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ORBUMP Pulsed Dipole Magnet Design for Fermilab Booster

Vladimir Kashikhin, David Harding, Yuenian Huang, David Johnson, Dino Karas

***Abstract*—Fermilab initiated the accelerator magnet system upgrade project PIP-II for future neutrino experiments. Old ORBUMP pulsed dipoles should be replaced with new, stronger magnets occupying the same space as old ones. Four of these magnets connected in series form dogleg type of proton beam orbit. The magnet field and 19 kA current pulse length are close to 1 ms. Old magnet cores were based on a ferrite material. A magnet gap field above 0.4 T for new magnets completely saturates ferrite material. So, for the magnet core, 0.127 mm thick laminations of low carbon steel with inorganic coating were placed in a vacuum box. Transient magnet parameters were investigated, including the skin effect in the iron core and the single-turn copper coil. The copper coil shimming improved the integrated field homogeneity. Simulated by OPERA3D, power losses were used for the thermal analysis by ANSYS code. The magnet performance is strongly coupled with the power source. The pulsed power source design included the dynamic magnet inductance and resistance. The paper presented the ORBUMP magnet system design.**

Keywords*— *Accelerator, Design, Dipole, Magnet, Magnetic field, Simulations, Skin effect.

I. INTRODUCTION

THE Fermilab Proton Improvement Plan II (PIP-II) [3] is an essential enhancement to the Fermilab accelerator complex, powering the world's most intense high-energy neutrino beam on its journey from Illinois to the Deep Underground Neutrino Experiment in South Dakota – a distance of 1,300 kilometers. DUNE scientists will use neutrinos to answer some of the most profound questions about our universe. In addition, over the next 50 years, PIP-II will drive a broad physics research program, delivering scientific breakthroughs and likely to reveal surprising answers to questions that are not yet contemplated.

The injection system for the Fermilab Booster was designed in the early 90s. It was upgraded in 2005 by increasing the magnet pulse repetition rate from 3 Hz to 15 Hz [1], [2]. The new neutrino PIP-II experiment [3] needed to increase the repetition rate to 20 Hz and about 30 % of the magnetic field in new ORBUMP magnets. This drives the magnetic design to the magnet core field above 0.4 T, at which previously used ferrite core saturates. Because of fast pulse ramps to reduce eddy current effects, thin low carbon steel laminations should be used, which complicates the magnet's mechanical design. The magnet is mounted in a vacuum box, and special care should be taken not to compromise the vacuum.

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V. Kashikhin (corr. author), kash@fnal.gov, D. Harding, harding@fnal.gov, Y. Huang, huangy@fnal.gov, D. Johnson, dej@fnal.gov, D. Karas, dkaras@fnal.gov are with the Fermi National Accelerator Laboratory, P.O. 500, Batavia, IL 60510 USA.

II. MAGNET SPECIFICATION

The magnet specification shown in Table I was designed on the base of beam optics analysis. The injected beam orbit has a dogleg trajectory formed by four identical ORBUMP dipole magnets connected in series. They are single-turn window frame magnets with water cooling.

TABLE I
MAGNET SPECIFICATION

Parameters	Units	Values
Proton Beam Energy	MeV	800
Magnetic field pulsed ramp up/down	ms	0.2 ÷ 0.4
Magnetic field pulse plato	ms	0.6
Pulses repetition rate	Hz	20
Beam bend direction		Vertical
Maximum integrated field	T-m	0.355
Field homogeneity in the aperture	%	± 0.05
Good field area width	mm	250
Peak current	kA	≤ 20
Magnet gap	mm	56
Laminated core length	mm	850
Total magnet length	m	≤ 1.09

Magnets will be mounted inside vacuum boxes and operate with low outgassing. To reduce fringe fields, special care should be taken to design external leads and bus bar connections. In [2], not optimized position of current leads produced a rather significant quadrupole field component in the magnet integrated field. In the new magnet, leads are placed symmetrically.

III. Magnet Design

The ORBUMP magnet design is based on the specification shown in Table 1. The window-frame magnet configuration can produce a homogeneous magnetic field in a parallel gap and a low fringe magnetic field.

A. Magnetic Design of Single Magnet

For the transient magnetic field, the analysis used an OPERA3D code [4]. The field simulation includes the skin effect in the single-turn copper coil. The simulated model is shown in Fig. 1.

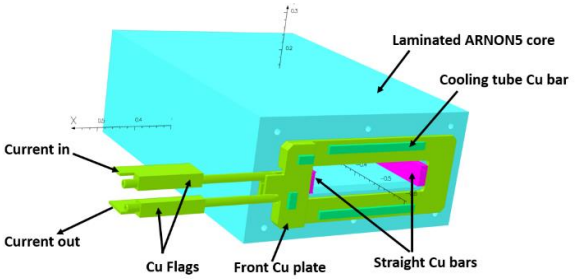

Fig. 1. ORBUMP magnet simulated model.

A capacitor-based pulsed power source powers the magnet. There were several iterations between magnet and power supply designs. We were initially supposed to use a PFN (pulse forming network) type source, usually used in kicker magnets, creating sharp ramps with high voltages. For this magnet, we have relatively modest 0.2 ms ramps to a peak current of 19 kA, and the final choice was for a capacitor-based power supply to reduce peak voltages.

Magnet transient analysis strongly depends on laminated core properties. For equivalent current ramp frequencies up to 1250 Hz, we choose ARNON5 [5], the thin 0.127 mm thick non-oriented low carbon steel. The toroidal laminated package of this steel was measured, and the results are shown in Fig. 2.

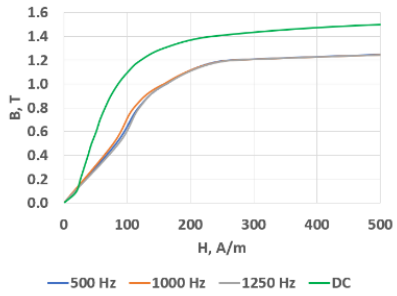

Fig. 2. ARNON5 steel B-H curves for different frequencies.

One could see that the chosen lamination thickness did not show property variations for 500-1250 Hz frequencies but a substantial drop from a DC mode.

Results of the magnet simulation are shown in Fig. 3 – Fig.10.

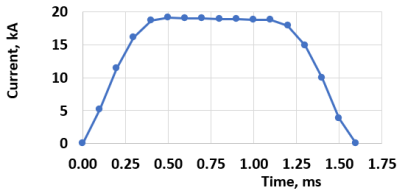

Fig. 3. Magnet current pulse.

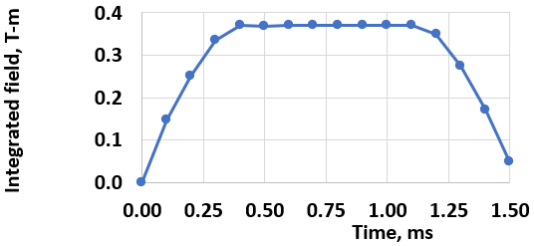

Fig. 4. Magnet integrated field.

At the pulse top, the current is 19 kA, which generates the gap center field of 0.415 T and 0.37 T-m. For the specified integrated field of 0.355 T-m, the operating current should be 18.2 kA. Because of the fast ramp, there were large coil inductance and resistance variations (see Fig. 5, Fig. 6).

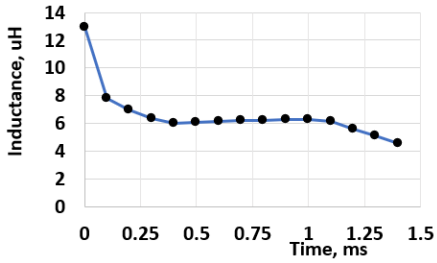

Fig. 5. Magnet inductance, six μH on the pulse top.

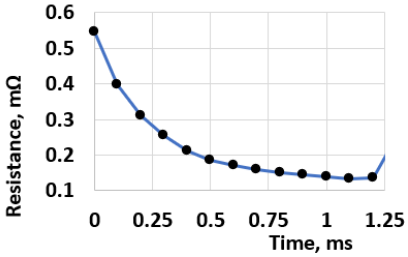

Fig. 6. Coil resistance exponentially decays with the field penetration in the copper conductor.

The magnet inductance and coil resistance data were used for the power source design to match the variable in time load.

The simulated integrated magnetic field homogeneity is shown in Fig. 7.

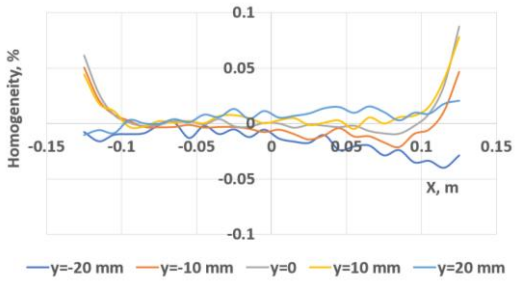

Fig. 7. The integrated magnetic field homogeneity in the magnet gap at 0.7 ms.

The field homogeneity fits the specified value ± 0.05 % in the good field area of ***dx*** = ± 125 mm, ***dy*** = ± 20 mm. This result was achieved by adding 2 mm x 2 mm copper shims to straight bars of copper coil shown in Fig. 8.

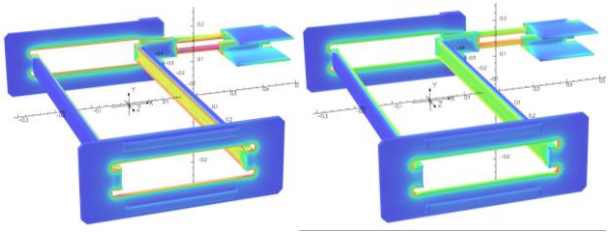

Fig. 8. Copper coil current density for 0.2 ms (left) and 0.7 ms (right). The peak current density is 150 A/mm^2 in straight copper bar corners.

The skin depth for 1250 Hz frequency is 0.137 mm for electrical steel, 1.94 mm for copper, and 12.3 mm for stainless steel. The magnetic field of the magnet iron core is concentrated in the corner close to the coil, as shown in Fig. 9.

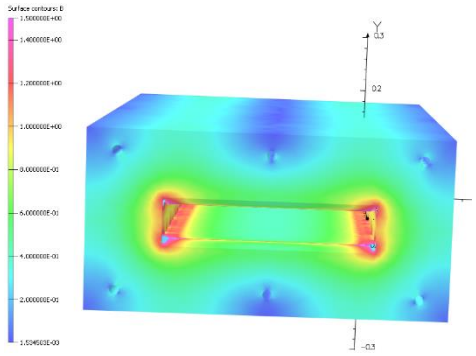

Fig. 9. Flux density in the iron core at peak current.

The peak field is 1.5 T, which is above the ferrite material's 0.4 T saturation. For core losses, calculations used experimental data shown in Table II. The formula approximated the steel losses at 1250 Hz (obtained from columns 1 and 2 of Table II):

$$\boldsymbol{W(B)} = 49.614\cdot\boldsymbol{B}^2 - 7.13\cdot\boldsymbol{B} + 4.05, \quad (1)$$

W(B) – power losses in W/kg, ***B*** – flux density.

TABLE II
ARNON5 STEEL CORE LOSSES IN W/KG

	Frequency, Hz			
Flux density, T	1000	1500	2000	2500
0.25	3.12	5.38	8.28	11.54
0.5	10.11	17.92	27.18	37.66
0.75	20.2	35.99	54.8	75.99
1.0	33.29	59.69	90.14	125.68
1.25	50.22	88.52	137.11	190.17
1.5	78.69	134.96	204.36	284.77

Using (1) power losses were calculated by integration through the core volume:

$$\boldsymbol{Pfe} = \int (\boldsymbol{d}\cdot\boldsymbol{W(B)})\cdot\boldsymbol{dV}, \quad (2)$$

Where ***Pfe*** – power losses in the laminated core, ***d – core density, W(B)*** is defined by (1), ***V*** – the volume of the iron core. In the same way, defined power losses in the copper coil:

$$\boldsymbol{Pcu} = \int (\boldsymbol{\rho}\cdot\boldsymbol{J}^2)\cdot\boldsymbol{dV}, \quad (3)$$

Pcu – power losses in the copper, ***ρ*** – copper resistivity, ***J*** – current density.
Fig. 10 shows losses depending on time.

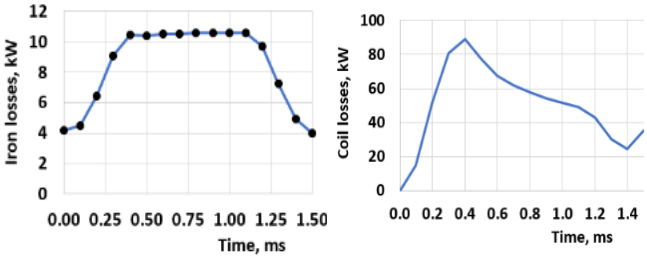

Fig. 10. Losses in iron core (left) and coil (right).

There are substantial peak losses, but because of the low (20 Hz, period 50 ms) pulse repetition rate and relatively pulse length of 1.5 ms, the average integrated core losses are ***Pfe***=260 W, ***Pcu***=1540 W.

B. Magnetic Design of Four Magnets

Four ORBUMP magnets will be connected in series (see Fig. 11). They are mounted relatively close, and overlapping fields between magnets could reduce the integrated magnetic field homogeneity. At the same time, because of symmetry and opposite field directions between inner and side magnets, theoretically, the total integrated field for four magnets should be zero. Some field distortions could be from current leads and connecting bars.

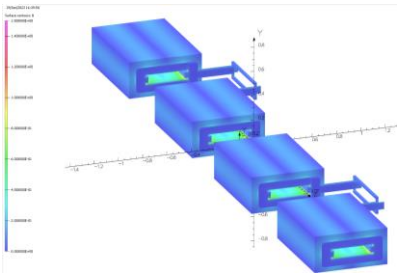

Fig. 11. Four ORBUMP magnets model.

Fig. 12. shows the magnetic field distribution along magnet centers at 18 kA coil current.

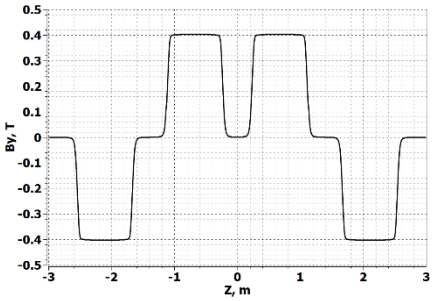

Fig. 12. Magnetic flux density distribution along the beam path.

The particle trajectories were simulated using a 3D field map for the magnet current pulse peak at 18 kA. The final acceptance of the four magnets field was made by tracking 800 MeV protons. Proton and ***Hmin*** particle tracks are shown in Fig. 13. The proton particle started traveling parallel *z*-axis at ***x***=84.48 mm, and ***Hmin*** at x= -125.52 mm, with *z*= -3.0 m. Both particles shifted to the same coordinate x= -20.4 mm at the magnet system center at z=0.

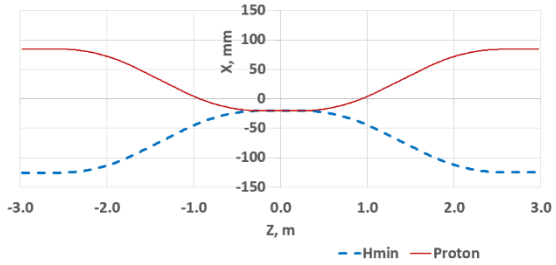

Fig. 13. Proton and ***Hmin*** particles tracks through 4 magnets started at different ***x*** - x-coordinates.

C. Magnet Thermal Analysis

Four ORBUMP magnets are powered in series from a single highly concentrated on one side of the copper conductor current with a skin depth of about 2 mm. OPERA3D calculates the heat load for each component of the copper coil. The average heat load within the magnet is 1540 W. The magnet is cooled with forced flow low conductivity water (LCW) at an inlet temperature of 32 °C within a 6.35 mm outer diameter copper tube. The heat transfer coefficient between the water and the cooling tube inner surface is calculated based on the flow velocity and water properties.

ANSYS [6] thermal model was used to simulate the magnet coil temperature when a heat load of 1540 W was applied to the copper coil. Copper electrical resistivity at 60 °C is used, so it is more conservative if the coil temperature obtained is below 60 °C. Fig 14 shows a simulated coil temperature profile when a heat load of 1540 W is applied. The coil peak temperature is 40 °C.

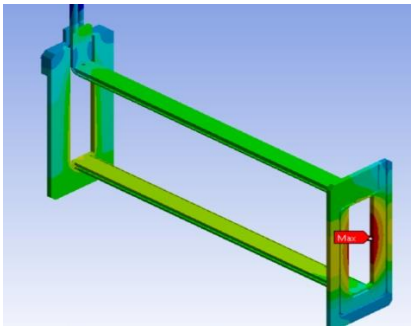

Fig. 14. Temperature distribution in the magnet coil.

D. Magnet System Design

ORBUMP magnets are mounted on the support girder to bend and inject the beam in the vertical plane (see. Fig. 15). On the top is shown connecting bus bars. Magnet single-turn copper coils and current leads are water-cooled. Each magnet is placed in a vacuum box.

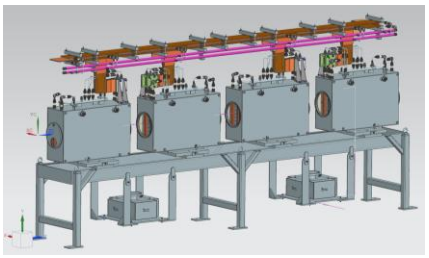

Fig. 15. Magnets mechanical design.

V. Conclusion

The magnet design described above meets the required ORBUMP magnet specifications. Nevertheless, deviations might exist in the iron's magnetic properties, machined parts, and assembly. The next most critical step is the power source design, which provides needed pulses of 18.2 kA currents. At Fermilab, the design and fabrication of magnetic field measurement systems have begun, including Hall probes, rotational coils, and stretch wire techniques. The measured results will be compared with simulations. Any unacceptable field deviations will be corrected after a first-item test.

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