THE REVERSING MAGNET OF THE 850 MEV STAGE OF MAMI*

H. Herminghaus, P. Jennewein, U. Ludwig-Mertin, G. Meyer, P. Zinnecker
Institut für Kernphysik der Universität, 6500 Mainz, Becherweg 45, F.R.G.

Abstract

These magnets with rough data 1.3 T, 450 tons and 10 square meters of pole face area each were manufactured from cast low carbon steel. Their field gradient of about 0.4% was essentially correctly predicted by PROFI computations. Surface coils on the pole faces have to improve the field homogeneity by about a factor of ten. A novel field clamp philosophy provides a very low stray field level outside the magnet. Design philosophy and preliminary performance are communicated.

Introduction

MAMI is a cascade of three race track microtrons using c.w. operated room temperature accelerating structure [1]. After successful operation of the two first stages ("MAMI A") over the past years, the machine as a whole is presently under construction [2, 3]. Fig. 1 shows a scaled scheme of the third stage, which will raise the electron beam energy from 180 to 855 MeV.

In an earlier design of this stage a flux density in the reversing magnets of 1.54 T was chosen. Computations by the PROFI code and measurements with a small model magnet had shown, however, that a field variation of a few percent was to be expected over the pole face area to be used [4], whereas a variation of a few parts in 10^{-4} would be required for proper beam optics. Therefore, a redesign was made reducing the flux density to 1.284 T (which gives a resonant energy gain of 7.50 MeV per turn).

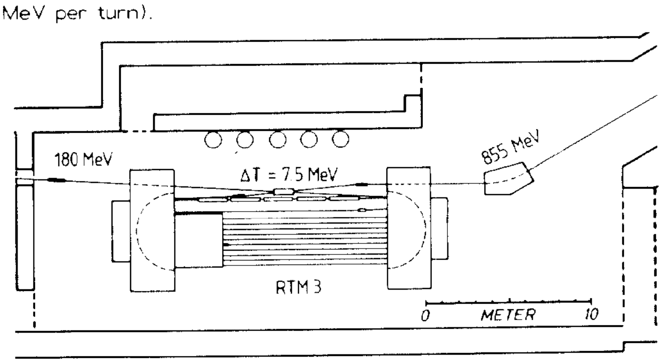

Fig. 1: Scaled scheme of the 3rd stage of MAMI in its final design.

These magnets have been manufactured and mounted in place meanwhile and one of them has been field mapped and has undergone a successful test of the homogenizing method to be used.

Mechanical Design

At 855 MeV and 1.284 T, the electron orbit diameter is 4.44 m. Taking in account the injection and extraction paths [1, 3] and a reasonable margin around the region of "good" field, a pole face diameter of 4.93 m is required. Fig. 2 shows a midplane cut through the magnet, showing pole face and return yokes of the main magnet, the reverse field magnet to cancel vertical defocusing [5] and the field clamp. Including the space required for the coils the yoke has to span a distance of 5.7 m. Thus, inevitably the pole pieces will be moved noticably by the magnetic force. Great care was taken, therefore, to make the yokes under given space and weight limitations as stiff as possible and to link the different parts in such a manner that the movement is kept strictly reproducible, i.e. avoiding possibile stick-slip action of the parts

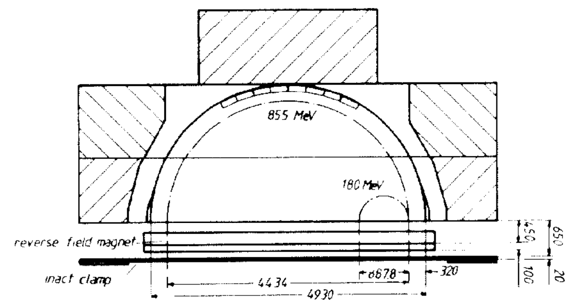

Fig. 2: Cut of the complete magnet along the midplane.

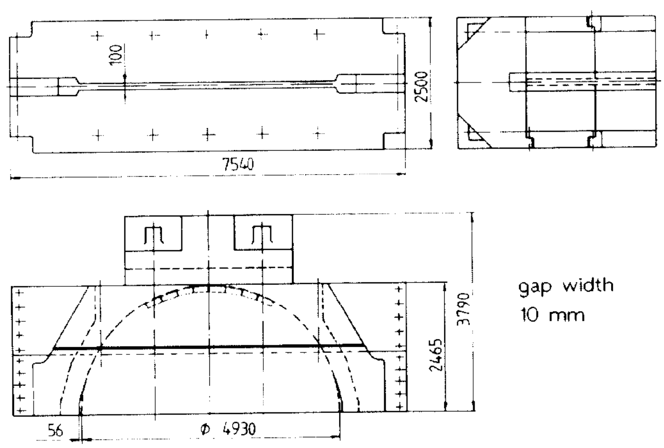

Fig. 3: Construction of the main magnet
(reverse field magnet and clamp omitted).

For these reasons the poles were realized as integral parts of the yokes. Since the weight of individual parts is limited to 80 tons by the crane in the accelerator hall, each pole had to be formed by two yoke bars. Therefore, a cut through the pole faces parallel to the front edge had to be accepted. Fig. 3 shows the resulting construction of the main magnet. It is supported by three hydraulically adjustable supports, one under the rear yoke and two under the opposite ends of the lower front yoke. Thus, the lower middle yoke is engaged between these two parts by supporting steps. The upper front yoke is hooked by a corresponding step on the upper middle yoke. This assembly is sustained by the lower yoke assembly by means of spacers at the opposite ends (acting as return yokes) and a spacer of unmagnetic stainless steel along

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the rear part of the pole face circumference. These assemblies are fixed by fitting bolts and bolted together by hydraulically biased screw bolts. All iron pieces are insulated by 25 micron Kapton foils against each other to prevent flow of possibly irreproducible eddy currents.

The need for weight limitation led to a relatively complicated outer shape of the pieces which would have been rather expensive to manufacture of forged steel. So all pieces were made of cast low carbon steel ("ZSH extra"), cast and machined by Thyssen A.G. We considered it a certain risk to have the poles made of cast steel. However, no evidence showed up after manufacture for any cavities or impurities in the critical pole regions.

Coil Design

The coils of the main magnets have 96 windings each, internally composed of 16 coils of 6 windings each. By this subdivision, braze joints inside a coil could be avoided. Cooling water is fed through the 16 coils in parallel such that the water outlet is opposite to the yoke parts. By this and by a thermal insulation between coil and steel, long term temperature drift is minimized. The coils have been manufactured by Bruker GmbH.

By the way, an occasionally observed mistake in coil design may be brought to attention here. Because of the resulting convenient access to both coil ends, it is tempting to compose a coil of pairs of pancakes, connected to each other at the inner side of the coil (Fig. 4). However, such an arrangement acts as a counterflow heat exchanger: the water flowing out heats up the incoming and much of the heat to be taken out is circulating inside the coil instead. In fact, the analysis shows that, with realistic assumptions about the heat conductivity between the windings, the inner part of the coil might be heated up to a substantially higher temperature than observed at the water outlet, leading to higher coil resistance, higher thermal stress and accelerated corrosion.

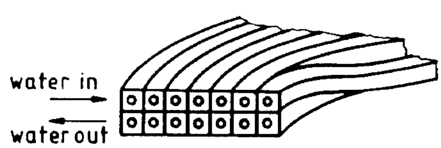

Fig. 4: Improper design of a coil.

Magnetic Design

We make use of the reverse field magnets as an active field clamp, besides using it to suppress the stray flux from the main yoke by inserting an air gap of proper width between reverse and main magnet. This may be seen qualitatively from Fig. 5 by the "Orthogonal Analog Model" [6], in which currents are replaced by sources, regions of high permeability replaced by regions of low conductivity and the magnetic flux lines are obtained as the orthogonal trajectories of the model flow: obviously, the additional gap ("throttle gap" in Fig. 5) provides some leakage for a model flow from the reverse magnet coils which is counteracting the stray flux from the main yoke and may cancel it if the gap is chosen properly.

The throttle gap width was optimized by POISSON computations. Since its evaluation is dependent on the magnetic properties of the steel a further clamp of 20 mm Armco sheet steel was

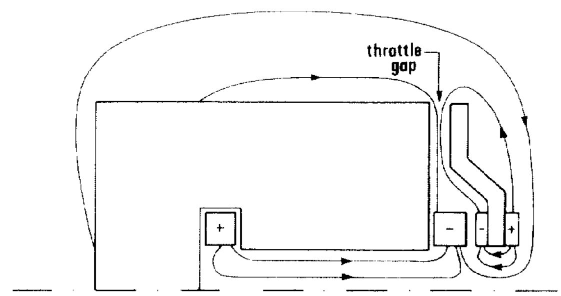

Fig. 5: Cancellation of stray flux explained by the orthogonal analog model.

added in front of the reverse field magnet bearing a coil for fine adjustment of cancellation (Fig. 6a). It turned out in practice that cancellation is achieved at rather weak excitation of this coil.

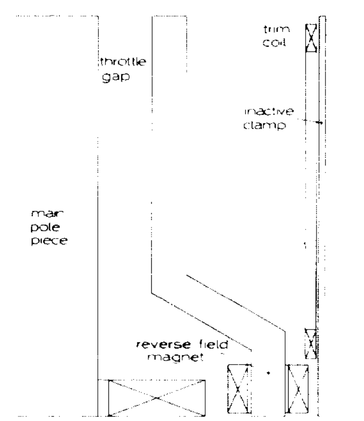

Fig. 6a: Magnet assembly with reverse field magnet, clamp and trim coil, upper front part.

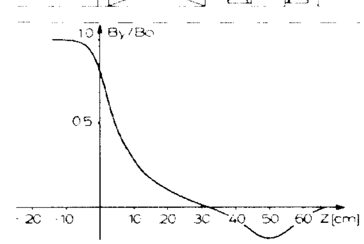

Fig. 6b: Field profile normal to the pole edge.

Measurements

So far, one of the two magnets has been investigated in detail. It is switched on by an internal 12 minutes linear current ramp of the power supply. It then takes about 2 hours until the field is stationary within 0.01%. Switching off is done abruptly allowing the current in the coils to decay slowly by means of the usual free wheel diodes across the coils. Doing so, identical history is achieved even in case of a sudden interlock. It takes about 6.5 hours until the field is decayed to its remanent level.

Measurements showed excellent reproducibility of the field distribution over many runs, although the upper and lower front yokes bend by as much as 0.2 mm each at 1.3 T by magnetic force. In fact, no noticeable permanent or occasional displacement of the yoke parts against each other could be observed.

Fig. 6b shows the field profile normal to the front poleface edge in a setting that would provide the proper beam optics.

Fig. 7 shows a field map of the whole magnet, including reverse field magnet and clamp. To represent the fringe field region the field profile of Fig. 6b, taken in the middle of the pole edge, has been subtracted over the fringe field region (i.e. starting 15 cm from the pole edge) along the whole pole edge prior to plotting.

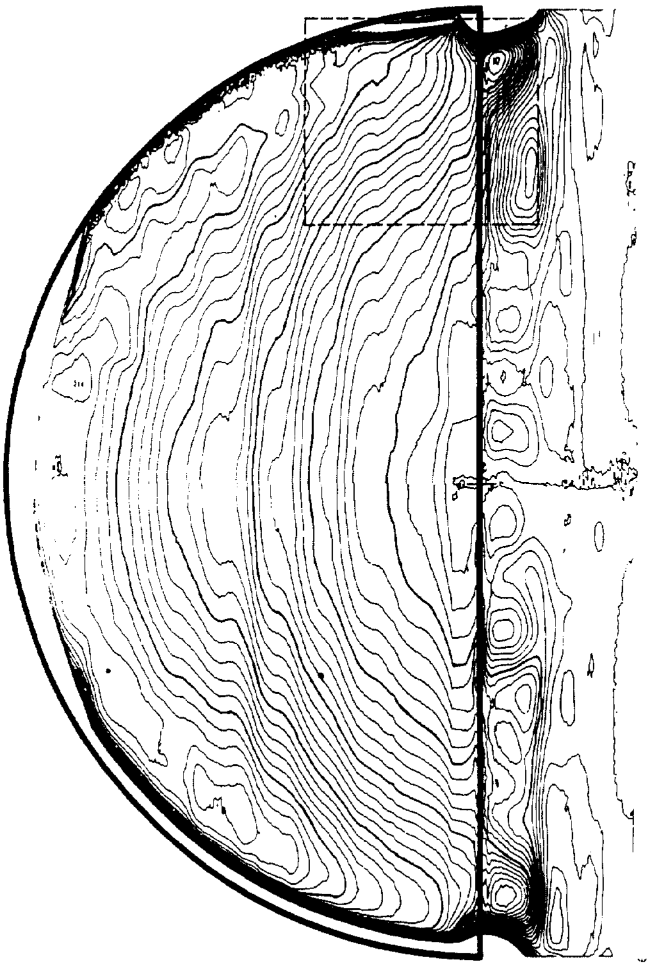

Fig. 7: Field map of the whole magnet at 1.284 T in steps of 2 Gauss each, reference fringe field being substracted.

Field Correction

Field inhomogeneities in a magnet can be corrected by flat correcting coils providing an appropriate tangential current distribution on the pole faces. In a linear approximation, the contours of the "windings" of such a coil are identical to the lines of equal flux density of the uncorrected magnet [7,8]. A more detailed analysis shows, that the optimum pattern for the coil is given by the arithmetic mean of two field maps, taken in planes parallel to the midplane at distances of ±30% of the gap width [9].

In the fringe region, it obviously does not make sense to try to compensate the natural field decay by the correcting coil. Instead, the difference between the actual field and some reference fringe field as in Fig. 7 should be used as pattern of the coil.

Whereas the correcting coils for the two smaller stages of MAMI could be manufactured of etched printed circuit board, for the third stage another technology had to be worked out allowing up to 25 A of correcting current. The windings are cut from 3 mm AlMg3 sheet by a keyhole-saw and put together on a heatable mounting plate. After temporary fixation by plastic bolts, the whole puzzle is soaken with a special epoxy (Araldit CW 229 with hardener HW 229 of Ciba Geigy which has the same expansion coefficient as aluminum) and covered with glass fiber tissue and perforated aluminum sheet as a substrate. Hardening takes 8 hours at 100°C.

As a test for both new correction philosophy and coil technology a pair of correcting coils has been prepared in the way described for the most crucial part of the magnet, namely a pole corner including fringe field region, indicated in Fig. 7 by the dashed rectangle. Fig. 8 shows in larger scale a map of the same region with properly excited correcting coils. As is seen, within a region starting 0.6 gap widths from the coil boundary and 1.8 gap widths from the pole boundary, the field homogeneity is improved by at least a factor of ten. Closer to the pole edge and outside the pole area, however, the field distribution is improved only by little. This is to be expected since the boundary condition necessary for the correcting coil philosophy, namely infinitely extending pole face planes, is not given there.

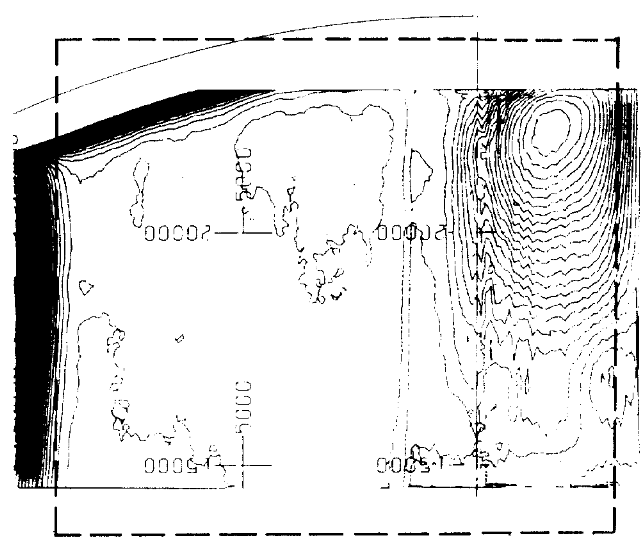

Fig. 8: Field map in steps of 1 Gauss each of dashed rectangle in Fig. 7 in larger scale with properly excited correcting coils.

Some tests using tappings at the coil showed, however, that even in the fringe region a fairly good correction can be achieved by feeding the windings of this region separately by an empirically optimized current which is 2 to 3 times higher than the one needed in the inner pole region. The pair of correcting coils for the whole magnet is presently being prepared using this experience.

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