ELECTRON COOLING IN NICA ACCELERATION COMPLEX

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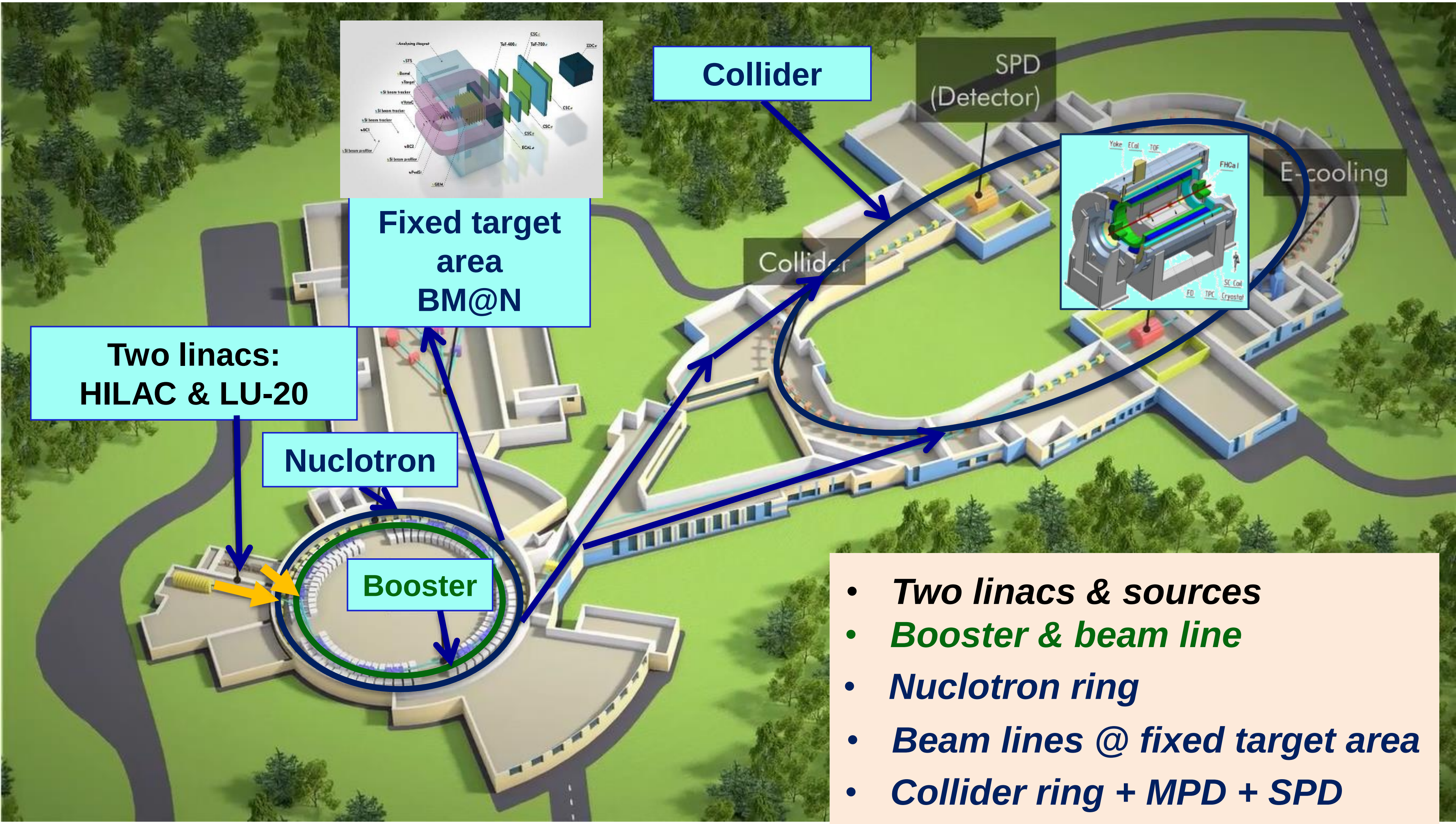
Veksler and Baldin Laboratory for High Energy Physics

Joint Institute for Nuclear Research

NICA: Nuclotron based Ion Collider fAcility

NICA complex layout



Collider

Fixed target area BM@N

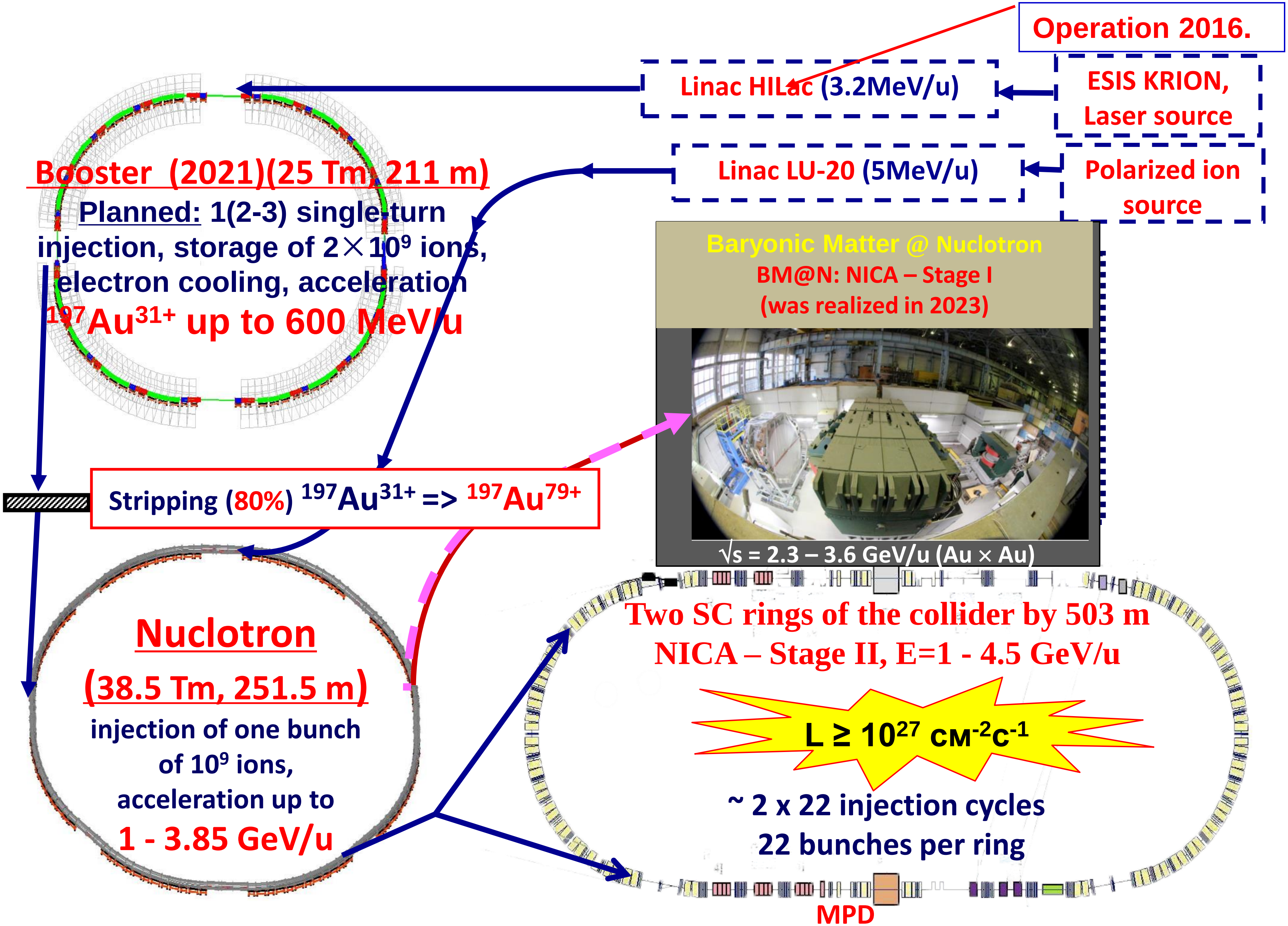
Two linacs:
HILAC & LU-20

Nuclotron

Booster

- *Two linacs & sources*
- *Booster & beam line*
- *Nuclotron ring*
- *Beam lines @ fixed target area*
- *Collider ring + MPD + SPD*

NICA – collisions for Heavy ion mode (parameters of ~2021)



Operation 2016.

Linac HILac (3.2MeV/u)

ESIS KRION,
Laser source

Linac LU-20 (5MeV/u)

Polarized ion
source

Booster (2021)(25 Tm, 211 m)

Planned: 1(2-3) single-turn injection, storage of 2×10^{9} ions, electron cooling, acceleration

$^{197}Au^{31+}$ up to 600 MeV/u

Stripping (80%) $^{197}Au^{31+} \Rightarrow {}^{197}Au^{79+}$

Baryonic Matter @ Nuclotron
BM@N: NICA – Stage I
(was realized in 2023)

$\sqrt{s}$ = 2.3 – 3.6 GeV/u (Au × Au)

Nuclotron

(38.5 Tm, 251.5 m)

injection of one bunch
of 10^{9} ions,
acceleration up to
1 - 3.85 GeV/u

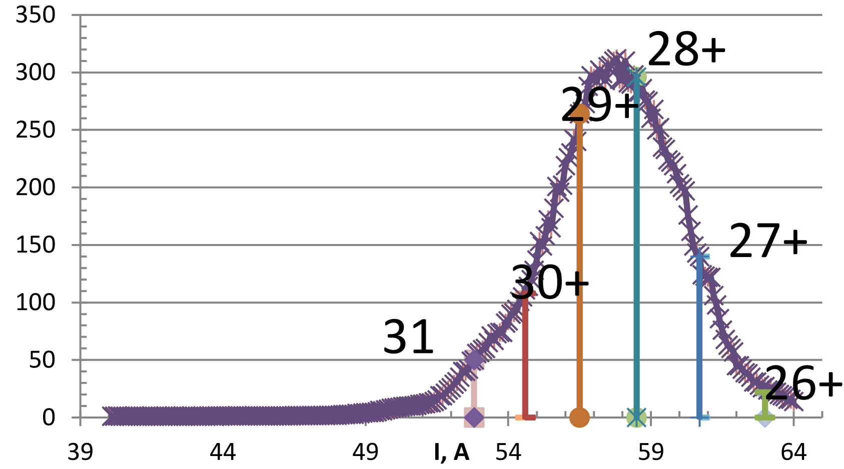
Two SC rings of the collider by 503 m
NICA – Stage II, E=1 - 4.5 GeV/u

$L \geq 10^{27}$ см$^{-2}$с$^{-1}$

~ 2 x 22 injection cycles
22 bunches per ring

MPD

Ion source KRION-6T



Xe ion charge distribution at KRION exit

Project ion intensity 2·10^9 Bi^{35+} per pulse

Достигнутые величины

Ar^{16+} - 5·10^8 ions per pulse

Xe^{28+} - 10^8 ions per pulse

Bi^{35+} - 10^8 ions per pulse

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

HILAC & Booster injection beam line

BEVATECH
Germany

Stable and reliable operation during Booster commissioning with Fe $^{14+}$ (Run II) and Xe $^{28+}$ (Run IV) beams

Heavy Ion Linear Accelerator

A/q (Target Ion Au^{31+})	*6.25*
Beam current	*< 10 emA*
Repetition rate	*< 10 Hz*
Output energy	*3.2 MeV/u*

Transmission of 2mA Fe^{14+} ions beam up to 75% from RFQ to the exit of the HILAc, 3.2 MeV/u

Commissioned in 2018

HILAc status

Stable and reliable operation with Ar^{13+} and Xe^{28+} in Run IV

C1 BwL DC1M 20.0 mV/div -199.50 mV

C2 BwL DC1M 20.0 mV/div -97.000 mV

C3 F B D1 2.00 mV/div -7.9000 mV

C4 F B D1 2.00 mV/div -8.2000 mV

-3.8 µs µs/div 5 GS/s

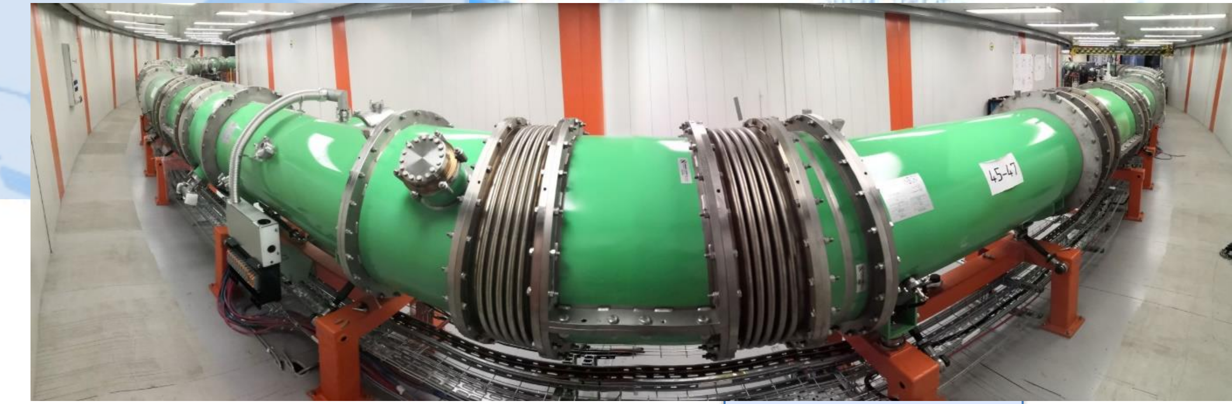
Синхр Ext/10 DC Ждущ. 410 mV Фронт

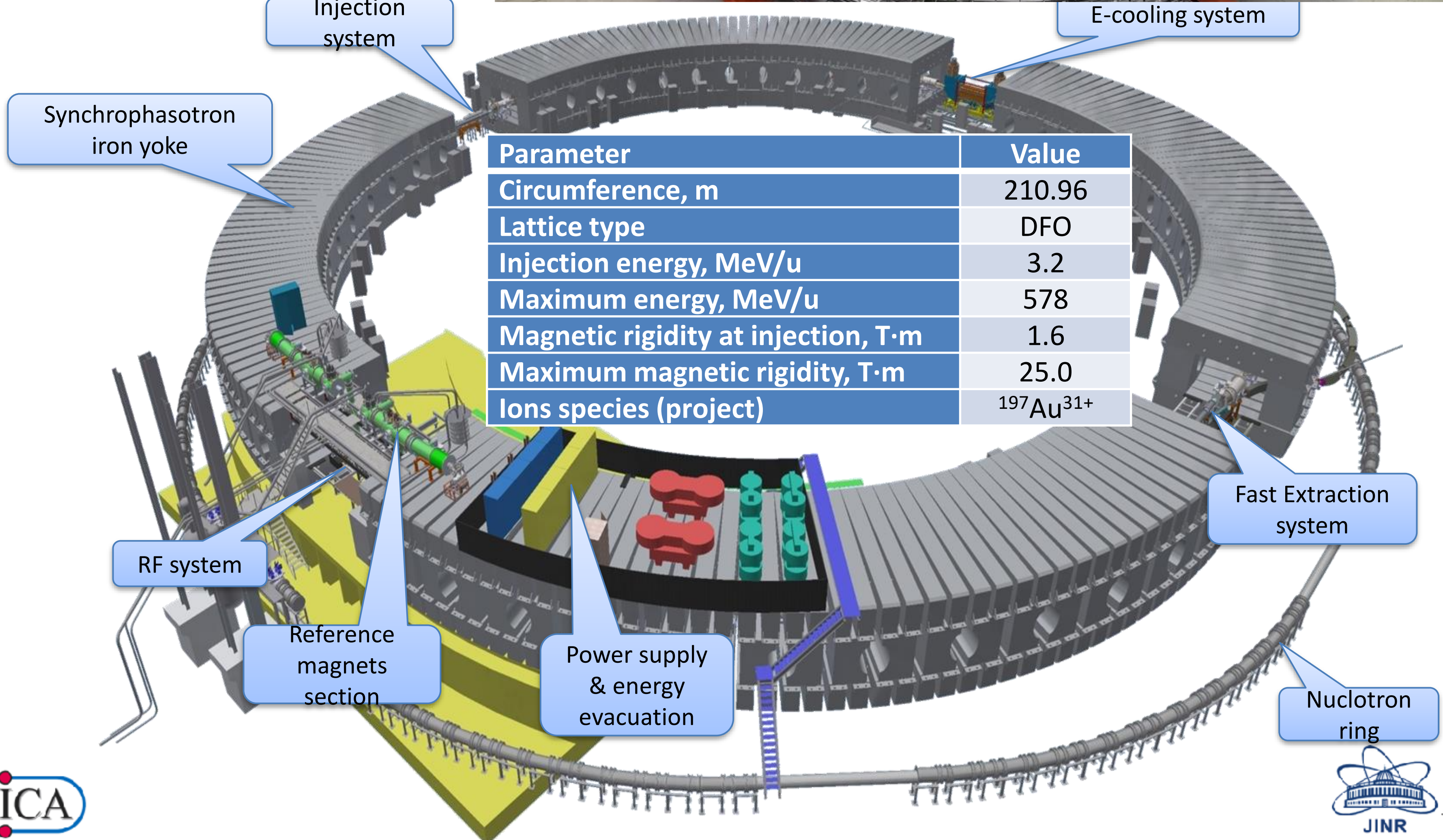
At RFQ exit I=100 μA (yellow line). At HILAC exit I=65 μA at ion pulse duration 22 μs (red line), about 70% at this pulse of target ions $^{124}Xe^{28+}$. **Number of ions accelerated in HILAC at energy 3,2 MeV/n is about 1×10^{8}.**

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 with electron cooling and upgrade of KRION-6T

Booster ring layout (2016)





Injection system

E-cooling system

Synchrophasotron iron yoke

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)	$^{197}Au^{31+}$

Fast Extraction system

RF system

Reference magnets section

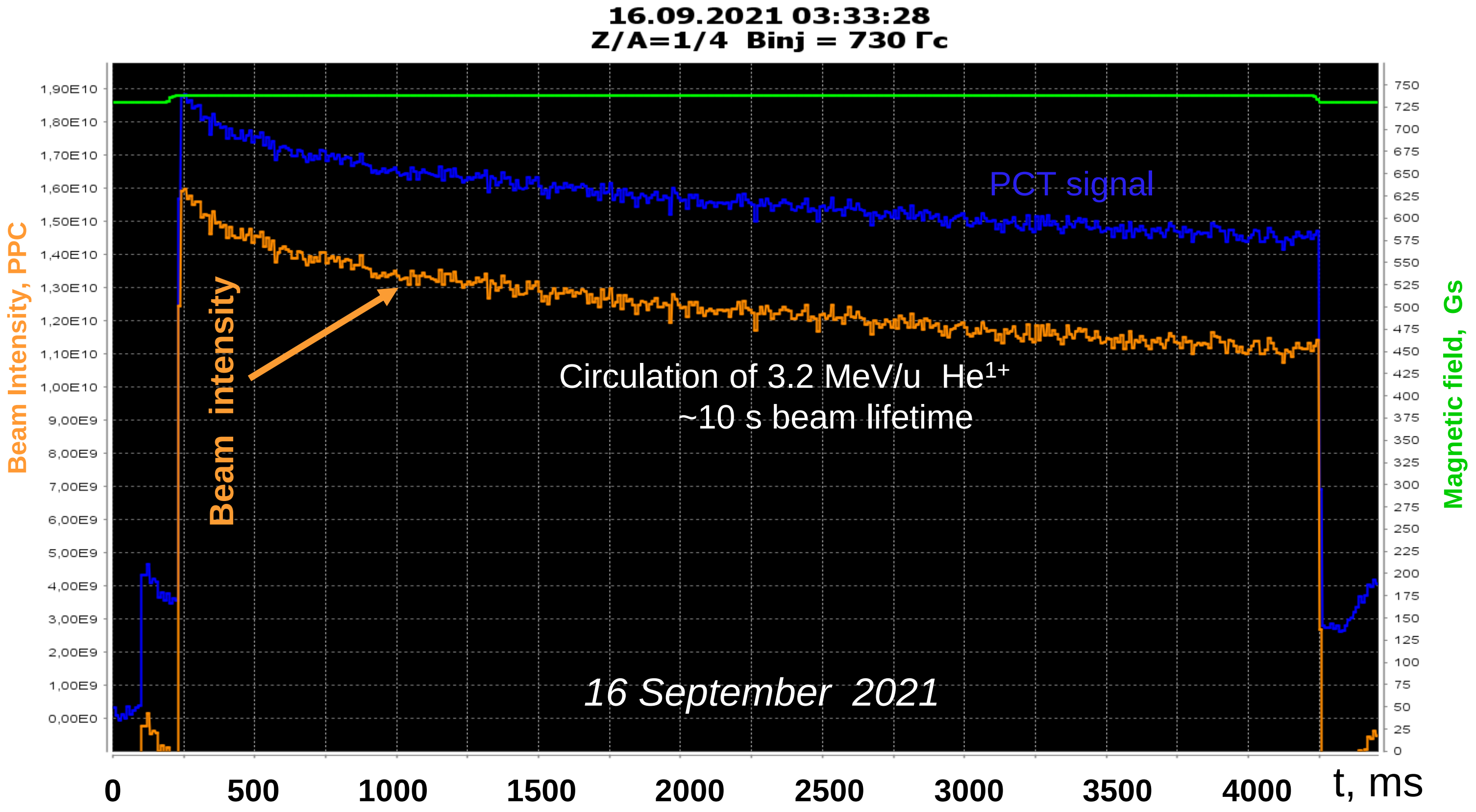
Power supply & energy evacuation

Nuclotron ring

Beam current & vacuum conditions

16.09.2021: Measurements of integral vacuum conditions by intensity decay of circulating He^{1+}

Parametric beam current transformer signal (DC mode)

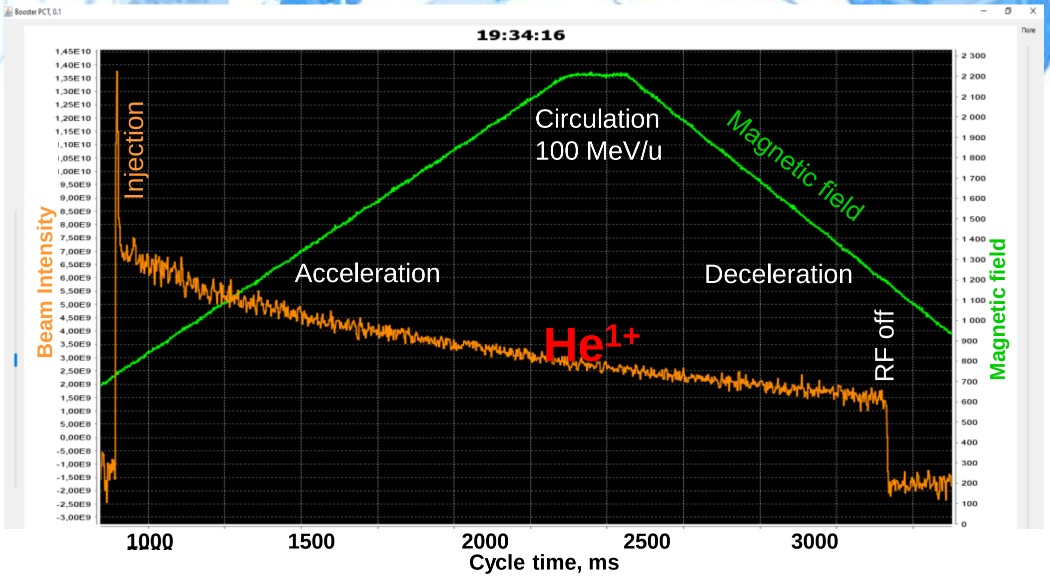


Circulation of 3.2 MeV/u He^{1+}
~10 s beam lifetime

16 September 2021

- ✓ ***Life-time up to 10 s (8x more), equivalent pressure of residual gas is about $5{\cdot}10^{-9}$ Pa***

Beam acceleration in Booster

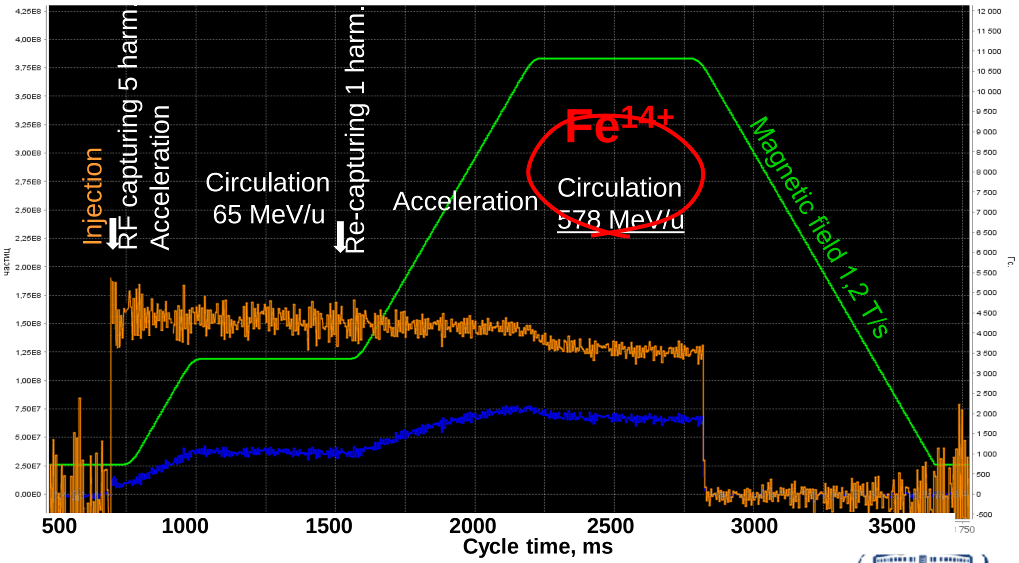


Step 1 of commissioning
December 2020, He^{1+}

PCT signal when beam injecting into rising field, capturing (~60%), accelerating & decelerating: no transient losses on the MF table & after.

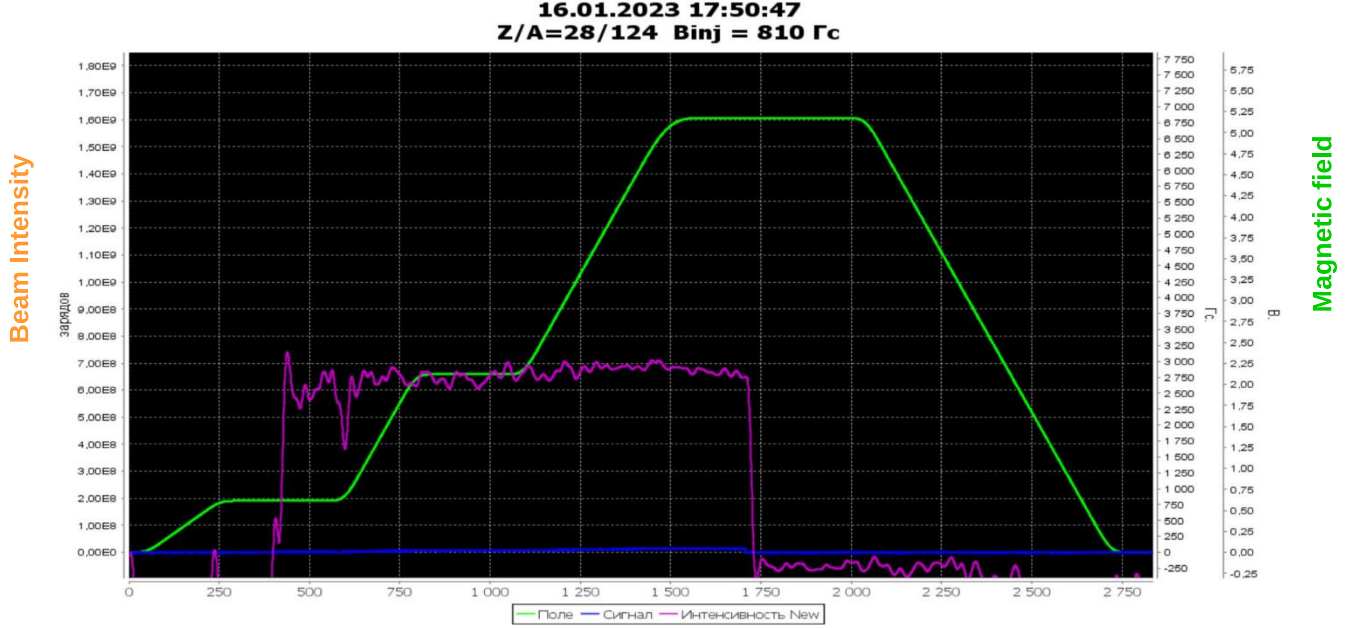
Step 2 of commissioning
14-23 of September 2021 Fe^{14+}

- *Beam injection with adiabatic capturing at 5th harmonic (>95%),*
- *accelerating up to 65 MeV/u,*
- *recapturing 1 harmonic (close to 100%)*
- *acceleration up to 578 Mev/u*
- *with dB/dt = 1.2 T/s*
- *electron cooling*



Booster Beam current

Parametric beam current transformer signal (DC mode)

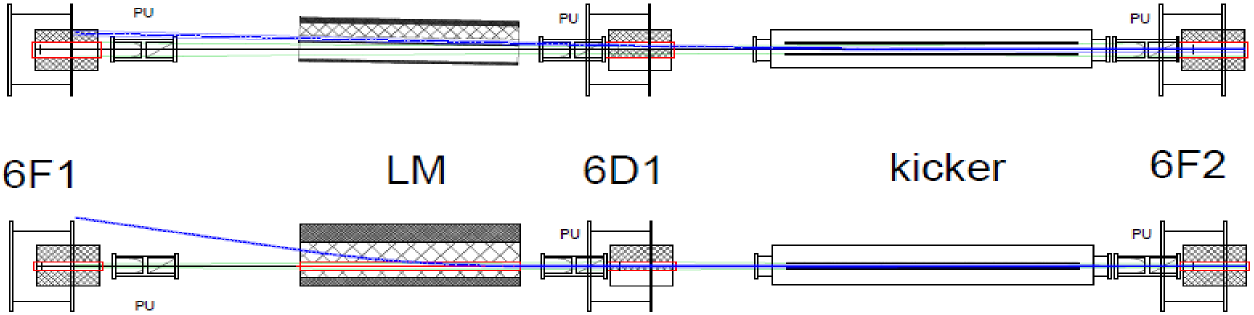


Booster-Nuclotron run - September 2022 - February 2023 for BM@N baryonic matter researches. Booster acceleration of ions$^{124}Xe^{28+}$ to energy 204,7 MeV/n, where they were stripped up to bare nucleus end extracted to Nuclotron.

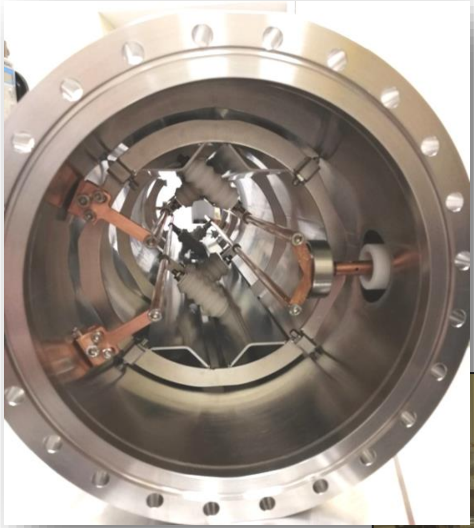
✓ ***$6\cdot10^8$ elementary charges ~ $2.5\cdot10^7$ of Xe^{28+}***

Beam injection to the Nuclotron ring

Installation was finished 31/12/2021

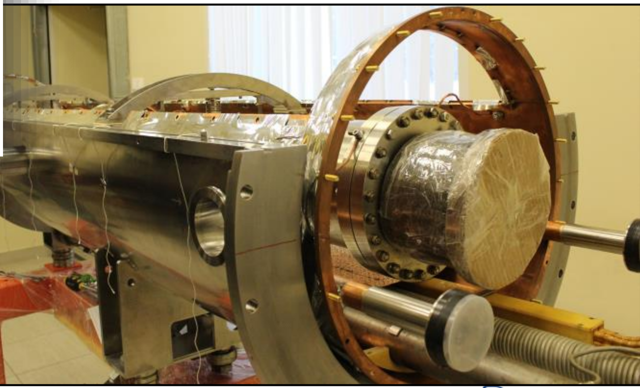


SC Lambertson magnet



Four-rod kicker

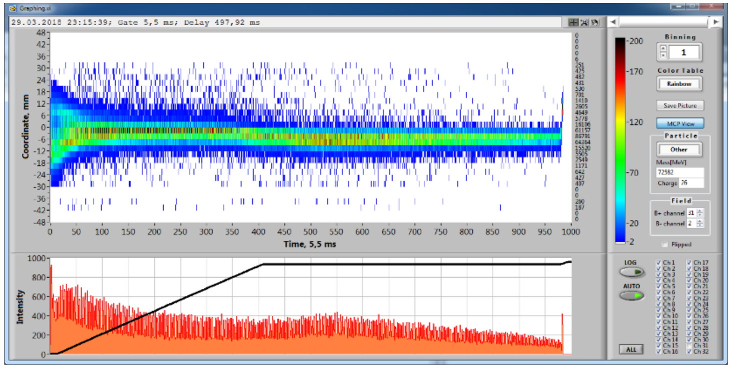
Designed – JINR, fabricated – VST (Belgorod)



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



29.03.2018 23:15:39; Gate 5,5 ms; Delay 497,92 ms

Binning 1

Color Table Rainbow

Particle Other

Mass[MeV] 72582

Charge 26

Field

B+ channel 31

B- channel 2

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

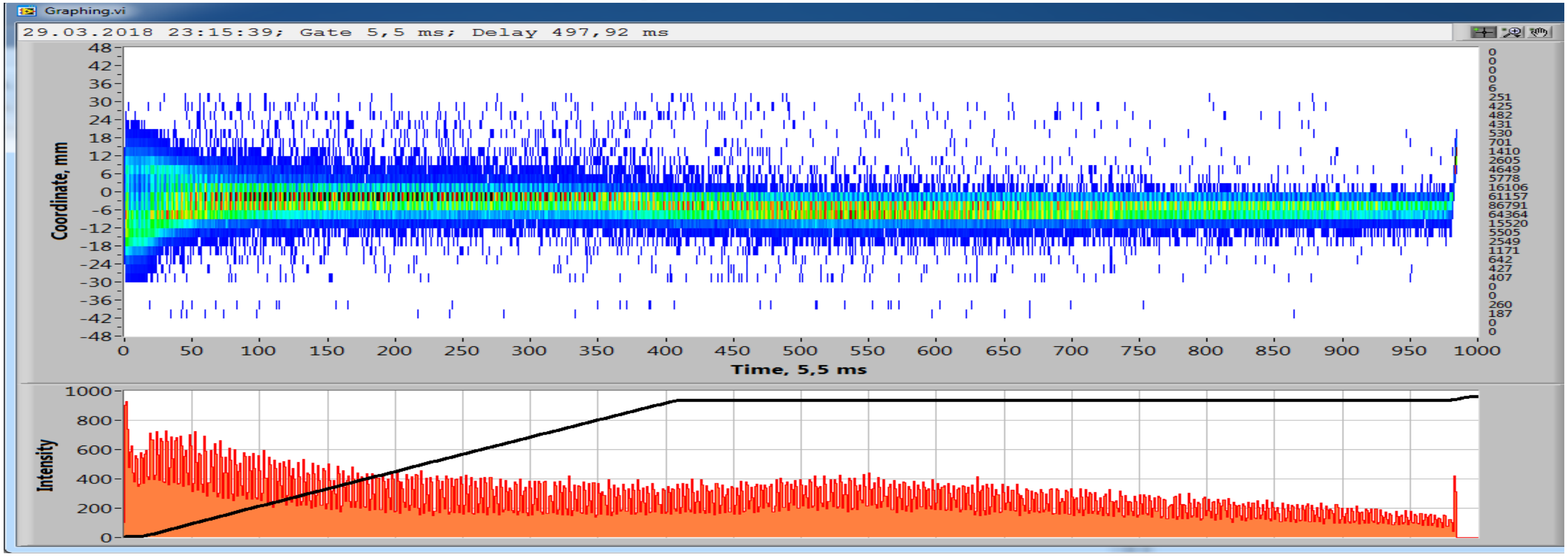
RUN #55

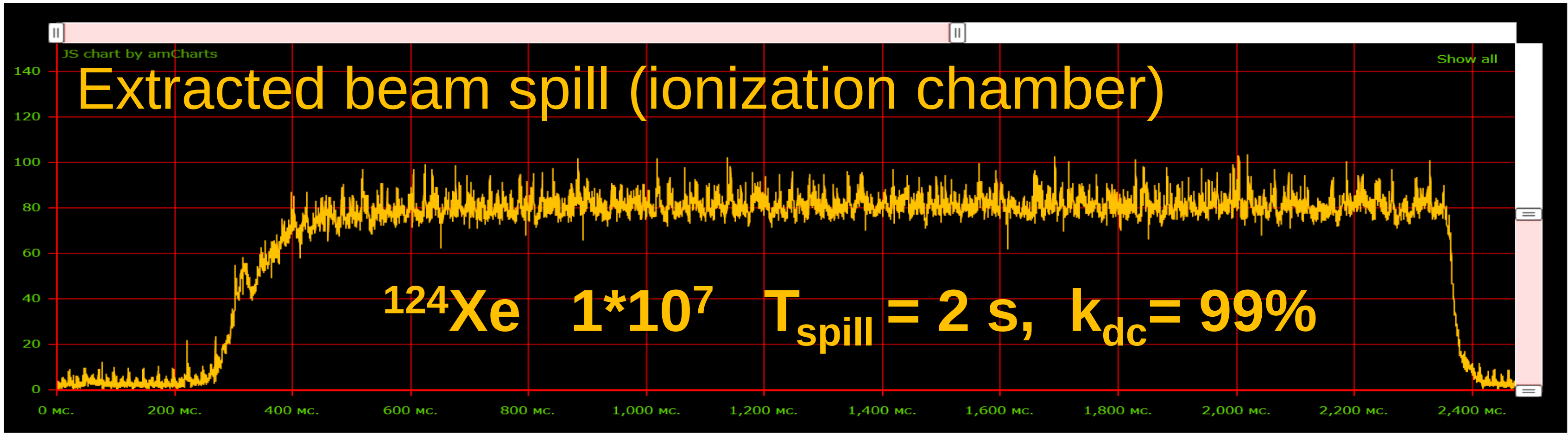
Intensity of xenon ion beam was increased by 3 orders of magnitude at Booster-Nuclotron run 2022-2023

Heavy ion beams acceleration and slow extraction

Jan. 2023

^{124}Xe^{+54} beam extraction (3,9 Gev/u) RUN #4 at NICA complex





Extracted beam spill (ionization chamber)

^{124}Xe 1*10^{7} T_{spill} = 2 s, k_{dc}= 99%

Electron Cooling

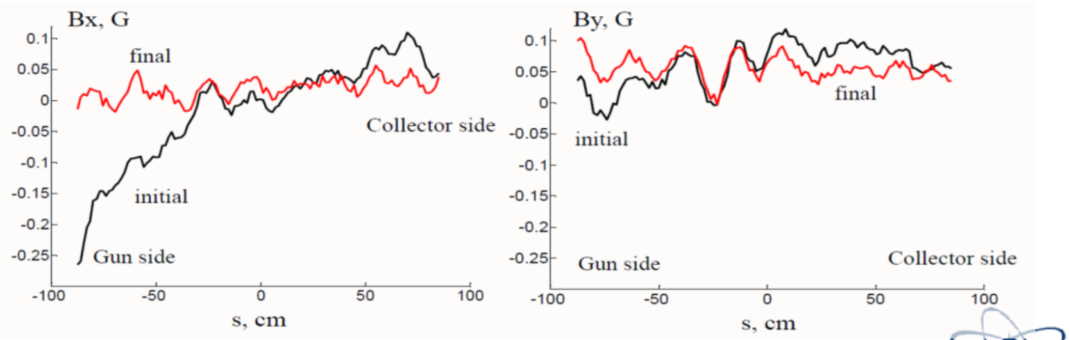
Electron cooling section

Contracted by BINP

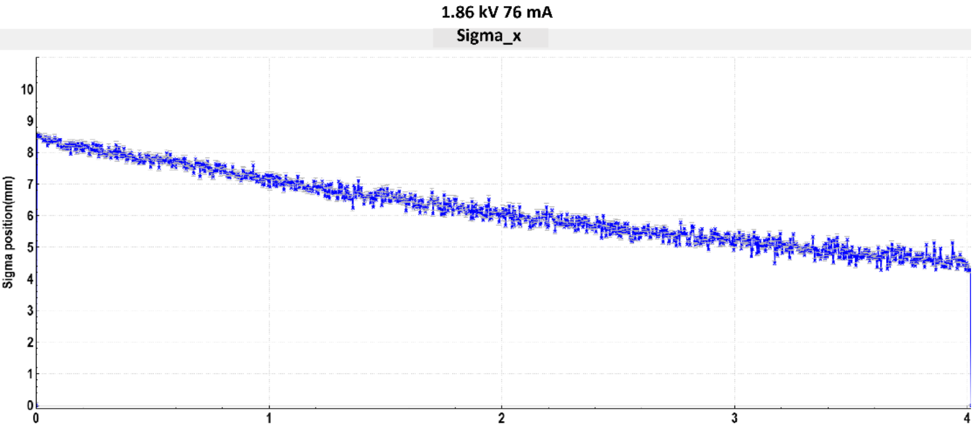
Achieved parameters	Value
Electron energy, keV	40
Electron current, A	1
Magnetic field, kGs	1
Filed homogeneity	2×10^{-5}
Vacuum pressure, Pa	3×10^{-9}

May 2016 – commissioned at BINP

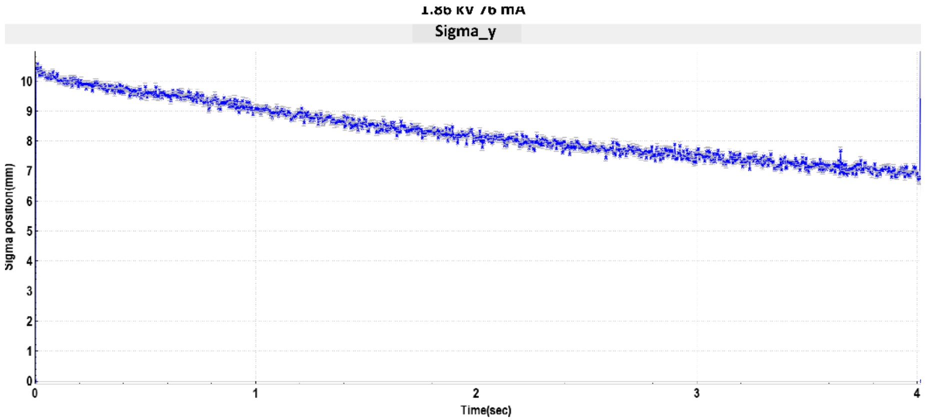
In Booster operation since 2021



First longitudinal and transverse electron cooling of Fe^{14+} ions at 3.2 MeV/u

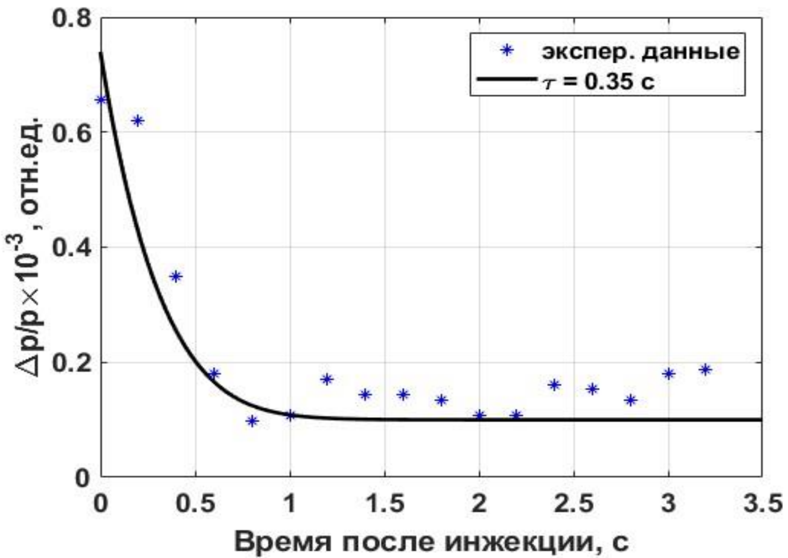


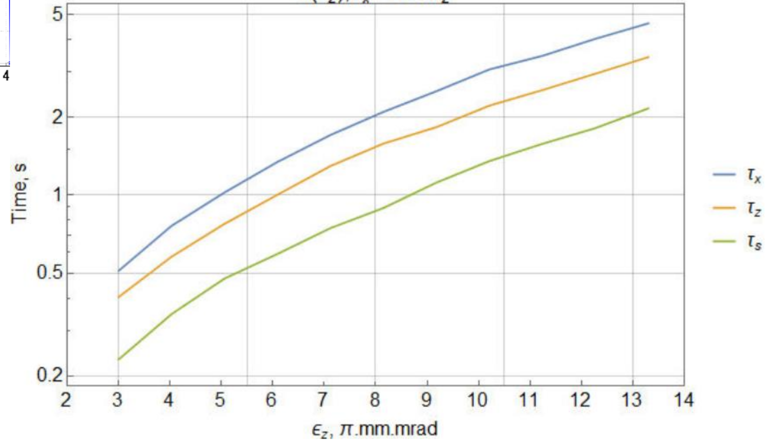
Horizontal cooling time t_{cool} =3.1 s



Vertical cooling time t_{cool} =4.4 s

Large emittances at a mismatched injection rms $\varepsilon_x/\varepsilon_y$=14/8 π·mm·mrad.



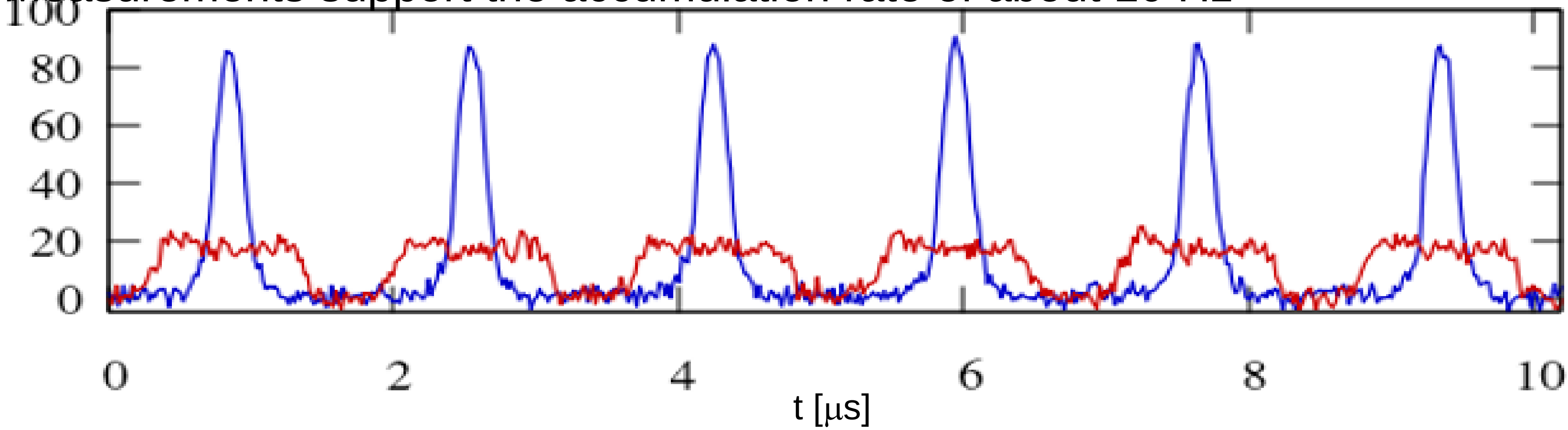


BETACOOL simulation Fe^{14+}
I=76 mA, $\varepsilon_x/\varepsilon_y$=14/8 π·mm·mrad
t_{cool}=2.1 s.

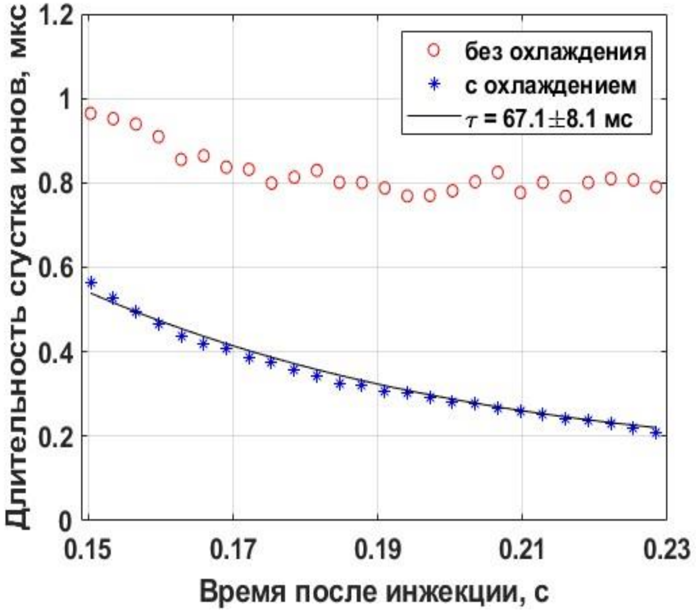
Project value
At multi cycle injection of Au^{31+} with rms $\varepsilon_x/\varepsilon_y$=11.5/3 π·mm·mrad simulated electron cooling time is 150 ms.

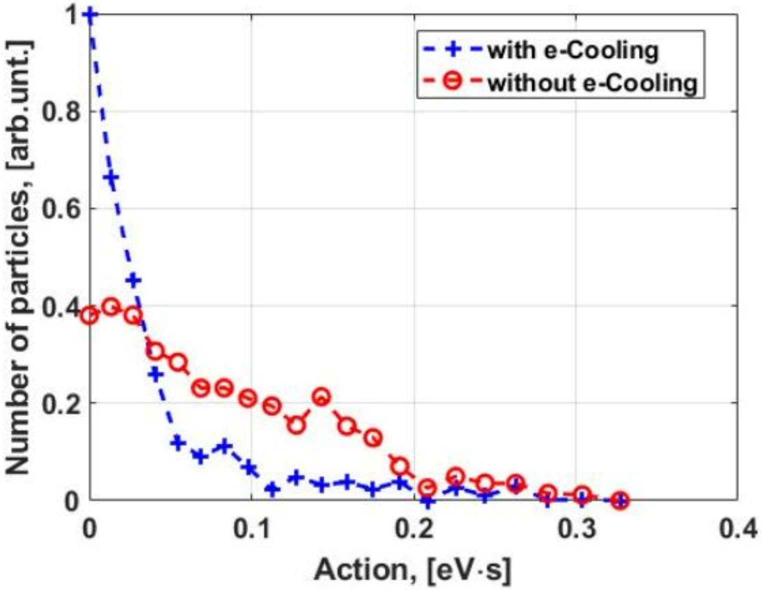
Electron Cooling in Booster in presence of RF

- ❑ 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}Xe28+ at electron beam current 50mA and energy 1,830 keV

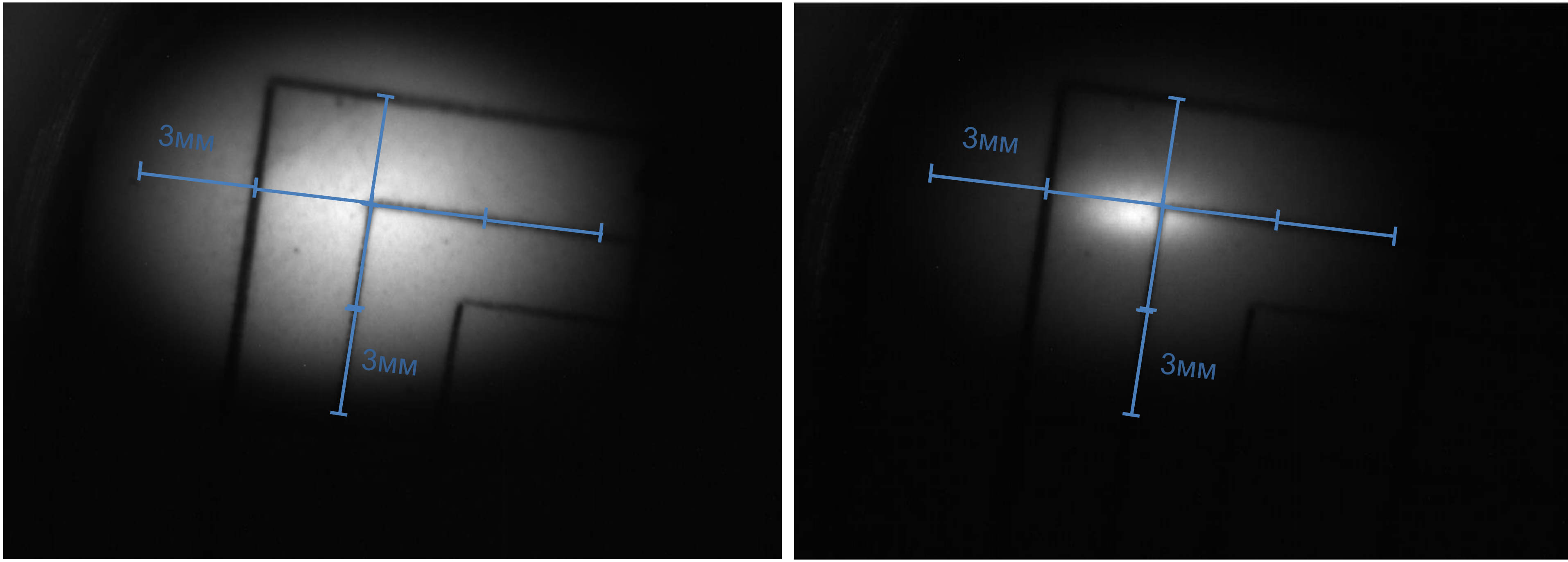
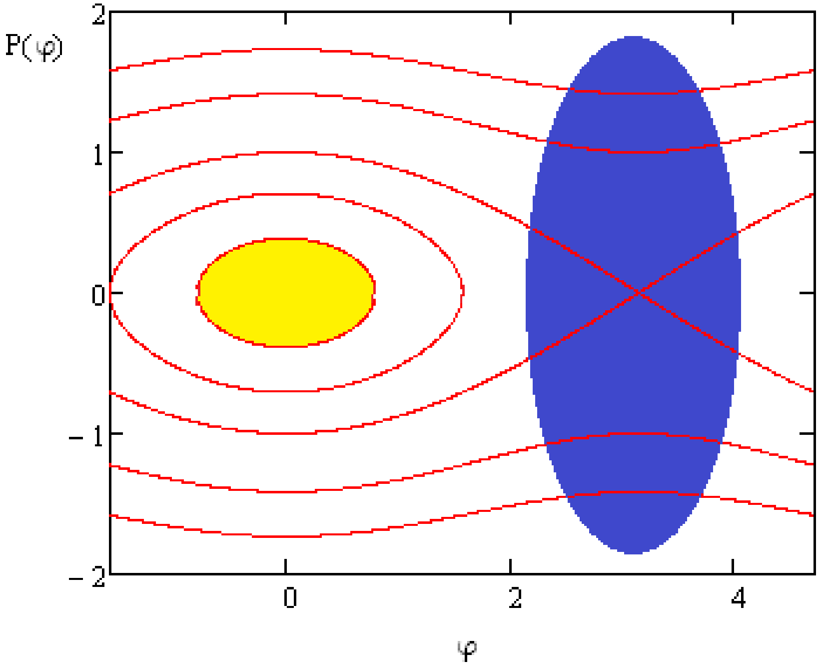


Image of electron beam at Nuclotron entrance without cooling and with cooling.

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

Further Development of Injection Complex

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 5-10 is planned. However application of electron cooling is restricted by ion bunch space charge effects at a level of $\cdot 10^9$ ***ions of*** Bi^{35+}

Preparation for the Next Run

- Goals for intensity increase
  - ~10 times will be obtained from beam accumulation in Booster with e-cooling
  - Other 10 times will be obtained from minimizing beam loss
- List of main actions
  - Upgrade of Krion-6 to obtain 4 us pulse
    - 10 Hz operation was already demonstrated
  - Upgrade of linac hardware to operate at 10 Hz
  - Correcting software generating ramp of main dipoles:
    - Matching acc. rate to possibilities of RF voltage
  - Bringing energy of Booster-Nuclotron transfers to the design value
  - Adding correctors to Nuclotron
  - Finalizing orbit correction software
  - Adding 10 Hz operation to synchronization system
  - An upgrade of IPM

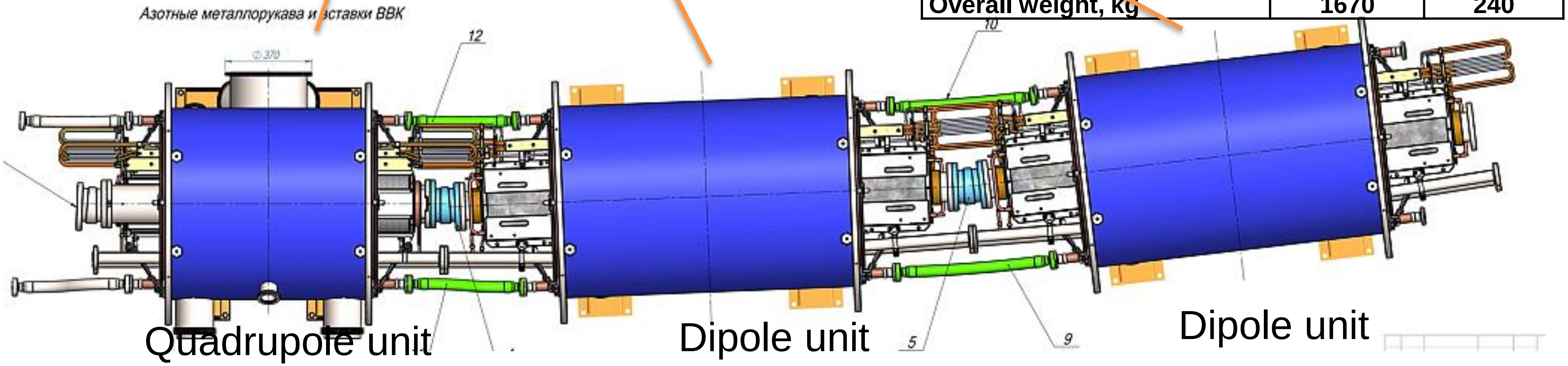
Collider

NICA collider parameters

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, $\Delta p/p$	±0.010		
Gamma-transition, γ_{tr}	7.088		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch	$3.2 \cdot 10^8$	$2.9 \cdot 10^9$	$3.1 \cdot 10^9$
Rms dp/p, 10^{-3}	0.7	1.4	1.9
Rms beam emittance, h/v, (unnormalized), π·mm·mrad	1.3/1.3	1.3/1.1	1.3/1.0
Luminosity, $cm^{-2}s^{-1}$	0.8e25	0.8e27	1e27
IBS growthe time, sec	160	460	2000

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

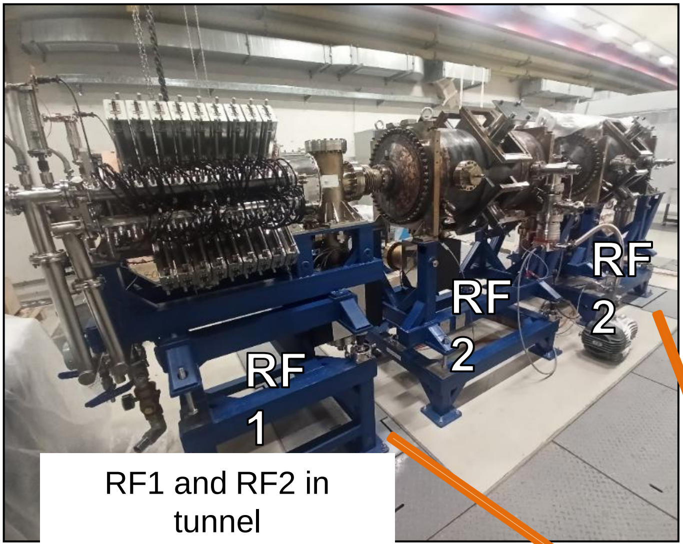


Quadrupole unit

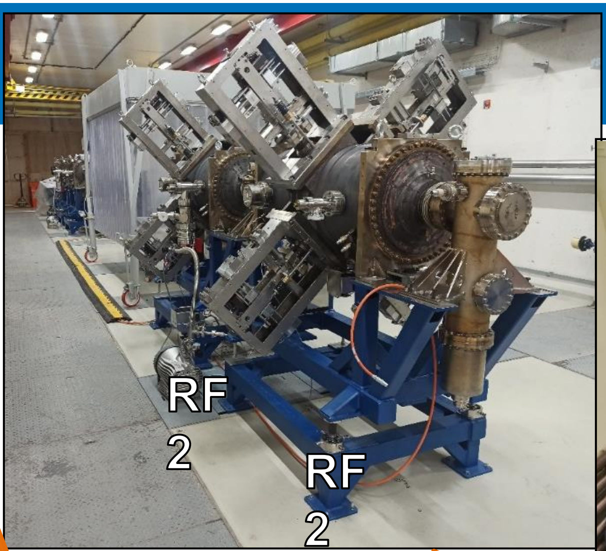
Dipole unit

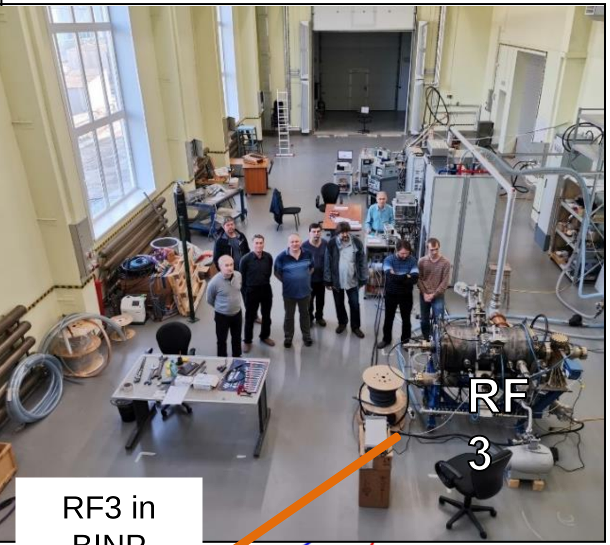
Dipole unit

R

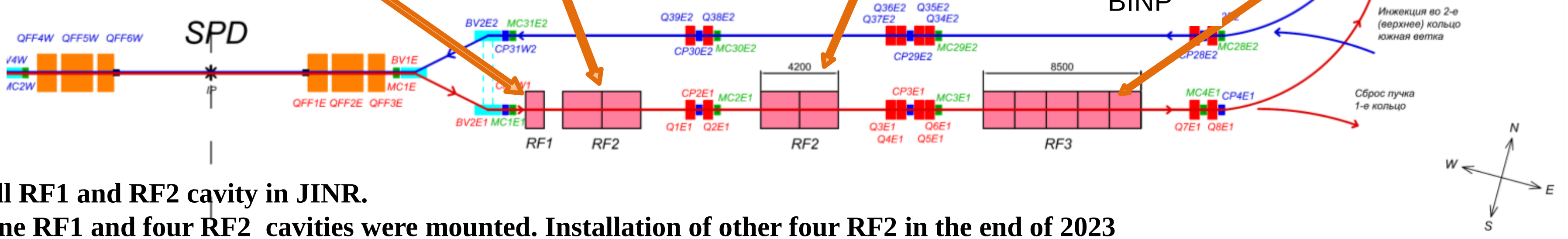


RF1 and RF2 in tunnel





RF3 in BINP



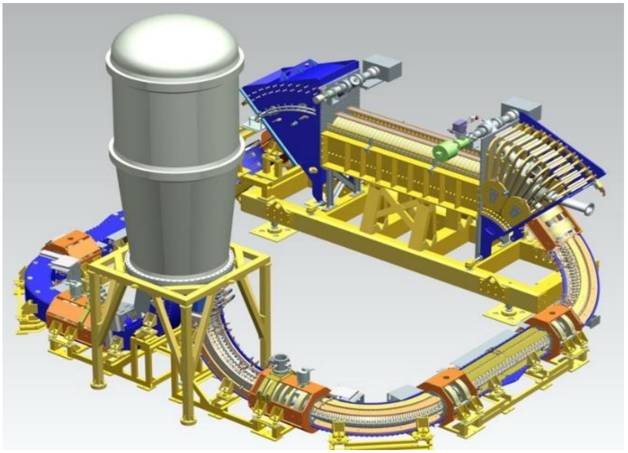
- **All RF1 and RF2 cavity in JINR.**
- **One RF1 and four RF2 cavities were mounted. Installation of other four RF2 in the end of 2023**
- **RF3 cavities and amplifier in BINP. Installation in the end of 2024**

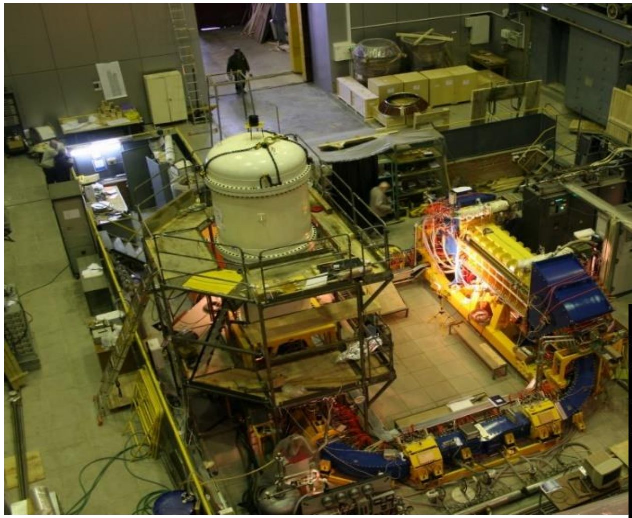
Two prototypes of NICA HV Electron cooler

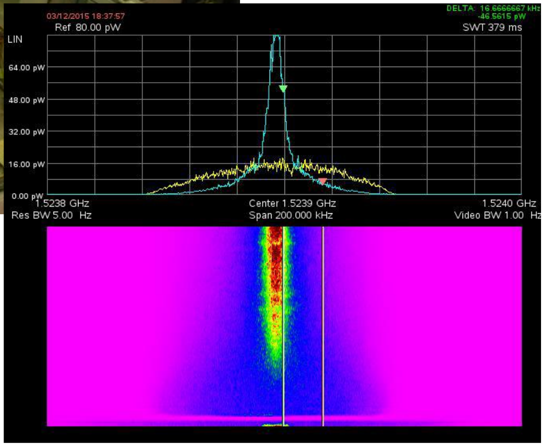
Fermilab (2005 - 2011)
S.Nagaitsev et al.

4.3 MeV, 0.5 A

BINP SB RAS
(2012)
V.V. Parkhomchuk et al
E-cooler for COSY
(from 2013)
2.0 MeV, 1.0 A

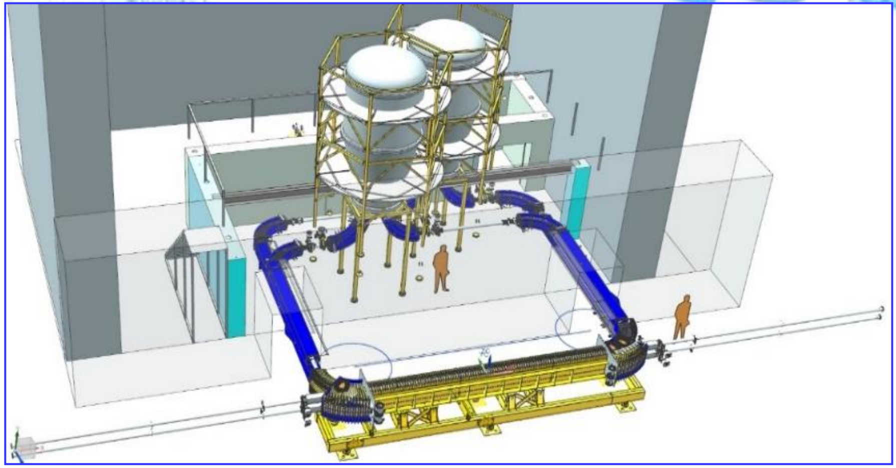






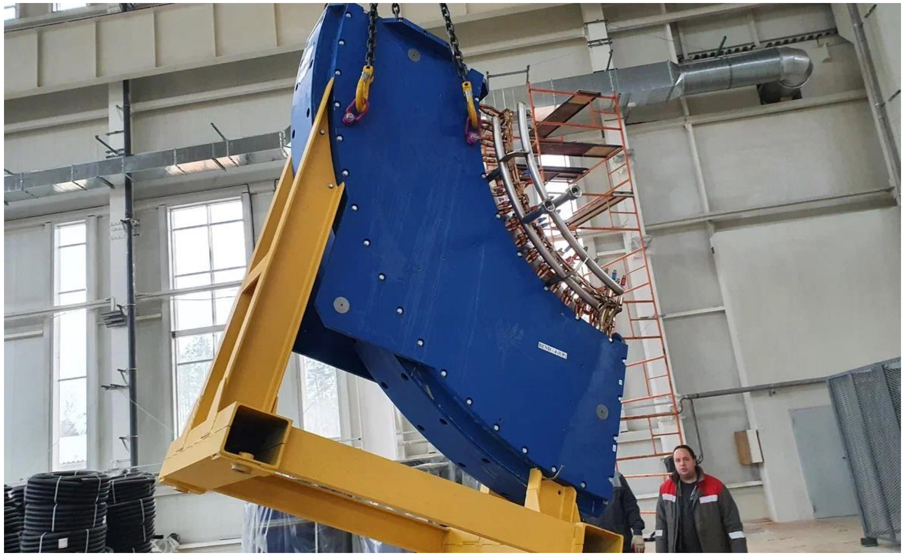
Electron Cooling System

Contract with BINP



Parameter	Value
Electron energy, MeV Energy instability, ΔE/E	0.2 – 2.5 $\leq 1{\cdot}10^{-4}$
Electron beam current, A	0.1 – 1.0
Cooling section length, m	6.0
Solenoid magnetic field, T Field inhomogeneity, ΔB/B	0.05 – 0.2 $\leq 1{\cdot}10^{-5}$

Main parts of the E-Cooler delivered to JINR and stored in SPD hall.



Beginning of mounting – Winter 2024 First beam tests – Autumn 2025

Plans

- Technological tests of collider equipment in 2024
- Bring the injection complex to the collider requirements by the beginning of 2025
- First beam operations in the second half of 2025

Thank you for attention

NICA

JINR

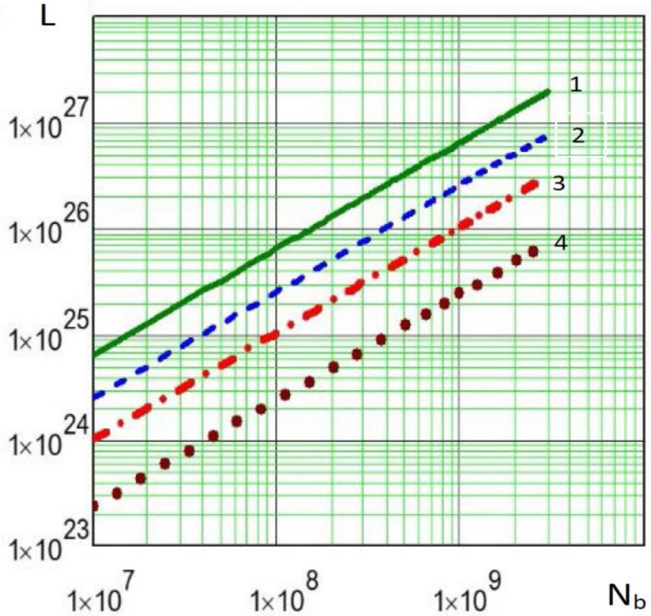
The first Collider run with beam

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 $\sigma \sim 2$ m per collider ring that 2e25 $cm^{-2} \cdot s^{-1}$. Maximum kinetic ion energy 2.5 GeV/n

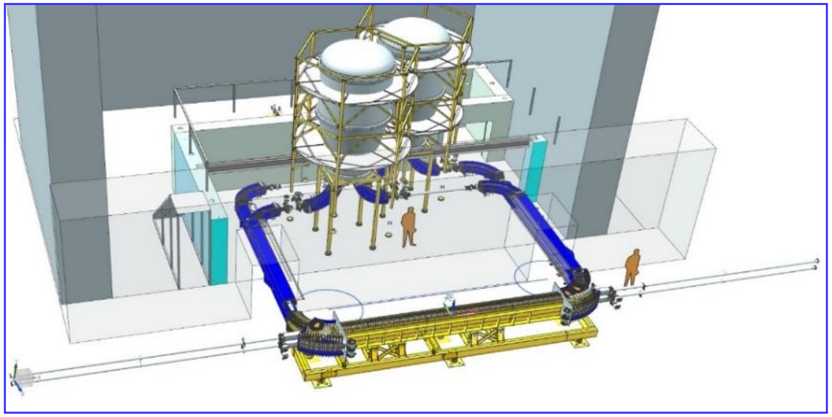
	Booster		Nuclotron		Collider
	Injection	Extraction	Injection	Extraction	
E	3,2 MeV/u	530 MeV/u	523 MeV/u	1,5-2,5 GeV/u	1,5-2,5 GeV/u
N	$5\cdot10^8$	$3.5*10^8$	$2.5*10^8$	$2*10^8$	$2*10^8$ (at injection) $4*10^9$ (at RF1 accumulation and formation of 22 bunches by RF2)
B_d, Тл	0,1	1,6	0,4	<1,2	<1.2



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

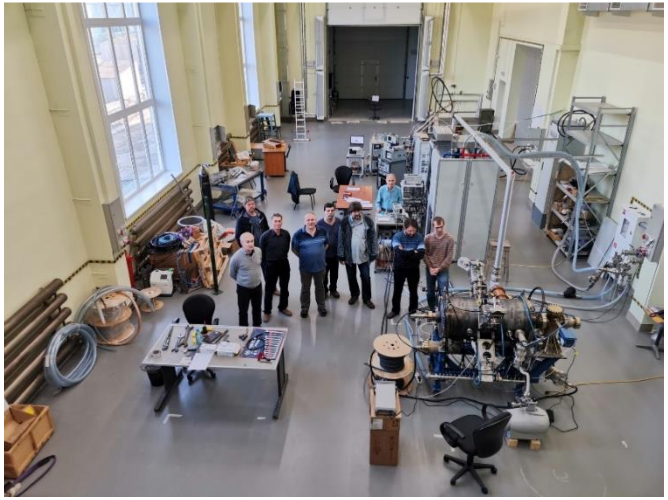
Electron Cooling System of NICA Collider



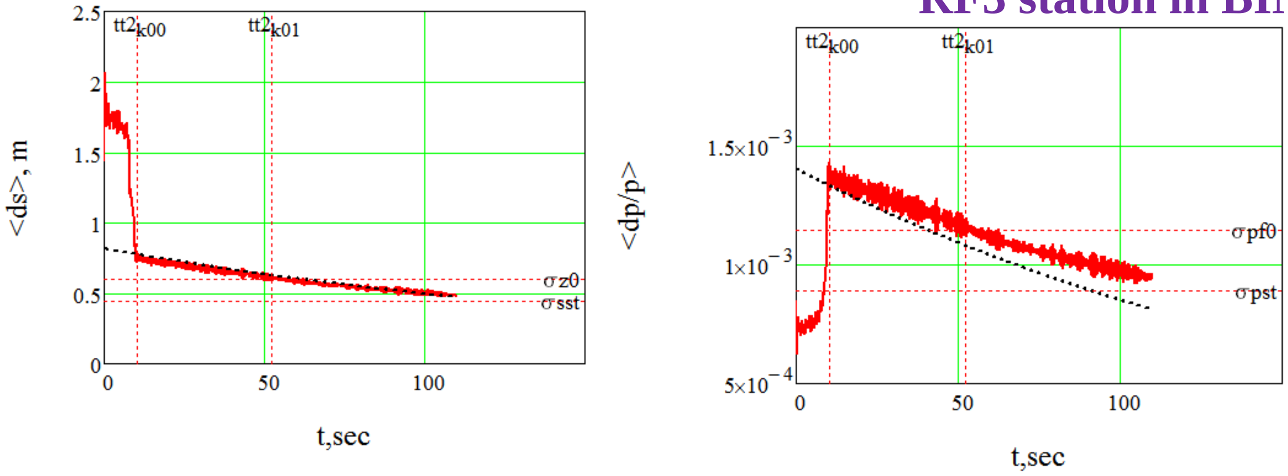
HV Electron Cooler for NICA Collider
Design and construction at BINP
Installation at NICA in 2023-2025

RF3 Bunching

Number of RF3 cavities per ring -8



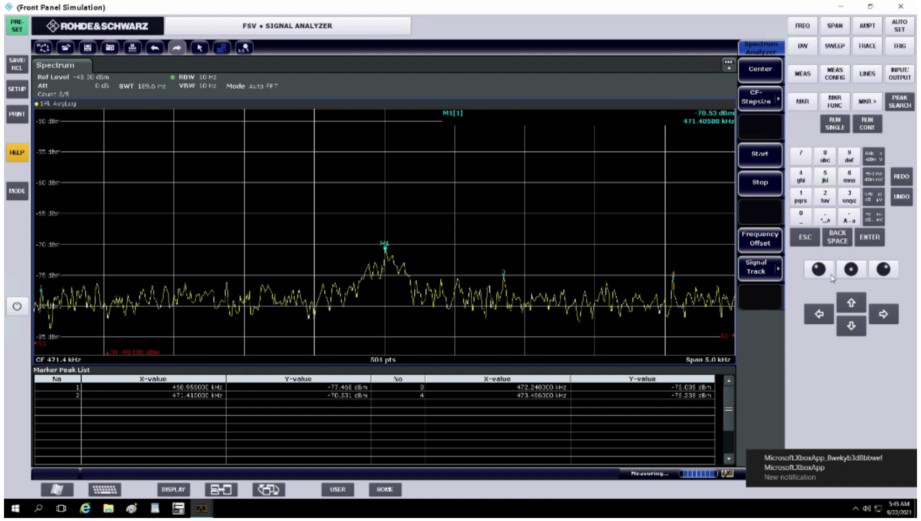
RF3 station in BINP, installation 2025



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

Electron cooling of Fe^{14+} ions at 3.2 MeV/u

1. **Ion beam circulation and acceleration from injection energy 3.2 MeV/n up 65 MeV/n, corresponding to energy of electron cooling, in Booster at ECOOL magnetic field 0.7 kG**
2. **Operation of ECOOL with effective recuperation at electron beam current range 30-150 mA.**



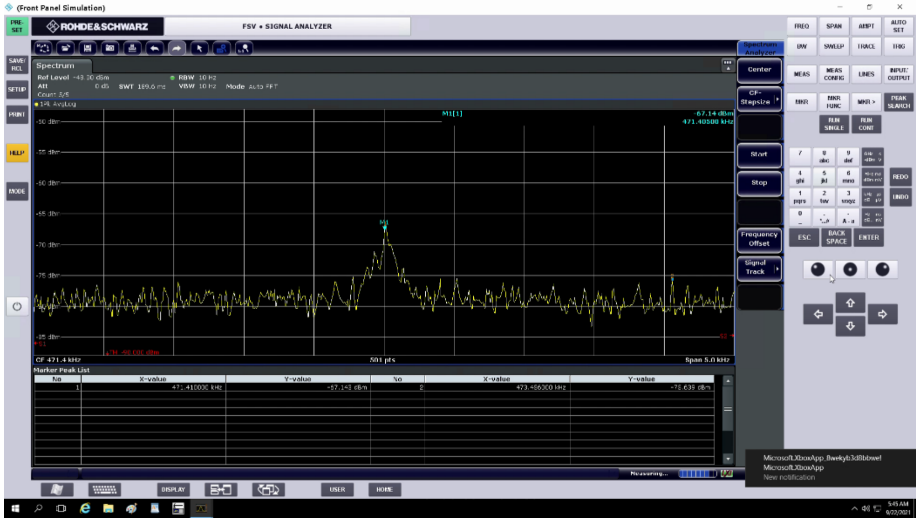
Ref Level -48.00 dBm RBW 10 Hz
Att 0 dB SWT 189.6 ms VBW 10 Hz Mode Auto FFT
Count 5/5
1Pk AvgLog

M1[1] -70.53 dBm 471.40500 kHz

Marker Peak List

No	X-value	Y-value	No	X-value	Y-value
1	458.955000 kHz	-77.458 dBm	3	472.240000 kHz	-75.035 dBm
2	471.410000 kHz	-70.531 dBm	4	473.456000 kHz	-75.238 dBm

FWHM dp/p=1.2E-3

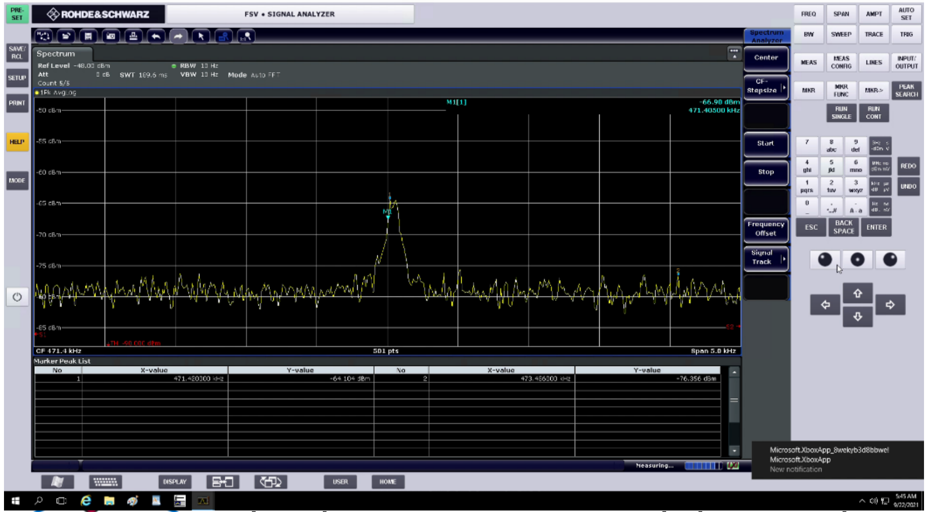


Ref Level -48.00 dBm RBW 10 Hz
Att 0 dB SWT 189.6 ms VBW 10 Hz Mode Auto FFT
Count 5/5
1Pk AvgLog

M1[1] -67.14 dBm 471.40500 kHz

Marker Peak List

No	X-value	Y-value	No	X-value	Y-value
1	471.410000 kHz	-67.143 dBm	2	473.486000 kHz	-76.639 dBm



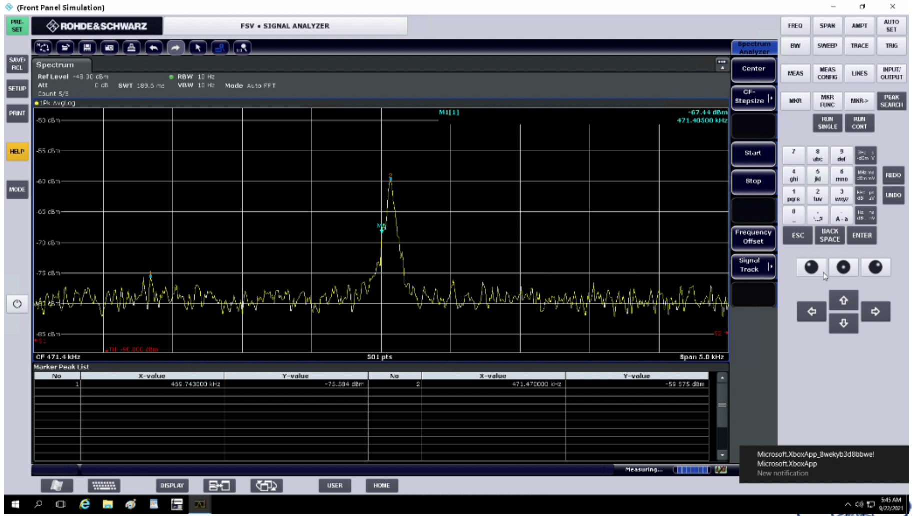
Ref Level -48.00 dBm RBW 10 Hz
Att 0 dB SWT 189.6 ms VBW 10 Hz Mode Auto FFT
Count 5/5
1Pk AvgLog

M1[1] -66.90 dBm 471.40500 kHz

Marker Peak List

No	X-value	Y-value	No	X-value	Y-value
1	471.420000 kHz	-64.104 dBm	2	473.486000 kHz	-76.356 dBm

Schottky spectrum at 4-th harmonics



Ref Level -48.00 dBm RBW 10 Hz
Att 0 dB SWT 189.6 ms VBW 10 Hz Mode Auto FFT
Count 5/5
1Pk AvgLog

M1[1] -67.44 dBm 471.40500 kHz

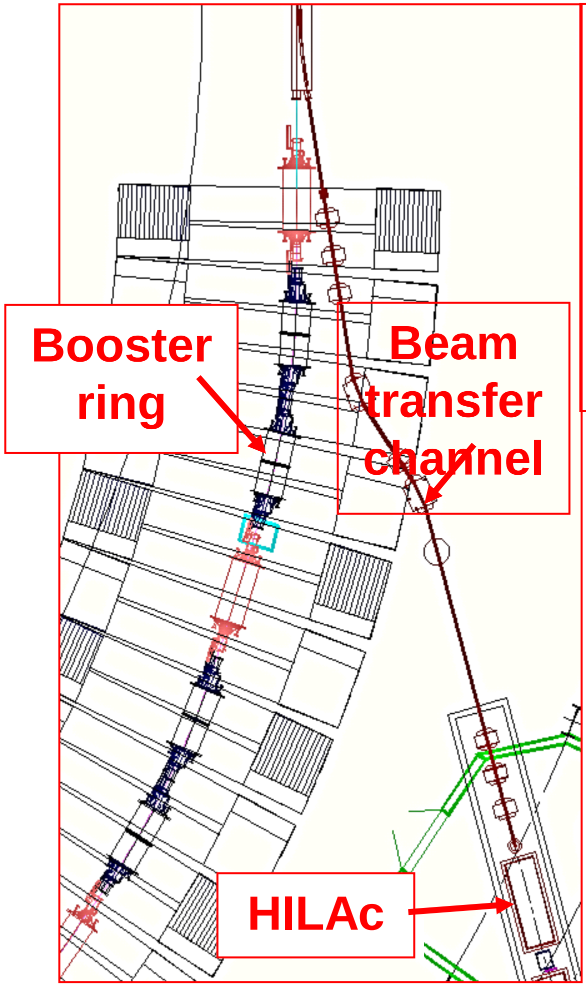
Marker Peak List

No	X-value	Y-value	No	X-value	Y-value
1	459.743000 kHz	-75.584 dBm	2	471.470000 kHz	-59.575 dBm

FWHM dp/p=4E-4

Booster electron cooling system

Why do we need an electron cooler for the Booster?



Booster ring

Beam transfer channel

HILAc

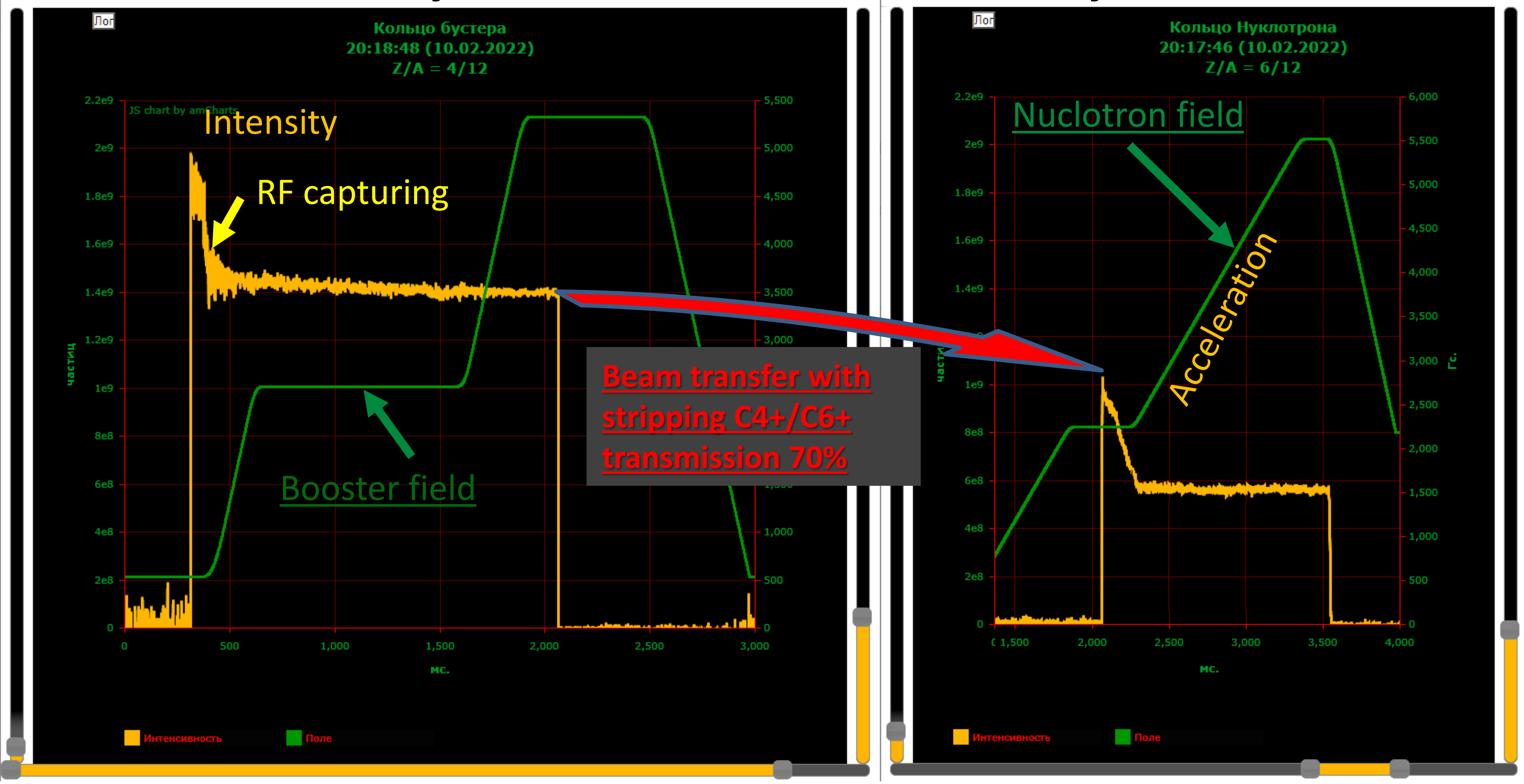
1. The beam injection methods:
- single-turn
- multiturn with e-cooling
- multiple with e-cooling

2. Reduction of beam emittance and momentum spread at 65 MeV/n at cooling time of 1 s to provide acceptable beam parameters after stripping target

Main results of RUN-3 (Booster + Nuclotron)

Winter 2022

Beam intensity in the Booster **intensity in the Nuclotron**



Beam transfer with stripping C4+/C6+ transmission 70%

Booster and Nuclotron beam DC current transformers signals

NICA accelerators

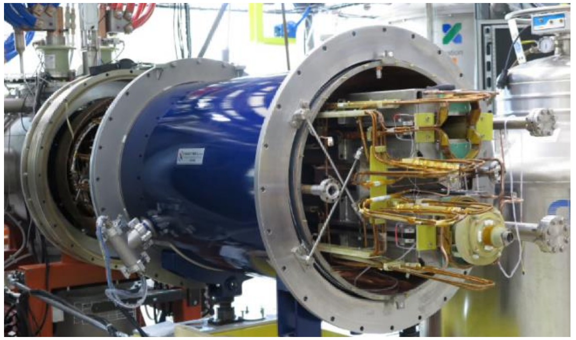
Collider

The Collider ring 503.04 m long has a racetrack shape and is based on double-aperture (top-to-bottom) superconducting magnets at maximum dipole field 1.8 T;

The major parameters of the NICA Collider are the following:
- magnetic rigidity = 45 T·m;
- ion kinetic energy range from 1 GeV/u to 4.5 GeV/u for Au^{79+};
- energy of polarized deuterons is 6 GeV/u, protons – 12 GeV,

- vacuum in a beam chamber: 10^{-11} Torr;
- zero beam crossing angle at IP;
- 9 m space for detector allocations at IP's;

Average luminosity 10^{27} cm^{-2}·s^{-1} for gold ion collisions at $\sqrt{s_{NN}}$ = 9 GeV.
The luminosity in the polarized mode is up to 10^{32} cm^{-2}·s^{-1}.



Commissioning –2021-2023
Technological run- September of 2024
First beam run –end of 2024