XIV Международный научный семинар памяти профессора В. П. Саранцева
«Проблемы коллайдеров и ускорителей заряженных частиц»

Beam Injection in the Booster of the NICA Accelerator Complex

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Alyshta, 21.09.2022

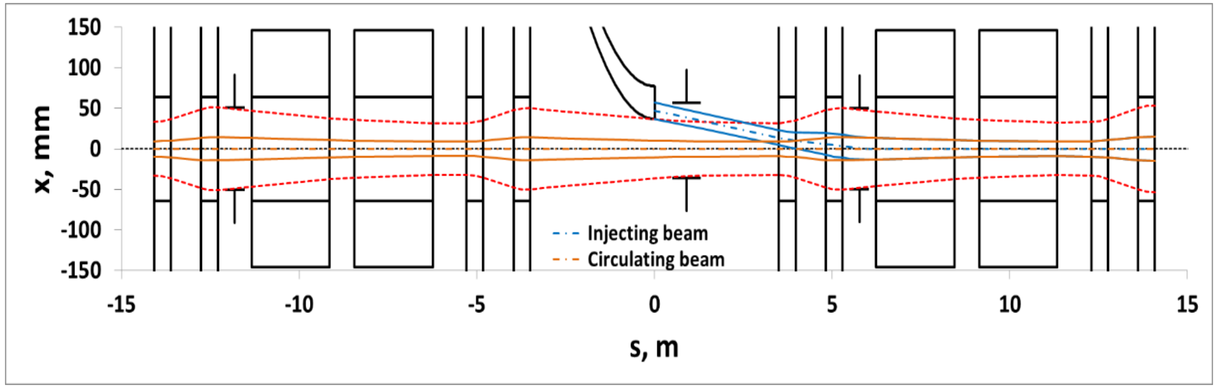
Single turn injection is the simplest method of beam injection into synchrotrons and storage rings. This method was used in all previous runs of the NICA accelerator complex, including the one that ended in the spring of this year (January 2, 2022 – April 1, 2022) with a $^{12}C^{4+}$ ion beam. During the injection process, the beam is introduced into the vacuum chamber of the Booster in the horizontal direction/plane and is planted in a closed orbit.

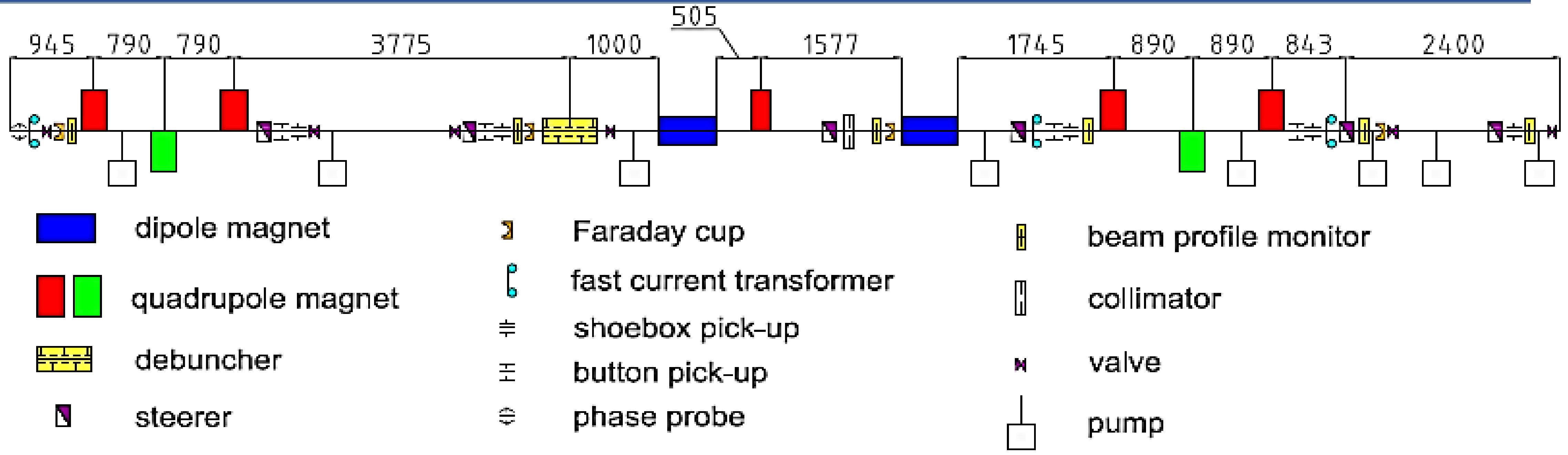
The paper considers the following:

1 single-turn injection tuning algorithms

2 results of the previous three runs

3 optimization of the tuning

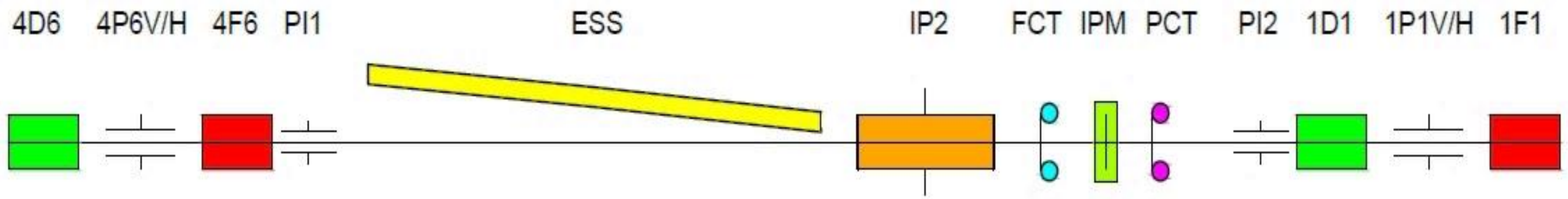


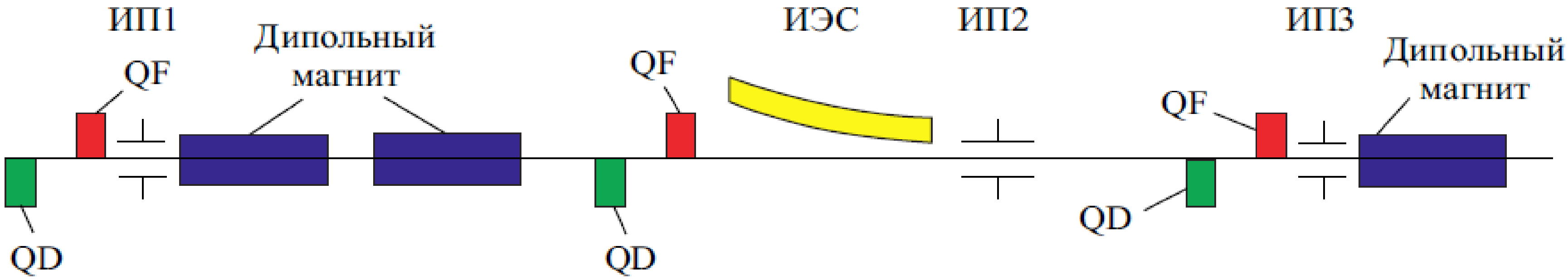


magnetic system
- two dipole magnets BM1-BM2
- 7 quadrupole magnets Q1-Q7
- two-coordinate dipole steerer CM1-CM6

- debuncher
- collimator

beam diagnostic system
- 4 Faraday cup FC1-FC4
- 3 fast current transformers CT2-CT4
- 5 shoebox pick-up PU1-PU5
- 4 button pick-up BPU1-BPU4
- 1 beam phase probe PP3
- 6 beam profile monitor PM1-PM6



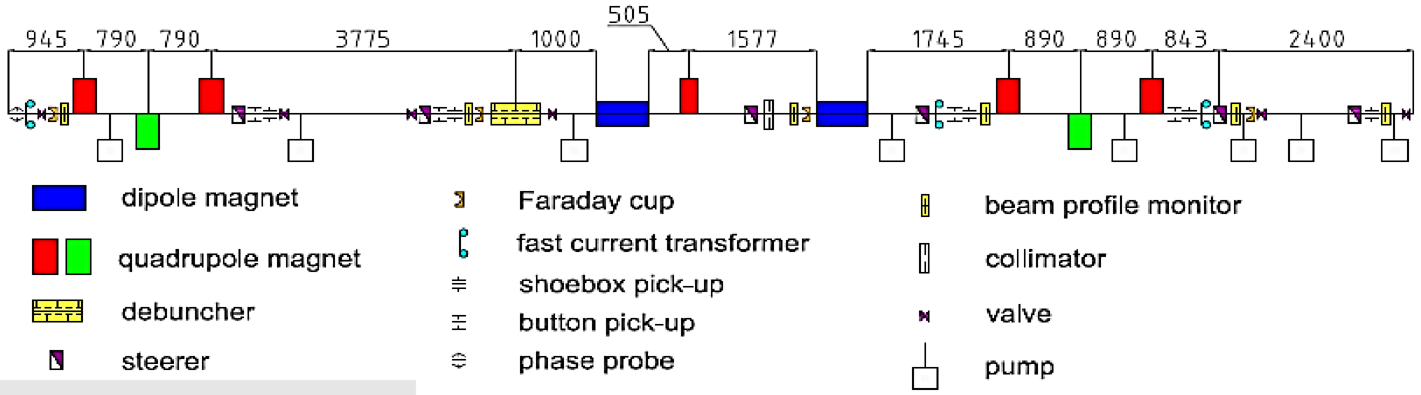


- modules of inflector plates IP1, IP2, IP3
- electrostatic septum – ESS
- beam diagnostic devices (1P1V / H and 4P6V / H - structural pick-ups installed in Booster lens doublets)
- fast and parametric current transformers (FCT and PCT)

The main tasks

1. Transportation of the beam in the channel
2. Beam injection through an electrostatic septum into the beam volume of the accelerator
3. Tuning of the guiding magnetic field and work point of the Booster, as well as correction of the closed orbit in order to match the guiding magnetic field with the energy of the injected beam and obtain its circulation
4. Local correction of a closed orbit in the injection region
5. Minimization of the amplitude of coherent betatron oscillations of the beam after injection

Tuning algorithms



1. tuning of lenses Q1-Q3
2. checking transverse beam parameters on PM1 and PM2
3. correction of the beam trajectory in the area in front of the debuncher

$$\varphi_{CM1,x} = -x'_{Q3-deb} - \frac{x_{CM1}}{L_{CM1-CM2}}$$
$$\varphi_{CM1,y} = -y'_{Q3-deb} - \frac{y_{CM1}}{L_{CM1-CM2}} \qquad (1)$$

where $L_{CM1-CM2}$ is the distance between the centers of the correctors CM1 and CM2

$$\varphi_{CM2,x} = \frac{x_{CM1}}{L_{CM1-CM2}}$$
$$\varphi_{CM2,y} = \frac{y_{CM1}}{L_{CM1-CM2}} \qquad (2)$$

4. switching on and tuning of dipole magnets BM1 and BM2
5. tuning of lenses Q4-Q7
6. checking transverse beam parameters on PM3 and PM6
7. correction of the beam trajectory in the area in front of the electrostatic septum (with the same equations (1), (2))

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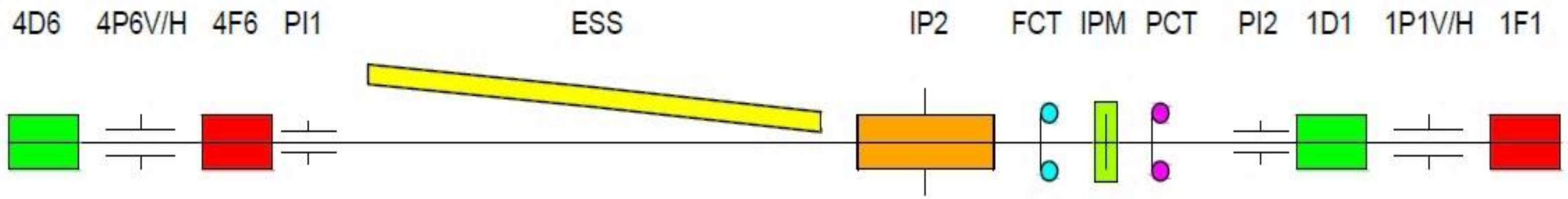
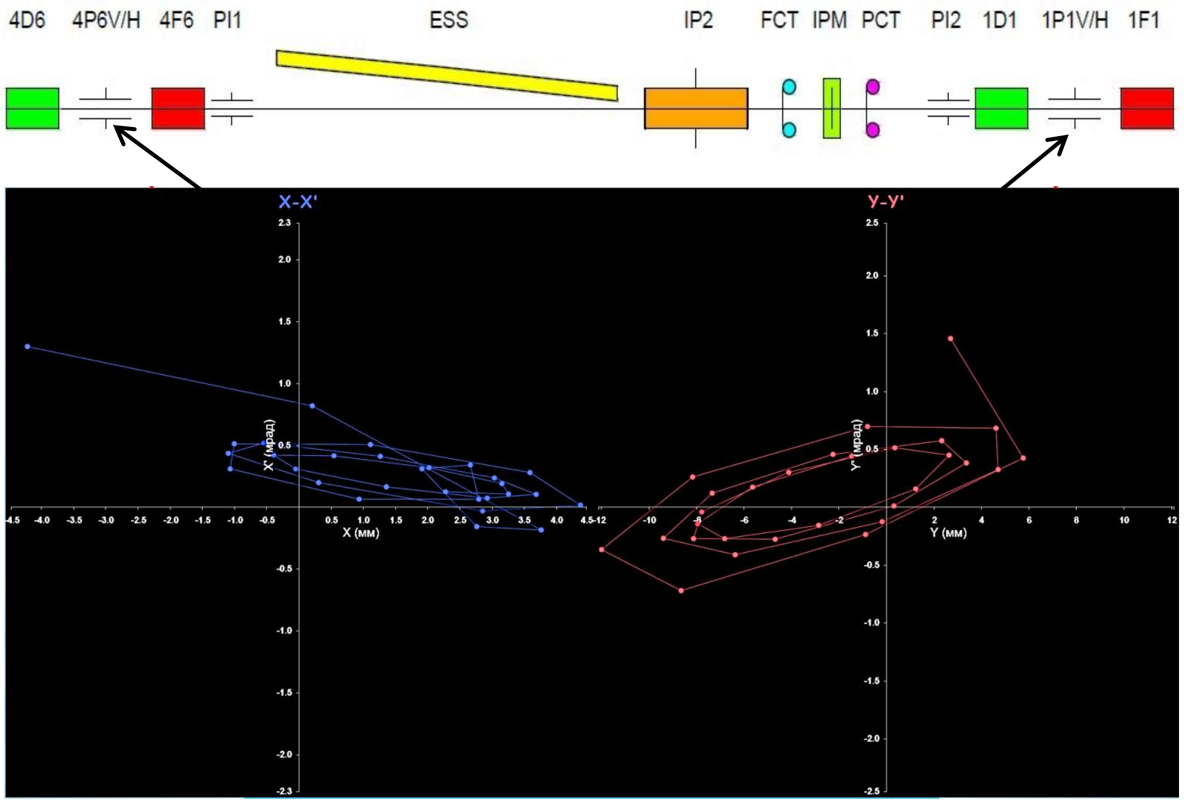


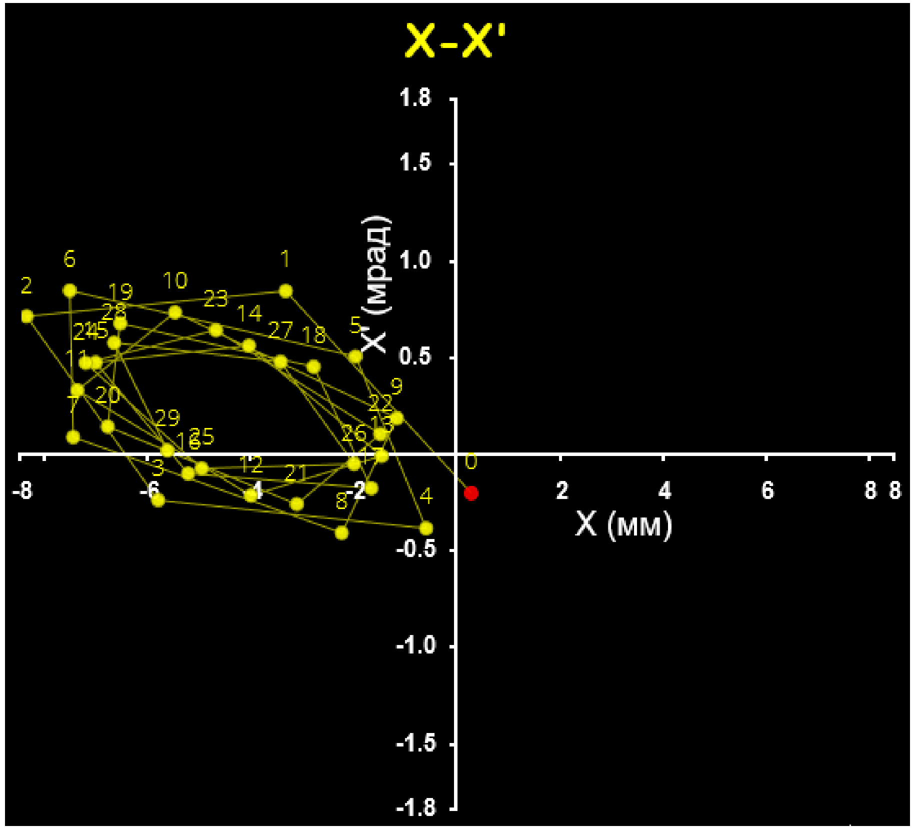
8. beam injection through an electrostatic septum into the beam volume of the accelerator

9. tuning of the guiding magnetic field, work point of the Booster, tuning of the IP1-IP3, and closed orbit correction

    - varying the current of the main power supply of the magnetic system
    - varying the output currents of two additional sources of current unbalance PIT-06, PIT-03

10. Local correction of a closed orbit in the injection region using the following correctors 4S5, 4S6, 1S1, and 1S2 to minimize the amplitude of coherent betatron oscillations of the beam after injection.





The virtual model of the accelerator is a computational-theoretical model supplemented with options for simulating beam diagnostics and means for controlling the accelerator and channel equipment.

Channel

- arrangement of elements
- setting the beam parameters at the energy of injection
- setting random errors of the magnetic structure
- assignment of currents in the windings of magnets
- mathematical model of the debunsher

Booster

- arrangement of elements
- setting the beam parameters at the energy of injection
- tuning of the magnet-optical structure
- tuning of the operating point according to the given forces of the magnets
- control of power sources of magnet-optical elements

MAD-X - Methodical Accelerator Design

2 algorithms for closed orbit correction

1. Local bump correction

The condition for a local impact is to leave the orbit unchanged in the first and last correctors, and beyond them. Thus, for each triple of correctors (1 2 3) (2 3 4) (3 4 5) (4 5 6) ect., correction conditions are set.

2. SVD

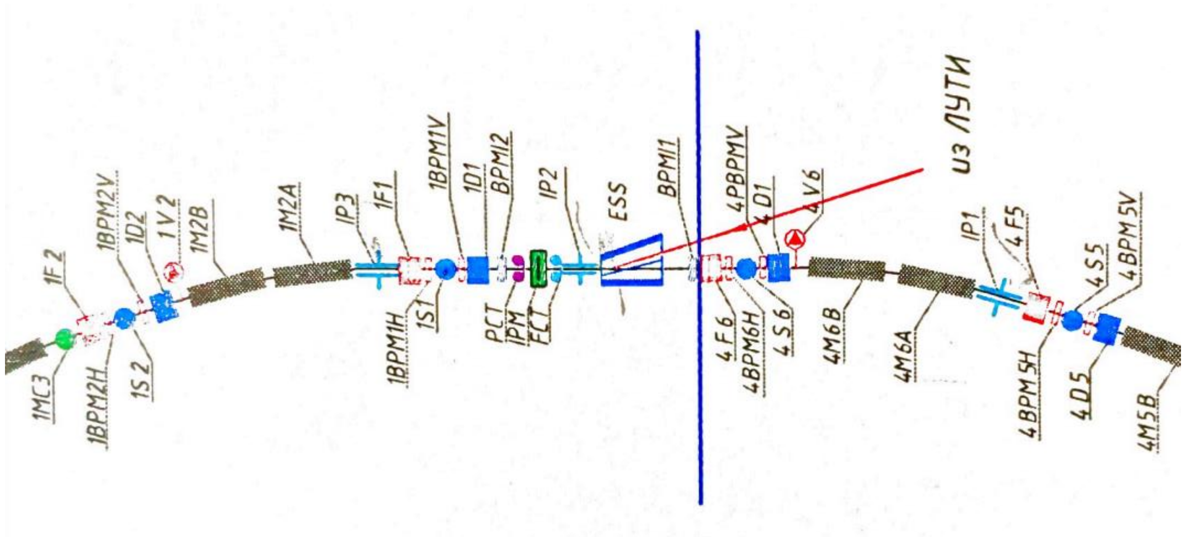
The principle of a SVD is the following: for any rectangular matrix A[m*n] with rank r, there exist unitary matrices U[m*m] such that

$$A = U \cdot \Sigma \cdot V^T \quad (3)$$

Coefficients for the local correction of a close orbit at the injection point

$$\Delta I_h = A_x\,\Delta x + B_x\,\Delta x' \\ \Delta I_v = A_y\,\Delta y + B_y\,\Delta y' \qquad (4)$$

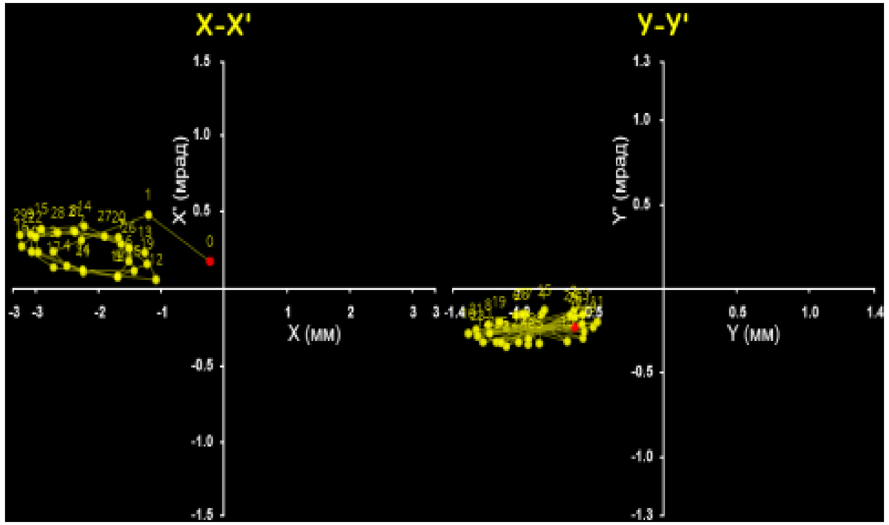
ΔI_h, ΔI_v - change in current in the horizontal and vertical windings of the corrector
Δx, Δx', Δy, Δy' is the required displacement of the closed orbit at the septum exit (in mm and mrad), which is inverse to the measured initial beam position.

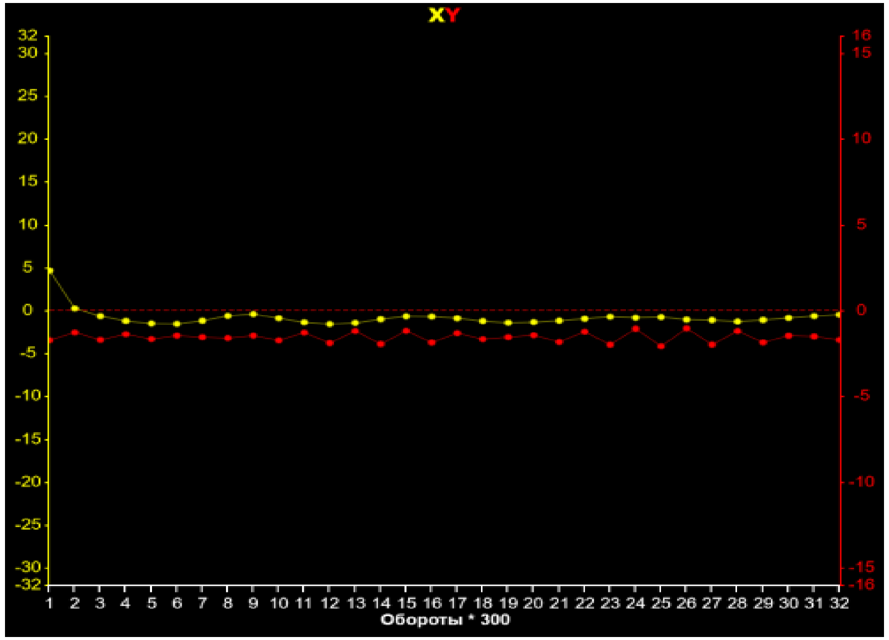


	A_x	B_x		A_y	B_y
4S5H	-43.5	-102	4S5V	-624	4472
4S6H	73	4594	4S6V	38	-2715
1S1H	-29.5	-2955	1S1V	-213	4505
1S2H	105	4858	1S2V	4	-50

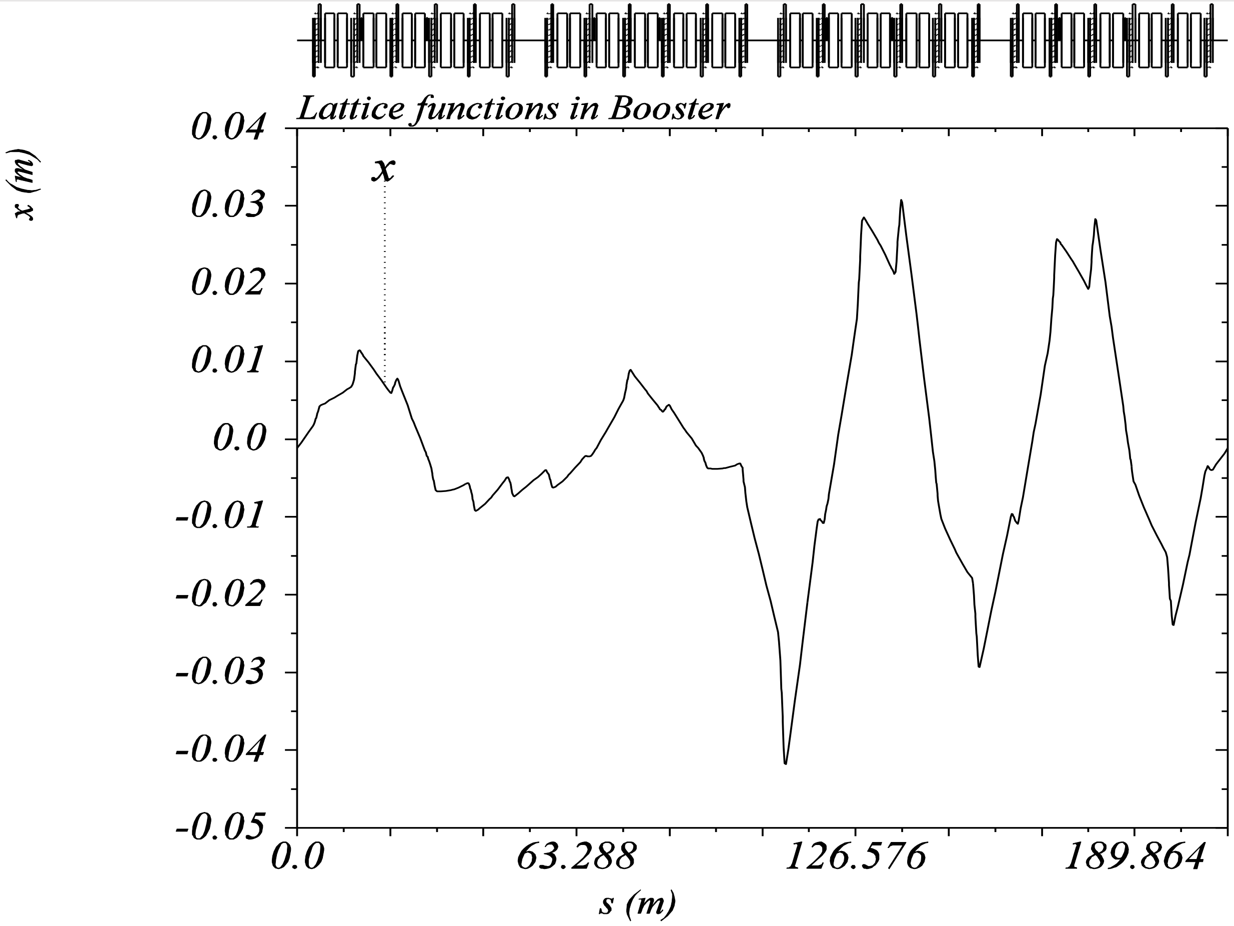
- control of the beam:
  - -current signals of the ion beam on current transformers CT2-CT4
  - -transverse profiles on beam profile monitor PM1-PM6
  - -beam current signal on the fast current transformer FCT at the first circulation turns
- tuning of the Q1-Q7 quadrupole lenses
- tuning of IP3
- varying the current of the main strength source PIT-10
- varying of the PIT-06, PIT-03

Beam injection with an amplitude of coherent oscillations of no more than 1 mm. In this case, the losses of the injected beam in the ring during the first circulation revolutions did not exceed 10%.





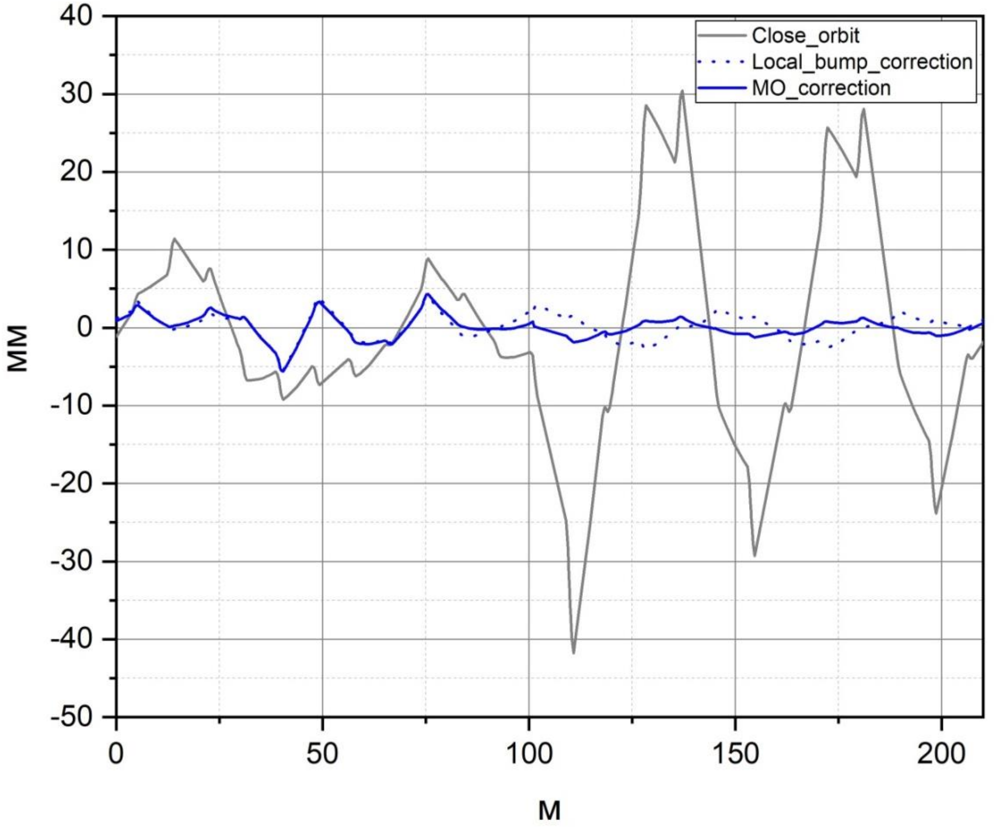
Closed orbit at the energy of injection corresponding to 3.1 MeV, at the point Qx=4.88, Qy=5.39



Orbit at the energy of injection for $^{12}C^{4+}$

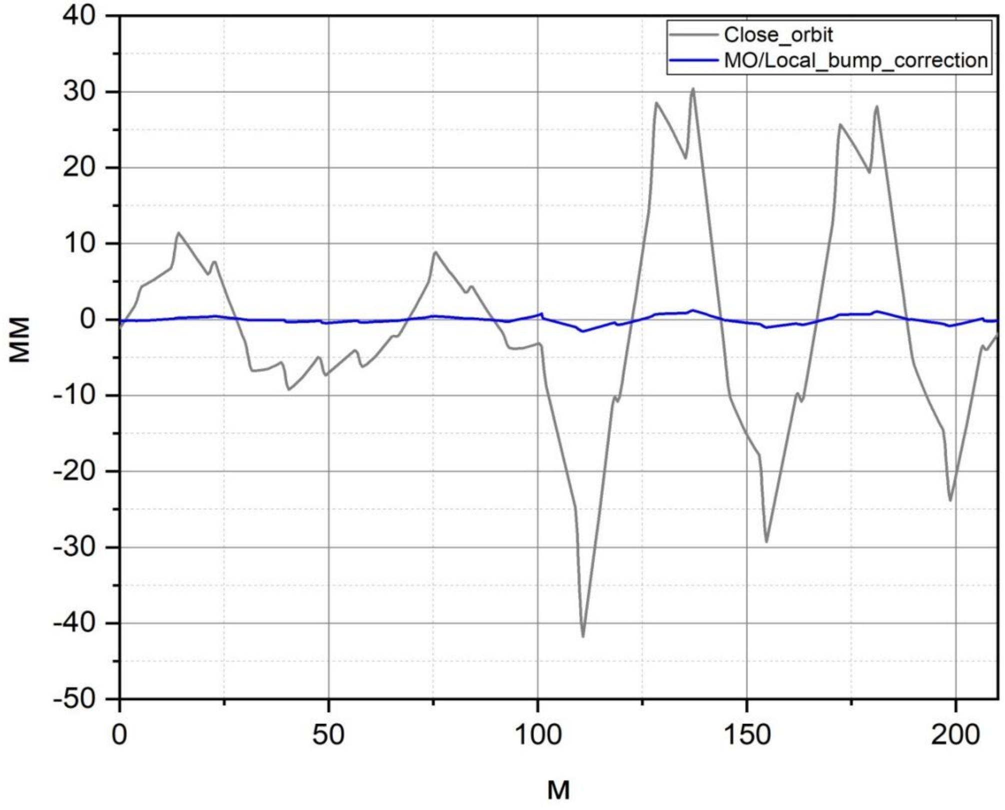
2 algorithms for closed orbit correction taking into account the identified error in the polarity of connecting power supplies of several correctors (2S2H, 2S6H, 3S1H, 4S2H, 4S6H)

Orbit correction without 2S2H, 2S6H, 3S1H, 4S2H, 4S6H correctors



X<2.5 mm

Orbit correction with all correctors



X<1 mm

Tuning results and work on virtual models

Work point, as in a real accelerator with the corresponding values of the PIT-03 and PIT-06, and measurements of the Booster structure functions at the energy of injection = 3.1 MeV at the project work point

	k_booster	I_booster	k_madx	I_madx
ПИТ-10	-	287	-	287
ПИТ-06	0,071000	20,377	0,07006	20,110
ПИТ-03	0,019500	5,596	0,02055	5,900

X	Function	Y
0,56	Alpha	-0,55
7,0	Beta	6,5

X	Функция	Y
1.429283504	Emittance	0.888335286
0.574583883	Alpha	-0.570653848
7.219938211	Beta	6.20645249
0.797411028	Q	0.851603058
-4.198065778	D0	0.174058153
-0.317748272	D0'	0.631089775

To work out of the algorithm of the injection during next runs

- iterate through each step
- tuning new

Development of virtual models

- adding data from runs
- expansion of the element base
- addition of a geometric aperture and IP1-IP3 modules for testing the main injection schemes

Development of software to automate the tuning of algorithms

- to implement automatic selection of gradients of Q1-Q7 quadrupole lenses (in T/m)
- automatic correction of the beam trajectory in the area in front of the debuncher
- automatic correction of the beam trajectory in the section before the electrostatic septum
- adjustment of the correctors of the final section of the channel and the electrostatic septum

The experience of tuning the beam injection into the Booster using the tuning techniques developed and tested in previous three runs will allow further development of methods for automated tuning of the channel and the Booster ring based on virtual models.

In the future - to achieve the required values of the beam parameters and tune parameters of the devices without manual correction of the settings by the operator, as well as to optimize the system operation.

Thank you for attention