NICA project:
challenges for heavy ion collider

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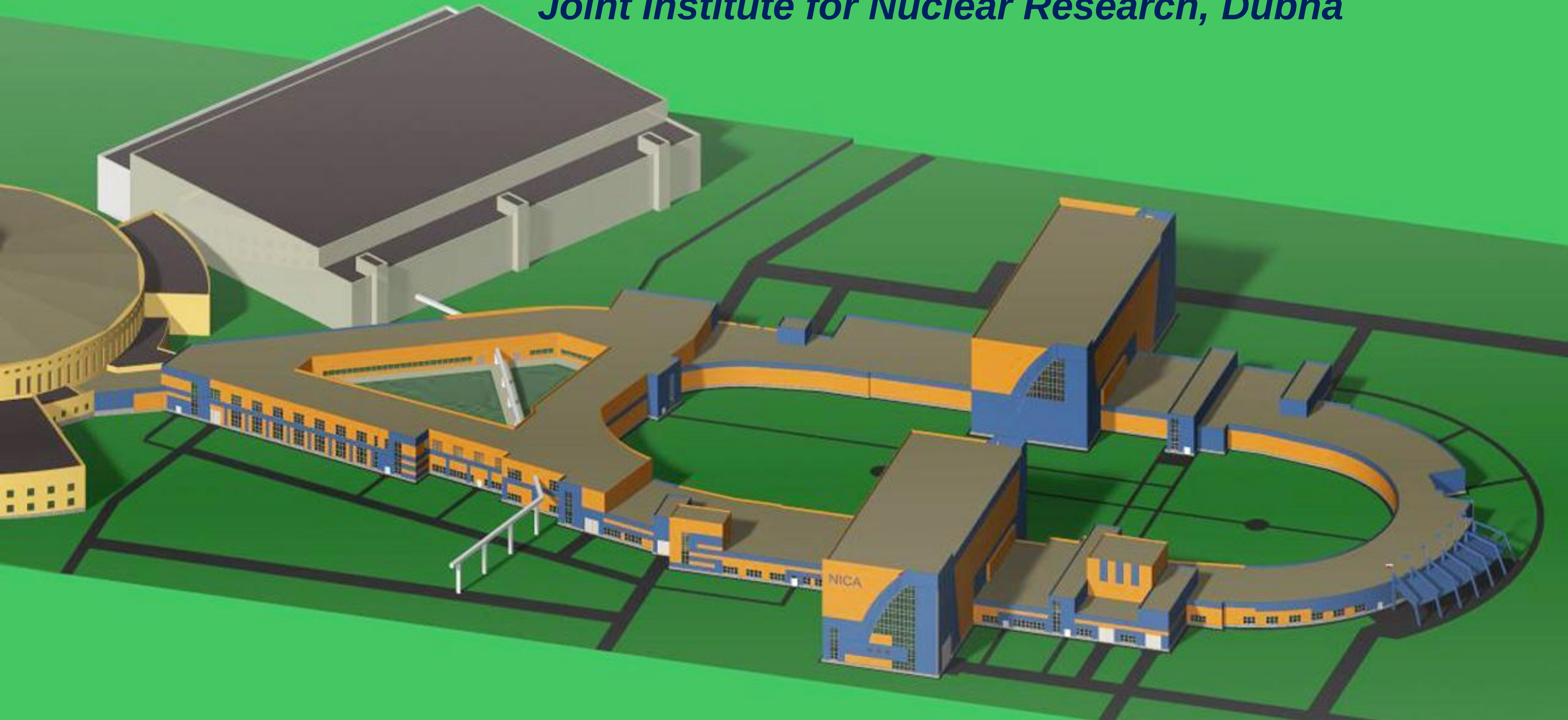


NICA: Nuclotron based Ion Collider fAcility

Contents

- NICA project: general information
- Challenges for heavy ion collider
- Status of the project

General information

NICA is an international project
realizing by international intergovernmental organization –
the Joint Institute for Nuclear Research
and brings the efforts of 16 member states and 6 associated countries.

Project NICA started as a part of the JINR Roadmap for 2009-2016
was described in the JINR 7-years Program.
It was approved by Scientific Council of JINR and
the Committee of Plenipotentiaries of JINR in 2009.
NICA is a flagship project of JINR presently.

In 2016 between RF and JINR was signed a contract
presuming start of operation of basic configuration of the NICA complex in 2024.

Project web-site: http://nica.jinr.ru/

The primary purpose of the NICA construction

The project comprises experimental studies of **fundamental** character
in the fields of the following directions:
- **Relativistic nuclear physics;**
- Spin physics in high and middle energy range of interacting particles;
- Radiobiology.

Applied researches based on particle beams generated at NICA
are dedicated to development of novel technologies in material science,
environmental problems resolution, energy generation,
particle beam therapy and others.

Education program is one of the first priority activities at JINR,
as formulated in JINR Roadmap.
The proposed NICA facility offers various possibilities for teaching
and qualification procedures including practice at experimental set ups,
preparation of diploma works, PhD, and doctoral theses.

Stages of the experimental program realization

Stage I

-**Fixed target experiment with heavy ions (2018)**

Stage II

-**Basic configuration of the collider and MPD (2024)**

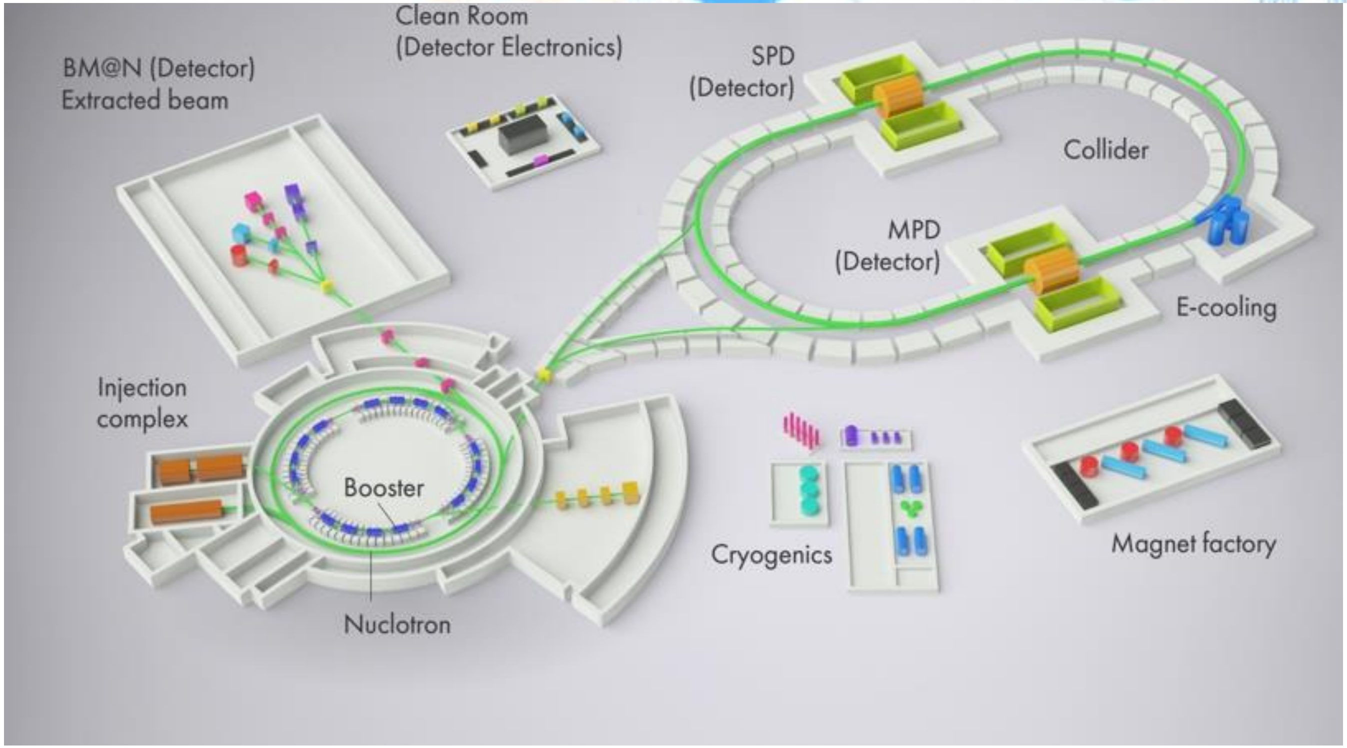
-**Full configuration, heavy ion collisions**

-**Collisions of heavy ions with light ions (protons)**

Stage III

-**Spin physics program**

The NICA complex includes:



- Set of accelerators providing the particle beams for fixed target and collider experiments,
- Experimental facilities (BM@N, MPD, SPD, IT, Area for applied researches)
- Line for assembling and cryogenic testing of SC-magnets,
- Workshops for construction of the detector elements,
- NICA innovation center,
- Required infrastructure.

Challenges for heavy ion collider

- Luminosity of the collider
- Space charge effects at low energy
- Requirements to low energy collider

Luminosity of the collider

The global scientific goal of the NICA/MPD
is to explore the phase diagram of strongly interacting matter
in the region of high compression.
The proposed program allows to search for possible signs
of the phase transitions and critical phenomena
in heavy ion (up to Bi) collisions
at centre-of-mass energies up to 11 GeV/u.

General requirement is optimum operation of the Multy Purpose Detector:

- Zero crossing angle in the interaction point,
- The luminosity has to be concentrated inside vertex detector

The collider has to be operated with a bunched beam
at the bunch length $\leq$ ***60 cm***

Luminosity of the collider

Required luminosity:

Event rate is limited by MPD electronics $\dot{N}_{event} \leq 7\ kHz$

The cross-section $\sigma \approx 7 \cdot 10^{-24}\ cm^{-2}$

$$L = \dot{N}_{event} / \sigma \ \leq 1 \cdot 10^{27}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

This level is typical for RHIC (Au-Au) and LHC (Pb-Pb),

However ***the ion kinetic energy is below 4.5 GeV/u***

Luminosity of the collider

Technical limit related with the ion production rate by injection chain:

$$\dot{N}_{pr} = \dot{N}_{loss}$$

$$\dot{N}_{loss} = \dot{N}_{event} + \dot{N}_{other\ loss}$$

$$L \le \dot{N}_{pr} / \sigma$$

NICA heavy ion injection chain is designed to provide 10^9 Au nuclei each 5 sec:

$$\dot{N}_{pr} = 2\cdot 10^8\ \mathrm{s}^{-1}$$

$$L \le 3\cdot 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Four orders of magnitude of the technical reserve permits
to use the injection chain for a few experiments in parallel.
The collider luminosity is limited by particle dynamics.

Luminosity of the collider

For round beams at the same cross-section

$$L = \frac{n_b N_b^2}{4\pi\varepsilon\beta^* T_{rev}} f\left(\frac{\sigma_s}{\beta^*}\right)$$

$$f\left(\frac{\sigma_s}{\beta^*}\right) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{\exp(-u^2)du}{\left[1+\left(\frac{u\sigma_s}{\beta^*}\right)^2\right]}$$

Number of bunches n_b has to be as large as possible, but the inter-bunch distance is to be large enough to avoid parasitic collisions inside detector

At high energies (Tevatron, RHIC, LHC)
the collider is used for the beam acceleration also
Train of bunches is prepared by injection chain
-the bunch intensity N_b has to be maximum,
-the emittance ε growth has to be minimized in all elements of injection chain

Beta function in collision point β^* has to be as small as possible, but comparable with bunch length σ_s to avoid luminosity reduction due to “hour-glass” factor

Space charge effects at low energy

The bunch brightness N_b/ε is limited by two main space charge effects:

Incoherent shift of the betatron tune (Laslett tune shift)

$$\Delta Q = -\frac{Z^2 r_p}{A}\frac{N_b}{4\pi\varepsilon\beta^2\gamma^3}F_{sc}F_b$$

$$F_b = \frac{C}{\sqrt{2\pi}\sigma_s}$$ - Bunching factor

Beam-beam parameter
(linear part of the tune shift due to fields of opposite bunch)

$$\xi = \frac{Z^2 r_p}{A}\frac{N_b}{4\pi\varepsilon\beta^2\gamma}\frac{1+\beta^2}{2}$$

The bunch brightness can be increased to the limit by beam cooling application:
-Synchrotron cooling at electron-positron colliders
-Stochastic cooling at RHIC

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Lasslett tune shift fast decreases with energy (as γ^3), because the magnetic field compensates electrical repulsion

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(linear part of the tune shift due to fields of opposite bunch)

$$\xi = \frac{Z^2 r_p}{A}\frac{N_b}{4\pi\varepsilon\beta^2\gamma}\boxed{\frac{1+\beta^2}{2}}$$

The beam-beam parameter decreases with energy as γ, because the magnetic field of the opposite bunch increases electrical repulsion

Space charge effects at low energy

At high energy (RHIC, LHC):
Lasslett tune shift is negligible,
the luminosity is limited by beam-beam parameter

At low energy:
Beam-beam parameter and Laslett tune shift can be comparable (RHIC BES)
or Laslett tune shift dominates (NICA: $\xi \sim 0.1 \cdot \Delta Q$)

***Important difference** ξ **does not depend on the ring circumference** C*
while** $\Delta Q \sim C$ **(via bunching factor)

Space charge effects at low energy

At low energy the beam brightness can be expressed
from maximum achievable tune shift ΔQ that gives for luminosity:

$$L = \frac{A}{Z^2 r_p}\frac{n_b N_b c}{\beta^*}\frac{\sqrt{2\pi}\sigma_s}{C^2}\gamma^3\beta^3 f\left(\frac{\sigma_s}{\beta^*}\right)\Delta Q \qquad \left(T_{rev} = \frac{C}{\beta c}\right)$$

This formula relates to the case when the bunch intensity is constant
and determined by injection chain performance

To reach this maximum value the beam emittance must be varied with energy

$$\varepsilon = \frac{Z^2 r_p}{A}\frac{N_b}{4\pi\beta^2\gamma^3\Delta Q}\frac{C}{\sqrt{2\pi}\sigma_s}$$

active formation of the beam phase volume (beam cooling) is mandatory

Space charge effects at low energy

The way to increase the luminosity is to vary bunch intensity with energy, in this case

$$L = \left(\frac{A}{Z^2 r_p}\right)^2 \frac{\varepsilon}{\beta^*} \frac{8\pi^2 \sigma_s^2 c}{C^2 l_{bb}} \gamma^6 \beta^5 f\left(\frac{\sigma_s}{\beta^*}\right) \Delta Q^2$$

(l_{bb} is the minimum inter-bunch distance approximately equal to the detector length)

In difference with high energy collider

$$L \sim \frac{\varepsilon \Delta Q^2}{C^2}$$

-The bunch intensity should be varied with energy

-The beam emittance has to be as large as possible (close to acceptance limit)

-The ring circumference has to be minimum

-The working point has to be far from low order resonances

Space charge effects at low energy

Important peculiarity of low energy collider:
Fast grows of the beam phase volume due to **Intra-Beam Scattering**:

RHIC ~ 4 h
LHC >> 10 h

NICA 3 ÷ 30 minutes

At large emittance the RF system of the collider should provide
large momentum spread of the bunch
(to avoid relaxation between degrees of freedom)

Beam cooling during experiment is mandatory

Challenges for low energy collider

-Minimum collider circumference

- Preliminary beam storage and bunch formation, adjustment of bunch intensity at each energy
(complicated structure of RF system)

-Maximum achievable beam emittance
(Large dynamic aperture of the ring)

-Large momentum spread corresponding to minimum IBS rates
(chromaticity correction has to provide large acceptance on momentum deviation)

-Control of tune spread to achieve maximum ΔQ
(octupole correction system)

-Beam cooling during storage, bunch formation and experiment
(High energy electron cooling (2.5 MeV), stochastic cooling of bunched beam)

NICA collider for gold-gold collisions

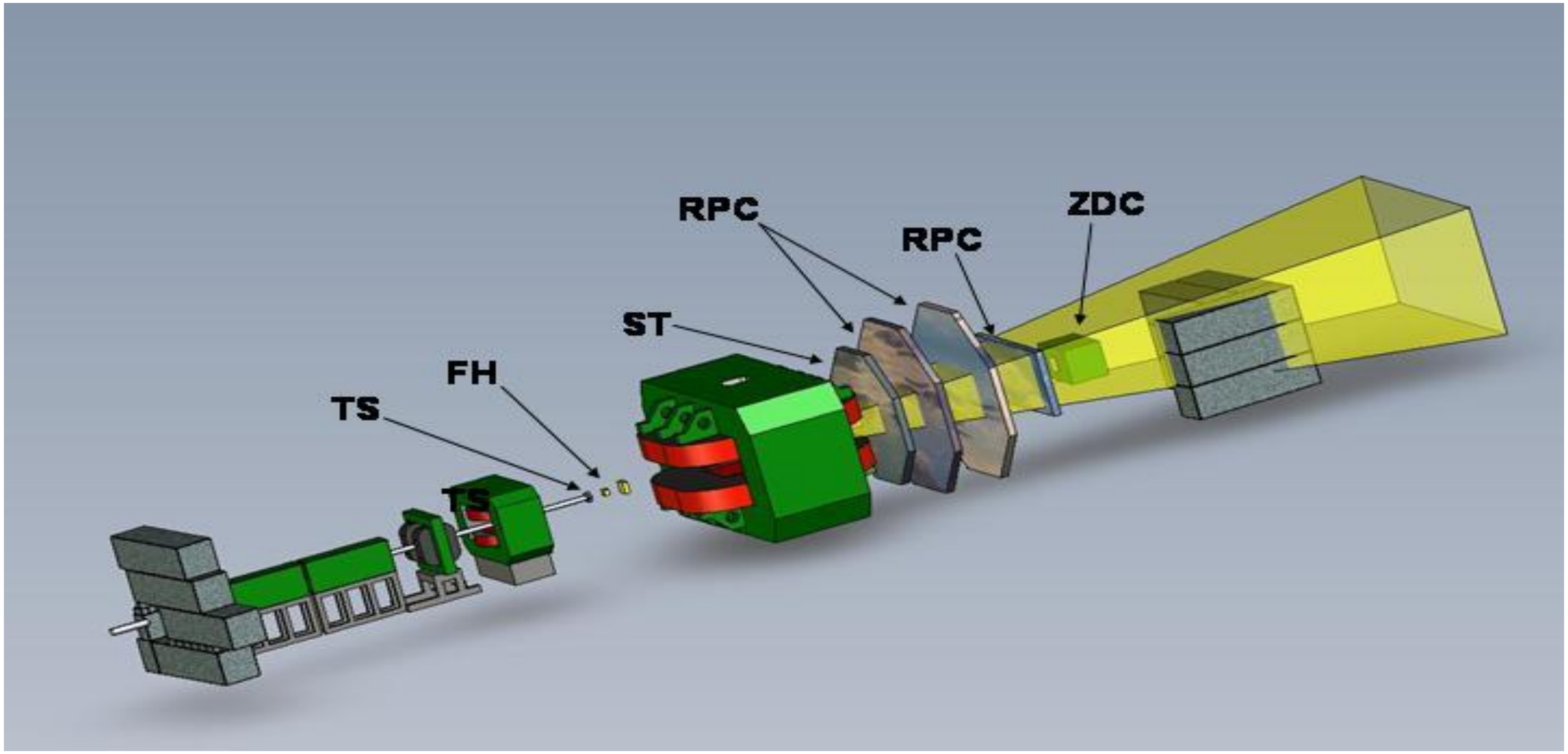
Circumference of the ring, m	503.04		
Structure of the bending arc	FODO, 12 cells		
Number of bunches	22		
R.m.s. bunch length, m	0.6		
β-function in IP, m	0.35		
Betatron frequinces, Q_x/Q_y	9.44/9.44		
Chromaticicities, Q'_x/Q'_y	-33/-28		
Acceptance, π mm·mrad	40		
Momentum acceptance, $\Delta p/p$	±0.010		
Critical energy factor , γtr	7.088		
Energy of Au^{79+}, GeV/u	1.0	3.0	4.5
Number of ions per bunch	$2.0 \cdot 10^{8}$	$2.4 \cdot 10^{9}$	$2.3 \cdot 10^{9}$
R.m.s. momentum spread, $\Delta p/p$	$0.55 \cdot 10^{-3}$	$1.15 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
R.m.s. emittance, π mm·mrad	1.1/0.95	1.1/0.85	1.1/0.75
Luminosity, cm^{-2} s^{-1}	$0.6 \cdot 10^{25}$	$1.0 \cdot 10^{27}$	$1.0 \cdot 10^{27}$
IBS growth time, s	160	460	1800

Status of the project

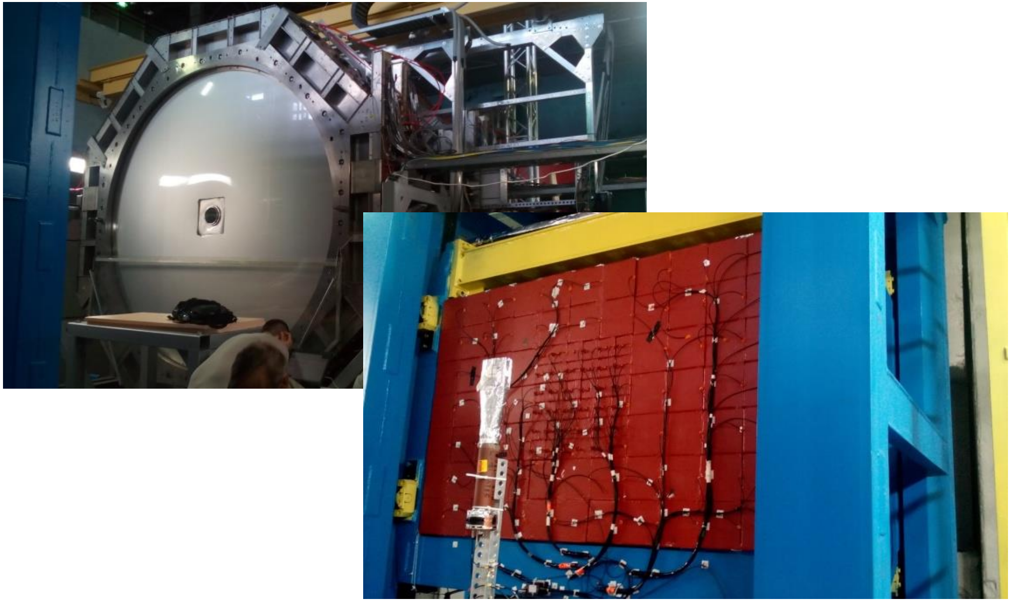
- Baryonic Matter at Nuclotron (BM@N)
- Elements of the accelerator complex
- Injection facility commissioning
- Collider construction

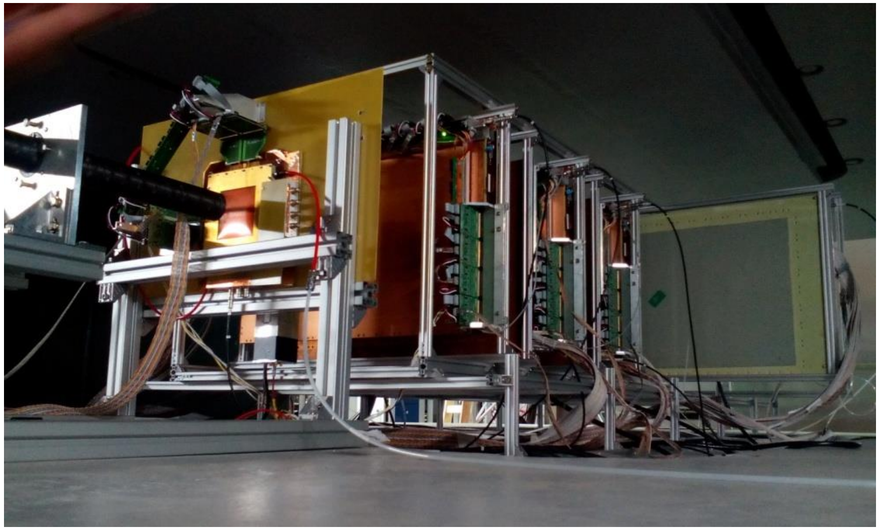
Baryonic Matter at Nuclotron (BM@N)

fixed target experiment at the Nuclotron extracted beams
which main goals are investigations of strange / multi-strange hyperon, hypernuclei production and short range correlations.



BM@N assembly

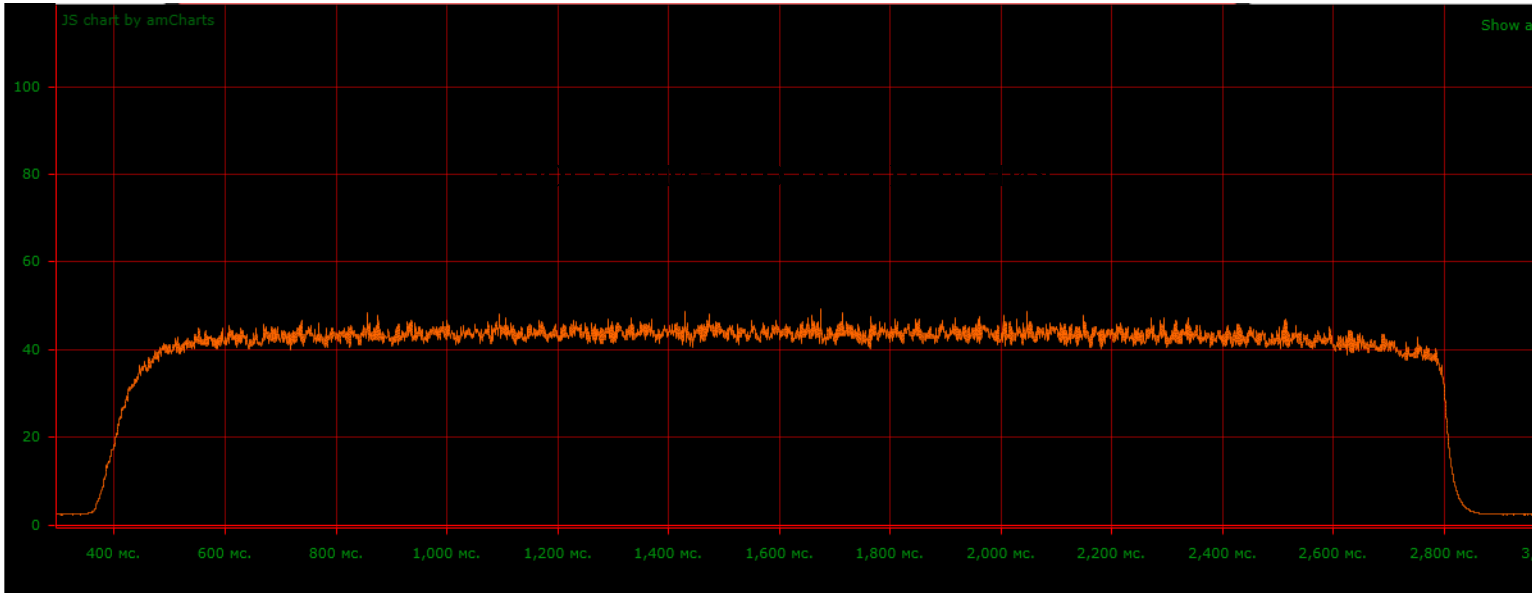




BM@N test at the Nuclotron beam

-Three technological runs (2016 – 2017)

-**5.02 – 4.04.2018 experiments** with C, Ar, Kr beams (Short range correlations, strange production)



Intensity of the extracted Kr beam. Spill duration 2.5 sec.
Up to $5 \cdot 10^5$ ions per cycle

NICA accelerators

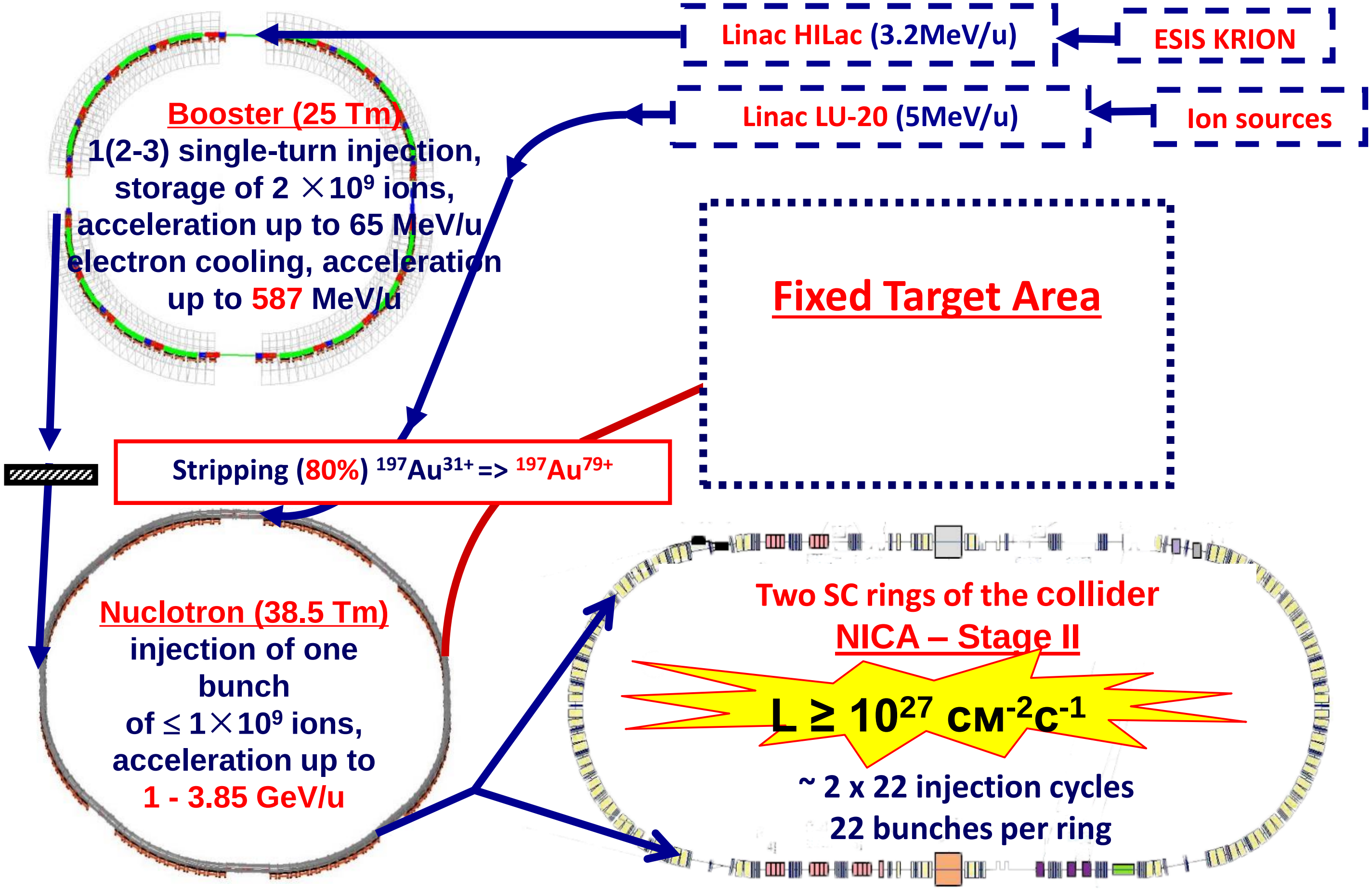
Main accelerator of the NICA complex is **the Nuclotron** –
superconducting ion synchrotron at magnetic rigidity of about 42 T·m
equipped with two injection chains: for heavy and for light ions.

Injection chain for heavy ions consists of:
the ion source (KRION-6N), heavy ion linear accelerator (HILac),
superconducting booster synchrotron (Booster) and required beam transport lines.

Injection chain for light ions includes:
Laser ion source (LIS), Source of polarized ions (SPI), Duoplasmatron,
RFQ accelerator as a foreinjector, Drift tube linac of Alvarec type (LU-20)
and required beam transport lines.

The collider experiments will be provided at two storage rings
with two interaction points (IP).

NICA accelerator complex



Linac HILac (3.2MeV/u)

ESIS KRION

Linac LU-20 (5MeV/u)

Ion sources

Booster (25 Tm)
1(2-3) single-turn injection,
storage of 2 $\times 10^9$ ions,
acceleration up to 65 MeV/u
electron cooling, acceleration
up to 587 MeV/u

Fixed Target Area

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

Nuclotron (38.5 Tm)
injection of one
bunch
of $\leq 1 \times 10^9$ ions,
acceleration up to
1 - 3.85 GeV/u

Two SC rings of the collider
NICA – Stage II

$L \geq 10^{27}$ см$^{-2}$с$^{-1}$

~ 2 x 22 injection cycles
22 bunches per ring

Heavy ions: ESIS + HILac + Booster + Nuclotron

Stages of the accelerator complex commissioning

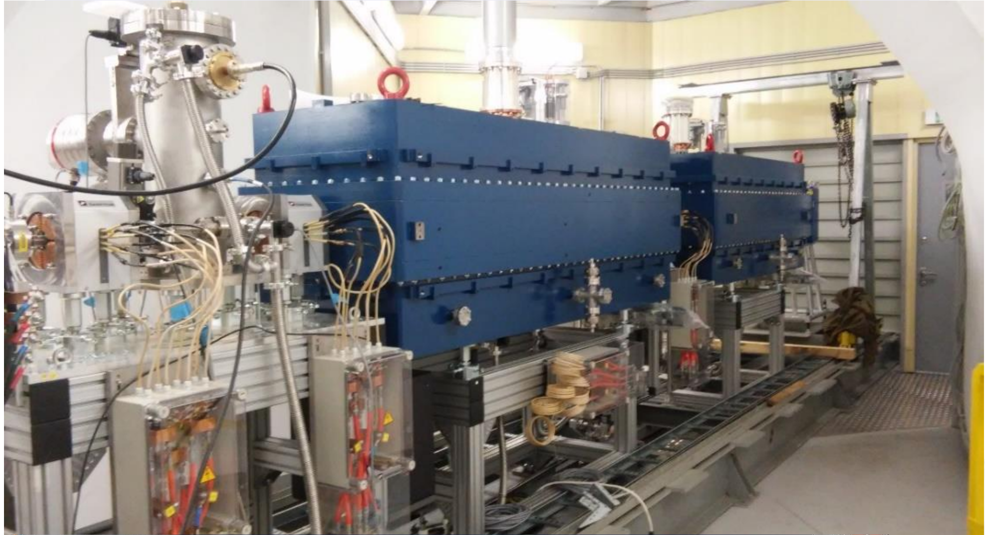
Started 2020

- HILAC + transfer line to Booster
- HILAC + Booster
- HILAC + Booster + transfer line to Nuclotron
- HILAC + Booster + Nuclotron + transfer line to BM@N
- ESIS + HILAC + Booster + modified Nuclotron + transfer line to BM@N

Completed 2023

HILAC + transfer line to Booster

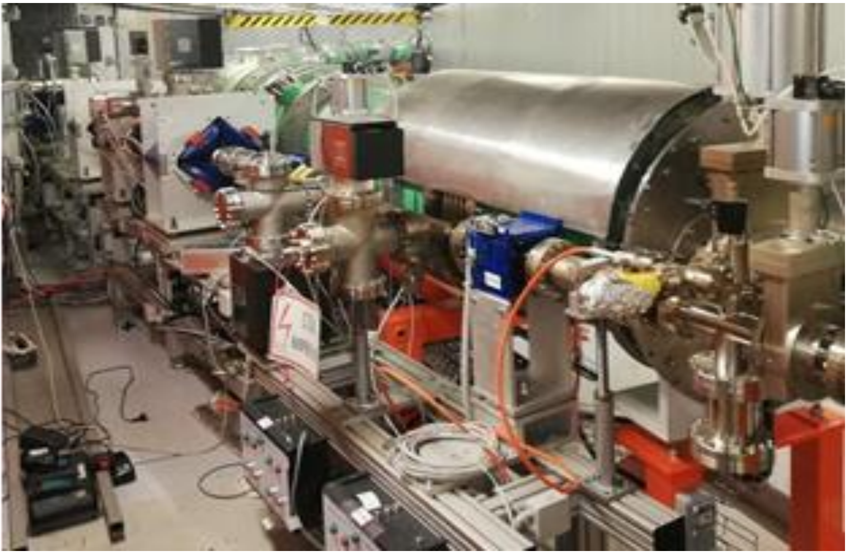
First beam: Oct. 16



$_4He^{1+}$ ion beam at HILAC exit measured by current transformer and Faraday Cup

Acceleration of $_{12}C^{2+}$ ions with A/Z=6.

Maximal ion $_4He^{1+}$ beam current at HILAC entrance corresponds to project value 10 mA, efficiency of beam transportation through second and third IH sections 78.5%.



Transfer line HILAC-Booster.
Efficiency of beam transportation -90%.

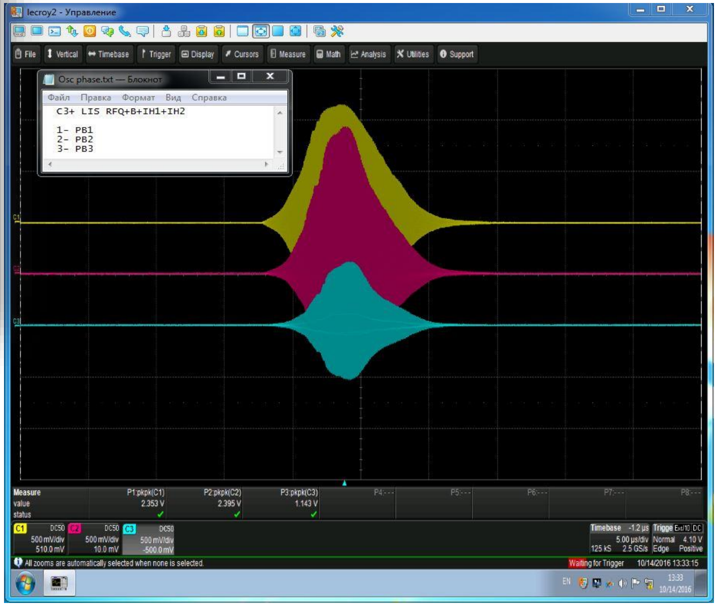
Stable and safe operation during complex commissioning with He^{1+} Fe $^{14+}$ C $^{4+}$ Ar $^{14+}$ Xe $^{28+}$ beams


Commissioned in 2018

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

Transmission of carbon ions about 70% from RFQ to the exit of linac, 3.2 MeV/u

Phase probe's signals
RFQ (red), IH1 (yellow), IH2 (blue)

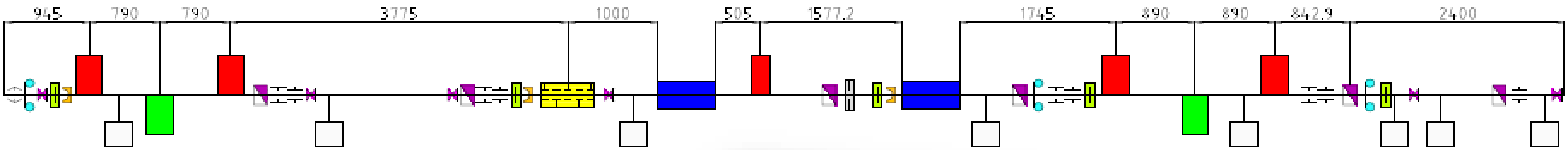


```
C3+ LIS RFQ+B+IH1+IH2

1- PB1
2- PB2
3- PB3
```

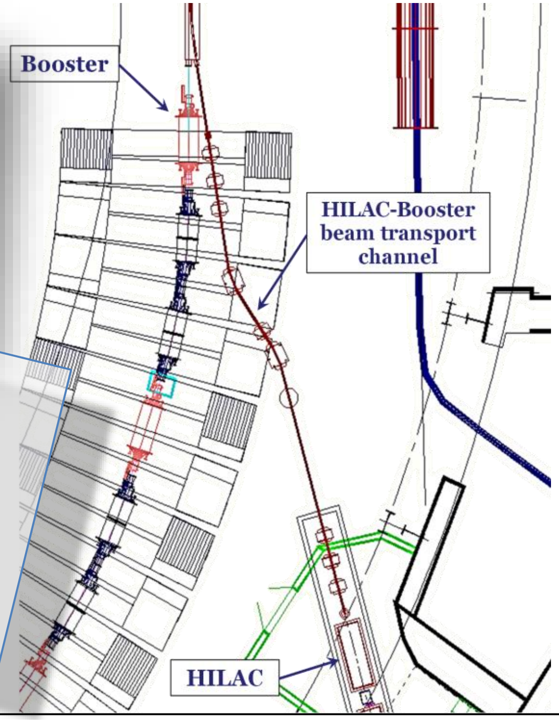
```
Measure   P1:pkpk(C1)   P2:pkpk(C2)   P3:pkpk(C3)   P4:---   P5:---   P6:---   P7:---   P8:---
value          2.353 V       2.395 V       1.143 V
status               ✓             ✓             ✓
C1      DC50   C2      DC50   C3      DC50                Timebase  -1.2 µs   Trigge Ext/10 DC
    500 mV/div     500 mV/div     500 mV/div                         5.00 µs/div   Normal   4.10 V
      510.0 mV        10.0 mV      -500.0 mV              125 kS    2.5 GS/s     Edge   Positive
All zooms are automatically selected when none is selected.        Waiting for Trigger   10/14/2016 13:33:15
```

Booster injection beam line



Commissioned

beam transmission ~75%



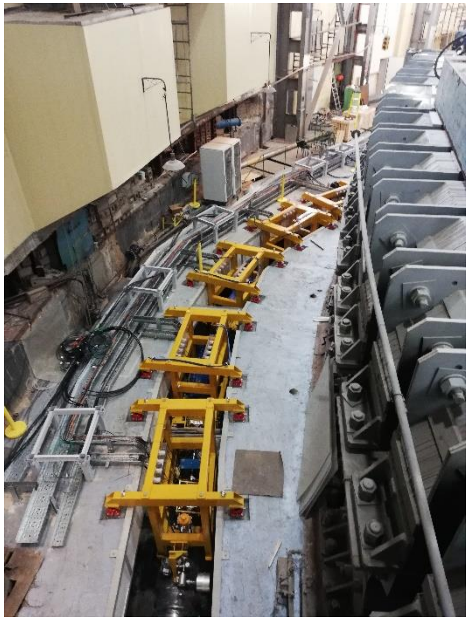
- ✓Debunching
- ✓Matching
- ✓Separation and adsorption of neighbor charge states of ions.
- ✓Provide different schemes of the beam injection into the Booster.

HILAC + Booster

First commissioning run 12.11 – 30.12. 2020, He^{1+} beam :

- assembly and test of vacuum system
- cooling, thermometry commissioning
- commissioning of quench protection system, tuning of power supply,
- tuning of the HILAC – Booster transfer line
- tuning He^{1+} beam circulating
- test of beam diagnostics, beam acceleration, test of electron cooling
- test of power supply, magnetic and cryogenic systems at design field

Assembly BNTL after the first run



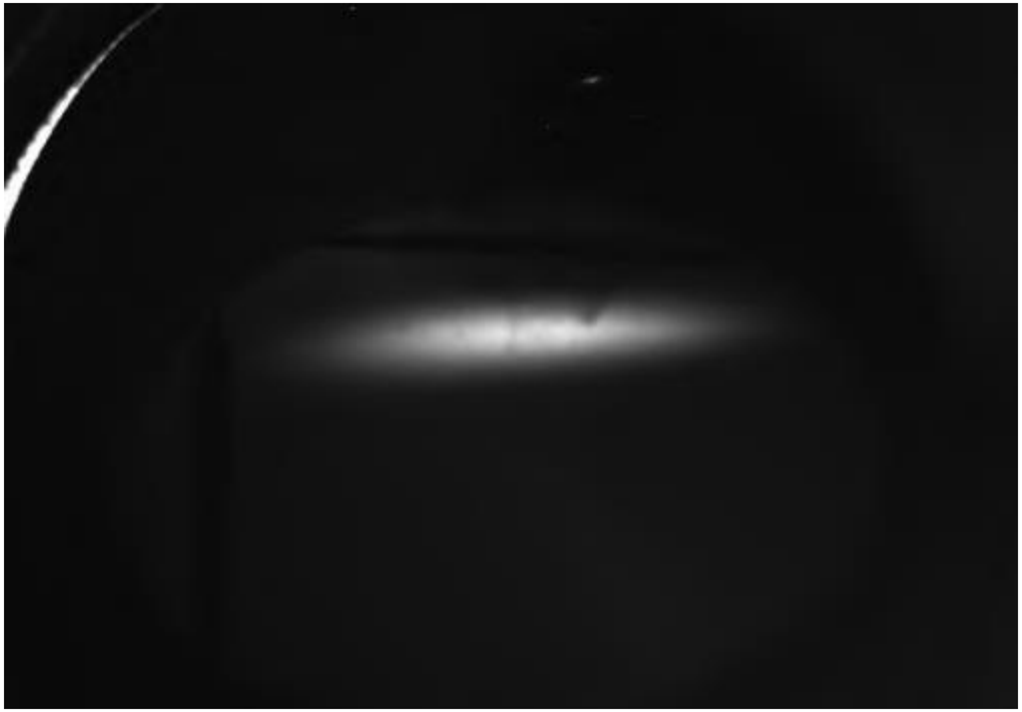
HILAC + Booster + transfer line to Nuclotron

Second commissioning run 06.10 – 24.10 2021, He^{1+}, Fe^{16+} Ions:

- Improvement of the vacuum conditions
- Optimization of the beam dynamics,
- Test of the Booster Electron Cooler
- **Test of the BNTL**

Beam transport from Booster to Nuclotron

The orbit bump system was tuned at the beam extraction,
The systems for the beam extraction from the Booster and transport line to the Nuclotron were put into operation and tuned,
Helium beam and then the iron $^{56}Fe^{14+}$ beam were transported through the beam transfer line.



Beam of Fe ions on the phosphor screen
at the end section of the Booster-Nuclotron transport line

HILAC + Booster + Nuclotron + transfer line to BM@N

Third commissioning run 2.01.2022 – 01.04.2022, C ions:

-Tuning of the Booster cycle:
- adiabatic capture at injection (5 harmonics),
- recapture at 65 MeV/u (1 harmonics),
- Single-turn extraction

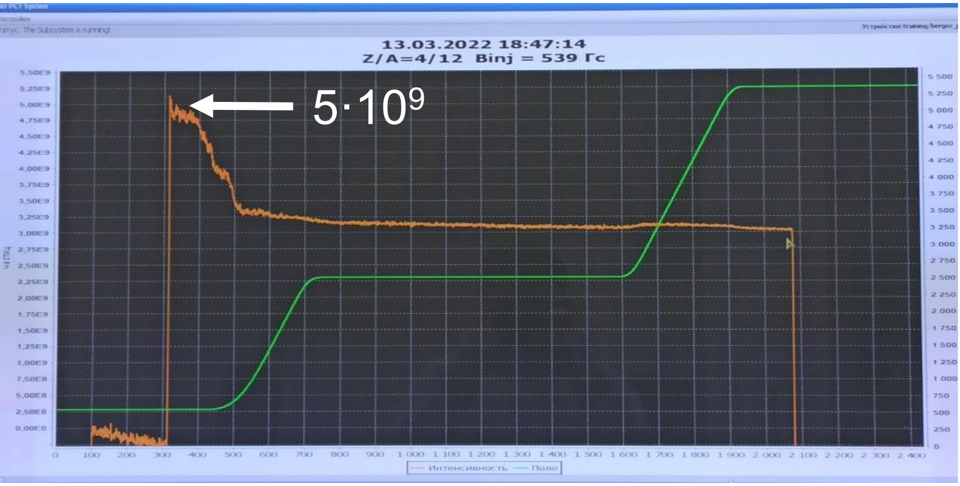
Transport Booster – Nuclotron:
- Stripping C^{4+} - C^{6+}

Nuclotron:
- Injection from Booster (new kicker and Lambertson magnet),
- adiabatic capture at 5th harmonics,
- acceleration to 3 Gev/u,
- Slow extraction during 6 sec.

Beam transport to BM@N area:
- Test of new power supply, diagnostic and control systems,
- Stable operation during 24 days

Tuning of the beam acceleration

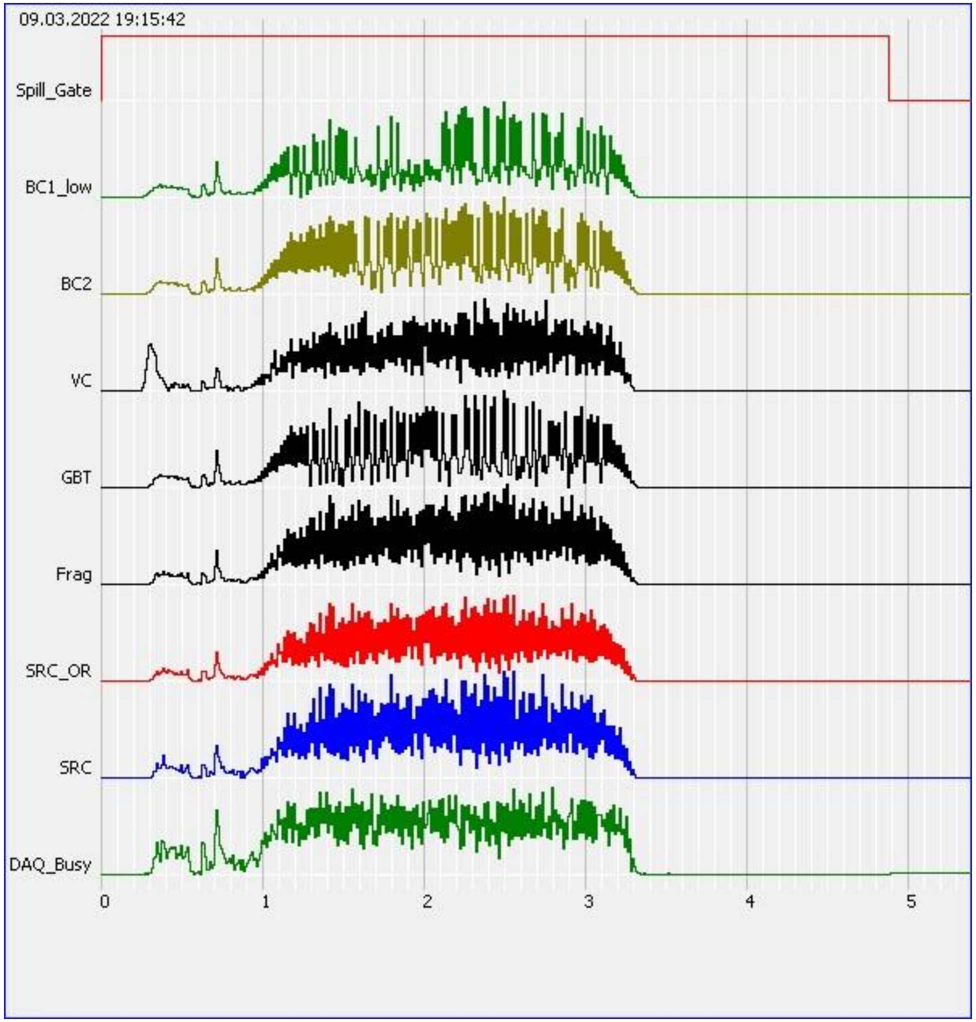
Booster



Nuclotron

Average efficiency ~ 30%:
- pulse-to-pulse variation of the injected beam parameters
- non-optimum stripping target thickness

SRC collaboration registered 185 MEvents of carbon interaction with hydrogen target



Intensities of the 3 GeV/u carbon beam as a function of time measured at the BM@N setup (SRC experiment) for one spill.
X axis shows time in seconds.
Colors indicate different trigger module channels, which correspond to some scintillator counters and combinations of those used as triggers.
The beam intensity at the BM@N area was around 10^6 ions per spill.

ESIS + HILAC + Booster + modified Nuclotron + transfer line to BM@N

- ESIS Krion-6T installed and tuned at HILAC
- Nuclotron structure was modified for installation of fast extraction

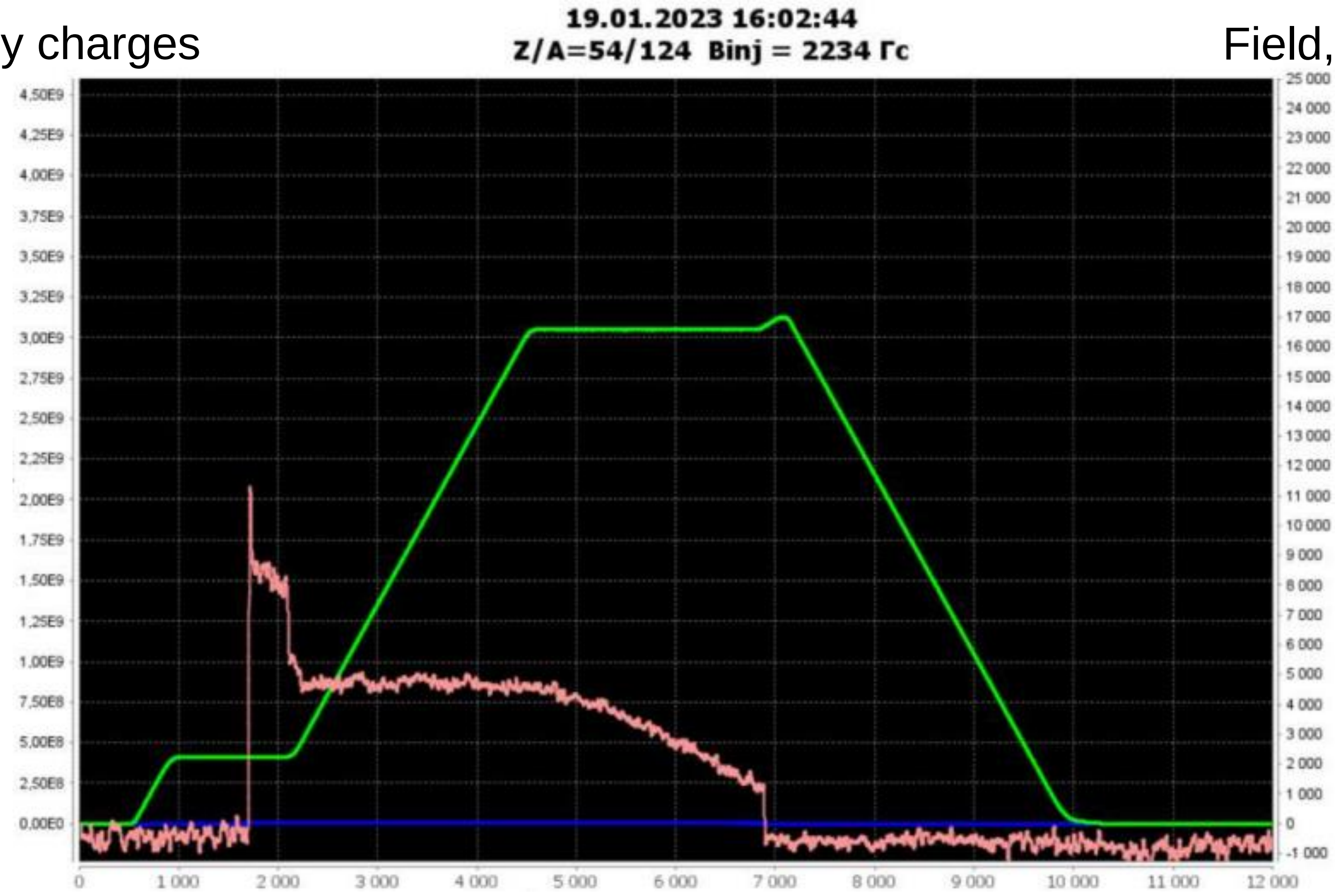
Forth commissioning run:
from 20.09.2022 to 03.02.2023 Ar, Xe ions

- Acceleration of Ar ions in the Booster, operation of SOCHI
- Tuning of Xe acceleration
- ARIADNA program
- BM@N II

Beam acceleration and slow extraction

Intensity,
elementary charges

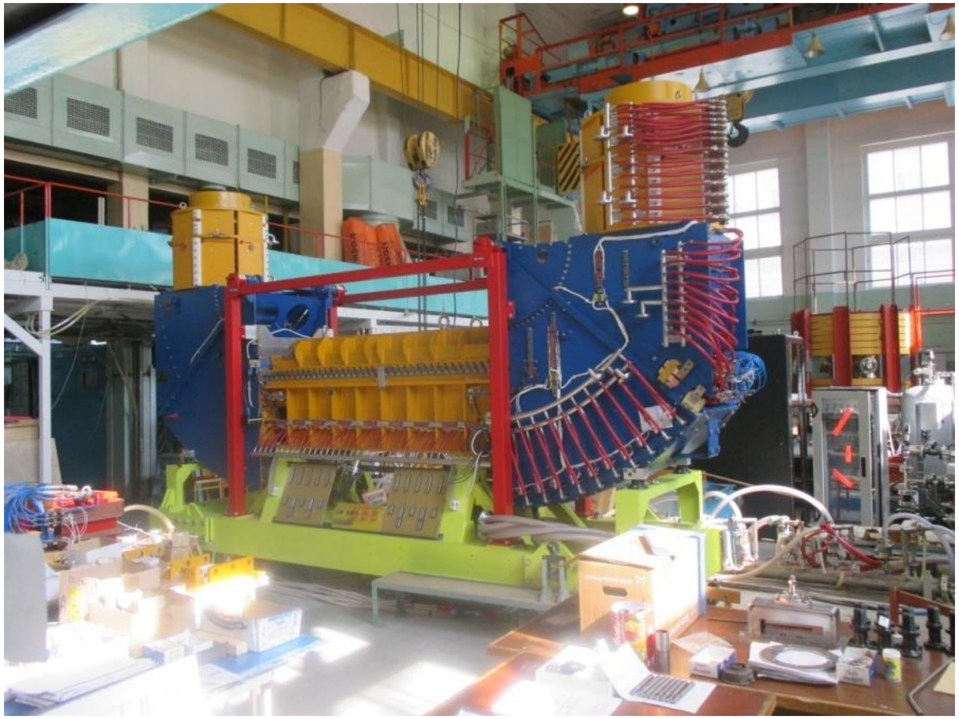
Field, Gs



Beam acceleration in the Nuclotron up to 1.65 T magnetic field plateau (about 3.6GeV/u).
Intensity of the accelerated beam up to about 2⋅10^7 ions.
Extracted beam spill duration up to 2 s (cycle period 12 s).

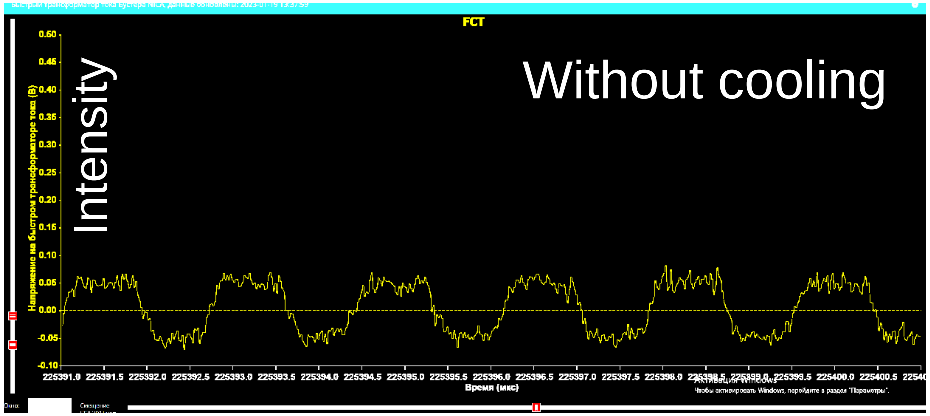
BM@N collaboration stored 500 MEvents

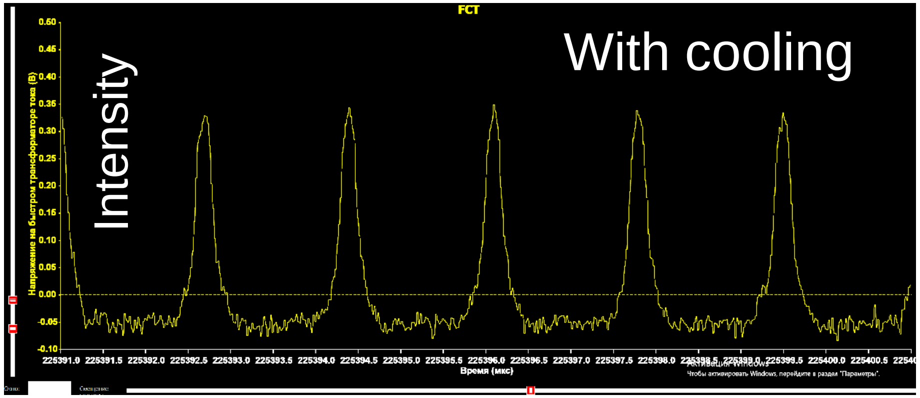
4th NICA technology run



Electron cooling system for NICA Booster (constructed at BINP)
during assembling 2017

Xe beam at injection energy

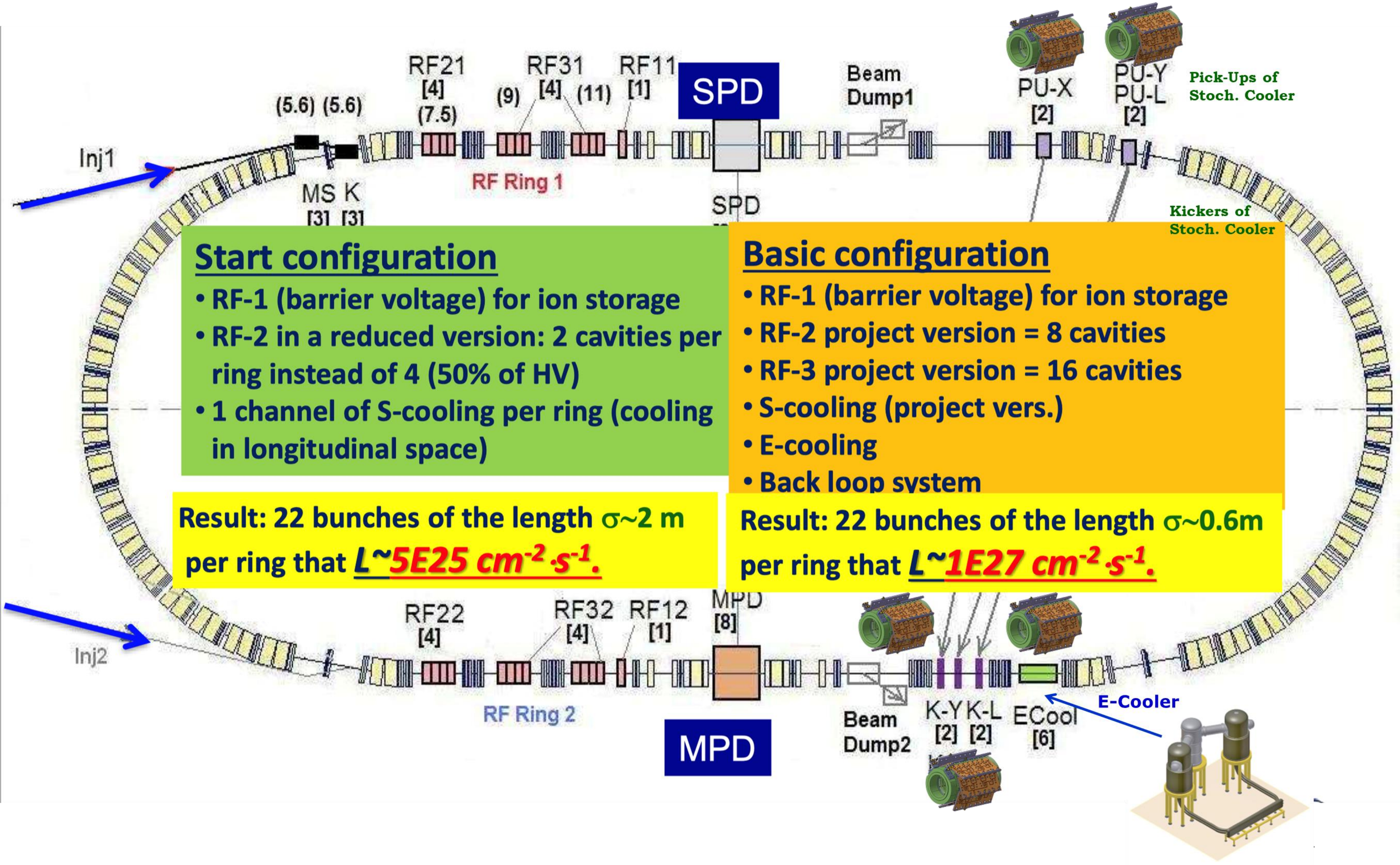




Bunch length measured with FCT

Cooling time ~ 100 ms

NICA collider: two rings separated vertically



Start configuration

- RF-1 (barrier voltage) for ion storage
- RF-2 in a reduced version: 2 cavities per ring instead of 4 (50% of HV)
- 1 channel of S-cooling per ring (cooling in longitudinal space)

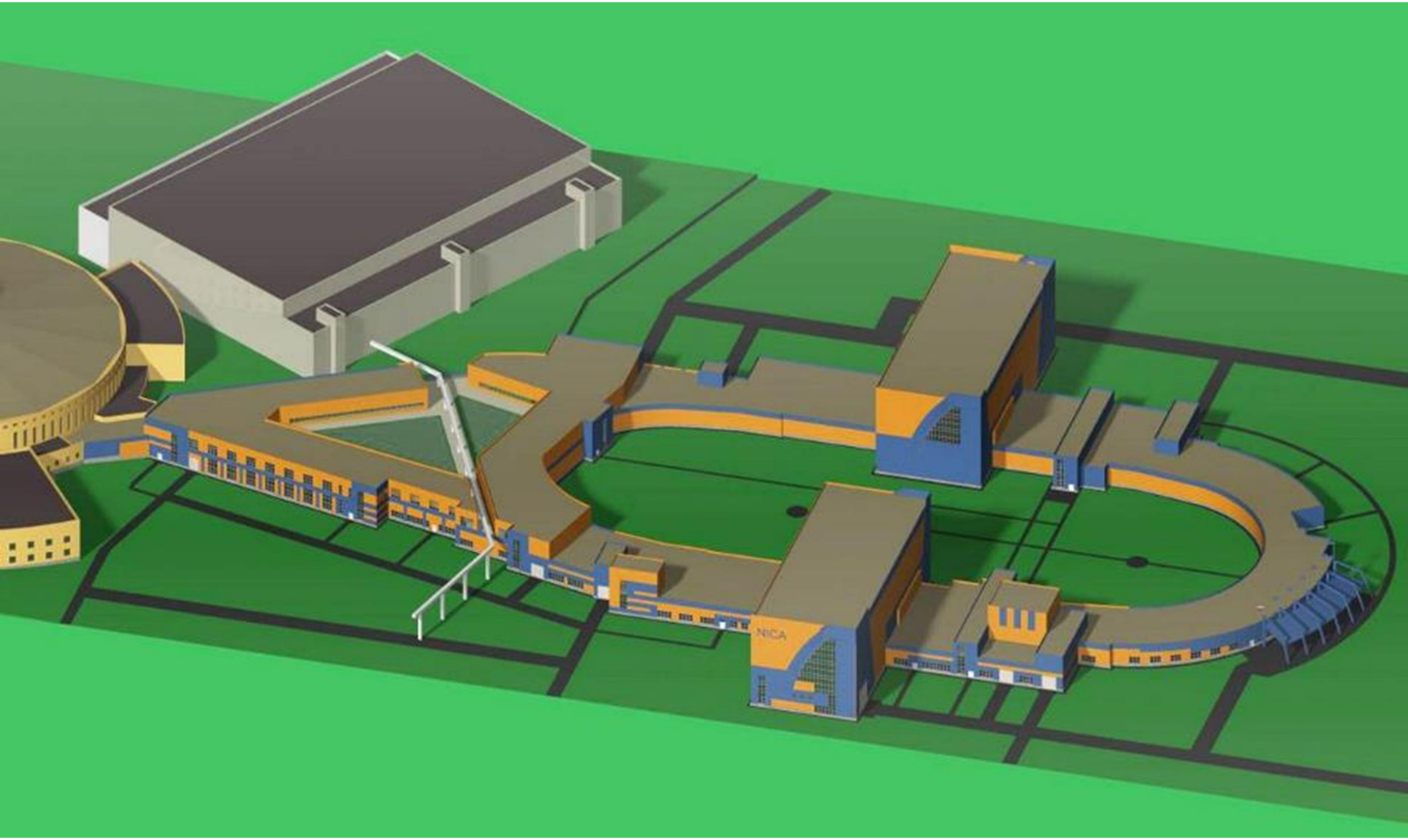
Result: 22 bunches of the length σ~2 m per ring that ***L~5E25 cm^{-2}·s^{-1}.***

Basic configuration

- RF-1 (barrier voltage) for ion storage
- RF-2 project version = 8 cavities
- RF-3 project version = 16 cavities
- S-cooling (project vers.)
- E-cooling
- Back loop system

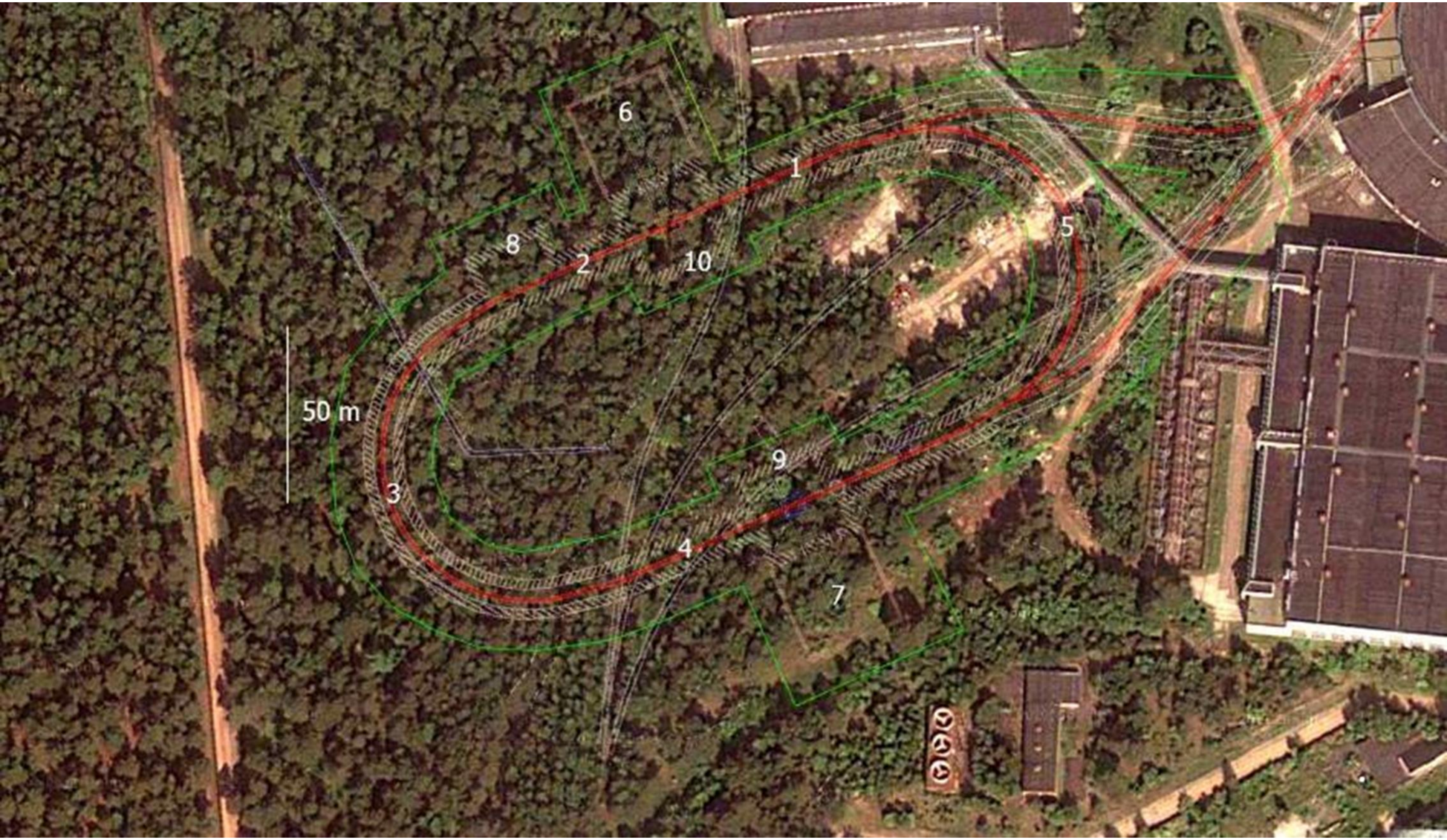
Result: 22 bunches of the length σ~0.6m per ring that ***L~1E27 cm^{-2}·s^{-1}.***

NICA collider: building construction



Technical project 2015

NICA collider: preparation of the site

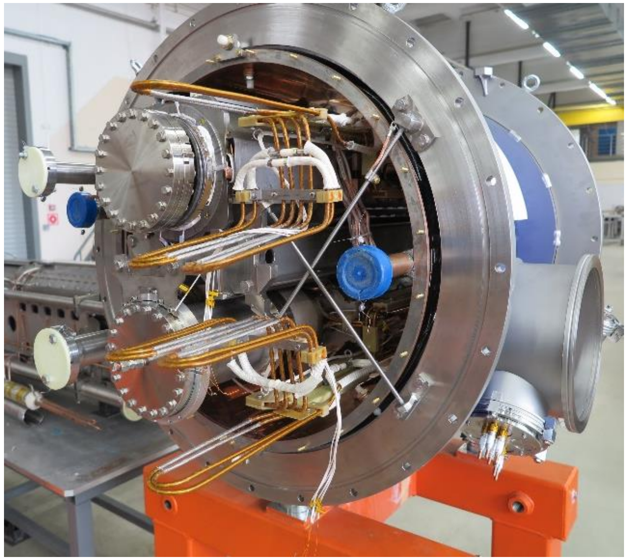




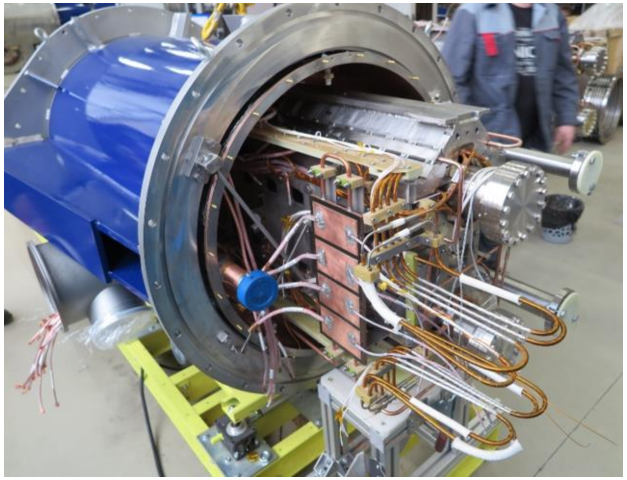

2016 – start of construction

2024

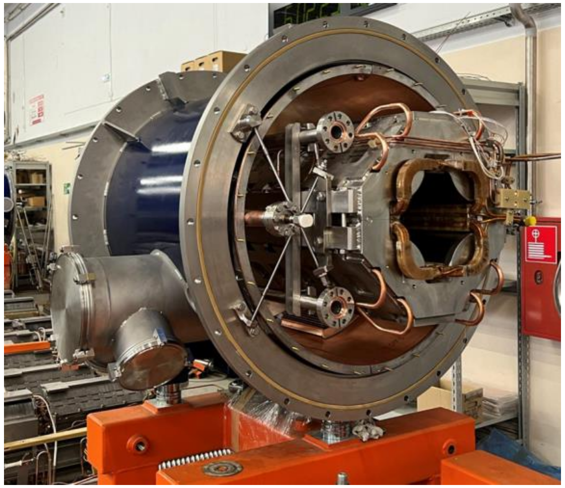
NICA collider: superconducting magnets



Vertical dipole for beam separation

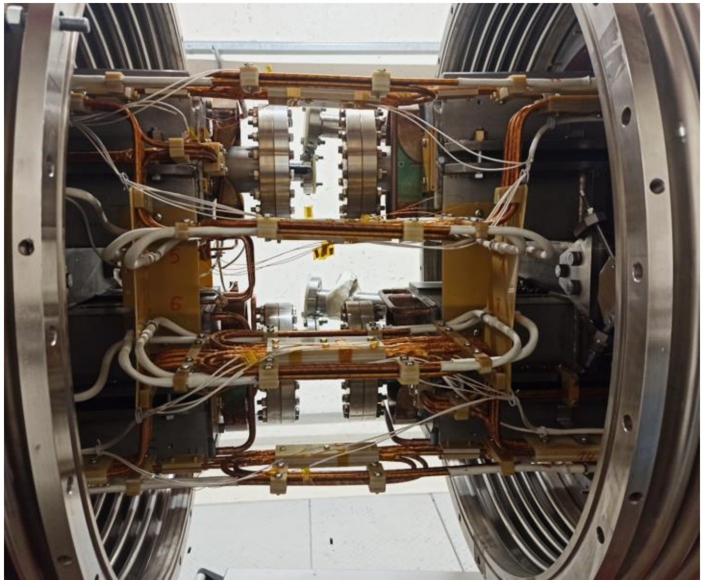


Twin aperture dipoles
and quadrupoles

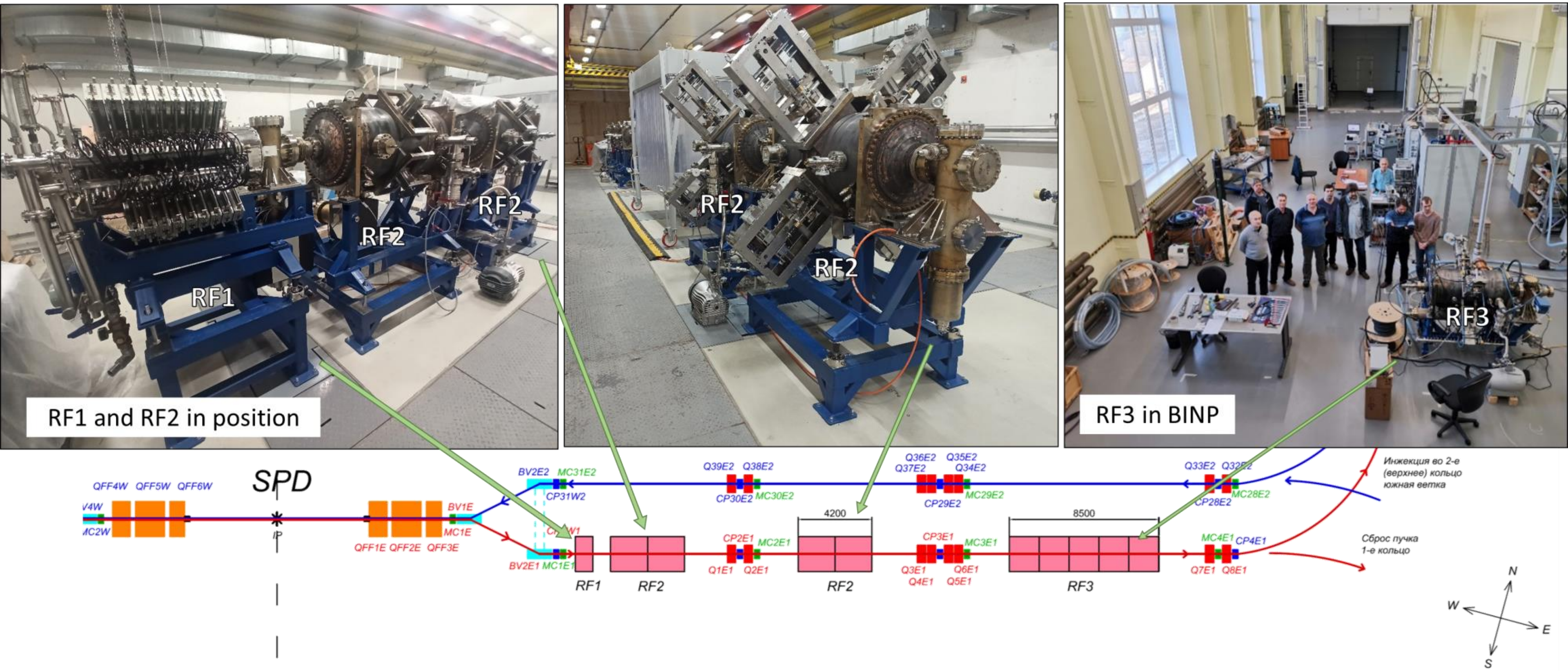


Final focus quadrupole

NICA collider: assembling of the magnetic structure



NICA collider: RF system


RF1 and RF2 in position

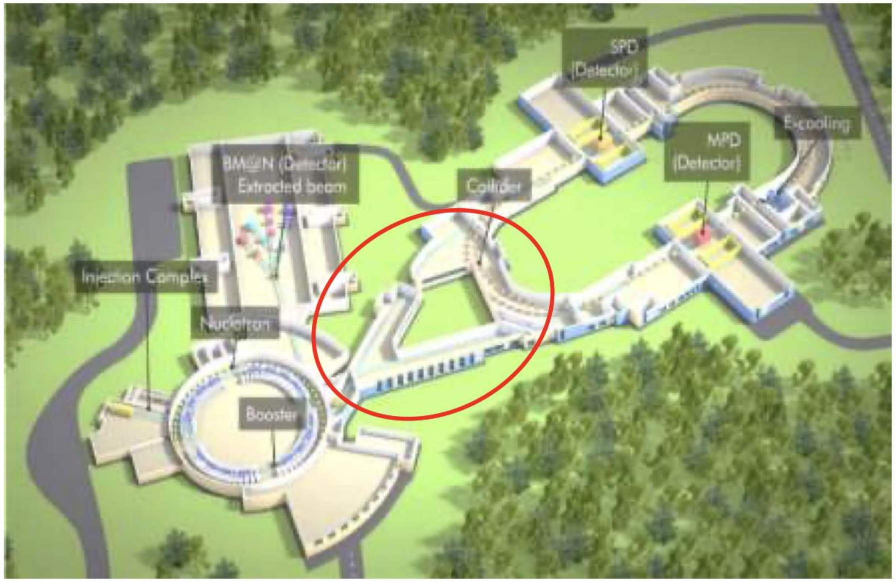
RF3 in BINP

Nuclotron-Collider beam transport channel

Sigma Phi

Nuclotron-Collider transfer line is under delivery and construction by Sigma Phi

Magnetic element	Number	Effective length, m	Max. magnetic field (grad), T (T/m)
Long dipole	21	2	1.5
Short dipole	6	1.2	1.5
Quadrupole	28	0.35/0,52	31
Steerer	33	0.466	0.114



90% of magnets delivered to JINR in February 2021

- **January 2022** – delivery of first parts of PS, beam diagnostics, support stands.
- **Fabruary 2022** – delivery of vacuum equipment.
- **July 2022** – second part of power supplies, profile monitors, control system.
- **September 2022** – start of commissioning of the channel equipment.
- **December 2022** – commissioning of the channel with a beam.

BLOCKED

Fabrication in RF will be finished 2024

NICA milestones

2009
Start of the project
2009 - 2013
Nuclotron modernization
2015
Technical project completion
2016
Start of the collider building construction
2018
BM@N I
2019 - 2021
The Booster assembly and commissioning
2022
SRC (BM@N)
2023
BM@N II, ARIADNA

Plans:

Creation of the collider in starting configuration permitting to provide experiments with colliding ion beams up to Bi^{+83} at mean luminosity of $L = 5\cdot10^{25}$ см^{-2} с^{-1} in the energy range $\sqrt{s_{NN}} = 8 – 11$ GeV/u

NICA:
Развитие национальных научных центров

ИЯФ СО РАН им Г.И.Будкера

- ВЧ система Бустера,
- Электронное охлаждение
- 3 системы ВЧ коллайдера
- Высоковольтная СЭО коллайдера
- Электроника, инжекция, каналы, и пр и пр

ИФВЭ НИЦ КИ (Протвино):

RFQ, динамика пучка, ВЧ,
Системы обратной связи

ИЯИ РАН (Троицк):

поляризованный источник,

Линейные ускорители, диагностика пучка

НПО ГЕЛИЙМАШ

КРИОГЕНМАШ

ВЭИ

ИТЭФ НИЦ КИ
Динамика пучка в коллайдере, Линейный ускоритель RFQ, линейный ускоритель SC

НИЦ «Курчатовский институт»
Токовводы, технологии ВТСП и т.д.

МГУ, МИФИ, МВТУ, МЭИ, МФТИ, СПбГУ, Казань, ...

Thank you for attention