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Beam Extraction from the MURA 50 Mev FFAG Accelerator*

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I. INTRODUCTION

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The 45 Mev stacked beam has been extracted in a single turn from the MURA 50 Mev electron accelerator. The method employed is similar to that used with the small spiral sector accelerator.^{1,2}

The extraction channel has been designed to be a model of a beam which would be used for neutrino experiments in a large FFAG proton accelerator. The fractional momentum width of the channel is 0.8%, corresponding to a two-second accumulation in a 12.5 Gev proton accelerator. The size of the beam in relation to the stability limit of the machine is chosen to resemble the beam in the high energy accelerator.

II. GENERAL DESCRIPTION OF THE SYSTEM

The main systematics of the extraction experiment can be seen by inspection of Fig. 1, a plan view of the extraction channel. The beam circulating in the accelerator passes through the aperture of element MX-1. In element MX-1 a magnetic field of approximately 170 gauss extending 12.5 cm is switched on in a time short compared to the 42 nsec period of revolution of the particles. This field deflects the beam by approximately 10 milliradians.

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One sector or approximately one-quarter betatron oscillation away from MX-1, the beam has reached its maximum deviation of 1 cm, and passes by the septum of MX-2. MX-2 is an air-cored pulsed magnet whose field strength is 4 kilogauss. MX-2 provides an additional bending of approximately 17° to the beam. It is this rather severe bending, necessary to extract the beam, which poses the greatest danger of aberrations.

Upon leaving MX-2 the beam proceeds across the pole of the next negative magnet which further deflects the beam outward. At this point it passes out of the main accelerator vacuum tank.

In order to miss the next magnet back leg, further bending is required. Because of the small amount of space available, another pulsed magnet, MX-3, is employed. MX-3 is a 5 kilogauss picture frame iron-cored magnet which bends the beam 24° .

MX-4 and MX-5 are dc 5 kilogauss magnets with adjustable entrance edge angles. With appropriate choice of edge angles, spacings and bending angles of MX-4 and MX-5, particles initially on different equilibrium orbits of the accelerator will all lie on a single line when leaving MX-5. MX-4 is placed 80 cm from MX-3 and bends the beam 30° . Its entrance edge angle is 1° (radially focusing). MX-5 is placed 1 meter from MX-4 and bends the beam 45° . Its entrance edge angle is 0.3° (radially focusing). The small entrance edge angles help to minimize the aberrations in the system.

At several places in the system electrostatic induction electrodes are provided to detect the position of the center of mass of the beam.

These are placed just before MX-3, MX-4, MX-5 and at the end of the extraction channel. At the entrance to MX-2 vertical and radial position may be detected by means of secondary emission flags which can be lowered into the path of the beam. The position of the beam in MX-1 can be inferred from measurements by other probes in the machine.

The vertical position of the beam in MX-1 can be controlled by two coils wound on accelerator magnet poles, each one-quarter of a vertical oscillation away from MX-1. Similarly, the vertical angle of the beam on leaving MX-1 can be controlled by two coils, one of which is located in the same magnet as MX-1, the other of which is located one-half vertical betatron wavelength downstream from MX-1. The radial position of MX-1 and MX-2 can be controlled remotely. MX-2 is positioned by placing it as close as possible to the circulating beam without interfering with it. The radial position of the extracted beam at MX-2 can then be controlled by the excitation strength of MX-1. Similarly, the radial position of the beam at MX-3 can be controlled by the excitation of MX-2. No vertical steering is provided between MX-2 and MX-3 since it was felt that positioning could be achieved with the coils described for MX-1.

III. DISCUSSION OF ORBITS

The choice of gradients in MX-1 and MX-2 and the choice of edge angles in MX-3 were dictated by several considerations. The first of these was to maintain the beam size within the channel width. The second of these was to facilitate the design of the chromatic system to be used for

analysis later. Further, the orbit considerations had to accommodate design problems in these elements.

A compromise solution between these often conflicting requirements was found. The field of MX-1 was chosen to be as uniform as possible. MX-2 was chosen to have a field which rose 5.5% from the septum across its 1.2 cm aperture. These gradients provide the radial focus and momentum crossover at the entrance to MX-3 discussed above in Section II.

During the design, digital computation procedures were used to obtain the orbits of particles in the extraction channel. The measured fields in MX-1 and MX-2 were used with the measured fields in the accelerator to calculate orbits. In Fig. 2 we have plotted the phase space ellipse corresponding to the radial beam size due to betatron oscillations in the accelerator just prior to extraction. The other two fixed points correspond to the equilibrium orbits of particles at the upper and lower energy extremes of the extraction channel. The ellipse and fixed points displaced to the right represent the beam entering MX-2. The transverse radial phase space of the beam as it enters MX-3 is plotted with the same origin as for the beam in the accelerator. Figure 3 is a plot for the vertical motion. The ellipse at the left is the beam at MX-1 and MX-2; the ellipse at the right is the beam at MX-3. The distortion of the phase ellipse is quite small even though the beam has traversed the peak of the magnetic field in the negative magnet just prior to MX-3.

The design of the chromatic system from this point to the exit from MX-5 was achieved by utilizing a beam transport program available

for use with our computer.³ Since at this writing this system has not been utilized, a complete description will not be given.

IV. COMPONENTS

A. MX-1

The field in MX-1 must rise in a time short compared to the revolution period of the particles and must then remain constant for one revolution period of the particles. There are three possible choices of ways to terminate the transmission line. (1) We may terminate it in its characteristic impedance, in which case we have electric and magnetic fields which deflect the beam almost equally; (2) we may leave the end open, in which case we have only an electric field to deflect the particles; or (3) we may short circuit the end so that we have only a magnetic field to deflect particles. All three choices deflect relativistic particles by about the same amount for a given voltage wave exciting the line. We have chosen the third method, since it requires no terminating resistor in the vacuum. Further, if the transit time along the line is shorter than the rise time of the voltage wave, the required electrical insulation strength of the vacuum feed-through is less than in either (1) or (2).

The magnet employed in the extraction system is shown in Fig. 4. The choice of electrode configuration was made on the basis of studies in an electrolytic tank. A 1 cm opening aperture with uniform field was obtained in a box whose height totaled 2.36 cm. The radial extent of good field is approximately 1 cm. The impedance of the magnet is 43 ohms.

It was not possible to avoid the slight mismatch at this point since the limited vertical height of the vacuum tank did not permit the design of a 50 ohm transmission line with the desired 1 cm of uniform field.

MX-1 is excited by discharge of the energy stored in a transmission line. Switching is accomplished by a sequence of spark gaps which achieve the required rise time. A three-element spark gap, shown in Fig. 5, provides a wave front whose rise time is approximately 20 nsec. This wave front propagates to a high pressure spark gap of very narrow spacing, shown in Fig. 6. By adjustment of gap spacing and pressure, the breakdown can be delayed until after the 20 nsec rise time of the arriving wave, thus sharpening the wave front. The storage cable is charged to 80 kv. This results in a 40 kv pulse.

Measurements of the current pulse in the line after the sharpening gap indicate an abrupt rise in approximately 1 nsec with ringing which persists for several nanoseconds. The mismatch suffered at the entry of the wave front to MX-1 causes ringing which damps out in several nanoseconds.

B. MX-2

MX-2 is an air-cored magnet consisting of a ten-turn coil shielded in a conducting box. The field in the useful aperture is the return flux which passes between the outside of the coil and the wall of the box. This minimizes the septum thickness. Proper boundary conditions are achieved in the electrolytic tank by equalizing the current flowing from coil elements

to the outside wall. This scheme was used to determine the configuration of the coil.

The fields of this magnet were measured with search coils. A long coil was used to measure the integrated field along the path of particles to determine the average radial gradient.

The coil was wound of 1.5 mm diameter hollow copper conductor and was water cooled. The coil was wound on a form of Kel-F plastic. The shielding box was constructed of copper and aluminum. Figure 7 shows MX-2 with one end plate removed. The physical size of this unit is approximately 3.2 cm x 8 cm x 17 cm.

MX-2 was powered by discharging a capacitor through the coil. The inductance is approximately $6 \mu\text{h}$ and currents of 2500 amperes were required to give a 4 kilogauss field. The capacitor was chosen so that the circuit was resonant at 50 kc. The capacitor voltage was then 8 kv.

C. MX-3

MX-3 is an iron-cored picture frame pulsed magnet with field strength of approximately 5 kilogauss. It has a radius of curvature of 30 cm and a bending angle of 24° . It is constructed of 29 gauge #52 transformer iron with additional insulation added to the laminations to reduce eddy currents. The picture-frame cross section is obtained by stacking separate L-shaped laminations. By stacking all laminations parallel, 12° entrance and exit edge angles are obtained. The mating surfaces are ground to assure uniform gap spacing. The top and bottom sections are cemented to Bakelite forms which contain water-cooling tubes, and which

clamp the two halves together. The coil is wound in two halves, each containing 100 turns of #22 ceramic-insulated wire. The vacuum tank which passes through the magnet is fabricated of Inconel-X to minimize attenuation of the magnetic field. The aperture through which the beam passes is 2 cm x 2 cm. Figure 8 is a photograph of the bottom half of MX-3 with the bottom coil half in place and a section of the vacuum tank in place.

This element is excited by discharging a capacitor through the windings. The resonant frequency is chosen to be 600 cycles. The fields were measured by means of a search coil and it was found that the deviation from uniformity of the magnetic field was less than 1%. Further, it was found that the fields at the exit and entrance behaved in the way expected with these edge angles.

V. RESULTS

At this time MX-1 and MX-2 have been installed and the accelerator reassembled. The beam has been extracted and allowed to pass through a thin window in the extraction port, just prior to the future location of MX-3. Visual measurements have been made with the aid of a fluorescent screen and television monitoring. Charge and current measurements have been made using a Faraday cup which stops the beam. The beam has been observed to come out the center of the channel with no auxiliary steering of the type described in Section II.

Studies with single accelerated beam pulses have shown that 85% of the beam circulating just prior to extraction is collected by the Faraday cup.

The beam pulse has been observed to last 37 nsec, or 33% of the 42 nsec revolution time of the particles. This is consistent with the rise time of MX-1. The instantaneous beam current has been observed and is constant throughout the beam pulse after the initial rise. Currents of 40 ma per pulse have been observed in the extracted beam, although no attempt has been made to optimize the accelerated beam since reassembly of the accelerator. Figure 9 shows the beam spot as observed by exposing x-ray film to the beam. The efficiency of extraction was measured as a function of the energy of the beam. The efficiency was uniform over more than the desired 0.4 Mev width.

Some preliminary results have been obtained in extracting stacked beams. Without serious attempts to optimize the beam stacking, it was found that after three beam pulses in the stack, the current in the accelerator and in the extracted beam did not increase proportionally to the number of pulses stacked. Presently we are attempting to optimize the beam stacking.

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FIGURE CAPTIONS

Fig. 1. Plan View of Extraction Channel.

Fig. 2. Phase Ellipses of the Radial Motion.

Fig. 3. Phase Ellipses of the Vertical Motion.

Fig. 4. MX-1 with End Plate Removed from Feed End.

Fig. 5. Three-Element Spark Gap in Operation.

Fig. 6. Sharpening Gap.

Fig. 7. MX-2 with End Plate Removed. Coil Form, Coil and Thin
Septum Visible.

Fig. 8. Bottom Half of MX-3 with Vacuum Chamber in Place. Laminations,
Bakelite Form, Coil Visible.

Fig. 9. Beam Spot Obtained by Exposure of X-Ray Film to Beam.