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First look at a 3 TeV c.o.m. collider optics

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Introduction

After a promising optics for a 750 GeV ring was established, the natural question arose whether the energy could be increased.

Issues:

- The IR quadrupole of the 750 GeV design are already long (up to 2 m) and strong.
- The IR dipoles too, inserted mainly for producing dispersive regions for the sextupoles, as well as the cell dipole are at the limit.

The 750 GeV optics is *not* scalable to 1.5 TeV. It is clear that something must be paid for the higher energy...

We started looking at a 1.5 TeV optics.

Constraints

Design constraints	
β_x^*, β_y^* $(\epsilon_x = \epsilon_y)$	10 mm
free space around IP	$\pm$ 6 m
$\lvert\alpha_p\rvert$	$\leq 1 \times 10^{-4}$
$\hat{g}$	$\leq$ 260 Tm^{-1}
$\hat{B}$	10 T
	(8 T in the IR)

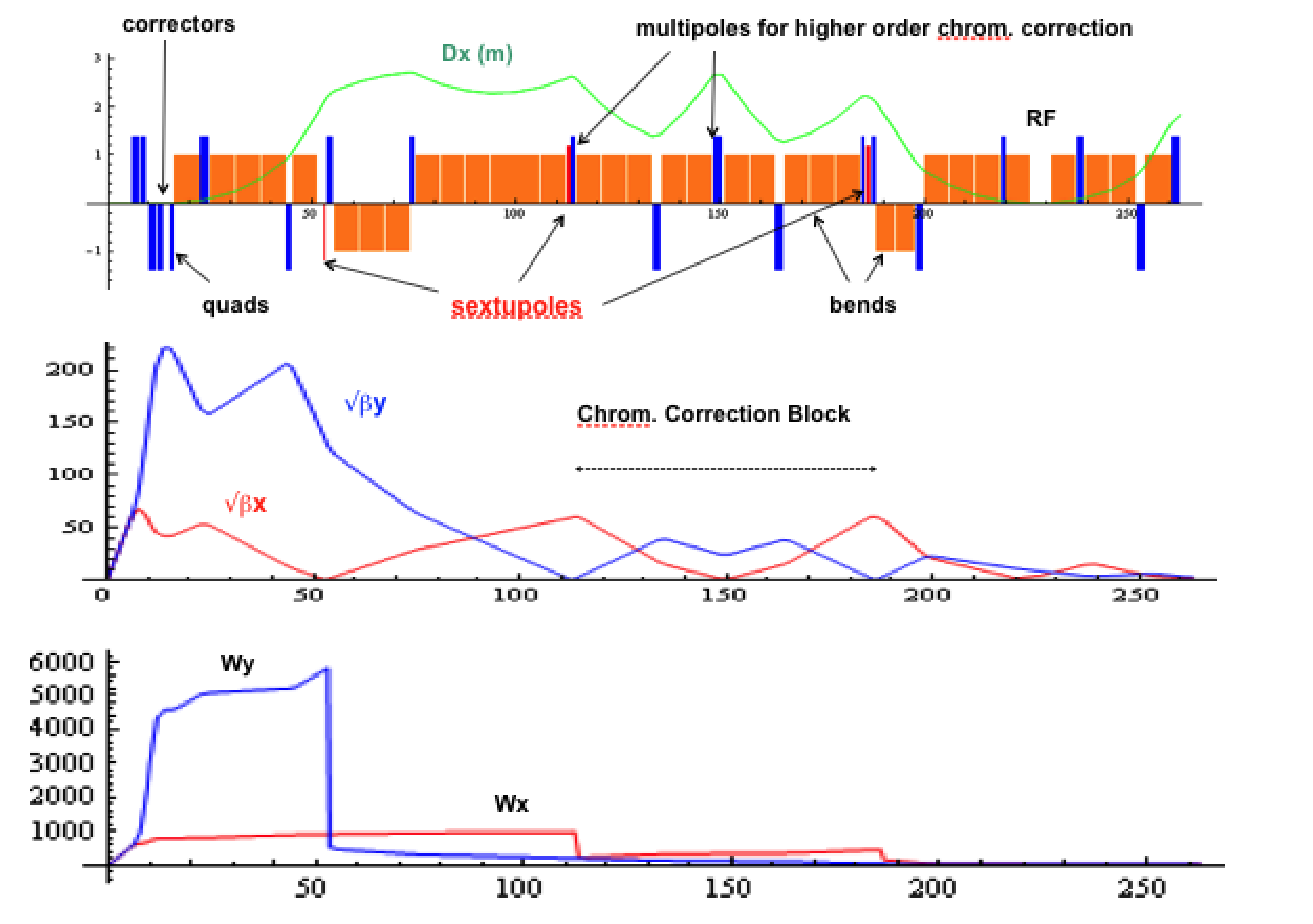
Moreover: $\ell_B \leq$ 6 m, $\ell_Q \leq$ 3 m.

Guidelines

As first attempt, IR and cell design are kept as close as possible to the 750 GeV optics one:

- Non-symmetric IR design: $\hat{\boldsymbol{\beta}}_{\boldsymbol{y}} \gg \hat{\boldsymbol{\beta}}_{\boldsymbol{x}}$.
- Local chromatic correction ("à la Montague") for the larger vertical chromatic wave with a *single* sextupole (one pair per IP) at a location with $\boldsymbol{\beta}_{\boldsymbol{x}} \simeq 0$ and $\boldsymbol{\Delta\mu}_{\boldsymbol{y}}=0$ from the perturbation source (the low beta quads).
- $-\boldsymbol{I}$ section for accommodating a pair of (non-interleaved) sextupoles correcting the horizontal chromatic wave.

IR layout (Yuri, MCDW, December 2009) [a]



[a]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.

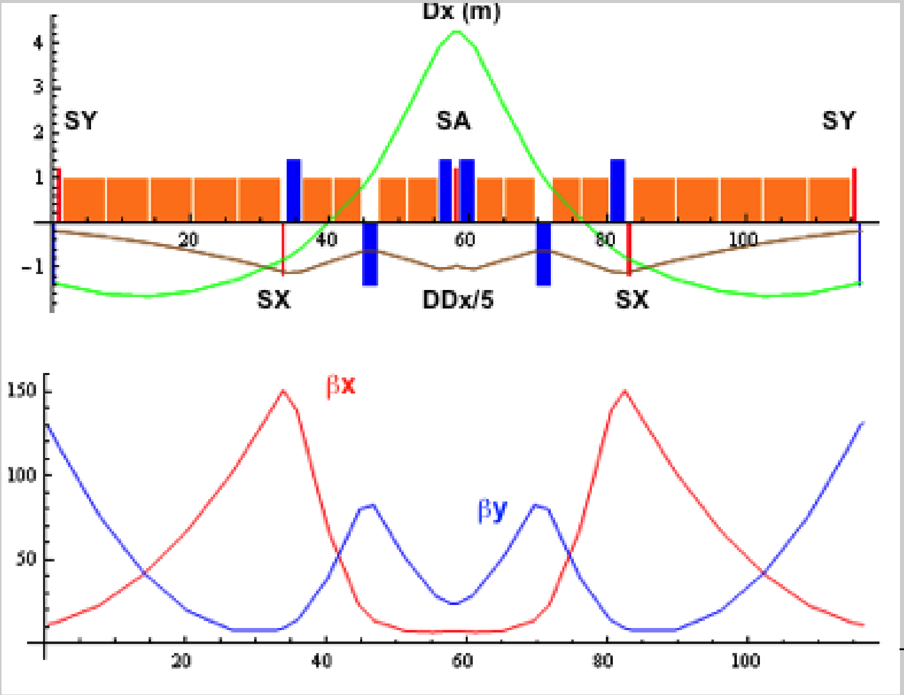
The IR in this design has a large positive contribution to α_p.

- arc cells must compensate it
- arc cells must be flexible enough to allow tune adjustments
- transformation between sextupoles of the same familly must be a (pseudo) $-I$ one 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

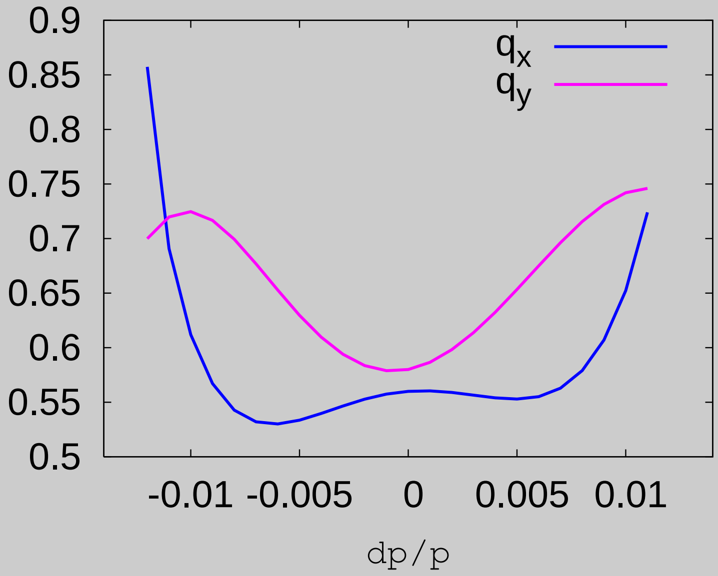
[a] $\frac{1}{\mathcal{L}}\int ds[\frac{1}{\rho}\frac{\partial D_x}{\partial \delta_p}+\frac{1}{2}D_x']$

(Y. Alexahin, MCDW December 2009)

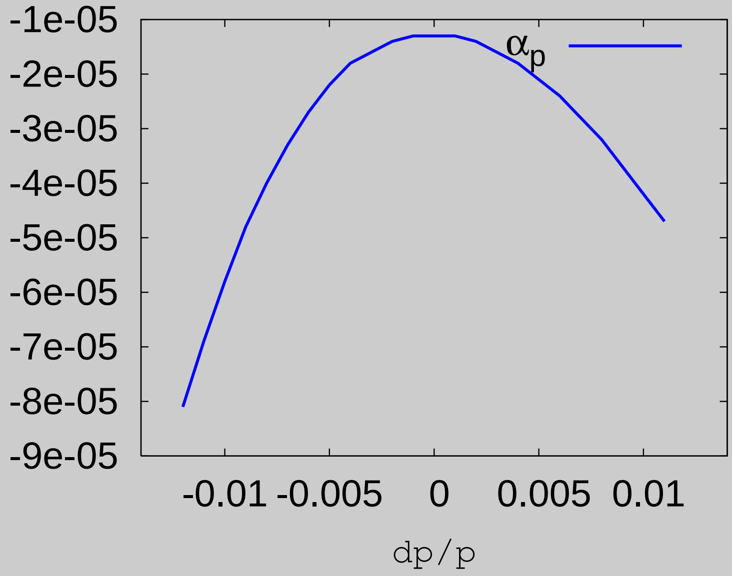
The cell is not flexible for adjusting tunes, unless the condition on the 3th order resonances is given up (to be tried). A *dispersion free* tuning section was introduced with plenty of space for RF cavities and whatever else (injection? dump?), but bad for neutrino radiation.

With 2727 m circumference, the 750 GeV ring is still *compact*.

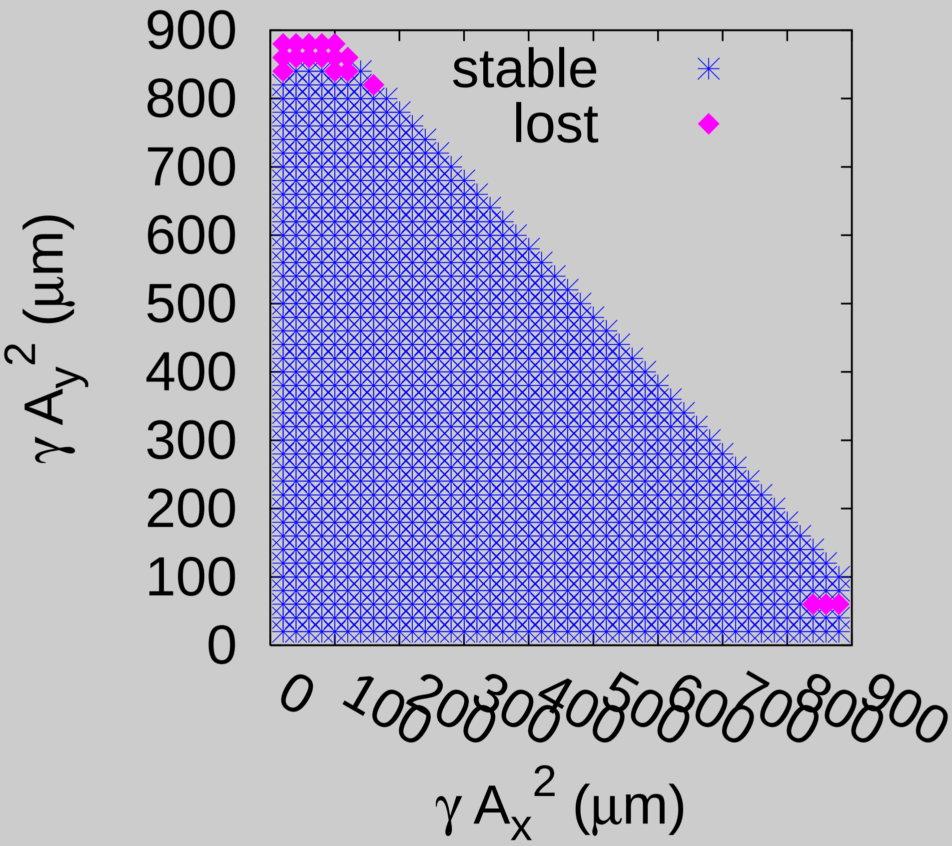
Non-interleaved IR chromatic correction optics



Tunes (fractional part) vs. dp/p



α_p vs. dp/p



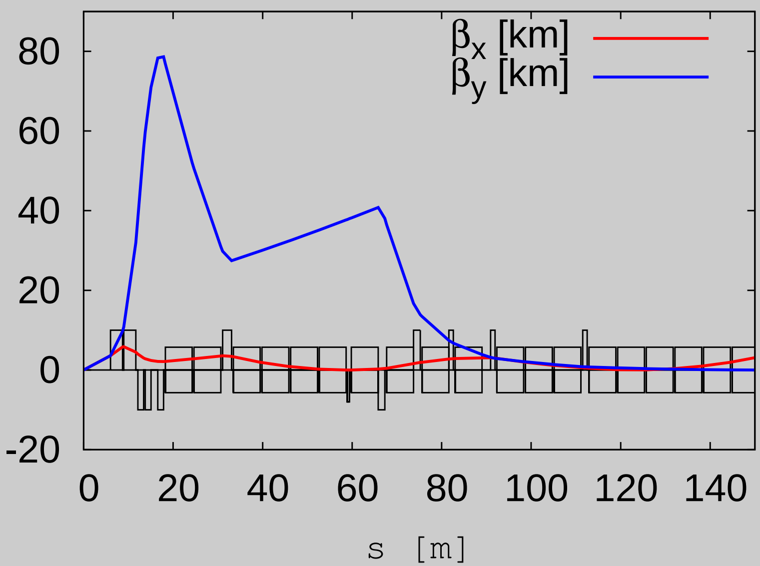
DA (on energy)

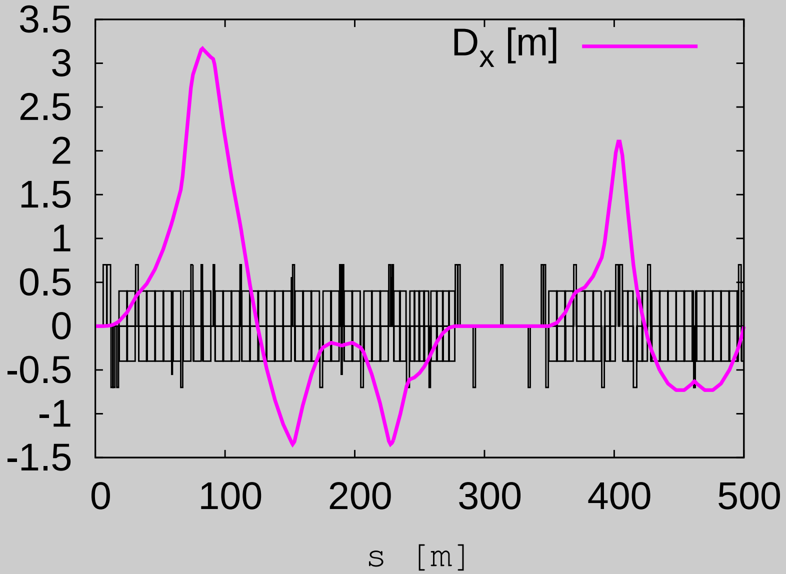
DA for $dp/p=0$ and without synchrotron oscillations is 5.7 σ for ϵ_N=25 μm.

The 1.5 TeV optics

- IR quadrupole length was increased (up to 2.7 m).
- The length of the IR dipoles, already 6 m long, was not changed: the bending angle becomes a factor 2 smaller with consequent decrease of IR dispersion.
- As the field of the arc dipoles was already 10 T, the closure is obtained by increasing the number of cells (30).
- The length of the 3.8 m cell dipoles could have been increased up to 6 m (25 cells instead of 30 needed) with little gain in arc length which is dominated anyway by the length of the dipoles.

The ring, including the RF and tuning section, became 5104 m long.

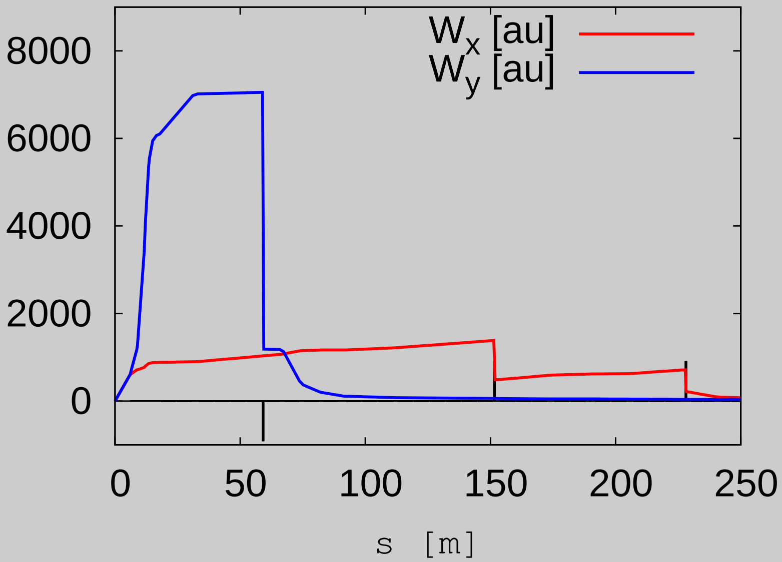


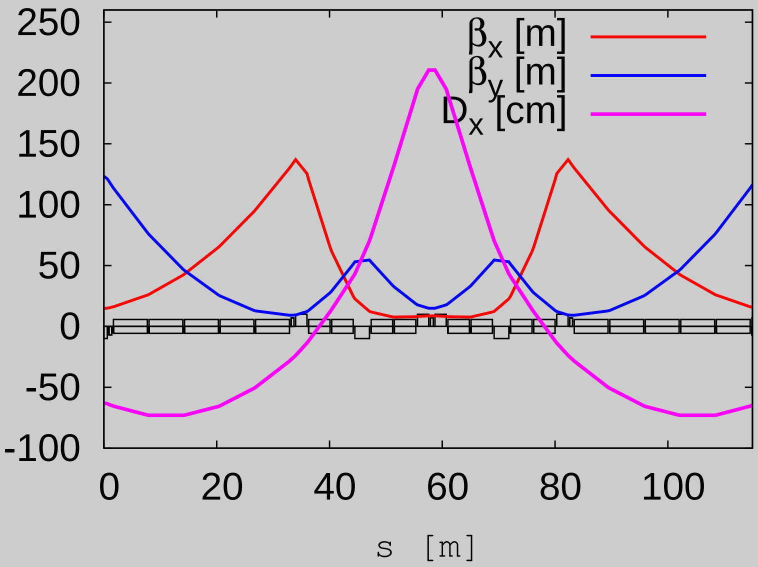


IR optics and layout

Dispersion along
IR, RF and arc matching sections

Wrt 750 GeV design, $\hat{\boldsymbol{\beta}}_{\boldsymbol{y}}$ increased by a factor 1.6 ($\boldsymbol{\sigma}_{\boldsymbol{y}}$ *decreases* by a factor 0.9), while $\hat{\boldsymbol{\beta}}_{\boldsymbol{x}}$ is unchanged.



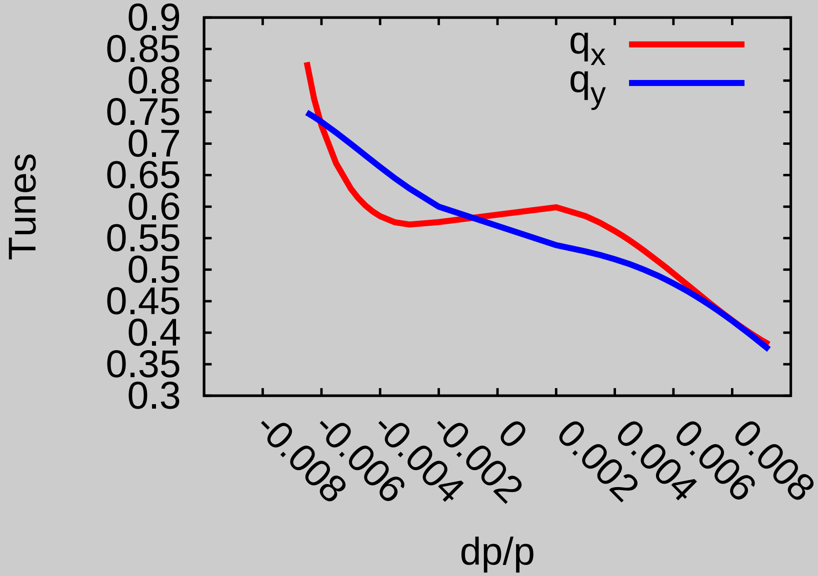


MAD-X chromatic functions

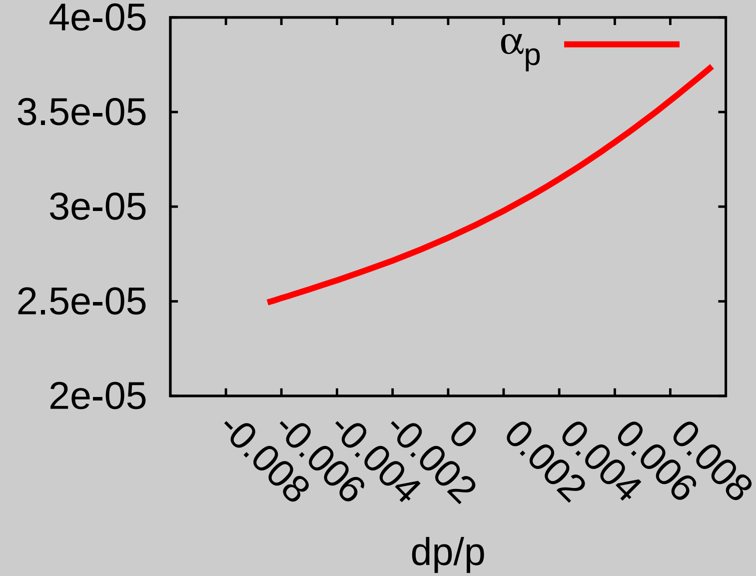
Black bars at 60, 150 and 230 m indicate the sextupole position.

Cell optics and layout

288 degrees phase advance, 15 cells/arc (3th order resonance driving terms cancel over 5 cells)



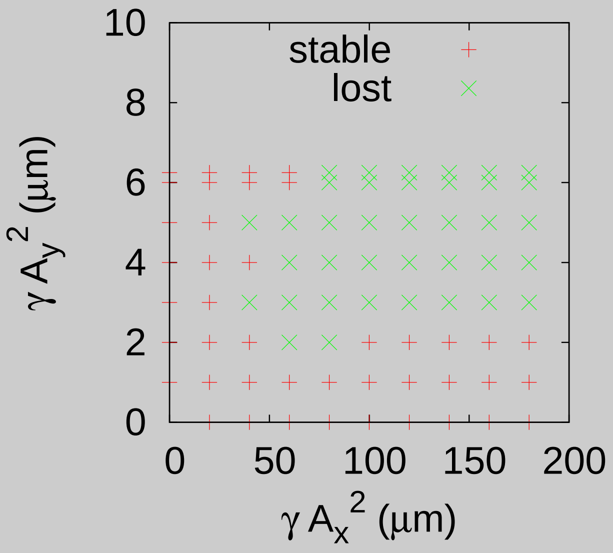
Tune dependence on momentum

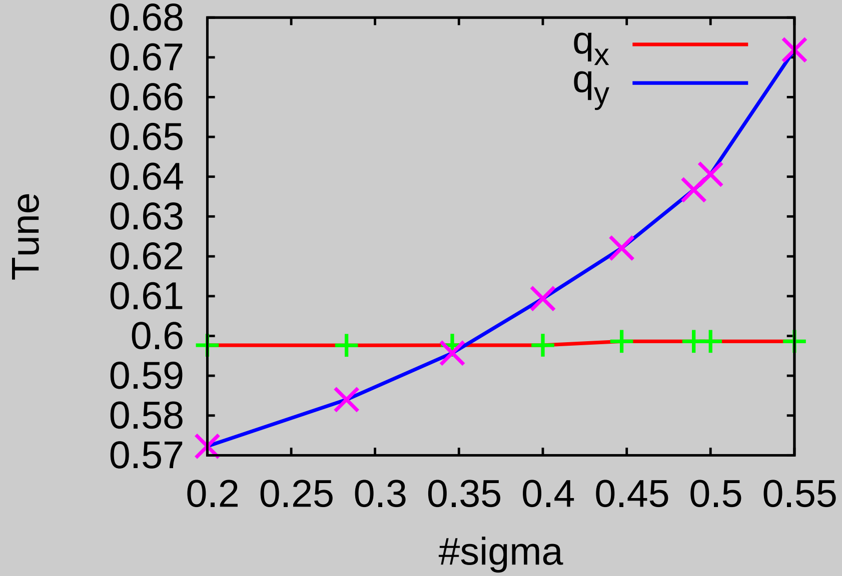


α_p dependence on momentum

Octupoles in dispersive region added; stability range was [-.25%:.+.35%] w/o.

Q_y crosses the half-integer at dp/p=.005





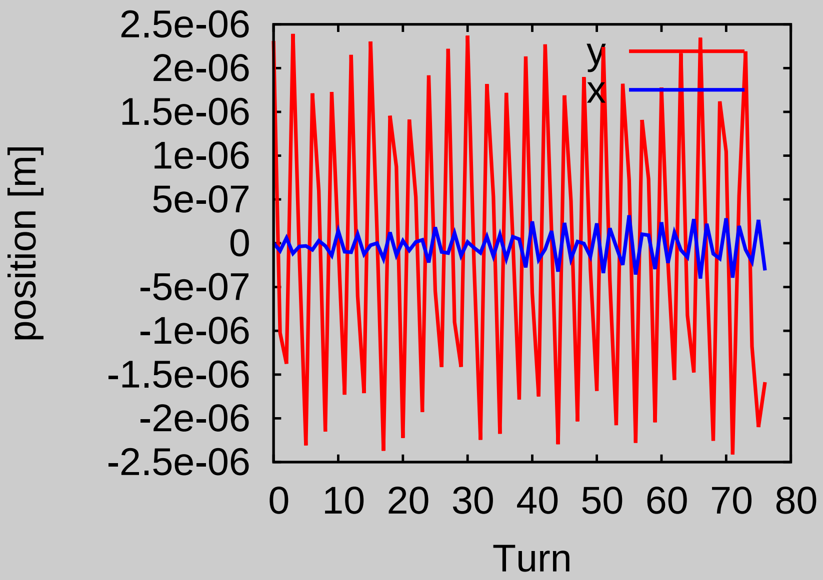
DA (1024 turns)

0.4 sigma's...

Tune dependence on amplitude

Large vertical detuning with amplitude.

TBT position for $(x_0, y_0)=(0.00, 0.55\sigma)$.



The particle is lost at turn #77

Tune Dependence on Amplitude *(MAD8 STATIC)*	
dQ_1/dE_1	0.27×10^7
dQ_1/dE_2	-0.20×10^7
dQ_2/dE_2	0.40×10^8

Preliminary correction with octupoles in non-dispersive regions gave marginal improvement of DA.

Conclusions

In summary:

- Linear optics looks fine.
- Likely, there is room for a better chromatic correction in this same optics.
- Optics should be improved for chromatic correction (larger dispersion where needed, better β separation).
- It may be considered the possibility of adding a quadrupole component to the bending magnets and/or a dipole component to the IR quadrupoles, to enhance dispersion.
- Revisit $D'_x(IP) \neq 0$ option?

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

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

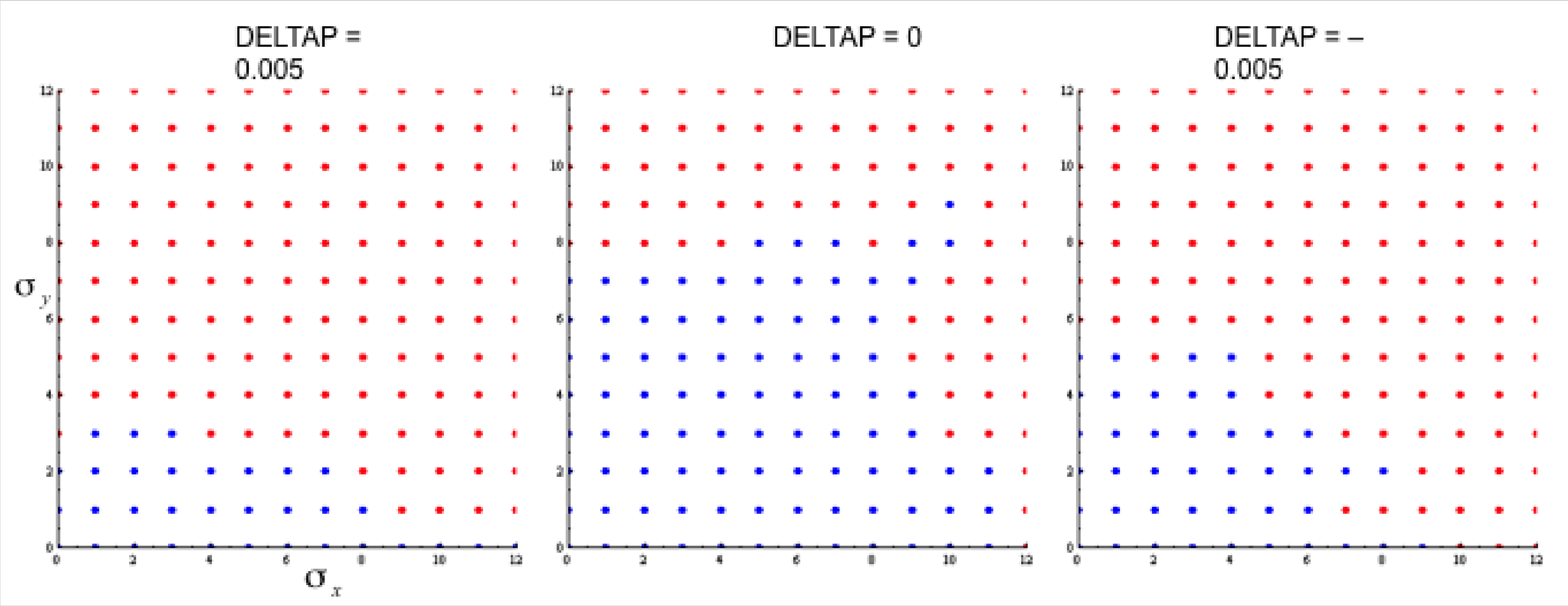
$$\frac{dB}{ds} = -2A\frac{d\mu}{ds} \quad \text{and} \quad \frac{dA}{ds} = 2B\frac{d\mu}{ds} + \sqrt{\beta(0)\beta(\delta)}\Delta K$$

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.

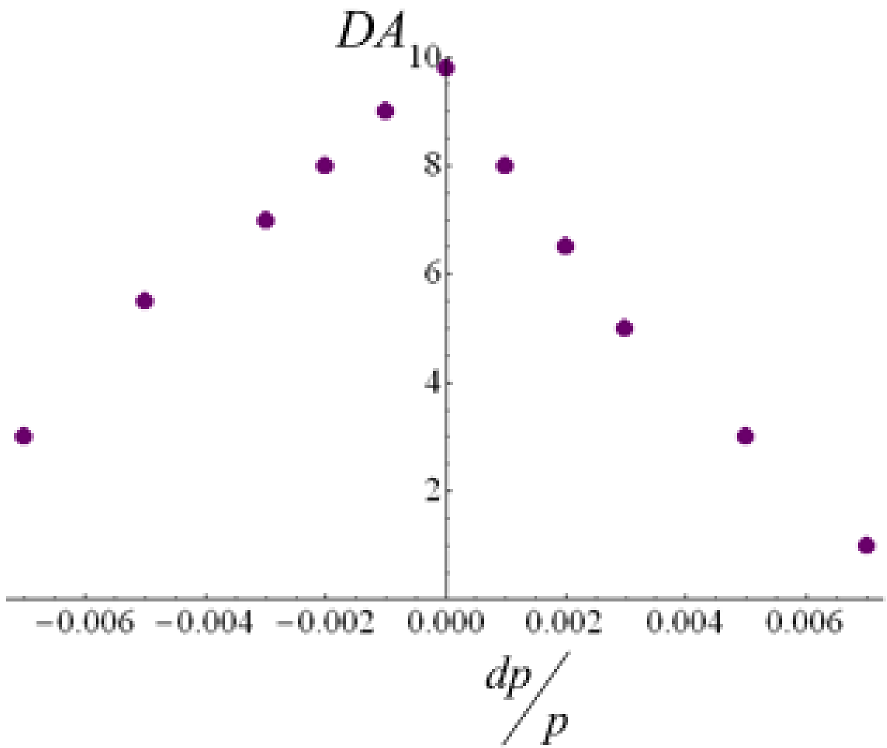
For $D_x = D'_x = 0$ at the IP, this requires introducing bending magnets close to the IP.

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.

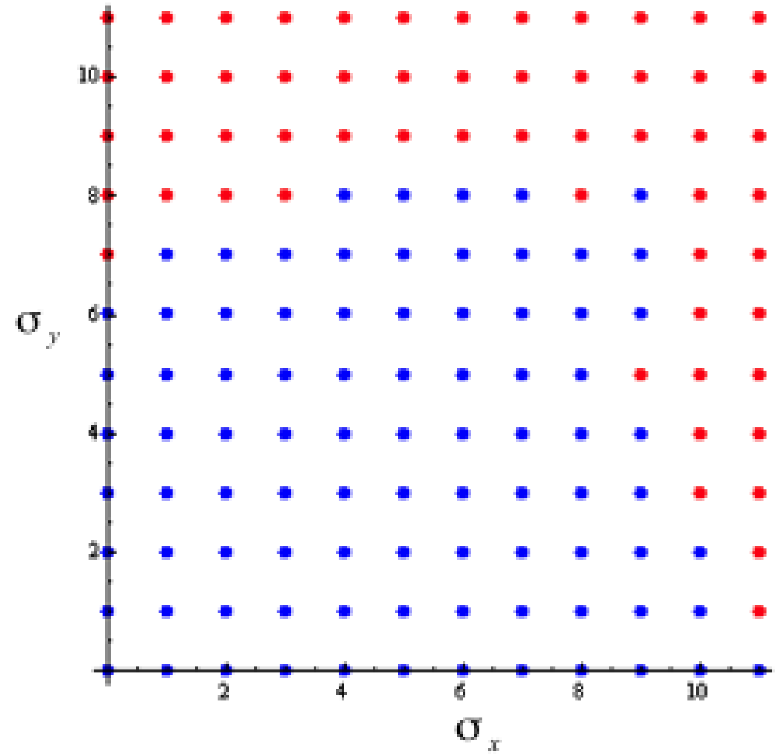


ϵ_N=10 μm (MAD8)

(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

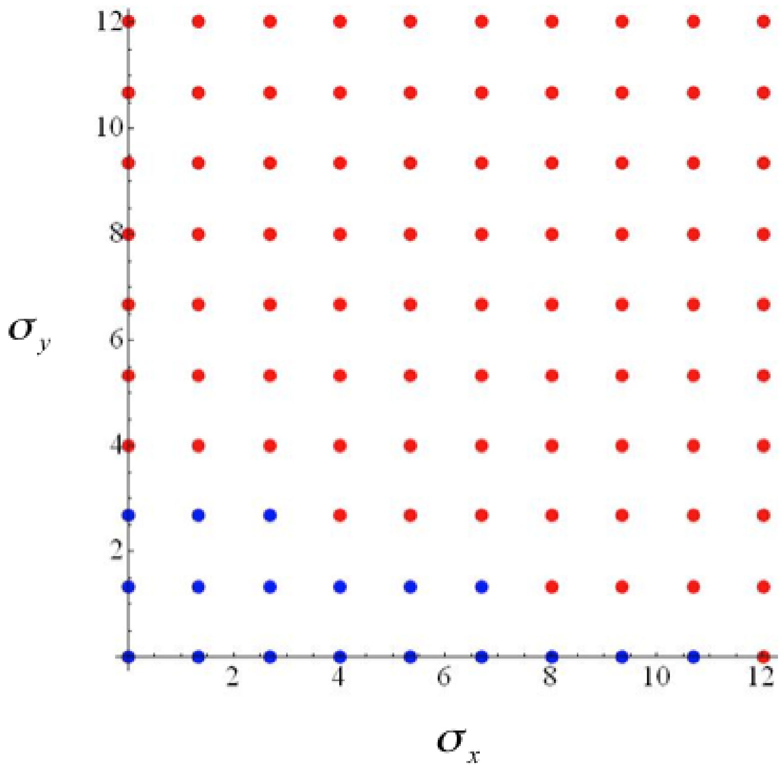
$f_{RF} = 800 MHz \qquad V_{RF} = 4 \times 16 MV$

$Q_s \cong 10^{-3}$

ϵ_N=10 μm

(A. Netepenko, MCDW December 2009)

Effect of multipole components in IR dipoles



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

After

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

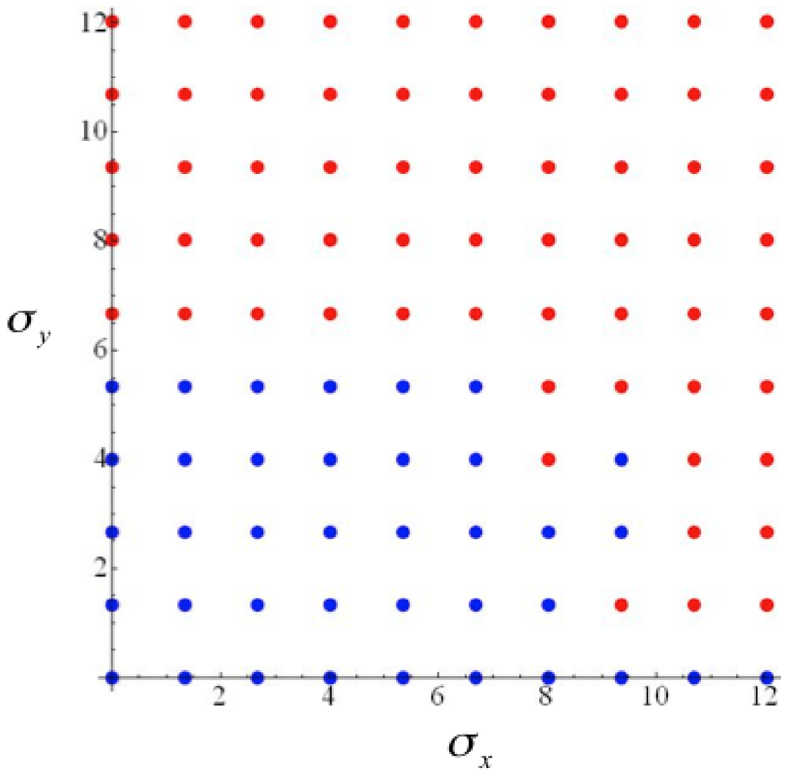
Before

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

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

$\epsilon_N = 10\ \mu$m

(A. Netepenko, NFMCC Meeting, January 2010)



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

After single octupole correction	Before
$\frac{dQ_y}{dE_y} = 6.52 \cdot 10^4$	$\frac{dQ_y}{dE_y} = 1.9 \cdot 10^6$
$\frac{dQ_x}{dE_y} = -1.85 \cdot 10^5$	$\frac{dQ_x}{dE_y} = -3.2 \cdot 10^5$
$\frac{dQ_x}{dE_x} = -1.31 \cdot 10^5$	$\frac{dQ_x}{dE_x} = -1.2 \cdot 10^5$

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

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

$\epsilon_N = 10\ \mu$m

(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 (in terms of γA^2) are almost unchanged.