DESIGN, FABRICATION, AND TEST OF A KICKER MAGNET AND MODULATOR FOR THE IPF BEAMLINE*

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Abstract

Design, fabrication and test of a kicker magnet and pulsed modulator for the Isotope Production facility at Los Alamos are described. The kicker deflects selected 100 MeV proton macropulses by 23º. The magnet yoke is made of flat laminations with Rogowski-profile end packs. Field clamps of a novel design are used to control coupling to nearby iron objects. The magnet meets stringent requirements for kicks given to trailing beam bunches by lingering fields along the unkicked beam trajectory.

1 REQUIREMENTS

Limited space was available for the kicker magnet. Accordingly, the kicker gap field relatively high for a pulsed magnet- almost 1 T. Also, space restrictions on one side of the beamline made it necessary to use a C-shaped yoke, with the return leg of the yoke on the side with the available space. The frequency response of the magnet and modulator field-pulse rise time and flattop requirements are set by the 120 Hz linac macropulse structure and the nominal macropulse length of 1 ms, together with the requirement that the macropulses trailing the deflected bunches are to be negligibly deflected by lingering kicker gap fields due to eddy currents, etc. Meeting the frequency response and lingering eddy-current field requirements was the most challenging part of the design. The basic requirements are summarized in Table 1.

Table I: Basic Design Requirements

Quantity	Value
Bend angle for 100 MeV protons	23°
Gap height	6.35 cm
Pole-piece length	60.0 cm
Pole-piece width	27.5 cm
Width of good-field region	13 cm
Central gap field	0.984 T
Total time available for pulse, including decay of eddy-current fields	15.6 ms
Pulse flattop time	2 ms
Pulse rise/fall time	4.5 ms
Allowable kick, trailing bunch	25 μrad

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2 DESIGN APPROACH

A major concern in design of the magnet/pulsed power supply was that there would be a too-large kick field lingering in the magnet gap at the time of arrival of an unkicked beam bunch passing through the kicker magnet immediately after deflection of the previous bunch into the IPF line. The allowable residual kick for trailing bunches is very small: 25 microradians. As a fraction of the 23 degrees nominal kick, this is 6.2×10^{-5}. The residual kick is computed by integrating the magnetic field along the straight trajectory of the unkicked beam, rather than the curved trajectory of the kicked beam. A flat lamination approach was chosen because the technology was more familiar and because it appeared to be easier and cheaper to construct than a very large gapped tape-wound core. Use of flat laminations in a pulsed magnet, however, made it necessary to use special yoke end packs with Rogowski profiles and with increased insulation gaps between laminations in the end packs to increase the magnetic reluctance for flux lines crossing from one lamination to another. The material chosen for the laminations was 0.014 in.-thick (0.36 mm) Armco standard M15 silicon iron with a rolling direction perpendicular to the pole-piece surface. The windings were subdivided into six individual coil sections to allow them to fit inside the magnet gap during magnet assembly, and then be moved up or down for placement around the one-piece yoke.

The major sources of lingering fields addressed during the design phase were power supply transients, ringing in the LC circuits formed by the leads, magnet inductance and winding capacitance, and eddy currents in the magnet windings and laminations. Power supply transients were addressed by incorporating limits to them in the specifications; the power-supply vendor was able to meet the specifications. Winding and lead capacitance effects were computed to be negligible for the required pulses; this was verified in the testing phase with the finished magnet and power supply. This left the question of eddy currents in the windings and laminations. The two were addressed separately. Effects of eddy currents in the windings on trailing bunches are dominated by the conductors at the ends of the windings. These effects were modeled in 2-D with a finite-element program (Opera-2D). Eddy-current effects in the laminations of main part of the windings were analyzed both with the finite-element code Opera-2D and by an analytic model, and found to be negligible with the 0.014-in thick laminations used, with the assumption that there were no shorts between laminations. Of greater concern were eddy currents in the end laminations and field clamps. No attempt was made to directly model them, but they were minimized by design. Removable end packs with a Rogowski profile were used to keep the flux lines from entering the wide faces of laminations at the ends. Also, in the end packs, the insulation thickness between laminations was increased to 0.002 in. A special epoxy formulation incorporating glass beads, developed at Fermilab, was used to produce the desired insulation gap. A final concern was eddy currents in the field clamps, which, because of beamline space constraints, had to be close to the windings. The two field clamps were made by wet-epoxy-winding oval cores out of ½ in. tape made of insulated lamination material, mounting the cores in a fiberglass support structure, curing the cores, and then cutting 2.5 in. gaps on one side. With this approach, the flux lines in the 2-D field region away from the sides of the pole-piece gap (i.e., where the beam goes) always enter the field clamp parallel to the laminations, and the eddy current effects are essentially those of ideal laminations and are small.

3 FABRICATION

The magnet was fabricated in Fermilab shops with laminations supplied by a commercial vendor[1]. Laminations were wet-coated with an epoxy mixture[2], stacked, compressed, and cured under pressure. For the end packs, glass beads were added to the epoxy, and again the laminations were wet-coated with the epoxy mixture, stacked, compressed, and cured under pressure. Glass bead size, bead fraction in the epoxy, and curing pressure were adjusted to give an average 0.002 in. insulating thickness in the end packs. After curing, the Rogowski profiles were machined in the end packs. End packs were attached to the main yoke by through bolts at the corners of the laminations. Fig. 1 is a photograph of the assembled magnet shortly after delivery to Los Alamos.

4 PULSED MODULATOR

The magnet power supply is a custom-built SCR-switched resonant modulator, designed and fabricated by a commercial vendor (Dynapower)[3] in accordance to Los Alamos performance specifications, with a design architecture based on an earlier, lower-power supply that was designed and built at Los Alamos National Laboratory. The basic performance specifications are given in Table II. During development, the modulator was tested at the factory with a dummy load that matched the design resistance and inductance of the magnet and leads.

Fig. 1. Photograph of the finished IPF kicker magnet shortly after delivery to Los Alamos.

Table II: Kicker Modulator Performance Specifications

Item	Value
Peak current	920 to 1050 A
Peak voltage	Approx. 4300 V
Pulse repetition rate	60 Hz
Load inductance	11 mH
Effective load resistance (including magnet pulsed losses)	0.03 ohms
Total pulse width	11.7 to 12.2 ms
Rise/fall time	5.35 ms
Flattop width	0.5 to 1.05 ms
Current flattop height repeatability (short term)	± 0.005%
Flattop droop, 1ms flattop	0.2%
Timing repeatability	5 ns
Leakage current between pulses	10 mA

After delivery of the modulator and magnet to Los Alamos, they were tested together. It was found in these tests that the magnet was somewhat more lossy than predicted by the design calculations, probably due to shorted laminations (low-field Q measurements gave a value of 50 instead of the predicted 100). Due to the significantly larger AC-resistive-loss term, and hence greater power loss than originally listed in the modulator specification, some compromises had to be made in the operation of the modulator to work with the magnet. One was to reduce the maximum operational repetition rate from the design value of 60 Hz to 30 Hz. With the present magnet, the modulator is power limited and unable to operate at full output current above approximately 35 Hz. In practice, this will not affect IPF operation because the target assembly is limited to 30 Hz operation with the existing beam current. Another was to extend the width of the flattop pulse from 1.05 ms to 2.25 ms, which allows for the eddy currents in the magnet coils to decay and still allow for a 1 ms flat top. Integral pulsed field measurements (described in the following section) showed that this stretching of the pulse length was allowable from the standpoint of lingering eddy-current fields at the time of the trailing beam bunch.

5 PULSED MAGNET MEASUREMENTS

After modulator testing was completed, pulsed field measurements were made using the new nominal modulator settings verify to pulsed performance. Measurements were made with an integral coil that was wound of 7 turns of 32 AWG copper wire on a 0.635 cm-wide by 91.4 cm-long form. The signal from the measurement coil and power supply's current transducer were read by a pair of HP-3458 digital multimeters set up to function as high resolution transient voltage digitizers. The integral coil was located 6 cm beam right of the centerline of the magnet, which is approximately the path of the unextracted beam. The magnet was pulsed at repetition rate of 20 Hz with current pulses of nominal amplitude and shape, i.e. a 12.5 ms long pulse with a 1040 A by 2 ms flat top. Data were recorded at a rate of 25 kHz for a time span long enough to capture 3 consecutive pulses. The short-term stability of the integral field over the flat top of the three consecutive pulses was found to be better than a few parts in 10^4, which meets specifications. When the kicker is used to extract pulses from a 120 Hz beam the following beam pulse will fall between 15 and 17 ms after the start of the modulator's current pulse. The integral field for this time interval was measured to be about +20 G-cm with an error estimated to be about ±20 G-cm. A field of 40 G-cm will steer the following pulse 27 μrad. This is at the level of 25 μrad that has been deemed acceptable.

6 CONCLUSIONS

The pulsed dipole magnet and modulator designed and built for the IPF facility meet all operational requirements, in particular the stringent requirements on lingering eddy-current fields (a residual kick for trailing beam bunches that is 6×10^{-5} of the preceding 23º kick). Measurement of the residual fields to this level was in itself a challenge. In achieving the design goals, several techniques for minimizing eddy-current effects were used, including use of special Rogowski-profile end packs and a novel type of tape-wound field clamp.

7 REFERENCES

[1] Laminations were stamped by Larsen Manufacturing, 906 E. High St., Mundelein IL 60060. Insulated M-15 sheet stock was manufactured by LSI Steel, 4444 Kildare Ave., Chicago, IL 60632.

[2] The epoxy mixture was Epon 826, 100 parts, NMA hardener, 90 parts, and DMP30 accelerant, 1 ½ parts. Cure cycle was 250º C for 15 hrs.

[3] Dynapower Corporation, 1020 Hineburg Rd, South Burlington, VT 05403