Report on the work in the frames of the MSC-230 isochronous cyclotron project.

Kiyan I.N.
DLNP, JINR

Calibration stand

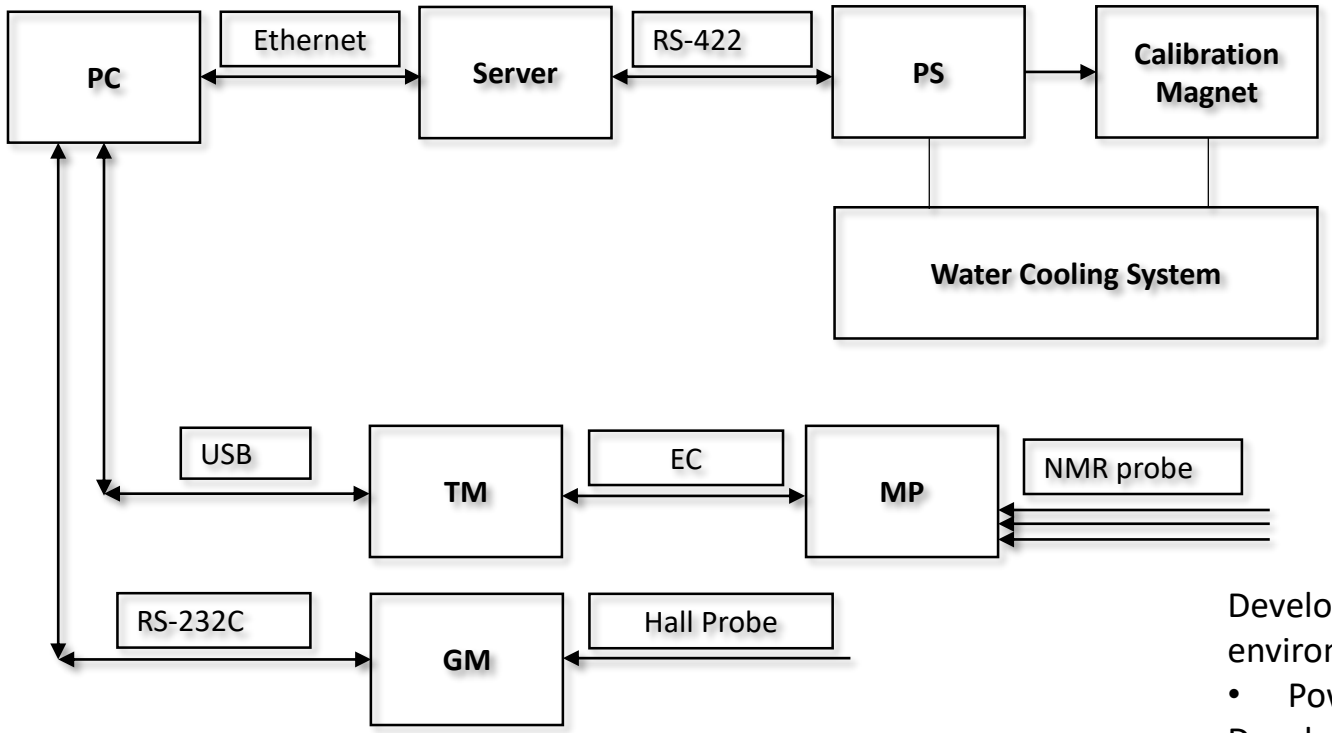

Fig. 1. Block diagram of calibration stand.

PC – Personal Computer.
Server – MOXA NPort 5150 Serial device server.
PS – Power Supply: Bruker 450 A x 120 V / DANFYSIK PSSYS 9700 800 A x 120 V.
TM – NMR Teslameter: Metrolab PT2026.
EC – Extension cable: Metrolab 3026-10M.
MP – Multiplexor: Metrolab MUX6026.
NMR Probe: Metrolab model 1526 (0,038 - 4,8 T).
GM – Gaussmeter: LakeShore 475 DSP.
Hall probe: LakeShore HMNT-4E04-VR, LakeShore HMMT-6J04-VF.

JINR theme: 08-2-1127-2016. “Advanced Studies of Systems of New-Generation Accelerators and Colliders for Fundamental and Applied Research”.
Theme leaders: G.V. Trubnikov, G.D. Shirkov, B.N. Gikal.
Project in the theme: 08-2-1127-1-2024/2027. “Creation of test benches for testing subsystems of the MSC-230 cyclotron”.
Project leaders: G.A. Karamysheva, S.L. Yakovenko.

Developed software in C++ in the MS Visual Studio programing environment:

- Power Supply Control Program 2014 - 2025 (PSCP 2014 - 2025).

Developer: Kiyan I.N.
Third party software:

- Metrolab P2026. Developer: Metrolab Technology SA.
- NPort Administrator Program . Developer: Moxa Technology Inc.

Development / Production / Operation: Chesnov A.F., Kiyan I.N., Lyapin I.D., Gerasimov V.A., Fedorenko S.B., Petrov D.S., Galkin R.V., Rogozin D.V., Maslennikov A.B.
Responsible: Kiyan I.N.

Calibration stand



Fig. 2. Calibration magnet.

Table 1. Calibration magnet parameters.

Parameter	Value (old poles / new poles)	Parameter	Value (old poles / new poles)
Number of half-windings	2	Maximum Current Density	16 / 8,5 A/mmx2
Number of sections in a half-winding	4	Total Cooling Water Consumption from a Parallel Collector at a Pressure Drop of 7.9 / 4 bar at 800 / 425 A (1 Loop per section)	35,7 / 23,5 l/min
Number of turns in a double-layer section	24	Cooling Water Outlet Temperature at the Above Consumption with an Inlet Water Temperature of 25°C	50 / 35 °C
Number of turns in a winding	192	Yoke and Pole Material	Steel 10
Conductor type	Cu; 8,5x8,5 mm Ø 5,3 mm	Total Weight of the Entire Winding	~111 kg
Length of conductor in one section	31 m	Mounted Magnet Weight	~540 kg
Nominal current (CC mode)	800 / 425 A	Pole Gap	13±0,05 mm
Nominal voltage on two half-windings	68,3 / 36,3 V	Magnetic flux density at the Center Point at 800 / 425 A	~2,8 / ~2,9 T
Total power consumption	54,6 / 15,4 kW	Magnetic flux density at the Center Point at 800 / 800 A	~2,8 / ~3,2 T

Calibration stand



Fig. 3. New poles.

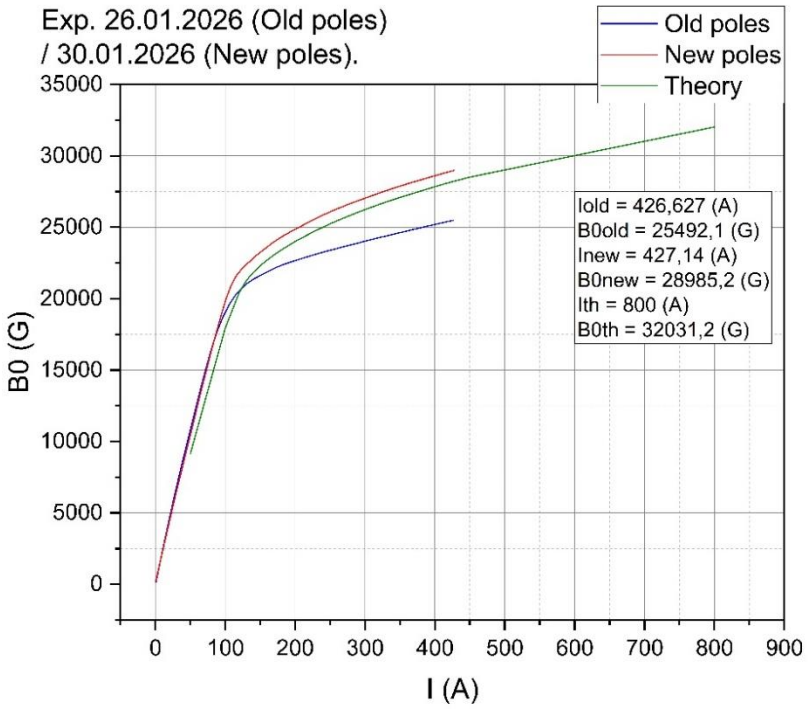

Fig.4. Calibration magnet with old / new poles: B0(I).

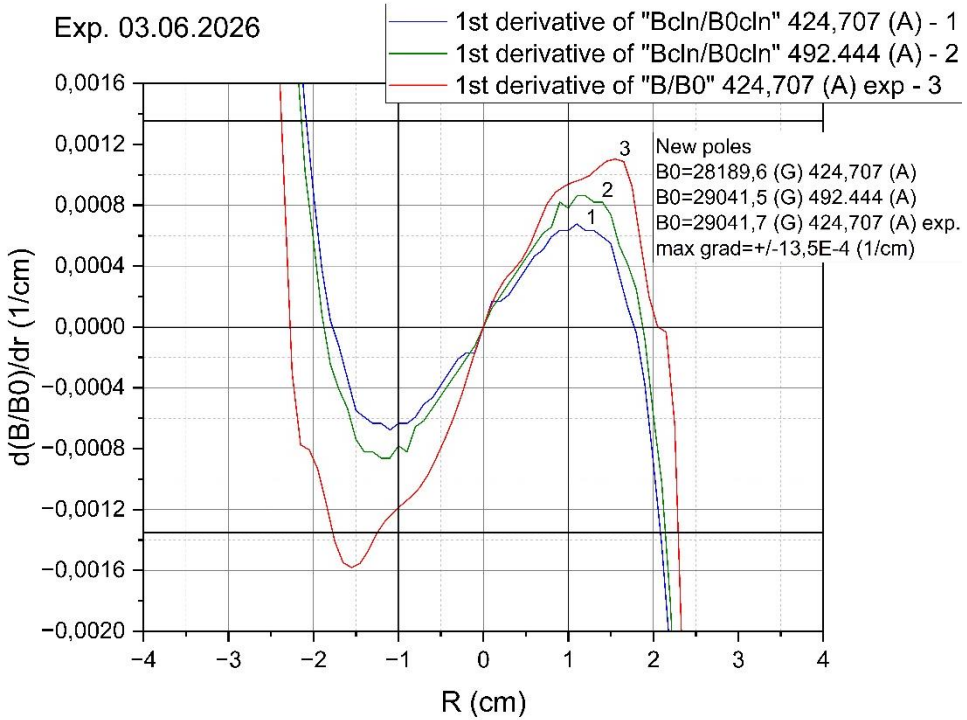

Fig. 5. Calibration magnet with new poles: Gradient.

Calibration stand



Fig. 6. DANFYSIK PSSYS 9700 Power Supply (800 (A) x 120 (V)): Package.

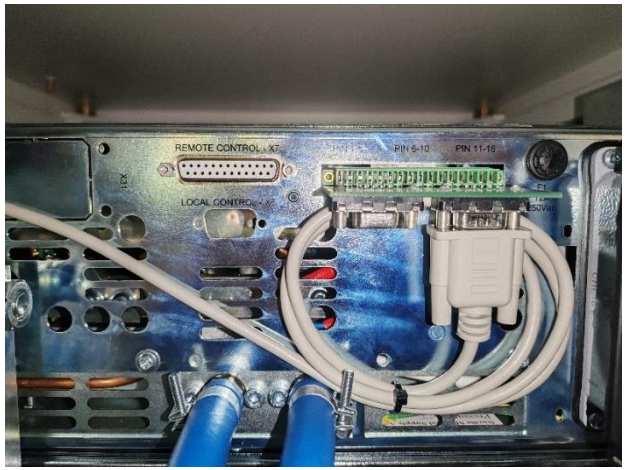

Fig. 7. DANFYSIK PSSYS 9700 Power Supply (800 (A) x 120 (V)): Back panel.

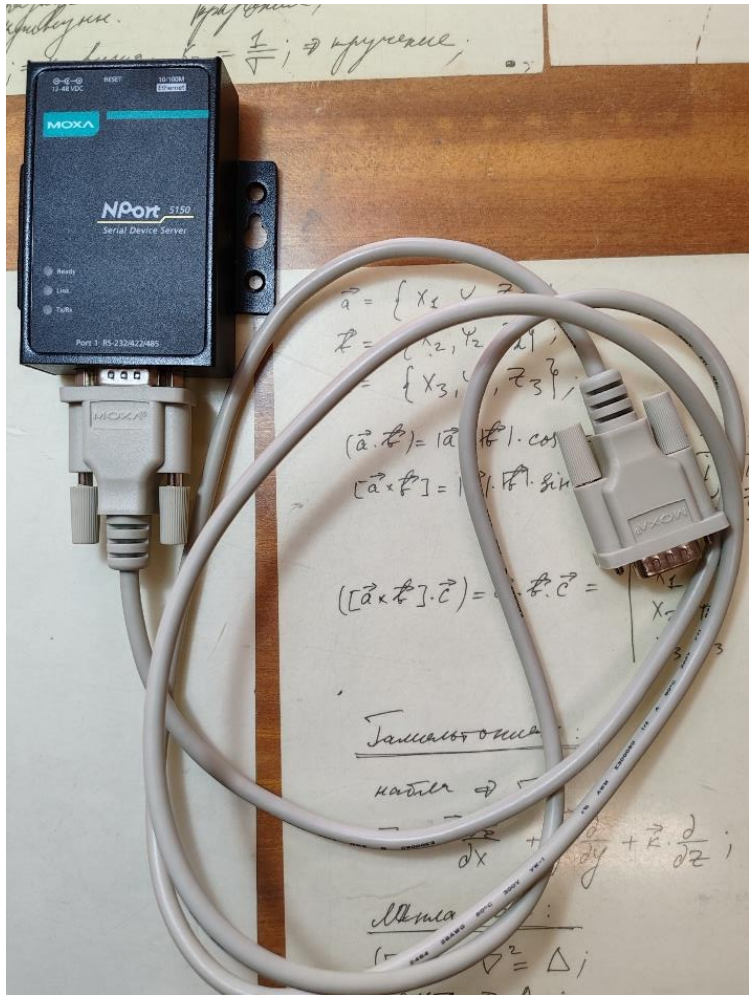

Fig. 8. Moxa NPort 5150 server.

Calibration stand

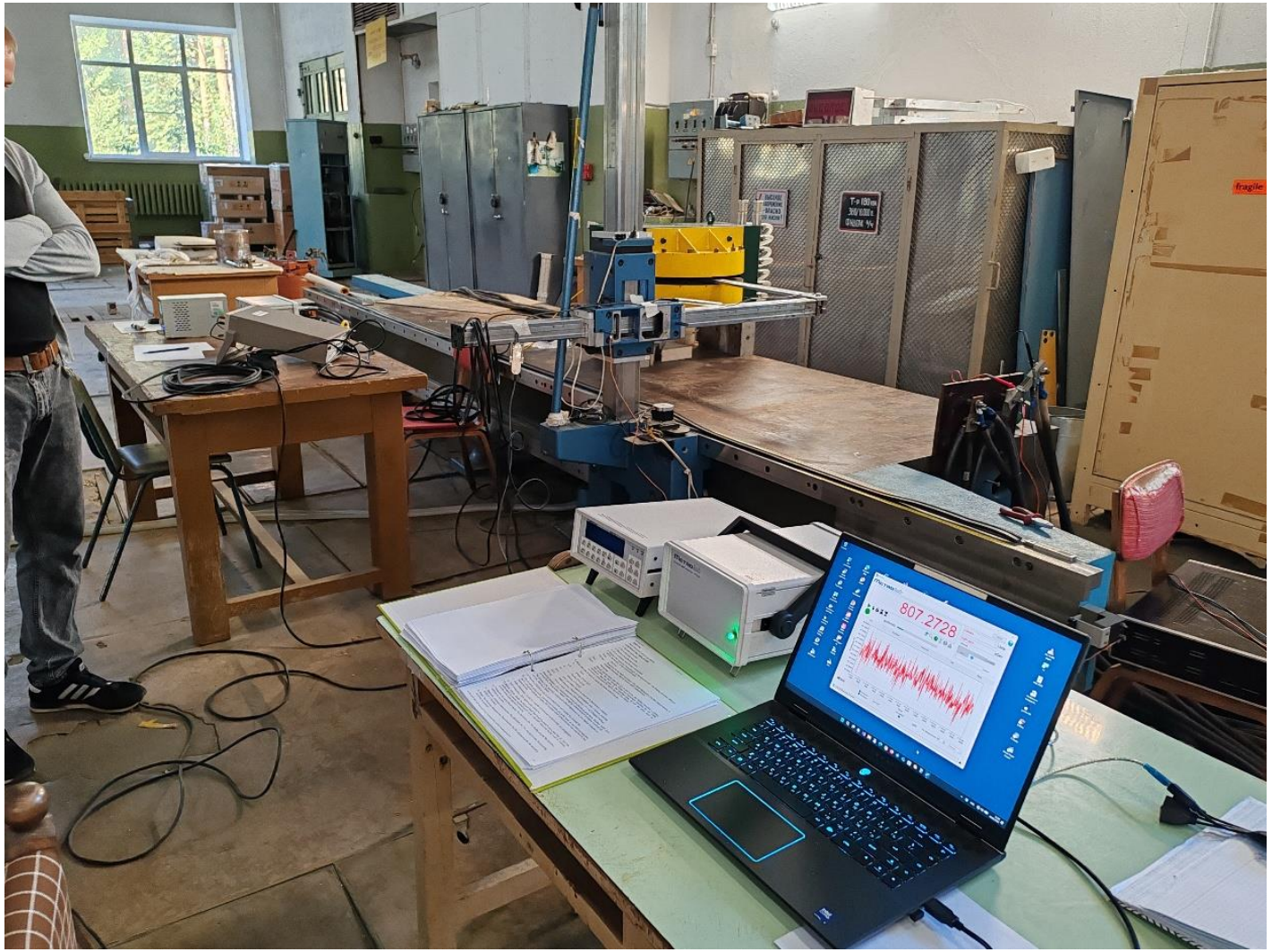

Fig. 9. Calibration stand testing. Experiment 28.08.2026.

Calibration stand testing without using Extension cable: Metrolab 3026-10M and Multiplexor: Metrolab MUX6026.

Calibration stand

```
<?xml version="1.0"?>
<MetrolabXmlRecord ver="1.0">
        <header>
                <src>PT2026 Software</src>
                <datTim8601>2026-08-28T11:45:44</datTim8601>
                <descr>PT2026 Measurement Record File, Metrolab Technology SA</descr>
        </header>
        <body type="tMXR_BODY_PT2026" ver="1.0">
<comment></comment>
<instr>PT2026 00787</instr>
<dataset type="tMXR_DATASET_PT2026_MEASUREMENT" ver="1.0">
<headings>Timestamp        Measurement sDev          Uniformity     Channel        Status</headings>
<parms>units=[Gauss]       ppmRef=0.00000000000000 measAvg=Off;1                 sigAvg=Off;1   ifLowHigh=AUTO
        rfPerWidth=AUTO          acqRateLenDelay=AUTO       probMatchTune=AUTO</parms>
<meas>496079               807.291610758000          NaN            0.165469       1              00</meas>
<meas>496129               807.312418033283          NaN            0.167987       1              00</meas>
<meas>496179               807.240174549274          NaN            0.136946       1              00</meas>
<meas>496229               807.226331962923          NaN            0.179357       1              00</meas>
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<meas>496329               807.438561633820          NaN            0.360532       1              00</meas>
<meas>496379               807.251457587526          NaN            0.150627       1              00</meas>
<meas>496429               807.472081265852          NaN            0.084665       1              00</meas>
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<meas>496579               807.247627196809          NaN            0.299846       1              00</meas>
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Fig. 10. Metrolab P2026: Resulting text file. Experiment 28.08.2026.

Magnetic measurement stand

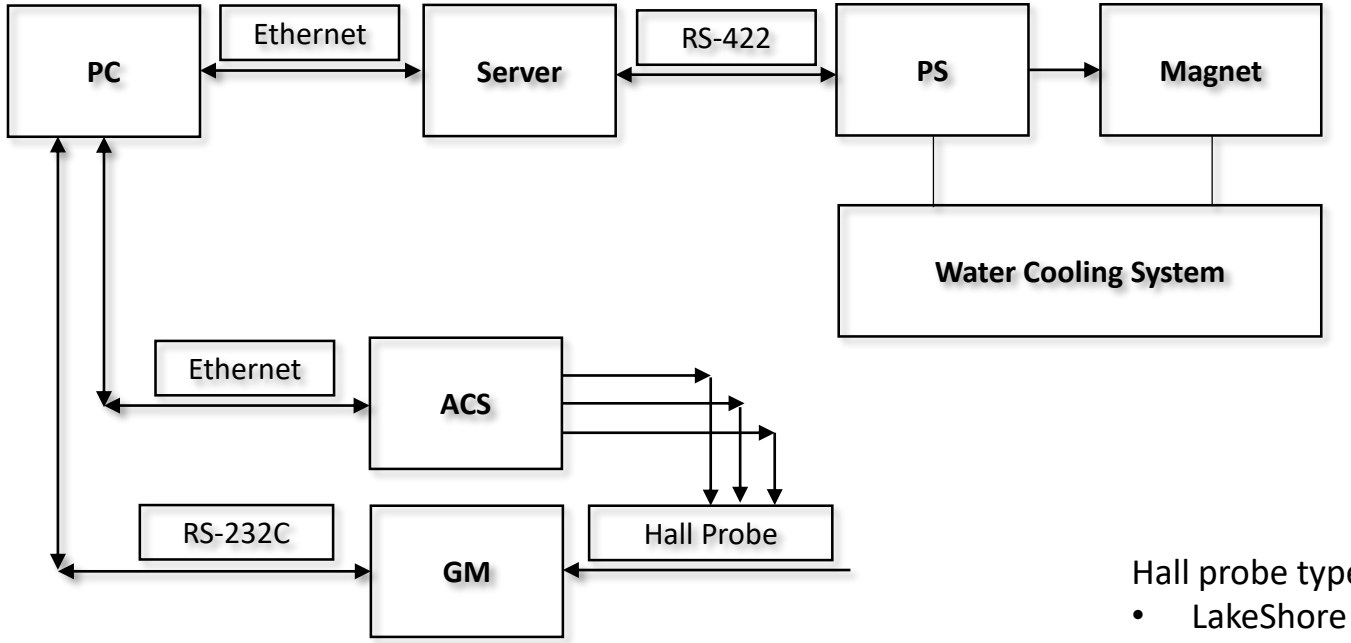


Fig. 11. Block diagram of magnetic measurement stand.

PC – Personal Computer.
Server – MOXA NPort 5150 Serial device server.
PS – Power Supply: Bruker 450 A x 120 V / DANFYSIK PSSYS 9700 800 A x 120 V.
ACS – Automated Control System to move probe in three directions:

- Controller (Siemens Simatic S7-1200);
- Driver x 3 (Leadshine CS – D508);
- Closed-Loop Stepper Motor x 3 (Leadshine CS – M22326).

GM – Gaussmeter: LakeShore 475 DSP.

Hall probe types:

- LakeShore HMNT-4E04-VR (HSE: 3,5 G - 35 kG, LakeShore 475 DSP: PTC + PFC => Measurement accuracy: ±3 G).
- LakeShore HMMT-6J04-VF (HST: 35 G – 350 kG, LakeShore 475 DSP: PTC + PFC => Measurement accuracy: ±1 G).
- LakeShore HGCT-3020 for MMS (China): Temperature coefficient of magnetic sensitivity: ±0,01%/K.
- Whist Group Sensor for MMS (Novocherkassk): Temperature coefficient of magnetic sensitivity: ±0,005 %/K.

Developed software in C++ in the MS Visual Studio programing environment:

- Power Supply Control Program 2014 - 2025 (PSCP 2014 - 2025).
- Magnetic Field Measurement Program 2019-2026 (MFMP 2019-2026).

Developer: Kiyan I.N.

JINR theme: 08-2-1127-2016. “Advanced Studies of Systems of New-Generation Accelerators and Colliders for Fundamental and Applied Research”.
Theme leaders: G.V. Trubnikov, G.D. Shirkov, B.N. Gikal.
Project in the theme: 08-2-1127-1-2024/2027. “Creation of test benches for testing subsystems of the MSC-230 cyclotron”.
Project leaders: G.A. Karamysheva, S.L. Yakovenko.

Development / Production / Operation: Chesnov A.F., Kiyan I.N., Lyapin I.D., Pivin R.V., Gerasimov V.A., Fedorenko S.B., Petrov D.S., Galkin R.V., Rogozin D.V., Maslennikov A.B.
Responsible: Petrov D.S.

Magnetic measurement stand

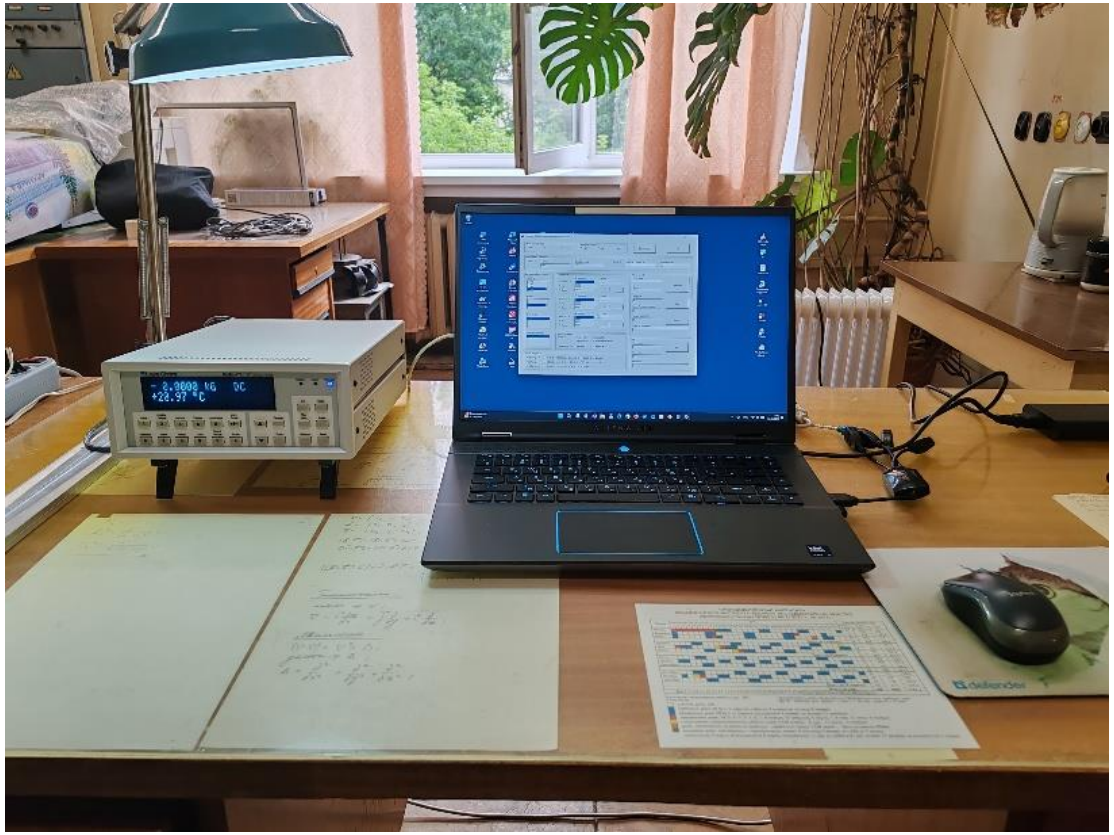


Fig. 12. LakeShore 475 DSP Gaussmeter.

LakeShore 475 DSP Gaussmeter key features:

- Probe temperature compensation.
- Probe field compensation.

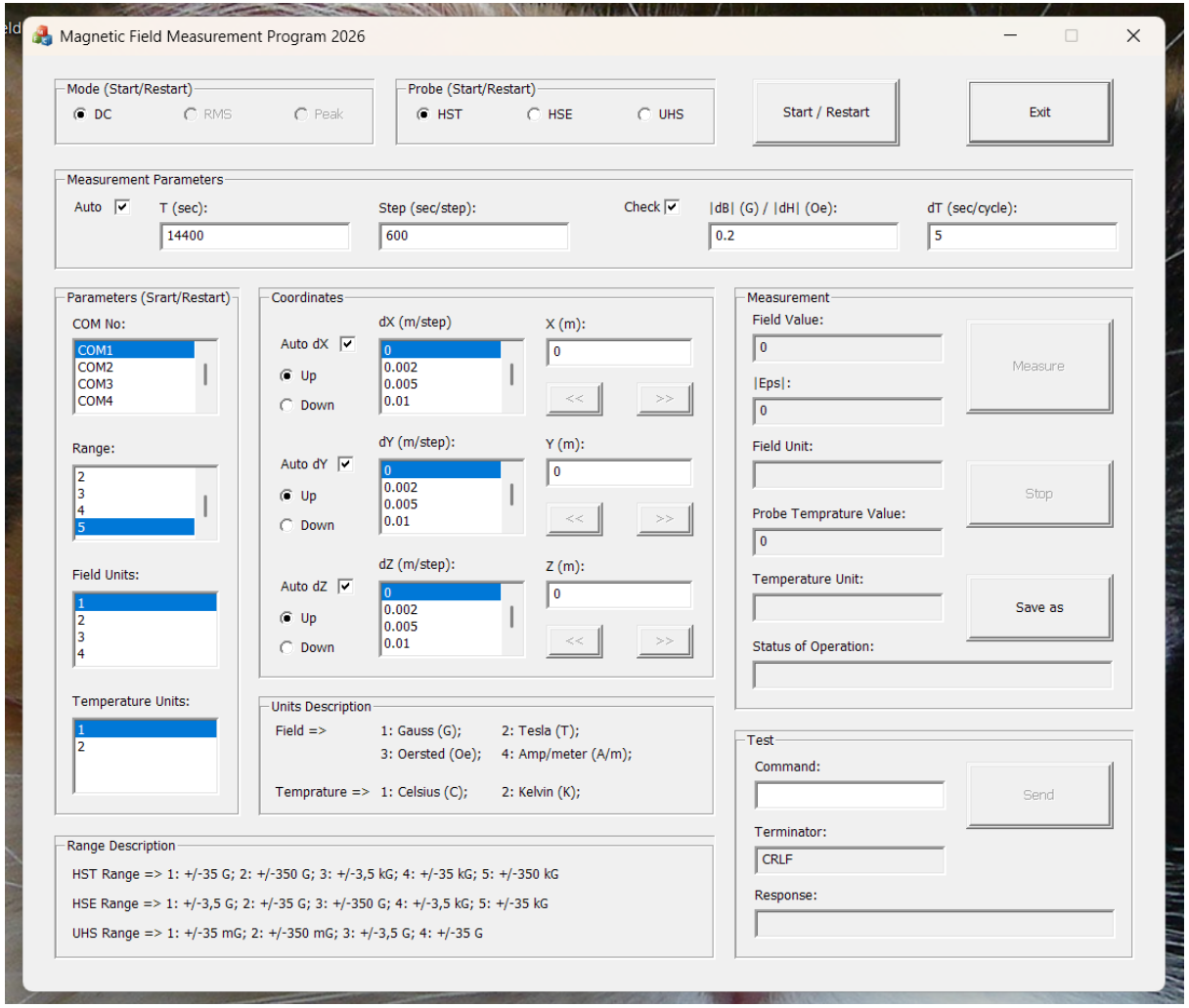


Fig. 13. MFMP 2019-2026: Main window of the DBA application.

Magnetic measurement stand

05.txt

No	Value	Eps	Unit	Status	Time Stamp	X (m)	Y (m)	Z (m)	
1	+1475.000	+.100	G	004	2026:6:3:12:38:28.301	-.200	+.000	+.000	
2	+1655.700	+.100	G	004	2026:6:3:12:38:41.338	-.195	+.000	+.000	
3	+1867.700	+.000	G	004	2026:6:3:12:38:54.288	-.190	+.000	+.000	
4	+2082.400	+.000	G	004	2026:6:3:12:39:8.604	-.185	+.000	+.000	
5	+2303.200	+.000	G	004	2026:6:3:12:39:23.535	-.180	+.000	+.000	
6	+2518.600	+.000	G	004	2026:6:3:12:39:37.735	-.175	+.000	+.000	
7	+2758.500	+.000	G	004	2026:6:3:12:39:57.488	-.170	+.000	+.000	
8	+2996.500	+.000	G	004	2026:6:3:12:40:29.549	-.165	+.000	+.000	
9	+3260.300	+.000	G	004	2026:6:3:12:40:48.691	-.160	+.000	+.000	
10	+3506.900	+.000	G	004	2026:6:3:12:41:4.105	-.155	+.000	+.000	
11	+3790.500	+.000	G	004	2026:6:3:12:41:18.573	-.150	+.000	+.000	
12	+4072.400	+.100	G	004	2026:6:3:12:41:33.512	-.145	+.000	+.000	
13	+4374.000	+.100	G	004	2026:6:3:12:41:47.897	-.140	+.000	+.000	
14	+4688.700	+.000	G	004	2026:6:3:12:42:3.269	-.135	+.000	+.000	
15	+5028.600	+.100	G	004	2026:6:3:12:42:18.245	-.130	+.000	+.000	
16	+5348.400	+.100	G	004	2026:6:3:12:42:32.584	-.125	+.000	+.000	
17	+5729.700	+.100	G	004	2026:6:3:12:42:47.148	-.120	+.000	+.000	
18	+6078.100	+.000	G	004	2026:6:3:12:43:.992	-.115	+.000	+.000	
19	+6470.900	+.100	G	004	2026:6:3:12:43:19.828	-.110	+.000	+.000	
20	+6873.200	+.100	G	004	2026:6:3:12:43:38.751	-.105	+.000	+.000	

Fig. 14. MFMP 2019-2026: Resulting text file. Experiment 03.06.2026.

Magnetic measurement system (China)



Fig. 15. MMS (China): Mechanical part.

Technical task:

- JINR, Dubna, Russia: Karamysheva G.A., Ivanenko I.A.

Development / Production / Testing:

- CAS Ion Medical and Technical Devices Co., Ltd., Hefei, China: Shiwen Xu (Shimming), Wei Zhang (mapping);
- JINR, Dubna, Russia: Kiyan I.N., Lyapin I.D., Gerasimov V.A.

Responsible: Lyapin I.D.



Fig. 16. MMS (China): Control part.

Magnetic measurement system (China)

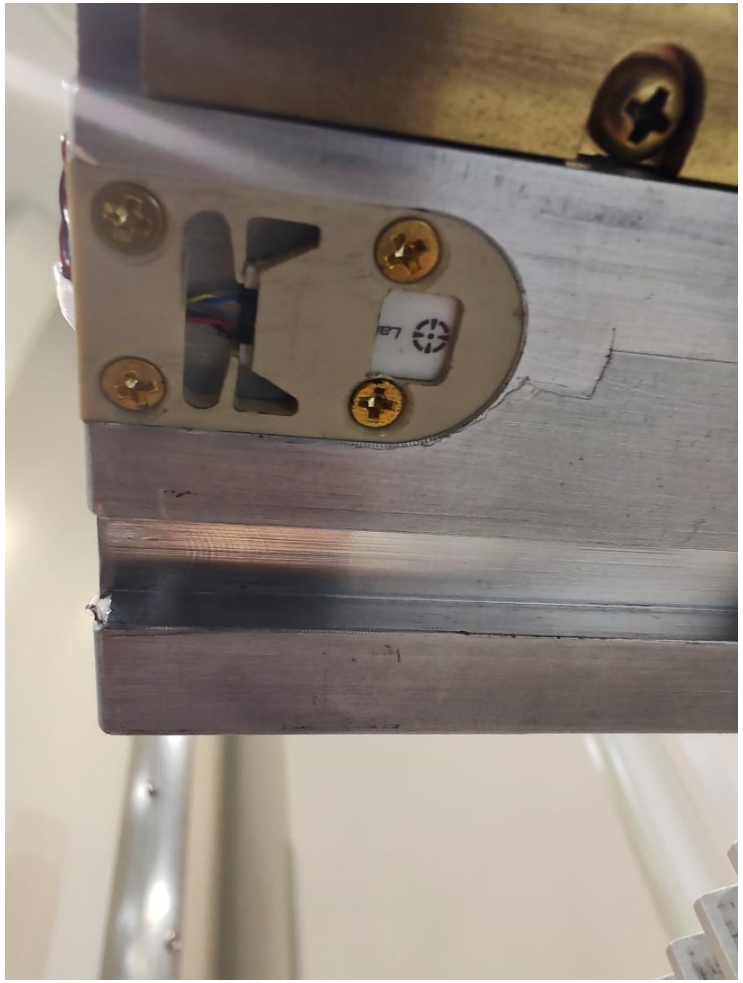


Fig. 17. MMS (China): LakeShore HGCT-3020 Hall probe.

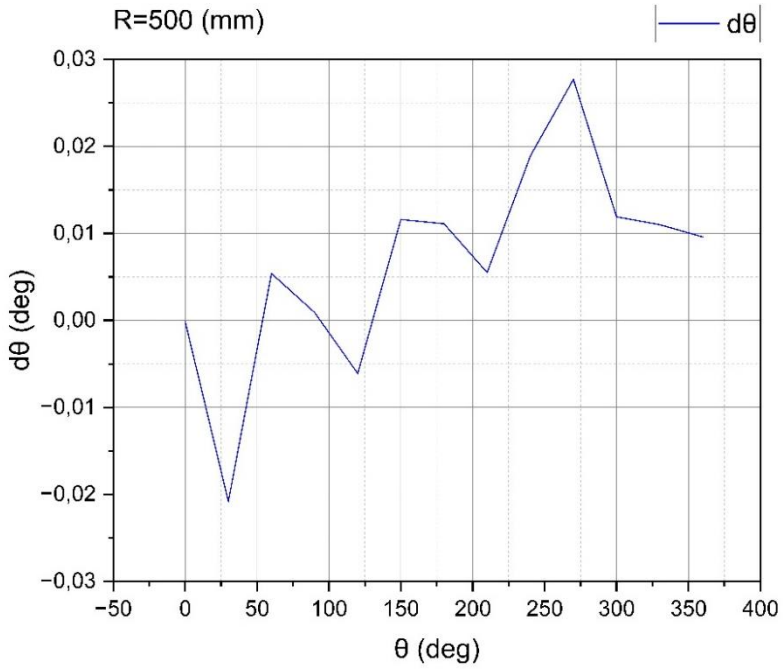
Table 2. Short equipment specification.

No	Name	Description
1	Industrial computer on base of Advantech IPC-610-L + monitor	Industrial computer on base of 4U 15-Slot Rackmount Chassis with Front-Accessible Fan + monitor
2	Keysight B2962B	Hall probe power source (CC mode)
3	Keithley DMM6500	High-precision multimeter (Hall probe voltage meter)
4	LakeShore HGCT-3020	Hall probe
5	Siemens Simotics 1FL6024 (Radial) / Siemens Simotics 1FL6032 (Angular)	1FL6 servomotors
6	SINAMICS V90	Basic Servo Drive System
7	Siemens Simatic S7-1200	Basic controller
8	GD-ROBOT-0634A-15m (LTK Cable for probe) 6FX30022DB201BA0 (Simotics Encoder cable, 10m) 6FX30025CK011BA0 (Simotics Motor cable, 10m) 6FX30025BK021BA0 (Simotics Brake cable, 10m)	Wire connections

Magnetic measurement system (China)

Table 3. Technical specifications.

No	Characteristic	Values
1	Radial step	≥1mm
2	Radial step accuracy	±0,2mm
3	Radial position accuracy	±0,2mm
4	Radial measuring range	-10mm～1170mm
5	Angular step	0,5°/1°/2°
6	Angular step accuracy	±0,05°
7	Angular position accuracy	±0,05°
8	Angular measurement range	-10°～370°



Laser tracker: HEXAGON Leica Absolute Tracker AT960.

Fig. 18. Positioning accuracy of the Hall probe with an azimuth step. Experiment 20.05.2026.

R = 500±0,1 mm; Θ = 0 ÷ 360°; dΘ = 30°.

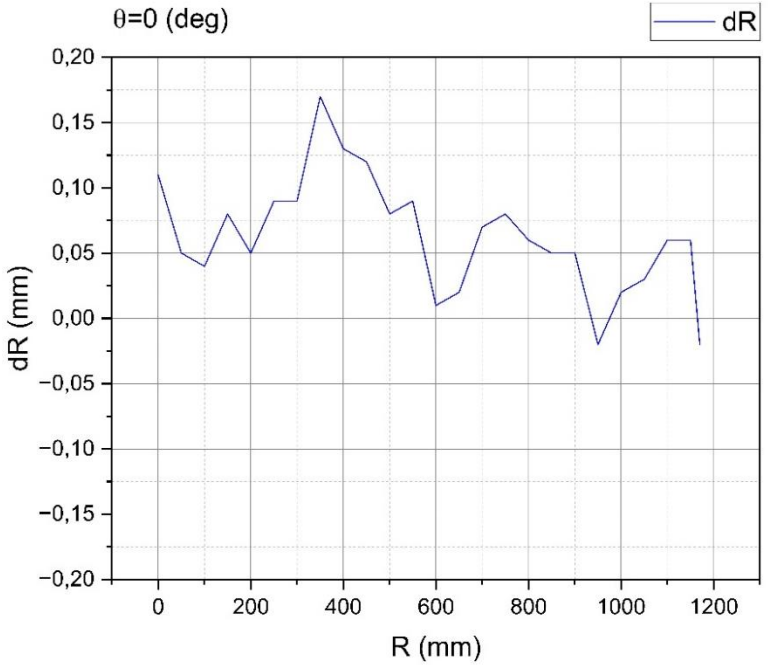


Fig. 19. Positioning accuracy of the Hall probe with an radius step. Experiment 20.05.2026.

Θ = 0°; R = 0 ÷ 1170 mm; dR = 50/20 mm.

Magnetic measurement system (China)

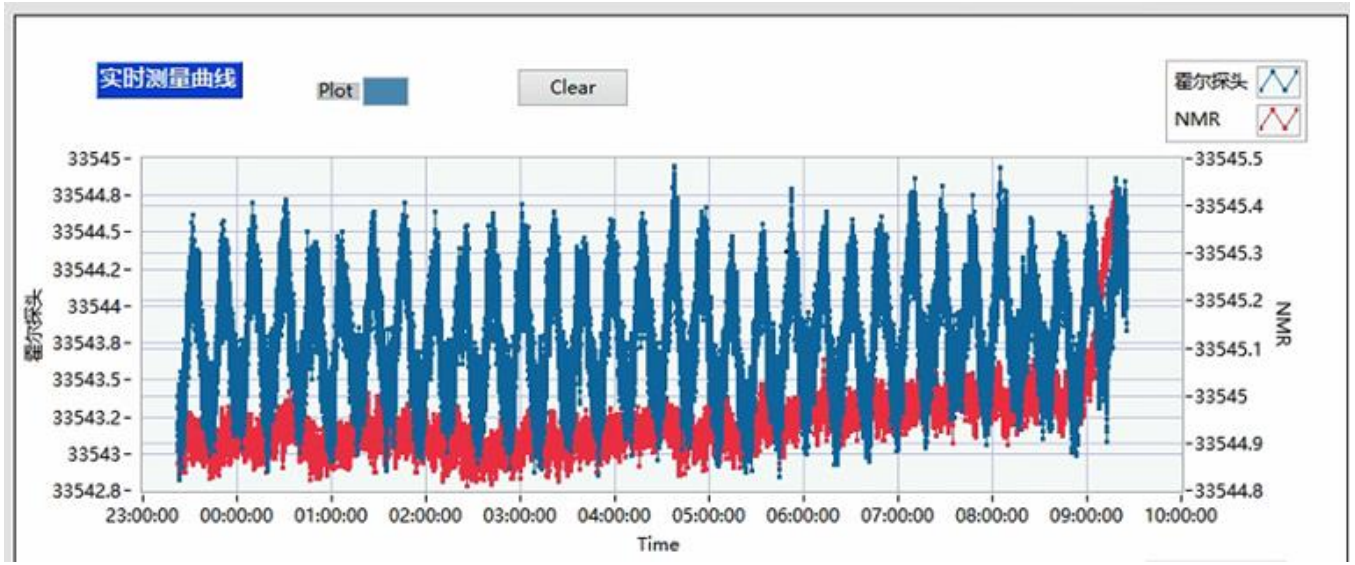


Fig. 20. MMS stability for LakeShore HGCT-3020 Hall probe. Experiment 20.05.2026.

NMR Teslameter: Metrolab PT2026.

$$\Delta\overline{B}_H = \left(\overline{B}_{H,s} - \overline{B}_{H,f}\right) - \left(\overline{B}_{NMR,s} - \overline{B}_{NMR,f}\right);$$

Readings change within 8 hours: $\Delta\overline{B}_H = \pm 0{,}1$ G.
Temperature: T= 25±1°C.

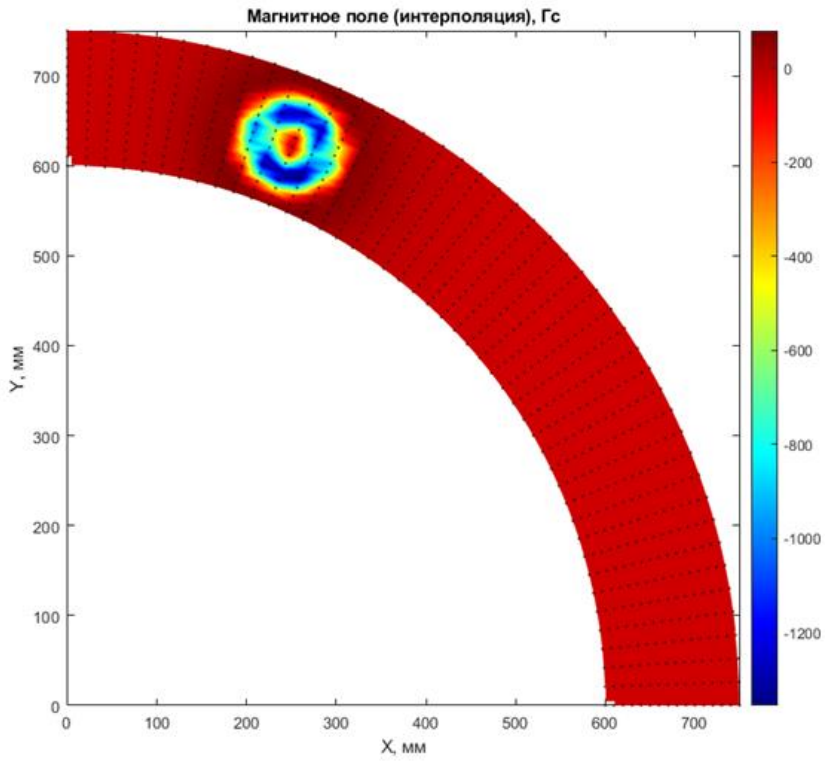


Fig. 21. Magnetic flux density. Experiment 20.05.2026.

ACS for Smith-Garren curves measurement

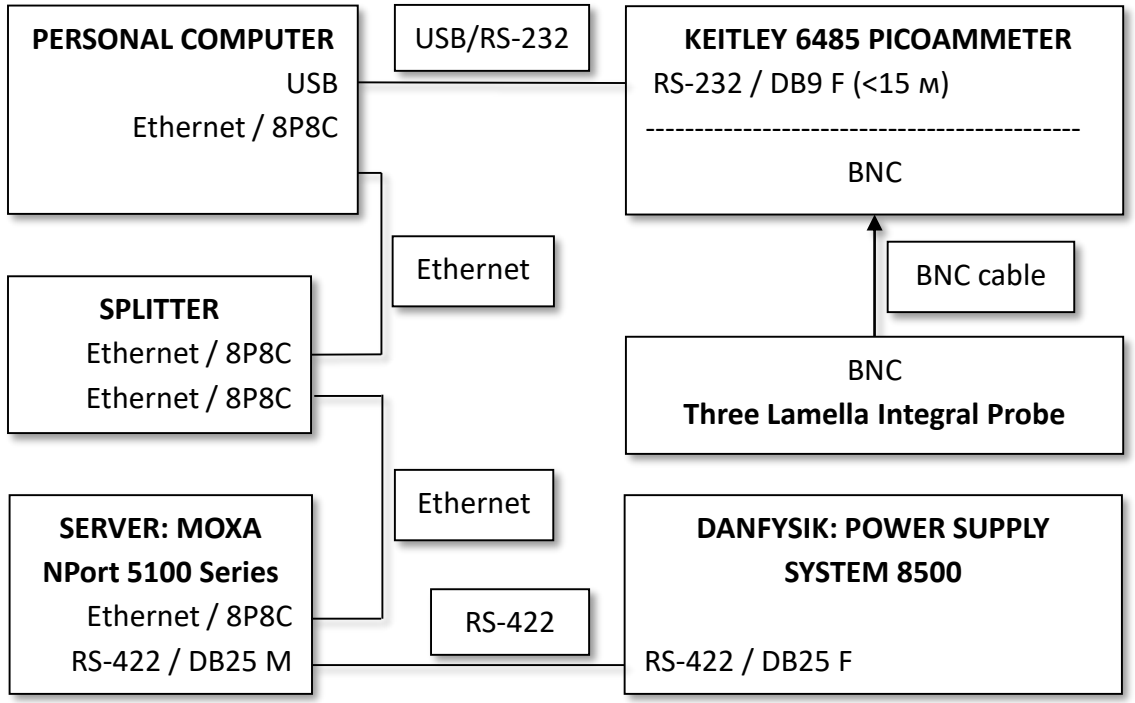


Fig. 22. ACS Block–diagram (AIC-144, INP PAS, Krakow, Poland).

Development / Operation: Kiyan I.N.
Responsible: Kiyan I.N.

Tab. 4. ACS Parameters (AIC-144, INP PAS, Krakow, Poland).

Parameter	Interface: USB/RS-232 between PC and PA	Interface: Ethernet/RS-422 between PC and PS
Line Address (0-255)	-	2
FIFO (Enable, Disable)	-	Disabled
Port Number	COMX	COMX (Virtual)
Baud Rate	9600	9600
Data Bits	8	8
Stop Bits	1	1
Parity	None	None
Flow Control	None	X_ON/X_OFF
Terminator (command)	CR	CR
Terminator (response)	LFCR	CR
Cable Type	Straight-throw	Straight-throw
Third-party Software	Moxa Technology Inc.: NPort Administrator Program	

Developed software in C++ in the MS Visual Studio programing environment:

- Smith Garren Curve Measurement Program I 2014 - 2025 (SGCMP I 2014 - 2025). Developer: Kiyan I.N.

ACS for Smith-Garren curves measurement

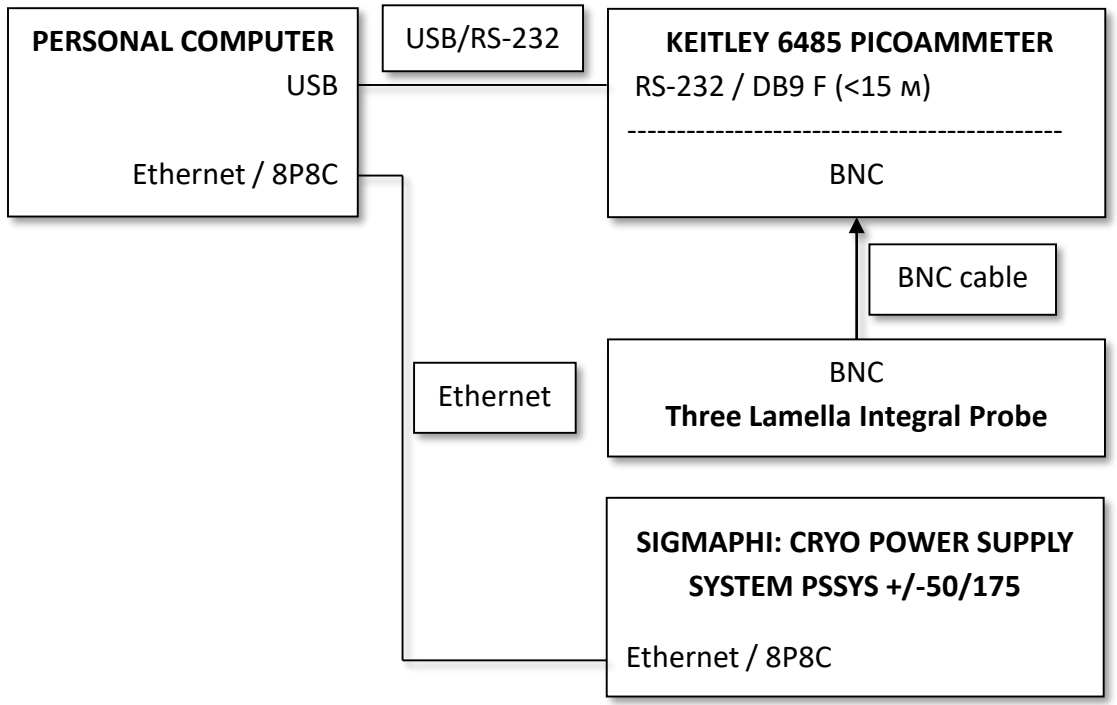


Fig. 23. ACS Block–diagram (SC-200, CAS Ion Medical and Technical Devices Co., Ltd., Hefei, China).

Development / Testing: Kiyan I.N.
Responsible: Kiyan I.N.

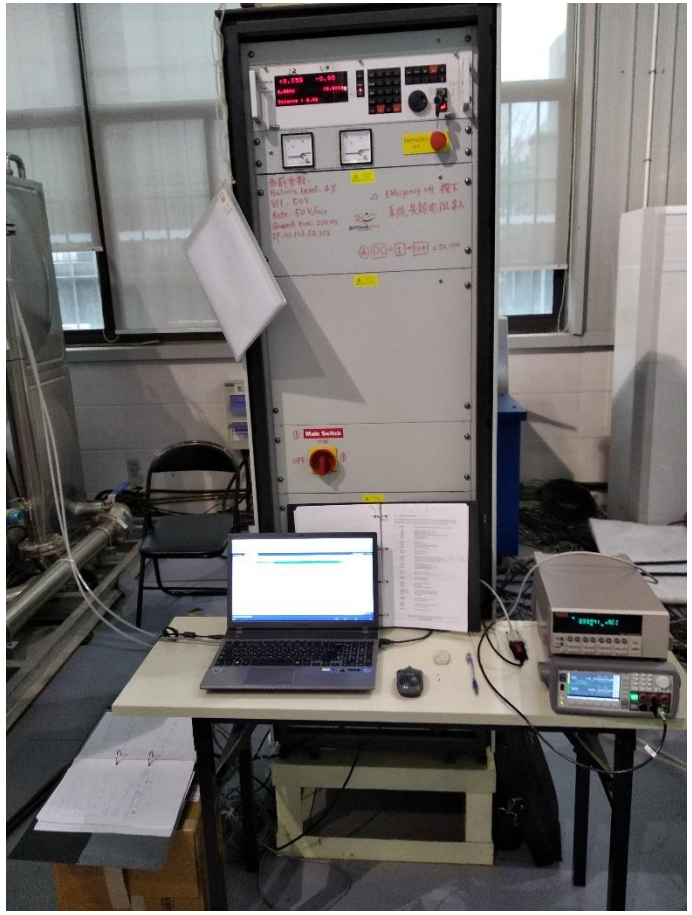
Tab. 5. ACS Parameters (SC-200, CAS Ion Medical and Technical Devices Co., Ltd., Hefei, China).

Parameter	Interface: USB/RS-232 between PC and PA	Interface: Ethernet between PC and PS
IP Address	-	XX.XXX.XX.XXX
IP Mask	-	255.255.255.0
Software Port Number	-	123
Port Number	COMX	-
Baud Rate	9600	-
Data Bits	8	-
Stop Bits	1	-
Parity	None	-
Flow Control	None	-
Terminator (command)	CR	CR
Terminator (response)	LFCR	CR
Cable Type	Straight-throw	Straight-throw

Developed software in C++ in the MS Visual Studio programing environment:

- Smith Garren Curve Measurement Program II 2017 - 2026 (SGCMP II 2017 - 2026). Developer: Kiyan I.N.

ACS for Smith-Garren curves measurement



Hardware:

- SIGMAPHI Cryo Power Supply System PSSYS +/-50/175.
- Power source: KEYSIGHT B2962A.
- Pico-ammeter: KEITHLEY 6485.



Fig. 25. Power source: KEYSIGHT B2962A.



Fig. 26. Pico-ammeter: KEITHLEY 6485.

Fig. 24. Smith-Garren curves measurement in beam current emulation mode. Experiment 07.12.2018. (SC-200, CAS Ion Medical and Technical Devices Co., Ltd., Hefei, China).

ACS for Smith-Garren curves measurement

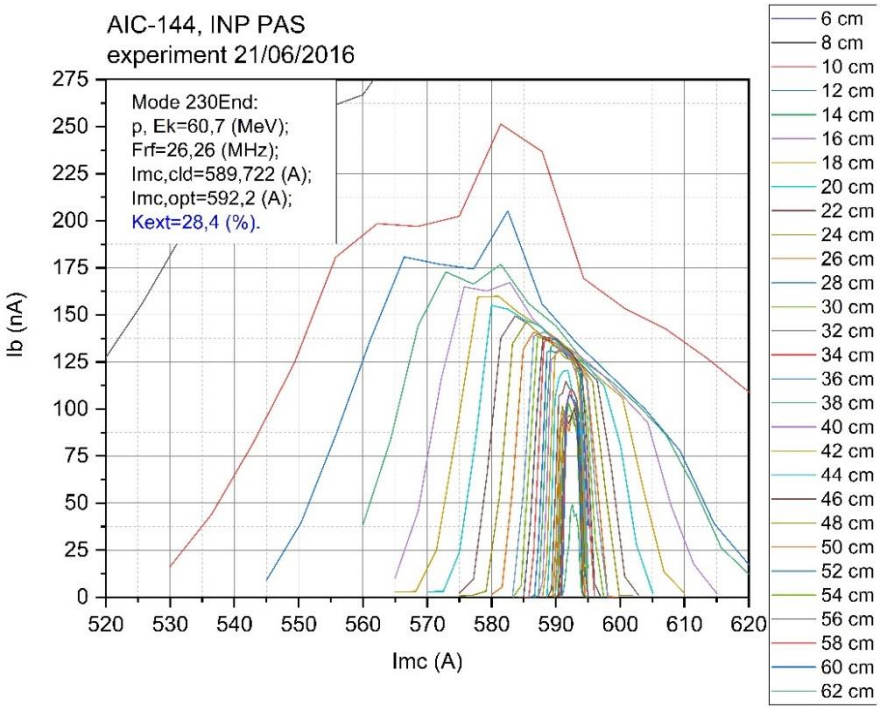


Fig. 27. SG curves. (Measured beam current on measured main coil current. R = 6÷62 (cm)).

SC-200, CAS Ion Medical and Technical Devices Co., Ltd., Hefei, China. Experiment 07.12.2018.

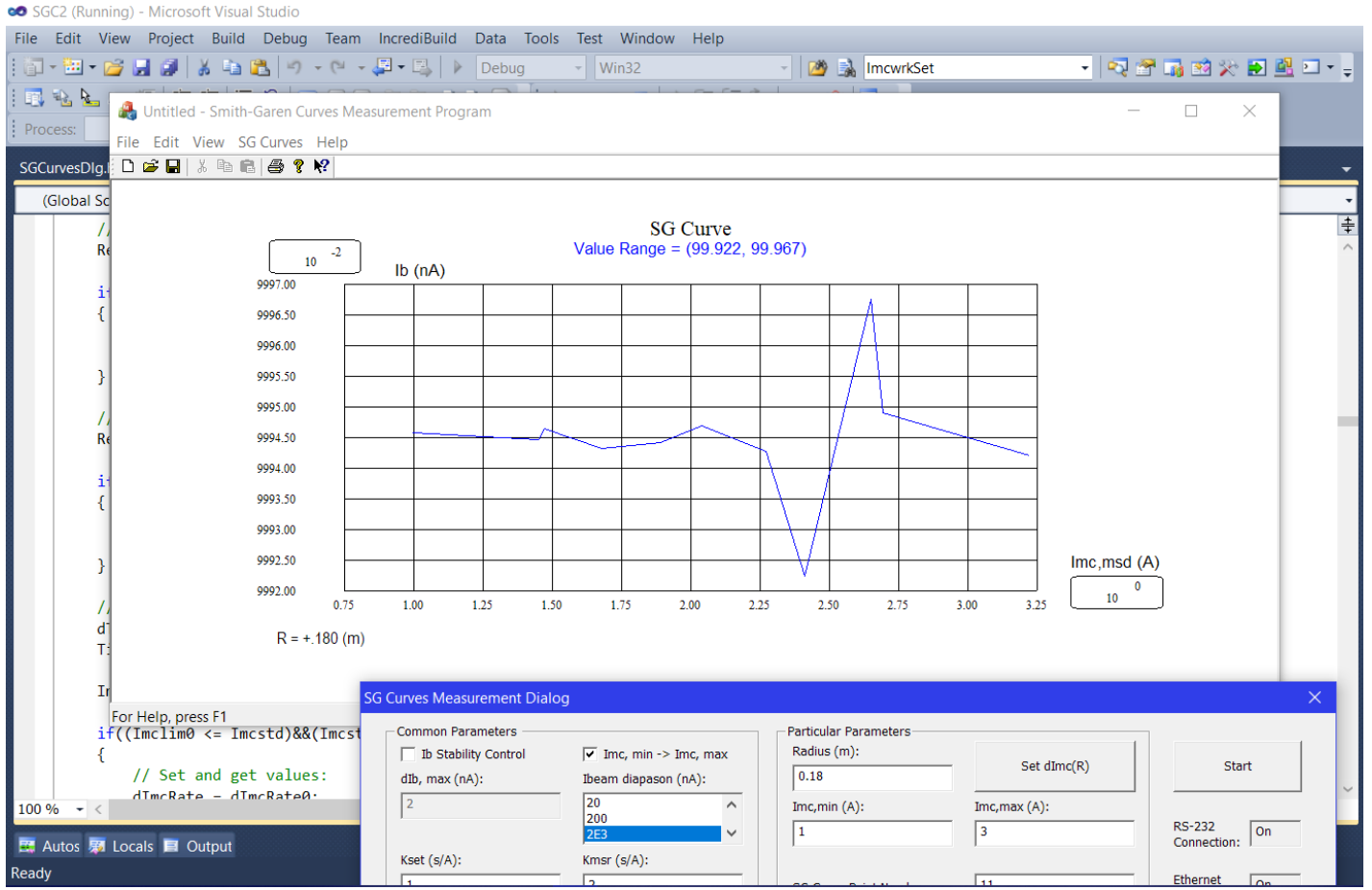


Fig. 28. SG curves. (Emulated beam current on measured main coil current).

ACS for Smith-Garren curves measurement

```
10.txt
Comment: PT
Path: D:\Experiment\Physical\2019\AIC-144\SG\SG Curves Source Data
2019.txt

Np
R (m)       Imc,msd (A) Ib (nA)     dIb (nA)

+25
+0.700      +594.054    +5.1        +0.0
+0.700      +593.911    +7.1        +0.0
+0.700      +593.748    +8.4        +0.0
+0.700      +593.638    +8.5        +0.2
+0.700      +593.521    +8.6        +0.0
+0.700      +593.300    +8.6        +0.1
+0.700      +593.150    +9.6        +0.1
+0.700      +593.007    +9.6        +0.0
+0.700      +592.877    +10.7       +0.0
+0.700      +592.721    +10.5       +0.1
+0.700      +592.572    +9.6        +0.2
+0.700      +592.448    +7.1        +0.1
+0.700      +592.292    +5.3        +0.0
+0.700      +592.169    +1.6        +0.0
+0.700      +592.019    +0.1        +0.00
+0.700      +591.883    -0.1        +0.0
+0.700      +591.694    -0.00       +0.00
+0.700      +591.545    -0.0        +0.00
+0.700      +591.421    +0.0        +0.00
+0.700      +591.265    +0.0        +0.1
+0.700      +591.109    +0.0        +0.0
+0.700      +590.986    -0.0        +0.0
+0.700      +590.836    +0.0        +0.1
+0.700      +590.680    -0.1        +0.0
+0.700      +590.550    -0.1        +0.1
```

Fig. 29. SGCMP I 2014 – 2025. Resulting text file. Experiment 08.02.2019.

ACS for beam current measurement

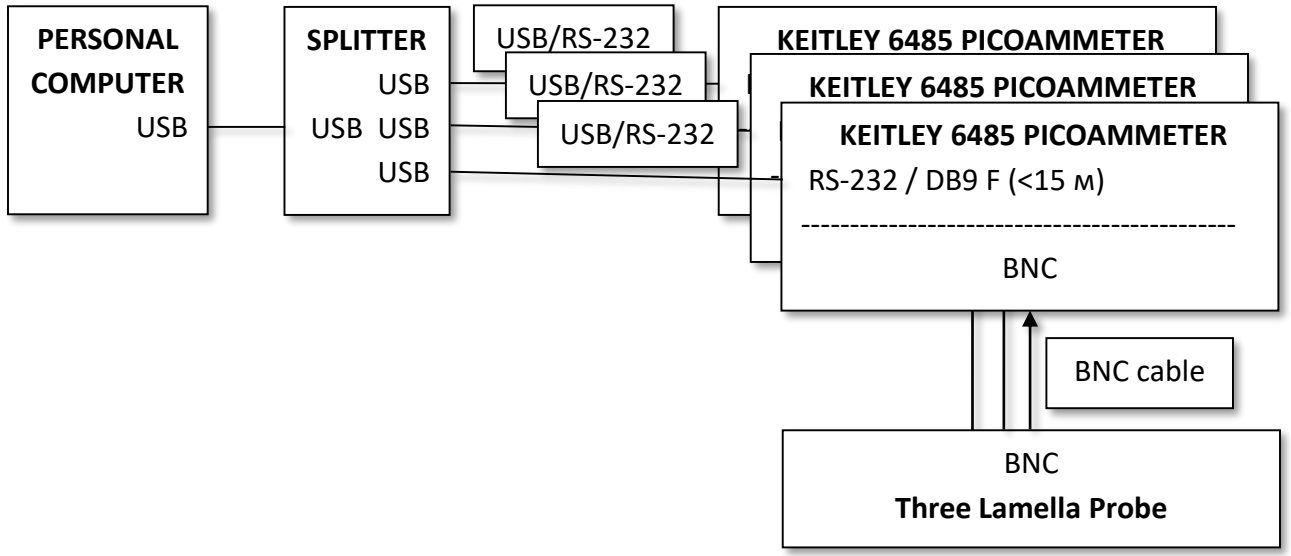


Fig. 30. ACS Block–diagram.

Development / Operation: Kiyan I.N.
Responsible: Kiyan I.N.

Developed software in C++ in the MS Visual Studio programing environment:

- Beam Current Measurement Program 2014–2025 (BCMP 2014–2025). Developer: Kiyan I.N.

ACS for beam current measurement

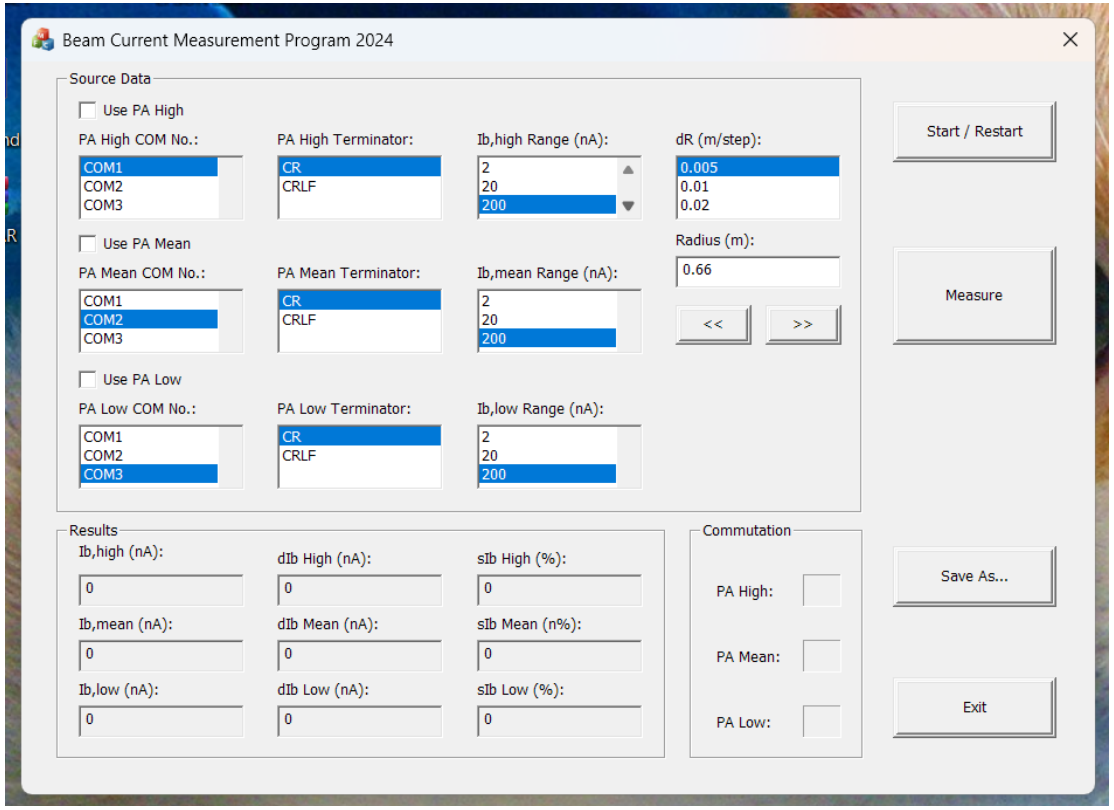


Fig. 31. BCMP 2019–2025: Main window of the DBA application.

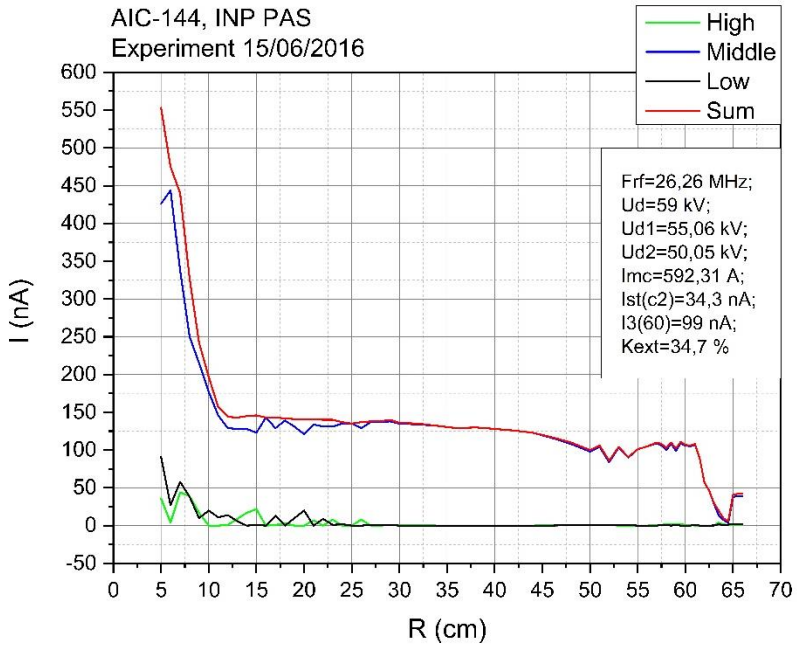


Fig. 32. Measured beam current.

ACS for beam current measurement

Test2.txt

R, (m)	Ib,h (nA)	Ib,m (nA)	Ib,l (nA)
+.660	+1.588	+13.126	+.084
+.655	+2.574	+15.806	+.986
+.650	+2.140	+16.591	+1.133
+.645	+1.744	+12.520	+1.273
+.640	+3.013	+.260	+.691
+.635	+1.056	+1.442	+.634
+.630	+1.082	+3.131	+.182
+.625	+.670	+16.073	+.069
+.620	+1.810	+25.829	+.126
+.615	+2.786	+35.088	+.174
+.610	+2.627	+48.483	+.221
+.605	+3.280	+49.090	+.253
+.600	+.688	+47.594	+1.571
+.595	+1.963	+49.422	+.846
+.590	+3.426	+47.876	+.503
+.585	+.779	+51.856	+.838
+.580	+1.222	+49.868	+2.657
+.575	+.955	+48.244	+1.403
+.570	+.939	+51.611	+.649
+.565	+1.840	+47.990	+.268
+.560	+.987	+49.998	+.216
+.555	+.632	+51.492	+.626
+.550	+.381	+47.531	+.289

Fig. 33. BCMP 2019–2025: Resulting text file. Experiment 09.12.2019.

New technique

New technique of phase motion measurement and magnetic field correction in isochronous cyclotrons.

JINR theme: 08-2-1127-2016. “Advanced Studies of Systems of New-Generation Accelerators and Colliders for Fundamental and Applied Research”.
Theme leaders: G.V. Trubnikov, G.D. Shirkov, B.N. Gikal.
Project in the theme: 08-2-1127-1-2024/2027. “Creation of test benches for testing subsystems of the MSC-230 cyclotron”.
Project leaders: G.A. Karamysheva, S.L. Yakovenko.

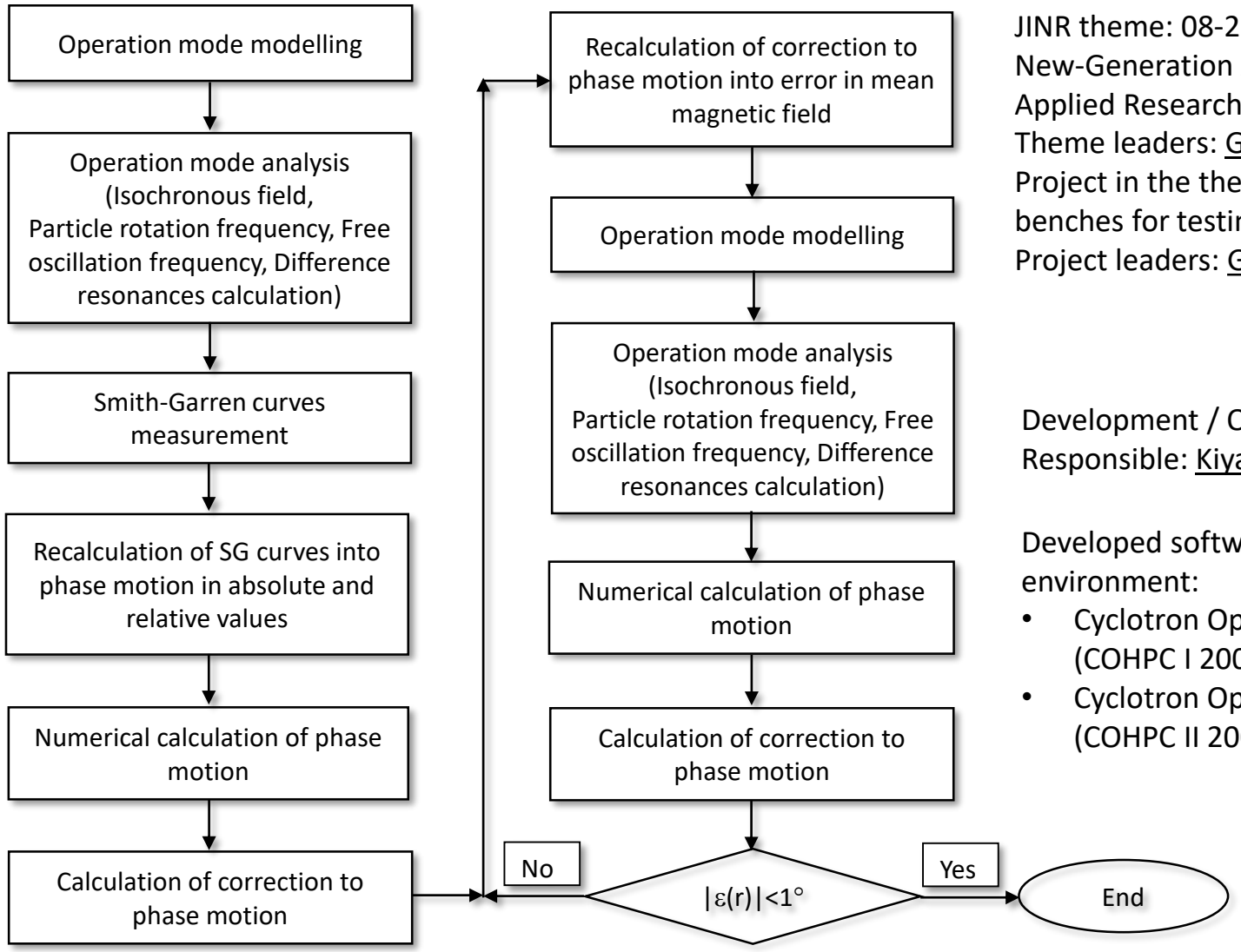


Fig. 34. Block-diagram of operation algorithm.

Development / Operation: Kiyan I.N.
Responsible: Kiyan I.N.

Developed software in C++ in the MS Visual Studio programing environment:

- Cyclotron Operator Help Program Complex I 2002–2026 (COHPC I 2002–2026): 7 programs. Developer: Kiyan I.N.
- Cyclotron Operator Help Program Complex II 2002–2026 (COHPC II 2002–2026): 7 programs. Developer: Kiyan I.N.

New technique

New technique of phase motion measurement and magnetic field correction in isochronous cyclotrons.

- References. Using Smith-Garren curves.

1. Herve Marie. *"How to use Smith and Garren curves to correct isochronism"*. // Internal report IBA. December 16, 1993.
2. C. Baumgarten, A. Geisler, U. Klein, D. Krischel, H. Rocken, M. Schillo, T. Stephani, J.H. Timmer. *"Isochronism of the ACCEL 250 MeV medical proton cyclotron"*. // Print ISSN: 0168–9002, Nuclear Instruments and Methods in Physics Research, Section A, 570 (2007), 10–14. © 2006 Elsevier B.V. 2007.

- References. Equations of motion.

1. V.P. Dmitrievsky. *"Meson factories"*. // I International School for Young Scientists. Problems of Charged Particle Accelerators. Uzhgorod. September. 1975. Pp. 168-194. Dubna, 1976.
2. V.V. Kolga. *"Mathematical simulation of dynamic processes at accelerators using computer".* // International School for Young Scientists. Problems of Charged Particle Accelerators. Minsk. September 17-25, 1979. Pp. 300-313. Dubna, 1980.
3. L.M. Onischenko, E.V. Samsonov. "Code PHASCOL for computation of space charge effects in the cyclotrons and synchrocyclotrons". // Problems of Atomic Science and Technology. 2001. No 5. Series: Nuclear Physics Investigations (39). Pp. 163-165.
4. S.A. Kostromin, L.M. Onischenko. *"Calculation of beam acceleration and extraction from the JINR Phasotron"*. // ISSN 1814–5957, Physics of Particles and Nuclei Letters, 2012, Vol. 9, No. 4-5(174-175), Pp. 640–646. JINR Publishing Department, Dubna, 2012.

VERSUS

1. I. V. Amirkhanov, G. A. Karmysheva, I. N. Kiyan, and Ya. Sulikowski. *"Mathematical Simulation of the Main Operation Mode of the AIC-144 Multipurpose Isochronous Cyclotron".* // ISSN 1814–5957, Physics of Particles and Nuclei Letters, 2012, Vol. 9, No. 4-5(174-175), Pp. 647–653. JINR Publishing Department, Dubna, 2012.
2. I. V. Amirkhanov, G. A. Karmysheva, I. N. Kiyan, and Ya. Sulikowski. *"Calculation of Proton Rotation Frequency in Static Equilibrium Orbits at the Isochronous Cyclotron"*. // ISSN 1814–5957, Physics of Particles and Nuclei Letters, 2015, Vol. 12, No. 3(194), Pp. 673–677. JINR Publishing Department, Dubna, 2015.

New technique

New technique of phase motion measurement and magnetic field correction in isochronous cyclotrons.

New mathematical models:

- Numerical calculation of phase motion (calculated phase motion):

$$\varphi(E) = \arcsin\left\{\sin\left(\varphi_0(E_0)\right) + \frac{2\pi h}{N_{acs} q} \cdot \int_{E_0}^{E} \frac{\Omega_{rev0}(E)}{U_d(E)} dE\right\};$$

$$\Omega_{rev0}(E) = \frac{f_{rev}(E) - f_{ref0}}{f_{rev}(E)}; \qquad f_{ref0} = \frac{f_{rf0}}{h}; \qquad U_d(E) > 0; \quad q > 0; \qquad (1)^*$$

- Numerical calculation of number of particle revolutions:

$$n(E) = \frac{1}{N_{acs} q} \cdot \int_{E_0}^{E} \frac{1}{U_d(E) \cdot cos\left(\varphi(E)\right)} dE; \qquad U_d(E) > 0; \quad q > 0; \qquad (2)^*$$

- Recalculating correction to phase motion into error in mean magnetic field:

$$d\bar{B}(E) = \frac{N_{acs} \cdot q}{2\pi h} \cdot U_d(E) \cdot \bar{B}(E) \cdot \cos\left(\varphi(E)\right) \cdot \frac{d\varphi(E)}{dE};$$

$$d\bar{B}(E) = \bar{B}(E) - \bar{B}_{is}(E); \qquad \varphi(E) = \varphi_{cld}(E) - \varphi_{msd}(E); \qquad U_d(E) > 0; \quad q > 0; \qquad (3)$$

C. Baumgarten mathematical model:

- Recalculating SG curves into phase motion in absolute values (reference phase motion):

$$\varphi(r) = \arcsin\left(2 \cdot \frac{\bar{I} - I_0}{\Delta I}\right); \qquad \bar{I} = \frac{1}{2} \cdot (I_l + I_h); \qquad \Delta I = I_h - I_l; \qquad (4)$$

New technique

New technique of phase motion measurement and magnetic field correction in isochronous cyclotrons.

New mathematical models:

- Recalculating SG curves into phase motion in relative values (measured phase motion):

$$\varphi(E) = \arcsin\left\{\sin\left(\varphi_0(E_0)\right) - \frac{2\pi h}{N_{acs} q} \cdot \int_{E_0}^{E}\left[\frac{d}{dE}\left(\int_{E_0}^{E}\frac{1}{U_d(E)}\,dE \cdot \mu(E) \cdot \sigma I_l(E)\right)\right] dE\right\};$$

$$\mu(E) = \int_{E_0}^{E}\frac{\lambda(E)}{U_d(E)}\,dE \Bigg/ \int_{E_0}^{E}\frac{1}{U_d(E)}\,dE\,; \qquad \lambda(E) = \frac{\partial \Omega_{rev}(E)}{\partial I} \cdot I_0; \qquad \Omega_{rev}(E) = \frac{f_{rev}(E) - f_{ref0}}{f_{rev}(E)};$$

$$\sigma I_l(E) = \frac{I_l(E) - I_0}{I_0}; \qquad U_d(E) > 0; \qquad q > 0; \qquad (5)^*$$

- Numerical calculation of mean radius of closed equilibrium orbit:

$$\overline{r}(E) = \overline{r_0}(E) \cdot (1 - \lambda(E) \cdot \sigma I); \qquad d\overline{r}(E) = -\overline{r_0}(E) \cdot \lambda(E) \cdot \sigma I_l(E);$$

$$\lambda(E) = \frac{\partial \Omega_{rev}(E)}{\partial I} \cdot I_0; \qquad \Omega_{rev}(E) = \frac{f_{rev}(E) - f_{ref0}}{f_{rev}(E)}; \qquad \sigma I_l(E) = \frac{I_l(E) - I_0}{I_0}; \qquad (6)^*$$

Standard mathematical model:

- Numerical calculation of phase-energy integral:

$$I(E) = \int_{E_0}^{E}\sin\left(\varphi(E)\right) \cdot dE; \qquad (7)$$

New technique

New technique of phase motion measurement and magnetic field correction in isochronous cyclotrons.

Lorentz-Newton equation / equations of motion:

$$m \cdot \ddot{\vec{r}} = q \cdot \left(\vec{E} + \left[\dot{\vec{r}} \times \vec{B} \right] - \frac{\dot{\vec{r}}}{c^2} \cdot \left(\dot{\vec{r}} \cdot \vec{E} \right) \right);$$

$$\begin{cases} \ddot{r}^* - \left[\dot{\varphi}^{*2} + \dfrac{K_1}{E} \cdot \dot{\varphi}^* \cdot {B_z}^* \right] \cdot r^* = -\dfrac{K_1}{E} \cdot \dot{z}^* \cdot {B_\varphi}^* + \\ + \dfrac{1}{E} \cdot \left[(K_2 - K_3 \cdot \dot{r}^{*2}) \cdot {E_r}^* - K_3 \cdot \dot{\varphi}^* \cdot \dot{r}^* \cdot r^* \cdot {E_\varphi}^* - K_3 \cdot \dot{z}^* \cdot \dot{r}^* \cdot {E_z}^* \right]; \\ \ddot{\varphi}^* + 2 \cdot \dfrac{\dot{r}^*}{r^*} \cdot \dot{\varphi}^* = \dfrac{K_1}{E} \cdot \left(\dfrac{\dot{z}^*}{r^*} \cdot {B_r}^* - \dfrac{\dot{r}^*}{r^*} \cdot {B_z}^* \right) + \\ + \dfrac{1}{E} \cdot \left[-K_3 \cdot \dot{r}^* \cdot \dot{\varphi}^* \cdot {E_r}^* + \left(\dfrac{K_2}{r^*} - K_3 \cdot r^* \cdot \dot{\varphi}^{*2} \right) \cdot {E_\varphi}^* - K_3 \cdot \dot{z}^* \cdot \dot{\varphi}^* \cdot {E_z}^* \right]; \\ \ddot{z}^* = \dfrac{K_1}{E} \cdot \left(\dot{r}^* \cdot {B_\varphi}^* - r^* \cdot \dot{\varphi}^* \cdot {B_r}^* \right) + \\ + \dfrac{1}{E} \cdot \left[-K_3 \cdot \dot{r}^* \cdot \dot{z}^* \cdot {E_r}^* - K_3 \cdot r^* \cdot \dot{\varphi}^* \cdot \dot{z}^* \cdot {E_\varphi}^* + (K_2 - K_3 \cdot \dot{z}^{*2}) \cdot {E_z}^* \right]; \end{cases}$$

$$\begin{cases} E = E_0 + E_k; \quad E_0 = m_0 \cdot c^2; \\ K_1 = q \cdot c^2 \cdot \hat{T}_0 \cdot \hat{B}_0; \\ K_2 = q \cdot c^2 \cdot {\hat{T}_0}^2 \cdot \dfrac{\hat{E}_0}{\hat{L}_0}; \\ K_3 = q \cdot \hat{E}_0 \cdot \hat{L}_0; \\ K_4 = \dfrac{c \cdot \hat{T}_0}{\hat{L}_0}; \\ \hat{B}_0 = 1(\text{T}); \quad \hat{E}_0 = 1\left(\dfrac{\text{B}}{\text{м}}\right); \\ \hat{L}_0 = 1(\text{м}); \quad \hat{T}_0 = \dfrac{1}{2\pi \cdot F_0}; \end{cases} \qquad \begin{cases} r_0^* = \dfrac{K_4}{1 + \sigma_N} \cdot \dfrac{\sqrt{2E_0E_k + E_k^2}}{E_0 + E_k}; \\ \varphi_0 = \varphi_N + \dfrac{3\pi}{2N}; \\ z_0^* = 0; \\ \dot{r}_0^* = \dfrac{\varepsilon_N N}{N^2 - 1} \cdot r_0^*; \\ \dot{\varphi}_0^* = 1; \\ \dot{z}_0^* = \sqrt{K_4^2 \cdot \dfrac{2E_0E_k + E_k^2}{(E_0 + E_k)^2} - {\dot{r}_0^*}^2 - {r_0^*}^2}; \end{cases} \tag{8}$$

$$\sigma_N(\bar{r}) = 0{,}25 \cdot \frac{\varepsilon_N^2(\bar{r}) \cdot N^2}{\lambda_N^2(\bar{r}) \cdot (N^2 - k(\bar{r}) - 1)^2}; \qquad \lambda_N(\bar{r}) = 0{,}5 + \sqrt{0{,}25 + \frac{\varepsilon_N^2(\bar{r})}{2 \cdot N^2} \cdot \left(1{,}5 + k(\bar{r}) + \frac{\bar{r}}{\varepsilon_N(\bar{r})} \cdot \frac{d\varepsilon_N(\bar{r})}{d\bar{r}} \right)};$$

$$\varepsilon_N(\bar{r}) = \frac{B_N(\bar{r})}{\bar{B}_z(\bar{r})}; \qquad k(\bar{r}) = \frac{\bar{r}}{\bar{B}_z(\bar{r})} \cdot \frac{d\bar{B}_z(\bar{r})}{d\bar{r}}; \tag{9}$$

Program complex

Developed software in C++ in the MS Visual Studio programing environment:

- Cyclotron Operator Help Program Complex I 2002–2026 (COHPC I 2002–2026): Program complex for operation mode simulation and beam dynamics calculation in isochronous cyclotrons.
  - Operation Mode Modelling Program 2004–2026 (OMMP 2004–2026): Program for simulation of operation modes of multipurpose isochronous cyclotrons.
  - B1Fi1 Correction Program 2009–2024 (B1Fi1CP 2009–2024): Program for computational and experimental correction of the first harmonic of magnetic field.
  - Isochronous Field Calculation Program 2002–2024 (IFCP 2002–2024): Program for isochronous magnetic field calculation based on M.M. Gordon's algorithm.
  - Equilibrium Orbit Research Program 2009–2024 (EORP 2009–2024): Program for particle revolution frequency calculation.
  - Free Oscillation Research Program 2002–2024 (FORP 2002–2024): Program for free oscillation frequencies and difference resonances calculation.
  - Phase Motion Calculation Program 2002–2025 (PMCP 2002–2025): Program for phase motion calculation by both analytical and numerical methods (calculated phase motion), and also for recalculation of correction to phase motion into error in mean magnetic field.
  - Beam Current Measurement Program 2014–2025 (BCMP 2014–2025): ACS Control program for beam current measurement from three-lamella probe to three picoammeters.

Developer: Kiyan I.N.

Program complex

Developed software in C++ in the MS Visual Studio programing environment:

- Cyclotron Operator Help Program Complex II 2002–2026 (COHPC II 2002–2026): Program complex for beam dynamics calculation and magnetic field correction in isochronous cyclotrons.
  - Operation Mode Modelling Program 2004–2026 (OMMP 2004–2026): Program for simulation of operation modes of multipurpose isochronous cyclotrons.
  - Isochronous Field Calculation Program 2002–2024 (IFCP 2002–2024): Program for isochronous magnetic field calculation based on M.M. Gordon's algorithm.
  - Equilibrium Orbit Research Program 2009–2024 (EORP 2009–2024): Program for particle revolution frequency calculation.
  - Free Oscillation Research Program 2002–2024 (FORP 2002–2024): Program for free oscillation frequencies and difference resonances calculation.
  - Smith–Garren Curves Measurement Program I/II 2014–2025/2017-2026 (SGCMP I/II 2014–2025/2017-2026): ACS Control program for Smith–Garren curves measurement at both “warm” (AIC-144, INP PAS, Krakow, Poland) and “superconducting” (SC-200, CAS Ion Medical and Technical Devices Co., Ltd., Hefei, China) isochronous cyclotrons.
  - Smith–Garren Phase Motion Program I/II 2018-2023/2023-2025 (SGPMP I/II 2018-2023/2023-2025): Program for recalculation of Smith–Garren curves into phase motion in both absolute (reference phase motion) and relative (measured phase motion) values, and also for phase-energy integral calculation.
  - Phase Motion Calculation Program 2002–2025 (PMCP 2002–2025): Program for phase motion calculation by both analytical and numerical methods (calculated phase motion), and also for recalculation of correction to phase motion into error in mean magnetic field.

Developer: Kiyan I.N.

New technique application

AIC-144 main operation mode: $p, E_k = 60{,}7\ (MeV), F_{rf} = 26{,}26\ (MHz), U_{dee} \sim 60\ (kV)$

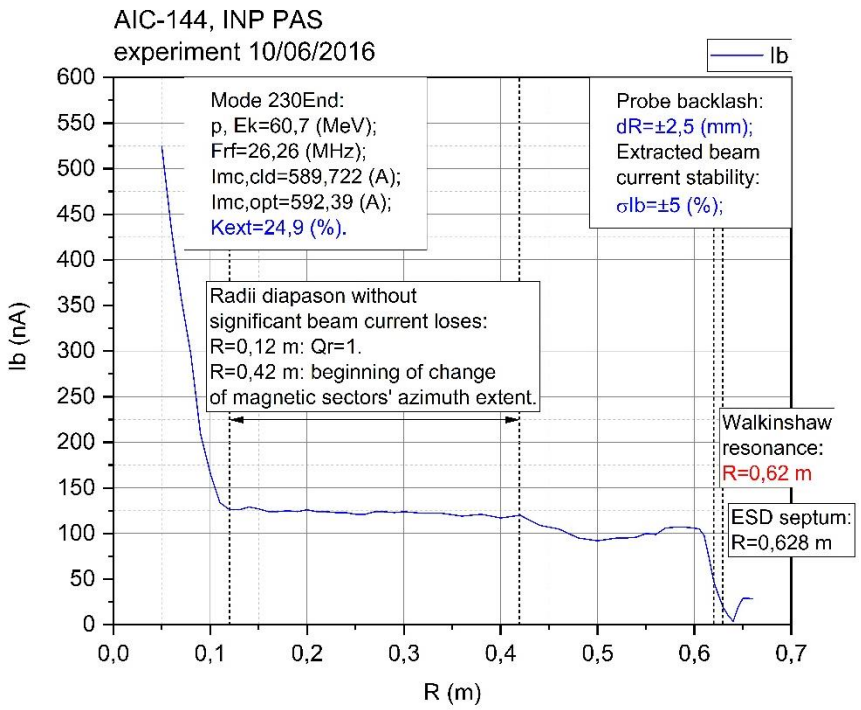


Fig. 35. Measured beam current.

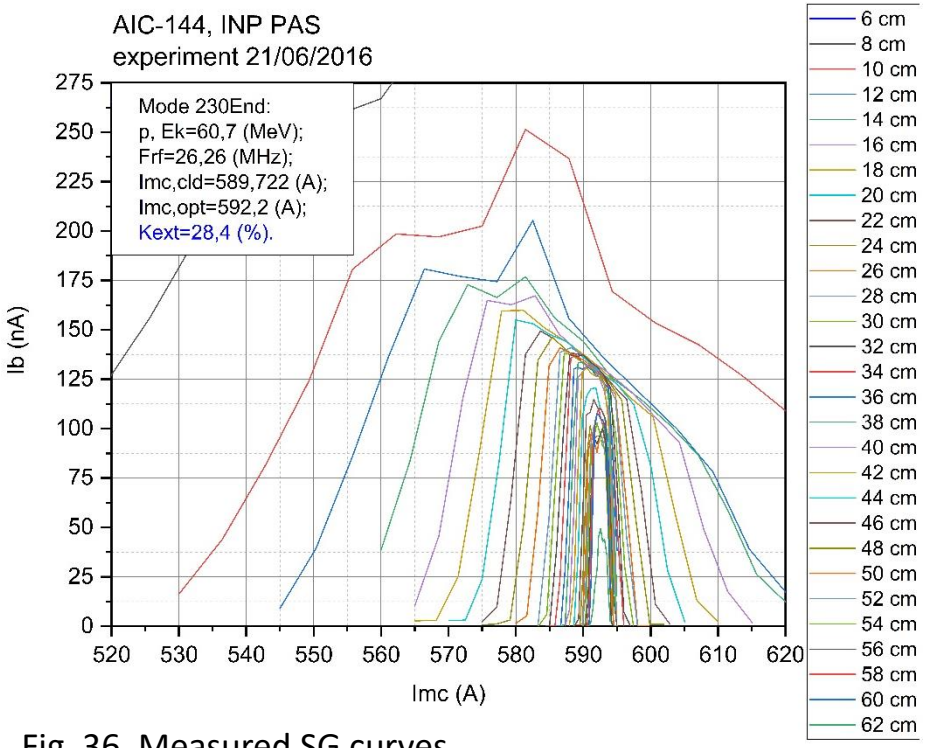


Fig. 36. Measured SG curves.

- Acceptable (within 15%) axial and phase beam current losses over the range of radii R=0.42-0.595 m and further to R=0.605 m.
- $I_{mc,cld} < I_{mc,opt}$

New technique application

AIC-144 main operation mode: $p, E_k = 60{,}7\ (MeV), F_{rf} = 26{,}26\ (MHz), U_{dee} \sim 60\ (kV)$

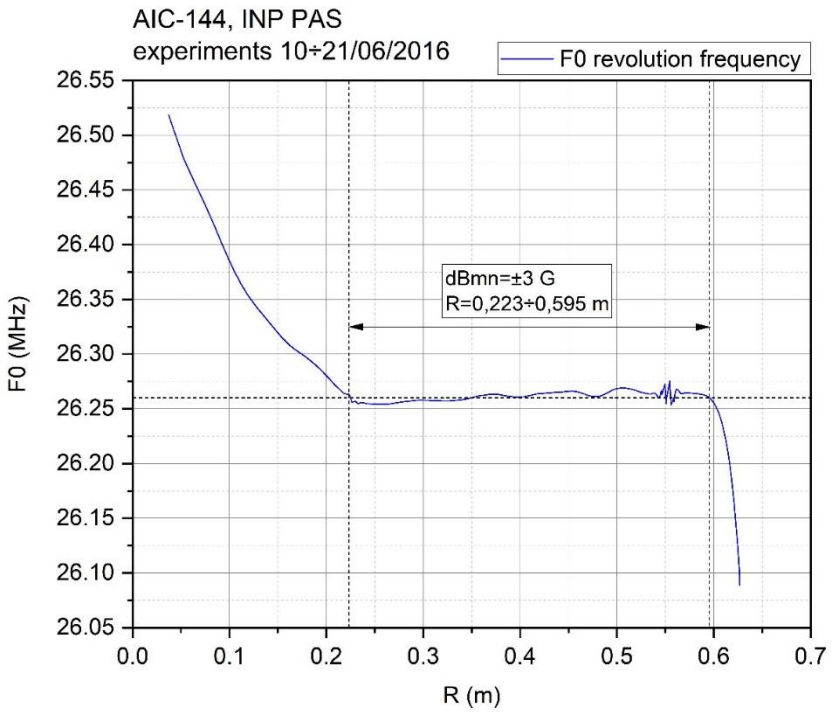


Fig. 37. Particle revolution frequency.

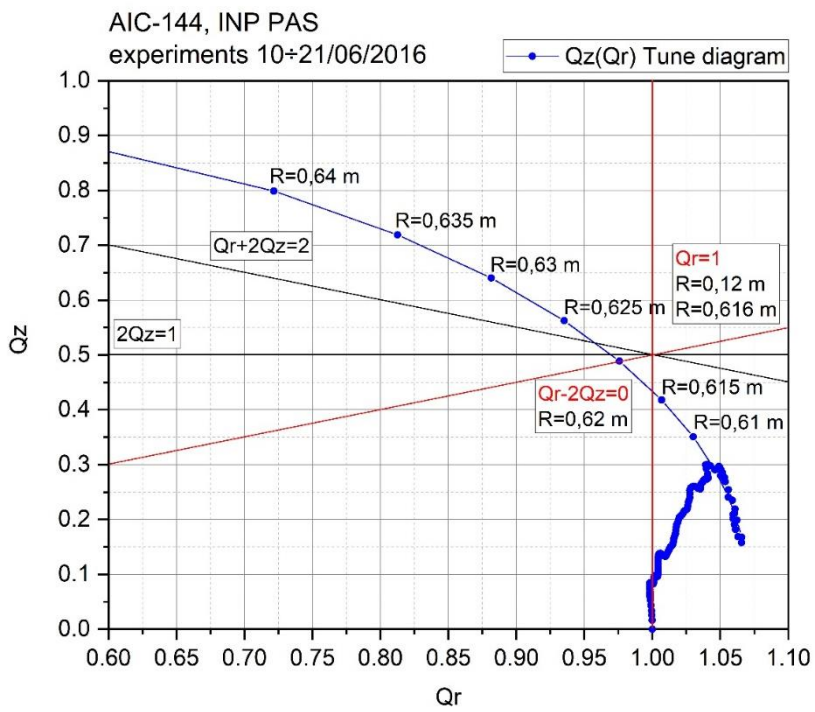


Fig. 38. Tune diagram.

N_{rev} = 554 (rev).

New technique application

AIC-144 main operation mode: $p, E_k = 60{,}7\ (MeV), F_{rf} = 26{,}26\ (MHz), U_{dee} \sim 60\ (kV)$

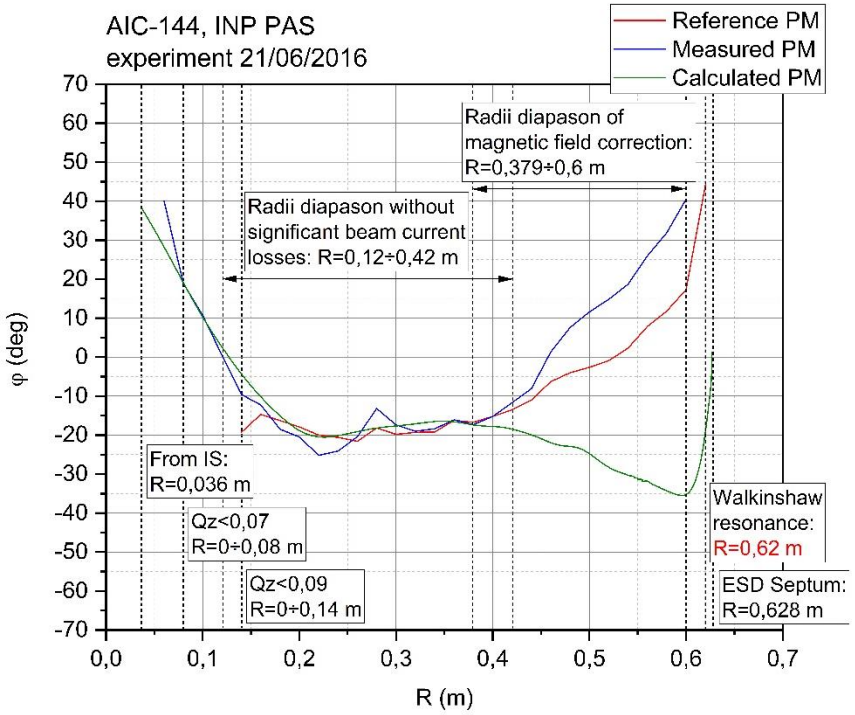


Fig. 39. Phase motion calculated by tree methods.

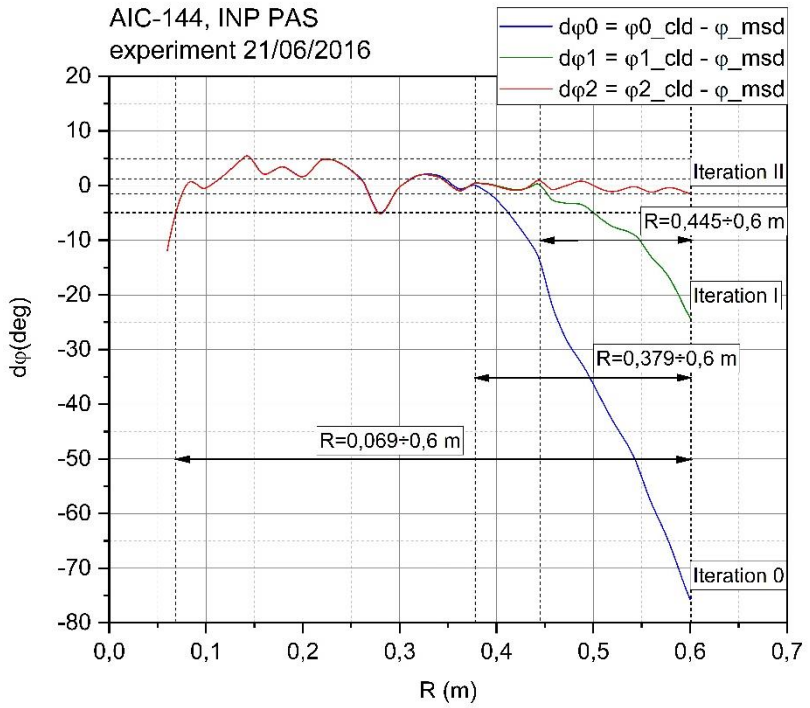


Fig. 40. Correction to phase motion.

- Exit from iteration cycle after 2 iterations.
- dφ(0,379÷0,6) = ±1,4°; dφ(0,069÷0,6) = ±5°.

New technique application

AIC-144 main operation mode: $p, E_k = 60{,}7\ (MeV), F_{rf} = 26{,}26\ (MHz), U_{dee} \sim 60\ (kV)$

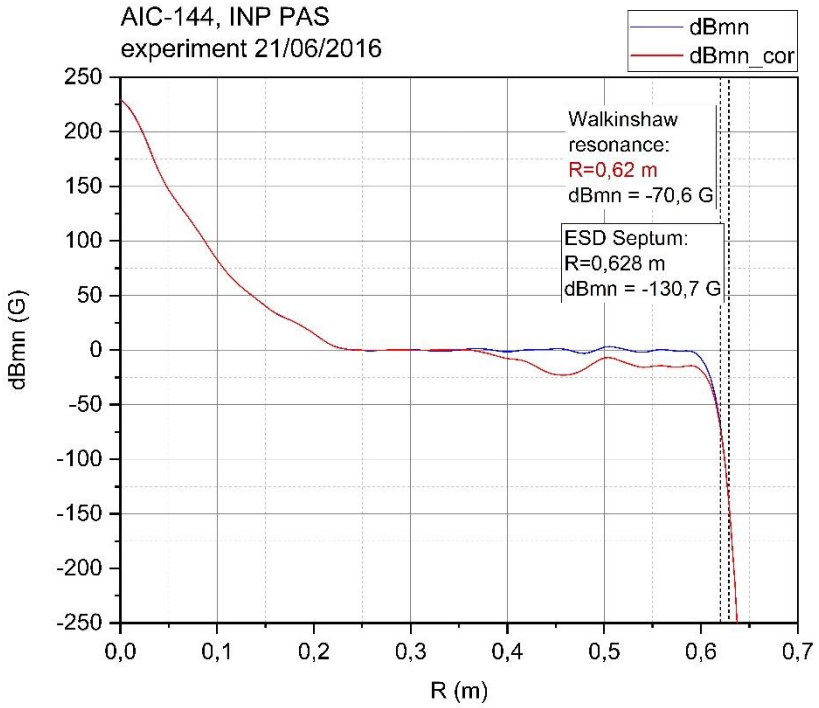


Fig. 41. Error of mean magnetic field.

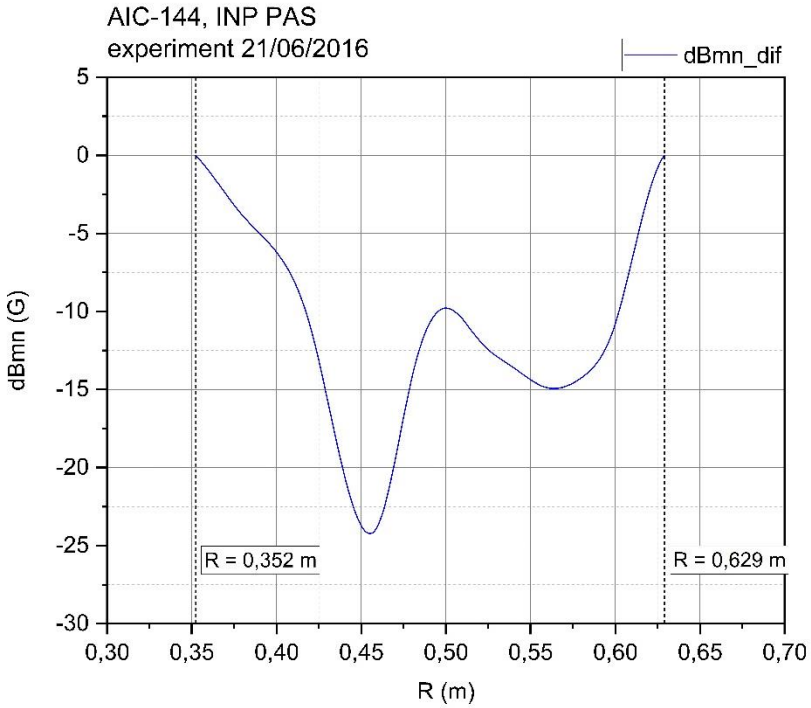


Fig. 42. Correction to mean magnetic field.

- Magnetic field change diapason: R=0,352÷0,629 (m).
- Acceptable (within 15%) axial and phase beam current losses diapason: R=0,42÷0,605 (m).

New technique application

AIC-144 main operation mode: $p, E_k = 60{,}7\ (MeV), F_{rf} = 26{,}26\ (MHz), U_{dee} \sim 60\ (kV)$

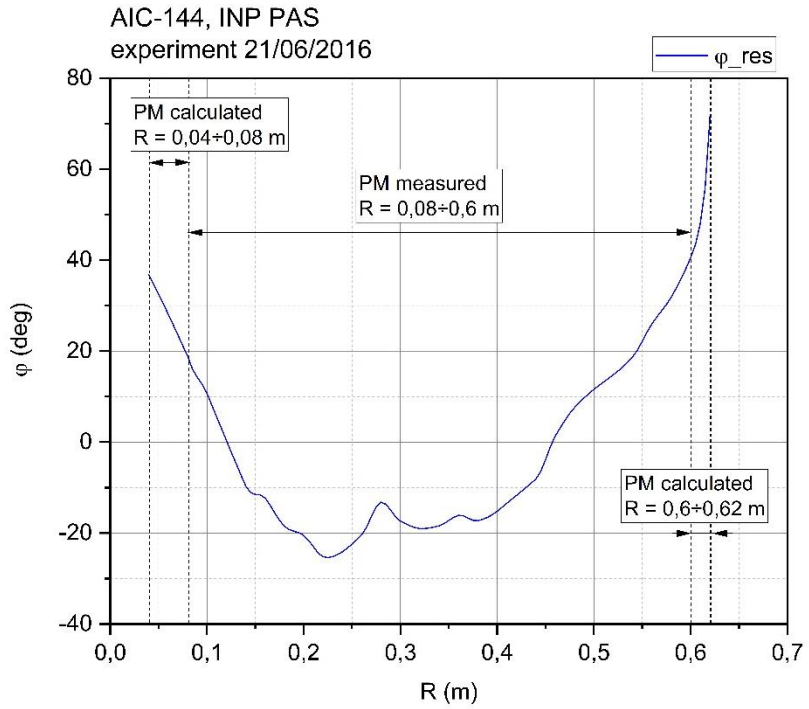


Fig. 43. Extrapolated measured phase motion.

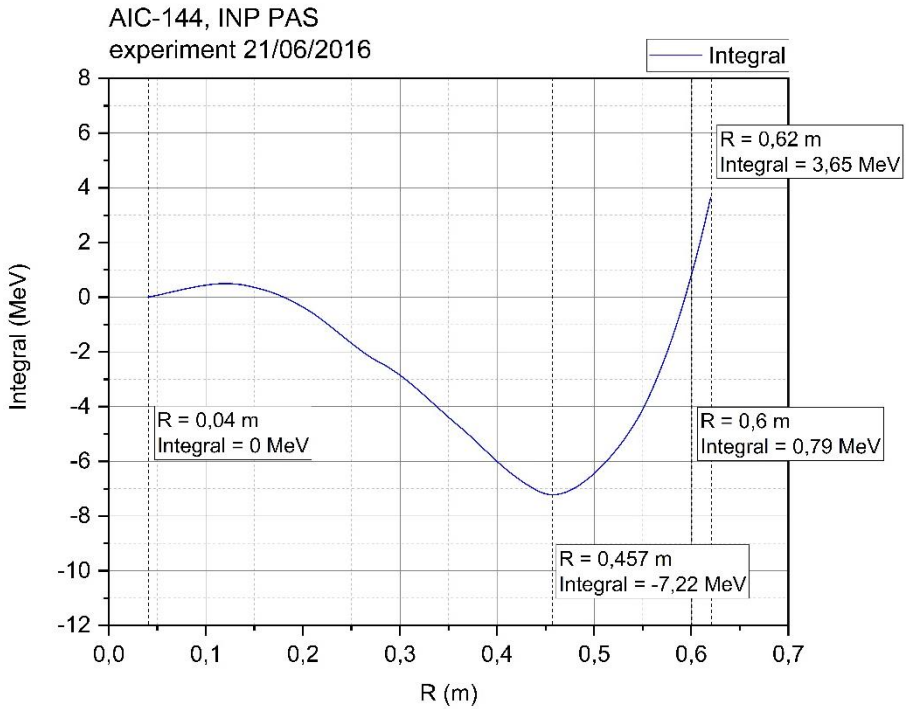


Fig. 44. Phase-energy integral.

- Particle initial phase: $\varphi_0(0{,}04) = 36{,}8°$.
- Particle final phase: $\varphi_f(0{,}62) = 71{,}7°$.
- Extraction efficiency: $k_{opt} = 30 \pm 5\ (\%)$.

New technique application

AIC-144 main operation mode: $p, E_k = 60{,}7\ (MeV), F_{rf} = 26{,}26\ (MHz), U_{dee} \sim 60\ (kV)$

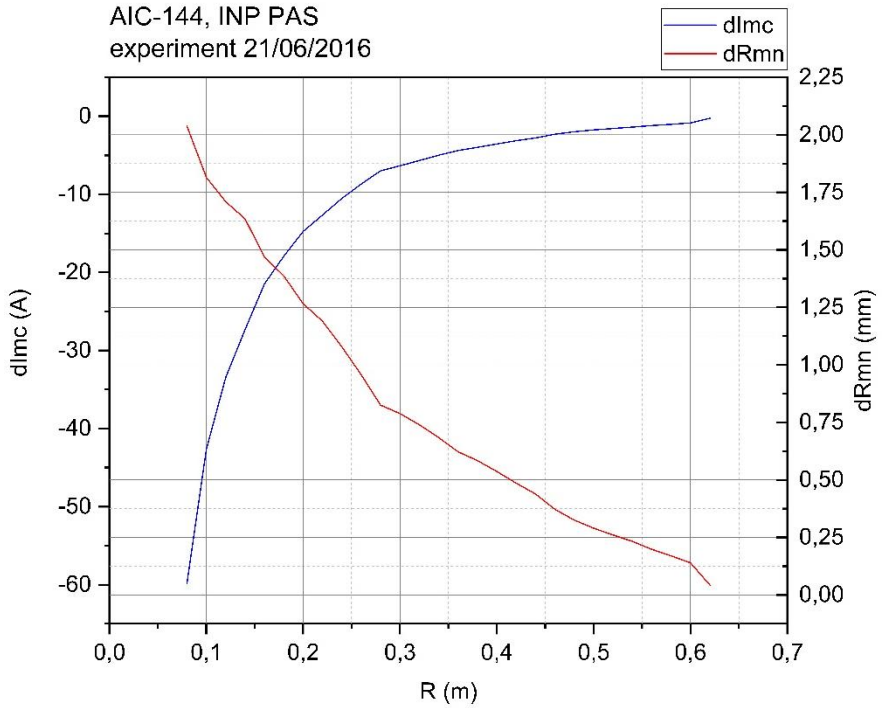


Figure 45. Drift of the mean radius.

- Equilibrium orbit closure accuracy: $dR = \pm 1\ (mm)$.
- Drift of the mean radius $dR < 1\ (mm)$ within diapason: $R = 0.253 - 0.62\ (m)$.
- Magnetic field correction diapason: $R = 0.379 - 0.6\ (m)$.
- Accuracy of conformity between calculated and measured phase motions was improved by a factor of 2.3 thanks to using SGPMP II 2023–2025.

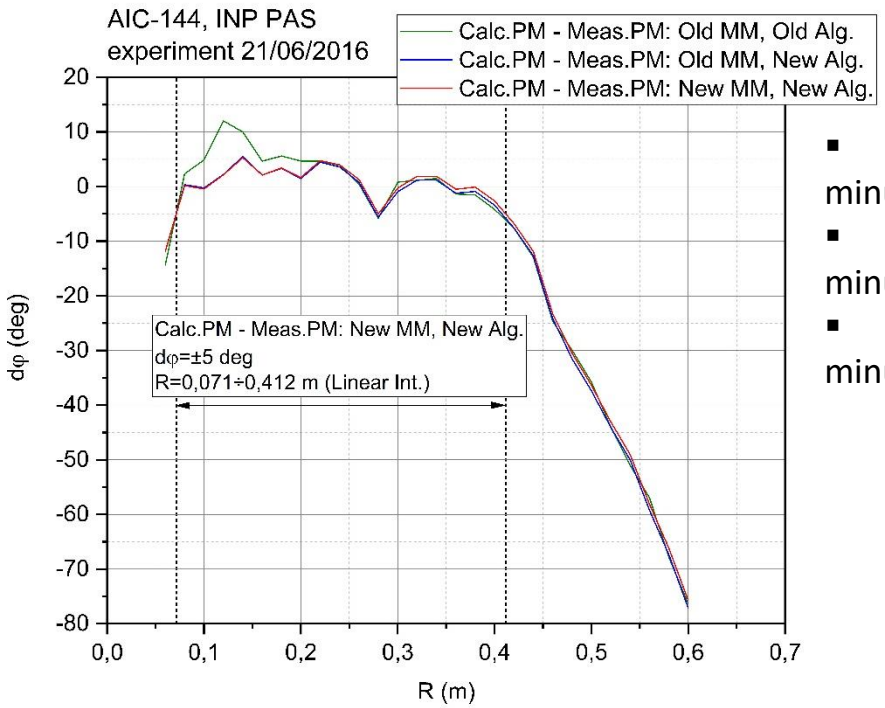


Figure 46. Cross-check: Difference between calculated and measured phase motions.

- Green curve: PMCP 2002–2025 minus Smith-Garren_3.
- Blue curve: PMCP 2002–2025 minus SGPMP I 2018–2023.
- Red curve: PMCP 2002–2025 minus SGPMP II 2023–2025.

Developed software in C++, MS Visual Studio. Developer: Kiyan I.N.:

- PMCP 2002–2025: calculated phase motion.
- SGPMP I 2018–2023: measured phase motion.
- SGPMP II 2023–2025: measured phase motion.

Developed software in Fortran, Compaq Visual Fortran. Developer: Samsonov E.V.:

- Smith-Garren_3: measured phase motion.

New technique application

AIC-144 main operation mode: $p, E_k = 60{,}7\ (MeV), F_{rf} = 26{,}26\ (MHz), U_{dee} \sim 60\ (kV)$

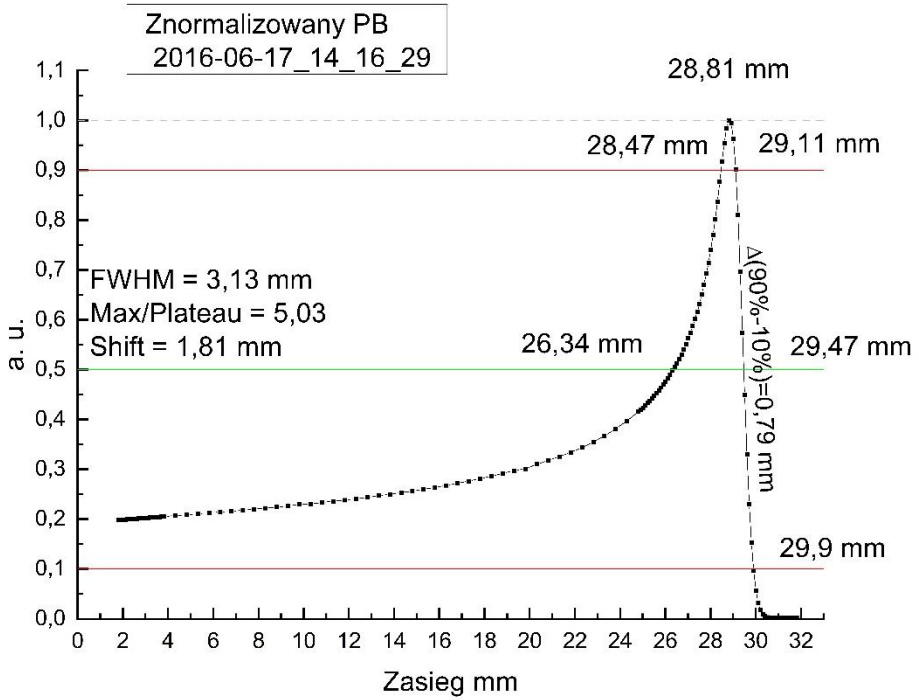


Fig. 47. Bragg peak. Experiment 17.06.2016.



Fig. 48. Cross-section profile of the proton beam. Experiment 26.11.2019.

- Permissible proton range: $\mathrm{L} = 28.8 \pm 0.18\ (\mathrm{mm})$.
- Proton kinetic energy with Bragg-Kleeman approximate formula: $\mathrm{E}(90\%) \sim 58\ (\mathrm{MeV})$.
- Proton kinetic energy losses in glass and air: $\mathrm{dE} \sim 2.7\ (\mathrm{MeV})$.

Conclusion

- Report and plans:

- A calibration stand for calibrating Hall sensors was created and successfully tested. In the plans:
  - ✓ Providing the possibility of the calibration stand further modernization. Development and creation by NAD team of a rail to calibrate Hall sensors. (Responsible Chesnov A.F.).
  - ✓ Replacement by DLNP team of the power supply the Bruker 450 A x 120 V with the DANFYSIK PSSYS 9700 800 A x 120 V. (Responsible Maslennikov A.B.).
  - ✓ Update of the software in C++ created in the MS Visual Studio programing environment to control the DANFYSIK PSSYS 9700 800 A x 120 V to use it to power both the calibration stand and ion source stand magnets. (Responsible Kiyan I.N.).
  - ✓ Replacement of the defective extension cable Metrolab 3026-10M with a new to attach the multiplexor Metrolab MUX6026 to automate Hall sensor calibration process. (Responsible Kiyan I.N.).
  - ✓ Carrying out by NAD team of the magnetic field measurements at the calibration magnet to specify magnetic field gradients and magnetic field uniformity over all current diapason. (Responsible Kiyan I.N.).
  - ✓ Carrying out by NAD team of the calibration of the WGS (Belarus) production Hall sensors to use them with both the MMS developed by the SRSPU (Novocherkassk, Russia) and magnetic measurement stand. (Responsible Kiyan I.N.).
  - ✓ Discussion by DLNP, FLNP, VBLHEP team of the possibility of both development of HTSC calibration magnet before 5 T and purchase of “super-conducting” power supply to power this magnet.
- A magnetic measurement stand was modernized. In the plans:
  - ✓ Providing the possibility of further modernization of the magnetic measurement stand. Development and creation by NAD team of an ACS to move Hall sensor in three directions. (Responsible Pivin R.V.).
  - ✓ Update of the software in C++ created in the MS Visual Studio programing environment to carry out high-precision magnetic measurements using the LakeShore 475 DSP Gaussmeter together with the ACS to move Hall sensor in three directions. (Responsible Kiyan I.N.).
  - ✓ Carrying out by NAD team of the magnetic field measurements at the ion source magnet. (Responsible Kiyan I.N.).

Conclusion

- The magnetic measurement system developed by CAS Ion Medical and Technical Devices Co., Ltd. (Hefei, China) for measuring magnetic field maps at the MSC-230 isochronous cyclotron was tested. In the plans:
  - ✓ Carrying out by NAD team of the magnetic field measurements at the MSC-230 isochronous cyclotron for beam dynamics calculation using both measured magnetic field maps and measured Smith-Garren curves. (Responsible Lyapin I.D.).
- An ACS for Smith-Garren curves measurement designed in two variants to work with both "warm" (AIC-144, INP PAS, Krakow, Poland) and "superconducting" (SC-200, CAS Ion Medical and Technical Devices Co., Ltd., Hefei, China) isochronous cyclotrons was developed and, respectively, implemented/tested. In the plans:
  - ✓ Update of the software in C++ created in the MS Visual Studio programing environment to measure Smith-Garren curves at the MSC-230 isochronous cyclotron. (Responsible Kiyan I.N.).
  - ✓ Carrying out by NAD team of Smith-Garren curves measurements at the MSC-230 isochronous cyclotron. (Responsible Kiyan I.N.).
- An automated control system for beam current measurement from a three-lamella probe to three picoammeters was developed and implemented. In the plans:
  - ✓ Carrying out by NAD team of the beam current measurements at the ion source stand. (Responsible Agapov A.V.).
  - ✓ Carrying out by NAD team of the beam current measurements at the MSC-230 isochronous cyclotron (Responsible Kiyan I.N.).
- A new technique of phase motion measurement and magnetic field correction in isochronous cyclotrons was created. The COHPC II 2002-2025 program complex developed in C++ in the MS Visual Studio programming environment for beam dynamics calculation and magnetic field correction in isochronous cyclotrons using both measured magnetic field maps and measured Smith-Garren curves was developed. The new technique application was tested by an example of the work with the AIC-144 multipurpose isochronous cyclotron (INP PAS, Krakow, Poland). In the plans:
  - ✓ Carrying out by NAD and RIEE (Saint Petersburg, Russia) team of both the final control of quality of isochronous magnetic field formation and final shimming magnetic sectors of the MSC-230 isochronous cyclotron. (Responsible from JINR side Kiyan I.N.).

❑ Kiyan I.N. Interest area:

- Mathematical modeling of nonlinear physical processes and operation modes of physical equipment. In the plans:
  - ✓ Calculation of beam dynamics based on solving the three-dimensional equations of motion, written in the representation of dynamic orbits, taking into account the spatial charge of particles.

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ОИЯИ, ЛЯП им. В.П. Джелепова, НЭОНУ, сектор No 3

Сектор №3 расчета, создания и формирования магнитных полей электрофизических установок.
Отчётный период 2021-2026 год.

Таблица 6. Списочный состав сектора на 01.09.2026.

No	ФИО	Должность	Уч. Степень
1	Киян Игорь Николаевич	начальник сектора	к.ф.-м.н.
2	Чеснов Александр Федорович	старший научный сотрудник	к.т.н.
3	Попов Дмитрий Всеволодович	научный сотрудник	
4	Рогозин Дмитрий Валерьевич	механик экспериментальных стендов и установок	
5	Дима Светлана Николаевна	специалист по информационным системам в медицине	
6	Кузин Денис Никитович	лаборант	
7	Малыш Дмитрий Александрович	специалист по работе с документами	
+1	Абраамян Унан Хачикович	инженер (совм.)	

Итого: 7 человек (+1 совм.).

Таблица 7. Увольнение из состава сектора за отчётный период.

No	ФИО	Должность	Уч. Степень.
1	Ворожцов Сергей Борисович	ведущий научный сотрудник	д.ф.-м.н.
2	Ворожцов Алексей Сергеевич	старший научный сотрудник	к.ф.-м.н.
3	Смирнов Виктор Леонидович	старший научный сотрудник	к.ф.-м.н.
4	Самсонов Евгений Васильевич	старший научный сотрудник	к.ф.-м.н.
5	Чеснова Светлана Ивановна	научный сотрудник	

Итого: 5 человек.

Thank You for Attention