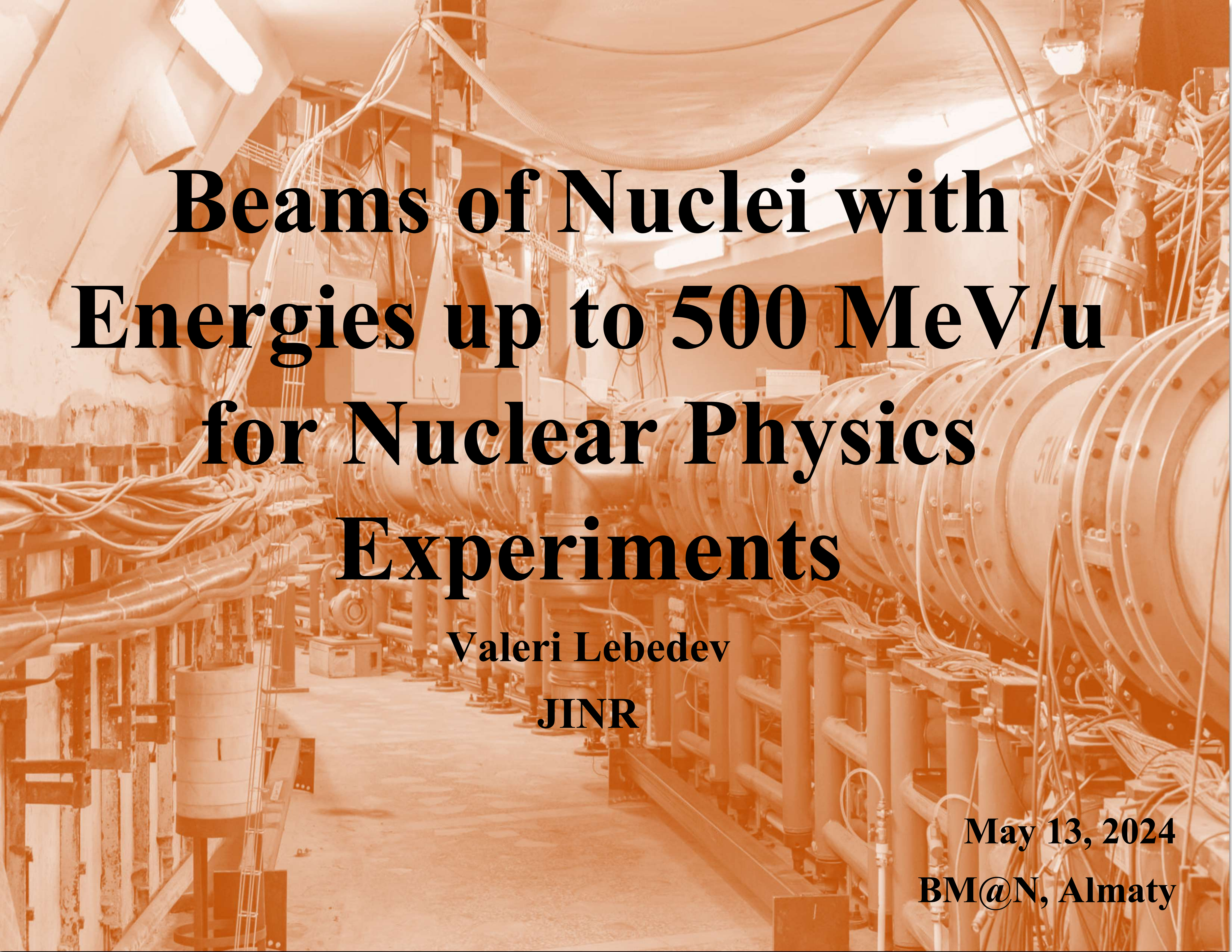

Beams of Nuclei with Energies up to 500 MeV/u for Nuclear Physics Experiments

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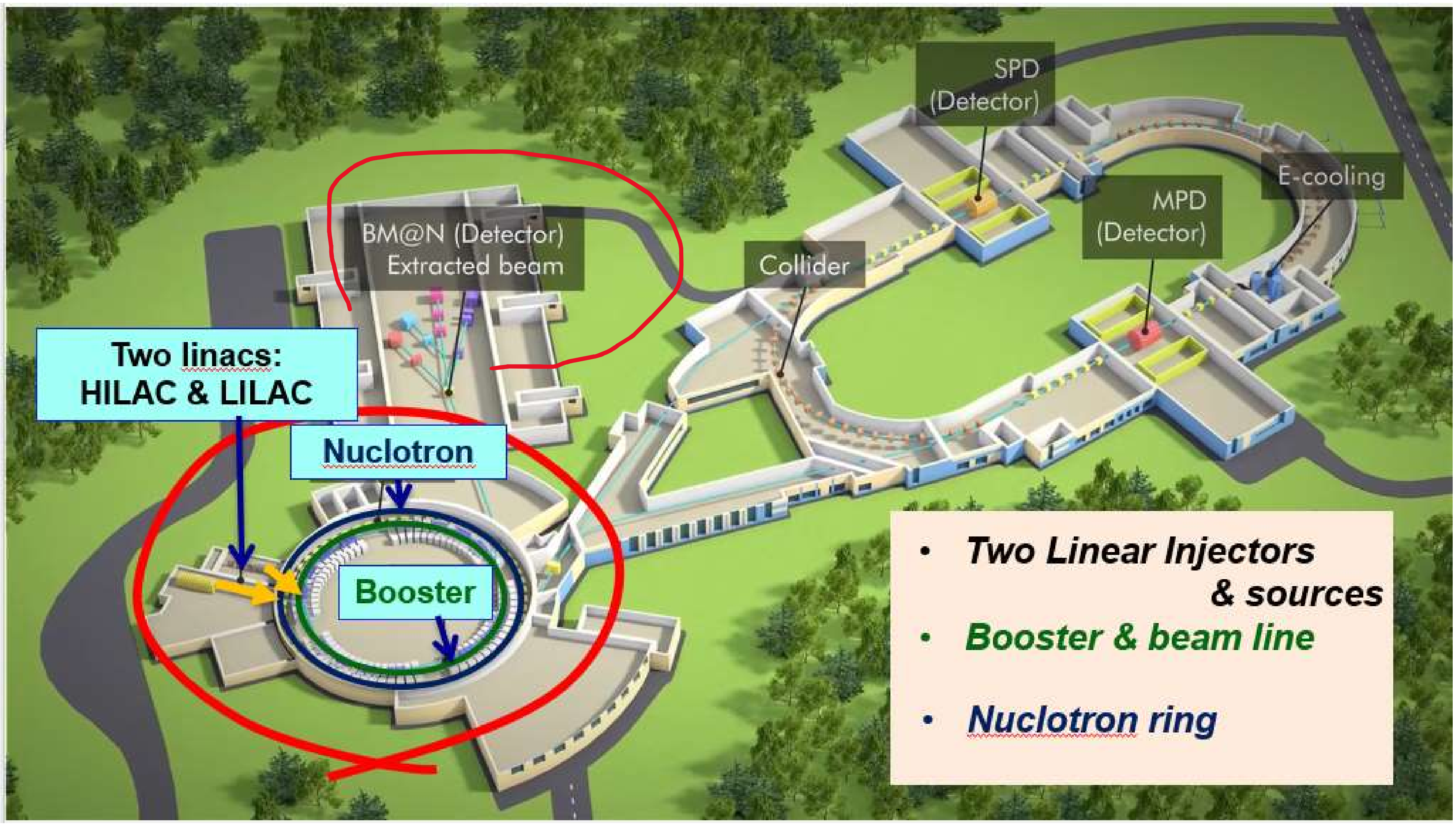
JINR

May 13, 2024

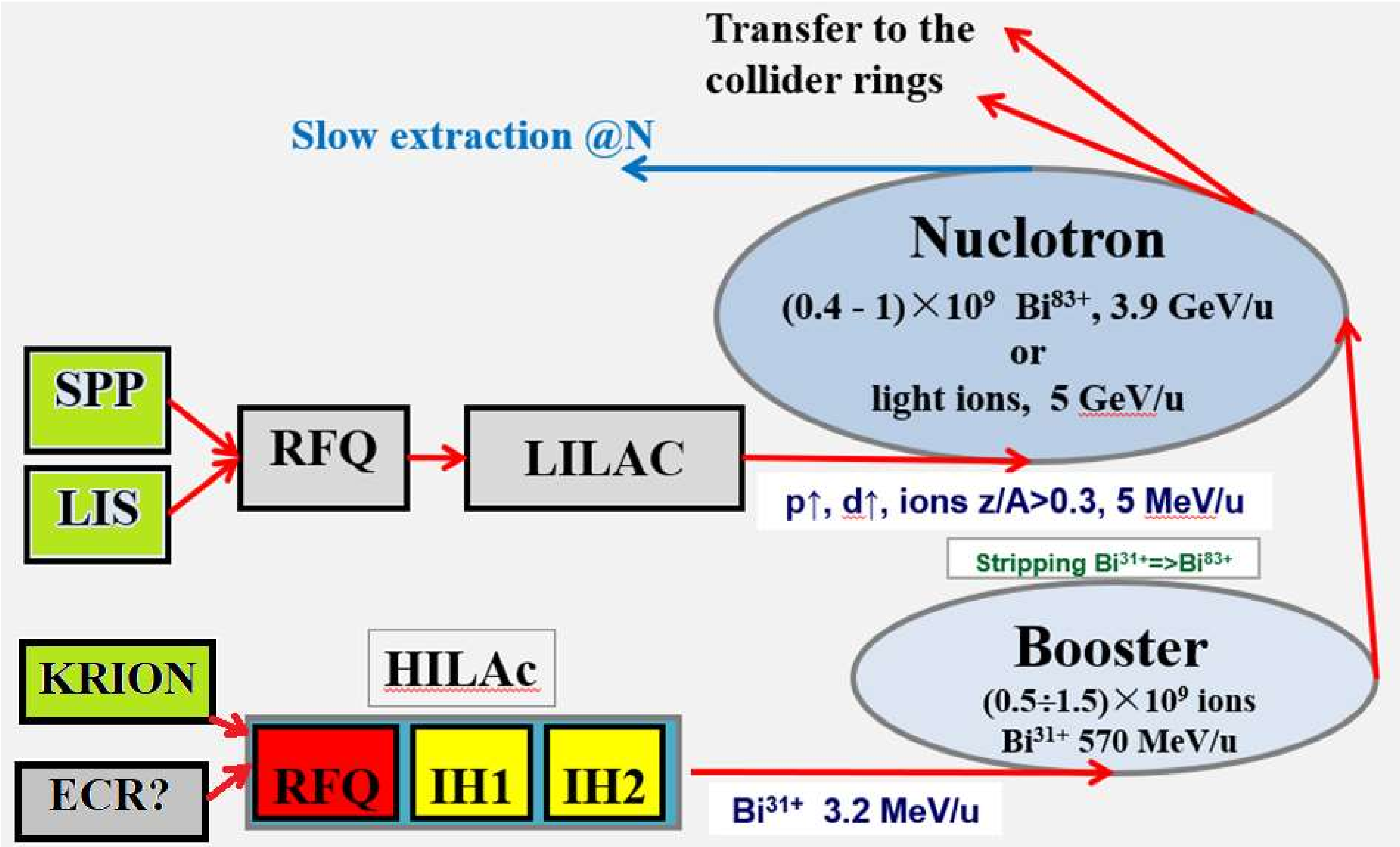
BM@N, Almaty

NICA Collider Complex Layout



- Injection complex is already in commissioning for few years
  - Intensity of (5-8)$\cdot 10^6$ fully stripped Xe ions at the top Nuclotron energy of 3.9 GeV/u was achieved – **certainly a record for heavy ions**
  - **The plan to get to ~10^9 heavy ions per cycle**

NICA Injection Complex Parameters (the goal)



- Injection of polarized ions to Booster is also discussed (in addition to Nuclotron injection)

Support of non-collider Experiments

- Normally, collider will use not more than ~20% of accelerator timeline
- We may and have to support other experiments
  i.e. experiments with “slowly” extracted beams
- To address it for heavy ions we plan to have 2 ion sources in HILAC
    - KRION – already present
    - To be added: the laser source (we already have) or possibly ECR
  - ♦ That will enable fast switching between types of ions; i.e. quasi-simultaneous operation of both ion sources
    - Switching time few Booster cycles; i.e. 15-30 s
    - Or switching ion type on every cycle
- Acceleration of light polarized ions (H, D & ^{3}He)
    - Initially in LU-20 and later in LILAC
    - It is desirable to have 2 ion sources (polarized & non-polarized)
  - ♦ Collisions of polarized beams (SPD) will come with considerable delay
  - ♦ Injection to both Booster and Nuclotron is discussed

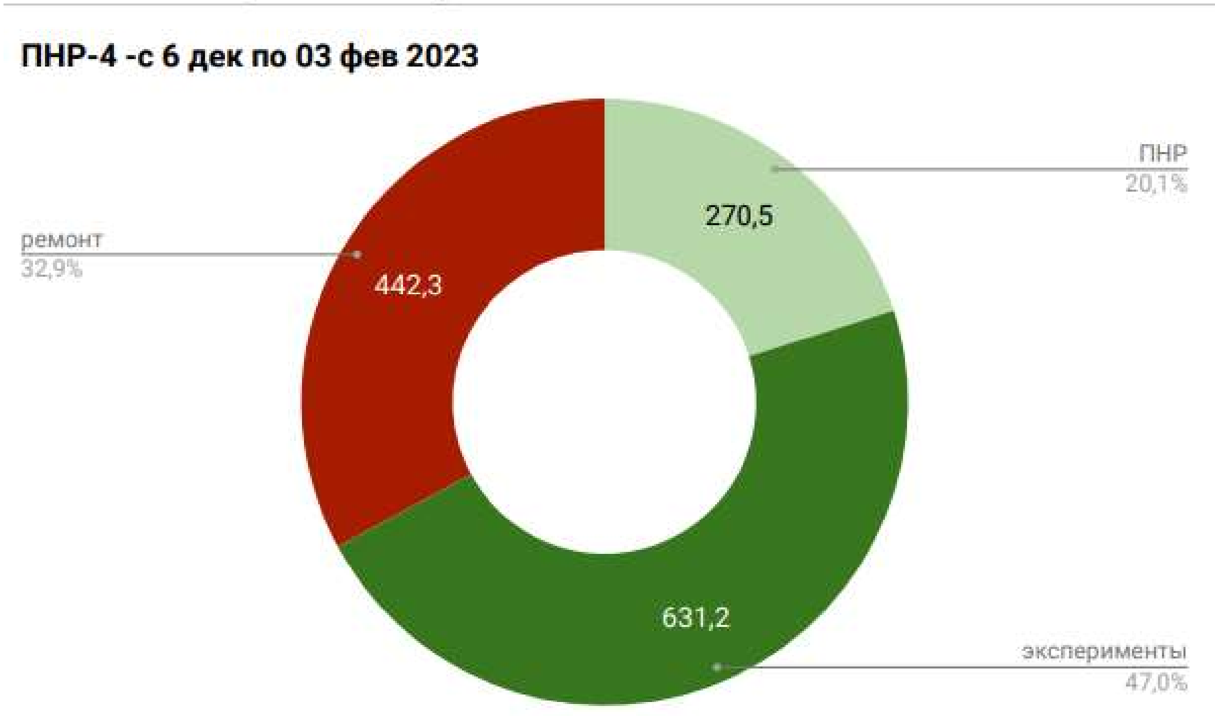
NICA Injection Complex

- There are two useful features of the accelerator complex which are very helpful for the experiments with slowly extracted beams
  - If an ion source does not have sufficient intensity, then the electron cooling enables a beam accumulation with about 10 Hz rep. rate
  - Two rings operating simultaneously allow us to accelerate ions in Booster while Nuclotron is used for slow beam extraction
    - ⇨ Almost uninterrupted "slow" beam extraction for energy below ~500 MeV/u
    - Depending on required beam energy (200-600 MeV/u) the cycle duration will be within 2-5 s range
- Quasi-simultaneous operation with heavy ions and polarized ions is also possible
- Intensity achieved in the last run was sufficient to support BM@N
  - The beam intensity required by collider is larger by ~100 times
  - Of course, it is not a problem to use a smaller intensity, but this excess creates a lot of possibilities

Some Achievements of the Run IV

- Stable operation of entire complex is achieved in the Run's 2nd half
- Record intensity of heavy ions delivered to the top Nuclotron energy. However, it needs to be noted that
  - Ion source delivered only about 10% of planned intensity
  - Accelerating efficiency was ~10%
- Orbit correction in both rings
  - Software was built to support the correction in all rings and lines
  - Dynamic correction through the entire Booster cycle was demonstrated
    - Hardware problems (i.e. trips of correctors) kept us from operating orbit correction through the rest of the Run
  - Nuclotron
    - Orbit correction at injection was demonstrated
    - Multiple hardware problems prevented operational usage
- Bunch-to-bunch Booster-Nuclotron transfers
- Characterization of RF systems
- Building a program for the injection complex upgrade

Statistics of Machine Operation in Run IV



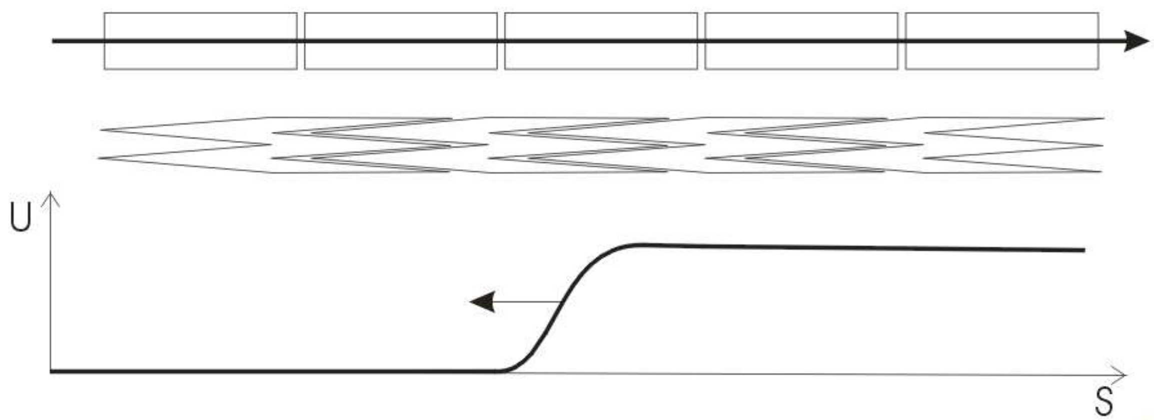
A. Alfeev

- We need great reduction of time lost on repairs and machine tuning
  - All high-power systems had problems during the Run
- Repairs and upgrades have been one of highest priorities in the course of coming shutdown
- We also need effective procedures for machine tuning supported by required hardware and software

Near Term Goals

Ion Source Upgrade

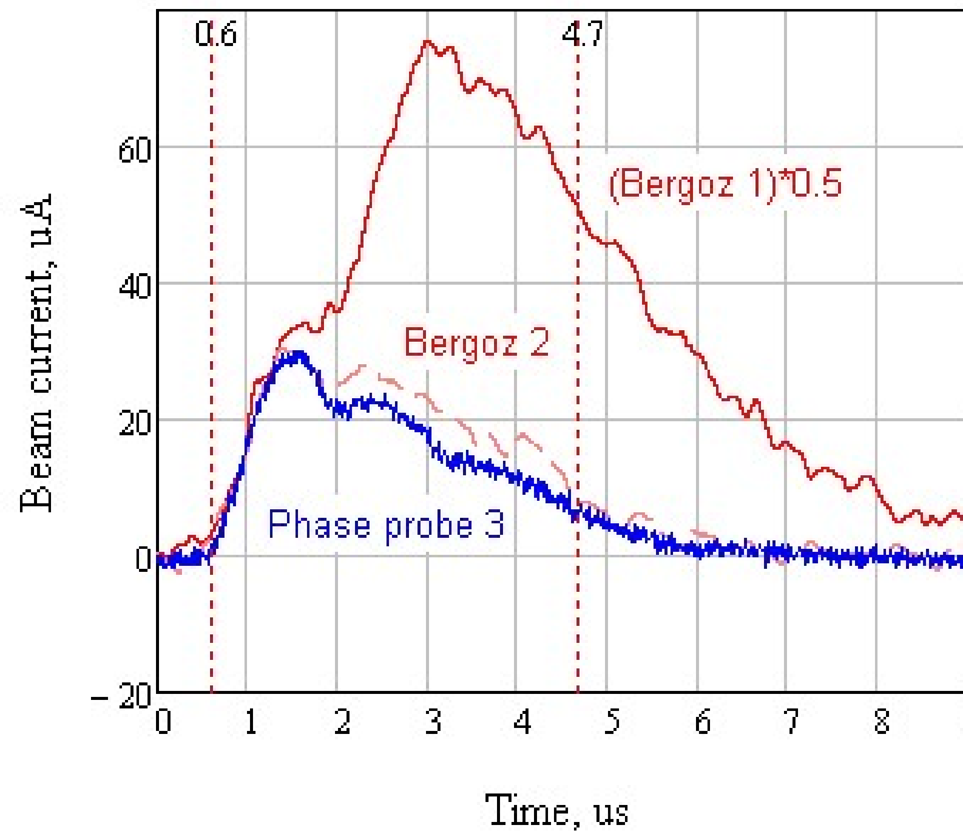
- The upgrade has 4 goals
  - Reduce the beam duration from ~(10 – 20) μs to 4 μs so that to support ion accumulation in the Booster longitudinal phase space
  - Reduce energy spread excited by extraction process (±1.4 kV -> ~0)
  - Make uniform density distribution along the beam pulse
  - Support 10 Hz operation



- It will be achieved by
  - Changing geometry of ion holding cylinders so that the extraction electric field would be uniform due to its penetration inside cylinders
  - Instead of resistive divider use a number of pulse generators, operating in delay line mode, to create a traveling wave propagating along ion column
- Quite challenging upgrade
  - We are in its middle

Ion Source Recent Progress (E.E.Donec & department)

- 10 Hz operation was demonstrated after official end of Run 4 (June 2023)
- Beam shortening was demonstrated in February of 2024
  - 2/3 of ion trap length because of hardware problems
  - Length is almost OK
  - More tuning and studies are required
    - They should deliver better understanding
  - Operation in according with specs is expected by June
    - 4 μs
    - >$1.5\cdot10^8$ Xe^{28+} ions at the ion source exit (eff. 22%, ions total: $6.7\cdot10^8$ Xe ions corresponding 3 nC)
    - 10 pulses at 10 Hz with 5.5 s rep. rate



Near Term Goals for ION Source and Linac

- Demonstrate reliable operation of ion source and linac with 10 pulses at 10 Hz with 5.5 s rep. rate
  - Water cooling for LEBT solenoid – done
  - Increased power for high voltage pulsed power supply, 100 kV
  - More powerful power supplies for pulsed magnets and solenoids
  - Synchronization between linac and ion source
    - Then, be ready for synchronization with Booster RF
- Measure beam emittance in LEBT (before RFQ)
  - Improved wire profile monitor should deliver data with better quality
- Characterize the beam loss through acceleration in the linac
- We got a vacuum accident in March and still did not completely recover

- **Expect to be ready for Booster operation in June**

Expected Linac Performance

- Measurements of ion source normalized emittance yield the rms value of ~0.1 – 0.15 μm
- Acceptance of the linac is estimated to be $\varepsilon_n \approx 0.4$ μm. (i.e. $\le 2\sigma$)
  - That is barely sufficient to accelerate the beam through linac without loss
  - To be on safe side we put expected beam loss at 50%

⇨ Number of ions injected to Booster – $7.5 \cdot 10^7$ per pulse
  - This is about 50% higher than we demonstrated in Run 4
- Presently we do not have means to measure a distribution of beam loss in linac
  - An installation of 2nd ion source will require bends and should enable accurate characterization both the ion source and linac

Booster Objectives

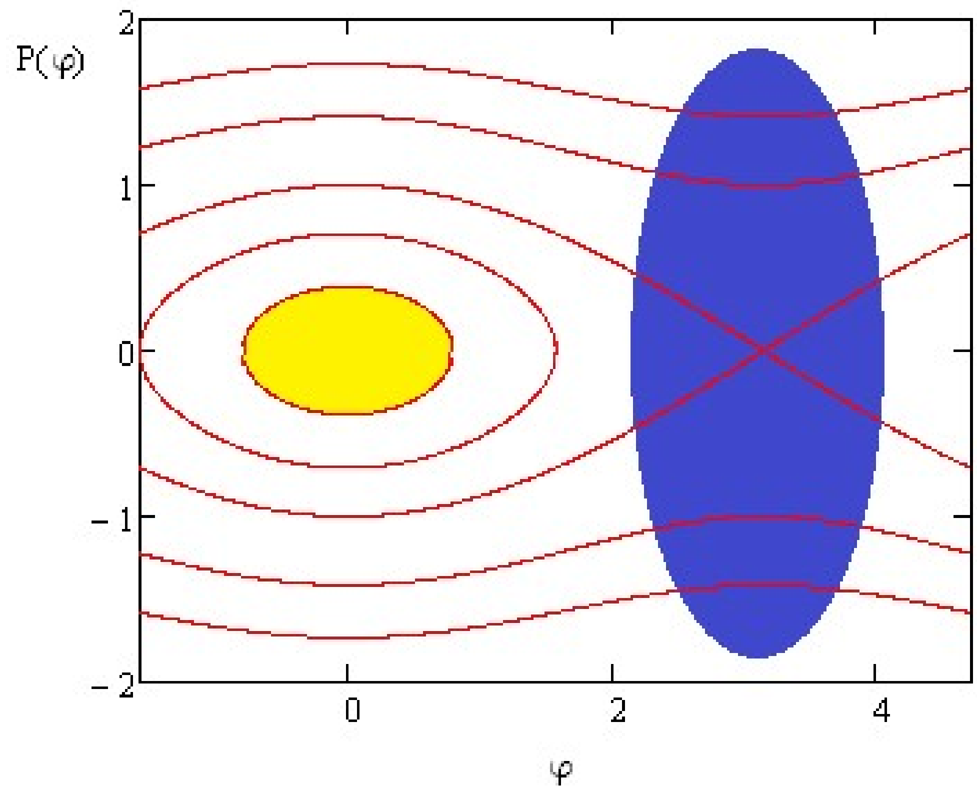
- Accumulate ~10 linac pulses to maximize the beam intensity
- Minimize the beam loss and emittance growth in the course of beam accumulation and acceleration. Acc. eff: 10% -> 70%

Main Booster Parameters

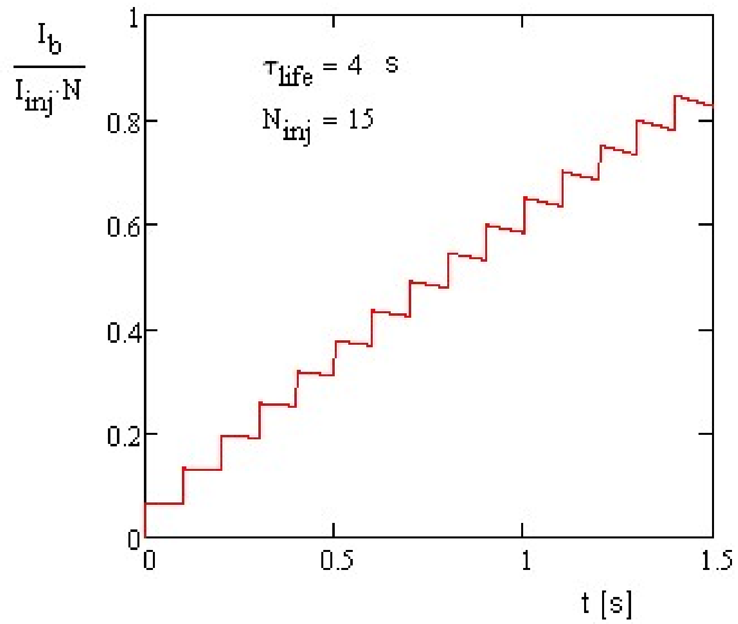
Circumference	210.96 m
Injection energy	3.2 MeV/u
Extraction energy	530 MeV/u
Extraction magnetic field	16 kG
Maximum growth rate of dipole field	10 kG/s
Number of injections from linac	10
Duration of injection cycle	5.5 s
RF harmonic number	1
Maximum Voltage of RF system (measured)	7.4 kV
RF voltage during beam accumulation	200

Beam Accumulation Scheme

- Each new injection happens after the previous one is cooled to the core
- The permanently present 1st harmonic RF weakly affects large amplitude particles – no cooling loss
- For small amplitude particles the cooling force may be intentionally reduced to avoid overcooling
- To avoid "anticooling" we need to match well the ring dipoles magnetic field at injection and e-beam energy
    - Anticooling happens since dF/dt changes sign after reaching the peak



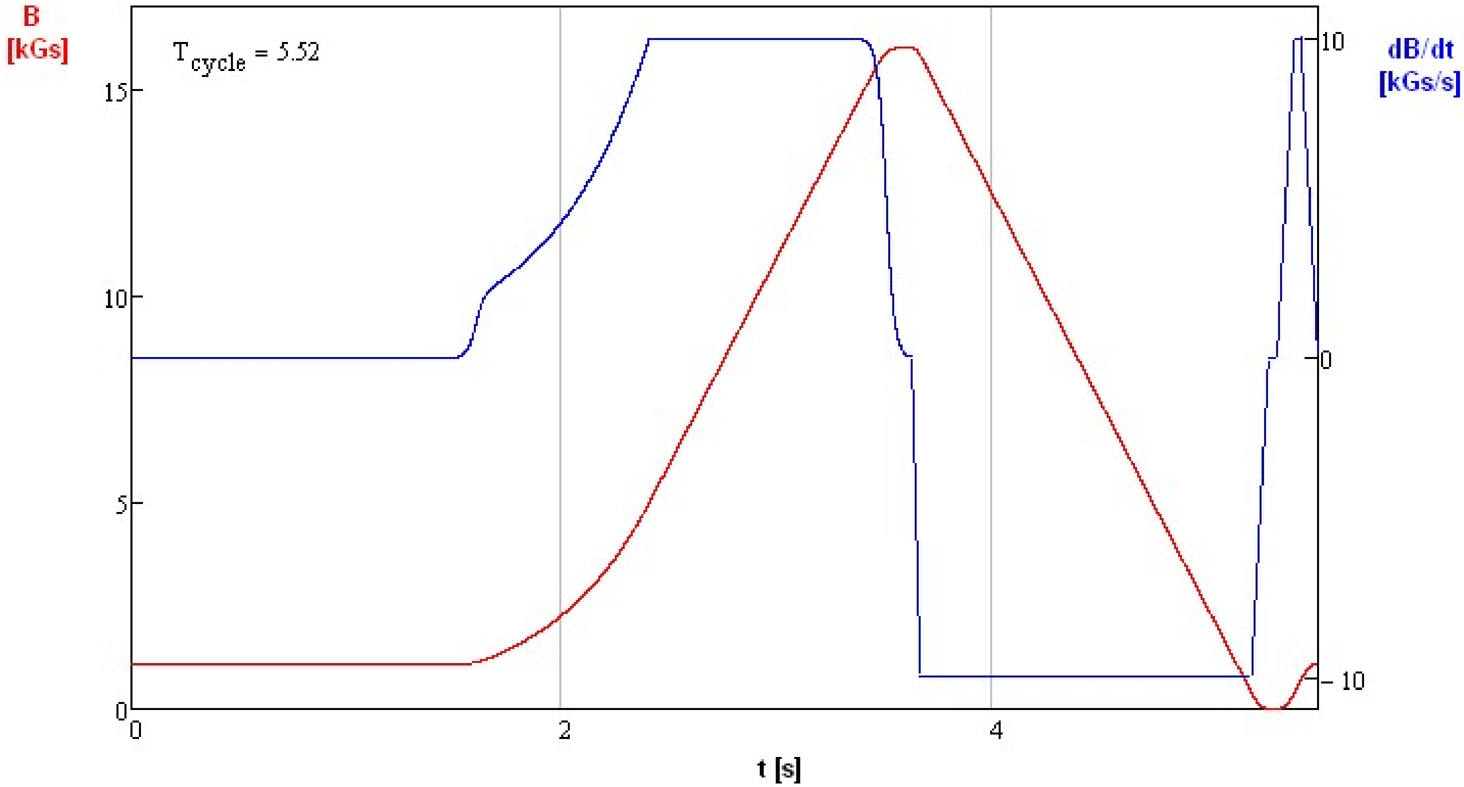
Beam Accumulation in Booster



- The number of injection cycles will be limited by the beam life time,
  while the beam intensity will be limited by the space charge effects
- The beam lifetime will be determined by electron capture from atoms of residual gas
  and by the electron capture from electron beam of electron cooler
  - Presently we assume that at the injection energy the beam lifetime will be 4 s. Actual value needs to be determined by experiment.
  - Electron capture from e-beam can be reduced by creating a hole in the center of electron beam
- In further estimates we assume: 15 injections with repetition rate of 10 Hz and the total stored intensity equal to 10^9 ions

Booster Magnetic Cycle

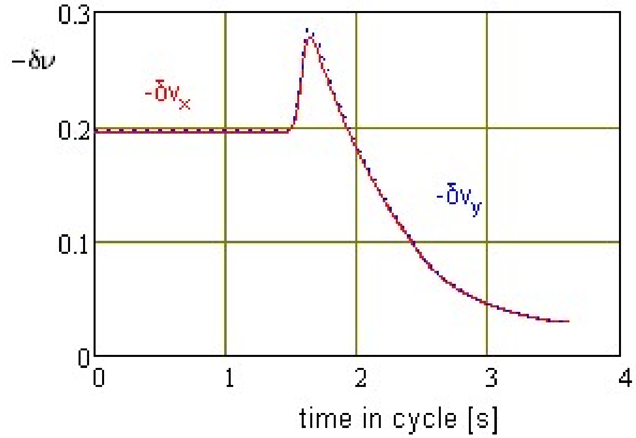
- The maximum rate of magnetic field growth is 10 kG/s
- At the cycle beginning the acceleration is slower to keep sufficiently large longitudinal acceptance determined by available RF voltage
- For 10 injections the total cycle duration is slightly longer than minimum duration of Nuclotron cycle
- Software, which uses new algorithm of magnetic cycle generation, is ready for testing



Betatron Tune Shift due to Beam Space Charge

- The main limitation on the beam intensity is the betatron tune shift due to beam space charge at the Booster injection

$$\delta\nu_{x,y} = \frac{Z^2}{A}\frac{r_p N_{ion}}{2\pi\beta^2\gamma^3}\frac{C}{\sqrt{2\pi}\sigma_s}\left\langle \frac{\beta_{x,y}}{\sigma_{x,y}\left(\sigma_x+\sigma_y\right)}\right\rangle_s$$

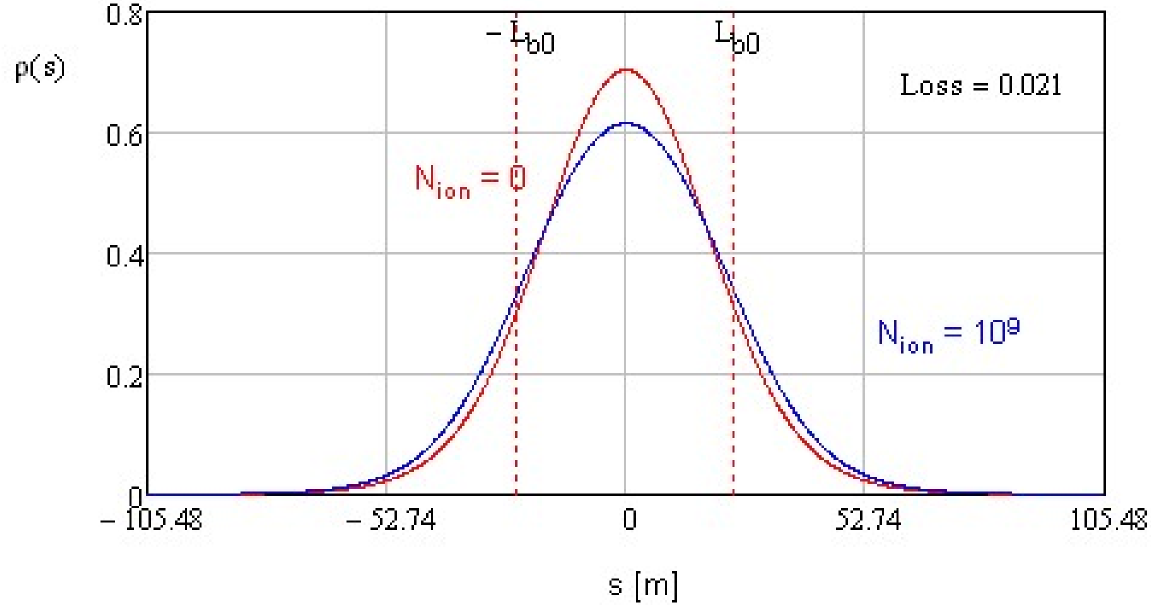


  - To maximize the number of ions they need to have the smallest charge which can be accelerated in HILAC, i.e. A/Z~6 => $N_i \approx (209/A)\cdot 10^9$

- The tune shifts are quite large and it is not obvious that we can achieve them without using additional "tricks"
  - Usage of barrier bucket can reduce the bunch density in the center and, consequently, tune shift during beam accumulation
  - Reducing ⊥ & || cooling at small velocities should reduce corresponding densities without sacrificing cooling at large amplitudes
  - Reduction of cooler magnetic field makes machine closer to super-periodicity which reduces sensitivity to beam space charge fields
    - High accuracy linear optics correction may be also helpful

Bunch Lengthening due to Beam Space Charge

- The beam space charge results in minor bunch lengthening
- Bunch momentum spread and, consequently, its length were chosen to free half of the orbit for newly injected particles
- In the future we plan to use the barrier bucket RF. Its use would enable obtaining smaller bunch density in center and, consequently, smaller betatron tune shifts

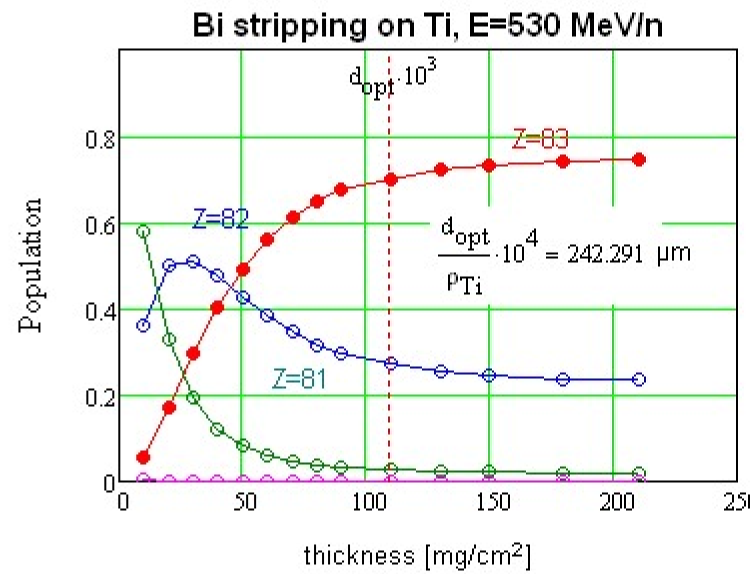


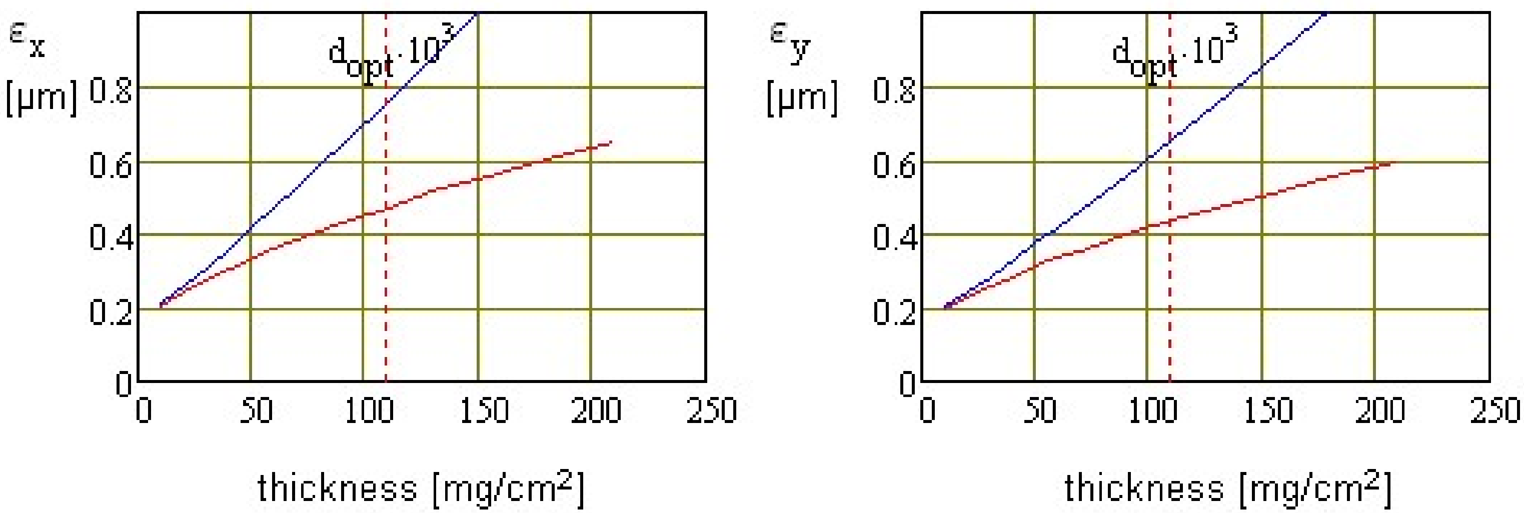
Longitudinal particle density on position along the ring for zero intensity (red line) and 10^9 ions (blue line). We assume gaussian distribution in momentum with $\sigma_p=5.04\cdot10^{-4}$. Longitudinal distribution obtained by solution of Haissinski equation with space charge impedance. 1.9% of particles are outside of half circumference.

Vertical lines show the bunch boundary for the bunch with zero momentum spread. In this case bunch has parabolic longitudinal distribution.

Ion Stripping at Booster-Nuclotron Transfers

- Ion stripping to bare nucleon happens at the Booster extraction
- Relatively small Booster energy limits the Bi stripping efficiency to about 70%
- Optimal thickness of the titanium stripping foil is ~110 mg/cm^2. Its further increase brings unacceptable emittance growth.

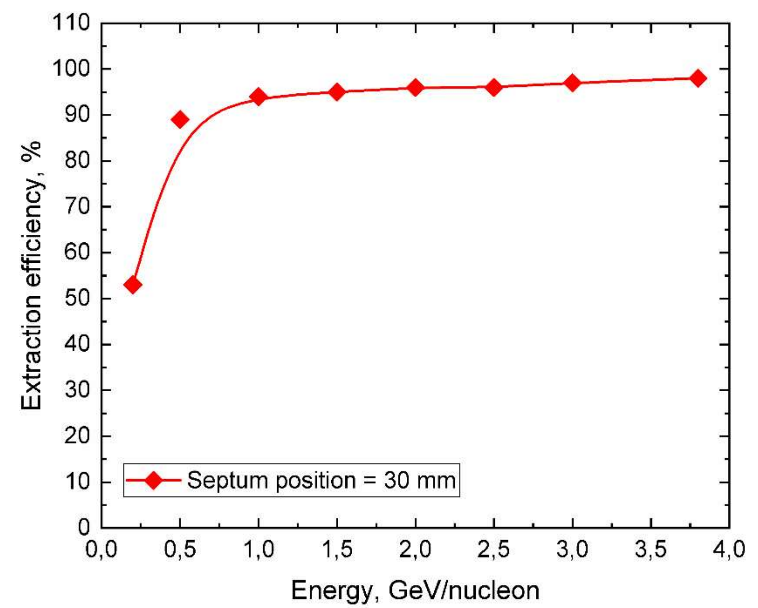




Dependence of beam emittance in Nuclotron thickness of stripping foil; red lines correspond to the case where the transfer line optics accounts scattering in the foil, blue lines – not accounts

Usage of Nuclotron

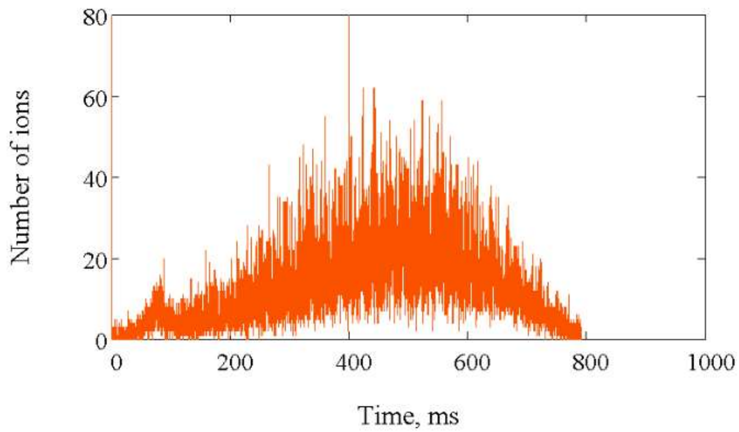
- For high energy operation we need stripping
  - That increases the bending strength of dipoles and results in higher energy (3.9 GeV/n for Z/A=6)
- For operation up to 500 MeV/u we do not need:
  - Stripping of the ions => no emittance growth
  - Acceleration: Booster delivers required energy
  - RF in Nuclotron & Bunch-to-bunch transfers => simpler operation
- We just use Nuclotron as a beam stretcher using slow extraction
  - Extraction efficiency depends on radio of aperture to the beam size
  - Cooling and orbit correction help



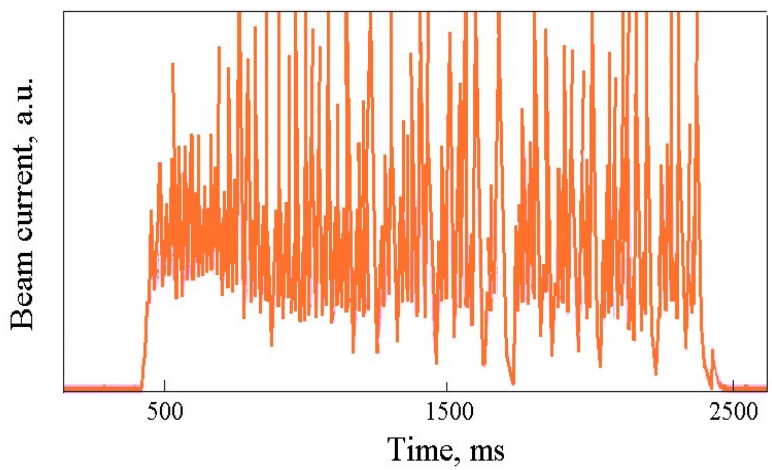
Calculated dependence of extraction efficiency on the energy

Slow Extraction

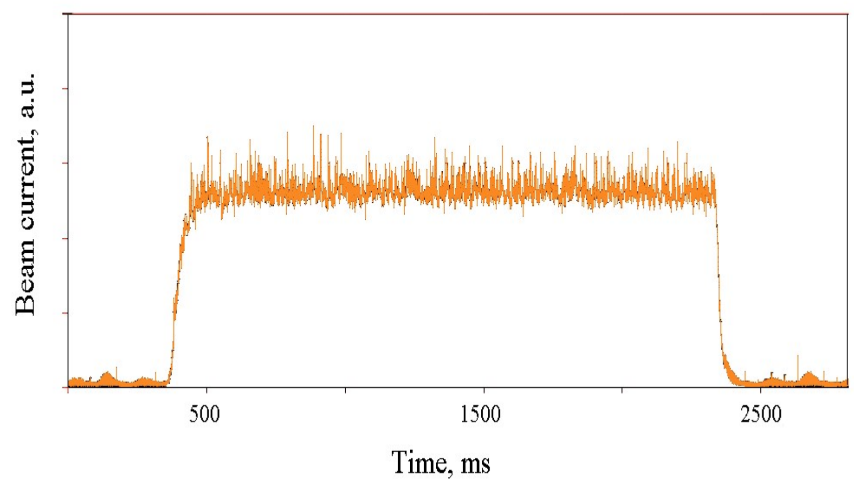
- We use a resonant extraction at the 3rd order betatron resonance



Measured beam intensity on time with feedback on: a) kicker is off, b) kicker is on



(a)

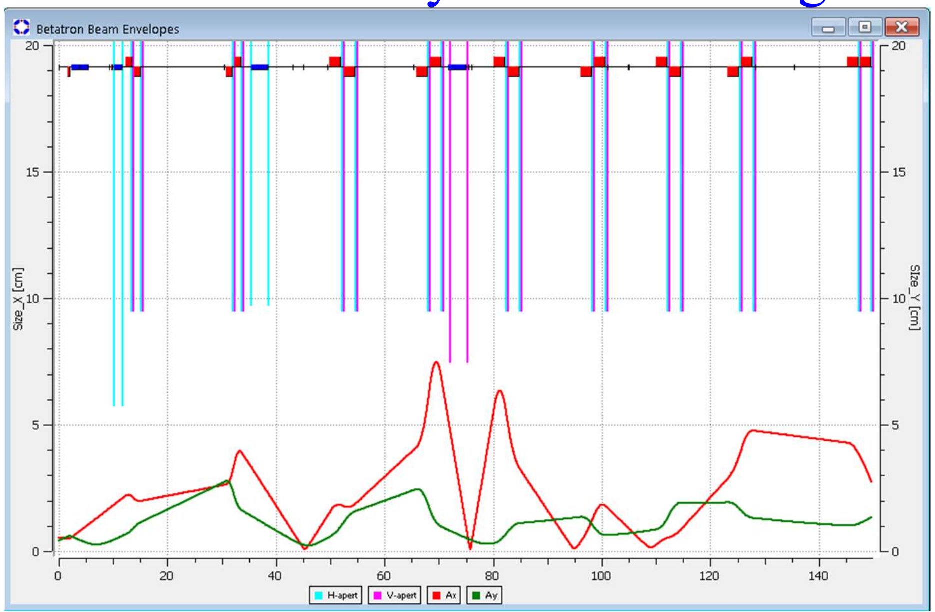


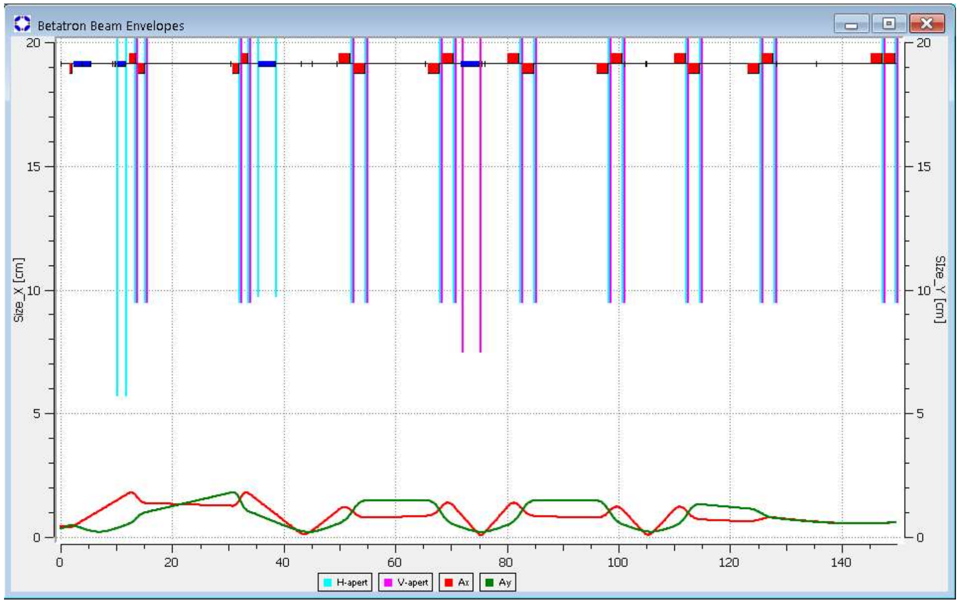
(б)

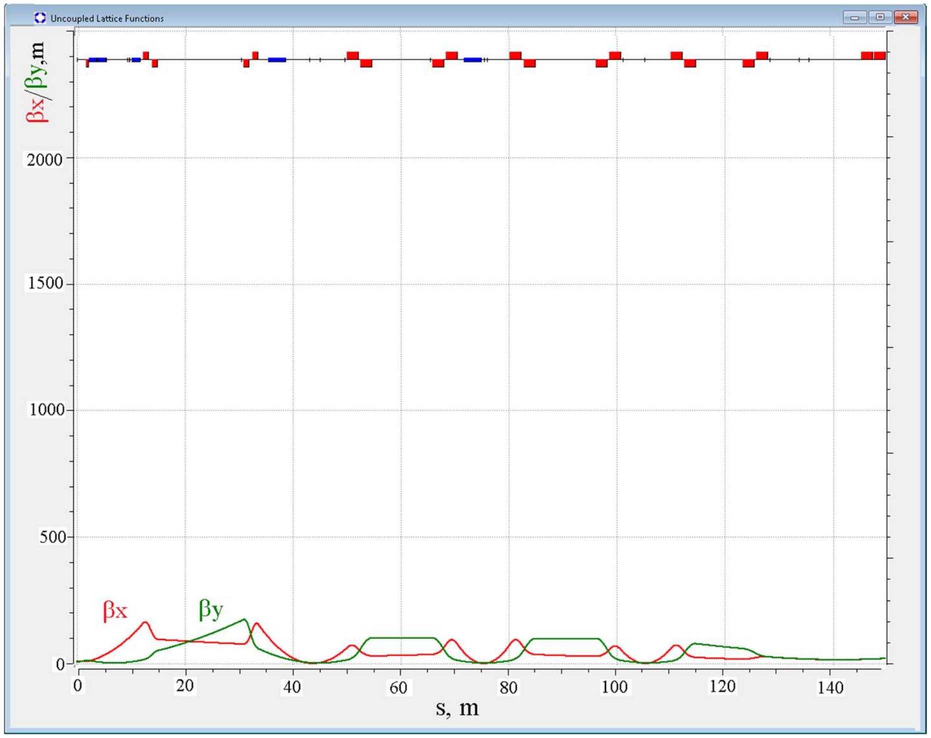
Measured beam intensity on time with feedback on: a) kicker is off, b) kicker is on

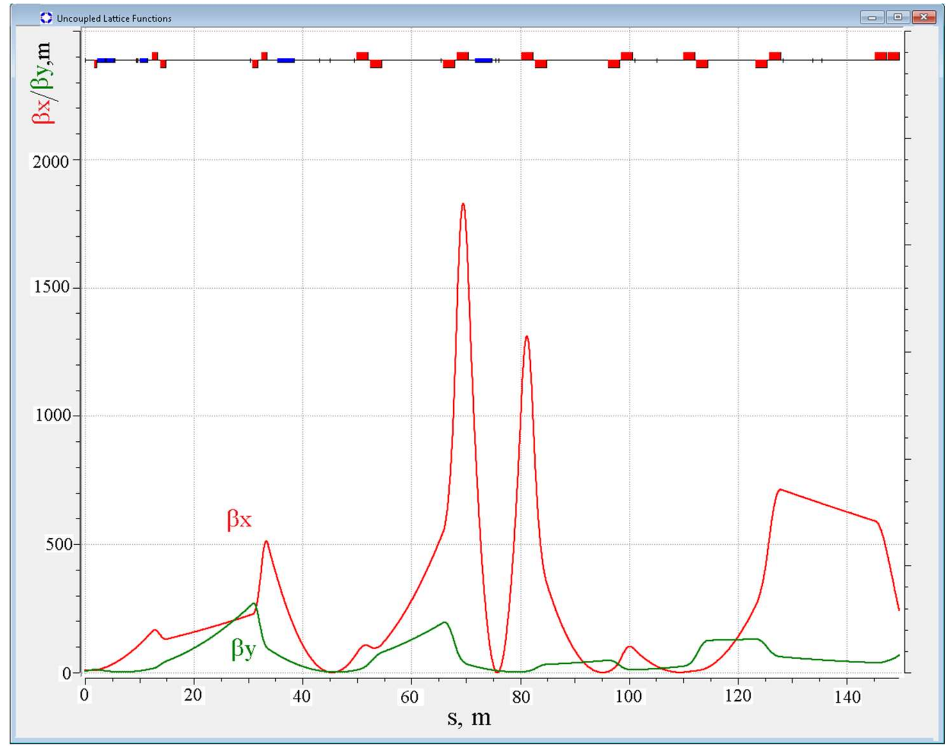
Slow Extraction and Beam Transport to BM@N

- Slow extraction
  - Measured efficiency of slow extraction is ~30%.
  - We plan to improve it to ~90%
    - Beam orbit correction in vicinity of electrostatic septum should address the problem
- Beam transport to BM@N
  - We reoptimized the beam transport through BM@N transport line
  - Smaller beam sizes => Reduced sensitivity to errors
  - Together with vacuuming the to-BM@N beam transport it has to drastically decrease background and improve line reproducibility









- Sensetivity to errors is proportional to the beta-functions
  - Should be reduced by an order of magnitude

Conclusions

- Constituents of planned beam intensity increase
  - Orbit and optics measurements and correction
  - Matching acceleration rate to the available RF
  - Increased energy for Booster-to-Nuclotron transfers
- Upgrades of the injection complex for collider will yield an intensity increase by about 2 orders of magnitude relative to what was demonstrated in Run 4
  - Maximum intensity of $\sim 10^8$ s^{-1} for heavy ions
  - It will create additional possibilities to use slowly extracted beams
    - Secondary particles
    - Tensor polarized heavy ions
    - …
- Quasi-simultaneous acceleration of multiple ions species
  - Heavy and medium weight ions
  - polarized p, D, ^{3}He is anticipated
- Improved slow extraction and beam transport experiments in Bldg. 205
- NICA injection complex will support a diverse program with slow extracted beam