ISBN: 978-3-95450-240-0 ISSN: 2673-5539 doi:10.18429/JACoW-RuPAC2021-WEPSC21

MAGNETS FOR LIGHT IONS ACCELERATOR

I. A. Yurin, S. M. Polozov, M. S. Dmitriev, E.N. Indyushnii, National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russian Federation.

Abstract

At the moment, the National Research Nuclear University (MEPhI) is developing an injector for an accelerator of light ions with an energy of 7.5 MeV / nucleon. The injector uses several tens of quadrupole magnets with a magnetic field gradient of 6-18 T / m and several units of dipole magnets. Key requirements for quadrupole magnets include large aperture, compact transverse dimensions, uniform shape and design, ease of fabrication from a manufacturing standpoint, field accuracy within 0.1%, and low power consumption. This article will describe the requirements, simulation results, and preliminary designs for quadrupole and dipole magnets.

INTRODUCTION

The new project of the injector for the proton and light ion accelerator will have several tens of quadrupole magnets, the range of the magnetic field gradient is 6-18 T / m, the aperture of the transport channel is 66.5 mm, the physical length of the lens is 100 mm, and the pulse repetition rate to 5 Hz. The original concept of a quadrupole magnet was continuous operation, since in any case the inductive component will be large enough and the transient time will not allow reducing the operating time with the power supply turned on. Based on the simulation results, for the maximum value of the magnetic field gradient (18 T / m), the active power of each cooling will be 582 W, and an active liquid system will also be required to maintain an acceptable temperature with a water flow rate of 0.415 liters / minute for each winding. According to the concept, the operating mode of the accelerator system is continuous (24/7), therefore, efficiency in terms of operation is also an important aspect. For example, for 10 quadrupole magnets (with the maximum gradient value), the electricity consumption per week will be 3.9×10^3 kW-hr, and the volume of water pumped will be 167 m^3. The optimal solution was to switch to a pulsed mode of operation.

MAGNET DESIGN

When developing the quadrupole, several important points were taken into account: the power source must be made on existing serial electronic components (in particular, IGBT transistors), the cooling system must be passive, the magnet design for all sections of the injector must be unified. The simulation resulted in a quadrupole magnet with the following parameters in Table 1.

Table 1: Quadrupole Specifications

Parameters	Value	Unit
Quadrupole gradient	18.0	T/m
Physical length	100	mm
Effective length	128.5	mm
Good field region	±15	mm
Number of turns per pole	48	
Conductor dimension	4×8	mm^2
Weight	138.25	kg
Steel	3408	
Operating temperature	48	°C
Total heat dissipation	10.55	W

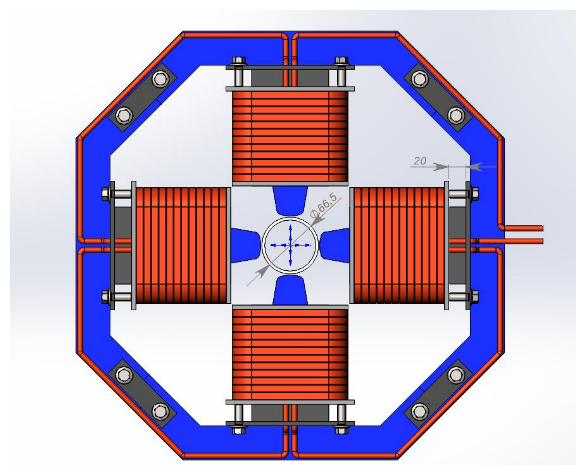

Figure 1: Front view of the pulse quadrupole.

The Pulsed Quadrupole was developed using 3D modeling software. To realize the maximum gradient of 18 T / m, the excitation current must be 180.5 A, the number of turns in coil is 48, the transverse dimensions of the conductor are 4×8 mm^2. A sketch of the model is shown in Fig. 1. The inductance of each coil is 3.17×10^{-3} H. The pole shape is built according to the equation [1]

$$xy = \frac{h^2}{2} \quad (1)$$

The magnet yoke is designed out of silicon steel, since this steel has a narrow hysteresis loop and, unlike low-carbon steel, will reduce the transient time by 5-6 times (for this model), in this case, steel grade 3408 is chosen. The yoke design is 4 connecting elements. The elements are packets of laminated steel with a thickness of 0.35 mm, this thickness is due to the decay time of eddy currents [2]

ISBN: 978-3-95450-240-0 ISSN: 2673-5539 doi:10.18429/JACoW-RuPAC2021-WEPSC21

$$\theta = \left(\frac{\sigma^2}{\pi \times \rho_{cm}}\right) \times 10^3 = 1.95\, ms \quad (2)$$

POWER SUPPLY CONCEPT

The power supply is an LC circuit [3], where the pre-charged capacitor C is the source, and the inductance L is the series-connected quadrupole coils. The schematic diagram is shown in Fig. 2.

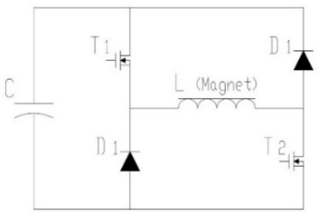

Figure 2: LC circuit.

This connection scheme was chosen in order to refuse from the pulse matching system, as when each coil is powered by a separate source. The pulse times are calculated from the allowable heat dissipation. The maximum allowable amount of heat load per coil is 10.6 W, at this load in steady state the temperature of the coils is 48 degrees Celsius. Temperature distribution is shown in Fig. 3.

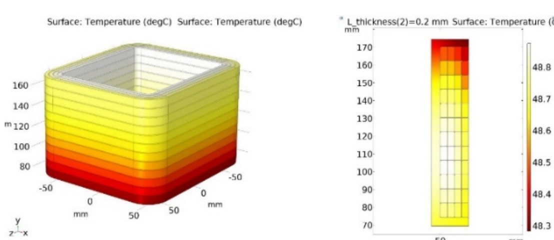

Figure 3: Coil temperature distribution.

For the operation at a frequency of 5Hz, the allowable pulse time is 5 ms, with the required pulse flat top time of 200 µs, the rise time is 2.49 ms. Calculated LC parameters are presented in Table 2 with other parameters.

Table 2: Power Supply Specifications

Parameters	Value	Unit
Magnet current maximum am-	180.6	A
Maximum amplitude of voltage	1510	V
Maximum pulse rep-rate	5	Hz
Pulse time	5	ms
Front time	2.9	ms
Flat top time	200	µs
Capacity	187	µF
Load parameters	13.54	mH, mΩ

PULSE OPERATION MODE SIMULATION

Simulation of the circuit was carried out in the program for modeling electrical circuits, taking into account the inductances and resistances of all sections of the circuit, both the coils themselves and the connecting wires, the fall of the pulse shelf within 200 µs is no more than 0.06%, the simulation results are presented in Fig. 4.

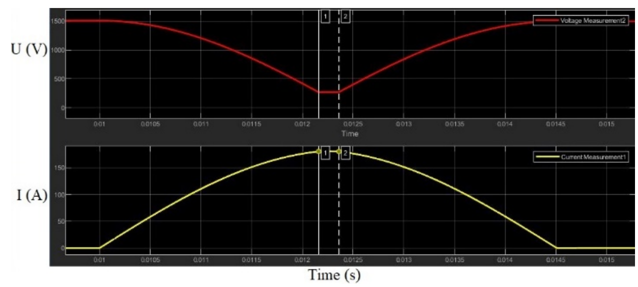

Figure 4: The values of the voltage across the capacitor and the current in the coil during the pulse.

The magnetic field gradient is corrected by shifting of the coil along the pole axis. From the zero point, where the field gradient is 18 T / m, a shift of ± 10 mm is possible, such a shift makes it possible to change the field gradient within 0.94%, which is sufficient since according to production conditions, the permissible deviation for the coils is 1%. The adjustment was simulated in the time domain in a 2D staging. With this technique, it is worth considering the conductivity of the yoke in the longitudinal direction, since the sheets of steel are located perpendicular to this direction. There are several approximations for determining the conductivity of the laminated core [4], according to these approximations, the conductivity in longitudinal direction is taken into account. The simulation results are presented in Fig. 5.

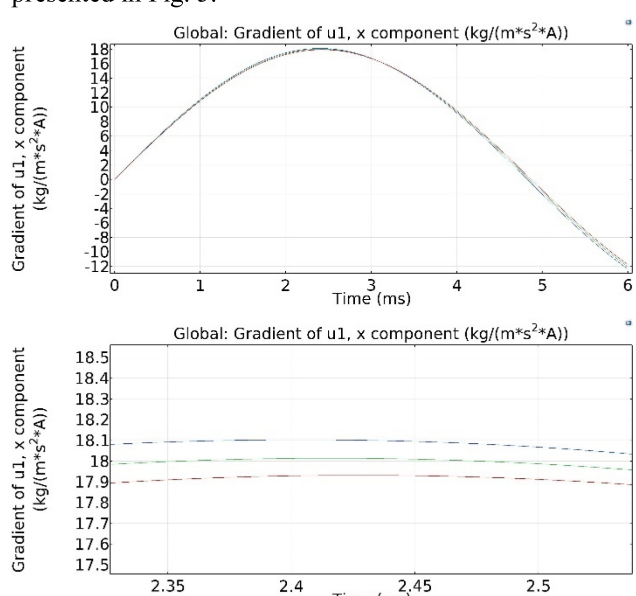

Figure 5: Adjusting the gradient

27th Russ. Part. Accel. Conf. RuPAC2021, Alushta, Crimea JACoW Publishing
ISBN: 978-3-95450-240-0 ISSN: 2673-5539 doi:10.18429/JACoW-RuPAC2021-WEPSC21

DIPOLE MAGNETS

Three types of dipole magnets are also being developed for LEBT to compose beam from four ion source and for HEBT to shift the beam after injector to the injection chicane 0.06 T, 0.2 T, 1.19 T. The type version, at 0.06 T will used for composing beams from two ion sources, in view of the relatively low field level, was designed without an active cooling system, cooling only by means of free convection. For the yoke of the magnet low-carbon steel of St 1010 is used, the mass of the yoke is 703 kg, the amount of heat generated per coil is 44 W, the maximum design temperature is 37 degrees Celsius. A sketch of this magnet is shown in Fig. 6.

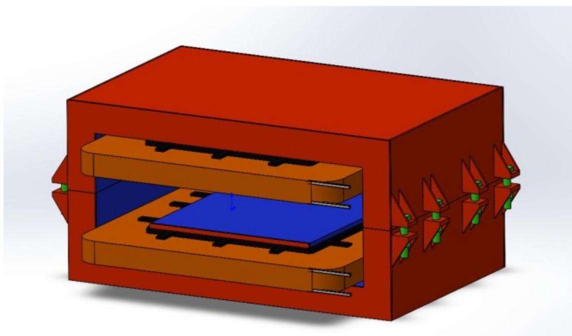

Figure 6: Dipole magnet 0.06 T.

The second dipole, with the field of 0.2 T will be used for composing of two trajectories in the final segment of LEBT. The shape of the dipole is due to the presence of two trajectories passing through the gap of the magnet. The yoke is steel St 1010, the mass of the yoke is ~500 kg, the amount of heat generated per coil is 700 W, the water consumption is 0.96 liters / minute, the maximum design temperature is 33 degrees Celsius. A sketch of magnet is shown in Fig. 7.

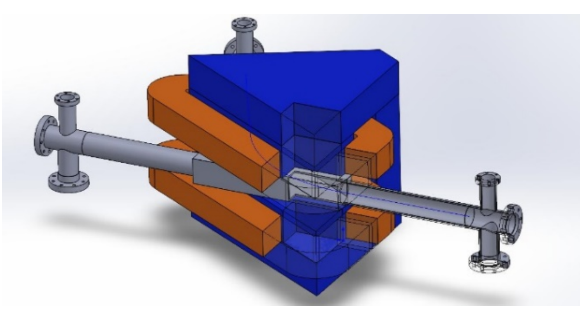

Figure 7: Dipole magnet 0.2 T.

The third dipole with a field level of 1.19 T will used for rotation the beam from the HEBT into the booster and it also uses an active cooling system. The yoke is steel St 1010, the mass of the yoke is 4400 kg, the amount of heat generated per coil is 3500 W, the water consumption is 5.14 liters / minute, the inlet pressure is 3.3 atm. The maximum design temperature is 31 degrees Celsius. A sketch of this magnet is shown in Fig. 8.

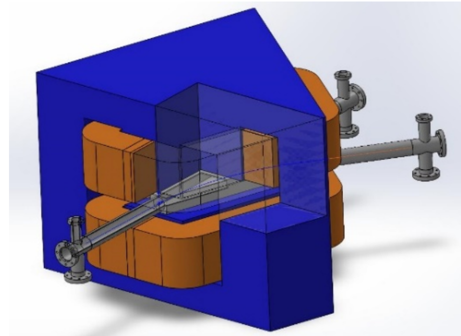

Figure 8: Dipole magnet 1.19 T.

CONCLUSION

The development of a pulsed quadrupole magnet was carried out taking into account the thermal load and the possibility of unifying the magnet for all sections of the accelerator. Requirements for the power supply were determined. Dipole magnets calculated. Further steps are to calculate the beam dynamics using obtained field distributions, example is shown in Fig. 9.

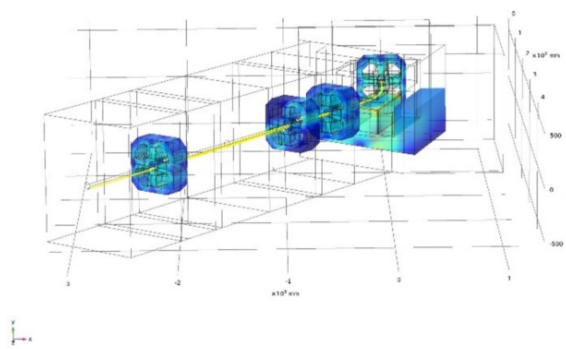

Figure 9: Beam dynamics in structure.

REFERENCES

[1] J. Tanabe, "Iron Dominated Electromagnets Design, Fabrication, Assembly and Measurements". Stanford Linear Accelerator Center, Stanford Synchrotron Radiation Laboratory, Stanford, USA, SLAC-R-754, 2005, p. 44.

[2] A. Ponomarenko, "Powerful impulse technology", MEPhI, Moscow, 2007.

[3] J.Wang *et al*., "Versatile dc/pulse switching mode power supply for an interleaving dipole magnet", in *Proc. EPAC'02,* Paris, France, June 2002, pp. 2508-2510.

[4] H.Neubert *et al., "*Homogenization approaches for laminated magnetic cores using the example of transient 3d transformer modeling", Technische Universität Dresden, Germany, Institute of Electromechanical and Electronic Design, 2ABB AG, Corporate Research Center Germany, Ladenburg, Germany, in *Proc. COMSOL'13,* Rotterdam, Netherlands, October 2013.