Conceptual Design of AC Dipole Magnet for μ to e- Experiment

Report for the period December 2007 – January 2008

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AC Dipole Magnetic Design

1. Introduction

The AC Dipole magnet should generate alternating dipole field with the frequency of 300 kHz in the 10 mm high and 50 mm wide aperture. The AC Dipole magnet system will consist of two dipole magnets. Each magnet has the effective length 2 meters.

H-shaped and C-shaped magnet versions were investigated. The simpler C-shaped magnet with just one carrying current conductor was selected as the base line design. We assumed that vacuum system allows using such materials as ferrite for the magnet yoke and the epoxy impregnated glass tape for the electrical insulation.

The main difference between this magnet and other pulsed magnets like kickers, bumps, etc is that it is continuously powered by a sine wave resulting in large power dissipations in the magnet yoke and driving conductor. So, the choice of materials is strongly coupled with the magnet design and performance. Besides that, there is a high voltage applied to the conductor and the electrical insulation reliability should be taken into account. The magnet specification is shown in the Table I below.

Table I. AC Dipole specification.

Parameter	Unit	Value
Integrated strength	T-m	0.12
Magnet gap	mm	10
Effective length	m	2.0
Good field area width	mm	50
Center field	T	0.06
Current form		Sine wave
Current frequency	kHz	300
Operational regime		Continuous
Radiation level		low

2. Magnetic Design

The magnetic field of the magnet was simulated by OPERA 2D and COMSOL codes. Because of high magnetic field frequency, the transient analysis was performed for the selected geometry. It allowed taking into account the eddy current effects and their influence on the field quality. At such frequency, the skin depth for copper is very small (~0.1 mm) and all currents flow in a very thin layer of bulk conductors. It increases the resistive energy losses, and, as a result, the power dissipated in the magnet placed in the vacuum box. It is proposed to use Litz cable to eliminate this effect for the current driving conductor. The magnet concept cross-section is shown in Fig. 1.

Another issue is a choice of material for the yoke. There are known two types of ferrite materials used for high frequency applications. The first one is NiZn ferrite. This material has a high saturation flux density of ~0.4 T and a very high DC volume resistivity of 10^8

Ohm-cm. In addition to containing the magnetic flux, it can serve as the high voltage insulation for the conductors. At the same time, because of relatively high coercive force of ~0.8 Oe this material has high hysteresis losses. The second type of material is MnZn ferrite, which at the same frequency and saturation flux density has 10 times lower losses, but also a fairly low DC volume resistivity of 500 Ohm-cm. That material was chosen for further investigations.

The base line C-shaped magnet is shown in Fig. 1. The magnet yoke is surrounded by an electromagnetic Al shield and has the straight current-driving conductor made of Litz cable with water cooling pipe inside. The ferrite yoke material is a high performance, low loss MnZn ferrite MN60LL from Ceramic Magnetics, Inc. (See Appendix 1) or equivalent. Two-meter long magnet has four 0.5 m long sections with a total of eight current leads. The magnet is mounted inside the vacuum box. Each magnet section is connected in series with the capacitor banks of the power supply, forming the high efficiency resonant circuits.

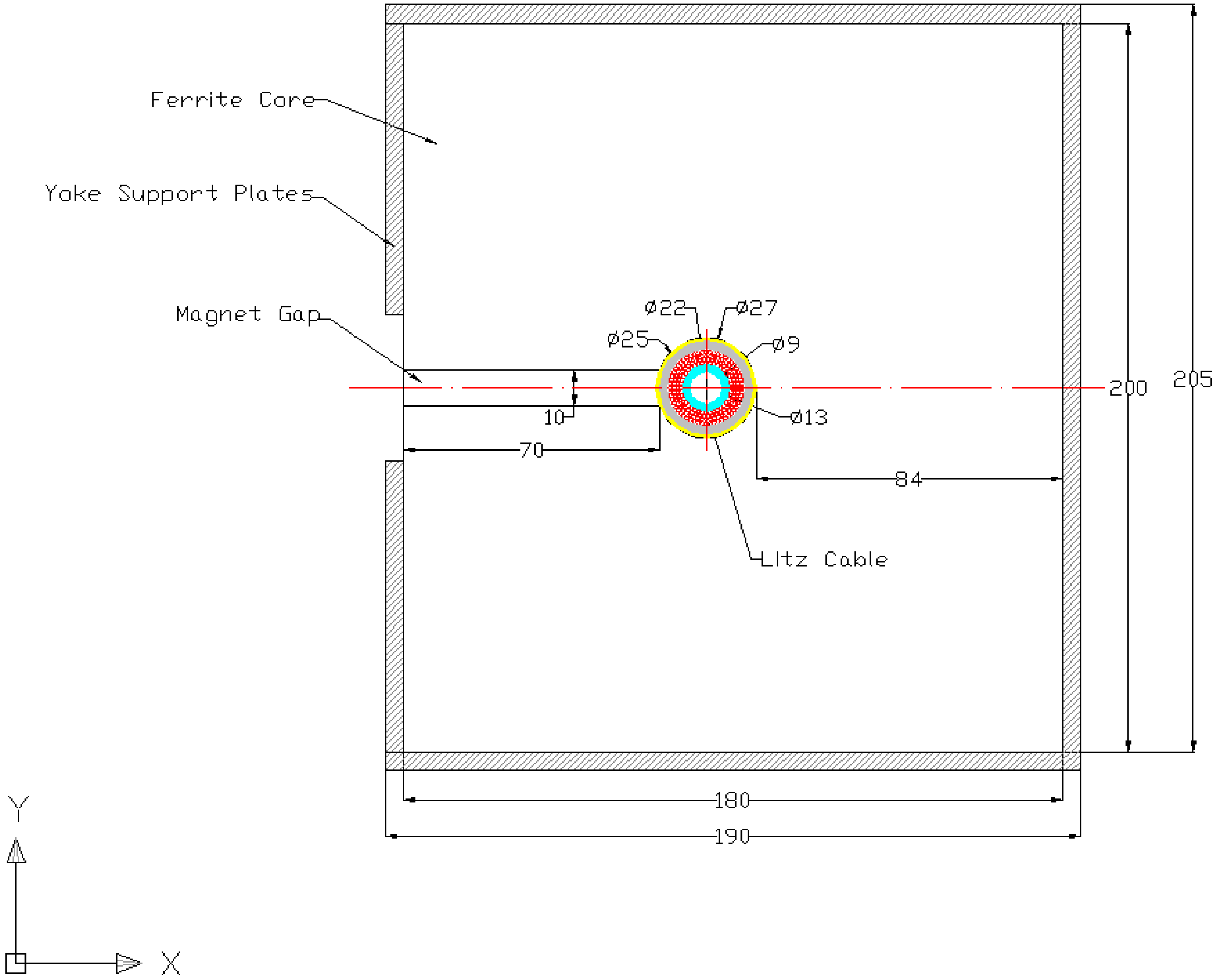

Fig. 1. Dipole magnet cross-section. All dimensions in mm.

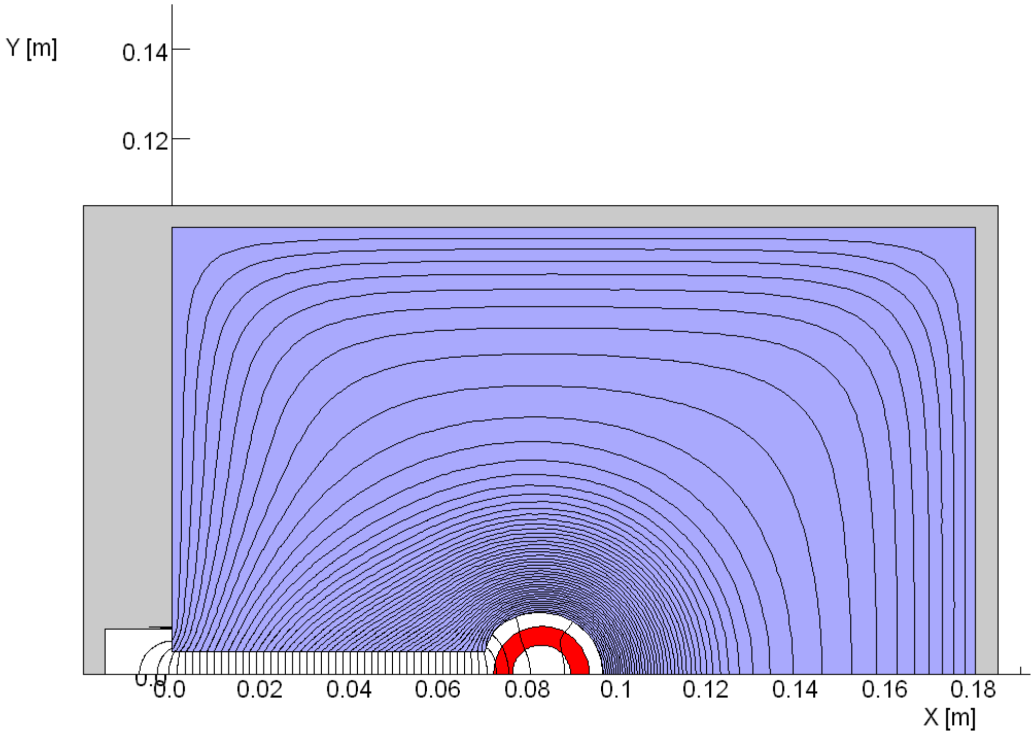

Fig. 2. C-shape magnet flux lines at peak current 500 A and time 0.83 µs.

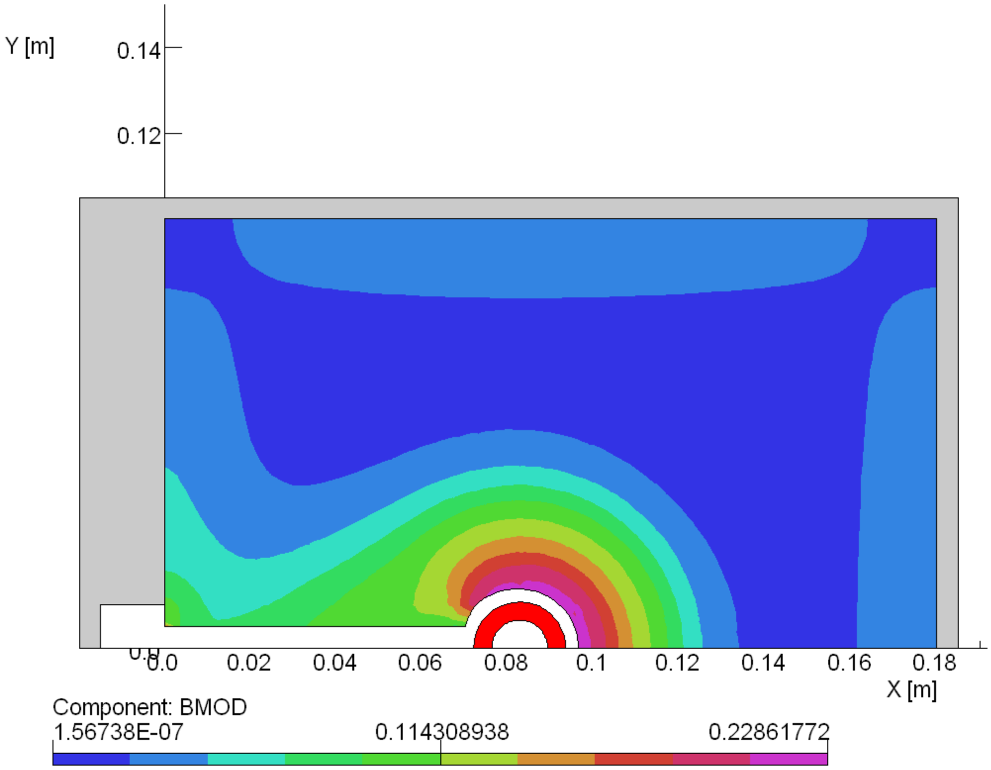

Fig. 3. Flux density distribution in the ferrite core at peak 500 A current and time 0.83 µs
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Fig. 3 shows the flux density distribution in the ferrite yoke. Only the inner yoke surface around the conductor is saturated. The yoke thickness and volume should be optimized during next design steps because of strong dependence between the ferrite volume, power losses, maximum ferrite temperature, and its magnetic efficiency.

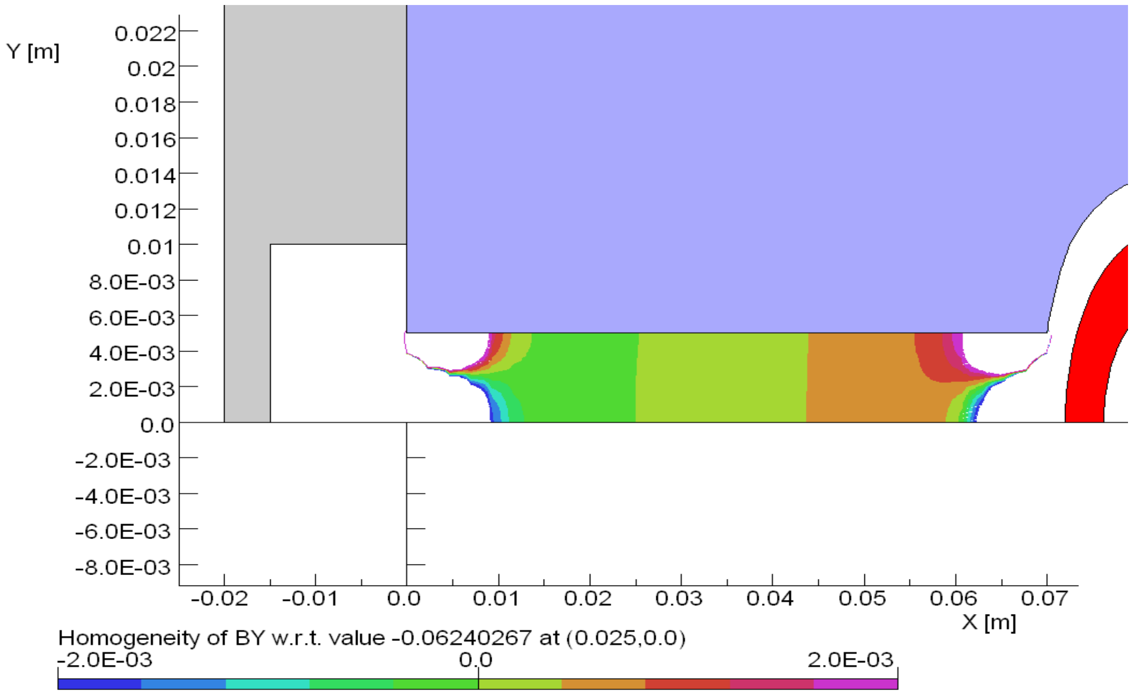


Fig. 4. Field homogeneity in the magnet gap at peak 500 A current. The range +/- 0.2 % is shown with the reference field -0.0624 T. The reference point has coordinates: x= 25 mm, y = 0.

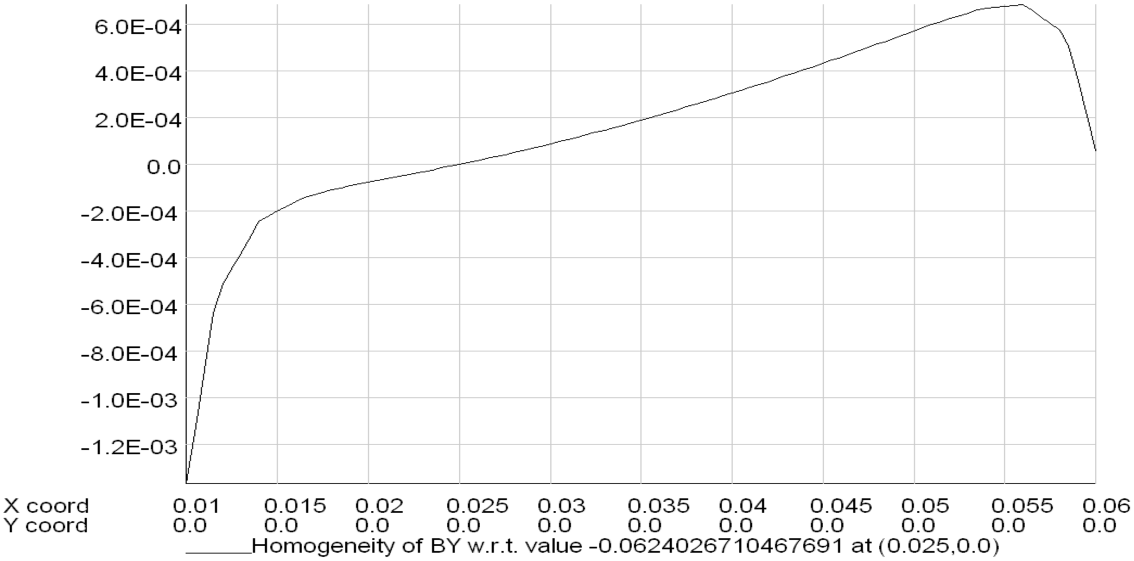


Fig. 5. Field homogeneity in the middle plane of magnet gap at peak 500 A.
The reference point has coordinates: x= 25 mm, y = 0.

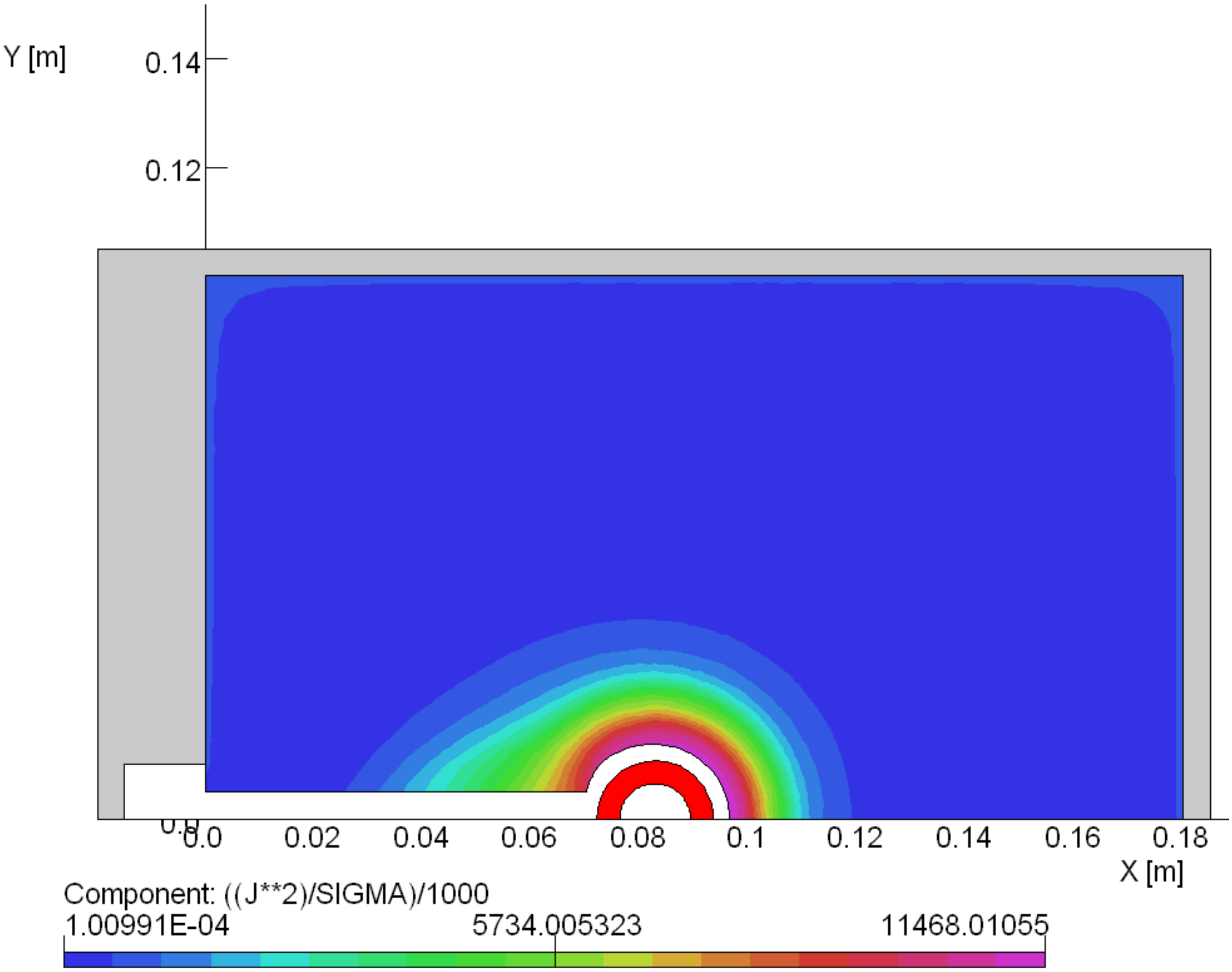


Fig. 6. Peak power loss distribution in the ferrite core, kW/m^3 at the time 1.8 μs.

Fig. 5 shows the field homogeneity distribution. One could see that there is a field drop near by the magnet pole edges. This effect could be reduced by proper shimming of the pole ends.

Fig. 6 shows the eddy current losses distribution in the ferrite yoke and Fig. 7 presents the power losses in the yoke and shield as functions of time. The mean integrated value of the power losses in the yoke is ~5 kW for 0.5 m long magnet section. The first quarter-period after switching the power supply on shows lower peak power losses in Fig. 7 because of the transient process. It converges to the normal AC profile in the next quarter-period. One can see that the maximum losses are in the yoke area close to the conductor, in the maximum magnetic field. These areas are close to the conductor water cooling pipe and will be effectively cooled. The outer magnet shield surface also has cooling pipes and provides an additional cooling.

It should be noted that this ferrite Curie temperature is only 185 C° and heating will reduce power losses without changing the ferrite magnetic permeability for the fields up to 0.1 T. The proper temperature analysis should be made to determine the cooling efficiency.

The outer magnetic shield in the magnet gap area may improve the field homogeneity but at the same time there are substantial eddy current losses in the gap area and it was decided to keep the gap open. The magnetic field drop at the pole end is compensated by the pole width increase from 60 mm to 70 mm.

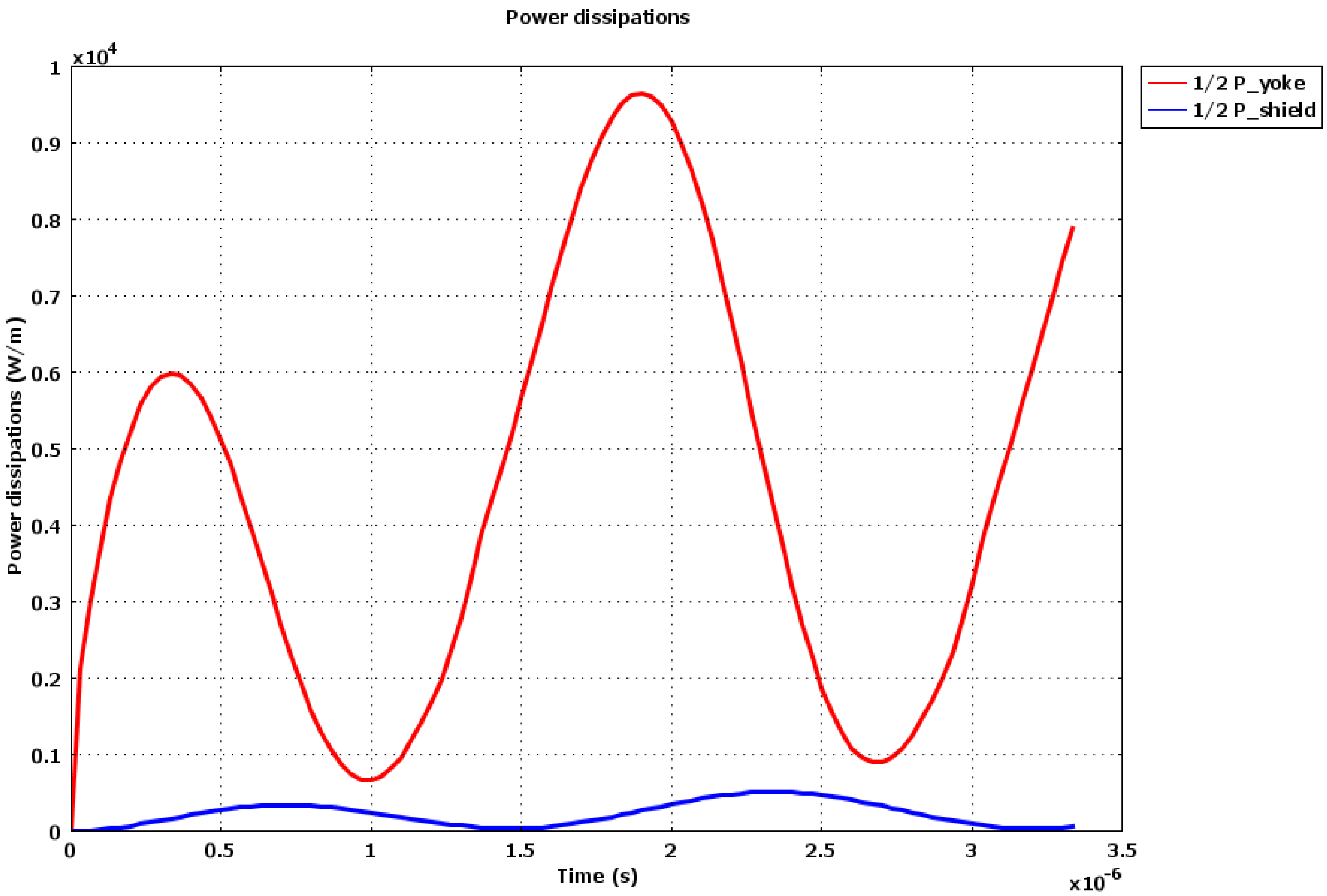


Fig. 7. Power losses in 0.5 m long ferrite yoke and Al shield as function of time. The peak power is 9.6 kW at time 1.8 μs.

2. Mechanical Conceptual Design

The mechanical conceptual design is presented on Fig. 8 – Fig. 10.

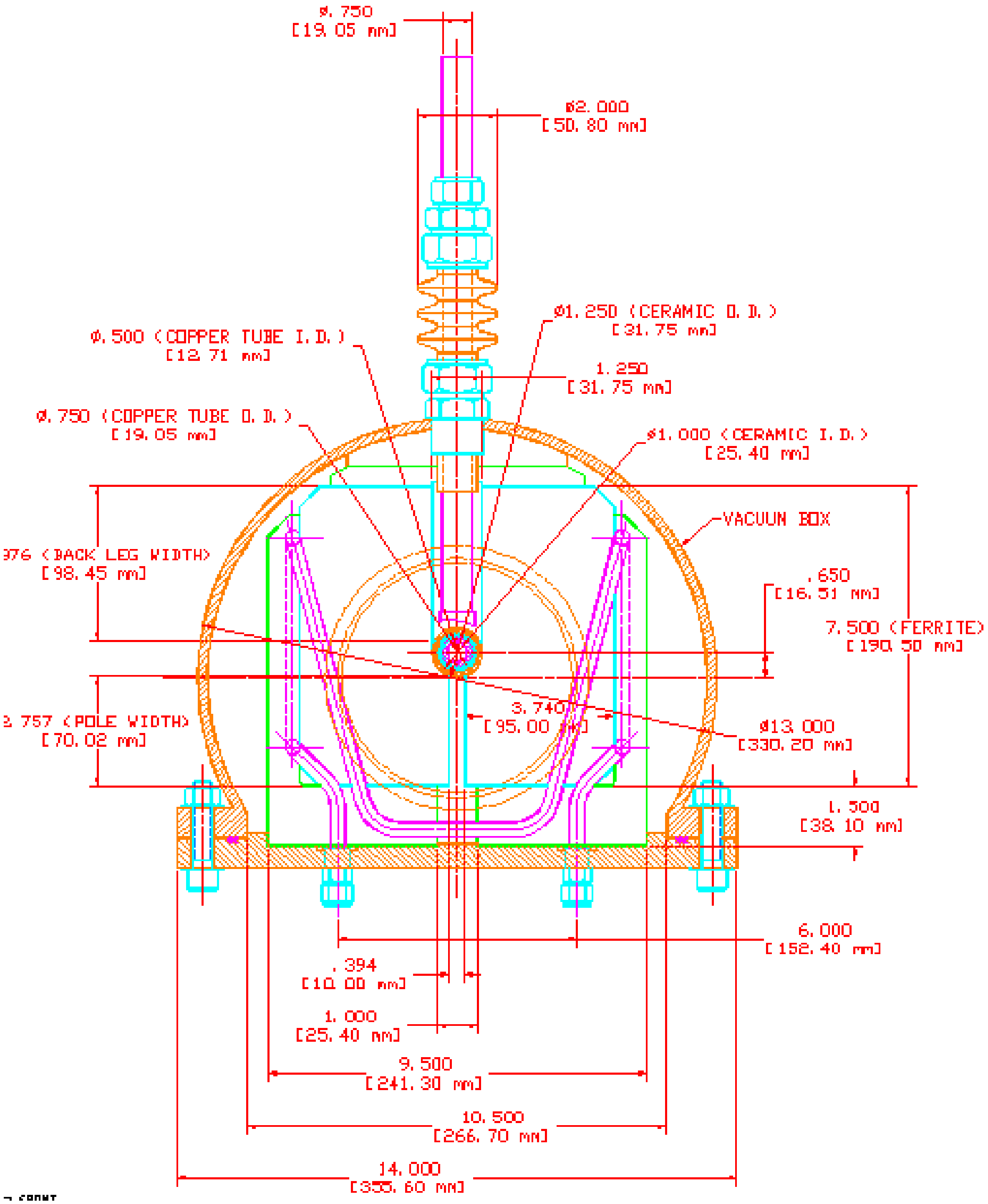


Fig. 8. Magnet cross-section front view.

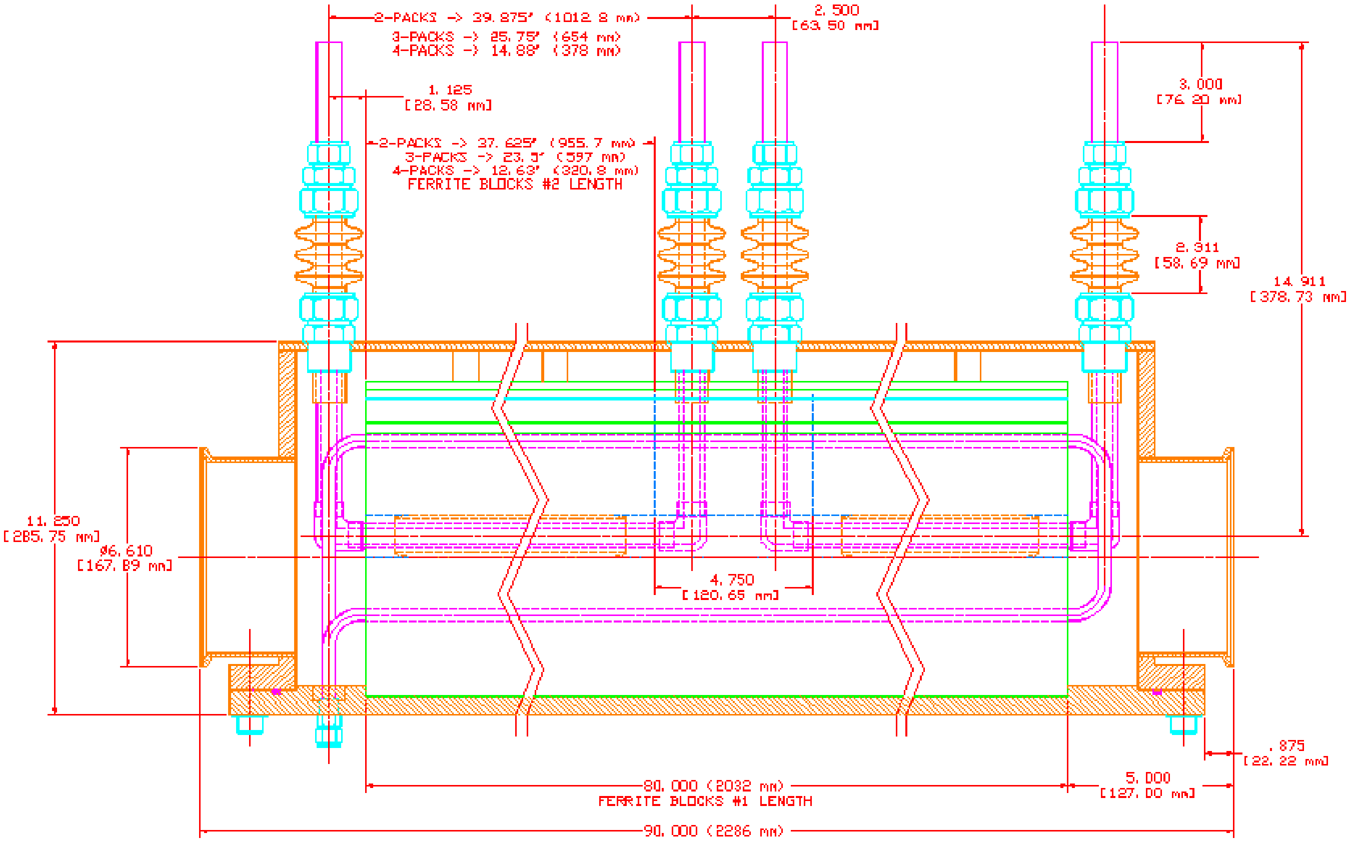


Fig. 9. Magnet cross-section side view.

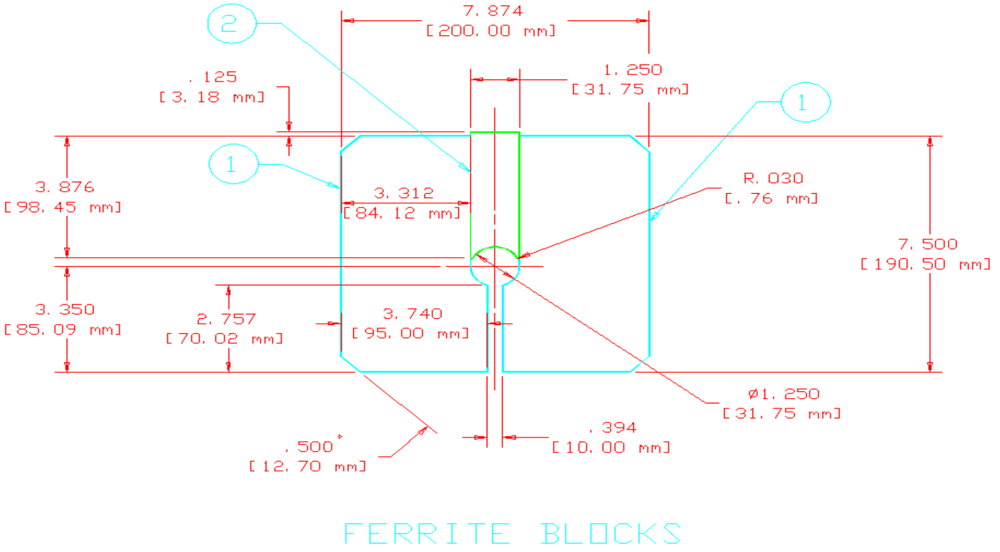


Fig. 10. The ferrite yoke cross-section. Blocks N1 and N2 are shown.

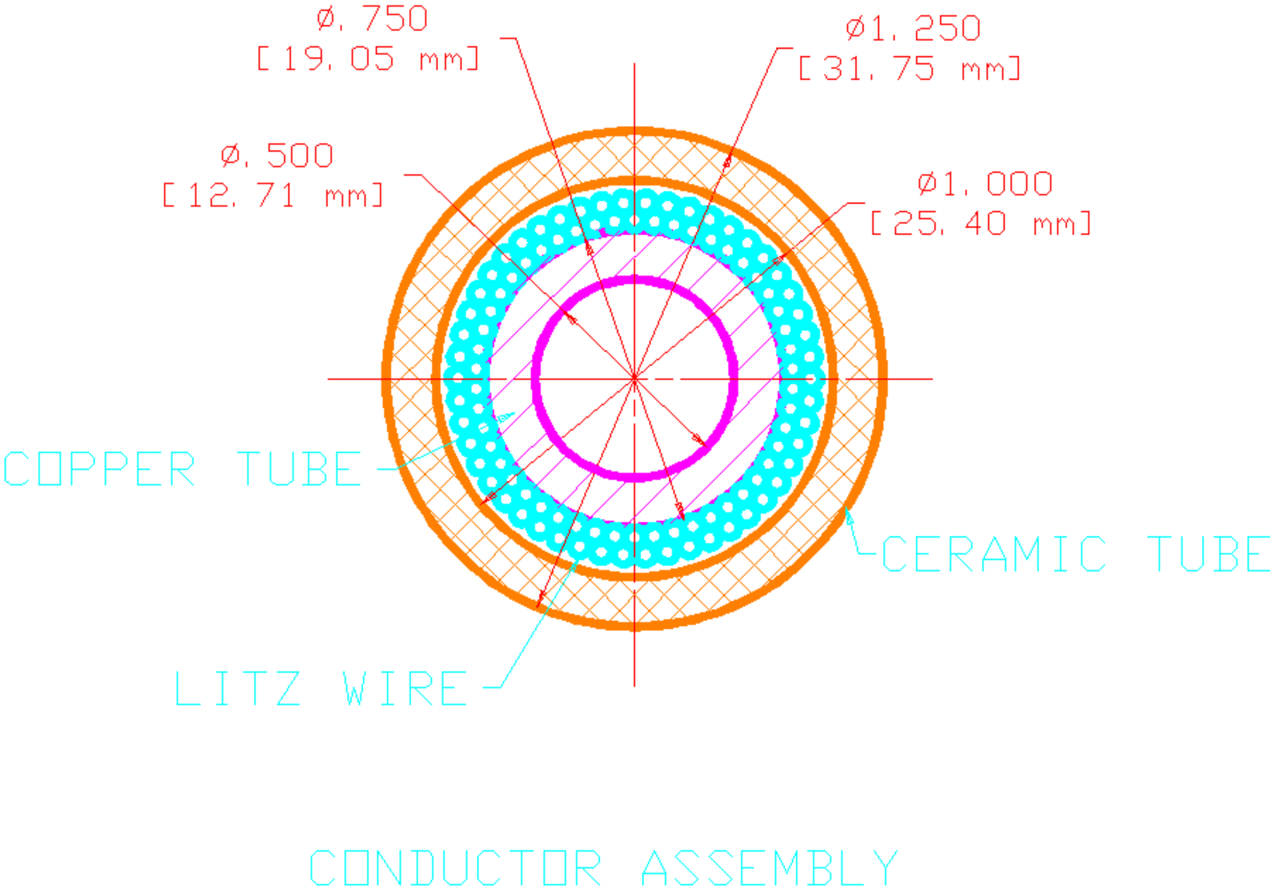


Fig. 11. The conductor cross-section.

The 2 m long magnet has four sections of 0.5 m in length mounted inside a vacuum box.. Each section has separate current leads. The magnet ferrite yoke placed into aluminum shield and glued to the shield by epoxy. The part of ferrite yoke in the magnet middle plane has been integrated with the conductor assembly and could be removed from the yoke during disassembly. This approach simplify the magnet assembly and repair.

The braided Litz cable with inner copper cooling pipe will be a vacuum impregnated with epoxy inside the ceramic pipe. Such assembly needed for reliability and long term high voltage operation. The coil section will be under ~ 5 kV continuous AC voltage during long periods of time. The ceramic tube will protect the insulation from partial corona discharges, residual gas ionization in insulation and following insulation breaks.

The magnet cooled by conductor cooling pipe and another cooling pipe inserted into the aluminum shield slots. It is expected ~ 6 kW total power losses per magnet 0.5 m long section.

3. Proposal for the short model manufacturing and tests

The proposed magnet concept should be tested by building the short 0.5 m long model. We will investigate all issues in the magnet design, fabrication, performance, and integration with power supply module.

The directions for investigation and possible issues:

1. High voltage long term operation.
2. High voltage tests of Litz cable with ceramic pipe.
3. Ferrite materials tests from different vendors and their comparison.
4. Ferrite yoke, outer shield, and Litz cable power losses.
5. Magnet cooling, ferrite hot spot temperature.
6. Vacuum box seals and feeds through.
7. Total magnet inductance and capacitance measurements to match power supply.
8. Field magnetic measurements at 300 kHz frequency.
9. Magnet manufacturing technology.
10. Magnet assembly, disassembly.
11. Accurate cost of materials and parts from vendors.
12. Higher frequency operation at ~ 400 kHz with larger gap.

4. Summary

The C-shaped AC dipole magnet concept is presented and discussed. The main issues for this magnet are the continuous high voltage operation and large power losses. The Litz cable modeling should prove the chosen design and will be performed soon. The voltage peak value decreased in 4 times by magnet sectioning but additional voltage drops on current leads should be investigated by 3D transient analysis.

The power losses in the ferrite yoke could be reduced by using the yoke laminated structure. The 3D modeling of fields and losses will be performed as the next step of the magnet design. In near future we are planning to rebuild the Test Stand for AC ferrite properties measurements to confirm the correct ferrite type choice and its properties.

Appendix 1

Ceramic Magnetics, Inc.
A THOMAS & SKINNER COMPANY
16 Law Drive • Fairfield, New Jersey • 07004 • USA
Phone: (973) 227 4222 • Fax: (973) 227 6735
http://www.cmi-ferrite.com

MN60LL HIGH PERFORMANCE, LOW LOSS FERRITE

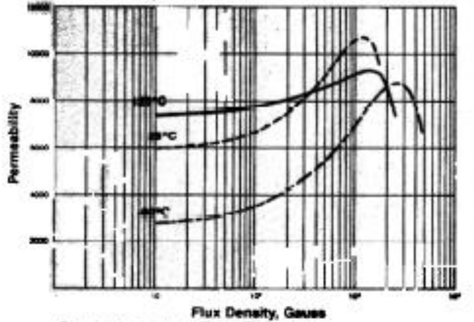
The ultimate in power efficiency materials, this high quality ferrite is especially suited for high power, high efficiency applications. It is ideal for applications where heat rise in the transformer cannot be tolerated.

Magnetic and Physical Characteristics

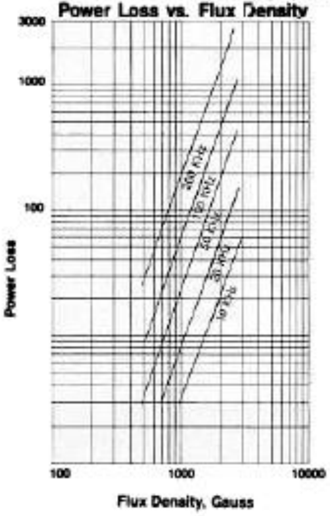
INITIAL PERMEABILITY	6500
MAXIMUM PERMEABILITY	10,500 typ.
MAXIMUM FLUX DENSITY	4300 gauss min.
REMANENT FLUX DENSITY	1200 gauss max.
COERCIVE FORCE	0.12 oersted max.
CURIE TEMPERATURE	185°C typ.
dc VOLUME RESISTIVITY	500 ohm-cm typ.

Typical Design Curves

Permeability vs. Flux Density



Power Loss vs. Flux Density



Power Loss
vs. Frequency at 125°C