MAGNETIC FIELD CONTROL IN THE MANITOBA CYCLOTRON

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Summary

Two unusual methods to make local changes in the magnetic field are described -- movable steel plugs at the centre and temperature-controlled Invar blocks at larger radii. The plugs have 2" holes at the centre, which produce a dip in the magnetic field. This appears to have no serious effect on the beam. Results of beam extraction by H^- ion stripping are reported.

The University of Manitoba cyclotron is a sector-focused machine designed primarily to accelerate protons to an energy of 50 Mev. Its first beam was obtained without any particular difficulty in October 1964. By the end of that month the cyclotron had accelerated ∼ 10 μamp protons and ∼ 0.3 μamp H^- ions to full energy. Since then we have concentrated on producing a usable external beam by stripping the electrons from H^- ions at full radius[1]. The deflected protons thus produced are focused by two pairs of quadrupoles onto a target in the experimental area ∼ 60 ft. from the cyclotron. There the beam spot is ∼ 5 mm in diameter. No losses have been observed during or after deflection within our present accuracy (∼ 20%).

Now that the cyclotron is operating, it seems an opportune time to describe some of its distinctive features. In particular, the methods of magnetic field control are unusual — movable steel plugs at the centre and temperature-controlled Invar blocks at larger radii[2].

The central field is determined by hollow steel plugs (fig. 1) in the upper and lower poles of the magnet. They can be moved in and out so as to produce a change in gap width. First compressed air is supplied to force the plugs out. The motor-driven stops are then adjusted. Finally the air pressure is released and the plugs are pulled back in against the stops by the magnetic forces. In this way we obtain discontinuous control of the plug positions during cyclotron operation. A 1" diameter ion source is inserted through the 2" diameter hole in the plug, giving it ±0.5" range of motion in both horizontal directions.

Beyond the centre, the magnetic field shape is varied by changing the temperature of Invar blocks[2]. Invar's ferromagnetic properties disappear gradually as it is heated from room temperature to its Curie point ∼ 280°C, so the Invar temperature affects the magnetic field in its vicinity. Fig. 2 shows the location of the Invar blocks. Between each hill and the pole tip are eight blocks, at different radii giving a total of 64.

A typical Invar block is shown in fig. 3. Our first concern was to keep the heat losses low to avoid undue heating of other parts and to facilitate control of the temperature by running at low power. Therefore the blocks are held in place by a minimum number (4-6) of long and slender stainless steel supports. They maintain a 0.05'' gap between the blocks and the hills and conduct only ∼ 1 watt each at maximum temperature. Since the blocks are surrounded by high vacuum, the only other source of heat loss is radiation, which is limited to ∼ 0.25 watt/inch^2 by silver plating. The heat is supplied by mineral insulated heating cables, which are sandwiched between the lower and upper halves of the blocks, together with a mineral insulated thermocouple and a stainless steel tube for rapid cooling. To ensure good heat contact the .01'' gap between the two halves and the tubes was filled with lead. Hard solder was tried originally, but the Invar developed cracks at the high temperatures required for soldering. The melting point of lead is a little low for comfort, but it is ductile, has a low vapor pressure, and is relatively easy to apply. In spite of the good heat contact and the low heat losses at the supports, there were some cool spots. Temperatures 10° - 15° lower than the average were observed at the supports and at the ends because of the very low thermal conductivity of Invar. However the temperature distributions were sufficiently reproducible so that they caused no observable time variation in the magnetic field.

The total power required for heating would be ∼ 1.2 kW if all blocks were kept at a temperature of 300°C. Under normal running conditions for protons the temperatures range from 60° to 240°C and ∼ .6 kW is needed. After initial out-gassing we have noticed no effect on the cyclotron vacuum.

Normally all eight Invar blocks at a given radius have their temperatures controlled together. An on-off potentiometer controller keeps the average temperature of each set constant by sensing eight thermocouples in series, thus controlling the average magnetic field at that radius. Differences in temperature between blocks in any set give rise to magnetic field harmonics, but these can be removed by adjusting rheostats in series with the individual heating elements. Harmonics arising from other causes can be reduced in the same way. We had to unbalance the temperatures in some sets by ±8°C to reduce first harmonics from ∼ 12 to ∼ 6 gauss. The average temperature of each set of blocks has an overall stability of $\pm 0.2^{o}C$ corresponding to less than ± 0.3 gauss. Individual blocks have the same short-time stability, but are subject to long-time fluctuations of $\pm 1^{o}C$.

It was necessary to measure the magnetic field in high vacuum, since the Invar could not be kept at its proper temperature at pressures higher than 10^{-3} mm Hg. The magnetic field sensor, a Hall generator, was held by an arm which in turn was supported on a shaft passing through a vacuum seal in the central hole of the magnet. The Hall plate could be moved radially and azimuthally in precise steps by an external automatic stepping device.

Fig. 4 shows the changes in the average magnetic field produced by each block separately when cooled from 240^{o} to $30^{o}C$, as well as the change produced by cooling all the blocks together. The effects are not additive since in a highly saturated magnet like ours the total magnetic flux tends to remain constant. To a large extent flux simply shifts from one location to another when the Invar temperatures are changed. The set of blocks near the centre has a much stronger effect than the others because it extends over the valleys as well (fig. 2). The field change produced by the central plug is also shown in fig. 4.

A fairly direct comparison between Invar and trimming coils is provided by the UCLA cyclotron[3], which has the same size and magnetic field as ours. The UCLA trimming coils give about the same integral change in field shape as the Invar but about one third the differential change at any radius. The trimming coils require an order of magnitude more power but respond immediately to changes in current while the Invar has a long time constant of the order of a few hours. Costs of the two systems are probably comparable.

The magnetic fields obtained for protons and deuterons are shown in fig.5, together with the Invar temperatures required to produce them. Further small changes to the hills could probably make the temperature distributions more systematic. The deuteron field is only a first rough approximation and we have not yet tried to accelerate deuterons. The proton field is our final measurement corrected by the changes that were found necessary to bring the beam to full radius. The only significant change was a considerable reduction in the central field. Before this change the field was isochronous at the centre but had a bump $\sim$ 300 gauss at 2'' radius like the one shown in the deuteron field. At best under these conditions the beam disappeared at about half radius. Removal of the bump brought the beam out to full radius. Presumably the beam was lost because of negative phase shift and the field reduction near the centre gives the particles a larger positive phase to start with. It should be noted that the dip in the centre of our operating field is contrary to the usual requirement of magnetic focusing, and emphasizes the importance of electric effects at small radii.

Fig. 6 shows the present behaviour of beam current vs radius. For protons the only losses take place near the centre and at $\sim$ 20'' radius. The latter loss is caused by inadequate vertical focusing but the former has not yet been investigated. In addition to these losses, the negative ions show a uniform attenuation because of stripping by the residual gas in the vacuum chamber (air $\sim 4 \times 10^{-6}$ mm Hg + hydrogen $\sim 2 \times 10^{-5}$ mm Hg). No evidence of electric field stripping[4] can be seen. The maximum field at full radius is $\sim$ 24 kilo-gauss. After improvements in the ion source and the vertical focusing we now are able to obtain $\sim$ 1 μamp on a target in the experimental area.

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[1] M. E. Rickey and R. Smythe, Nuclear Instr. and Methods 18, 66 (1962).

[2] K. G. Standing, J. J. Burgerjon, and F. Konopasek, Nuclear Instr. and Methods 18, 111 (1962).

[3] D. J. Clark, R. R. Richardson and B. T. Wright, Nuclear Instr. and Methods 18, 1 (1962) and UCLA Technical Report, January 1962 (unpublished).

[4] D. L. Judd, Nuclear Instr. and Methods 18, 70 (1962).

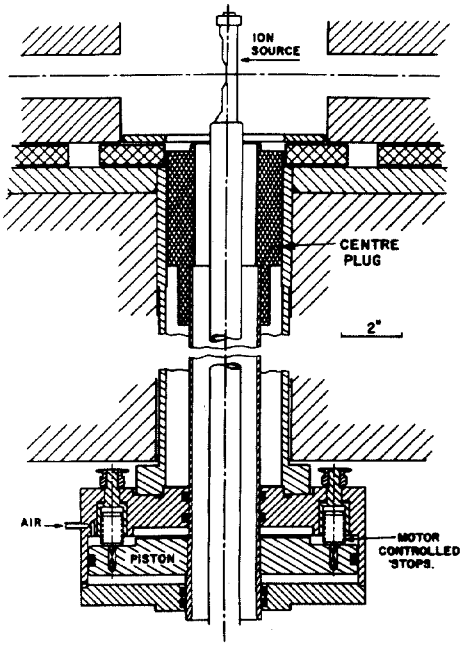

Fig. 1. Construction of center plug.

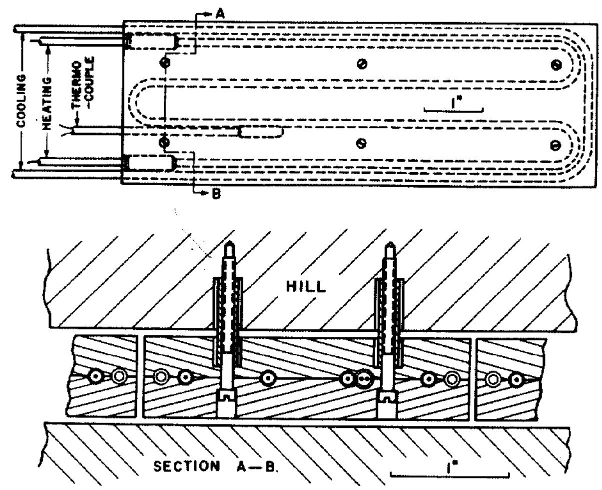

Fig. 3. Construction of a typical Invar block.

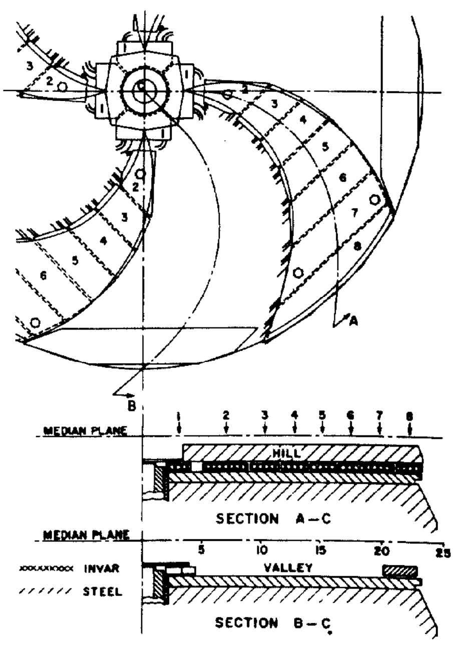

Fig. 2. Location of Invar blocks.

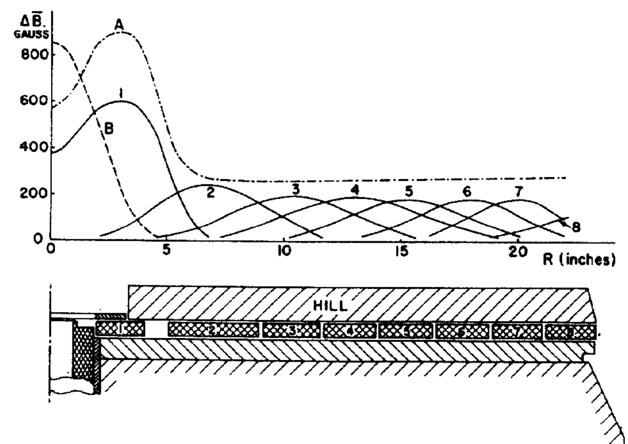

Fig. 4. Changes in magnetic field, produced by Invar blocks and center plugs. The curves 1-8 represent the changes produced by corresponding invar blocks, when varied individually from 24O° to 30° C. Curve A represents the change produced when all invar blocks are changed simultaneously from 24O° to 30° C. Curve B represents the change produced by moving the center plugs .4" towards the median plane.

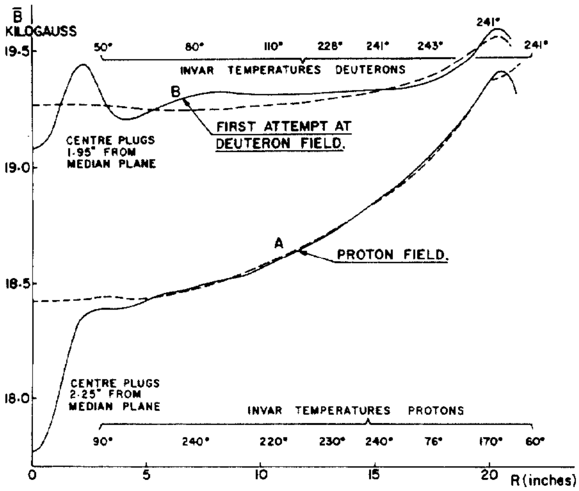

Fig. 5. Average magnetic field. Curve A represents the magnetic field for protons corrected for the changes in temperature of the invar blocks and position of the center plugs, required to accelerate the beam out to the extraction radius. Curve B represents a rough attempt at a field for deuterons, as measured with the Hall proble. The dashed lines indicate the isochronous fields.

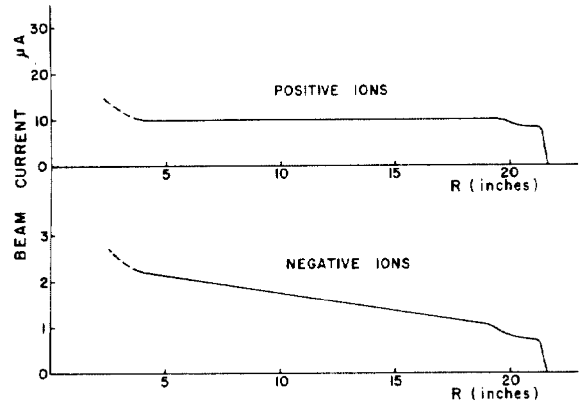

Fig. 6. Beam current versus radius for 50 MeV protons.

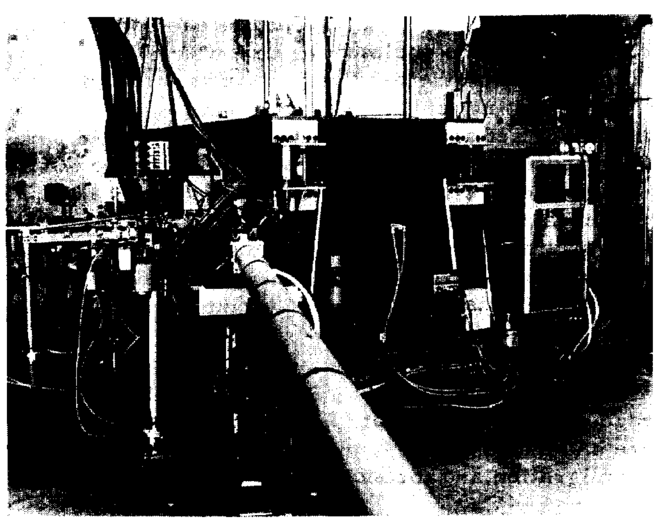

Fig. 7. The Manitoba Cyclotron.