Accelerating Complex NICA

Valeri Lebedev

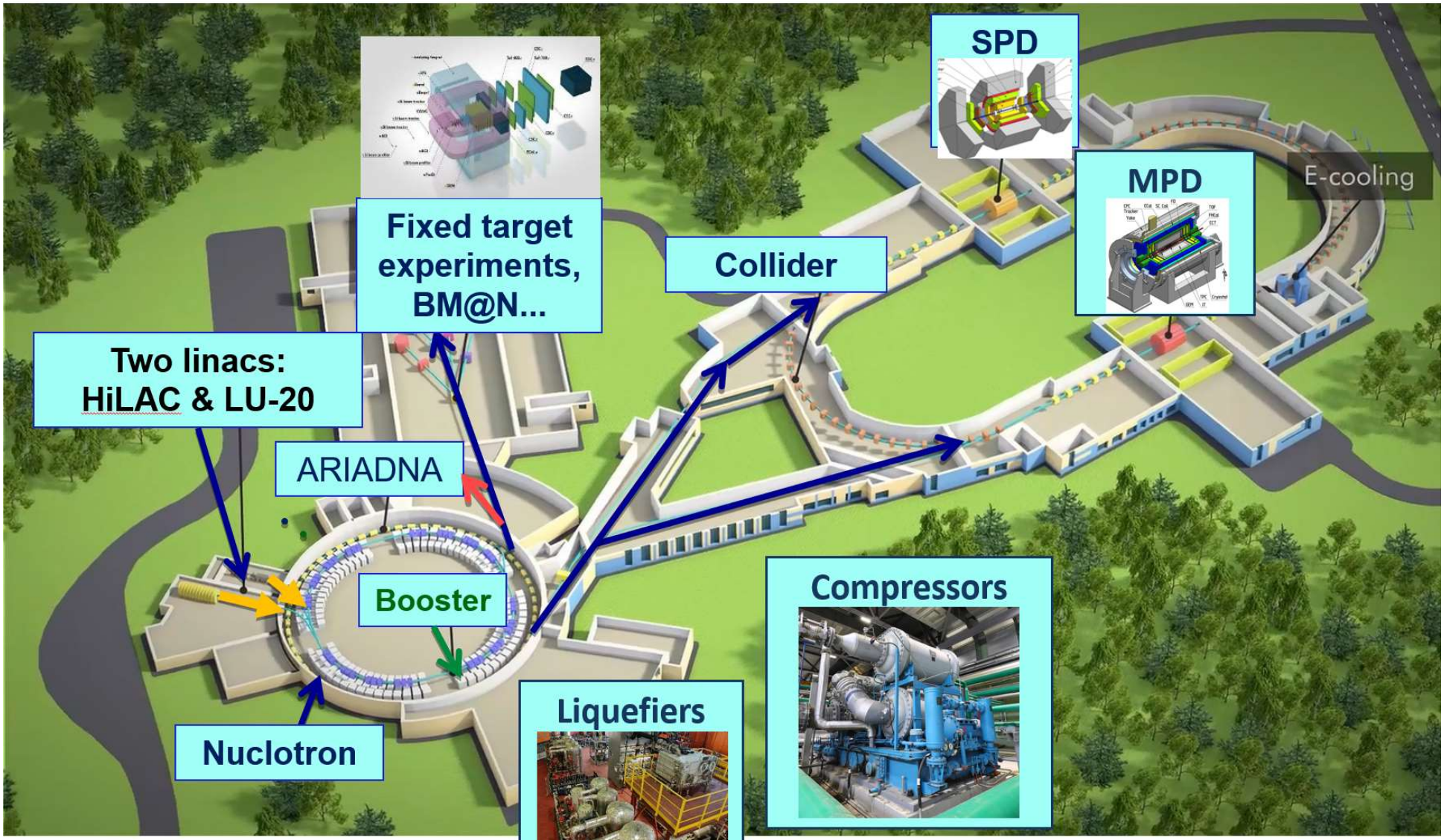
LHEP/JINR

Outline

- Injection complex -achievements and problems
- Results of collider pre-commissioning work
- Preparations for collider operation and near plans

Spring School on quark-gluon Plasma,
Dubna,
Apr 10-14, 2026

Accelerating Complex NICA



Goals of Near Future Operations

- The accelerating complex will support both the collider operation and the fixed target experiments
  - Collider store duration - 5-15 hours with filling time of ~1 hour
  - Other time - operation on the external/internal targets
    - BM&N
    - Applications: Ariadna

      …
- Accelerator part of Collider commissioning is expected to take ~10-30% of beam time
- What was tested at the pre-commissioning Run
  - We obtained stable beam circulation in both collider rings with lifetime of ~1 hour at 1.73 GeV/n kinetic energy and Xenon beams
    - Major factors limiting the beam energy:
      - pulser generators for injection kickers,
      - quenches of magnets at large magnetic field
  - Tested system: vacuum, cryo-magnetic, major power supplies and some correctors, BPMs, Nuclotron-Collider transfer lines, …

Present Status

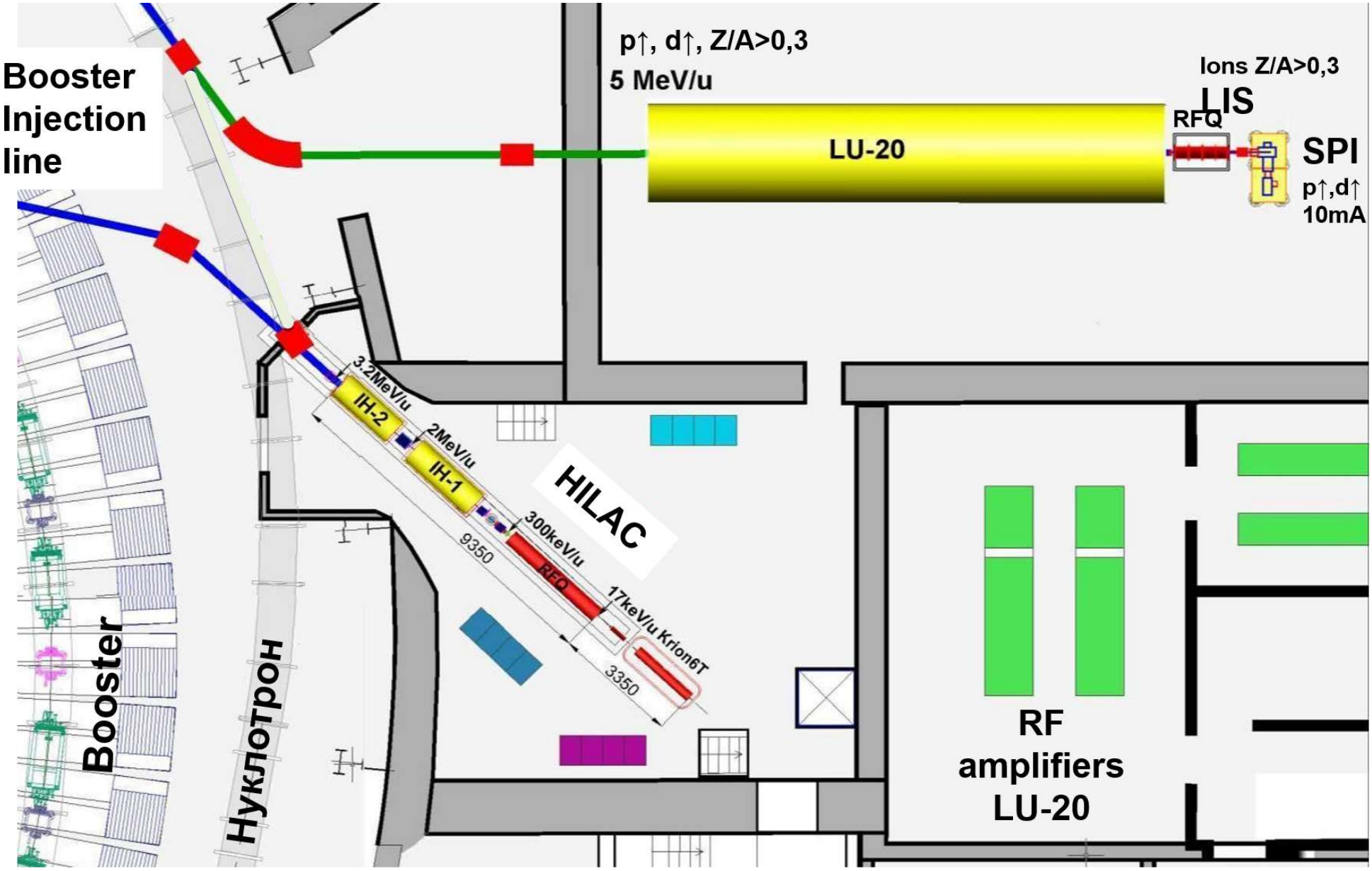
- Since a week ago we are in half year shutdown
- Major problems to be addressed
  - Ending of civil construction work in Collider building (bldg. 17)
  - Fixing vacuum leaks in Nuclotron
  - Fixing few problems of collider SC magnets
  - Connecting all other collider power supplies
    - Dipole quadrupole and sextupole correctors
  - Installation/commissioning of RF systems: RF1, RF2 & RF3
    - Full completion – summer 2027
  - Installation of stochastic cooling
  - Installation of cooling sections of electron cooling
    - Start of electron cooling operation is expected in 2nd half of 2027
  - Development of software: BPMs, save/restore, …
- Expect
  - Start Injection complex operation – September/October 2026
  - Start of Collider operation – November/December
    - Includes MPD detector rolled in

Injection Complex

Goals & Actions Formulated in 2023

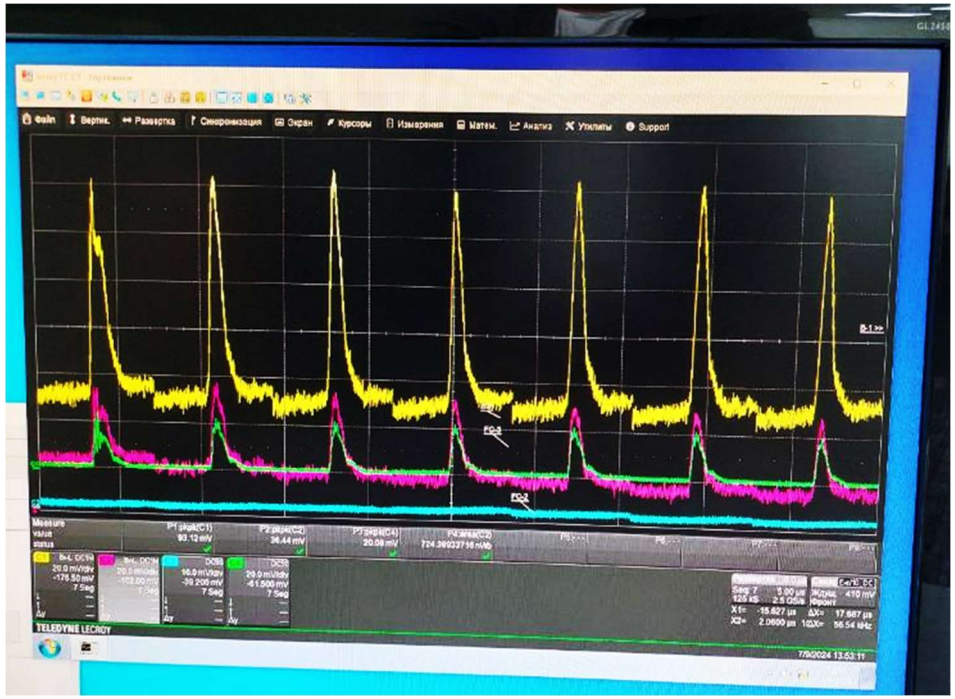
- To support the collider operation, we should increase the heavy ion flux by well above an order of magnitude compared to the 2022-23 Run. – **We are well on the way but still not there**
  - Xenon ions: $(0.55\text{-}1)\cdot10^7$ (3 years ago) → $9\cdot10^7$ (demonstrated)
    → $20\cdot10^7$ (near term plan)
    This will determine the collider filling time of about hour (depends on E)
- Means
  - Beam accumulation in Booster: 10 pulses at ~3 Hz
    ≈$0.9\cdot10^8$ ions (10 pulses at ~4 Hz) were demonstrated in 2025
  - Drastic increase of accelerator efficiency: (5 - 10)% → (80 - 90)%
    - Lossless acceleration in Buster was demonstrated
    - Loss due to stripping is expected to make the major contribution
- Action items
  - Modernization of ion source **– OK, 4 μs bunches at 10 Hz obtained**
  - Modernization of HILAC power supplies for higher rep. rate **- OK**
  - Orbit correction - done - in Booster, in process – in Nuclotron
    – Orbit in Nuclotron still incomplete: BPMs, corrector strength
  - Reoptimized magnetic cycle: $B(t)$ is designed to avoid beam loss due to reduction of RF bucket size in acceleration **– OK**

Linacs and Ion Sources



KRION-6T Ion Source

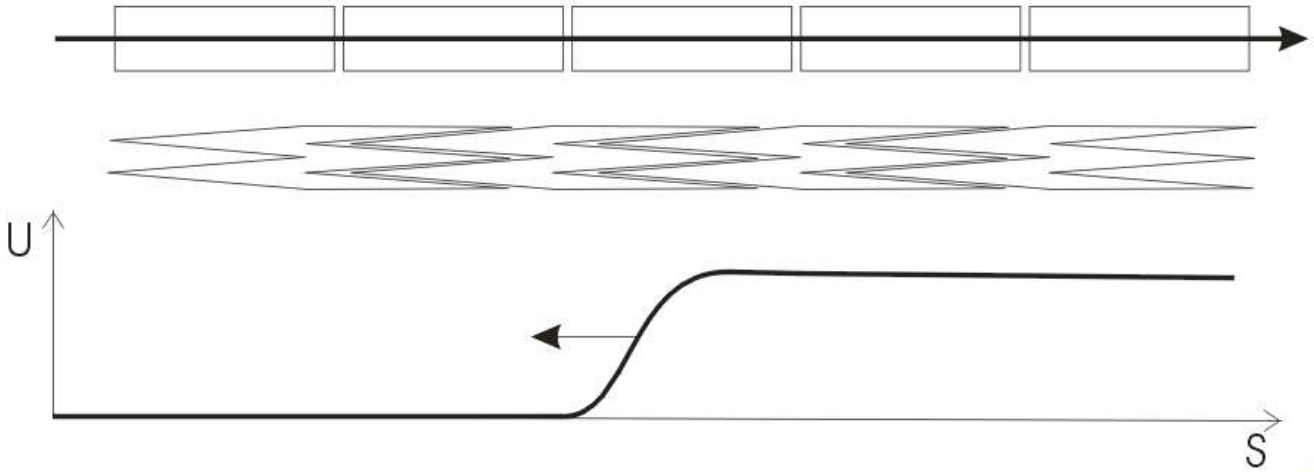




- In 2022 the KRION-6T was installed in HILAC and since then supports Beam operations
  - Normally we use Xe. We also used He, N, Ar.
- The ion source was modernized in 2023 to support the beam accumulation in Booster
  - 10 pulses up to 10 Hz in 6 s accelerating cycle (2 nC/pulse in all Q_n)
  - Bunch duration was reduced from 12-20μs to ~4-6μs (on the base)

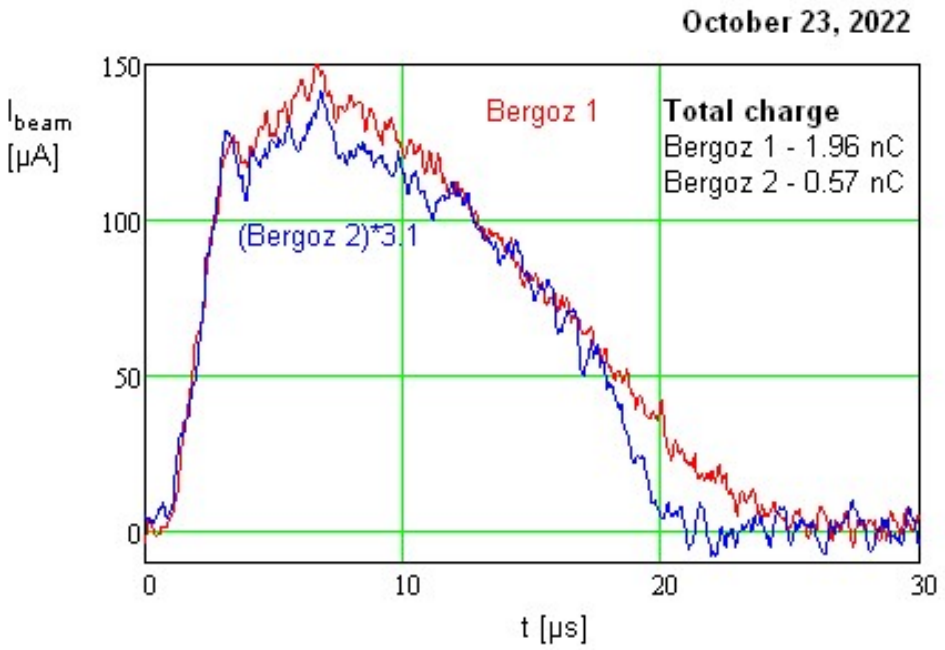
KRION-6T Bunch Duration

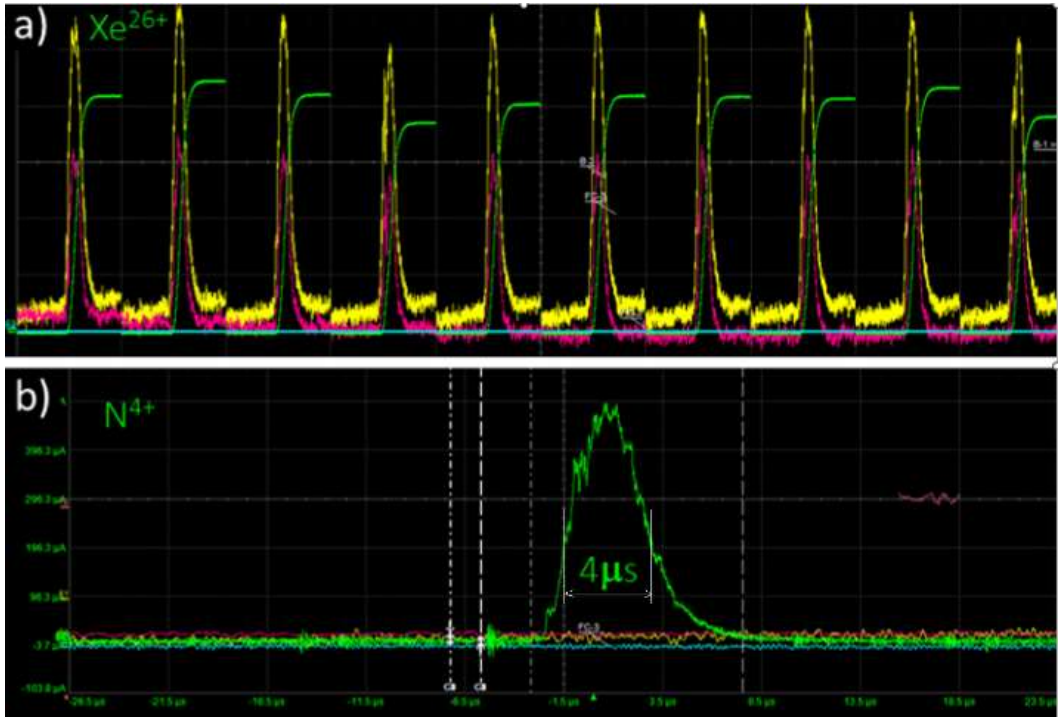
- Before upgrade the bunch duration was determined by time of plasma outflow out from each of ion holding cylinders where extraction field does not penetrate
  - 15 cylinders: 50 mm long, Ø4 mm
- New ion holding structure was manufactured
  - Same length and diameter but with mutually penetrating teeth making uniform extraction field
- Now we have about the same number of ions injected to Booster in a single pulse
  - We have the same charge of 2 nC stored in the ion column and same emittance
- Hardware for extraction by travelling wave is prepared but not used yet in experiments



Ion Pulse Before and after Upgrade

- Ion source demonstrated good reliability but there are still questions which require convincing answers
  - Beam emittance (rms norm, 70-150 nm) looks much larger than its theoretical estimate
  - An origin of long tail is unclear. Electrons suspected
  - How electrons of ionized atoms come out of the ion column
  - Presently, only ~5% of ions are accepted to Booster. It is ~¼ of expected 20% – *i.e.* ions with targeted charge of $^{26+}Xe^{124}$

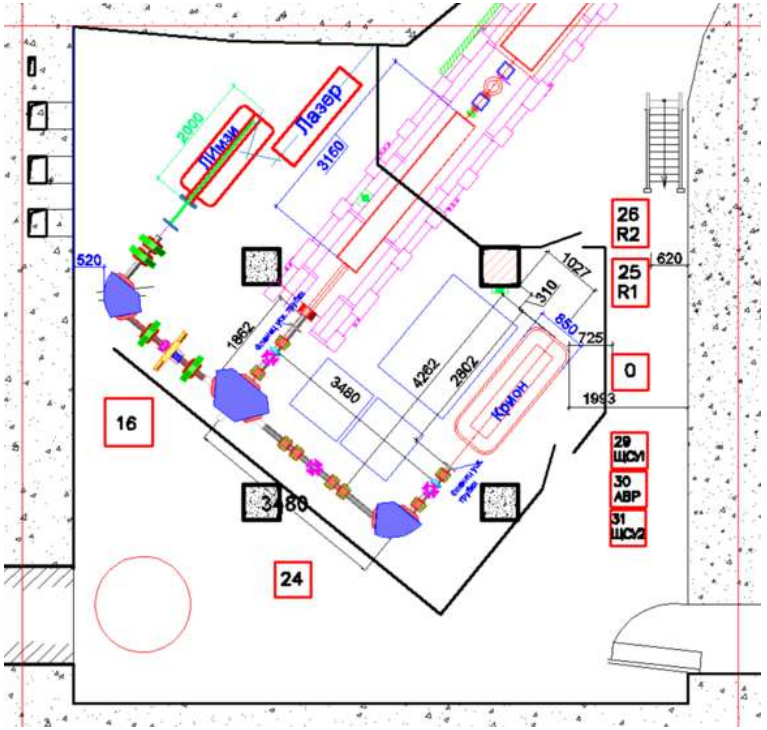




HILAC

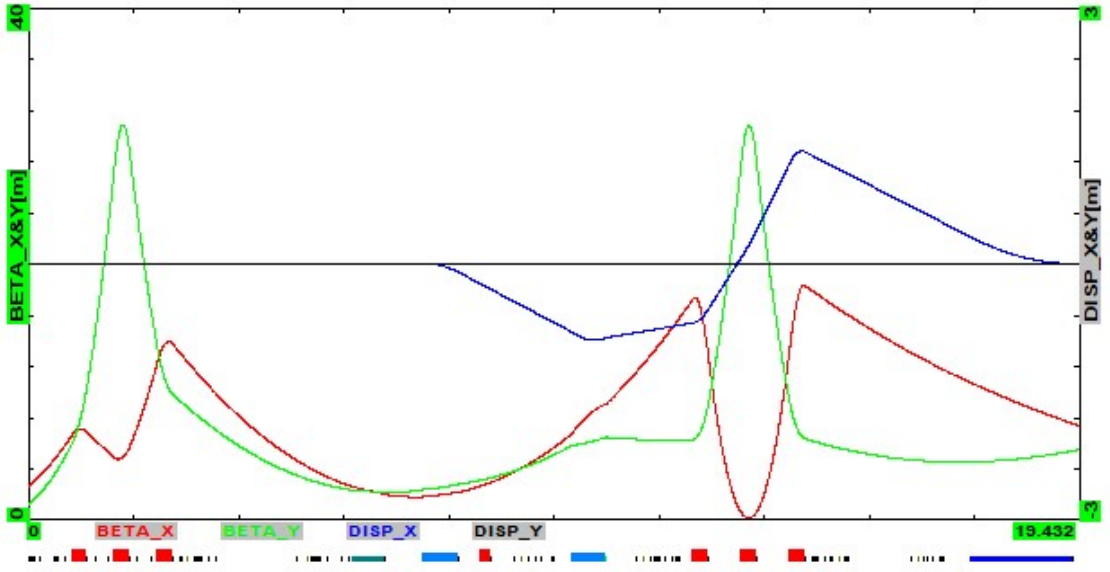


- After upgrade of power supplies HILAC demonstrated relatively stable operation.
- Linac accelerates few charge species of xenon beam simultaneously
  - An absence of magnetic bends in LEBT complicates KRION tuning
- Upgrade of LEBT will introduce bends enabling to see separately different charge species. It will also allow us to install the 2nd ion source
  - Laser source will support program with medium mass ions (Fe, …) thus widening program for fixed target experiments



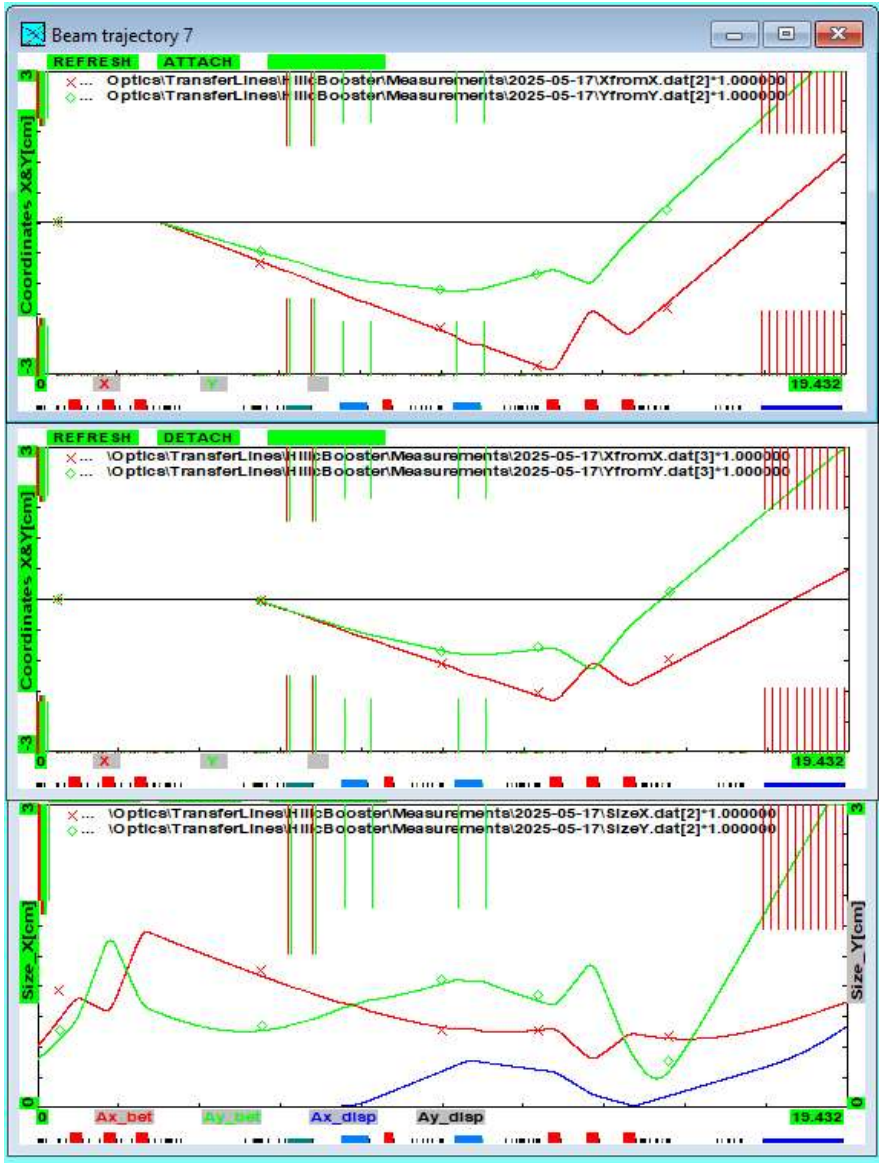
HILAC-Booster Transfer Line

- The rate of electron cooling used for beam accumulation strongly depends on initial velocities in the ion beam. That requires:
  - Good match for ∥ and ⊥ planes between linac and Booster
  - Beam injection without coherent betatron and synchrotron oscillations
- To minimize coherent betatron oscillations we compute complex amplitude of betatron motion from a turn-by-turn positions of Booster BPM
  - For each plane the corrections are done by 2 actuators
  - Automation is tested and used in operations
- Analog and digital synchronous detectors are used to minimize synchrotron motion excited by errors in the energy and bunch arrival time. The detectors use Booster FCT (Fast Current Transformer) signal.



Optics Measurements in HILAC-Booster Beamline

- Differential optics measurements were done with multiwire monitors
  - BPMs could not work because of scraping of nearby charge states
  - After correction of edge focusing in dipoles, we obtained good agreement between measurements and the model
  - Finding initial Twiss parameters is problematic because of presence of multiple charge species and non-Gaussian beam profiles
  - After the measurements and data analysis the beamline lattice was rematched to match the line to Booster
  - Fine tuning still needs to be done. That requires better calibration of IPM



Booster - SC Synchrotron

Inj. energy – 3.2 MeV/n

Extr. energy – ~500 MeV/n?

Circumference – 210.96 m

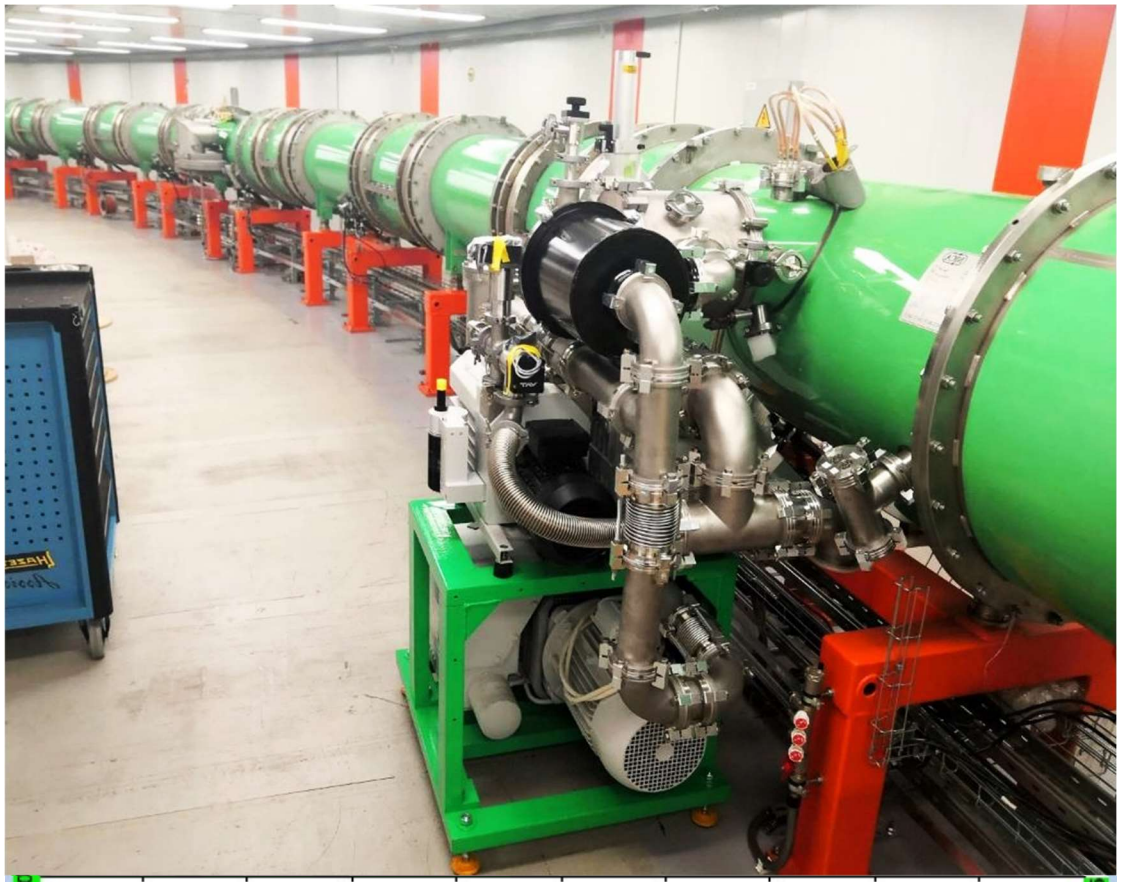
- 25 T·m(superferric 1.8 T)

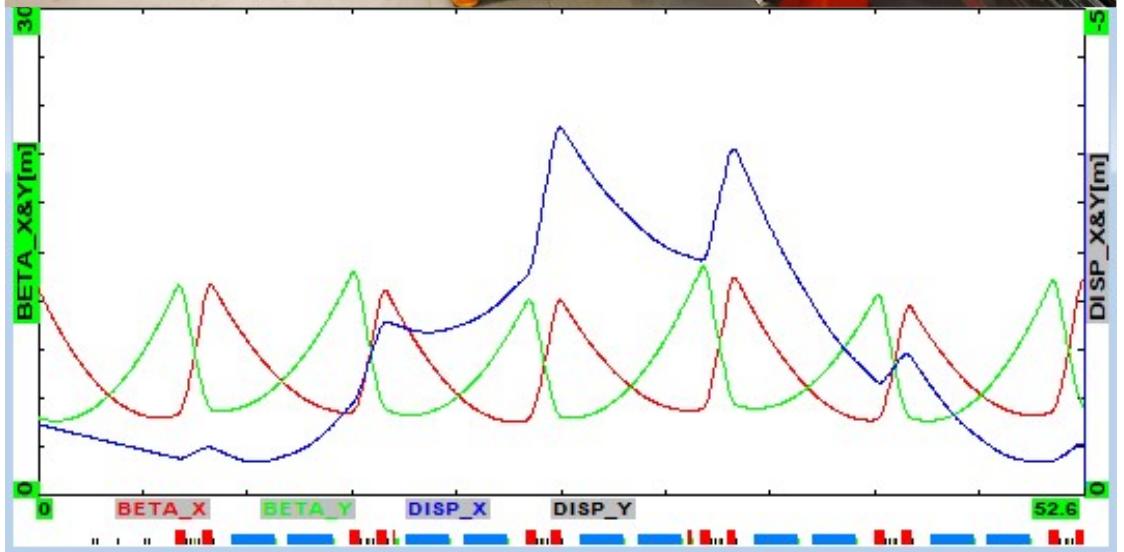
24 periods in 4 superperiods

- Doublet focusing
- Tune correction with two circuits, range [4.7-5.3]

10 (7.4) kV RF voltage

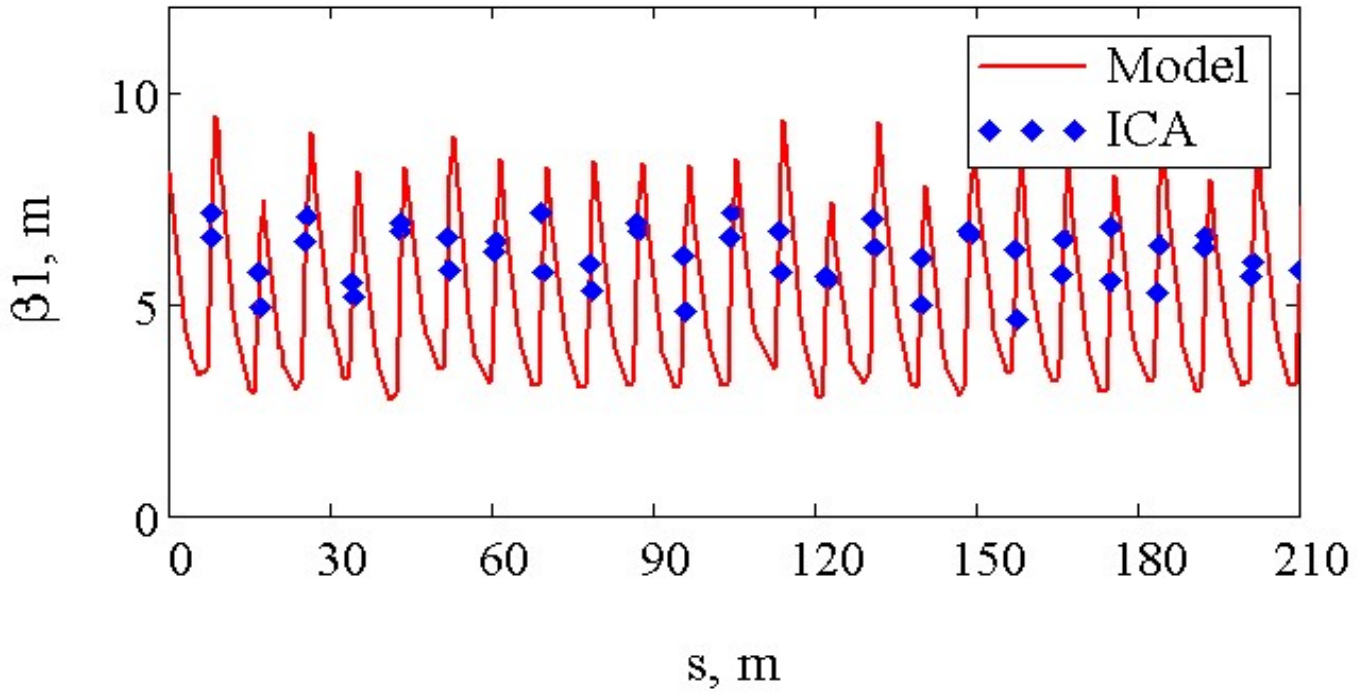
- f_{RF}: 0.5-5 MHz
- Beam accumulation and acceleration with h=1
  - Frequencies at injection (f~117 kHz) and for initial acceleration f<0.5 MHz
    ⇨ Reduced RF voltage





Optics Measurements in Booster

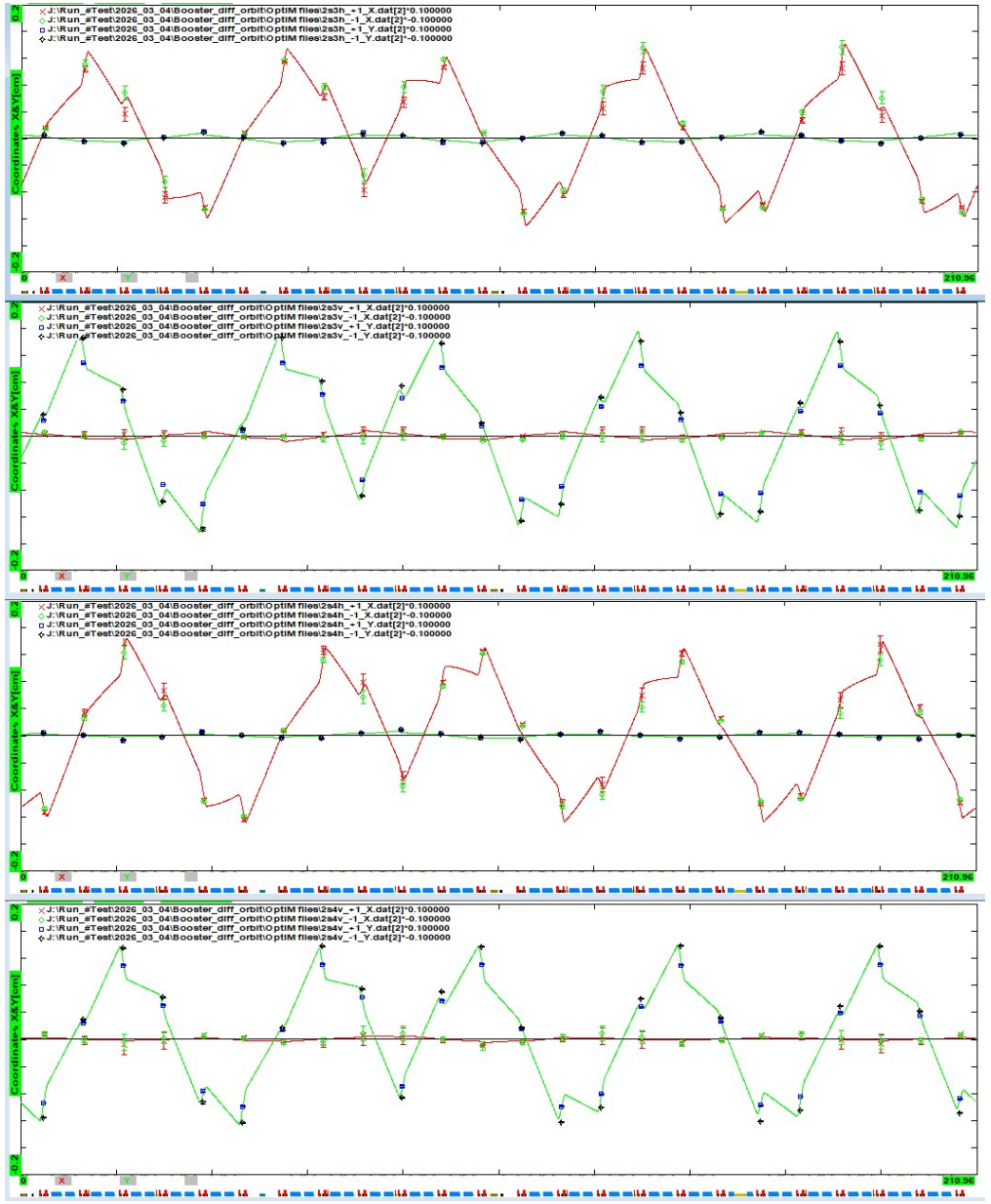
- We acquired both the differential orbit measurements and turn-by-turn data in Booster
  - Preliminary analysis shows that the measured β-functions are well within ~20% of design and, presently, optics mismatch does not play significant role
  - Additional data was taken recently. The detailed data analysis will follow shortly. The goal is the *x-y* planes decoupling.



Optics Measurements in Booster

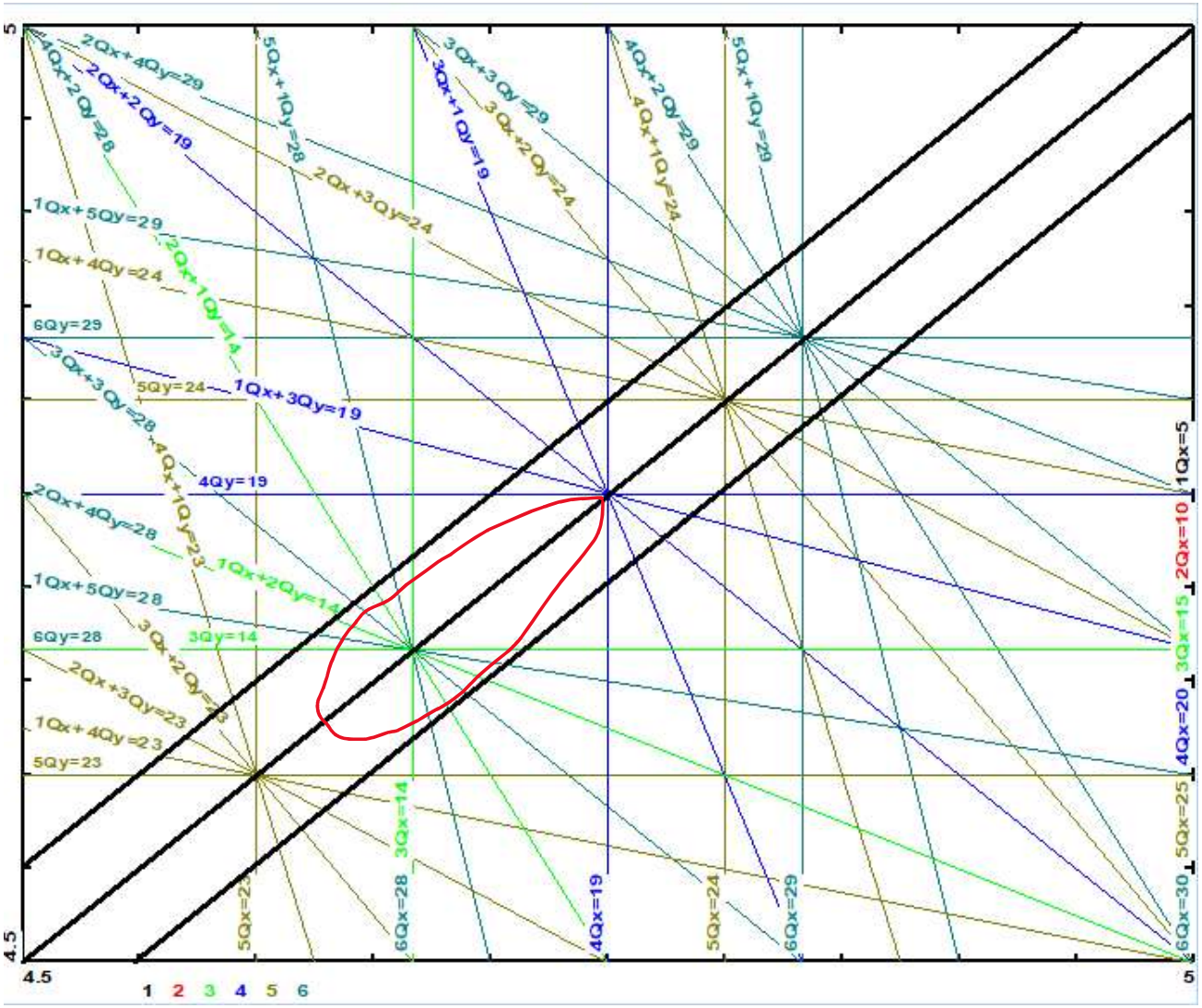
- Effect of coupling
  - At the injection energy the nominal 700 G field of the electron cooling solenoid does not produce
    - significant emittance growth related to betatron coupling
    - or an increase of the ion ⊥ velocity in the cooling solenoid.

    However, it introduces strong coupling with tune split of 0.05.
  - We already tested operation at 350 G – Cooling OK
  - Next step 250 – it should deliver $\Delta\nu \sim 0.015$
    - It should be sufficient to get to good working point (betatron tunes)



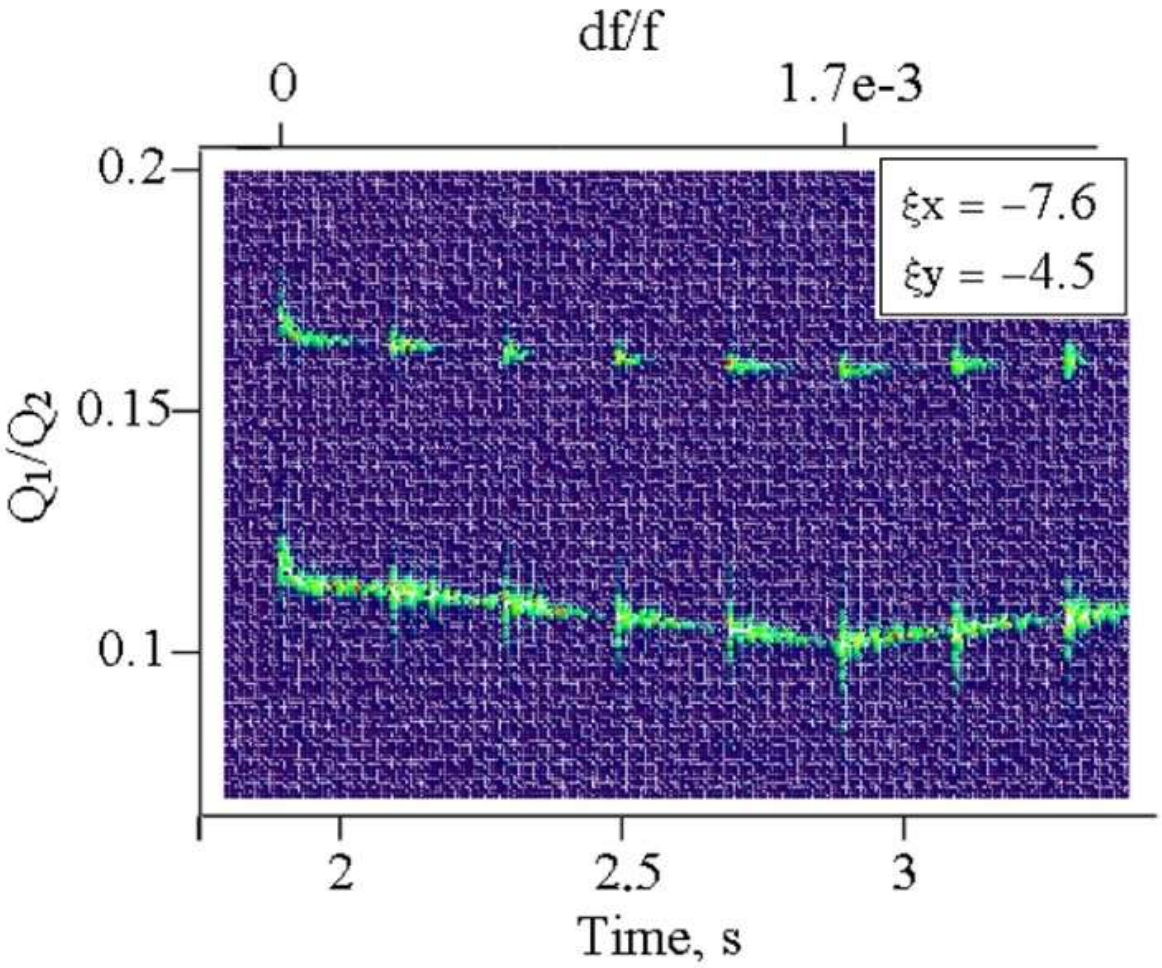
Tune Diagram

- An experience accumulated by community states that in the case of strong space charge an operation near coupling resonance is preferred
- Requirement D=0 determines $Q_x \approx 4.75$
- Nominal 700 G solenoid field yields $\Delta\nu$=0.05 - too large to get to good tunes
- Solenoid field decree-se to 350 G decreases $\Delta\nu$ by 2 times ($\Delta Q \propto B$). It was tested & OK
- Optics data analysis is required to find out required actions
- We can get tune split <0.015; $Q_x \approx Q_y \approx 4.73$?

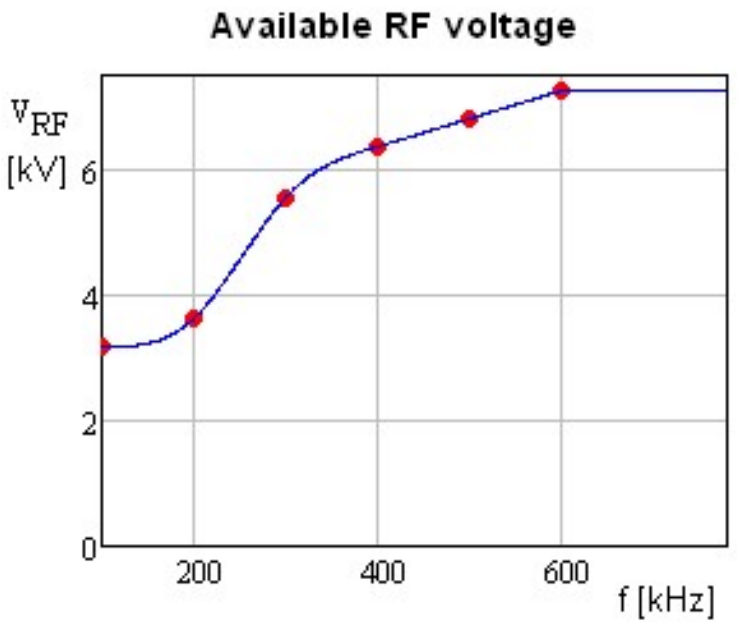


Booster Chromaticity and Dispersion

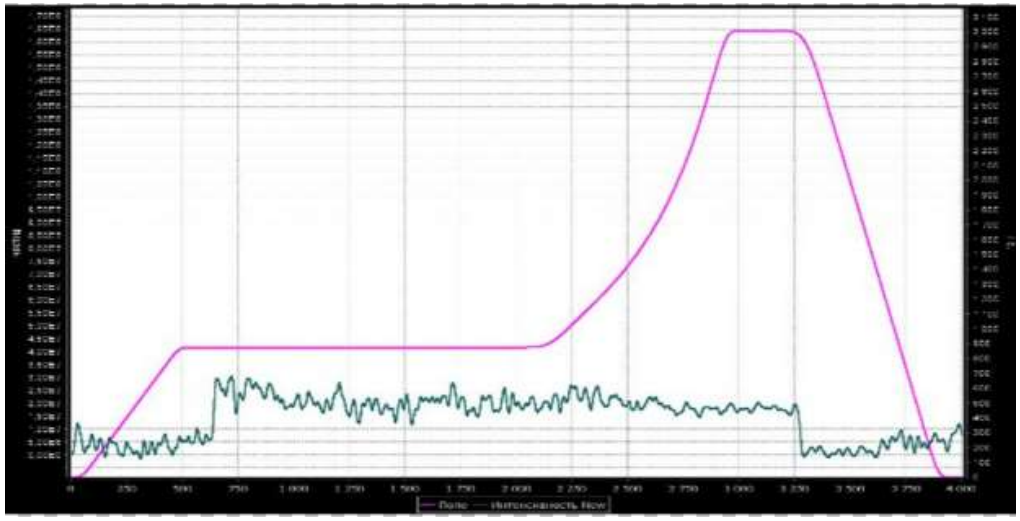
- To measure dispersions and chromaticities at the injection energy we swept RF frequency by $2 \cdot 10^{-3}$ ($\Delta f/f$) at the bottom flat and made small periodic horizontal kicks in the process
  - Due to strong betatron coupling the beam motion was visible at vertical BPMs as well as at the horizontal ones
  - Data from the turn-by-turn BPMs was acquired after each kick



Optimal Beam Acceleration



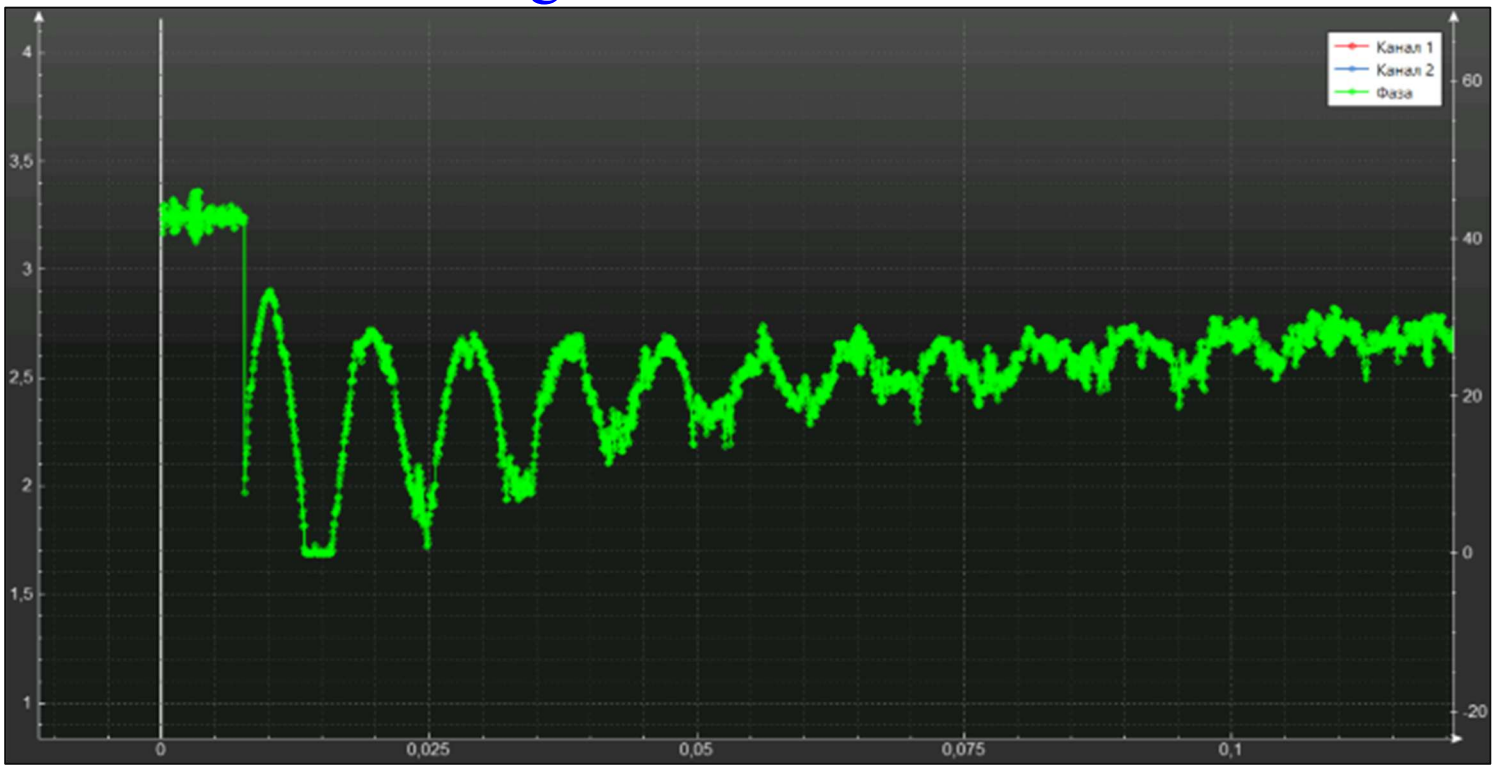
- In the previous Run, the beam loss was observed at the start of acceleration in both Booster and Nuclotron
- The reason was tracked to the loss of RF bucket size at the beginning of acceleration due to too fast acceleration
- We rewrote the algorithm of magnetic field generation so that it would not generate decrease of || acceptance and account for available RF voltage



  - It has been even more important because we chose acceleration at the first harmonic since we already use it for beam accumulation
  - Lengthening of cycle duration was compensated by an absence of medium flat for adiabatic rebunching (h: 4→1)

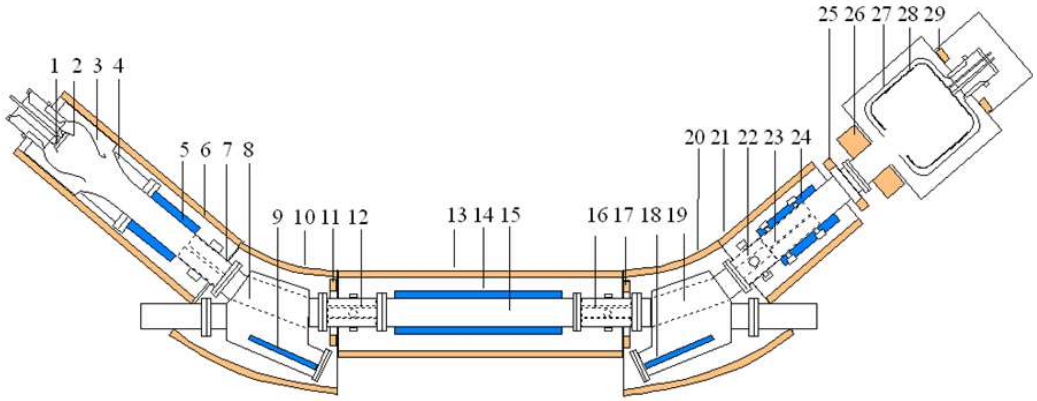
Phase Monitor

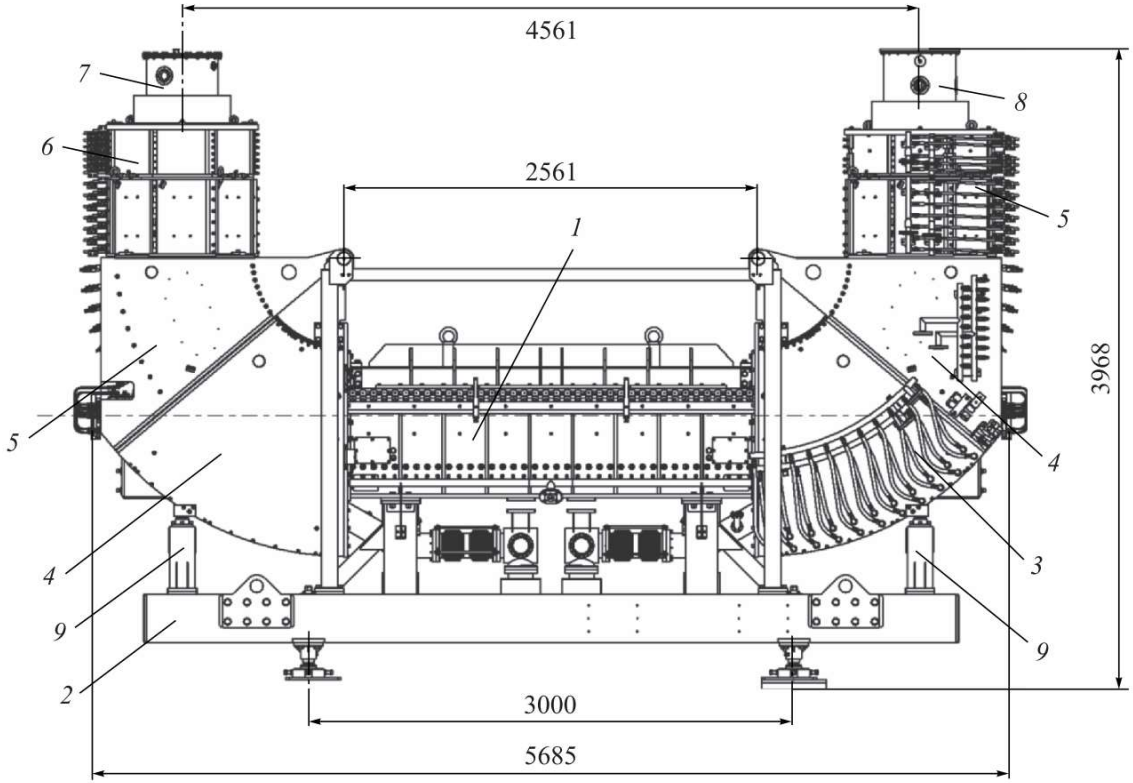
- To see synchrotron motion of the injected bunch we use phase detector using RF and FCT signals
  - That allows us to do online correction for the energy of injected beam and its arrival time
  - Automation is coming



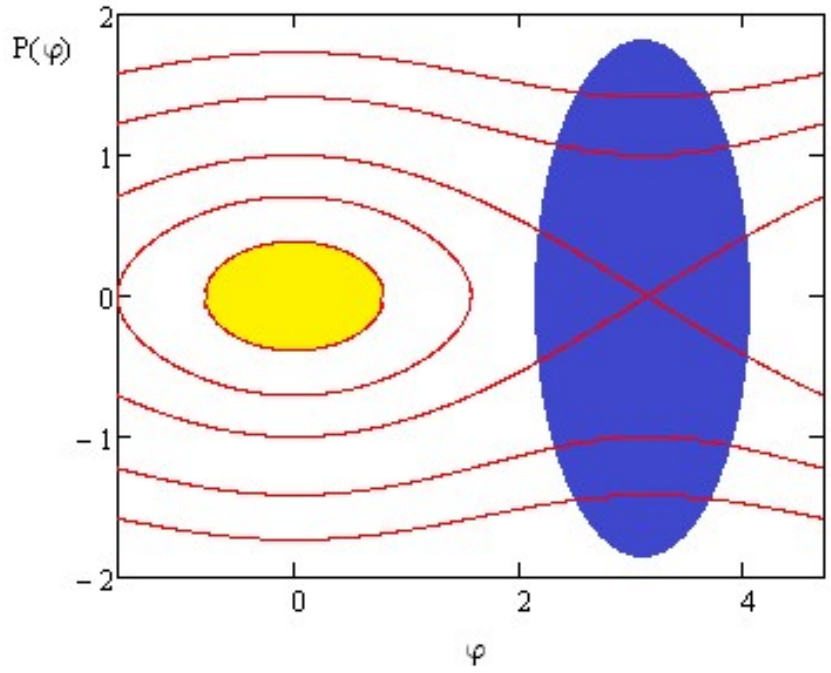
Electron Cooling

- Electron cooling is extremely important asset in Booster
- Invented in 1966 by A. M. Budker
  - In the beam frame - heavy particles come into equilibrium with electron gas
- Tested experimentally in 1974-79 at NAP-M (BINP, Novosibirsk)
  - 35 MeV electron beam (65 MeV per nucleon)
- Booster cooler was designed and built by BINP
- Cooler parameters:
  - Maximal: E_e=100 kV, I_e=1 A, B_0=1 kG
  - Required for accumulation: E_e=1.8 kV, I_e=15 mA, B_0<0.7 kG





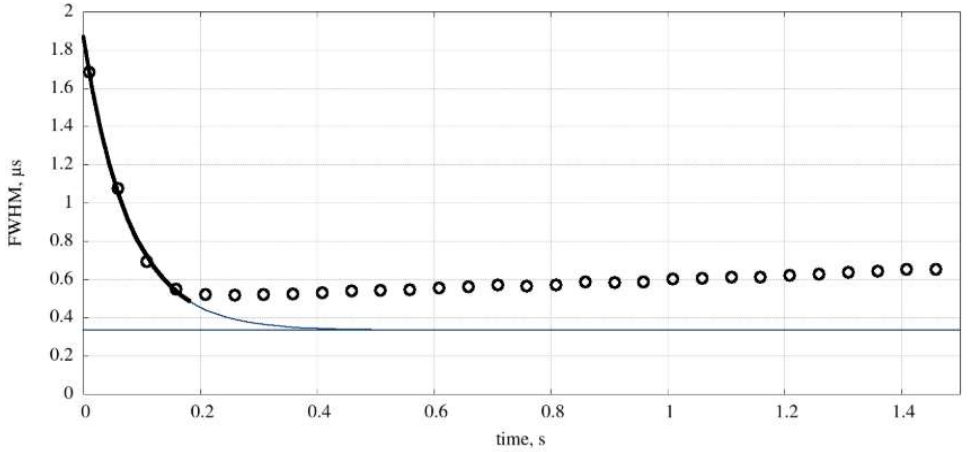
Beam Accumulation

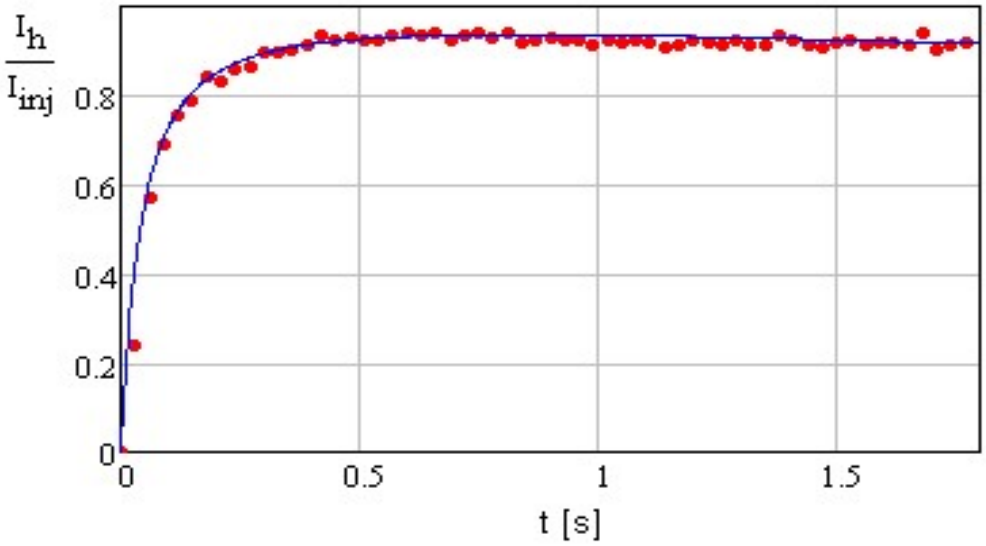


- 1st injection goes to RF bucket center
  - Other 9 to the opposite phase
- Optimal time between injections 250-300 ms, τ_{cool} ~70 ms
- Small amplitude cooling is much faster than large amplitude
  - A short dense bunch is formed greatly amplifying effect of non-linearities introduced by beam space charge: $\Delta\nu_{SC}\approx 0.05$ for 10^8 ions
    - As result we have high sensitivity to tunes
- Two remedies will be used
  - The 2nd harmonic in bunch lengthening mode reduces $\Delta\nu_{SC}$ by more than twice – already tested but not implemented
  - Finding optimal betatron tunes
    - The first tune scan was done. Few good tunes found.
    - Good decoupling is required. Optics data taken. After data analyses we decouple Booster and then perform tune scan

Electron Cooling

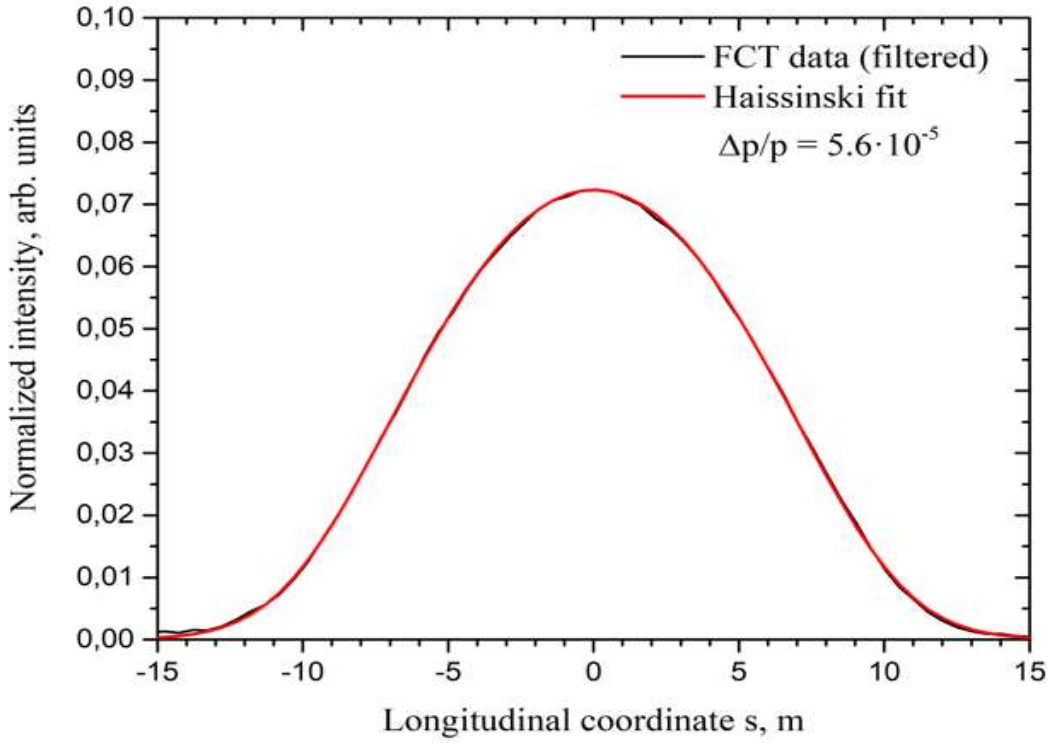
- Longitudinal electron cooling strongly depends on transverse angles in the ion beam
  - After correcting betatron match between linac and Booster we obtained cooling time of ~70 ms
  - It also required beam optics with small dispersion in the cooling section
- The time required for the beam injected out of RF bucket to be cooled into the 4 μs core is ~400 ms
  - That determines the accumulation rate of ~3 Hz (300 ms)
  - Optimal electron beam current is ~15 mA (potential droop in e-beam)





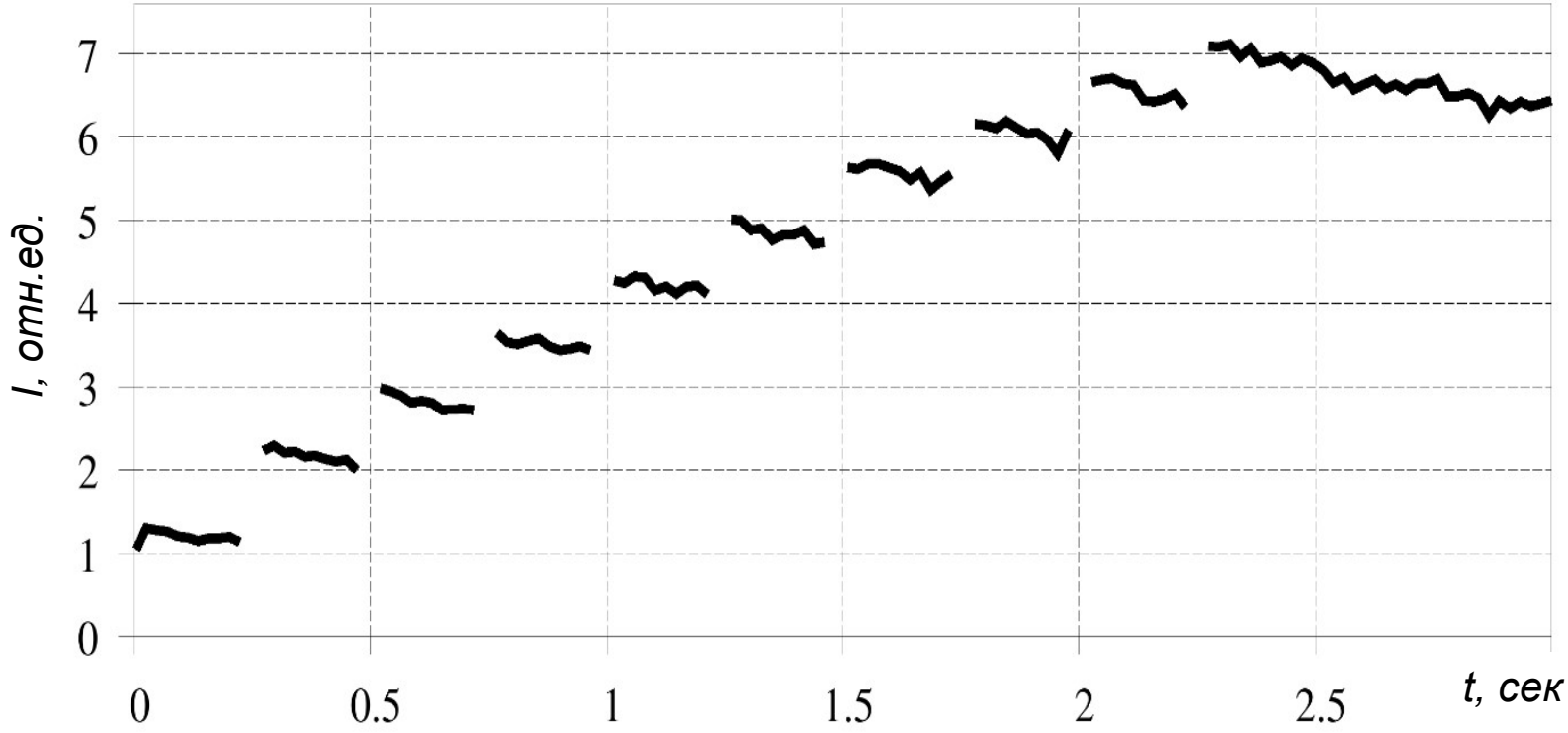
Bunch Length and Momentum Spread

- Since longitudinal cooling is much faster than transverse cooling, $T_{||}$ in deeply cooled ion beam is much smaller than $T_{\perp}$
- The longitudinal momentum spread is so small that the longitudinal beam density is mainly determined by the beam space charge which compensates the force induced by RF cavity
- Fitting a solution of Haissinski Eq. to the experimental data yields $\sigma_p = 5.6 \cdot 10^{-5}$ for $N_i = 2.3 \cdot 10^7$ ($^{26+}$Xe), $V_{RF} = 100$ V
  - Estimate of IBS yields close result
  - The total bunch length is about 1/10 of circumference
    - For space charge dominated beam: bunch length $\propto N_i^{1/3}$



Beam Accumulation Tests

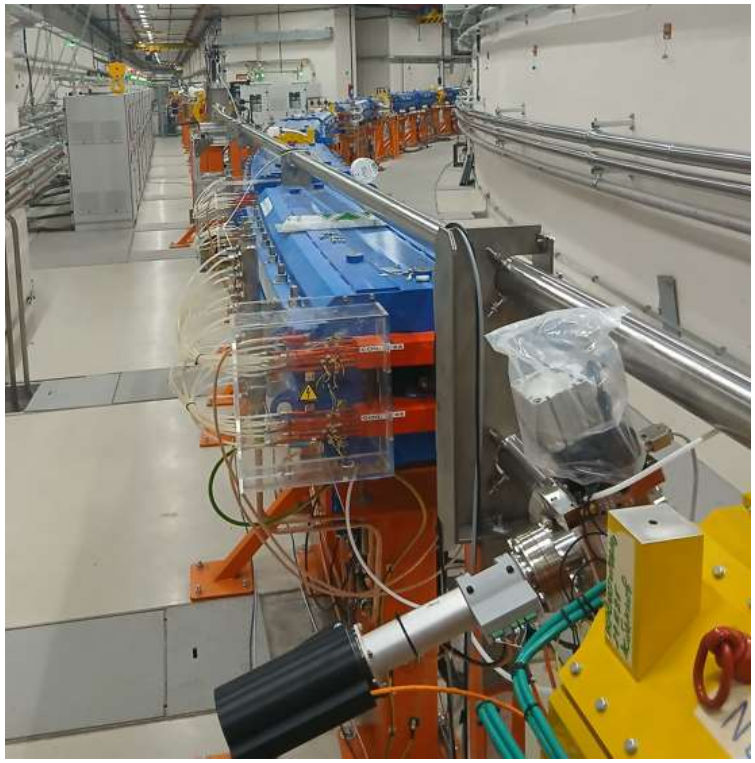
- The best beam accumulation, we obtained: $0.9 \cdot 10^8$ $^{26+}$Xe ions from 10 pulses at 300 ms rep. rate
  - Accumulation efficiency ~80%
  - Beam lifetime ~25 s measured at small ion beam intensity
    - sum of losses from vacuum and electron cooling with 15 mA electron beam



Fast Extraction from Nuclotron

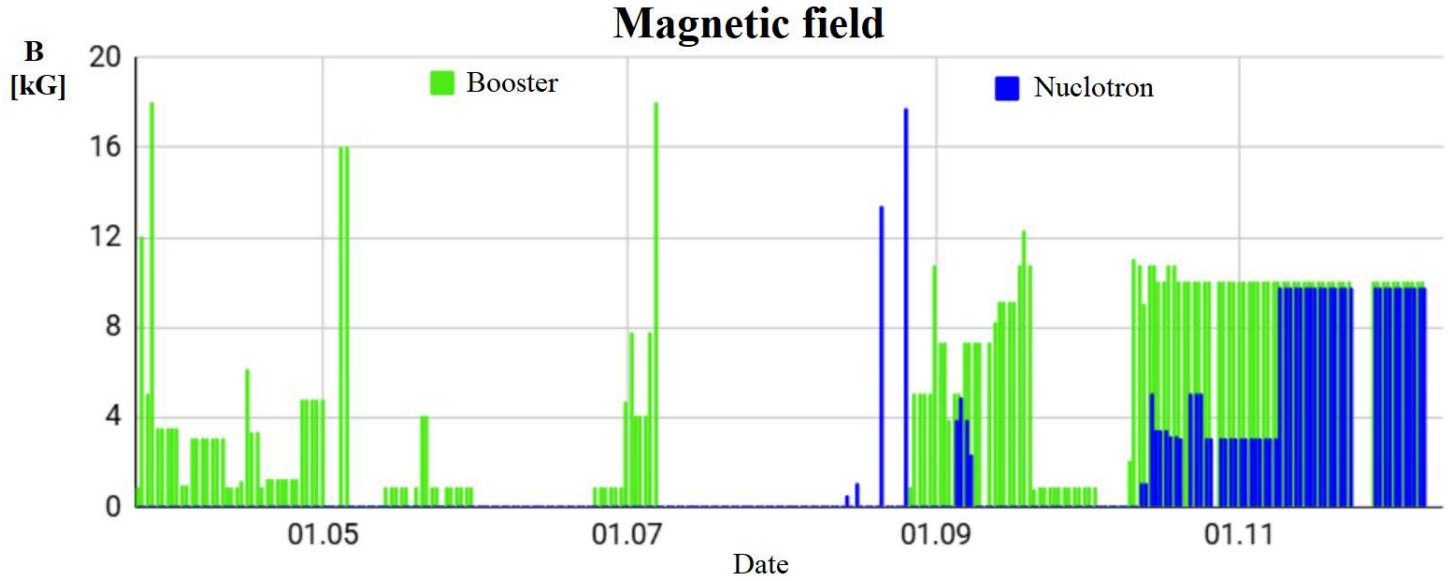
- For the collider operation the fast extraction was added to Nuclotron
- Nuclotron was built in 90th – Already quite old machine => Fragile
- Painful and long work on addition of the fast extraction
- Work took longer time than expected
  - Incompliances in drawings
  - Most of work was done in the middle of summer
    - ⇨ Vacuum leaks due to corrosion in brazed ceramic-metal interfaces induced by high humidity
    - ⇨ Leak search and fix
  - Quench and subsequent loss of SC feeding line -> repair





Nuclotron Commissioning

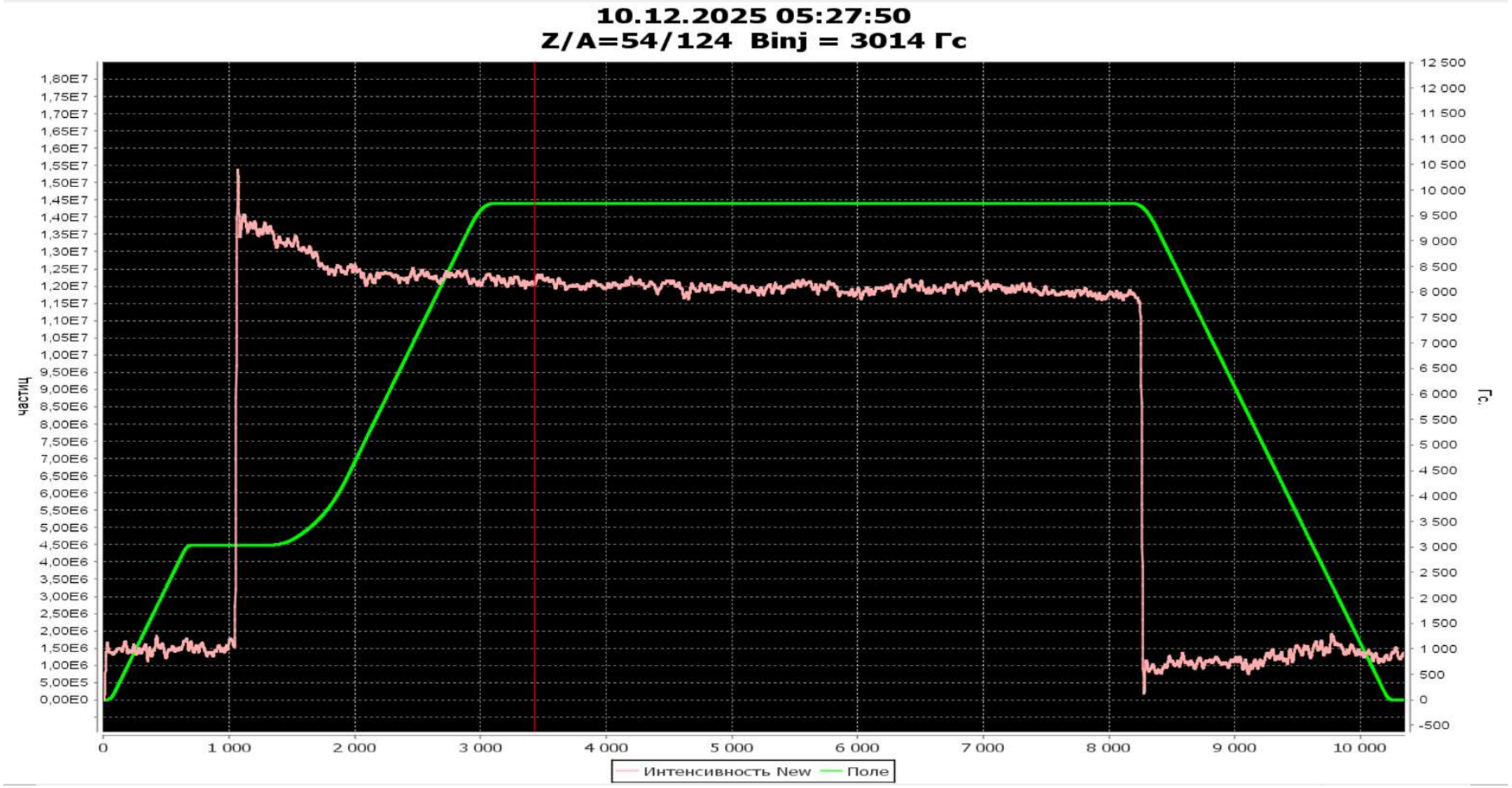
- Painful and long Nuclotron recommissioning
  - Multiple software and hardware problems: kickers, power supplies, synchronization, BPMs, …
    - Each problem is addressed relatively fast but altogether it resulted in many months delay
  - Collider installation work put additional limitation on operating time and available personal
  - Hardware problems and lack of experience resulted very slow recommissioning of slow extraction



Inj. complex operation Mar.25-Dec.12.2025. Gaps in Booster operation due to work in Nuclotron

Acceleration in Nuclotron

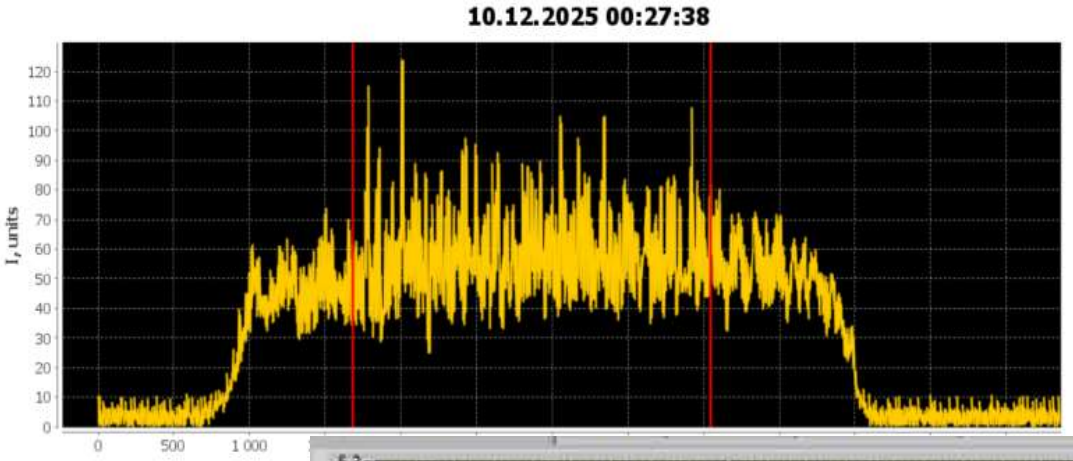
- Overall, we achieved much better acceleration efficiency than in the previous Run (2022-2023)

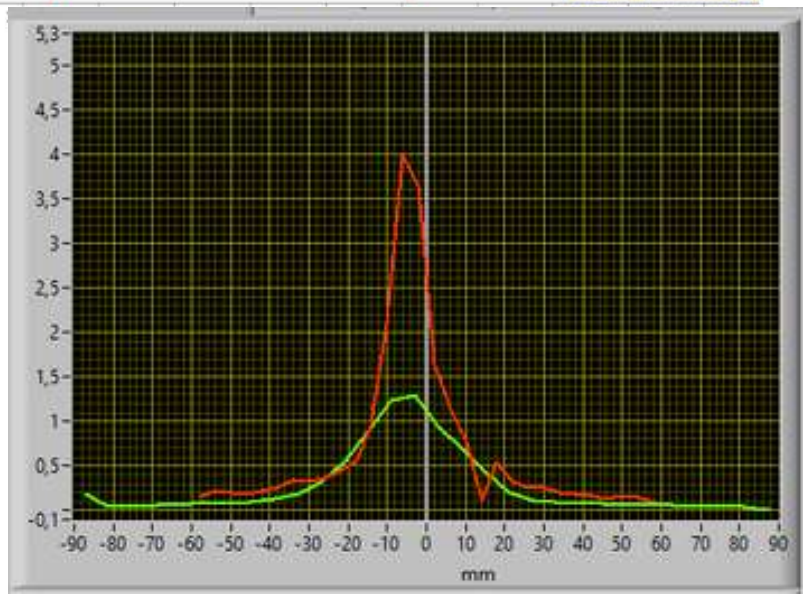


- Many improvements are still required to get to the injection complex performance required for the collider

Fast and Slow Extraction

- We have been sending beam to BM@N for few months with relatively good efficiency
- Slow extraction improvements
  - An increase of extraction efficiency
    - Orbit correction near el. static septum
    - Optimization of sextupole strength
  - Optics and orbit correction in the BM@N transfer line
  - Measure extracted emittance and built means for its fast measurements
- Fast extraction from Nuclotron to collider was demonstrated
  - Transfer lines to the collider were installed
  - Beam was threaded through both branches to Collider





Collider Run 0

NICA Construction

- Although slower than it was expected years ago the NICA collider construction has proceeded relatively well





- First beam injection happened in January of 2026

Collider Commissioning

- Tested systems: vacuum, cryomagnetic, transfer lines, kickers and septa, main power supplies and dipole correctors, collider BPMs, RF2, …
- Achievements
  - Obtained beam circulation at 1.73 GeV/n with beam lifetime of ~0.5 – 1 hour
  - Measured beam orbit and beam optics
    - Data analysis started
  - Measured betatron tunes => chromaticity estimates
  - Synchrotron tunes
    - RF voltage calibration was verified
  - Vacuum measurements (density of electrons)
    - Beam deceleration was measured
      $P=1.8\cdot10^{-9}$ torr (molecular H_2 equivalent, T=300 K)
      $(d(\Delta p/p)/dt=2.6\cdot10^{-7}\ s^{-1}$ @ 1.73 GeV/n)
    - Estimates show that we can operate collider with this vacuum

Collider Commissioning Problems

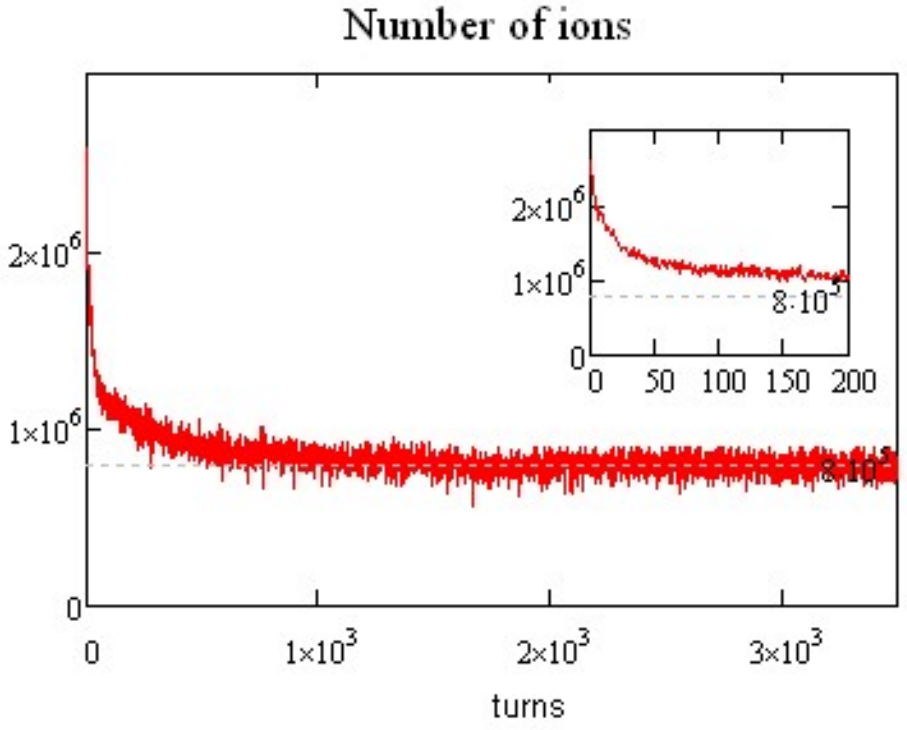
- Did not achieve the design magnetic field
  - Problems were observed at few places
    - Extensive repairs are required
- Low efficiency Nuclotron-Collider beam transfer, ~10%
  - Incomplete set of instrumentation
- Getting the first turn in collider rings was difficult and time expensive

  – BPMs were blind up to ~10 turns
  - very large EMIs in the east arc – cannot see the first turn at all
  - Large EMI for many other BPMs
  - Low efficiency Nuclotron-Collider beam transfer reduced sensitivity of BPMs and made Libera electronics incapable to produce single turn and turn-by turn measurements
    - Raw data were measured. With offline analysis they have sufficiently good accuracy. Data processing will follow.

Beam Loss Observations

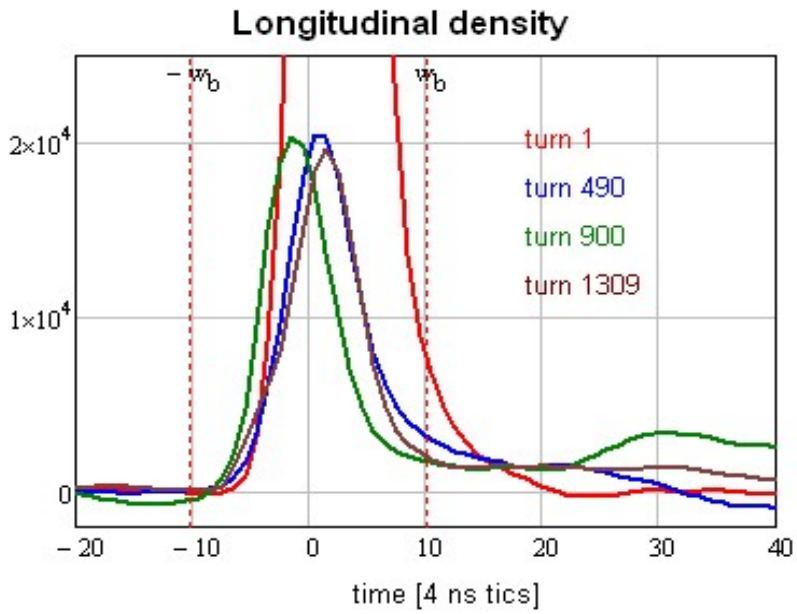
- In the case of bunched beam, we can separate 4 timescales in the beam loss – 4 mechanisms correspond to these 4 timescales
  - ⊥ loss due to betatron motion - ~50-100 turns
  - Particles landed outside of RF bucket walk away from the bunch to DC – ½ synchrotron period = ~800 turns
  - Particles landed inside RF bucket near its boundary are shaken out by RF noise to DC
    – 10 minutes
  - Vacuum loss
    – many hours
    - In these measurements ~1 hour due to multiple scattering on the residual gas amplified by small acceptance

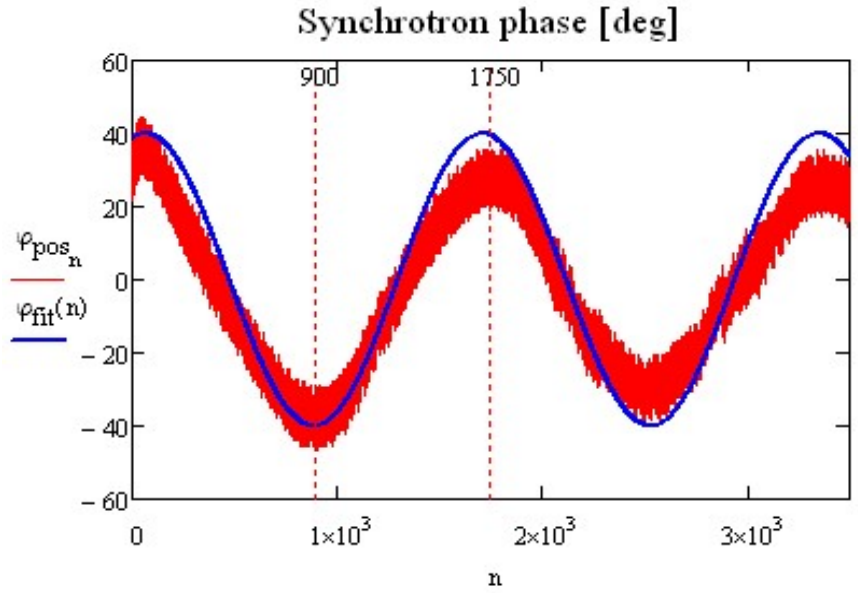
      Loss strongly depends on orbit correction, *i.e.* on the available transverse acceptance



Loss for Particles Landed outside of RF Bucket

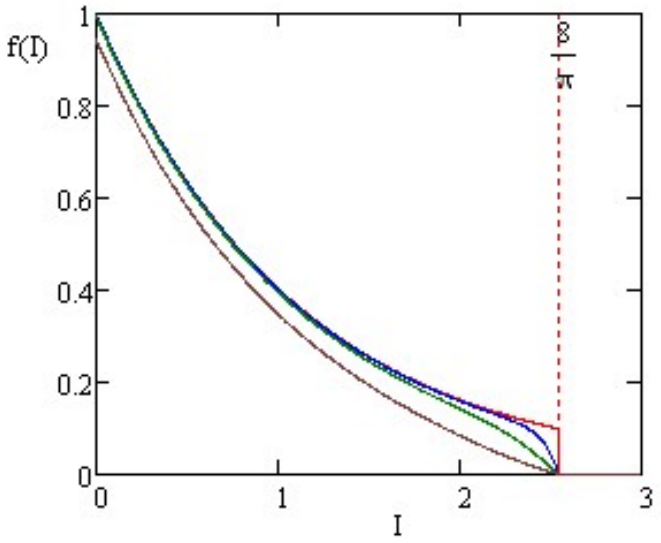
- Formally the bunch coming from Nuclotron should fit into collider RF bucket. However, due to injection time and energy errors some particles land outside of RF bucket
  - Consequently, these particles leave the bucket but not necessarily the beam
  - An absence of phase monitor did not allow to see stability of injections and to make good tuning of the transfer
  - Both pictures on the right point out on the injection time error of ½ radian, while RF frequency was chosen correctly for the beam energy
  - RF voltage was chosen correctly
    - ⇨ Still small quadrupole synchrotron motion was observed (bunch length oscil.)

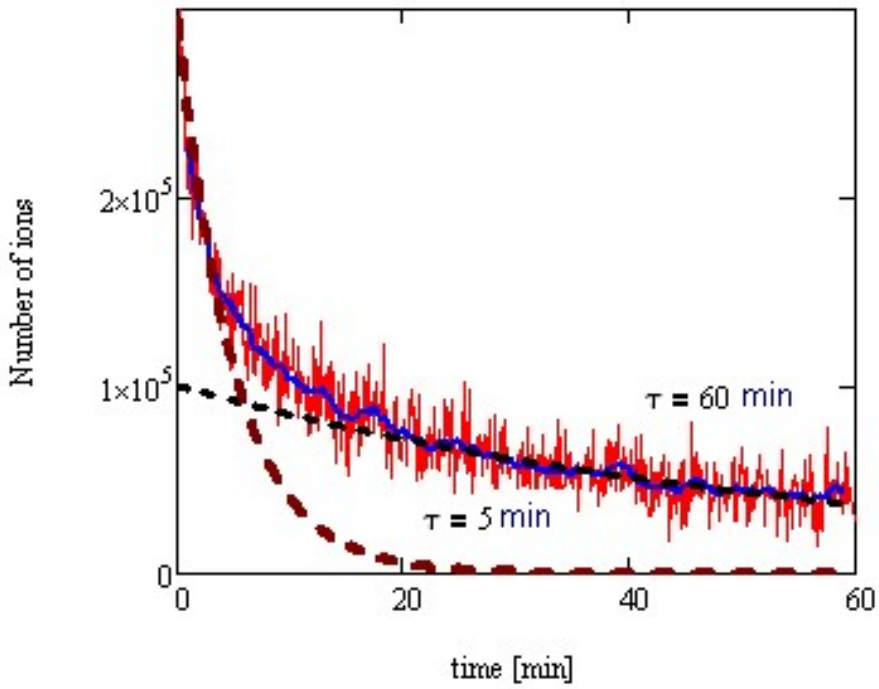




Beam Loss from RF Bucket and Vacuum Loss

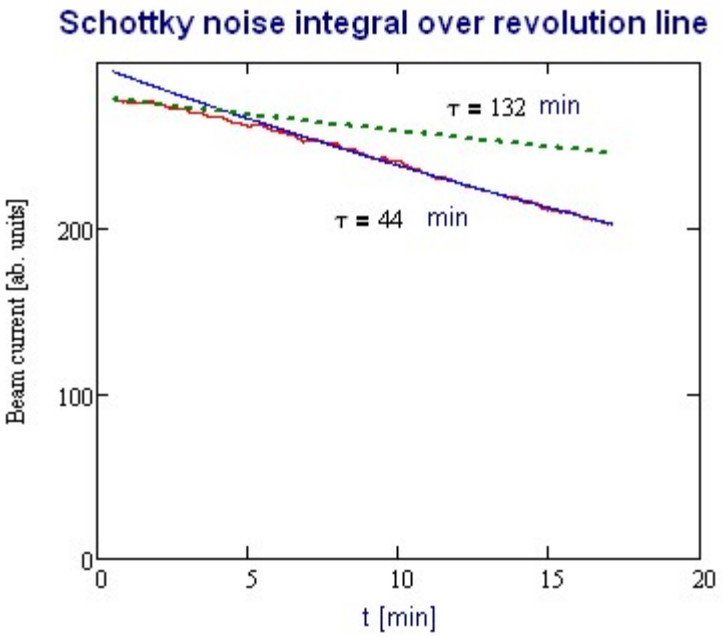
- The discontinuity in the longitudinal distribution makes the beam susceptible to diffusion
- The diffusion comes from RF noise which shakes out particles near separatrix
  - The process is amplified by very large spectral density of RF noise near the carrier $\frac{d}{dt}\overline{\varphi^2(t)} = \pi\Omega_s{}^2 P_\psi(\Omega_s)$
- Measurements of RF noise and detailed analysis of distribution dynamics will follow
- After the boundary particles are gone the beam loss is mainly driven by loss due to multiple scattering on the residual gas





Beam Lifetime Measurements and Lifetime Projections

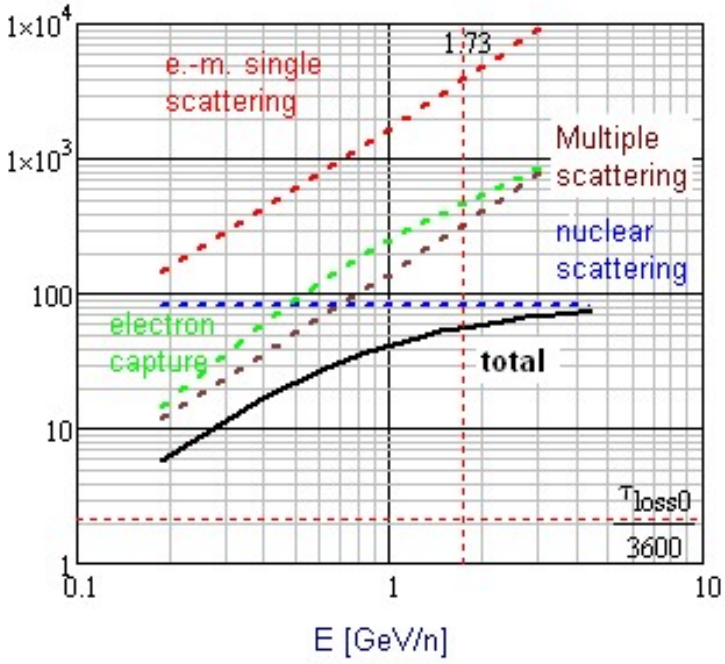
- Mechanisms of beam loss
  - Elastic e.-m. scattering
  - Nuclear scattering
  - Electron capture
  - Multiple scattering
- Beam lifetime of 56 hour computed from vacuum measurements is well above the measured one
  - Present belief that beam loss is driven by multiple scatte-ring amplified by reduced acceptance
- Obtained vacuum looks acceptable in the entire energy range for Xe



Used gas composition

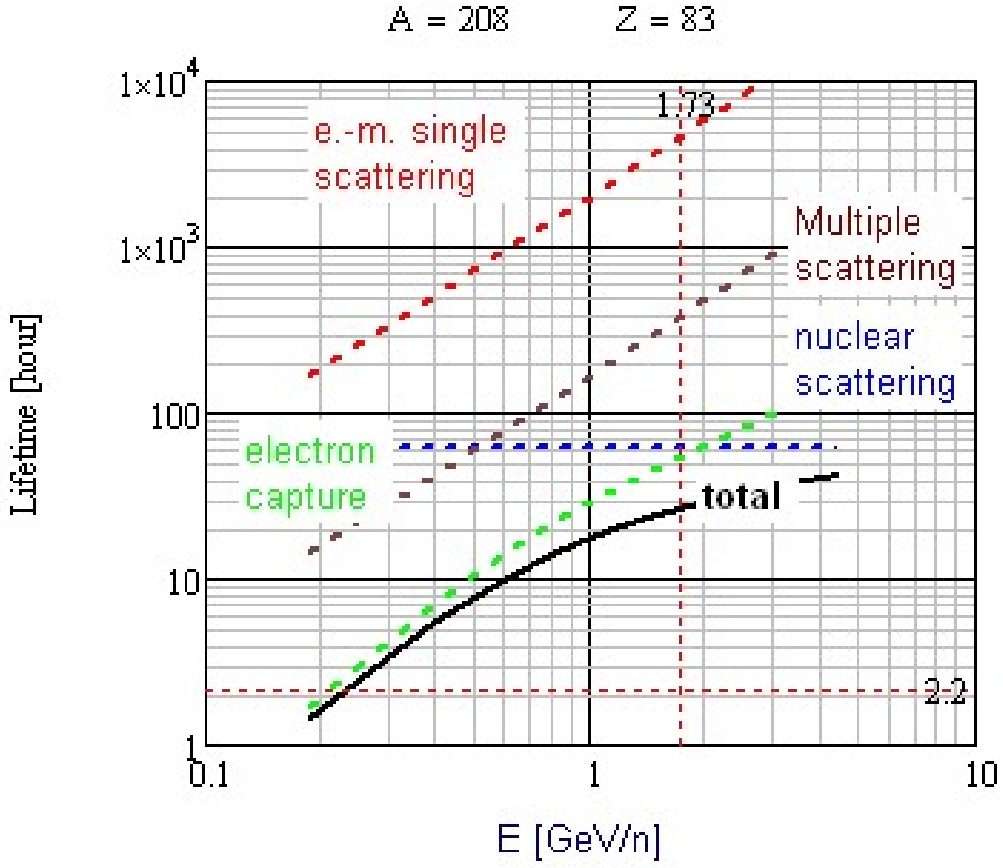
$P_1 = 7.72 \times 10^{-10}$ torr

$\frac{P}{P_1}$		
0	H	
1	H_2	
0.05	CO	
0.05	N_2	Torr
0.01	C_2H_2	
0.01	$C{\cdot}H_4$	
0.01	CO_2	
0.05	Ar	



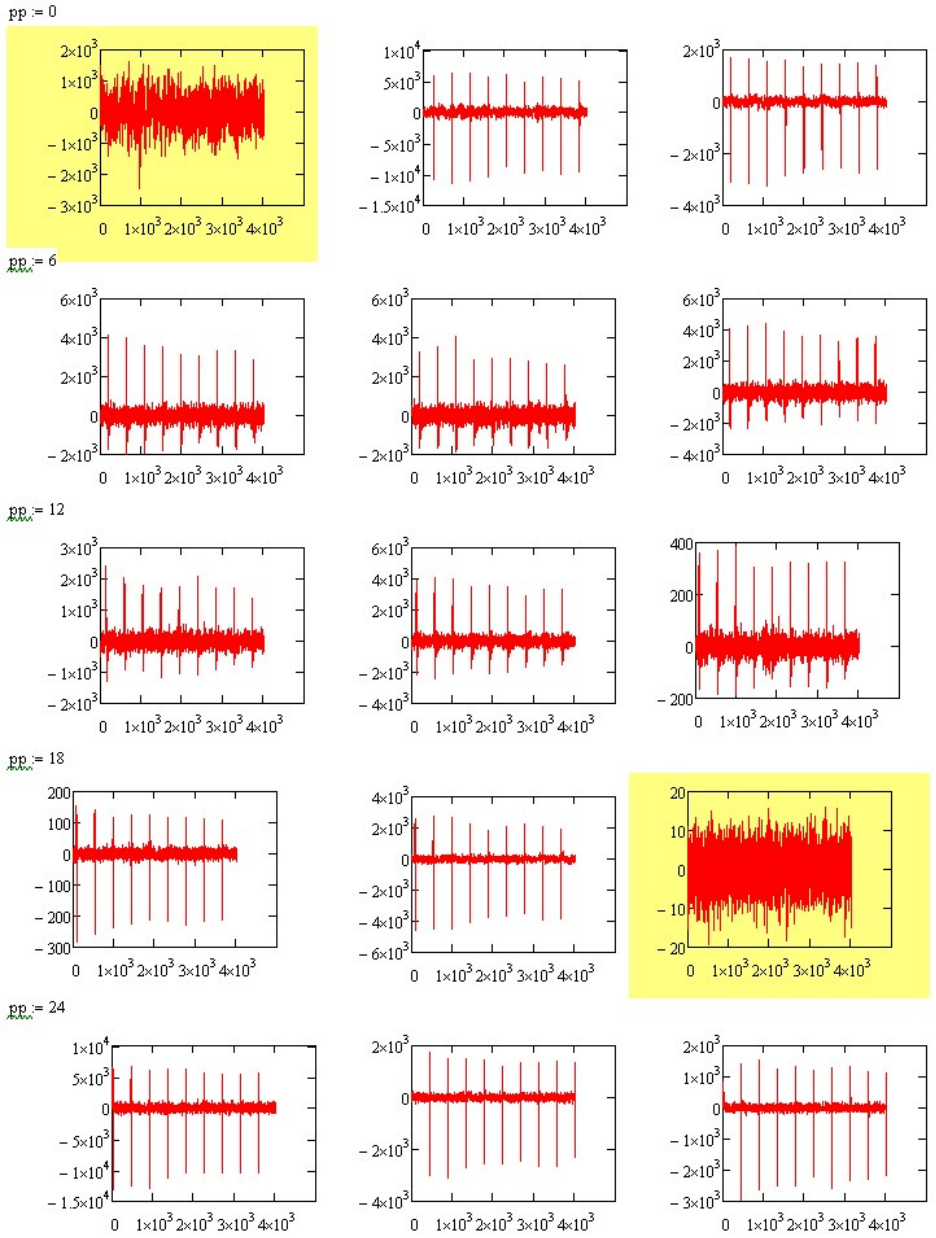
Beam Lifetime Projections for Bismuth

- Beam lifetime gets worse for Bismuth; mostly due to much larger electron capture (still insignificant above 2.5 GeV)
  - 3 times better vacuum is desired – it will come naturally with time if we will keep vacuum "hygienic" at high level



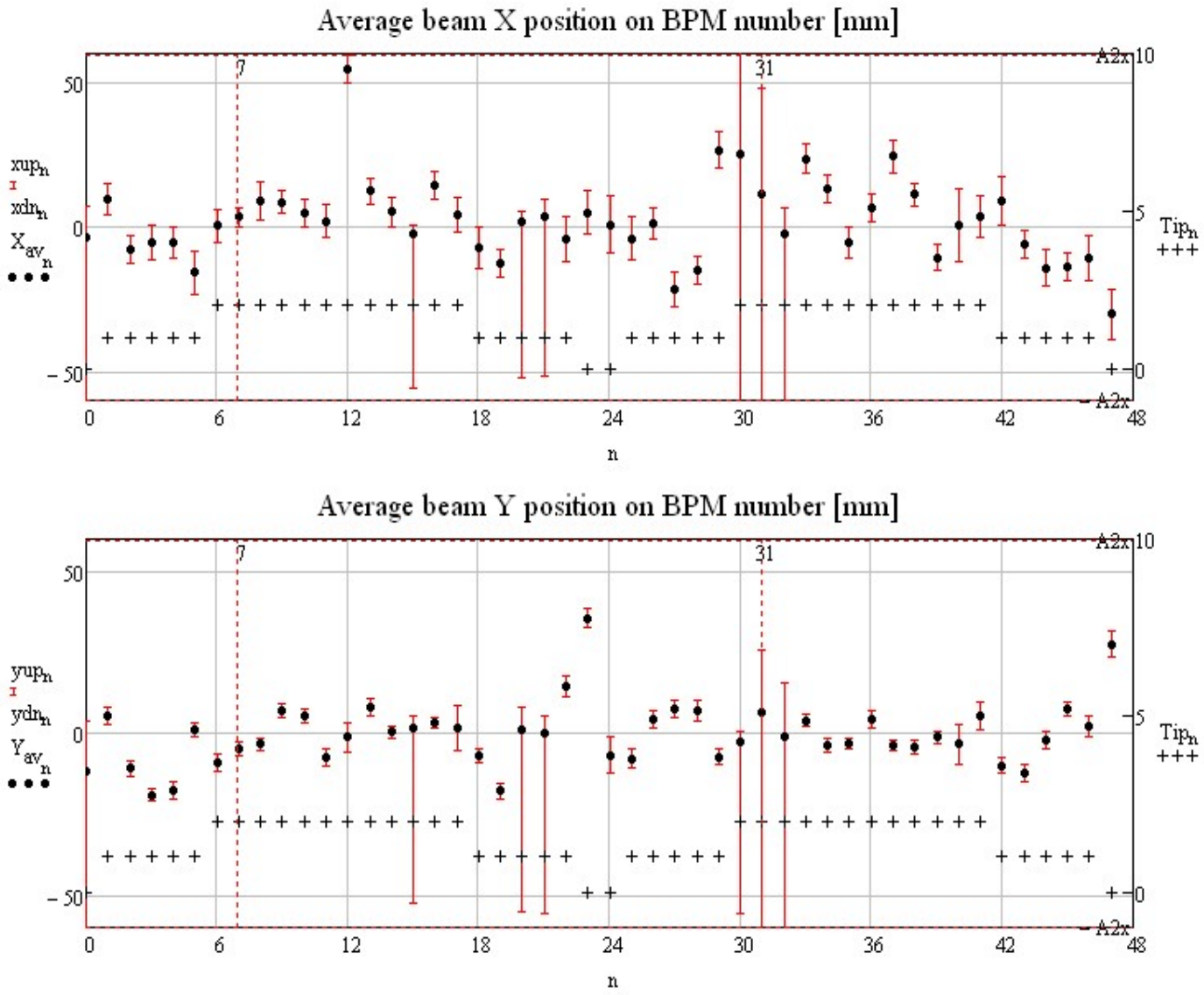
Beam Position Monitors

- Obtaining beam circulation would not be possible without BPMs
- However, we encountered many problems which we should address before next Run
  - Very large EMI from kickers in the est arc. All BPMs inside cryostat were blind for ~5-to-10 turns
  - An absence of online software for orbit measurements and turn-by-turn measurements
- Large EMI on other nearby BPMs
- Strip-line BPMs showed better performance than Shoe-boxes
  - Less susceptible to EMIs and to the beam loss



Beam Orbit Measurements

- To measure the beam orbit and beam optics in collider we acquired row data which will be used in offline analysis.
- Rms errors per turn are: x/y≈5/3 mm
  - After averaging over acquired revolutions we expect to get 200/160 μm That is good enough to understand machine optics
  - For each plane 39 BPMs out of 48 delivered good signals



Collider Commissioning: Next Steps, Ideas &Plans

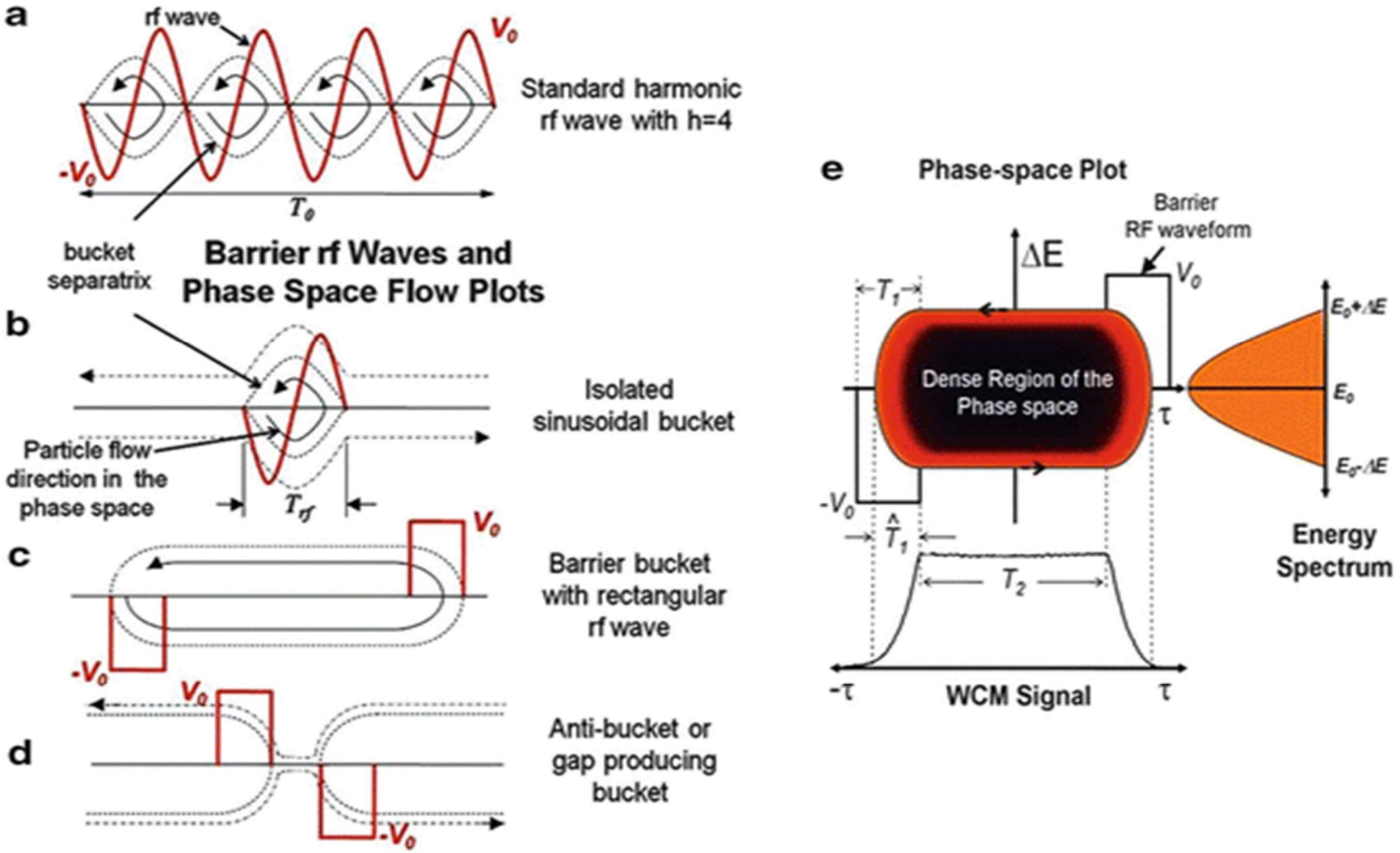
Big Picture of the Shutdown work

- Ending construction work in bldg. 17
- Fix MANY problems we already got on the way
- Installation of RF and cooling systems in collider

Future Steps in Collider Commissioning

- Injection complex – September – November of 2026
  - Finalize beam accumulation in Booster – the goal >$2 \cdot 10^8$ ions/cycle
  - Fix problems with kicker pulsers so that to be able to operate the Booster-Nuclotron transfers at energy >350 MeV/n
  - Finish beam optics work in Nuclotron and transfer lines
  - Obtain accelerating efficiency above 90%
  - Intensity extracted from Nuclotron >$1.5 \cdot 10^8$
- Collider (November 2026 – Summer 2027) – $E_{kin} \approx 2.5$ GeV/n
  - Commission optics and orbit correction in collider rings and Nuclotron-Collider transfer lines
  - Demonstrate luminosity with 2^x2 stored bunches
  - Commissioning of RF2 (Barrier-bucket)
    - Demonstrate beam accumulation (no stochastic cooling)
  - Commissioning 1 out of 4 longitudinal stochastic cooling systems /ring
    - Demonstrate beam accumulation with || stochastic cooling
  - Commission RF3
  - Commission 1 out of 4 transverse stochastic cooling system /ring
  - At this point NICA becomes real collider, i.e. can make real luminosity

Beam Manipulations with RF barriers



A schematic view of standard and barrier RF wave forms and RF buckets (left). The dashed, solid, and dashed-dot curves indicate bucket boundaries, particle flow directions in longitudinal phase space, and flow directions of particles outside the buckets, respectively. A schematic of (ΔE, τ)-phase space distribution of particles in a rectangular barrier RF bucket with its line charge distribution (wall current monitor-WCM signal) and energy distribution are shown on the right

Stochastic Cooling



- Invented in 1969 by Simon van der Meer
- Naïve cooling model
  - 90 deg. between pickup and kicker

$$\delta\theta = -g\theta$$

Averaging over betatron oscillations yields

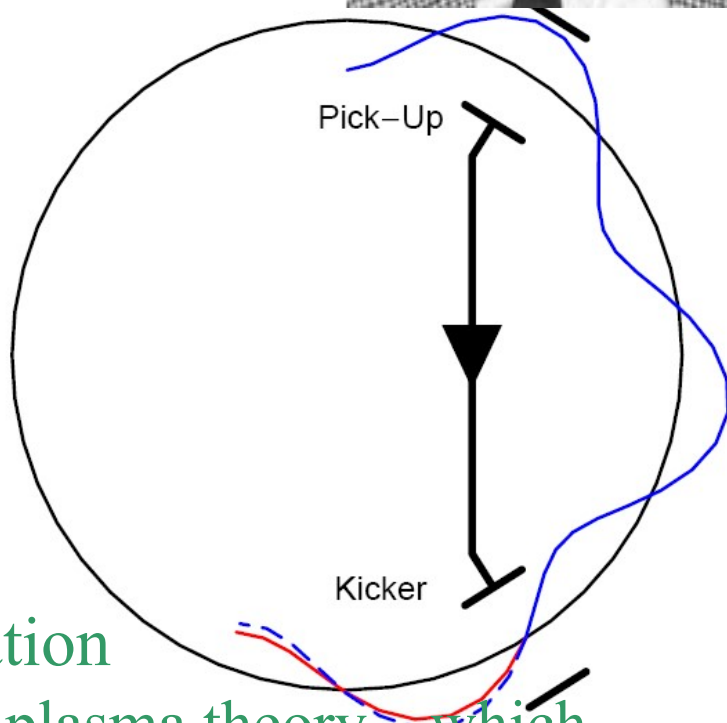
$$\delta\overline{\theta^2} = -\frac{1}{2}2g\overline{\theta^2} \equiv -g\overline{\theta^2}$$

Adding noise of other particles yields

$$\delta\overline{\theta^2} = -g\overline{\theta^2} + N_{sample}g^2\overline{\theta^2} \equiv -\left(g - N_{sample}g^2\right)\overline{\theta^2}$$

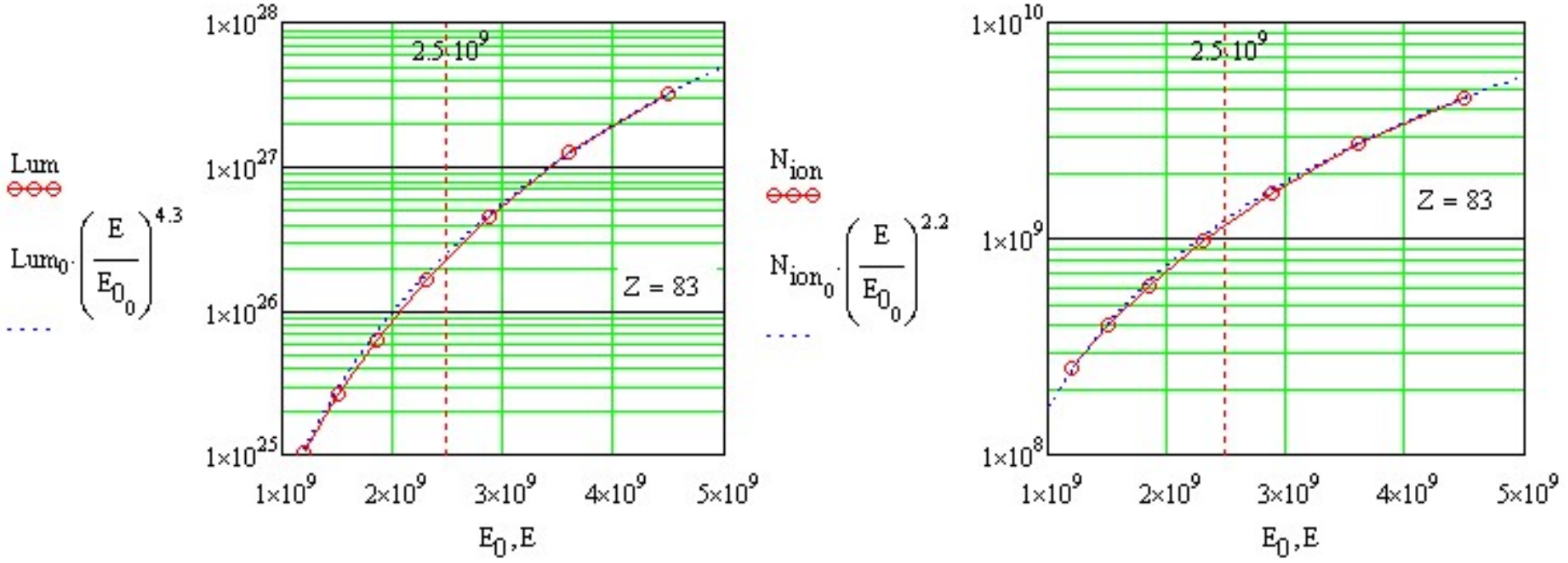
That yields

$$\delta\overline{\theta^2} = -\frac{1}{2}g_{opt}\overline{\theta^2} \quad , \quad g_{opt} = \frac{1}{2N_{sample}} \quad , \quad N_{sample} \approx N\frac{f_0}{W}$$



- In accurate analytical theory the cooling process is described by Fokker-Planck equation
  - The theory is built on the same principle as plasma theory – which is a perturbation theory (large number of particles in the Debye sphere versus large number of particles in the sample)

Projected Luminosity



- Due to the beam space charge the luminosity strongly depends on the beam energy: $L \propto E_{kin}^{4.3}$
  - ⇨It is desirable to start at the maximum energy we can reliably obtain at the commissioning start
    - For now, we assume that 2.5 GeV will be supported by all collider systems and the injection complex

First Demonstration of Luminosity in Collider

- We inject 2 bunches to each ring: $1.7 \cdot 10^8$ ions/bunch
  - Kicker pulsers enable to inject 2 bunches at opposite ring sides
  - Rms emittances: $\varepsilon_x/\varepsilon_y$ = 0.68/055 μm, ε_s=5 meV·s
    - We do RF gymnastic in Nuclotron to shorten bunches before injection to Collider
    - V_{RF2} is adiabatically increased from 15 kV to 75 kV
      ⇨ $\sigma_p=3.8 \cdot 10^{-4}$, σ_s=120 cm
- Peak luminosity – $2.3 \cdot 10^{23}$ $cm^{-2}s^{-1}$ (~0.1% of design - $2.5 \cdot 10^{26}$ $cm^{-2}s^{-1}$)
  ⇒ Corresponding collision rate – 1.1 Hz
  - IBS drives longitudinal emittance growth with 5 min growth rate
    - Little effect on the luminosity
  - After coming to quasi-equilibrium, the overall emittance growth rate will be about ~5 hour
  - We can refill collider every 5-10 min if required
- Next step could be accumulation of ~20-30 bunches with RF1.
  - That can increase the luminosity by an order of magnitude

Getting to Real Collider with Xe Collisions

- To get to the design luminosity at 2.5 GeV/n we need to accumulate 420 injections in each ring with $1.3 \cdot 10^8$ ions per cycle
  - That requires beam cooling and RF1 capable to move injected bunches to the core
  - Total injection time =1.5 hour
- In difference to electron cooling the stochastic cooling does not cause loss of ions

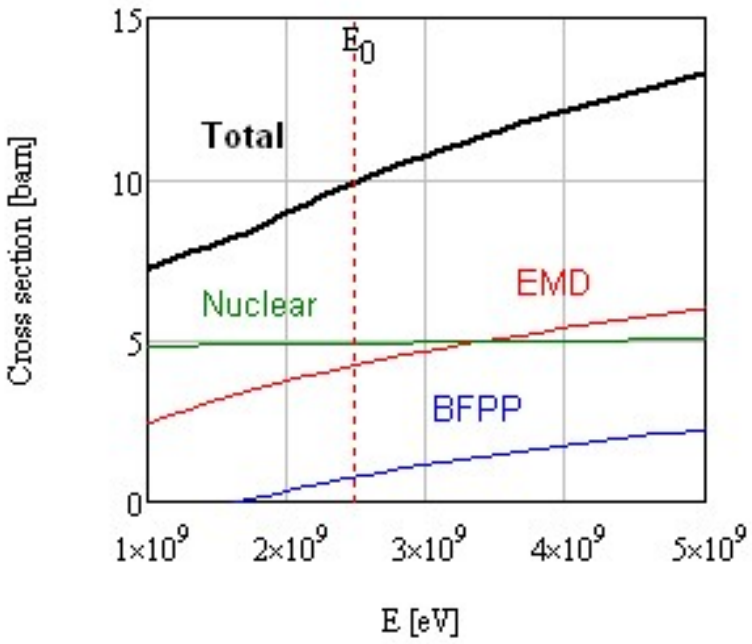
⇨ Luminosity lifetime well above 10 hours

Beam cooling will suppress multiple scattering on the residual gas

- Already demonstrated vacuum should support vacuum lifetime >80 hour.
  Beam lifetime due to Luminosity =6000 hour.

⇨ Collider refill – 1-2 times in 24 hour

The ions left to the store end will be reused. That significantly reduces time of each next collider fill



Conclusions

- Projected performance of injection complex, $2 \cdot 10^8$, should enable to reach luminosity close to its design value at 2.5 GeV/n with Xe
  - That requires minimization of emittance growth and beam loss through the accelerator chain to be achieved by orbit and optics correction and good control of all RF manipulations
    - It cannot be achieved without drastic improvement of machine reliability and efficiency of operations (software, hardware, personnel and management).
- Collider commissioning has to proceed in parallel to the operation with the fixed target experiments supported by slow beam extraction from Nuclotron
- As far as we can estimate for now it will take about 2 years to complete and commission all collider systems. By this time, we should be to reach luminosity where physics results will appear

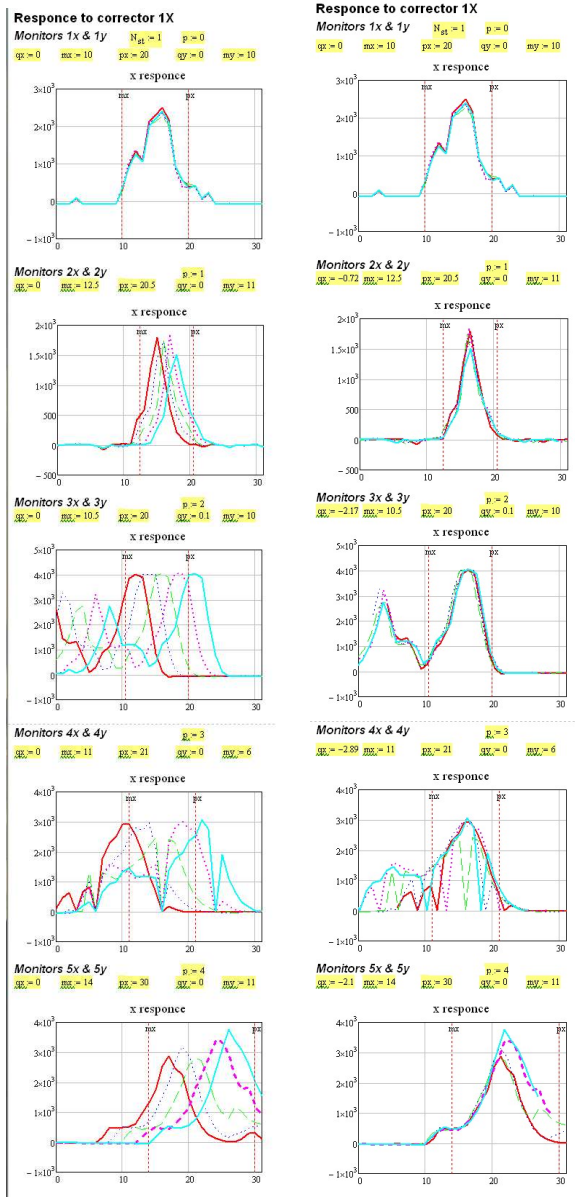
Backup slides

HILAC & Ion Source Problems & Plans

- Ion source
  - Emittance coming out of ion source is well above expected
    - Reasons and remedies for problem correction are not known
  - Related questions
    - Unclear why H & V emittances are different
    - Understanding of dependence of beam current on time can help
    - An introduction of bending magnets in LEBT also can help
  - Better understanding is required => corresponding studies
    - We still did not test beam extraction by running wave
- HILAC
  - We measure doubling of emittance in HILAC (from LEBT to the linac end) – we do not understand why – studies just now
- Looks like we lose well above half of Xe ions
  - 2 nC of $^{26+}$Xe with 22% in the target charge = 10^8 ions
    but typically we capture in Booster $(2 - 2.5)\cdot 10^7$ ions
- We should have to figure out how to double the beam intensity
  - The program of actions is being formulated

Profile Monitors Usage for Dif. Orb. Measurements

- The multiwire monitors were used for the differential optics measurements
- Five different corrector settings were used for each of 4 used correctors
  - 2H and 2V at the line beginning
- The displacement was calculated from coincidence of beam shapes for shifts of the profiles
  - Presently we are testing software for automatic computation of the shifts
  - Submillimeter beam position accuracy was achieved for 2 mm wire pitch
- Multiple ion species do not complicate differential orbit measurements but make difficult to estimate the beam emittance and Twiss parameters for the targeted ion charge

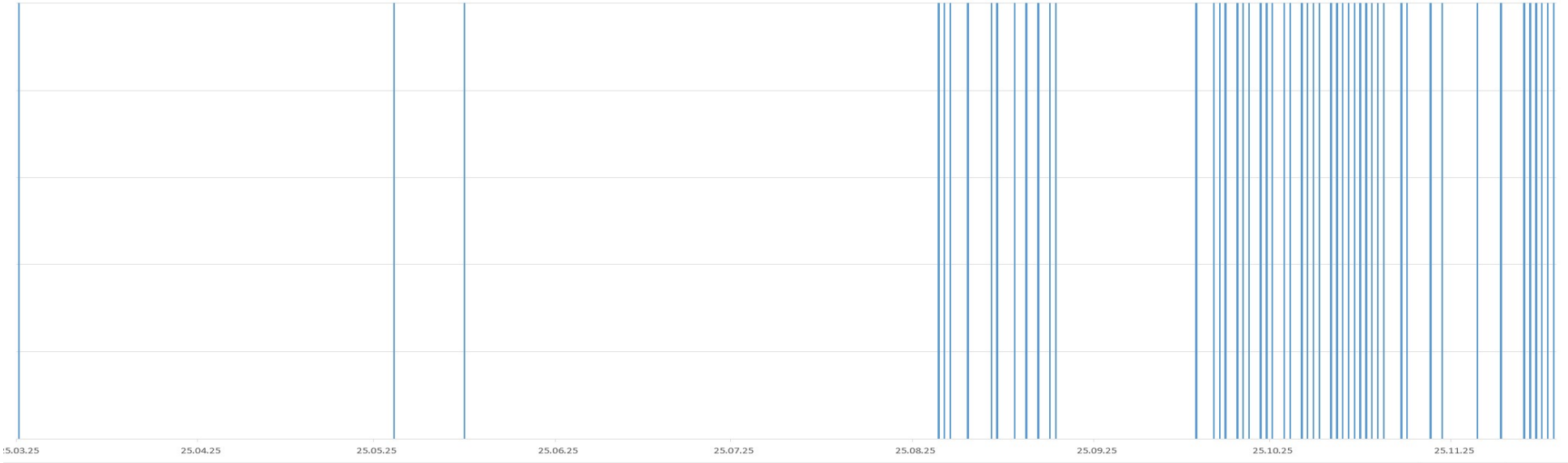


Raw data

After Δx correction

Reliability of Hardware

- Presently reliability of hardware represents very serious challenge for future operations
- We mostly overcame problems with main power supplies and instrumentation
  - Presently generators of injection/extraction kickers represent the most challenging problem



Mulfunctioning and repairs of injection complex kickers: Mar.25-Dec.12.2025.
Altogether 99 events

- Drastic improvement of machine reliability is required

Tentative Parameters of Injected Beam

- Rms transverse beam emittance at Collider injection at 2.5 GeV/n
  - Emittance extracted from Nuclotron: ε=0.5 μm
    - ε set in Booster: 2.5σ in Cooler =14 mm => ε_n=0.31μm (ε=3.7μm)
    - Emit. growth at stripping (400 MeV/n, Cu 20 μm, Eff=83%): x1.62
  - Scattering in foils in Booster-Nuclotron line (2x50 μm, SS): $\Delta\varepsilon\approx$0.17 μm
  - Summing we obtain average the emittance: 0.5($\varepsilon_x+\varepsilon_y$) $\varepsilon\approx$0.62 μm
    - Design rms emittance is 0.7 μm
  - Initially optics match will be poor => $\varepsilon_f=2\varepsilon_i$ => $\varepsilon_f\approx$1.2 mm
    - That means that we should expect minor scraping at injection
- Longitudinal beam emittance
  - Booster emittance estimate for $2\cdot10^8$ ions: $\sigma_p=5\cdot10^{-4}$, σ_s=15 m
    ⇨ ε_s=1.16 meV·s
  - Measured rms emit. in collider: ε_s=5.5 meV·s
    (1.7 GeV/n, $\sigma_p=2.3\cdot10^{-4}$, σ_t=10.5 ns)
  - For further estimates we assume: ε_s=5 meV·s
- Beam intensity
  - Accounting accelerator efficiency we obtain $1.7\cdot10^8$ ions injected to collider if we accumulate $2\cdot10^8$ ions in Booster

Preparations for Collider beam Commissioning (till ~Nov)

- Injection complex hardware
  - An addition of vertical kicker to Booster (rotation ИП-2 by 90 deg)
    - Acceptance increase, optics measurements,
  - Find and fix vacuum leaks in Nuclotron
    - Beam-based measurements yield: $P=2.8\cdot10^{-6}$ torr (molecular H_2 equivalent, T=300 K)
    - Is separation of the beam and isolating vacuums possible?
  - Modify electronics in e-cool BPMs to be able to see the ion beam position with good accuracy
  - Do we need additional protection for e-cool solenoids?
  - Repair/replace pulse generators for kickers to get 400 MeV energy in Booster-Nuclotron transfers and 2.5 GeV/n in Nuclotron collider transfers
    - Why these energies are important?
      - Larger RF bucket at injection to Nuclotron
      - Smaller beam size in Booster-Nuclotron line
    - Have to have it at minimum 25% margin in design and verify it at the test stand

- Injection complex software, studies and tuning
  - Getting beam accumulation to $2 \cdot 10^8$ Xe ions
    - Optics measurements and decoupling in Booster
    - Calibration of ion profile monitor
  - Obtaining reliable operation –That implies that we have means to monitor drifts and mistuning, and means for fast diagnosis of problems
  - Commissioning RF feedback for suppression of synchrotron oscillations and keeping the beam in the center of vacuum chamber
  - Make all Nuclotron BPMs operating at the entire accelerating cycle
    - Subtracting RF EMI signal from beam signal
  - Find "golden" orbit in Nuclotron
  - "Save/restore/compare" for absolutely all parameters
  - Alarms
  - Data logging for all critical parameters
- The Booster-Nuclotron transfer line
  - The goal - getting transfer efficiency to >80%
  - Optics measurements in Booster-Nuclotron line. Optics and orbit correction – Can we use BPMs for the measurements?
    - Prevention of emittance growth and beam loss at transfers

- The Nuclotron-Collider line
  - The goal - getting transfer efficiency to >98% (it was 10%)
  - Nuclotron-Collider transfer line (beam energy >2.5 GeV/n)
  - Install all required BPMs and at least 3 viewers for each line
    - Stripline BPMs are preferable
  - Leave only two 100 μm SS foils on the beam way (no air)
  - Commission both lines before the end of collider cooldown
    – Orbit correction & optics measurements
  - Finding & fixing sources of beam jitter.
- Collider
  - Repair cryo-magnetic system and verify its operation; goal – 1.8 T
  - Connect and verify operation of all correctors, quads & sextupoles
  - Install scrapers (decide on a necessity of momentum collimation)
  - Finish RF2 cavities installation and verify their operation; goal - 100 kV
  - Commission RF1 and verify mechanics of its operation without beam
  - Install the band 2 longitudinal stochastic system to the shutdown end
    - Transverse band 2 systems may come with 3-4 months delay