NICA: from the Collider Concept to its Implementation

Valeri Lebedev, JINR

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Vladikavkaz

Talk Objectives

- Consider main ideas behind the NICA conceptual proposal
- Short survey of what was changed in the course of project development
- Asses recent progress in commissioning of the injection complex
- Look into expectations for collider commissioning

Objectives for the Collider Proposal

- Maximize the luminosity basing on the experience already obtained by accelerator physics community
- Look into optimal strategy & Parameter interdependence
- Only operation with heavy ions is considered (Au^{79+}, Bi^{83+})
  - Proton mode requires additional insight and, may be, an additional place in the straight lines: snakes, etc.
  - presently we assume the same optics as for heavy ions, but it may be changed in the future
- Major effects limiting the luminosity
  - Beam-beam and space charge
  - Beam optics including non-linear effects
  - IBS
  - Cooling
  - Luminosity lifetime
  - Instabilities

Betatron Tune Shift due to Beam Space Charge

- Dependence of betatron tunes on the betatron amplitude results in that the tunes of some particles stay at non-linear resonances
  - Consequently, particle amplitudes grow resulting in the beam loss
  - SC effect is diminishing fast with beam energy

$$\begin{bmatrix}\delta\nu_{SC_X}\\ \delta\nu_{SCY}\end{bmatrix} = \frac{r_p Z^2 N_i}{2\pi A\beta^2\gamma^3}\frac{C}{\sqrt{2\pi}\sigma_s}\left\langle \frac{1}{\left(\sigma_x+\sigma_y\right)}\begin{bmatrix}\beta_x/\sigma_x\\ \beta_y/\sigma_y\end{bmatrix}\right\rangle_s , \quad \sigma_{x,y}=\sqrt{\beta_{x,y}\varepsilon_{x,y}+\left(D_{x,y}\sigma_p\right)^2}$$

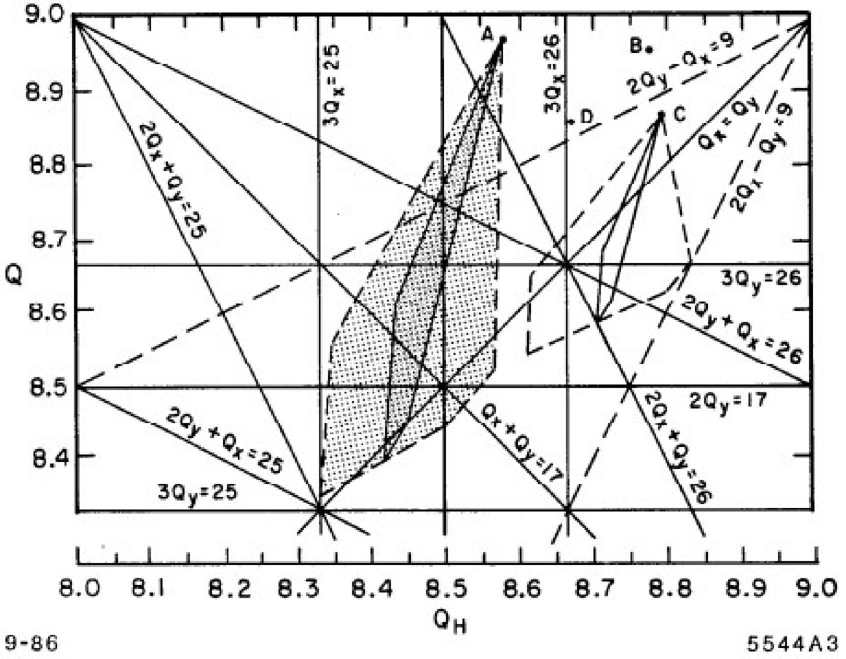


Fig. 3. Space charge tune shift of the AGS.

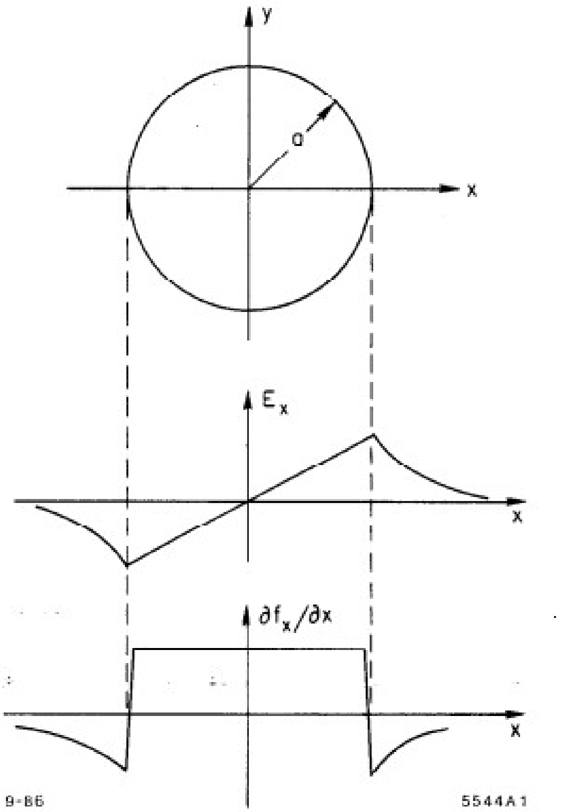


Fig. 1. Space Charge force of a uniform cylindrical beam.

- Beam magnetic field ~β^2, partially compensates electric field, $1-\beta^2=1/\gamma^2$

Beam-beam Effects

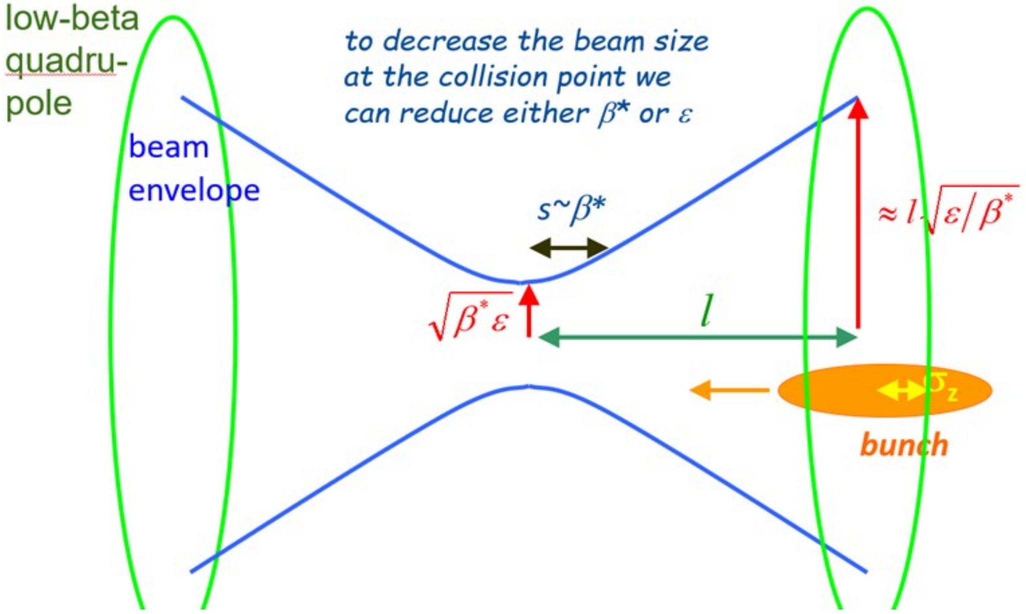
- The beam-beam tune shift is similar to the space charge tune shift but is engaged in the IPs only. The tune shift per IP:

$$\begin{bmatrix} \delta\nu_{BB_X} \\ \delta\nu_{BB\,y} \end{bmatrix} = \frac{r_p Z^2 N_i}{4\pi A\beta^2\gamma}\frac{1+\beta^2}{\left(\sigma_x+\sigma_y\right)}\begin{bmatrix} \beta_x^*/\sigma_x \\ \beta_y^*/\sigma_y \end{bmatrix}, \quad \sigma_{x,y} = \sqrt{\beta_{x,y}^{\ *}\varepsilon_{x,y} + \left(D_{x,y}^*\sigma_p\right)^2}$$

For round beam

$$\delta\nu_{SC_X} = \frac{r_p Z^2 N_i}{8\pi A\beta^2\gamma}\frac{1+\beta^2}{\varepsilon}$$

  - ♦ Magnetic field of counter rotating beam almost doubles force, $1+\beta^2$
  - ♦ Note that for large synchrotron amplitude the tune shift increase due to larger beta-function with longitudinal displacement is compensated by decrease of space charge field
    => no dependance on bunch length



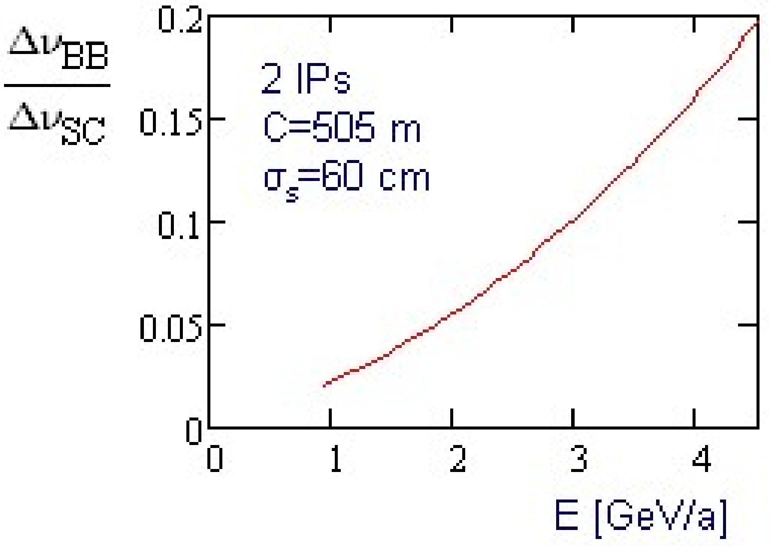
to decrease the beam size at the collision point we can reduce either β^* or ε

- Smaller β^* yields larger β-function and beam size in quads

$$\beta(s) = \beta^* + s^2 / \beta^*$$

Possible Values of Tune Shifts

- Achieved values of tune shifts
  - Space charge
    - NAPM ~0.15 (strong el. cooling, 200000 turns)
    - Fermilab Booster ~0.3 (only ~2000 turns at low energy)
    - JPARK, PS Booster ~ 0.5-0.6 (high accuracy of super-periodicity)
  - Beam-beam
    - VEPP-2 ~0.2 (round beams)
    - Typical e^+e^- ~0.05 (fast SR damping)
    - Typical hadron beams (Tevatron, LHC) ~0.01-0.015 per IP
    - Low energy RHIC ~0.1 (bad life time)

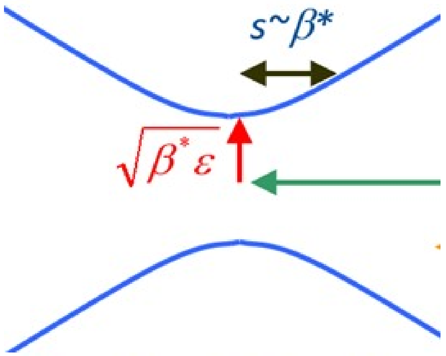


- Ratio of tune shifts: $$\frac{\delta\nu_{BB}}{\delta\nu_{SC}} = N_{IPs}\sqrt{\frac{\pi}{2}}\frac{\sigma_s}{C}\gamma^2\left(1+\beta^2\right)$$
- For the present NICA parameters, the beam-beam tune shifts are much smaller than the space charge ones and, in the first approximation, can be neglected
- Note that for the same tune shift the beam-beam effect is more destructive than the space charge due to kick concentration near IPs
- For NICA we choose total $\Delta\nu = \Delta\nu_{SC} + 2\Delta\nu_{BB}$ ~0.05

Luminosity Limitation due to Beam Space Charge

- Luminosity of round beams ($\beta_x^*=\beta_y^*$ & head-on collisions)

$$L=\frac{f_0 n_b N_i^2}{4\pi\beta^*\varepsilon}H_L(\sigma_s/\beta^*)\,,\quad H_L(x)=\frac{2}{\sqrt{\pi}}\int_0^\infty\frac{\exp(-y^2)}{1+x^2y^2}dx$$



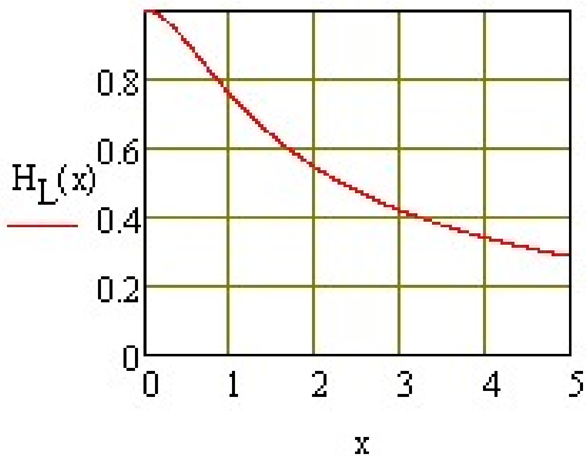
- SC tune shift: round beam, smooth focusing & D=0

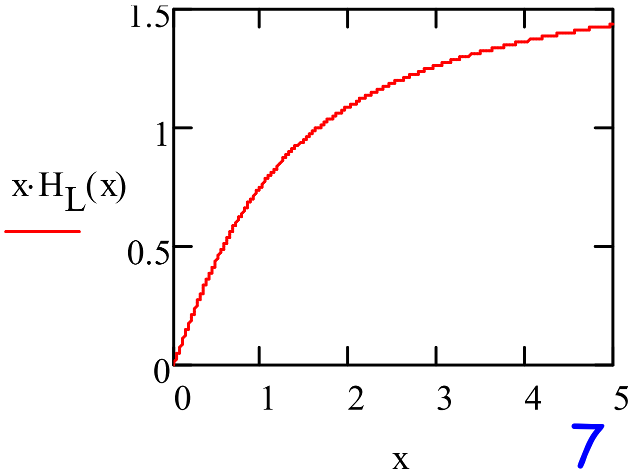
$$\delta\nu_{SC}\approx\frac{r_p Z^2 N_i}{4\pi A\beta^2\gamma^3\varepsilon}\frac{C}{\sqrt{2\pi}\sigma_s}$$

  - Weak dependence of SC tune shifts on optics
- SC limits the beam longitudinal density, N_i/σ_s
- Combining the above equations, one obtains a luminosity limitation

$$\boxed{L=\frac{\sqrt{2\pi}A\beta^2\gamma^3}{r_p Z^2}\frac{f_0 N_i}{(C/n_b)}\left(\frac{\sigma_s}{\beta^*}H\left(\frac{\sigma_s}{\beta^*}\right)\right)\delta\nu_{SC}}$$

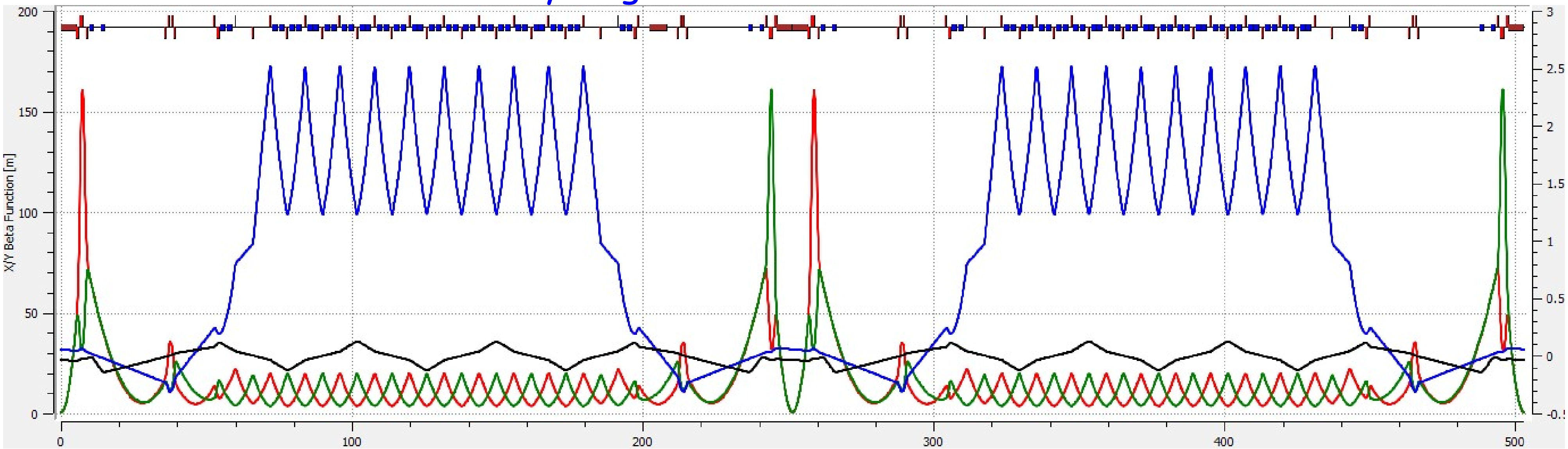
  - Strong dependence of L on the beam energy
  - Longer bunch => larger luminosity
    - Still collisions must be within detector
    - Luminosity distribution along IP has the rms length of $\sigma_s/\sqrt{2}$ ~42 cm
  - $\varepsilon\propto N_i$ => larger luminosity -> larger acceptance





Comments on SC and BB

- Since both the space charge tune shift and the beam-beam effects diminish fast with energy, the beam injection at the collision energy is highly desirable
  - Rigidity of Nuclotron determines the maximum energy of 3.9 GeV/a
    - ⇒ Acceleration in the collider for operation at the top energy
- Note that for smooth focusing there are no emittance growth and beam loss
  - time dependence of the force leads to problems
  - larger variations – larger problems
    - Collider needs very large beta-function variations



Luminosity Lifetime

- Sources of particle loss
  - Scattering at the residual gas
    - Rutherford scattering
    - Nuclear scattering
    - Capture of residual gas electrons
    - Multiple small-angle scattering leading to $d\varepsilon/dt$ in cooling absence
      - In cooling absence more powerful mechanism than the single scattering
  - Nuclear and Rutherford scattering in the IPs
  - Noise in RF system (phase and amplitude)
  - Electron capture in the electron cooler (~1-5 hour)
  - Non-linear resonances due to space charge and beam-beam effects
    - Very powerful mechanism typically observed at the store beginning in the absence of cooling
    - Electron cooling rate growth fast with decrease of amplitude. That can lead to overcooling and particle loss increase with time
      - Observed in Fermilab Recycler

Scattering in IPs

- The most principle irreducible mechanism

$$\tau^{-1} = \frac{L\sigma}{N}$$

- In the Tevatron Run II about 40% of particles were burned in luminosity
  - It should be the ultimate goal.
- Cross-sections of particle loss for Au-Au collisions

Nuclear, Au-Au,	7 barn
Electro-magnetic, $\theta > 12$ mrad (6σ)	70 mbarn

⇨ Intensity lifetime – 360 hour for 2 IPs and $L=7.1\cdot10^{27}$ $cm^{-2}s^{-1}$

- Luminosity loss can be compensated by cooling

⇨ Events per collision – $3.6\cdot10^{-3}$ (47 kHz)

⇨ Long stores are possible (>24 h) if other sources of particle loss could be made insignificant!!!

Scattering at Residual Gas

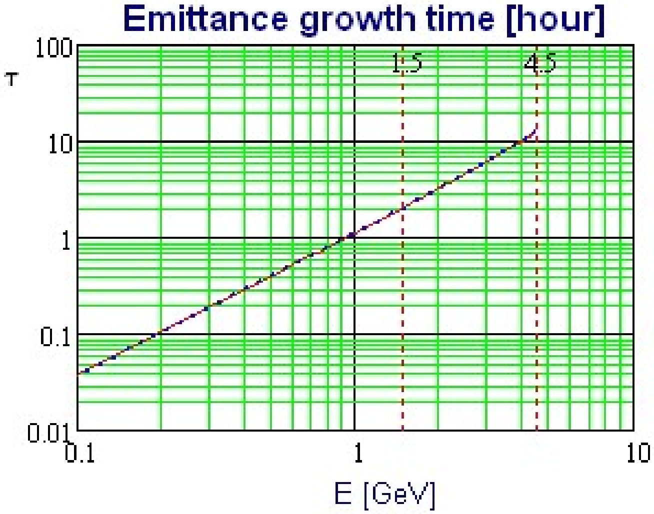
- Tevatron vacuum beam lifetime - ~1000 hour
  - Store duration - 16 hour
- At much lower energy we will have lower lifetime
  - Ultra-high vacuum is the must
- Good vacuum is assumed in below estimate

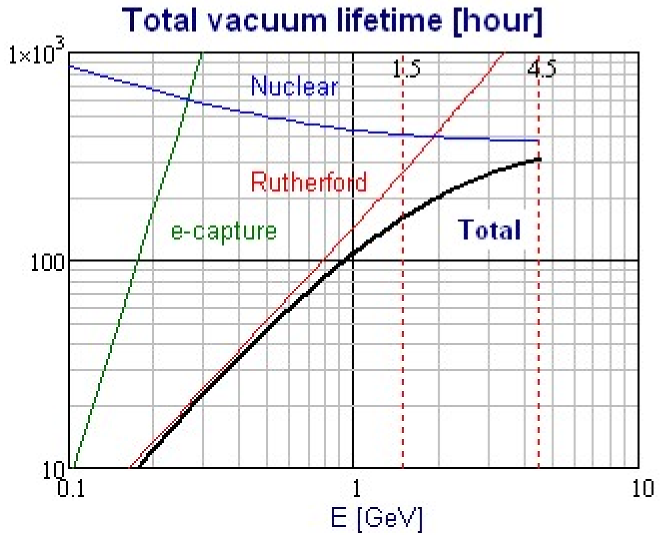
  Effective pressure:

  $\sum_i P_i Z_i (Z_i + 1)$ = 1.7·10^{-9} Torr atomic hydrogen equivalent
  - Emittance growth compensated by cooling
  - Nuclear scattering: τ > 400 hour
  - Rutherford scattering is the main mechanism of the beam loss but does not represent a real problem if vacuum is sufficiently good
- Electron capture
  - There is no good & trusted model in the entire energy range.
  - An estimate shows that the capture starts to dominate below ~0.5 GeV;

    i.e. it is not a problem for the collider

$$\begin{pmatrix} 2 \\ 6 \\ 0.2 \\ 0.2 \\ 0.2 \\ 0.2 \\ 0.2 \\ 0.1 \end{pmatrix} \begin{pmatrix} H \\ H_2 \\ CO \\ N_2 \\ C_2H_2 \\ C{\cdot}H_4 \\ CO_2 \\ Ar \end{pmatrix} \quad \text{torr } [10^{-11}]$$


Emittance growth time [hour]


Total vacuum lifetime [hour]

Expected Store Duration

- Store duration will be determined by the following phenomena
    - How good vacuum will we achieve?
    - Will we be forced to use electron cooling at collisions?
        - If stochastic cooling will work, as it should, it will be the only cooling at energies above 2.5 – 3 GeV
- Thus, if we achieve the design vacuum and stochastic cooling performance the store duration will be more than 24 hours for energies above 2.5-3 GeV

Intrabeam Scattering

- Intrabeam scattering is determined by two major mechanisms
  - Temperature exchange between degrees of freedom
    - Landau collision integral describes the temperature exchange:

$$\frac{\partial f}{\partial t} = -\frac{2\pi e^4 n L_c}{m^2}\frac{\partial}{\partial \mathrm{v}_i}\int\left(f\frac{\partial f'}{\partial \mathrm{v}'_j} - f'\frac{\partial f}{\partial \mathrm{v}_j}\right)\frac{u^2\delta_{ij} - u_i u_j}{u^3}d^3\mathrm{v}'$$

$$\mathbf{u} = \mathbf{v} - \mathbf{v}', \quad \int f d^3\mathrm{v} = 1$$

  - Additional heating related to non-zero dispersion
    - Scattering with particle momentum change results in additional betatron oscillations due to instant change of reference orbit

$$\Delta x = D\frac{\Delta p}{p} \xrightarrow[\textit{approximation}]{\textit{smooth lattice}} \Delta\varepsilon_x = \frac{1}{2}\frac{\Delta x^2}{\beta_x} = \frac{D^2}{2\beta_x}\left(\frac{\Delta p}{p}\right)^2$$

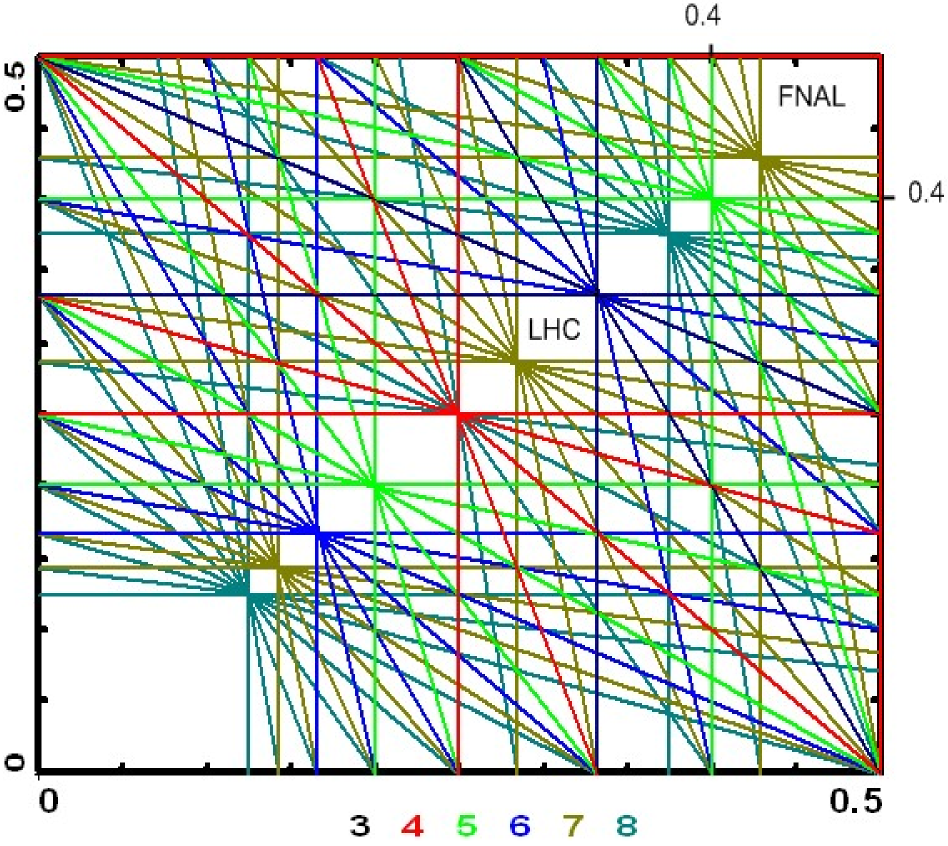
- Relatively simple equations in the smooth lattice approximation
  - Below transition there is an equilibrium state where no emittance growth
  - Particle mass changes "its sign" above the transition. That yields unlimited emittance growth (energy is taken from the beam energy)

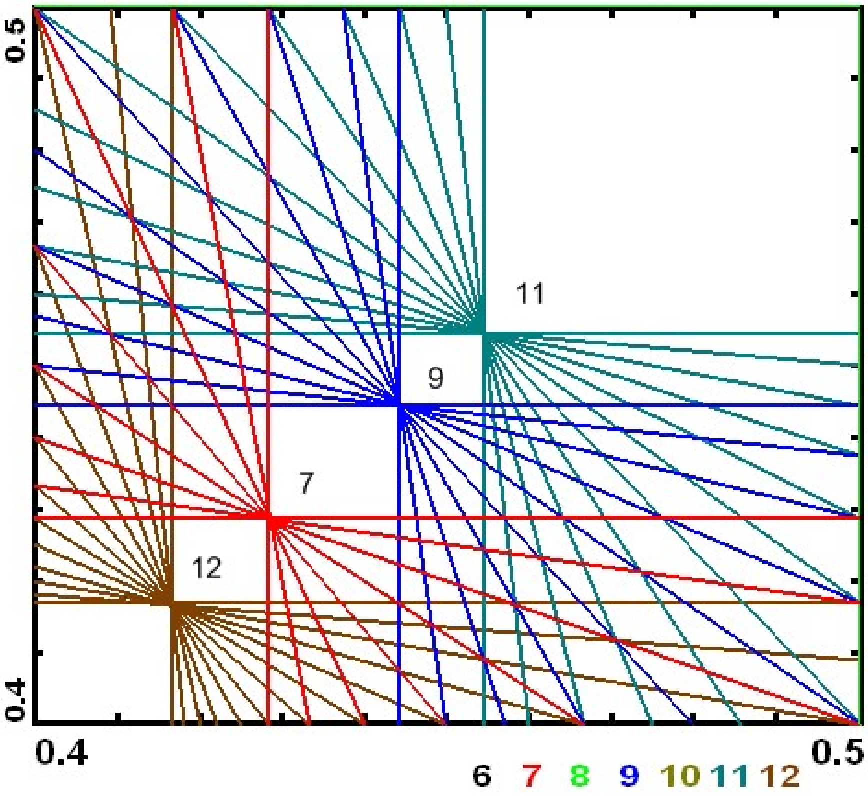
Design Choices for Optics

- Racetrack with 2 IPs
- ±5 m for particle detector
- Triplet focusing in IPs and straights
- FODO in arcs with phase advance per cell of 90 deg.
  - Cancelation of nonlinearity of sextupoles located at $\delta\nu$=180 deg.
  - 4 families of sextupoles
    - 2nd order chromaticity correction which is excited by IR quads
- Dispersion zeroing in straight sections done with missed dipoles
- Large acceptance is limited by
    - Non-linearity of edge focusing in IR quads (large NICA acceptance)
    - Resonances excited by chromaticity correction sextupoles
- Type of magnets and circumference
  - There is considerable contribution to the circumference from straights
  - Therefore, superferric dipoles and quads (B<2 T) look as good choice
    - Cold vacuum chamber helps in obtaining good average vacuum
- Vertical beam separation
  - Small vertical dispersion is excited by one step orbit elevation
    - We plan to have both dispersions equal to zero in IPs.

Collider Betatron Tunes

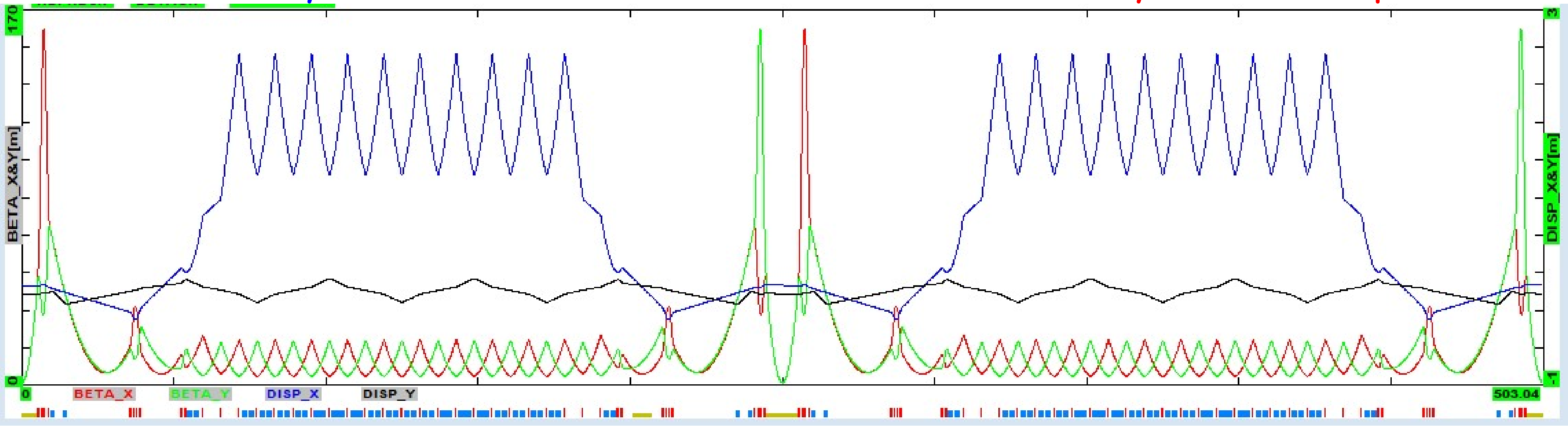
- Stochastic cooling requires betatron tunes close to half-integer to avoid the Schottky band overlap
- Odd resonances are suppressed in the absence of parasitic collisions
- Tunes ~[x.42, x.46] (same as Recycler)
  - Inversion of Tevatron tunes (~0.582 -> 0.418)
- Tevatron suffers from 7-th order (parasitic collisions) and 12-th order (will be suppressed by cooling in NICA)

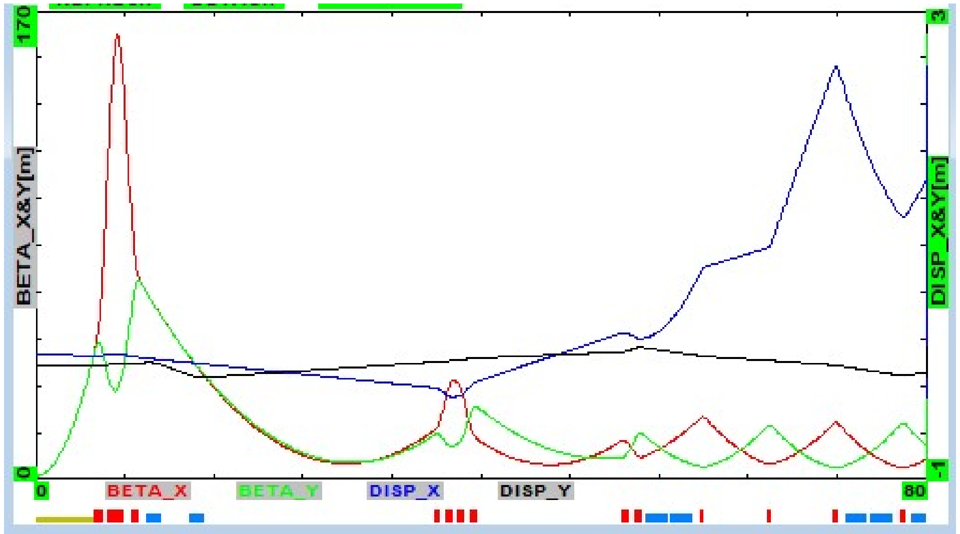


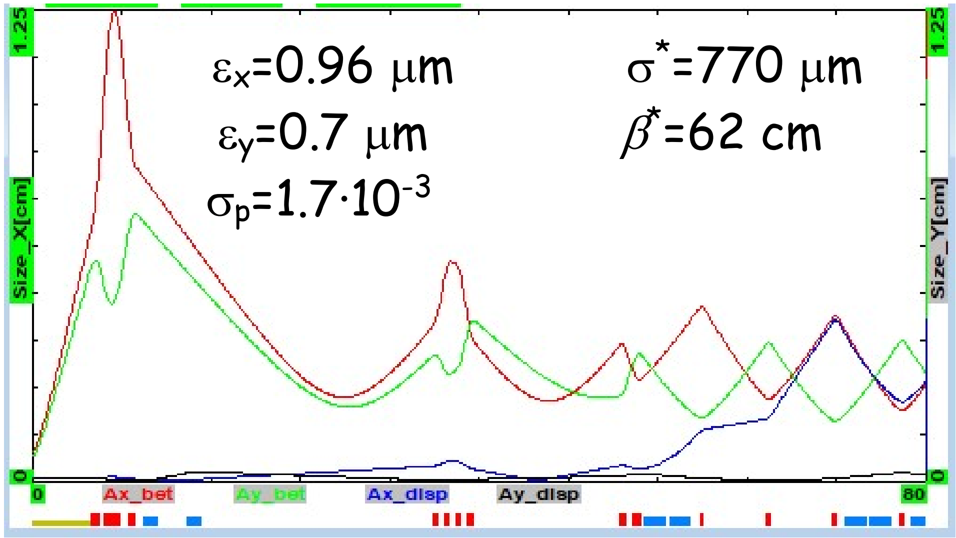


Present NICA Optics

- Two superperiods
- FODO in arcs, triplet/doublet in straights
- All quads and dipoles are at the same 10 kA bus
  - ♦ Relatively small current additions/subtractions => very inflexible optics







ε_x=0.96 μm

ε_y=0.7 μm

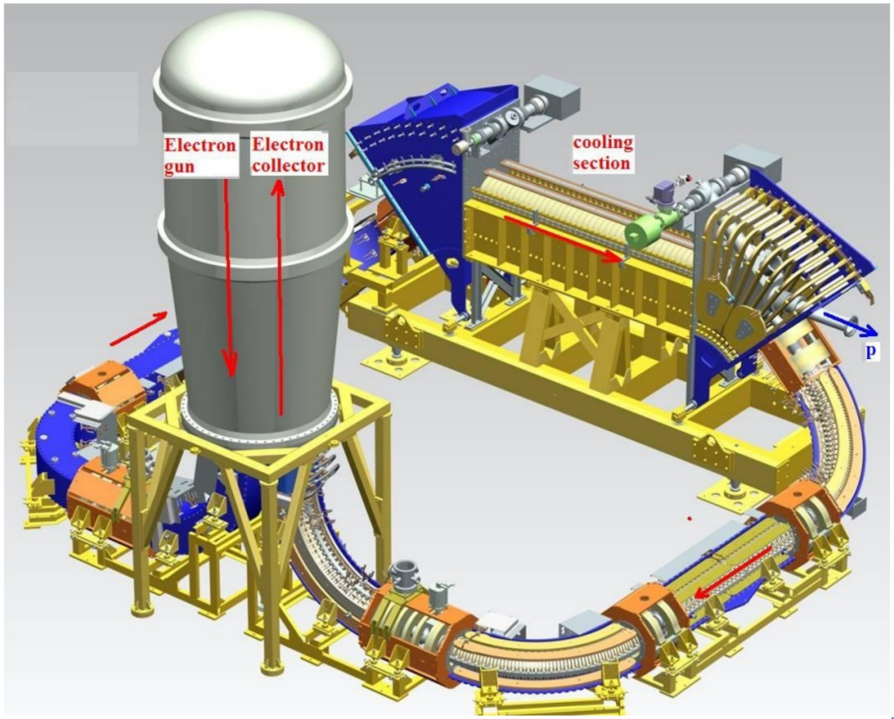
$\sigma_p=1.7\cdot10^{-3}$

σ^*=770 μm

β^*=62 cm

Beam Cooling

- Two systems of beam cooling will be present in NICA: electron cooling and stochastic cooling
- They are complimentary
- Stochastic cooling
  - Initially was expected to be as the main and only cooling system
  - Lack of expertise strongly delayed its development
  - Still, we plan it be ready in ~2 years
  - Quite challenging system to cool a bunched beam. Very little margin for errors for cooling at the collisions. Poor performance below 2.5 GeV



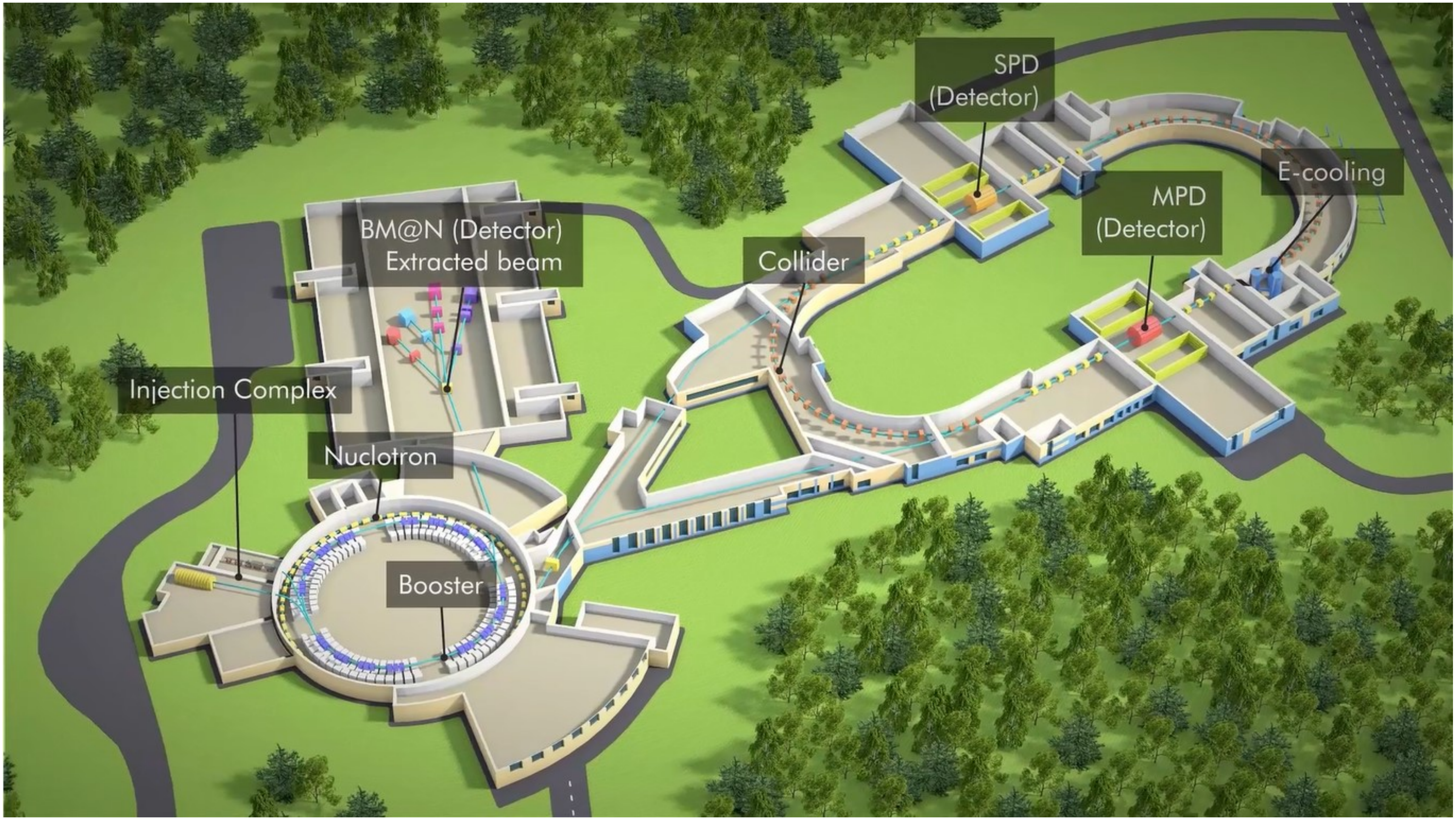
- Electron cooling
  - Good expertise accumulated in Novosibirsk for high energy cooling
    - 2 MeV system supplied to COSY, Julich, Germany
  - Very good cooling of small amplitudes. Much lower cooling rate at high amplitudes where help from stochastic cooling would be valuable
  - Poor beam lifetime due to capture of electrons

Main Collider Parameters*

	1 GeV/n	3 GeV/n	4.5 GeV/n
Ring circumference, m	503		
Momentum compaction	0.0202		
Betatron tunes	9.44		
Number of bunches		22	
Particles per bunch	$0.2\cdot10^{9}$	$2.4\cdot10^{9}$	$2.3\cdot10^{9}$
Beam current, A	0.041	0.63	0.5
Ring acceptance, mm mrad	40		
Ring long. acceptance, $\Delta p/p$	±0.01		
RMS emittance, $\varepsilon_x/\varepsilon_y$	1.1/0.95	1.11/0.85	1.1/0.0.75
RMS momentum spread	$0.55\cdot10^{-3}$	$1.15\cdot10^{-3}$	$1.5\cdot10^{-3}$
IP beta-function, cm	60		
Bunch length, cm	60	60	60
IBS growth time, s	160	460	1800
Luminosity, $cm^{-2}\ s^{-1}$	$0.6\cdot10^{25}$	$1\cdot10^{27}$	$1\cdot10^{27}$

- These are relatively conservative numbers taken from the NICA design report. However, it will take years to get to them.

NICA Layout

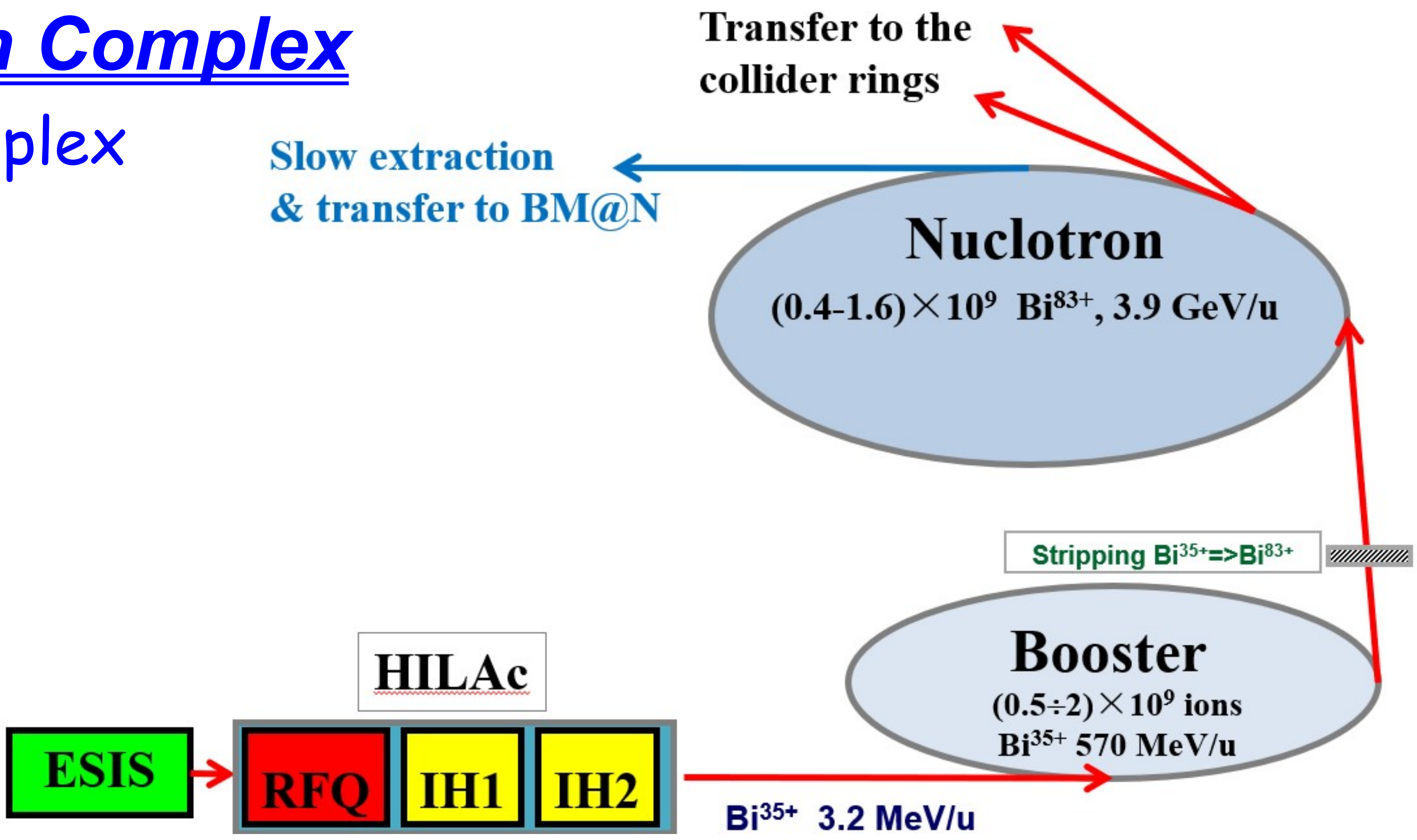

SPD
(Detector)
E-cooling
MPD
(Detector)
BM@N (Detector)
Extracted beam
Collider
Injection Complex
Nuclotron
Booster

Run IV of the Injection Complex (Sep. 2022 – Feb. 2023)

- Goals
  - Commissioning of the injection complex
    - Make hardware working,
    - orbit correction,
    - optics measurements,
    - test of instrumentation,
    - cryogenics
    - …
  - Delivering $2 \cdot 10^9$ Xe ion events to BM@N
  - Build a program of upgrades to achieve performance required by the collider

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 Run IV we demonstrated an acceleration of ~5·10^6 fully stripped Xe ions accelerated to the top energy of Nuclotron
  - 3 orders of magnitude higher than the previous run with Xe

However, that is at least ~100 times smaller than required

Achieved Performance of the Injection Complex at Run 4

- Number of ions accelerated to the Nuclotron flat top (3.9 GeV/n)
  - At the best performance without e-cool, the injection complex delivered ~$(5\text{-}8)\cdot 10^{6}$ Xe ions to the Nuclotron flat-top
    - In the number of nuclei it is about 100 times below the ion flux required by the collider design report
      (Design Report requires $(5\text{-}20)\cdot 10^{8}$ Bi ions per cycle)
    - The loss may be somewhat larger for the Bi ions which charge will be larger while capacity of the ion source expressed in the total ion charge is expected to be about same
- Slow extraction
  - The extraction was stable and had sufficiently small variations during a spill
  - However, the extraction efficiency of about 30% is low
  - Inability of Nuclotron to stay at large magnetic field significantly reduced the number of ions delivered to BM@N experiment
    - At maximum energy 3.9 GeV/n (~18 kG) the flat top time was ~2 s

Beam Intensity through the Accelerating Complex

- From the ion source we extracted ~2.4 nC per pulse.
  - that corresponds to $1.5\cdot10^{10}$ elem. charges or $5.3\cdot10^{8}$ Xe^{+28} ions
- We estimate that ~20% are the ions of targeted charge, *i.e.* the ion source produces ~10^{8} Xe^{+28} ions per pulse

⇨ We lose ~95% of these ions in the course of beam acceleration and transfers (*i.e.* only ~5% of ions are accelerated to the top energy)

  - The goal is to reduce the loss to below ~30%
    - ⇒ The major fraction of these 30% loss is expected to come from stripping occurring in Booster-Nuclotron transfers
- In other words, we need to increase the acceleration efficiency from ~5% to 70%.
- That should yield ~$7\cdot10^{7}$ ions per pulse – still ~10 times below the required ion flux

⇨ To address this lack of intensity, we plan an accumulation of ~10-20 ion source pulses at Booster injection

⇨ Electron cooling is capable to support ~10 Hz injection to Booster

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

Run IV Achievements in Beam Operations

- Managed to operate the entire complex
- Some highlights
  - Understanding how to shorten the Krion-6 pulse from ~15-20 to 4 μs
  - Dynamic orbit correction in Booster
  - Orbit correction at Nuclotron at the injection energy
  - Restored knowledge on operation of slow extraction
  - Calibration of Booster RF voltage
  - Booster-to-Nuclotron bunch-to-bunch transfers
  - Measurements of particle loss through the accelerator chain
  - Operation of BPMs at very low intensity
  - Operation of Electron cooler required for Beam accumulation
- Most important: Built the concept of how to achieve the beam parameters required by the collider
- Now we have a long list of actions to be done for the next Run

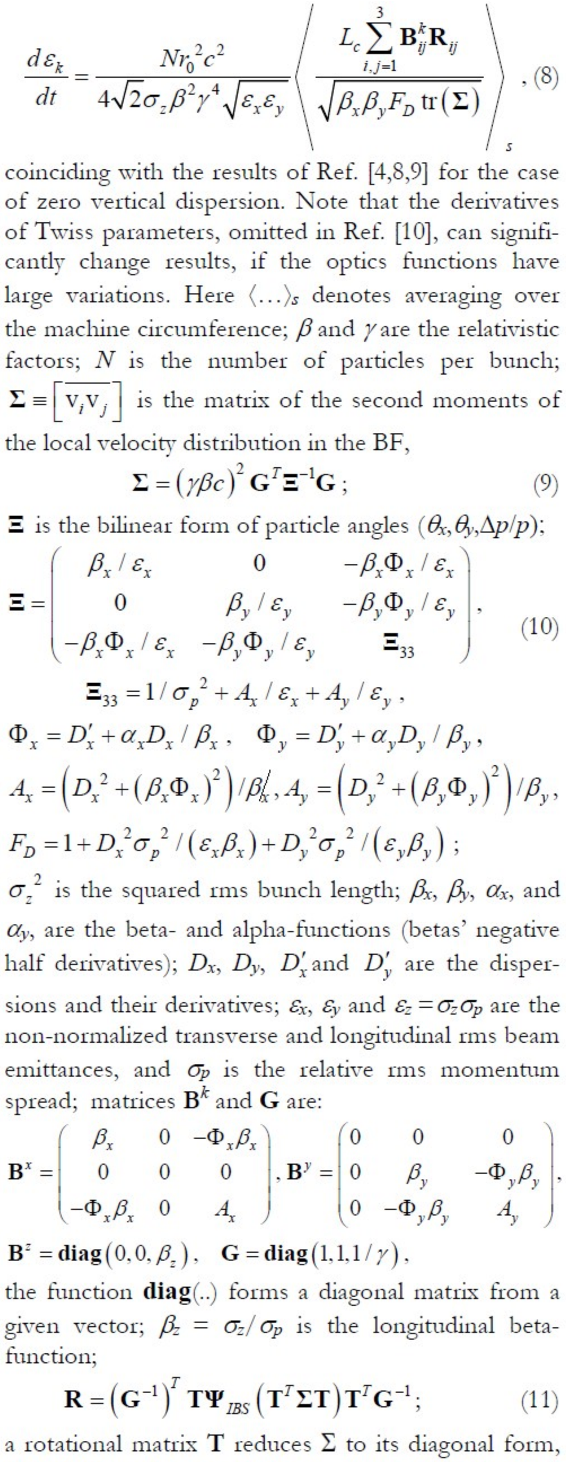
Conclusions

- It is clear that the collider construction has considerable delay
  - Both internal and external reasons are present
- For now, our delay is still “not too outstanding” relative to the delays observed at other already bult colliders
- The delay in construction allows us to bring the injection complex to the parameters required for collider – the work which has to be done in any scenario
  - Note that for slow extraction we already achieved the particle flux required by BM@N experiment
  - However, for the collider operation we need a particle flux increase by about 2 orders of magnitude
- Present collider optics is rigid and we will have limited abilities to address not-anticipated issues
  - To address this problem, we started to rebuild the straight-line quads so that each quad could be powered independently
- There has not been a collider which operates exactly as it was designed
  - We will work to exceed the design luminosity, which happened with many other machines

Backup slides

Intrabeam Scattering (2)

- In the general case the IBS is described by quite lengthy expressions (Piwinsky, Derbenev, Bjorken-Mtingwa)
  - Accurately accounts all required optics details
  - Assumes Gaussian beam distribution and applicability of plasma perturbation theory, $L_C >> 1$
  - Still not internally consistent
    - In the process of coming to the equilibrium a Gaussian distribution is not converted to a Gaussian distribution
  - However, good coincidence with experiment (Recycler, Tevatron)



$$\frac{d\varepsilon_k}{dt} = \frac{N r_0{}^2 c^2}{4\sqrt{2}\sigma_z \beta^2 \gamma^4 \sqrt{\varepsilon_x \varepsilon_y}} \left\langle \frac{L_c \sum_{i,j=1}^{3} \mathbf{B}_{ij}^k \mathbf{R}_{ij}}{\sqrt{\beta_x \beta_y F_D \operatorname{tr}(\boldsymbol{\Sigma})}} \right\rangle_s , \quad (8)$$

coinciding with the results of Ref. [4,8,9] for the case of zero vertical dispersion. Note that the derivatives of Twiss parameters, omitted in Ref. [10], can significantly change results, if the optics functions have large variations. Here $\langle \dots \rangle_s$ denotes averaging over the machine circumference; β and γ are the relativistic factors; N is the number of particles per bunch; $\boldsymbol{\Sigma} \equiv \left[\overline{\mathrm{v}_i \mathrm{v}_j}\right]$ is the matrix of the second moments of the local velocity distribution in the BF,

$$\boldsymbol{\Sigma} = (\gamma\beta c)^2 \mathbf{G}^T \boldsymbol{\Xi}^{-1} \mathbf{G} ; \quad (9)$$

$\boldsymbol{\Xi}$ is the bilinear form of particle angles $(\theta_x, \theta_y, \Delta p/p)$;

$$\boldsymbol{\Xi} = \begin{pmatrix} \beta_x / \varepsilon_x & 0 & -\beta_x \Phi_x / \varepsilon_x \\ 0 & \beta_y / \varepsilon_y & -\beta_y \Phi_y / \varepsilon_y \\ -\beta_x \Phi_x / \varepsilon_x & -\beta_y \Phi_y / \varepsilon_y & \boldsymbol{\Xi}_{33} \end{pmatrix}, \quad (10)$$

$$\boldsymbol{\Xi}_{33} = 1/\sigma_p{}^2 + A_x/\varepsilon_x + A_y/\varepsilon_y ,$$

$$\Phi_x = D'_x + \alpha_x D_x / \beta_x , \quad \Phi_y = D'_y + \alpha_y D_y / \beta_y ,$$

$$A_x = \left(D_x{}^2 + (\beta_x \Phi_x)^2\right)/\beta_x , A_y = \left(D_y{}^2 + (\beta_y \Phi_y)^2\right)/\beta_y ,$$

$$F_D = 1 + D_x{}^2 \sigma_p{}^2 / (\varepsilon_x \beta_x) + D_y{}^2 \sigma_p{}^2 / (\varepsilon_y \beta_y) ;$$

$\sigma_z{}^2$ is the squared rms bunch length; β_x, β_y, α_x, and α_y, are the beta- and alpha-functions (betas' negative half derivatives); D_x, D_y, D'_x and D'_y are the dispersions and their derivatives; ε_x, ε_y and $\varepsilon_z = \sigma_z \sigma_p$ are the non-normalized transverse and longitudinal rms beam emittances, and σ_p is the relative rms momentum spread; matrices $\mathbf{B}^k$ and $\mathbf{G}$ are:

$$\mathbf{B}^x = \begin{pmatrix} \beta_x & 0 & -\Phi_x \beta_x \\ 0 & 0 & 0 \\ -\Phi_x \beta_x & 0 & A_x \end{pmatrix}, \mathbf{B}^y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \beta_y & -\Phi_y \beta_y \\ 0 & -\Phi_y \beta_y & A_y \end{pmatrix},$$

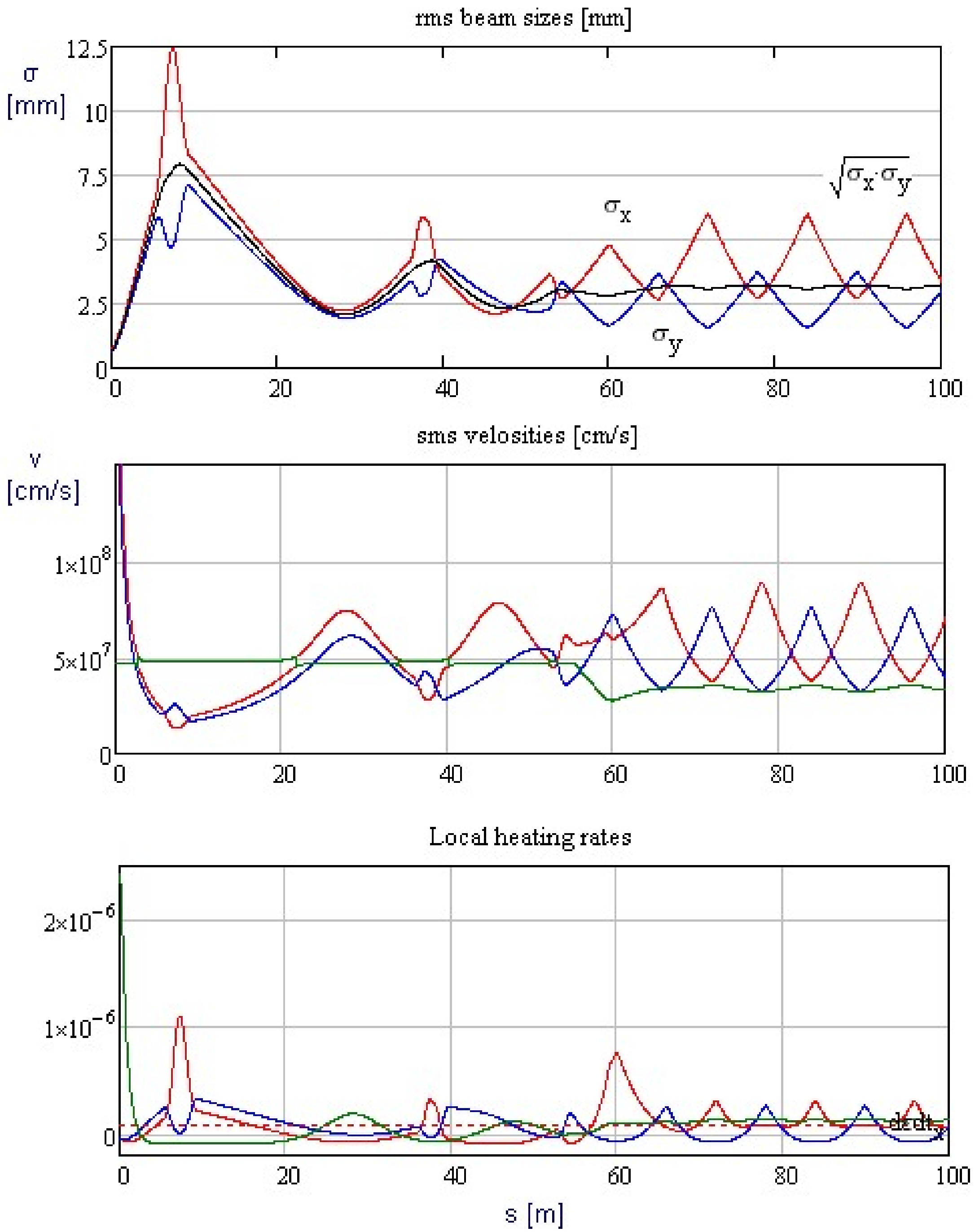
$$\mathbf{B}^z = \mathbf{diag}(0, 0, \beta_z), \quad \mathbf{G} = \mathbf{diag}(1, 1, 1/\gamma),$$

the function **diag**(..) forms a diagonal matrix from a given vector; $\beta_z = \sigma_z / \sigma_p$ is the longitudinal beta-function;

$$\mathbf{R} = \left(\mathbf{G}^{-1}\right)^T \mathbf{T} \boldsymbol{\Psi}_{IBS} \left(\mathbf{T}^T \boldsymbol{\Sigma} \mathbf{T}\right) \mathbf{T}^T \mathbf{G}^{-1} ; \quad (11)$$

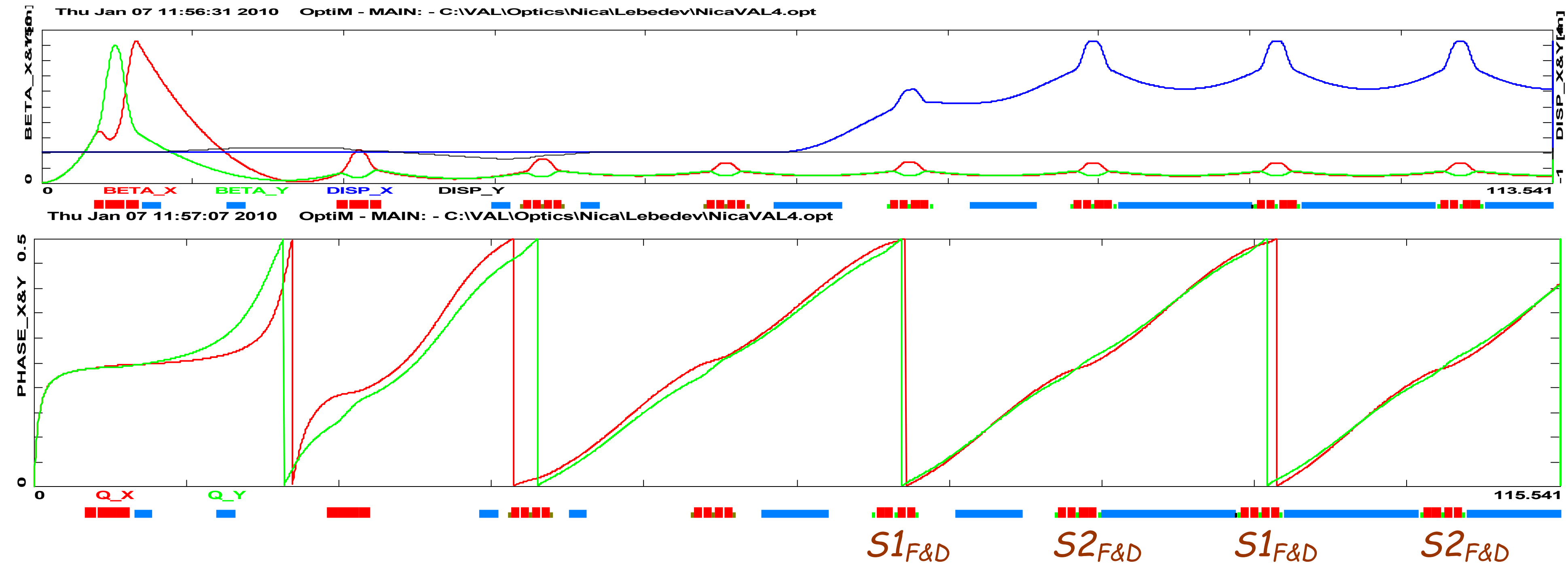
a rotational matrix $\mathbf{T}$ reduces Σ to its diagonal form,

Intrabeam Scattering in NICA

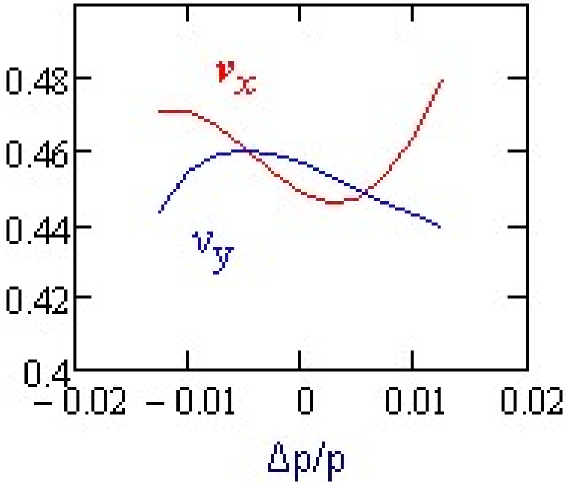


- For NICA parameters the beam gravitates to a quasi-equilibrium state where all temperatures are approximately equal
- In this state we achieve the minimum heating of 6D emittance
    - Such situation was observed in Recycler which operated well below transition
- Large β-function variations make major contribution to IBS; therefore, in the final design the FODO lattice in arcs was preferred

Chromaticities of tunes and β-functions



- Tune dependence on the momentum is very nonlinear even for ideal dipoles and quads
- Sextupoles were used to minimize tune variations
- Natural chromaticities:
  $\xi_x = -27.1$, $\xi_y = -23.2$ ($\Delta\xi_{xy}$~-17 from 2 IPs)
- Corrected chromaticities:
  $\xi_x = -1.54$, $\xi_y = -1.50$



	S_F [kG/cm^2]	S_D [kG/cm^2]
S_1	0.386	-0.290
S_2	0.386	-0.336

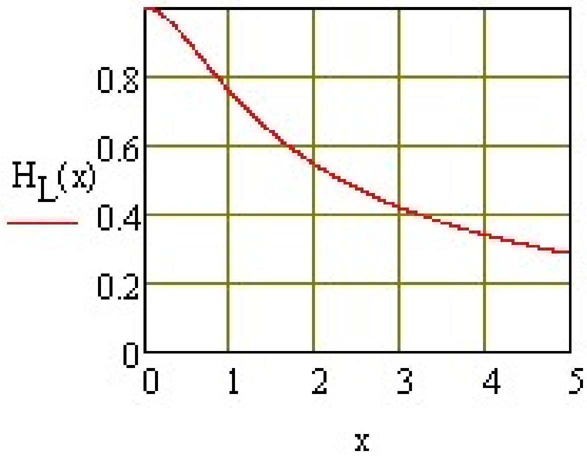
Choice of β*

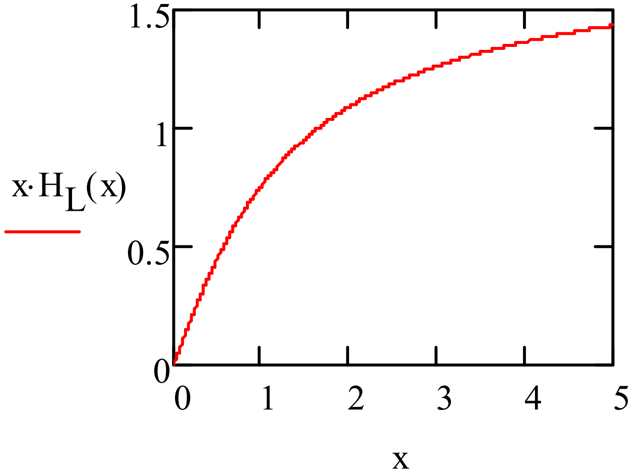
- Typically, the beam-beam limits the luminosity.
    - In this case luminosity grows with β* redaction and short bunch is required
- Due to relatively small energy of NICA its luminosity is limited by the beam space charge
    - In this case the luminosity is set by ratio σ_s/β^*

$$\boxed{L=\frac{\sqrt{2\pi}A\beta^2\gamma^3}{r_pZ^2}\frac{f_0N_i}{(C/n_b)}\left(\frac{\sigma_s}{\beta^*}H\left(\frac{\sigma_s}{\beta^*}\right)\right)\delta\nu_{SC}}$$

where $N_i=\frac{4\pi A\beta^2\gamma^3\delta\nu_{SC}}{r_pZ^2}\frac{\sqrt{2\pi}\sigma_s}{C}\varepsilon$

⇨ One wants large bunch length but it is limited by the interaction length





- Numerical study showed that if we reduce β^* below ~60 cm we start losing the ring acceptance and, consequently, the luminosity.
- Present optics is rigid and does not allow change of β^*. We plan to rebuild the quads in the straights to have independent control of β^*.
    - Longer bunch => larger luminosity