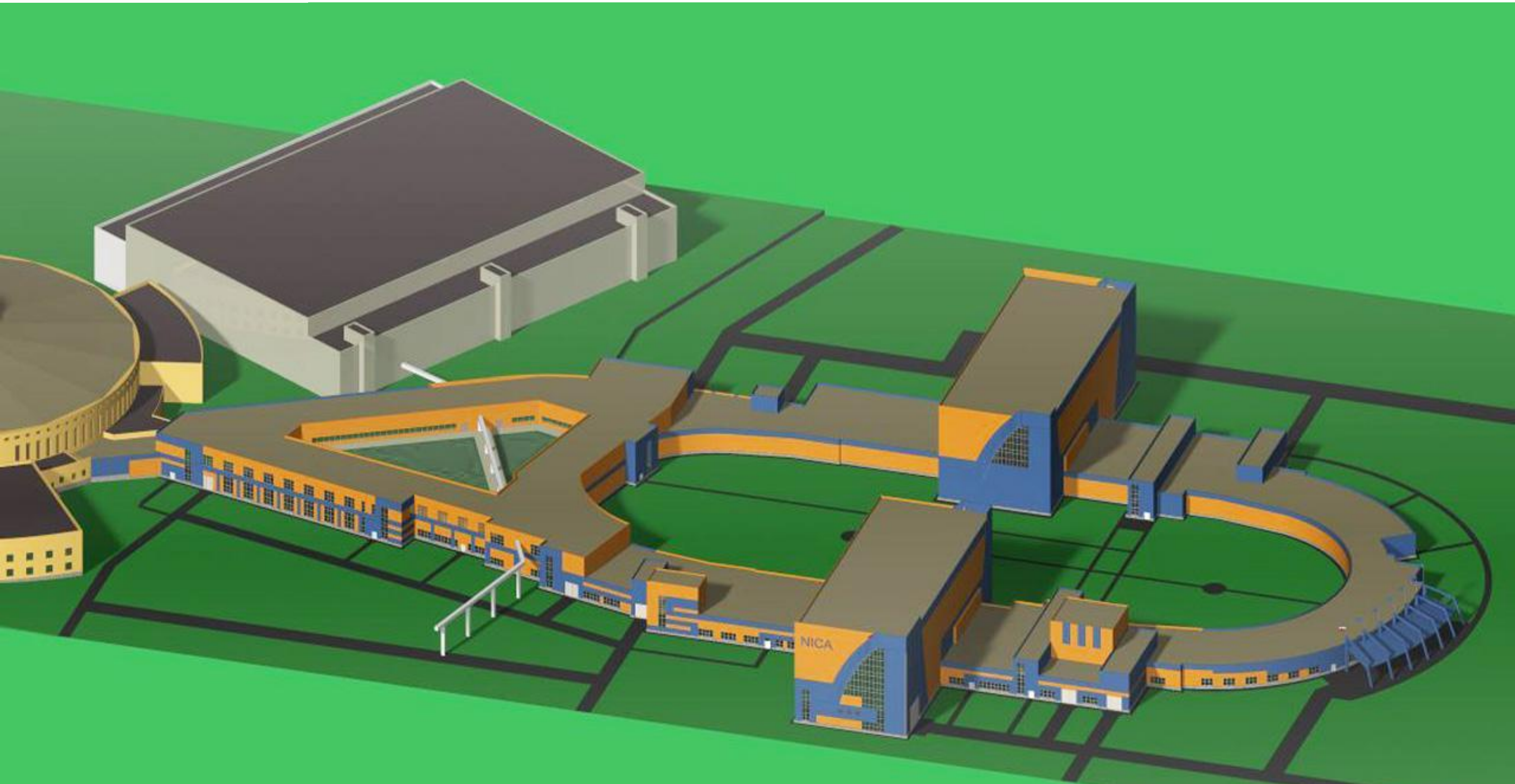
Collider NICA status and plans of its first operation

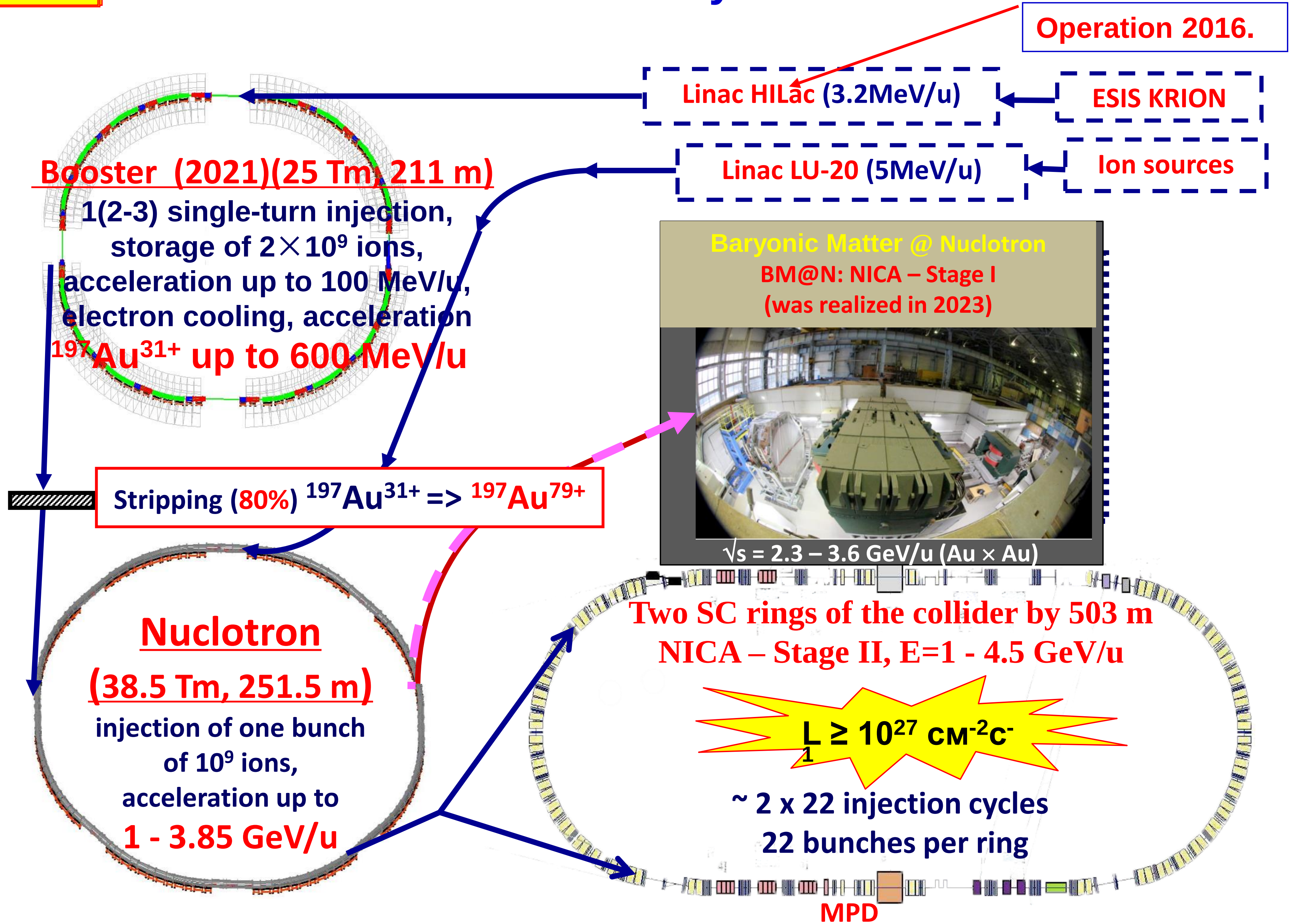
Evgeny Syresin on behalf of Accelerator division



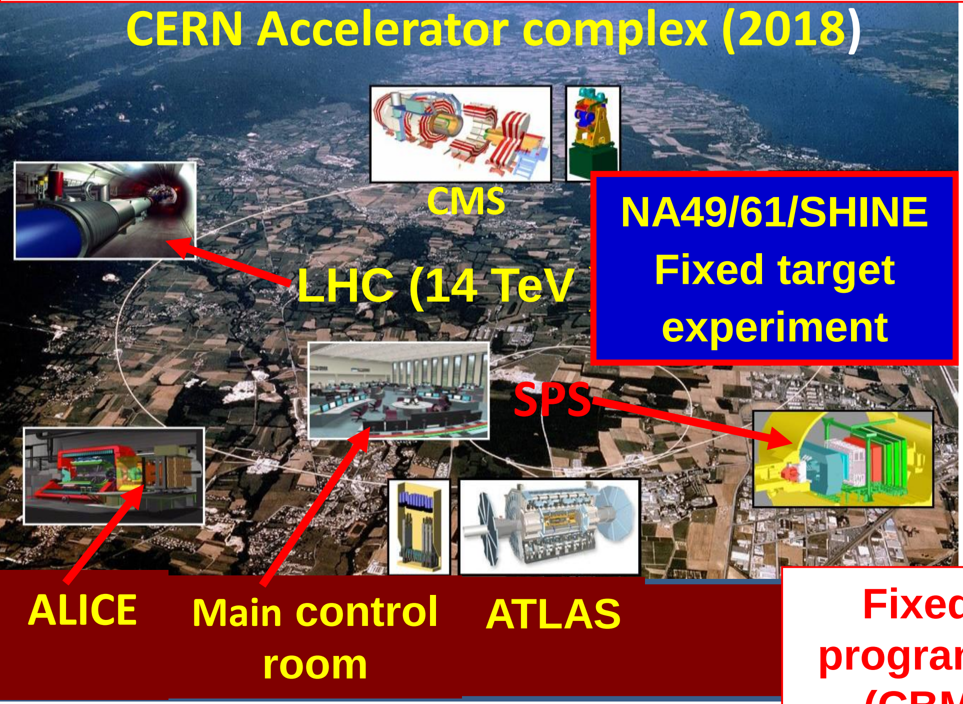
NICA: Nuclotron based Ion Collider fAcility

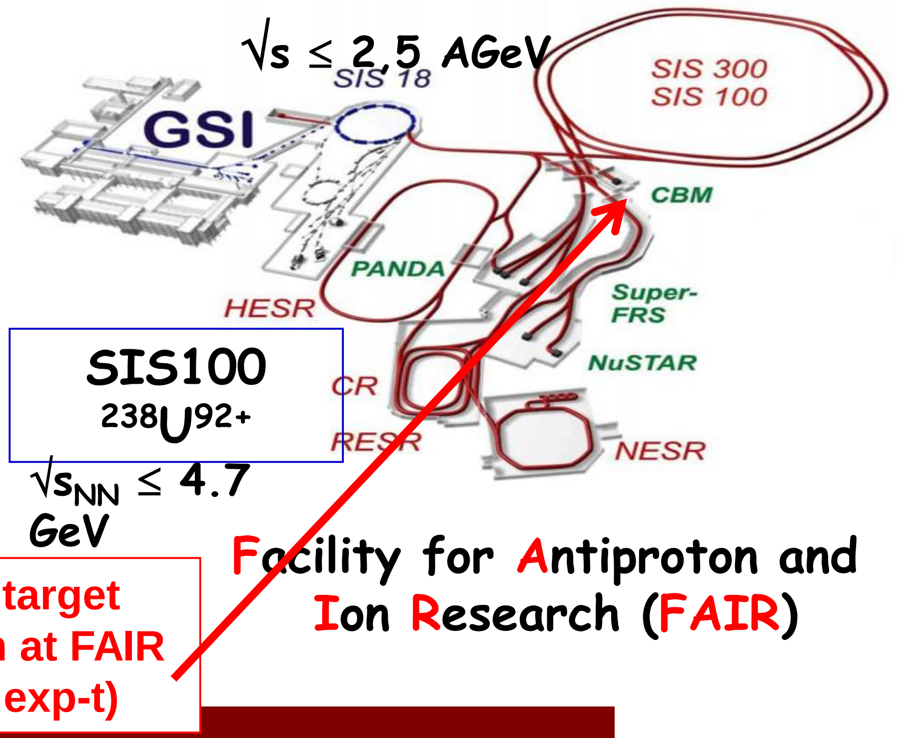
2024

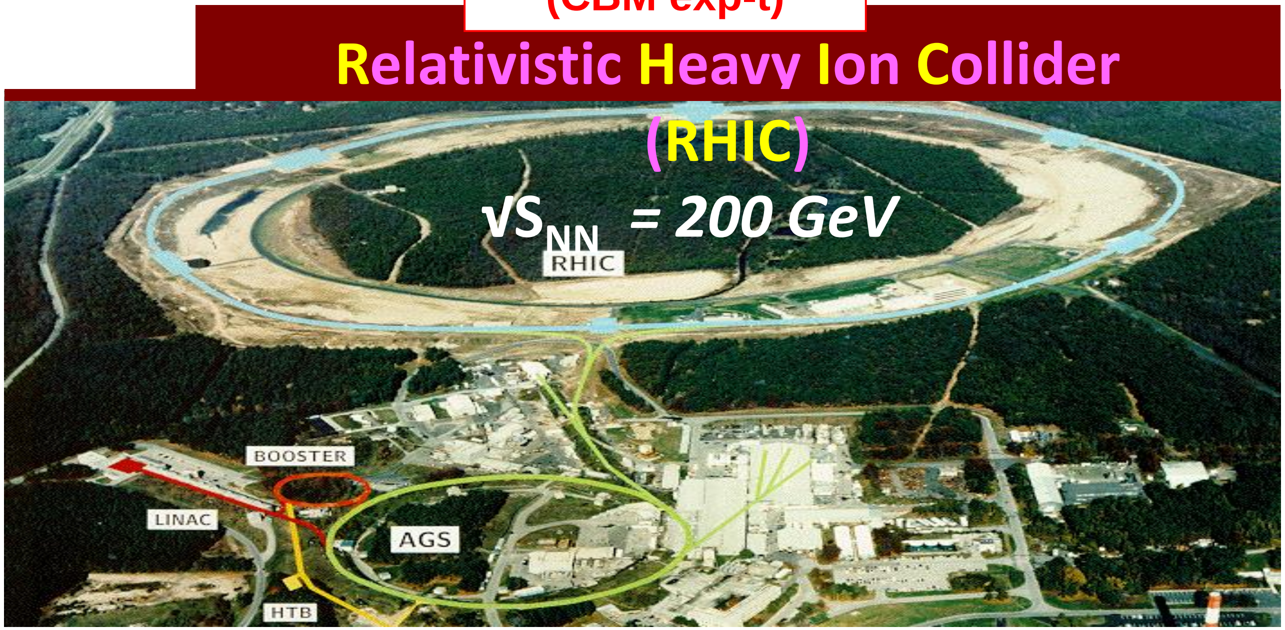
NICA – collisions for Heavy ion mode



3. Ускорители и Коллайдеры тяжёлых ионов







Luminosity ⟷ Beam Space Charge

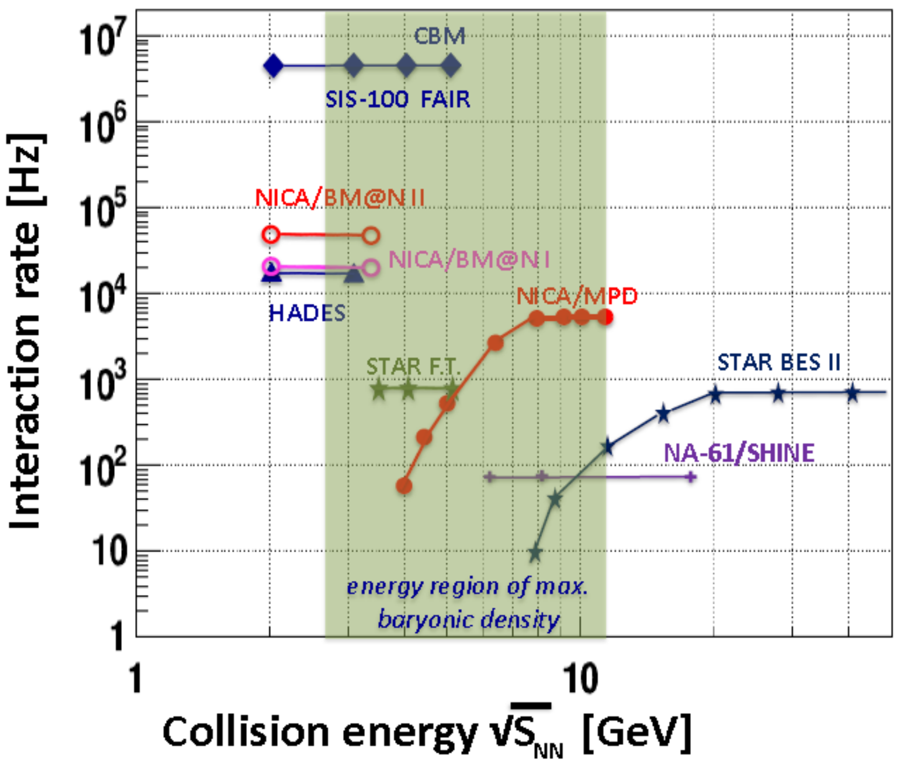
$$\delta \nu = \delta \nu_{sc} + 2 \cdot \delta \nu_{bb}$$

<0.05

$$L = 8\pi^2 \frac{A^2 c \beta^5 \gamma^6}{Z^4 r_p^2} \frac{n_b \sigma_s \varepsilon}{C^3} \left(\frac{\sigma_s}{\beta^*} H\left(\frac{\sigma_s}{\beta^*} \right) \right) \delta \nu_{SC}^2$$

Large luminosity requires:

- **Large emittance <=> large acceptance**
- **Short separation length,** C/n_b
- **Small circumference,** C
- **Proper value of** σ_s/β^*



NICA

Nuclotron-based
Ion Collider fAcility

Basic information

- The Collider ring 503.04 m long has a racetrack shape and is based on double-aperture (top-to-bottom)
- Superconducting magnets with maximum dipole field 1.8 T;
- Magnetic rigidity = 45 T·m;
- Ion kinetic energy range from 1 GeV/u to 4.5 GeV/u for Au79+;
- Energy of polarized deuterons is 6 GeV/u, protons – 12 GeV;
- Vacuum in a beam chamber: 2×10^{-9} Pa;
- Zero beam crossing angle at IP;
- 9 m space for detector's allocations at IP;
- Average luminosity 10^{27} $cm^{-2}\cdot s^{-1}$ for gold ion collisions at $\sqrt{s_{NN}}$ = 11 GeV.
- The luminosity in the polarized mode is up to 10^{32} $cm^{-2}\cdot s$–1.
- Technological run at cryomagnetic system testing– Summer 2024
- Commissioning – Autumn 2024
- First beam run – the end of 2024

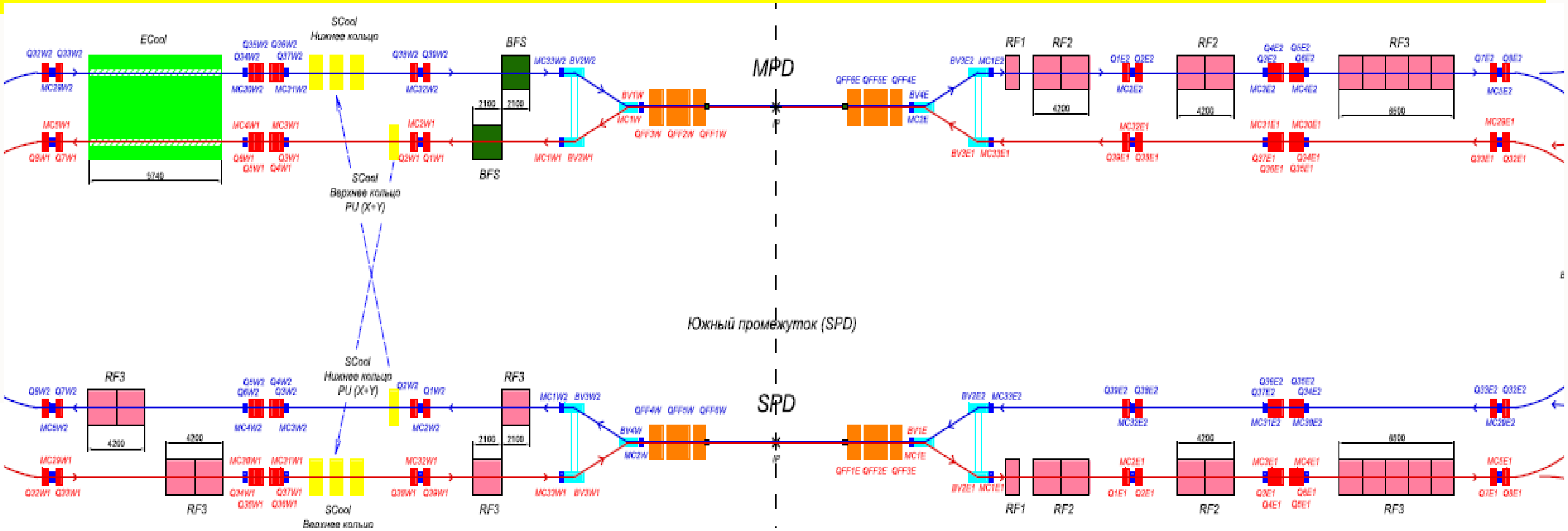
Ring circumference, m	503,04		
Number of bunches	22		
RMS bunch length, m	0.6		
Beta-function in the IP, m	0.6		
Betatron tunes, Qx/Qy	9.44/9.44		
Ring acceptance	40 π·mm·mrad		
Long. acceptance, Δp/p	±0.01		
Gamma-transition, γ_{tr}	7.084		
Ion energy, GeV/u	1	3	4.5
Ion number per bunch, 10^9	0.28	3	2.98
RMS Δp/p, 10^{-3}	0.63	1.29	1.69
RMS beam emittance, h/v, (unnormalized), π·mm·mrad	1.1/1.07	1.1/0.95	1.1/0.81
Luminosity, 10^{27} $cm^{-2}s^{-1}$	0.01	1	1
IBS grow the time, sec	300	1000	3100

NICA Stage II-a (basic configuration):

1. Injector chain: KRION => Booster => BTL BN => Nuclotron
2. BTL Nuclotron => Collider
3. Collider equipped with

- RF-1 (barrier voltage system) for ion storage
- RF-2 : 4 cavities per ring instead (100 kV RF amplitude)
- 1 channel of S-cooling per ring (cooling of longitudinal deg. of freedom)

Result: 22 bunches of the length σ ~ 2 m per collider ring that 5e25 $cm^{-2}\cdot s^{-1}$, ion kinetic energy E=2.5 GeV/n



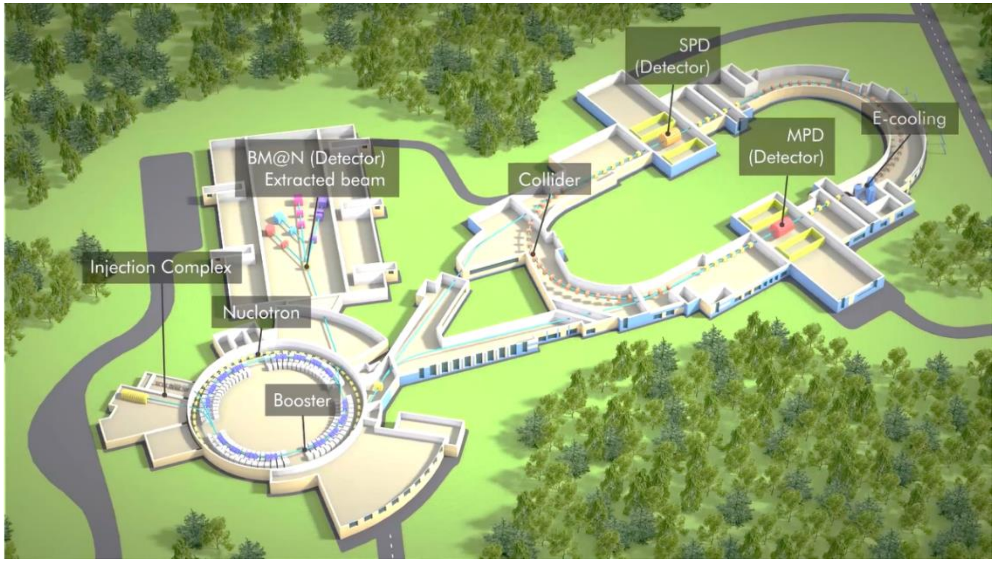
NICA Stage II-b (full configuration):

Collider

+ RF-3 systems in the project version
+ S-cooling (transverse)
+ E-cooling

Result: 22 bunches of the length σ ~ 0.6 m per collider ring that 1e27 $cm^{-2}\cdot s^{-1}$, ion kinetic energy E=4.5 GeV/n

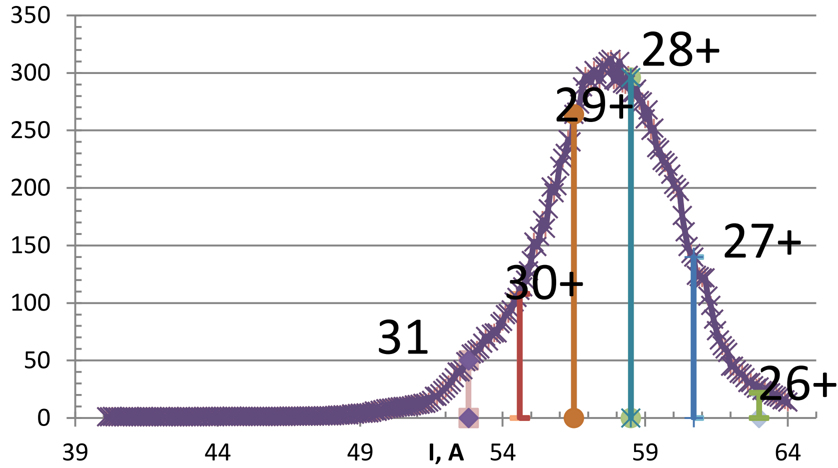
Booster-Nuclotron-Collider beam injection/extraction systems



Beam Parameters

	Booster injection	Booster extraction	Nuclotron injection	Nuclotron extraction	Collider injection
Ions	Au^{31+}	Au^{31+} / Au^{79+} (stripping)	Au^{79+}	Au^{79+}	Au^{79+}
Energy of ions, MeV/u	3.2	578	572	1000 ÷ 3800	1000 ÷ 3800
Maximum magnetic rigidity, T·m	1.64	25	10	14 ÷ 38.5	14 ÷ 38.5
Ion number	$2 \cdot 10^9$	$1.5 \cdot 10^9$	$1.3 \cdot 10^9$	$1 \cdot 10^9$	$1 \cdot 10^9$

Ion source KRION-6T



Xe ion charge distribution at KRION exit

Project ion intensity $2 \cdot 10^9$ Bi^{35+} per pulse

Достигнутые величины

Ar^{16+} - $5 \cdot 10^8$ ions per pulse

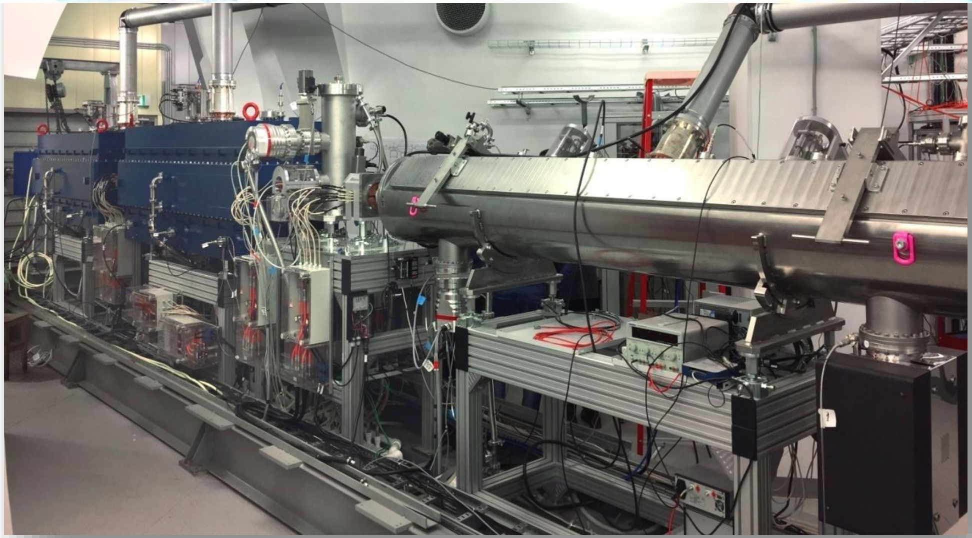
Xe^{28+} - $2 \cdot 10^8$ ions per pulse

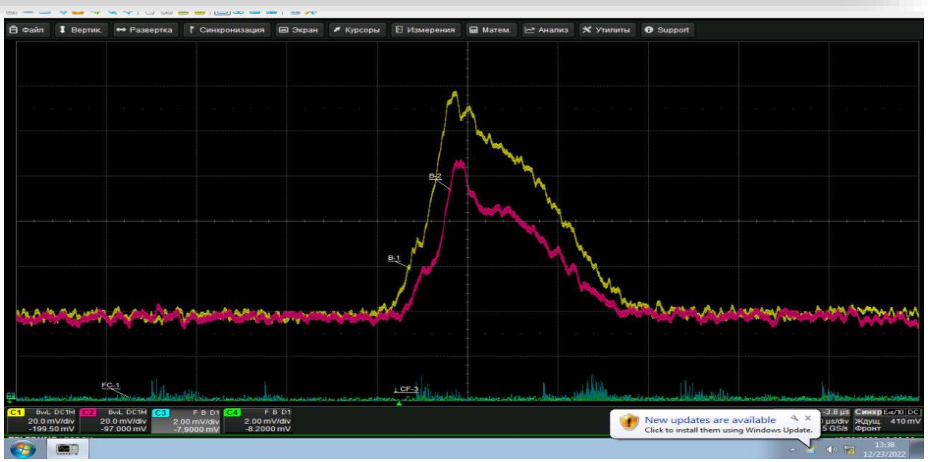
Bi^{35+} - $2 \cdot 10^8$ ions per pulse

First Collider beam run is planed with Xe^{28+} и Bi^{35+} ions

HILAc status

Stable and safe HILAC operation during with Ar^{13+} and Xe^{28+} beams





At RFQ exit I=100 μA (yellow line). At HILAC exit I=65 μA at ion pulse duration 22 μs (red line), about 70% at this pulse of target ions $^{124}Xe^{28+}$.

Number of ions accelerated in HILAC at energy 3,2 MeV/n is about 1×10^{8}.

Project HILAC intensity $^{209}Bi^{35+}$ at energy 3,2 MeV/n is about 1.8×10^{9} per pulse.

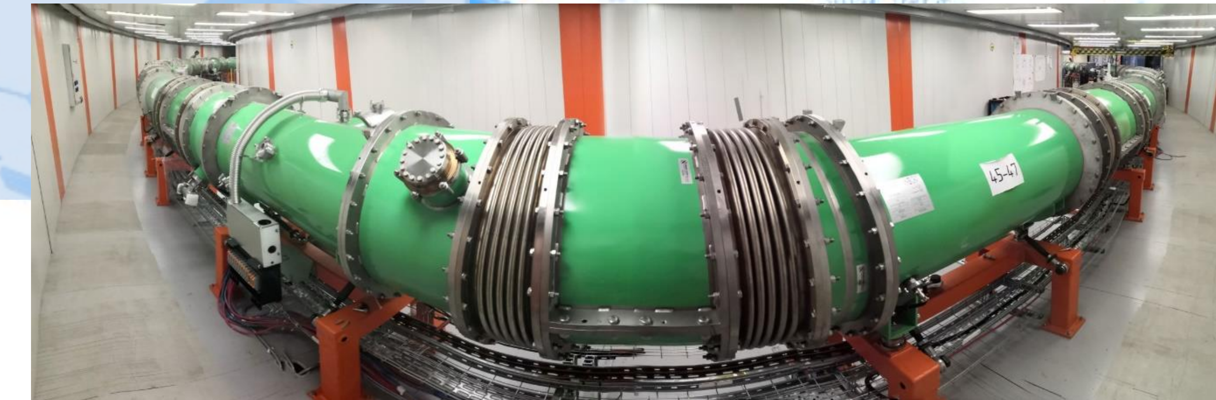
Further development

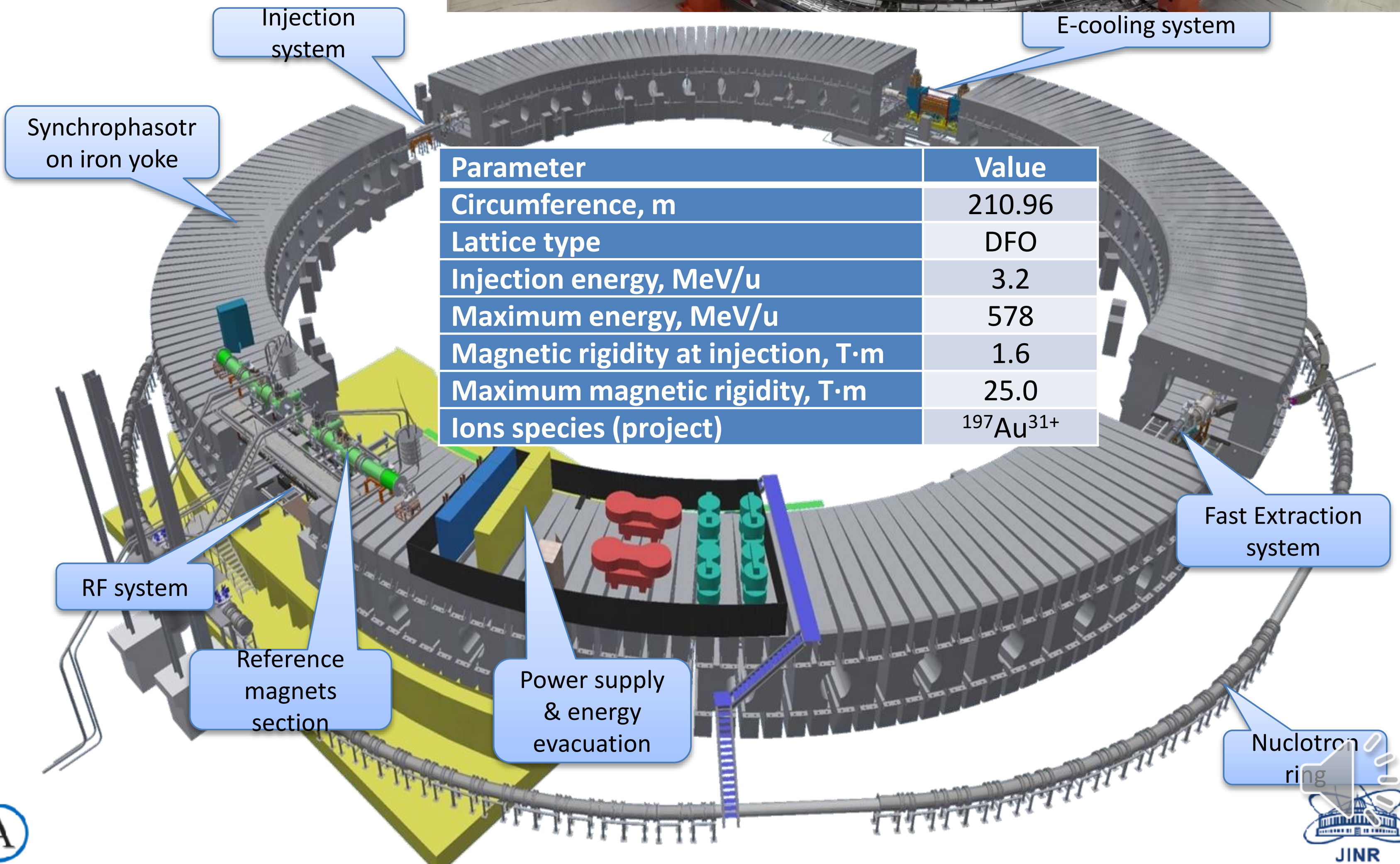
Realization of multy cycle injection and upgrade of KRION-6T

NICA

JINR

Booster ring layout (2016)



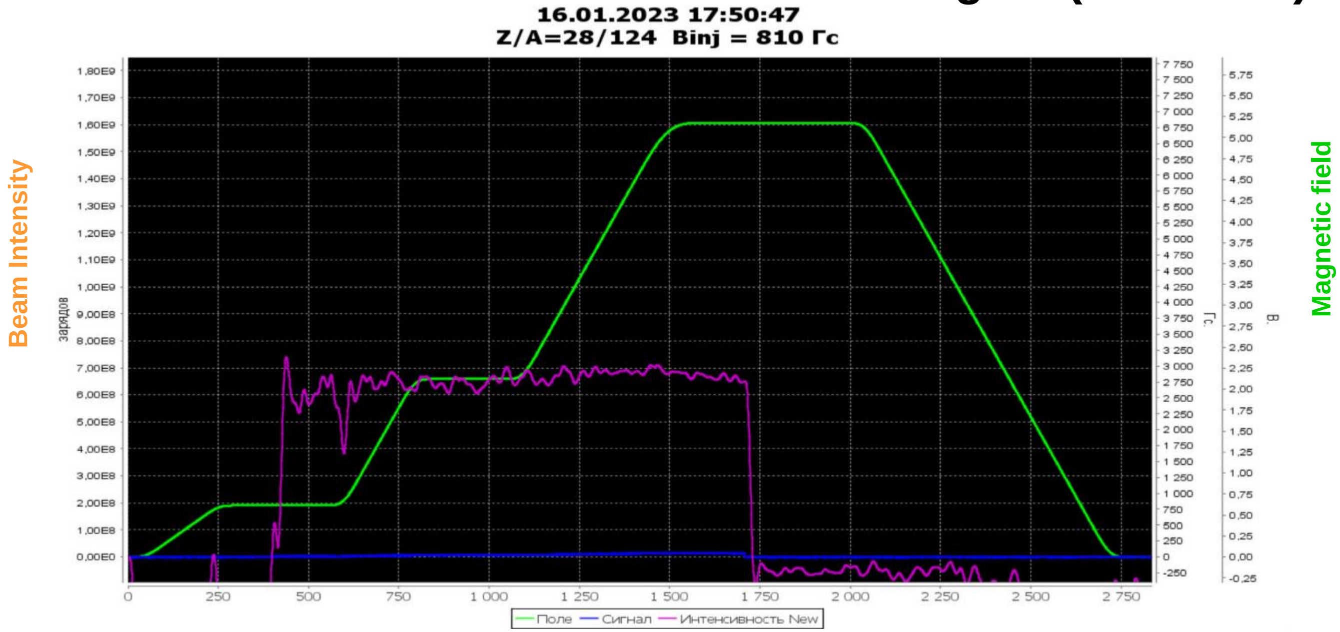


Parameter	Value
Circumference, m	210.96
Lattice type	DFO
Injection energy, MeV/u	3.2
Maximum energy, MeV/u	578
Magnetic rigidity at injection, T·m	1.6
Maximum magnetic rigidity, T·m	25.0
Ions species (project)	$^{197}Au^{31+}$

NICA JINR

Booster Beam current

Parametric beam current transformer signal (DC mode)

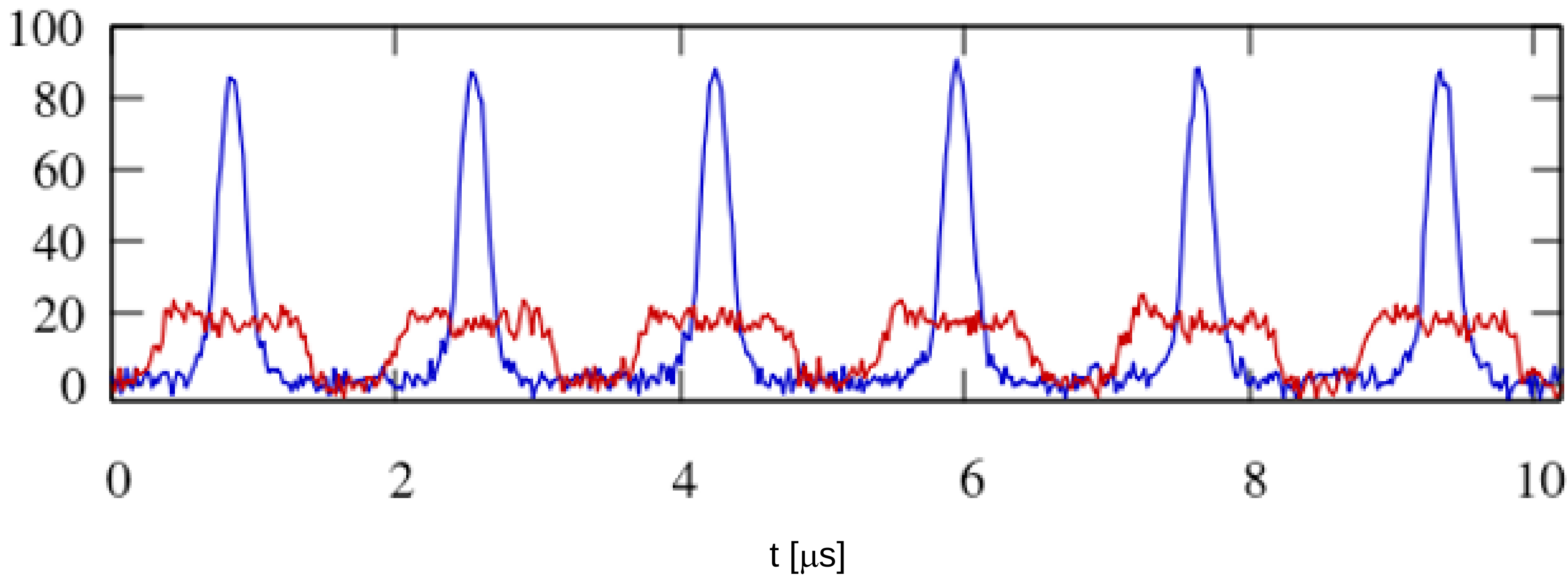


Booster-Nuclotron run - September 2022 - February 2023 for BM@N baryonic matter researches. Booster acceleration of ions $^{124}Xe^{28+}$ to energy 204,7 MeV/n, where they were stripped up to bare nucleus end extracted in Nuclotron.

- ✓ ***$6{\cdot}10^8$ elementary charges ~ $2.5{\cdot}10^7$ of Xe^{28+}***

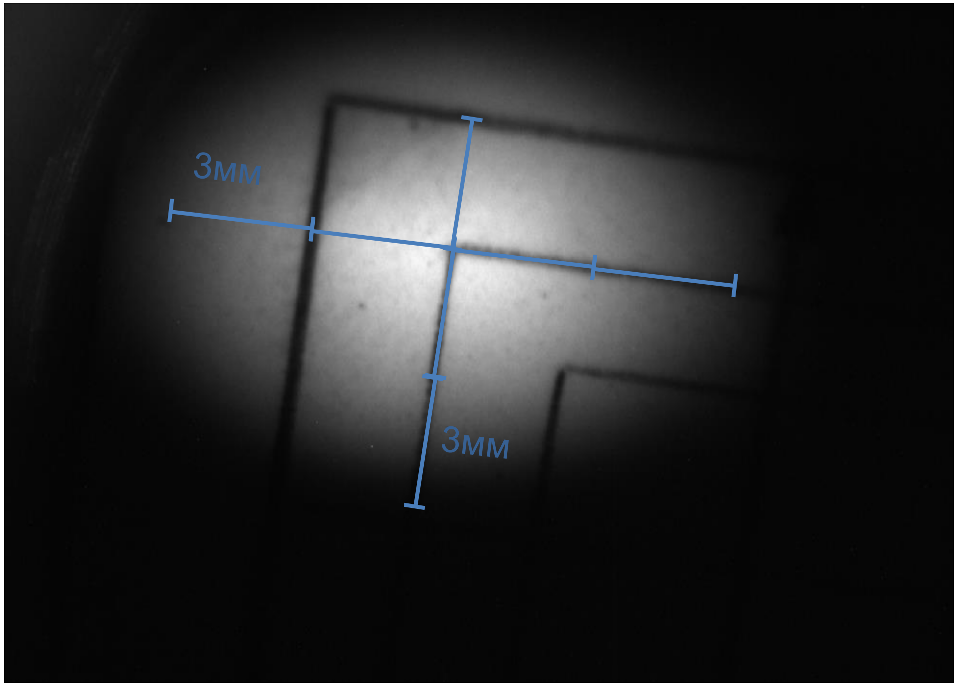
Electron Cooling in Booster

- Electron cooling was demonstrated with the RF voltage present as it is required for beam accumulation
- Measurements support the accumulation rate of about 10 Hz



Beam current dependence on time with and without electron cooling. Rf harmonic number – 5. Cooling cycle duration - 200 ms. Electron beam current 50 mA. Electron beam voltage 1.83 keV

Electron cooling of $^{124}Xe^{28+}$ at electron beam current 50mA and energy 1,830 keV



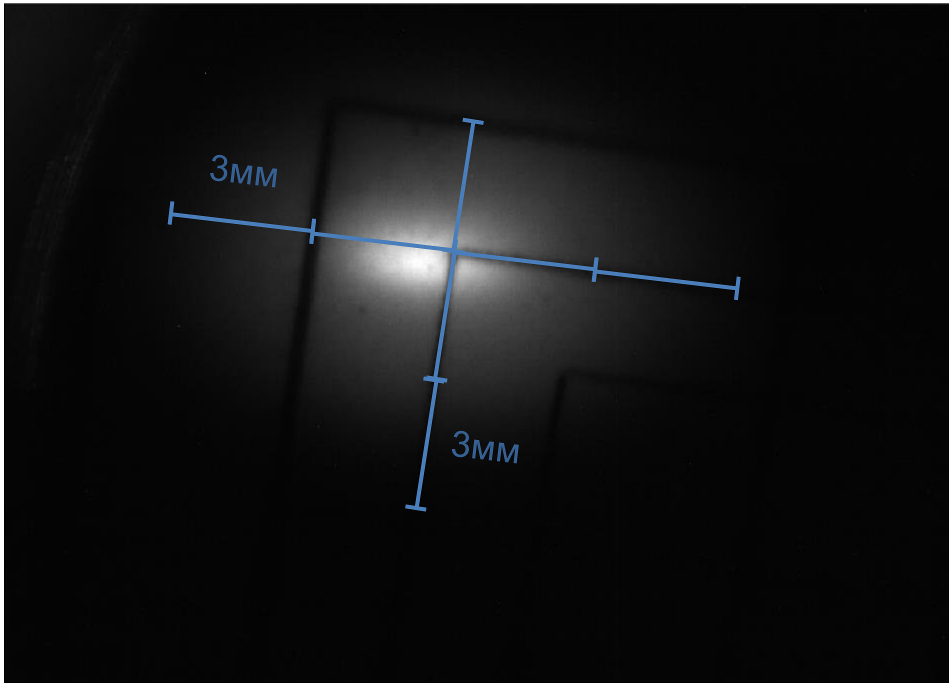
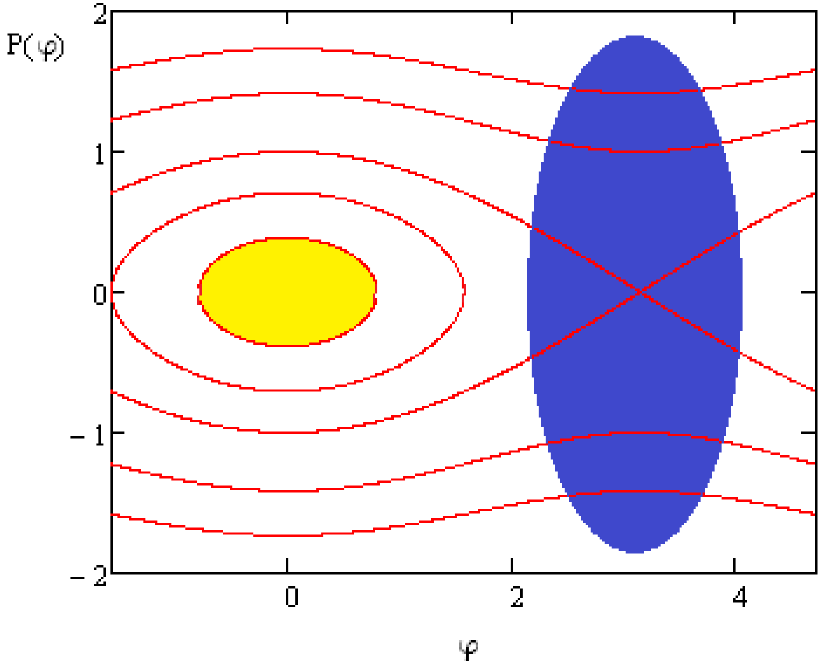


Image of electron beam at Nuclotron entrance without cooling and with cooling.

At electron cooling the rate of events in BM@N *was increased by 2 times*.

Beam Accumulation at electron cooling

- Beam accumulation happens in the longitudinal plane at Booster injection
  - 4 μs bunch – 8 μs revolution time
- Each new injection happens after the previous one is cooled to the core
  - Expected injection rate – 10 Hz
  - 10 – 15 injections will require
  - Total cycle duration ~5 s
- The permanently present 1st RF harmonic weakly affects large amplitude particles
- For small amplitude particles the cooling force will be intentionally reduced to avoid overcooling
- To avoid anticoolig we need to match well the injection magnetic field and e-beam energy
  - It happens since for large Δ*p*/*p*, *dF*/*dt* changes sign after reaching the peak

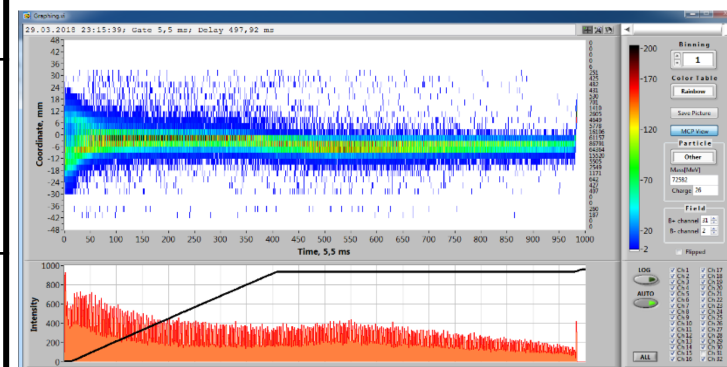


An increase of ion accumulation intensity by a factor of 5 is planned. However application of electron cooling is restricted by ion bunch space charge effects at a level of ·10⁹ ions of Bi^{35+}

Ion beams in Nuclotron

Parameter	Project	Status (June 2018)
Max. magn. field, T	2	2 (1.7 T routine)
B-field ramp, T/s	1	0.8 (0.7 routine)
Accelerated particles	p–U, d↑	p↑, d↑, p – Xe
Max. energy, GeV/u	12 (p), 5.8 (d) 4.5($^{197}Au^{79+}$)	5.6 (d, ^{12}C), 3.6 ($^{40}Ar^{16+}$)
Intensity, ions/cycle	1E11(p,d), 2E9 (A > 100)	d $4*10^{10}$ ($2*10^{10}$ routine), $^{7}Li^{3+}$ $3*10^{9}$ $^{12}C^{6+}$ $2*10^{9}$ $^{40}Ar^{16+}$ $1*10^{6}$ $^{78}Kr^{26+}$ $2*10^{5}$ $^{124}Xe^{42+}$ $1*10^{4}$

Nuclotron since operation 1993

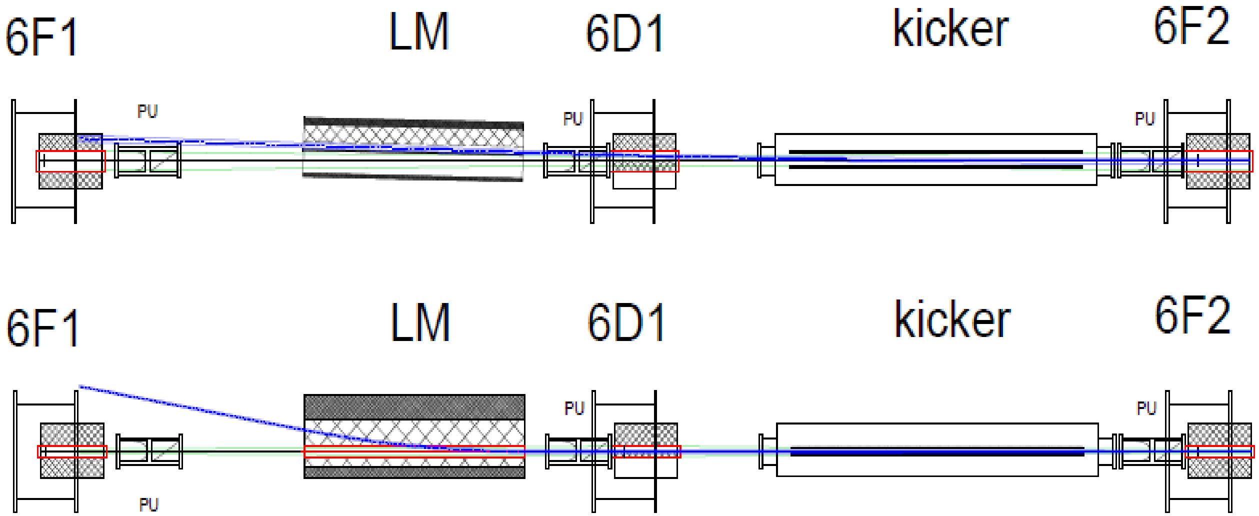


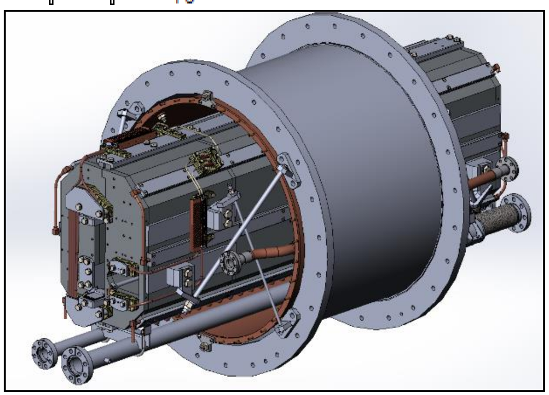
$^{78}Kr^{+26}$ beam acceleration (3,2 GeV/u)

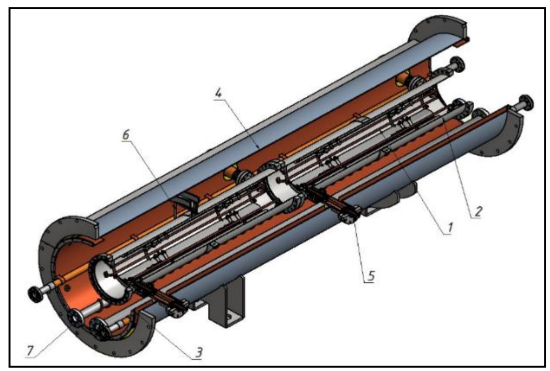
RUN #55

Intensity of xenon ion beam was increased by 3 orders of magnitude at Booster-Nuclotron run 2022-2023

Beam injection system (Nuclotron)

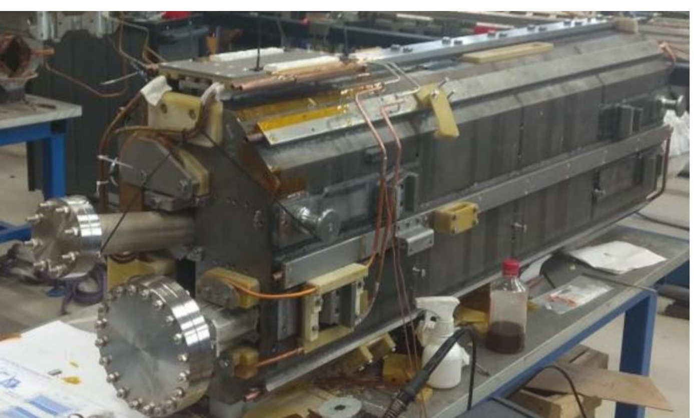


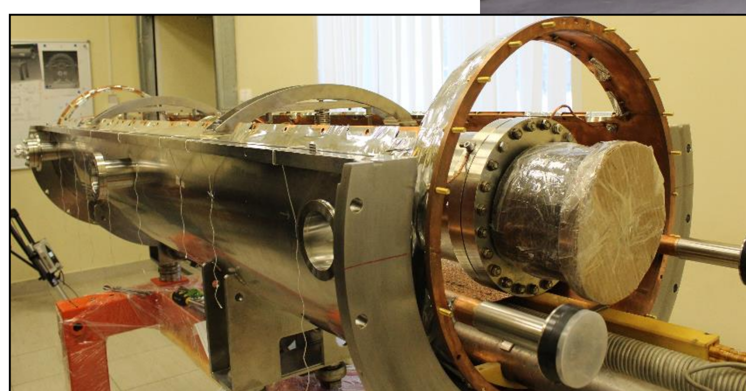




- ❑ Lambertson magnet
11.2021
- ❑ 4-rod kicker
11.2021
- ❑ Testing & mounting
Decem. 2021

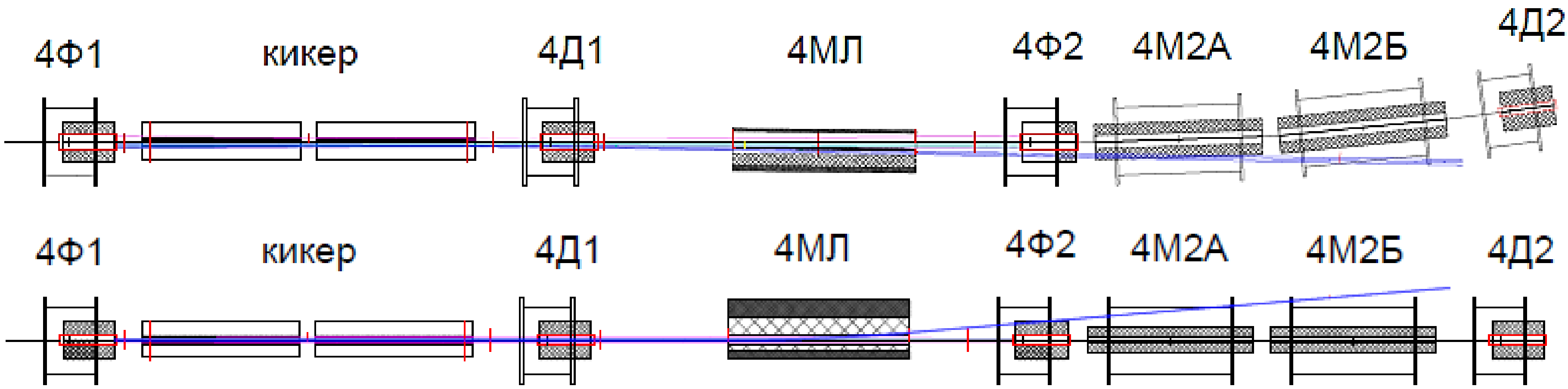
HILAC-Booster-Nuclotron run - December 2021-January 2022



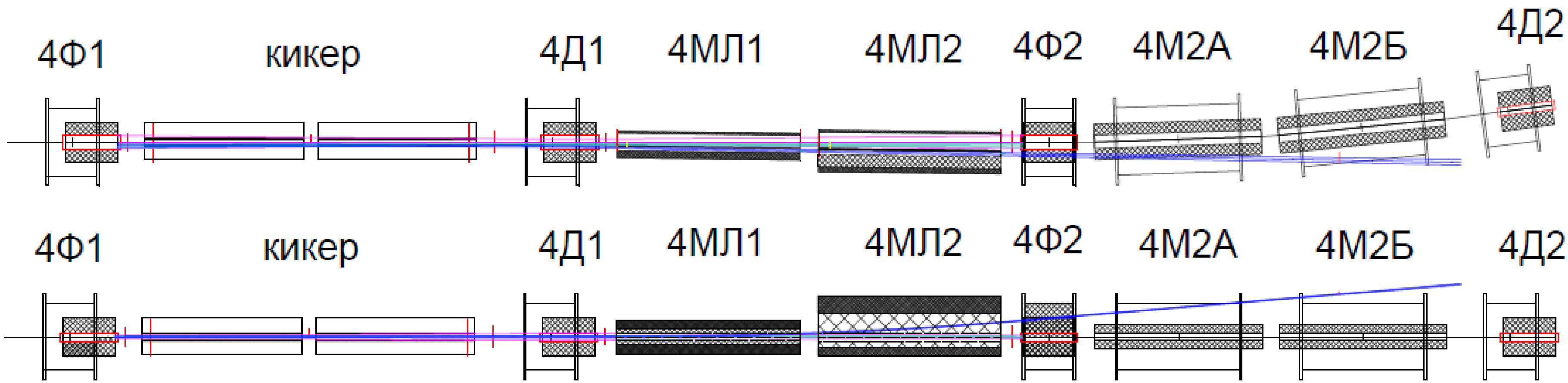


Nuclotron extraction system

Start configuration (magnetic rigidity up to 29 T·m)



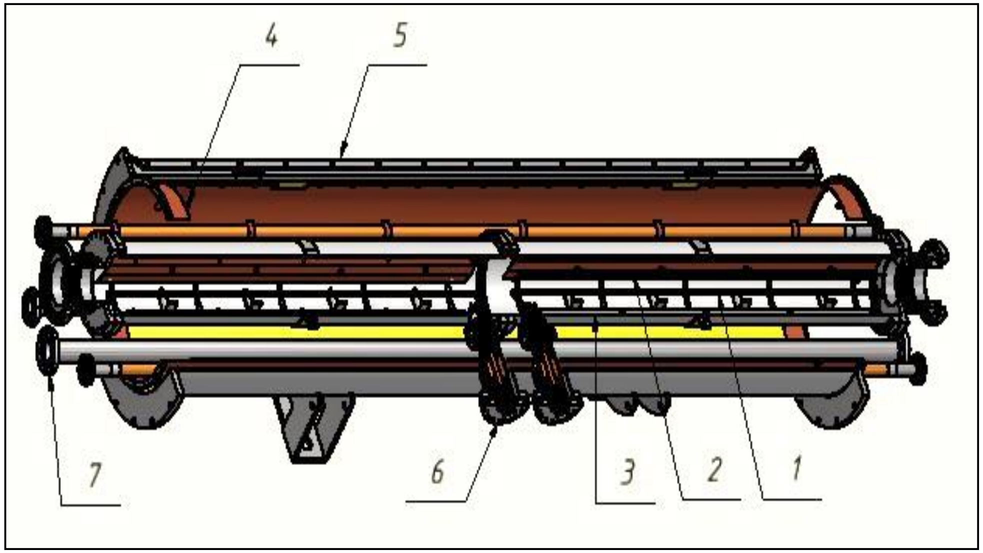
Full configuration (magnetic rigidity up to 38.5 T·m)

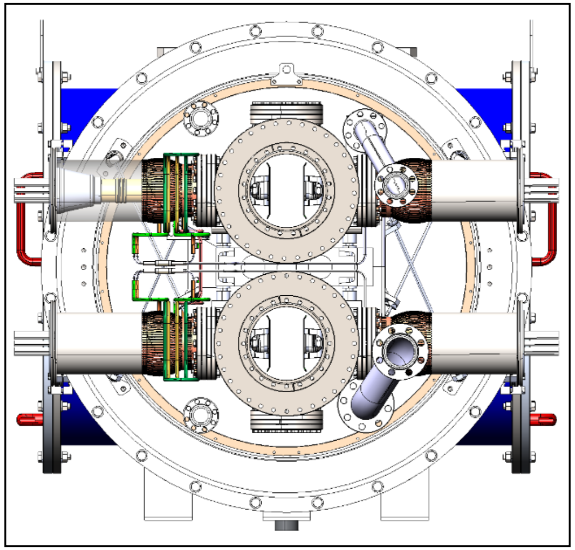


Application of one extraction Lambertson magnet permits to reach the maximal kinetic ion energy 2.5 GeV/n in first Collider beam runs

Kickers of Nuclotron and Collider

	Extraction from Nuclotron	Injection into Collider
Effective length, m	2×1.3	3×1.3
Max. field, T	0.13	0.055
Bending angle, mrad	8.4	5
Pulse duration, ns:		
rise	550	200
plateau	200	200
fall	600	200
Current amplitude, kA	27	11

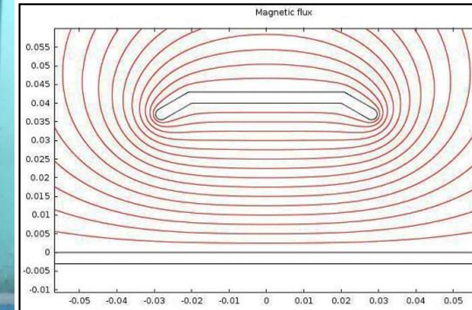




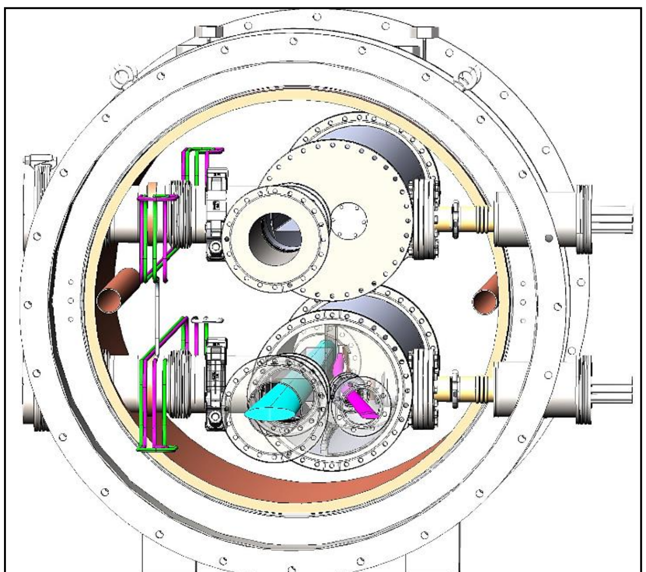
Extraction kicker – in production, injection kickers – start of fabrication, construction should be finished in middle of 2024

Collider beam injection septa

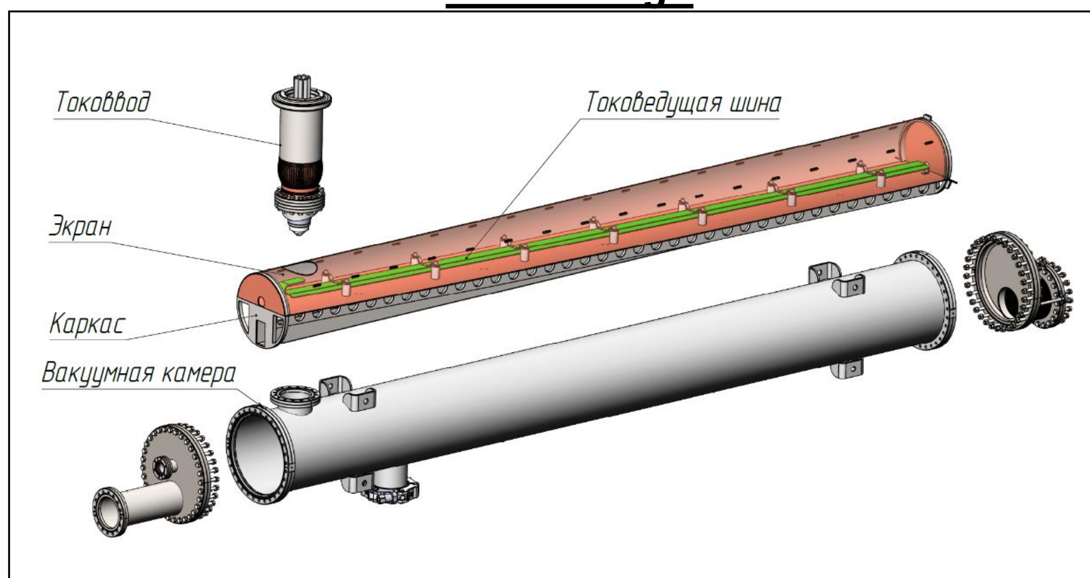
Effective length, m	2.5
Max. magnetic field, T	0.42
Bending angle, mrad	24
Gap, mm	30
Septum thickness, mm	3
Current, кA	50
Pulse duration, µs	10



Septum cryostat module



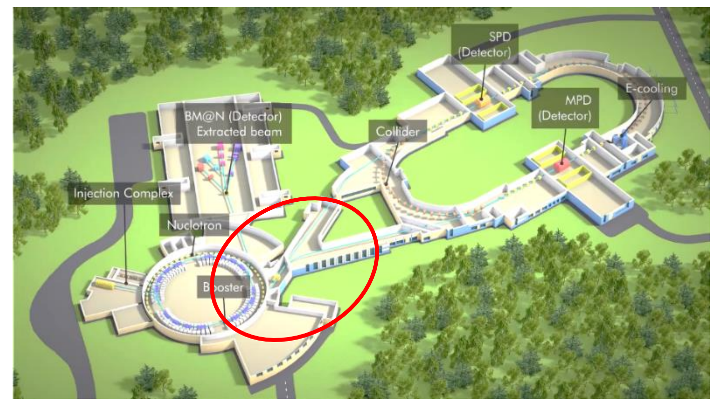
Septum's internal chamber with feedthrough



Nuclotron-Collider beam transport channel

Parameters of pulsed magnet elements

Magnetic element	Number	Effective length, m	Max. magnetic field (gradient), T (T/m)
Long dipole	21	2	1.5
Short dipole	6	1.2	1.5
Quadrupole Q10	22	0.353	31
Quadrupole Q15	6	0.519	31
Steerer	33	0.466	0.114



Magnets delivery in JINR in February 2021

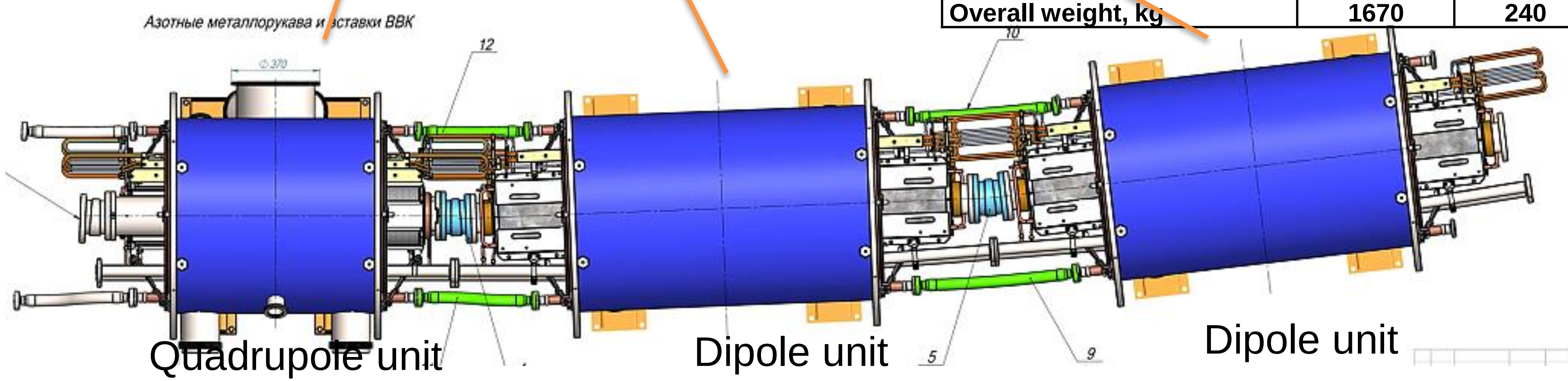
Nuclotron-Collider transfer line was contracted by France firm Sigma Phi

JINR can not obtain part of ready equipment: power supplies, beam diagnostics, vacuum chambers and support stands.

JINR restarts construction and production of this equipment in Summer 2023. We plan to produce this equipment in middle of 2024

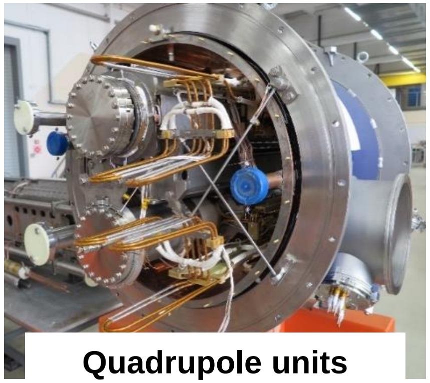
The magnetic system: regular period

Parameter	Dipole	Lens
Number of magnets (units), pcs	80	46
Max. magnetic field (gradient)	1.8 T	23.1 T/m
Effective magnetic length, m	1.94	0.47
Beam pipe aperture (h/v), mm	120 / 70	
Distance between beams, mm	320	
Overall weight, kg	1670	240

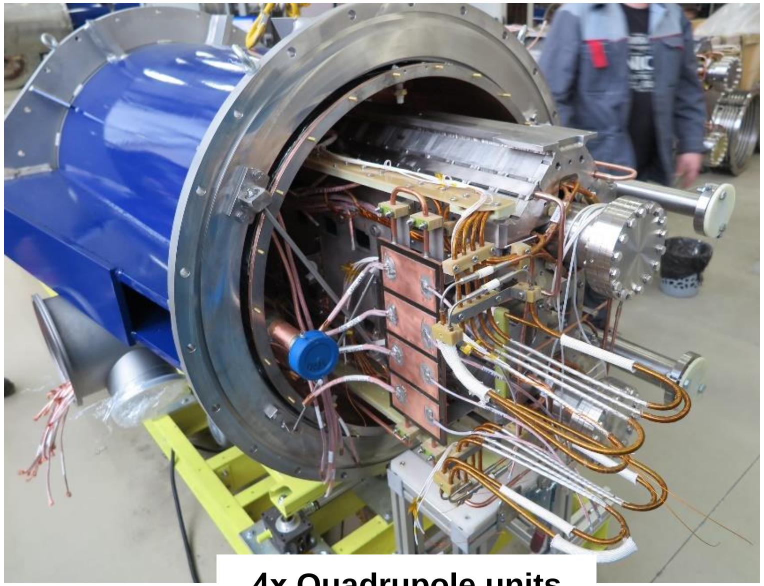


The magnetic system: magnets

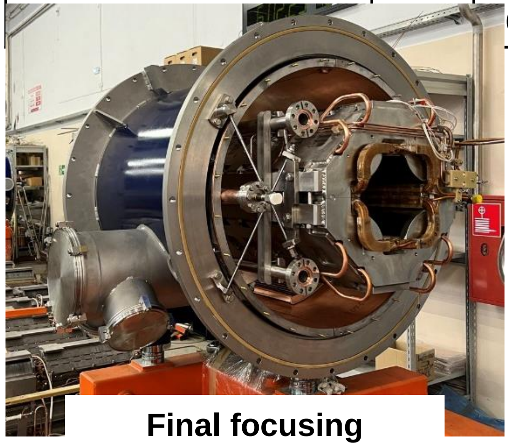
Title	Nes.	Fin.	Prod. %
2×ap Dipole units	80+1	84	100
2×ap Quadrupole units	46	46	100
4×ap Quadrupole units	12	2	80
BI vertical 1×ap dipole units	4	0	80
BI vertical 2×ap dipole units	4	0	80
		0	



Quadrupole units



4x Quadrupole units

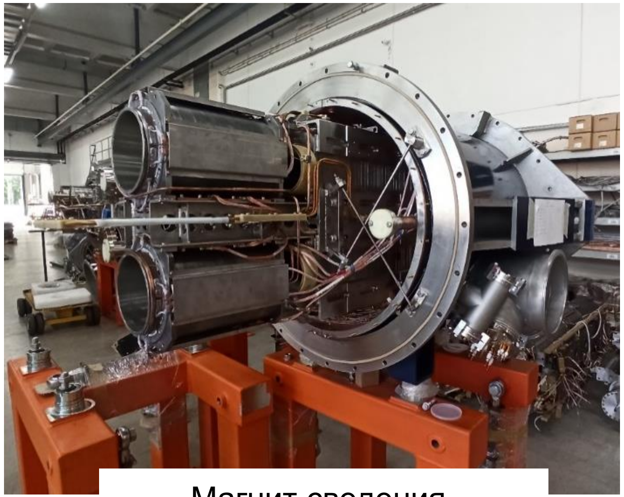


Final focusing quadrupoles

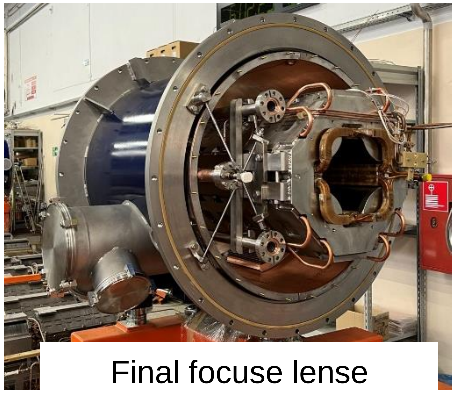
BI vertical 1x dipole units

Straight sections: magnets

Участок блоков линз



Магнит сведения-разведения

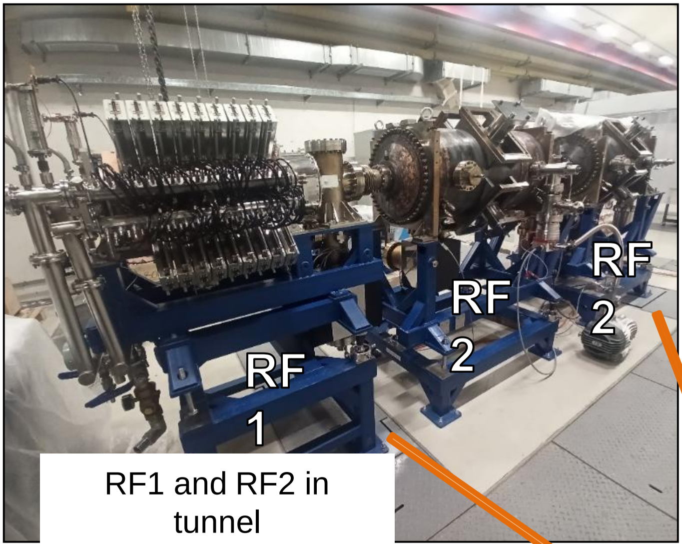


Final focuse lense

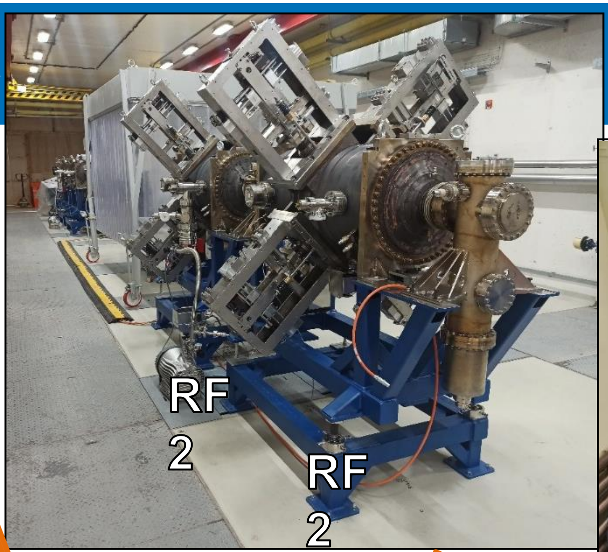
Блок линз

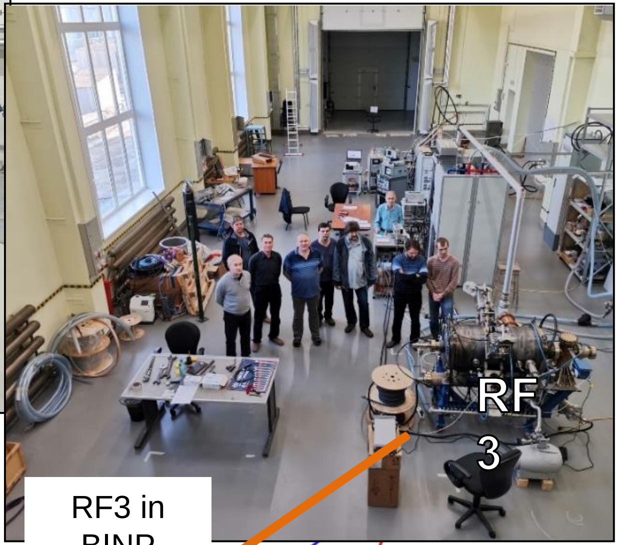
Участок сведения – разведения x4

R

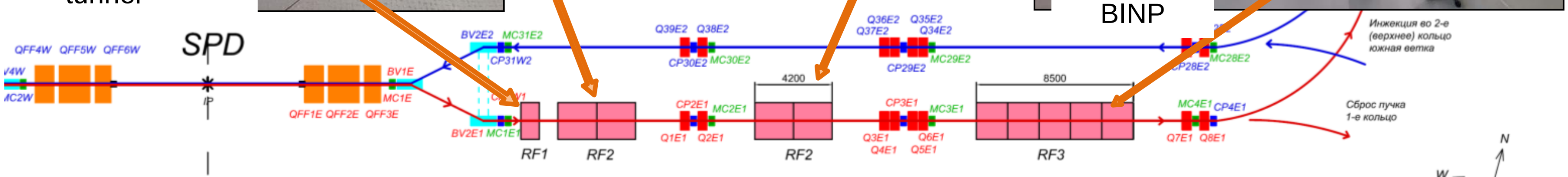


RF1 and RF2 in tunnel





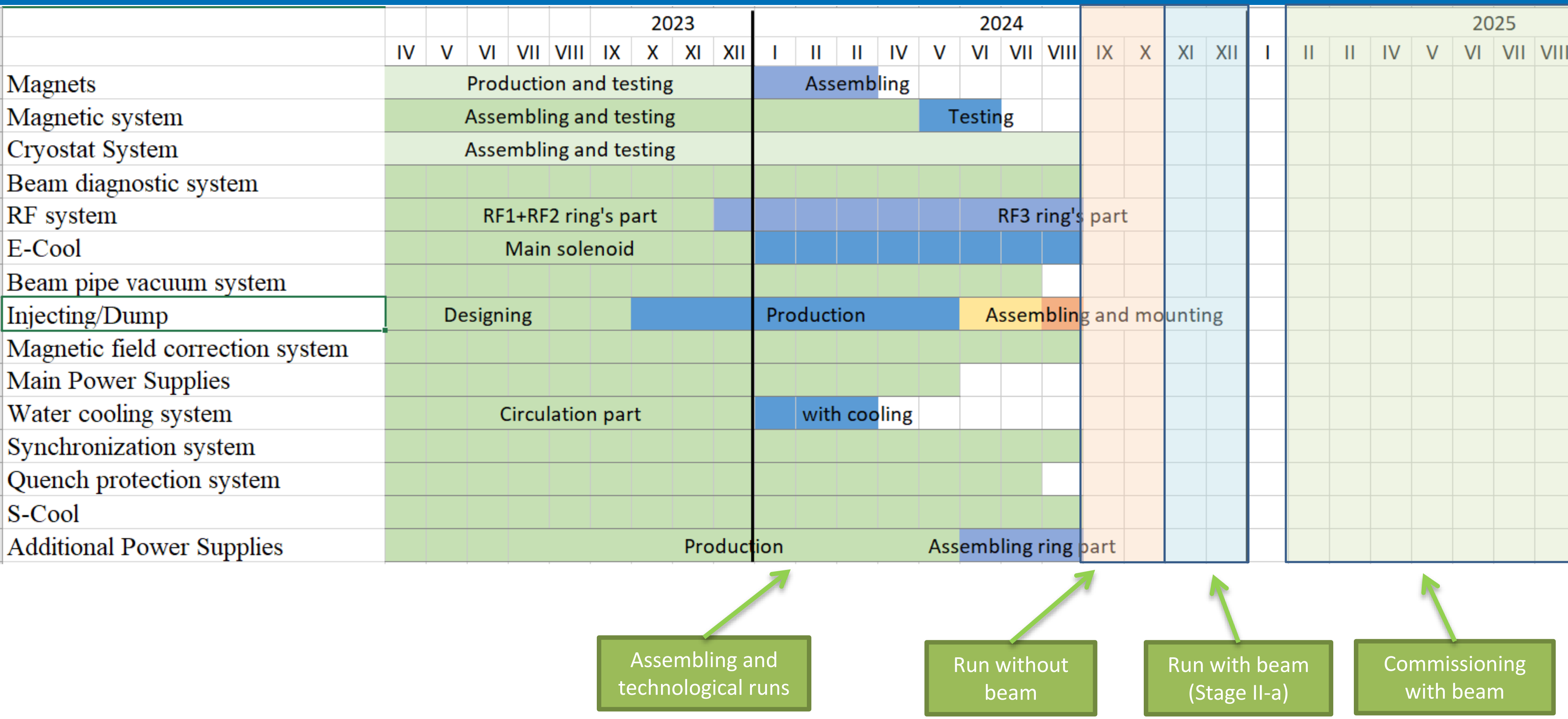
RF3 in BINP



- **All RF1 and RF2 cavity in JINR.**
- **One RF1 and four RF2 cavities were mounted. Installation of other four RF2 in the end of 2023**
- **RF3 cavities and amplifier in BINP. Installation in the end of 2024**

Nuclotron-based
Ion Collider fAcility

Schedules



Program of the September 2024 Collider technological run

- I. Collider cryomagnetic tests:
- Tests of Power supplies on an equivalent load
- Tests of energy evacuation switchers
- Vacuum of isolation volume
- High vacuum of beam chamber
- Operation of control system
- Magnet system cryogenic cooling
- Thermometry tests
- Operation of quench protection and evacuation system
- Formation of magnetic cycle, power supplies tuning
- Corrector system tuning

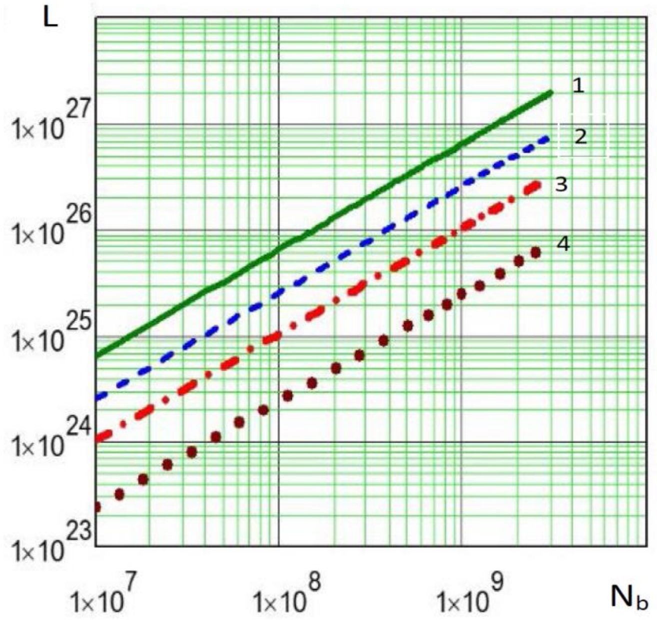
The first Collider run with beam

NICA Stage II-a (basic configuration):

1. Injector chain: KRION => Booster => BTL BN => Nuclotron
2. BTL Nuclotron => Collider
3. Collider equipped with
- RF-1 - (barrier voltage system) for ion storage
- RF-2 - 4 cavities per ring (100 kV RF amplitude)

Result: 22 bunches of the length σ ~ 2 m per collider ring that 2e25 $cm^{-2} \cdot s^{-1}$. Maximum kinetic ion energy 2.5 GeV/n

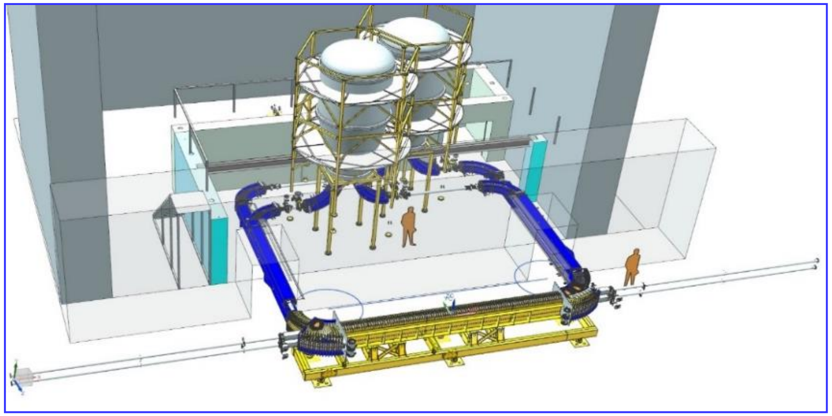
	Booster		Nuclotron		Collider
	Injection	Extraction	Injection	Extraction	
E	3,2 MeV/u	530 MeV/u	523 MeV/u	1,5-2,5 GeV/u	1,5-2,5 GeV/u
N	$5 \cdot 10^8$	$3.5*10^8$	$2.5*10^8$	$2*10^8$	$2*10^8$ (at injection) $4*10^9$ (at RF1 accumulation and formation of 22 bunches by RF2)
B_d, Тл	0,1	1,6	0,4	<1,2	<1.2



Dependence of luminosity on number ions per buch at different energies (1) 4.5 GeV/u (2) 3GeV/u, (3) 2 GeV/u, (4) 1 GeV/u.

Increase of luminosity for project value

Electron Cooling System of NICA Collider

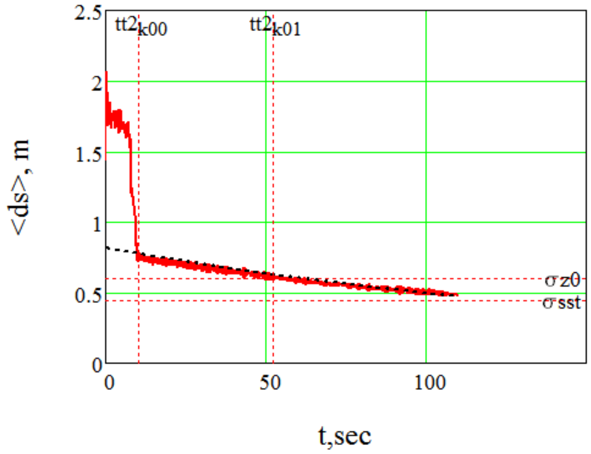


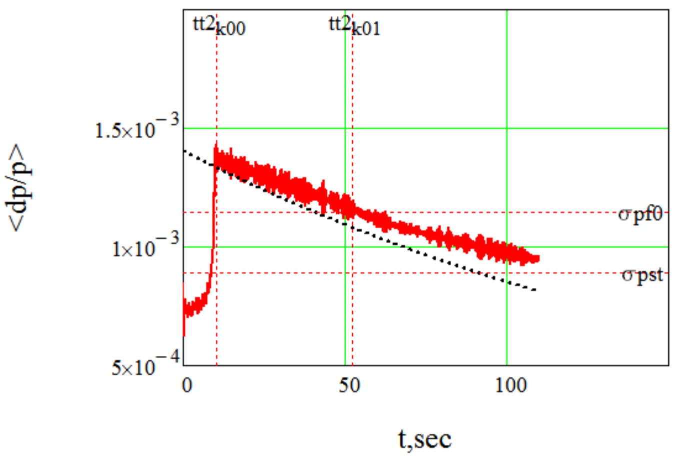
HV Electron Cooler for NICA Collider
Design and construction at BINP
Installation at NICA in 2023-2024

RF3 Bunching

Number of RF3 cavities per ring -8

RF3 station in BINP, installation 2025





Dependence of bunch length and momentum spread on time at cooling time of 100 s.

Installation in Nuclotron of two Lambertson magnets to reach project energy 4.5 GeV/u


Thank you for attention