Colliders and NICA

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NICA Injection complex
Run 4 Retreat
April 1, 2023
Tsey

Outline

- Historical Review of Colliders
- NICA – the First Hadron Collider in Russia
- NICA Injection Complex and Results of its Recent Run
- Conclusions

Collision Energy and Luminosity

- Collision energy for equal mass relativistic particles
  - One particle is stationary

$$E_{cm} \approx \sqrt{2mc^2\left(E_k + 2mc^2\right)} \approx \begin{cases} \sqrt{2mc^2 E_k}, & E_k \gg mc^2 \\ 2mc^2 + E_k/2, & E_k \ll mc^2 \end{cases}$$

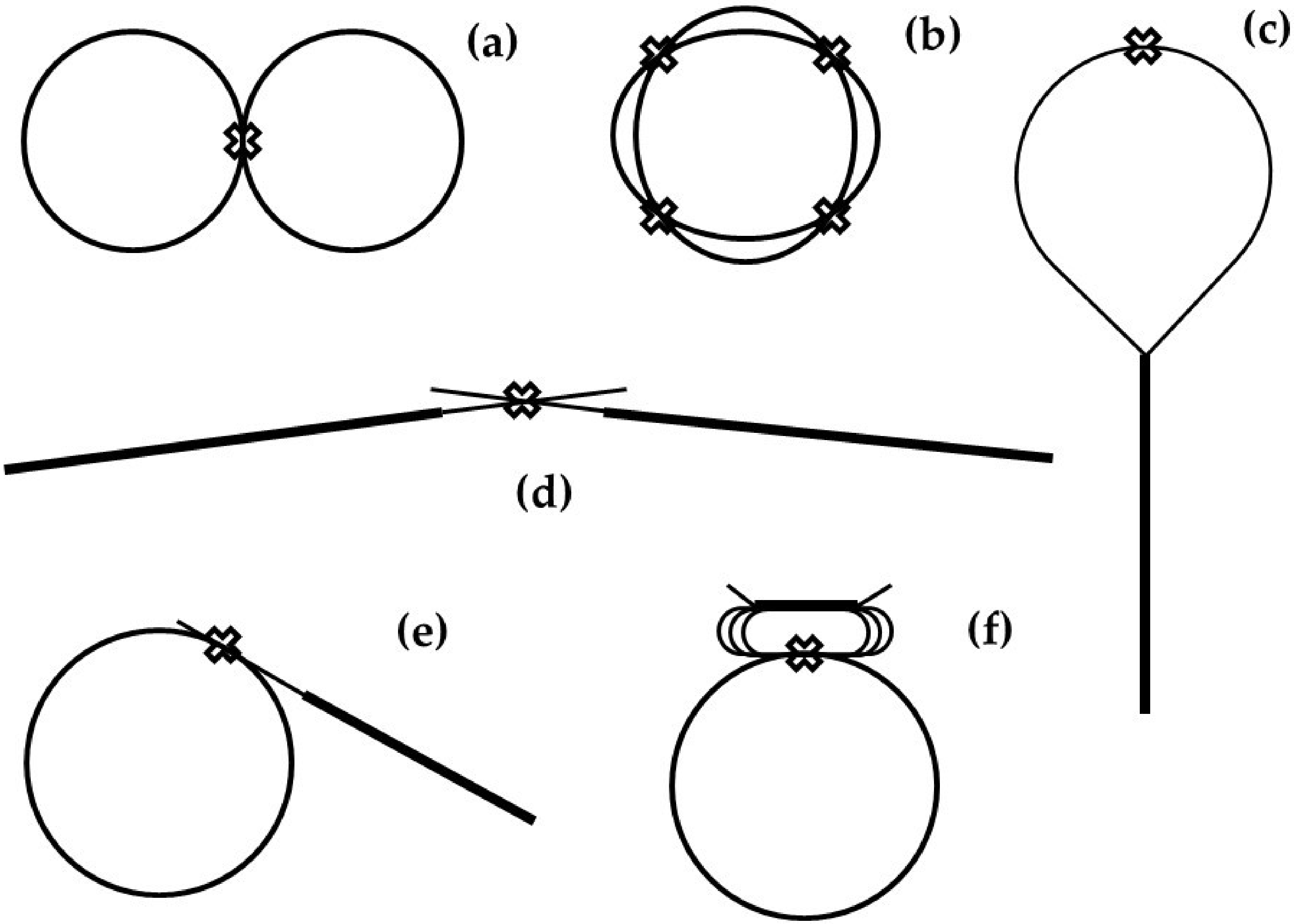
  - Both particles move: $E_{cm} = 2E$

    (120 times gain for the LHC)
- NICA collision energy for heavy ions
  - External target (equal masses): 3.9 GeV/n => $E_{cm}-2mc^2=1.4$ GeV/n
  - Collisions: 1.5-4.5 GeV/n => $E_{cm}-2mc^2=3\text{-}9$ GeV/n
- Luminosity
  - Number of events in collisions:

$$\frac{dN}{dt} = L\sigma$$

    L is the luminosity
  - Detectors want constant luminosity, as large as they can digest

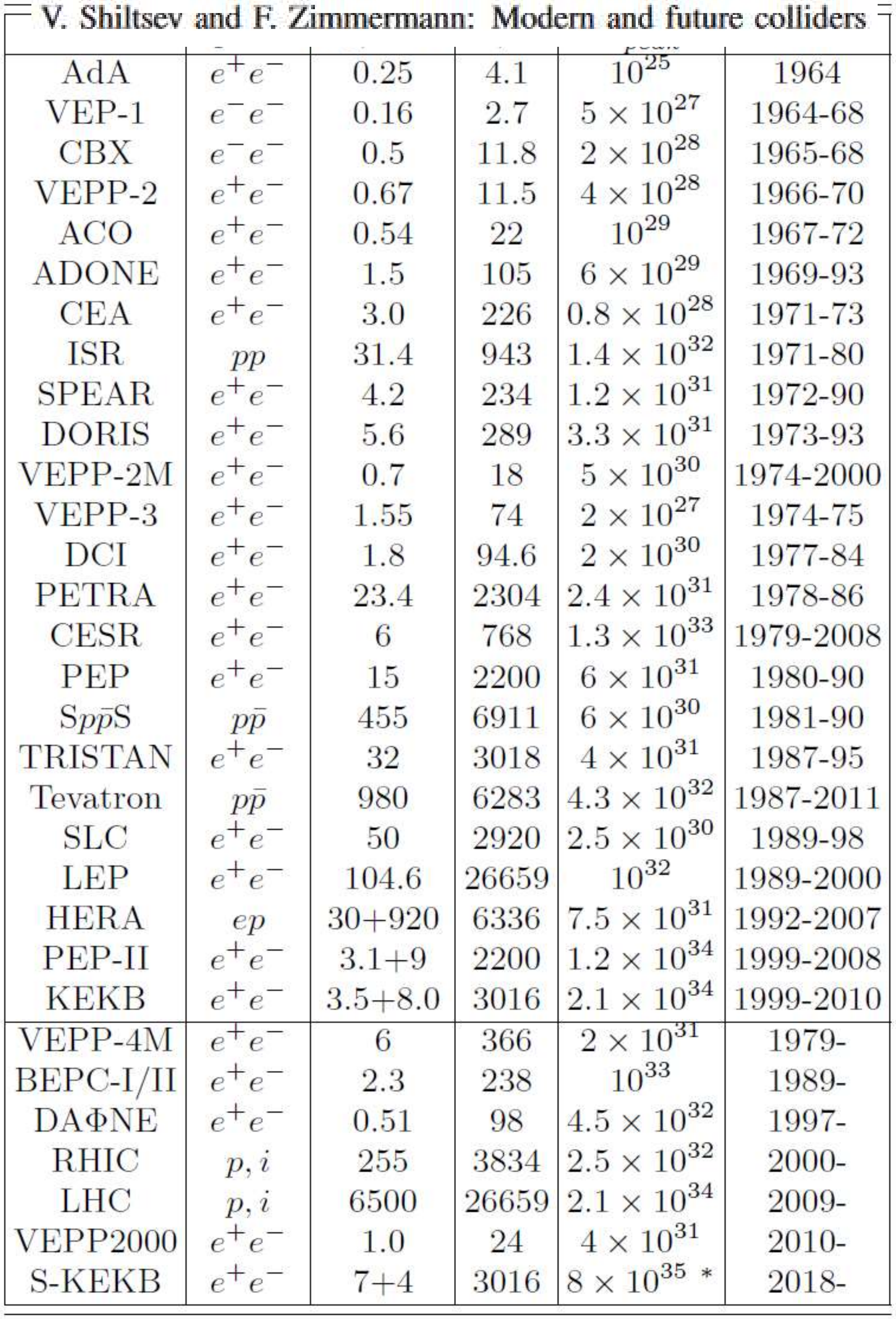
Types of Colliding Beam Facilities



- Since 60’s colliders have been the major instrument in the particle physics

Colliders Landscape

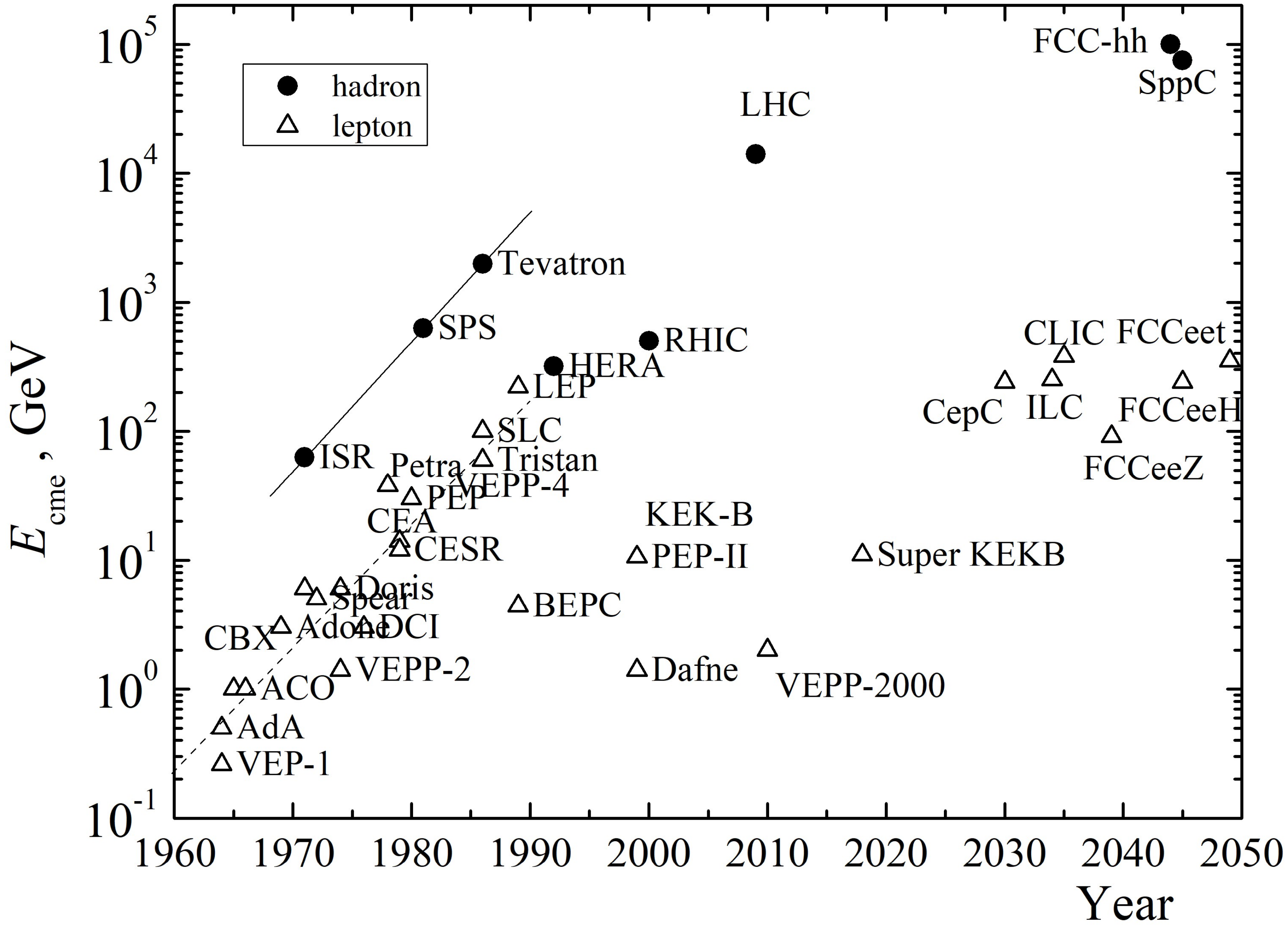
- 59 years since 1st collisions
    - Spring 1964 AdA and VEP-1
- 31 operated since
- 7 in operations now
    - S-KEKB, VEPP-2000, VEPP-4M, BEPC, DAFNE
    - LHC, RHIC
- 1 under construction
    - NICA
- One in an initial project phase
    - EIC
- Far plans
    - Higgs/Electroweak factories
        - ILC
        - FCC: e^+e^-
    - Frontier hadron (E >> E_{LHC})
        - FCC: pp



V. Shiltsev and F. Zimmermann: Modern and future colliders

AdA	e^+e^-	0.25	4.1	10^{25}	1964
VEP-1	e^-e^-	0.16	2.7	5×10^{27}	1964-68
CBX	e^-e^-	0.5	11.8	2×10^{28}	1965-68
VEPP-2	e^+e^-	0.67	11.5	4×10^{28}	1966-70
ACO	e^+e^-	0.54	22	10^{29}	1967-72
ADONE	e^+e^-	1.5	105	6×10^{29}	1969-93
CEA	e^+e^-	3.0	226	0.8×10^{28}	1971-73
ISR	pp	31.4	943	1.4×10^{32}	1971-80
SPEAR	e^+e^-	4.2	234	1.2×10^{31}	1972-90
DORIS	e^+e^-	5.6	289	3.3×10^{31}	1973-93
VEPP-2M	e^+e^-	0.7	18	5×10^{30}	1974-2000
VEPP-3	e^+e^-	1.55	74	2×10^{27}	1974-75
DCI	e^+e^-	1.8	94.6	2×10^{30}	1977-84
PETRA	e^+e^-	23.4	2304	2.4×10^{31}	1978-86
CESR	e^+e^-	6	768	1.3×10^{33}	1979-2008
PEP	e^+e^-	15	2200	6×10^{31}	1980-90
S$p\bar{p}$S	$p\bar{p}$	455	6911	6×10^{30}	1981-90
TRISTAN	e^+e^-	32	3018	4×10^{31}	1987-95
Tevatron	$p\bar{p}$	980	6283	4.3×10^{32}	1987-2011
SLC	e^+e^-	50	2920	2.5×10^{30}	1989-98
LEP	e^+e^-	104.6	26659	10^{32}	1989-2000
HERA	ep	30+920	6336	7.5×10^{31}	1992-2007
PEP-II	e^+e^-	3.1+9	2200	1.2×10^{34}	1999-2008
KEKB	e^+e^-	3.5+8.0	3016	2.1×10^{34}	1999-2010
VEPP-4M	e^+e^-	6	366	2×10^{31}	1979-
BEPC-I/II	e^+e^-	2.3	238	10^{33}	1989-
DAΦNE	e^+e^-	0.51	98	4.5×10^{32}	1997-
RHIC	p, i	255	3834	2.5×10^{32}	2000-
LHC	p, i	6500	26659	2.1×10^{34}	2009-
VEPP2000	e^+e^-	1.0	24	4×10^{31}	2010-
S-KEKB	e^+e^-	7+4	3016	8×10^{35} *	2018-

Colliders: Energy



Colliders: Luminosity

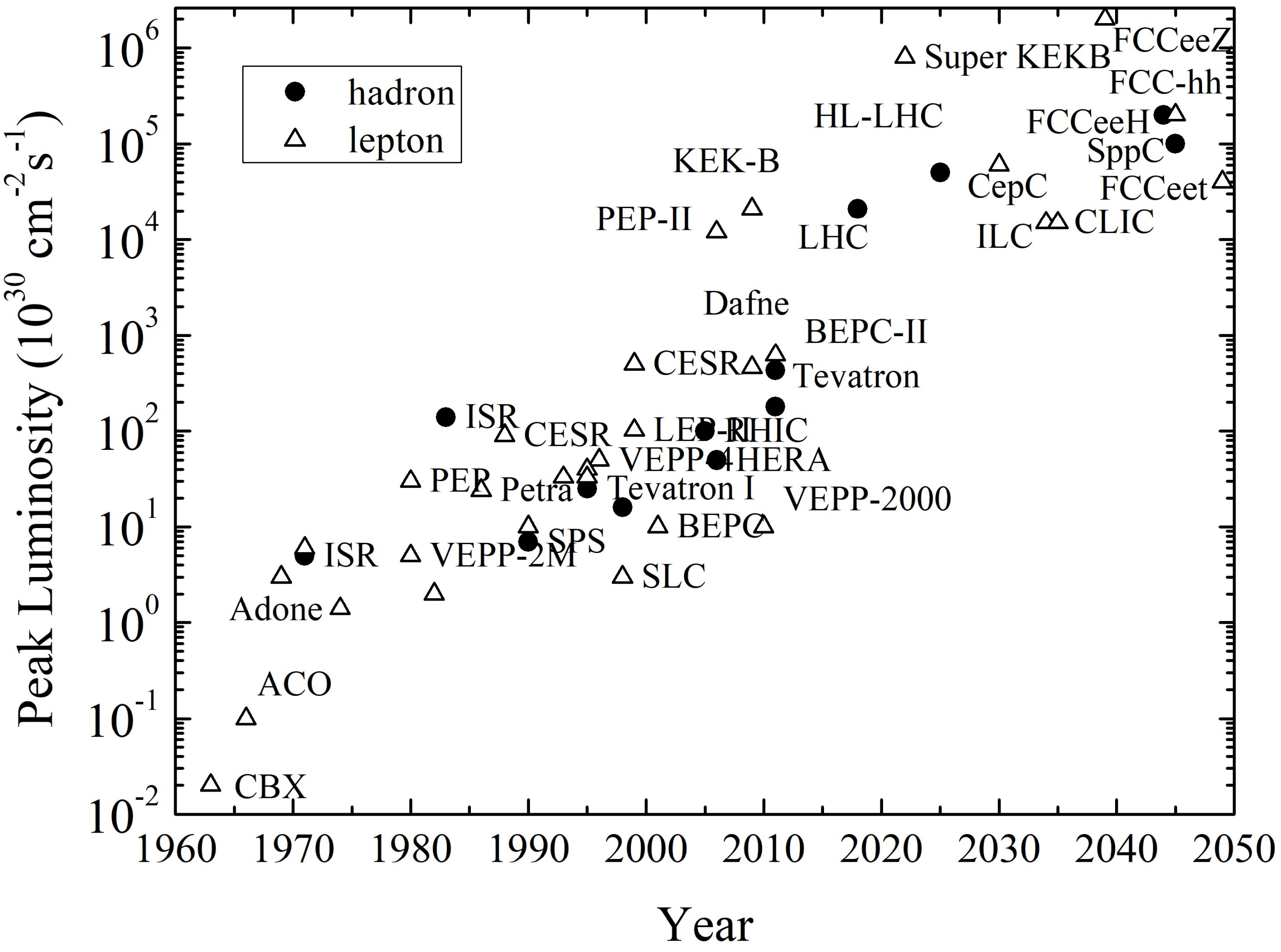


FIG. 3. Luminosities of particle colliders (triangles are lepton colliders and full circles are hadron colliders, adapted from [37]). Values are per collision point.

Highest Energy = Highest Field SC Magnets

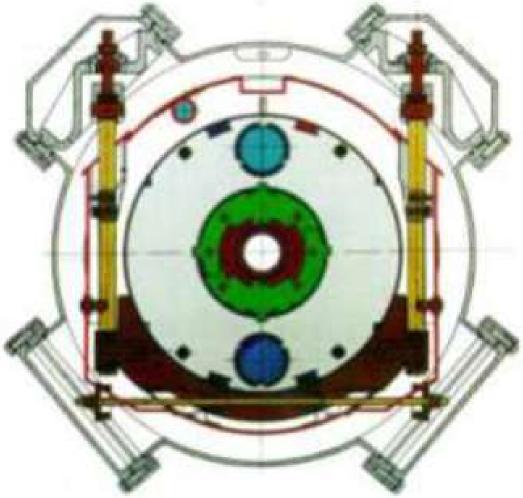
4.5T

Tevatron,
6 m, 76 mm
774 dipoles

4.5 K He, NbTi
+ warm iron
small He-plant

5.3T

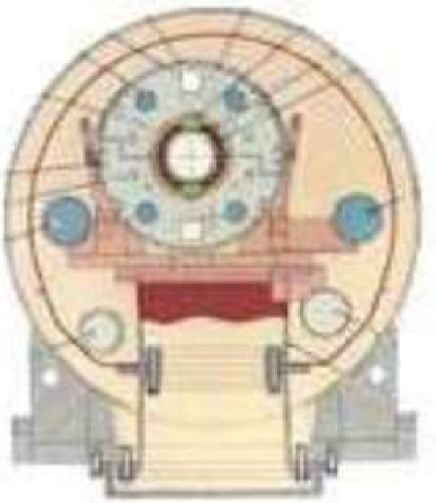
HERA,
9 m, 75 mm
416 dipoles



NbTi cable
cold iron
Al collar

3.5T

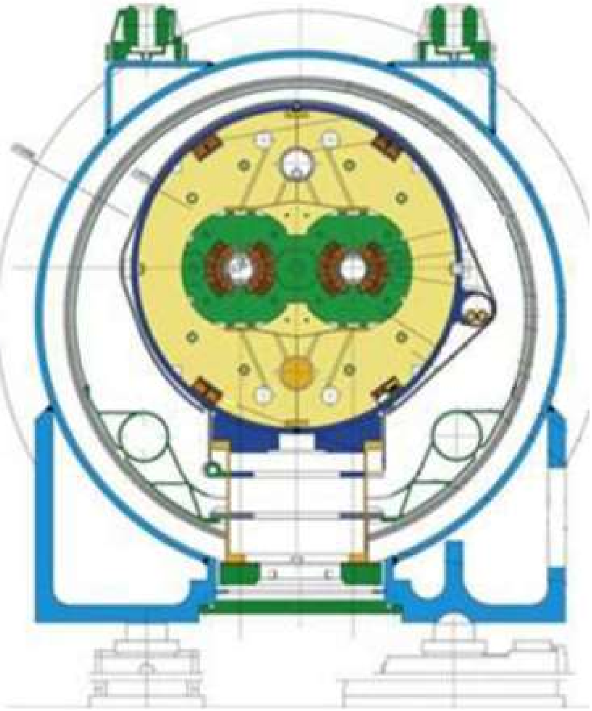
RHIC,
9 m, 80 mm
264 dipoles



NbTi cable
simple &
cheap

8.3T

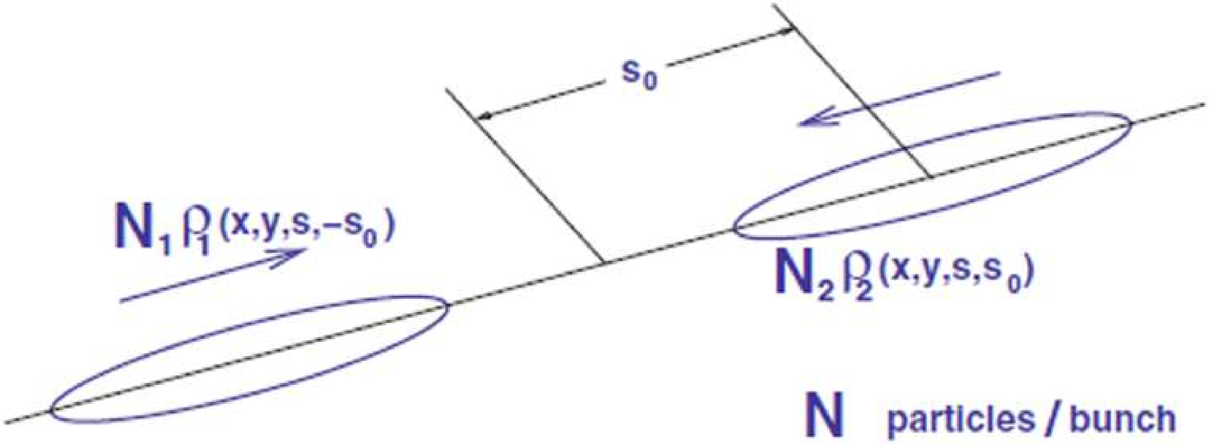
LHC,
15 m, 56 mm
1276 dipoles



NbTi cable
2K He
two bores

Luminosity

$$N_{\rm exp} = \sigma_{\rm exp} \cdot \int \mathcal{L}(t)\,dt$$



N particles / bunch

ρ density ≠ const.

For (same size) Gaussian bunches:

$$\mathcal{L} = f_{\rm coll}\frac{N_1 N_2}{4\pi\sigma_x^*\sigma_y^*}$$

Luminosity Evolution in the Absence of Cooling

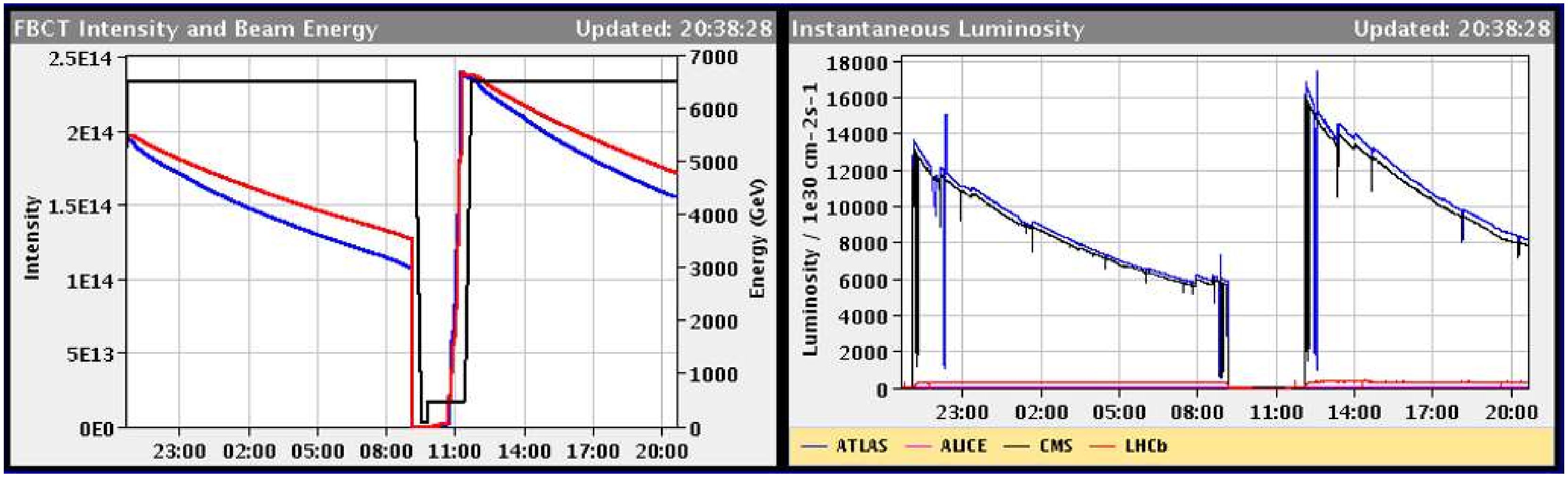
$$L = \gamma f_B \frac{N_1 N_2}{4\pi\beta^*\varepsilon} H(\sigma_s / \beta^*)$$

- Factors change in time:

$$L(t) = C\frac{N_1(t)N_2(t)}{\varepsilon(t)}H(t)$$

- Therefore, in the absence of cooling the lifetime

$$\tau_L^{-1} = \frac{dL(t)}{L(t)dt} = \tau_{N1}^{-1} + \tau_{N2}^{-1} - \tau_{\varepsilon}^{-1} + \tau_H^{-1}$$



LHC luminosity plot

- Cooling at the collision energy enables to exclude a dependence of luminosity on time

NICA – the First Hadron Collider in Russia

Why NICA?

Main Parameters of The NICA Collider

Parameter			
Circumference, m	503,04		
Bunch number per ring	22		
Mean-square bunch size, m	0.6		
Min. beta-function (β*), m	0.6		
Ion energy, GeV/u	1.0	3.0	4.5
Ion number per bunch, 1e9	0.275	2.4	2.2
Peak luminosity, cm^{-2}·s^{-1}	0.9e25	0.9e27	6.3e27

- NICA is built to answer two questions
  - What are the phases of strongly interacting matter, and what roles do they play in the cosmos?
  - Understand the spin structure of the proton/deuteron (g-factor)
- Unique niche
  - Two major competitors (LHC & RHIC) have too large energy to get to the ultimate luminosity in the interesting region of low energy of few GeV/n

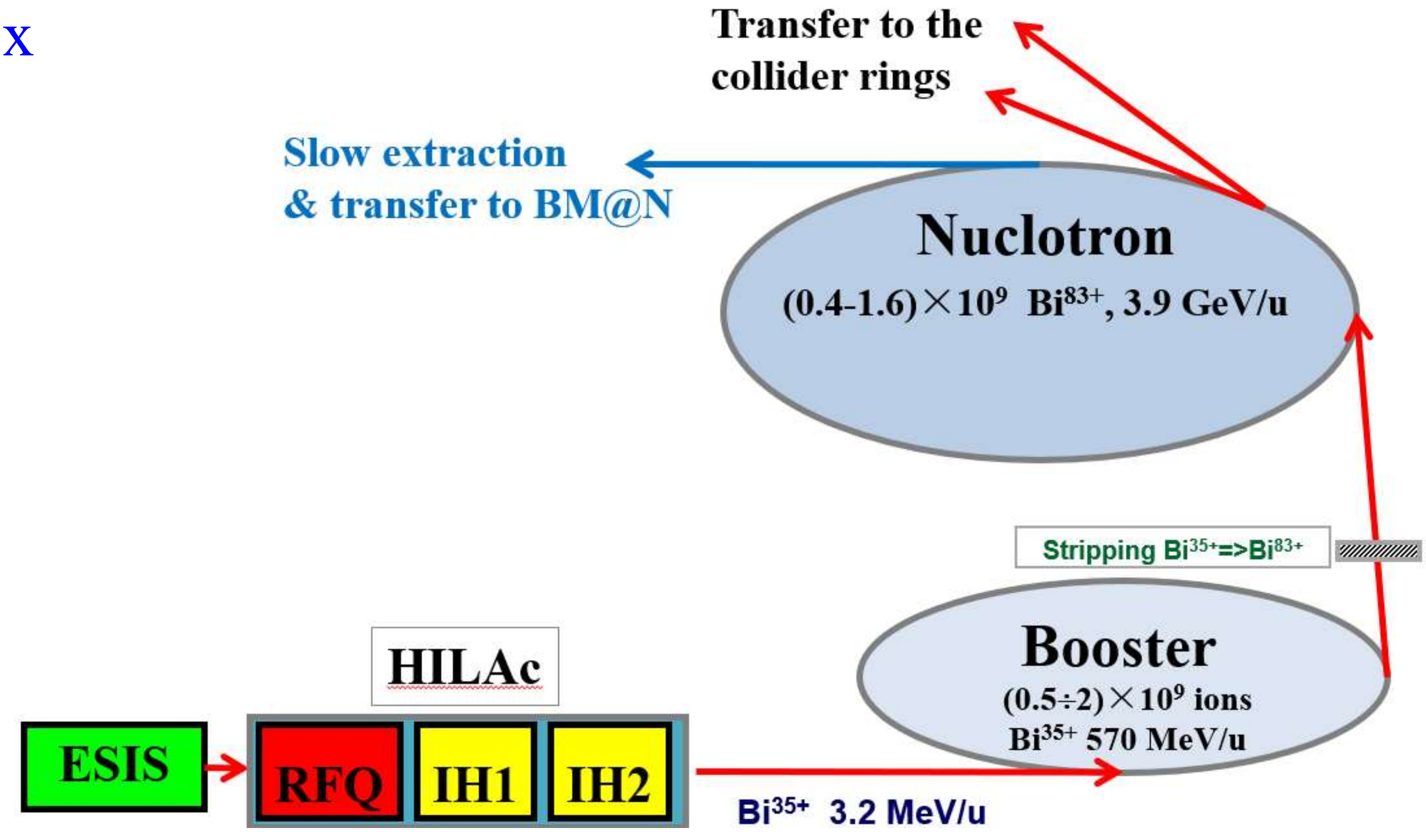
NICA Challenges

- From accelerator physics point of view NICA has complete set of problems/technologies present in modern hadron colliders
  - Ultrahigh vacuum
  - Superconducting magnets
  - Large beam current results in beam instabilities => their suppression
  - Low-beta optics brings dynamic aperture limitations
    - Careful design of machine optics, optical measurements and correction
  - Electron and stochastic cooling at collisions
  - Instrumentation and controls required for modern colliders
  - …

NICA Injection Complex and Results of its Recent Run

NICA Injection Complex

- Injection complex includes:
  - Ion source
  - Linac
  - Booster
  - Nuclotron



Injection complex parameters (RuPAC-2021 with Au->Bi and accounted beam loss at stripping))

- In the course of recent Run (ended in the beginning of February 2023) we demonstrated acceleration of ~$5 \cdot 10^6$ Xe ions accelerated to the top energy of Nuclotron
  - That is at least ~100 times smaller than required

<u>How critical is this loss?</u>

Requirements and Possibilities

$$L = f_{coll}\frac{N_1 N_2}{4\pi\sigma_x^*\sigma_y^*} \xrightarrow[N_1=N_2=N]{\varepsilon=\varepsilon_x=\varepsilon_y,\,\beta^*=\beta_x^*=\beta_y^*} f_{coll}\frac{N^2}{4\pi\varepsilon\beta^*}$$

- To support the design luminosity, we need a lot of particles in collider rings supplied within relatively small time:
  - The design presented at RuPAC-21 assumes ~$6.8\cdot10^{10}$ Bi ions in each ring (0.5 A average beam current!!!)
  - With $5\cdot10^{8}$ accelerated in Nuclotron we will need 270 injections to fill both rings
  - For cycle duration of 5 s it will require ~22 min of injection complex operation
    - This time becomes comparable to the store duration and its further increase will negatively affect the luminosity integral
- Thus, the luminosity will critically depend on the flux of particles from the injection complex
  - Consequently, an achievement of the design number of ions accelerated in one cycle becomes very high priority item

Number of Ions through the Accelerator Complex

	Energy [MeV]	Rev. freq. [kHz]	Number of ions [10^6]
Ion source	0.0166	n/a	~100
Booster injection	3.203*	117.6	~50
Booster flat top	203.8*	812.58	~30
Nuclotron injection (1st turn)	201.87*	679.21	~10
Nuclotron extraction	3.896	1169.30	~5

* Measurement is based on the revolution frequency assuming the following circumferences: Booster – 210.96 m (design), Nuclotron – 251.52 m.

Major sources of poor acceleration efficiency (no e-cooling)

- Too long bunch coming out of the ion source (~ ×0.6)
- Insufficient RF voltage in Booster (~ ×0.7)
- Poor orbit correction through entire machine => small acceptances (~ ×0.5)
- Stripping efficiency (~ ×0.8)
- Longitudinal emittance growth in Booster acceleration (~ ×0.5)
- Insufficient RF voltage in Nuclotron (~ ×0.7)

$0.6*0.7*0.5*0.8*0.5*0.7=0.059$

What was and what was not done

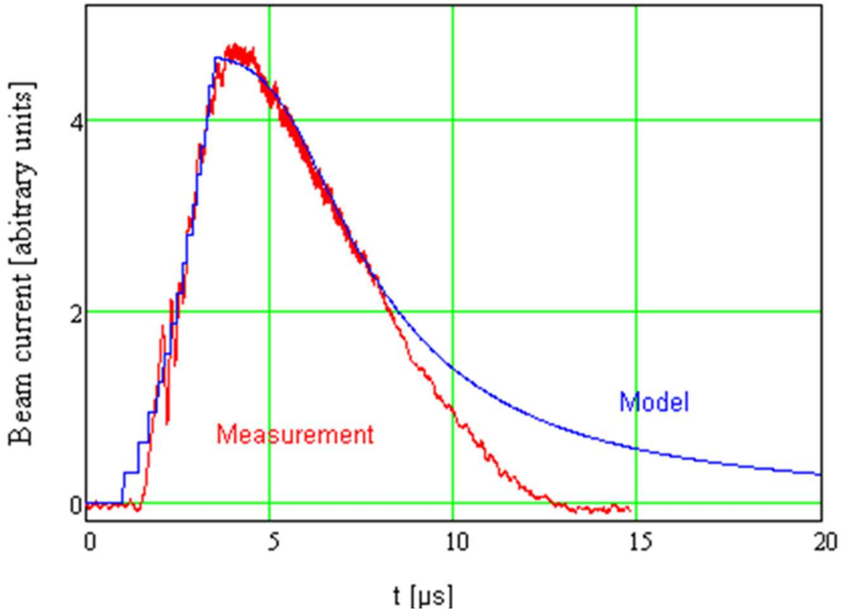
- Ion source and linac
  - Tuned as well as we could
  - Obtained good experience with the source operation
  - Got some understanding of why beam pulse is long and what needs to be done to make it shorter
  - We do not know why the beam current is significantly smaller than expected
  - We did not measure the beam emittance
    - still expect that the accumulated data will give some clue
- Ion source and linac
  - Tuned as well as we could
  - Did not measure beam optics
  - Insufficient understanding of beam loss distribution along linac
    - Little understanding of linac aperture limitations / alignment

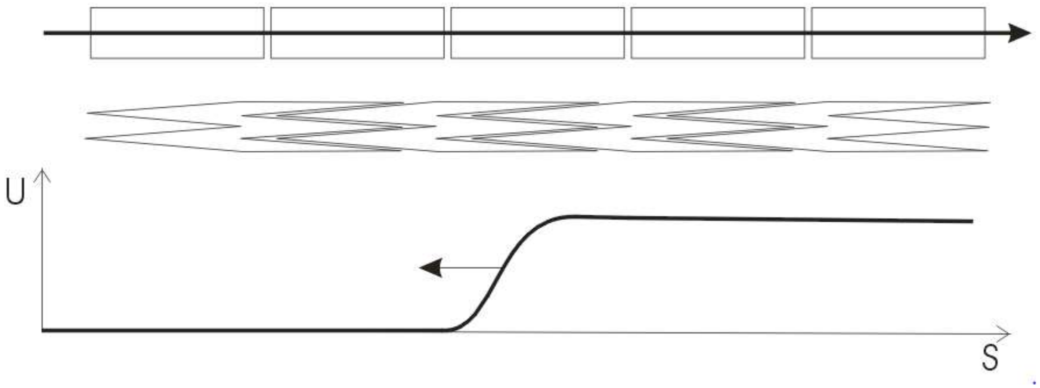
What was and what was not done

- Booster and Nuclotron
  - Orbit correction
  - Chromaticity measurements
  - Tune measurements
  - Optics measurements including coupling
  - Orbit centering on apertures
  - Acceptance measurements
  - Electron cooling
- Transfer lines
  - Optics measurements and matching to rings
  - Aperture characterization
  - Study and optimization of scattering on the stripping foil

Ion Source

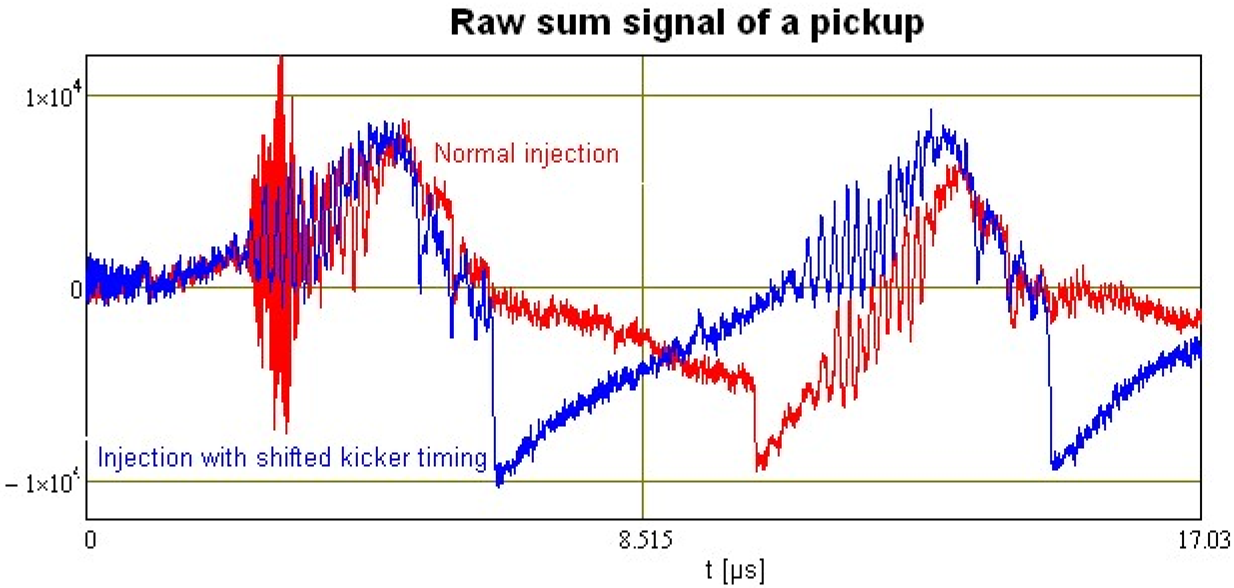
- Presently the total duration of ion source pulse is ~10-20 μs
  - Only 8 μs fit to the Booster circumference
  - Large duration of the pulse is related to the slow exit from ion source pipes used for extraction
  - This problem is going to be addressed in the upgrade
- The upgrade of ion source includes
  - Changing geometry of ion holding cylinders so that the extraction electric field would be penetrating into cylinders
  - Instead of resistive divider a use of delay line to create a traveling wave propagating along the ion column



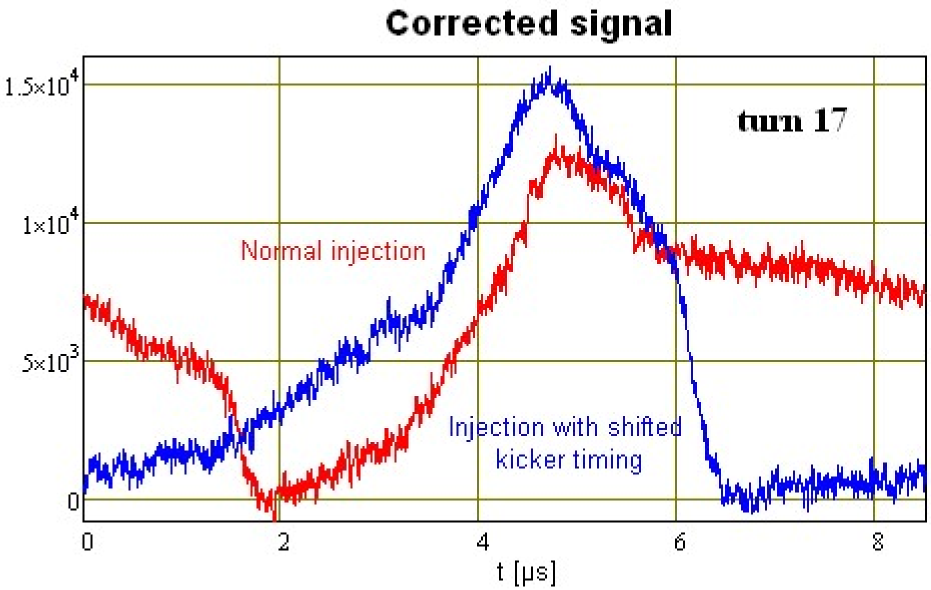


Longitudinal Emittance of Beam Injected to Booster

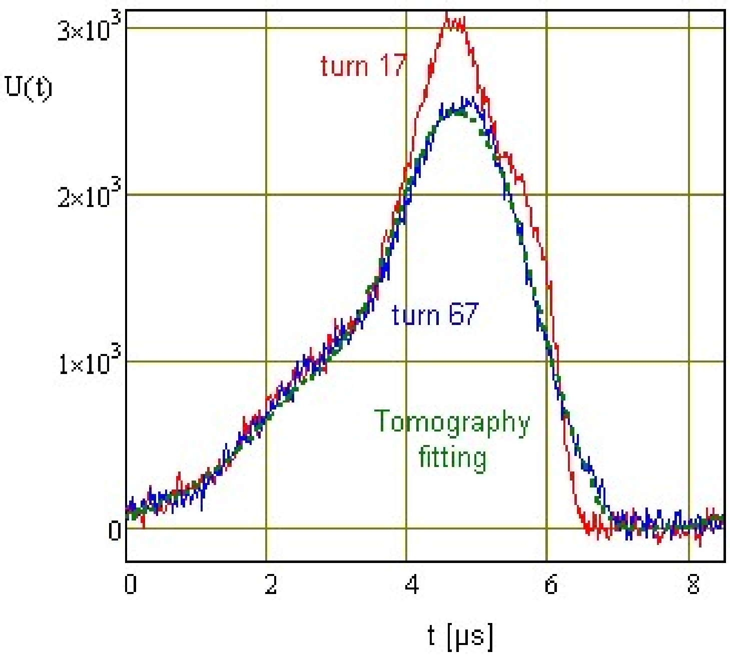
- To perform the tomography of injected beam we shifted the kicker pulse so that to free about half of the orbit

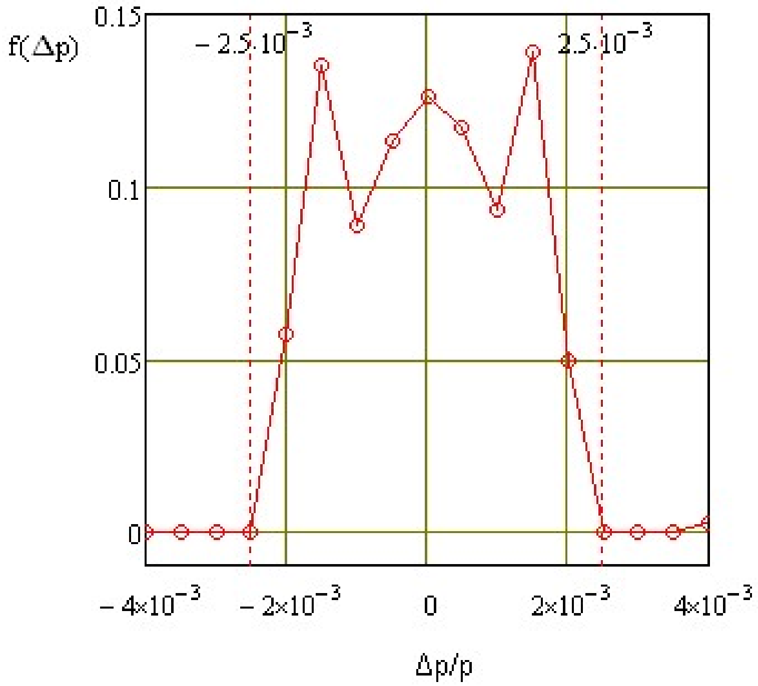


- Correction of pickup frequency response yields actual beam current
- Tomography assumes that $f(s,p,t)=f(s,t)f(p)$ It should be comparatively good approximation since the beam loading is small



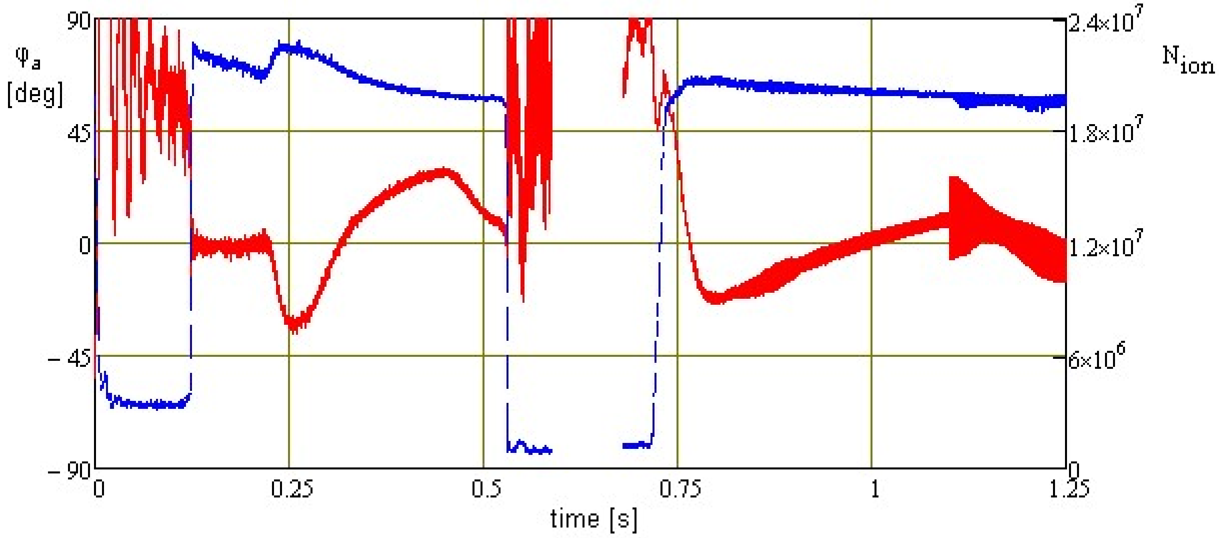
Longitudinal Tomography Results



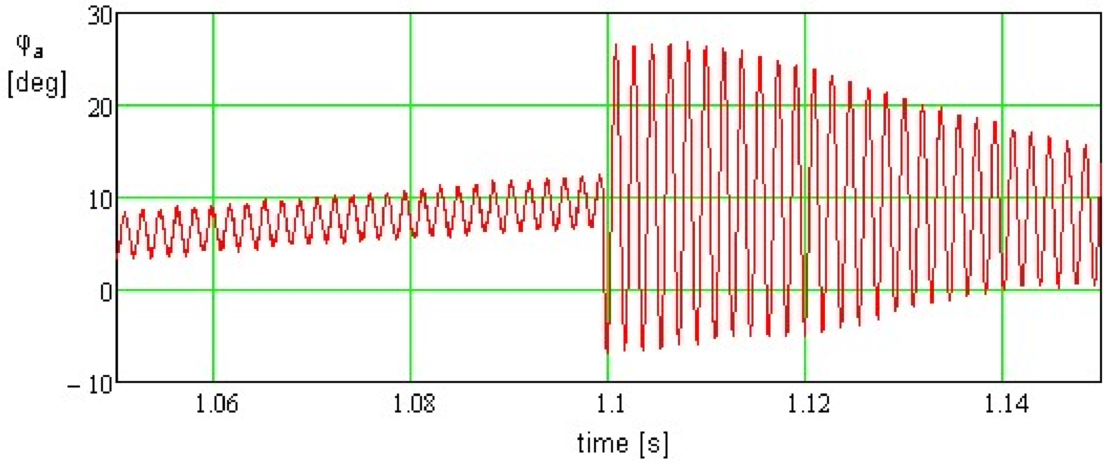


- Total longitudinal momentum spread of $\pm 2.5\cdot 10^{-3}$ corresponds to the total longitudinal emittance (total area) equal to 0.27 eV·s
  - Through most of the Run the total longitudinal emittance of extracted beam is 0.58 eV s (data acquired at Dec. 12, 2022, see https://ad-docs.jinr.ru/cgi-bin/sso/ShowDocument?docid=8)
    - *i.e.* during acceleration the Booster L. emittance grows ~2 times
    - If we could prevent the emittance growth, we would not have longitudinal loss at Booster-Nuclotron transfers and at the capture in Nuclotron

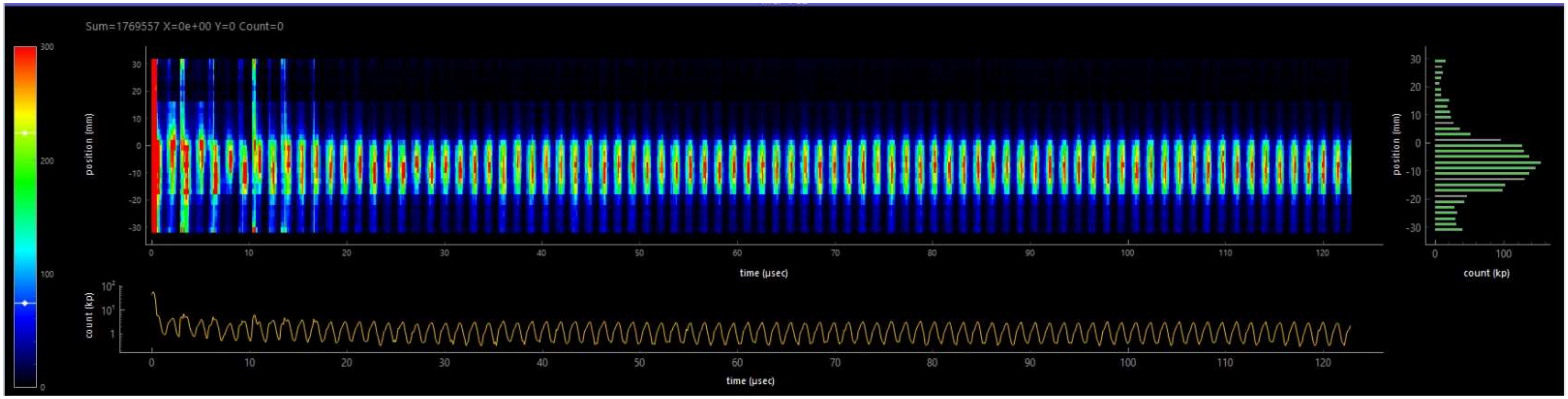
Longitudinal Acceptance Conservation during Acceleration



- Incorrect setting of RF frequency in Booster was present during major fraction of Run 4
  - It resulted in doubling of longitudinal emittance and significant increase of beam loss in Nuclotron
- Considerable amplitude of synchrotron motion was also present due to minor errors in Booster RF setting and poor reproducibility in magnetic cycles and also it may be in the reference magnet hardware



Beam Sizes and IPM Measurements

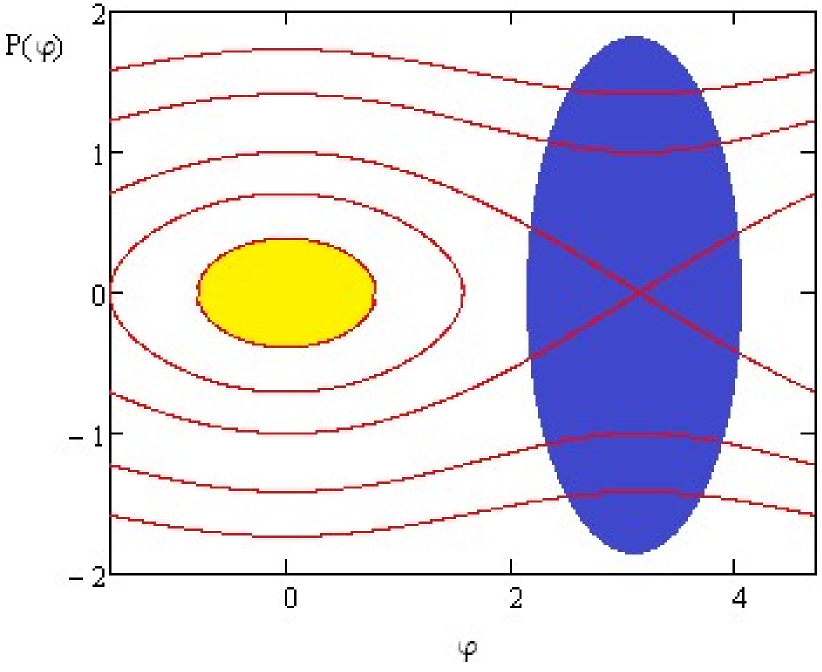


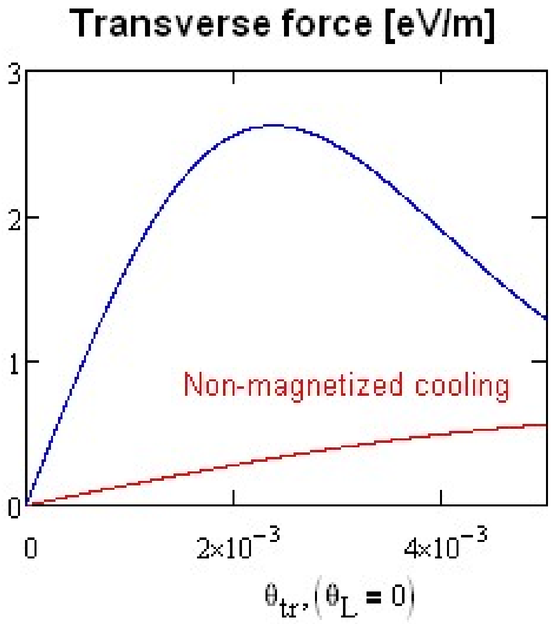
Graphical view of Nuclotron vertical IPM at injection

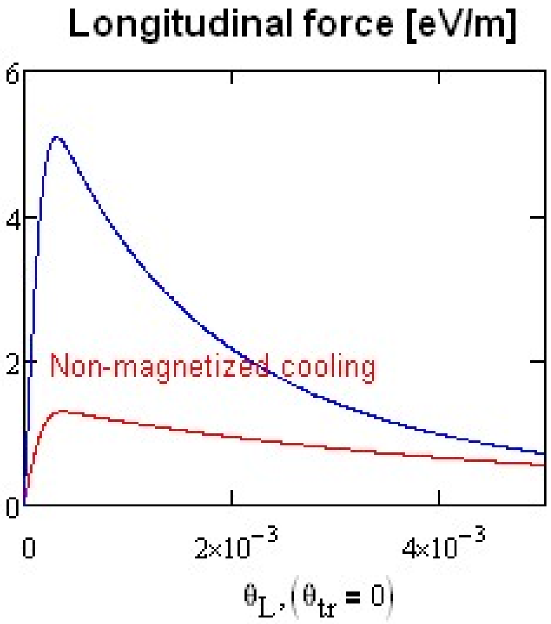
- Single bunch in Nuclotron can be clearly seen by IPM
  - Time spread of single pulse potentially enables to measure the residual gas composition at the IPM location
- Looks like that the distorted profiles at the beginning are related to the beam loss
- Data which IPM is expected to report in the future
  - Beam profiles
  - Rms beam sizes
  - Characterize the dipole and quadrupole oscillations due to injection errors

Beam Accumulation Scheme

- Each new injection happens after the previous one and is cooled to the core
- The permanently present 1st harmonic RF weakly affects large amplitude particles
- For small amplitude particles the cooling force will be intentionally reduced to avoid overcooling
- To avoid anticoolig we need to match well the injection magnetic field and e-beam energy
    - It happens since *dF*/*dt* changes sign after reaching the peak
- Presently it looks like that additional cooling at 65 MeV/n is not required




Transverse force [eV/m]

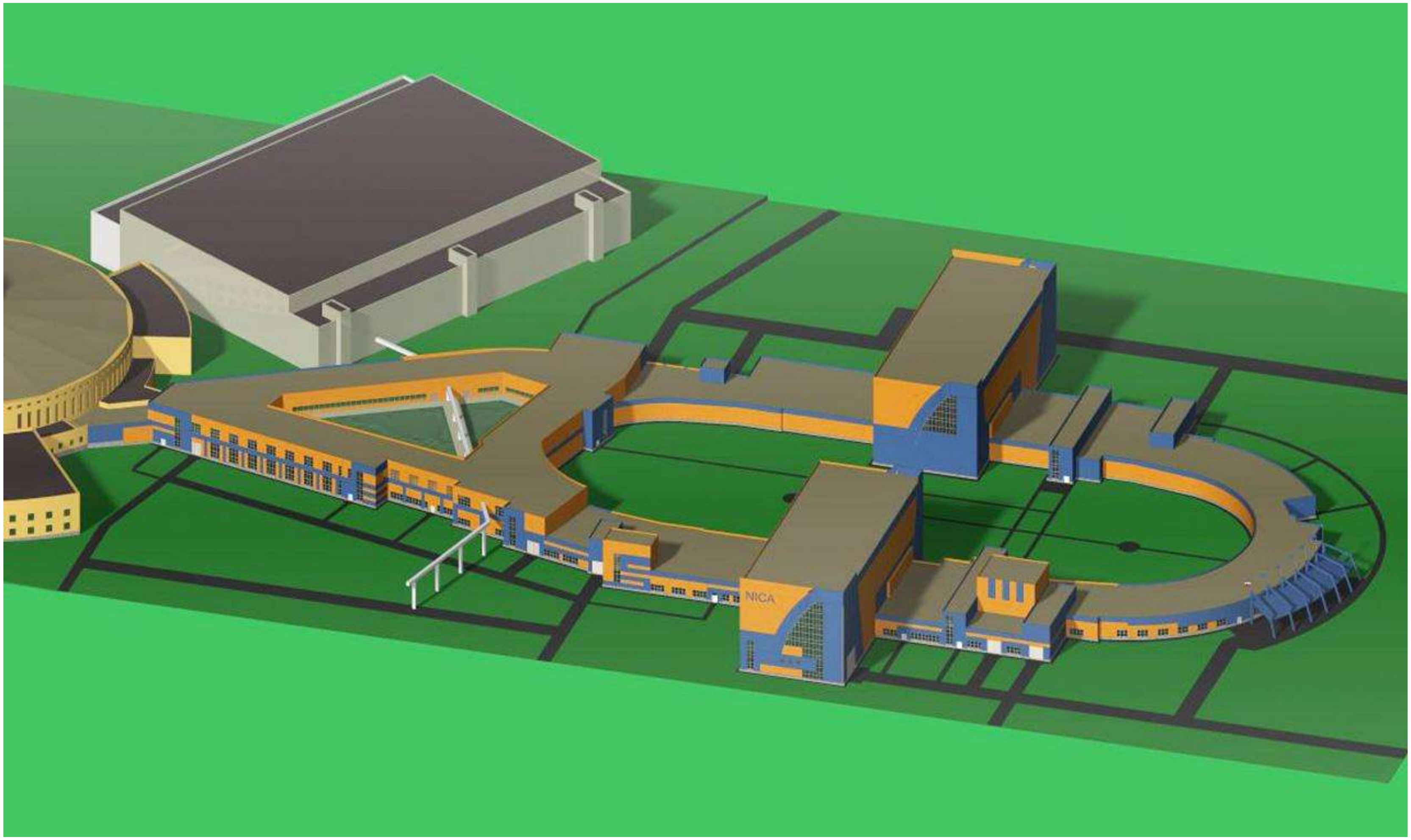

Longitudinal force [eV/m]

Conclusions

- We must to increase a number of accelerated ions by 2 orders of magnitude
  - It will be achieved by
    - an upgrade of the ion source
    - accumulation of ions in Booster with help of electron cooling
    - a reduction of beam loss in the course of acceleration
- Each of the above items presents a great challenge and their addressing will require considerable time
  - We start preparations for the next Run now
- The most important directions for this shutdown
  - Ion source
  - Bringing hardware and software to the next level of reliability and readiness required by the next Run
- This meeting has to result in
  - a list of items we need to do
  - and a plan of work to be done for the next Run

Conclusions (2)

- The most important achievement of this Run:
  we formulated a conception of injection complex upgrade
- Administrative actions
  - We move to professional operations
  - We have to reduce number of people required for complex operation from 20+ to ~7
    - The head of each control room has to present actions to support the transition
      - ⇒ Hardware
      - ⇒ Software
      - ⇒ Training (instructions and manuals)
    - Details need to be understood and finalized



- In the course of next decade there will be interesting and challenging work at the very frontier of accelerator and nuclear physics

World class accelerator and nuclear physics