NICA heavy ion collider

Beam Dynamics

Required luminosity

Main parameters:
- beam energy – *E*
- luminosity - *L*

MPD electronics → $\dot{N}_{event} \leq 7\ kHz$

Event rate $\dot{N}_{event} = L * \sigma$

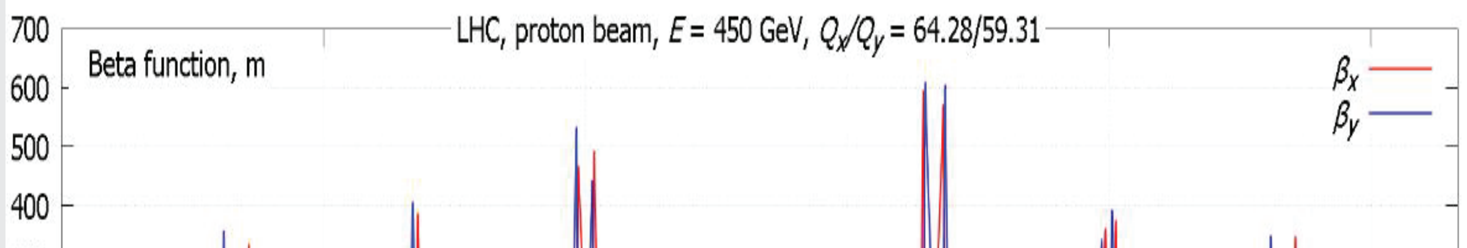
The cross-section $\sigma \approx 7 \cdot 10^{-24}\ cm^{-2}$ → $L = \frac{\dot{N}_{event}}{\sigma} \leq 1 * 10^{27} sm^{-2}s^{-1}$

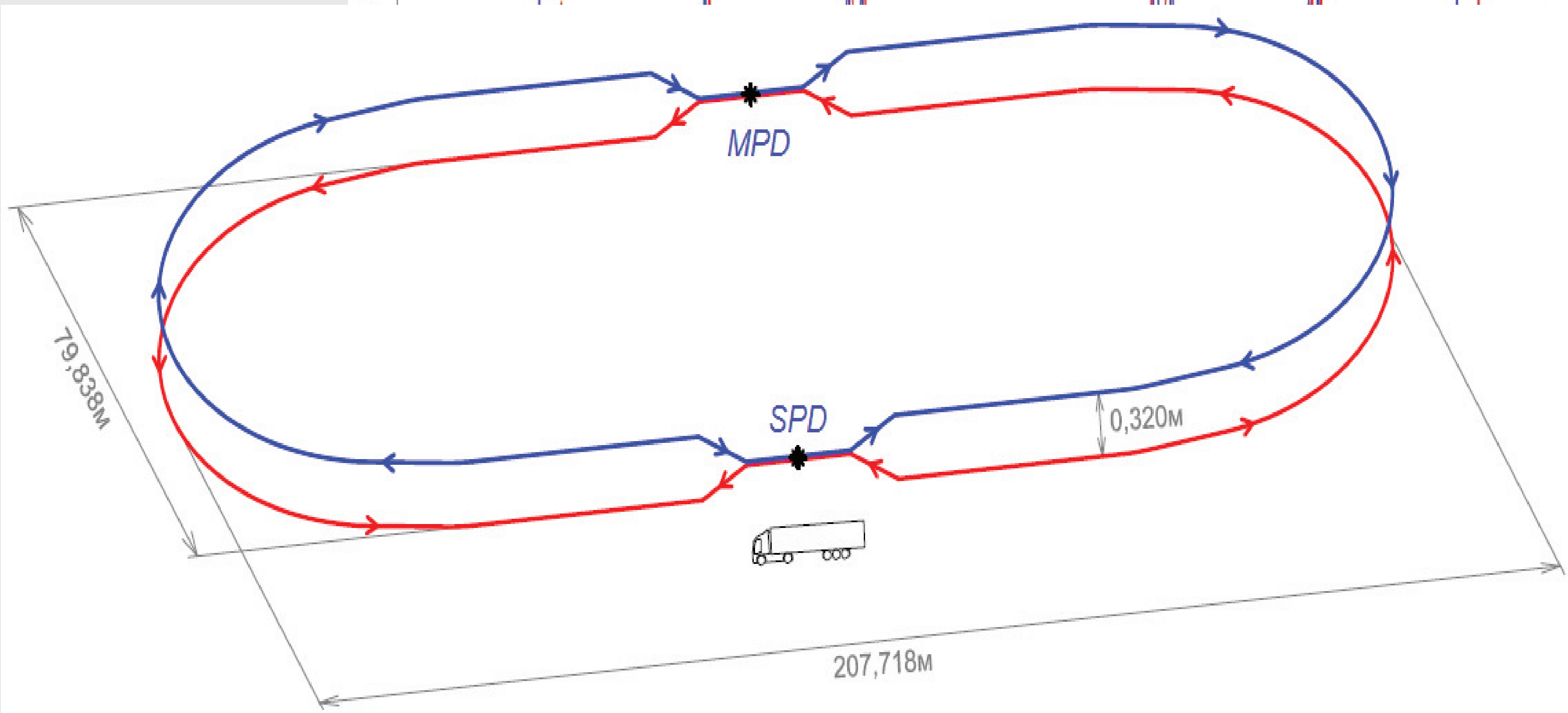
typical for RHIC (Au-Au) and LHC (Pb-Pb)

	NICA	RHIC	LHC
L * 10^27	1	8.7	3.6
E [GeV/n]	4.5	100	2510

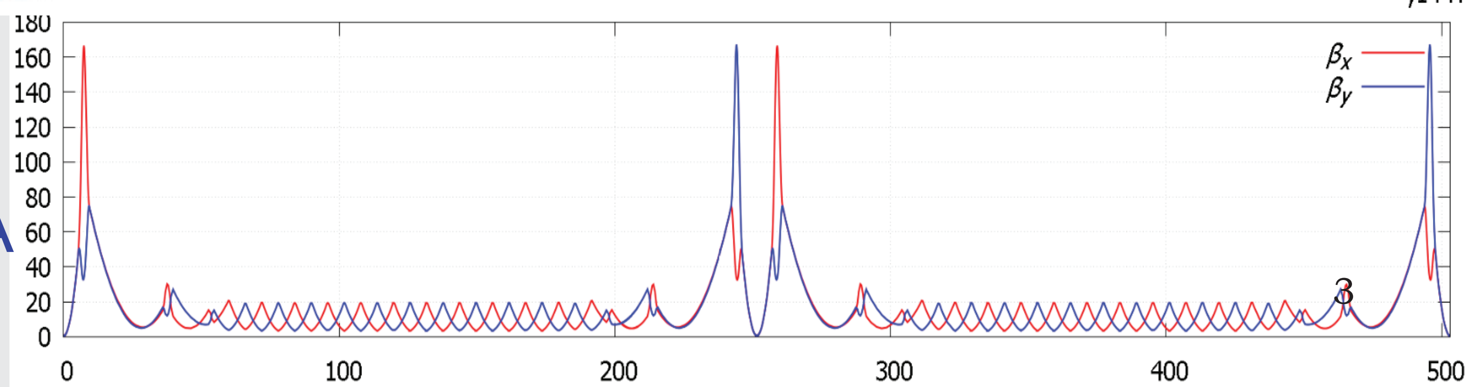
…however, ***the ion kinetic energy is below 4.5 GeV/n***

How does NICA collider look like?

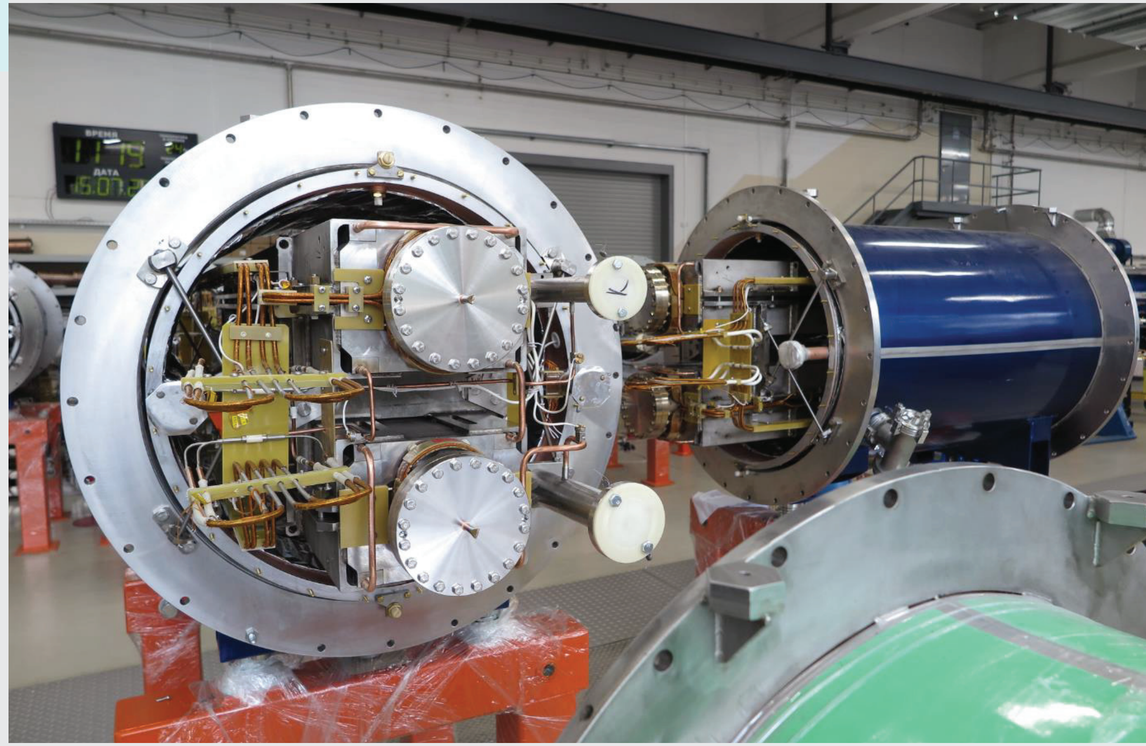


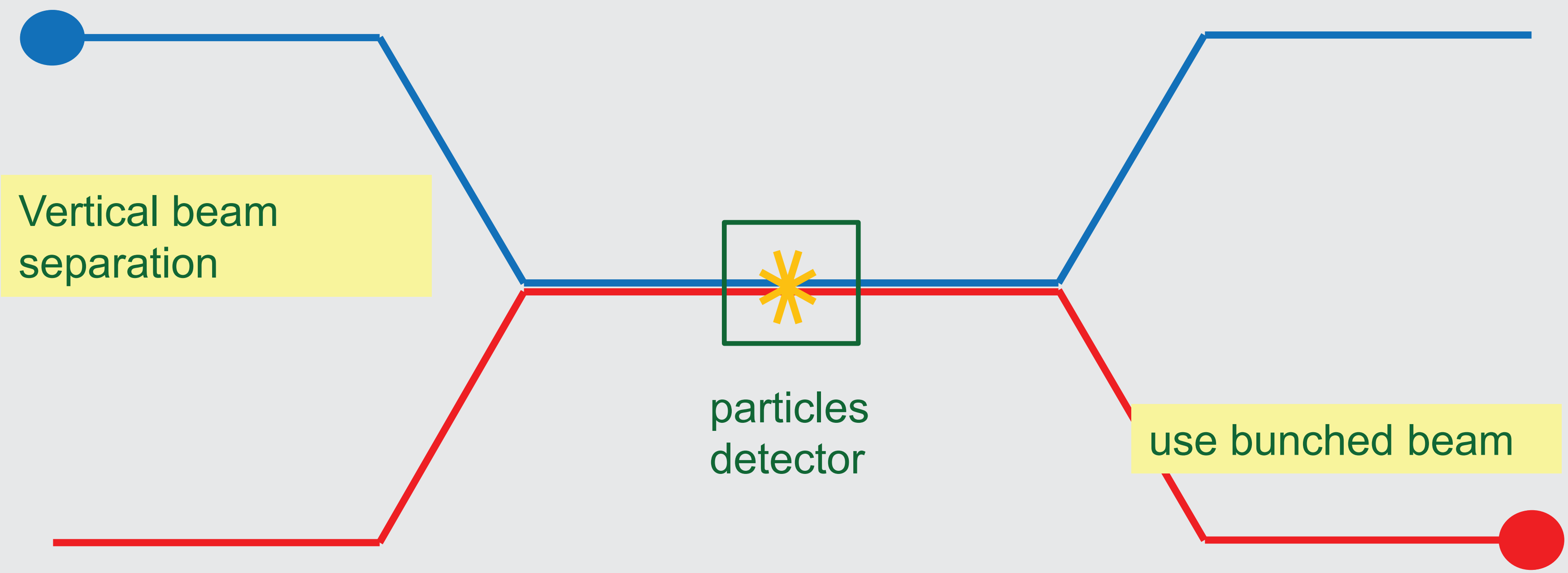


NICA

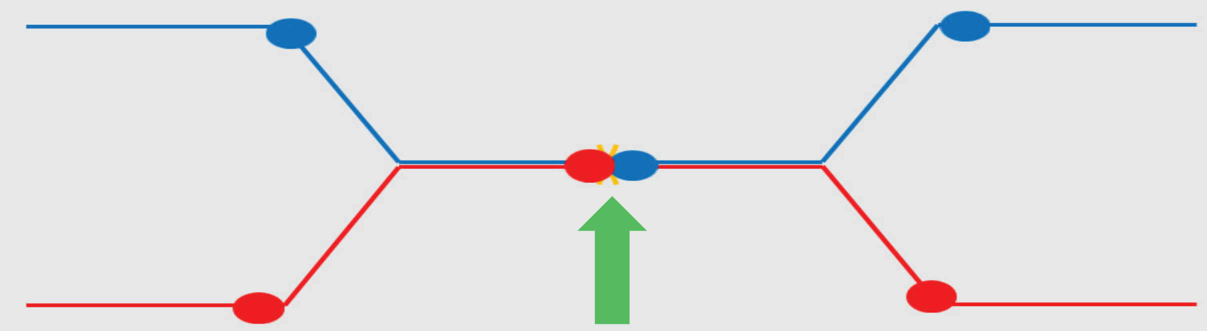


- preparation of the collisions

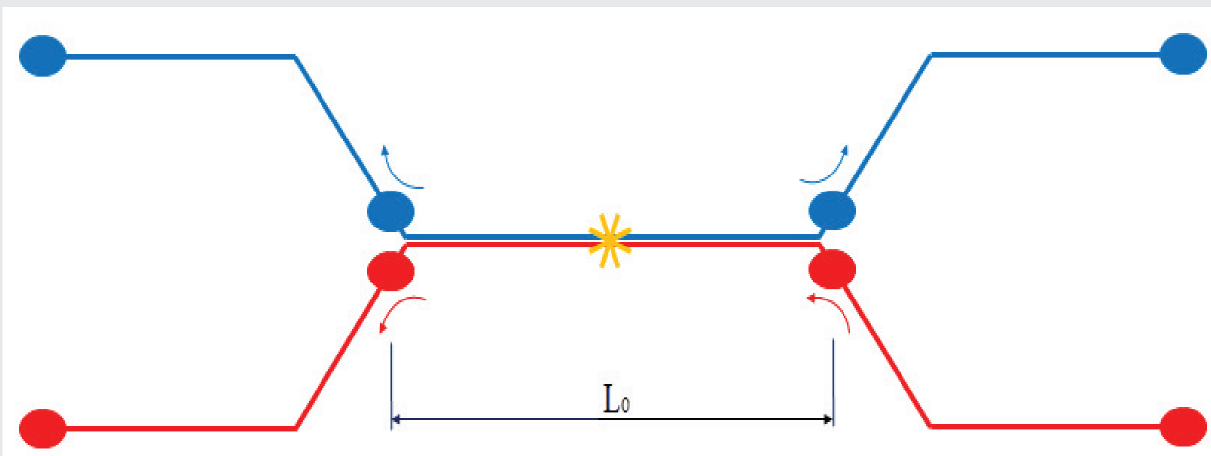


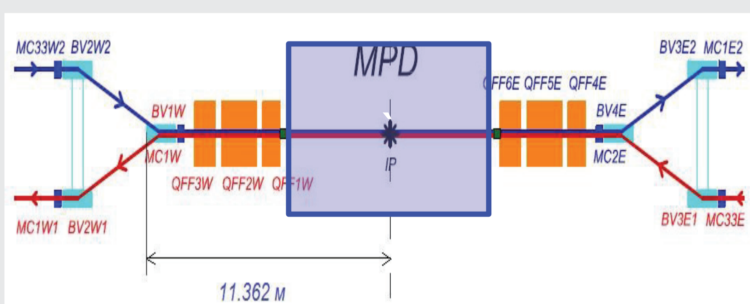


- preparation of the collisions



Detector



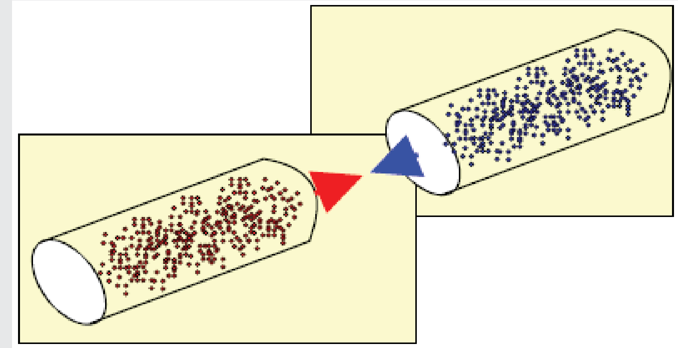


inter-bunch distance is to be large enough to avoid parasitic collisions
=>
fixed number of bunches in the ring

$$n_b = \frac{C_{ring}}{L_0}$$

• Luminosity

For round beams and head-on collisions



$$L = \frac{f_0 n_b N_i^2}{4\pi\beta^* \sqrt{\varepsilon_x \varepsilon_y}} H\left(\frac{\sigma_s}{\beta^*}\right)$$

- ***Number of bunches n_b has to be as large as possible***

but the inter-bunch distance is to be large enough to avoid parasitic collisions

$$L = \frac{f_0 n_b N_i^2}{4\pi\beta^* \sqrt{\varepsilon_x \varepsilon_y}} H\left(\frac{\sigma_s}{\beta^*}\right)$$

- ***the bunch intensity N_b has to be maximal***
- ***the emittance ε growth has to be minimized in all elements of injection chain***
- ***beta function in collision point β^* has to be as small as possible***

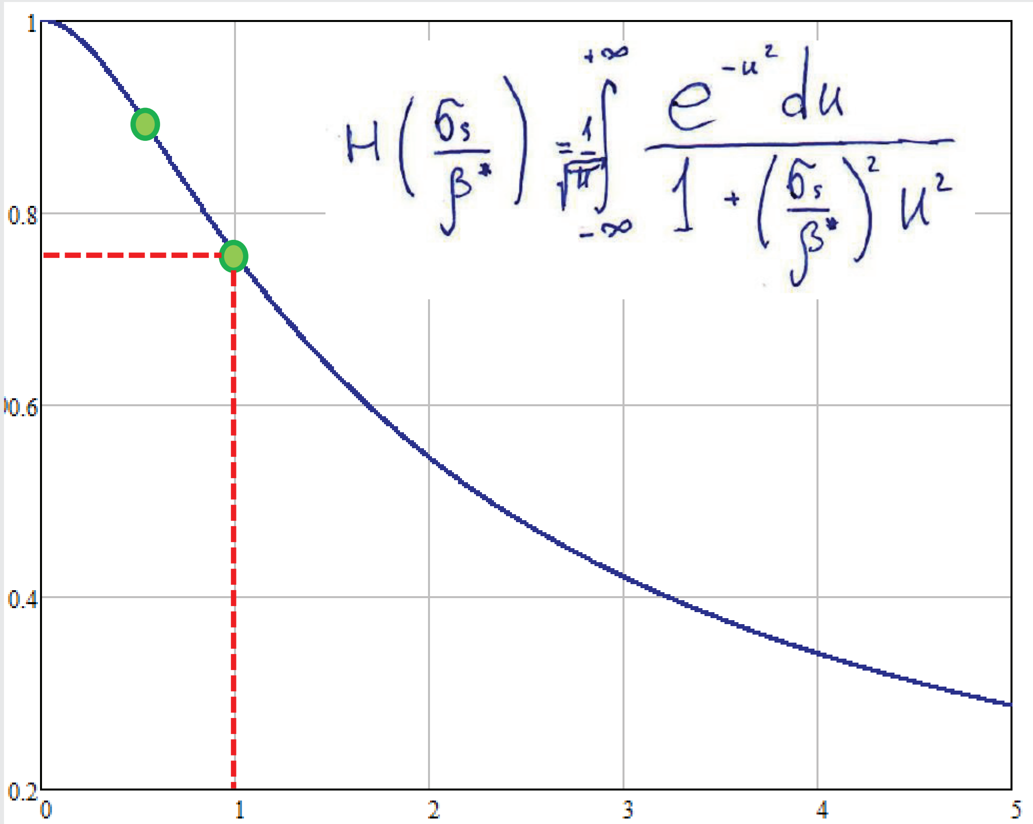
but comparable with bunch length σ_s to avoid luminosity reduction due to "hour-glass" factor

Major effects limiting the luminosity

- *IBS*
- *Space charge*
- *Luminosity lifetime*
- *Ring optics*
- *Cooling*
- *Instabilities*

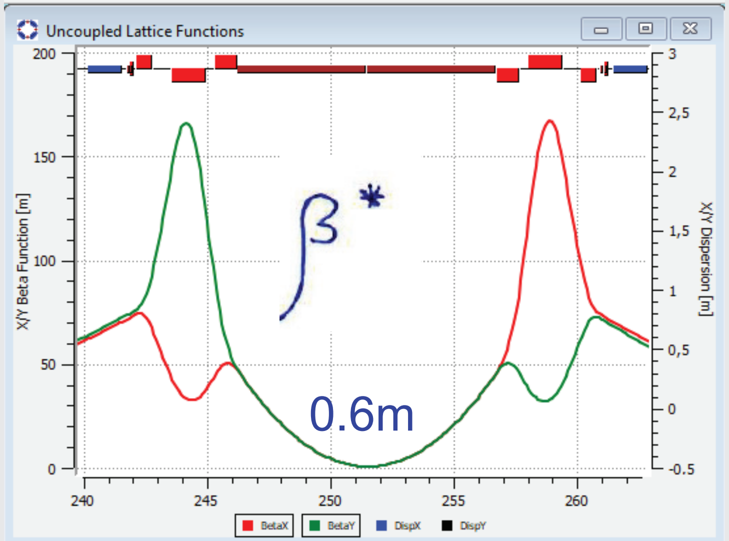
- Luminosity reduction due to hour-glass effect

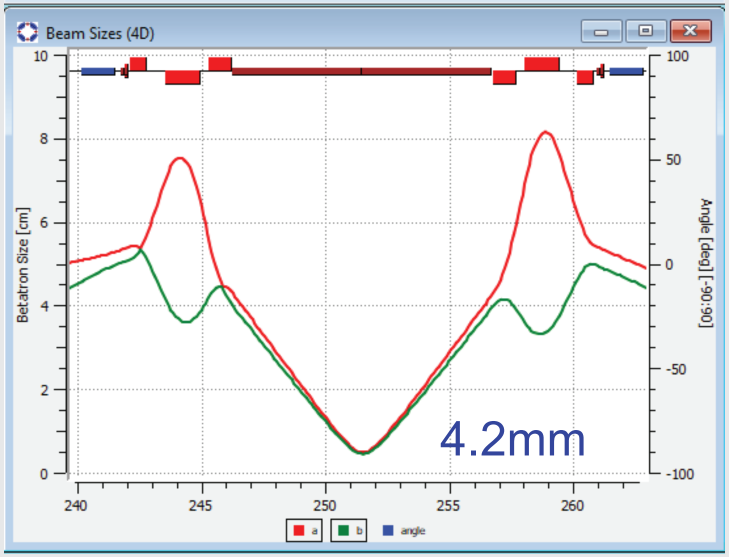
$$L = \frac{f_0 n_b N_i^2}{4\pi\beta^* \sqrt{\varepsilon_x \varepsilon_y}} H\left(\frac{\sigma_s}{\beta^*}\right)$$



$$\sigma_s \cong \beta^*$$

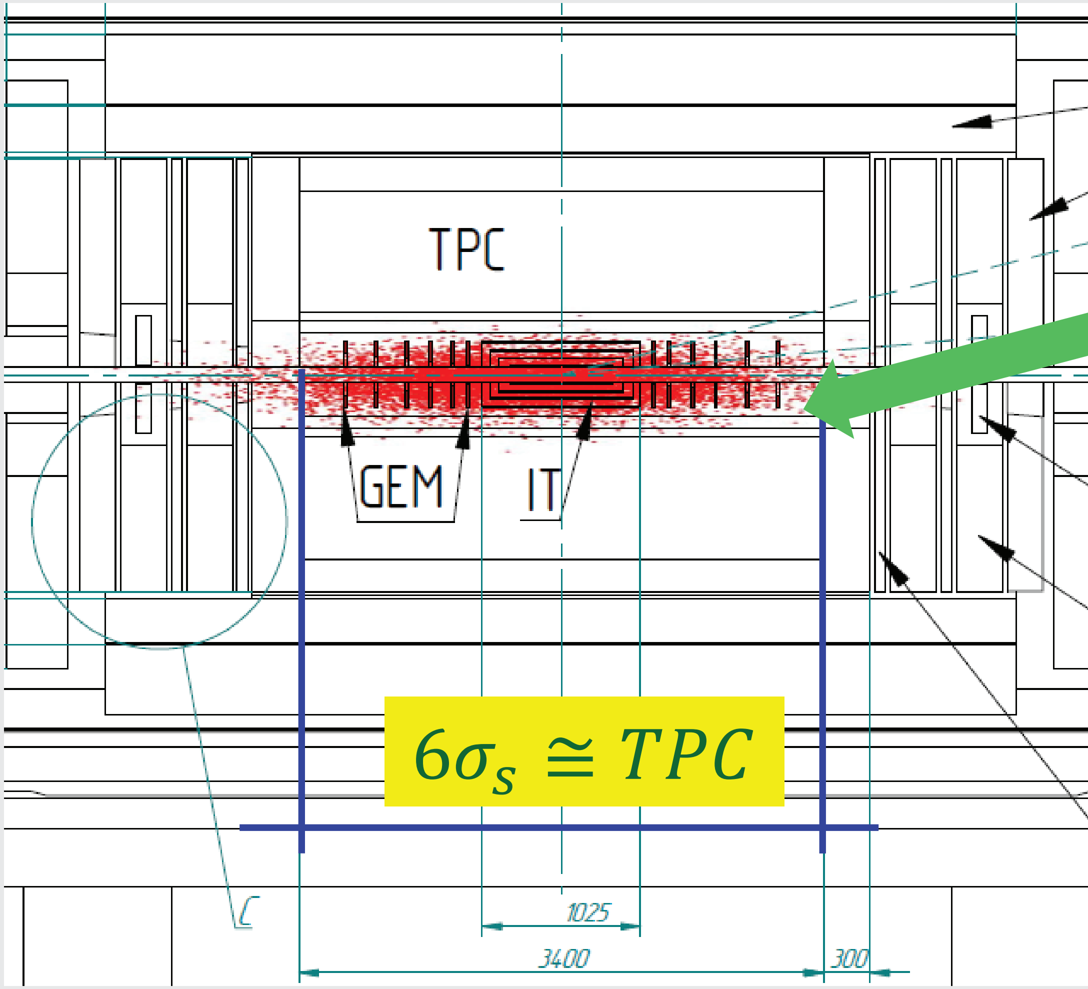
Interaction point



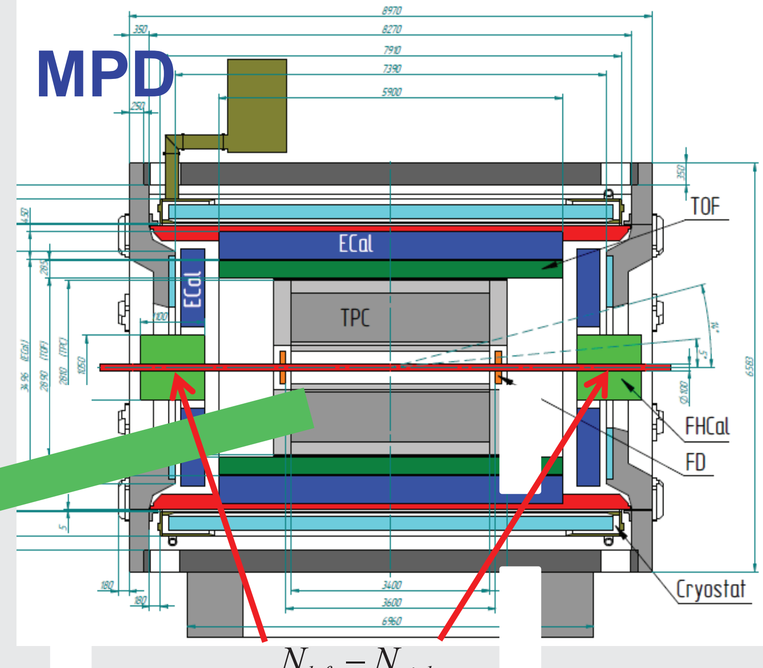


6-sigma rms beam-size

- Required bunch long size ← Particles Detector



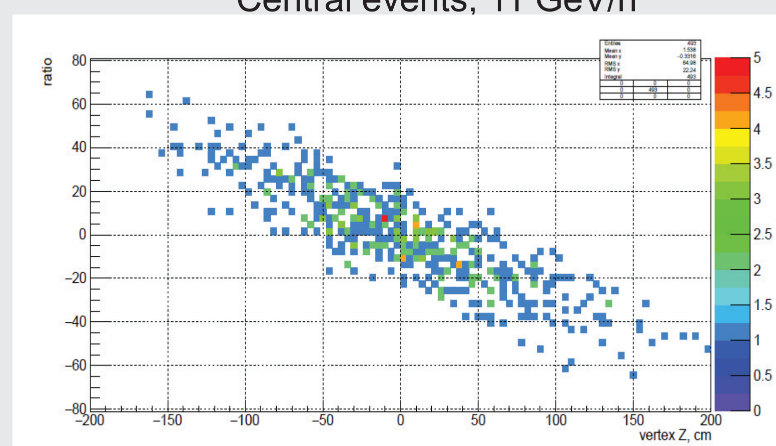
$$6\sigma_s \cong TPC$$



$$R = \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

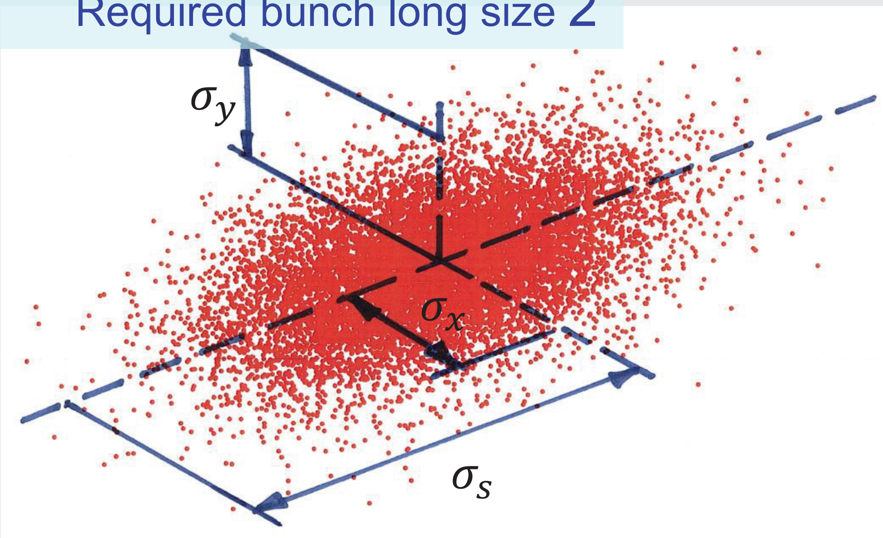
Asymmetry of energy deposited in the left-right forward Hadron Calorimeters

Central events, 11 GeV/n



$$\sigma_s, \sigma_p \rightarrow U_{RF}$$

- Required bunch long size 2

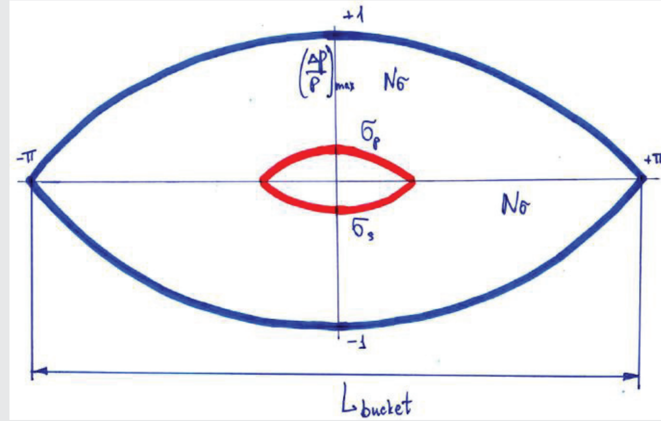


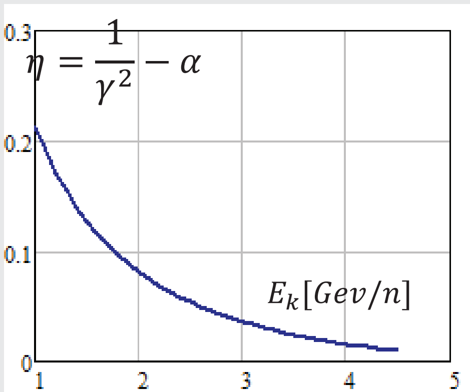
$N\sigma_{RF} = 4$

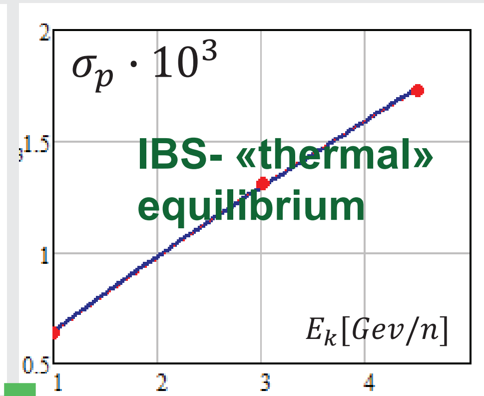
$6\sigma_s \cong TPC$

0.6m

$$L_{bucket-desired} = N\sigma_{RF} \cdot \sigma_s \cdot \pi = 7.5m$$





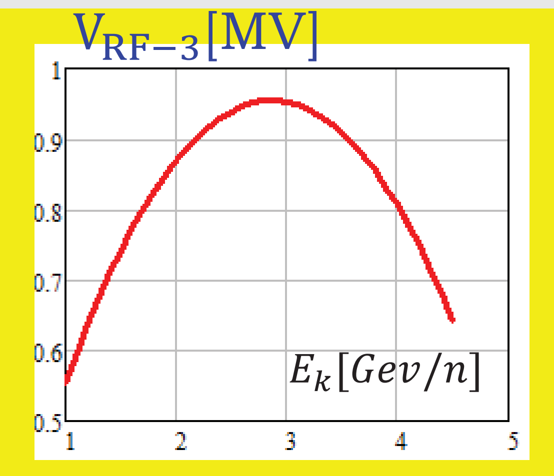


$n_b = 22 \quad (= \frac{C_{ring}}{L_0})$

$h = 3 \cdot n_b = 66$

$$L_{bucket-RF} = \frac{C_{ring}}{h} = 7.6m$$

$$V = \left(\frac{C_{ring}\,\sigma_p}{\sigma_s}\right)^2 \cdot \frac{\beta^2\gamma}{2\pi h} \cdot \frac{A m_n}{Z} |\eta|$$



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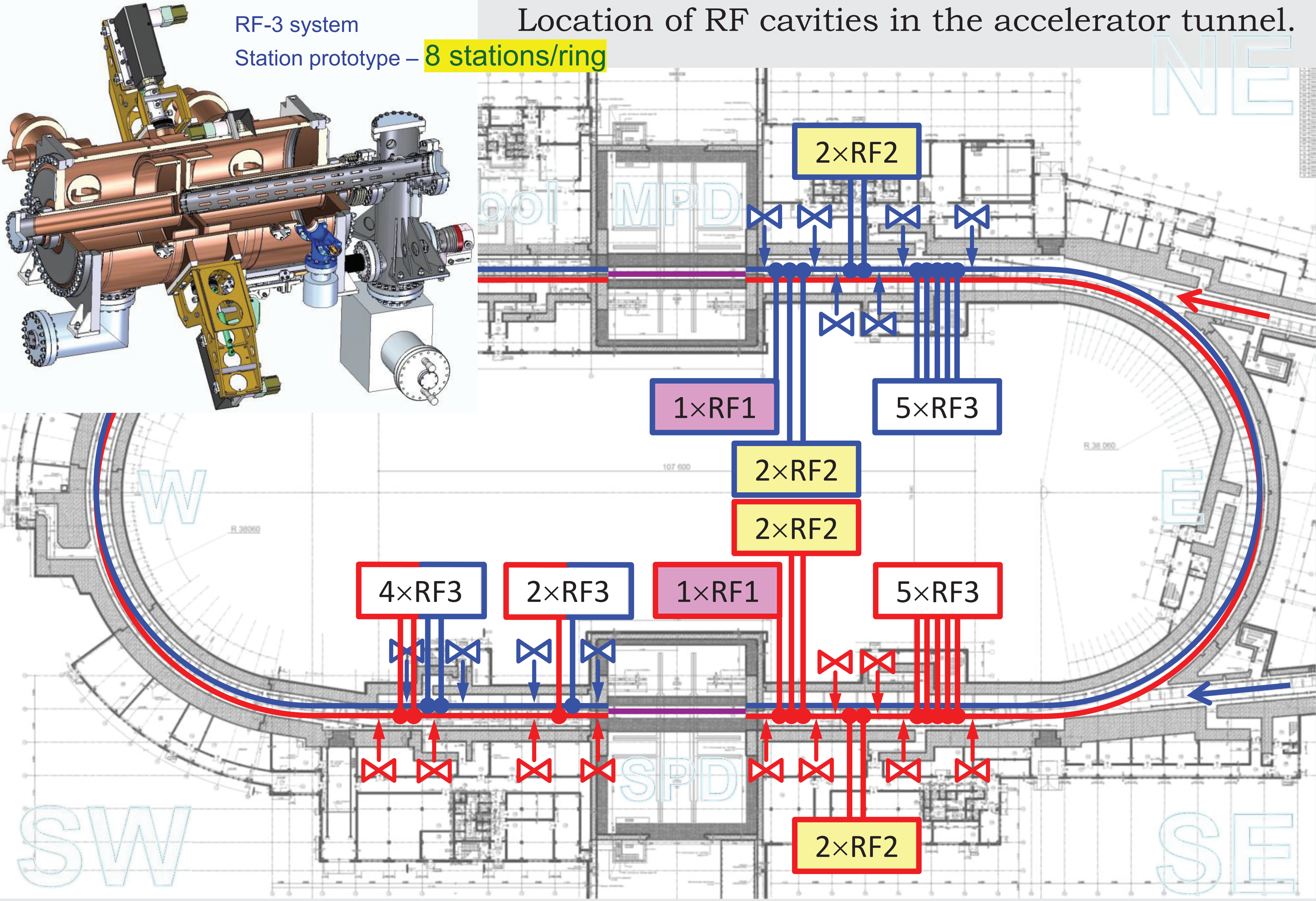
Location of RF cavities in the accelerator tunnel.

RF-3 system

Station prototype – 8 stations/ring



Intra-Beam Scattering

$$\begin{cases} \frac{1}{\tau_x} = \frac{1}{\varepsilon_x}\frac{d\varepsilon_x}{dt} \\ \frac{1}{\tau_y} = \frac{1}{\varepsilon_y}\frac{d\varepsilon_y}{dt} \\ \frac{1}{\tau_p} = \frac{1}{\sigma_p^2}\frac{d(\sigma_p^2)}{dt} \end{cases}$$

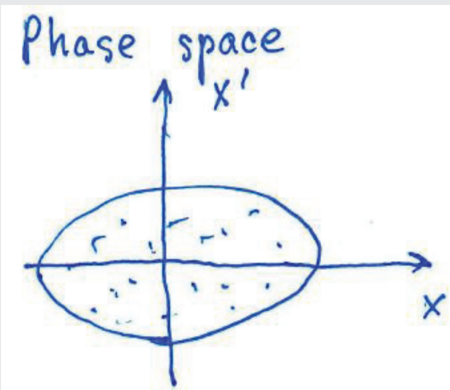
IBS - Coulomb scattering of charged particles in a beam results in an exchange of energy between different degrees of freedom

➔ Causes the beam size to grow up ➔ limits luminosity lifetime

IBS is important constraint for circular machines

Cyclotrons	skipped
Synchrotrons	skipped
Colliders	effect

Visible effect in 10th to 1000th seconds



distr. function.

$$f(x,x') = \frac{1}{2\pi\sigma_x\sigma_{x'}} \exp\left\{-\frac{x^2}{2\sigma_x^2} - \frac{x'^2}{2\sigma_{x'}^2}\right\}$$

Beam temp.

$$T \stackrel{def}{=} \frac{m\sigma_{x'}^2}{2k_B} \equiv \frac{m\sigma_{v_x}^2}{2k_B}$$

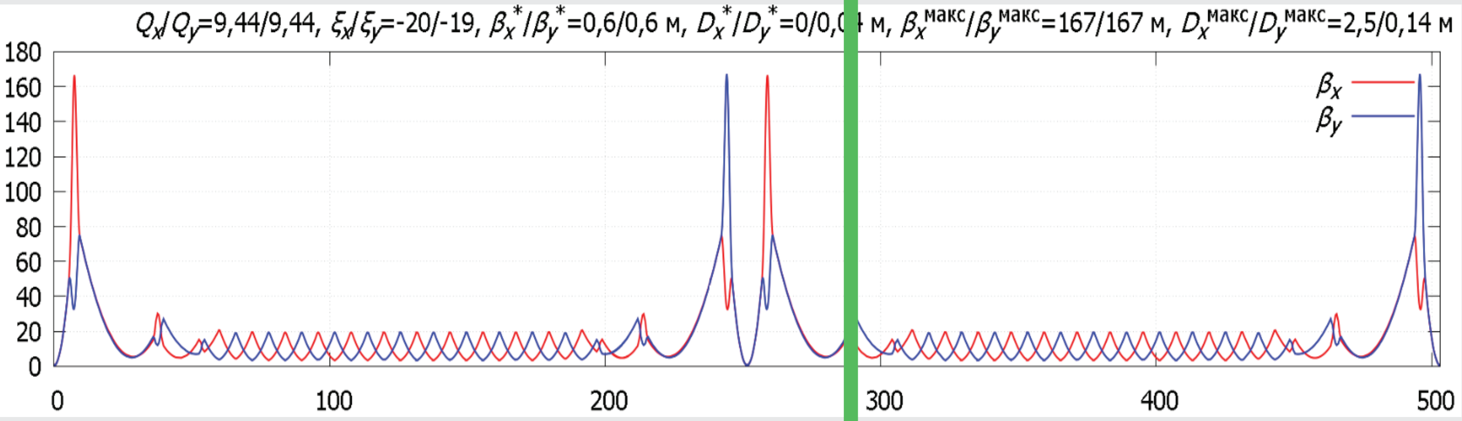
$$\sigma_{v_x} \equiv \sqrt{\overline{v_x^2}}$$

IBS leads to

- relaxation (equation) between 3 “temperatures” in the beam faster than 6D-emmitance growth rate
- infinite beam 6D-phase space volume growth in circular machines

Intra-Beam Scattering

U_{RF}



E, GeV/u	$N, 10^9$	ε_x, π mm · mrad	ε_y, π mm · mrad	σ_s, m	$\sigma_p, 10^{-3}$	τ_x, s	τ_y, s	τ_s, s
4.5	2.8		0.82		1.73	2500	2500	2500
3	2.71	1.1	0.95	0.6	1.31	770	770	770
1	0.28		1.08		0.64	220	220	220

- operation in vicinity of thermal equilibrium still significantly reduces IBS heating

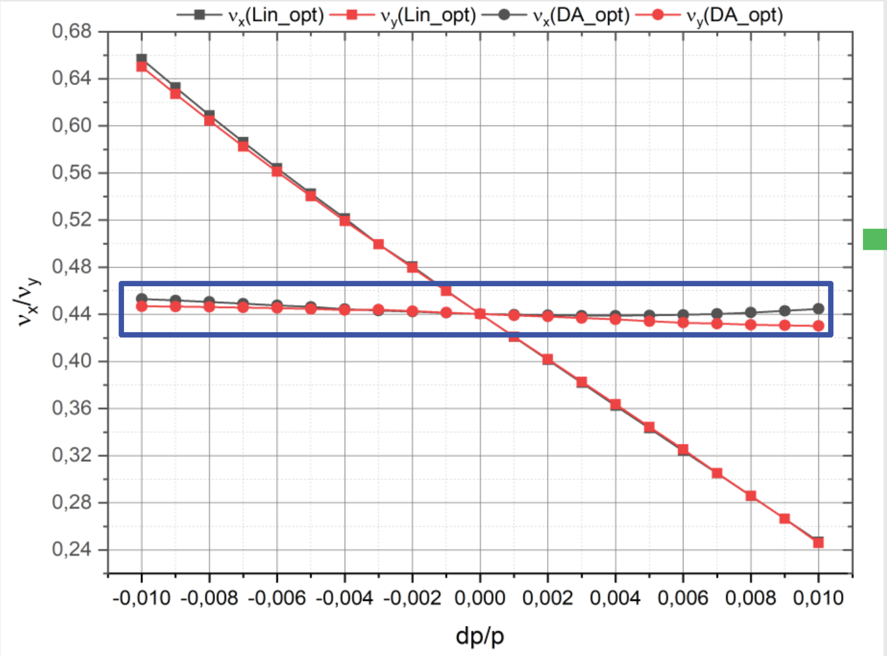
$$\frac{d\varepsilon}{dt} \sim \left(\frac{Z^2}{A}\right)^2 \cdot N_i \cdot L_c \cdot \frac{1}{\beta^2\gamma^4} \cdot \frac{1}{\sigma_x \sigma_y \sigma_s}$$

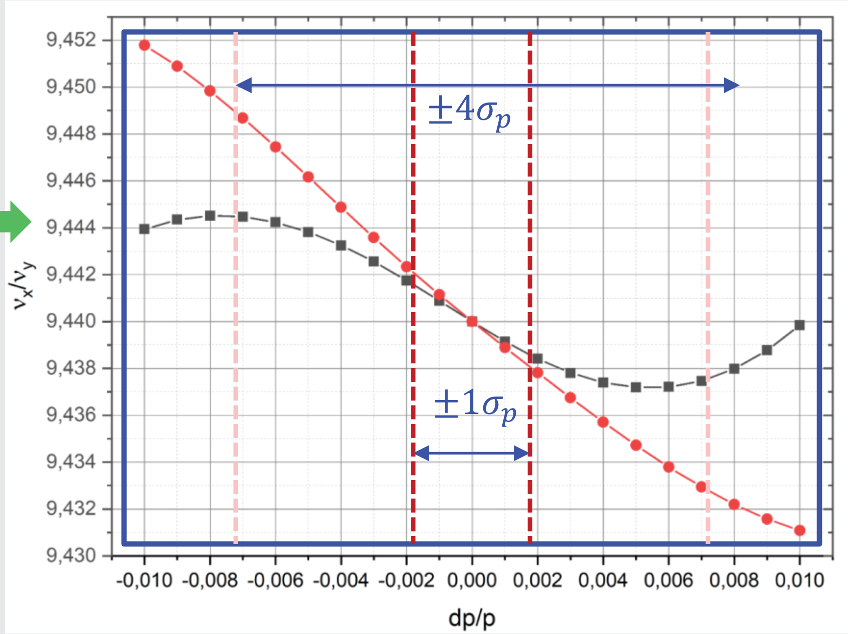
Fast grows of the beam phase volume due to **Intra-Beam Scattering**:

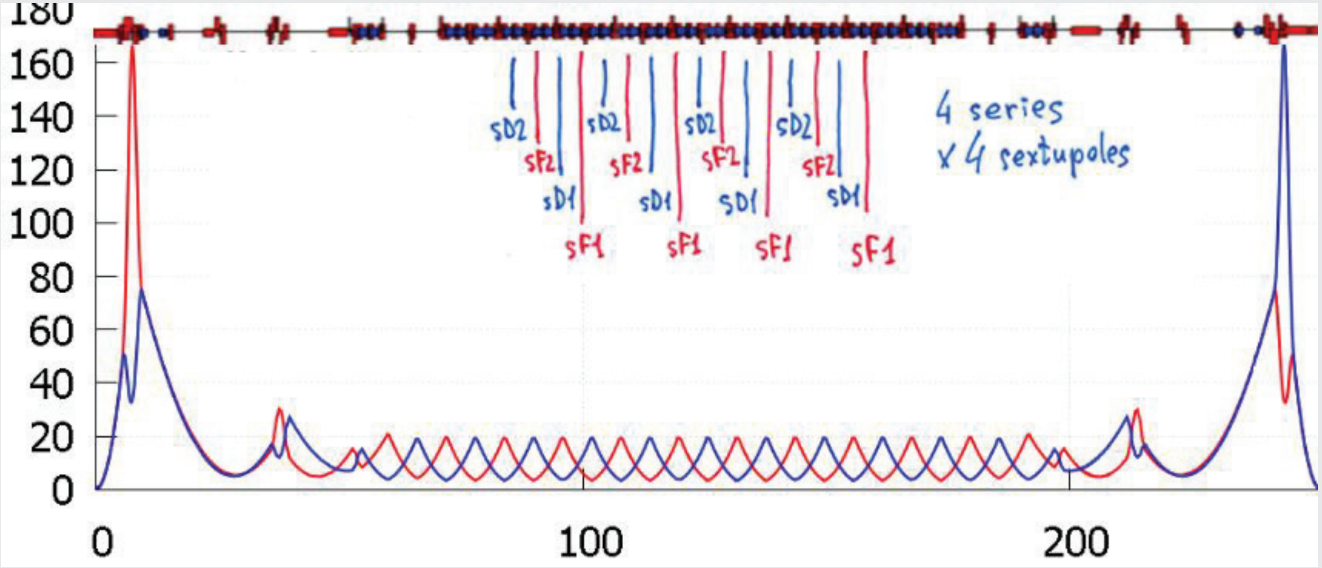
RHIC ~ 4 h
LHC >> 10 h
NICA 3 ÷ 30 minutes → Beam cooling during experiment is mandatory

Requirements to cooling systems

• Collider non-linearities 1







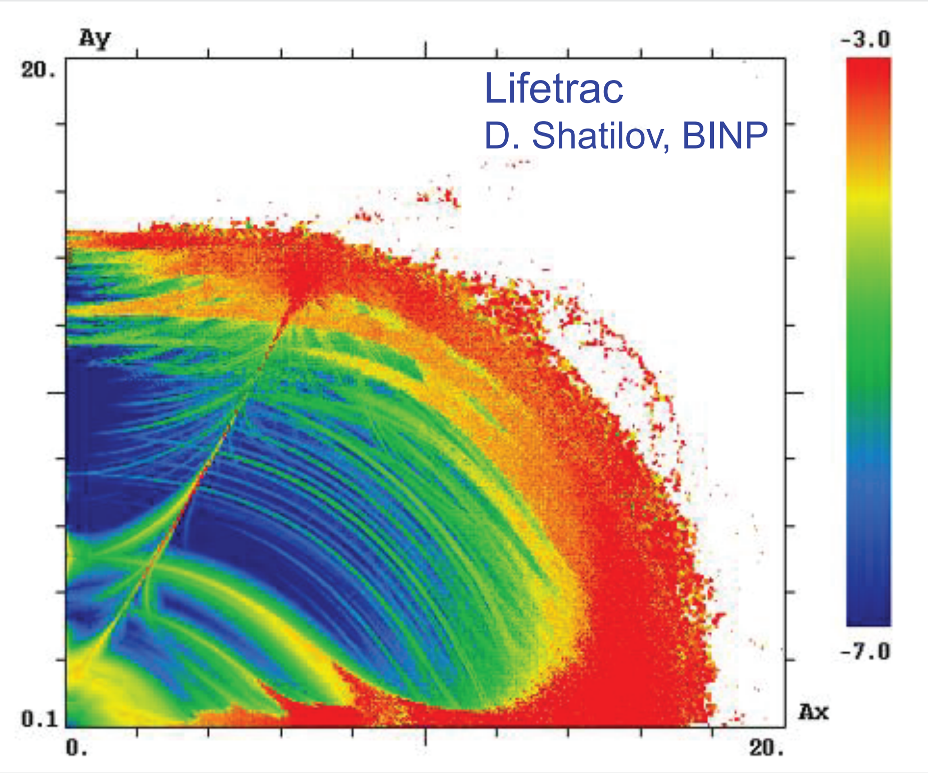
sF1=-47 T/m^2
sD1=11 T/m^2

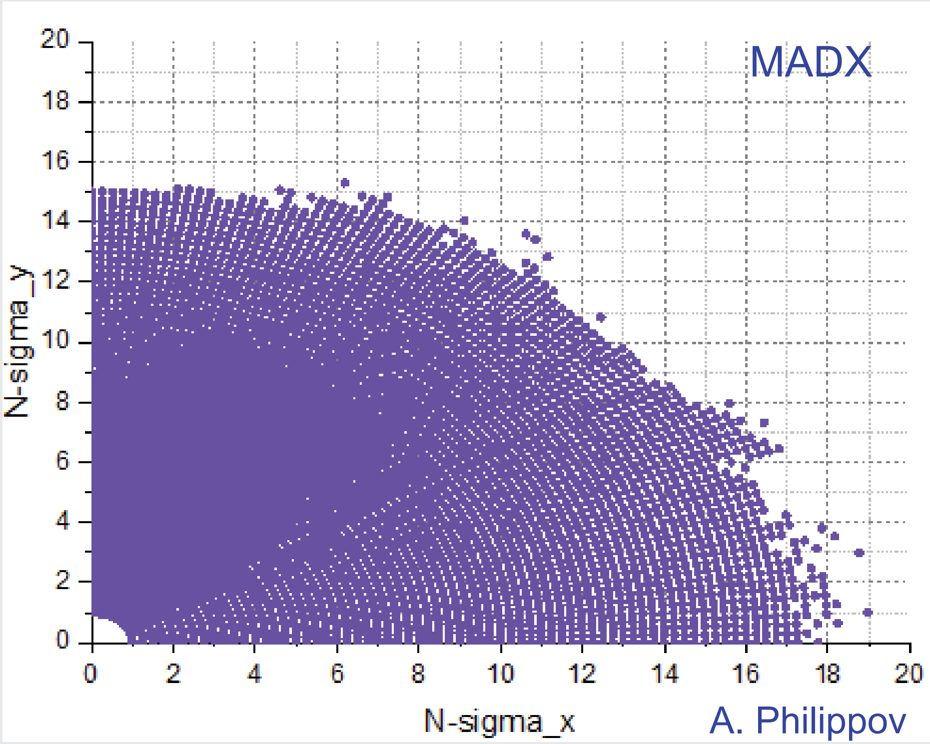
sF2=-48 T/m^2
sD2=10 T/m^2

DA ??

- DA

Linear optics ← chromaticity correction





DA $\approx 16 \div 18\ \sigma$

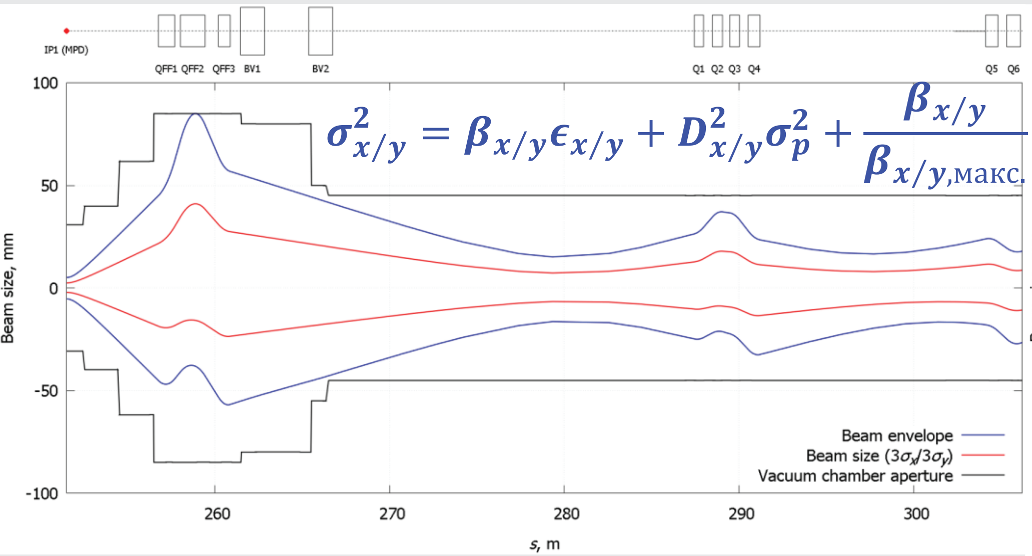
Transverse beam size

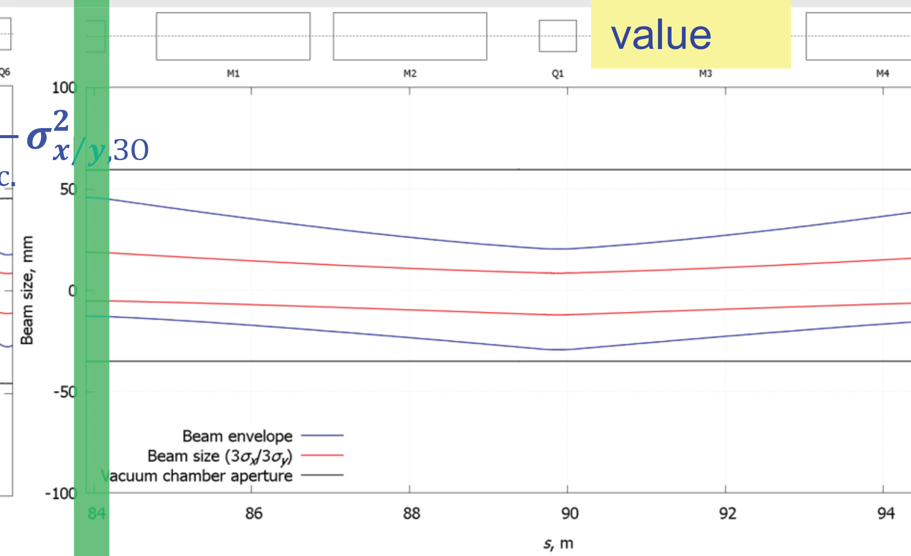
E, GeV/u	$N, 10^9$	ε_x, π mm · mrad	ε_y, π mm · mrad	σ_s, m	$\sigma_p, 10^{-3}$	τ_x, s	τ_y, s	τ_s, s
4.5	2.8	1.1	0.82	0.6	1.73			
3	2.71		0.95		1.31			
1	0.28		1.08		0.64	220	220	220

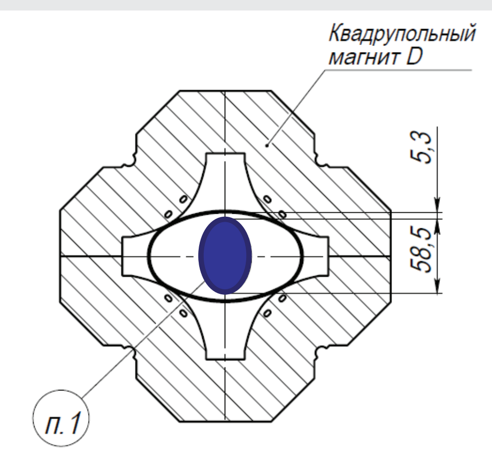
Intra-Beam Scattering

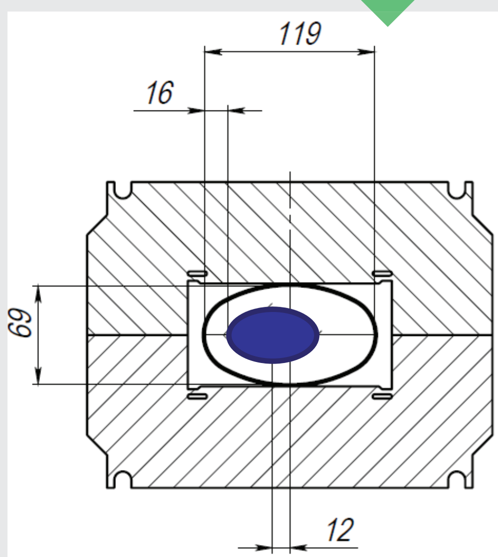
Ref. value

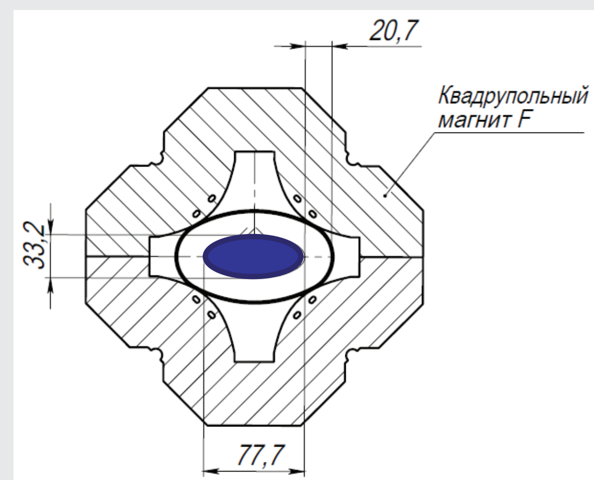
$$\sigma_{x/y}^2 = \beta_{x/y}\epsilon_{x/y} + D_{x/y}^2\sigma_p^2 + \frac{\beta_{x/y}}{\beta_{x/y,\text{макс.}}}\sigma_{x/y,30}^2$$









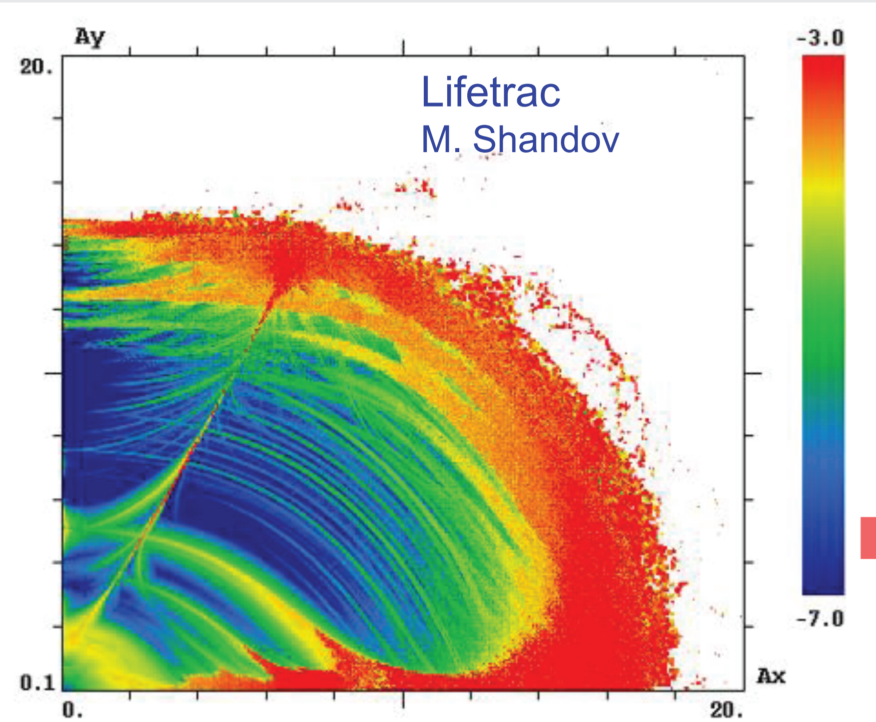


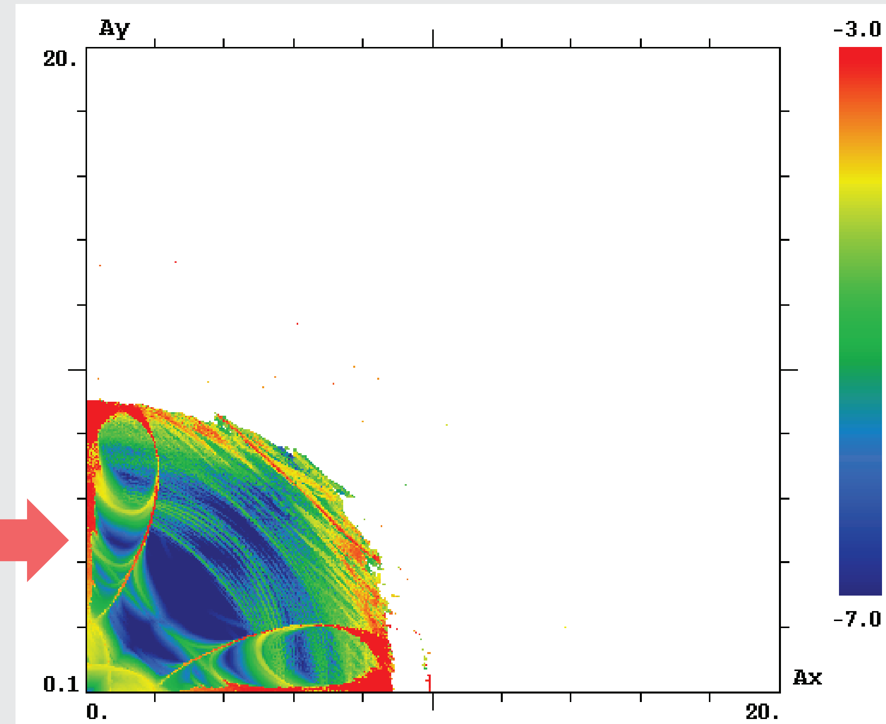
- DA

Linear optics

chromaticity correction

fringe fields

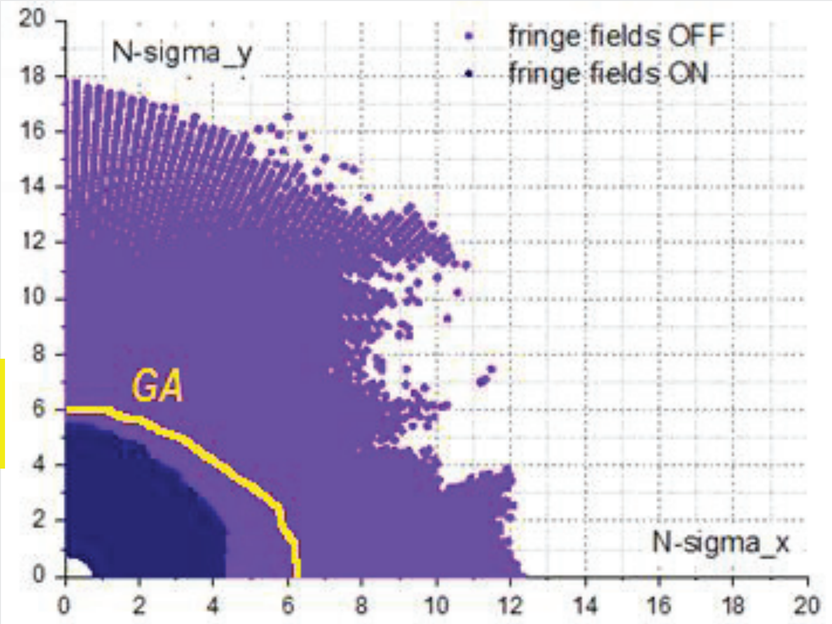




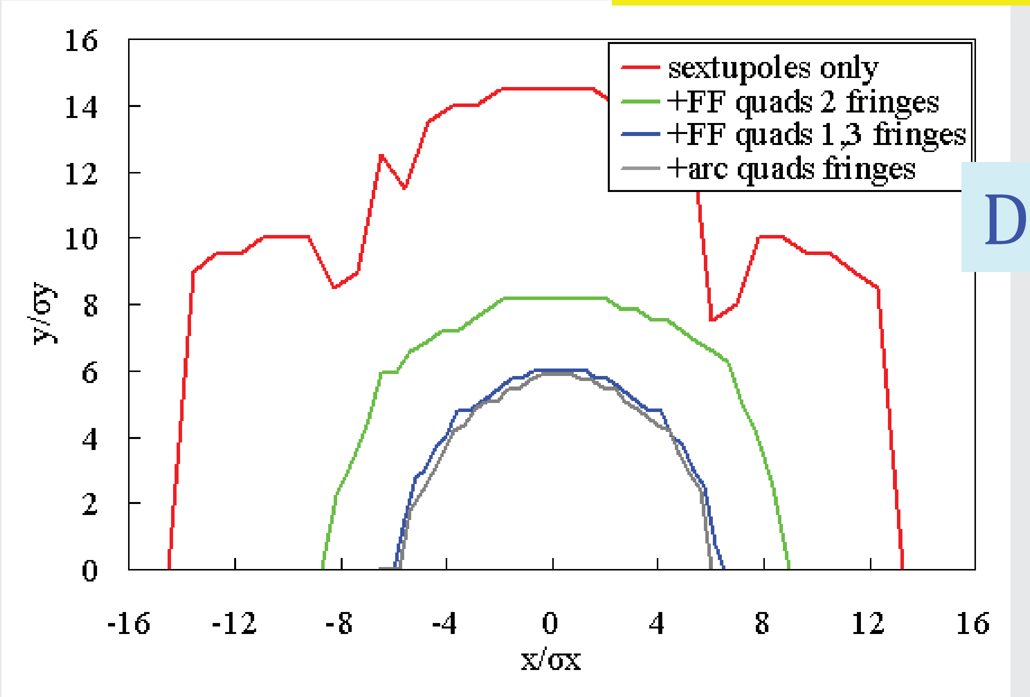
$DA \approx 16 \div 18\ \sigma$

$DA \approx 8 \div 9\ \sigma$

FF-quads fringe fields shrink DA



Initially designed $\beta^* = 0.35$ m

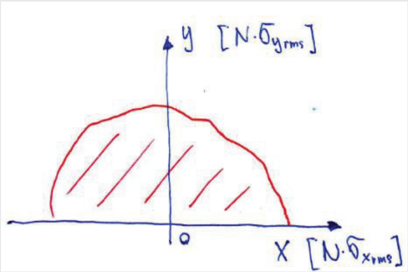


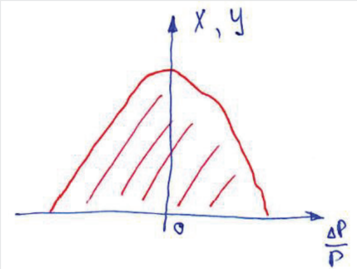
DA $\approx 4 \div 5\ \sigma$

$\beta^* = 0.35$ m

$\beta^* = 0.60$ m

S.A. Glukhov, E.B. Levichev, RuPAC-2016

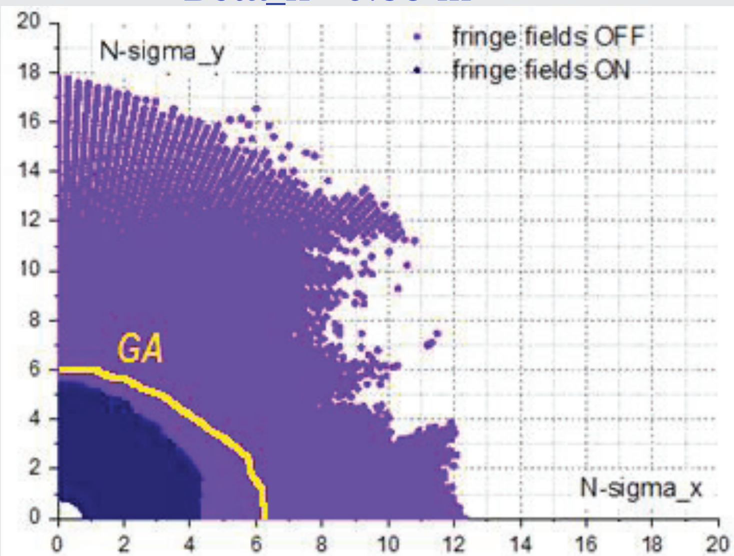




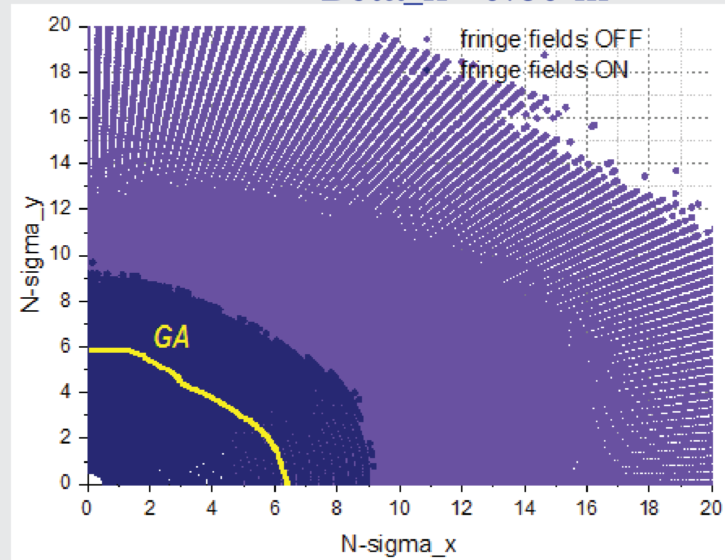
- Collider non-linearities

FF-quads fringe fields shrink DA

Beta_IP=0.35 m



Beta_IP=0.60 m



$$L = \frac{f_0 n_b N_i^2}{4\pi\beta^* \sqrt{\varepsilon_x \varepsilon_y}} H\left(\frac{\sigma_s}{\beta^*}\right)$$

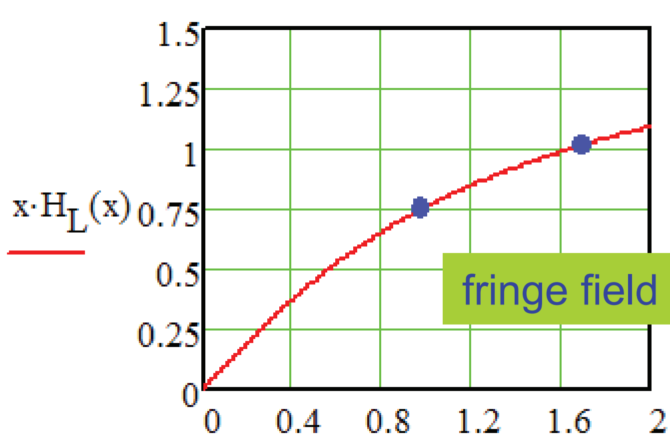
25 % luminosity decrease

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

$\beta^* = 0.35$ m

$\beta^* = 0.60$ m

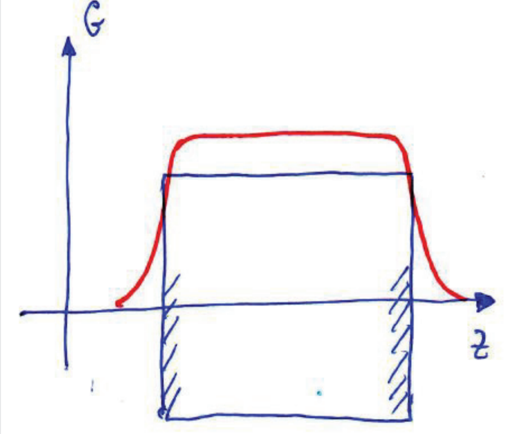
$$\frac{\sigma_s}{\beta_{IP}} \cdot H_L\left(\frac{\sigma_s}{\beta_{IP}}\right) = 1.02$$



$$\frac{\sigma_s}{\beta_{IP}} \cdot H_L\left(\frac{\sigma_s}{\beta_{IP}}\right) = 0.758$$

fringe field effect need to be corrected

Quadrupoles' fringe field effect



$$\varphi(x,y,z) = -G(z)\cdot x\cdot y + \frac{x^3y + xy^3}{12}\cdot\frac{d^2}{dz^2}G(z)$$

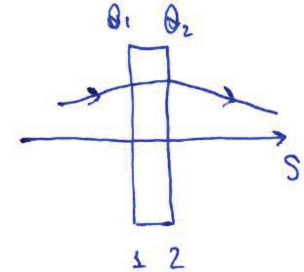
Вход/выход в линзу (F)

$$\Delta X = \pm\frac{k_1}{12}(x^3 + 3xy^2)$$

$$\Delta P_x = \mp\frac{k_1}{4}\left[(x^2+y^2)P_x - 2xy\cdot P_y\right]$$

$$\Delta Y = \mp\frac{k_1}{12}(y^3 + 3x^2y)$$

$$\Delta P_y = \pm\frac{k_1}{4}\left[(x^2+y^2)P_y - 2xy\,P_x\right]$$



тонкая линза:

$$\Delta X = 0 = \Delta Y$$

$$\Delta P_x = \Delta P_{x_2} + \Delta P_{x_1} =$$

$$= \frac{k_1}{4}\left[(x^2+y^2)(\underset{\theta_{x_2}-\theta_{x_1}}{P_{x_2} - P_{x_1}}) - 2xy(\underset{\theta_{y_2}-\theta_{y_1}}{P_{y_2} - P_{y_1}})\right] =$$

$$= \frac{k_1}{4}\left[-(x^2+y^2)\frac{x}{F} - 2xy\frac{y}{F}\right] =$$

$$= \frac{k_1^2 L}{4}\left[-x(x^2+y^2) - 2xy^2\right] = -\frac{x k_1^2 L}{4}(x^2+3y^2)$$

если $y \equiv 0$

$$\Delta P_x \cong \Delta\left(\frac{dX}{dS}\right) \cong \Delta\theta_x = -\frac{k_1^2 L}{4}x^3$$

$$\frac{\Delta\theta_x}{\theta_x} = \frac{\Delta\theta_x}{\sqrt{\frac{\varepsilon}{\beta_x}}} = -\sqrt{\frac{\beta_x}{\varepsilon}}\,\frac{k_1^2 L}{4}\left(\sqrt{\varepsilon\beta_x}\right)^3 = \boxed{-\frac{1}{4}\beta\cdot\varepsilon\cdot L\cdot k_1^2}$$

	β, [m]	k1, [1/m^2]	L, [m]	ε*10^-6 [m*rad]	ff-effect
LHC	235	0,0084	5,5	2	0,05
RHIC	145	0,052	3,4	1	0,4
NICA	120	0,4	1,65	1	7,9

In NICA effect 2-3 orders stronger due to "lower" energy range

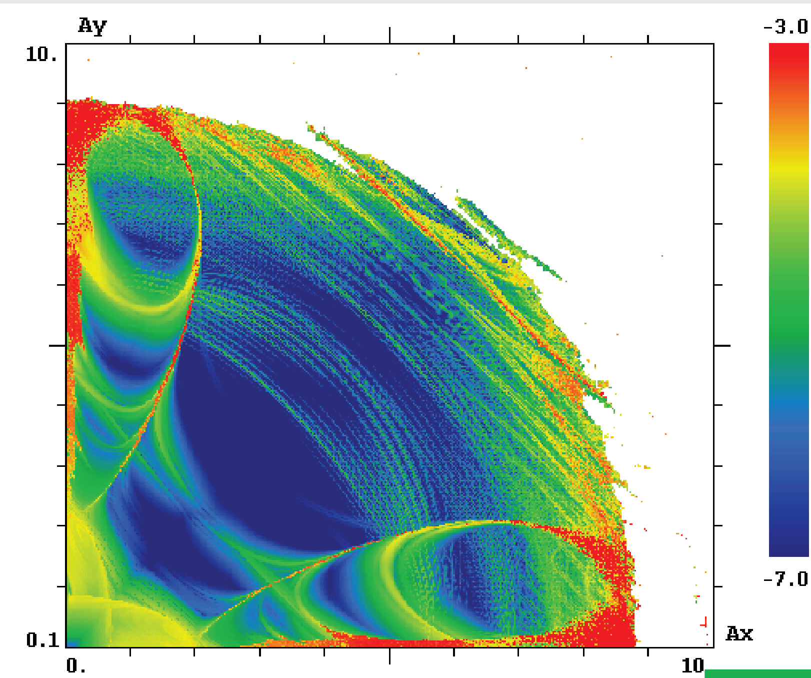
- DA

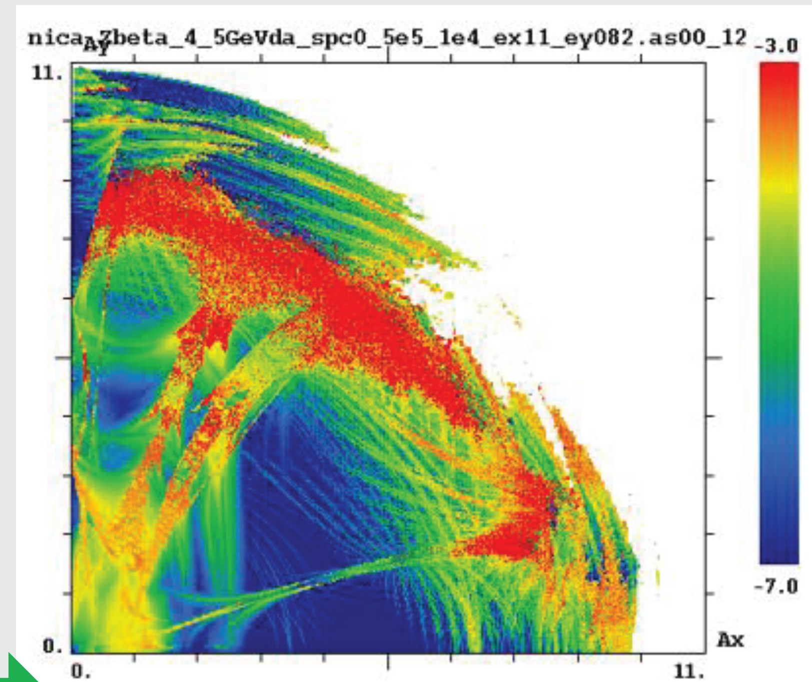
Linear optics

chromaticity correction

fringe fields

Octupole correction of fringe field effect



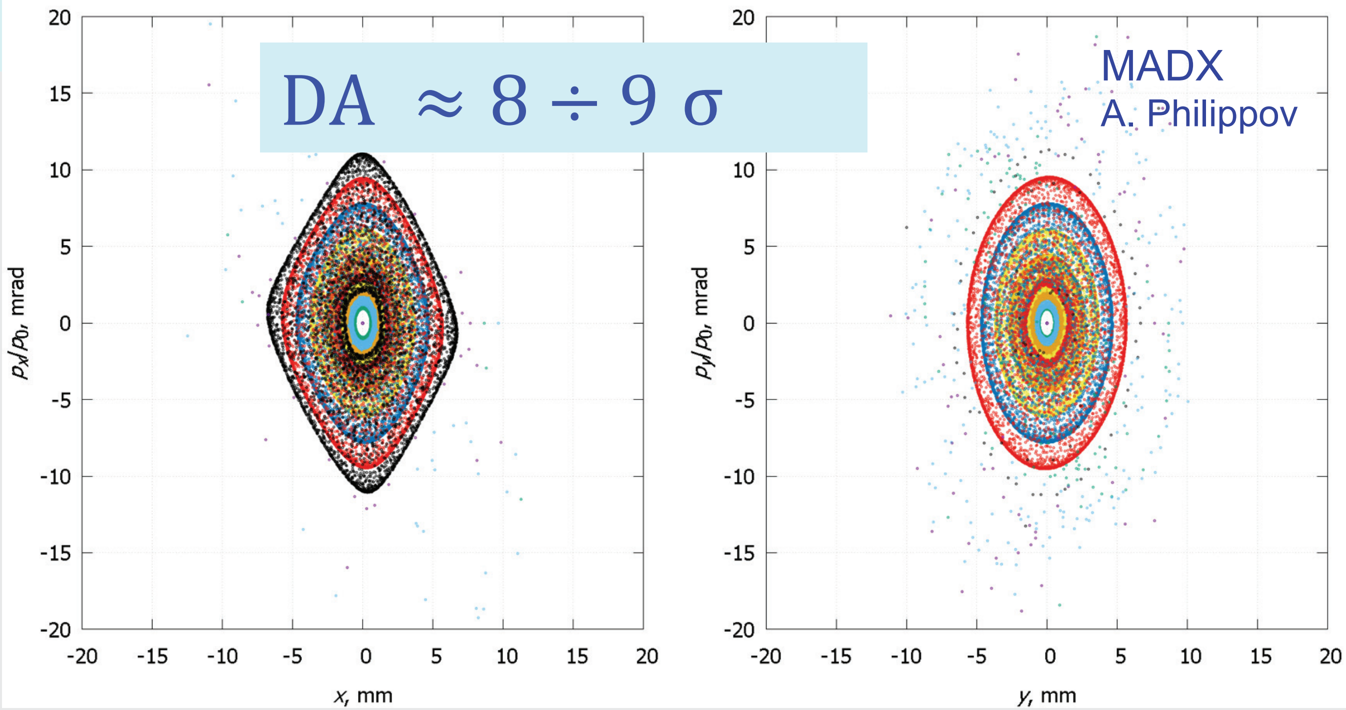


$DA \approx 8 \div 9\ \sigma$

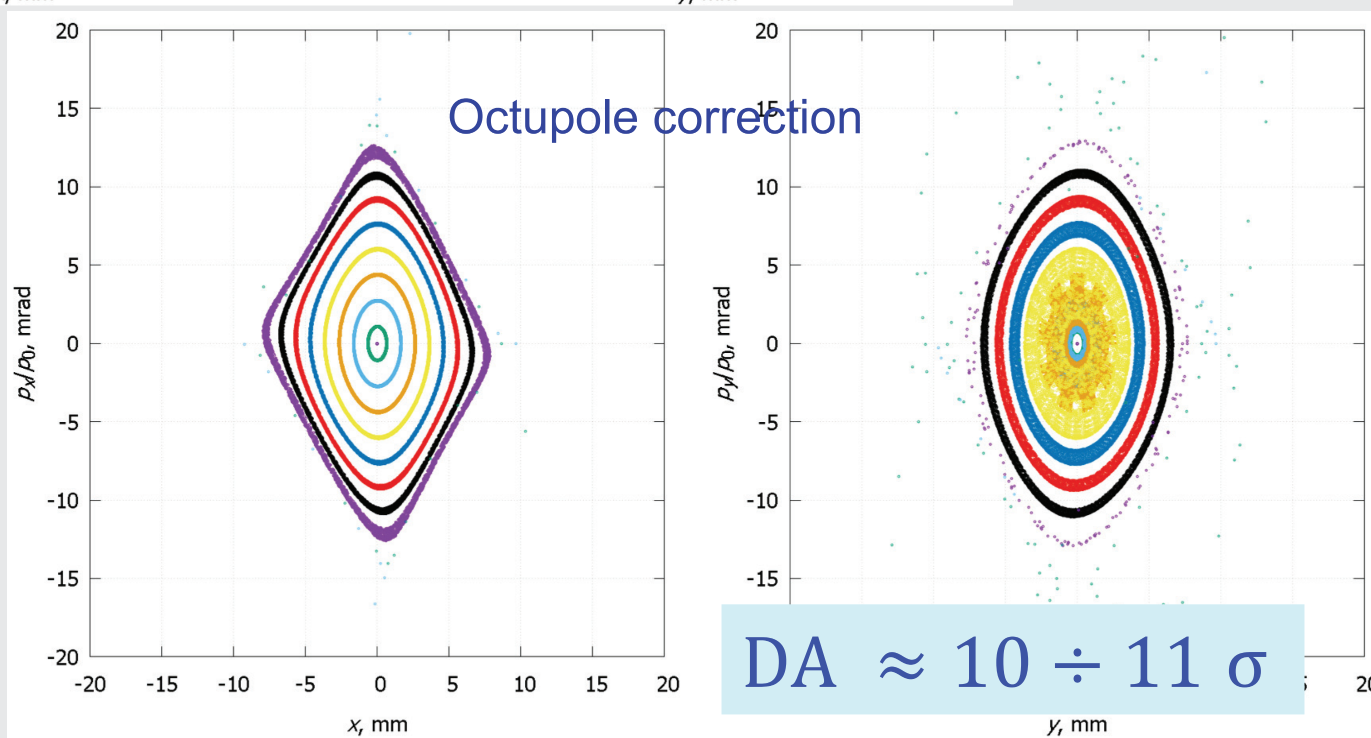
Octupole correction

$DA \approx 10 \div 11\ \sigma$

- DA

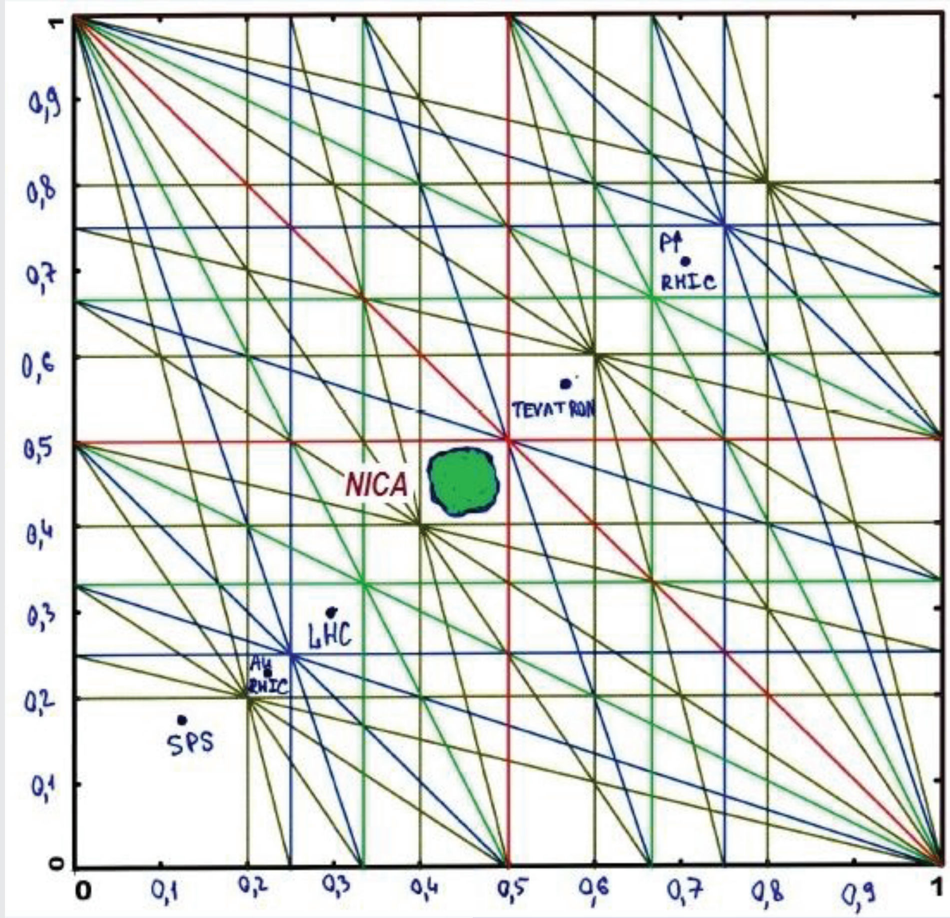


DA ≈ 8 ÷ 9 σ
MADX
A. Philippov
p_x/p_0, mrad
x, mm
p_y/p_0, mrad
y, mm



Octupole correction
DA ≈ 10 ÷ 11 σ
p_x/p_0, mrad
x, mm
p_y/p_0, mrad
y, mm

Ring tune



ideal if
= **const** for all particles in the beam

$$Q = Q_0 + \delta Q_{sc} + \delta Q_{bb} + \xi_1 \frac{\delta p}{p} + \xi_2 \left(\frac{\delta p}{p}\right)^2$$

$\Delta Q < 0,05$

- self space charge effect
- beam-beam effect
- tunes vs dp/p:

$$F_b = \frac{C}{\sqrt{2\pi}\sigma_s}$$

Space charge

The bunch brightness N_b/ε is limited by two main space charge effects:

$$\Delta Q = \Delta Q_L + 2\Delta Q_{BB}$$

- shift of the betatron tune due to action of beam self space charge field (Laslett tune shift)

$$\Delta Q = -\frac{Z^2 r_p}{A}\frac{N_b}{4\pi\varepsilon\beta^2\gamma^3}F_b$$ (for round beam and smooth focusing)

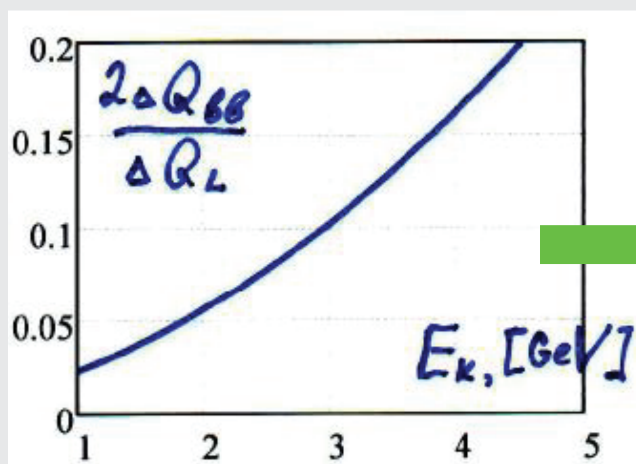
$F_b = \frac{C}{\sqrt{2\pi}\sigma_s}$ - bunching factor

- shift of the betatron tune due to action of the colliding bunch field (beam-beam parameter)

$$\xi = \frac{Z^2 r_p}{A}\frac{N_b}{4\pi\varepsilon\beta^2\gamma}\frac{1+\beta^2}{2}$$

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

For NICA collider parameters

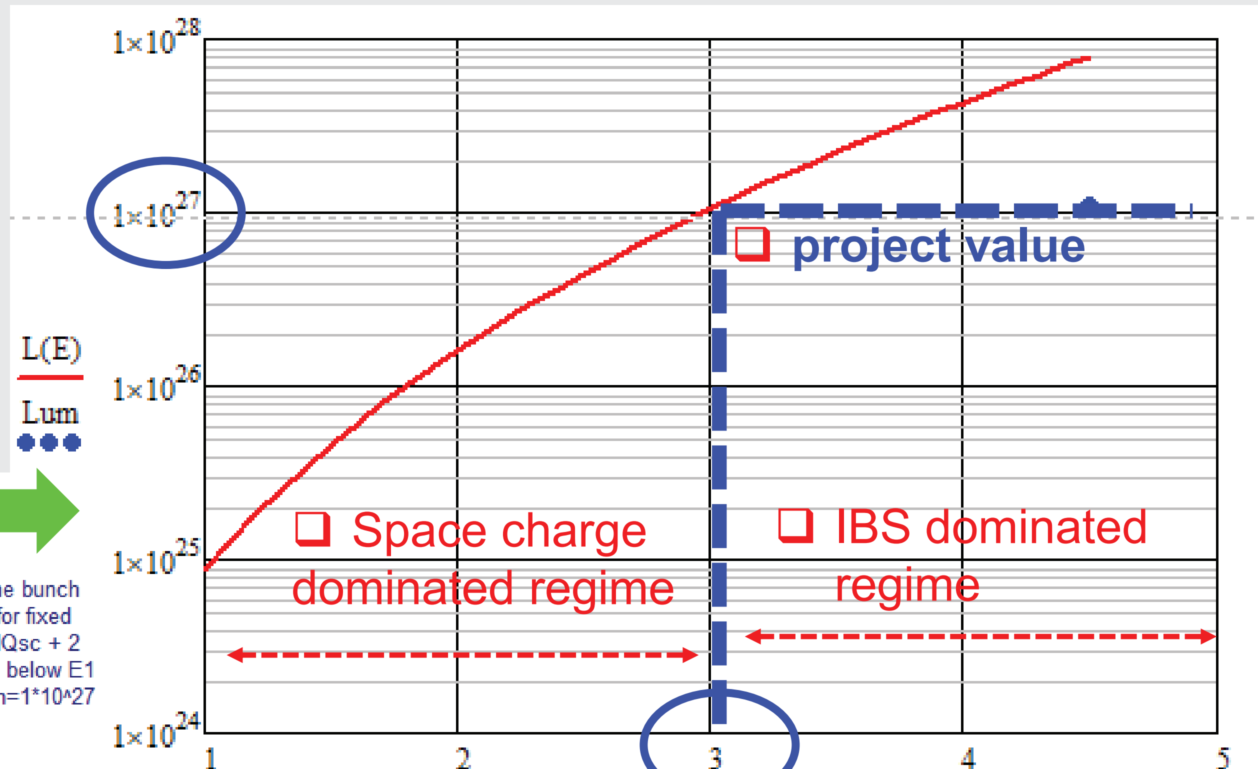


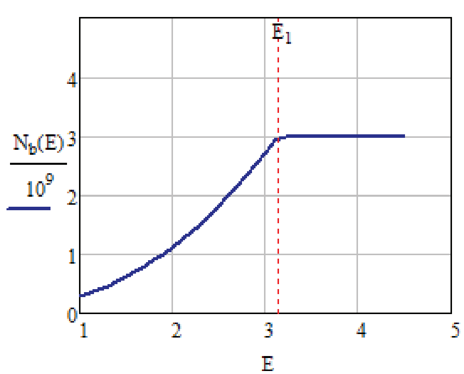
$$\Delta Q \simeq \Delta Q_L$$

$\Delta Q < 0{,}05$ → $\delta Q_L = \dfrac{r_p Z^2 N_i}{4\pi A \beta^2 \gamma^3 \varepsilon} \dfrac{C}{\sqrt{2\pi}\sigma_s}$ → $L = \dfrac{f_0 n_b N_i^{\,2}}{4\pi\beta^* \sqrt{\varepsilon_x \varepsilon_y}} H\left(\dfrac{\sigma_s}{\beta^*}\right)$

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

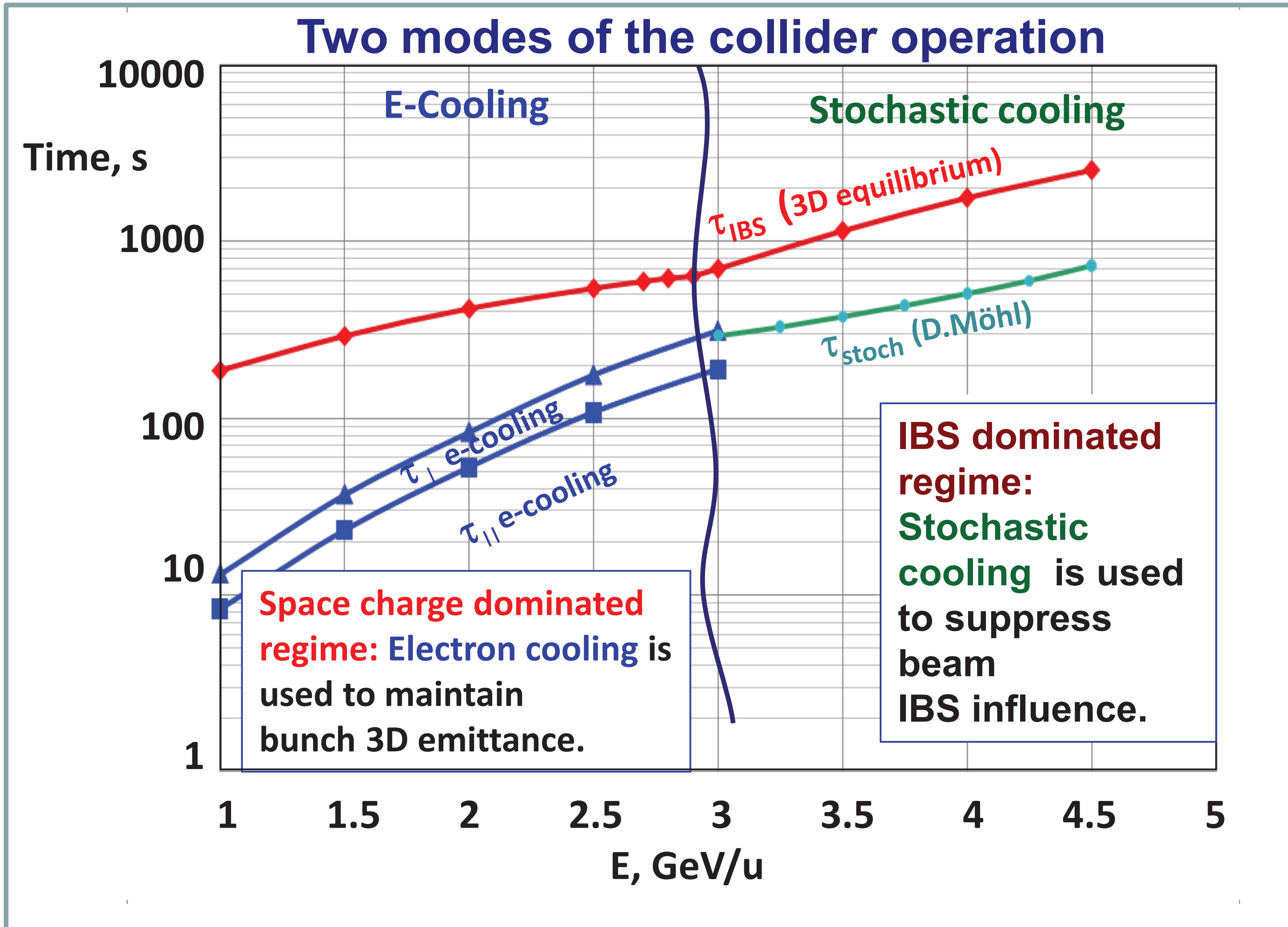
The beam **space charge** creates the **major luminosity limitation**





N-ions in the bunch via energy for fixed delta-Q = dQsc + 2 dQbb=0.05 below E1 and for Lum=1*10^27 above E1

Beam Maintenance in Collider Rings with Cooling Technique



Space charge dominated mode (ΔQ ≤0.05)	IBS dominated mode
ε and dp/p are optimized independently. The bunch <u>relaxation?</u> is suppressed by cooling. Luminosity is limited by space charge effects	ε and dp/p are "equi-partitioned", either fast bunch relaxation. Luminosity can be obtained at small ΔQ<0.05

I.N. Meshkov

- DA

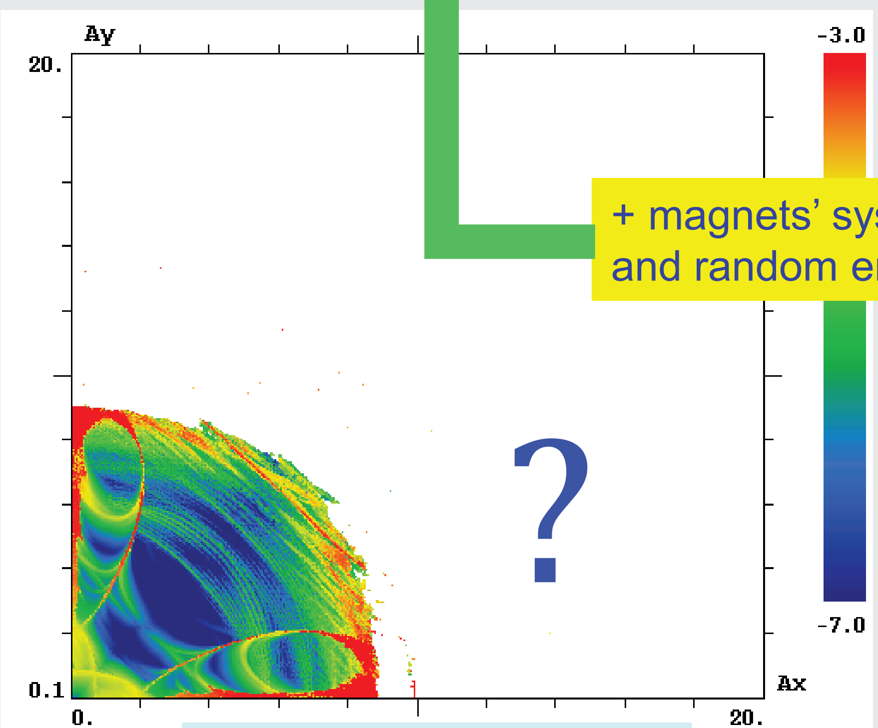
Linear optics

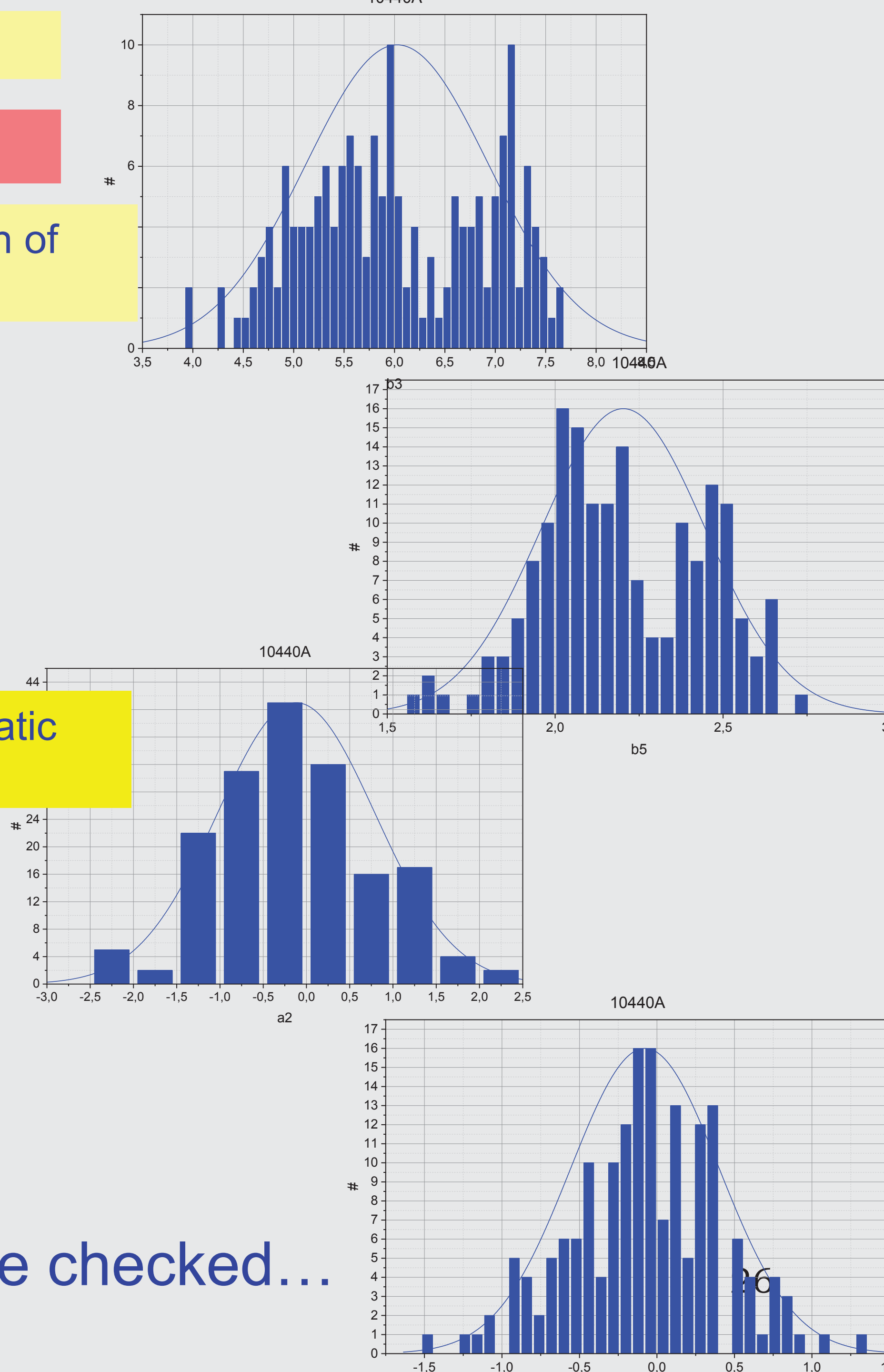
chromaticity correction

fringe fields

Octupole correction of fringe field effect

+ magnets' systematic and random errors





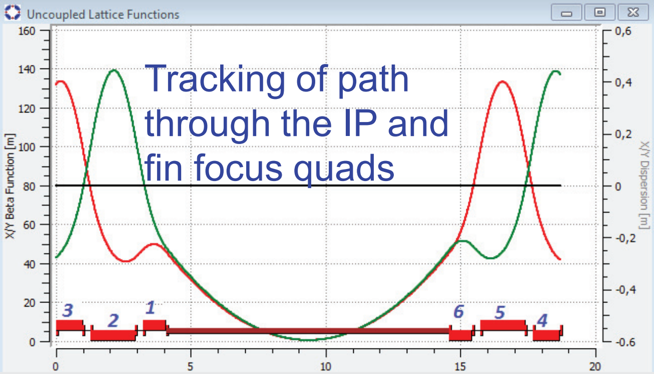
$DA \approx 8 \div 9\ \sigma$ need to be checked…

- DA

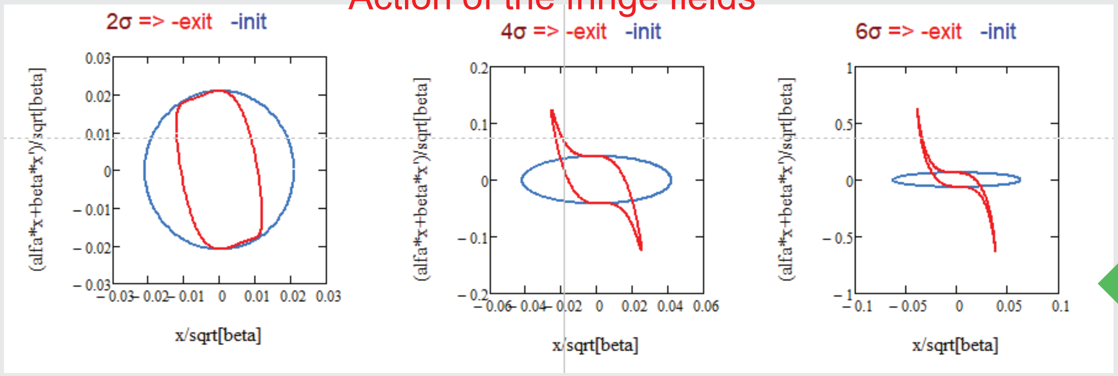
to be solved:

how calculate mitigation scheme for main DA limitation factor ?

Magnets' fringe fields

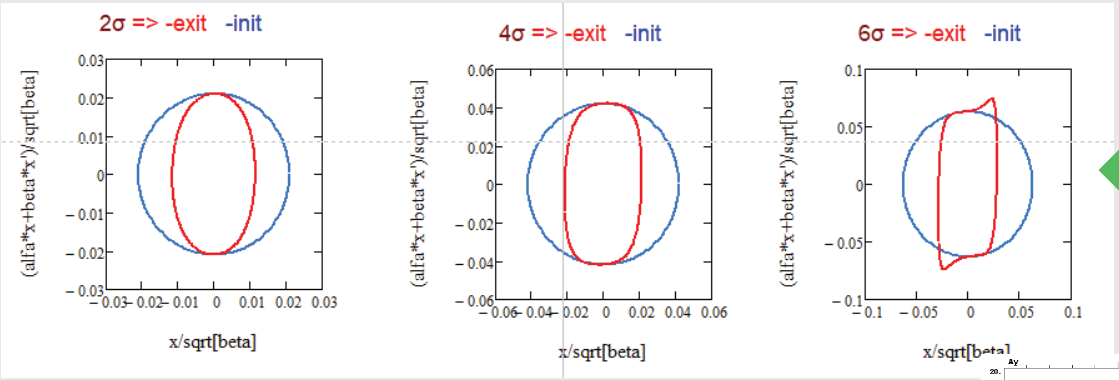


Action of the fringe fields



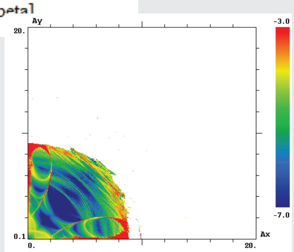
$$
\mathrm{Edge}(X,k_0) := \left|
\begin{aligned}
&Y_0 \leftarrow X_0 + \frac{k_0}{12}\left[(X_0)^3 + 3\cdot(X_2)^2\cdot X_0\right]\\
&Y_1 \leftarrow X_1 + \frac{k_0}{4}\left[2\cdot X_0\cdot X_2\cdot X_3 - \left[(X_0)^2 + (X_2)^2\right]\cdot X_1\right]\\
&Y_2 \leftarrow X_2 - \frac{k_0}{12}\left[(X_2)^3 + 3\cdot(X_0)^2\cdot X_2\right]\\
&Y_3 \leftarrow X_3 - \frac{k_0}{4}\left[2\cdot X_0\cdot X_2\cdot X_1 - \left[(X_0)^2 + (X_2)^2\right]\cdot X_3\right]\\
&Y
\end{aligned}
\right.
$$

Distortion of the phase space



$$
\mathrm{TrOct}(V,k3dL) := \left|
\begin{aligned}
&k3dL \leftarrow k3dL\\
&V_{f_0} \leftarrow V_0\\
&V_{f_1} \leftarrow V_1 - \frac{(k3dL)\cdot\left[(V_0)^3 - 3\cdot(V_0)\cdot(V_2)^2\right]}{6}\\
&V_{f_2} \leftarrow V_2\\
&V_{f_3} \leftarrow V_3 - \frac{(k3dL)\cdot\left[(V_2)^3 - 3\cdot(V_0)^2\cdot(V_2)\right]}{6}\\
&V_{f_4} \leftarrow V_4\\
&V_{f_5} \leftarrow V_5\\
&V_f
\end{aligned}
\right.
$$

Fringe fields + octupoles

…seems better but did not confirmed by  yet…


Thank you