could be made to accept. Phase space tracking of the stable fixed points for the orbits as seen at aximuth zero showed great improvement over that for the initial field.

The changes in amount of iron and location of this iron in the magnet gap in order to produce the incremental change in magnetic field to match the hypothetical field was then calculated and installed. Several measurements and readjustments were necessary to approximate the hypothetical field. The degree of approximation sought and obtained was one giving orbit calculations with suitable exit energy for the beam at an acceptable radius and radial momentum.

Final Measurements

Additional shielding iron was added to the walls of the extraction channel until measured values of field were obtained to indicate a favorable chance for the beam to traverse the channel.

After all the additional iron was added to the channel and the changes in compensation were made, final measurements were made of the field in each channel section and a map of the field external to the channel from 40 to 70 inches radius in one-inch radial and 5° azimuthal steps, except where limited by the channel or other obstacles.

The orbits within the cyclotron were calculated by the orbit code. It was found that stable orbits exist up to 315 MeV. Those protons at 300 MeV having large initial radial oscillation would be extractable, however, it was not clear whether their phase coordinates during extraction would match the requirements for traversing the channel. However, inward adjustment of the regenerator would reduce the energy from 315 MeV to 300 MeV and could alter the phase coordinates to match the acceptance of the channel.

Final Adjustments

The measured magnetic field gave indications that extraction would be successful; however, since some adjustments on start-up would probably be required, additional orbit calculations were made to indicate the degree of adjustment which might be made. Of particular interest was the amount of motion of the regenerator that might be required and the effect that such motion might have.

Calculations for Positioning the Regenerator

Magnetic measurement indicated that the 300 MeV system was quite close to a final alignment. However, uncertainties in phase space of the accelerated beam indicated the need for additional adjustments at start-up.

These adjustments consisted of finding the optimum position of the regenerator, retuning and focusing the channel. The fringe field effects outside the pole tips required additional adjustment of the last three channel sections.

To aid in finding the optimum position of the regenerator and to correct possible errors in computer integration caused by using data on too coarse a grid, the magnetic field data were modified. Field values every one degree were used instead of every five degrees as measured. This was done by a four-point interpolation between points where the field change was gradual and adjusting from one-degree data previously taken in the vicinity of the peeler and regenerator where the changes were rapid. Those field values in the region occupied by the regenerator were shifted inward by a four-point interpolation between points at a given azimuth. This procedure permitted study of the effect of moving the regenerator.

Phase space plots were made for the regenerator moved from its initial point inward by one inch, 1.25 inches and 1.5 inches. These phase space plots in cyclotron units and dimensionless radial momentum units shows the phase space area of particles still unextracted at a given energy as well as the exit phase space coordinates of the particles being extracted. These phase plots all showed the conditions at the azimuth of the channel entrance.

As shown in Figure 4 at a given setting of the regenerator the area of stable phase space goes down as the energy goes up, as expected. At the lower energy, only particles having large initial horizontal oscillations enter the effective peeler-regenerator field. As energy and radius increases the amount of initial oscillation required to bring particles to the peeler and regenerator decreases; also the value of radial momentum at the center of the magnetic channel decreases. Thus lower-energy particles having high enough radial oscillation to be acted upon by the peeler-regenerator will be brought out to the channel and enter at a steep angle while particles of higher energy enter the channel at a less steep angle.

As the regenerator is moved inward not only is the phase space area at a given energy increased but the entrance angle also decreases. The regenerator must therefore be in a position where it extracts protons of the proper energy and also where it extracts them with the best angle of entry to the channel.

Figure 5 shows the energy of those protons being brought to the entrance of the channel with the best angle for entry as a function of regenerator position. It appears from this figure that setting the regenerator at any of these positions can give protons of an acceptable energy; however, vertical instability may become a problem with the smaller regenerator setting.

Adjusting the Channel

The amount of shielding required in the channel and the focusing properties of the channel were computed originally for 300 MeV protons and an arbitrary source location and size.

The actual energy of protons brought to the entrance of the channel is very dependent upon the unknown initial oscillation about the equilibrium orbits and on the regenerator position. To ascertain the energy at extraction, Dr. K. M. Crowe suggested use of a detector to indicate the time of extraction and to observe the R.F. frequency at that time. The orbit calculations showing frequency at different energies gave data on energy versus frequency.

By making autoradiographs of foils inserted in the first several sections of the channel after bombardment by the beam and by making frequency measurements, the settings of the regenerator giving strong beams at the entrance of the channel and corresponding energies were found. These measurements led to a regenerator setting of 65¼ inches which indicated peak beam intensity at 314 MeV. The walls of the channel were then altered to give fields and gradients to accept this energy and to approximate the desired focusing.

By calculation of the incremental change in fields and gradients relative to the previous measured values, new field and gradient values were obtained. Beam measurements and radiographs of foils showed this configuration to be acceptable. Figure 6.

It appears that some of the beam entering the channel may be so far off axis vertically and so far off energy that there is no possibility of retaining it.

Acknowledgements

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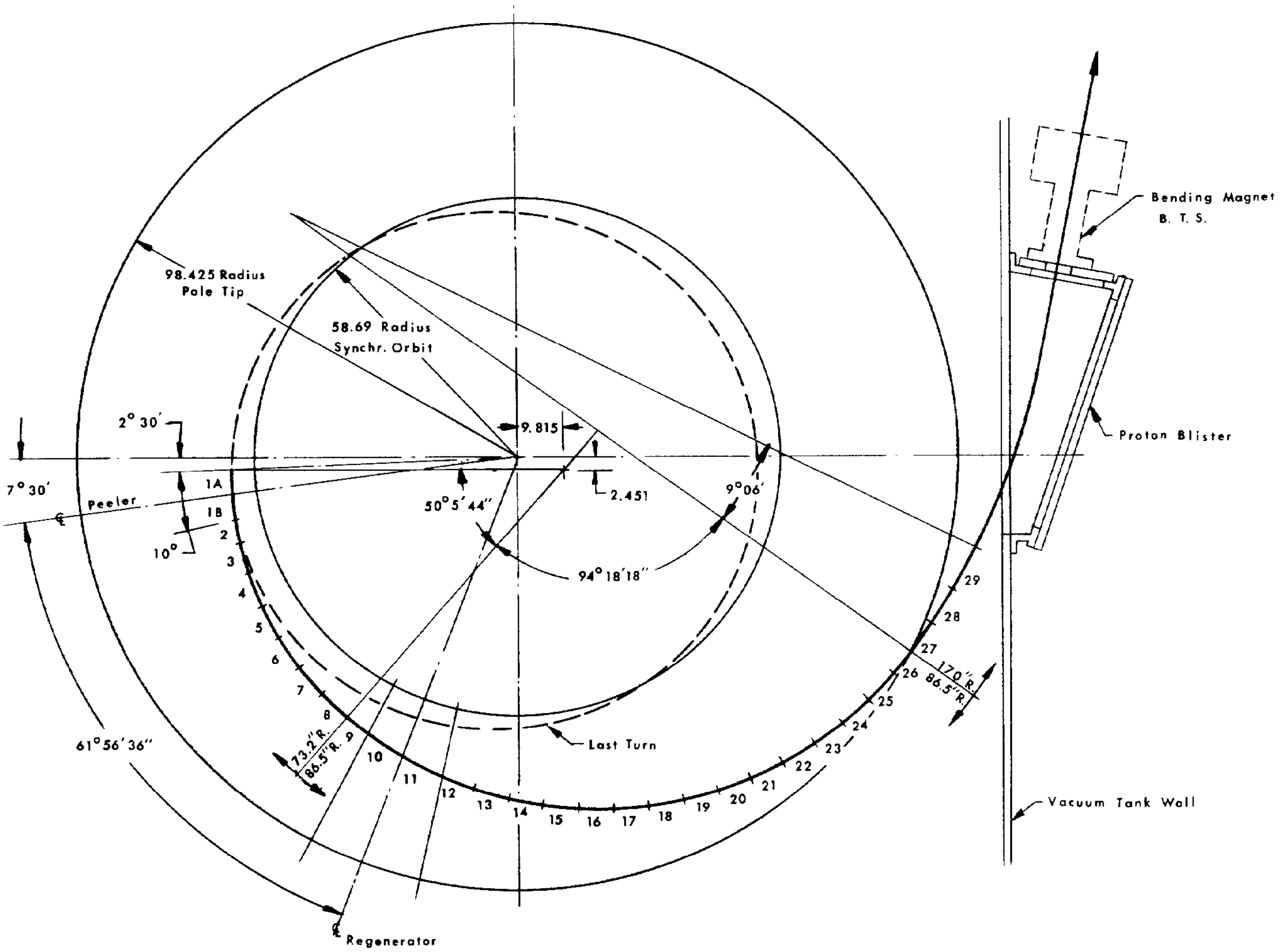


Fig. 1. Arrangement of Extraction System.

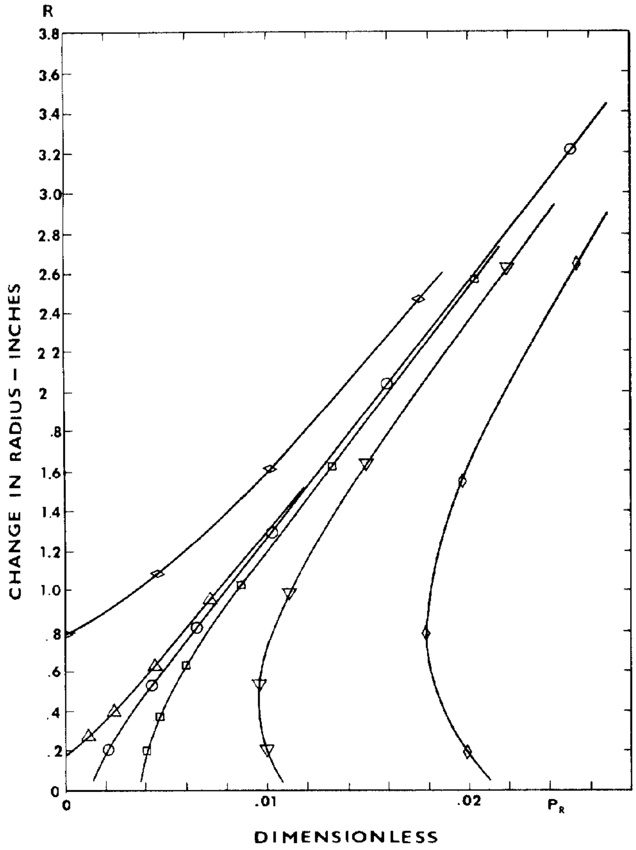


Fig. 2. Phase Space Tracing for Regenerative Extraction.

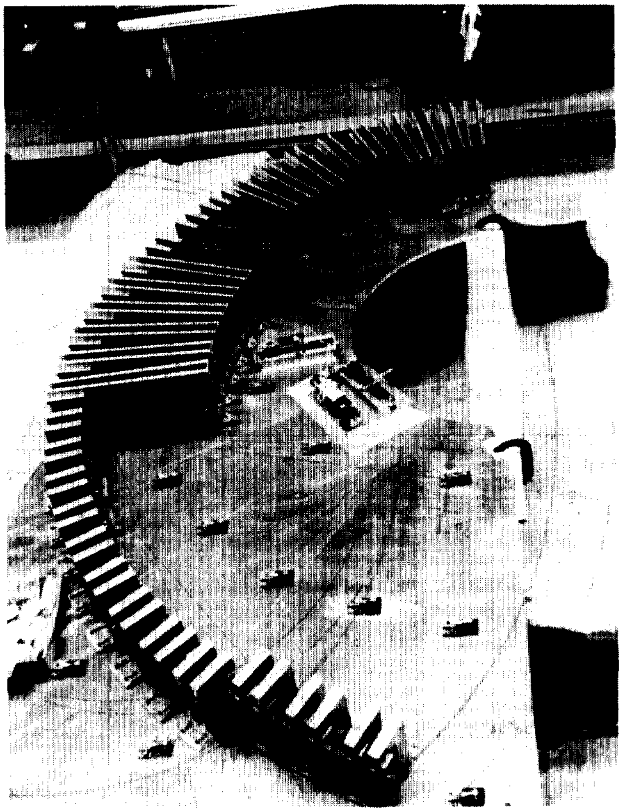


Fig. 3. Extraction System on Platter.

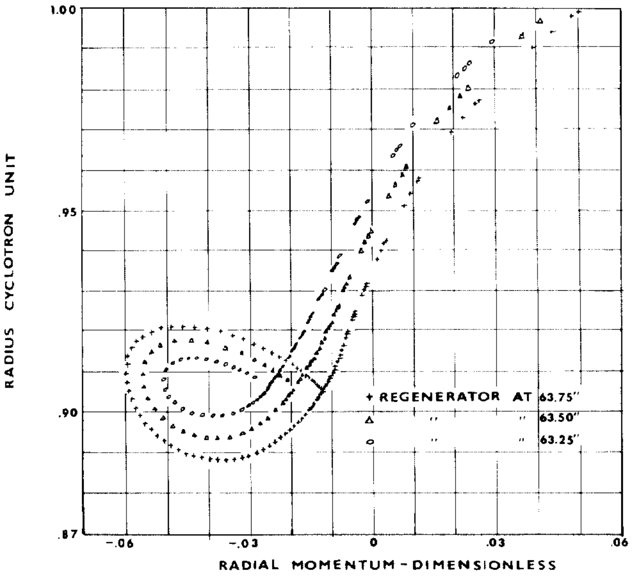


Fig. 4. Phase Space Plots at Different Regenerator Positions.

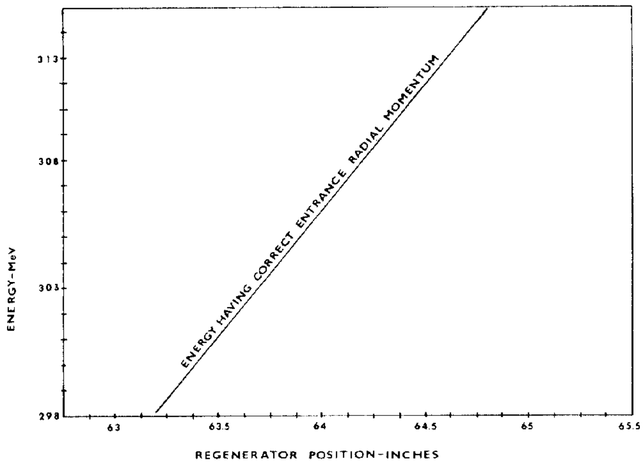
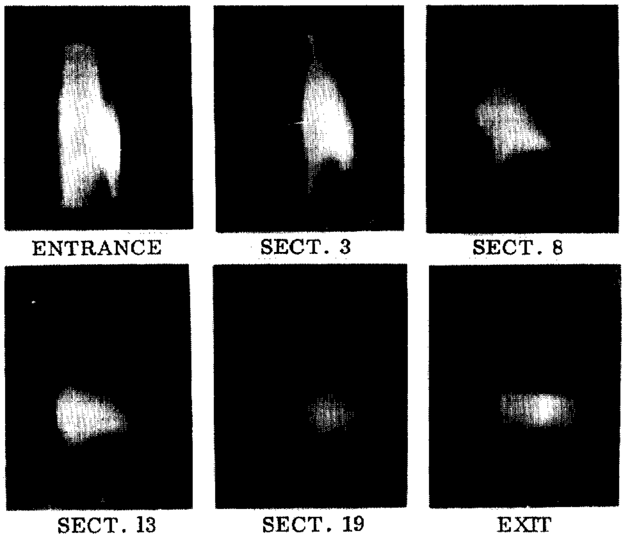


Fig. 5. Particle Energy for Different Regenerator Positions.



ENTRANCE SECT. 3 SECT. 8

SECT. 13 SECT. 19 EXIT

Fig. 6. Radiographs of Beam in Channel

Entrance	Sect. 3	Sect. 8
Sect. 13	Sect. 19	Exit