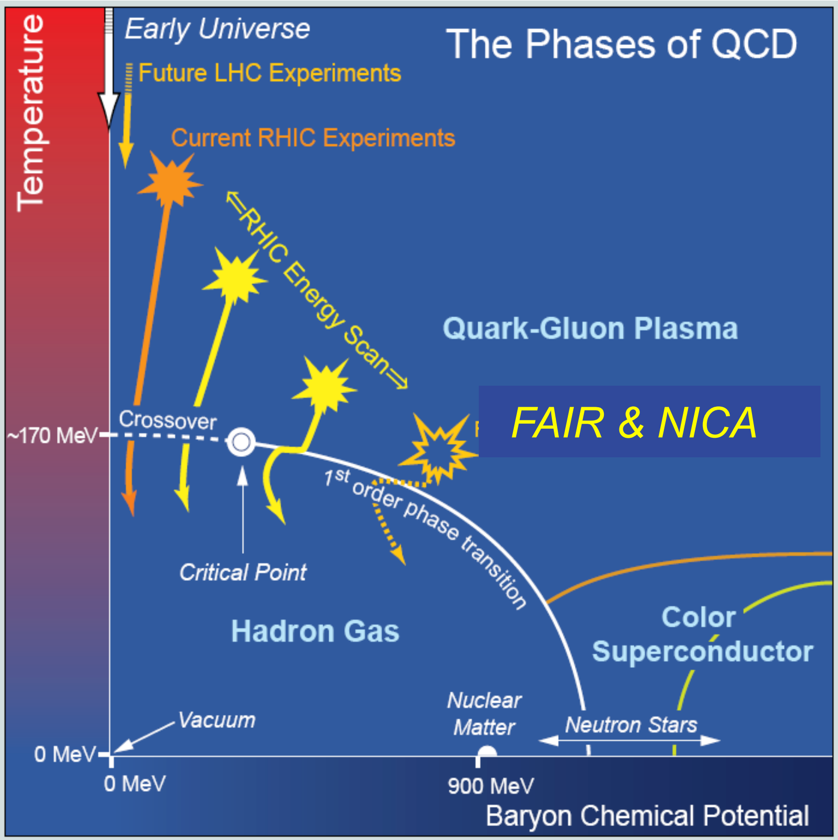
COOL'15
Workshop on Beam Cooling and Related Topics
Sept. 28 - Oct. 2, 2015
Jefferson Lab
Newport News, Virginia USA
JSA Jefferson Lab

# Status of the NICA project at JINR Dubna

*G.Trubnikov on behalf of team*

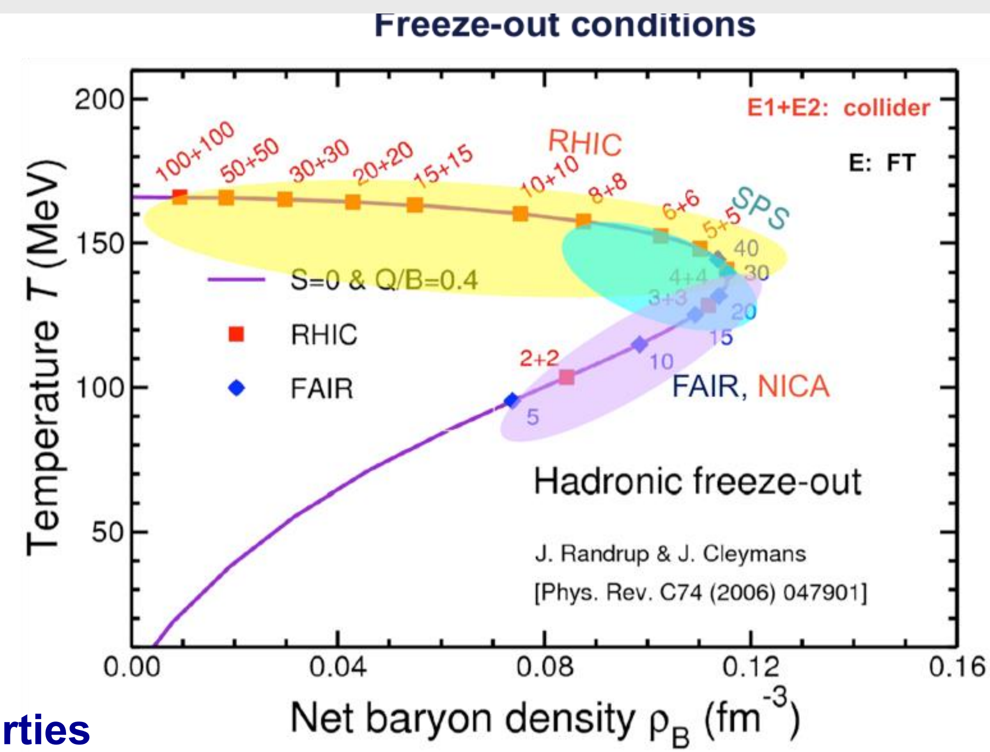
NICA

# Physics




## QCD matter at NICA :

- *Highest net baryon density*
- *Energy range covers onset of deconfinement*
- *Complementary to the RHIC/BES, FAIR and CERN experimental programs*




- **Bulk properties, EOS** - *particle yields & spectra, ratios, femtoscopy, flow*
- **In-Medium modification of hadron properties**
- **Deconfinement (chiral), phase transition at high $\rho_B$** - *enhanced strangeness production*
- **QCD Critical Point -** *event-by-event fluctuations & correlations*
- **Strangeness in nuclear matter** - *hypernuclei*

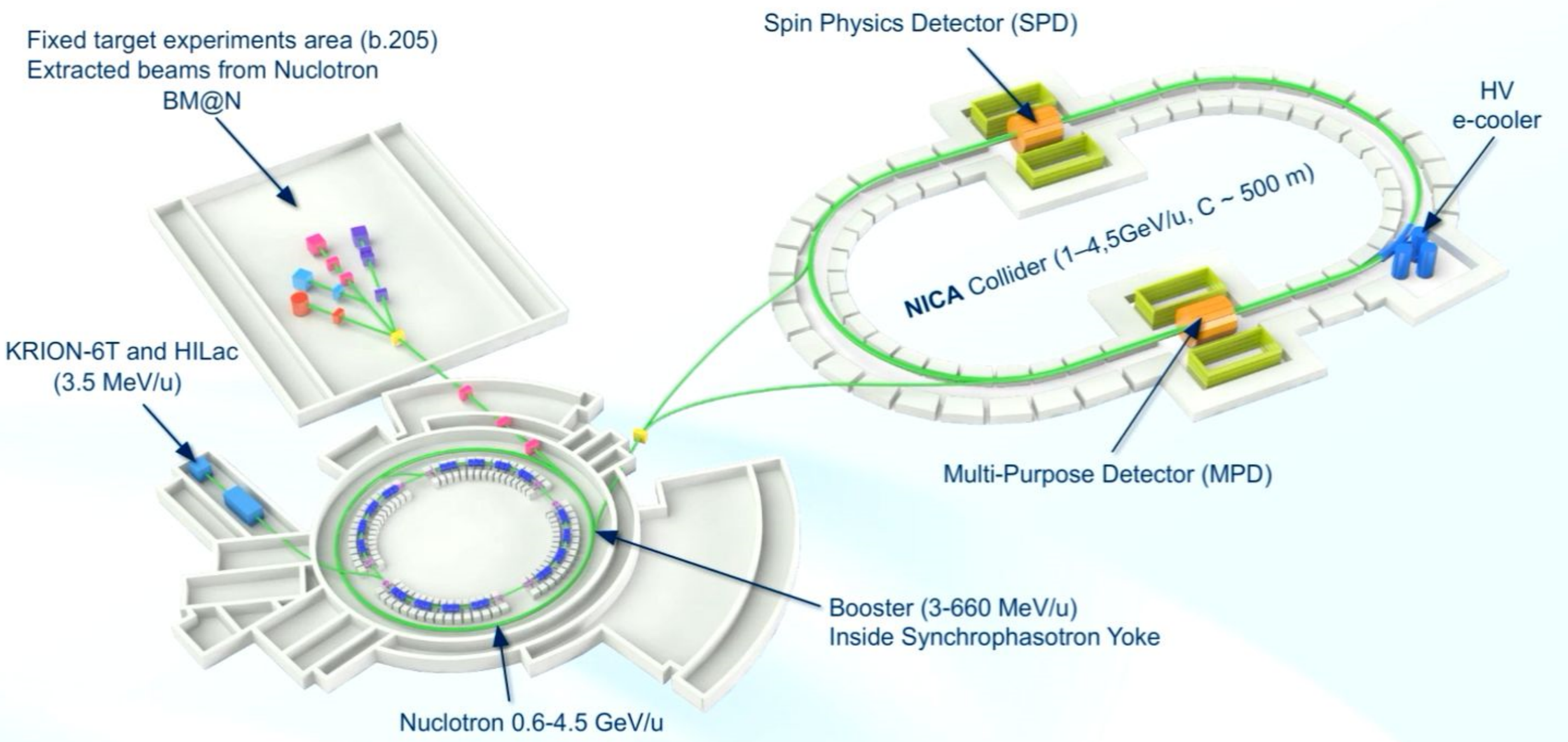
## NICA basic parameters:

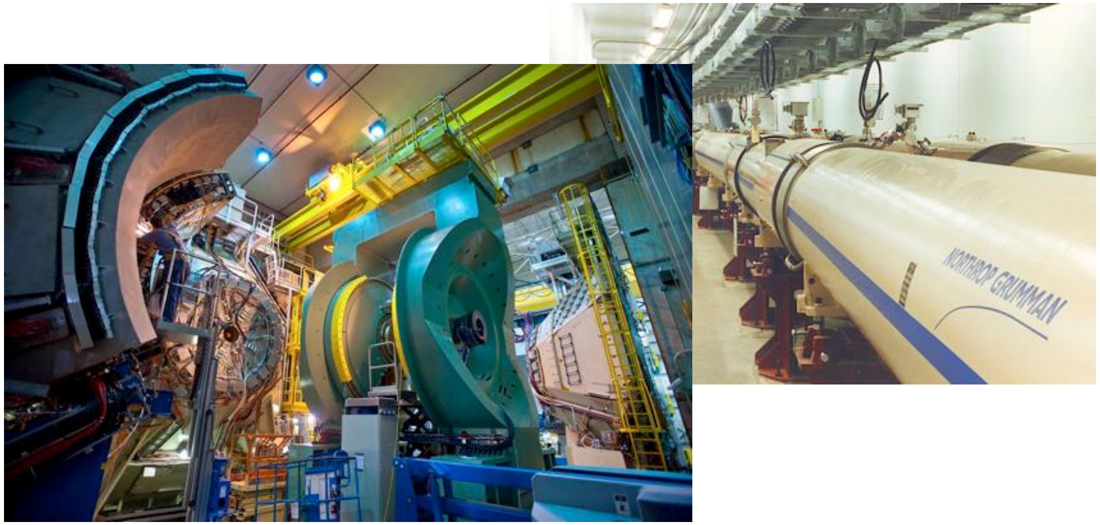
$\sqrt{s_{NN}}$ = **4 - 11** GeV; ***beams** from* **p** to **Au** @ **L** ~ **10**$^{27}$ cm$^{-2}$ c$^{-1}$ (Au),

$\sqrt{s_{NN}}$ = **6 - 26** GeV; p↑ and d↑ ***beams*** @ **L** ~ **10**$^{32}$ cm$^{-2}$ c$^{-1}$

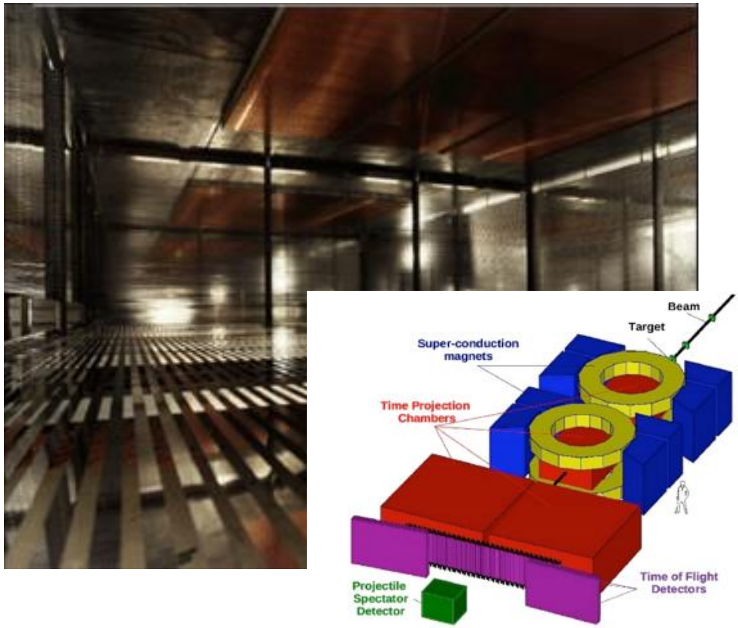
The NICA accelerator facility:

- cryogenic heavy ion source KRION of ESIS type + source of polarized protons and deuterons,
- modernized linac LU-20 (existing) + a new heavy ion linear accelerator (HILac)
- a new superconducting Booster synchrotron + existing SC HI ring of Nuclotron
- collider: two new superconducting storage rings with two interaction points






**STAR/PHENIX @ BNL/RHIC.**
designed for high energy research ($\sqrt{s_{NN}}$ = 20-200 GeV),
low luminosity for LES program L<$10^{26}$ $cm^{-2}s^{-1}$ for $Au^{79+}$

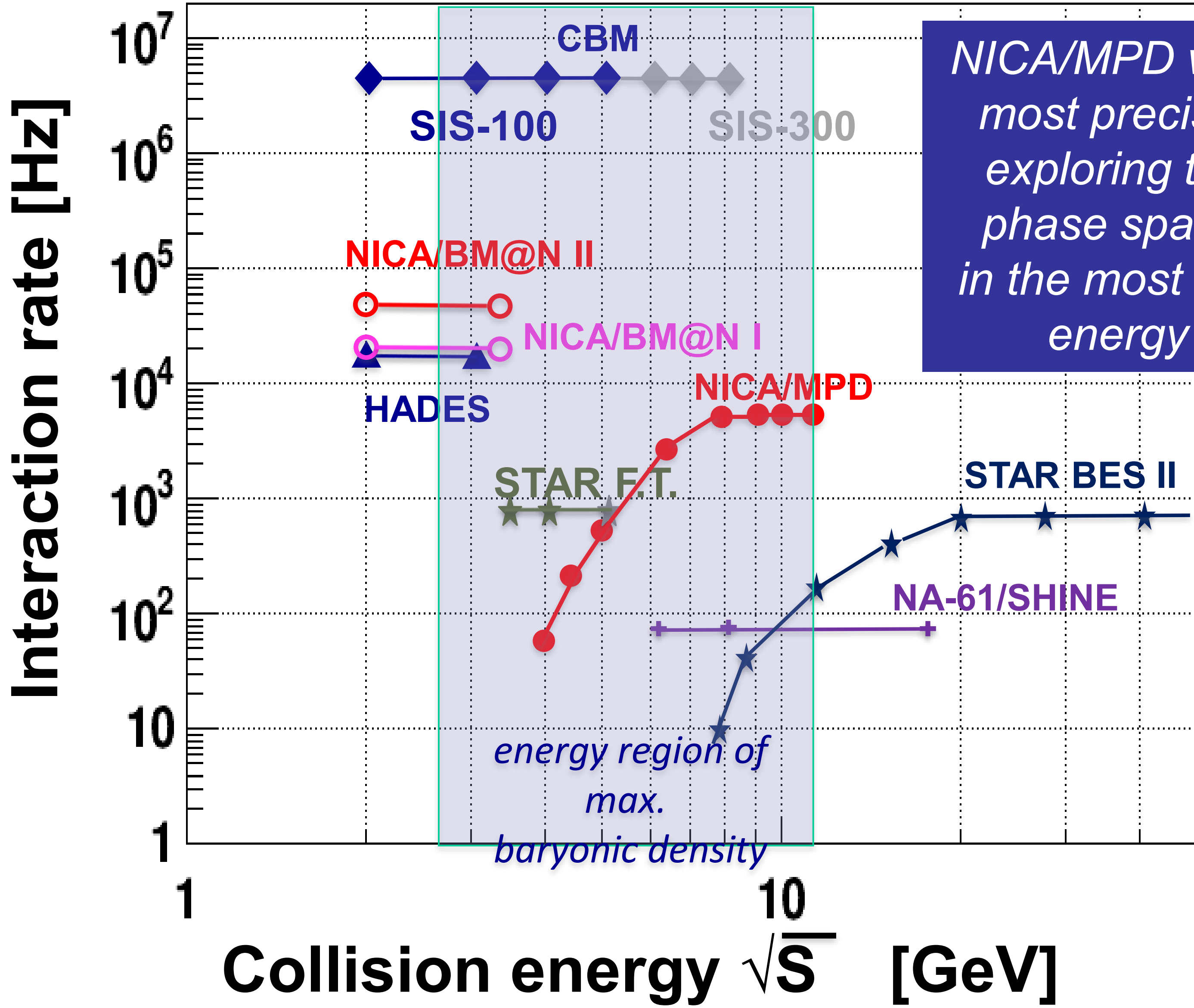



**NA61 @ CERN/SPS.**
Fixed target, non-uniform acceptance,
few energies (10,20,30,40,80,160A GeV)

**MPD @ NICA.**
Collider: $\sqrt{s_{NN}}$ = 4-11 GeV (~100 MeV/u energy step, variety of ions). L~$10^{27}$ $cm^{-2}s^{-1}$ for $Au^{79+}$

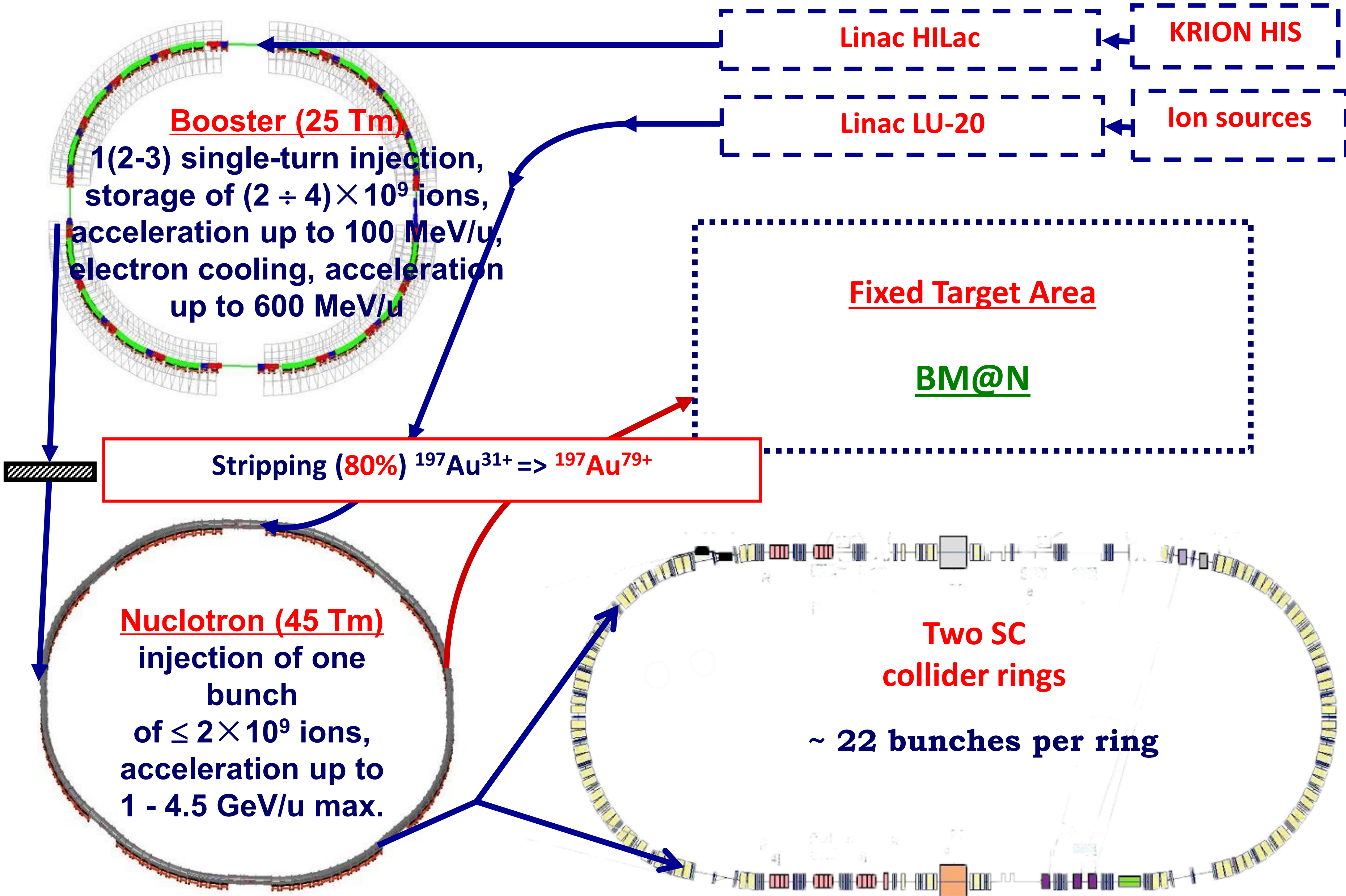
**CBM @ FAIR/SIS-100/300**
Fixed target, $\sqrt{s_{NN}}$= 2-5(9) GeV, high luminosity

# Present and future HI experiments/machines




*NICA/MPD will provide most precise results exploring the whole phase space region in the most interesting energy range*

# NICA: Structure and Operation Regimes (Heavy Ion Mode)

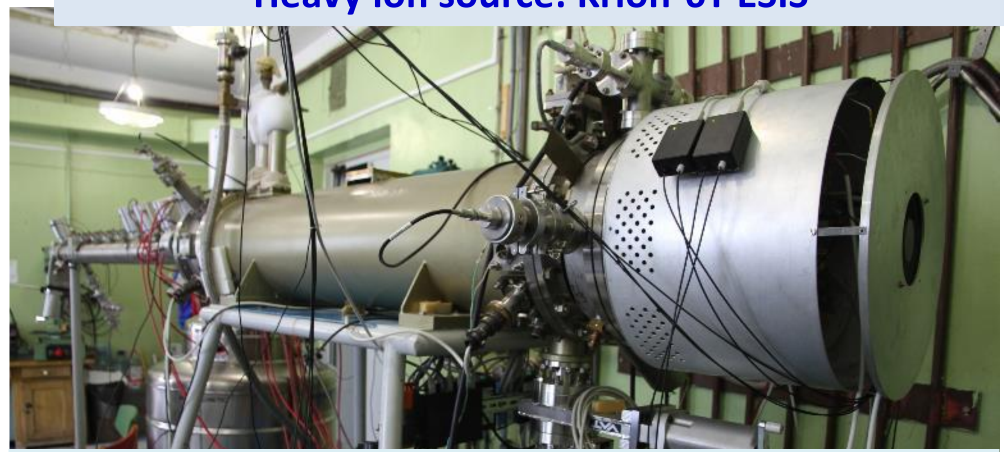


# NICA injection complex (ion sources + HILac)

**Source for polarized particles (SPP)**

**Source assembled in 2013 now is commissioned to achieve $10^{10}$ ppp. First beam run in beg.2016**

**Heavy ion source: Krion-6T ESIS**



B= 5.4T reached. Test Au beams produced:

- Au$^{30+}$ ÷ Au32$^{32+}$, 610$^{8}$, $T_{ioniz}$= 20 ms for
- Au$^{32+}$ -> repetition rate 50 Hz.
- ion beams Au$^{51+}$÷ Au$^{54+}$ are produced.

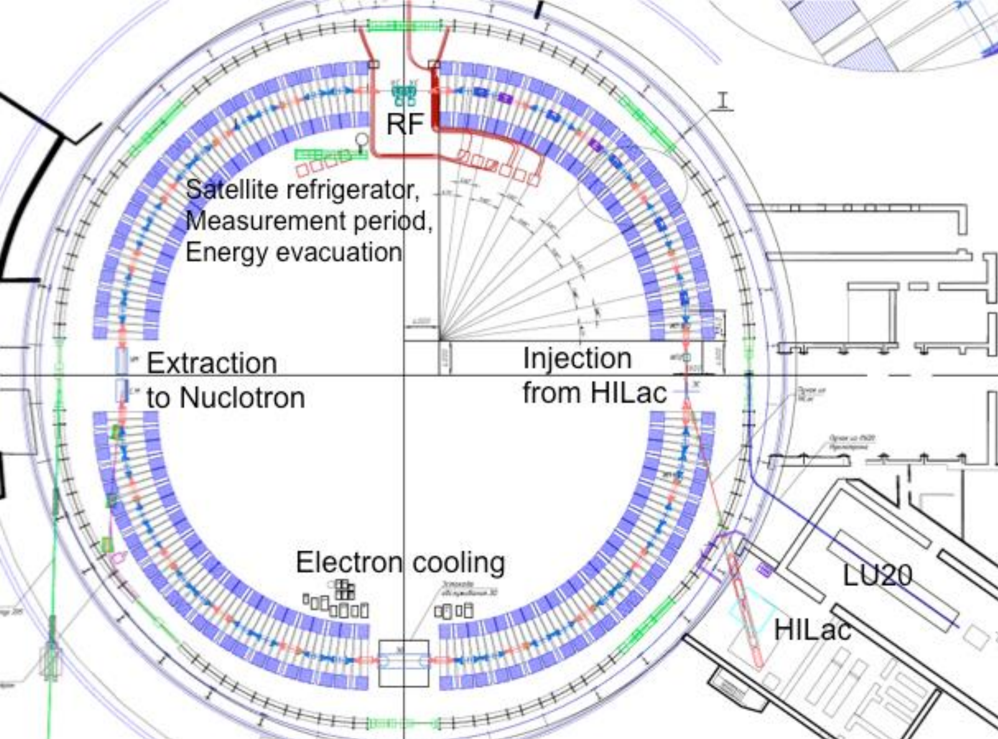

**Heavy Ion Linac delivered to JINR. Commissioning scheduled for Oct'15**

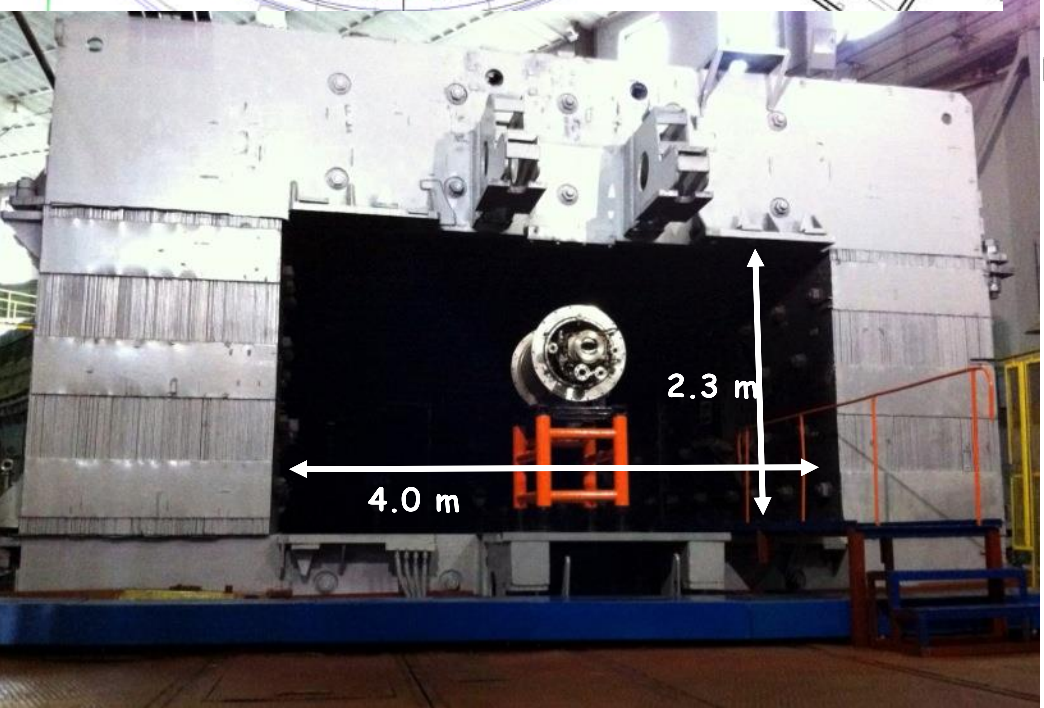
**NICA light ion injector (LU-20): RFQ linac, 150 keV**

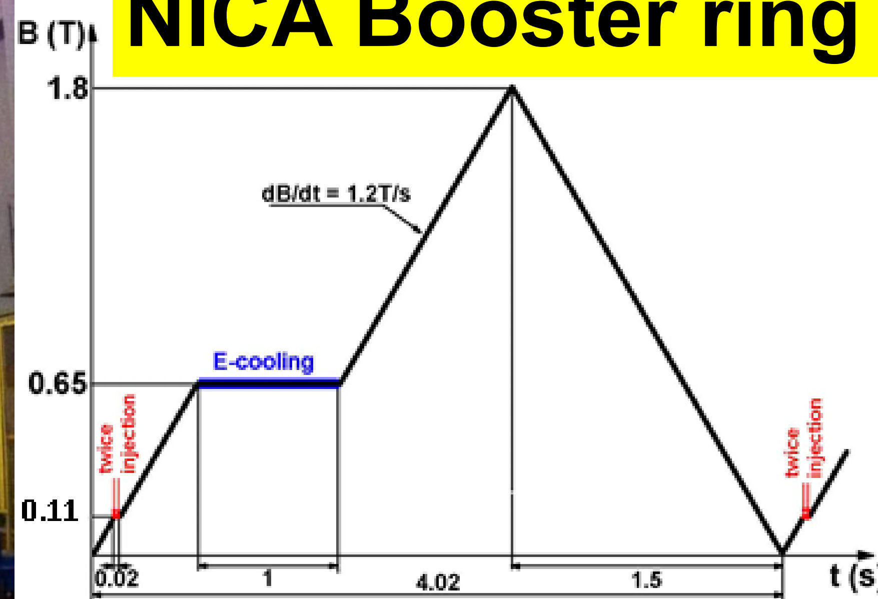
# NICA Booster ring

| Particles | p | $^{197}Au^{31+}$ |
|---|---|---|
| Injection energy, MeV/u | 3 | |
| Maximum energy, GeV/u | 6.4 | 0.58 |
| Magnetic rigidity, T·m | 1.55 ÷ 25.0 | |
| Circumference, m | 211.2 | |

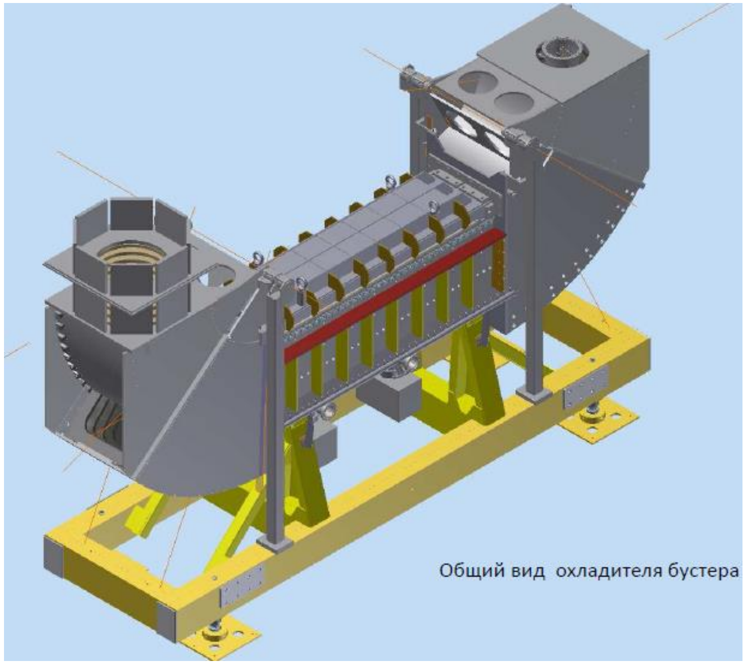
| | |
|---|---|
| Fold symmetry | 4 |
| # of DFO lattice cells per arc | 6 |
| Number of straight sections | 4 |
| Length of straight sections, m | 7 |
| Betatron tunes | 4.8/4.85 |
| Maximal energy, MeV/u | 660 |

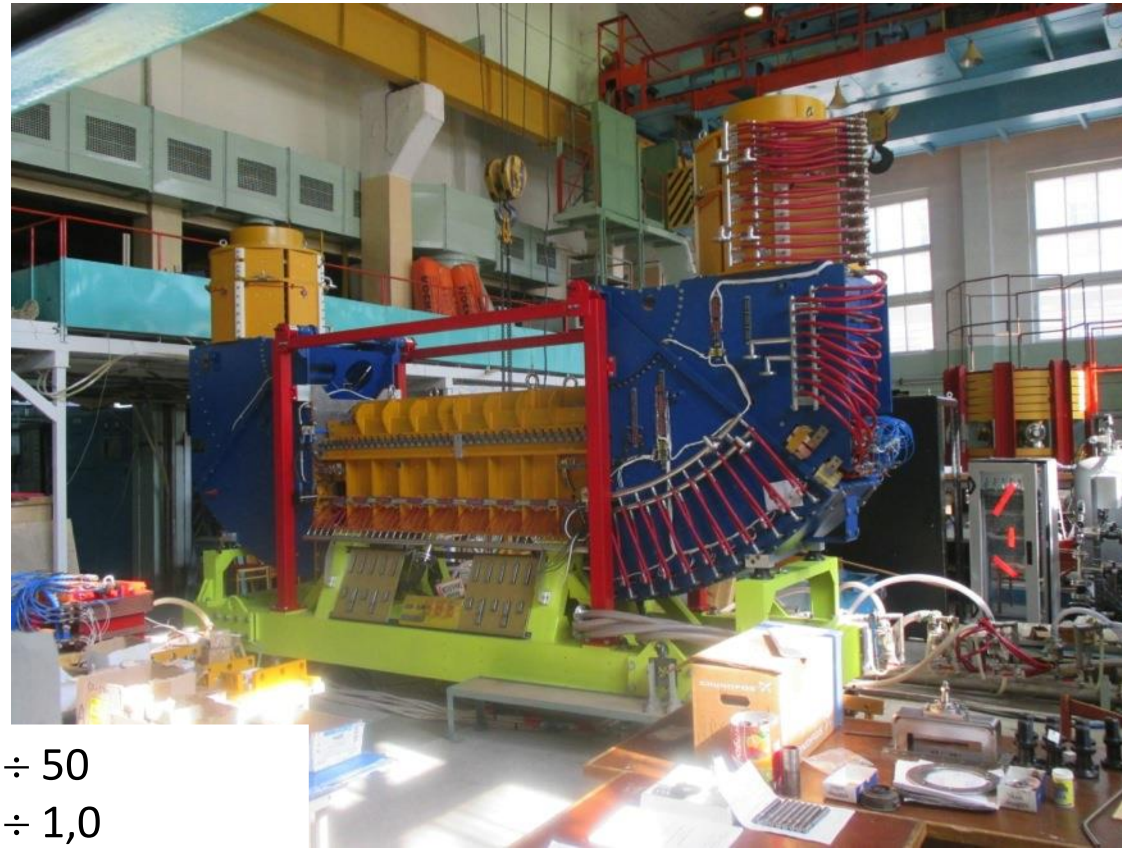


# Electron cooling system for booster



| | |
|---|---|
| Electron energy, keV | 1,5 ÷ 50 |
| Ie, A | 0,2 ÷ 1,0 |
| Accuracy and adjustment $\Delta E/E$ | $\leq 1\cdot10^{-5}$ |
| Current stability, $\Delta I/I$ | $\leq 1\cdot10^{-4}$ |
| Length of system/solenoid, m | 6.2/2.8 |
| e-current losses, $\delta I/I$ | $\leq 3\cdot10^{-5}$ |
| Bfield, T | 0,1 ÷ 0,2 |
| $\Delta B/B$ @ main solenoid | $\leq 3\cdot10^{-5}$ |
| T_transverse_e, eV | ≤ 0,3 |

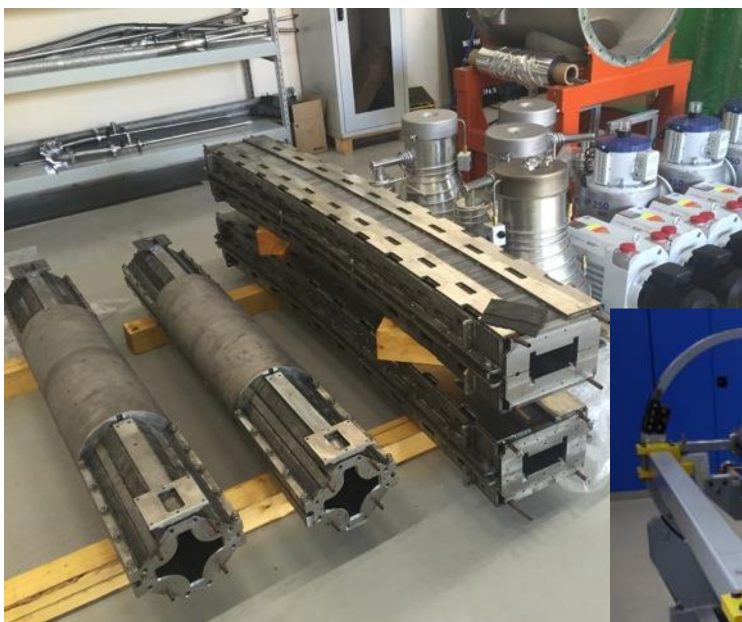
Ion trajectory: (dX,mm ≤ 1,0, dTheta, mrad ≤ 1,0)

**Electron Cooling for:**

- **Beam adjustment for effective injection to Nuclotron;**
- **Accumulation at injection/multiple injection (up to 4e9 ipp);**
- **Beam adjustment for applied research;**

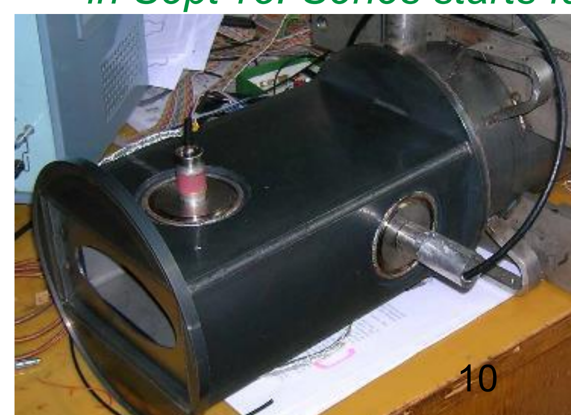
# Booster systems: progress is going

**Booster RF system and RF test bench**



Serial production of cryostats and thermal shields – is in final stage. Serial production of dipole and quadrupole magnets started in Dec’2014 (2 y’s)

*First prototype of Booster PU-station tested in Bulgaria in Sept’15. Series starts fast*



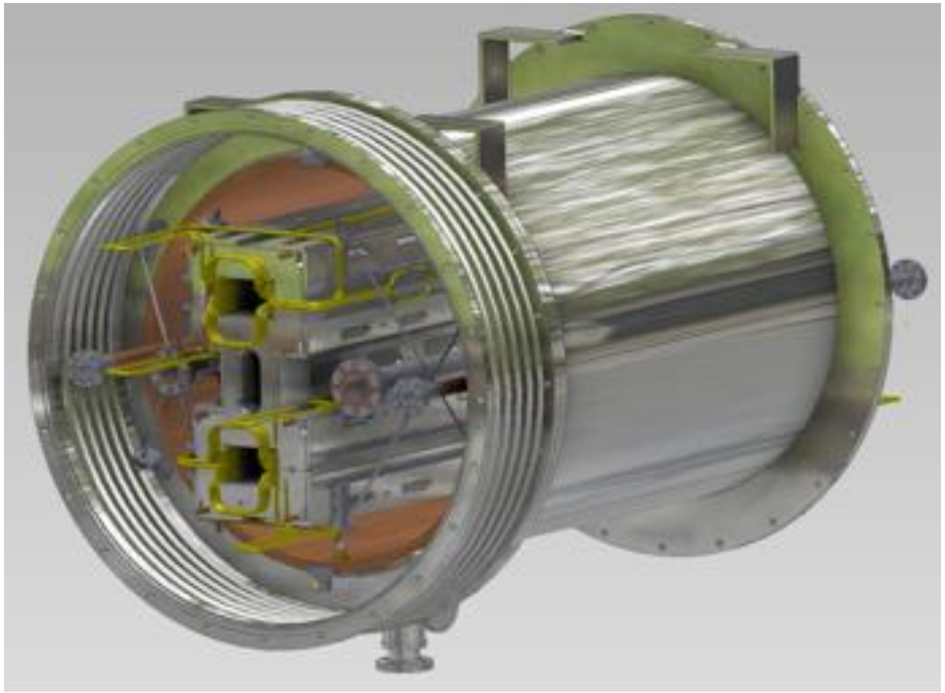
**New low energy (4-11 GeV/u) collider with extremely high luminosity L=1e27**
**Scientific leader: Igor MESHKOV**

**Fruitful collaboration between JINR and FNAL, BNL, GSI, FZJ, BINP, CERN, INR RAS**

For similar round-shape bunches colliding at zero angle:

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

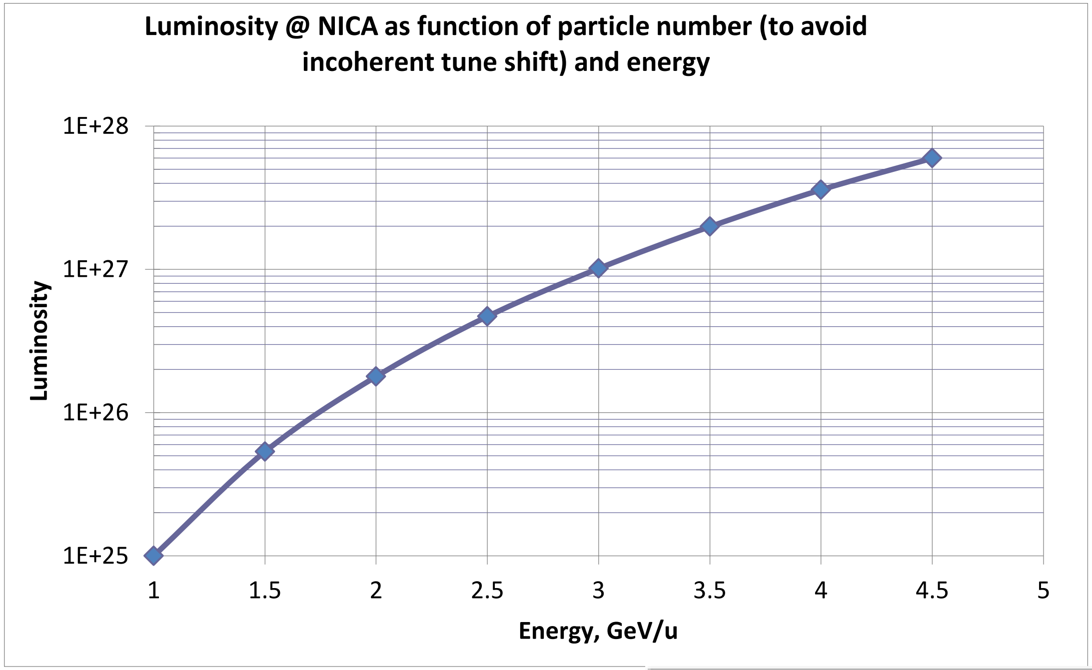
$$f\left(\frac{\sigma_s}{\beta^*}\right) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{\exp(-u^2)du}{\left[1+\left(\frac{u\sigma_s}{\beta^*}\right)^2\right]}$$

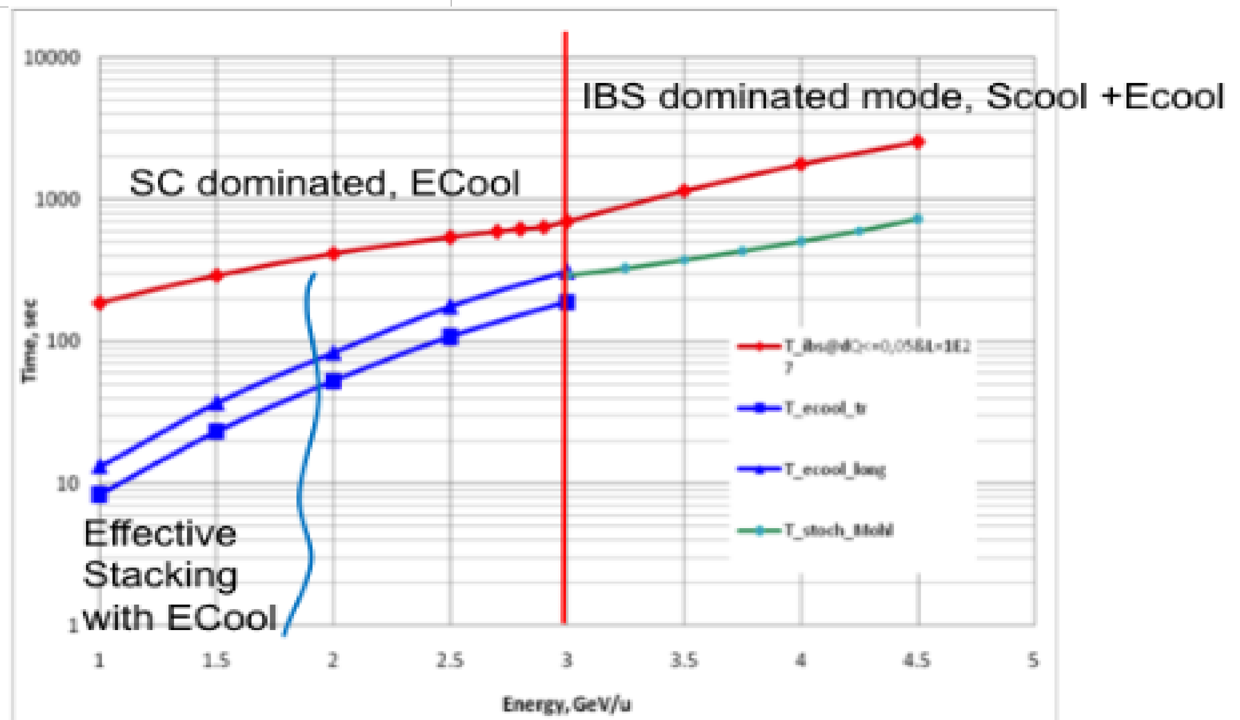


- to increase number of bunches -> parasitic collisions;
- to increase bunch current -> coherent instability;
- to decrease emittance (bunch size) –> incoherent tune shift -> resonanses;
- to decrease $\boldsymbol{\beta^*}$ -> severe demands to FF QL, chromaticity;
- to increase rev. frequency -> to decrease circumference (no space for equipment)
- to have optimal bunch length ("hour-glass" effect).

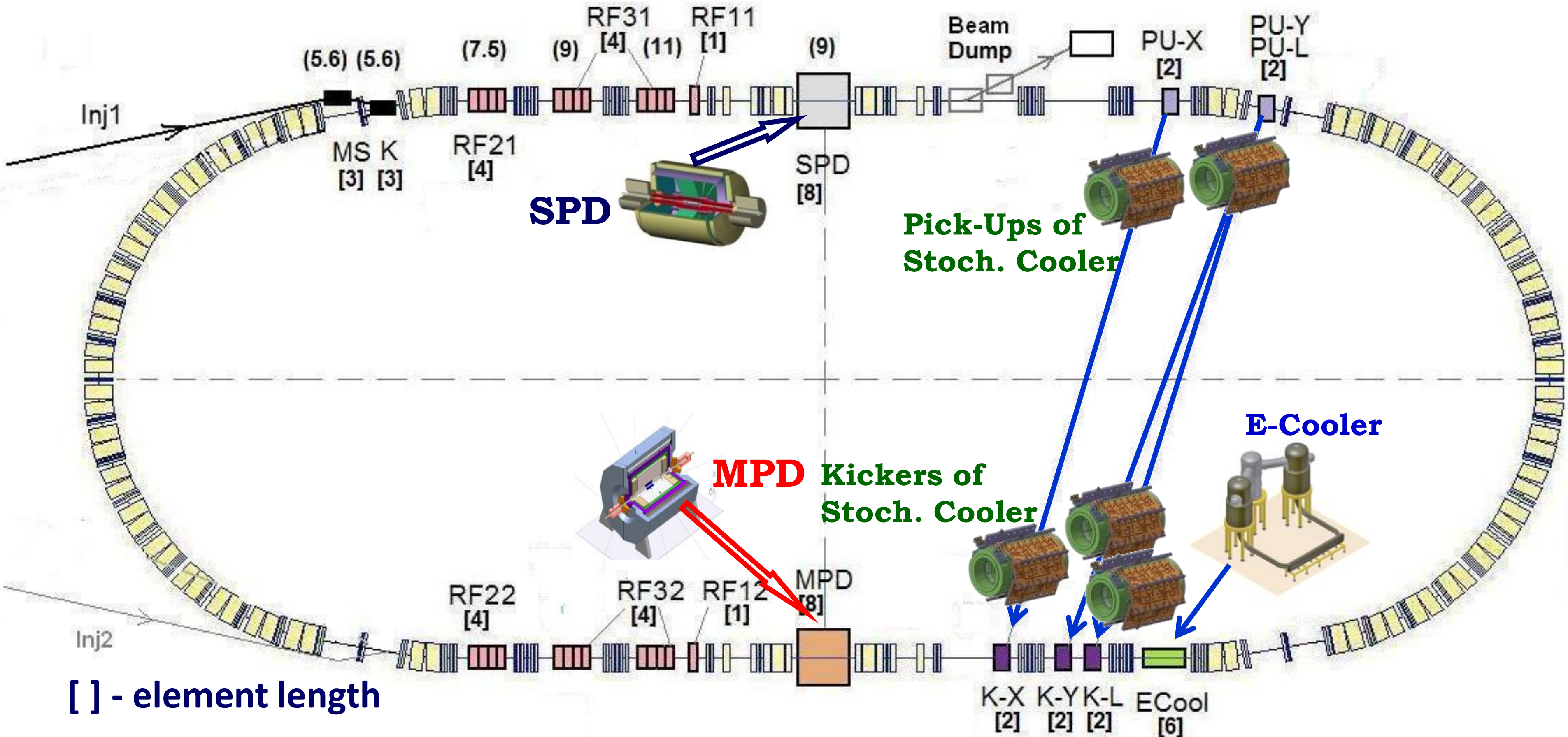
# Parameters of the Au-Au bunches

| | | | |
|---|---|---|---|
| Circumference of the ring, m | 503.04 | | |
| Number of bunches | 22 | | |
| R.m.s. bunch length, m | 0.6 | | |
| $\beta$-function in IP, m | 0.35 | | |
| Betatron frequinces, $Q_x/Q_y$ | 9.44/9.44 | | |
| Chromaticities, $Q'_x/Q'_y$ | -33/-28 | | |
| Acceptance of the ring, $\pi$ mm·mrad | 40 | | |
| Momentum acceptance, $\Delta p/p$ | ±0.010 | | |
| Critical energy factor , $\gamma tr$ | 7.088 | | |
| Energy of $_{79}$Au, 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, $\Delta p/p$, $10^{-3}$ | 0.55 | 1.15 | 1.5 |
| H/V R.m.s. emittance, $\pi$ 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 |
| Tune shift, $\Delta Q_{total} = \Delta Q_{SC} + 2\xi$ | -0.050 | -0.037 | -0.011 |


Luminosity @ NICA as function of particle number (to avoid incoherent tune shift) and energy
Luminosity
1E+28
1E+27
1E+26
1E+25
1
1.5
2
2.5
3
3.5
4
4.5
5
Energy, GeV/u


IBS dominated mode, Scool +Ecool
SC dominated, ECool
Effective
Stacking
with ECool
Time, sec
10000
1000
100
10
1
1
1.5
2
2.5
3
3.5
4
4.5
5
Energy, GeV/u
T_ecool_tr
T_ecool_long
T_stoch_Mohl

# NICA: configuration of the Collider for Heavy Ion mode




[ ] - element length

( ) - distance between elements

Au(+79) ion mode

# NICA Structure and Operation Regimes (Heavy Ion Mode)

<u>Stage 1:</u> Cooling and stacking with RF1 barrier voltage (5kV). Accumulation efficiency ~ 95%, about 110 - 120 injection pulses (55-60 to each ring) every 5 sec. Total accumulation time ~ 10 min. dP/p is limited by microwave instability.

<u>Stages 2-3.</u> Formation of the short ion bunches in presence of cooling, <u>RF-2 (</u>100 kV, 4 resonators) + <u>RF-3 (1MV, 8 resonators).</u>

*From coasting beam => to 22nd harmonics = > 66th harmonics*

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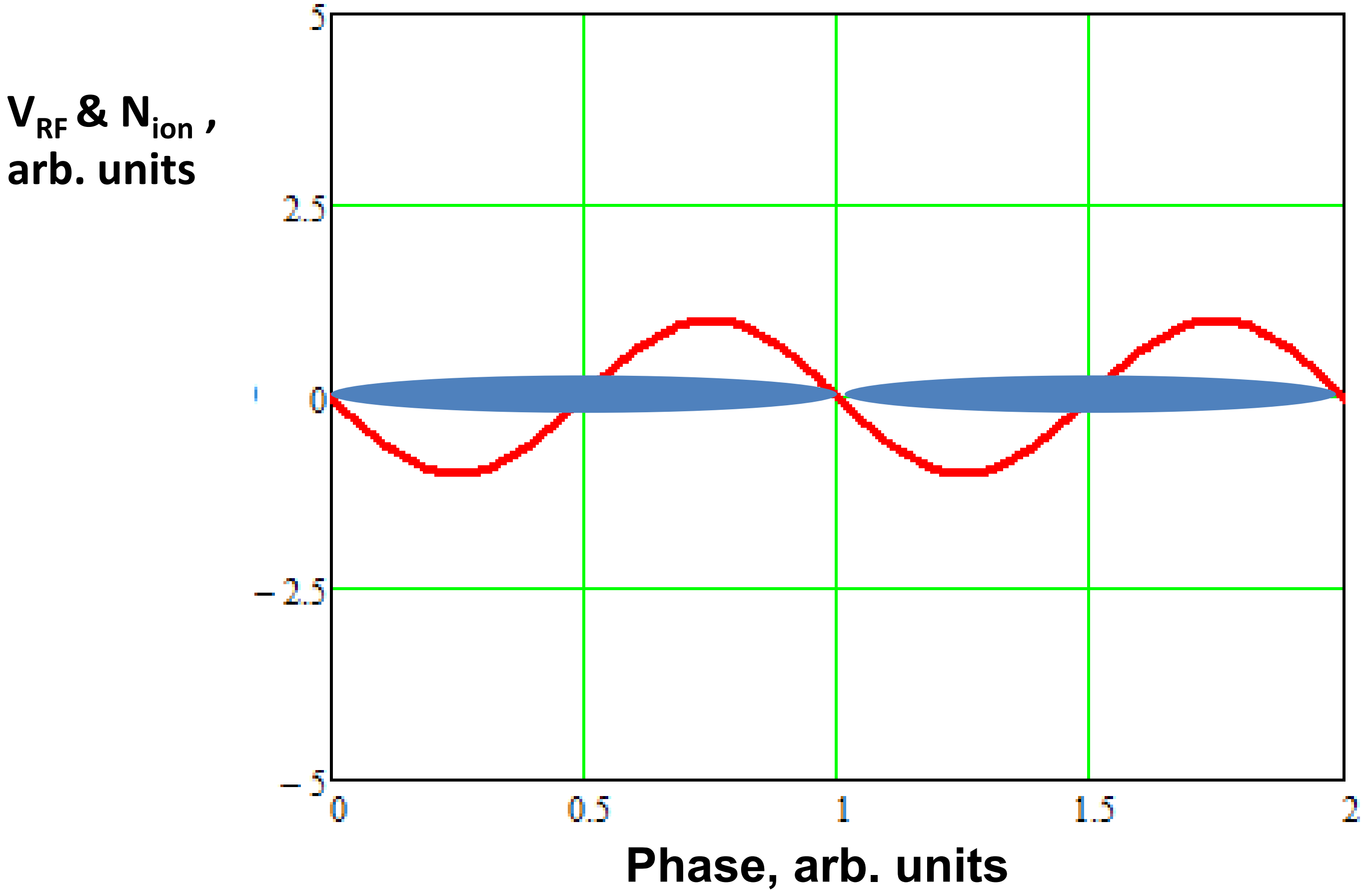

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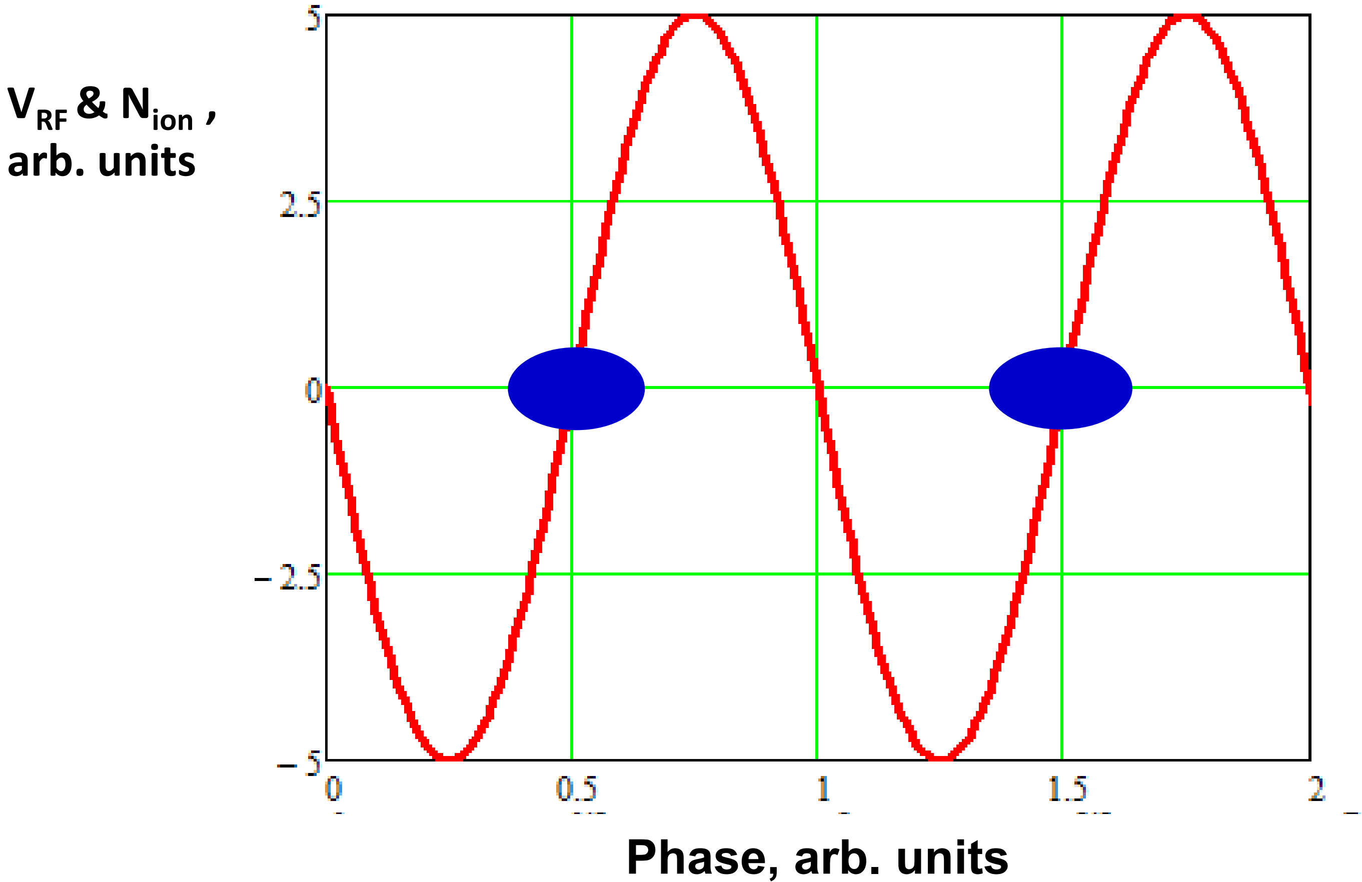

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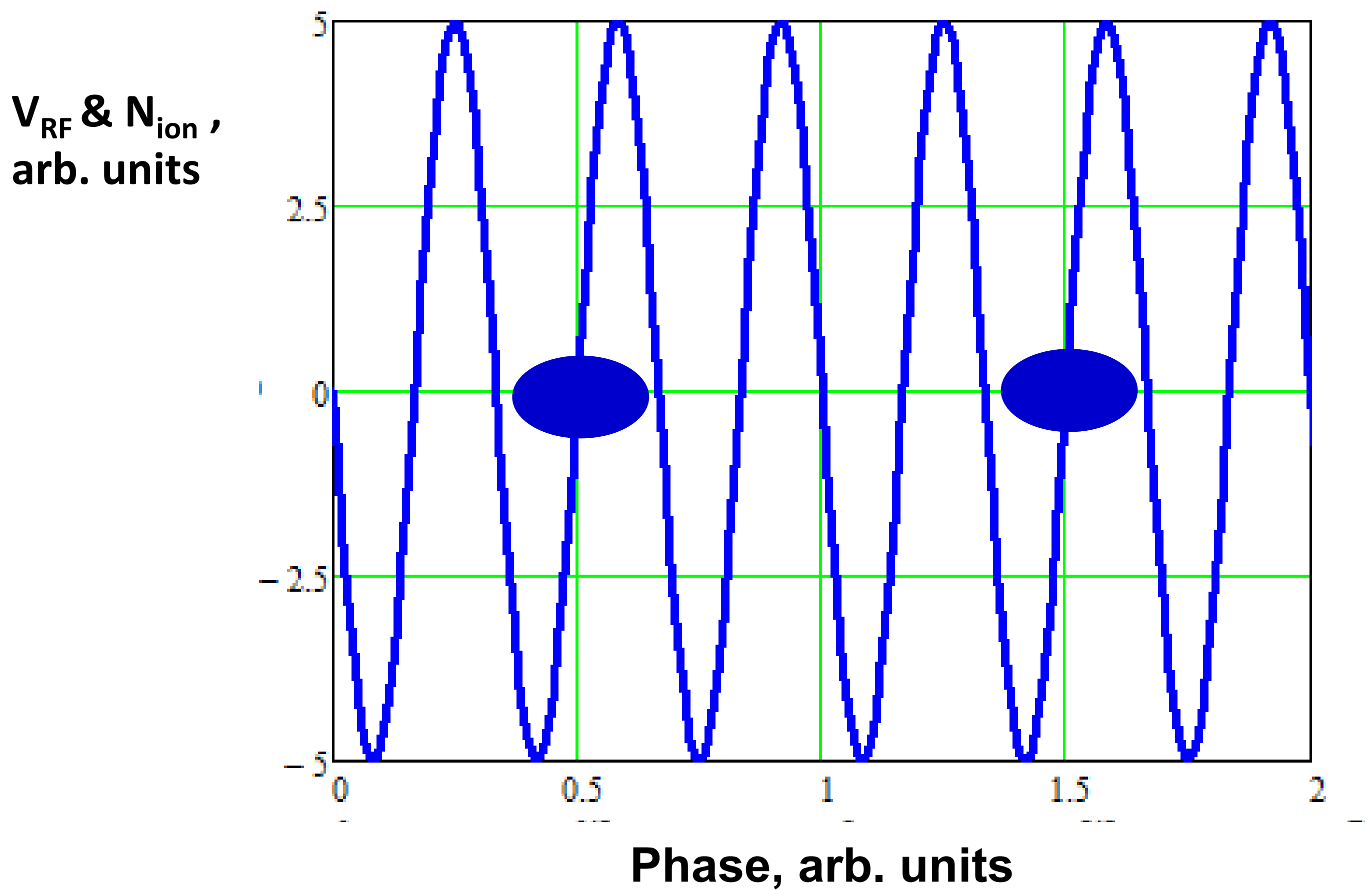

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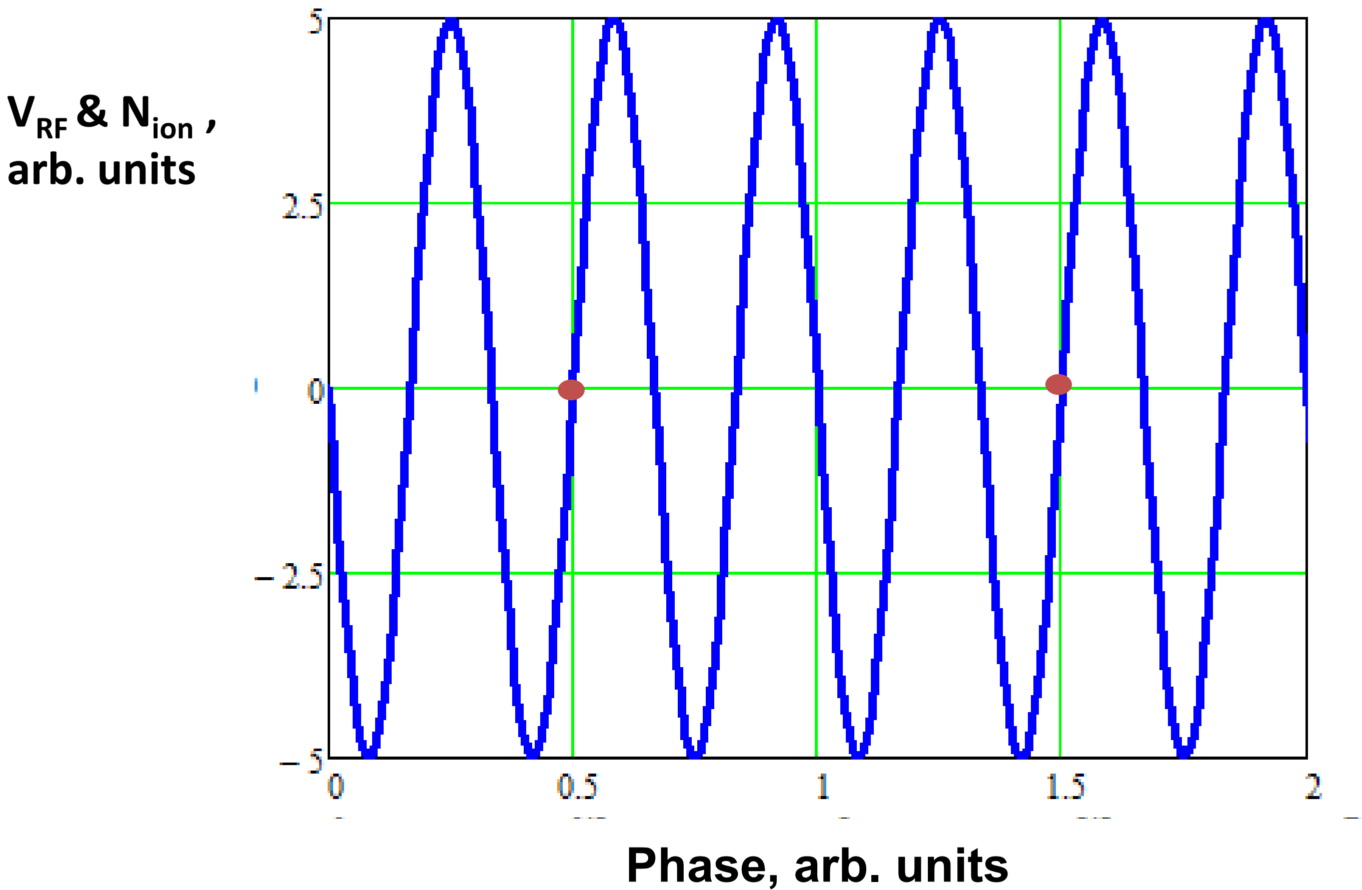

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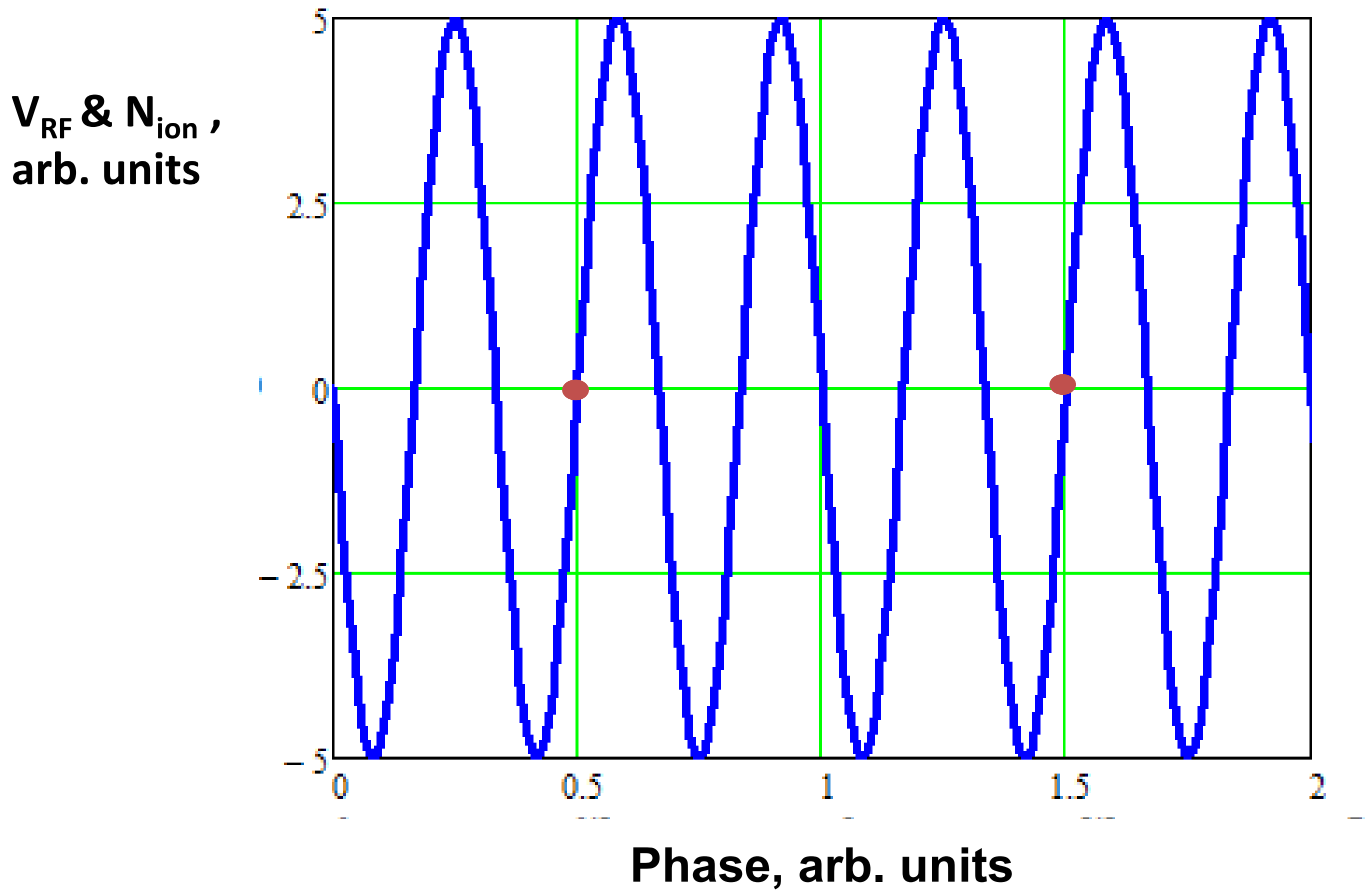
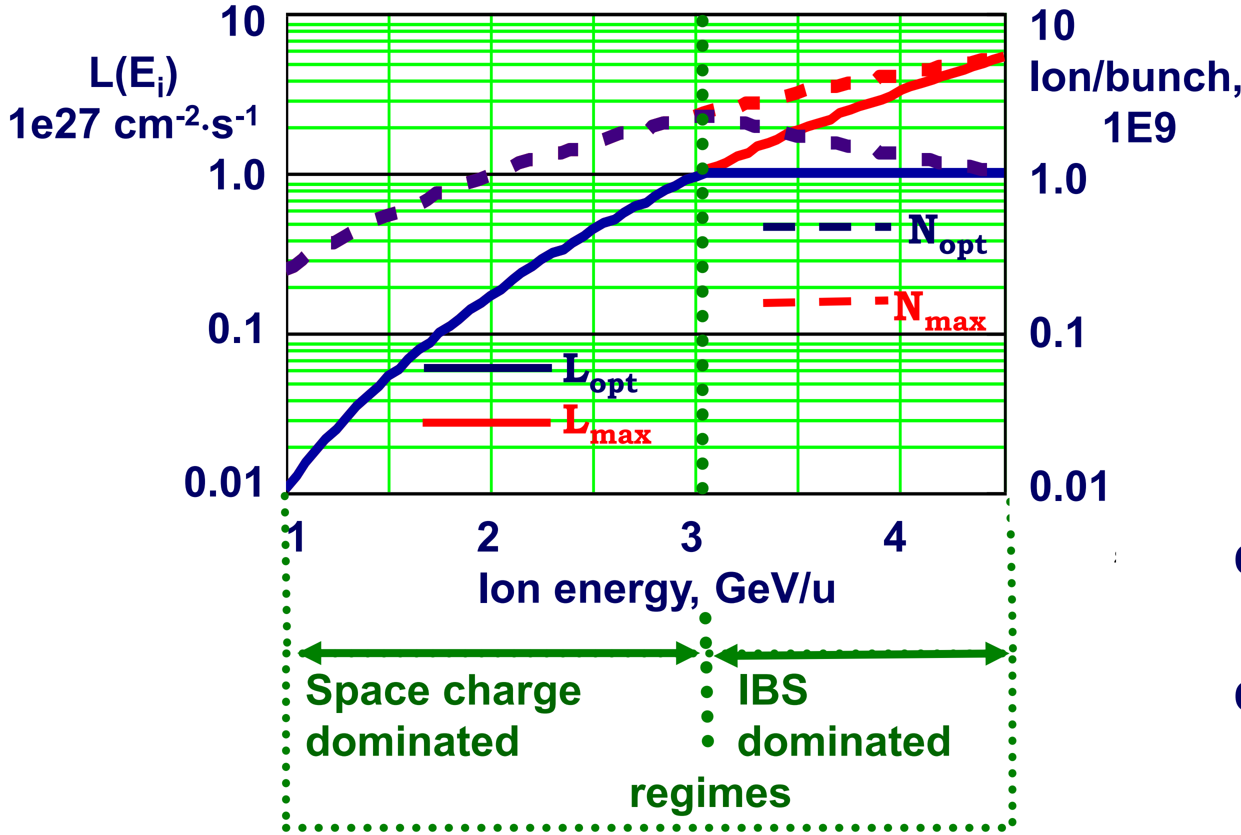


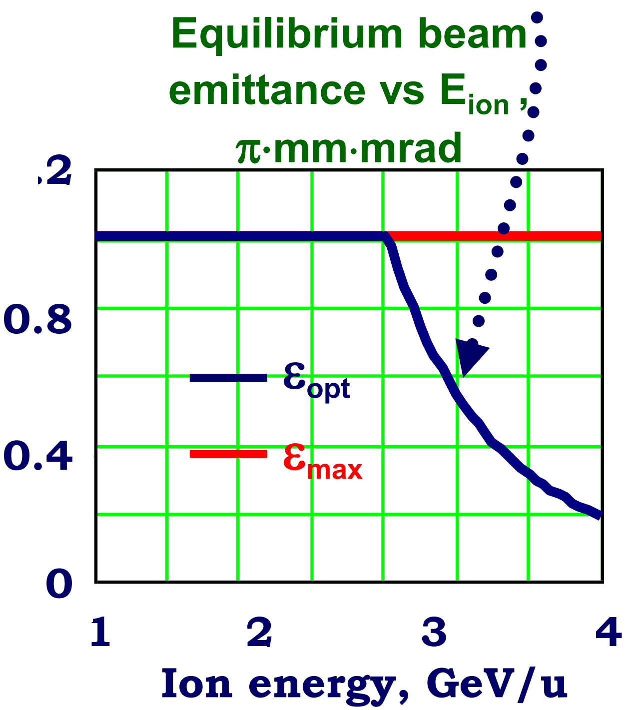
# NICA. Structure and Operation Regimes
# (Heavy Ion Mode)

## Two operation regimes




Electron and stochastic cooling application!

Emittance reduction with energy:



# Strategy to achieve luminosity

1. Maximal r.m.s. bunch length is chosen equal to **0.6m** in order to have the "luminosity concentration" at Inner Tracker (IT) of MPD

2. Maximal peak luminosity (limited by Lasslett tune shift) is achieved at maximal emittance: $\mathcal{E}_{rms} = 1.1\ \pi\cdot$mm$\cdot$mrad (radius = 1/6 aperture)

**3. The ratio between Horizontal, Vertical emittances and dP/P is defined from the equillibrium of IBS rates**

4. Maximal number of particles in bunch is limited by tune shift $\leq 0.05$

5. Number of bunches = 22 -> to cancel parasitic collisions

6. RF multiplicity = 3 -> separatrix area is by 25 times exceeds longitudinal emitance

# Average luminosity

1. Effective scheme of accumulation and bunch formation

2. Beam lifetime (due to scattering on residual atoms) ~ 10 hours

3. “Head-tail” and multibunch instabilities are supressed by feed-back systems

4. Supression of the emitance growth (due to IBS) – by beam cooling systems:
   1 – 3 GeV/u – with electron cooling
   3 – 4.5 GeV/u – with 3D stochastic cooling (longitudinal – Palmer method)

# Start-up configuration

- No electron cooling
- No feed-back systems (as soon as beam intensity decreased)
- “Light” RF-2 composition: 4 -> 2 resonators per ring)
- No RF-3 (bunch length = 1.2m, 50 kV, 8 -> 0 resonators per ring)
- No transverse stochastic cooling (1 channel instead of 3 per ring)

To achieve luminosity  (Au-Au):

Bunch accumulation scheme stays the same;

It is enough only longitudinal cooling (filter cooling – easy);

Expected transverse emittance $0.1 \div 0.3\ \pi \cdot$mm$\cdot$mrad

*(It is required to increase transverse emittance)*

Making 22 bunches with RF-2 -> bunch length $\leq$ 1.2m

dP/P at 50 kV is $3.5 \div 5.5 \cdot 10^{-4}$  (3 times less than for full NICA).

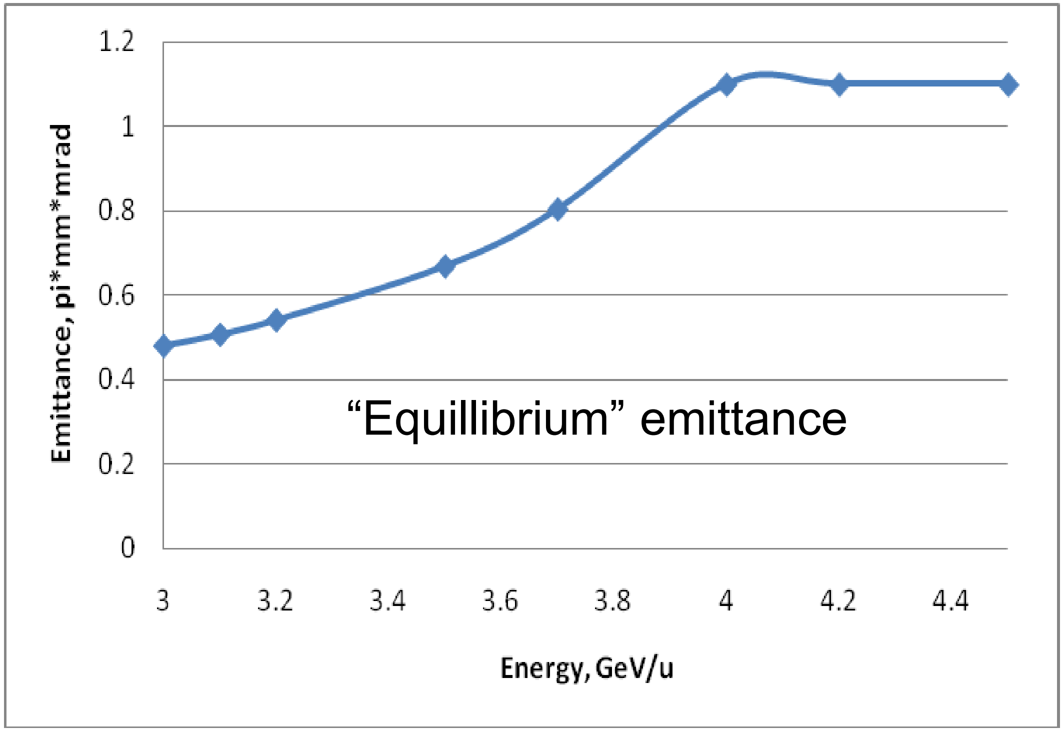
# Phase volume stabilization

*Long.temperature less than transverse by order of magnitude*

IBS leads to 2 effects:
- Pumping of energy from transverse degrees of freedom to longitudinal (relaxation)
- Growth of the 6-dimensional phase volume.

dP/P growth rate much more higher than for emittances
At equal emittances: horizontal increases, vertical decreases. $Q_h \approx Q_v$ – coupled.

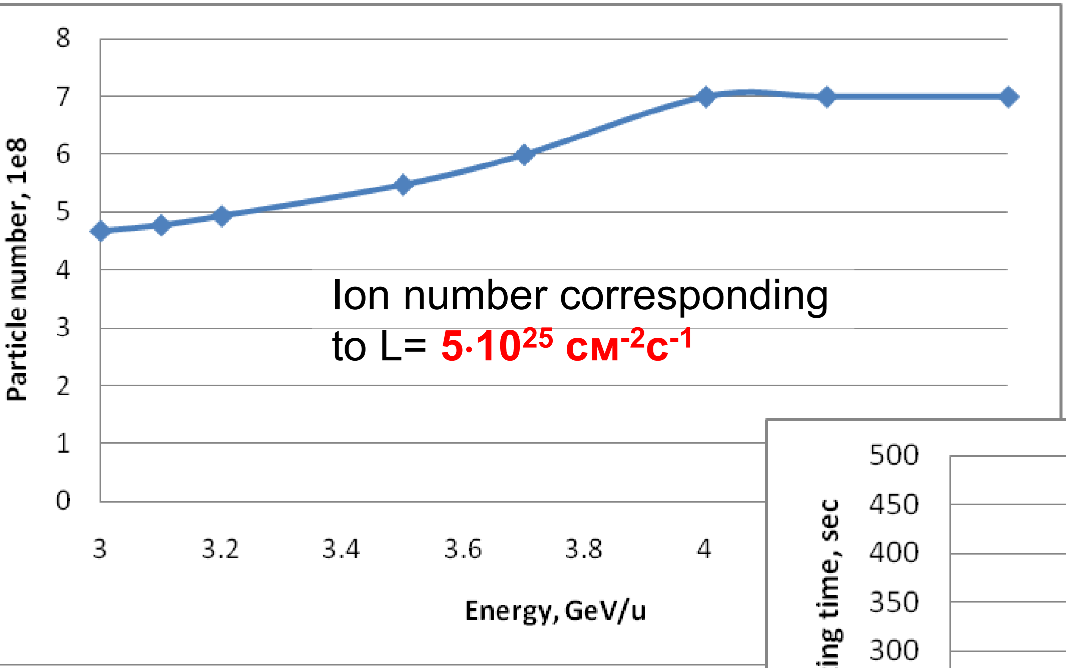
For definite dP/P we can adjust emittance value when horizontal "heating" is compensated by vertical "cooling".



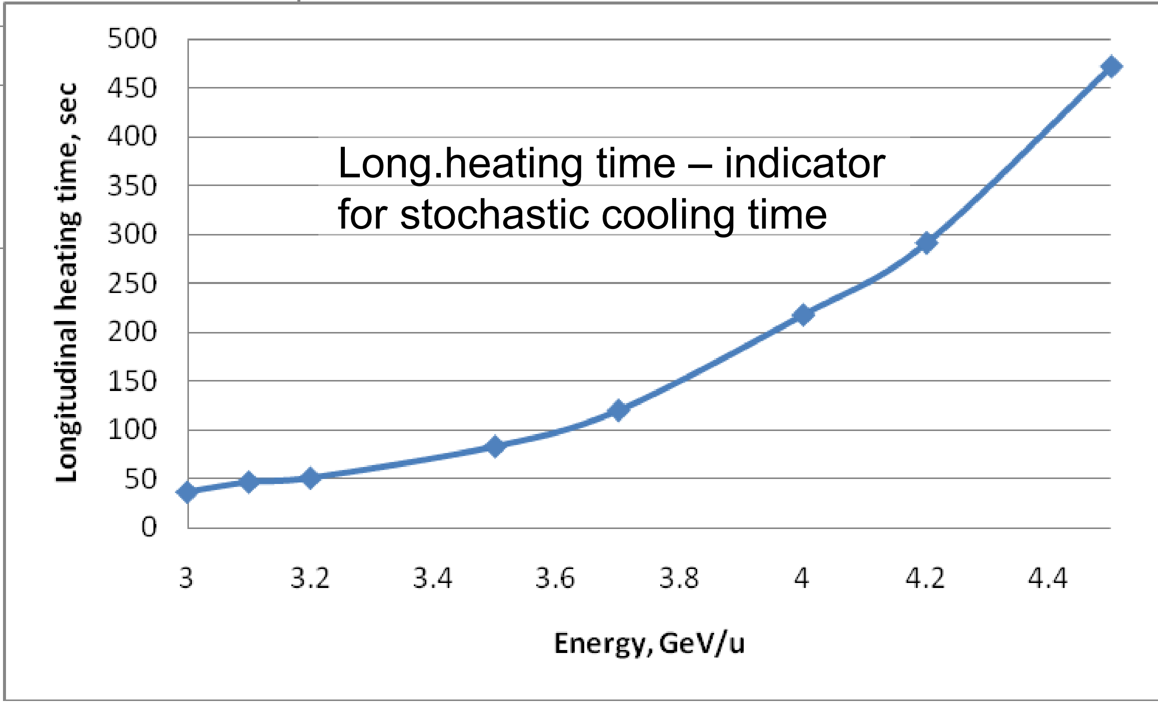

When E > 4 GeV/u the equillibrium emittance exceeds acceptance.

At maximal accepted emittance, the growth time ~ 15 hours

# Cooling conditions

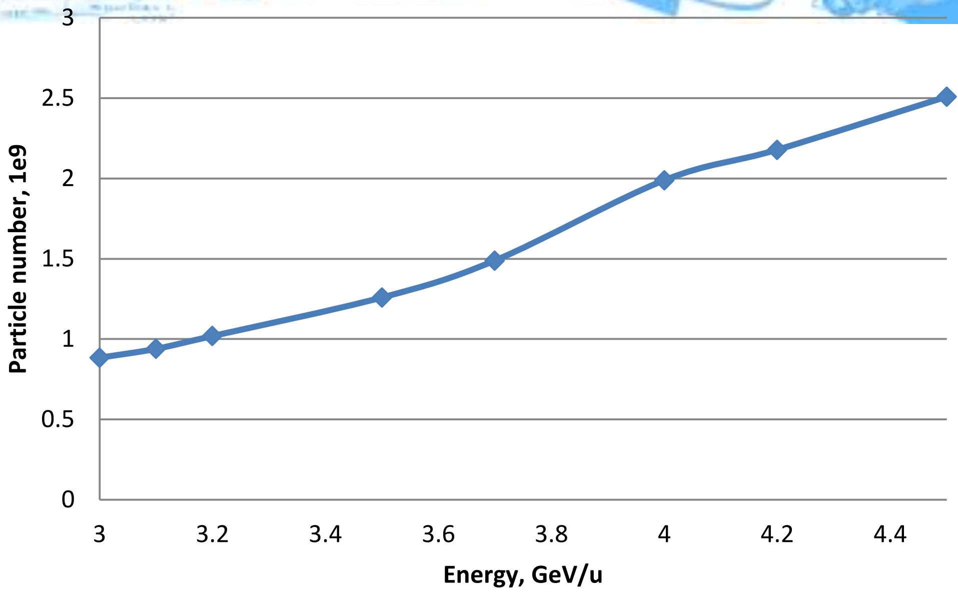



Ion number corresponding to L= **5·10$^{25}$ см$^{-2}$с$^{-1}$**

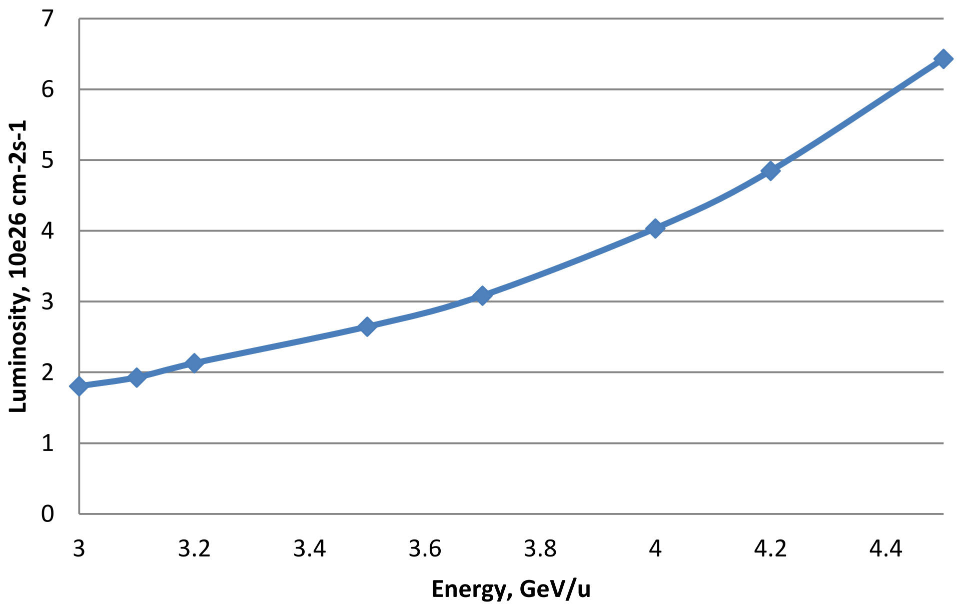



Long.heating time – indicator for stochastic cooling time

# Heating – cooling equillibrium (Au-Au)




Particle number corresponds to equilibrium between heating and cooling




Luminosity ~ $10^{26}$ $cm^{-2}s^{-1}$

Heating-cooling growth times: 20 - 140 sec

# Luminosity for different ion spices

IBS growth rate is proportional to $Z^2/A$ (the best ion is – deutron :-)

$$\frac{1}{\tau_{IBS}} \sim N\frac{Z^2}{A} \qquad \frac{1}{\tau_{sc}} \sim \frac{1}{N} \qquad L \sim N^2 \sim \frac{A}{Z^2}$$

dP/P (at fixed bunch length and RF voltage) ~ sqrt(A/Z).

**Optimal energy for stochastic cooling ~ 3.7 GeV/u**

| | $\sigma_p$, $10^{-4}$ | ε, π·mm·mrad | $N_b$ | L |
|---|---|---|---|---|
| $_{197}Au^{79+}$ | 4.14 | 0.805 | $1.49\cdot10^9$ | $3.05\cdot10^{26}$ |
| $_{124}Xe^{42+}$ | 3.8 | 0.678 | $2.53\cdot10^9$ | $8.9\cdot10^{26}$ |
| $_{84}Kr^{36+}$ | 4.28 | 0.86 | $3.31\cdot10^9$ | $1.52\cdot10^{27}$ |
| $_{40}Ar^{18+}$ | 4.39 | 0.92 | $6.75\cdot10^9$ | $5.53\cdot10^{27}$ |

Heating-cooling growth times ~ 50 - 200 sec

# What we gain at full-scale configuration?

1. Enlargement of energy range – thanks to electron cooling
2. Luminosity @ 3 ÷ 4.5 ГэВ/н

$$\frac{1}{\tau_{IBS}} = NC_{IBS} \qquad \frac{1}{\tau_{sc}} = \frac{C_{sc}}{N}$$

At equillibrium:

$$\frac{1}{\tau_{IBS}} = -\frac{1}{\tau_{cool}}$$

$$L \sim N^2 \sim \frac{C_{cool}}{C_{IBS}}$$

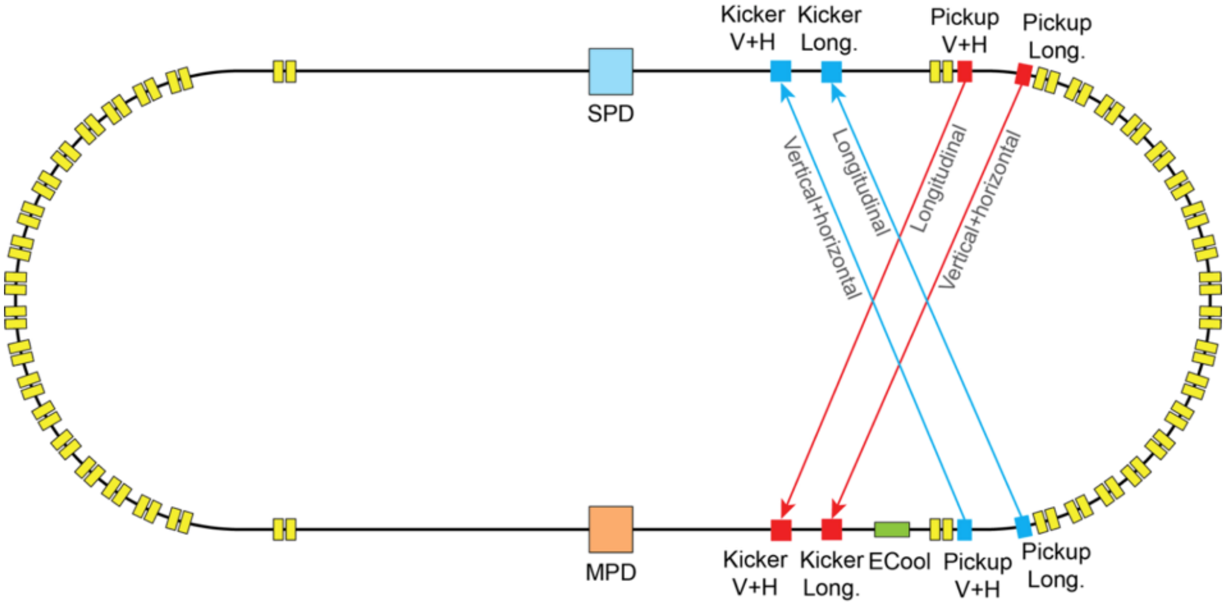
$$\frac{L}{L_{start-up}} = \frac{C_{IBS}}{C_{IBS\_start-up}}$$

**Gain:**

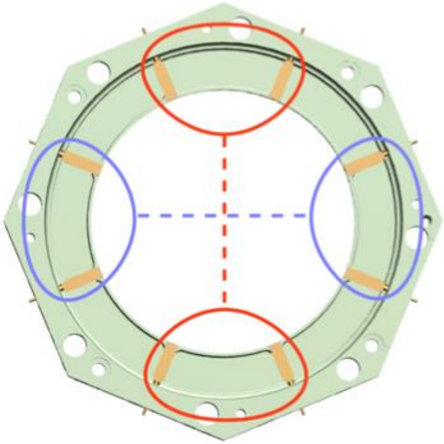
**from by 58 (3 GeV/u)**

**to by 13 (4.5 GeV) times**

# Stochastic cooling at collider




**Design power of amplifiers: 500 W per channel, Kicker ~ 2 m**



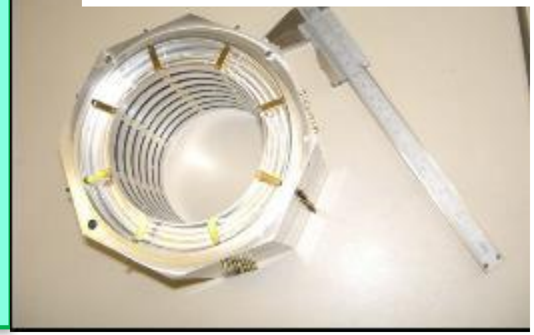
Design of the kicker allows to connect in parallel groups of electrodes to their amplifiers, summarizing total power going to the beam

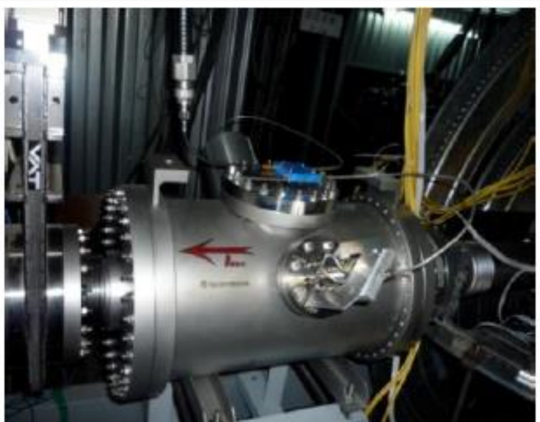
Kicker of the Nuclotron SCS: 16 rings (30 sm) ~ 80 W

# Stochastic Cooling System

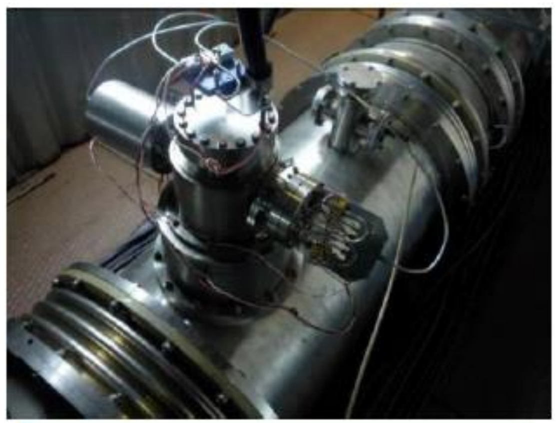
**Stochastic Cooling System installed at Nuclotron - is a prototype for the NICA Collider:**
**W=2-4 HGz, P = up to 60 W**
**Collaboration:**
**JINR – IKP Juelich + CERN**

**Ring slot-coupler RF structure (design FZJ)**





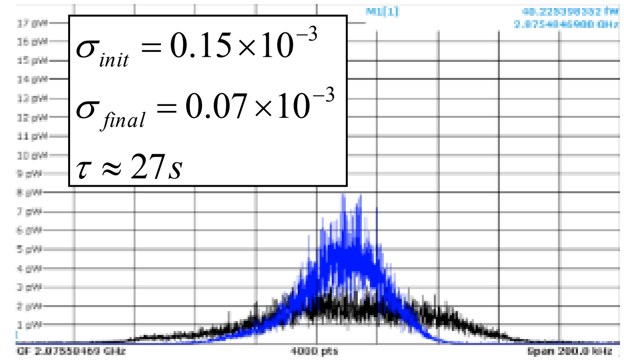
**Kicker station**



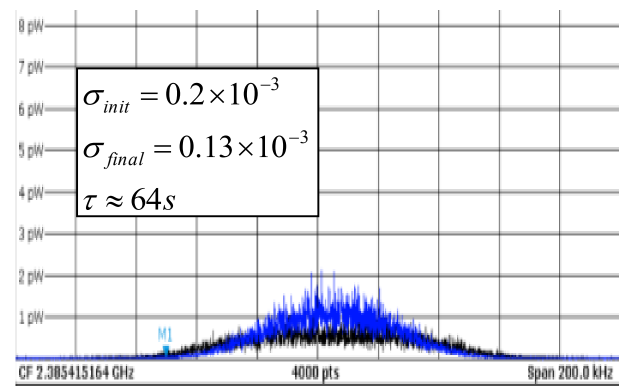
**Pick-Up station**

Spectrum analyzer

Coasting beam




**Bunched beam**



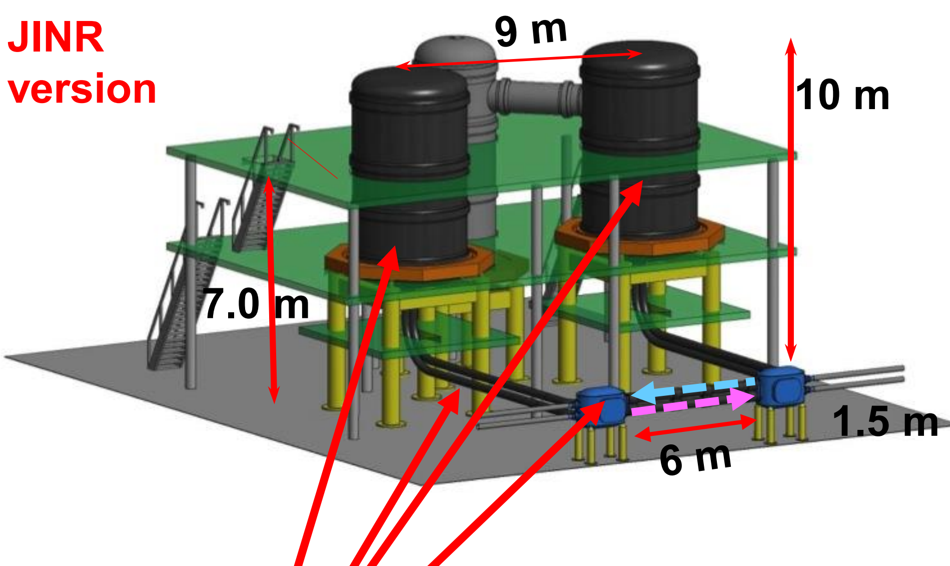

Intensity ~ $2 \cdot 10^{8}$ ions, ~ 2.5 bunches,
$dP/P_{init}$ ~ $2 \cdot 10^{-4}$, $T_{cool}$ ~ 60 seconds at 60W.
Bunching factor ~ 4.8 (for NICA SUC 7.6, $I_{ion}$ ~ $4 \cdot 10^{8}$).
Estimations: at opt. gain $T_{cool}$ will be ~3 sec

**Experimental results (2013): stochastic cooling of the carbon (C6+) beam, E = 2.5 GeV/u**

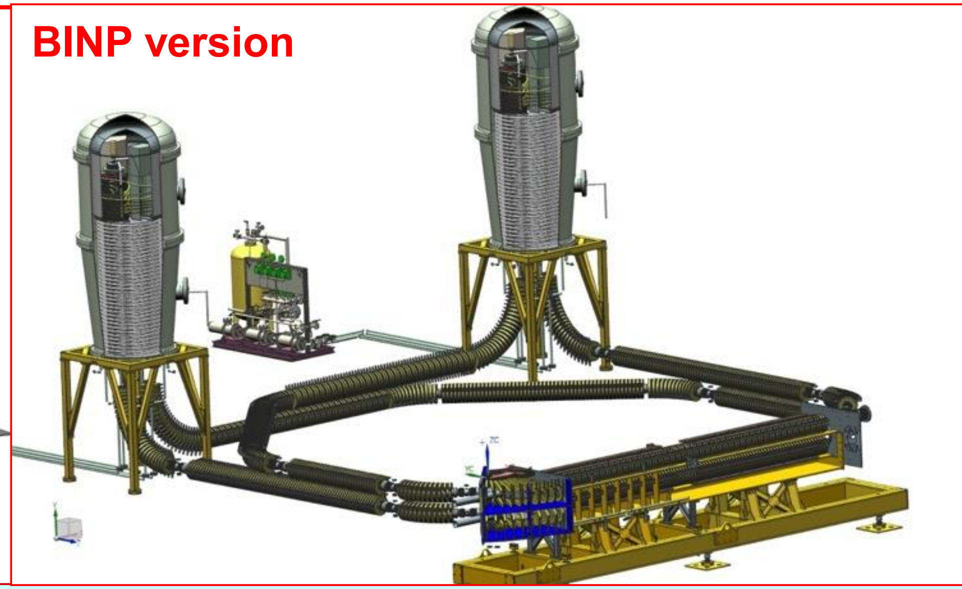
# NICA Elements Fabrication in Collaboration …

## Electron Cooler for NICA Collider – Two Versions

JINR version




BINP version



Electron energy 0.5 ÷ 2.5 MeV, electron beam current 0.1 ÷ 1 A

NbTi cable $\phi$ *0.5* мм L = 275 km $ 250,000

HTSC band 12 x 0.5 мм$^2$ L = 11.5 km $ 350,000

SC solenoids

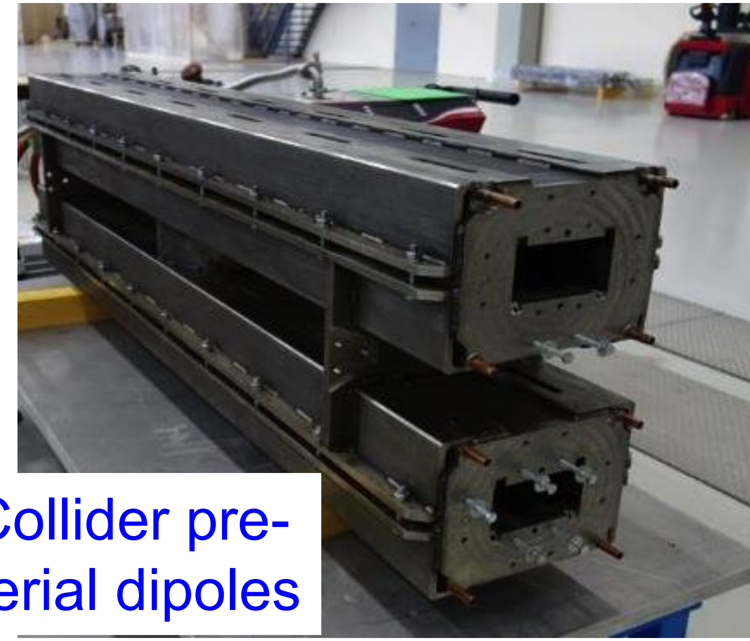
(JINR version)

| | |
|---|---|
| Maximum electron energy, MeV | 2.5 |
| Electron beam current, A | 0.1 – 1.0 |
| Solenoids' magnetic field, T | 0.2 |

# R&D for Collider and Booster


**Ultra-high vacuum**

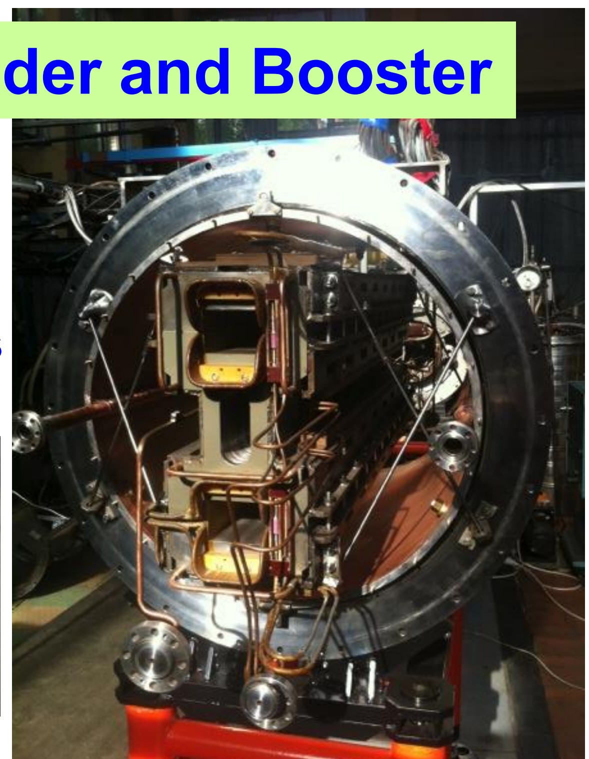
**High-temp Superconductivity**



Collider pre-serial dipoles

**Magnetic measurements**

Curved UHV chambers

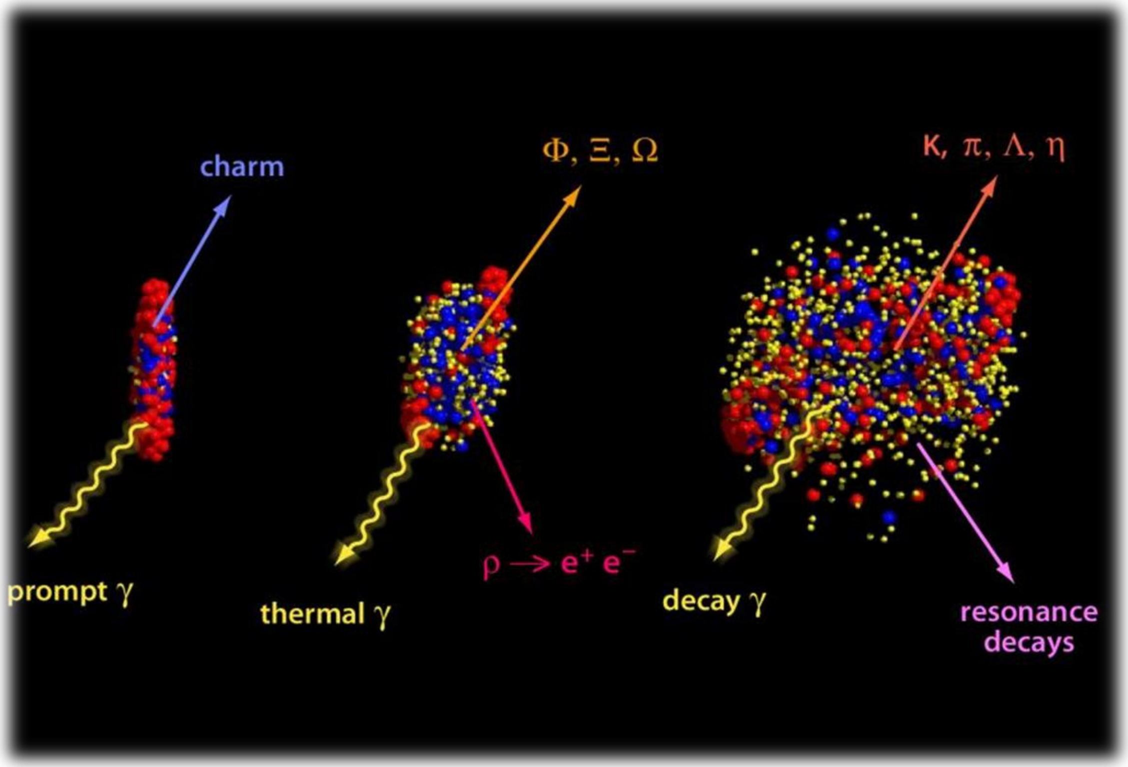


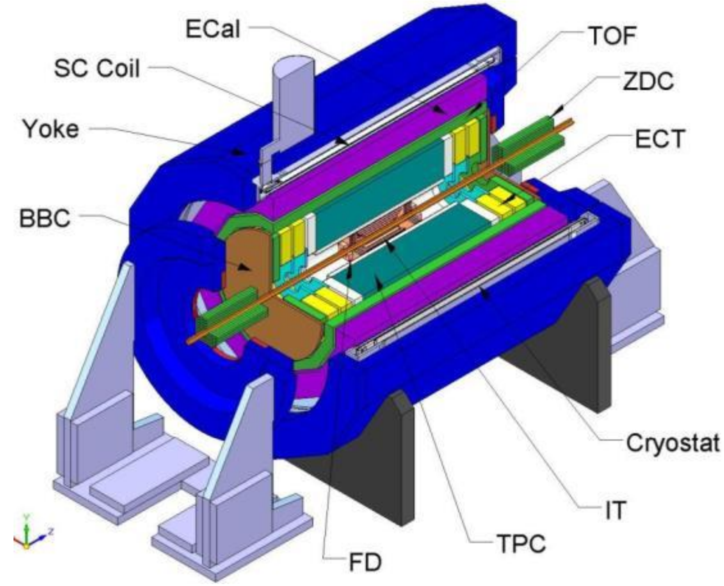
**Test Facility for SC magnets of NICA and FAIR: excellent collaboration of JINR and Germany (BMBF). Start of operation – December'14. Serial assembly and cold tests (6 arms) – December 2015**

**Test Facility for SC magnets of NICA and FAIR: excellent collaboration of JINR and Germany (BMBF). Start of operation – December'14.**
**Serial assembly and cold tests (6 arms) – December 2015**

| | | 2015 | | | | 2016 | | | | 2017 | | | | 2018 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I | II | III | IV | I | II | III | IV | I | II | III | IV | I | II | III | IV | I |
| **Booster** | | | | | | | | | | | | | | | | | | |
| *dipoles* | 40+3 | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | |
| *quadrupoles* | 48+6 | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | |
| *multipole correctors* | 40+4 | | | | | ■ | ■ | ■ | ■ | | | | | | | | | |
| **Collider** | | | | | | | | | | | | | | | | | | |
| *dipoles* | 80+5 | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |
| *quadrupoles* | 86+5 | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |
| *multipole correctors* | | | | | | | | | | | | | | | | | | |
| *nonstructurals* | | | | | | | | | | | | | | | | | | |

**+ 173 of SIS100 quadrupoles until 2019**

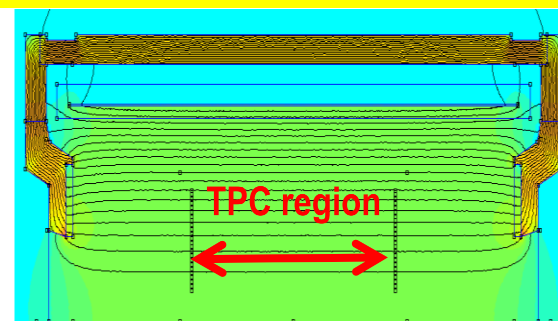



**Magnet:** ***0.66T SC solenoid***
**Tracking:** ***TPC, IT, ECT***
**ParticleID:** ***TOF, ECAL, TPC***
**T0, Triggering:** ***FFD***
**Centrality, Event plane: ZDC**

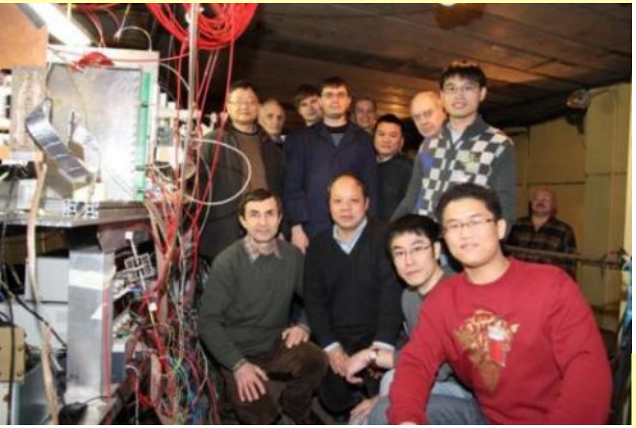
**MPD observables:**

- ✓ *Event-by-event fluctuations*
- ✓ *Femtoscopy involving π, K, p, Λ*
- ✓ *Hadron multiplicities (4-π particle yields : π, K, p, Λ, Ξ, Ω)*
- ✓ *Collective flow for identified hadron species and resonances*
- ✓ *Electromagnetic probes: e-, γ, vector meson decays*
- ✓ *Hyper Nuclei & other exotic*



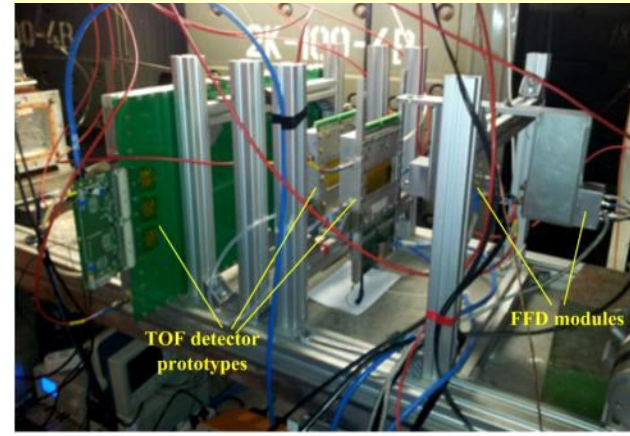

**MPD Superconducting solenoid,** $B_0$=0.66 T: **challenging project** *- to reach high level (~ $10^{-4}$) of magnetic field homogeneity.* Technical *completed*;
Survey for contractors: *the cold coil / cryostat; cryogenics.*

**RPC deam test at NUCLOTRON: cooperation with SPb, China**



**Preproduction ECAL prototypes: co-operation with ISM *(Kharkiv, Ukraine)***

**FFD tested with beam: achieved time resolution (38 ps) is better than required**

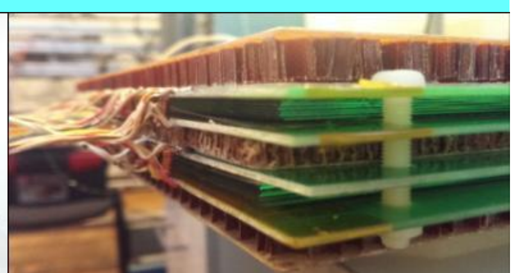



**TPC: Cylinder C3 manufactured in Dec' 13**

**ZDC coverage confirmed: 2.2<|η|< 4.8**


**Readout Electronics developed for *TPC, TOF, and ECAL (*64 ch,13-bit,65 MSPS*)***

**RPC performance** : ***required efficiency, rate capability & time resolution (63 ps) are reached***



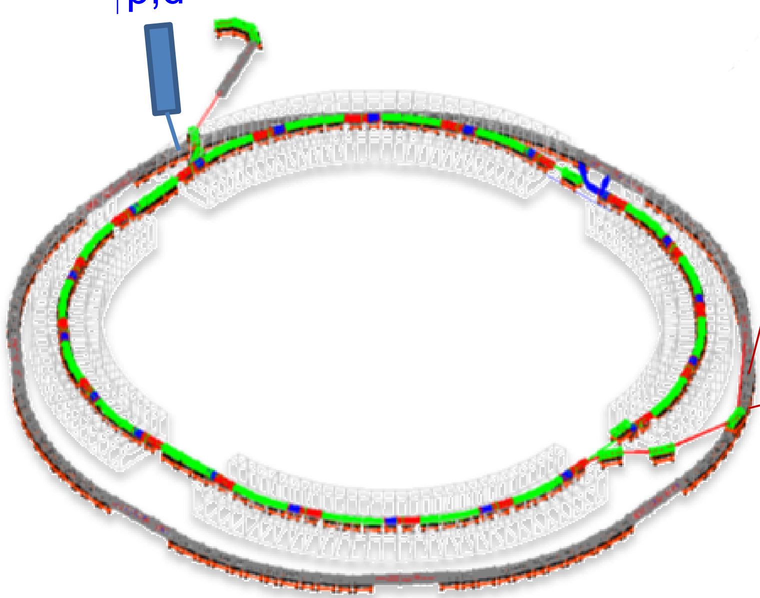
**The CBM - MPD consortium:** *development & production of STS for* ***CBM*** (FAIR)**,** ***MPD*** & ***BM@N***

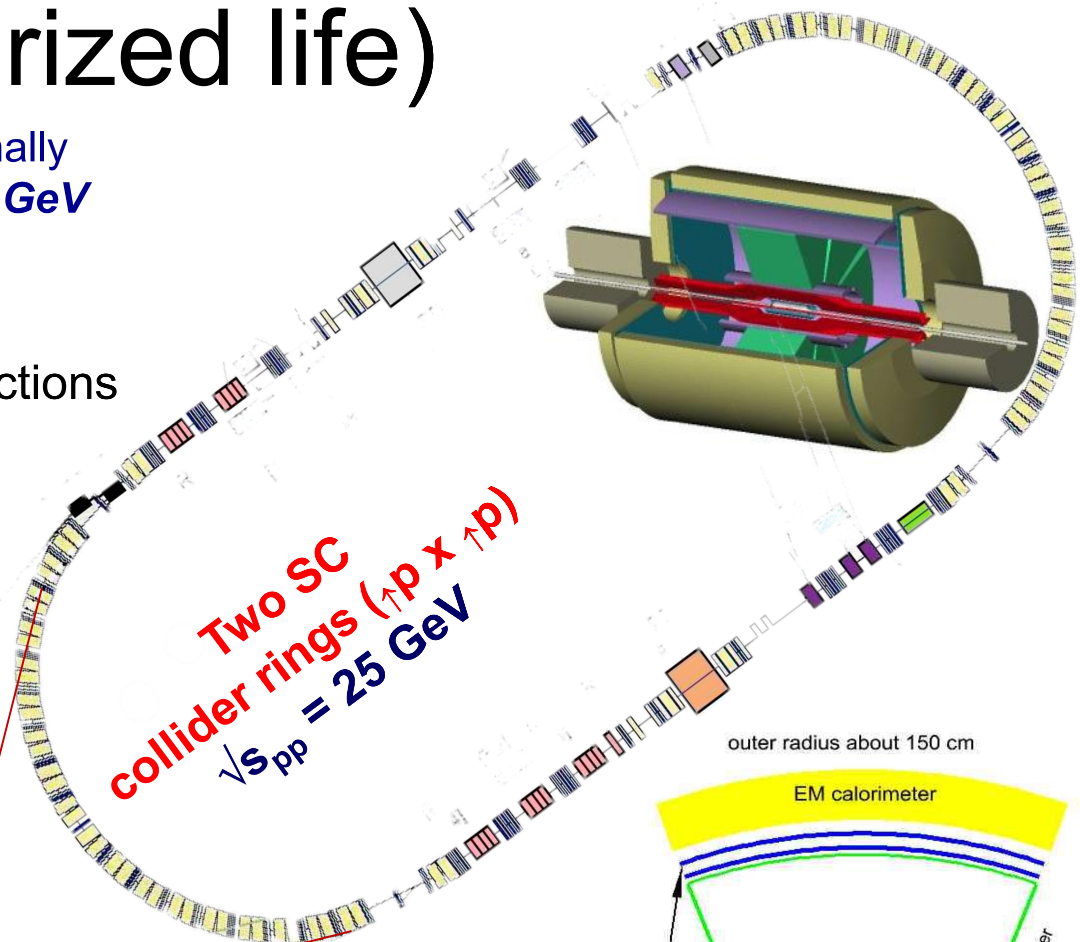
*mock-up carbon-fiber ladder (15 g / 1m)*

# NICA- III (polarized life)

Collision of both: transversally & longitudinally polarized ***p*** & ***d*** *with energy up to* $\sqrt{S}$ *=* ***27 GeV***

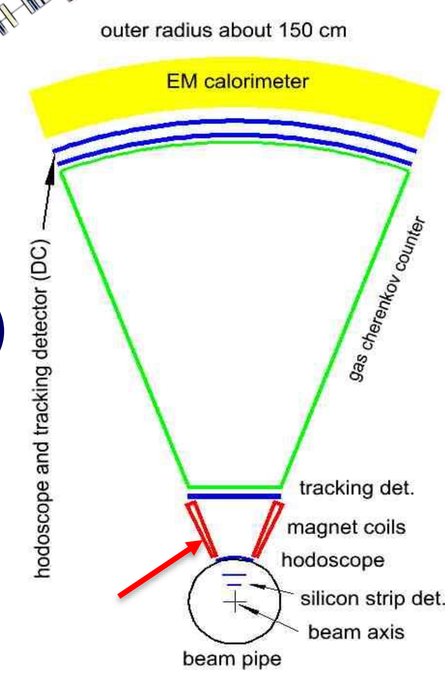
- MMT (Drell-Yan) processes
- J/**ψ** production processes
- Spin effects in inclusive high-pT reactions
- Spin effects in 1- and 2-hadron production processes
- Polarization effects in HI collisions




**Spin Physics Detector (SPD)**

- **IT: Silicon or MicroMega**
- **Straw or Drift chamber**
- **Cherenkov counter**
- **EM calorimeter**
- **Trigger counters**
- **EndCap detectors**

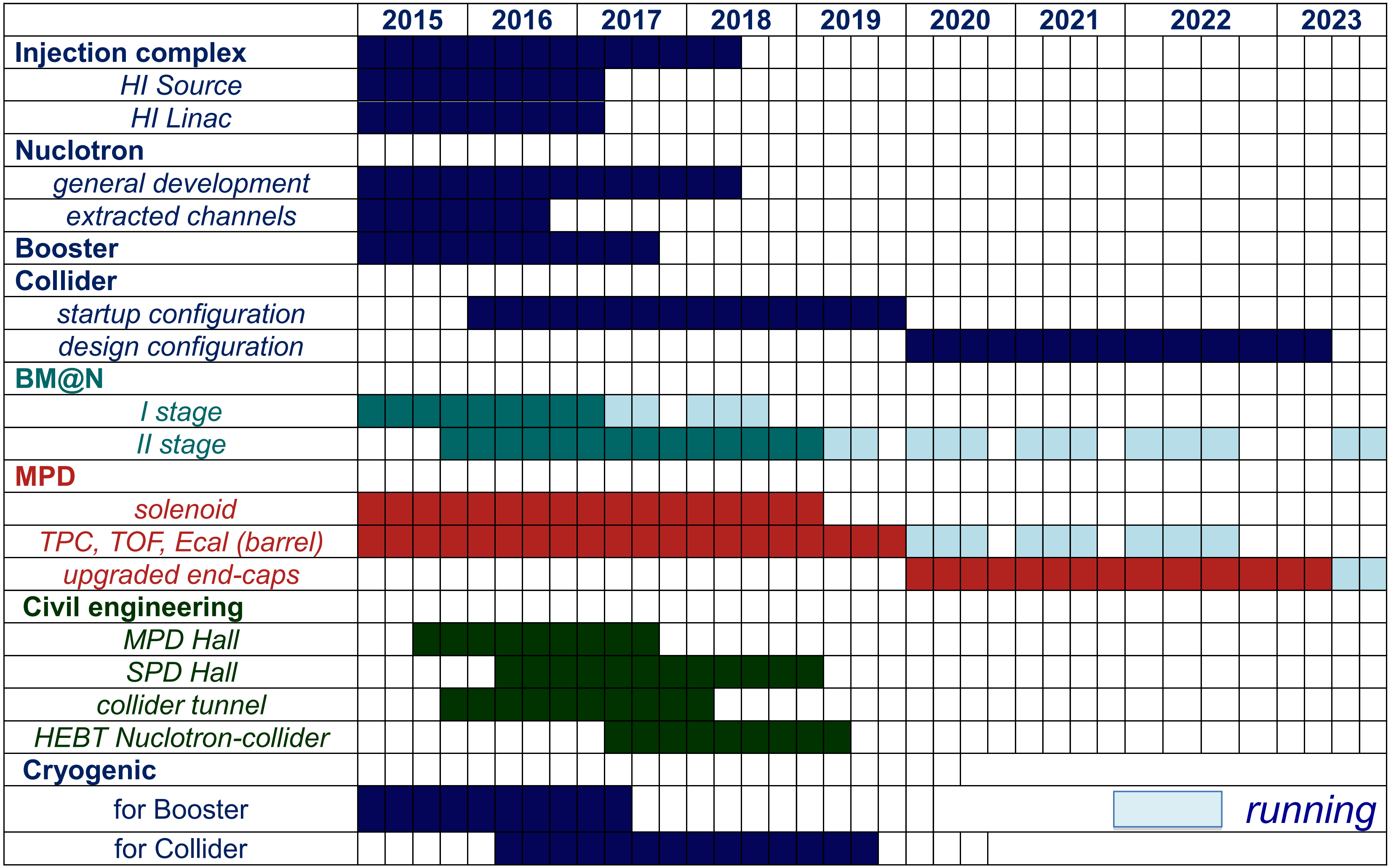


# NICA Civil Construction

Contract for Working Documentation signed in Aug’14. Ready WDR – mid’ 15


Signed!

# NICA schedule




**The decommissioning is foreseen after 2040**

## What NEXT? … Prospects for NICA at 20 years Horizon

- Experiments on the observation of spontaneous electron–positron pair creation in supercritical Coulomb fields (new 2 compact SC rings with merging bare Uranium beams).

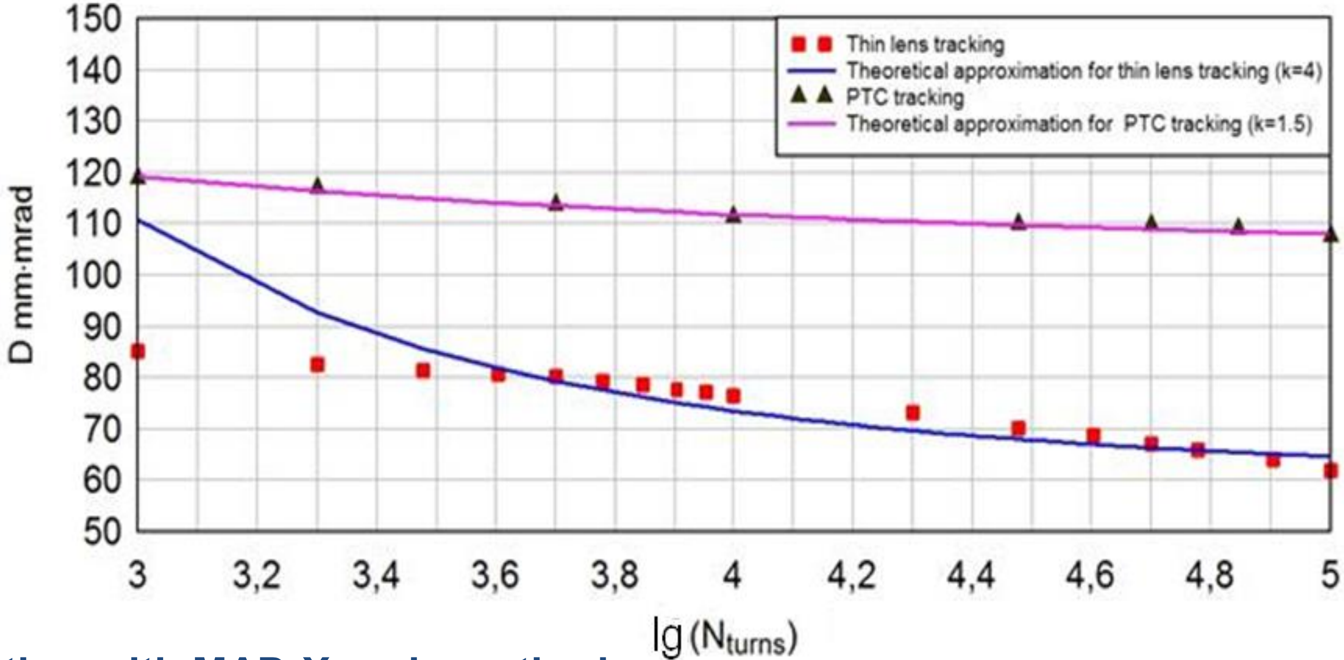
- Mass-spectroscopy of radioactive heavy ion beams in isochronous mode (using booster or collider ring) + measurement of nuclei PDF with colliding/merging electron beam (up to 1 GeV).

- Accelerator physics R&D in:
    - SC linear injector for protons (MW beam as a goal)
    - high-field magnets - up to 5T
    - high brightness beams (Extrahigh luminosity mode)

- Detector R&D in:
    - silicon trackers
    - large SC magnets and solenoids using HTSC

Thank you for your attention!

# Dynamic Aperture




**DA simulation with MAD-X code methods:**

1. **PTC – Polymorphic Tracking Code – Symplectic integration of particle motion;**
2. **Thin lenses approximation – Symplecticity + Space Charge .**

$$\sqrt{D(N)} = \sqrt{D_{\infty}}(1 + b/[log(N)]^k)$$

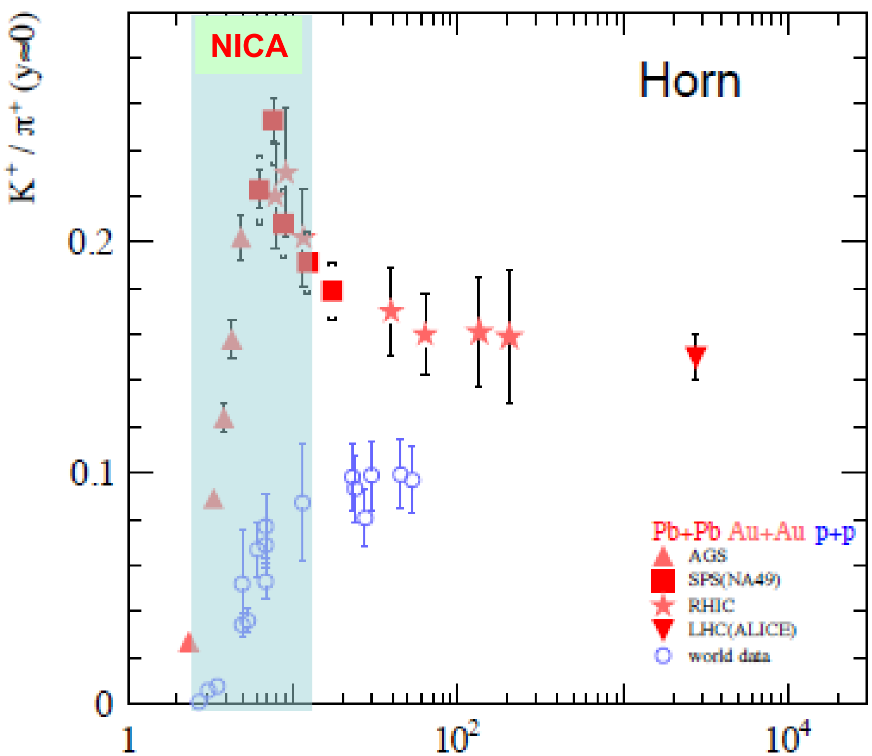
**Conditions:**

**RF cavities, Chromaticity sextupoles, Dipole nonlinearities (odd harmonics) – ON**

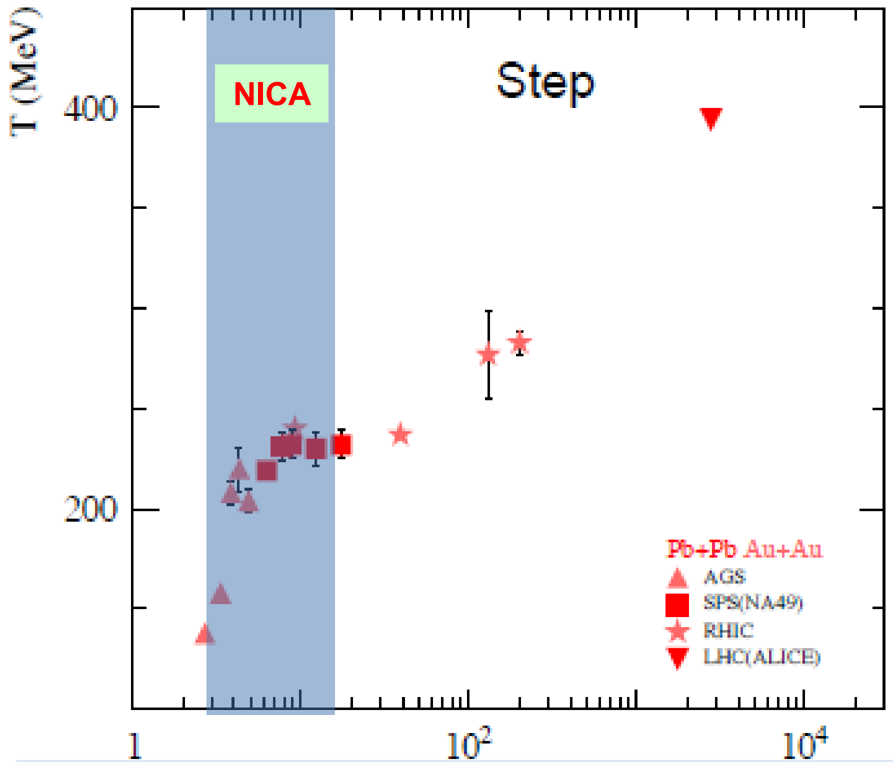
**$N_{part}=10^3$ – number of particles: $N_{turn}=10^5$ – number of turns.**

**Results: Asymptotical DA for $Q_{x,y}$ =9.44/9.44 working point:**

**$D_{\infty}=100\ \pi$ mm·mrad (PTC), $60\pi$ mm·mrad (thin lens) > $A_{x,y}=40\ \pi$ mm·mrad**




Non-monotonic energy dependence of the K+/π+ ratio (“Horn”) – onset of deconfinement?




Plateau in the apparent temperature of the kaon spectra (“Step”) – signal of the mixed phase?

- Maximum in $K^+/\pi^+$ ratio is in the NICA energy region,
- Maximum in $\Lambda/\pi$ ratio is in the NICA energy region,
- Maximum in the net baryon density is in the NICA energy region,
- Transition from a Baryon dominated system to a Meson dominated one happens in the NICA energy region.