Status of the NICA Collider

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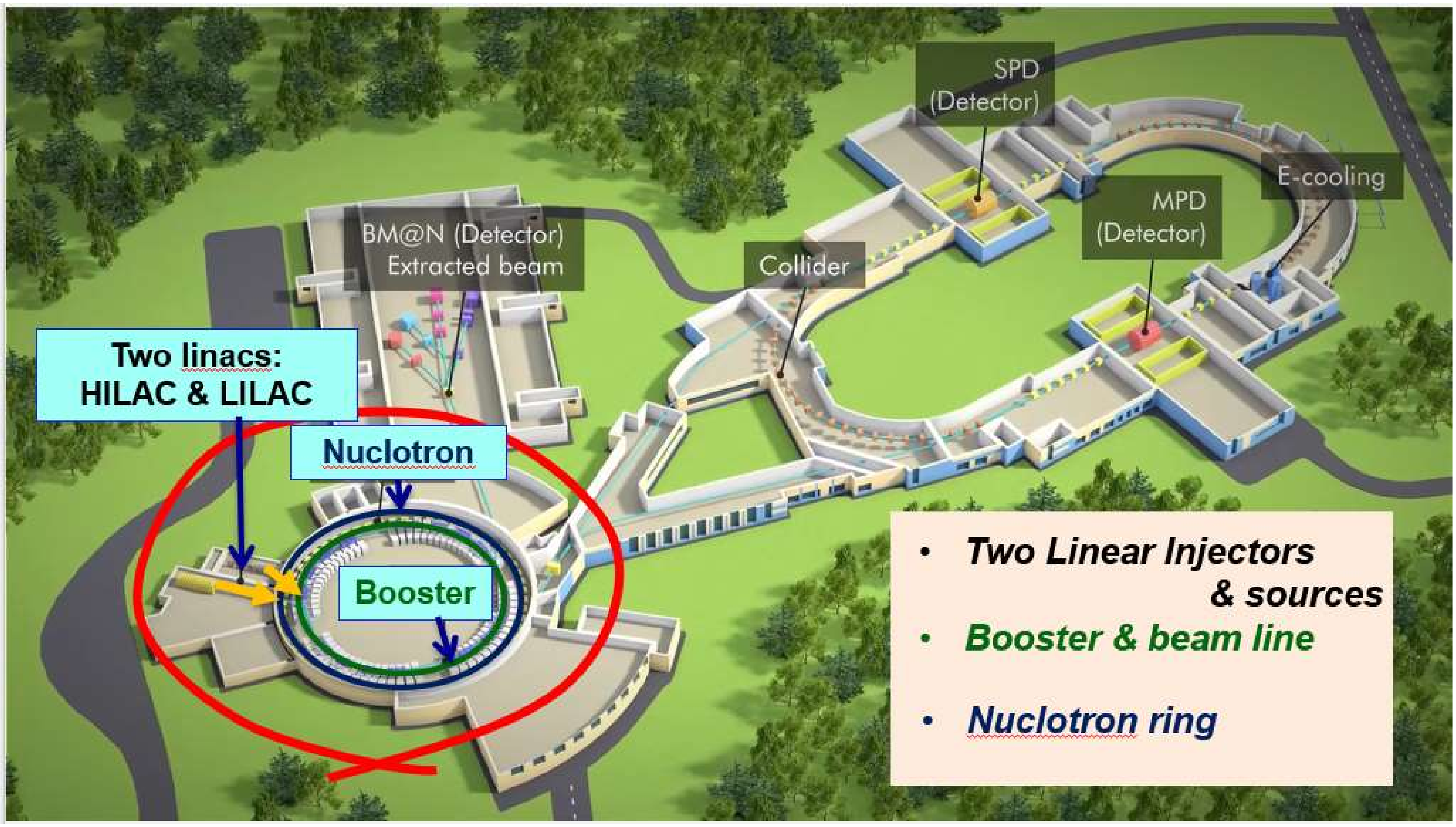
NICA Collider Complex Layout



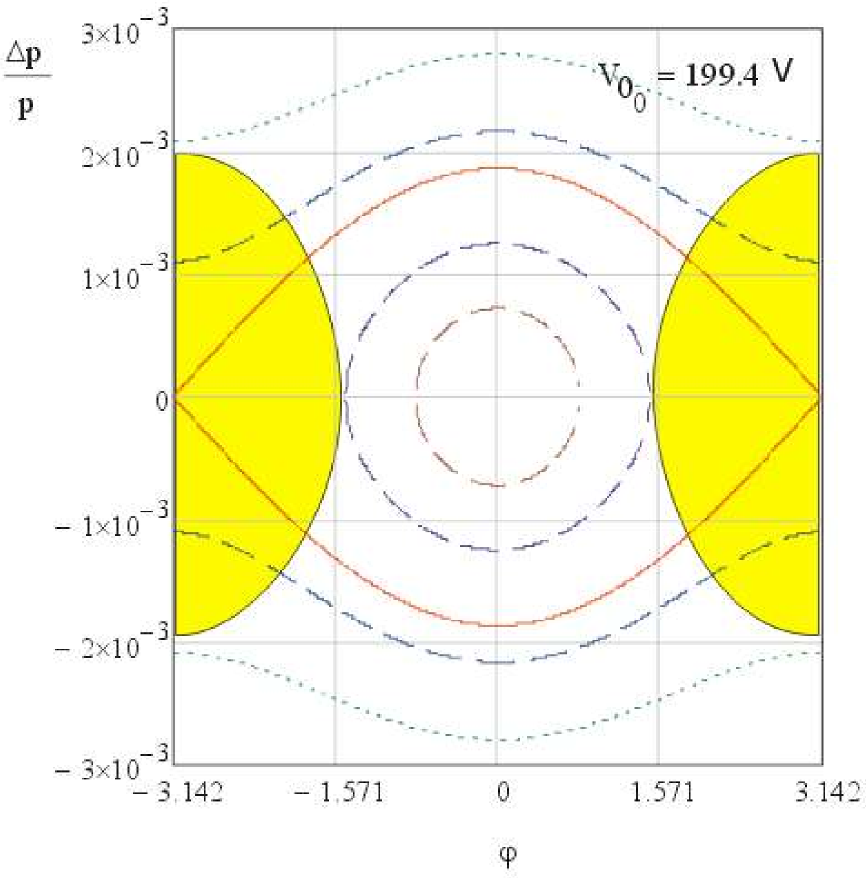
- Injection complex is already in commissioning for few years
  - Previous Run achievement (Feb.2023): $(5\text{-}8)\cdot 10^6$ fully stripped Xe ions at the top Nuclotron energy of 3.9 GeV/u was achieved
  - Collider operation needs: $(2\text{-}10)\cdot 10^8$
- New Run of the Injection complex started in Feb. 2025

Goals of the New Run

- Increase the number of Xe ions accelerated to the top Nuclotron energy to above $2 \cdot 10^8$
  - Reduction of the beam loss
  - Beam accumulation in the Booster (10 pulses, 5-10 Hz)
- Improve efficiency of beam operations
  - Reshaping of beam operations department
    - Hiring new staff members (operators)
    - Education of operators
    - Training of operators in the control room
  - Introduction of electronic log book (https://elog.jinr.ru/)
  - Addition of new software and hardware
    - FCT based beam current monitor
      - Addresses the poor sensitivity of parametric current transformer (DC measurements)
    - Feedback for suppression of synchrotron oscillations
    - Addinal algorithm for LIBERA for turn-by-turn measurements
    - …

Beam Accumulation in Booster

- Generation of 10 pulses in the ion source (KRION) at 10 Hz was demonstrated in 2023
  - Upgraded ion source has bunch duration < 6 μs instead of 20 μs of previous run. That is good enough
    - ~4 μs is required for lossless injection
  - However, presently we still have problem to generate 10 pulses
    - It will take time to find a remedy
    - It is not a problem for collider commissioning but will be a problem for achievement maximum collider luminosity

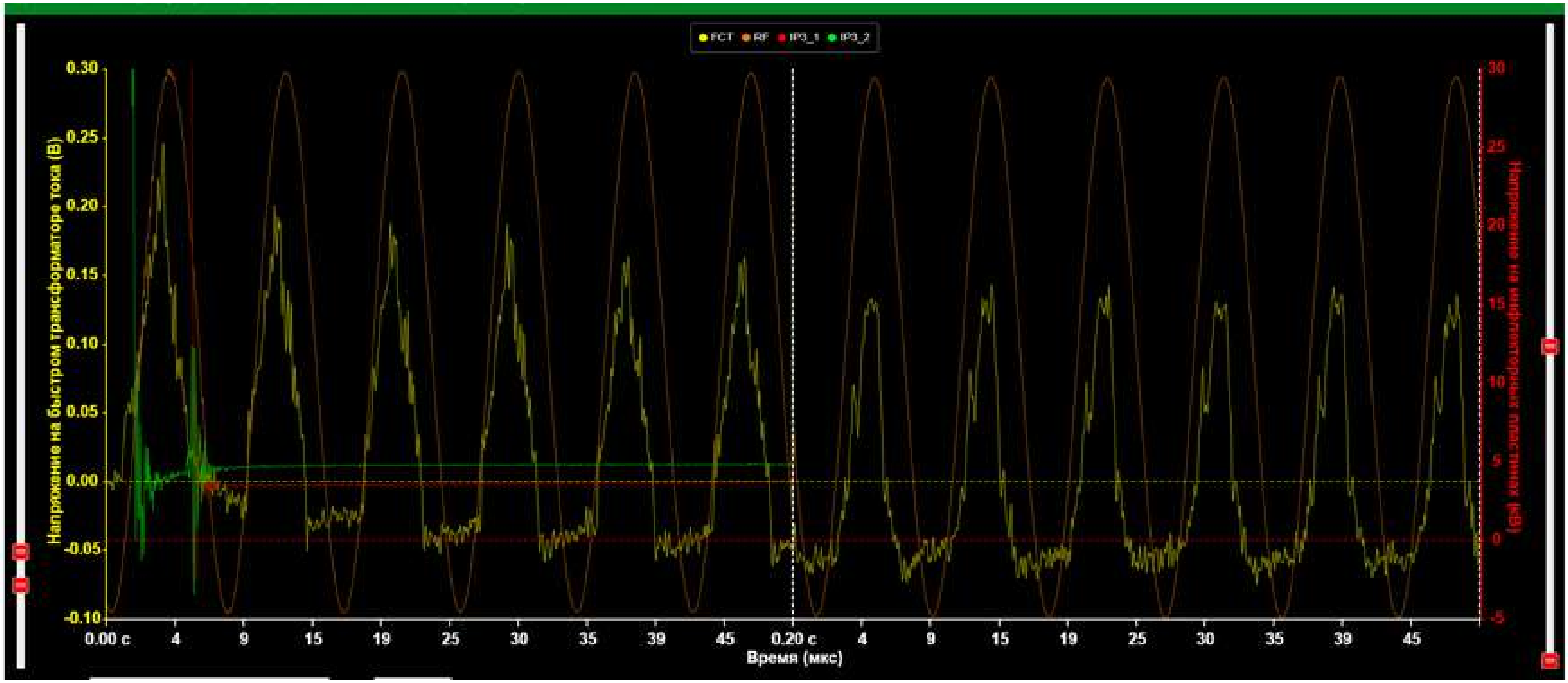


- Booster RF voltage of 200 V was chosen so that maximum momentum deviation would not exceed $3\cdot10^{-3}$

Booster Run Achievements: Aiming into Booster

- We established the golden beam orbit
  - Orbit is centered on the apertures with its measurement performed with three-corrector bumps
  - Effective software for orbit correction
  - All hardware problems with correctors and BPMs were addressed
  - We permanently keep the beam on the golden orbit: orbit correction software and hardware work well
- Aiming the injected beam into the golden orbit: *i.e.* the beam injection without betatron oscillations
  - Prototype script has been used for correction of beam injection
    - Based on the turn-by-turn BP measurements in Booster
    - Manual adjustments (0.5-1 hour)
  - After correction of aiming the beam loss at injection <10-20%
  - Writing software for the automatic aiming is happening
    - The correction will take only few Booster cycles
  - Addinal algorithm to be added to LIBERA FPGA for fast computation of turn-by-turn BPM (required to operate at small intensity)

Booster Run Achievements: Beam Loss at Injection



Dependence of beam current on time after beam injection

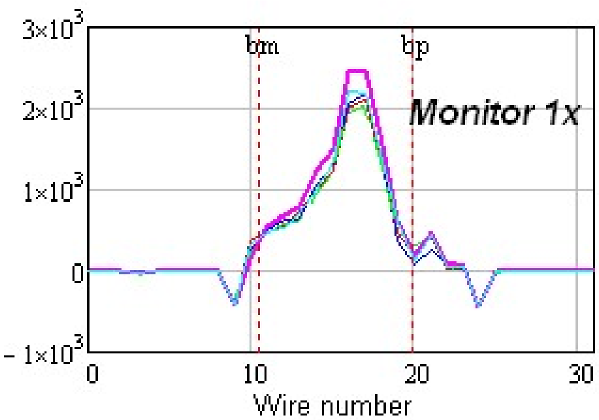
- At the first turn we also see ions with other (not targeted) ions

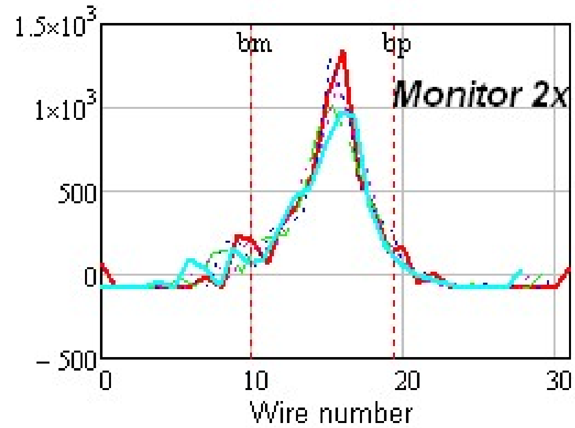
Booster Run Achievements: Betatron Match

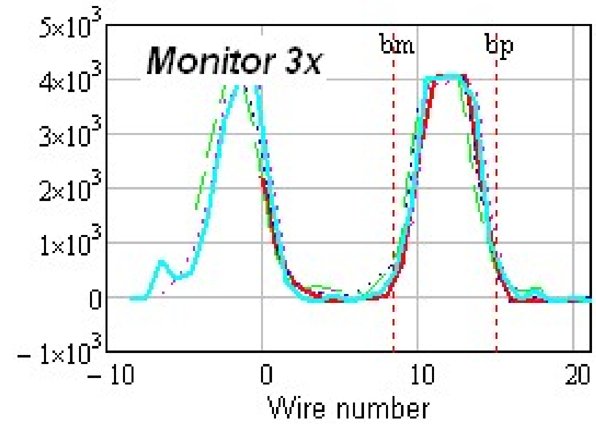
- We have considerable mismatch in the betatron functions
  - It results in ~3-fold increase in the beam emittance and, consecutive, strong reduction of electron cooling rate
- Addressing the problem is complicated by presence of few charge species coming out of Booster
- Standard procedure
  - measurements of optics functions at the linac exit,
  - and measurements of transfer line beam optics using differential beam optics based on BPMs

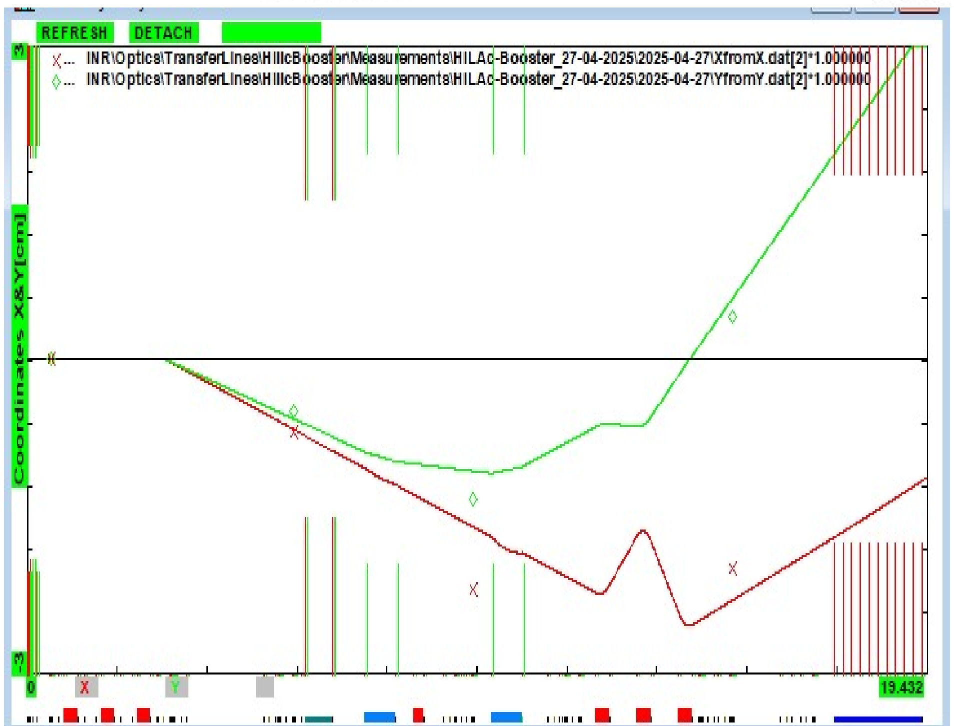
  fails due to presence of multiple charge species in the beam
- New procedure based on the measurements with beam profile monitors is being implemented right now
  - Fortunately, we have enough beam profile beam monitors (5) to do such measurements

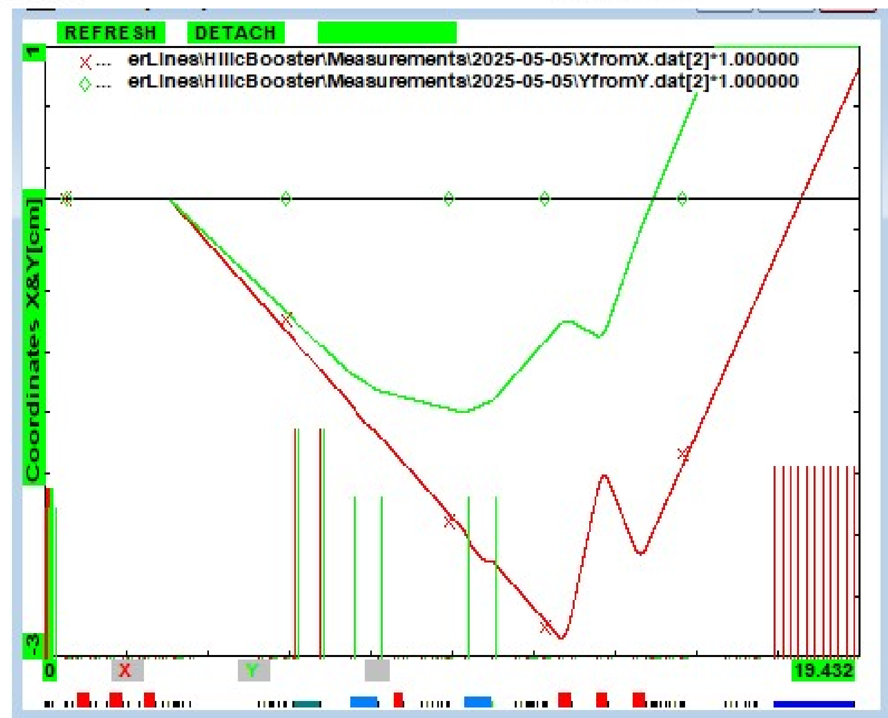
Booster Run Achievements: Betatron Match (2)









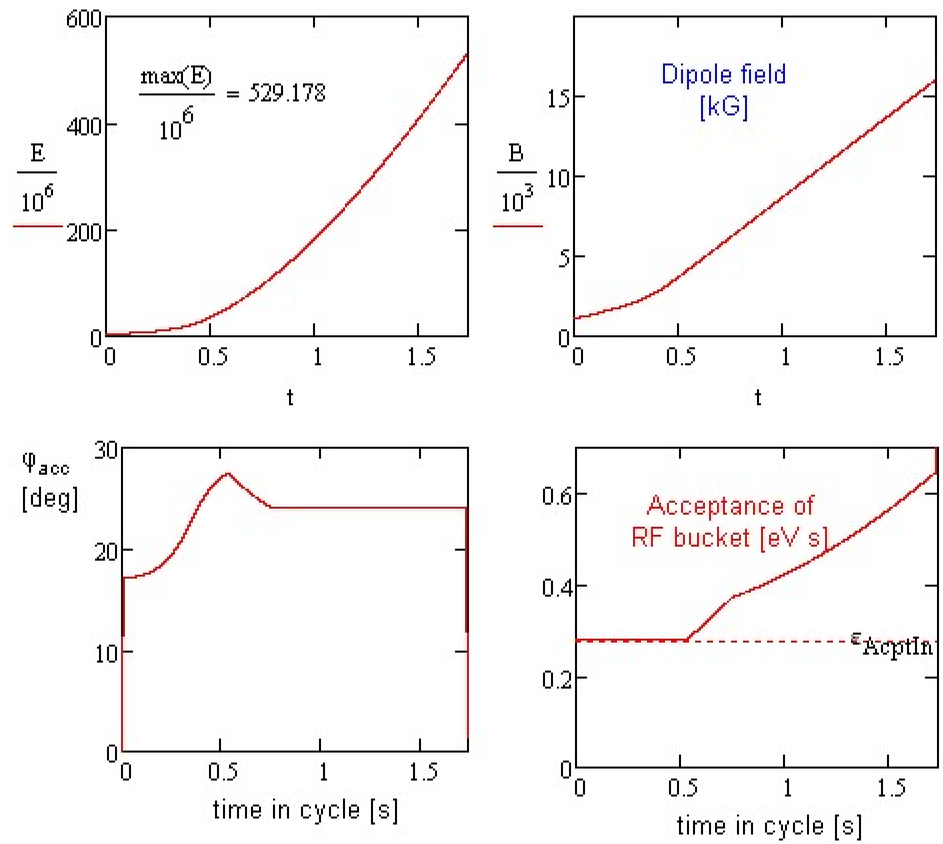


Results of differential orbit measurements with beam profile monitors

- New corrected optics is expected to be ready within 1-2 weeks

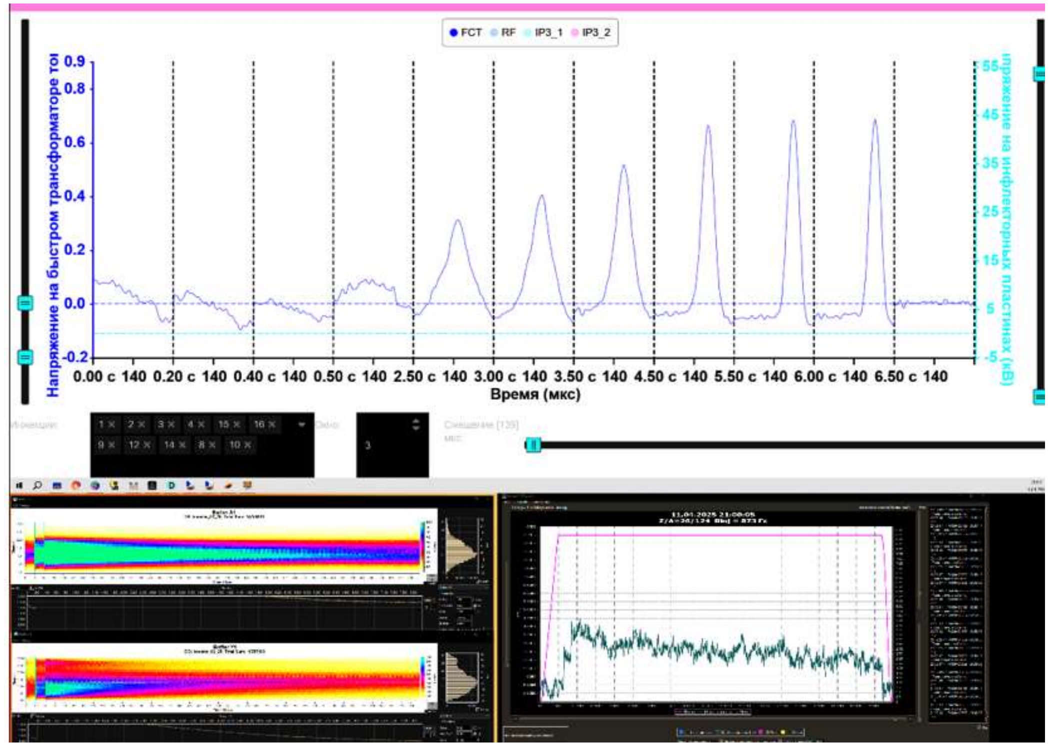
Booster Run Achievements: Magnetic Field Sycle

- In the previous Run we had beam loss at the start on beam acceleration in both Booster and Nuclotron
  - The reason was too fast acceleration at the cycle beginning resulting in drastic decrease of the longitudinal acceptance (aria inside separatrix)
- New algorithm accounts available RF voltage
  - B field growth is set so that the RF bucket area would not decrease in the course of acceleration



- Beam accumulation is happening in the longitudinal space at the 1st RF harmonic. We eliminated adiabatic bunching/rebunching. Consequently, both the beam accumulation and acceleration are done with 1st harmonic
- Lossless beam acceleration was demonstrated

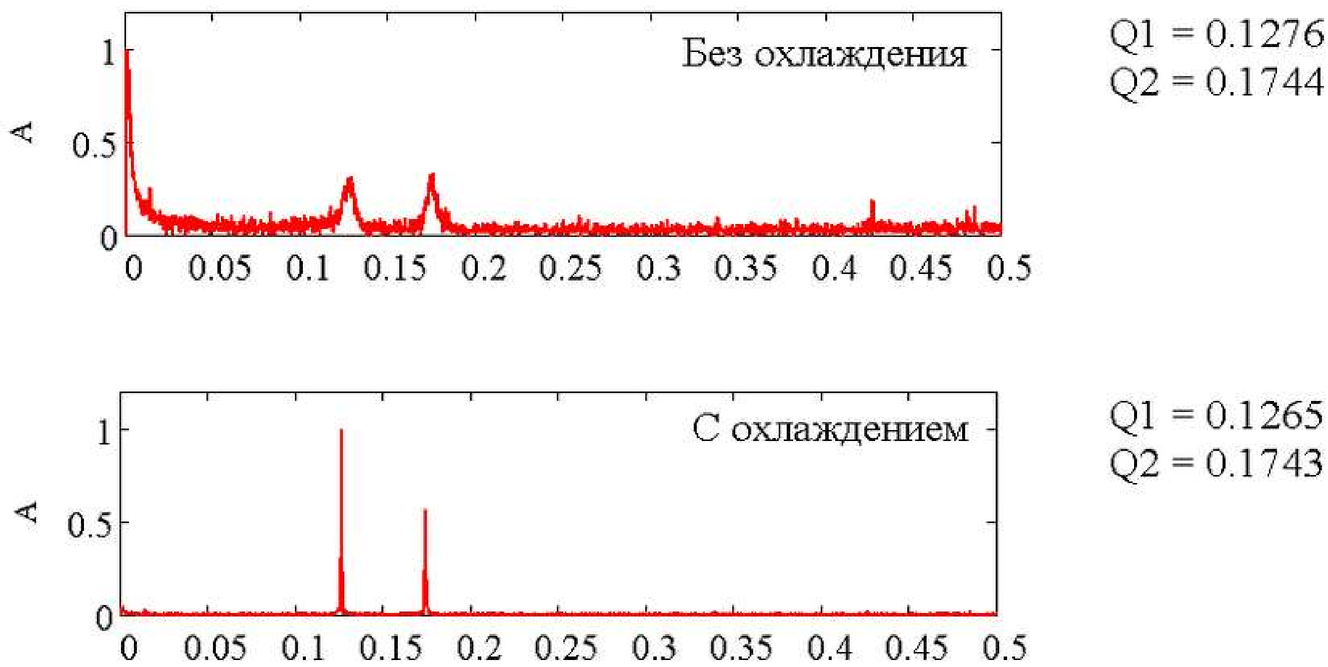
Booster Run Achievements: Electron Cooling



- Expected cooling times are: $\tau_{\|} \le 0.1$ s, $\tau_{\perp} \le 1.5$ s
  - However, we measure $\tau_{\|} \approx 1$ s
- The major problem making this loss is the large betatron mismatch. That yields large emittance increase in Booster (6 times). Consequently, the beam size is larger than the electron beam size (~2 times)
  - It is being addressed now
- Measured beam lifetime at injection with electron cooling>10 s
  - It is sufficient for beam accumulation
  - The vacuum beam lifetime is ~20 s
  - The major reason for beam loss is an electron capture from the residual gas and electron beam

Booster Beam Optics

- Software and hardware for measurements are mostly done
  - Further improvements in software will follow
- High quality optics data are taken
  - Analysis and building the real machine optics will follow
- Measured machine acceptance is close to its geometric acceptance
- Chromaticities are close to the design
- Electron cooling helps to obtain high quality data



- There are no problems in Booster optics which could limit its performance

Nuclotron

- Placing the fast extraction hardware to Nuclotron (required for Collider) was finished at the very end of April
  - There are vacuum leaks
    – finding and fixing them will take time
- We expect the beam delivery to BM@N to start at the beginning of June
  - Night shifts we will work for BM@N
  - Day shifts will be used for machine studies and the construction work needed for collider
    (similar to the operations mode used during recent months)
- There is long list of works needed to be finished before we will be fully ready for Collider operation
  - Overall, it looks realistic to get the injection complex ready for the collider before the end of collider construction

Collider Assembly

- The west collider arc is assembled
  - There are vacuum leaks which need to be found and fixed before we can cool the arc and start its test powering
- The east arc will follow with couple months delay
- Some hardware parts of Nuclotron-to-Collider transfer lines are still in production
- The beam injection into Collider is expected to happen in the 2nd half of 2025
  - Still there are very large number of systems which need to be mounted/assembled and finalized before we will inject the beam into collider

Plans for Collider Operation

- To start collider operation, we need beam cooling systems
- The first longitudinal stochastic cooling system out of 4 is expected to start its operation by the spring of 2026
  - To get the complete set of stochastic cooling systems will take another year
  - Thus, we can expect the stochastic cooling fully operational in the first quarter of 2027
  - An installation of the system will not require long interruption of beam operations
- Assembly of electron cooling will start in the second half of this year
  - It will take at least 1 year
  - Assembly of electron cooling will require a complete stop of collider beam operation for few months
- It is difficult to predict which cooling system will be ready first for beam operation
  - Readiness of any of them would enable getting luminosity

Conclusions

- We expect the first collisions with detectable luminosity in the 1st half of 2026
- It will take at least another year to get a "reasonable" luminosity
- During next few months we will concentrate our efforts on the injection complex commissioning
  - Beam delivery to the BM@N and other users is going to be extremely helpful to achieve reliable and predictable operation of the injection complex
  - Test operation with polarized deuterons is also in plans