

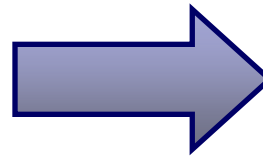


JINR NUCLOTRON BASED ION COLLIDER FACILITY NICA

Optics design for NICA collider

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FNAL, Batavia, Illinois, USA, Yu.Senichev, IKP, Juelich, Germany

Main requirements from physics experiment:



The goal of the project is

construction at JINR of a new accelerator facility, that provides

- 1a) Heavy ion colliding beams $^{197}\text{Au}^{79+} \times ^{197}\text{Au}^{79+}$ at
 $\sqrt{s_{\text{NN}}} = 4 \div 11 \text{ GeV}$ (1 \div 4.5 GeV/u ion kinetic energy)
at $L_{\text{average}} = 1\text{E}27 \text{ cm}^{-2}\cdot\text{s}^{-1}$ (at $\sqrt{s_{\text{NN}}} = 9 \text{ GeV}$)
- 1b) Light-Heavy ion colliding beams of the same energy range and luminosity
- 2) Polarized beams of protons and deuterons in collider mode:
 $p\uparrow p\uparrow \sqrt{s_{\text{pp}}} = 12 \div 27 \text{ GeV}$ (5 \div 12.6 GeV kinetic energy)
 $d\uparrow d\uparrow \sqrt{s_{\text{NN}}} = 4 \div 13.8 \text{ GeV}$ (2 \div 5.9 GeV/u ion kinetic energy)
 $L_{\text{average}} \geq 1\text{E}30 \text{ cm}^{-2}\cdot\text{s}^{-1}$ (at $\sqrt{s_{\text{pp}}} = 27 \text{ GeV}$)
- 3) The beams of light ions and polarized protons and deuterons for fixed target experiments:
 $\text{Li} \div \text{Au} = 1 \div 4.5 \text{ GeV /u}$ ion kinetic energy
 $p, p\uparrow = 5 \div 12.6 \text{ GeV}$ kinetic energy
 $d, d\uparrow = 2 \div 5.9 \text{ GeV/u}$ ion kinetic energy
- 4) Applied research on ion beams at kinetic energy from 0.5 GeV/u
up to 12.6 GeV (p) and 4.5 GeV /u (Au)



G.Trubnikov,

NICA project

September, 2010 Novosibirsk

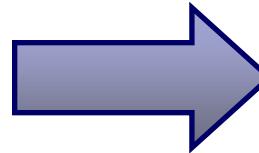
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Main requirements from physics experiment:

- changeable experiment energy for heavy ions collisions:
Au + Au (4.5, 3.5, 1.5) GeV/u
 $\gamma = 5.8, 4.7, 2.6$

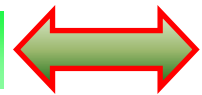
with luminosity $\sim 10^{27}$ (at 4.5 GeV/u)

- operation with **proton** beams
(12.5 GeV - $\gamma = 14.3$)



Objectives for optics design

Possibility of variation of
gamma-tr $\sim 3 \div 15$



For bunched beam with Gaussian distribution in all planes

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

For round beam, smooth focusing and sufficiently small dispersion

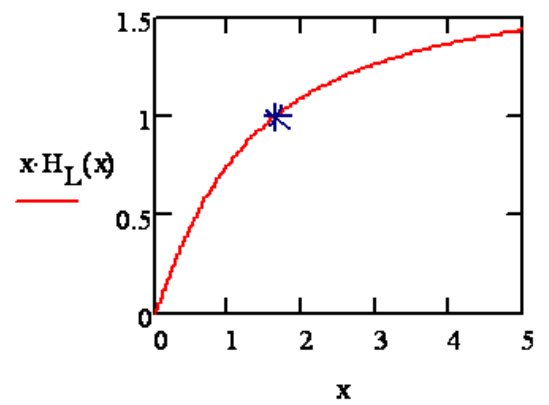
$$\delta v_{SC} = \frac{r_p Z^2 N_i}{4\pi A \beta^2 \gamma^3 \varepsilon} \frac{C}{\sqrt{2\pi} \sigma_s} \quad - \text{limits beam longitudinal density, } N_i / \sigma_s$$

For $\beta_x^* = \beta_y^*$ and head-on collisions the luminosity is

$$L = \frac{f_0 n_b N_i^2}{4\pi \beta^* \sqrt{\varepsilon_x \varepsilon_y}} H\left(\frac{\sigma_s}{\beta^*}\right), \quad H(x) = \frac{2}{\sqrt{\pi}} \int_0^\infty \frac{e^{-y^2}}{1+x^2 y^2} dy$$

assuming $\varepsilon_x = \varepsilon_y$ one obtains a luminosity limitation

$$L = \frac{\sqrt{2\pi} A \beta^2 \gamma^3}{r_p Z^2} \frac{f_0 N_i}{(C/n_b)} \left(\frac{\sigma_s}{\beta^*} H\left(\frac{\sigma_s}{\beta^*}\right) \right) \delta v_{SC} \quad \Rightarrow \quad L = 8\pi^2 \frac{A^2 c \beta^5 \gamma^6}{Z^4 r_p^2} \frac{n_b \sigma_s \varepsilon}{C^3} \left(\frac{\sigma_s}{\beta^*} H\left(\frac{\sigma_s}{\beta^*}\right) \right) \delta v_{SC}^2$$



Luminosity



limitation due to Beam Space Charge

For the case of fixed ring acceptance and circumference one should also exclude N_i . That results in

$$L = 8\pi^2 \frac{A^2 c \beta^5 \gamma^6}{Z^4 r_p^2} \frac{n_b \sigma_s \varepsilon}{C^3} \left(\frac{\sigma_s}{\beta^*} H \left(\frac{\sigma_s}{\beta^*} \right) \right) \delta v_{SC}^2$$

Large luminosity requires:

Large emittance => large acceptance

Short separation length, C/n_b

Small circumference, C

Large value of σ_s/β^*

Possibility of variation of gamma-tr ~3 ÷ 15

Large acceptance

Small perimeter

Small beta-function at IP

Acceptable IBS rates

Objectives for optics design



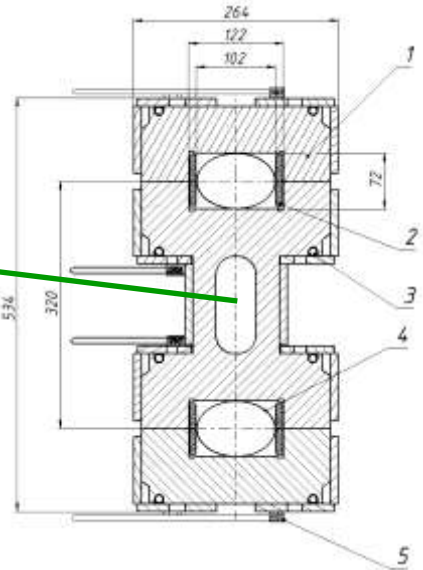
Racetrack with 2 IPs

Optics optimized for **Au+Au** collisions at **4.5 GeV/n** ($\gamma \approx 5.8$)

$\gamma_{tr} \approx 7.6$

Slip factor
 $\eta = 1/\gamma_{tr}^2 - 1/\gamma^2$
 ≈ 0.013

- ± 4.5 m for particle detector
- Phase advance **90°** per FODO-cell
- Dispersion zeroing in straight sections
- Vertical beam separation
- Tunes $\sim \mathbf{x.44}$ (same as in FNAL Recycler)



Cross-section view of the NICA Collider dipole magnet

variation of gamma-tr:



decrease phase advance per cell
90° -> 60° -> 30°

“resonance” optic structure* with
variation of D through the ring

$$\alpha = \frac{1}{C} \int \frac{D(s)}{\rho(s)} ds \quad \text{- orbit compaction factor (OCF)}$$

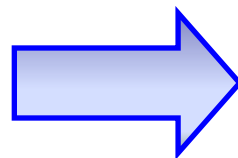
$$\frac{d^2 D}{ds^2} + [K(s) + \varepsilon k(s)]D = \frac{1}{\rho(s)} \quad , \text{ where} \quad K(s) = \frac{eG(s)}{p} \quad \varepsilon k(s) = \frac{e\Delta G(s)}{p} \quad \varepsilon \cdot k(\phi) = \sum_{k=0}^{\infty} g_k \cos k\phi$$

$$\frac{1}{\rho(\phi)} = \frac{1}{R} \left(1 + \sum_{n=1}^{\infty} r_n \cos n\phi \right)$$

Correlated change of dispersion through the orbit moves alpha close to zero or to negative values

$$D(\phi) = \bar{D} + \tilde{D}(\phi)$$

$$\frac{1}{\rho(\phi)} = \frac{1}{R} (1 + \tilde{r}(\phi))$$



$$\alpha = \frac{\bar{D}}{\bar{R}} + \frac{\overline{\tilde{D}(\phi) \cdot \tilde{r}(\phi)}}{\bar{R}}$$

variation of gamma-tr:

- The solution of equation $\frac{d^2 D}{ds^2} + [K(s) + \varepsilon k(s)]D = \frac{1}{\rho(s)}$

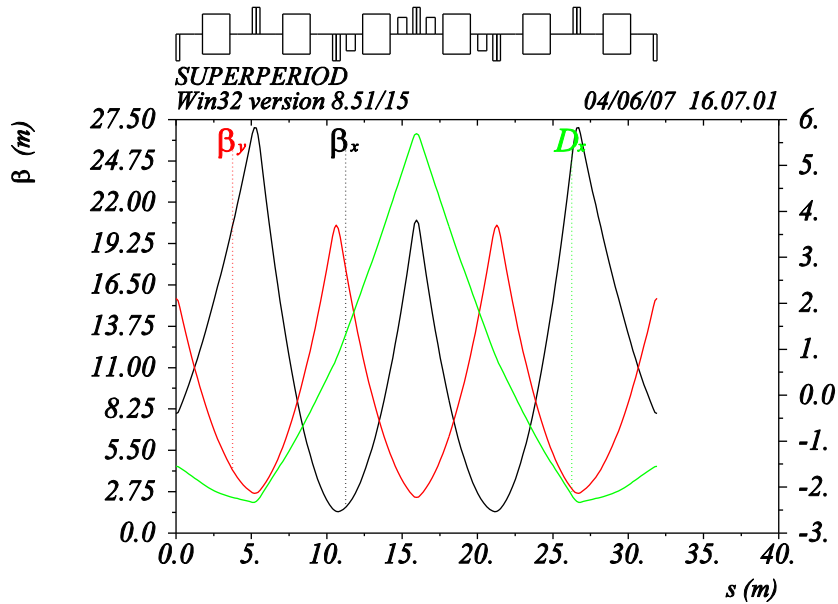
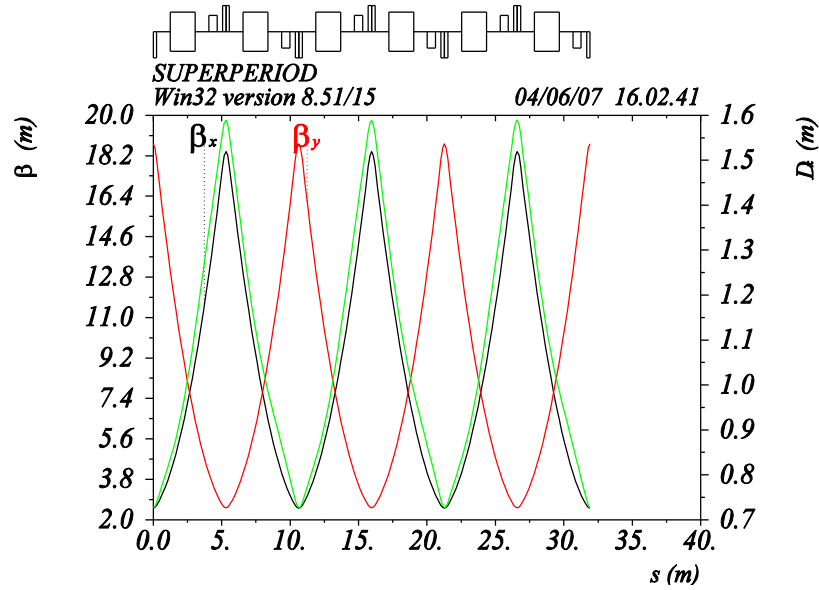
- with modulation of gradient and curvature:

$$\varepsilon k(\phi) = \sum_{k=0}^{\infty} g_k \cos k\phi \qquad \frac{1}{\rho(\phi)} = \frac{1}{R} \left(1 + \sum_{n=1}^{\infty} r_n \cos n\phi \right)$$

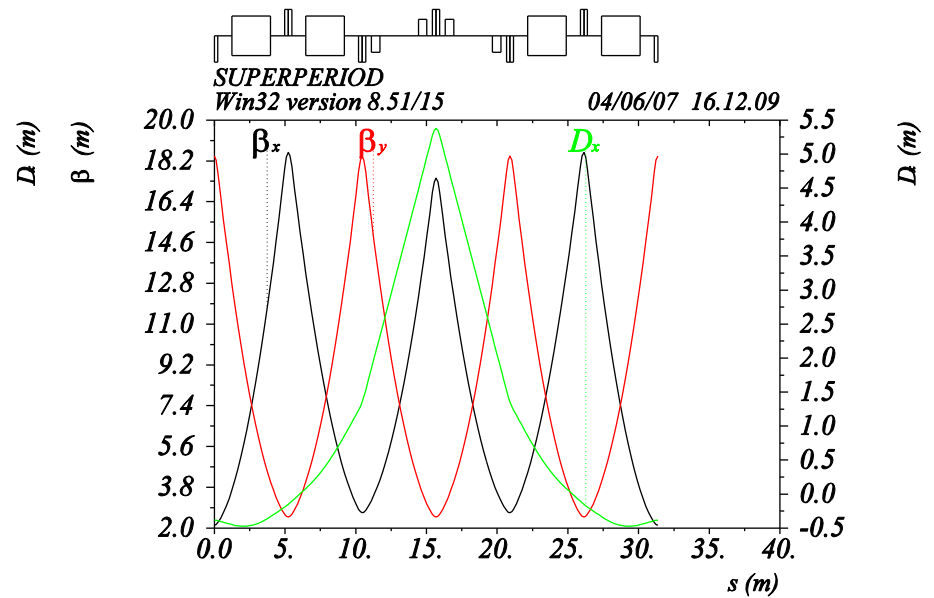
- gives the expression for OCF:

$$\alpha_s = \frac{1}{\nu^2} \left\{ 1 + \frac{1}{4 \cdot (1 - kS/\nu)} \cdot \left[\left(\frac{\bar{R}}{\nu} \right)^2 \frac{g_k}{[1 - (1 - kS/\nu)^2]} - r_k \right]^2 \right\}$$

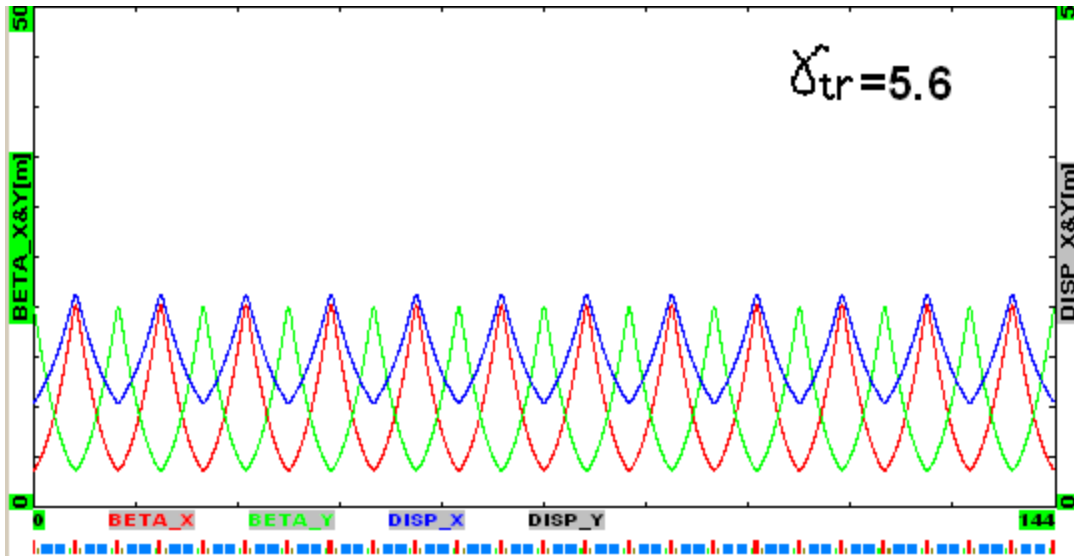
Regular structure



Modulated dispersion



Modulated radius of curvature



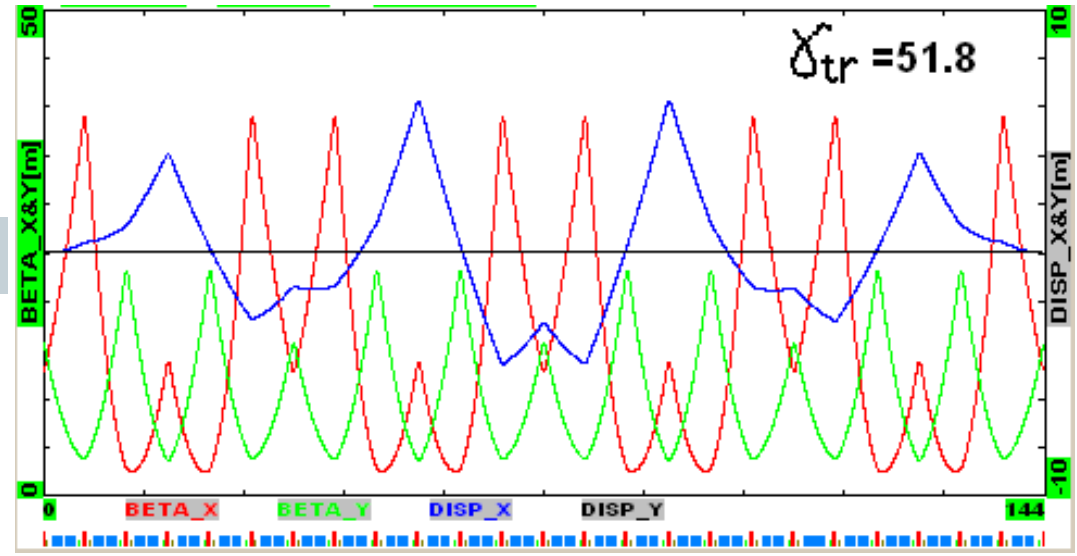
Regular structure

12 Cell * 90° => Q_x arc=3

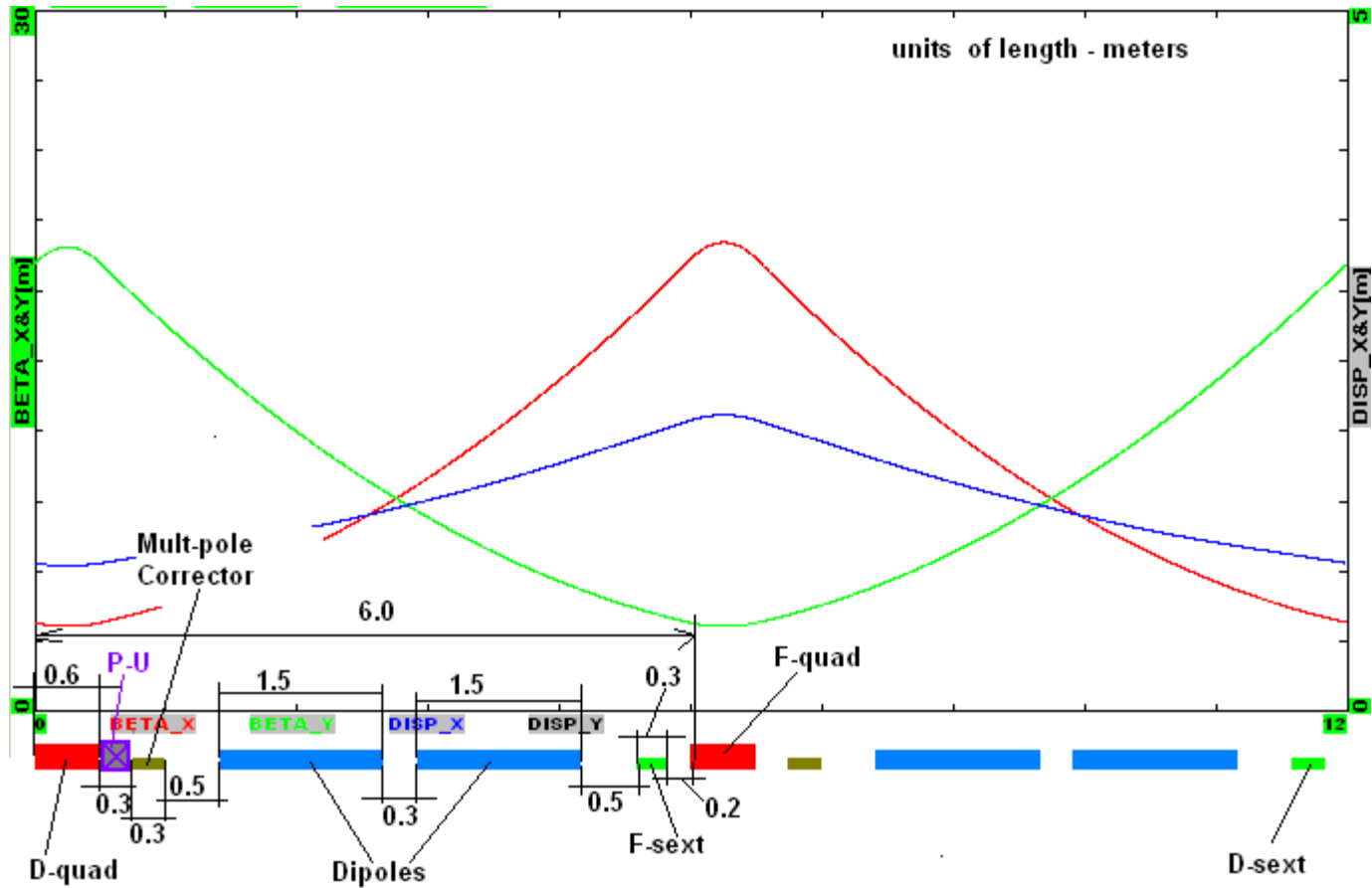
4 Superperiods * 3 Cell

$D_y = 0$

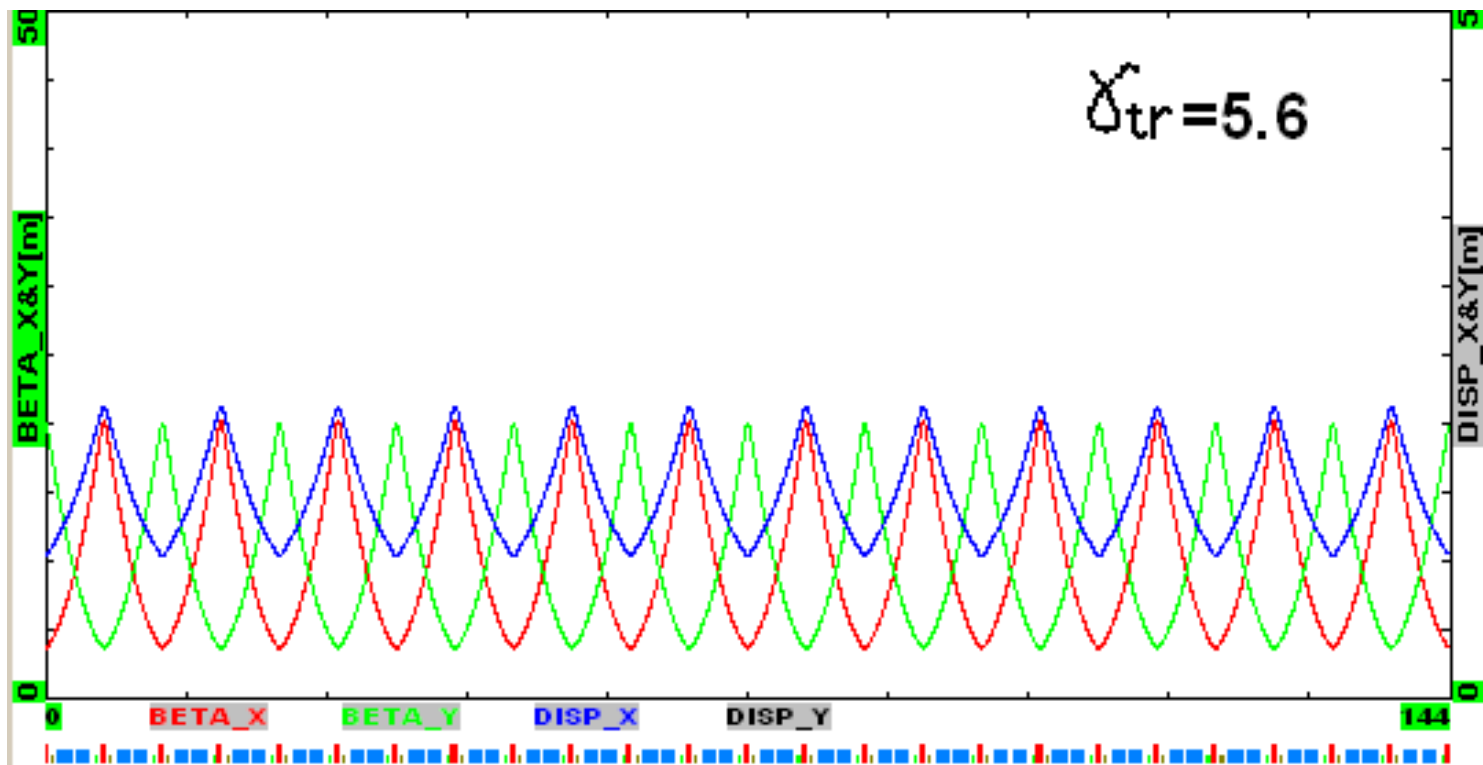
Modulated dispersion



Cell dimensions



90° phase advance for Au 4.5 GeV/n

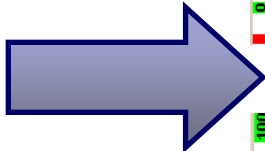


12 cell x 90° phase advance

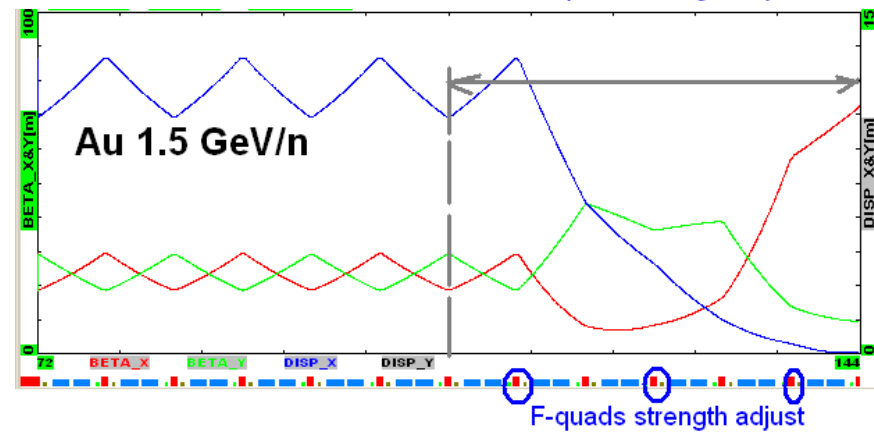
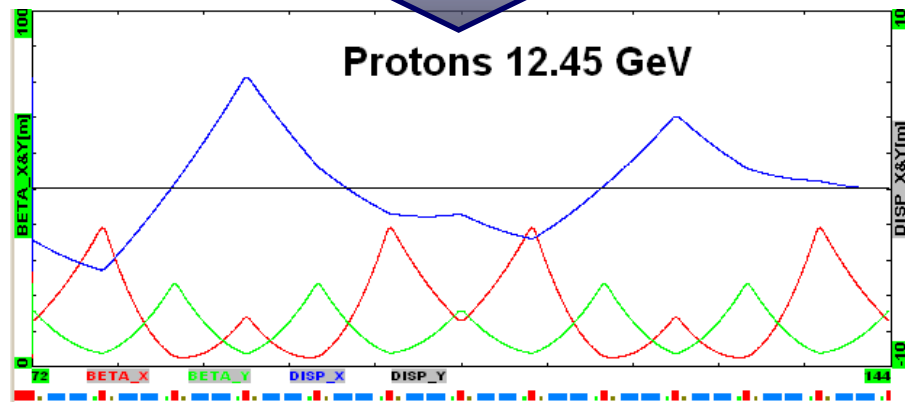
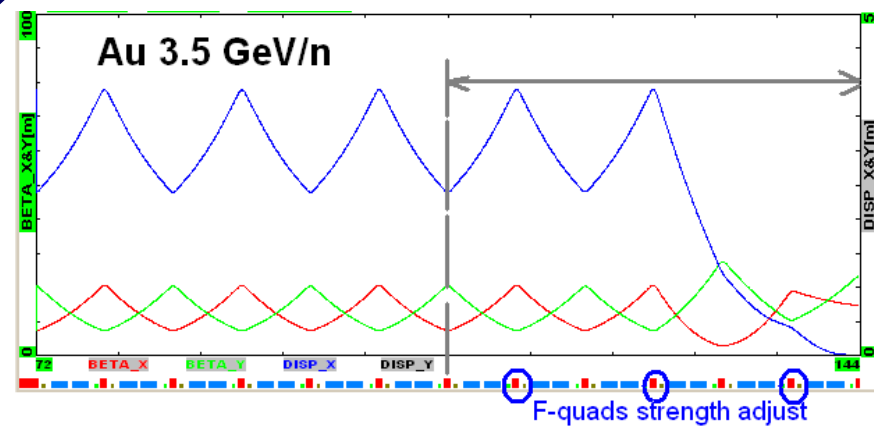
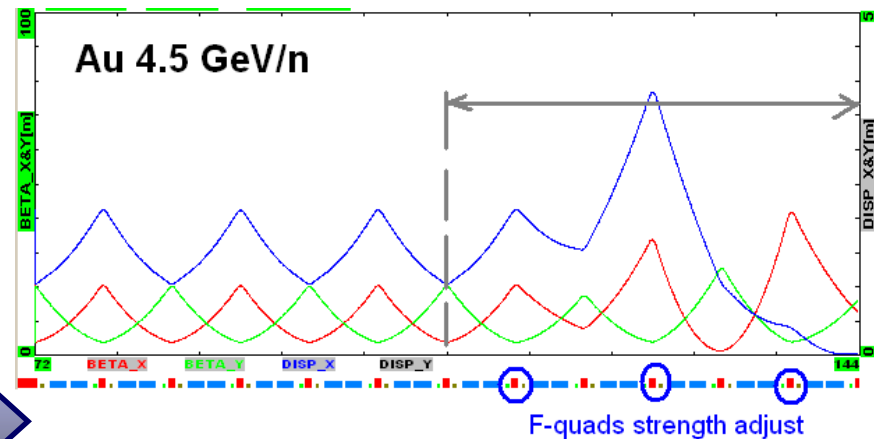
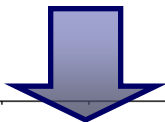
Dispersion suppression

-using special quads gradients in edges cells

(possible to adjust for the different γ_{tr} i.e. different phase advance in arc)

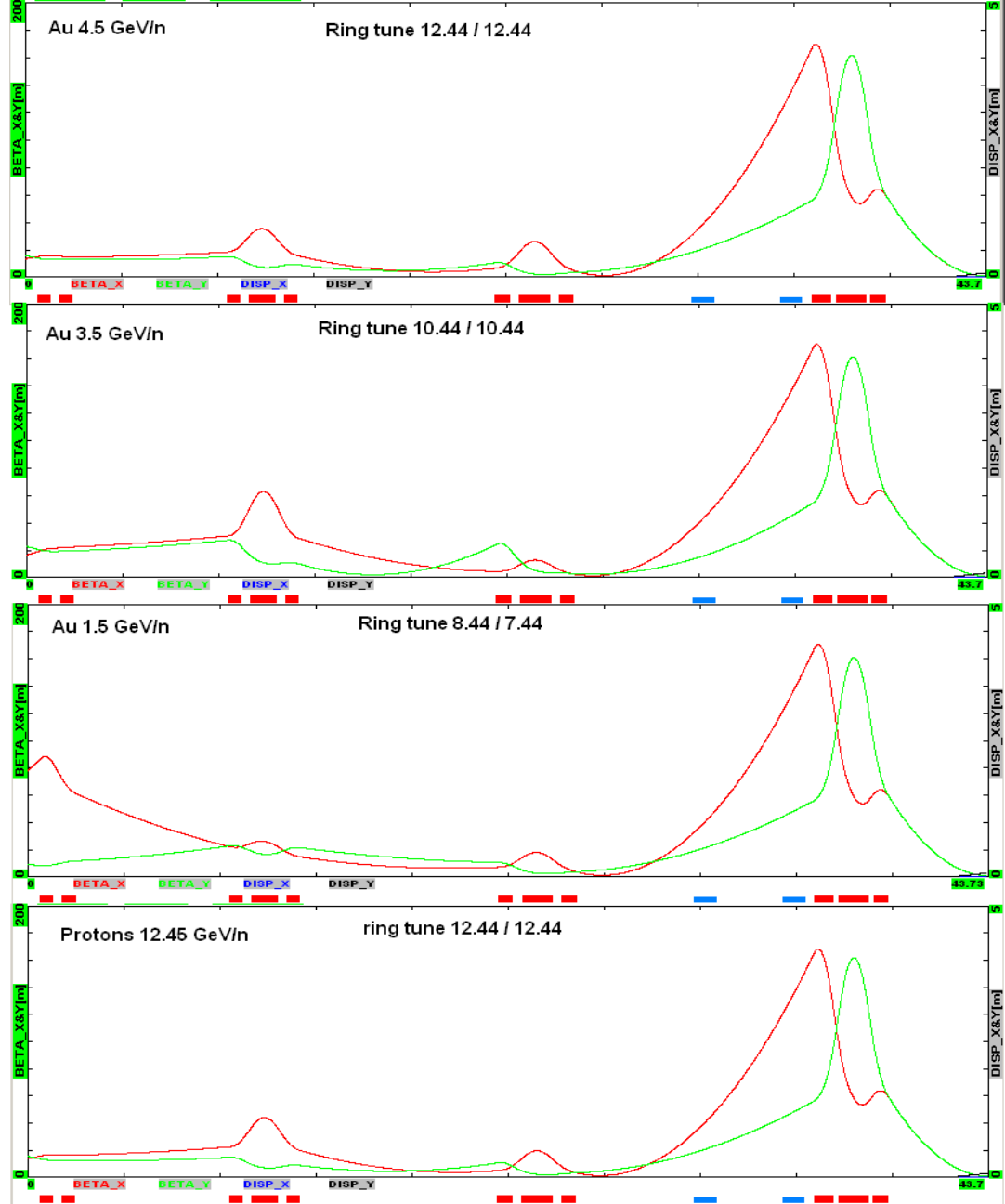


• $D=0$ due to $2\pi \cdot n$ – phase advance per Arc

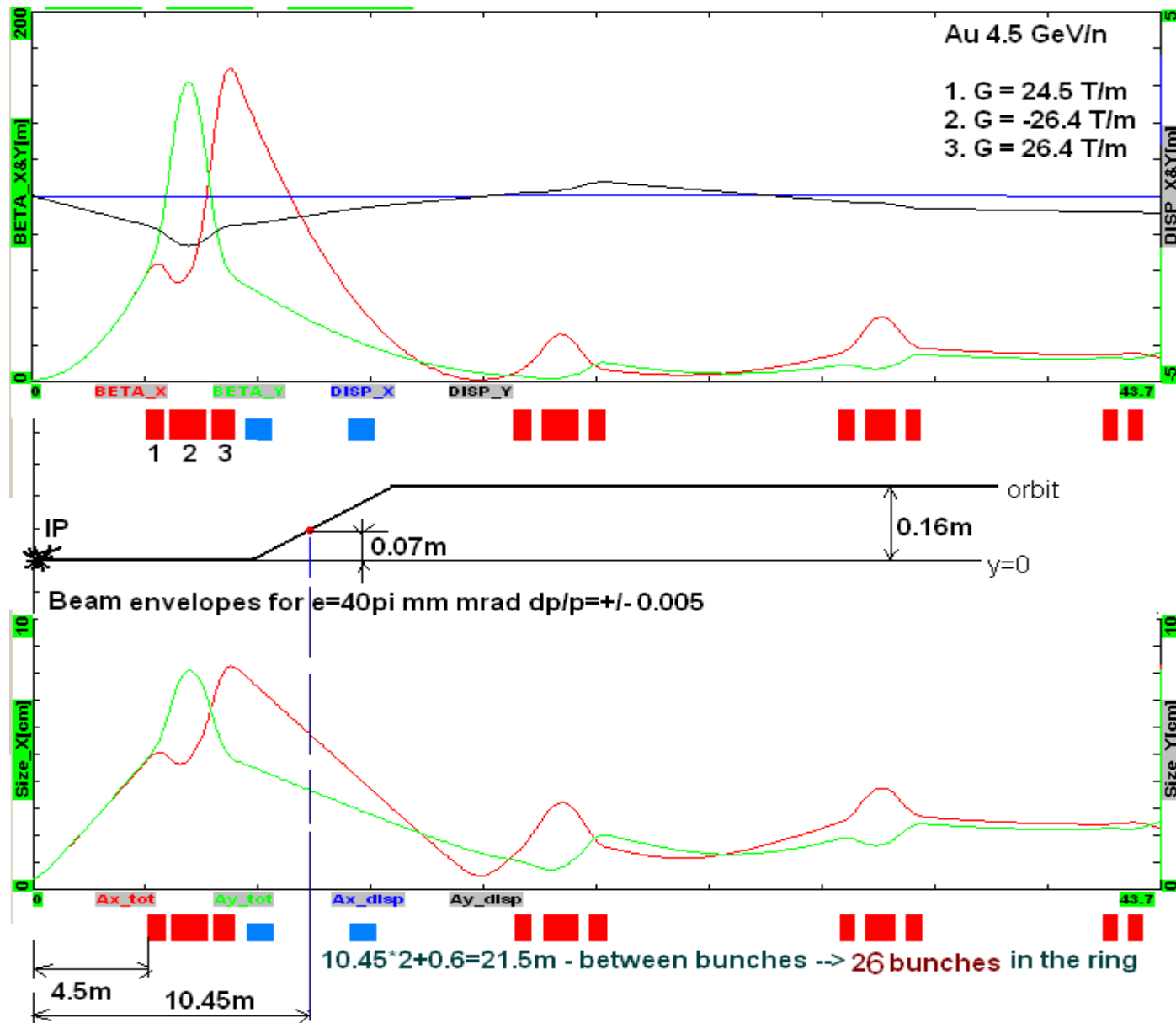


Straight sections

- β^* at IP ~ 35 cm
- vertical beam separation
- enough space for non structural equipment: RF-resonators, PU for SC, injection, spin rotators...
- keep total tune of the ring $x.44$



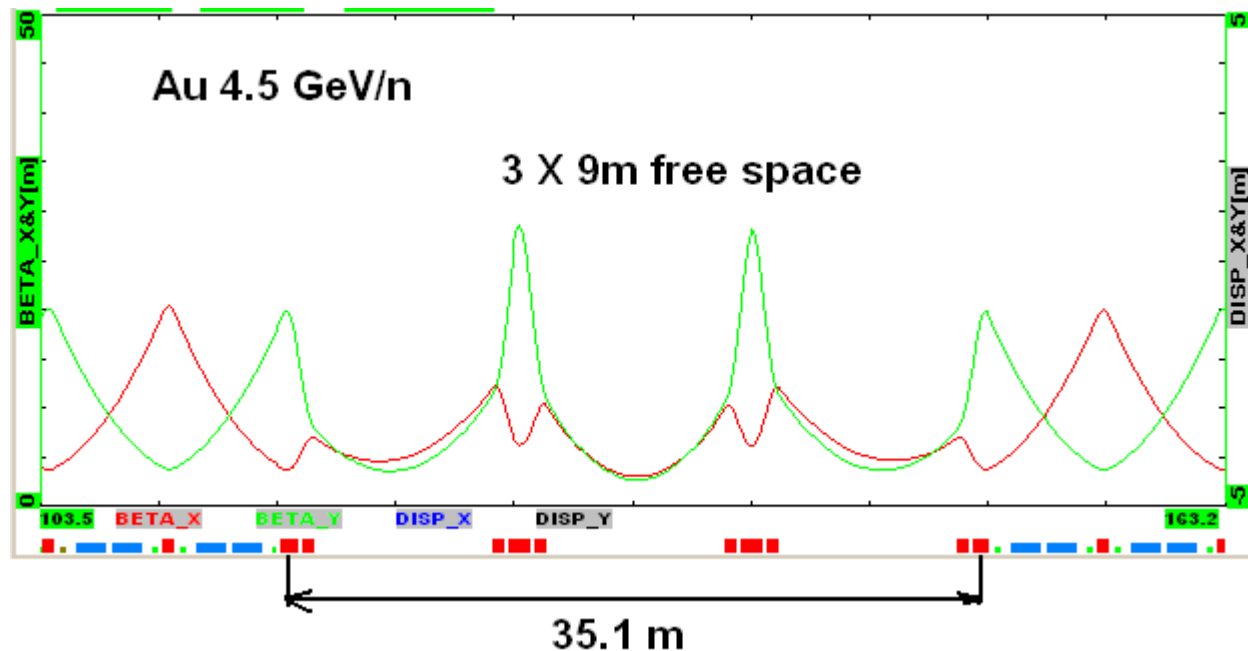
Straight sections



Straight insertions in arcs

2π phase advance

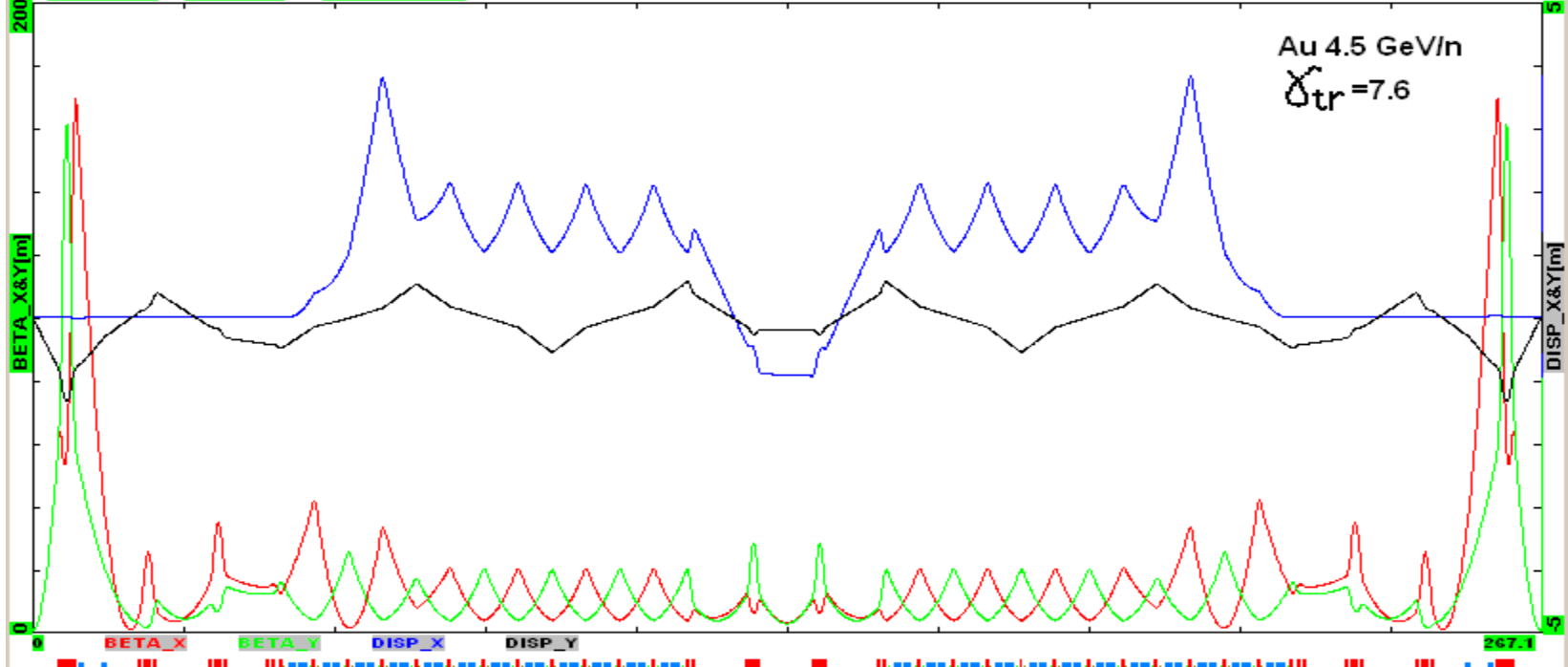
- additional space for non structural equipment: e-cooler, injection, spin rotators...



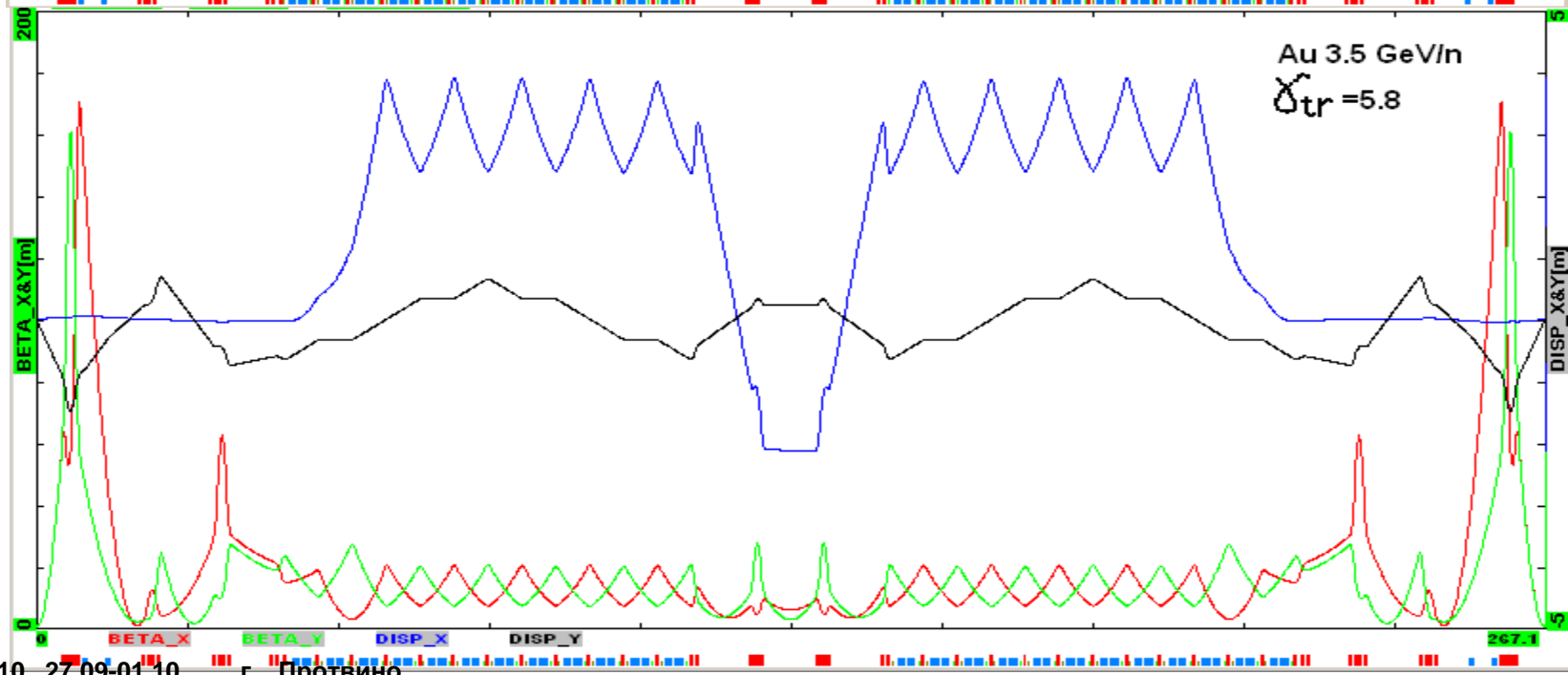
Full optics

534.2m
perimeter

$\xi_x = -38$
 $\xi_y = -37$



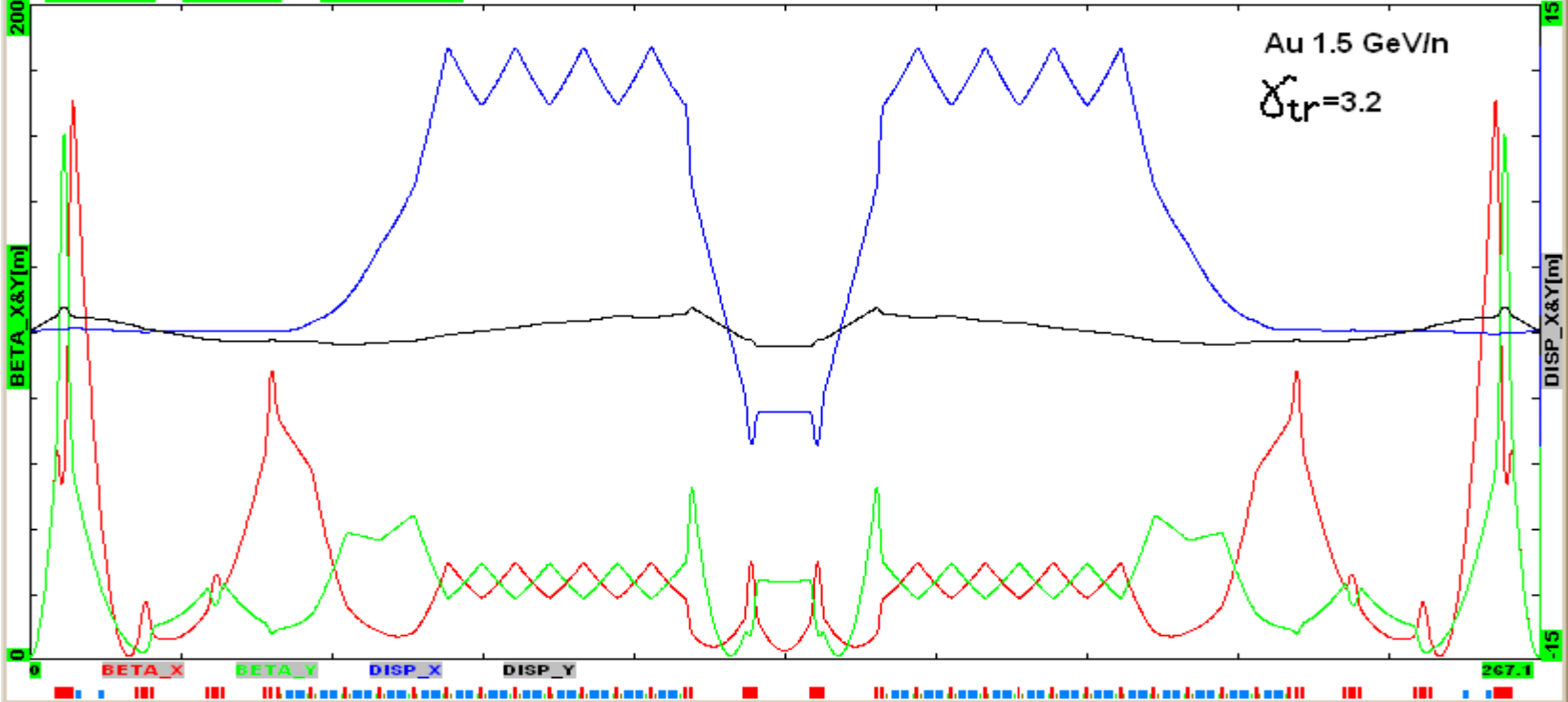
$\xi_x = -29$
 $\xi_y = -32$



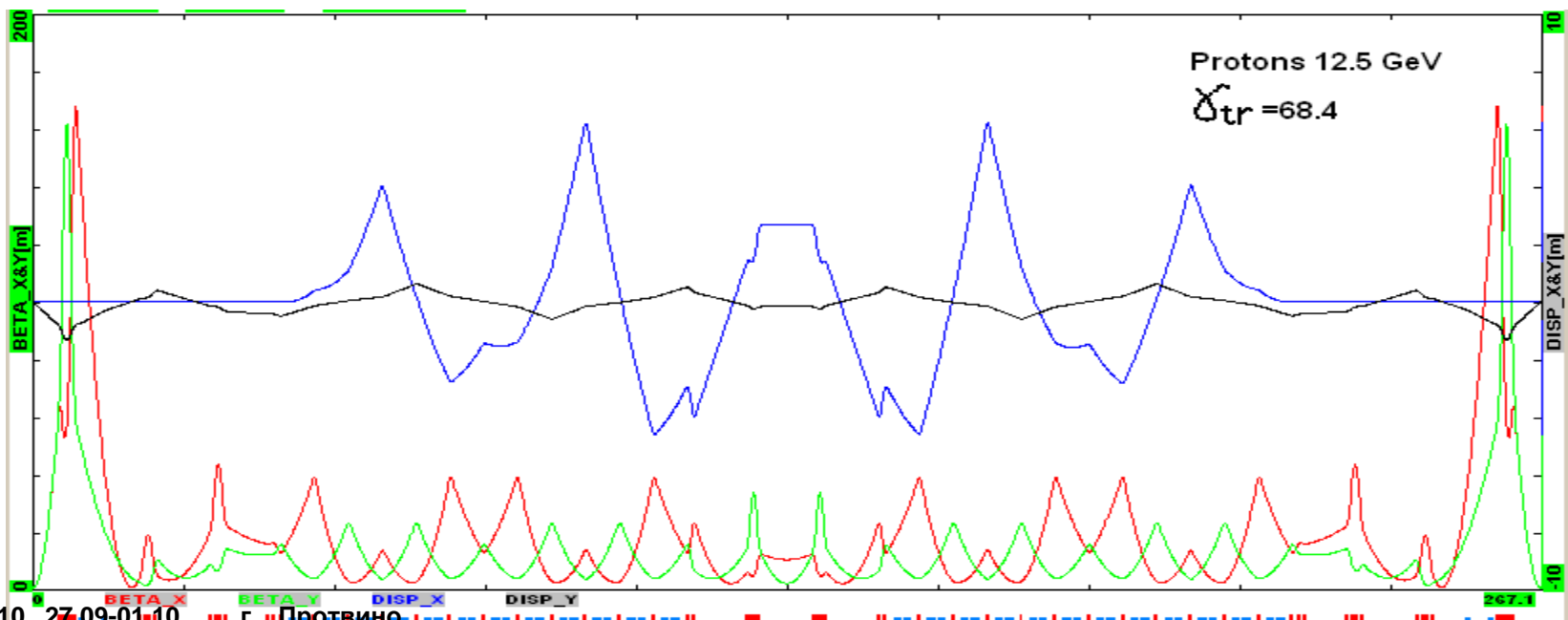
Full optics

534.2m
perimeter

$\xi_x = -29$
 $\xi_y = -28$

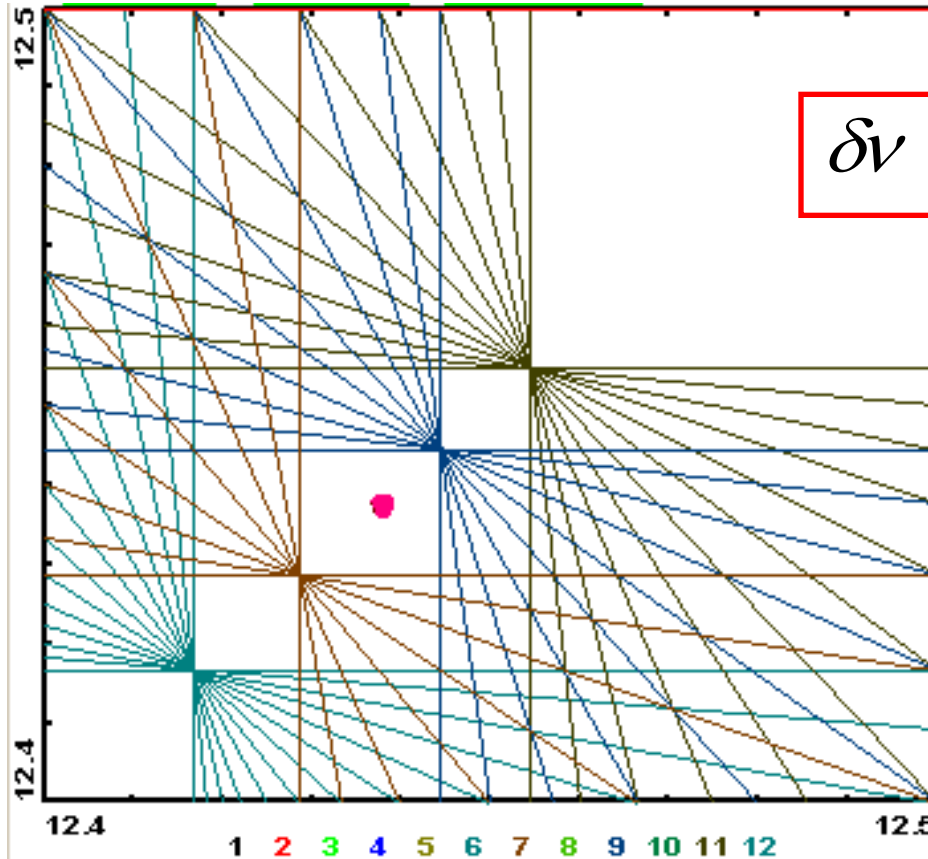


$\xi_x = -37$
 $\xi_y = -34$



Ring tune

x.44

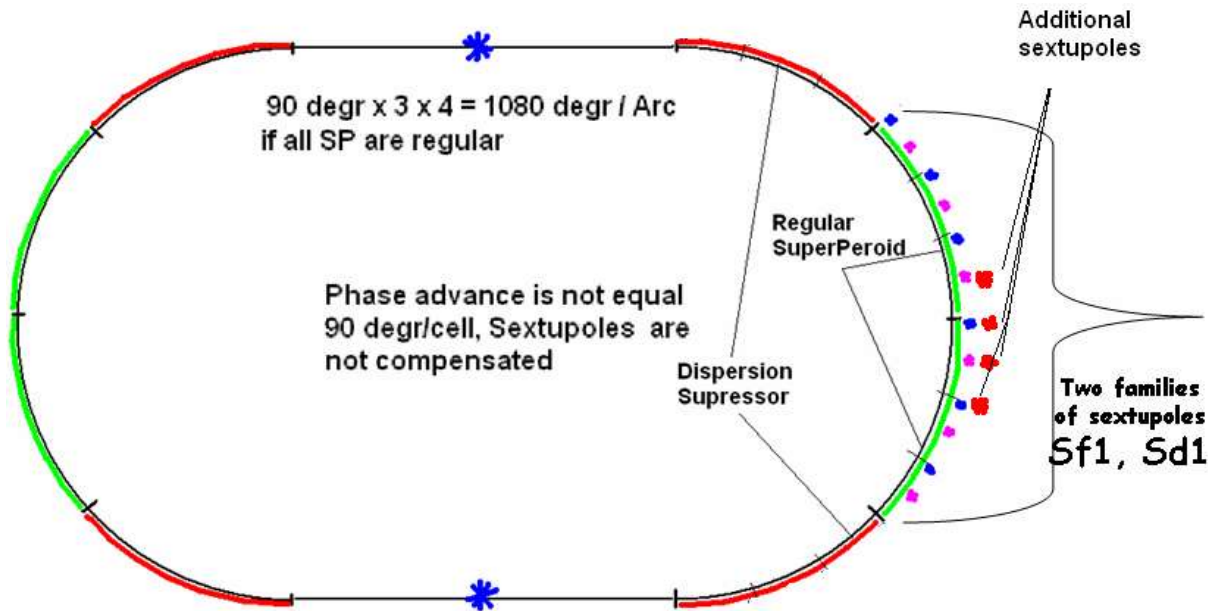


$$\delta\nu = \delta\nu_{sc} + 2 \cdot \delta\nu_{bb} < 0.05$$

Tune diagram (fractional part) with sum resonances up to 12th order

Chromaticity correction

1. Au 4.5 GeV/n



Two families of
sextupoles
(16 total)

Sf1=0.154 kG/cm²
Sd1=-0.264 kG/cm²

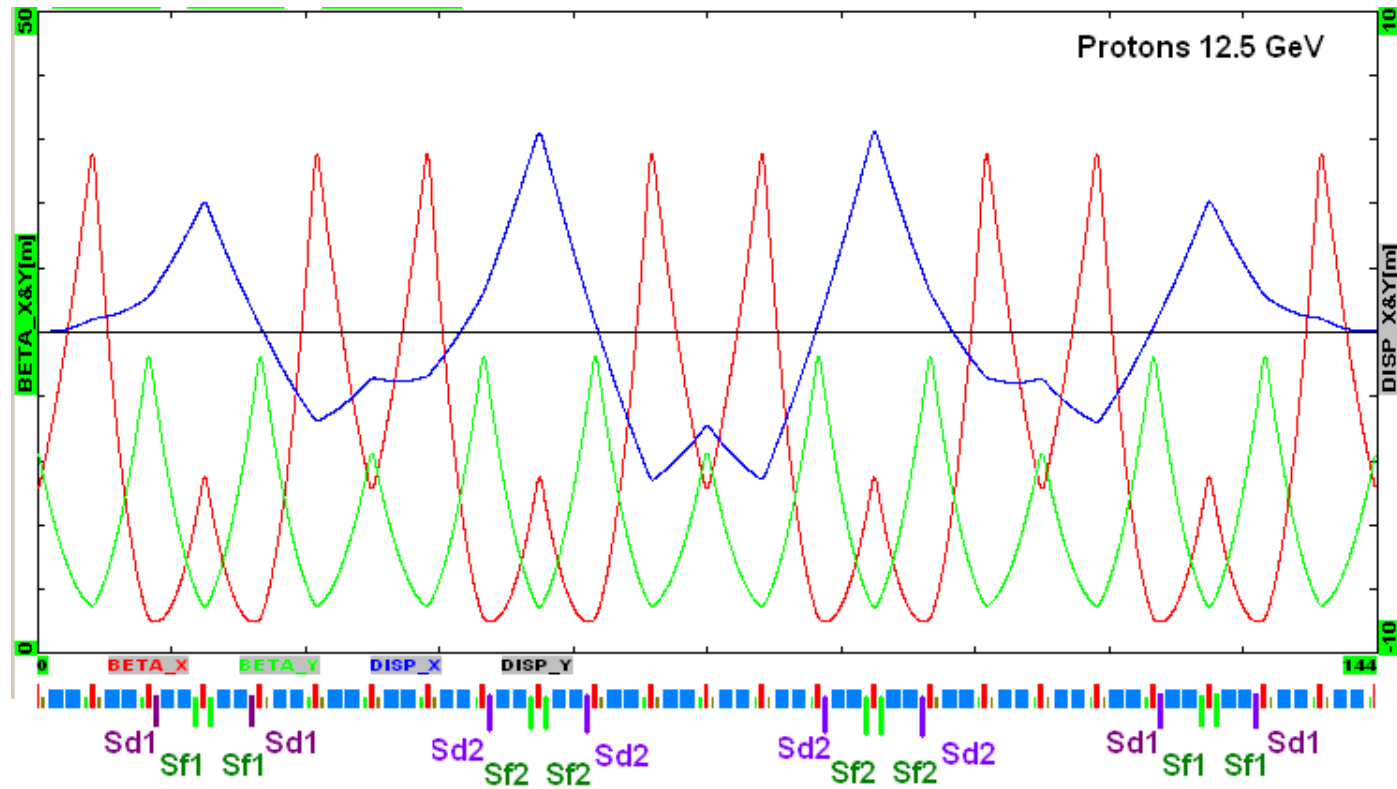
2, 3. Au 3.5 GeV/n, Au 1.5 GeV/n

All sextupoles in the arc (near each quad) are used for chromaticity correction (24 total)

Sf1=0.054 kG/cm²
Sd1=-0.085 kG/cm²

Chromaticity correction

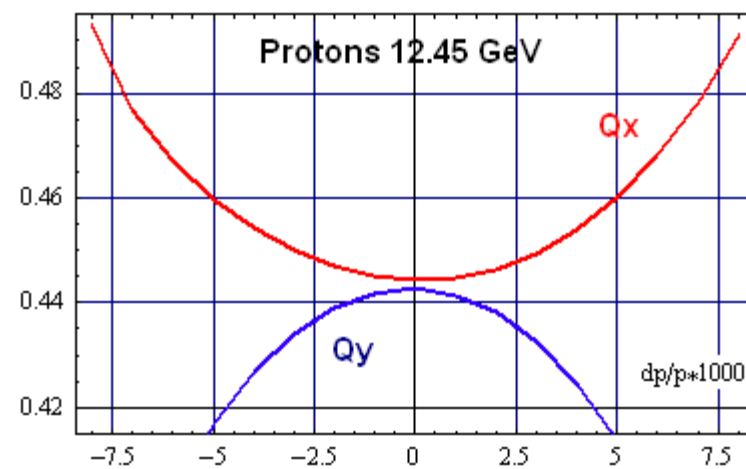
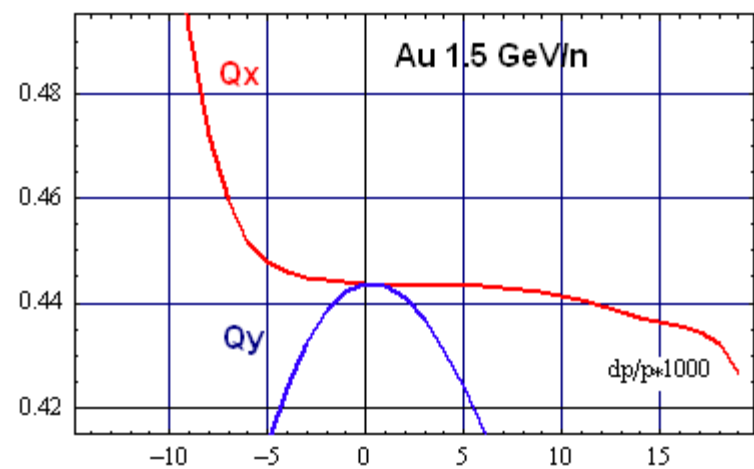
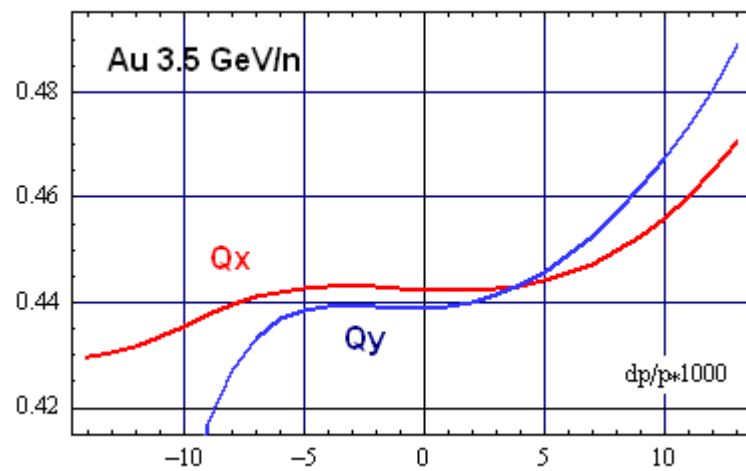
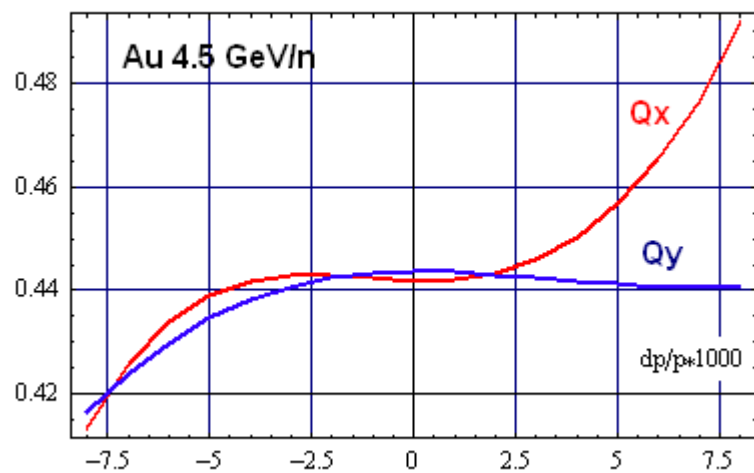
4. Protons 12.45 GeV



Only sextupoles near central lenses (four families) in each superperiod (where dispersion function are positive) are used (16 total)

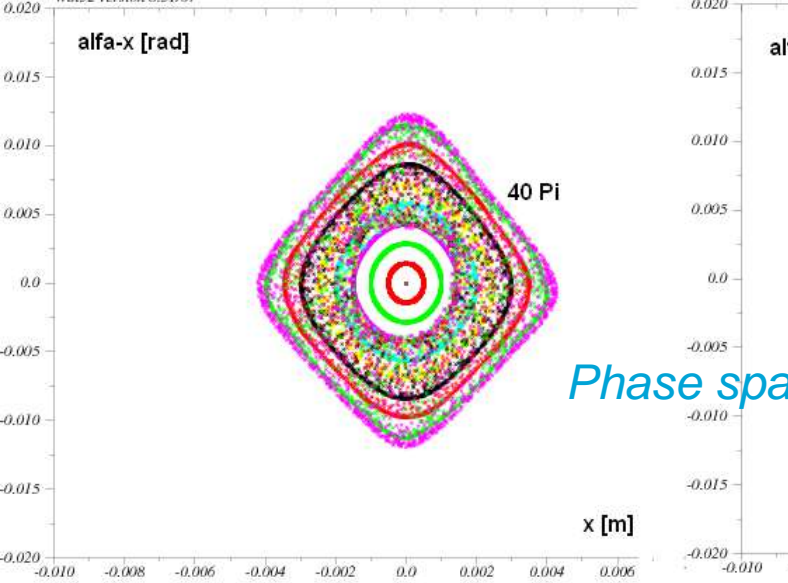
$Sf1=0.072 \text{ kG/cm}^2$
 $Sd1=-0.207 \text{ kG/cm}^2$

$Sf2=0.110 \text{ kG/cm}^2$
 $Sd2=-0.284 \text{ kG/cm}^2$

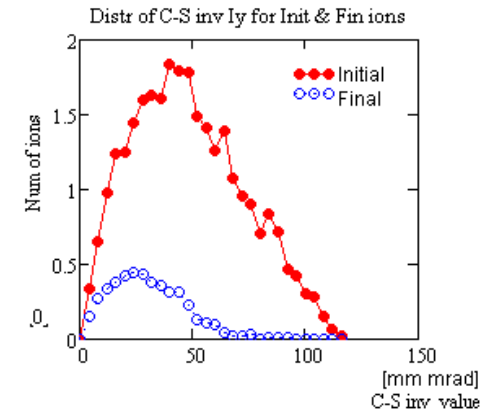
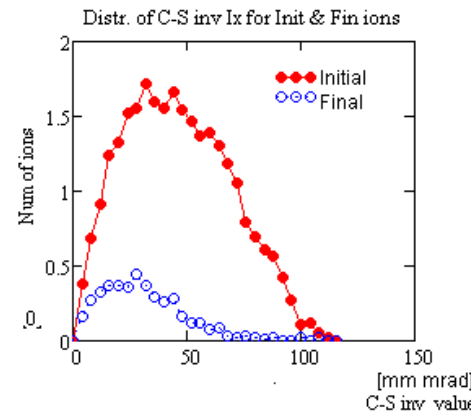
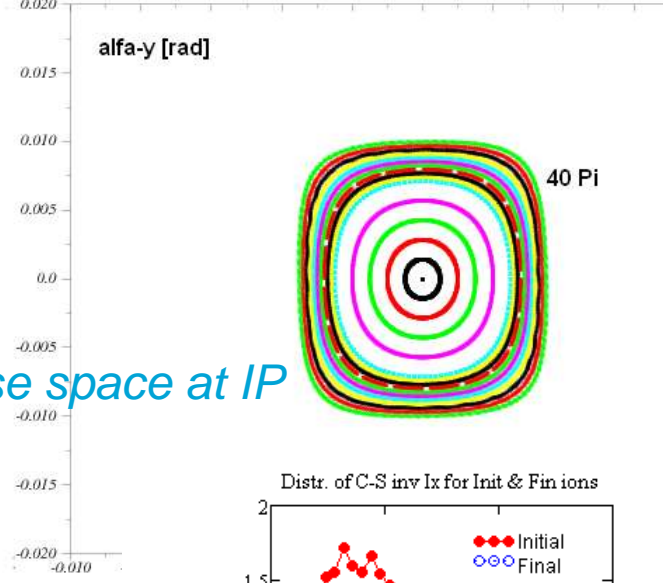


Dependence of the ring tune on dp/p

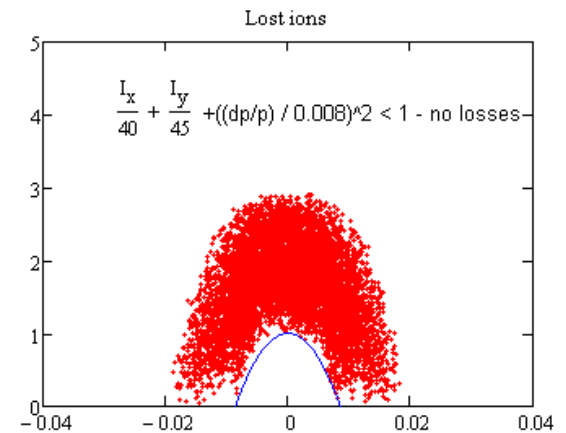
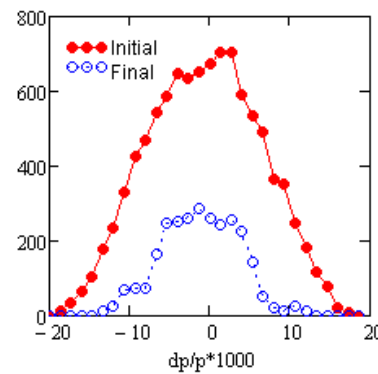
Au 4.5 GeV/n

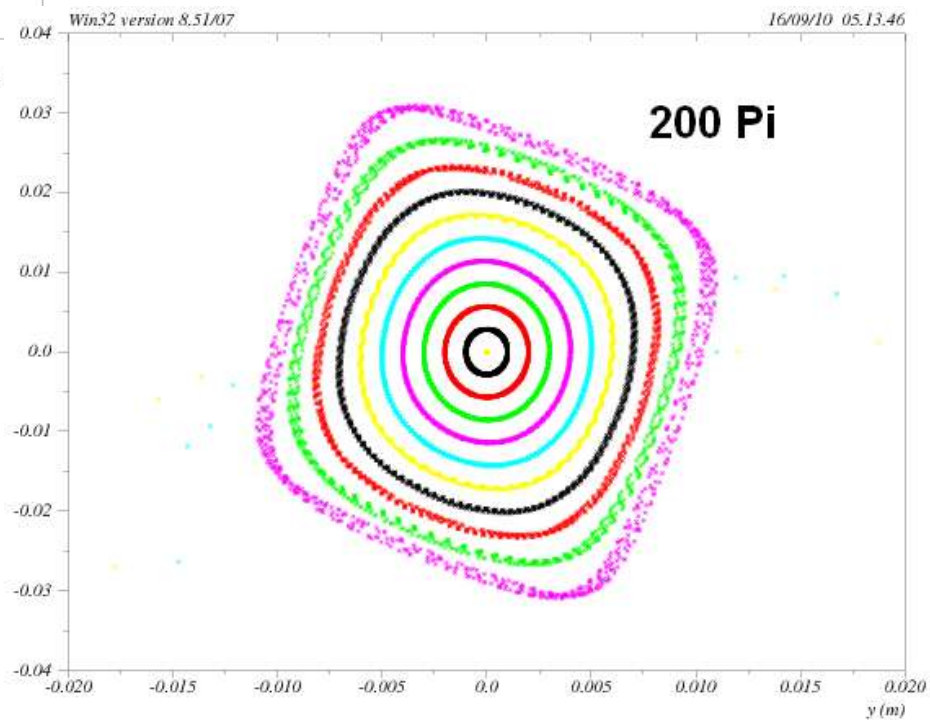
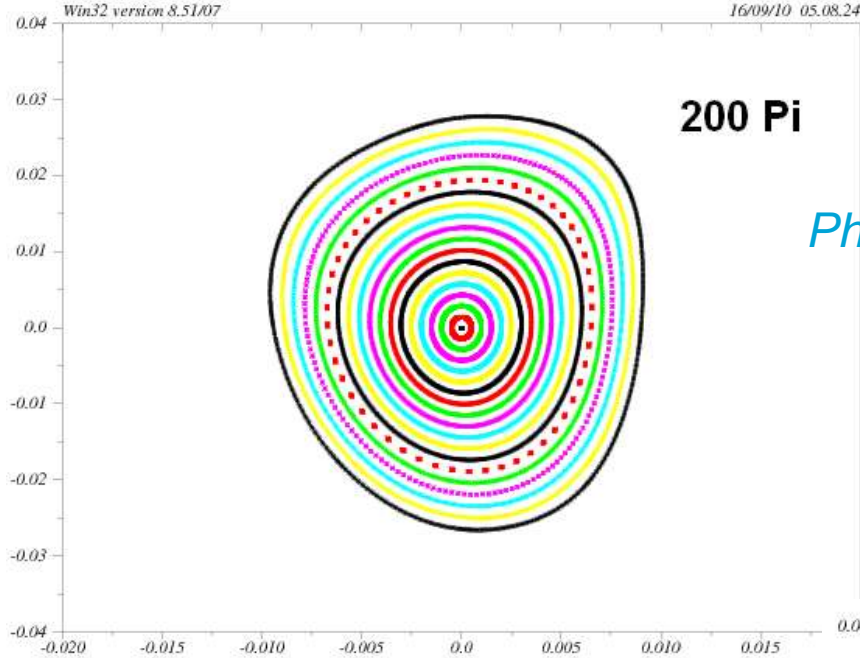


Phase space at IP



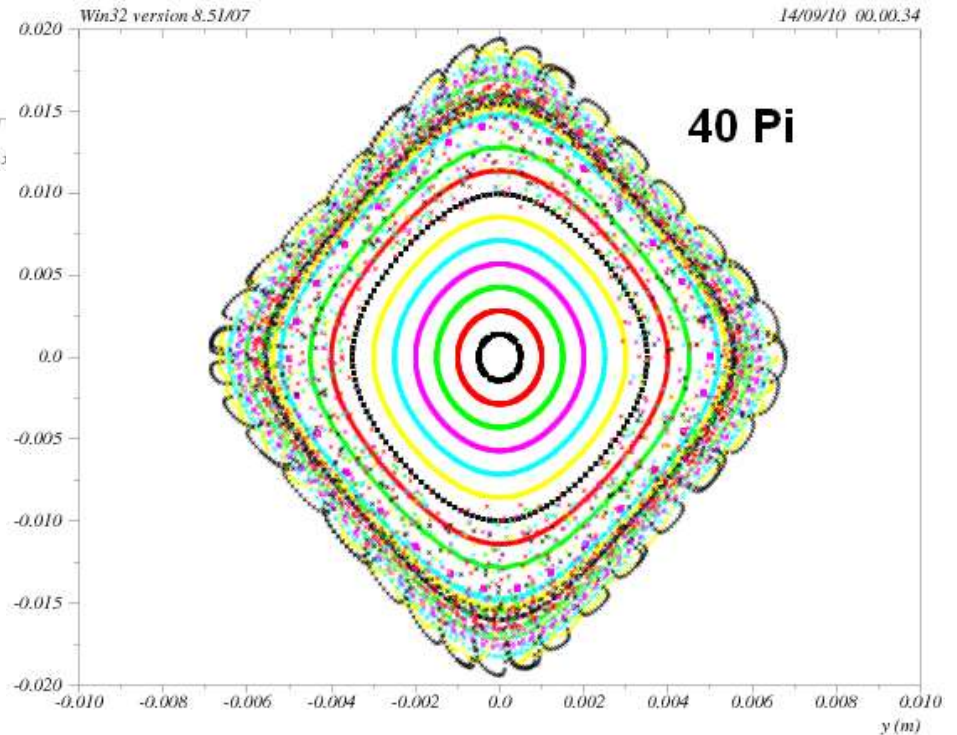
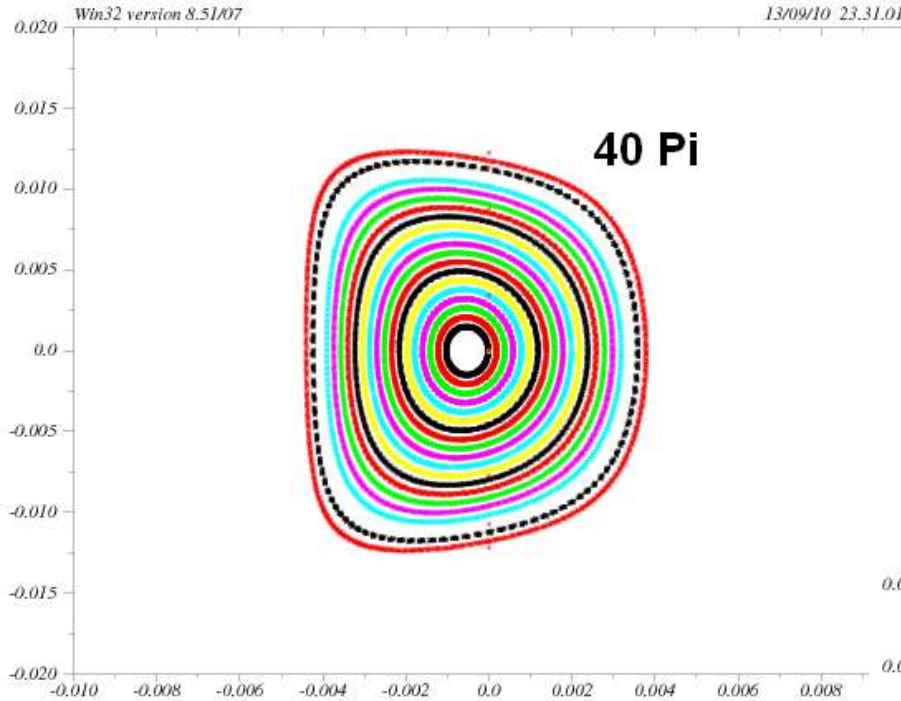
...tracking in MAD, OptiM





Phase space at IP

Protons 12.45 GeV/n

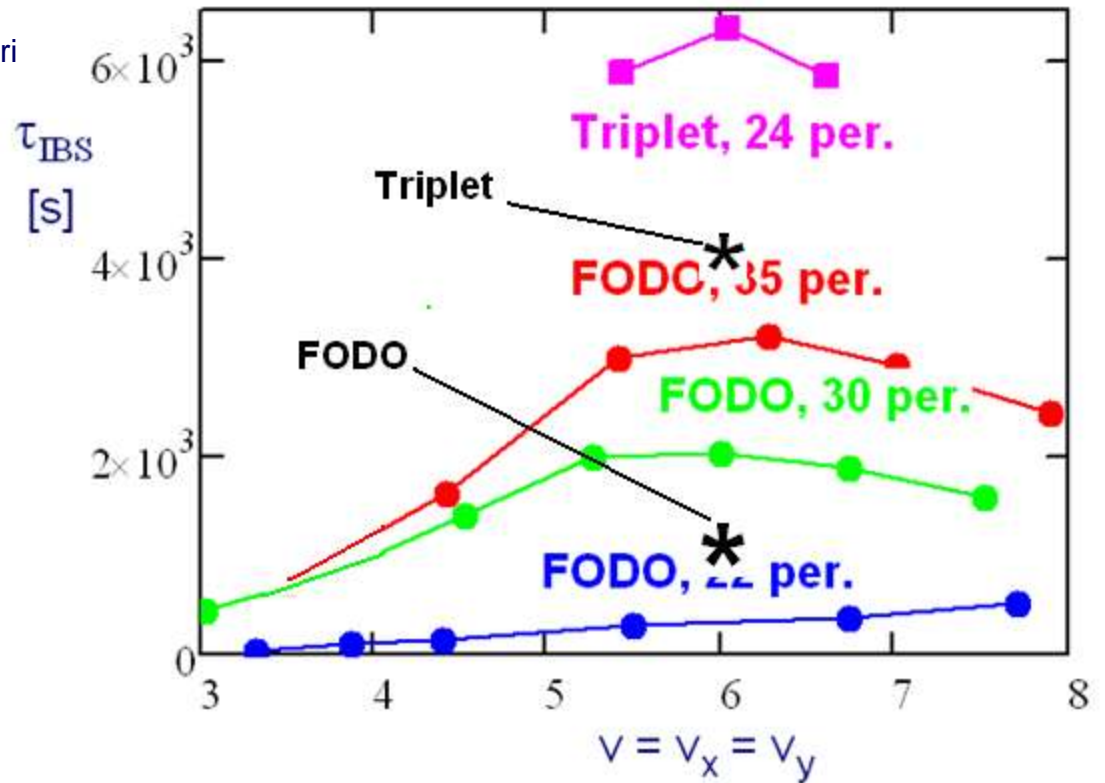


Acceptable IBS rates

IBS

NICA: Conceptual Proposal for Collider, Valeri Lebedev, Fermilab, January 11, 2010

...Triplet focusing looks preferable. It results in essential increasing IBS growth time...



IBS rates were tested for full ring FODO- & ODFDO- structures

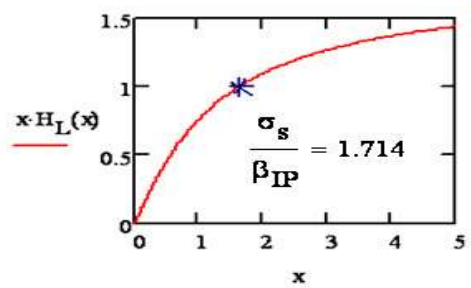
	E_0 ГэВ/н	N_{ion} $\times 10^9$	σ_s [см]	ϵ_x ϵ_y мм•мрад	σ_p $\times 10^{-3}$	$6 \cdot \sigma_{x max}$ $6 \cdot \sigma_{y max}$ [см]	τ [сек]	γ γ_{tr}	$\delta v_{x sc}$ $\delta v_{y sc}$	$2 \cdot \delta v_{x BB}$ $2 \cdot \delta v_{y BB}$	L $\times 10^{17}$
VAL4 optics, V. Lebedev $L_{ring}=454.2M$	4.5	5.3 $n_b=20$	60	1.12 0.60	1.79	7.5 5.5	1120	5.80 6.22	-0.026 -0.039	-0.007 -0.010	6.046
ODFDO, Au, full optics $L_{ring}=392.46M$ Fit to VAL4	4.5	5.3 $n_b=20$	60	0.86 0.86	1.89	3.8 7.6	1320	5.80 8.64	-0.026 -0.031	-0.008 -0.008	6.628
ODFDO, Au, full optics $L_{ring}=402.2M$	4.5	5.3 $n_b=20$	60	0.90 0.79	1.58	4.5 8.0	770	5.80 8.35	-0.028 -0.034	-0.008 -0.009	6.624
FODO, Au, full optics $L_{ring}=363.26M$ Fit to VAL4	4.5	5.3 $n_b=20$	60	1.14 0.76	1.62	4.5 5.4	890	5.80 6.95	-0.021 -0.029	-0.007 -0.008	6.629
FODO, Au, full optics $L_{ring}=374.30M$	4.5	5.3 $n_b=20$	60	0.93 0.89	1.46	4.5 9.0	560	5.80 7.13	-0.024 -0.030	-0.008 -0.008	6.628
FODO, Au, full optics $L_{ring}=343.50M$	4.5	5.3 $n_b=20$	60	1.26 0.77	1.69	10.1 6.3	760	5.80 6.83	-0.019 -0.026	-0.006 -0.008	6.610

Difference is due to different straight section structure

IBS rates for full FODO- ring optics is ~60% from ODFDO- ring optics

Collider Luminosity

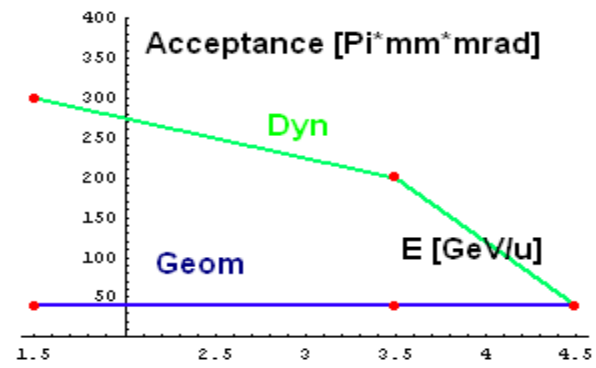
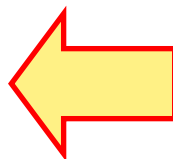
$$\delta\nu = \delta\nu_{sc} + 2 \cdot \delta\nu_{bb} < 0.05$$



Adjust ϵ_x, ϵ_y & σ_p (σ_s -fixed)

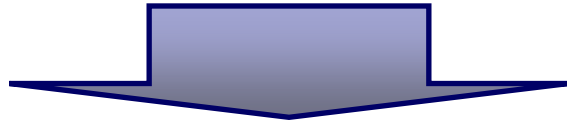
until $\left(\frac{d\epsilon dt_x}{\epsilon_x}\right)^{-1} = \left(\frac{d\epsilon dt_y}{\epsilon_y}\right)^{-1} = \left(\frac{d\sigma^2 dt_p}{\sigma_p^2}\right)^{-1}$

Increase ϵ_x, ϵ_y & σ_p proportionally staying in the ring acceptance



Increase N_i ions in the bunch keeping

$$\delta\nu = \delta\nu_{sc} + 2 \cdot \delta\nu_{bb} < 0.05$$



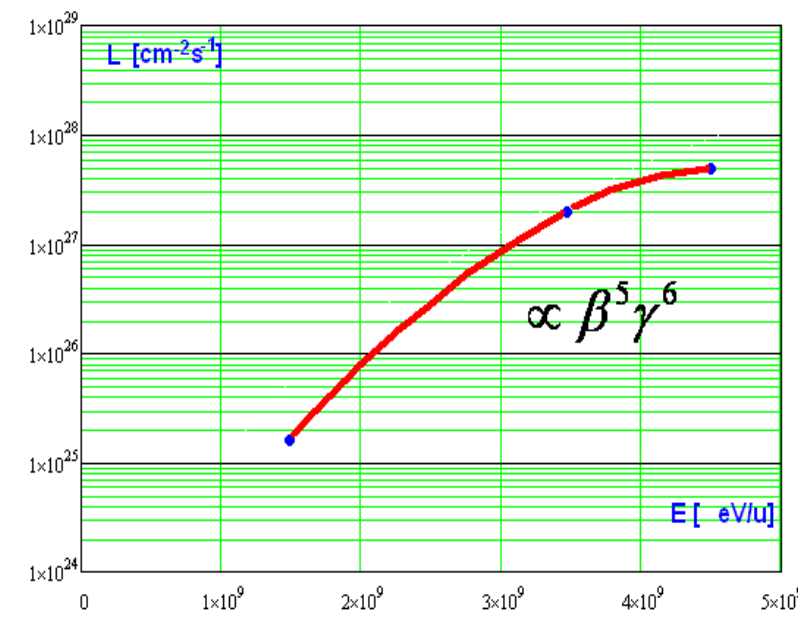
IBS rates

Luminosity

$$\left(\frac{d\epsilon dt_x}{\epsilon_x}\right)^{-1} = \left(\frac{d\epsilon dt_y}{\epsilon_y}\right)^{-1} = \left(\frac{d\sigma^2 dt_p}{\sigma_p^2}\right)^{-1}$$

$$\text{Lum} := \frac{f_0 \cdot n_b \cdot N_{\text{ion}}^2}{4 \cdot \pi \cdot \beta_{\text{IP}} \cdot \sqrt{\epsilon_x \cdot \epsilon_y}} \cdot H_L \left(\frac{\sigma_s}{\beta_{\text{IP}}} \right)$$

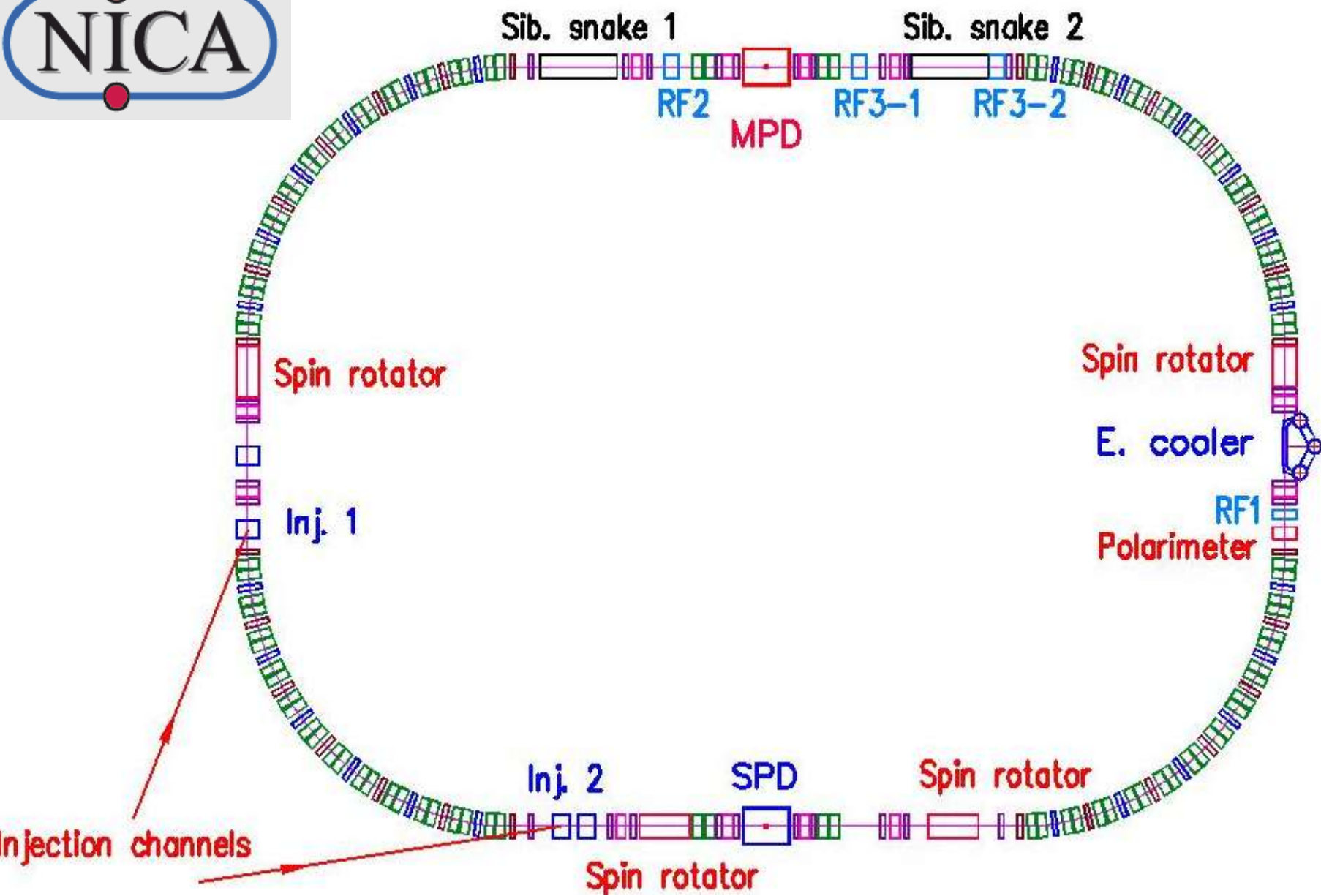
Energy of the experiment	Ion-ion and collisions			Polarize d protons 5÷12 GeV
	1.5 GeV/n	3.5 GeV/u	4.5 GeV/u	
Ring acceptance, $\pi \cdot \text{mm} \cdot \text{mrad}$	300/300	200/200	40/40	40/70
Ring long. acceptance, $\Delta p/p$	± 0.005			± 0.005
Maximum acceptable RMS emittance, ϵ_x/ϵ_y $\pi \cdot \text{mm} \cdot \text{mrad}$	1.1/0.5	1.1/0.6	1.2/0.6	1.1/0.6
RMS momentum spread	$0.6 \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$
Particle per bunch corresponding to tune shift $\Delta Q = 0.05$	$0.4 \cdot 10^9$	$2.5 \cdot 10^9$	$4.9 \cdot 10^9$	$2.5 \cdot 10^{11}$
IBS growth time, s	110	600	710	8700
Maximum achievable luminosity, $\text{cm}^{-2} \text{s}^{-1}$	$1.8 \cdot 10^{25}$	$2.0 \cdot 10^{27}$	$4.2 \cdot 10^{27}$	$4.2 \cdot 10^{31}$



$$L = 8\pi^2 \frac{A^2 c \beta^5 \gamma^6}{Z^4 r_p^2} \frac{n_b \sigma_s \epsilon}{C^3} \left(\frac{\sigma_s}{\beta^*} H \left(\frac{\sigma_s}{\beta^*} \right) \right) \delta v_{SC}^2$$

■ Main Parameters of the NICA collider

Energy of the experiment	Ion-ion and ion-proton collisions			Polarized protons 5-12 GeV
	1.5 GeV/n	3.5 GeV/u	4.5 GeV/u	
Ring circumference, m	534.2			
Transition energy, γ_{tr}	3.2	5.8	7.6	68
Phase advance per cell, °	30	60	90	varied
Slippage factor, η_ω	0.051	0.015	0.013	0.004
Betatron tune Q_x/Q_y	8.44/7.44	10.44/10.44	12.44/12.44	12.44/12.44
Number of bunches, n_{bunch}	26			
• Total chromaticity of the ring (before correction), ξ_x/ξ_y	-28.8/ -27.5	-29.6/ -32.4	-38.3/ -36.6	-37.2/ -33.5
Ring acceptance, $\pi \cdot \text{mm} \cdot \text{mrad}$	200/300	200/200	40/40	40/70
Ring long. acceptance, $\Delta p/p$	± 0.005			± 0.005
Maximum acceptable RMS emittance, $\varepsilon_x/\varepsilon_y \pi \cdot \text{mm} \cdot \text{mrad}$	1.1/0.5	1.1/0.6	1.2/0.6	1.1/0.6
RMS momentum spread	$0.6 \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$
Particle per bunch corresponding to tune shift $\Delta Q = 0.05$	$0.4 \cdot 10^9$	$2.5 \cdot 10^9$	$4.9 \cdot 10^9$	$2.5 \cdot 10^{11}$
β^* , cm	35			35
Bunch length, cm	60	60	60	60
IBS growth time, s	110	600	710	8700
Maximum achievable luminosity, $\text{cm}^{-2} \text{s}^{-1}$	$1.8 \cdot 10^{25}$	$2.0 \cdot 10^{27}$	$4.2 \cdot 10^{27}$	$4.2 \cdot 10^{31}$



Thank you

Classic optic structure:

$$\alpha = \bar{D} / \bar{R} \quad \bar{D} = \frac{\bar{R}}{v^2} \quad \alpha = \frac{1}{v^2}$$

“Resonance” optic structure*
for super-period:

$$\alpha_s = \frac{1}{v^2} \left\{ 1 + \frac{1}{4} \left(\frac{\bar{R}}{v} \right)^4 \sum_{k=-\infty}^{\infty} \frac{g_k^2}{(1 - kS/v)[1 - (1 - kS/v)^2]^2} + \frac{1}{4} \sum_{k=-\infty}^{\infty} \frac{r_k^2}{1 - kS/v} \right. \\ \left. - \frac{1}{2} \left(\frac{\bar{R}}{v} \right)^2 \sum_{k=-\infty}^{\infty} \frac{r_k g_k}{(1 - kS/v)[1 - (1 - kS/v)^2]} - \frac{1}{2} \left(\frac{\bar{R}}{v} \right)^2 \sum_{k=-\infty}^{\infty} \frac{r_k g_k}{[1 - (1 - kS/v)^2]} \right. \\ \left. + O(g_k^i \cdot r_k^j, i + j \geq 3) \right\}$$

Orbit compaction factor
for structure with str. sec.:

$$\alpha = \alpha_s \frac{S \cdot L_s}{S \cdot L_s + L_{str}}$$

$\min\{kS - v\} \Rightarrow$ maximum influence to
orbit compaction factor


$$kS > v$$

$$\frac{2 \cdot \pi \cdot v}{S \cdot N_{cell}} = 60^\circ \div 100^\circ$$



3 ÷ 5 Cells per super-period

* Построение «резонансных» магнитооптических структур с контролируемой критической энергией
Ю.В. Сеничев^{a,*} и А.Н. Чеченин^b

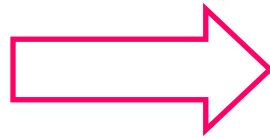
• $D=0$ at straight sections in resonance structure $\Rightarrow 2\pi \cdot n$ -  $Q_{x_{arc}}$ - integer
 phase advance per Arc

S_{arc} - number of super-periods in Arc

$$\min[v_{arc} - kS_{arc}] = -1$$

Sextupoles compensation:

S_{arc} - even
 $Q_{x_{arc}}$ - odd



$$\frac{2 \cdot \pi \cdot v_{arc}}{S_{arc}} \cdot \frac{S_{arc}}{2} = \pi \cdot v_{arc}$$

Phase advance between Cells through $S_{arc}/2$ super-periods

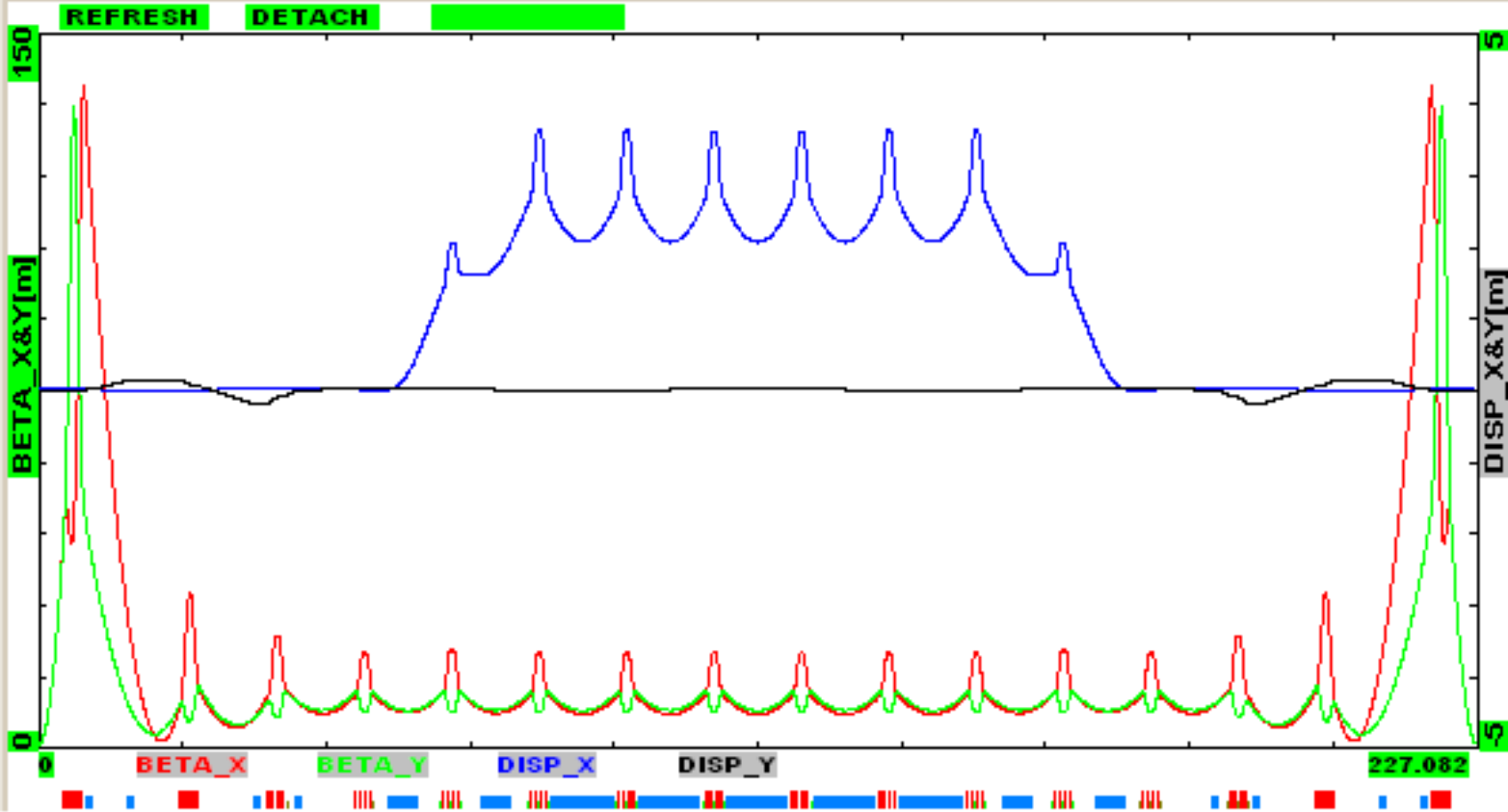
$$4.5 \text{ GeV/n}; \gamma=5.8 \Rightarrow Q_{x_{arc}} \gamma_{tr} > 6$$

$$N_{arc}=2 \Rightarrow Q_{x_{arc}}=3 (\gamma_{tr} \approx Q_x)$$

$$\min[Q_{x_{arc}} - 1 \cdot S_{arc}] = -1 \Rightarrow S_{arc}=4$$

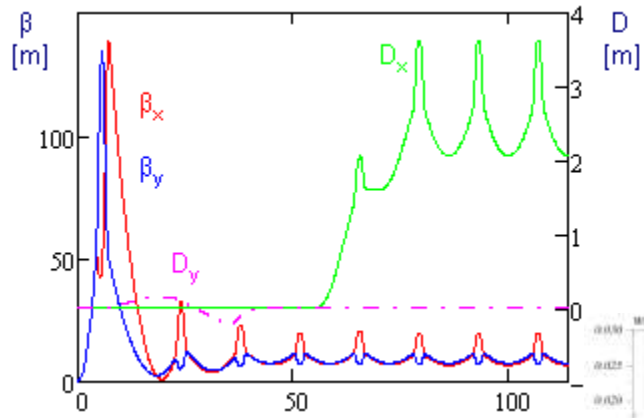
$3/2\pi$ - ph. ad. per super-per.

3Cell * 90° - superperiod



NICA: Conceptual Proposal for Collider, Valeri Lebedev, Fermilab, January 11, 2010

• Large acceptance ➔ Calc. of Dynamic Aperture & compensation of nonlinearities

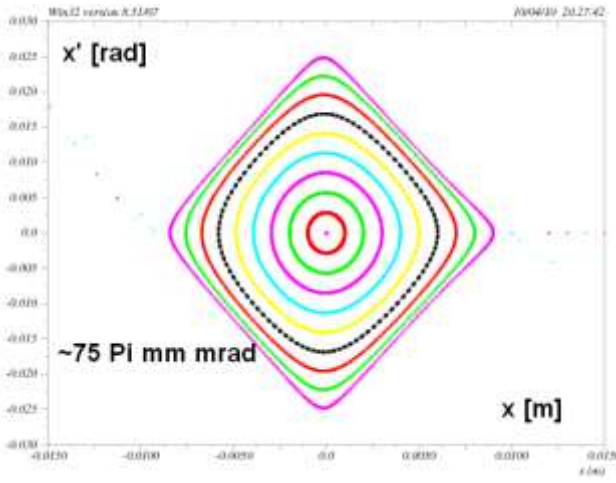
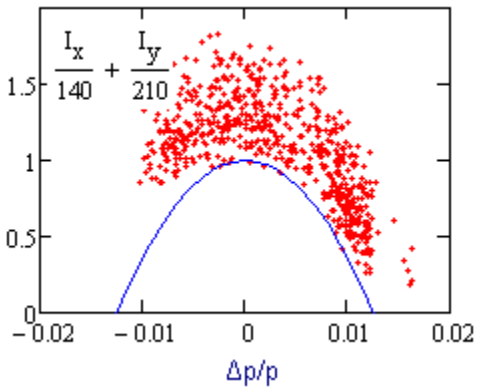


NICA: Conceptual Proposal for Collider, Valeri Lebedev, Fermilab, January 11, 2010

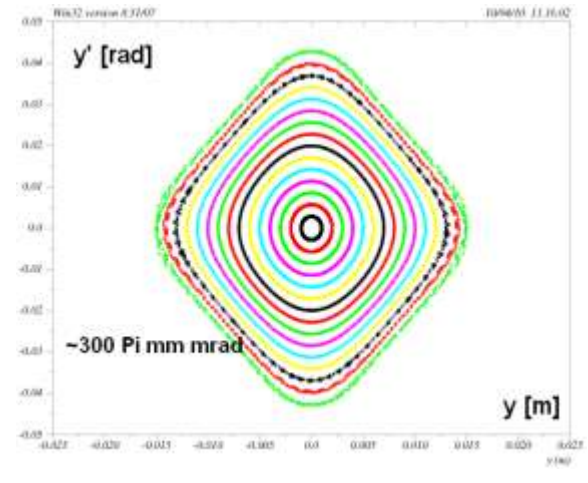
- ref. point

NicaVAL4

Tracking in MAD:



(X,X')-phase plane at IP



(Y,Y')-phase plane at IP

Actions (C-S inv.) in IP for initial coordinates of particles lost after 5000 turns, $\epsilon_{xmax}=140$ mm mrad, $\epsilon_{ymax} = 210$ mm mrad, $(\Delta p/p)_{max}=0.0125$

$$\frac{I_x}{\epsilon_{x_{max}}} + \frac{I_y}{\epsilon_{y_{max}}} + \left(\frac{\Delta p/p}{(\Delta p/p)_{max}} \right)^2 < 1$$

■ Dynamic aperture exceeds the requirement of 40 mm mrad by ~2 times

Agreement between tracking in MAD and OptiM (MAD used for further investigations...)

Luminosity Limitation due to Beam-beam Effects

■ For bunched beam with Gaussian distribution

$$\begin{bmatrix} \delta\nu_{BBx} \\ \delta\nu_{BBY} \end{bmatrix} = \frac{r_p Z^2 N_i}{4\pi A \beta^2 \gamma} \frac{1 + \beta^2}{\sqrt{\epsilon_x} + \sqrt{\epsilon_y}} \begin{bmatrix} 1/\epsilon_x \\ 1/\epsilon_y \end{bmatrix}$$

■ For round beam \Rightarrow

$$\delta\nu_{BB} = \frac{r_p Z^2 N_i}{4\pi A \beta^2 \gamma \epsilon} \left(\frac{1 + \beta^2}{2} \right)$$

■ Combining the above equation with the equation for space charge tune shift one obtains

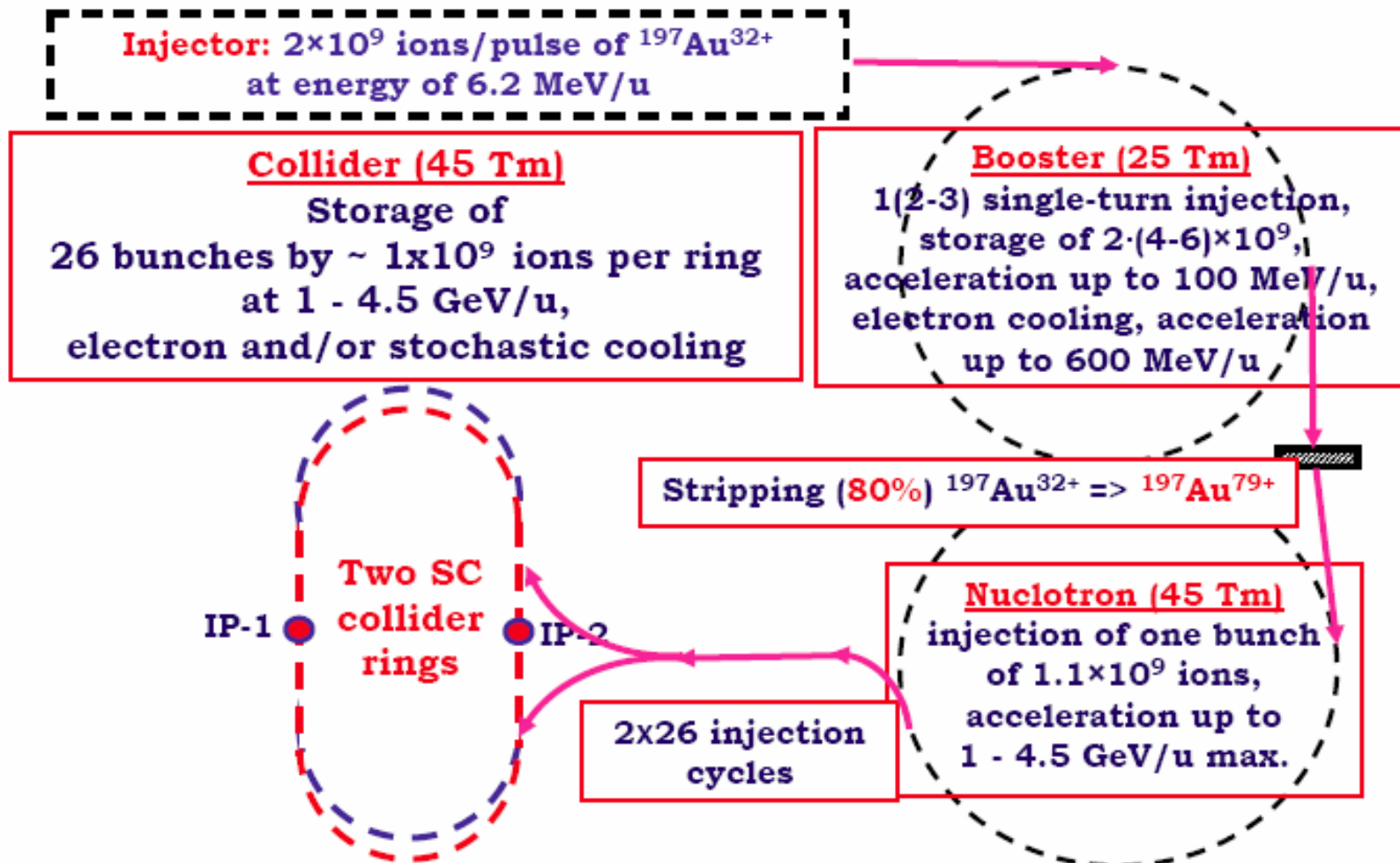
$$\delta\nu_{BB} = \delta\nu_{SC} \sqrt{\frac{\pi}{2}} \frac{\sigma_s}{C} \gamma^2 (1 + \beta^2)$$

■ For NICA parameters the space charge tune shift is significantly smaller than the tune shift due to beam space charge

■ Small β^* results small σ_s and, consequently, small $\delta\nu_{SC}$

■ Large value of σ_s/β^* results in phase averaging for high order resonances and significantly mitigates the beam-beam effects

Heavy Ion Mode: Operation Regime and Parameters



2.3. Luminosity preservation

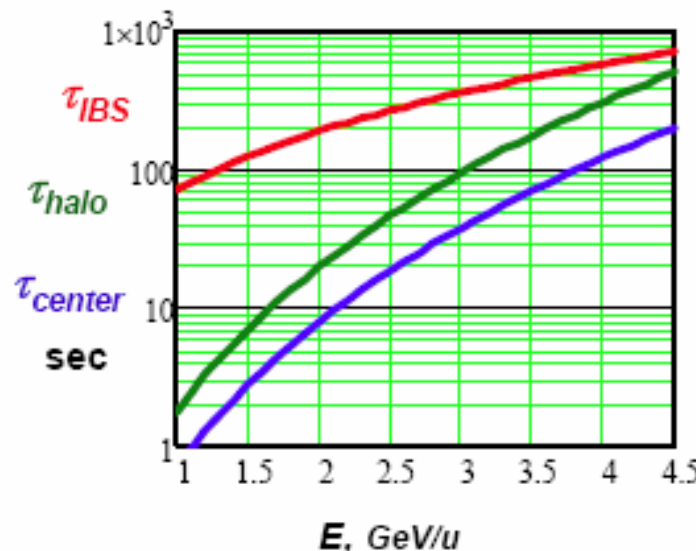
Beam life time defined by IBS

If ΔQ is fixed as before then beam life time by IBS is proportional to

$$\tau_{IBS} \propto \frac{A}{Z^2} \cdot \frac{\beta^2 \gamma^2 \varepsilon_{geom} \cdot (\Delta p / p) \cdot \sigma_s}{\Delta Q} \cdot f(\sigma_x, \sigma_y, \sigma_s, \text{lattice functions})$$

Collider 2T - 534

τ_{IBS} and τ_{cool} ($I_e = 1$ A) vs ion energy

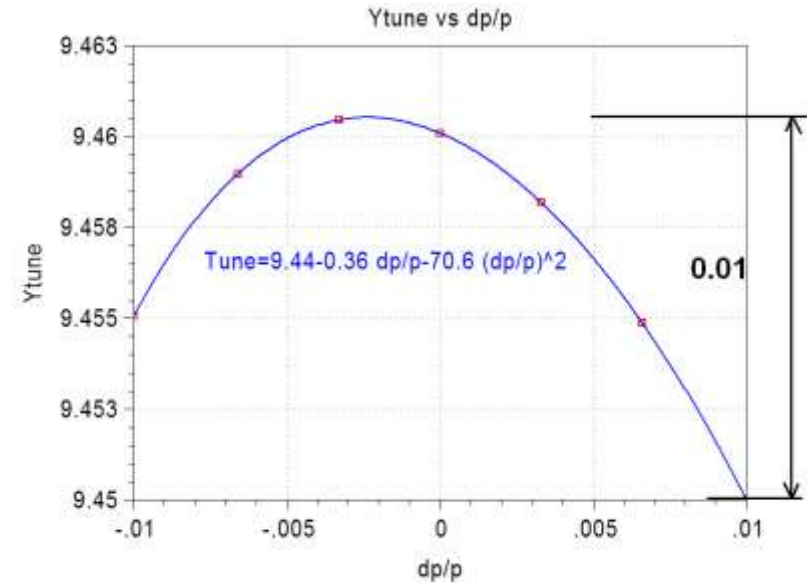
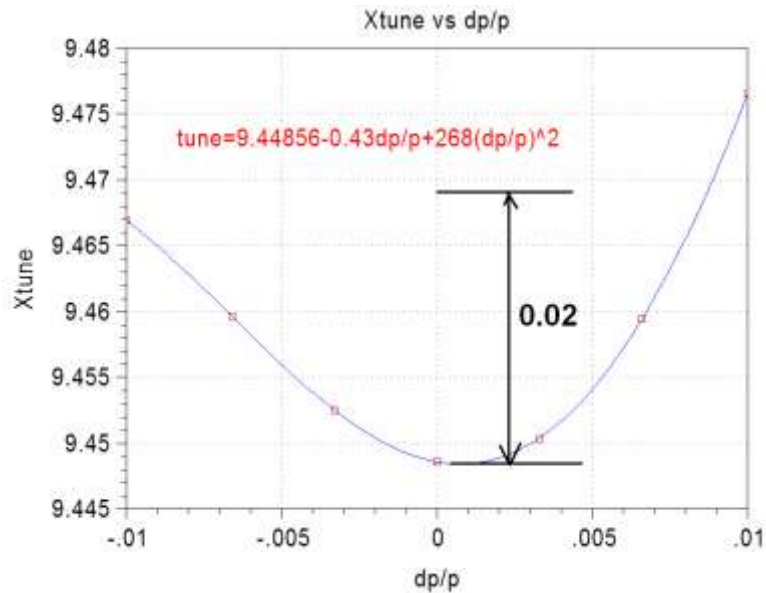


How to resolve the problem?

- ⇒ Smooth lattice functions to increase τ_{IBS}
(S.Kostromin, JINR & V.Lebedev, FNAL)
- ⇒ Stochastic cooling at
2.5 GeV/u < E < 4.5 GeV/u
(T.Katayama, G.Trubnikov, N.Shurkhno);
- ⇒ Electron cooling at
1.0 GeV/u < E < 2.5 GeV/u .

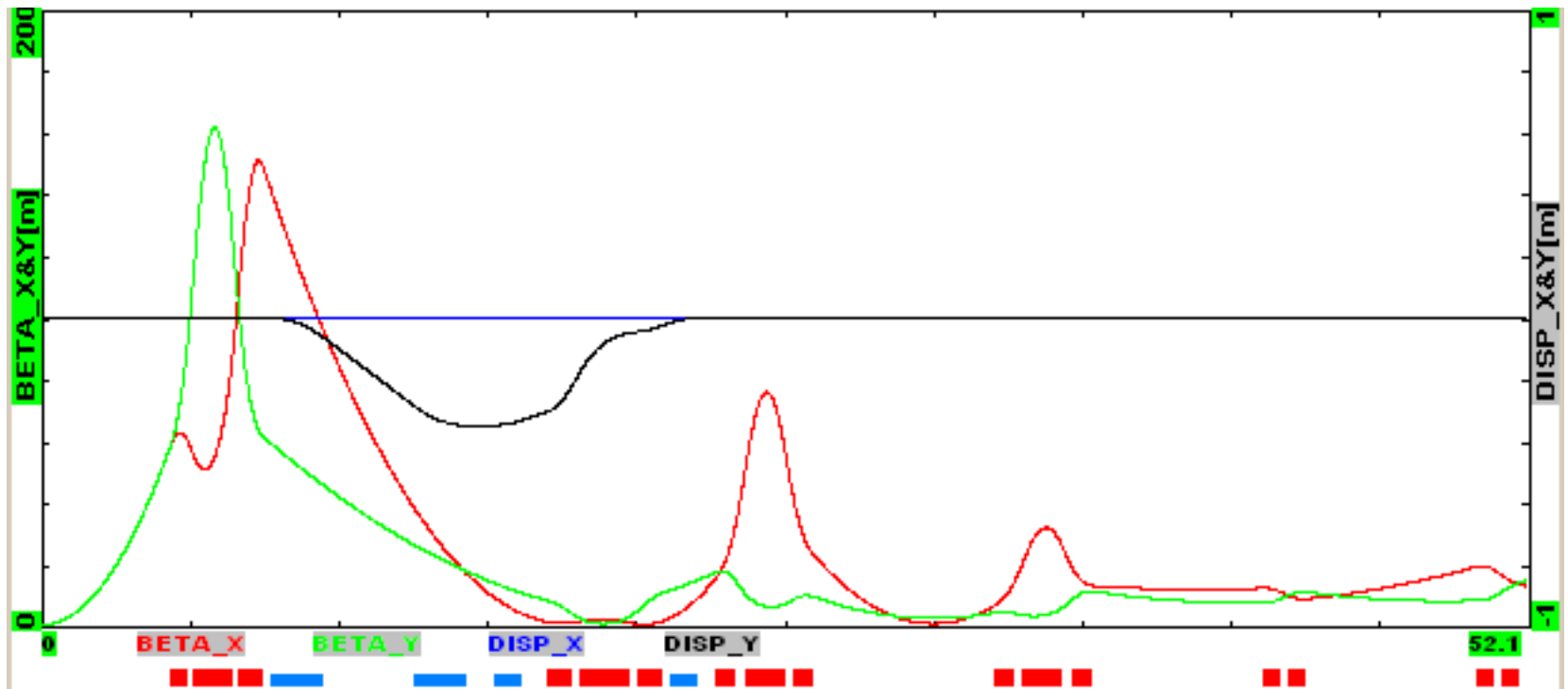


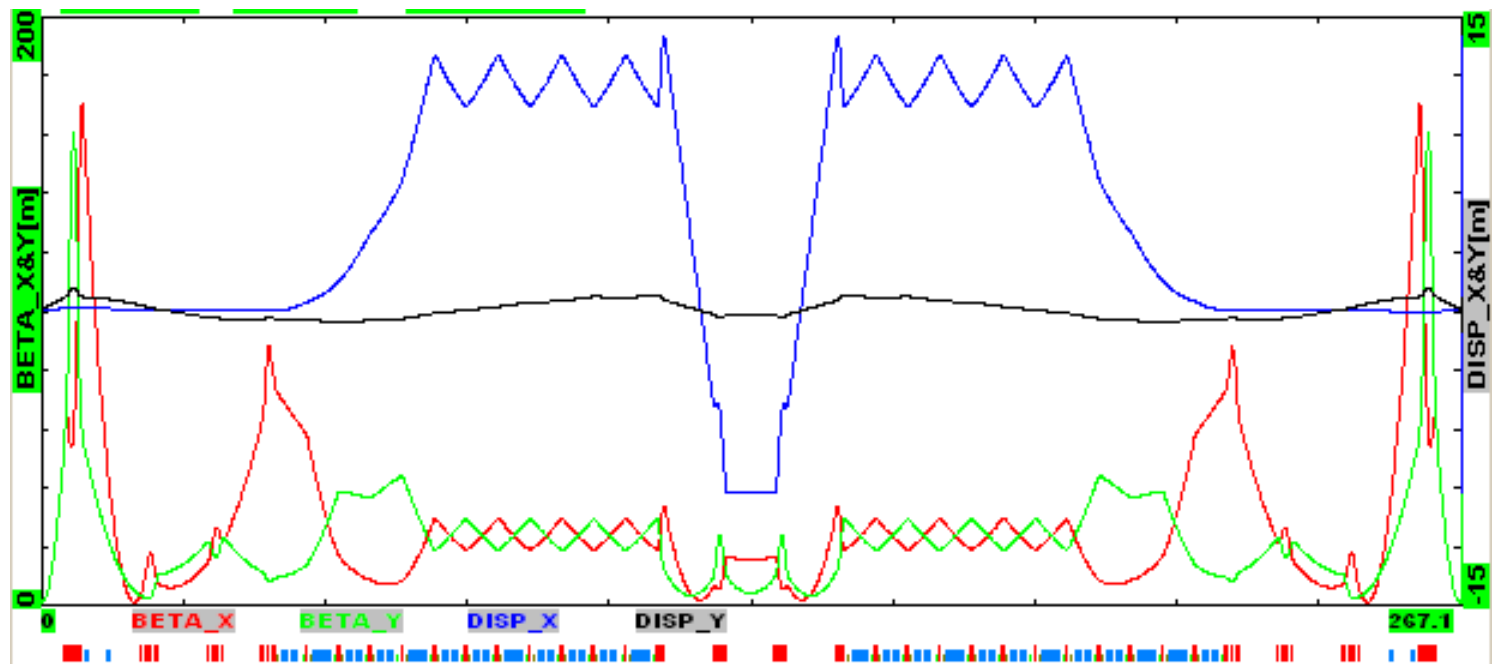
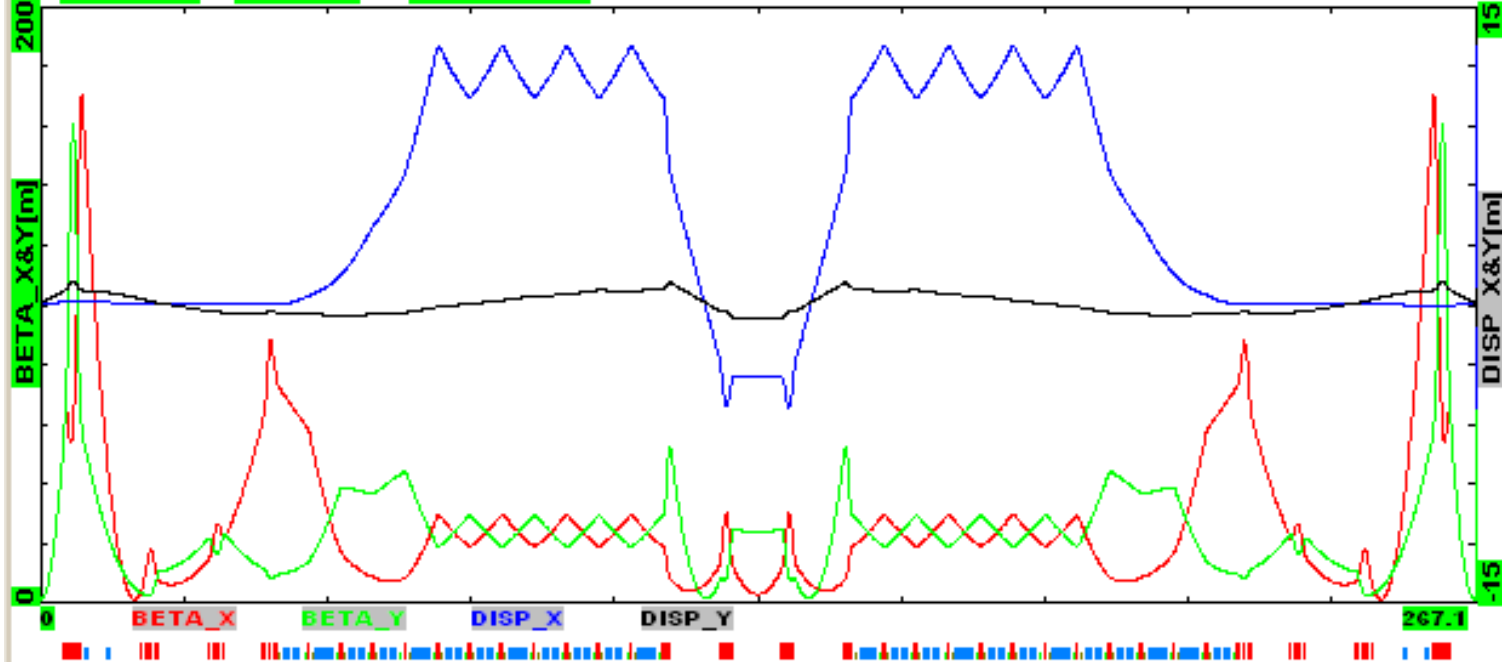
NicaVAL4 Tunes vs dp/p: first and second order chromaticity correction



$$v = v_0 + \delta v_{sc} + \delta v_{bb} + \xi_1 \frac{\delta p}{p} + \xi_2 \left(\frac{\delta p}{p} \right)^2$$

<0.05 (depends on working point location)





variation of gamma-tr:



decrease phase advance per cell
90° -> 60° -> 30°

“resonance” optic structure* with
variation of D through the ring

$$\alpha = \frac{1}{C} \int \frac{D(s)}{\rho(s)} ds \quad \text{- orbit compaction factor (OCF)}$$

$$\frac{d^2 D}{ds^2} + [K(s) + \varepsilon k(s)]D = \frac{1}{\rho(s)} \quad , \text{ where } \quad K(s) = \frac{eG(s)}{p} \quad \varepsilon k(s) = \frac{e\Delta G(s)}{p}$$

$$\varepsilon \cdot k(\phi) = \sum_{k=0}^{\infty} g_k \cos k\phi \quad \text{with} \quad g_k = \frac{e}{p} \cdot \frac{1}{\pi} \int_{-\pi}^{\pi} \Delta G \cos k\phi d\phi \quad \phi = 2\pi \cdot s / L_s$$

$$\frac{1}{\rho(\phi)} = \frac{1}{\bar{R}} \left(1 + \sum_{n=1}^{\infty} r_n \cos n\phi \right) \quad , \text{ where } \quad r_n = \frac{\bar{R}}{\pi} \int_{\pi}^{-\pi} \frac{\cos n\phi}{\rho(\phi)} d\phi$$

Correlated change of dispersion through the orbit moves alpha close to zero or to negative values

$$\left\{ \begin{array}{l} D(\phi) = \bar{D} + \tilde{D}(\phi) \\ \frac{1}{\rho(\phi)} = \frac{1}{\bar{R}} (1 + \tilde{r}(\phi)) \end{array} \right. \quad \Rightarrow \quad \alpha = \frac{\bar{D}}{\bar{R}} + \frac{\overline{\tilde{D}(\phi) \cdot \tilde{r}(\phi)}}{\bar{R}}$$

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