MC lattice design status

MCTF Meeting, March 25, 2010

Contents:

- Requirements and issues
- A bit of history: previous designs
- Recent designs

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Requirements and related issues

Required average luminosity for a 2× 750 GeV collider: $\geq 2\times10^{\mathbf{34}}$ cm$^{\mathbf{-2}}$ s$^{\mathbf{-1}}$.

Machine parameters vary depending on the available number of muons and their emittance.

Expectations:

	high transv. emittance	*low transv. emittance*
$N_b \times N_{muons}$/bunch	$1 \times 20 \cdot 10^{11}$	$10 \times 1 \cdot 10^{11}$
$\boldsymbol{\Delta p/p}$	0.1%	1%
$\boldsymbol{\epsilon_N}$	25 μm	2 μm

Design guide lines:

- β^* (≤ 1 cm)
- small circumference (luminosity!)
- small momentum compaction factor ($|\alpha_p| \lesssim 1{\times}10^{-4}$) to achieve 1 cm long bunches with a reasonable RF voltage
- large momentum acceptance
- sufficient Dynamic Aperture ($\gtrsim 3\sigma$)

Issues:

- the large β at the strong IR quads, consequence of the low[a] β^*, means

  -large sensitivity to alignment and field errors of the IR quadrupoles

  -large chromatic effects

- large chromatic effects limit the momentum acceptance and require strong correction sextupoles
- large non-linearities limit the Dynamic Aperture
- muon decay sets severe background conditions and calls for a close work with magnet and detector designers; a group of experts has been formed to address these issues

The only "advantage" (wrt. hadron machines): long term stability is not required !

In the past 3 years, attempts to design a Muon Collider have resumed at Fermilab, with the primary goal of addressing these issues.

[a] for comparison: the LHC IR upgrade foresees β^*=0.25 m; HERA-p (920 GeV) β^*_y was 0.18 m

A bit of History

The idea of a MC being not new, there are around several more or less mature designs.

The “previous generation” of Muon Collider design were aiming to extremely small β^*.

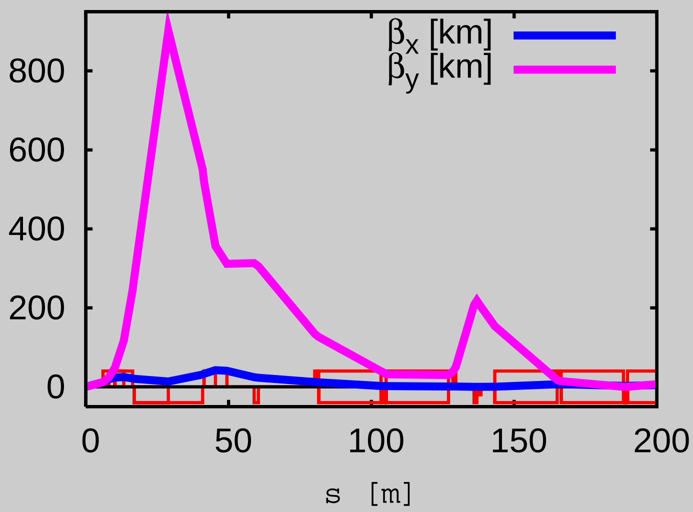
Several optics versions with $\beta^* = 3$ mm and $|\alpha_p| \lesssim 1\times10^{-4}$ are found in the literature, but none of these designs fulfills all requirements, apart for the design due to K. Oide:

- non-interleaved chromaticity correction scheme for both IR and arcs
- large energy acceptance through the optimization of sextupoles (22 families), octupoles and decapoles
- very large DA even in presence of energy oscillations

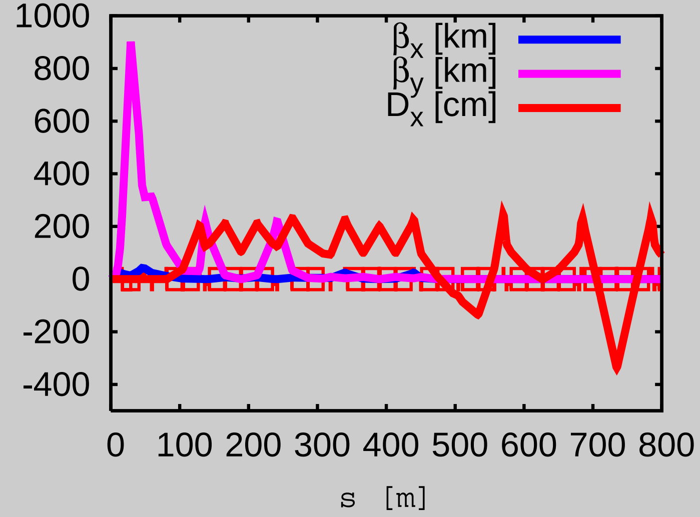
The non-interleaved scheme requires an optics “ad hoc”: the transfer matrix between couple of sextupoles must be a pseudo[a] $-I$ in *both* planes so that the kicks on a particle going through one sextupole is canceled by the next one. The contributions to the tune shift with amplitude cancel too.

[a] $\alpha_1 = \alpha_0$ not needed

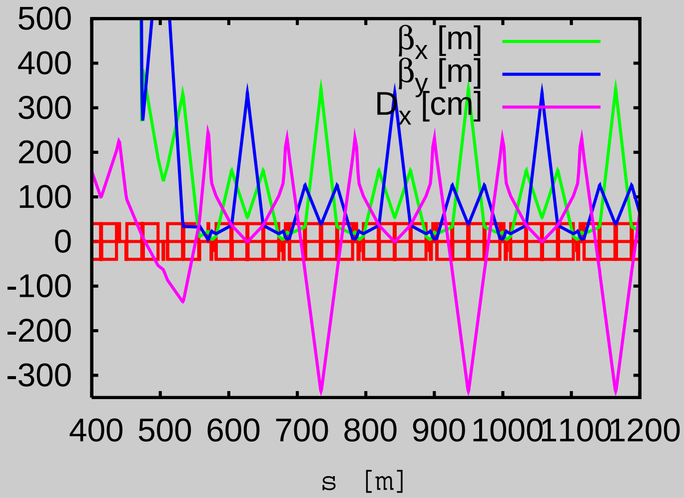
Oide optics



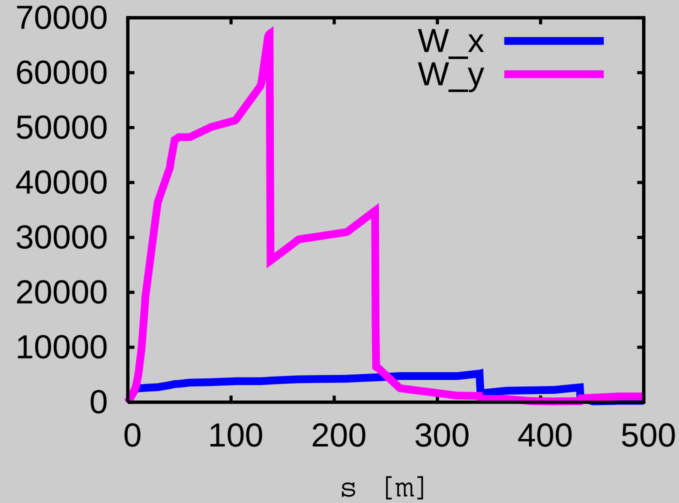
IR



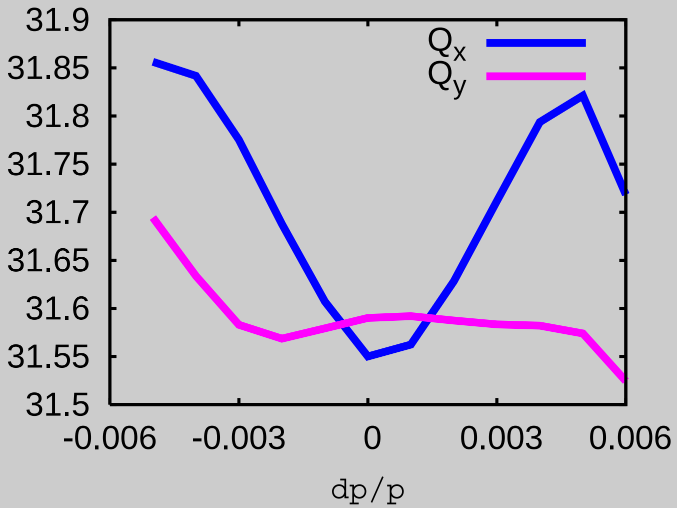
Matching section



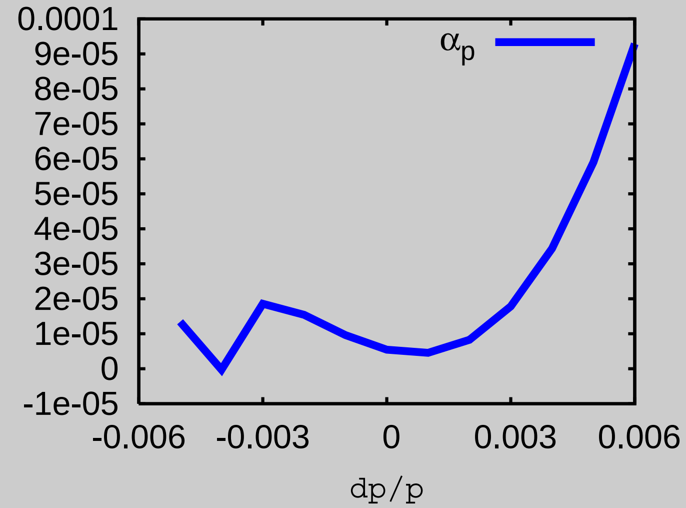
Arc (2.5 π cells, as KEKB)



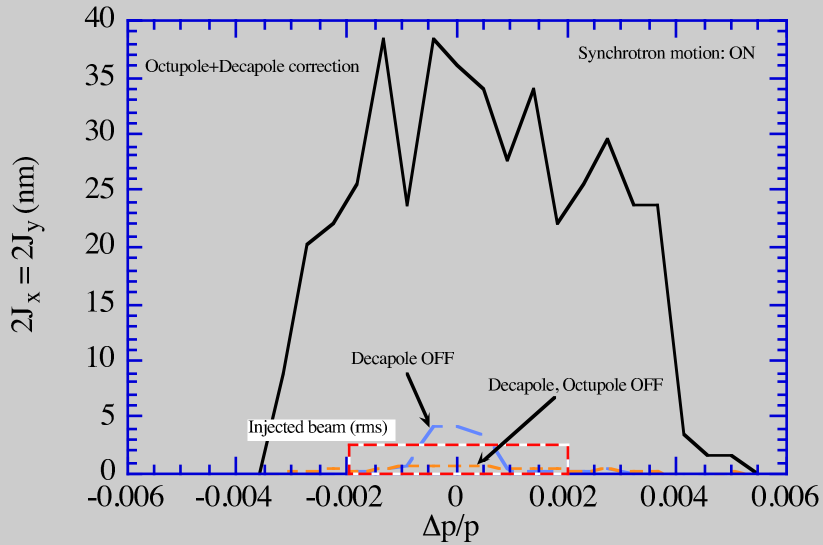
MAD-X chromatic functions



Tunes vs. dp/p



α_p vs. dp/p



Dynamic aperture with synchrotron oscillations, SAD calculation including quadrupole fringe fields: 3 σ at $\Delta p/p = 0$ for ϵ_N=25 μm.

(K. Oide courtesy)

But...

- relatively long ($\mathcal{L}$=5700 m, one IP)
- $\hat{\boldsymbol{\beta}}$= 900 km and thus large sensitivity to misalignment errors (MCDW, Dec 2007)
- too strong sextupoles
- cumbersome optimization in practice

Recent design attempts

Constraints

Design constraints	
β_x^*, β_y^* $(\epsilon_x = \epsilon_y)$	10 mm
free space around IP	$\pm$ 6 m
$\lvert\alpha_p\rvert$	$\leq 1 \times 10^{-4}$
$\hat{g}$	$\leq$ 220 Tm^{-1}
	$\downarrow$
	$\boxed{\text{k} \leq 0.09 \text{ m}^{-2} \text{ @ 750 GeV}}$
$\hat{B}$	10 T

Why 6 m free space? A compromise between magnet strength and $\hat{\beta}$

$$s = f = \frac{1}{K\ell} \simeq \sqrt{\hat{\beta}\beta^*}$$

Larger gradient, if available (and if experiments can cope with smaller space), would help reducing chromaticity

$$K\ell\,\hat{\beta} \simeq \sqrt{\frac{\hat{\beta}}{\beta^*}}$$

We quickly learned that chromaticity correction was a big issue and that the traditional way of correcting it by sextupoles in the arcs would not work.

Recent optics:

- "dipole first" with "local" chromatic correction
- Oide IR concept ($\hat{\boldsymbol{\beta}}_{\boldsymbol{x}} \ll \hat{\boldsymbol{\beta}}_{\boldsymbol{y}}$), but with $\boldsymbol{\beta}^{*}$=10 mm and "local" IR chromaticity compensation in the vertical plane, where chromaticity is larger.

Local chromatic correction

Montague *chromatic functions*, A and B, describing the change of the twiss parameters with momentum $\delta \equiv \Delta p/p$

$$B \equiv \frac{\Delta\beta}{\beta} \qquad \text{and} \qquad A \equiv \beta\Delta\left(\frac{\alpha}{\beta}\right)$$

$$\frac{dB}{ds} = -2A\frac{d\mu}{ds} \quad \text{and} \quad \frac{dA}{ds} = 2B\frac{d\mu}{ds} + \sqrt{\beta(0)\beta(\delta)}\Delta K$$

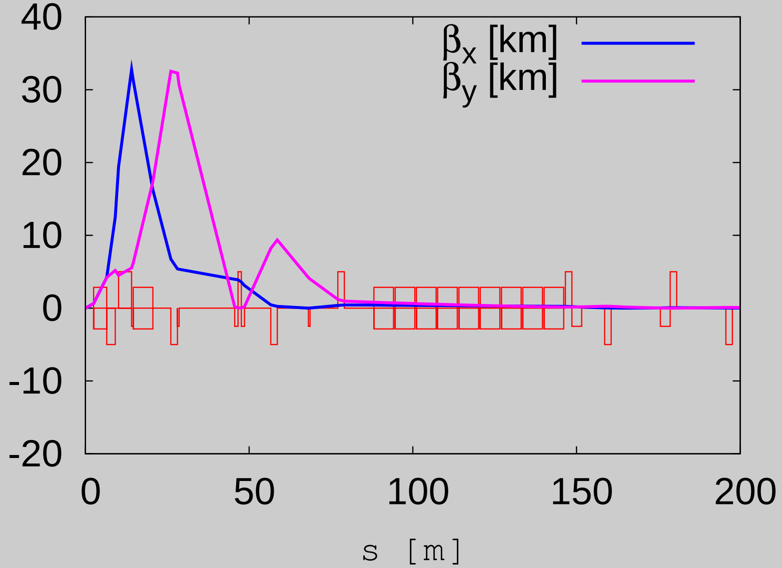
As long as $d\mu/ds = 0$ it is $B=0 \Rightarrow \beta$ and phase are momentum independent.

Idea: the large chromatic beta wave created by the IR quadrupoles should be compensated *locally*, that is before the phase advance changes after the first quadrupole.

For $D_x = D'_x = 0$ at the IP, this requires introducing bending magnets close to the IP.

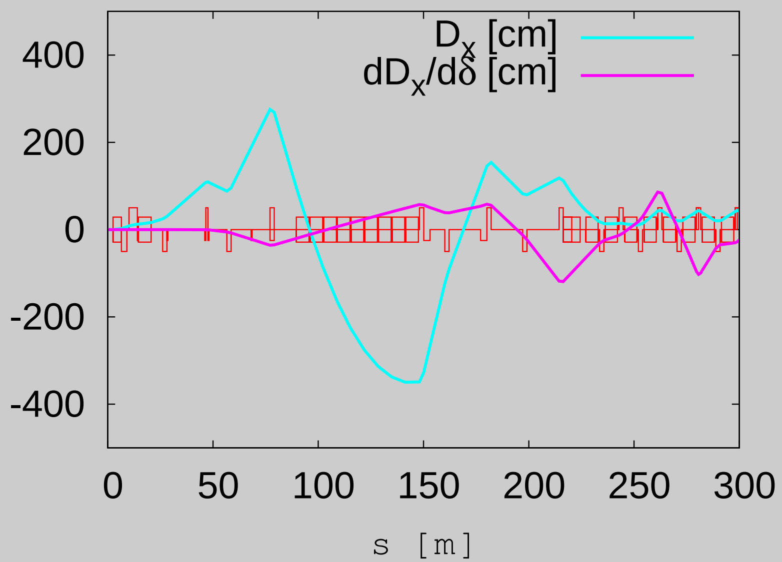
Dipole First Optics

It requires a relatively strong bend magnet ($\boldsymbol{B}$=7.5 T, $\boldsymbol{\ell}$=4 m) at 2.5 m from the IP for local correction to be effective



IR Twiss functions

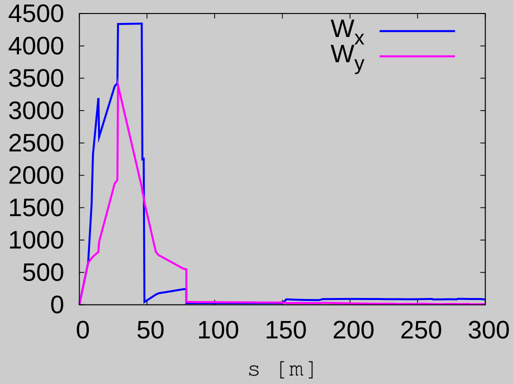
$\hat{\boldsymbol{\beta}}_{\boldsymbol{x}} \simeq \hat{\boldsymbol{\beta}}_{\boldsymbol{y}}$



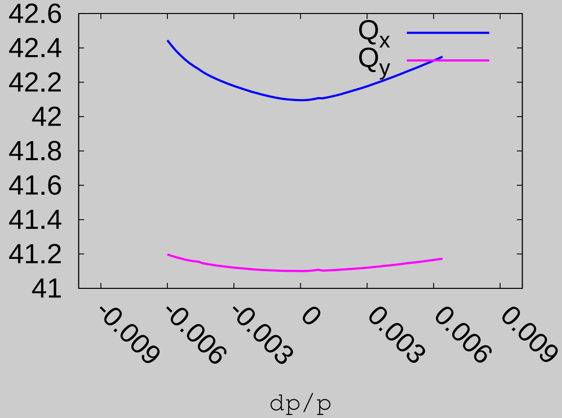
IR Dispersion

Negative $\boldsymbol{\alpha_p}$ IR contribution

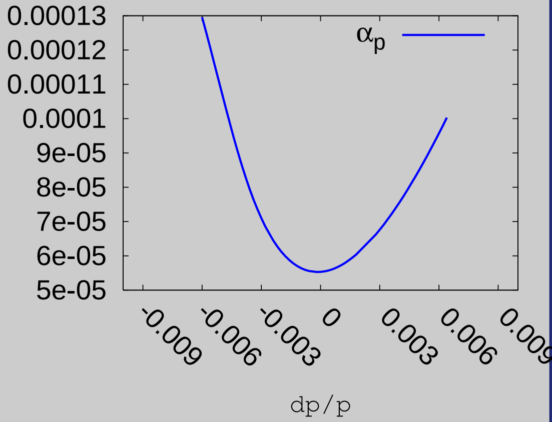
- IR chromaticity *locally* corrected by (interleaved) sextupoles
- sextupoles correct 2th order dispersion
- 108 deg FODO cell arcs, with chromaticity corrected simply by 2 families of interleaved sextupoles.
- Relatively compact ($\mathcal{L} = 3110$ m, 2 IP's).



MAD chromatic functions

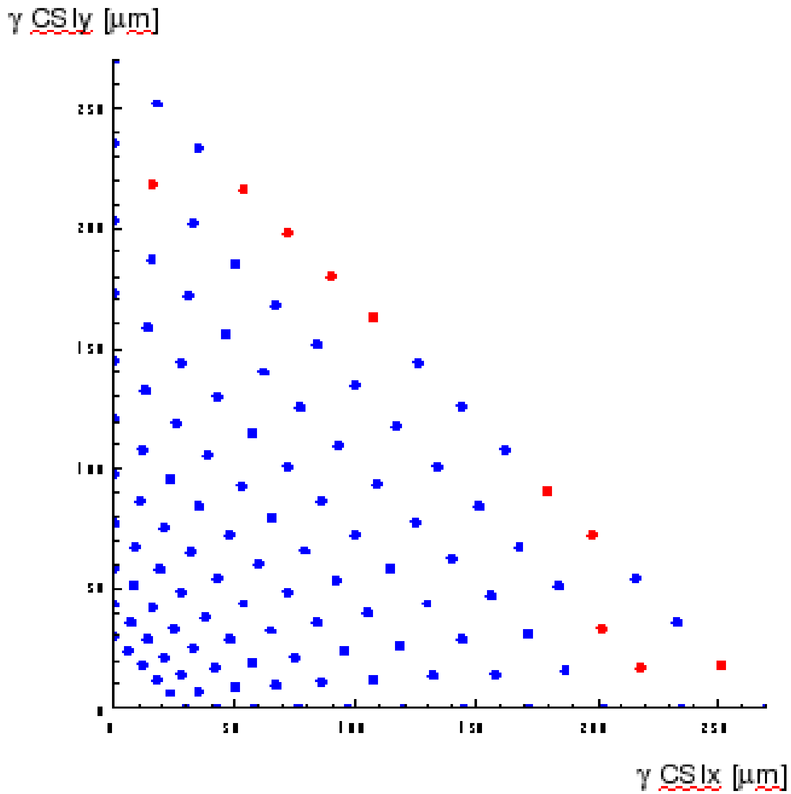


Tunes vs. dp/p



α_p vs. dp/p

Detuning with amplitude introduced by the IR sextupoles is compensated by *octupoles*. Acceptable DA (Y. Alexahin, MCDW, JLAB Dec 2008) [a]



One would expect

$$\gamma CSI_{\max} = \gamma\,\Delta Q/(dQ/dE) \approx$$
$$\approx 7\cdot 10^3 \times 0.4/2.4\cdot 10^8 \approx 120\cdot 10^{-6}$$

```
Second order chromaticity:
Q1''      =   24074.96031867
Q2''      =    4020.58313978
Normalized anharmonicities:
dQ1/dE1 =   0.25242152E+08
dQ1/dE2 =   0.19616977E+08
dQ2/dE2 =   0.18515914E+08
```

The 1024 turns DA is now marginally sufficient for the high-emittance option: ~3σ for $\varepsilon_{\perp N}$=25 μm and is O.K. for low- and medium-emittance option.

It can be increased by compensating detuning with stronger octupoles

However:

- fringe fields not included yet
- optics errors will reduce DA
- we need good LONG-TERM DA to work with protons

[a] DA shown in terms of *particle* emittance (square of the oscillation amplitude $\boldsymbol{A}$) times the relativistic γ factor. Number of sigma's: $n = \sqrt{A^2\gamma/\epsilon_N}$.

To make use of the local chromaticity correction w/o introducing the "nasty" (?) bending magnet near the IP and keeping $\boldsymbol{D_x}$=0 at the IP, it must be $\boldsymbol{D'_x \neq 0}$ at IP.

It was suggested for instance by Pantaleo-Zimmermann who got good results, at least when closing the ring with a *linear transfer matrix*.

A. Netepenko (see LEMCW 2009) tried such a scheme, but it turned out to be very bad and for good reasons.

The dispersion antisymmetry implies that the sextupole left and right of the IP must have *opposite* strength.

- sextupole effect on tune shift with amplitude sums up
- sextupole effect on 2th order dispersion sums up
- kicks through sextupoles add up

Non-interleaved IR chromatic correction optics

Try to combine the best of both chromaticity correction schemes (E. Gianfelice, MUTAC April 2009):

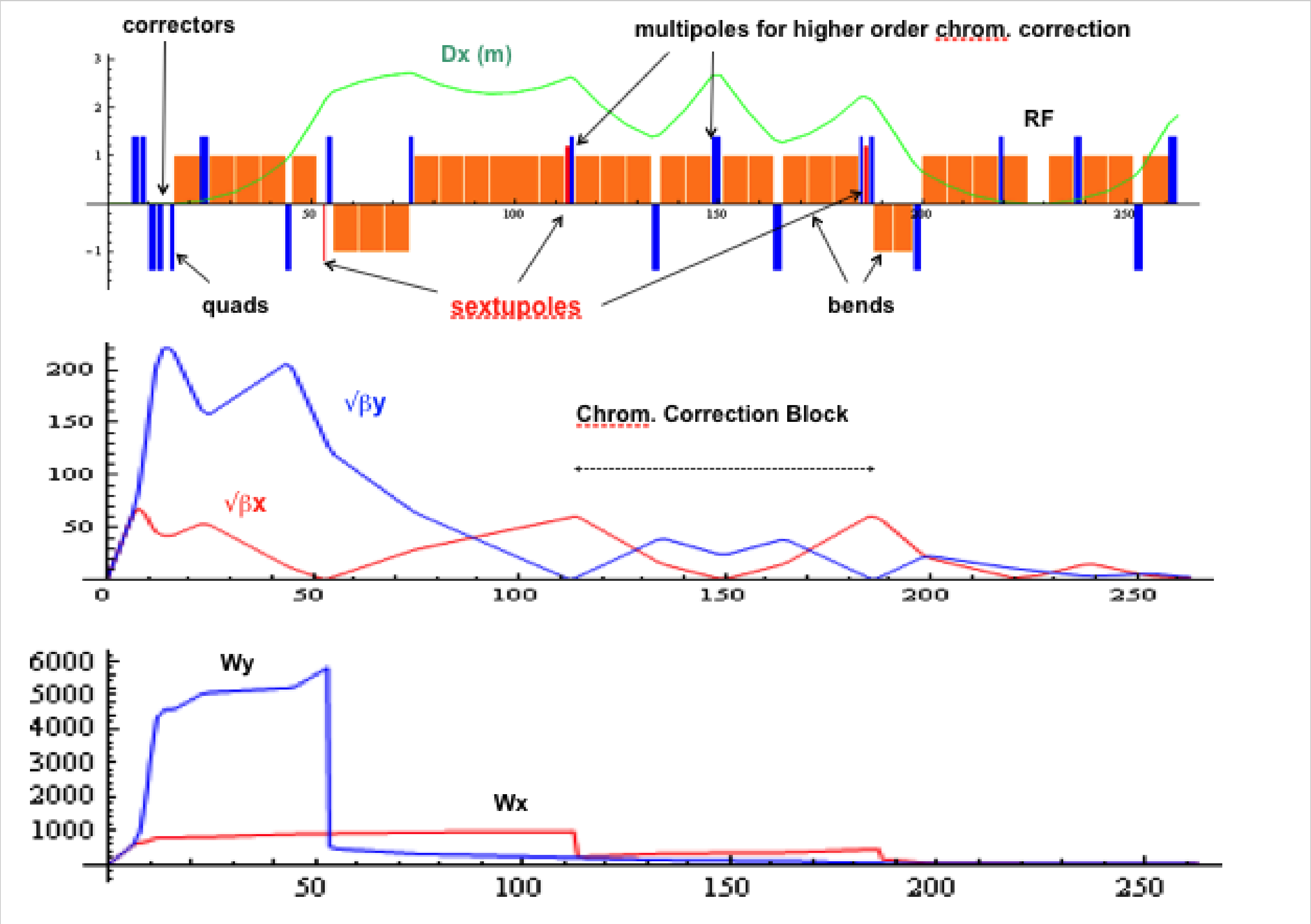
- Let be, for instance, $\hat{\boldsymbol{\beta}}_{\boldsymbol{y}} \gg \hat{\boldsymbol{\beta}}_{\boldsymbol{x}}$, and correct *locally* the largest (vertical) chromaticity with one sextupole at $\boldsymbol{\Delta\mu}$=0 from the source (the low beta quads).
- Use non-interleaved scheme for correcting the smaller chromaticity with a pair of sextupoles: the first sextupole is located in the first, after the vertical sextupole, knot of the chromatic beta wave while the subsequent optics is designed so that the transfer matrix between the horizontal sextupole pair is a pseudo $-\boldsymbol{I}$ transformation and the dispersion is almost the same.

For this we must create some dispersion in the IR, but a “dipole first” is not needed. In addition to dipoles, some extra dispersion was obtained by horizontal offsetting some of the IR quads.

The correction in the vertical plane is *intrinsically* non-interleaved the phase advance across the IP being π and the optics symmetric.

Moreover, choosing $\hat{\beta}_y > \hat{\beta}_x$ it is convenient because the tune shift with amplitude due to a *normal* sextupole is proportional to β_x: a sextupole compensating for the vertical β wave, located where $\beta_y \gg \beta_x$, will introduce a negligible tune dependence on amplitude.

Last Yuri IR layout (MCDW, December 2009) includes IR quads radial offsets and Zlobin recommendations for extra spaces and safety margins for the magnetic strengths



The α_p issue

A second important issue with the MC design is related to α_p which must be small and as constant as possible for the large range of momenta required.

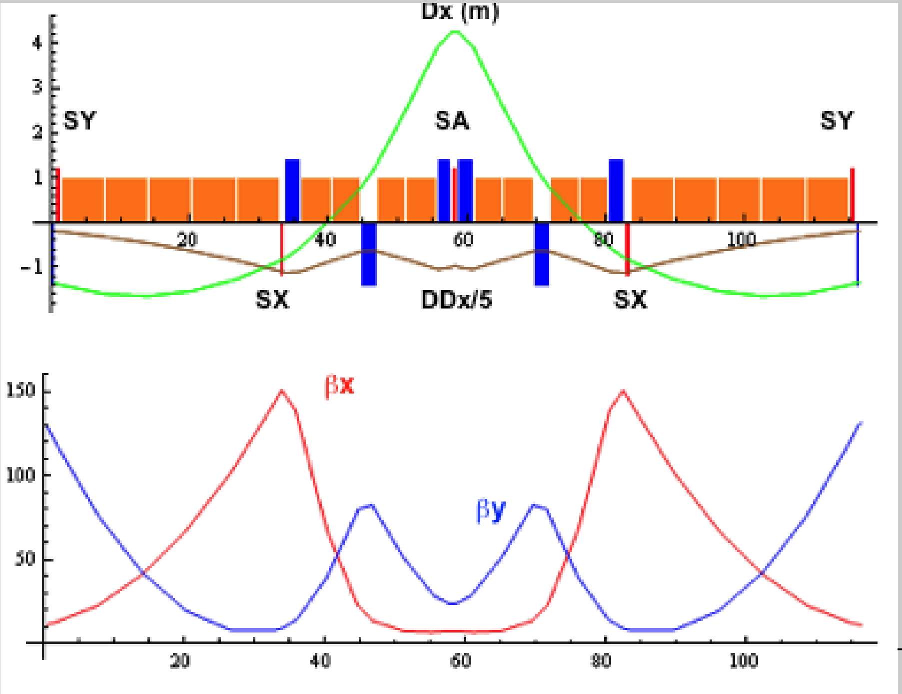
The IR in this design has a large positive contribution to α_p.

- arc cells must give a negative contribution to α_p
- must be flexible enough to allow tune adjustments
- transformation between sextupoles must be a pseudo $-I$ or at least the phase advance between sextupoles must be optimized to avoid driving 3th order resonances

All this while keeping the ring closure...

The chromaticity of the arcs being small we gave up the non-interleaving condition.

We tried several kind of arc cells.
Finally Yuri found a good cell fulfilling almost all conditions.



cell layout and Twiss functions

- almost orthogonal chromaticity correction with just one family/plane
- 300 deg phase advance/cell: cancellation over 6 cells
- α_p and its dependence on momentum [a] controlled through the middle quadrupole and sextupole

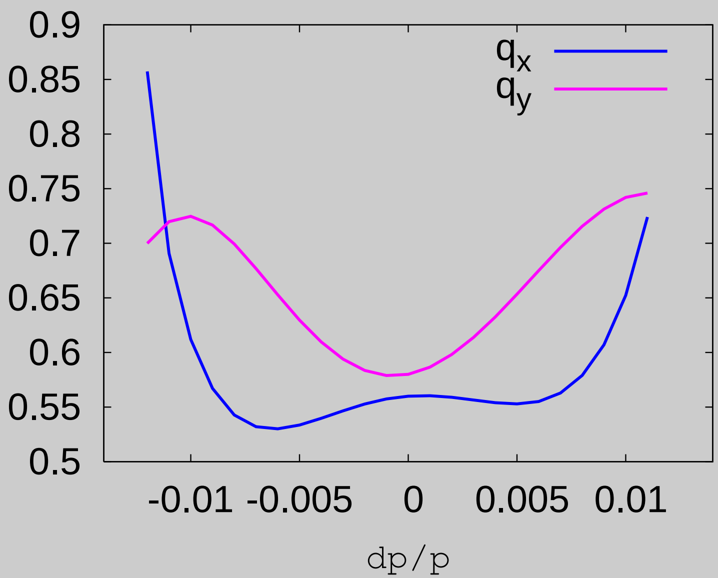
[a] $\frac{1}{\mathcal{L}}\int ds[\frac{1}{\rho}\frac{\partial D_x}{\partial \delta_p}+\frac{1}{2}D_x']$

(Y. Alexahin, MCDW December 2009)

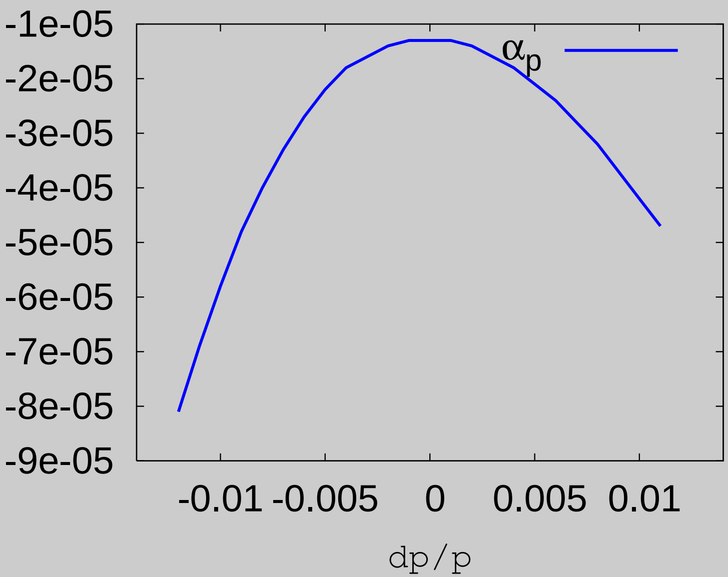
The cell is not flexible for adjusting tunes, unless the condition on the 3th order resonances is given up. To be tried!!

A *dispersion free* tuning section was introduced with plenty of space for RF cavities and whatever else (injection? dump?), but bad for neutrino radiation. The ring is still compact ($\mathcal{L}$=2727 m). A shorter tuning section was not as flexible.

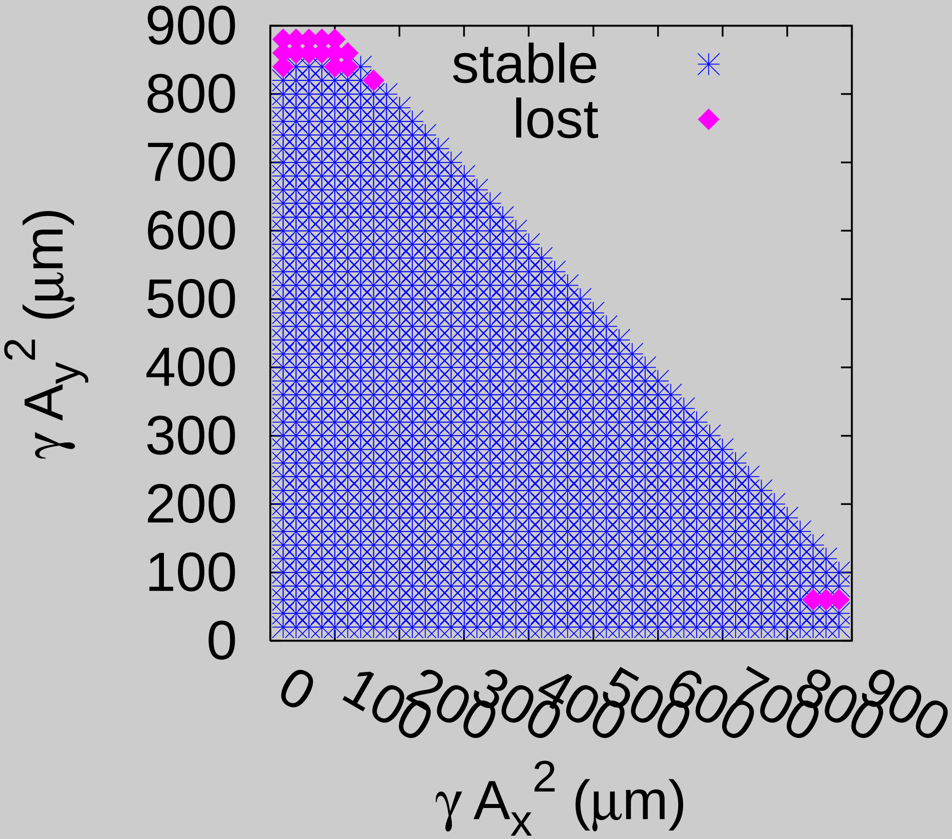
Non-interleaved IR chromatic correction optics



Tunes (fractional part) vs. dp/p



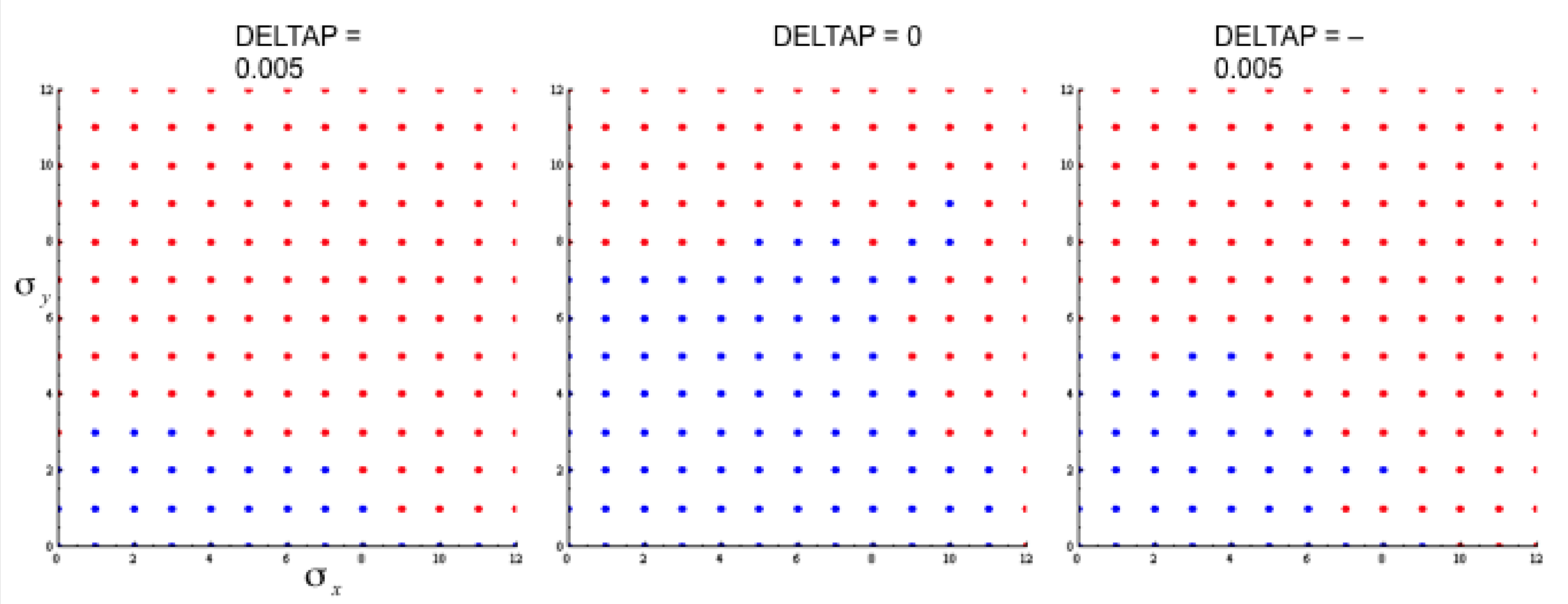
α_p vs. dp/p



DA (on energy)

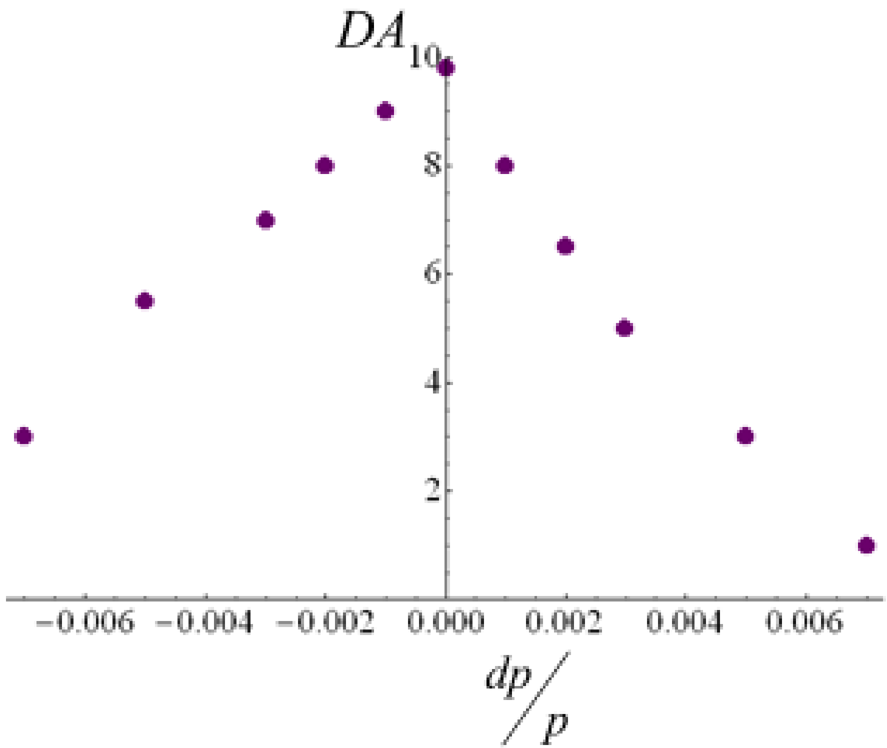
DA for dp/p=0 and without synchrotron oscillations is 5.7 $\boldsymbol{\sigma}$ for $\boldsymbol{\epsilon_N}$=25 $\boldsymbol{\mu}$m, a bit larger then shown in NFMCC Jan 2010, thanks to an extra couple of octupoles.

A. Netepenko looked at the effects on DA of energy offset, synchrotron oscillations, magnetic imperfection of IR dipoles and beam-beam interaction for the previous lattice version (w/o tuning section) by using several tracking algorithms.

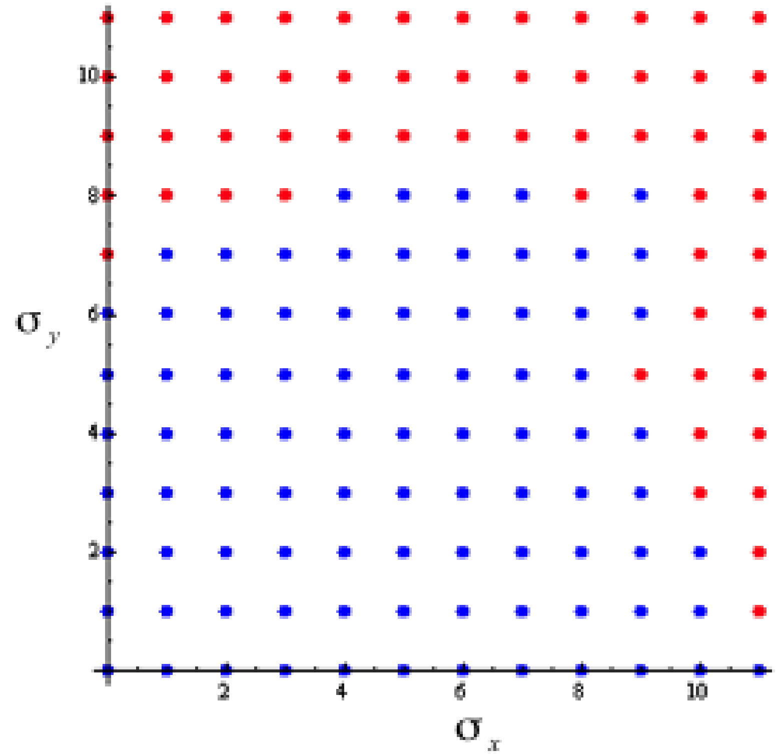


ϵ_N=10 μm (MAD8)

(A. Netepenko, MCDW December 2009)



Diagonal DA, MAD-8 calculation (4D tracking) for different constant dp/p, BeamBeam included, 1024 turns



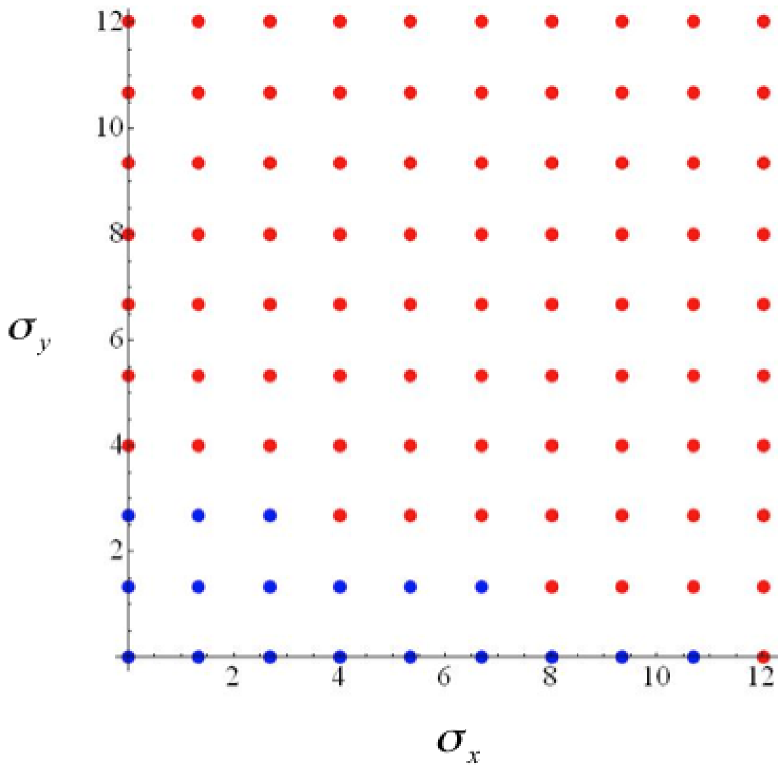
MAD-X calculation 6D tracking with synchrotron oscillations, no BeamBeam, 1024 turns

$f_{RF} = 800MHz \quad V_{RF} = 4 \times 16MV$

$Q_s \cong 10^{-3}$

ϵ_N=10 μm

(A. Netepenko, MCDW December 2009)



MAD-X calculation 4D tracking ,
no Beam-Beam, 1024 turns

After

$$\frac{dQ_y}{dE_y} = 1.9 \cdot 10^6$$
$$\frac{dQ_x}{dE_y} = -3.2 \cdot 10^5$$
$$\frac{dQ_x}{dE_x} = -1.2 \cdot 10^5$$

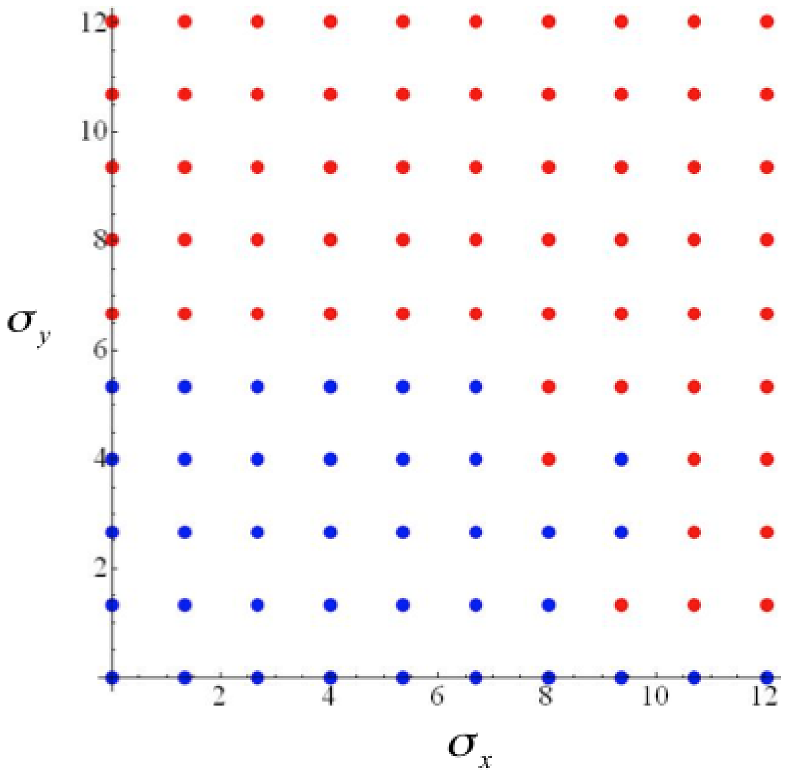
Before

$$\frac{dQ_y}{dE_y} = -1.5 \cdot 10^5$$
$$\frac{dQ_x}{dE_y} = 9.4 \cdot 10^4$$
$$\frac{dQ_x}{dE_x} = -1.2 \cdot 10^5$$

$$\frac{dQ_y}{dE_y} \sim b_2^2 \beta_x \beta_y^2, \quad \frac{dQ_x}{dE_x} \sim b_2^2 \beta_x^3$$

ϵ_N=10 μm

(A. Netepenko, NFMCC Meeting, January 2010)



MAD-X calculation 4D tracking , no Beam-Beam, 1024 turns

After single octupole correction

$$\frac{dQ_y}{dE_y} = 6.52\cdot 10^4$$

$$\frac{dQ_x}{dE_y} = -1.85\cdot 10^5$$

$$\frac{dQ_x}{dE_x} = -1.31\cdot 10^5$$

Before

$$\frac{dQ_y}{dE_y} = 1.9\cdot 10^6$$

$$\frac{dQ_x}{dE_y} = -3.2\cdot 10^5$$

$$\frac{dQ_x}{dE_x} = -1.2\cdot 10^5$$

So it's clear that we can deal with BM filed sextupole nonlinearities using octupole correction, or combining both sextupole and octupole correctors

$$\frac{dQ_y}{dE_y} = \frac{1}{2\pi}\sum_j \frac{3}{4} b_{3j}\beta_{yj}^2$$

ϵ_N=10 μm

(A. Netepenko, February 2010)

Finally we have looked into the possibility of changing β^* w/o changing the layout.

$\beta^* = 20$ and 5 mm have been considered.

Without changing the magnet strengths of IR and arcs, by adjusting the transition section to set total tunes and match arc optics, with some retuning of the non-linear corrections, stability momentum range as well as DA are almost unchanged.

Conclusions

We are on the right track and in the position now of attacking the ... "higher order approximation" aspects as

- practical layout
- fringe fields
- magnet misalignment and imperfections
- ...