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Abstract

Following the success of a test electrostatic regenerator unit in the Berkeley 88-in. cyclotron, a new regenerative deflection system was built. The system was comprised of a regenerator unit and an electrostatic channel.

The regenerator unit was positioned opposite the dee near extraction radius. This unit having a positive voltage gives the last few accelerating internal beam orbits such a bump off their normal orbit paths that their turn-to-turn separation was increased at the entrance to the deflector channel. This separation decreased the amount of beam dumped on the septum and thus increased the efficiency of the deflector.

The electrostatic channel consisted of three pairs of electrodes. Each end of each electrode was positioned remotely from the control room where its radial position was also read. This was made possible by the use of a flexible linear ball-bearing unit connected between the electrode end and a motor drive unit located outside the cyclotron vacuum barrier. This same motor unit also drove a system of selsyns for position readout. The entrance septum elevation was also remotely adjustable. The septum was mounted on a linear ball-bearing wedge driven by a unit similar to that used in positioning the electrodes.

The regenerative deflector was installed in November 1965 and delivered beam when first tried. It is presently undergoing beam development alternately with delivery of experimental beam.

In early 1964, an analytic study of a regenerative deflector system for the 88-inch cyclotron was undertaken. Based on the results of this study and with the Birmingham 40-inch cyclotron beam extractor[1] used as a guide, design of a new deflector was started.

The first step was to build a test regenerator unit. This unit was to test the practicality of the analytic study and the effects of a regenerator on internal beam in the 88-inch cyclotron. Since the expected "life" of this test unit was to be very limited, many conservatively "safe" rules in design were broken for convenience: Specially made position-readout potentiometers were mounted inside the vacuum and magnetic fringe field; support insulators for the high-voltage element were also positioned there; positioning lead screws operated inside the vacuum chamber; liberal use was made of carbon, copper, and aluminum materials for various parts which were usually fabricated from nickel and stainless steel alloys. Not only did the test of the regenerator effect on the beam prove successful, but the experience and information gained was subsequently applied in other areas of the 88-inch cyclotron.

The regenerative deflector was designed to replace an existing electrostatic deflector.[2] The same space and maintenance restrictions still applied as with the first deflector. As many overall features were retained as possible to allow interchanging the deflectors during the development stages of the new one. Perhaps some of the basic parameters for the deflector design should be reviewed here (see Fig. 1).

The cyclotron has a horizontal magnet gap of 5-3/4 inches between trim coil liners. It has one 180° dee. The beam is accelerated counterclockwise. The deflector delivers beam to the external beam tubes that are normal to a radial line 104° from the dee exit. The deflector is mounted in an opening in the dee tank opposite the dee, and is removed on rails straight back from this opening through an opening in the accelerator vault to an area outside the shielding (not shown on Fig. 1). Although the first deflector had two high-voltage electrodes and a ground plane, for the regenerative reflector we decided to use three deflector elements for more versatility. With the addition of the regenerator elements and an entrance septum jack, this meant there would have to be 15 points of adjustment instead of the previous seven. But the required location and length of the regenerator unit created a space problem near the middle ground electrode. Since the shape and length of the regenerator unit were fairly well fixed, we had to design a deflector ground electrode which was fairly thin. All electrodes were water cooled. The entrance septum was originally designed to have water cooling on the flanges; but since it had to be about 0.020-inch thick in the median plane area, and because past experience with tungsten septa made the benefit of water cooling debatable, we decided not to use water cooling in the initial design stages. It was desirable to have all electrodes "floating" electrically so that beam could be read on meters in the control room; this would aid in beam development of the new deflector. The high-voltage elements were made as small in area as practical to cut down on capacitance to ground. These are only a few of the basic parameters but there are many more.[3] It was quite apparent from the outset that different designs had to be used in several areas.

Figure 2 is an overall view of the deflector as it was designed and built. The vertical faceplate formed the dee-tank vacuum barrier and supported the entire regenerative deflector assembly. The horizontal main-support plate cantilevered out from the faceplate when the deflector assembly was rolled out of the cyclotron. On the leading edge of the main support were four small rollers which rested on the trim coil liners when the deflector was mounted in the cyclotron gap. Aluminum alloy 6061-T6 was used in both the main support plate and the faceplate for several reasons: it is readily available, is easily machined, has good strength characteristics, and has a short half life. The danger of "spraying" aluminum was essentially eliminated by lining the areas above and below the high-voltage elements with tungsten spark anodes.[3]

The electrode assemblies and associated cooling water lines were all mounted on this large support plate. The high-voltage and ground pairs of electrodes broke down to three basic cross-sectional designs (Fig. 3).

The regenerator ground electrode sets up two ground planes inclined 45° and symmetrical to the midplane. The aperture between the upper and lower ground-electrode sections was 3/4 inch. Parallel cooling water paths were machined into both sections. The high-voltage element mounted between these ground planes carried a positive voltage. The face of this electrode was designed to assume a hyperbolic shape for a minimum height of 3/4 inch. With a design gap (the distance between the intersection of the 45° ground planes and the front face of the high-voltage electrode) of one inch, a cross-sectional radius of 1.053 inches departed from a hyperbolic shape by approximately 0.003 inch at the extremities and was acceptable.

The deflector's high-voltage electrodes all had similar cross sections. They were all made from 1-1/2-in. o.d. tubing with a nominal 1-in. flat face welded in place. The end caps were machined for cooling-water inlet and outlet, and for electrode-support pivots. The water was simply fed in one end and out the other with no reversing channels inside the electrode.

The entrance-septum electrode separated that beam which is in its last orbits inside the cyclotron from the beam which is acceptable to the deflector's electrostatic channel for external delivery. This septum is the weakest link in the 88-inch cyclotron as far as beam intensity is concerned. Since the design of this element is an elaborate study far beyond the scope of this paper, we will discuss only what was done in the initial design of this deflector. As stated earlier, a water-cooled copper septum was considered in the design-layout stage, with the expectation that we would eventually build one. Only tungsten septa were seriously considered for the first trials because of ease of fabrication and the past experience in the design of them. The first septum was made from a 2-inch-high section of tungsten 0.060-inch thick, ground to 0.010-inch thick through a 13/16-inch-high section symmetrical to the midplane. This was bent longitudinally to match the curvature of the deflector channel. An inward-sloping vee slot was put in by spark erosion. The vee was made as sharp as possible to minimize the blunt face for beam deposit. This tungsten web was screwed to flanges (Inconel alloy 600) for support. The only cooling of the unit was by radiation. Future considerations for this element are copper with water cooling, tungsten webs with water-cooled flanges, and hafnium carbide webs with water-cooled flanges.

The mid and exit ground electrodes were made as thin as practical to minimize the space problem in the area of the regenerator unit (Fig. 4). They were machined from 1/2-inch-thick Inconel bar stock. An 1/8-inch-wide water channel was centered in the electrodes. Although the simple mechanical rigidity of these electrodes was considered to be sufficient for this design, internal cooling-water pressure of 120 psig, giving the curved electrode a straightening "bourdon tube" effect, was checked with a test model. An internal pressure of 150 psig showed a simple-beam mid-point deflection of approximately 0.0035 inch.

All electrodes (except those of the regenerator ground and entrance septum) were machined longitudinally flat to the required finished cross sectional dimensions; they were then bent to match templates. The templates were machined on a tape-controlled milling machine to match computed values[4] for extracted 130-MeV α beam orbit. The installed electrodes matched the templates generally within 0.002 inch, with a few localized departures of about 0.006 inch. These templates were also used as drill jigs to make subsequent replacement electrodes to match the originals without the need of recalibrating the replacement's radial positions.

Fabrication of the support insulators for the high-voltage electrodes appeared to be a serious problem. Alumina ceramic of 97.6% purity was chosen for the insulating material because of its electrical strength, mechanical properties, and good thermal shock resistance. Since it is desirable to have a large surface contact between the metal conductive supports and the insulating material to minimize "hot spots", we tried several times to braze the metal to the inside as well as to the outside end surfaces. But the difference in thermal expansions of the metal and ceramic materials made brazing unsuccessful. Figure 5 shows our compromise solution. Retaining-ring grooves were ground into the ends of the insulator. The section of the insulator between the groove and the ends were coated with silver for the required electrical-surface contact, and an indium washer was sandwiched between the insulator ends and the metal end caps to further eliminate point contact. A corona bell housing mounted over the insulator protected the insulator from coating action inside the cyclotron and provided a spark gap away from the insulator surface.

All electrode ends were mounted on rectilinear ball carriages which in turn were mounted on the large, main, horizontal support plate. The ball carriage races were 90° vee grooves machined into the edges of Inconel plates with a relief for ball-retainer clearance. Here again Inconel alloy 600 was used for its magnetic permeability, ability to hold up under higher temperatures, and the unusual property of cold working to a good hardness. The races could be machined to medium precision and then cold worked by the balls themselves to the precision and hardness required. The balls were precision-ground and polished alumina. Some migration of the balls was experienced in the test models. This was minimized by making the retainers match the ball diameter to close tolerances. The balls were intentionally of an insulating material to eliminate electrical pitting--also once the balls did become coated, any sparking would only "clean" them.

The septum jack was a similarly ball-mounted sliding wedge (see Fig. 6). The plane of the inclined ball raceways had a slope of 10:1 to the horizontal plane. This inclination allowed very precise adjustment of the septum-slot elevation. The septum "sees" no horizontal motion whatever from the adjustment motion of the jack.

The positioning drive motions were transmitted from external drives to the ball carriages through a flexible, rectilinear, ball-bearing remote-control cable made by the Controlex Corporation of America (see Fig. 7). These cables are commercially available. All materials in them are nonmagnetic stainless steel and run without lubrication. Some backlash in the electrode positioning is experienced with the use of these cables. When all precautions are taken in assembling these units in curved paths, this backlash is 0.006 inch or less, a figure we consider of marginal desirability. We may eventually have to devise a method to correct this backlash should it prove troublesome, but there are many possibilities.

The drive units provide remote electrode positioning control and readout from the control room. It was desirable to read (1) radial position of the ground electrodes, (2) gap between the ground and high-voltage electrodes and (3) septum jack elevation. It was also desirable to be able to move ground and high-voltage electrodes either independently or together and thus keep a constant gap. Figure 8 schematically shows our solution to the problems. The key parameters in determining this design were gap readout and constant gap motion.

The drive units were mounted on the atmosphere side of the dee-tank cover plate. The vacuum seal was a welded multiple-diaphragm bellows with a low spring constant. The remote-control cable in the vacuum area and the drive in atmosphere connected to a common linkage inside this bellows with no moving vacuum seals.

The translation motion from the drive units was provided by lead screws and rotating quill nuts mounted on preloaded angular-contact ball bearings. The drives for an adjustment point of the ground electrodes and the corresponding high-voltage electrode point were paired and driven by a common high-speed gear-reduced aircraft-type motor. Independent electrode motion was provided by use of magnetic clutches. Each quill nut was geared to a transmitter synchro and digital counter. The control-room readout panel had receiver synchros for reading radial position of ground electrode, and differential receiver synchros for reading gap, both by use of digital counters.

There was a total of seven pairs of these drive units for deflector and regenerator electrode position and one individual unit for septum jack readout (see Fig. 9). Mounting these units on the dee-tank plate eliminated the necessity for mechanical uncoupling from the deflector assembly and related evils such as loss of calibration, backlash through additional linkages, and the time of removal for some maintenance problem inside the vacuum area. This approach also proved quite compatible to the interchanging of the regenerative deflector and the previous deflector.

As already mentioned in this article, several things were learned in the regenerator test unit. One of these was our ability to use sleeve bearings made of molybdenum disulfide-epoxy resin in areas where a dielectrical dry lube material is desired. The 50/50 formula used has an electrical strength of 45 volts/mil and a coefficient of friction of about 0.15, and is easily machined. This material is used on the electrically "floating" ground electrodes. Only time will tell its radiation characteristics but it seems to be holding up quite well so far.

At present, development of water-cooled tungsten septa is in the trial stage. First results show a definite increase in the beam-holding capacity--enough to warrant further development.

Footnote and References

*This work was performed under the auspices of the U. S. Atomic Energy Commission.

1. H. Kim, G. H. Mackenzie, W. B. Powell and P. J. Waterton, Proceedings of the International Conference on Sector-Focused Cyclotrons and Meson Factories, Geneva, 1963 (CERN 63-19, 1963), p. 73.
2. R. Peters, Proceedings of the International Conference on Sector-Focused Cyclotrons, Los Angeles, Calif., 1962 (North Holland, Amsterdam, 1962), p. 252.
3. B. H. Smith and H. A. Grunder, Proceedings of the International Conference on Sector-Focused Cyclotrons and Meson Factories, Geneva, 1963 (CERN 63-19, 1963), p. 304.

4. D. J. Clark, E. Close, H. A. Grunder, Hogil Kim, P. Pellissier, B. H. Smith, Regenerative Beam Extraction for the Berkeley 88-Inch Cyclotron, this Proceeding, p.

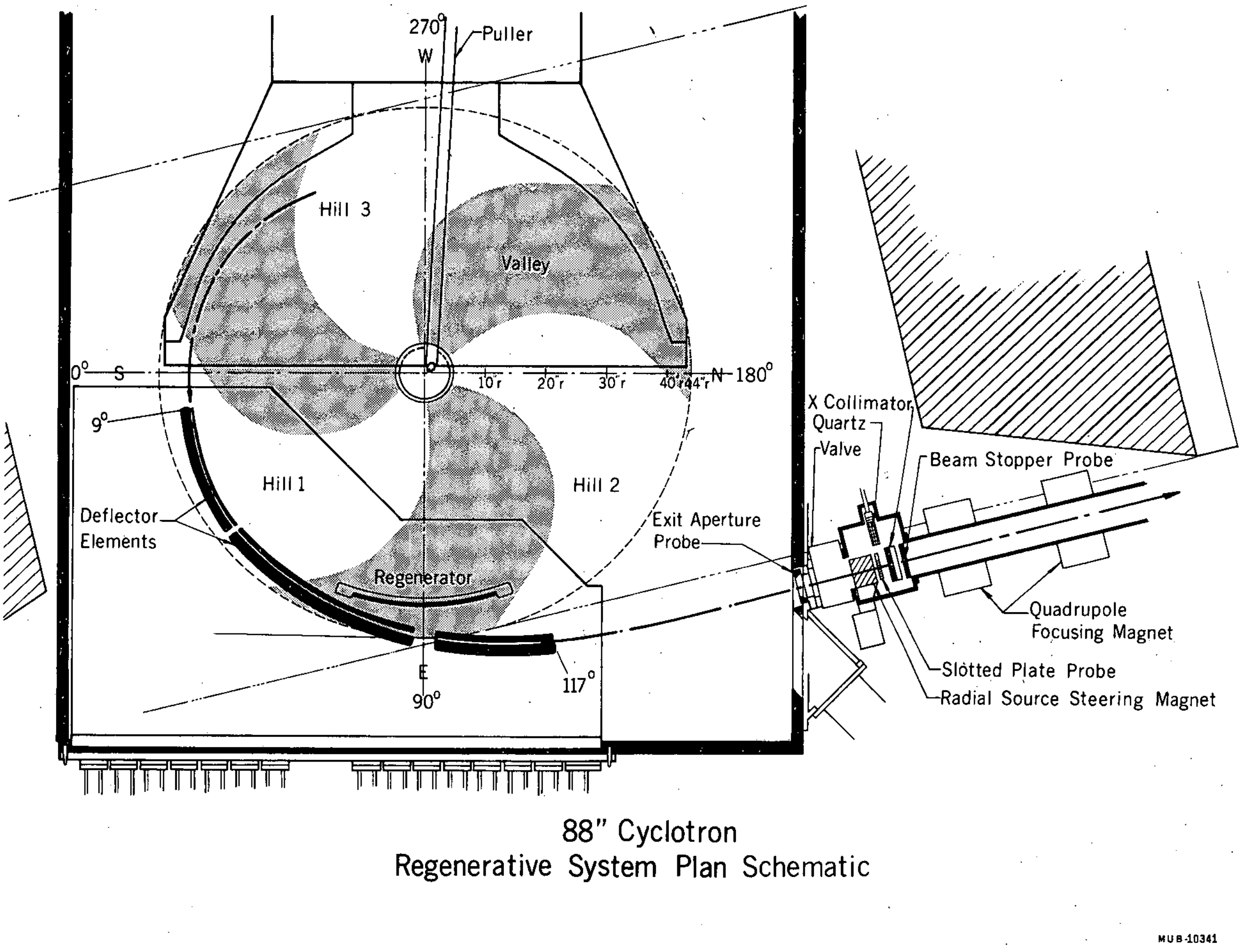

Fig. 1. Plan schematic of 88" cyclotron and regenerative deflector.

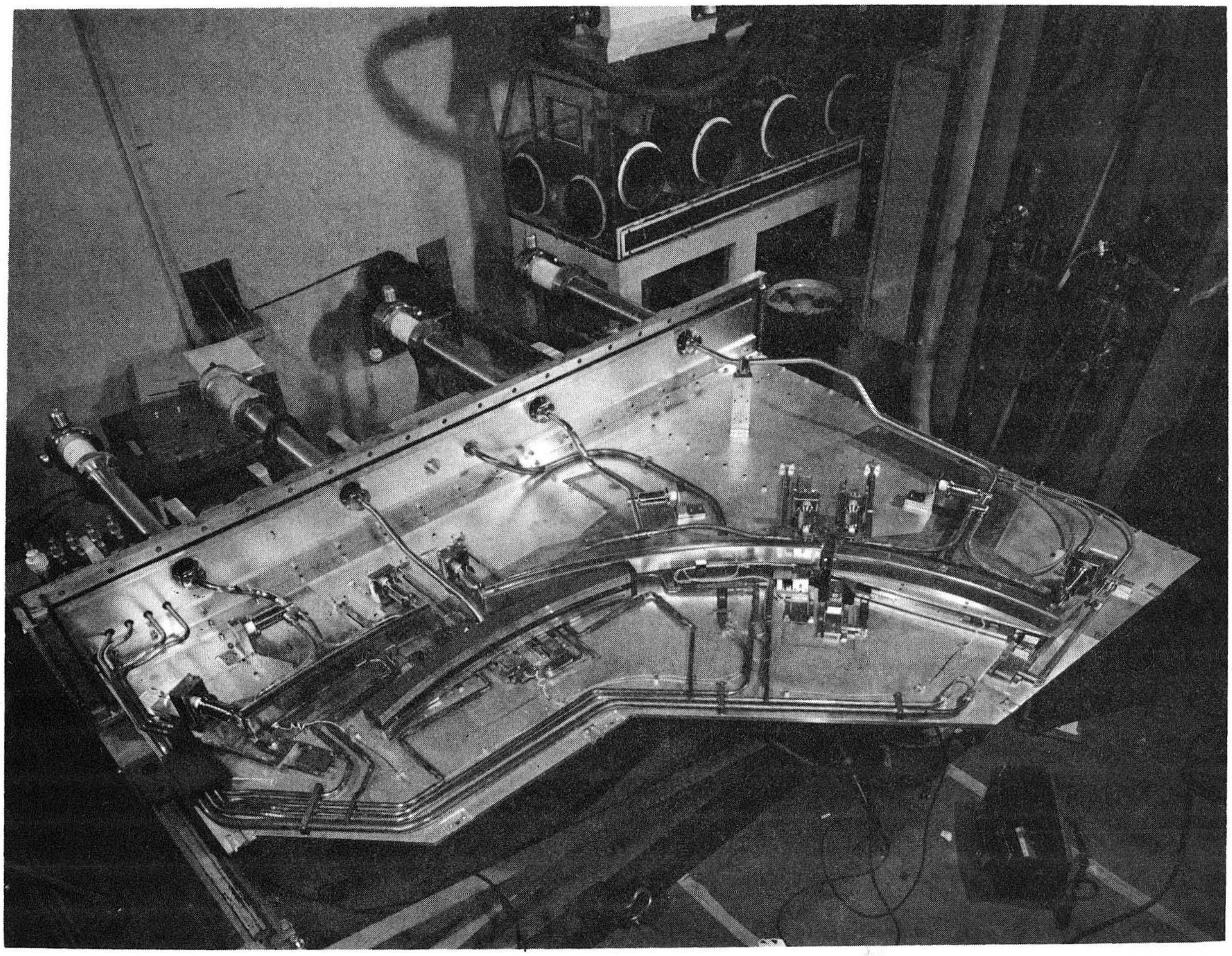

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Fig. 2. Regenerative deflector assembly.

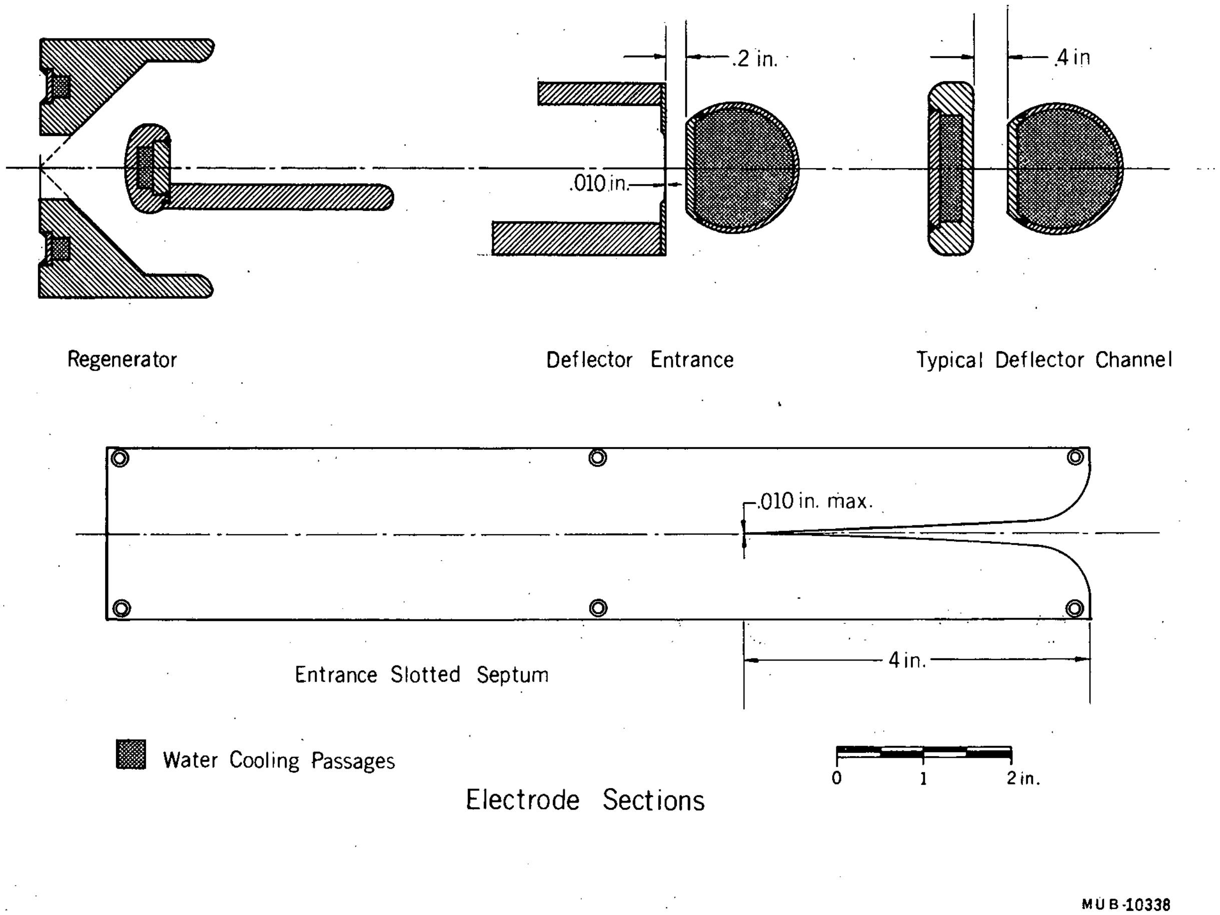

Fig. 3. Typical cross section through electrodes.

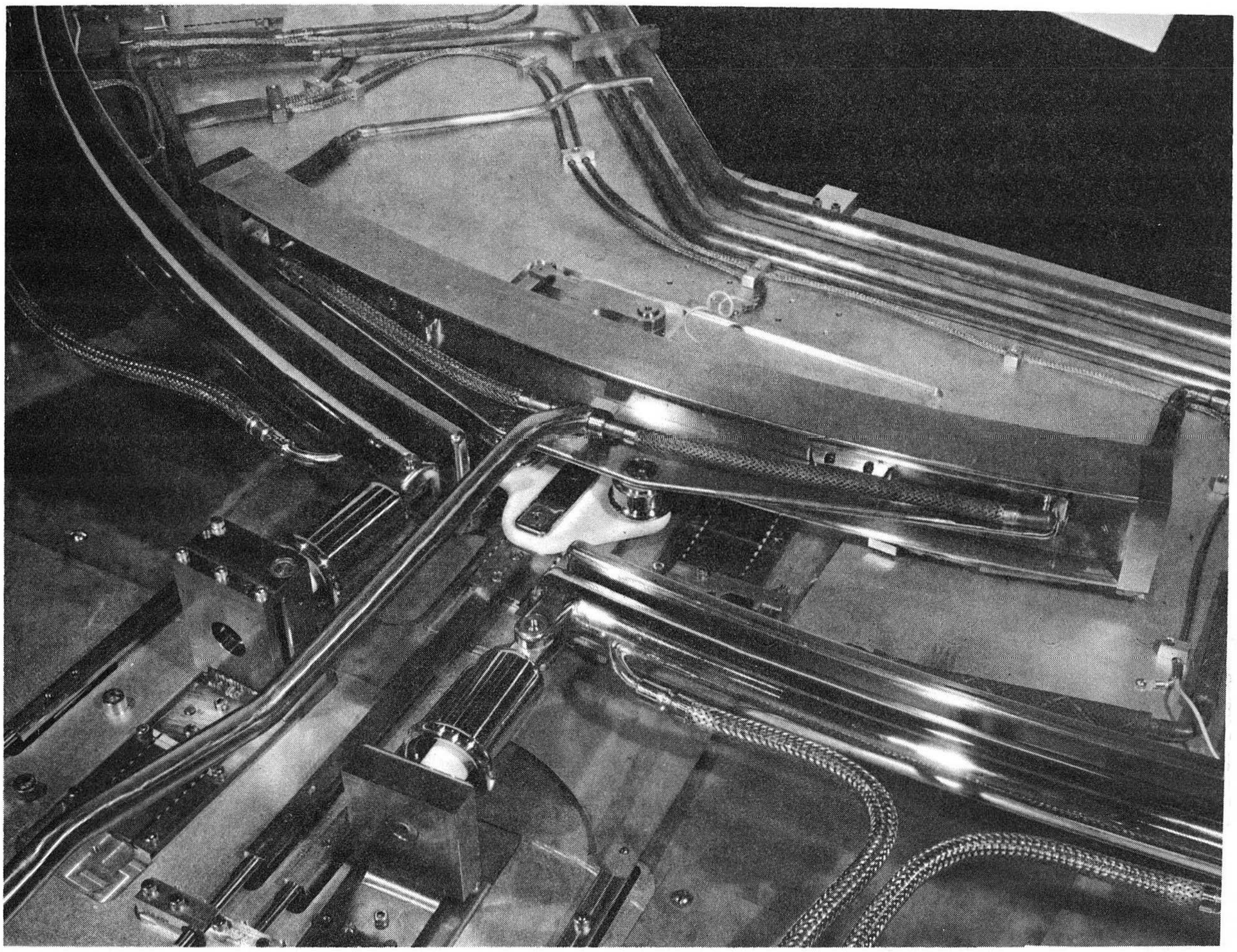

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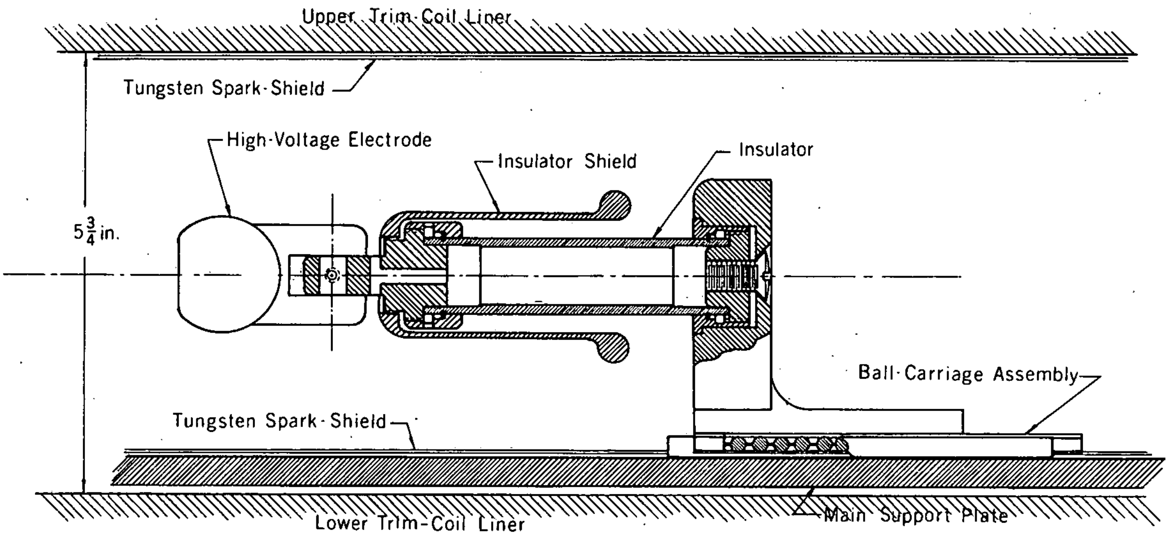
Fig. 4. Regenerator unit, rear view.



High-Voltage Electrode Support

MUB-10340

Fig. 5. Cross section of typical support for high-voltage electrode of deflector, and ball carriage assembly.

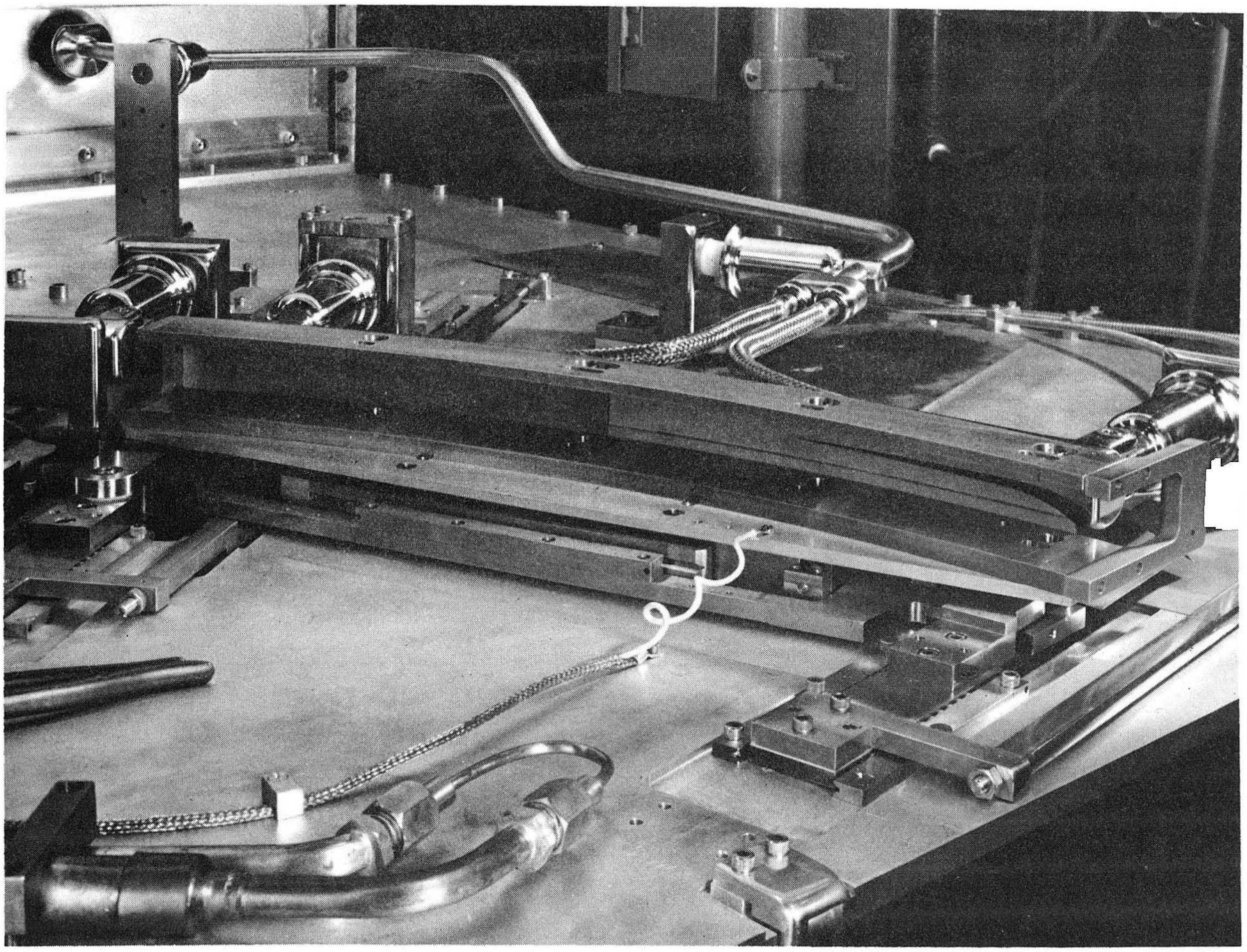


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Fig. 6. Septum and septum-jack assembly.

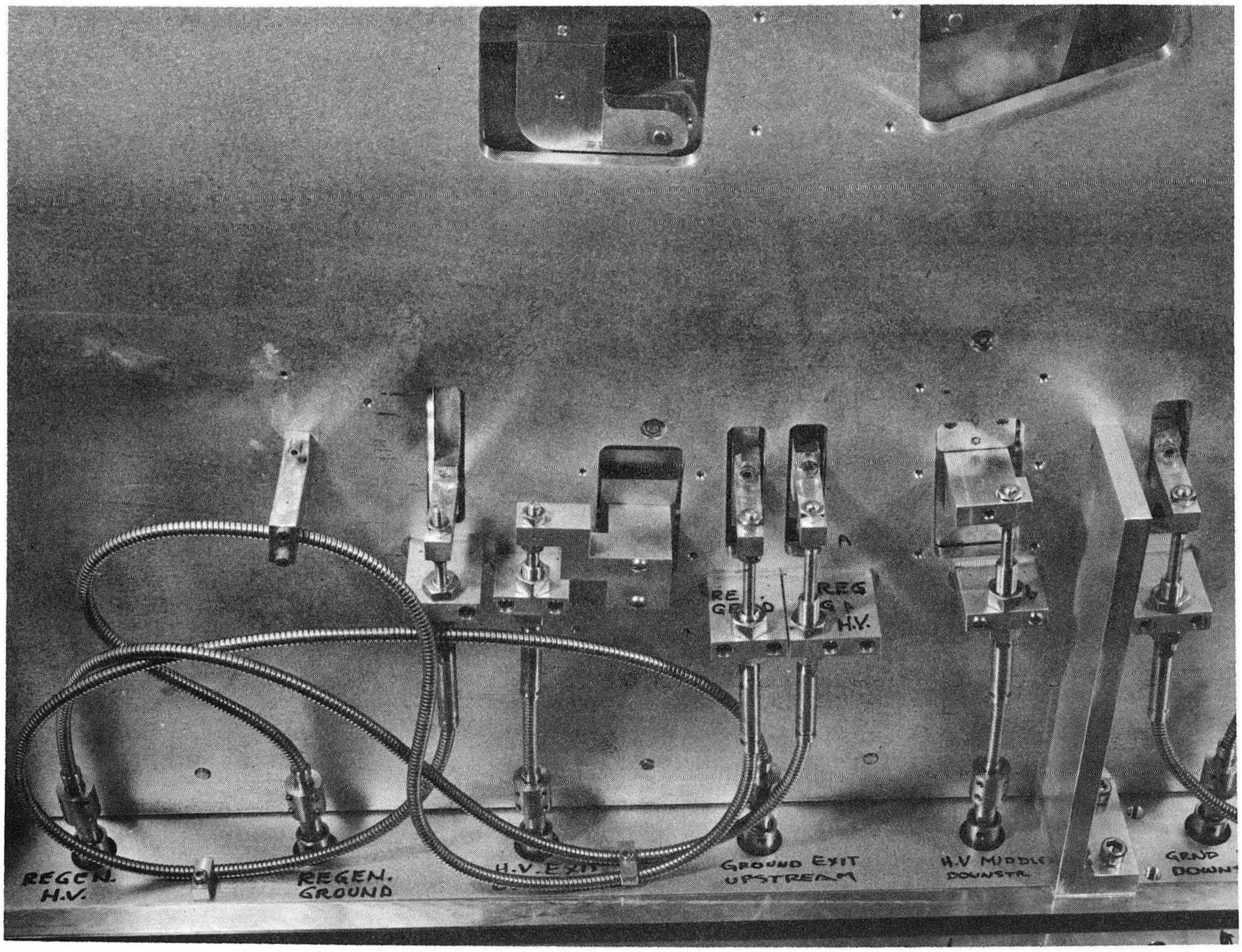

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Fig. 7. Control cable installation.

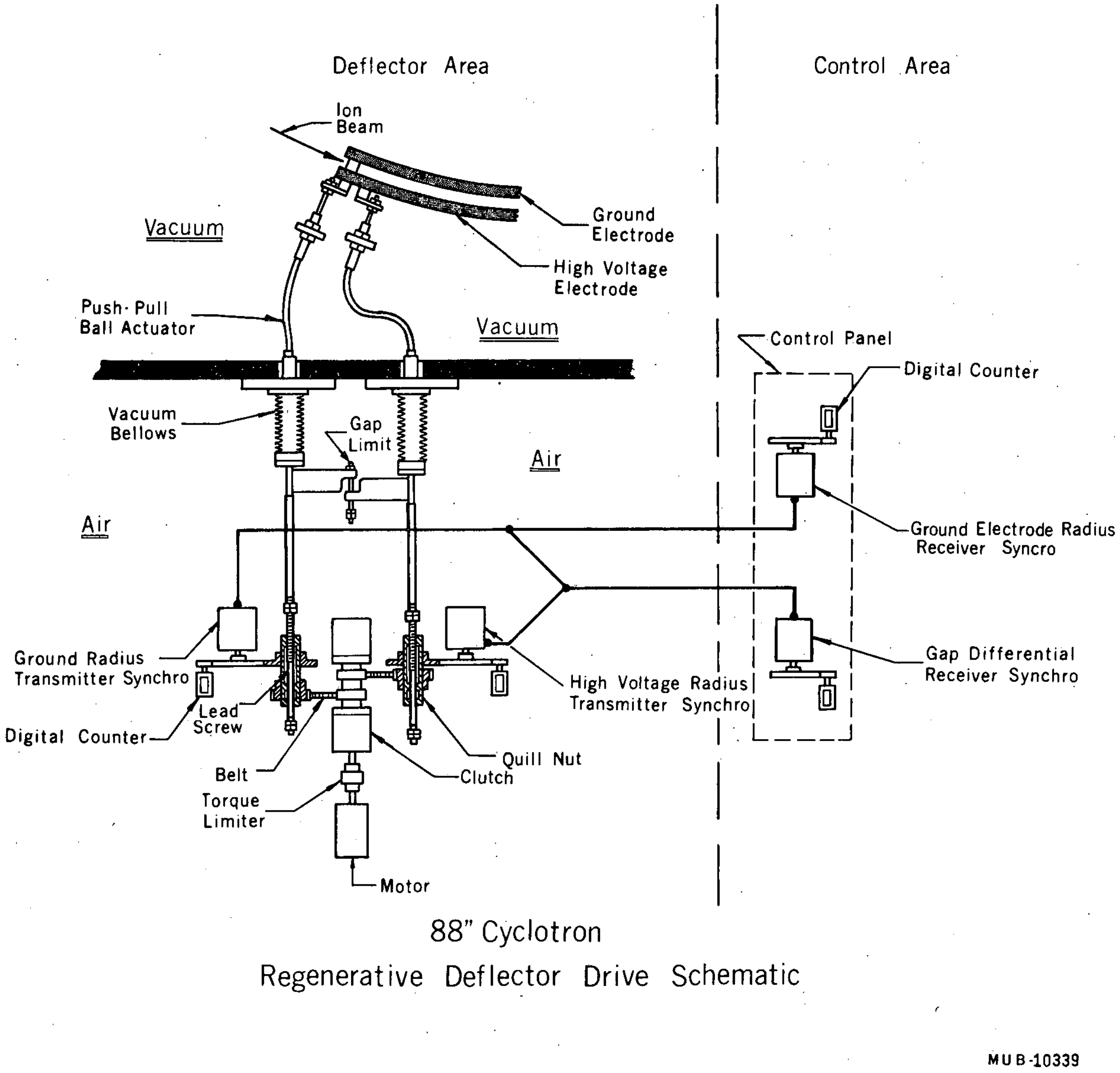

Fig. 8. Schematic of drive and readout mechanisms.

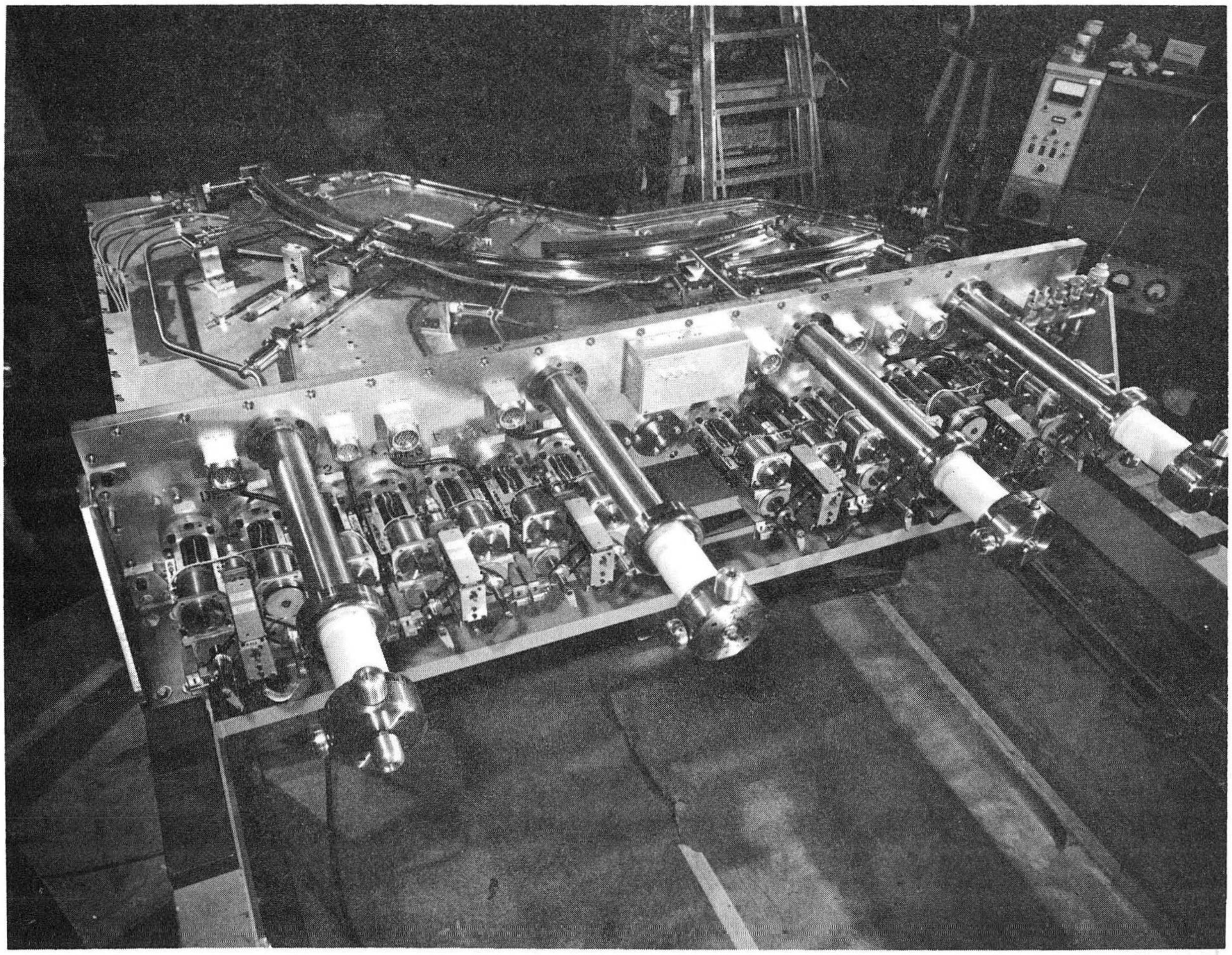

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Fig. 9.. Deflector drive assemblies.