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MAGNET FOR BRANCHING THE ELECTRON BEAMS OF THE MAC RECIRCULATOR

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A distinctive feature of the multi-turn recirculators lattice is the need for magnets that combine and separate electron beams with a large energy difference. Consequently, they must have a fairly wide aperture with a uniform magnetic field. This paper examines the specific parameters of such magnets for the MAC recirculator at the National Science Center "Kharkiv Institute of Physics and Technology" (NSC KIPT). The results of calculations and the development of a preliminary design for the magnet are presented.

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INTRODUCTION

In terms of beam utilization, linear electron accelerators offer the best capabilities for physics research. This is due to the stability of the beam parameters, low emittance, and the ease of controlling these parameters. Since the main cost of an accelerator is the cost of the accelerating structure, a beam recirculation scheme can be used to obtain a beam of a specified maximum energy at the lowest cost. This scheme uses a magnetic system to transport the beam through the accelerating structure several times. This scheme allows for the simplicity of controlling beam parameters during experiments and significantly reduces the cost of the accelerator complex.

The simplest scheme is to double the energy by having the beam pass through the accelerator a second time using some magnetic lattice. It was implemented on an injector at MAX-lab [1] and the MIT Center for Accelerator Science and Technology [2]. The electron energy in the accelerators at these laboratories was increased to 500 and 1000 MeV.

The requirements for the magnet lattice of the recirculator increase significantly as the number of recirculations increases [3–12].

As can be seen from the recirculation diagram at the CEBAF complex [3] following its latest upgrade, it features a highly branched system of arcs arranged in space.

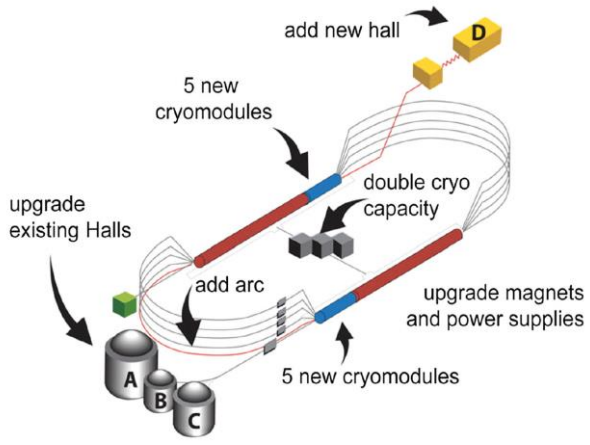


Fig. 1. Modernization of the CEBAF facility [3]

A rather complex system of magnets is used to properly distribute the beam along the arcs (Fig. 1). As can be seen from the beam distribution diagram (Fig. 2), it requires magnets with a wide aperture.

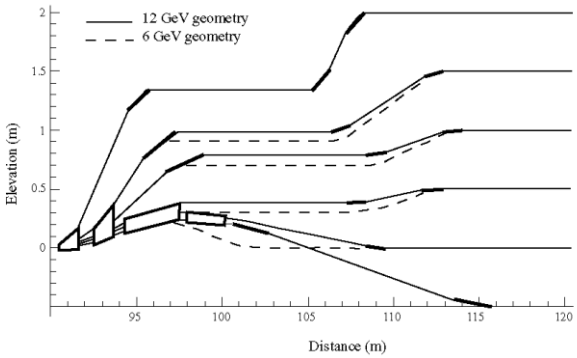


Fig. 2. Schematic of the magnetic system for beam distribution along the arcs at CEBAF [4]

Similar problems arise in other systems with multiple arcs [5, 8–12].

1. FEATURES OF THE MAC RECIRCULATOR'S MAGNETIC SYSTEM

The magnet lattice with triple-pass acceleration structures chosen for the MAC recirculator project [13, 14] is quite simple and significantly reduces the cost of the facility. The two recirculator arcs and the acceleration system are arranged in a single plane. As a result, there are two points where beams of different energies are combined and split, as shown in Figs. 3 and 4.

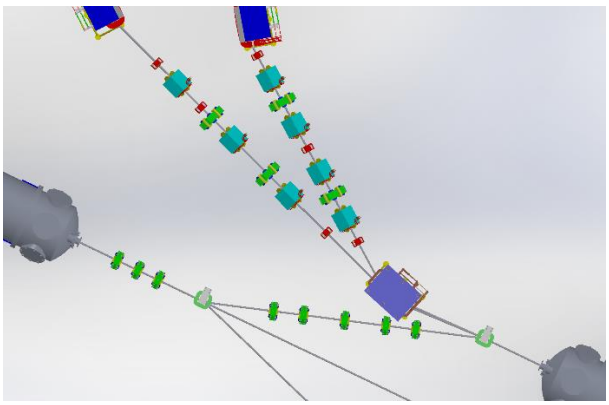


Fig. 3. Combination of beams of two arcs

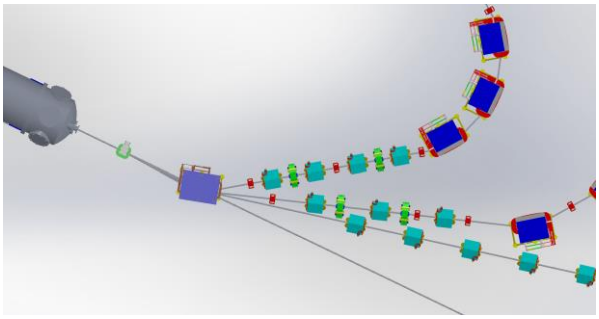


Fig. 4. Branching of beams at the exit of the accelerating structure

2. SELECTION OF MAGNET PARAMETERS

The bending angle in the trajectory splitter when passing the beam in the first circle of the recirculator should be 39 degrees [13, 14], which determines the radius of the trajectory and, accordingly, the magnetic field for a given magnet length. The radius of the trajectories in the second circle and in the beam output channel with the maximum energy are proportional to the ratio of the corresponding energies to the energy of the electrons in the first circle of the recirculator – 204 MeV. The trajectories of the electron beams in this case shown in Fig. 5.

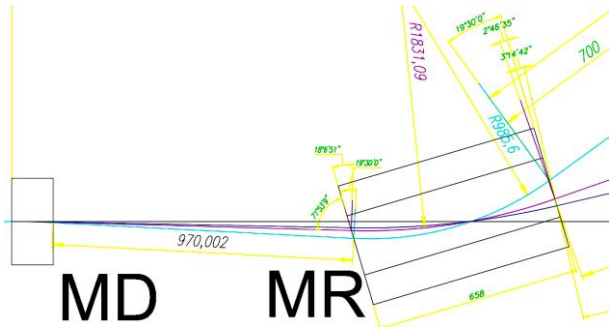


Fig. 5. Trajectories of electron beams after the accelerator module. Light blue – 204 MeV; purple – 379 MeV; blue – 554 MeV; 204 MeV – MR magnet turned off

The calculation of the magnet parameters, which meets the requirements of the beam dynamics in the recirculator, was carried out using the 2-dimensional program Maxwell SV [15].

A quarter of a magnet was used for the calculations. The boundary conditions at the edges of this region are as follows: the magnet field lines are parallel to the boundary in the middle of the magnet and are perpendicular to the median plane. At the outer boundaries, the boundary condition of an infinite distance was chosen. The excitation current was chosen to be 6960 AW per pole, which corresponds to 116 A of the source current.

The distribution of the magnet field lines under such conditions is shown in Fig. 6.

The field distribution in the median plane is shown in Fig. 7.

To illustrate the uniformity of the field, Fig. 8 shows the distribution of the relative deviation of the field from the field at the center of the magnet.

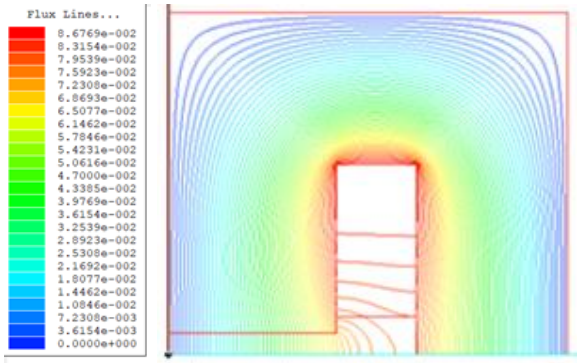


Fig. 6. Distribution of lines of force in 1/4 of a magnet

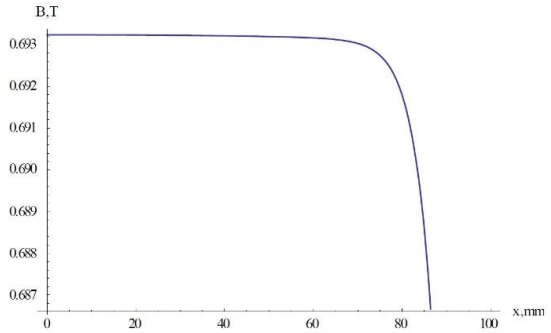


Fig. 7. Field distribution in the median plane

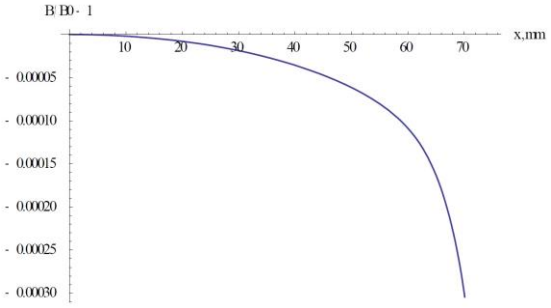


Fig. 8. Relative deviation of the field from the field at the center of the magnet

The electrons trajectory radius in the calculated field of 0.69 T at the energy of 204 MeV will be 0.99 m, 379 MeV – 1.83 m, 554 MeV – 2.68 m.

According to the generally accepted method, we calculate the effective length of the field, which after reduction by the length of the pole gives the field decay length relative to the edge of the magnet. In our case, for a gap in the magnet of 25 mm, the field decay length is 18.86 mm with an effective magnet length of 648 mm (610 mm along the iron).

Calculation parameters were as follows:

- Field value at the magnet center in longitudinal plane is 0.7 T;
- conductor is copper tube with a square cross section of 7x7 with a hole diameter of 5 mm;
- winding is of 60 turns for a current of 116 A;
- length of the turn is 1.8 m;
- length of the winding is 217 m;
- winding resistance 0.122 Ω;
- source voltage is 15 V;
- source power is 1700 W.

The heat removal is carried out by 8 parallel cooling circuits, each of which removes 210 W of power. For the selected temperature difference of 5 degrees, the pressure drop in the collectors should be 7 kPa, the

coolant flow (demineralized water) is 4.8 l/min. In this case, the water speed is 0.51 m/s, which ensures a turbulent water flow regime (which is optimal).

Based on the simulation, a preliminary design of the magnet was developed. The general view of the magnet is shown in Fig. 9.

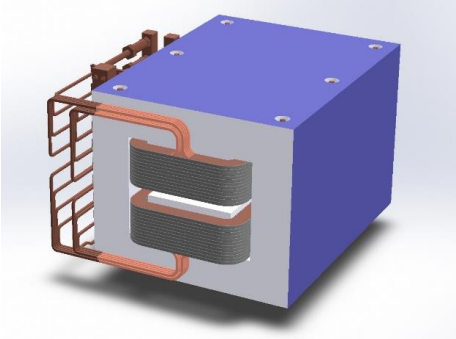


Fig. 9. Magnet with a pole width of 200 mm

Fig. 10 shows the placement of the developed splitter in the recirculator lattice. As can be seen from the figure, all beam trajectories pass in the magnetic field with a field uniformity of 10^{-4}, which meets the requirements of beam dynamics in the structure. The channel with an energy of 204 MeV planned to develop a neutron source, will operate with the field turned off in the magnet.

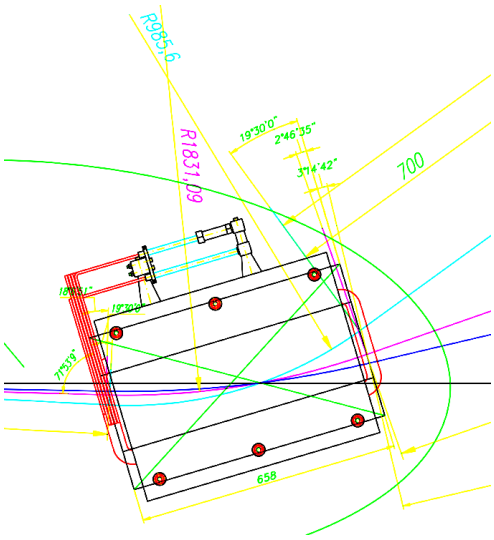


Fig. 10. Placement of the magnet-branch in the struture

REFERENCES

1. B. Anderberg, A. Andersson, M. Demirkan, M. Eriksson, M. Georgsson, G. LeBlanc, L-J. Lindgren, and S. Werin. The 500 MeV injector for max-lab using a recirculated linac // *Proceedings of EPAC 2000*, Vienna, Austria, p. 1687-1689.
2. A Proposal to the Office of Science of the United States Department of Energy for the MIT Center for Accelerator Science and Technology, December 22, 2004, MIT Center for Accelerator Science and Technology.
3. P.A. Adderley. The Continuous Electron Beam Accelerator Facility at 12 GeV // *Phys. Rev. Accel. Beams*. 2024, v. 27, p. 084802; DOI: 10.1103/PhysRevAccelBeams.27.084802
4. JEFFERSON LAB // https://www.jlab.org/
5. Michaela Arnold, Jonny Birkhan, Jonas Pforr, Norbert Pietralla, Felix Schließmann, Manuel Steinhorst. First operation of the superconducting Darmstadt linear electron accelerator as an energy recovery linac // *Phys. Rev. Accel. Beams*. 2020, v. 23, p. 020101; DOI: 10.1103/PhysRevAccelBeams.23.020101
6. J.S. Berg et al. CBETA ffag beam optics design, 59th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs ERL2017, 52-57, Geneva, Switzerland; doi:10.18429/JACoW-ERL2017-TUIDCC004
7. R.J. Michnoff et al. CBETA – novel superconducting ERL // *10th Int. Particle Accelerator Conf. IPAC2019*, Melbourne, Australia, 1651-1653; doi:10.18429/JACoW-IPAC2019-TUPGW102
8. Florian Hug. MESA – a fully instrumented ERL project for nuclear and particle physics experiments, ERL Workshop 2022, October 3rd 2022, Hug-MESA_Overview_ERL_2022.pptx.
9. Kevin Andre, Deepa Angal-Kalinin, et al. The Development of Energy-Recovery Linacs; https://hep.ph.liv.ac.uk/~mklein/LWUv13622.pdf
10. O.A. Shevchenko et al. The Novosibirsk Free Electron Laser Facility // *AIP Conference Proceedings*. 2020, v. 2299, 020001; https://doi.org/10.1063/5.0031513 Published Online: 17 November 2020
11. D. Angal-Kalinin et al. PERLE. Powerful energy recovery linac for experiments. Conceptual design report // *J. Phys. G: Nucl. Part. Phys*. 2018, v. 45, 065003, 71 p.; https://doi.org/10.1088/1361-6471/aaa171
12. ERL22_PERLE Status report- October 3rd 2022_FV.pptx
13. M.F. Shulga, G.D. Kovalenko, I.S. Guk, P.I. Gladkikh, D.Yu. Shakhov. Optimization of the focusing lattice of the magneto-optical structure of the multifunctional accelerator complex NSC KIPT // *Problems of Atomic Science and Technology*. 2024, N 3(151), p. 50-54; https://doi.org/10.46813/2024-151-050
14. П.І. Гладких, І.С. Гук, Г.Д. Коваленко, С.І. Прохорець, Є.В. Рудичев, Д.Ю. Шахов. *Багатофункціональний прискорювальний комплекс ННЦ ХФТІ*. Харків: «ФОП Панов А.М.», 2026, 124 с.; https://www.researchgate.net/publication/39473592
15. MAXWELL SV, http://www.ansoft.com/maxwellsv/

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МАГНІТ ДЛЯ РОЗГАЛУДЖЕННЯ ЕЛЕКТРОННИХ ПУЧКІВ РЕЦИРКУЛЯТОРА БПК

П.І. Гладких, І.С. Гук, А.Ю. Мициков

Особливістю магнітно-оптичної структури багатообертових рециркуляторів є потреба в магнітах, які об'єднують і роз'єднують пучки електронів із великою різницею по енергіях. У зв'язку з цим вони повинні мати доволі широку апертуру з однорідним магнітним полем. Розглянуто особливості параметрів таких магнітів для рециркулятора БПК ННЦ ХФТІ. Наведено результати розрахунку та розробки ескізного проєкту магніту.