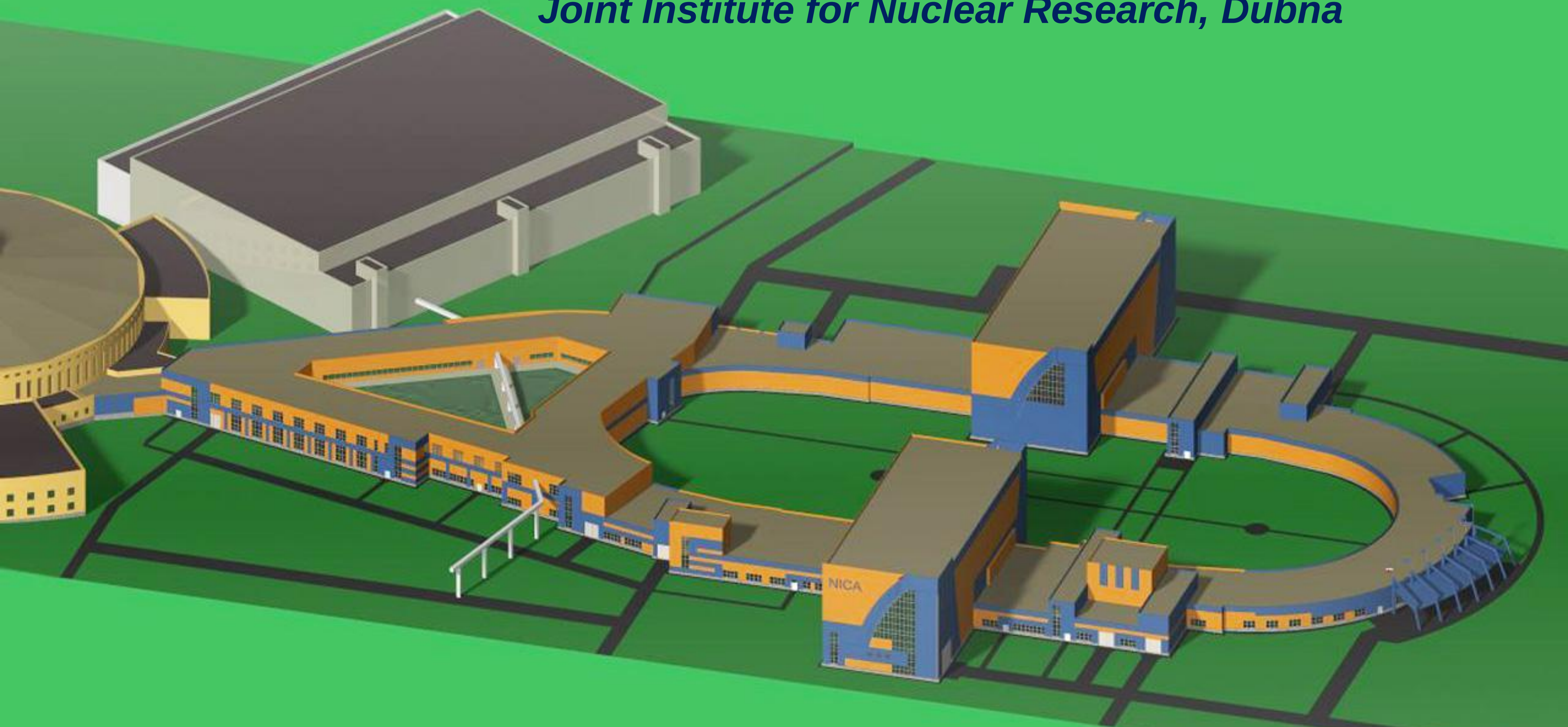
NICA project:
challenges for heavy ion collider

Anatoly Sidorin

Veksler and Baldin laboratory for high energy physics
Joint Institute for Nuclear Research, Dubna



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 18 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 2020.

In 2017 the project was included into ESFRI road map.

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 detector (2020)

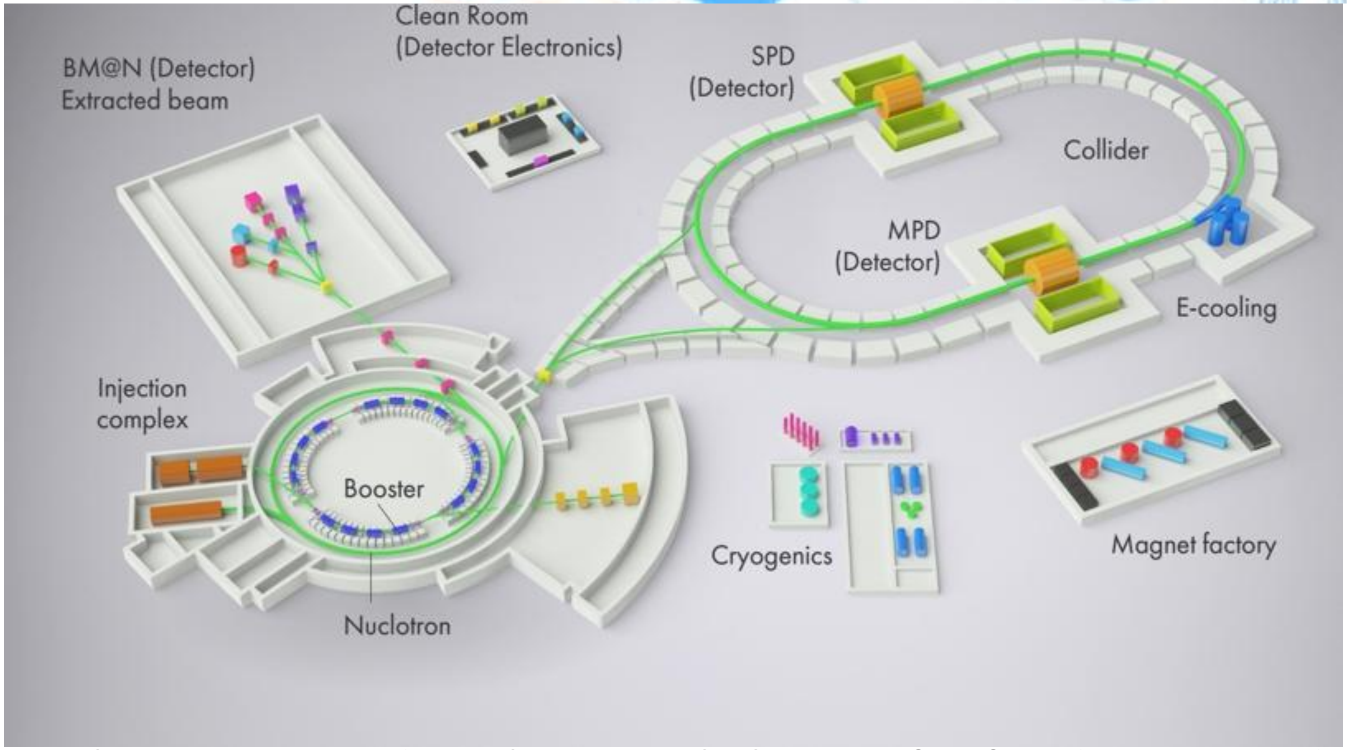
-Full configuration, heavy ion collisions

-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 Au) 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:

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

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

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

$$L = \frac{n_b N_b^2}{4\pi\varepsilon\beta^* T_{rev}} f\left(\frac{\sigma_s}{\beta^*}\right) \qquad f\left(\frac{\sigma_s}{\beta^*}\right) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{\exp(-u^2)du}{\left[1+\left(\frac{u\sigma_s}{\beta^*}\right)^2\right]}$$

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

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)

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

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

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 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

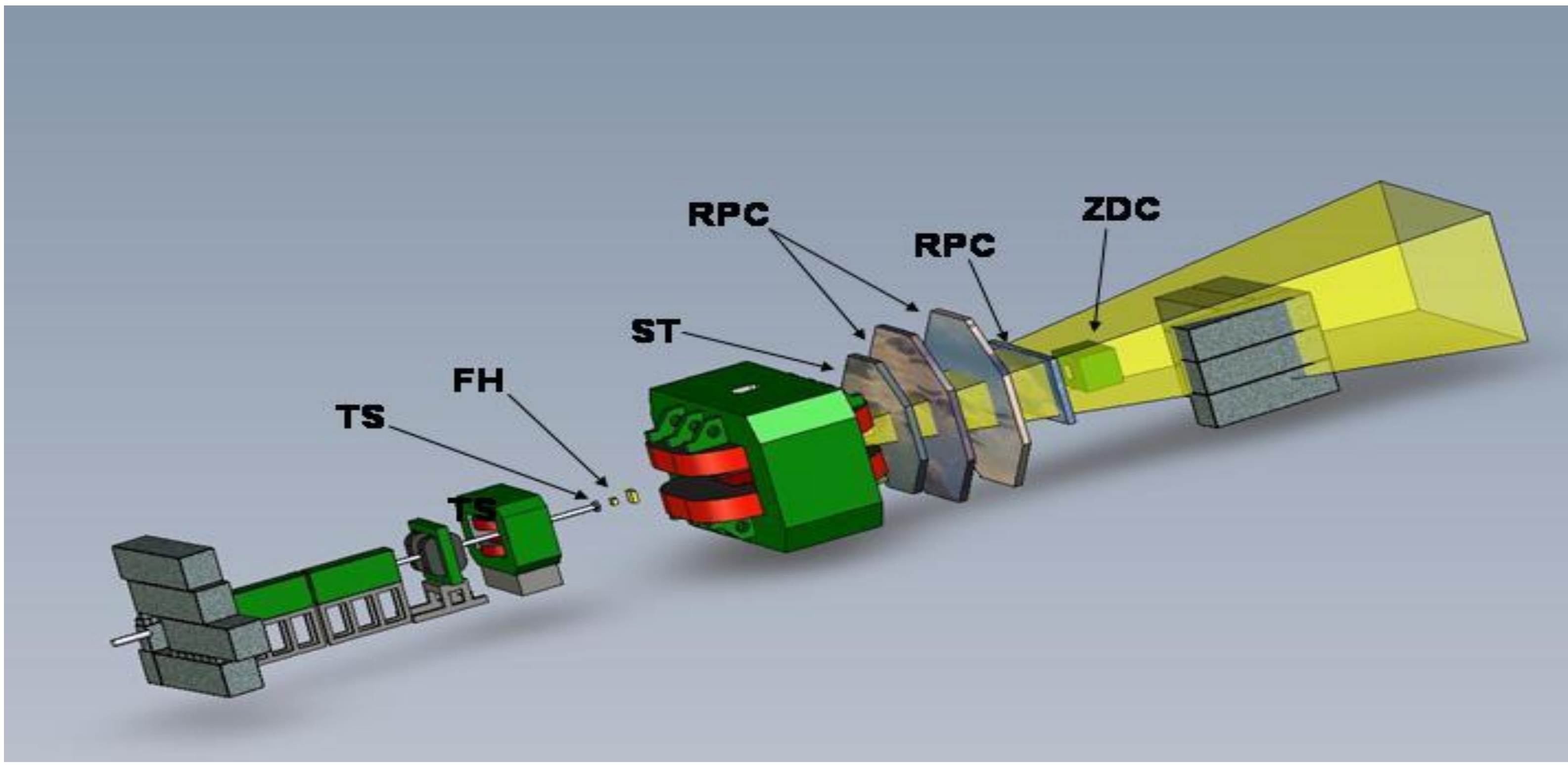
Circumference of the ring, m	503.04		
Structure of the bending arc	FODO, 12 cells		
Number of bunches	22		
R.m.s. bunch length, m	0.6		
β-function in IP, m	0.35		
Betatron frequinces, Q_x/Q_y	9.44/9.44		
Chromaticities, Q'_x/Q'_y	-33/-28		
Acceptance, π mm·mrad	40		
Momentum acceptance, $\Delta p/p$	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

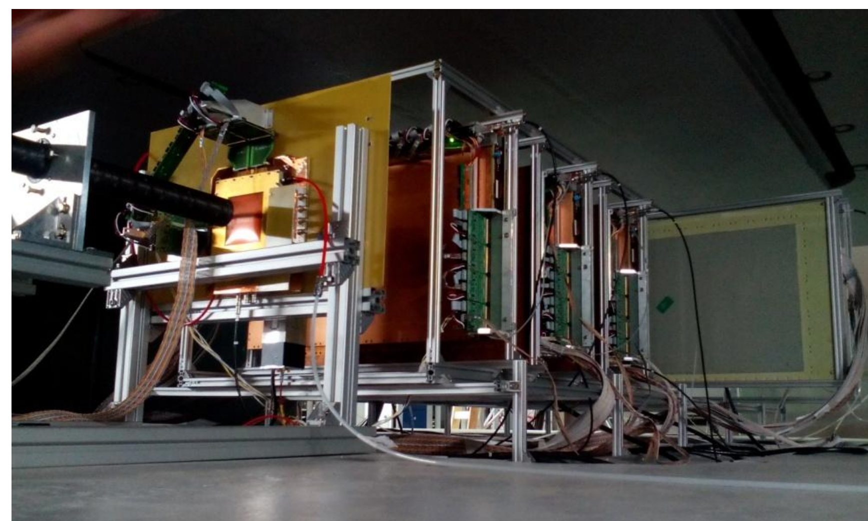
- Baryonic Matter at Nuclotron (BM@N)
- Elements of the accelerator complex
- Status of MPD construction
- Civil construction

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.



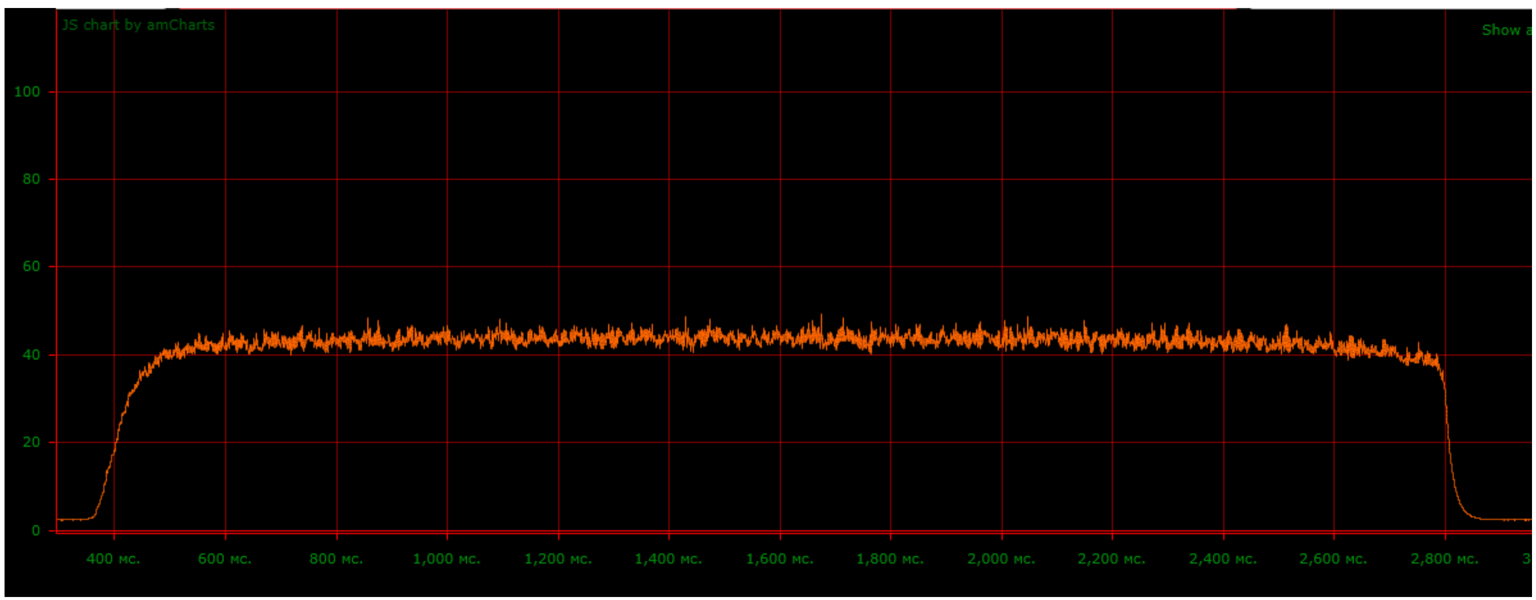
BM@N assembly



BM@N test at the Nuclotron beam

-Three technological runs (2016 – 2017)

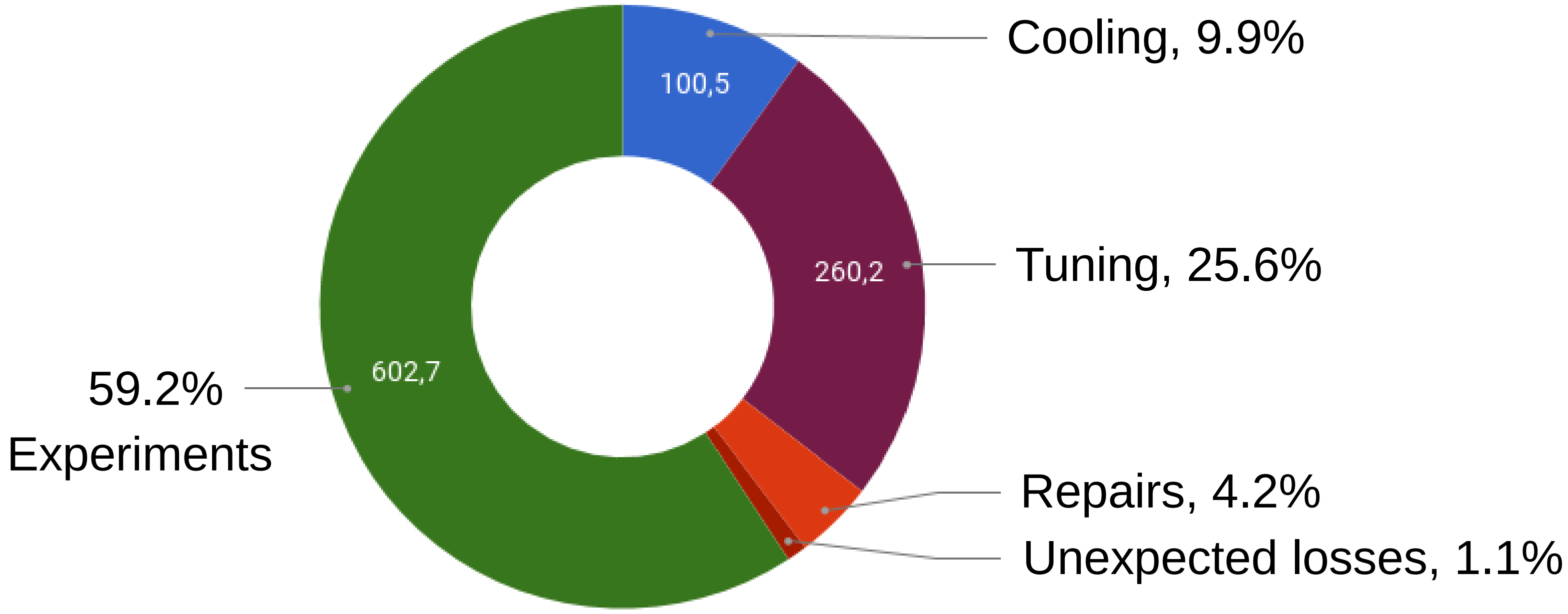
-**5.02 – 4.04.2018 experiments** with C, Ar, Kr beams (Short range correlations, strange production)



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

Nuclotron: RUN 55 statistics

Run #55 22.02 - 05.04.2018



1018 h

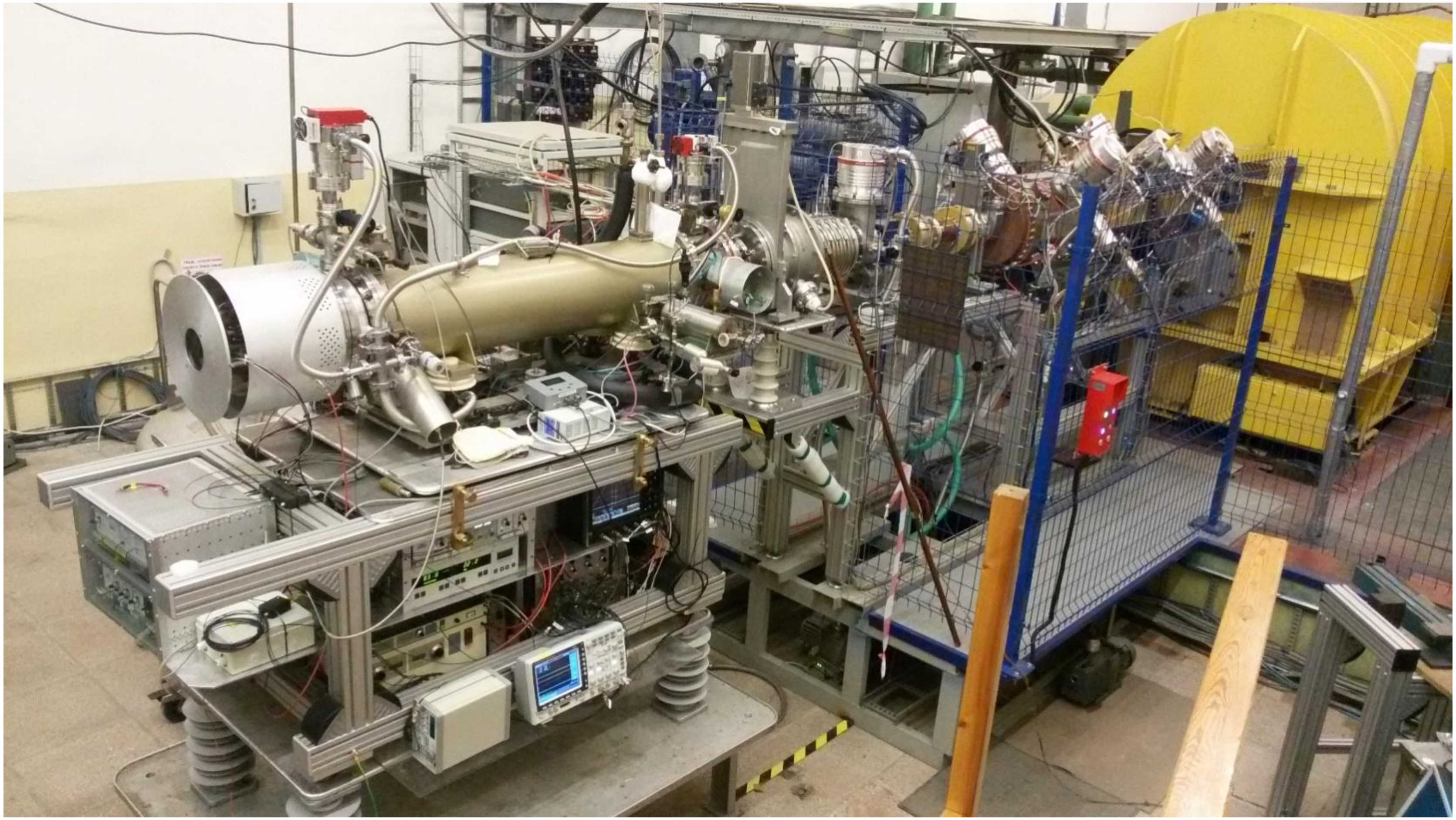
Injection chain for heavy ions

Cryogenic heavy ion source KRION

of Electron String Ion Source (ESIS) type
provides up to $2.5 \cdot 10^9$ Au^{31+} particles per cycle
at repetition frequency up to 10 Hz

Two runs at Nuclotron (2014, 2018)

KRION 6T –during Nuclotron RUN #55 (2018)



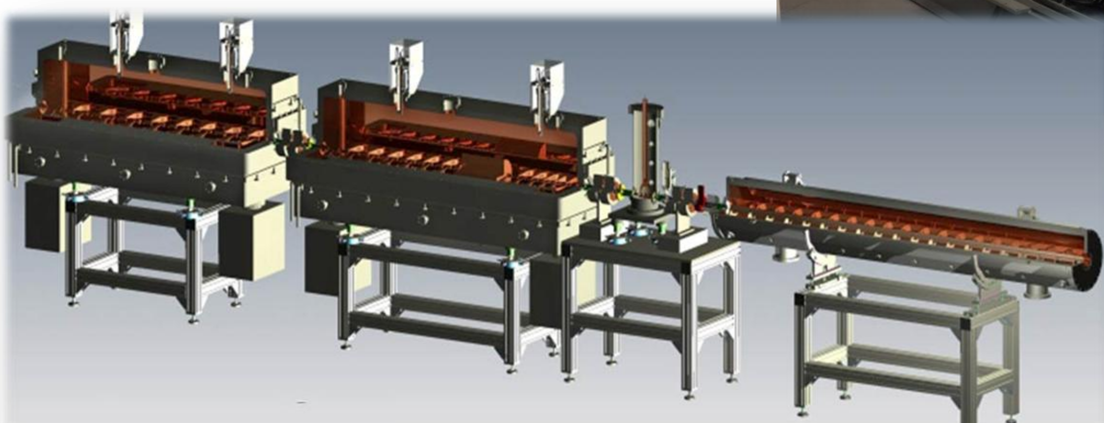
SRC & BM@N experiments, radiobiology researches

Injection chain for heavy ions

Heavy ion linear accelerator (HILac)

First in Russia
high current (10 mA) heavy ion Linac
(designed and constructed in Germany)

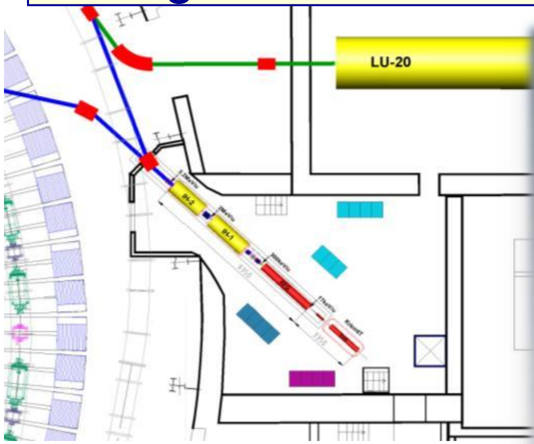
First Linac with transistor RF amplifier
(fabricated in Australia)

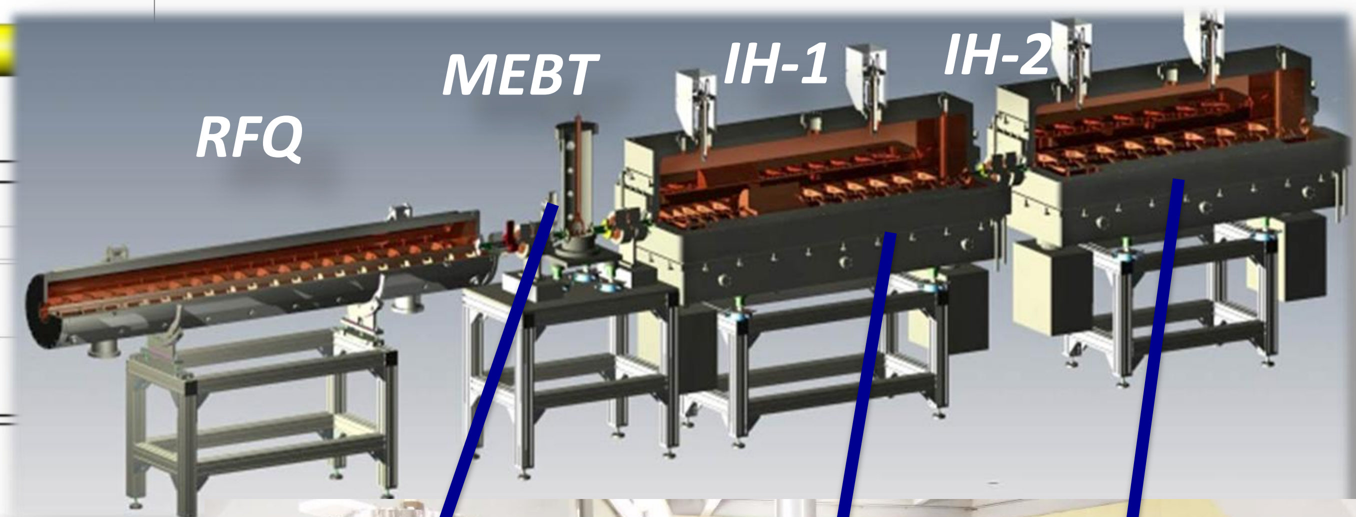


Heavy Ion Linear Accelerator ***HILAc***

high current (10 mA), the first Linac with transistor RF amplifier

Design and fabrication by “BEVATECH OHG” Germany, Offenbach/Mainz





overall commissioning: Oct. 16

Injection chain for heavy ions

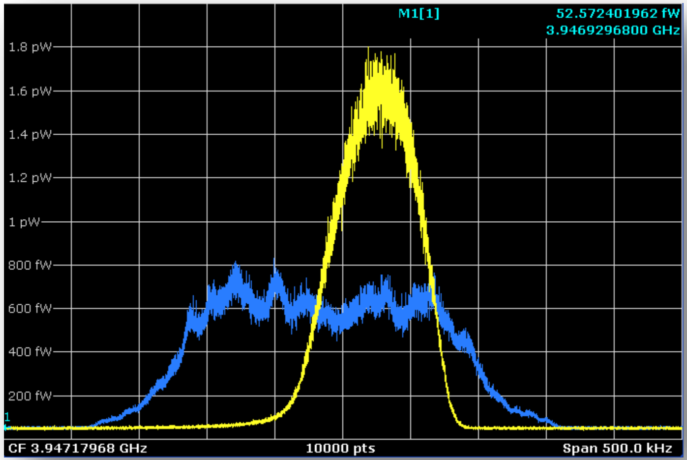
The Booster should accelerate ions up to 600 MeV/u (for ions with $Z/A = 1/6$).
The magnetic ring of 211 m long is placed inside the window of the Synchrophasotron yoke.

Fabrication of the magnetic system is completed.

Start of assembly – September 2018.

First (technological) run – end of 2018.

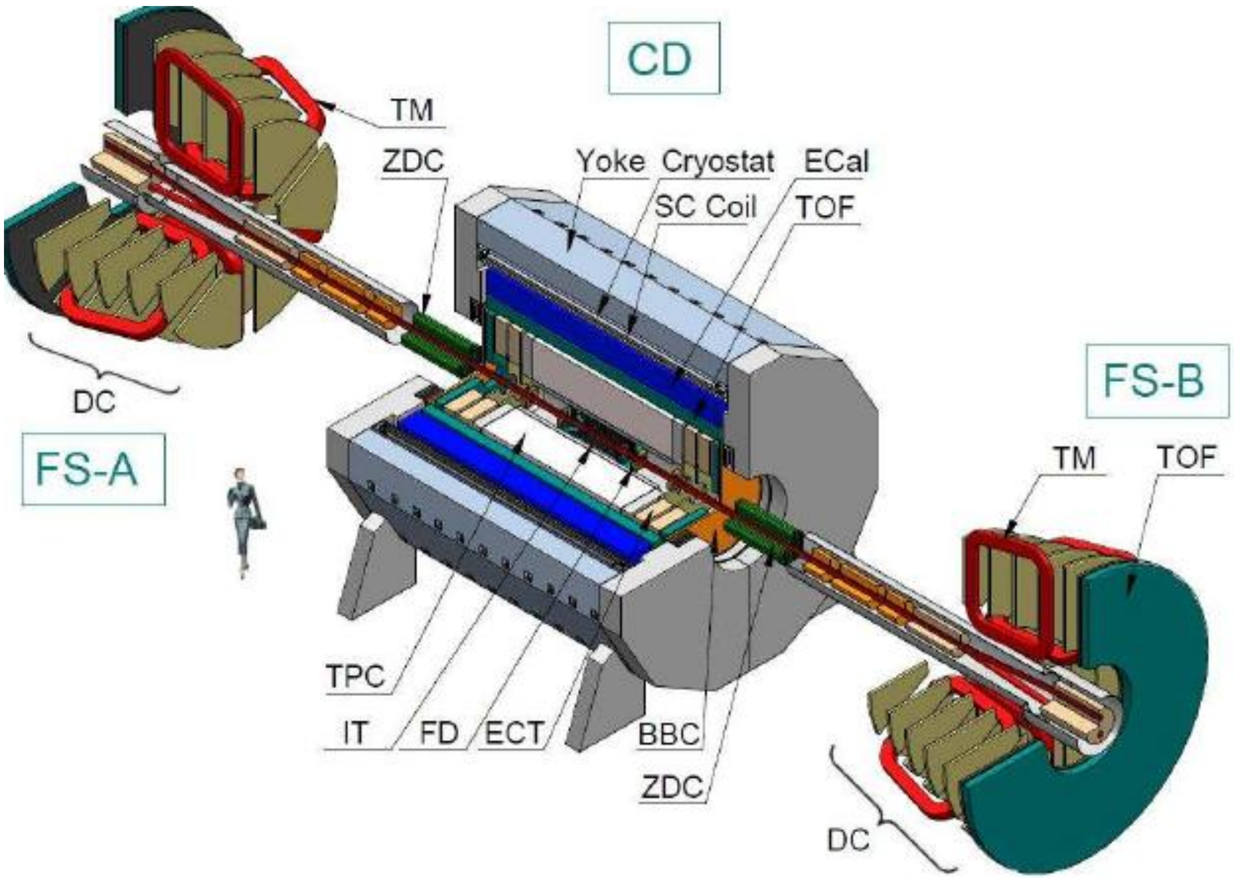
R&D for Collider Stochastic cooling system



Successive test at the Nuclotron 2013

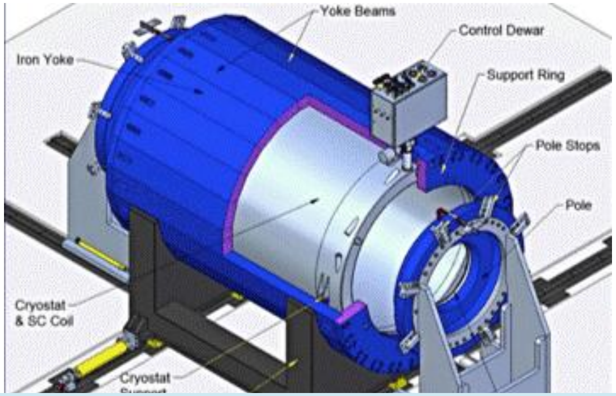
Multi Purpose Detector (MPD)

aiming to study of hot and dense strongly interacting matter in heavy ion (up to Au) collisions at the centre-of-mass energy range of max baryonic density (up to 11 GeV).



MPD solenoid

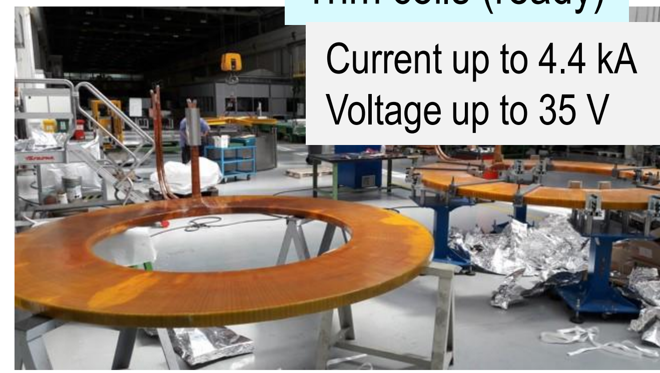
B_0=0.5 T Weight ~ 900 t B inhomogeneity ~$3 \cdot 10^{-4}$



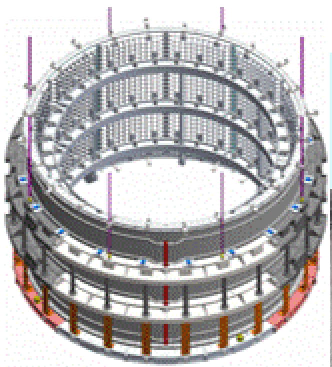
Solenoid cylinder (all 3 ready)

Trim coils (ready)

Current up to 4.4 kA
Voltage up to 35 V



ASG superconductors (Genova, Italy)**:**



Vacuum kiln & tooling
for coil compounding

Vacuum vessel

Winding of SC coil

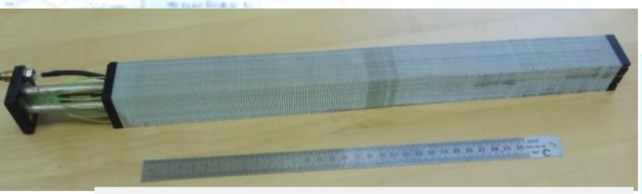
Control assembling & tests (AGS) – August’18-March’19

Control assembling at JINR – May-August 2019

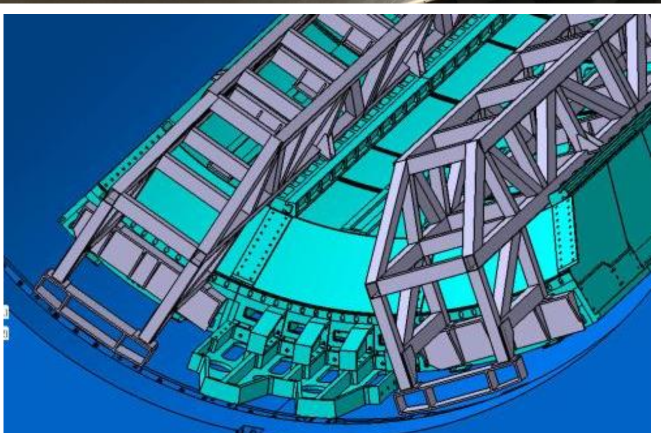
MPD inner tracker

CREMLIN WP2 Working Meeting
„Exchange on Policy- and ESFRI-related Issues", April 2016, Dubna

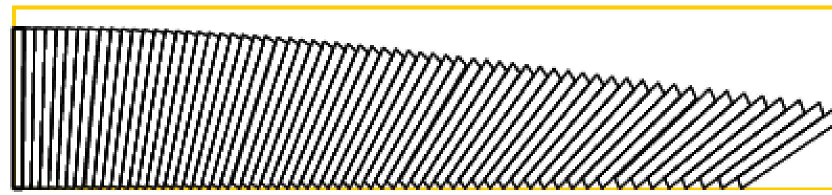
MPD Electromagnetic Calorimeter (ECAL)



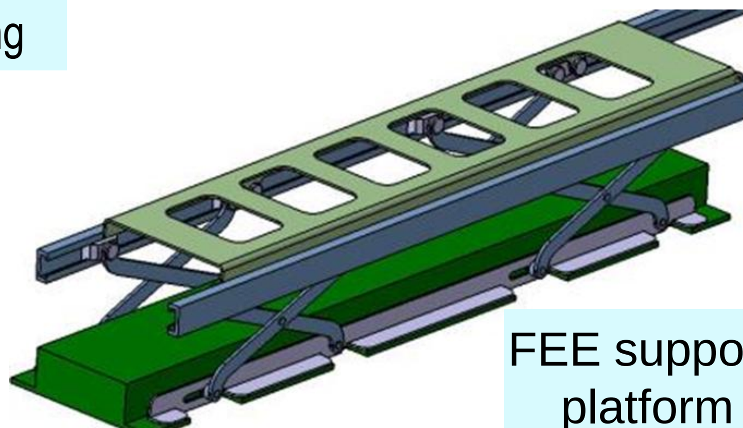
Pb+Scint. (14 X_0 ,4x4 cm^2)
WLS fibers + MAPD



- **Finalizing ECAL geometry (design and simulation) – ITEP team**
- **Mass-production technology testing – 3 workshops at JINR, IHEP, and Tsinghua**
- **ECAL integration scenario – JINR and ProgressTech Ltd.**
- **TDR preparation - All**



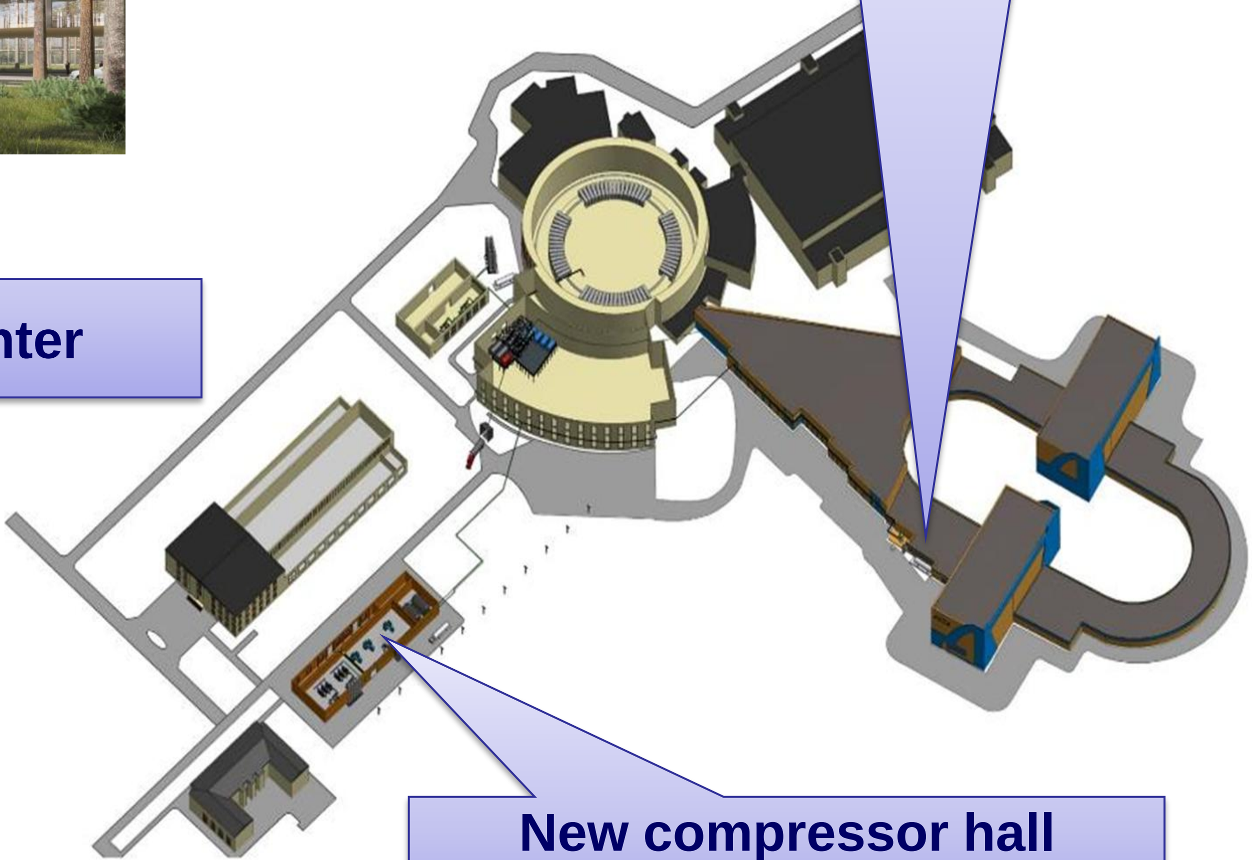
ECAL module assembling



FEE support platform

Civil construction

NICA innovation center



Collider building

New compressor hall building

Collider building

Official start up of the construction 25 March 2016

Collider building

2017

Collider building online

http://nucloweb.jinr.ru/nucloserv/205corp.htm

NICA innovation center

Start of construction - end 2018

- cluster of JINR computer center dedicated to collect and process the data from NICA detectors,
- 500 offices for scientists,
- laboratory rooms for preparation of experimental equipment and fast analysis of results,
- conference hall

Cryogenic facility

New helium liquefier (1000 l/h)

Finally the cooling power should be doubled from 4 kW to 8 kW @ 4.5K

Largest in Russia

Commissioned in May 2016

Line for assembling and cryogenic testing of SC-magnets

Main production areas:

- **Incoming inspection zone**
- **SC cable production hall**
- **SC coils production hall**
- **Area for assembling the magnets**
- **Area for the magnetic measurements under the room temperature**
- **Leakage test area**
- **Area for mounting the SC-magnets inside cryostats**
- **Cryogenic tests bench**

450 magnets for NICA and FAIR projects

Official start up

28 November 2016

Collider

-Serial production of SC magnets is in progress

-RF and electron cooling system are under construction at BINP

-Beam transfer line from Nuclotron to collider

is under construction at Sigma-Fi

-Stochastic cooling in co-operation with FZJ

NICA accelerator complex