Сессия-конференция Секции ядерной физики ОФН РАН

ИЯФ им. Г.И.Будкера СО РАН

10 – 12 марта 2020

Accelerator Complex
of
The Megaproject “Nuclotron-based Ion Collider fAcility”
NICA

Igor Meshkov for the NICA Team

Joint Institute for Nuclear Research
Dubna, Russia

Outline

1. Goals for Experimental Research of the NICA Project

We intend to study *extremely dense and hot baryonic matter* and wish to try to understand *the nature of particle spin.*

2. Stages of The NICA Accelerator Complex

Stage Ia: Heavy ion beam for fixed target experiment "The Baryonic Matter at Nuclotron" (BM@N) 2021

Stage Ib: First heavy ion colliding beams at reduced luminosity for the MPD test and very first experiments

STAGE I 2022

Stage II: Heavy ion colliding beams of the project luminosity for search for the Mixed Phase and New Physics

Stage III: Polarized $p\uparrow$ & $d\uparrow$ colliding beams of the NICA Collider

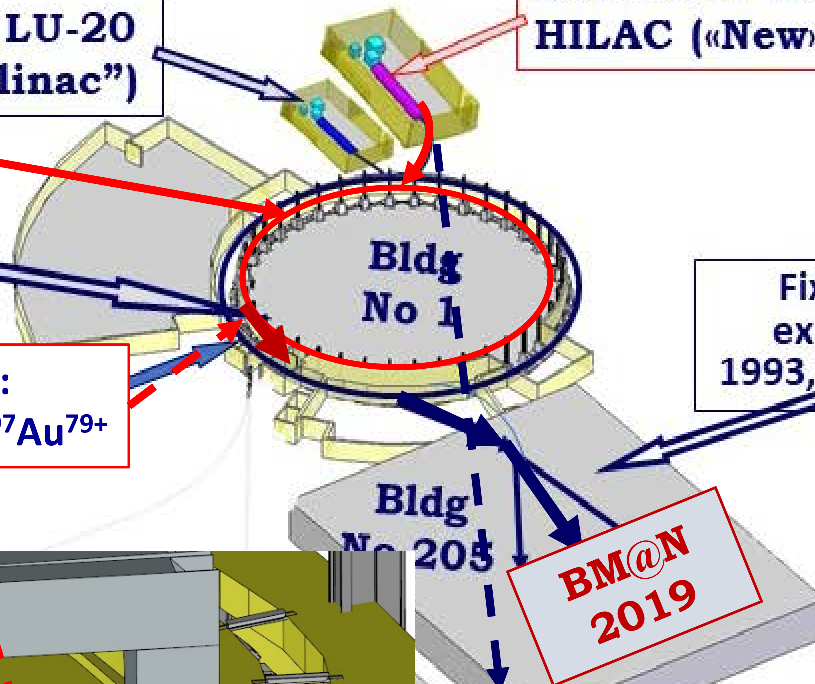
2. Stages of The NICA Accelerator Complex

NICA – Stage Ia (STAGE I)

Synchrophasotron yoke

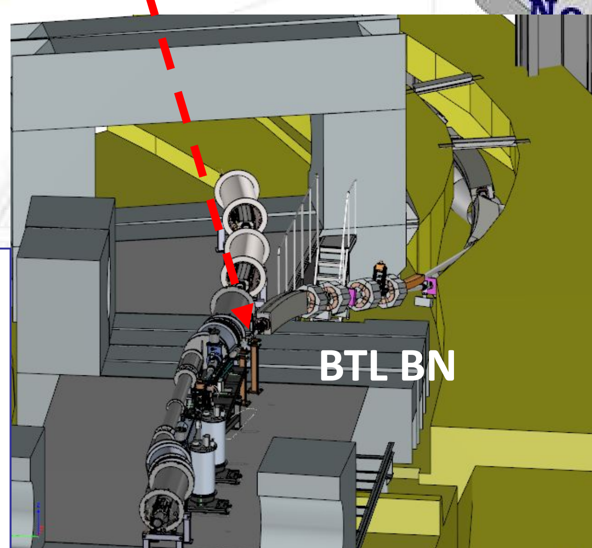
SPI & LU-20 (“Old linac”)

KRION-6T & HILAC («New» linac)



Fixed target experiments 1993, 1994,…2020

Ion stripping: $^{197}Au^{31+} \Rightarrow {}^{197}Au^{79+}$



Beam transfer line (BTL) Booster – Nuclotron => => under fabrication at BINP; mounting – July 2020

2. Stages of The NICA Accelerator Complex

Why do we need a booster-synchrotron?

1. The main reason: low charge state of ion generated in the injector chain KRION – HILAc (e.g. $^{197}Au^{79+}$). Ion stripping to bare state requires sufficient ion energy. In NICA case it is 600 MeV/u.

The bare ion (nucleus) state allows one to accelerate them up to maximum energy achievable at Nuclotron (3.81 GeV/u for Gold nuclei).

2. The Booster allows us to store ions at injection energy (multiple injection).

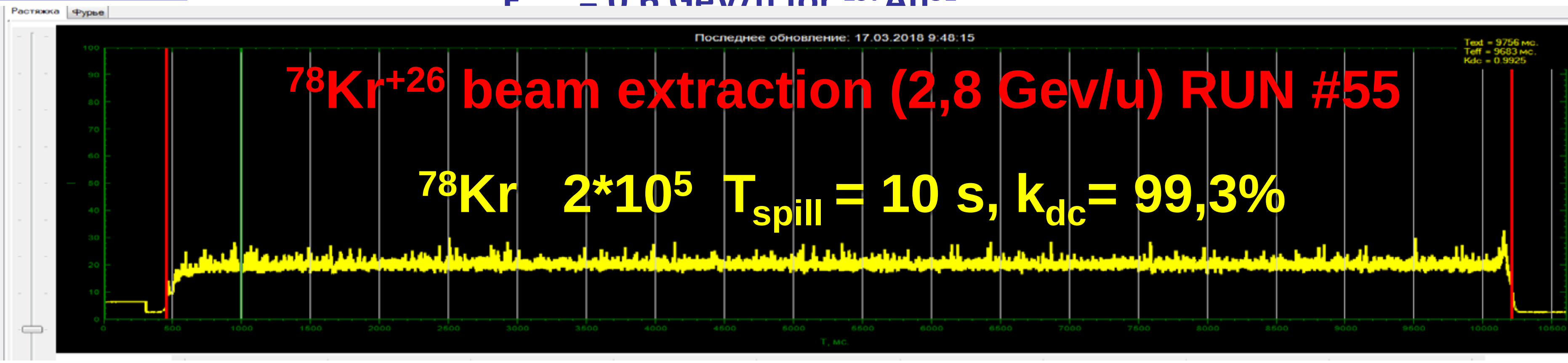
3. Application of electron cooling at medium ion energy (60 MeV/u for NICA booster that is well developed cooling technology) provides a small 6D emittance of the ion bunch at rather high its intensity.

2. Stages of The NICA Accelerator Complex

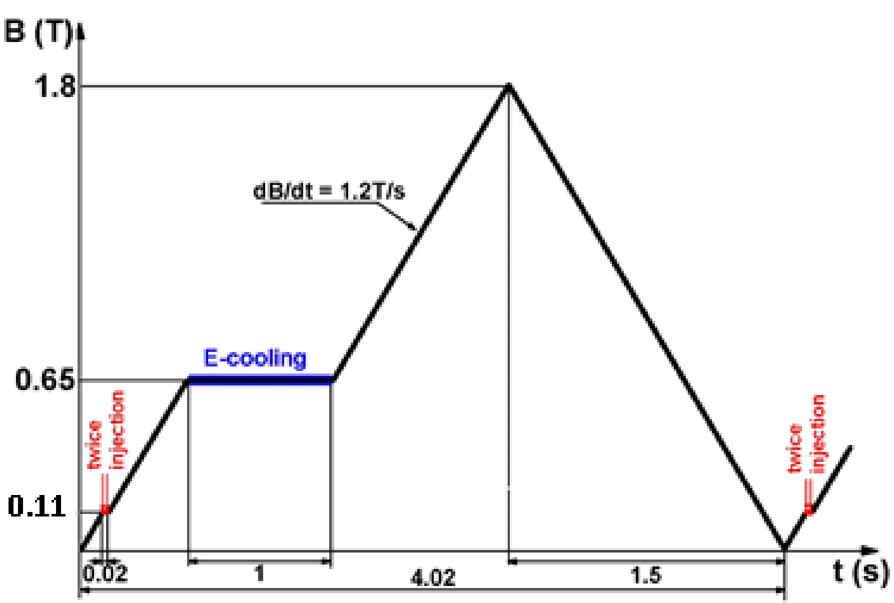
Stage Ia

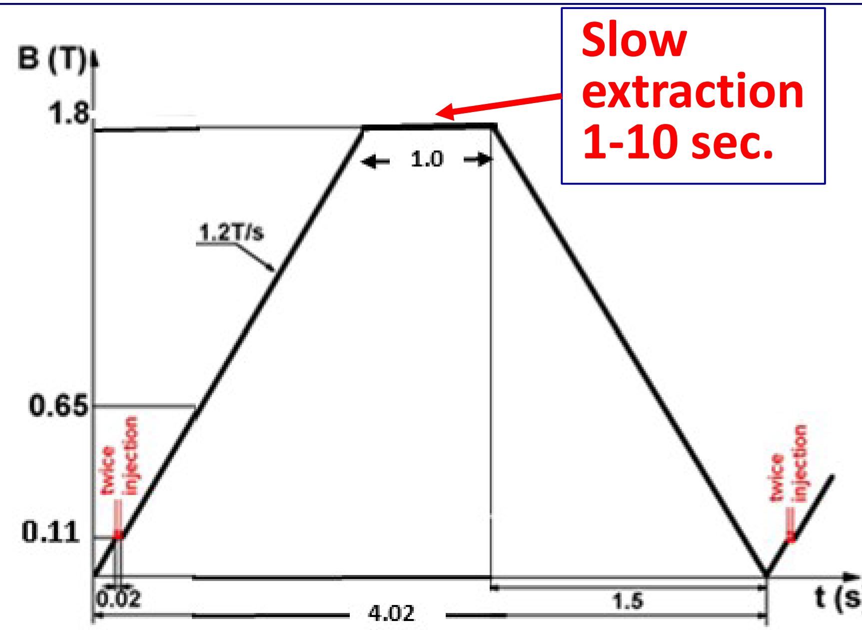
Booster: Bρ = 25.0 T·m

E = 0.6 GeV/u for $^{197}Au^{31+}$



Booster cycle **Nuclotron cycle at BM@N experiment**





2. Stages of The NICA Accelerator Complex

Stage Ia	Electron cooling system at the Booster

Budker INP (Novosibirsk) is the Birthplace of the electron cooling method and well known "fabric" of electron coolers. E-coolers both for the Booster and for the Collider are designed and fabricated at BNP.

V. Parkhomchuk – Father of e-coolers for NICA and for many other projects...

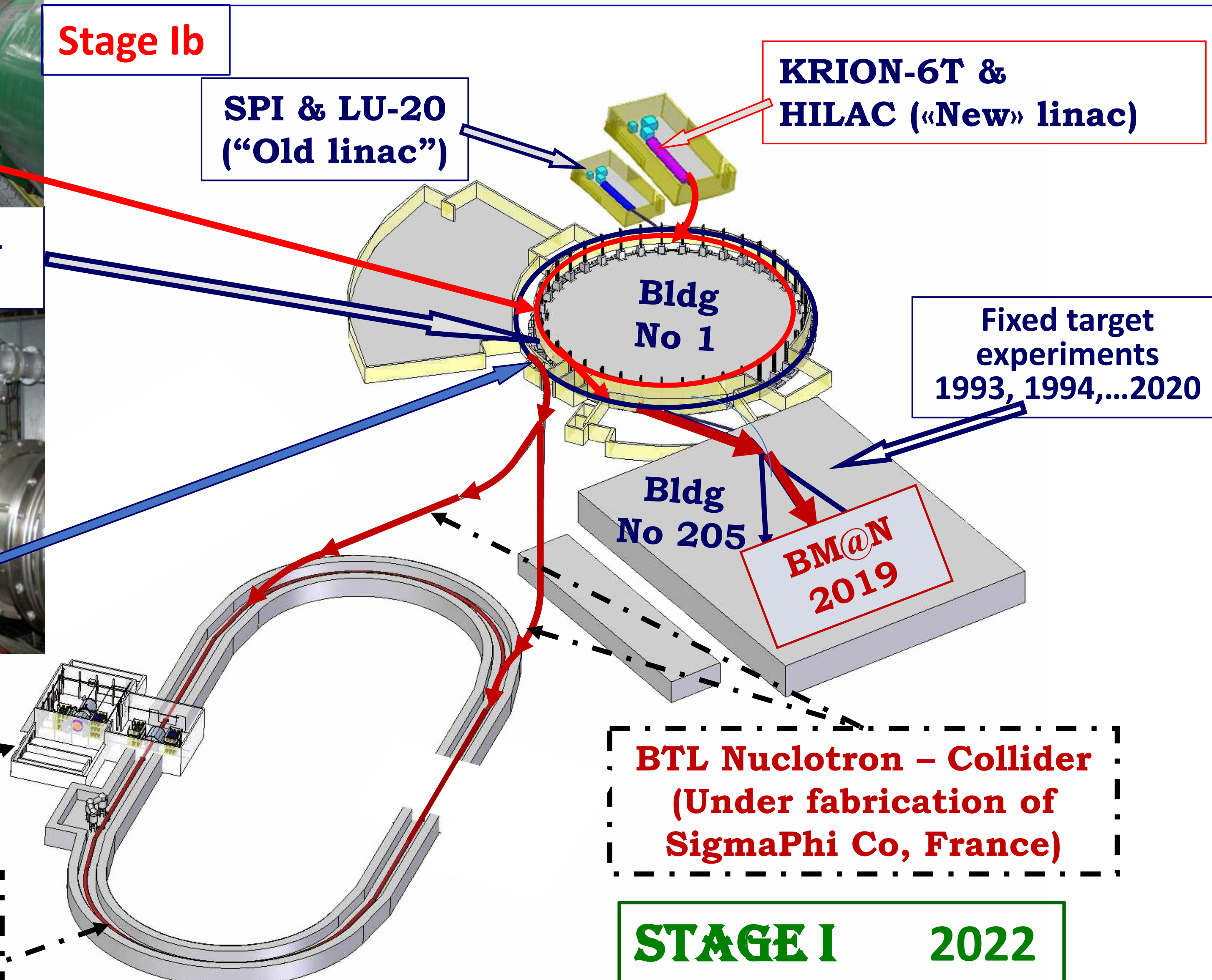
Parameter	Value
Ions to be cooled	p => $^{197}Au^{31+}$
Electron energy, *keV*	1.5 – 50
Beam current, *Amp*	0.2 – 1.0
Cooling section length, *m*	1.9
Field ripples, *ΔB/B* on 15 cm	$\leq 3\cdot10^{-5}$

NICA team studying e-cooler

...and his team

2. Stages of The NICA Accelerator Complex

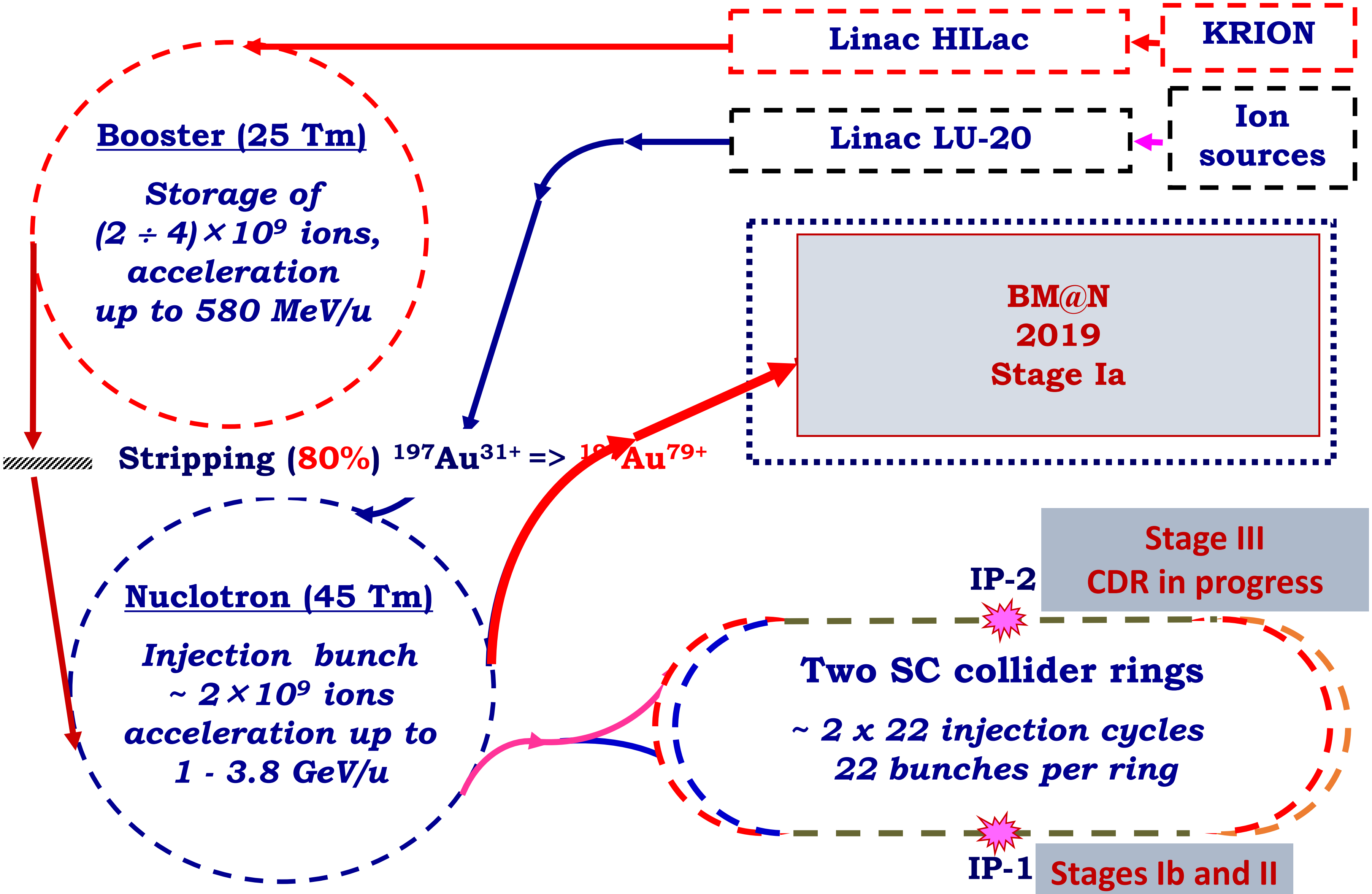
Synchrophasotron yoke



2. Stages of The NICA Accelerator Complex: Summary

STAGE II 2023 - 2027

Structure and Operation Regimes



3. Strategy of The Project Luminosity Achievement

NICA Collider General Parameters

Parameter	Value	
Particles	$^{197}Au^{79+}$	p↑ (d↑)
Total particle energy per nucleon, $\sqrt{s_{NN}}$, GeV/u	4 ÷ 11	27 (13.5)
Ion kinetic energy, GeV/u	1 ÷ 4.5	12.6 (6.3)
Ring circumference, m	503.04	
Maximum injection energy from Nuclotron, GeV/u	3.8	10.5 (4.9)
Maximum magnetic rigidity, T·m	44.5	
Maximum dipole field, T	1.8	
Maximum quadrupole gradient, T/m	23	
Magnetic field growth rate, T/s	0.1	
Beta-function in IP, m	0.6	
Betatron tunes, Q_x / Q_y	9.44/9.44	
Beam injection scheme	One-turn, multiple	
Beam extraction (dumping) scheme	One-turn	
Vacuum pressure in beam pipe, Pa	10^{-9}	

Reducing beta-function at IP up to 0.35 m is possible and will be tested at commissioning of the Collider. Working point Q_x/Q_y = 9.1/9.1 is foreseen as well.

3. Strategy of The Project Luminosity Achievement

To have a high luminosity we need

1. An intense ion beam stored in the collider;

2. Application of electron and/or stochastic cooling at the beam storage;

3. Formation of a stored coasting beam of a small transverse emittance by the cooling application;

4. Formation of a bunched beam with the bunch length $\sigma_b \leq 60$ cm;

5. Application of the ring focusing structure with beta-function values at interaction points (IP) $\beta^* \leq \sigma_b$ (to minimize so called hour-glass effect).

All the conditions are to be met in a collider.

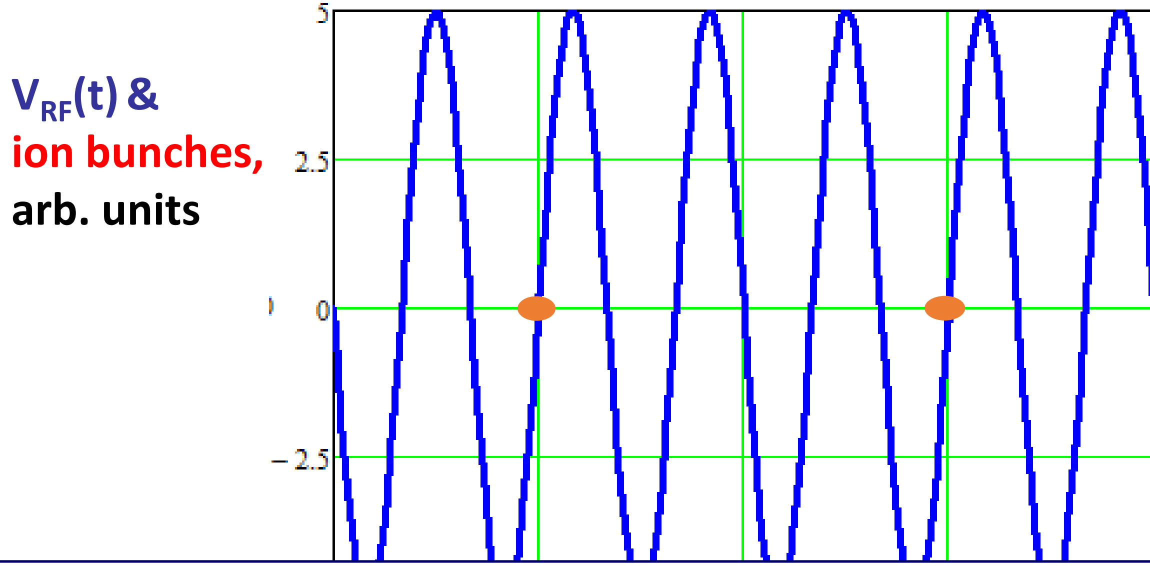
3. Strategy of The Project Luminosity Achievement

RF Gymnastics in the Collider

Step 1: Cooling and stacking with **RF1** barrier voltage (< 5 kV) coasting beam
Accumulation efficiency ~ 95%, 110 - 120 injection pulses (55-60 to each ring) every 4 sec. Total accumulation time ~ 10 min. Ion momentum spread is limited by microwave instability.

Step 2: Formation of the short ion bunches at presence of cooling:
RF-2 (22^{nd} harmonics, up to 100 kV increasing amplitude, 4 resonators)

Step 3: **RF-3** (1MV, 8 resonators). Interception of 22 bunches into the buckets of 66^{th} harmonics.

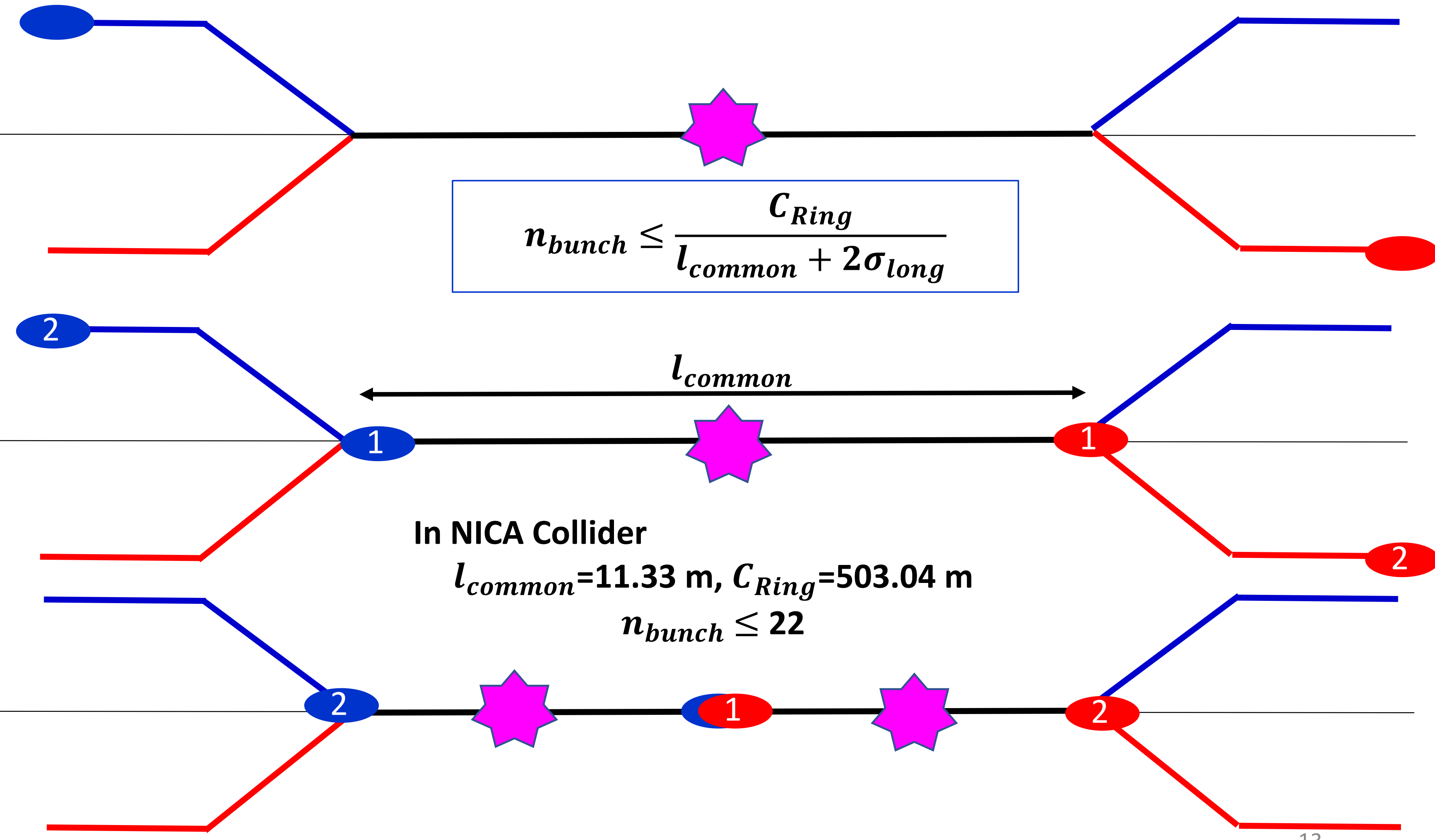


Final beam structure

3. Strategy of The Project Luminosity Achievement

RF Gymnastics in the Collider

Why do we have 22 bunches only:



$$n_{bunch} \leq \frac{C_{Ring}}{l_{common} + 2\sigma_{long}}$$

In NICA Collider

l_{common}=11.33 m, C_{Ring}=503.04 m

$n_{bunch} \leq 22$

3. Strategy of The Project Luminosity Achievement

Space Charge Effects in the Collider

[ЭЧАЯ 50 (2019) 776]

Two most serious effects:

1. Influence of own electromagnetic field of a bunch on its individual particles - - so called Laslett effect, Δq betatron tune shift;
2. Influence of electromagnetic field of a bunch on particles of the colliding (counterpropagating) bunch – so called "beam-beam effect", ξ tune shift.

For the NICA Collider both effects both effects act differently on particle motion depending of their energy: at low energy the Laslett effect dominates, when at relatively high energy the beam-beam effect begin to play a visible role (Fig.1 below) .

Optimization of the Collider parameters can give us maximum luminosity (Fig. 2)

Dependence of the ion collider parameters with the bunched $^{197}Au^{79+}$ beams; $\Delta q_{max} = 0.05$.

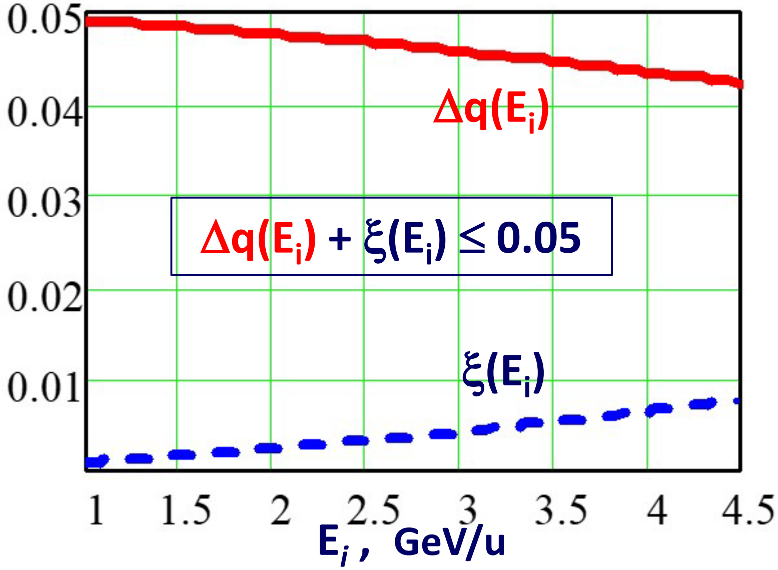


Fig.1. Laslett parameter *Δq* (red curve) and the beam-beam parameter *ξ* (blue curve)

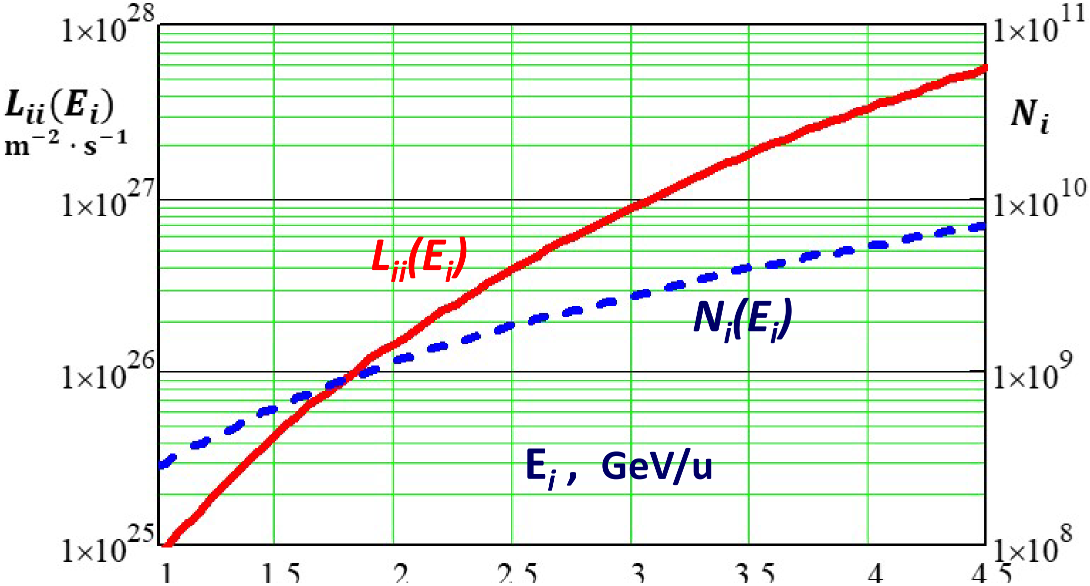


Fig.2. Collider luminosity L_{ii} (red curve) and the number of particles per bunch N_i (blue curve)

3. Strategy of The Project Luminosity Achievement

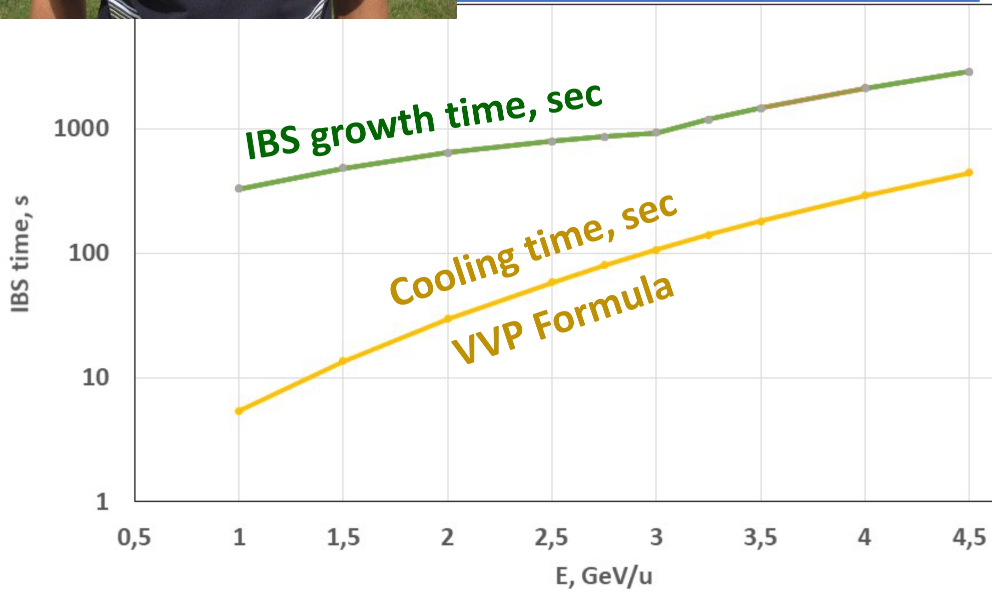
Intrabeam Scattering (IBS)

) beam emittance that reduces the Collider luminc

:am halo that leads to ion loss and decreasing the

design beam parameters IBS limited lifetime is as

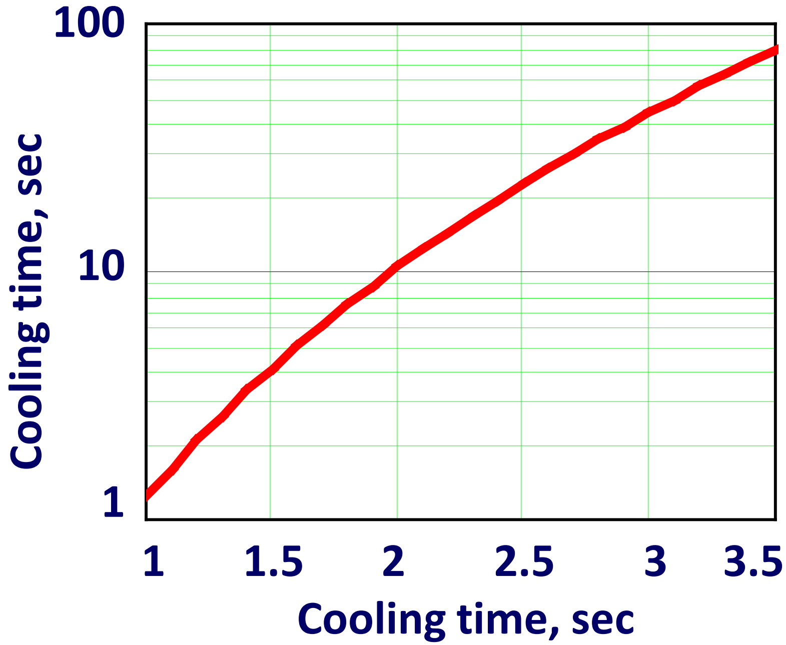
librium beam $\tau_x = \tau_y = \tau_s$



Parameters of quasi-qui	
Parameter	Value
Ion number per bunch, 1e9	0.3 – 2.8
Emittance, mm·mrad	1.1
Bunch length, m	0.6
Momentum spread, 1e-3	0.6 – 1.7
Betatron tune shift ΔQ	0.04 – 0.05
Luminosity, $cm^{-2} \cdot s^{-1}$, 1e27	0.01 – 0.9

Beam emittance growth under IBS action *can be* and *must be suppressed* by cooling – both electron and stochastic if $\tau_{cool} < \tau_{IBS}$.

Electron Cooling Time at Injection



Parameters of the bunch injected from Nuclotron	
Parameter	**Value**
Ion energy, GeV/u	1.0 - 3.8
Ion number per bunch	1e9
Emittance, mm·mrad	3.0
Bunch length, m	0.6
Momentum spread	2e-4

Electron cooling time of injected beam at 3 GeV/u is 43.7 sec.
For equilibrium beam it is 53.2 sec.

Numerical Simulations and 6D Tracking (D.Shatilov, BINP)

1. Calculation of DA with and w/o space charge
2. Calculation of DA with large number of turns (10^5-10^6)
3. Software development for calculating space charge effects
4. Calculation of space charge effects taking into account the transverse dimensions of the vacuum chamber
5. Study of beam dynamics taking into account the action of space charge
6. Modeling particle dynamics taking into account the effects of IBS and electron cooling
7. Software preparation for modeling beam-beam effects with lattice nonlinearities, IBS, cooling, space charge, etc.
8. Luminosity distribution over the length of interaction area
9. Search for ways to increase luminosity, analysis of the possibility to achieve maximum luminosity using an electron cooling system

Numerical Simulations and 6D Tracking (D.Shatilov, BINP)

Main results:

1) With a nominal bunch population of $2.3\cdot10^9$ ions, at the energy of 4.5 GeV/u beam-beam tune shift is: $\xi_{x,y} \approx 0.0015$ **per IP.**

2) Total tune shifts by the space charge are:

$$\delta\nu_x \approx 0.0159,\ \delta\nu_y \approx 0.0177.$$

3) The luminosity for 22 bunches and $\beta^* = 0.6$ m is

$$L = 6.8e26\ cm^{-2}\cdot s^{-1}.$$

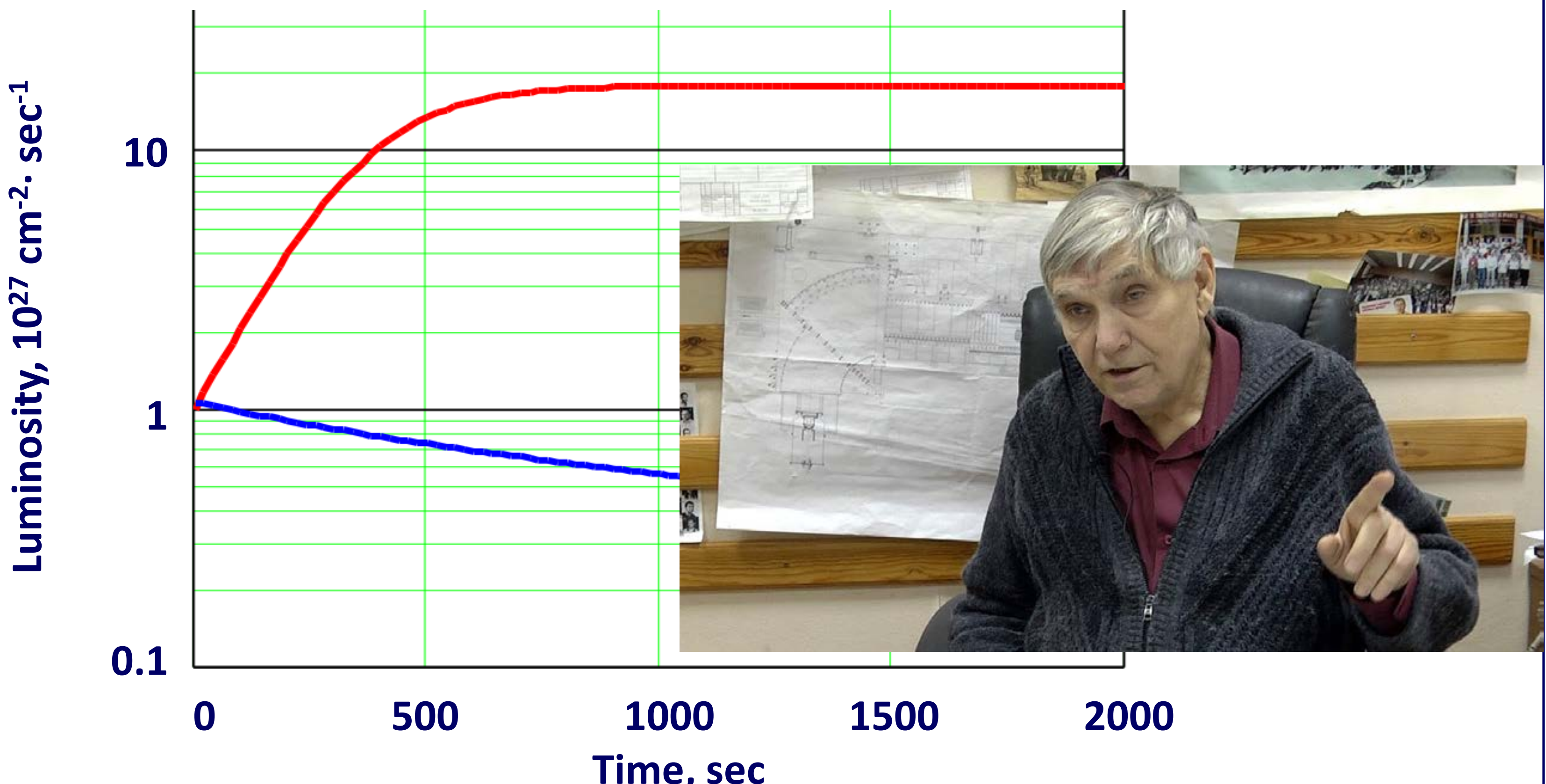
At $\beta^* = 35$ cm $\xi_{x,y}$ will not change, and the luminosity will increase to 1.16e27 $cm^{-2}\cdot s^{-1}$.

But a more correct way to increase luminosity is *to reduce emittances and energy spread using cooling systems*. In this case, the length of the bunch will also decrease, and it will be possible to decrease β^* accordingly.

Of course, reducing emittances will lead to an increase in $\xi_{x,y}$, but we still have a margin for that. It is not yet clear how far one can advance in this direction.

As mentioned above, in order to conduct an appropriate simulation, all factors must be considered, including IBS. When this module is put into operation, work will continue.

One More Statement (V. Parkhomchuk, BINP)



Что даст электронное охлаждение коллайдеру НИКА?

Без охлаждения пучок расширяется со временем и светимость падает.

С охлаждением ионный пучок сжимается и светимость растёт.

Можно повысить светимость более чем в 20 раз!

(эквивалентно созданию 20 NICA)

4. NICA Fabrication

Factory of the Miracles

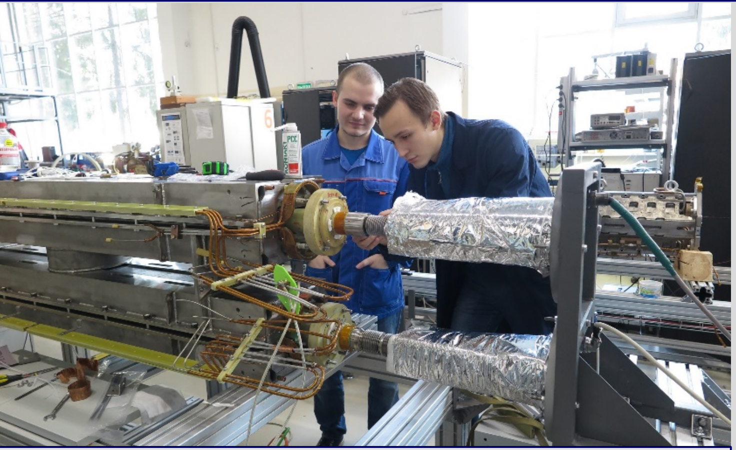
August 2017

4. NICA Fabrication

Factory of the Miracles: home technology

SC cable production machine

Workshop for SC coil production

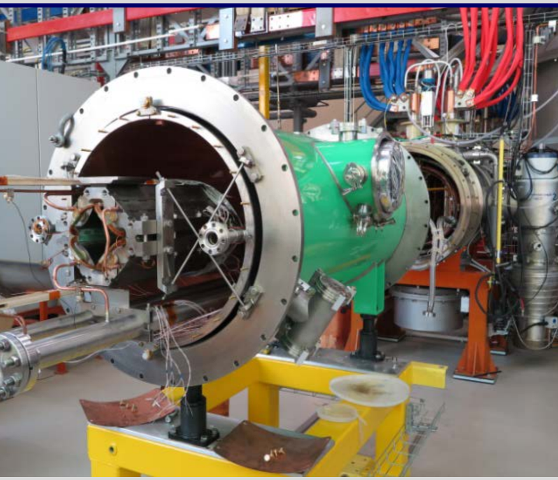


Collider dipole preparation for test

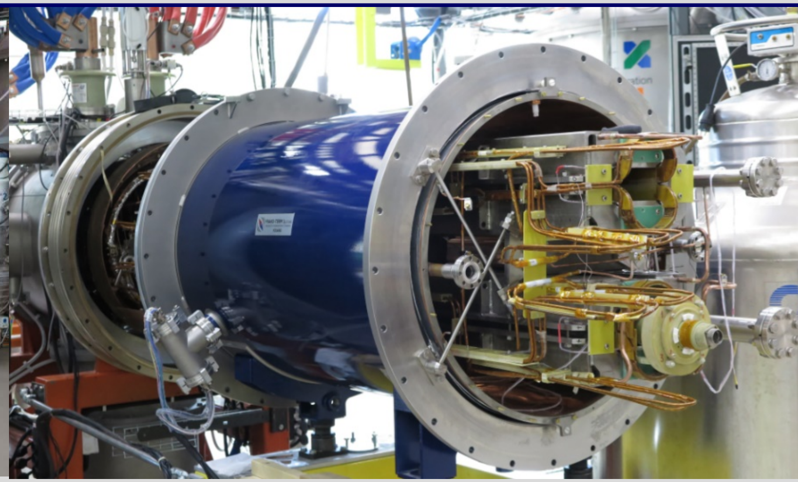
To be completed… (Booster magnet yokes, 2017)

4. NICA Fabrication

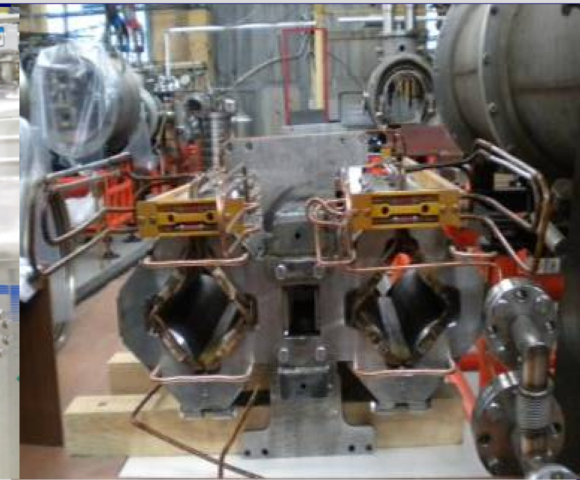
Factory of the Miracles: ready samples



Booster dipole

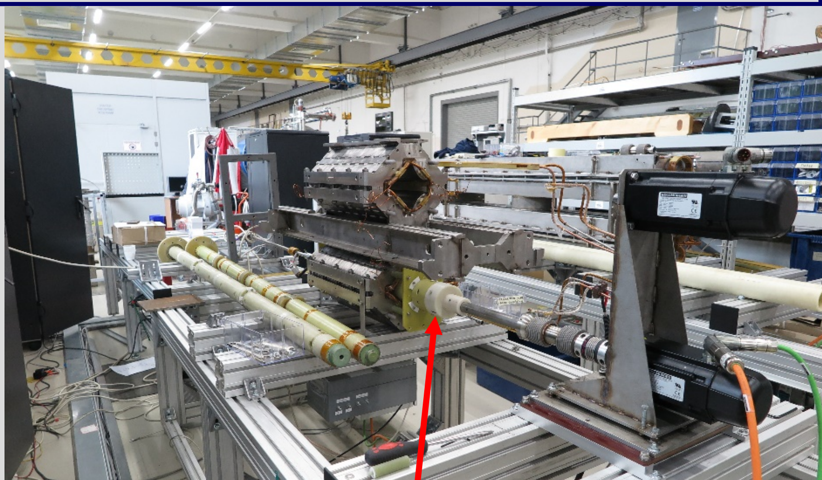


Collider dipole



Collider quadrupole

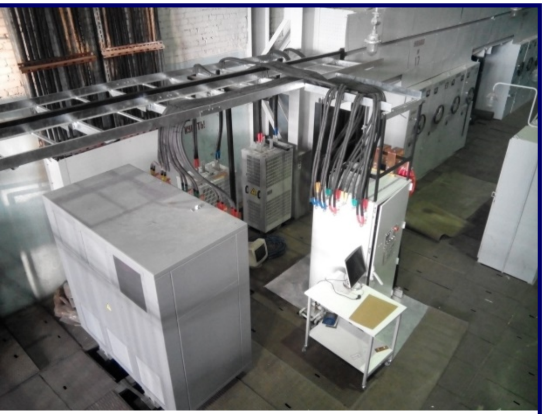
Quadrupole & sextupole for SIS-100



Collider quadrupole ready for test

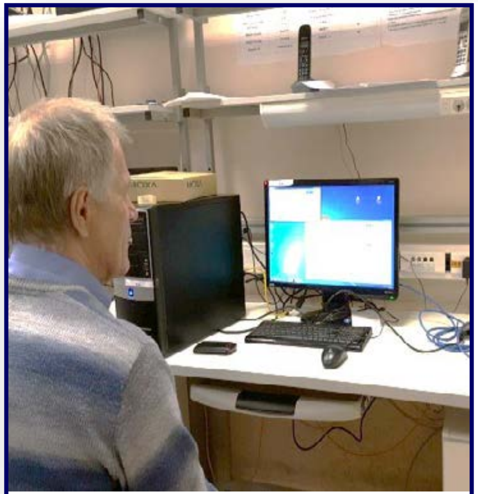
4. NICA Fabrication

Development of Powerful Electronics



PS for BM@N magnet

Booster PSs placed on the top of the Synchrophasotron yoke



Remote control system

Booster PS systems placed in the “cellar” under the Synchrophasotron

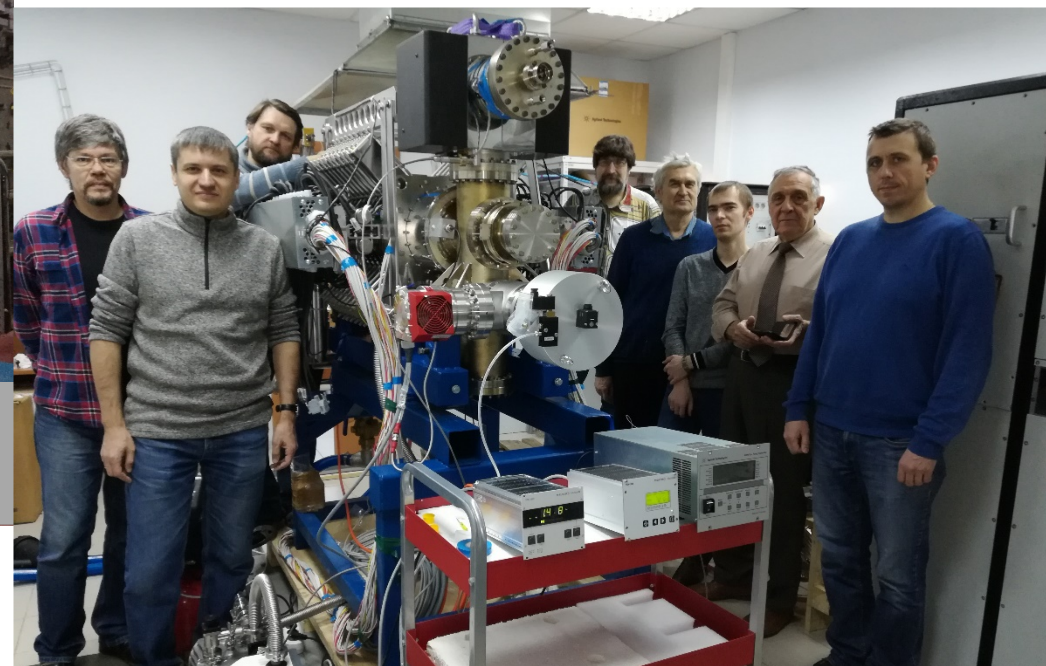
4. NICA Fabrication

RF Acceleration Systems for the Booster and the Collider: Development by Budker INP - the main NICA collaborator

Two RF stations for the Booster are ready for mounting (25.12.2019)...

...and mounted already.

(05.02.2019)



The RF barrier voltage station for the Collider (stage I) at the test bench in LHEP JINR after tests by BINP and NICA teams (20.12.2019).

4. NICA Fabrication

Two rings of the NICA Collider will be equipped with the following devises allowing to control parameters of the ion beams:

Device	Stage I (number per ring)	Stage II (number per ring)
RF-1 (ion storage and acceleration/deceleration)	1	1
RF-2 (ion bunching)	2	4
RF-3 (short bunch formation)	0	8
HV Electron cooler	1 beam	1 beam
Stochastic cooling system	1 channel (cooling of longitudinal degree of freedom)	3 channels (3D cooling)
Feedback system	1 channel (low frequency)	1 channel (high frequency) ?

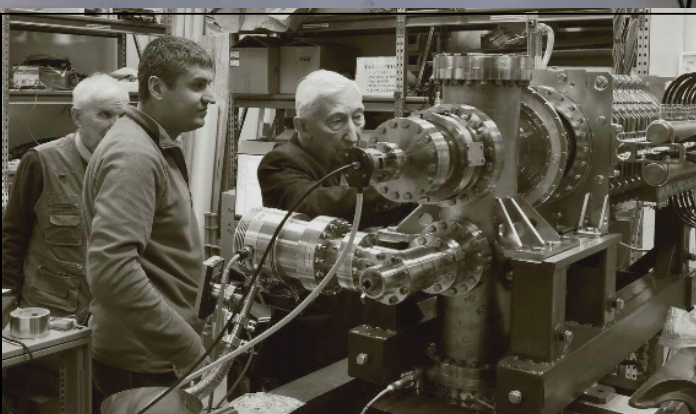
4. NICA Fabrication

RF Acceleration Systems for the Booster and the Collider: Development by Budker INP - the main NICA collaborator

Harmonic systems RF2 and RF3 for the Collider


23.09.2019 RF-2 and all the Team


24.09.2019 RF-2 Visit of the NICA MAC members

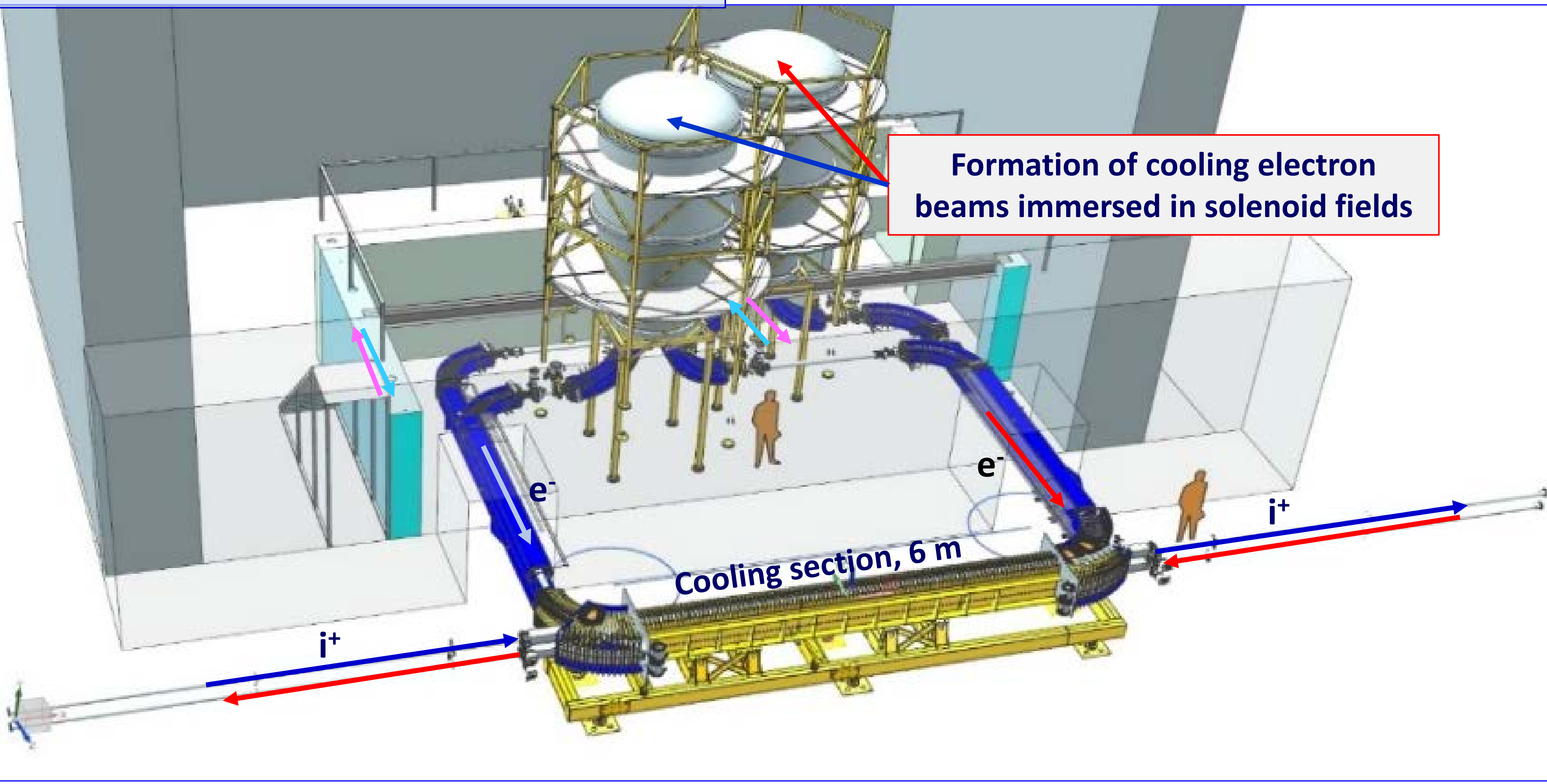

RF-1 at friendly inspection 21.03.2019


24.09.2019 The same and RF-3

4. NICA Fabrication

High Voltage Electron Cooler (HV ECS) for the Collider Under development at BINP – Stage II

V. Parkhomchuk & the team BINP SB RAS



4. NICA Fabrication

High Voltage Electron Cooler (HV ECS) for the Collider

Under development at BINP – Stage II (end)

Parameter
Energy range, MeV
High voltage stability (ΔU/U)
Electron current, A
Length of the cooling section, m
Magnetic field in the cooling section, k
Vacuum pressure in the cooling sectior
Transverse temperature of electrons, e
Longitudinal temperature of electrons,
Life time of electrons due to recombin
Energy consumption, kW

Acceleration system of HV ECS

High precision “twin
cooling section – key element of an electron cooler; in NICA HV ECS $\Delta B/B \leq 1e\text{-}5$

high voltage generation

Commissioning 2021

4. NICA Fabrication

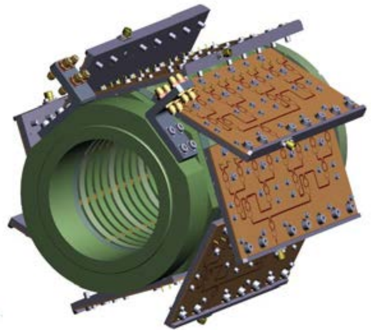
Stochastic Cooling System (SCS) for the Collider

JINR – stages I and II

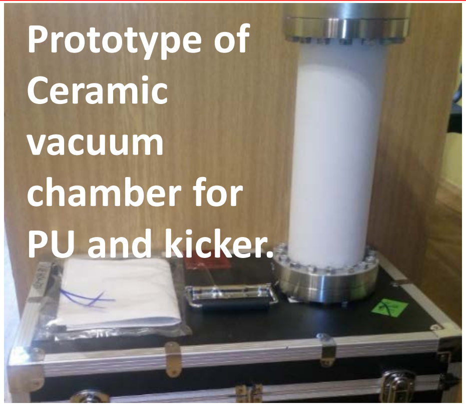
Parameters of the collider stochastic cooling system (stage I)

Parameter	Value
Energy range, GeV/u	3.0 ÷ 4.5
Bandwidth, GHz	0.7 ÷ 3.2
Gain range, dB	84 ÷ 122 ± 0,5
Range of the delay, ps	537 816 ÷ 544 453 ± 1
Average power of one SCS channel, W	500

Basic structure – 16 rings (development of FZJ)



Length – 200 mm



Fabrication at Kunshan Guoli electronic tech. Co., Ltd (China)

Prototype of PU and kicker of SCS (LHEP, June2019)

Commissioning 2022 (Stage I) – 2023 (stage II)

6. Expertise and Approval of the NICA Accelerator Complex Project

Final Decision: JINR Committee for Plenipotentiaries

3rd level | JINR Scientific Council

2nd level | Program Advisory Committee for Particle Physics

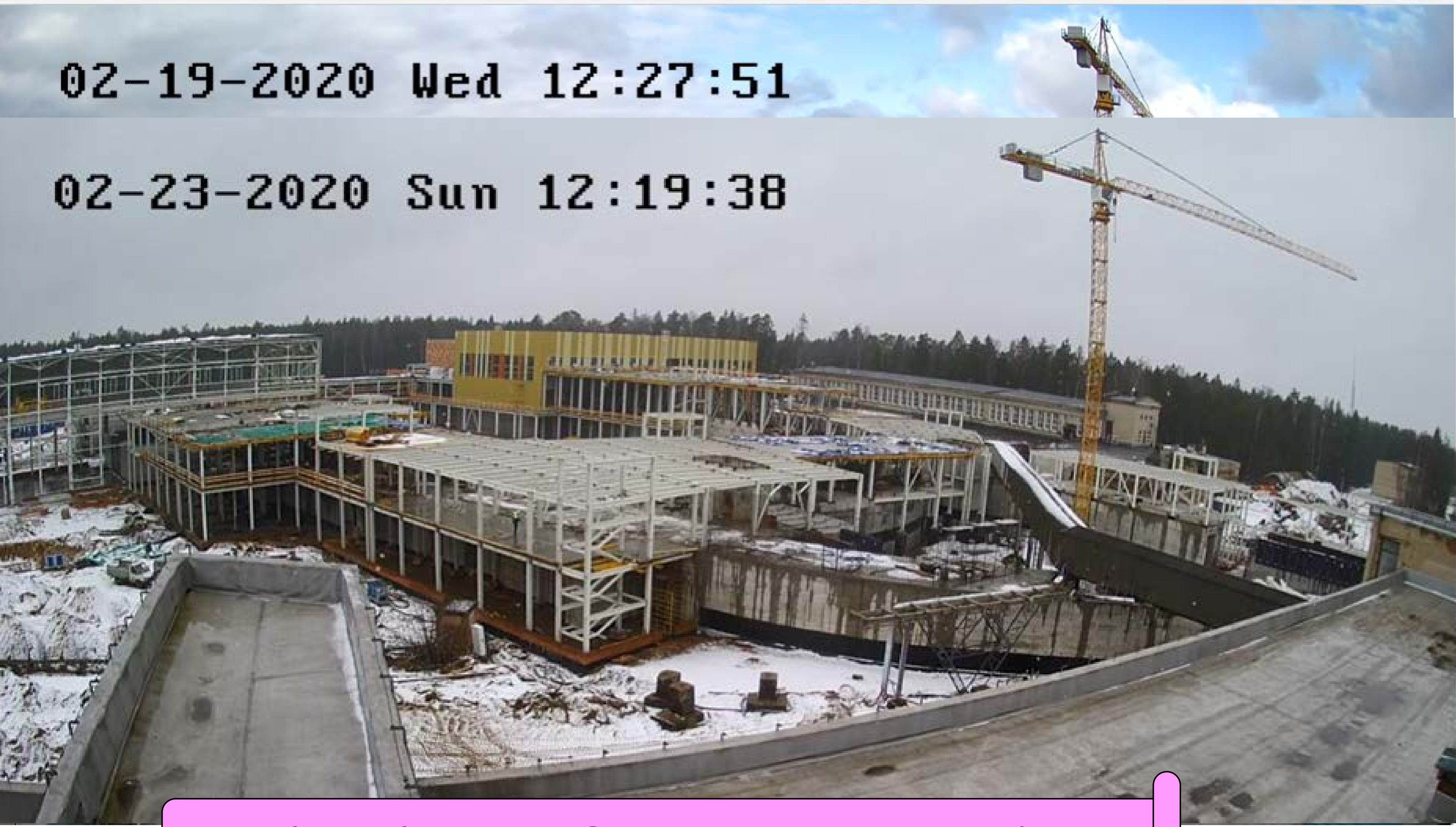
1st level

Machine Advisory Committee for the Project of NICA Accelerator Complex

1. I. Arkharov	Bauman MSTU, RF
2. A. Feshchenko	INR RAS, RF
3. S. Ivanov	IHEP, RF
4. T.Катаяма	Nihon Univ., Japan
5. V. Lebedev	FNAL, USA
6. E. Levichev	Budker INP, RF
7. R. Scrivens	CERN
8. Yu. Senichev	MPEI, RF
9. A. Seryi	Jlab, USA
10. R. Stassen	FZJ, FRG
11. M. Steck	GSI, FRG - Chairman
12. P. Zenkevich	ITEP, RF

NICA Accelerator Project: Approved in 2011 and prolonged in 2015 until 2020

NICA MAC
2008 – 2019
10 sessions



Thank you for your attention!
Спасибо за внимание!