https://doi.org/10.46813/2024-151-092

LINEAR ACCELERATOR MAGNETIC SYSTEM OF THE NSC KIPT SUBCRITICAL ASSEMBLY "NEUTRON SOURCE"

I.M. Karnaukhov, A.O. Mytsykov, A.V. Rezaev, V.E. Rudenko, D.V. Tarasov, A.Yu. Zelinsky
National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: zelinsky@kipt.kharkov.ua

In NSC KIPT Department of nuclear and accelerator systems the work on Subcritical Assembly "Neutron Source" commissioning is in progress [1, 2]. The driver of the facility is 100 MeV/100 kW electron linear accelerator [3]. One of the important accelerator systems is magnetic system. In the paper the features and characteristics of the NSC 100 MeV/100 kW linear accelerator are represented.

PACS: 29.17+w.Dh, 29.25.Dz

INTRODUCTION

During 2010–2017 years 100 MeV/100 kW electron linear accelerator was designed by NSC KIPT, Kharkiv, Ukraine and IHEP, Beijing, China [3], manufactured in IHEP, delivered to NSC KIPT, installed, put in operation and adjusted for the facility physical start up in 2019–2020 [4]. The main accelerator parameters are shown in Table 1.

Table 1

The main NSC KIPT accelerator parameters

Parameter	Value
Operation frequency, MHz	2856
Beam energy, MeV	100
Operation beam current, A	0.6
Average beam power, kW	100
Energy spread, %	± 3
Emittance, m·rad	$5\cdot10^{-7}$
Beam pulse duration, μs	2.7
Repetition rate, Hz	625
Maximum electron gun beam current, A	2

Table 2

The list of the accelerator magnetic system components

Injection part	Gun focusing magnets	4
	Gun beam correctors	2
	Solenoids	21
Chicane and linear accelerator	Correctors	7
	Chicane dipole magnets	4
	Focusing quadrupole triplets	6
Electron beam transportation channel	Quadrupole magnets	6
	Dipole magnet	2
Scanning system	Vertical and horizontal scanning magnets	2

One of the important accelerator systems is magnetic system, that provides formation, transportation and delivery of the electron beam to the neutron generating target. Conditionally the magnetic system can be separated on the injection accelerator part, electromagnetic chicane and regular accelerator part, electron beam transportation channel and electron beam density distribution system. The magnetic system components are listed in Table 2.

Before delivery to NSC KIPT all magnetic elements were tested in IHEP at magnetic bench with Hall probes. After delivery to NSC KIPT and before installation at the accelerator all elements were tested with gaussmeter DX-180 by NSC KIPT staff. Measurement results were in a good agreement to each other.

The layout of the magnetic element distribution along NSC KIPT SCA accelerator is shown in Fig. 1.

1. ACCELERATOR MAGNETIC SYSTEM ELEMENTS

1.1. SOLENOIDS

To provide low energy electron beam focusing (freezing) at the injection part of the accelerator three different types of the solenoids are used. The main solenoid parameters are listed in Table 3. Fig. 2 shows the drawings of the solenoids. The solenoids are winded with wire of 1.95×3.72 mm cross section and equipped with two loops water cooling. The water pressure in the cooling pipes is no less than 0.4 MPa with maximum water flow of about 10 l/min. In addition, four weak solenoids GF1-GF4 are installed the electron gun and pre-buncher, to provide preliminary electron beam focusing.

Table 3

Main solenoid parameters

Parameter	S1,S2	S3,S4	S5-S21
Number	2	2	17
Inside diameter, mm	112	216	245
Maximum length, mm	80	120	50
Maximum magnetic field, Gs	330	800	800
Ampere turn number, AT	7200	17600	4900
Maximum current, A	10	10	10
Turn number	720	1760	490
Resistance, Ω	1.83	8.03	2.16
Voltage, V	18.25	80.30	21.57
Maximum outside diameter, mm	340	580	560

Solenoids S1 and S2 are set above pre-buncher and buncher. Solenoids S3-S21 are set above the accelerator injection section. The view of the accelerator injection part is shown in Fig. 3.

1.2. CORRECTORS

7 electron beam position correctors are allocated along the accelerator. Correctors are the duplex correctors that provide correction of the electron beam direction in horizontal and vertical plane. All correctors are installed above the accelerating sections along the accelerator. Fig. 4 shows the view of the corrector. The main corrector parameters are listed in Table 4. Fig. 5 shows installed corrector pair at the accelerator section.

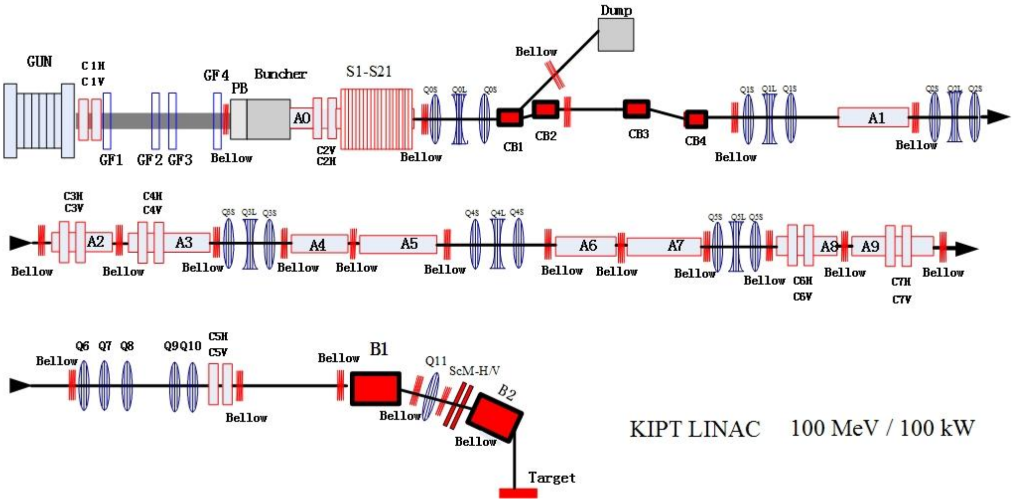


Fig. 1. The layout of the linear accelerator equipment distribution along the 100 MeV/100 kW NSC KIPT accelerator

GF1-GF4 are focusing solenoids of the injection part of the accelerator, C1H-C5H are electron beam position correctors in horizontal plane, C1V-C5V are electron beam position correctors in vertical plane, S1-S21 are solenoids of the injection section, CB1-CB4 are dipole magnets of the chicane, Q0S-Q5S and Q0L-Q5L are the quadrupole lenses of the accelerator focusing triplets, Q6-Q11 are quadrupole lenses of the accelerator electron beam transportation channel, B1-B2 are dipole magnets of the accelerator transportation channel.

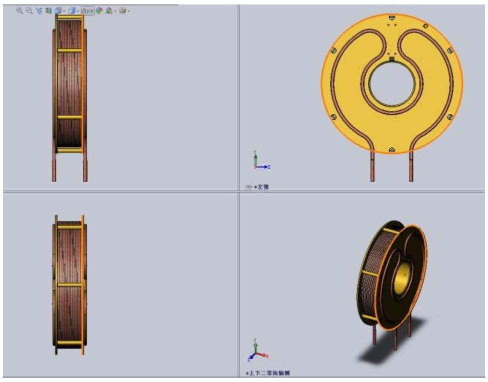


Fig. 2. The view of the accelerator S3,4 and S25-31 type solenoids

Fig. 3. The view of installed accelerator solenoids

Fig. 4. The view of the accelerator corrector

Table 4

Main corrector parameters

Parameter	Value
Integral magnetic field, Gs	≧2000
Magnetic field in the center, Gs	≧80
Wind number	149
Operation current, A	0…10
Length, mm	280

Fig. 5. NSC KIPT corrector installed at the accelerator section

To provide addition opportunity to correct electron beam position before the bending part of the transportation channel two new electron beam correctors of the dipole type were designed and manufactured Fig. 6. The correctors main parameters are listed in Table 5.

Table 5

Main parameters of the addition correctors of the transportation channel

Parameter	Value
Number, unit.	2
Sizes, mm	151×151×60
Air gap, mm	113
Wire cross section, mm^2	7.41(1.95×3.8)
Wind number	55
Operation current, A	0…15
Efficient lenght, mm	170.428

Fig. 6. Electron beam corrector

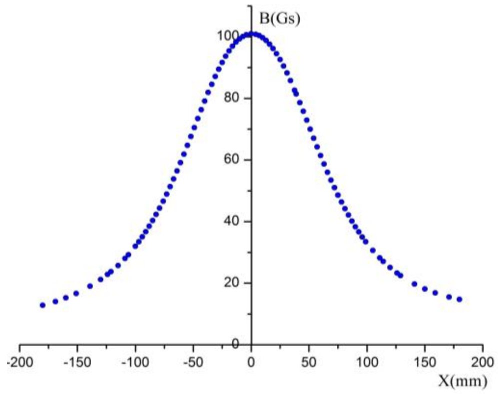


Fig. 7. Magnetic field distribution in x direction with maximum excitation current of 15 A. The Hall probe position was changed between -180 and +180 mm. Measured corrector effective length was 170.4 mm

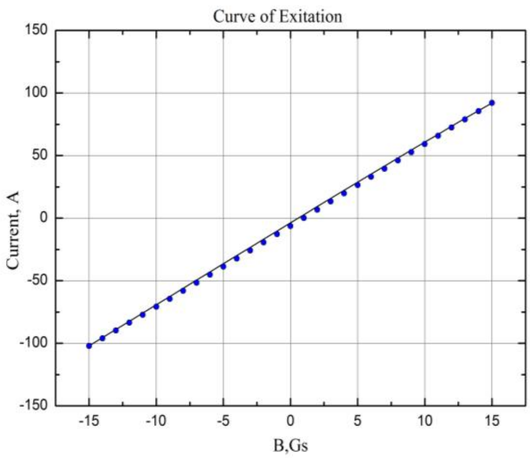


Fig. 8. NSC KIPT corrector excitation curve

After corrector manufacture and assembling the magnetic measurement were done with Hall probe bench.

The measurement results are shown, that magnetic field along the corrector has Gaussian distribution with 15 Gs magnetic field in the center of the corrector and 170.4 mm efficient length. The results of the magnetic measurements are shown Figs. 7, 8.

1.3. CHICANE DIPOLE MAGNETS

To eliminate low and high energy electron beam tails from the further acceleration process and, as a sequence, to decrease the electron beam losses along the accelerator, the accelerator was equipped with four magnet (CB1-CB4) electromagnetic chicane with movable wall collimator in the middle (Figs. 9–11).

Table 6

Parameters of the chicane dipole magnets

Magnet name	CB1	CB2/CB3/CB4
Magnet type	H-Type	H-Type
Air gap, mm	50	50
Efficient length, mm	225	225
Field flat area, mm	50	50
Field in the middle, T	0.06	0.06
Bending radius, mm	1289.16	1289.16
Bend angle, degree	10	10
Number of winds (per pole)	36	50
Maximum wind current, A	34	24
Yoke length, mm	180	180
Resistance, Ω	0.03344	0.0721
Power losses, kW	0.038	0.042
Induction, H	0.0055	0.0107
Sizes LxWxH, mm	352x462x320	352x350x320
Weight, kg	280	95

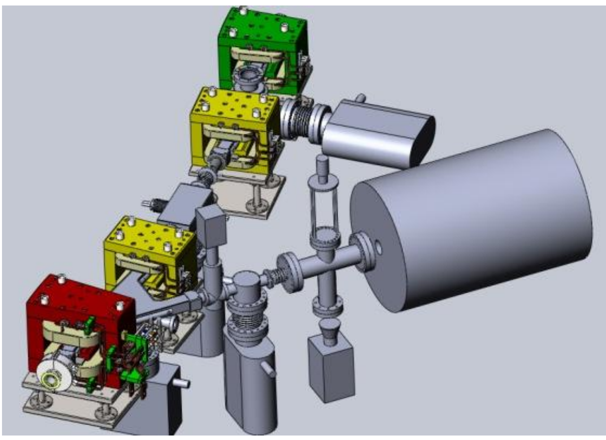


Fig. 9. Electromagnetic chicane with electron beam energy measurement channel

In addition, the first chicane magnet (CB1) can bend the beam in horizontal plain and provide measure of the electron beam energy and energy spread with installed at the magnet exit screen lime monitor and beam dump. It makes possible to tune injection part of the accelerator. CB1 is provided with water cooling. For magnets CB2-CB4 water cooling does not need (maximum magnetic field value is 600 Gs). The main parameters of the electromagnetic chicane magnets are shown in Table 6.

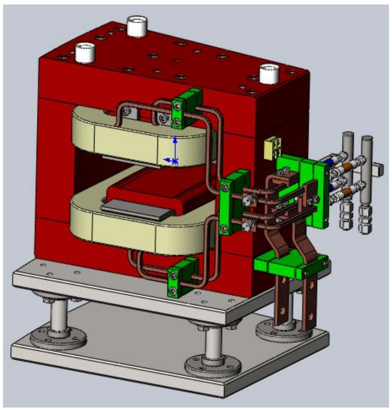


Fig. 10. Chicane dipole magnet CB1

Fig. 11. Electromagnetic chicane with installed dipole magnets CB1-CB4, electron beam collimator and electron beam energy measurement channel

The results of magnetic measurements for the dipole magnets CB1 and CB2 are shown in Figs. 12, 13. The results of the measurements for the dipole magnets CB3, CB4 are the similar.

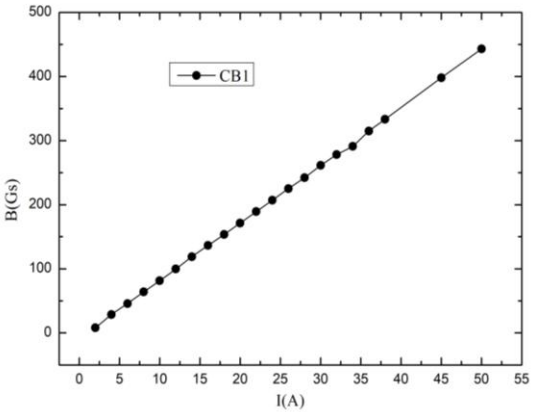


Fig. 12. Dipole magnet CB1 excitation curve

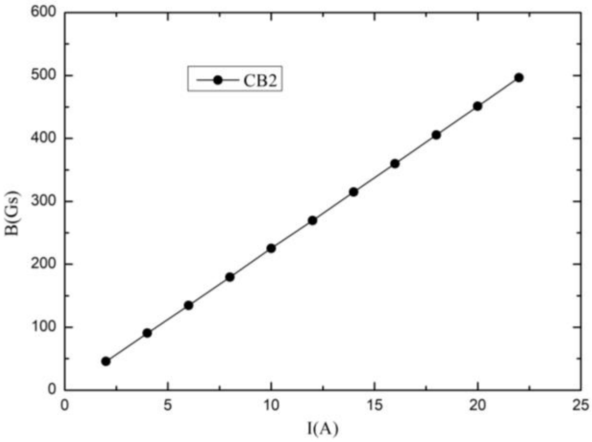


Fig. 13. Dipole magnet CB2 excitation curve

1.4. TRIPLET QUADRUPOLE MAGNETS

To provide electron beam focusing along accelerator six quadrupole triplets are used (Fig. 14). The triplet consists of two short focusing quadrupole magnets (SQ) and one middle defocusing quadrupole magnet of twice length (LQ). The distance between magnets is 100 mm. The total triplet length is 450 mm.

Triplet quadrupole magnet parameters are shown in Table 7. Results of the magnetic measurements are shown in Fig. 15. During the measurements Hall probe was set at X=18 mm, Y=Z=0 mm. Nonlinearity of the excitation curves is less then 1.0%.

Fig. 14. Focusing quadrupole magnet triplet

Table 7

Triplet quadrupole magnet parameters

Parameter	SQ	LQ
Aperture, mm	44	44
Effective length, mm	50	100
Field gradient, T/m	6.30	6.30
Magnet number	10	5
Wind number (per pole)	44	44
Max current, A	28	28
Yoke length, mm	43.5	87
Resistance, Ω	0.0475	0.063
Voltage, V	1.31	1.74
Power losses, W	36	48
Weight, kg	16	31

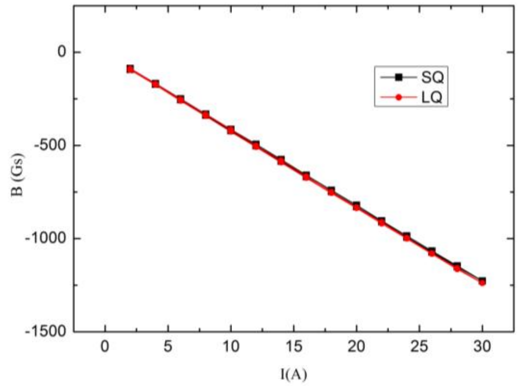


Fig. 15. Excitation curves of SQ and LQ triplet quadrupole magnets

Horizontal distribution of the magnetic field (Fig. 16) is in a good agreement with simulation results. The measurements were done within a range of Hall probe X position of -18…18 mm and Y=Z=0 mm position. The excitation current during the measurement was 28 A.

The integral magnetic field distribution along triplet quadrupole magnet is shown in Fig. 17. The measurements were done with Hall probe X position of -18, -9, 9, and 18 mm, and with 3 mm step in longitudinal Z direction. The position in vertical direction Y was equal to 0 mm. The excitation wind current was equal to 28 A. The amplitudes of the magnetic field inside aperture of the quadrupole magnets are satisfied to the requirements.

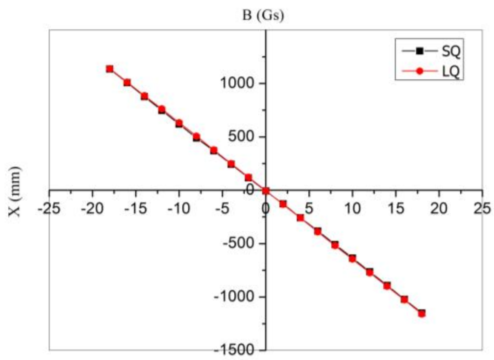


Fig. 16. Triplet quadrupole magnet magnetic field distribution in horizontal plane (X = -18…18 mm; Y, Z = 0 mm)

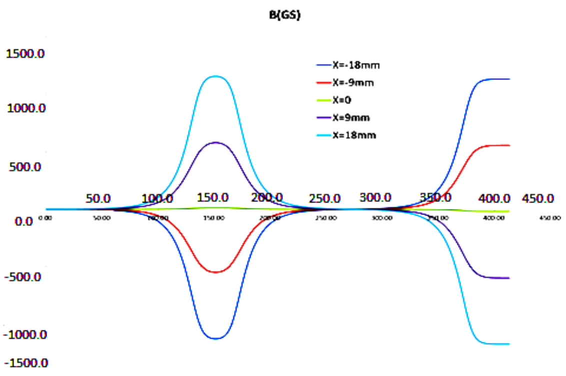


Fig. 17. Triplet quadrupole magnet magnetic field distribution in longitudinal direction (X = -18; -9; 9; 18 mm; Y= 0 mm)

1.5. QUADRUPOLE MAGNETS OF THE TRANSPORTATION CHANNEL

There are 6 identical quadrupole magnets in the accelerator transportation channel. Because of the high current the magnet windings are provided with water cooling of 0.4 MPa water pressure and water flow of 10 l/min. Fig. 18 shows the drawing of the magnet and installed quadrupole magnets at the accelerator transportation channel. The magnet parameters are shown in Table 8. Results of the magnetic measurement are shown in Figs. 19–21. The results of the magnetic measurements showed the effective magnetic length of the quadrupole magnets equal to 125 mm.

1.6. DIPOLE MAGNETS OF THE ACCELERATOR TRANSPORTATION CHANNEL

The accelerator transportation channel is equipped with two 45° sector dipole magnets TB1 and TB2. Because of the high current the magnet windings are provided with water cooling of 0.4 MPa water pressure and water flow of 10 l/min. The view of the accelerator dipole magnet is shown in Fig. 22. The dipole magnet parameters are shown in Table 9. The magnetic measurement results are shown in Figs. 23–27.

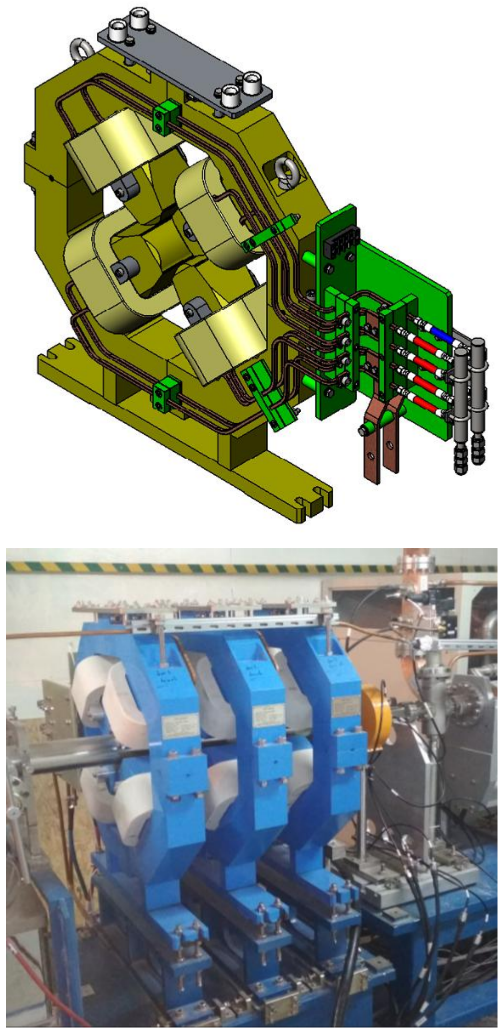


Fig. 18. Quadrupole magnet of the accelerator transportation channel

Table 8
Transportation channel quadrupole magnet parameters

Parameter	Value
Aperture, mm	80
Effective length, mm	100
Gradient, T/m	12
Number of magnets	6
Wind number (per pole)	48
Max winding current, A	160
Voltage, V	10,5
Yoke length, mm	84
Resistance, Ω	0.066
Power losses, kW	1.80
Sizes *L x W x H*, mm	160 x 670 x 670
Weight, kg	200

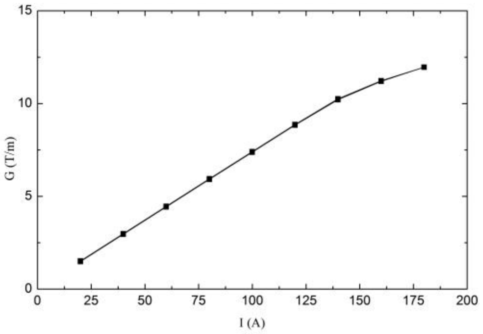


Fig. 19. Excitation curve of the accelerator quadrupole magnet. The curve non-linearity is about 2.0%

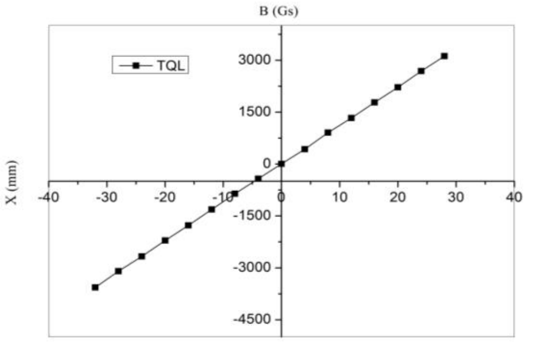


Fig. 20. Horizontal distribution of the transportation channel quadrupole magnet. Hall probe position in horizontal direction was changed as X=-32…32 mm; Y=Z=0. The winding current was 159.975 A

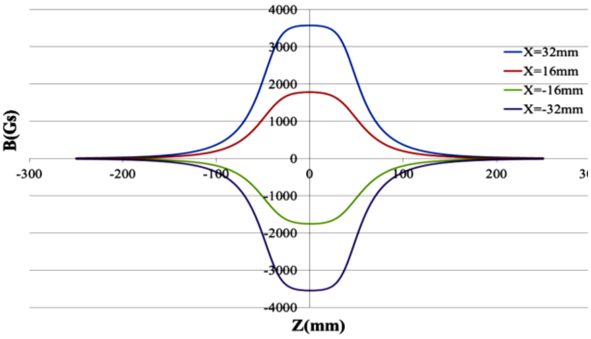


Fig. 21. Integral magnetic field distribution along quadrupole magnet. Hall probe positions were X=-32, -16, 16, 32 mm; Y= 0 mm. Z positions were changed with step 3 mm along the magnet longitudinal axis. Winding current was 159.975 A

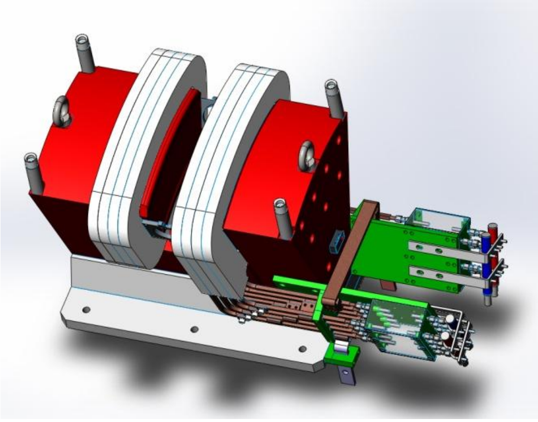


Fig. 22. The dipole magnet of the accelerator transportation channel

Table 9
The accelerator transportation channel dipole magnet parameters

Parameter	Value
Type	C-Type, sector
Gap, mm	80
Effective length, mm	400
Good field area, mm	60
Central field, T	0.7
Bending radius, mm	509.296
Bending angle (degree)	45.0
Number of magnets	2
Wind number	96
Max current, A	478
Yoke length, mm	355
Resistance, Ω	0.024
Power losses, kW	5.5
Induction, H	0.015
Sizes *L x W x H*, mm	420 x 550 x 640
Weight, kg	850

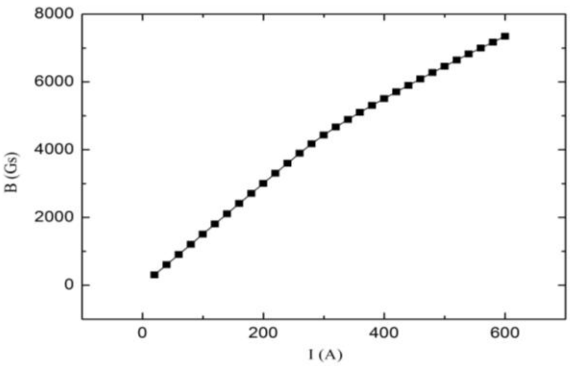


Fig. 23. TB1 dipole magnet excitation curve. Curve non-linearity is about 4.0%

The Hall probe was moved along four arcs with different vertical coordinates Y=0, 10, 20, and 30 mm correspondingly and X=0 mm. The step of Z coordinate shifting was 5 mm. The radius of arc was 509.296 mm and its length was 641 mm.

Fig. 23 shows TB1 excitation curve. The non-linearity of the curve is about 4.0%. Figs. 24, 25 shows magnetic field distribution along transportation channel dipole magnet for two values of the winding excitation current (480 and 560 A).

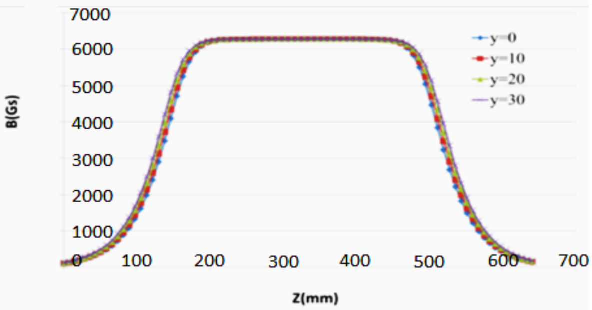


Fig. 24. Magnetic field distribution in transportation channel dipole magnet with 480 A winding excitation current

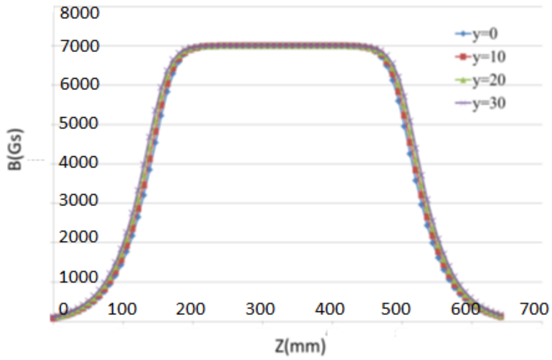


Fig. 25. Magnetic field distribution in transportation channel dipole magnet with 560 A winding excitation current

The results of the magnetic measurement in NSC KIPT are shown in Figs. 26, 27. One can see that measurement results of IHEP and NSC KIPT are identical.

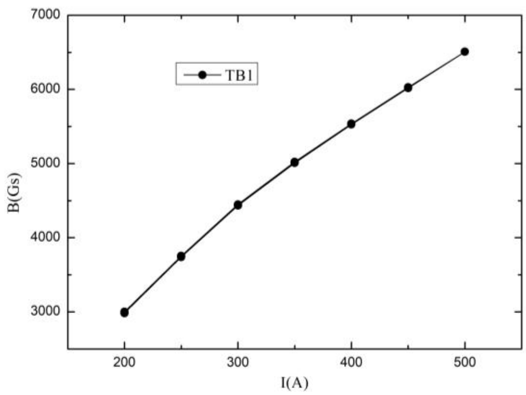
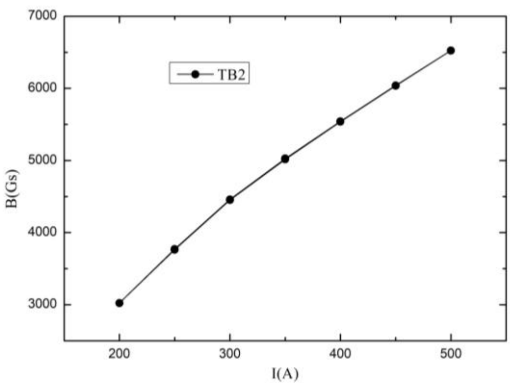


Fig. 26. The excitation curve of the TB1 transportation channel dipole magnet measured in NSC KIPT



Fig, 27. The excitation curve of the TB2 transportation channel dipole magnet measured in NSC KIPT

1.7. SCANNING MAGNET

Scanning magnet is combination of two dipole magnets with horizontal (X) and vertical (Y) magnetic field direction and supplied with two independent pulse power supply current sources. Such combination allows to provide uniform distribution of the electron beam density at the surface of the neutron generating target [5, 6]. The scanning magnets are installed before TB2. The view of one of the scanning magnet is shown in Fig. 28. The scanning magnet parameters are shown in Table 10. Magnetic field measurement results are shown in Fig. 29, 30. The Hall probe positions were changed as X= -30…30 mm, Y= 0, Z=-350…350 mm. Z coordinate Hall probe shifting step was 3 mm. Winding excitation current is 150.0 A.

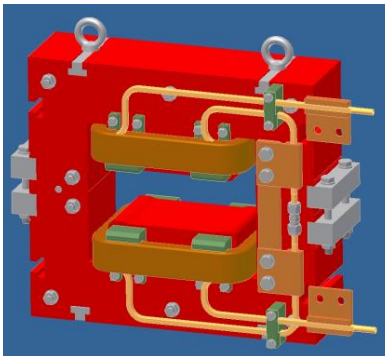


Fig. 28. The view of the accelerator scanning magnet

Table 10

Scanning magnet parameters

Parameter	Value
Type	H-Type
Gap, mm	76
Effective length, mm	150
Max magnetic field, T	0.050
Number	2
Umber of winds (per pole)	10
Bending angle, degree.	110
Yoke length, mm	150
Max wind current, A	0.074/0.6
Resistance, Ω/Inductivity, mH	0.17
Size *L x W x H*, mm^3	185x460x370
Waight, kg	120

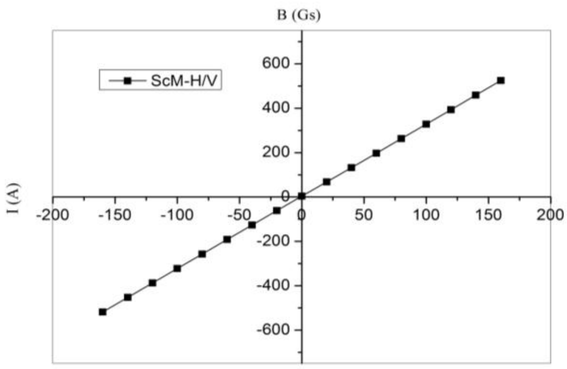


Fig. 29. Excitation curve of the scanning magnet. Hall probe position is X=Y=Z=0 mm. The curve non-linearity is less than 1.0 %

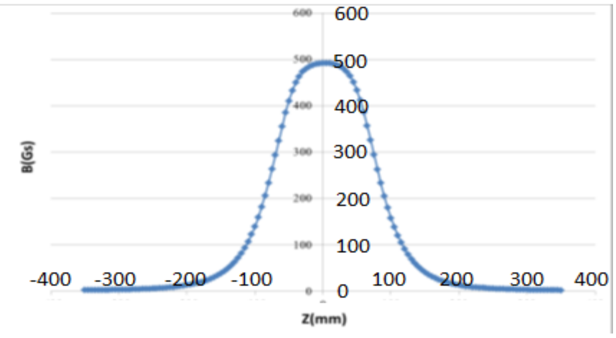


Fig. 30. Scanning magnet integral distribution of the magnetic field. The Hall probe positions are X=-30…30 mm; Y= 0; Z=-350…350 mm. Z coordinate Hall probe shifting step is 3 mm. Winding excitation current is 150.0 A

1.8. POWER SUPPLY FOR MAGNETS

Power supply of the accelerator magnetic elements is carried out with individual current sources of different power. The current sources of the solenoids, correctors, focusing triplets do not supplied with water cooling. Current sources of the transportation channel quadrupoles, transportation channel dipole magnets and scanning magnets are provided with water cooling. Each current source equipped with digital local control panel and opportunity to be controlled remotely from the facility control room. Power supply sources installed in 6 cabinets that placed in the facility klystron gallery (Fig. 31). Power supply source parameters are shown in Table 11. The view of the power supply sources of different types are shown in Figs. 32, 33. The scanning magnet has separate current source, which provides change of the magnet in both horizontal directions in accordance with set current and repetition rate.

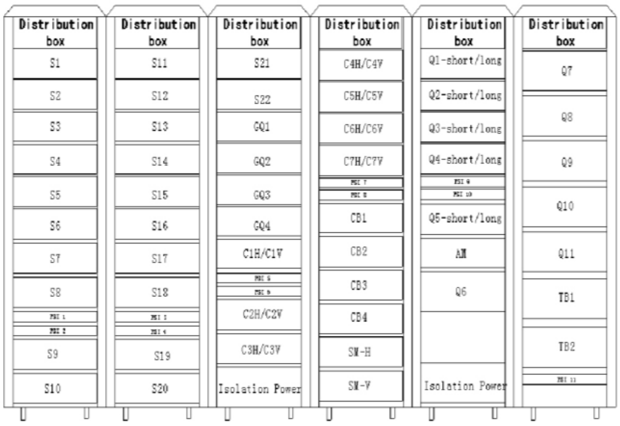


Fig. 31. Layout of the magnetic system power supply source installations

Fig. 32. Power supply source with water cooling

Fig. 33. Power supply source without water cooling

Table 11

Specification of the accelerator magnetic system power supply sources

№	Magnet name	Requirements	Source specification
PSI 1			
1-4	GQ1-GQ4	1Ω, 6A	15A/15V
5-8	CB1-CB4	34A, 1.5V	40A/3V
PSI 2			
9-16	S1-S8	1.58Ω, 10A	15A/15V
PSI 3			
17-24	S9-S16	1.93Ω, 10A	15A/15V
PSI 4			
25-30	S17-S22	1.93Ω, 10A	15A/15V
PSI 5			
31-37	C1H/C1V - C7H/C7V	X:0.5Ω,6A/Y:0.5Ω,6A	8A/7V–8A/7V
PSI 6			
38-43	TQ1-TQ5	Short:1.33V, 28A; Long:1.8V, 28A	30A/5V–30A/5V
44-51	Q6-Q8	160A, 10.5V	200A/20V
PSI 7			
51-53	Q9-Q11	160A, 10.5V	200A/20V
54-55	SM-H/SM-V	150A, 11.4V	180A/20V
55-56	TB1-TB2	478A, 11.5V	600A/25V

Control system of the magnetic system is organized on the base of EPICS and is operated from the accelerator control panel from the facility control room. The view of the control panel is shown in Fig. 34. There is possibility to save the proper modes of the magnetic elements and use them in the further operation. In addition, each power supply source can be controlled with local control panel (Fig. 35).

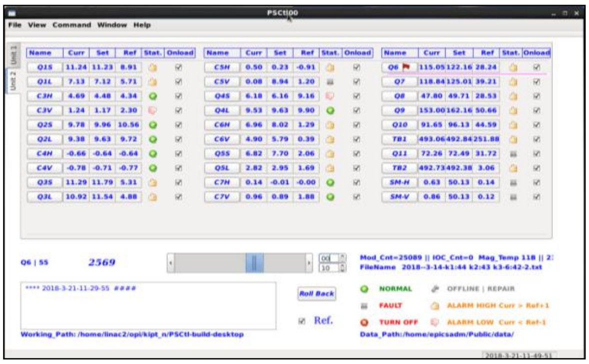


Fig. 34. Power supply remote control panel

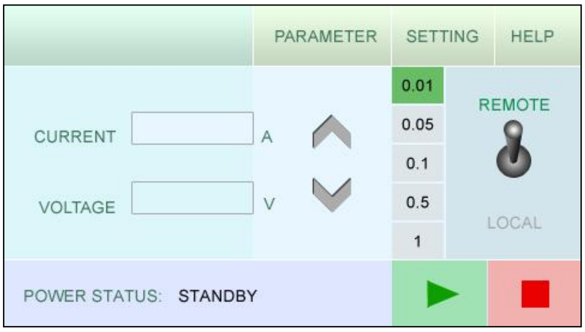


Fig. 35. Power supply local control panel

CONCLUSIONS

During 2010–2021 years in NSC KIPT, Kharkiv, Ukraine along with IHEP, Beiging, China and Argon National Laboratory, Chicago, USA electron linear accelerator – driver of the Subcritical Assembly "Neutron Source" was designed, developed, installed, tested and prepared for the facility start-up.

During preliminary accelerator tests and system adjustments the magnetic system showed design parameters, good performance and capability to provide design parameters of the electron beam for the facility pilot and industrial operation. Installation of the additional electron beam position correctors at the transportation channel will allow to provide accurate beam position correction during at the neutron generating target.

REFERENCES

1. A. Zelinsky, O. Bezditko, P. Demchenko, et al. NSC KIPT neutron source on the base of subcritical assembly driven with electron linear accelerator // *Proceedings of IPAC 2013*. 2013, p. 3481-3483.

2. A. Zelinsky, M.I. Ayzatskiy, B.V. Borts, et al. NSC KIPT neutron source // *Problems of Atomic Science and Technology*. *Series "Nuclear Physics Investigations".* 2012, N 3, p. 3-9.

3. A. Zelinsky, Y. Chi, S. Pei, et al. Design studies on 100 MeV/100 kW electron linac for NSC KIPT neutron source on the base of subcritical assembly driven by linac // *Proceedings of IPAC11*. 2011, p. 1075-1077.

4. A. Zelinsky, O. Bezditko, O. Gordienko, et al. 100 MeV/100 kW accelerator adjustment for the NSC KIPT neutron source physical start up // *Problems of Atomic Science and Technology*. *Series "Nuclear Physics Investigations".* 2020, N 5, p. 135-142.

5. A. Zelinsky, I.M. Karnaukhov, W. Liu. Proposals for electron beam transportation channel to provide homogeneous beam density distribution at a target surface // *Proceedings of IPAC 2011*. 2011, p. 1084-1086.

6. A. Zelinsky, I.M. Karnaukhov. Distribution of the beam desity at the target of subcritical facility "Neutron Source"// *Problems of Atomic Science and Technology*. *Series "Nuclear Physics Investigations".* 2021, N 3, p. 3-10.

Article received 30.04.2024

МАГНІТНА СИСТЕМА ЛІНІЙНОГО ПРИСКОРЮВАЧА ПІДКРИТИЧНОЇ СБІРКИ «ДЖЕРЕЛО НЕЙТРОНІВ» ННЦ ХФТІ

І.М. Карнаухов, А.О. Мициков, О.В. Рєзаєв, В.Є. Руденко, Д.В. Тарасов, А.Ю. Зелінський

У підрозділі ядерних та прискорювальних систем ННЦ ХФТІ триває введення в експлуатацію Підкритичної збірки «Джерело нейтронів». Драйвером цієї установки є 100 МеВ/100 кВт лінійний прискорювач електронів. Однією з важливих систем прискорювача є його магнітна система. У статті наведено основні особливості магнітної системи та характеристики 100 МеВ/100 кВт лінійного прискорювача електронів ННЦ ХФТІ.