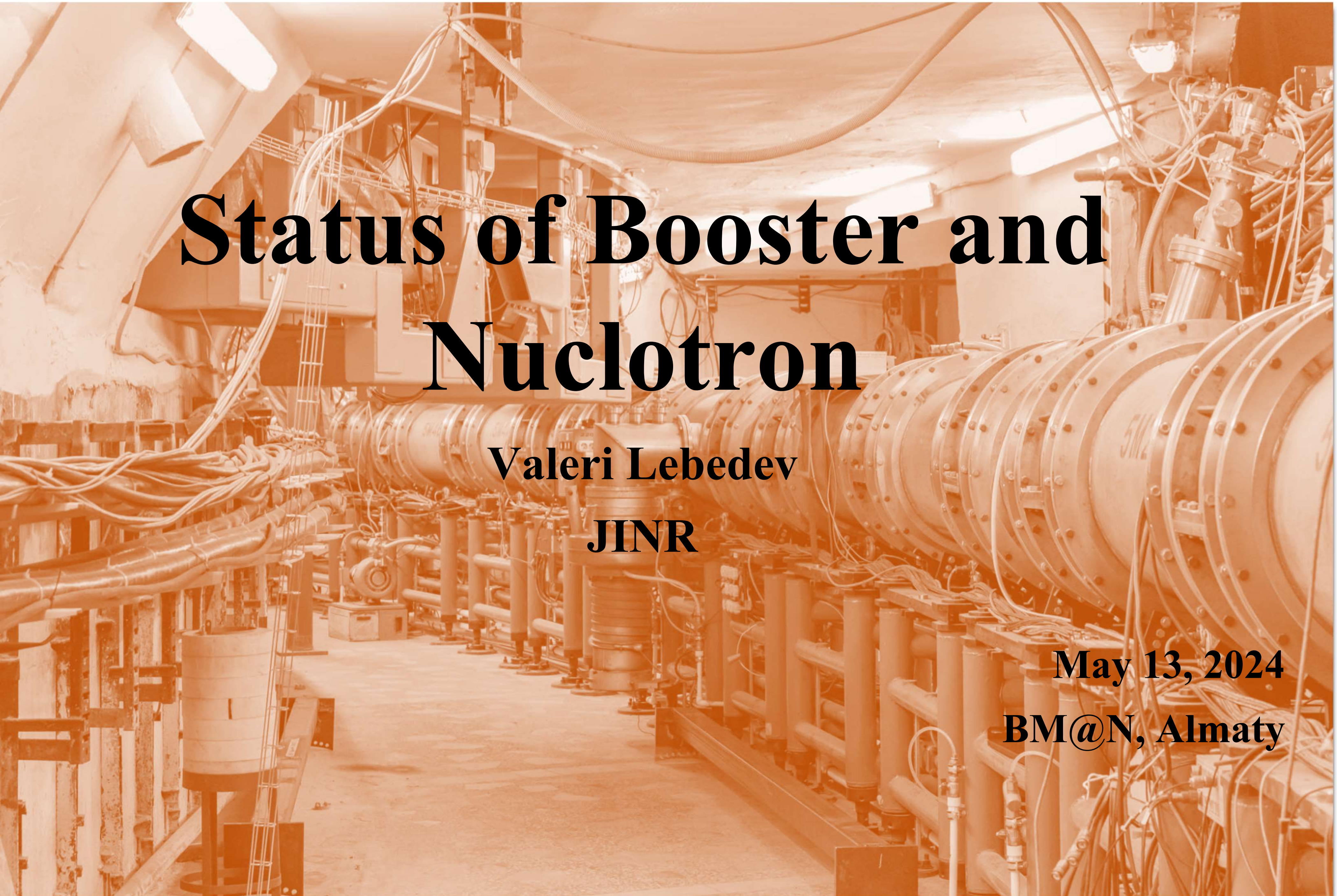


Status of Booster and Nuclotron

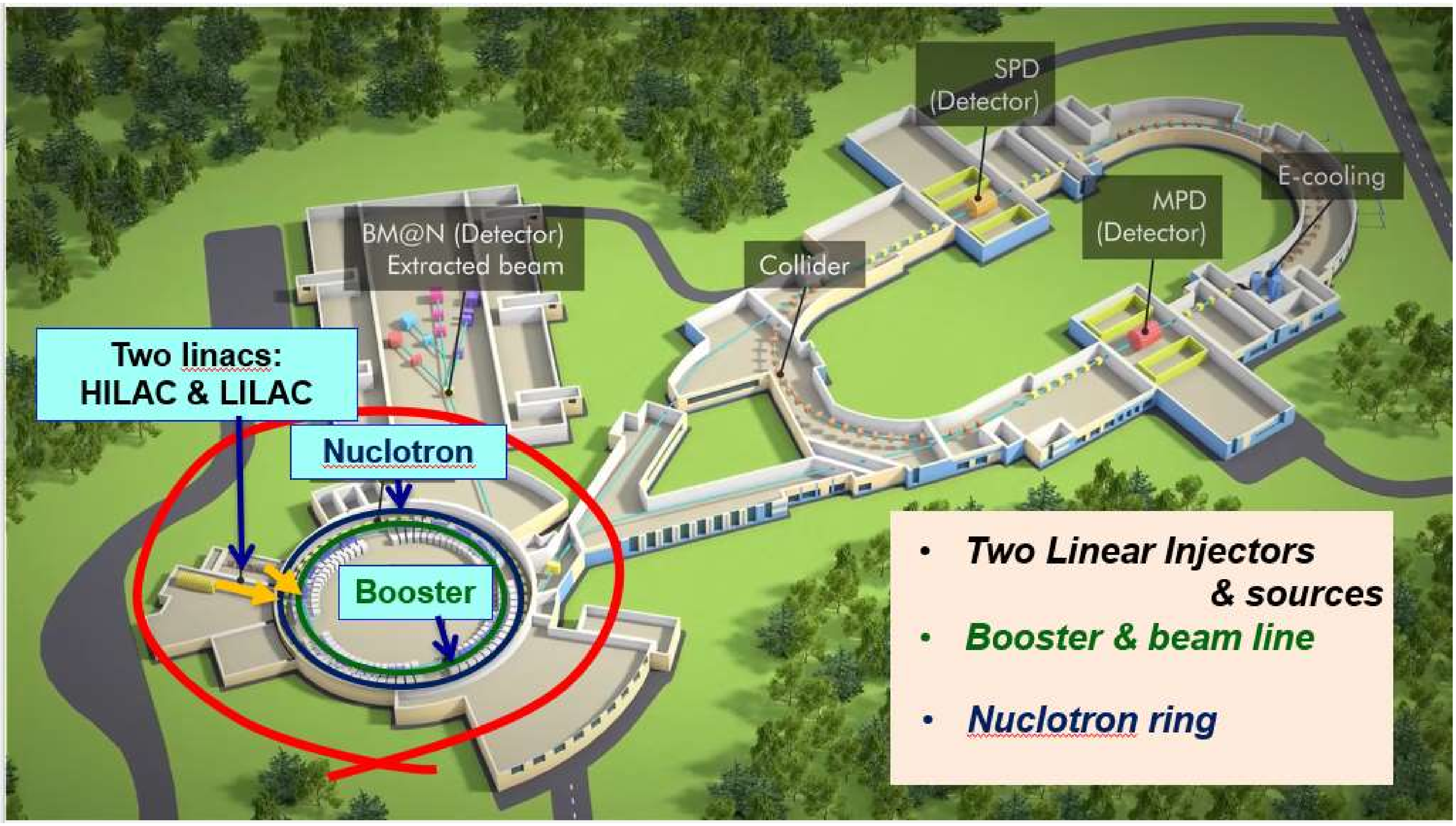
Valeri Lebedev

JINR

May 13, 2024

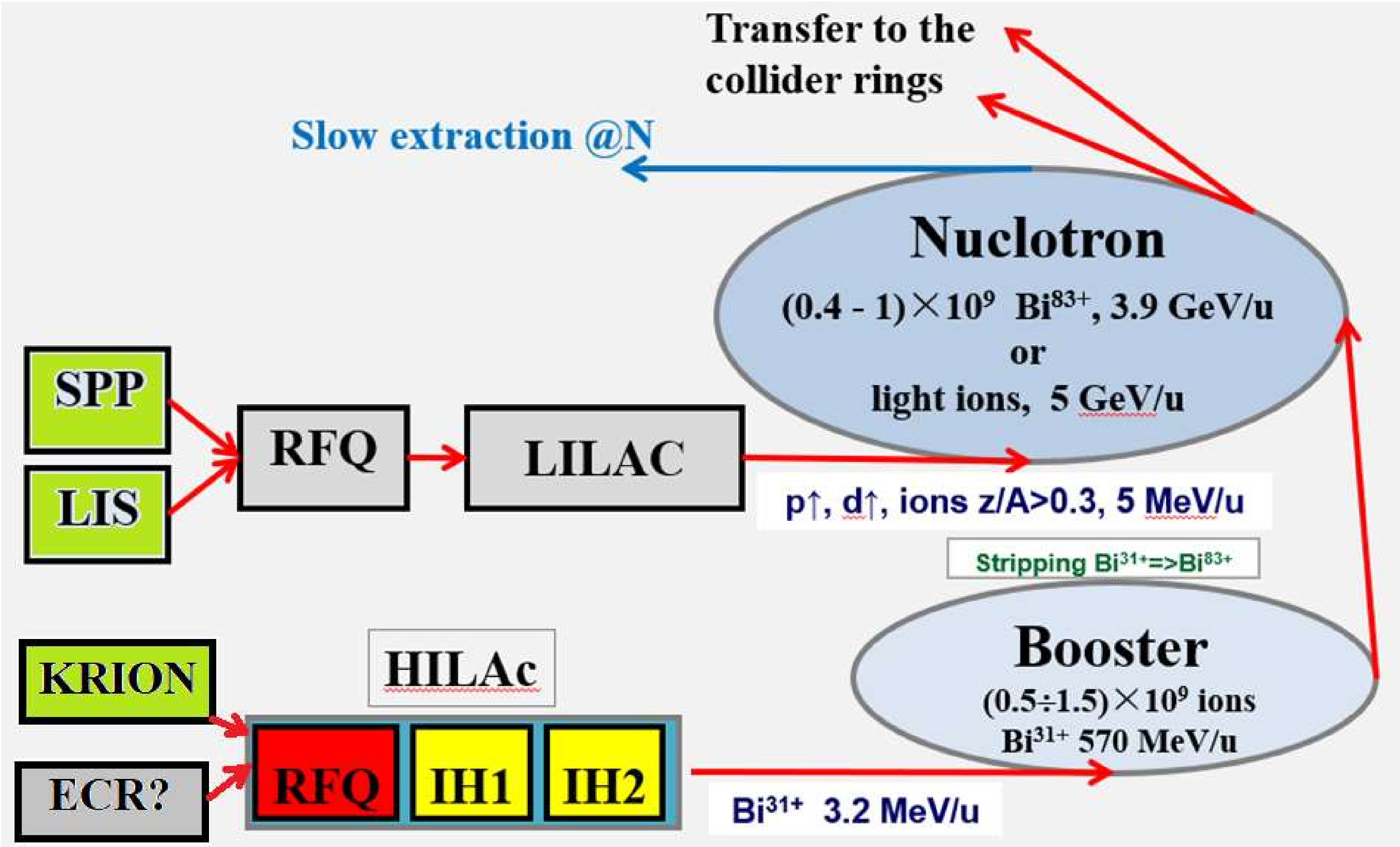
BM@N, Almaty

NICA Collider Complex Layout



- Injection complex is already in commissioning for few years
  - Intensity of (5-8)·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

- 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: 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

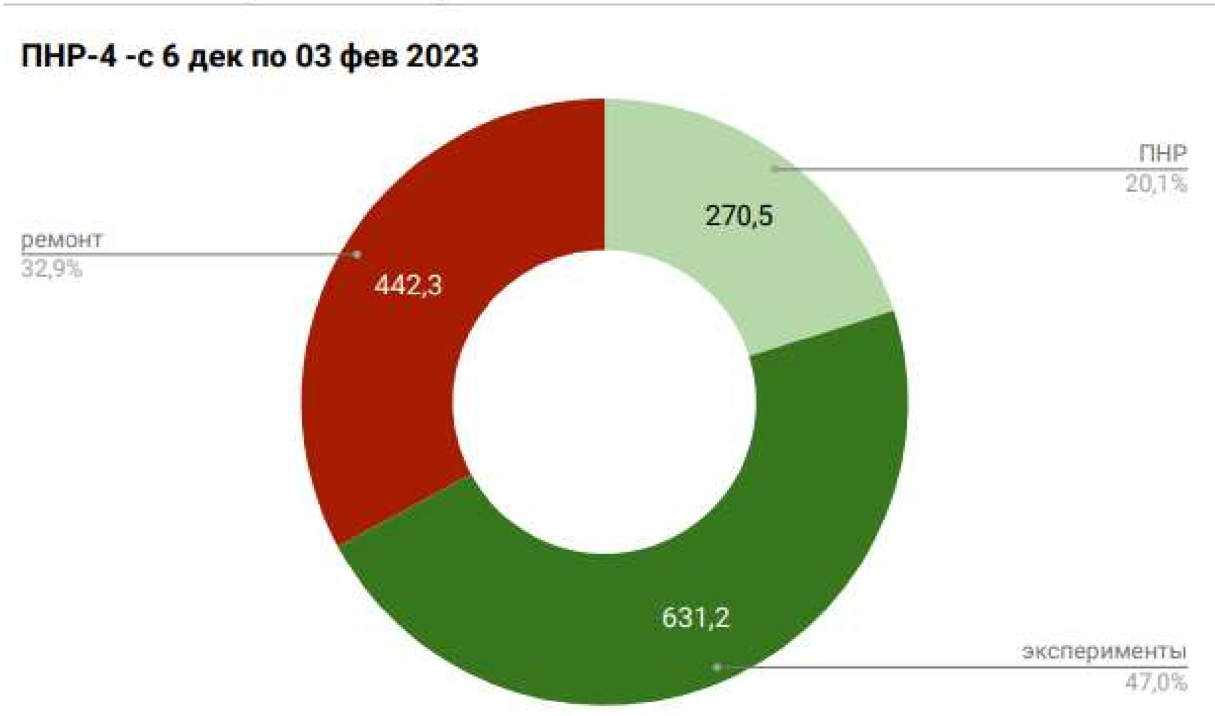
- There are two useful features of the accelerator complex which are very helpful for the experiments with slowly extracted beams
  - ♦ If an ion source does not have sufficient intensity, then the electron cooling enables beam accumulation with about 10 Hz rep. rate
  - ♦ Two rings operating simultaneously 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 2^{nd} half
- Record intensity of heavy ions delivered to the top Nuclotron energy. However, we need to note 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

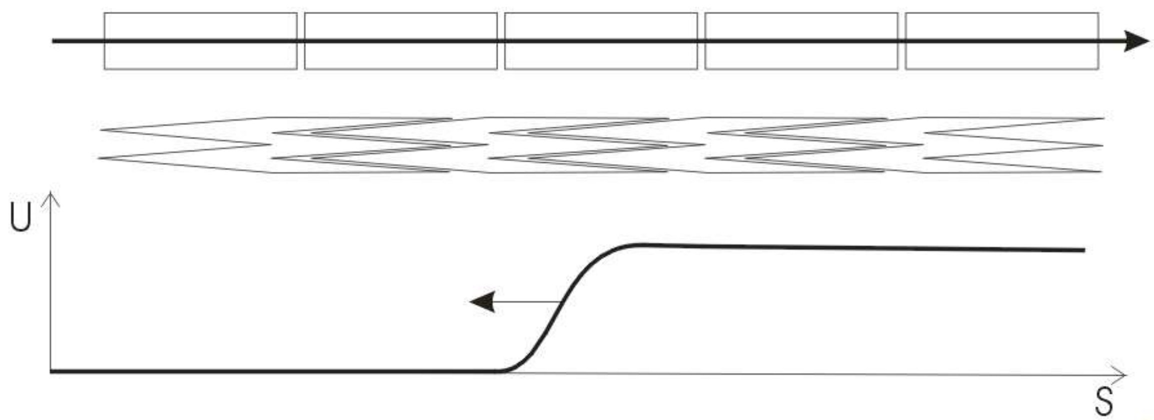


- We need great reduction of time lost on repairs and machine tuning
  - All high-power systems had problems during the Run
- Repairs and upgrades have been one of highest priorities in the course of coming shutdown
- We also need effective procedures for machine tuning supported by required hardware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

Near Term Goals

Ion Source Upgrade

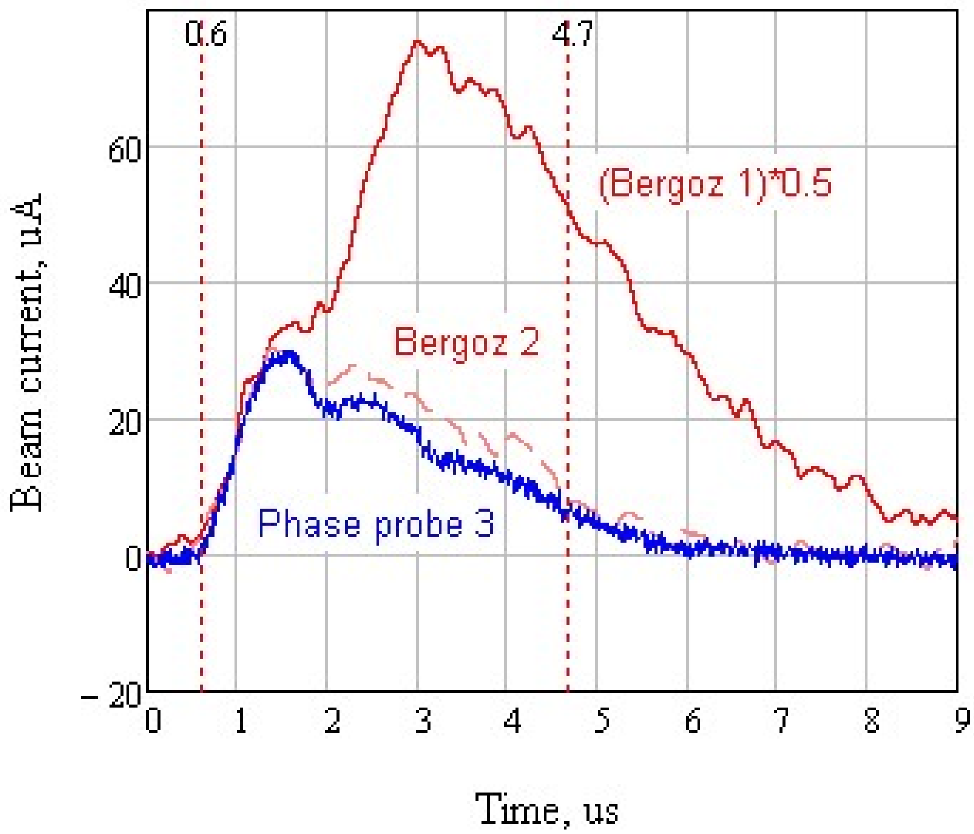
- The upgrade has 4 goals
  - Reduce the beam duration from ~(10 – 20) μs to 4 μs so that to support ion accumulation in the Booster longitudinal phase space
  - Reduce energy spread excited by extraction process (±1.4 kV -> ~0)
  - Make uniform density distribution along the beam pulse
  - Support 10 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
    - >1.5·10[8] Xe^{28+} ions at the ion source exit (eff. 22%, ions total: 6.7·10[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**

Booster Objectives

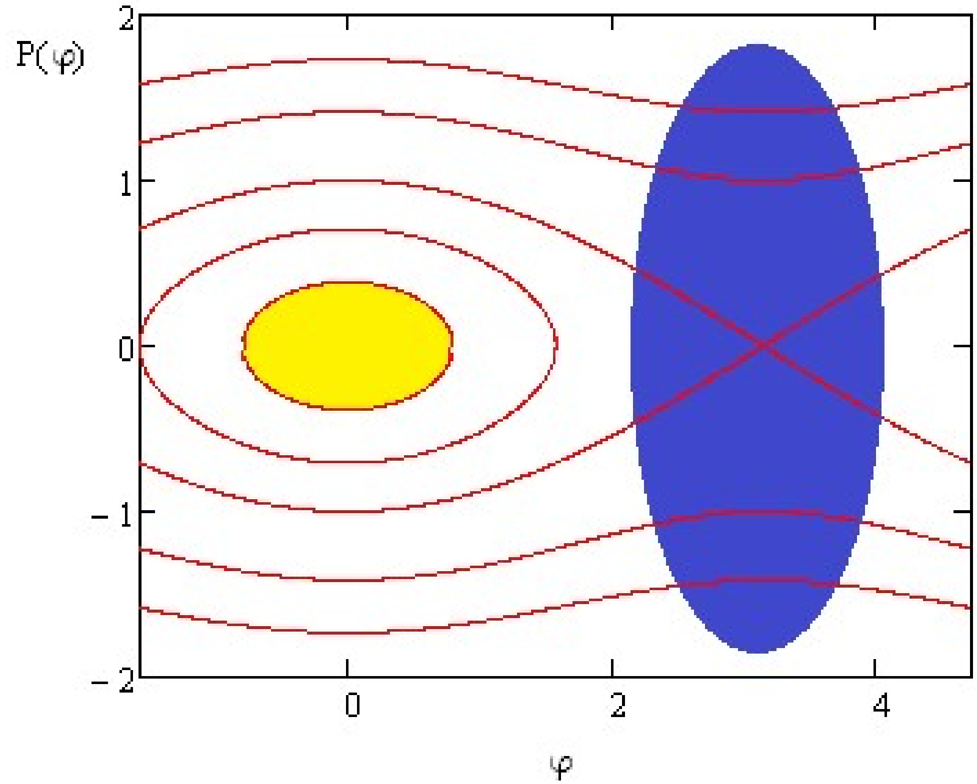
- Accumulate ~10 linac pulses to maximize the beam intensity
- Minimize the beam loss and emittance growth in the course of beam accumulation and acceleration. Acc. eff: 10% -> 70%

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

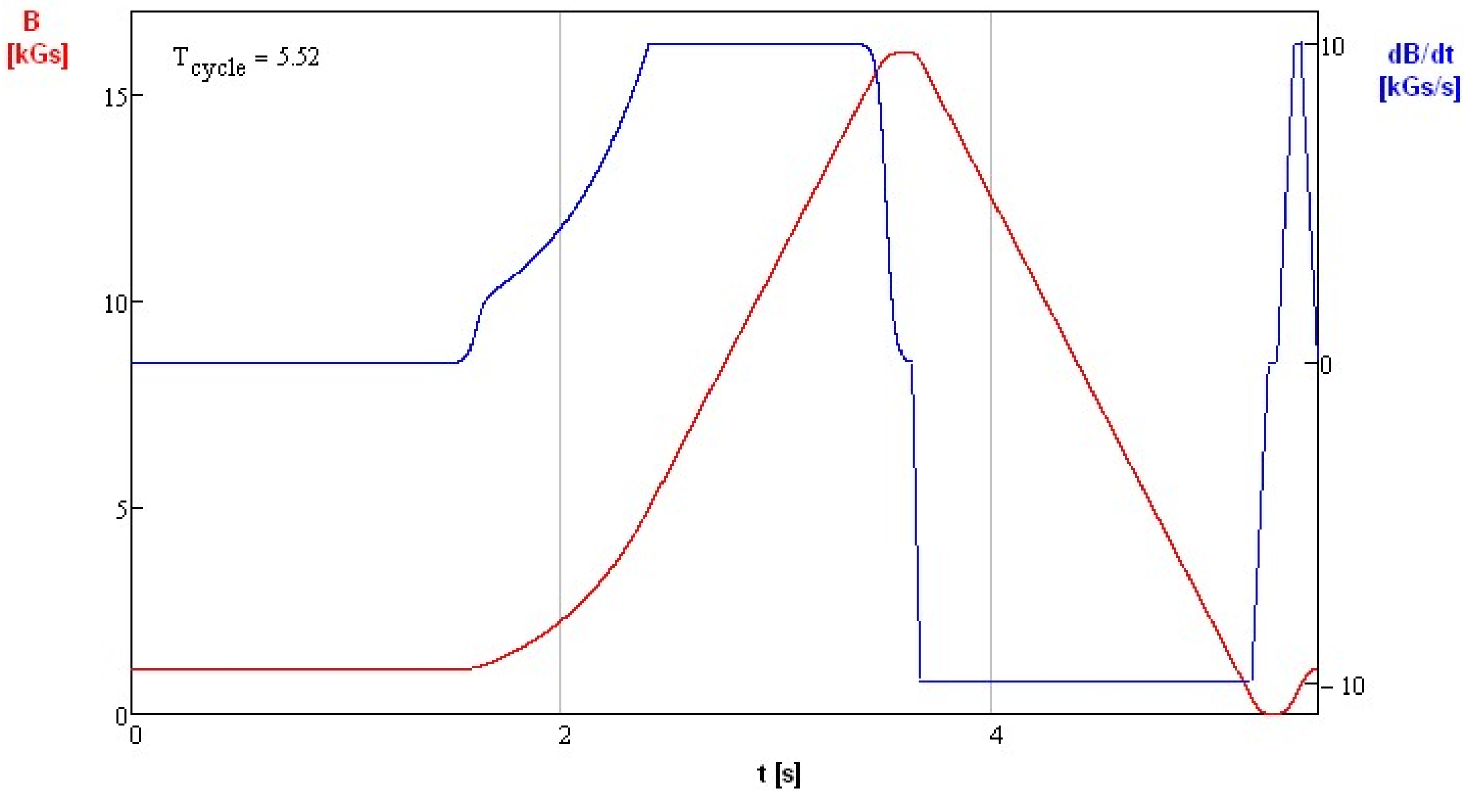
Beam Accumulation Scheme

- 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



Booster Magnetic Cycle

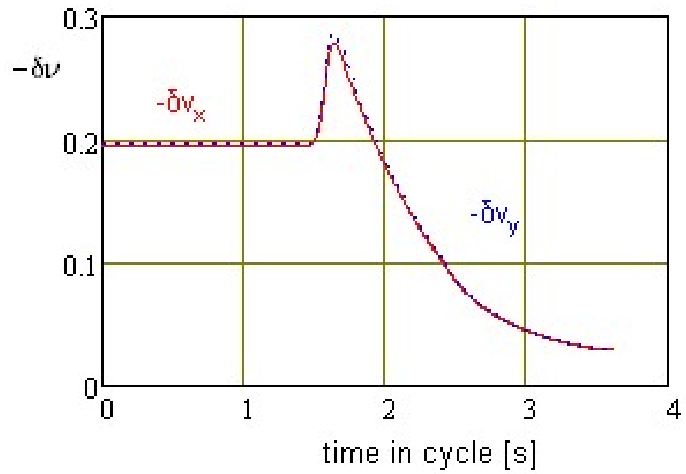
- The maximum rate of magnetic field growth is 10 kG/c
- At the cycle beginning the acceleration is slower to keep sufficiently large longitudinal acceptance determined by available RF voltage
- For 10 injections the total cycle duration is slightly longer than minimum duration of Nuclotron cycle
- Software,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

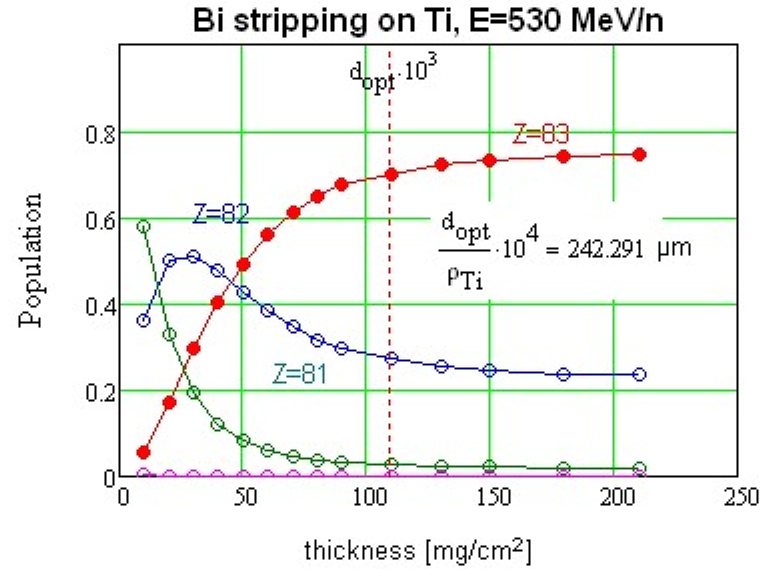
$$\delta\nu_{x,y} = \frac{Z^2}{A}\frac{r_p N_{ion}}{2\pi\beta^2\gamma^3}\frac{C}{\sqrt{2\pi}\sigma_s}\left\langle \frac{\beta_{x,y}}{\sigma_{x,y}\left(\sigma_x+\sigma_y\right)}\right\rangle_s$$

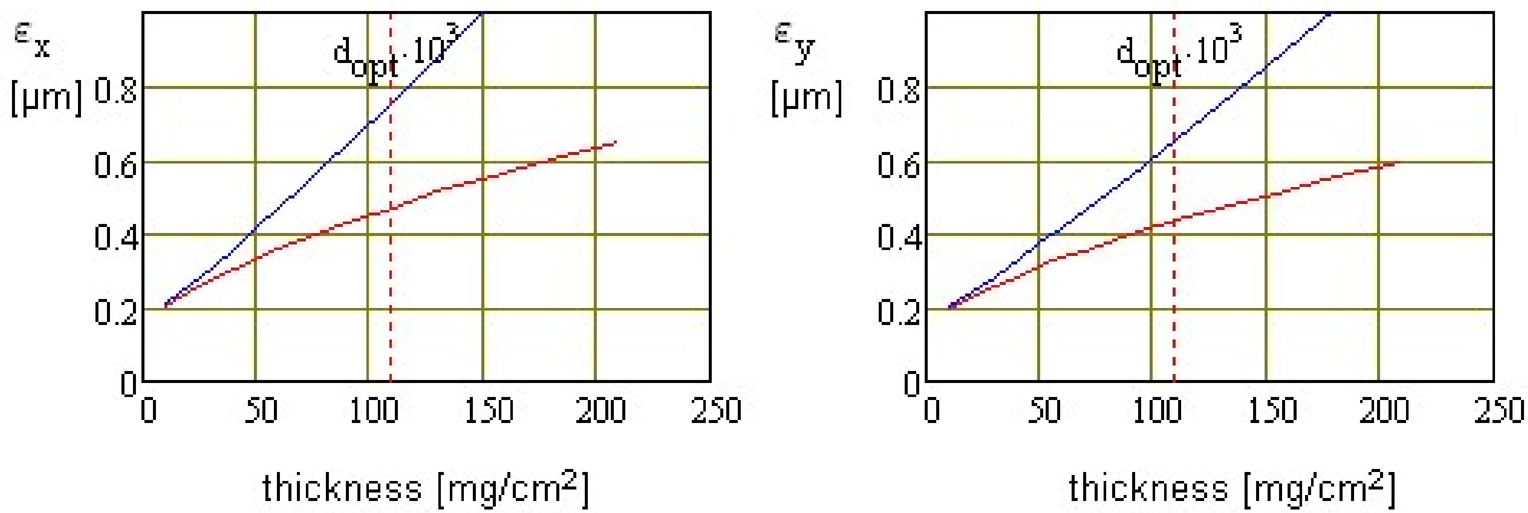


- The tune shifts are quite large and it is not obvious that we can achieve it without using additional "tricks"
- Possible means to achieve 10^9 ions
  - Usage of barrier bucket can reduce the bunch density in the center and, consequently, tune shift during beam accumulation
  - Reducing ⊥ & || cooling 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

Ion Stripping at Booster-Nuclotron Transfers

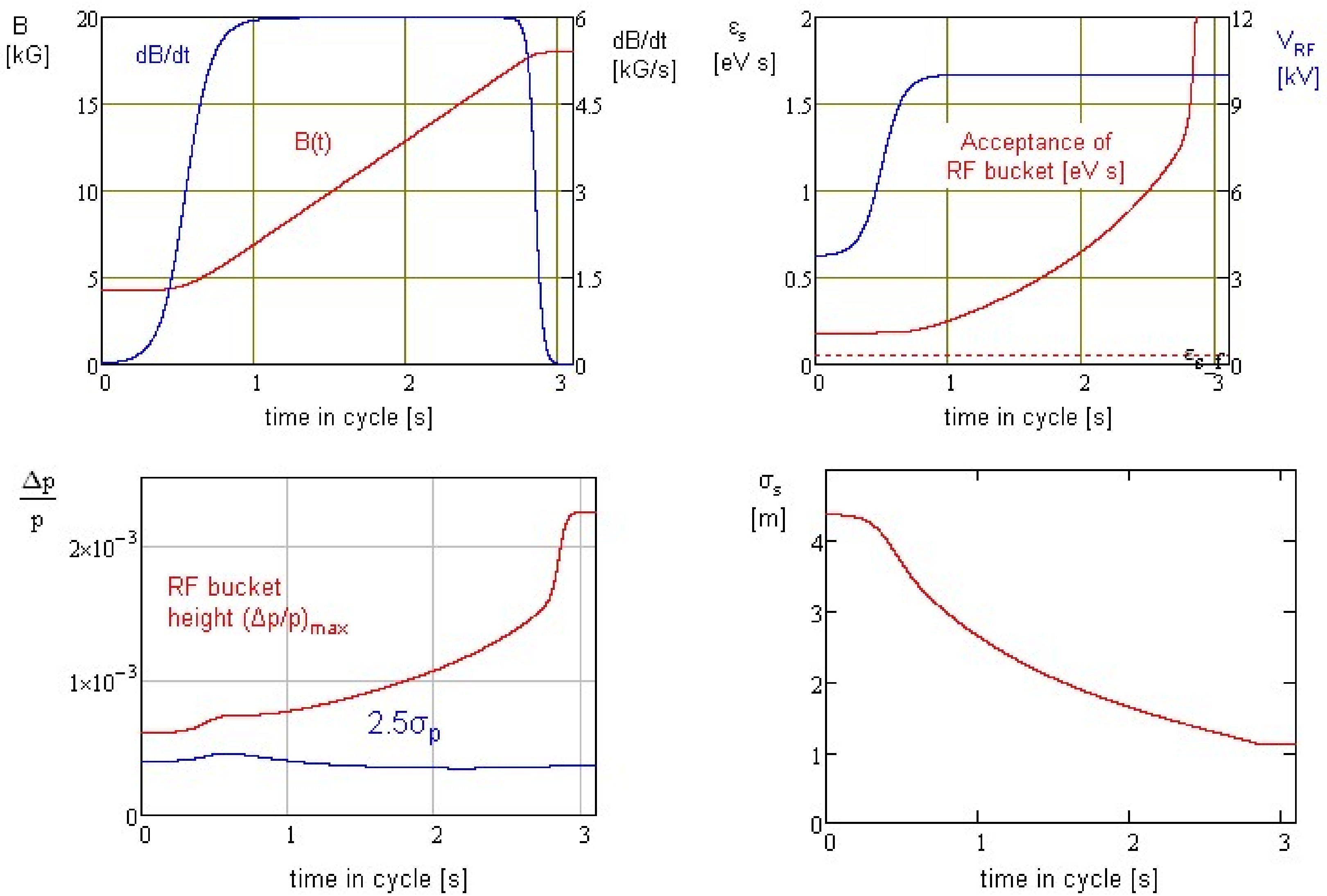
- Ion stripping to bare nucleon happens at the Booster extraction
- Relatively small Booster energy limits the Bi stripping efficiency to about 70%
- Optimal thickness of the titanium stripping foil is ~110 mg/cm^2. Its further increase brings unacceptable emittance growth.





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

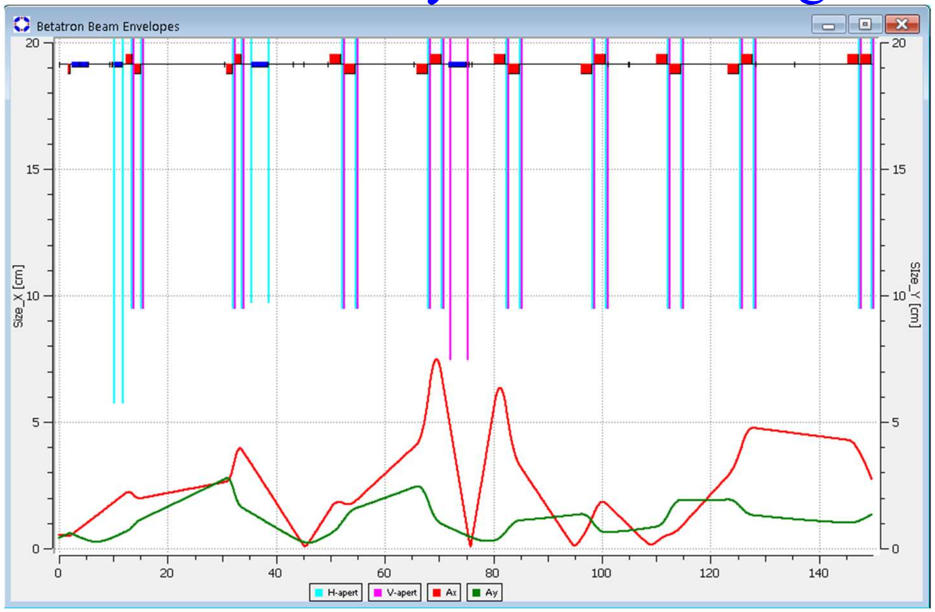
Acceleration in Nuclotron to Maximum Energy, 3.9 GeV/n

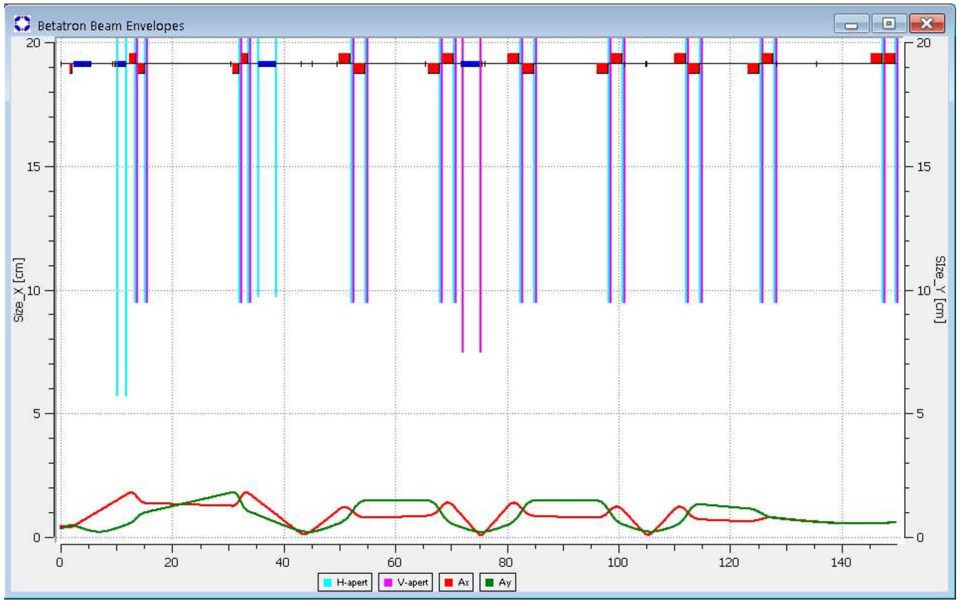


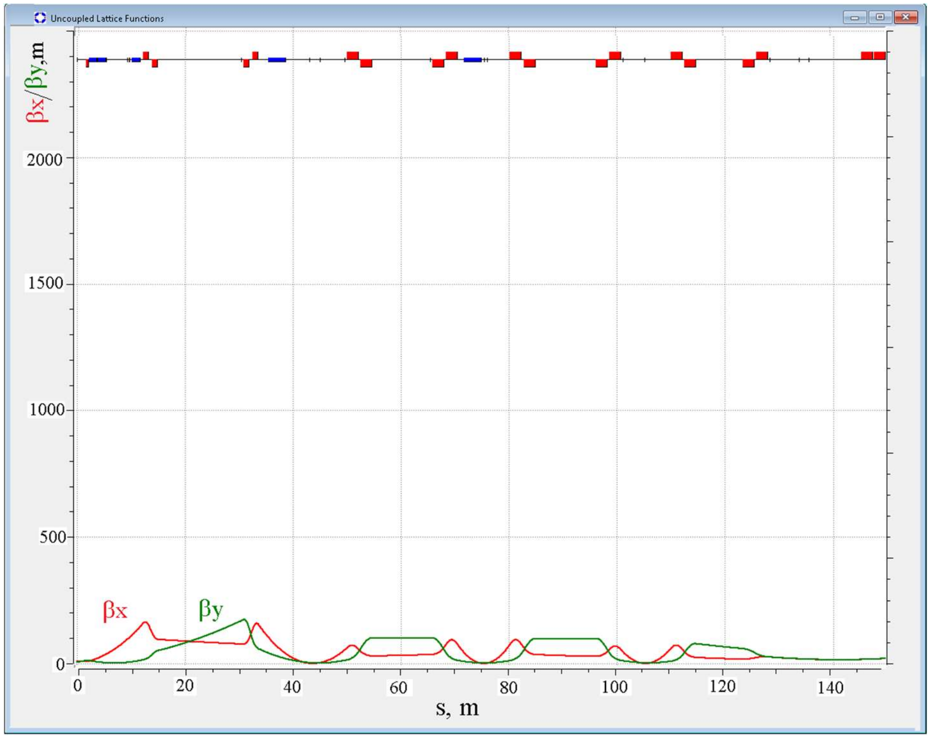
- Acceleration in Nuclotron will be slowed down at the ramp beginning to avoid a reduction of the RF bucket size during acceleration

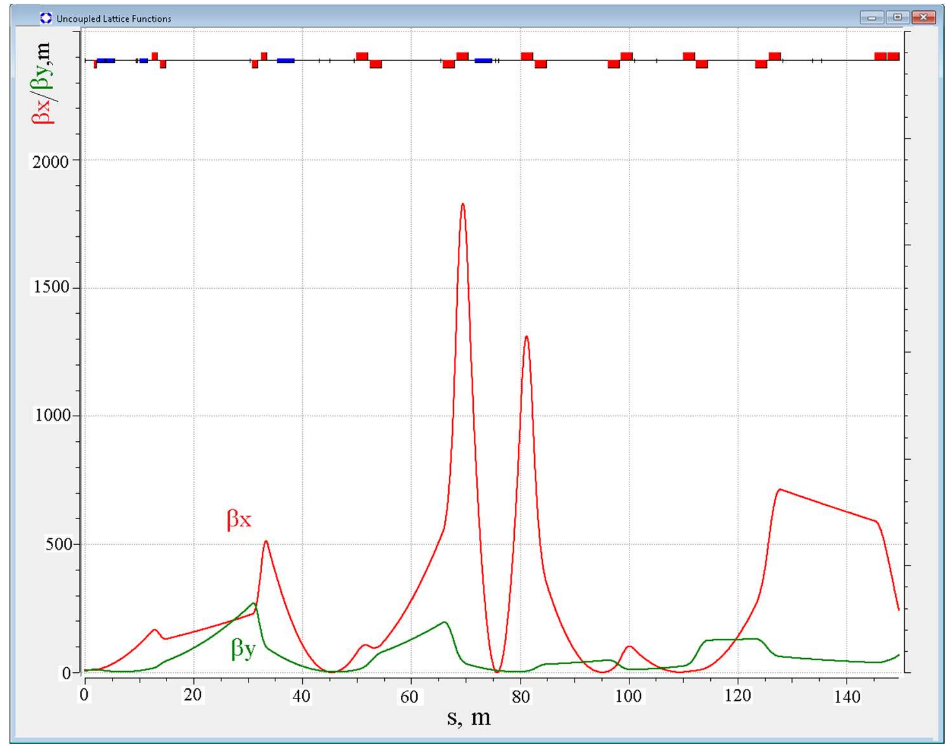
Slow Extraction and Beam transport to BM@N

- Slow extraction
  - 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 to BM@N
- Nuclotron cryogenic filters were cleaned. It may increase the extraction flat-top duration to more than 2 s which were used in the last run