The Conference "RFBR Grants for NICA"

NICA Accelerator Complex

the Megaproject “Nuclotron-based Ion Collider fAcility”

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(with I.Meshkov, S.Kostromin, A.Butenko)

for the NICA Team

Joint Institute for Nuclear Research

Dubna, Russia, 20 Oct 2020

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

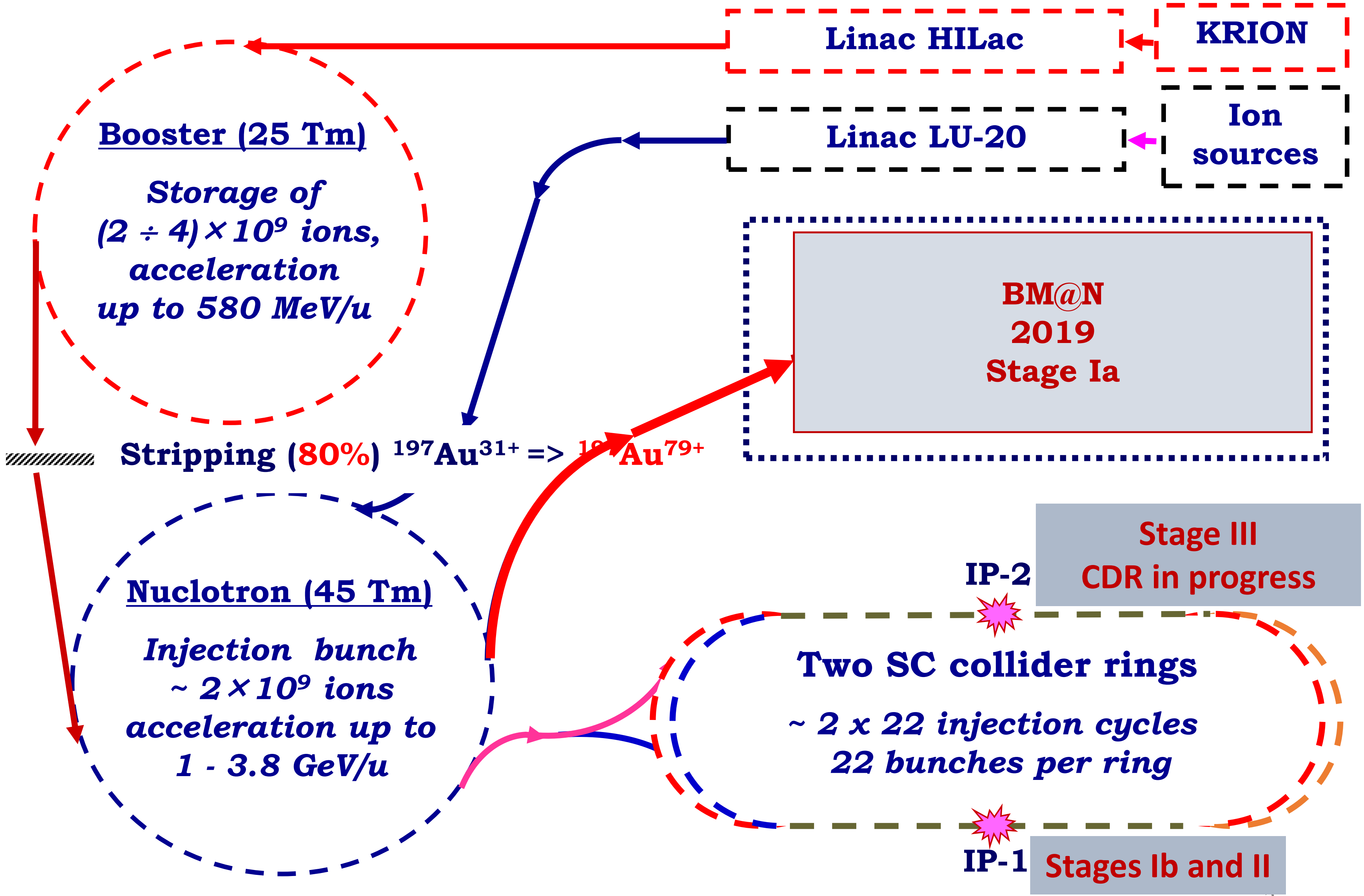
Stage II: Heavy ion colliding beams of the design luminosity for search for the Mixed Phase and New Physics

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

2. Stages of The NICA Accelerator Complex: Summary

STAGE II 2024 - 2027

Structure and Operation Regimes



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 state allows one to accelerate them up to max. energy achievable at Nuclotron (3.8 GeV/u for Au 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.

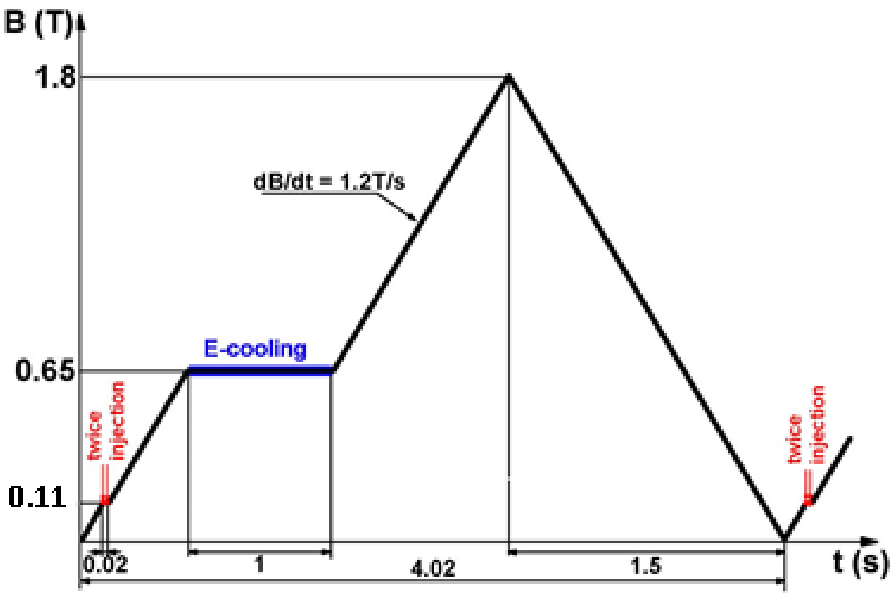
2. Stages of The NICA Accelerator Complex

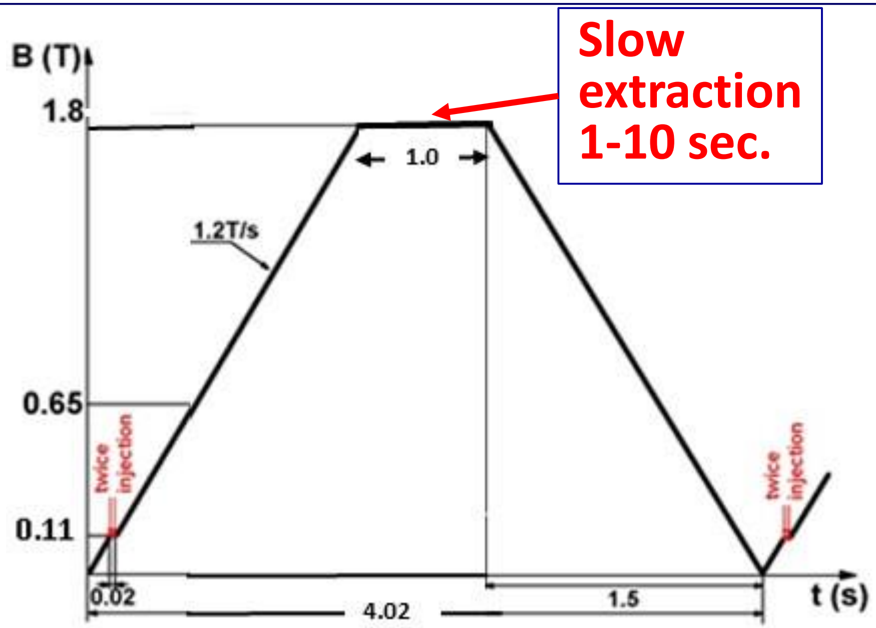
Stage Ia

Booster: $B\rho$ = 25.0 T·m
E_{max} = 0.6 GeV/u for $^{197}Au^{31+}$
Ion bunch max. intensity 2e9

Nuclotron: $B\rho$ = 38.5 T·m, E_{max} = 3.8 GeV/u for $^{197}Au^{79+}$,
Fixed target experiment Au×Au $\sqrt{s}$ = 3.275 GeV/u
Ion bunch max. intensity 1e9
Average ion flux to the target 3.6e8 1/s

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



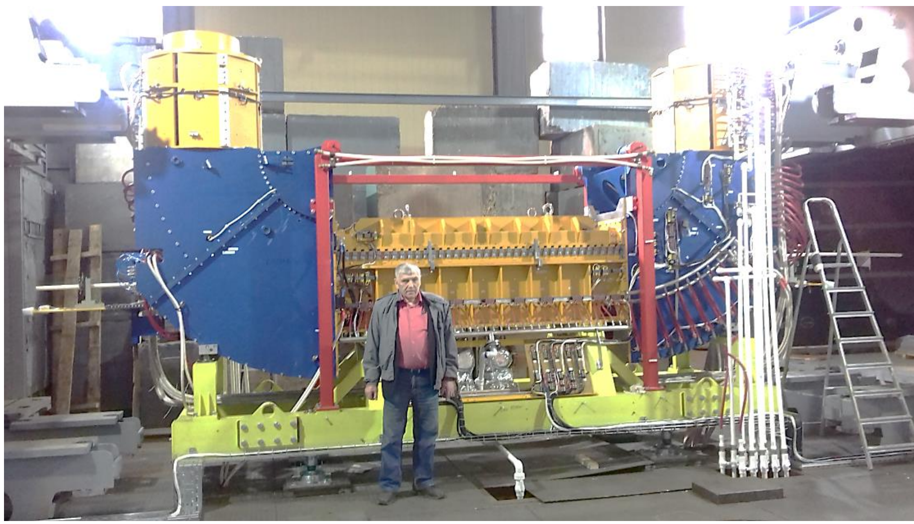


2. Stages of The NICA Accelerator Complex

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.

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	$\leq 3\cdot10^{-5}$



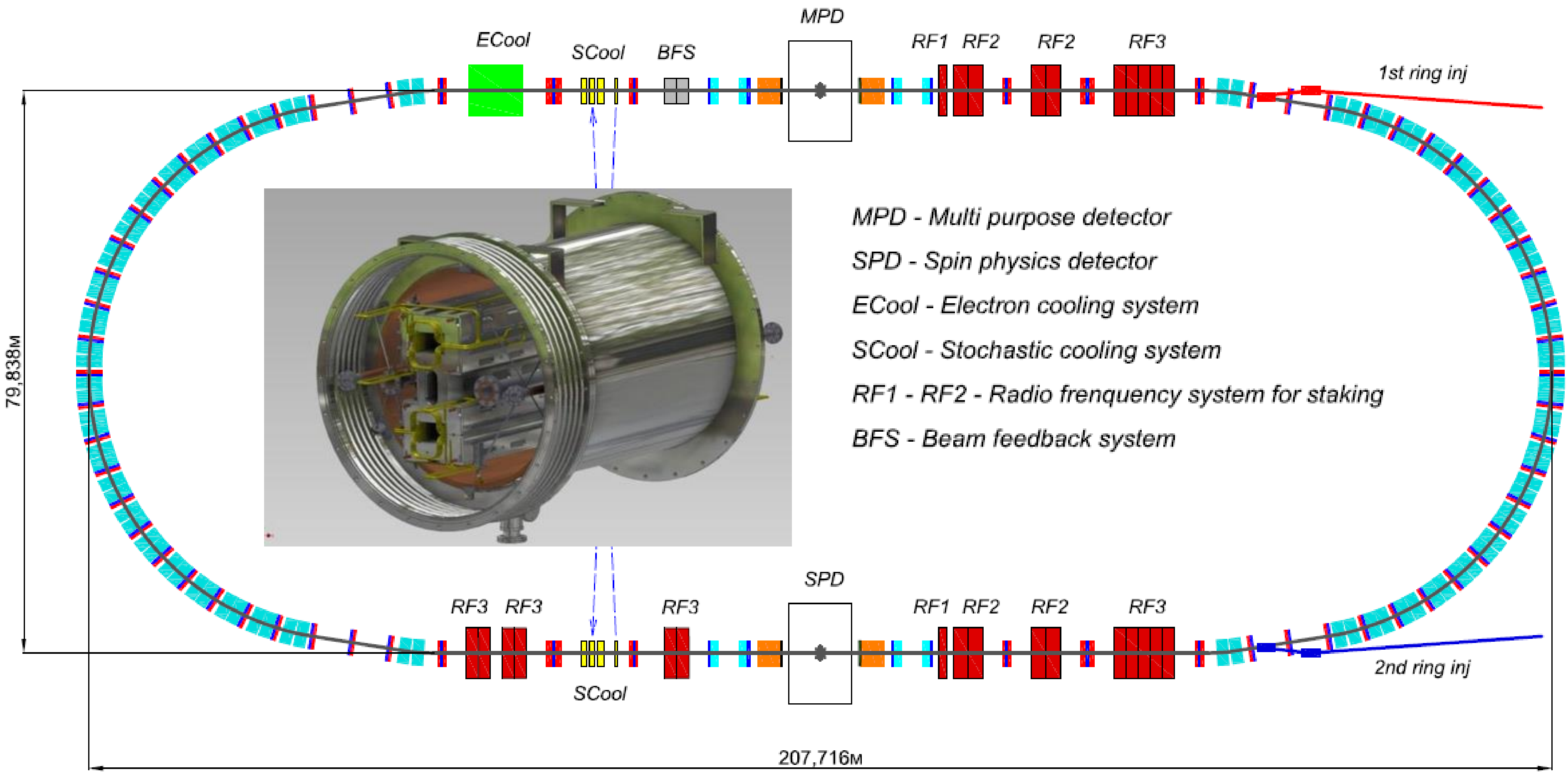
V. Parkhomchuk – Father of e-coolers for NICA and for many other projects...

NICA team studying e-cooler

Booster sc-magnets system

- ✓ ***all magnets in the tunel***
- ✓ ***95% connected***
- ✓ ***ring He-system*** assembled 95%, tested 50%
- ✓ ***beam pipe 55%***

NICA Collider



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

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; $\Delta q_{max} = 0.05$.

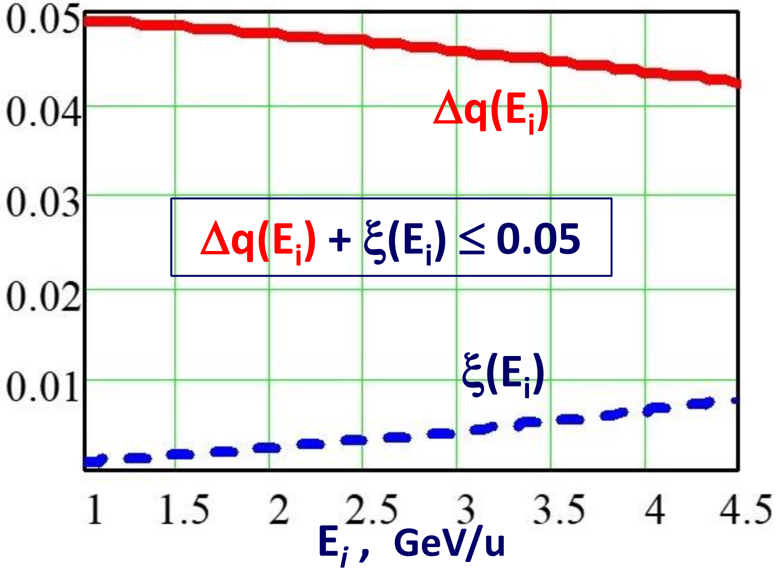


Fig.1. Laslett parameter Δq (red curve) and the beam-beam parameter ξ (blue curve)

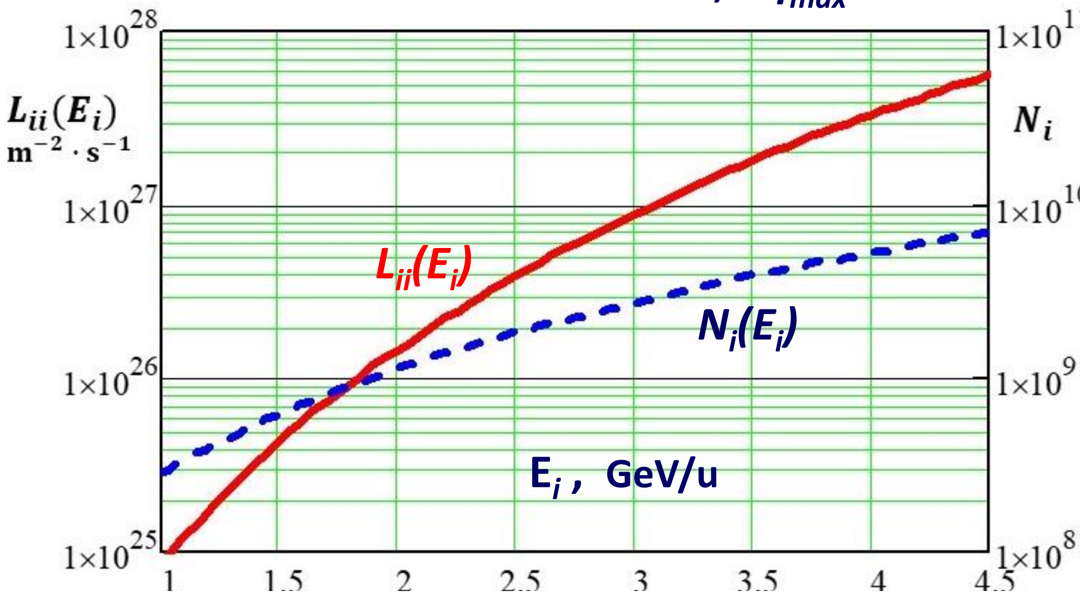


Fig.2. Collider luminosity L_{ii} (red curve) and the number of particles per bunch N_i (blue curve)

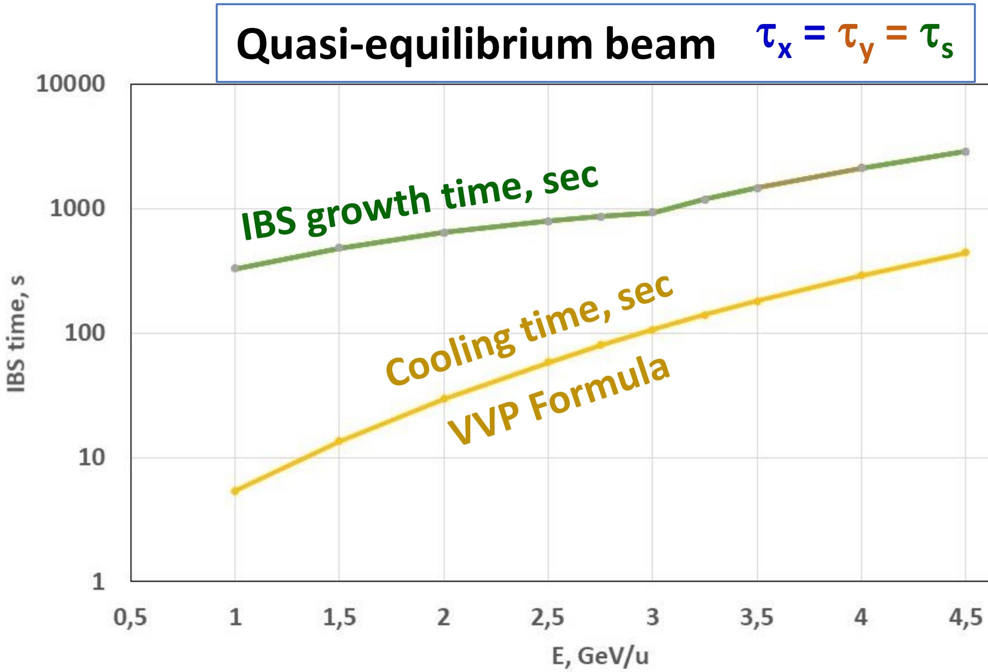
3. Strategy of The Project Luminosity Achievement

Intrabeam Scattering (IBS)

The problems:

- **It increases 6D beam emittance that reduces the Collider luminosity,**
- **generates a beam halo that leads to ion loss and decreasing the beam lifetime.**

In NICA Collider at design beam parameters IBS limited lifetime is as follows:

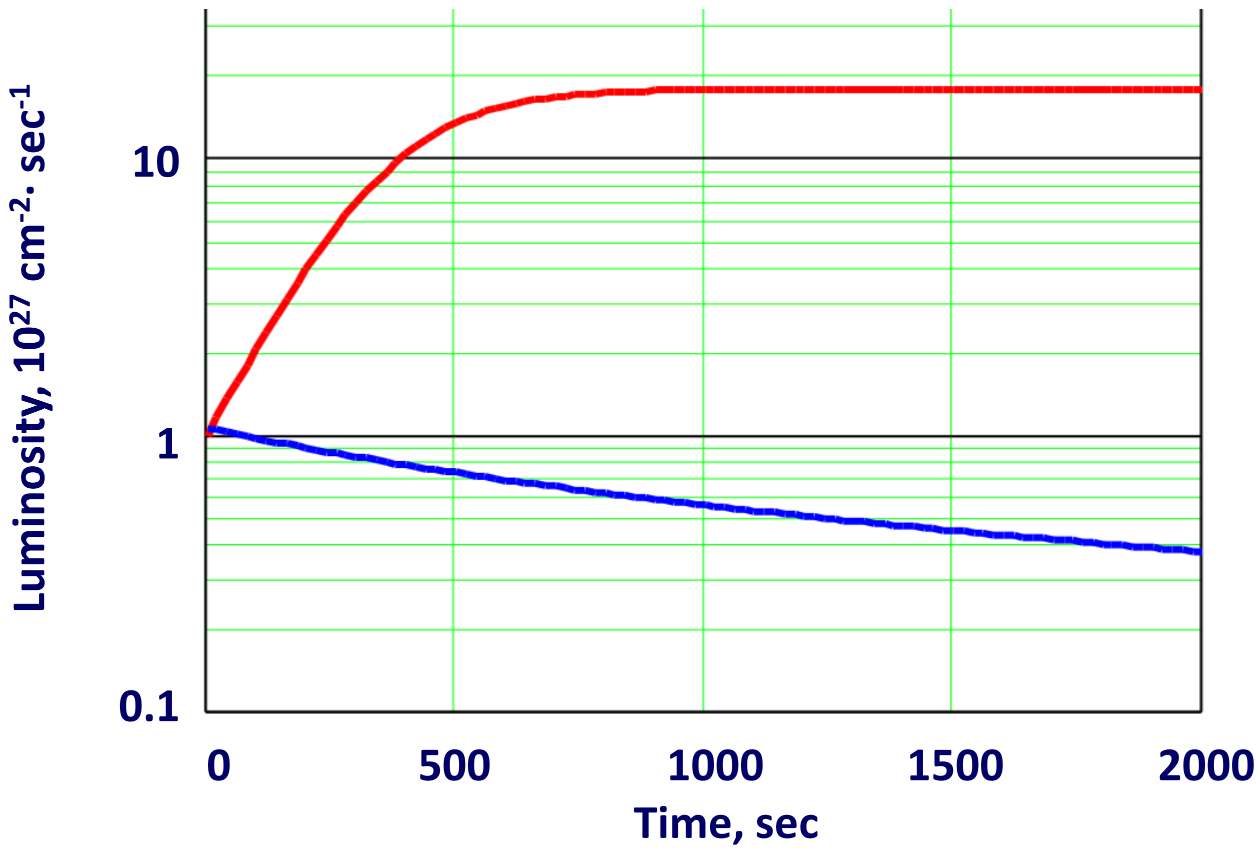


Parameters of quasi-quilibrium beam	
Parameter	Value
Ion number per bunch, 1e9	0.3 – 2.8
Emittance, mm·mrad	1.1
Bunch length, m	0.6
Momentum spread, 1e-3	0.6 – 1.7
Betatron tune shift ΔQ	0.04 – 0.05
Luminosity, $cm^{-2} \cdot s^{-1}$, 1e27	0.01 – 0.9

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

3. Strategy of The Project Luminosity Achievement

One More Statement (V. Parkhomchuk, BINP)



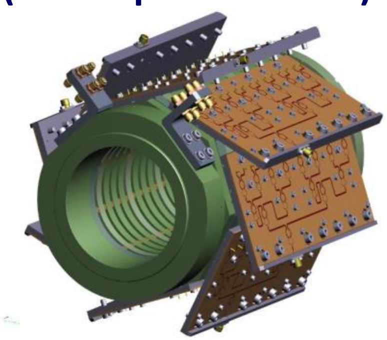
What gives electron cooling to the NICA collider ??
Without cooling the ion beam grows in time and luminosity drops down
With cooling the ion beam shrinks and luminosity grows
We can increase luminosity by more than 20 times !!!
(equivalent of 20 NICA's)

4. NICA Fabrication
Stochastic Cooling System (SCS) for the Collider
JINR – stages I and II

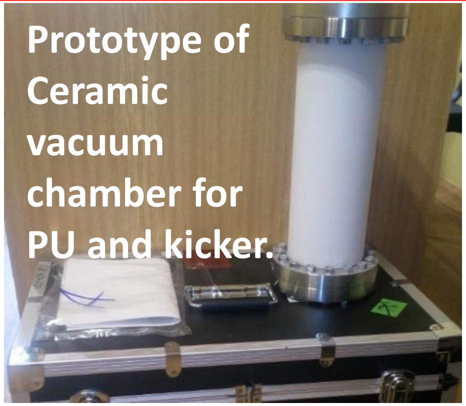
Parameters of the collider stochastic cooling system (stage I)

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)

Challenge #1:
Low energy ultra-high intensity Collider

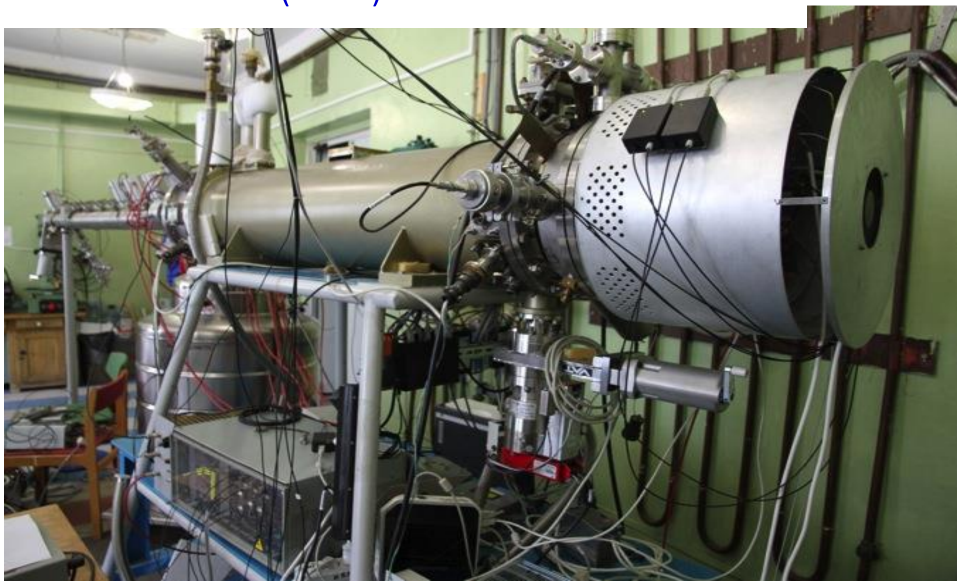
Collider:
2 x 503 m SC rings in one cryostat, separated vertically by 320 mm

Collider lattice: FODO, 12 cells x 90^0 each arc
Electron & stochastic beam cooling

RF gymnastics:
From coasting beam to 22nd harmonics => 66th harmonics.
Cooling and stacking with RF1 barrier voltage (< 5 kV).
Accumulation efficiency ~ 95%, about 110 - 120 injection pulses (55-60 to each ring) every 5 sec. Total accumulation time ~ 10 min.
Steps 2-3. Formation of the short ion bunches at presence of cooling: RF-2 (100 kV, 4 resonators) => RF-3 (1MV, 8 resonators).

Challenge #2: Intense Heavy ion sources ESIS/EBIS type

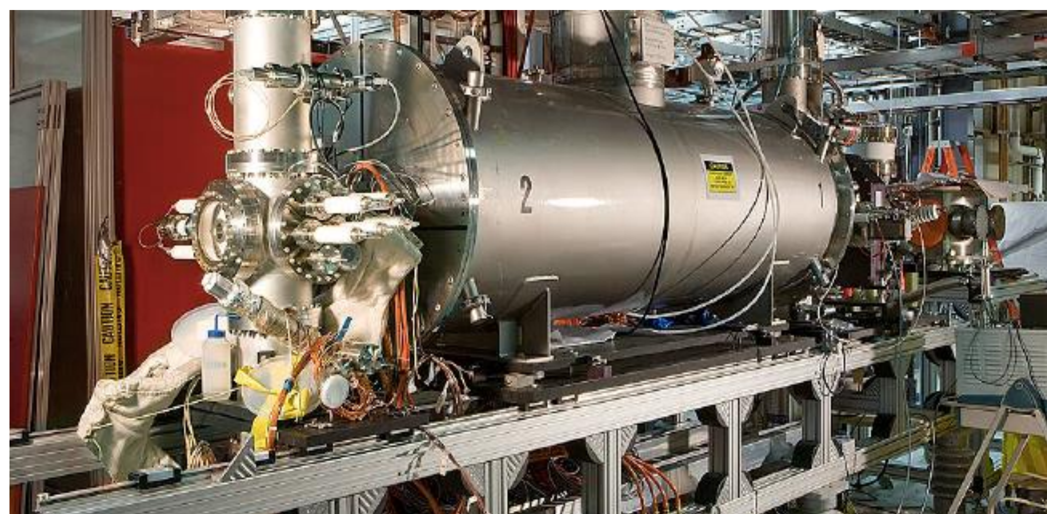
JINR Krion-6T (ESIS) for NICA



B = 6 (5.4) T !!!
Ee = 25 keV
J_el (design) = 1000 A/cm^2
Au^{30+32+} : 2.5*10^9 ppp,
t_{ion} = 20 ms @ 50 Hz.
Frequency 0.6 – 10 Hz

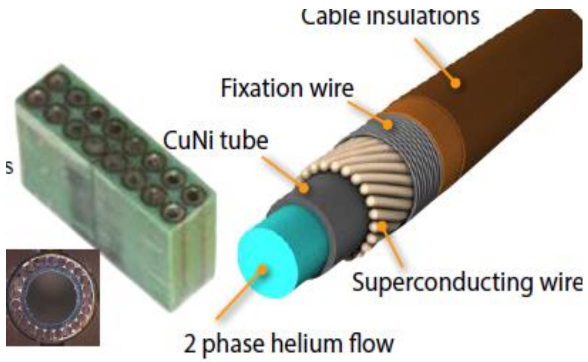
Au (32+): 2.3*10^9 ions/pp@5Hz

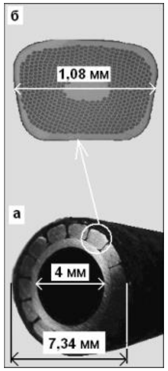
I_e = (7 –10) A
L_trap = 188 cm
E_e = (20 –24) kV
J_e= (300–500) A/cm2



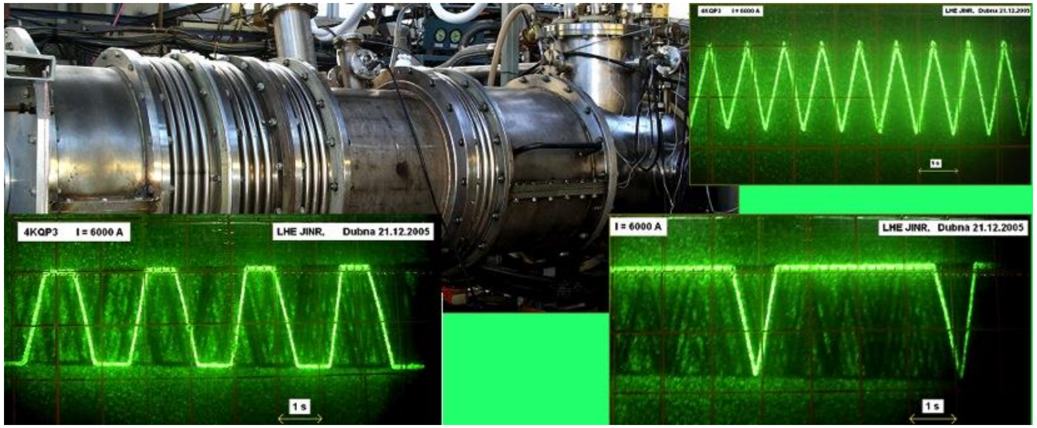
BNL 5T EBIS (for RHIC and NSRL)

Challenge # 3: Unique SC magnets
(from fast-cycling mode to long plateu @ high field)



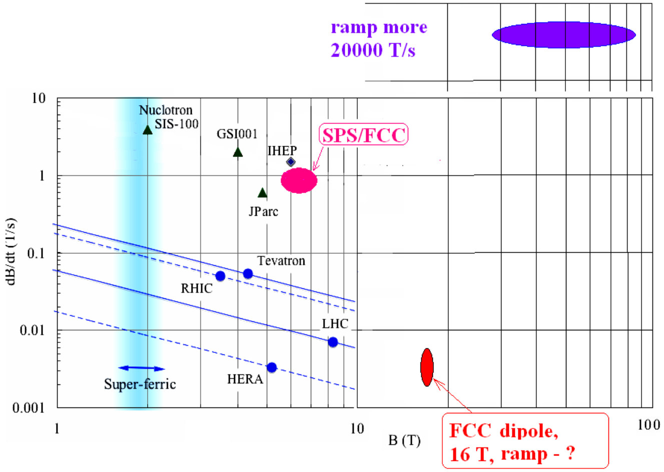


“Nuclotron cable” – hollow SC cable



NICA Booster and Collider, FAIR SIS-100, HIAF rings:
B ~2T, I=10–17 kA, Ramp rate – up to 4T/s@1Hz, Stored E ~0.4MJ

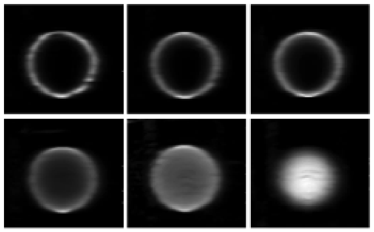
24/7 Factory for SC magnets



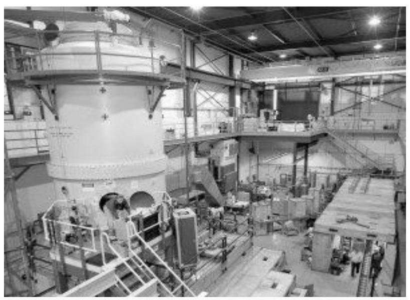
Very near future: fast (up to 4 T/s) ramped 4-6T dipoles and large aperture quadrupoles (FFL). Perspective -> 50 GeV (p)

Challenge #4. Beam cooling systems: Electron and Stochastic

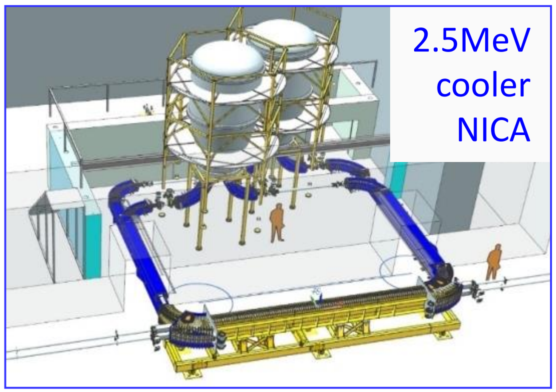
Ultra-high energy of electron beam
Use of cryogenic cathodes
Hollow electron beam



2 MeV cooler COSY FZJ



FNAL: 4 MeV Pelletron

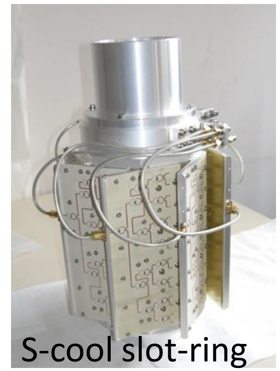


2.5MeV cooler NICA

Electron cooling: for booster – typical system, for collider – the most challenging in the world. JINR together with BINP. Electron Energy: 0.2-2.5 MeV, Electron current 0.1-1A, hollow beam, B=0.2T, cooling time in range 1÷3 GeV/u ~ 10÷300 sec

Main challenges: high voltage generation; power transmission to high potential; generation of magnetic guiding field.

We are constructing stochastic cooling system 2-4 GHz band and the slot-ring-coupler (designed and produced for Nuclotron at FZJ as prototype for NICA) collaborating strongly with FZJ (COSY, HESR) and FAIR, FNAL.



S-cool slot-ring coupler structure

FZ Juelich, COSY

To perform the horizontal and vertical cooling, we plan additionally ~ 10 Watt per each direction as the gain is 70~75 dB. Totally ~ 400 Watt is the required power.

TDR: 32 rings per each pick-up, and 64 rings per each kicker, ~ 400 rings for total system.

Challenge: advanced Notch-filter, accuracy of delay 1ps, effective 3D-cooling in 3÷4.5GeV/u@ 300÷700s, vacuum conditions for pick-up (warm section) 10^{-11} Torr, simultaneous operation with beam accumulation

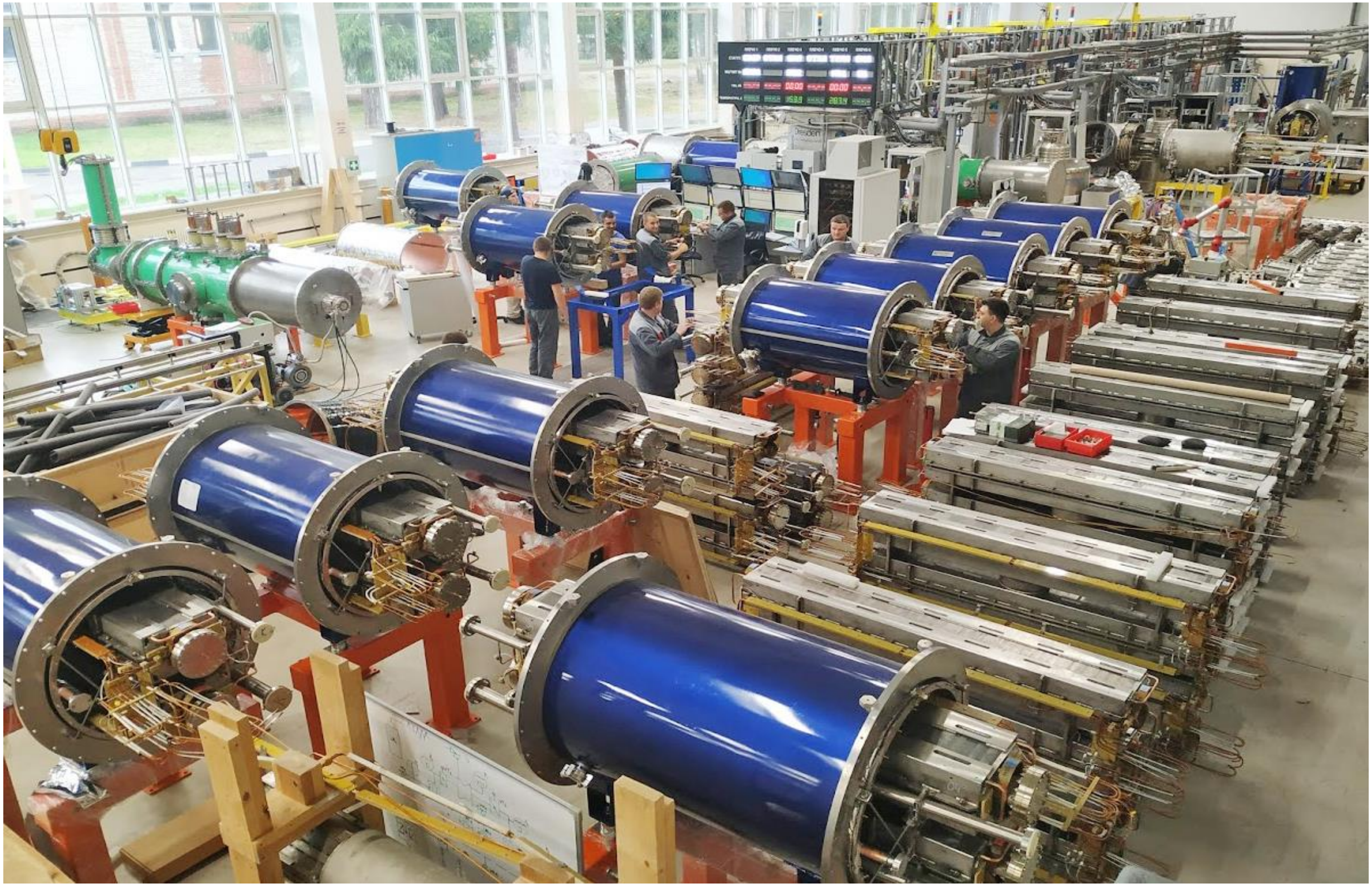
4. NICA Stages

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

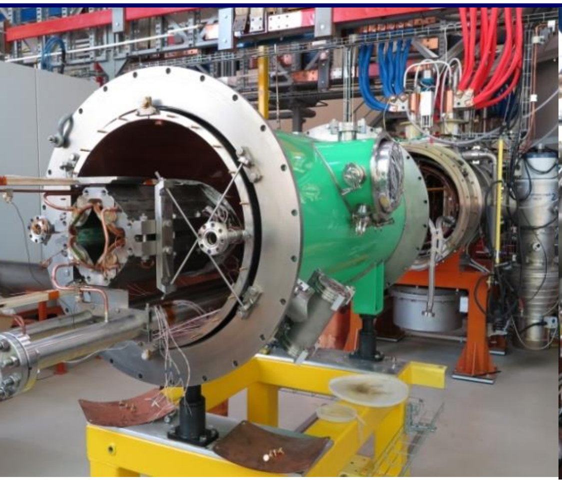
Factory of the Miracles



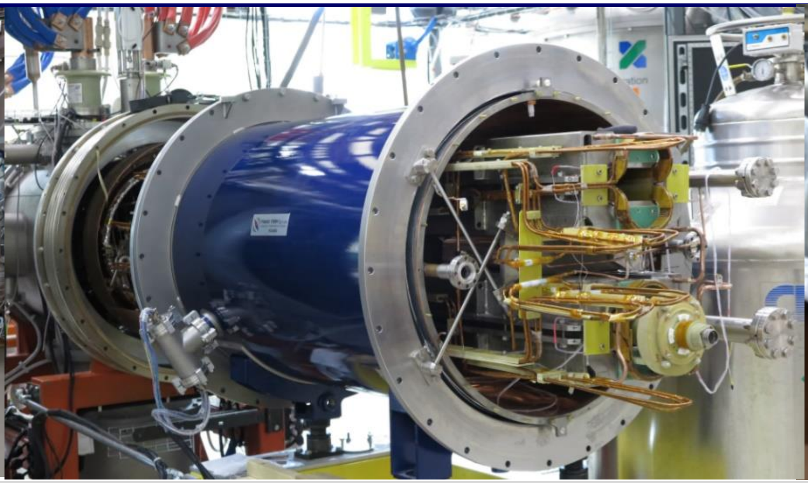
August 2020

4. NICA Fabrication

Factory of the Miracles: ready samples

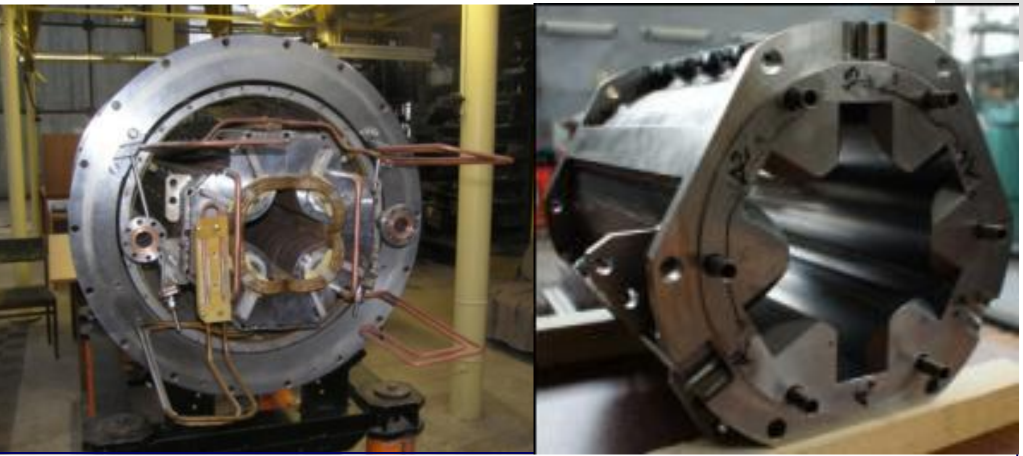


Booster dipole

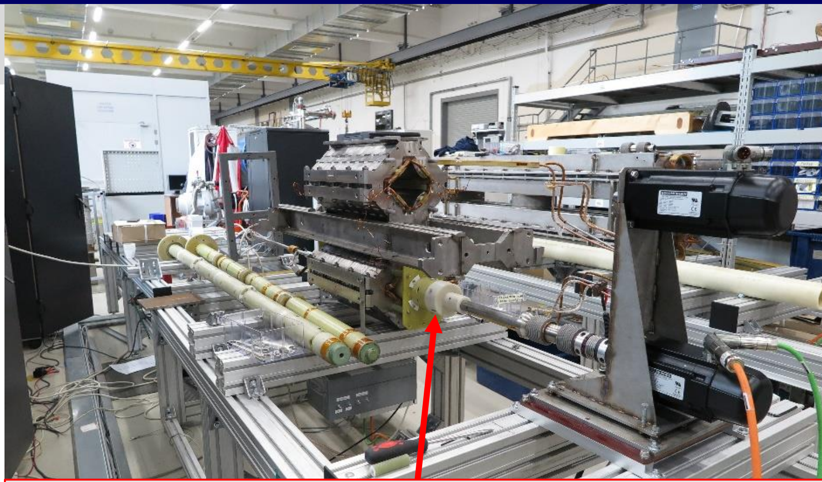


Collider dipole

Collider quadrupole



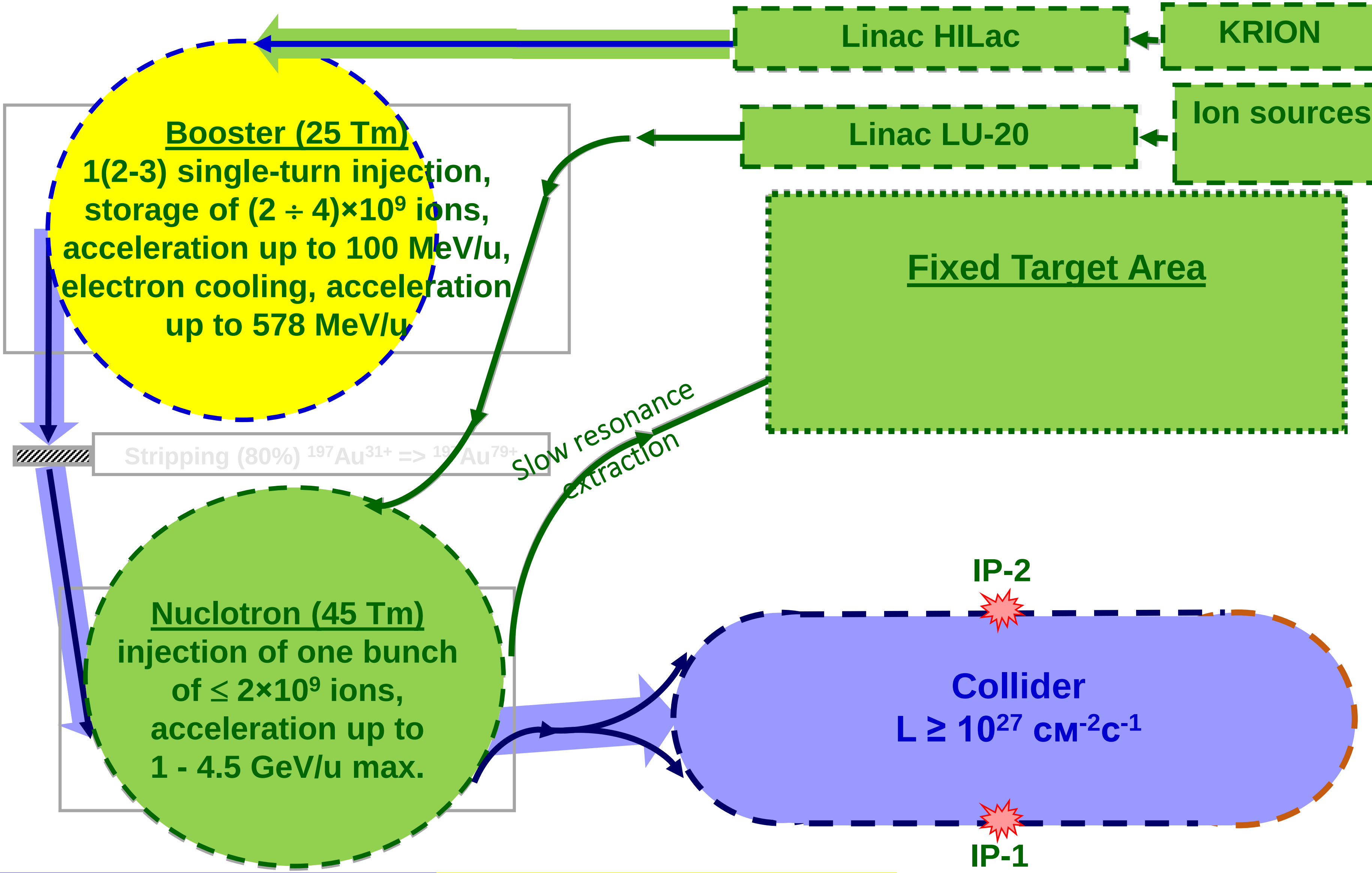
Quadrupole & sextupole for SIS-100



Collider quadrupole ready for test

Facility components – status

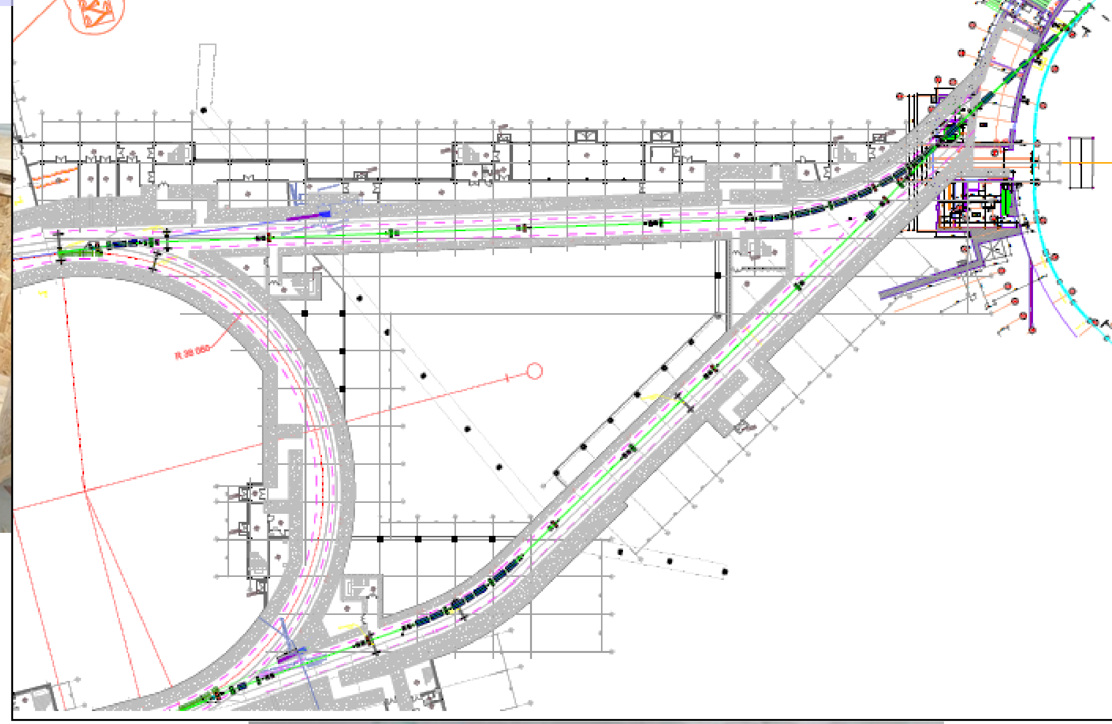
2020



work in progress	early commissioning	commissioned / existing

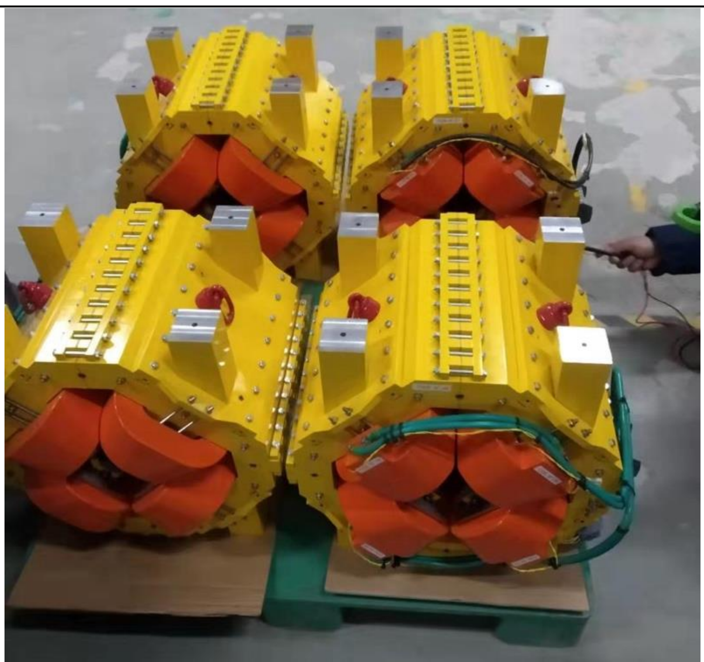
Nuclotron-Collider beam transport channel

A.Tuzikov



JINR has prepared a temporary storage in the Collider tunnel and ready to receive the channel magnets

- delivery => Q4 2020
- assembly=> Q4 2021
- commissioning => Q2,Q3 2021



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, E-cooler 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

Acceleration system of HV E-cooler

Commissioning 2021

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**

Steering Committee of the NICA Project:

NICA Accelerator Project:
Approved in 2011 and prolonged in 2015 until 2020 (2022)

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. Katayama	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 MAC
2008 – 2020
11 sessions

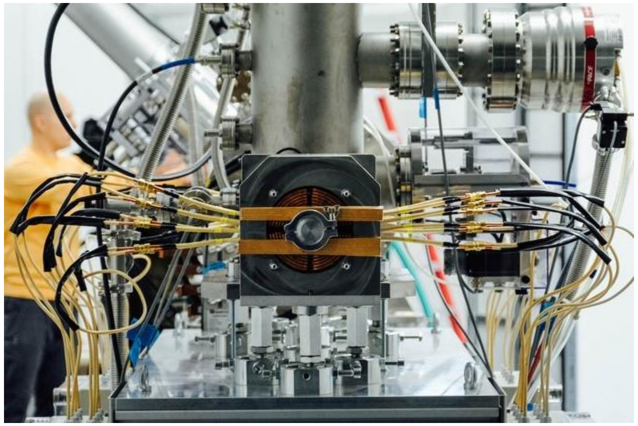
NICA DAC
2010 – 2020
8 sessions

INNOVATIONS @ NICA

Innovative cluster:

• Areas for an innovative and applied researches with use of linear accelerators and Nuclotron extracted beams;

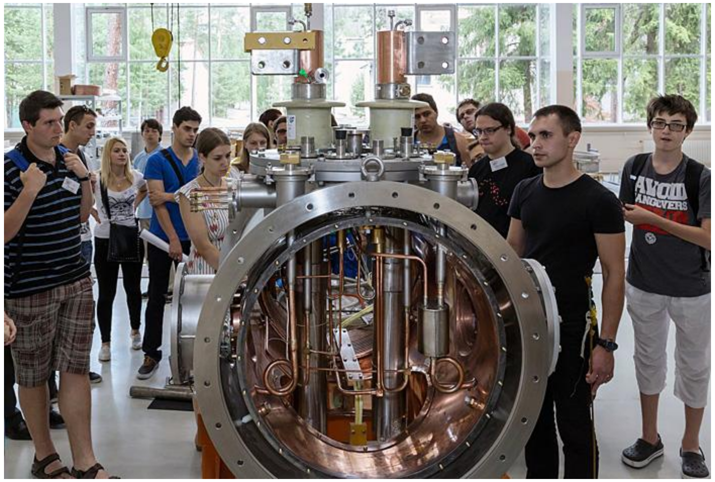
• Areas for an innovative and applied researches on the booster and Nuclotron beams;



Infrastructure cluster:

• NICA user's center;

• IT complex for experimental data storage and analysis;



Education field:

• Areas equipped with use of modern technologies for school, university and special education (i.e. engineering, etc);

Collider building

*to be completed –**2021***

comissioning of builing =>
sub stages:
MPD** - mid**’20
***collider magnets**– beg‘**21**;*

tunnel arc

Thank you for your attention!