Studies for a Muon Collider Optics

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Requirements

Required average luminosity for a $2\times$ 750 GeV collider: $\geq 2\times10^{34}$ cm^{-2} s^{-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	$1 \times 20 \cdot 10^{11}$	$10 \times 1 \cdot 10^{11}$
$\Delta p/p$	0.1%	1%
ϵ_N	25 μm	2 μm

Orientative design guide lines:

- β^* (≤ 1 cm)
- small circumference (luminosity!)
- small momentum compaction factor ($|\alpha_p| \lesssim 1\times10^{-4}$) to achieve 1 cm long bunches with a reasonable RF voltage
- large momentum acceptance
- sufficient Dynamic Aperture ($\gtrsim 3\sigma$)

Issues:

- 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

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

The situation so far

The idea of a MC is not new [a]. There are around several more or less mature designs, but currently none fullfills *all* requirements.

The most recent and promising ones are presented. Some of the older studies include extensive considerations on background and shielding, not considered here.

People working on the MC optics design (beside myself):

Y.Alexahin, A. Bogacz, C. Johnstone, P. Snopok.

Some people are currently mostly concentrated on different aspects of the project.

In the next future we will profit of the help of W. Wan (LBNL) and PhD student A. Netepenko.

[a] proposed by Budker in 1967

Non-interleaved Sextupoles Optics

The non-interleaved scheme requires an optics "ad hoc": the transfer matrix between couple of sextupoles must be a pseudo[b] $-I$ in *both* planes so that the kicks on a particle going through one sextupole is canceled by the next one.

Original Oide design (from 1996):

- β^*=3 mm ($\hat{\beta}$= 900 km !)
- $\mathcal{L}$=5700 m, one IP, 2.5π cell arcs (with negative α_p^{cell}), α_p=5×10^{-5}
- IR chromaticity is corrected by 2 pairs of non-interleaved sextupoles located at the closest $D_x \neq 0$ *knot* location of the chromatic $\beta-$wave
- non-interleaved chromaticity correction scheme for the arcs
- very large DA [c], even in presence of energy oscillations
- large energy acceptance obtained by optimizing sextupoles (22 families, very strong), octupoles and decapoles.

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[b] $\alpha_1 \neq \alpha_0$

[c] computed by SAD, fringe fields included

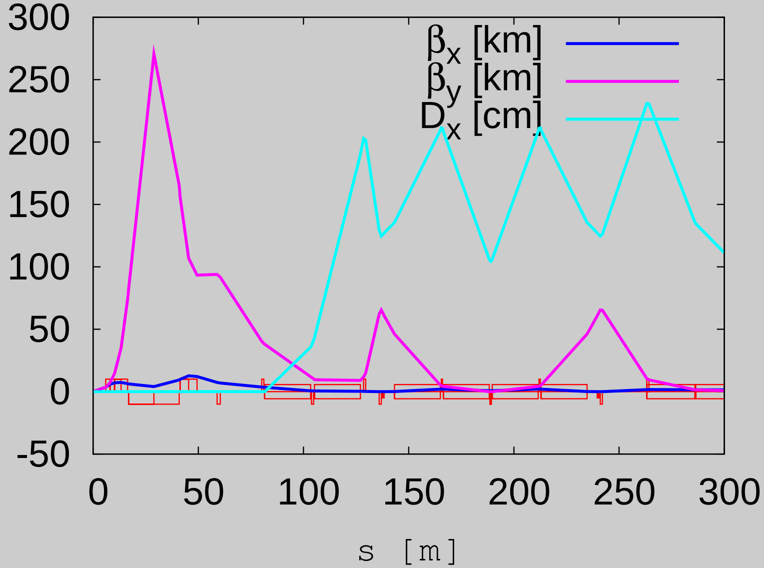
The optics is very sensitive to misalignment errors (Y. Alexahin, MCD Workshop, BNL Dec 2007) and therefore unfeasible "as it is".
A larger β^*, and thus more reasonable $\hat{\beta}$, should help.

"Oide inspired" optics

A first attempt

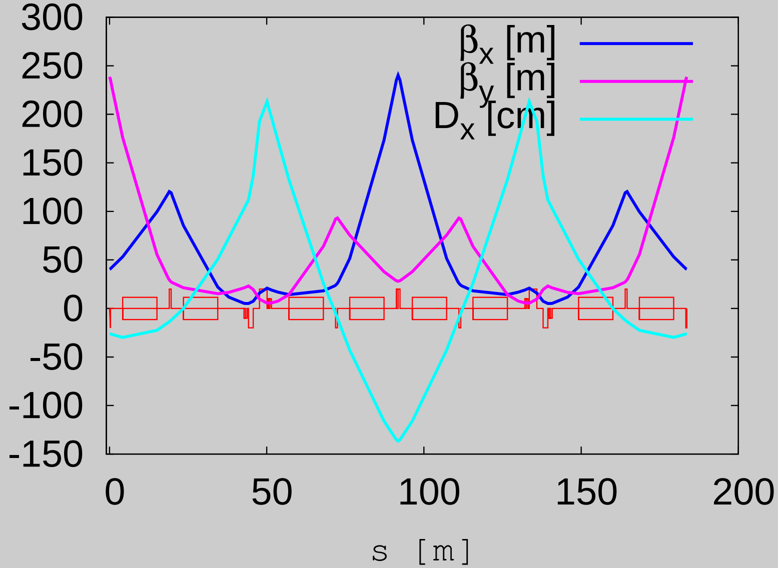
- IR magnets *unchanged* wrt Oide design, but β^* increased to 10 mm $\longrightarrow \hat{\beta}_y$=275 km
- add a dispersion free section for RF cavities and tuning quadrupoles
- use 2.5π cells, but reduce magnet length (Oide bends: L=22 m long, B=3.7 T @ 750 GeV) $\longrightarrow \mathcal{L}$=4855 m (one IP)
- use 2 different cell bending angles to get an handle on arc dispersion, yet α_p=1.8e-4 !
- tunes, Q_x=30.55 and Q_y=30.45, are chosen to get maximum stability range under the assumption that the machine is stable near the half integer (KEKB does it!).

IR



300
250
200
150
100
50
0
-50
0
50
100
150
200
250
300
s [m]
β_x [km]
β_y [km]
D_x [cm]

2.5π Cell



300
250
200
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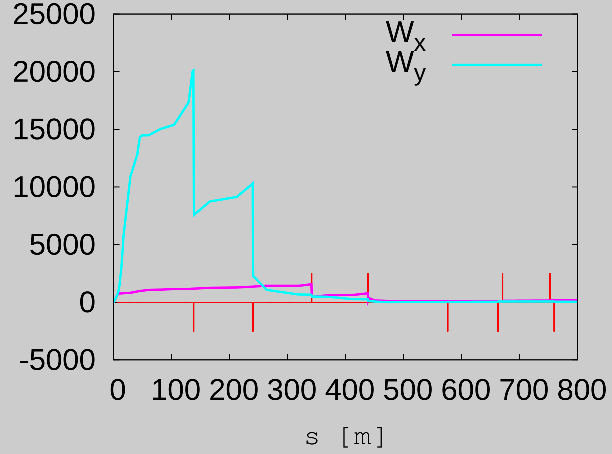
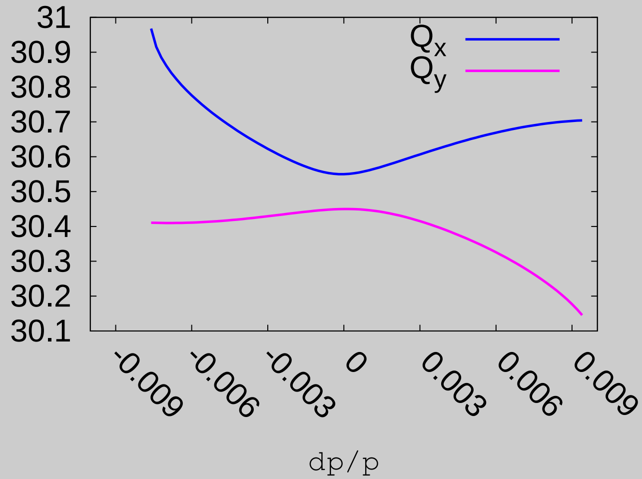
50
0
-50
-100
-150
0
50
100
150
200
s [m]
β_x [m]
β_y [m]
D_x [cm]

- IR chromaticity corrected with *one couple* of sextupoles per plane
- ring chromaticity corrected with *one family* per plane

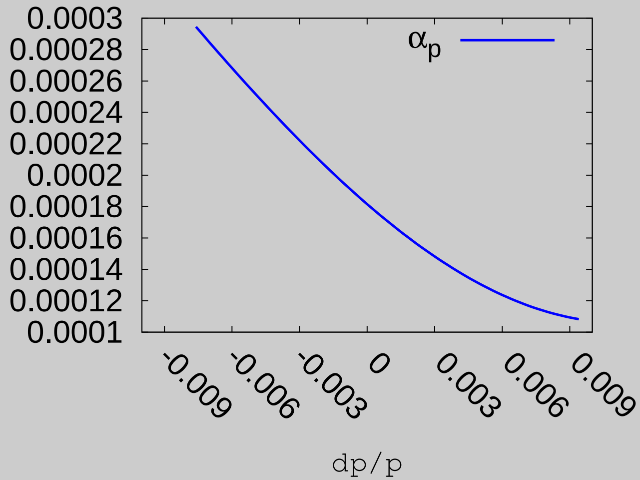
MAD chromatic functions



Tunes vs. dp/p



$\boldsymbol{\alpha_p}$ vs. dp/p



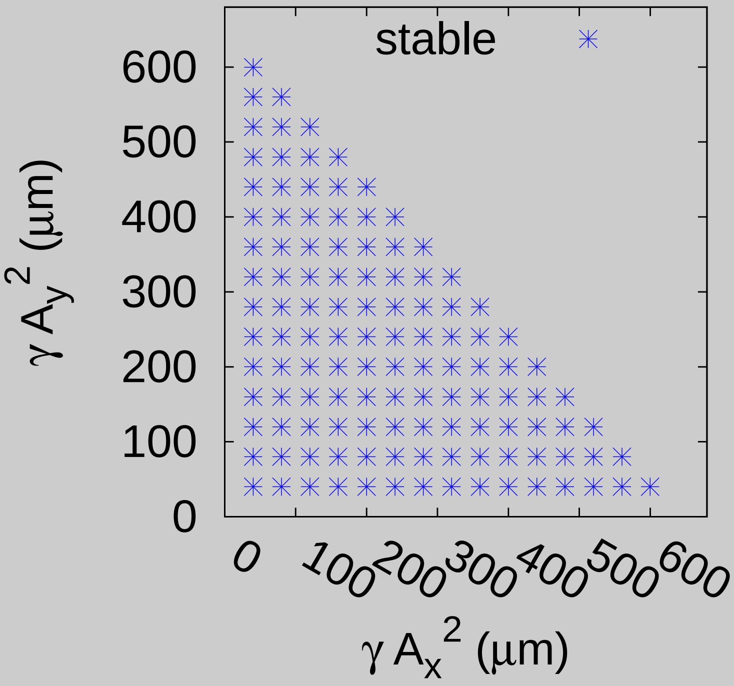
nb: the momentum compaction is too large for a 1 cm long bunch

Dynamic Aperture

Tune Dependence on Amplitude (no octupoles) *(MAD8 STATIC)*	
dQ_1/dE_1	0.50×10^{3}
dQ_1/dE_2	0.30×10^{4}
dQ_2/dE_2	-0.16×10^{7}

Dynamic Aperture (on energy)

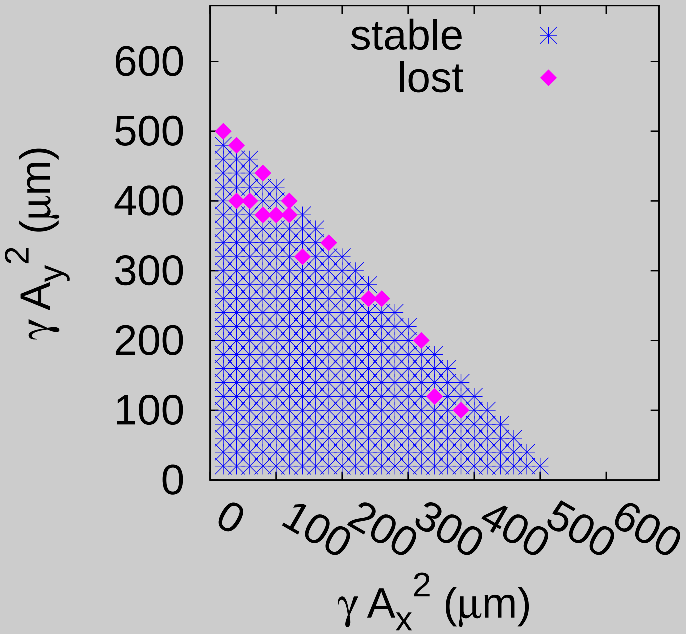
(MAD-X PTC)



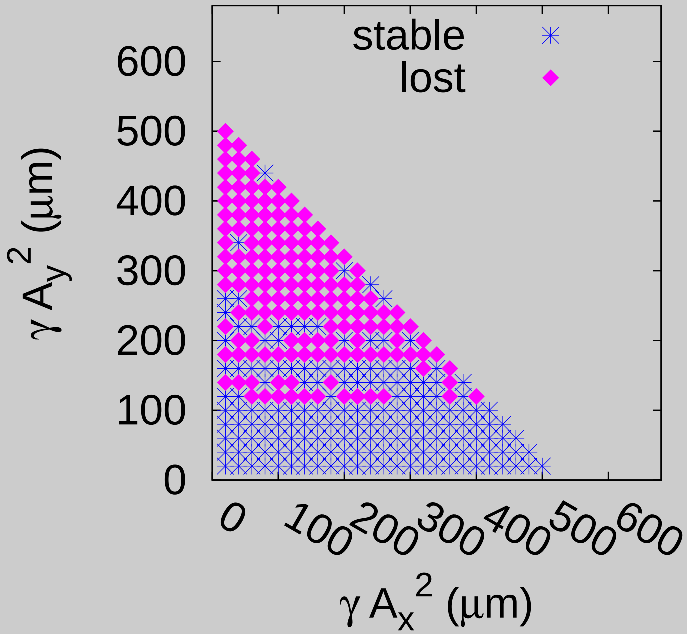
at least ∼5 sigma's (ϵ_N=25 μm) !

Off energy DA with Synchrotron Motion (MAD8)

$\Delta p/p$=5e-3



$\Delta p/p$=7e-3



“Dipole First”

Local chromatic correction

Montague *chromatic functions* 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.

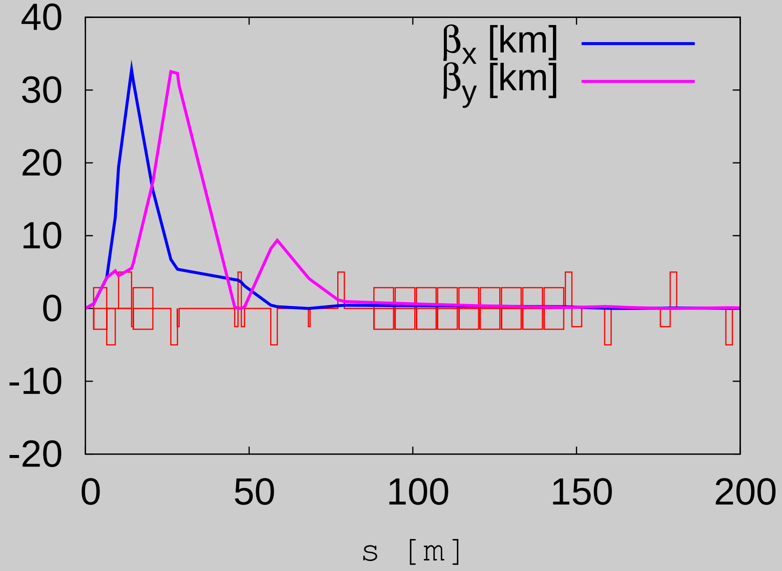
Dipole First [a]

- Local IR chromaticity correction *(à la Montague)*. It needs a relatively strong bend magnet ($\boldsymbol{B}$=7.5 T, $\boldsymbol{\ell}$=4 m) at 2.5 m from the IP.
- 2 interleaved sextupole families in the 108 deg FODO based arcs.
- compact: $\boldsymbol{\mathcal{L}} = 3110$ m, 2 IP's

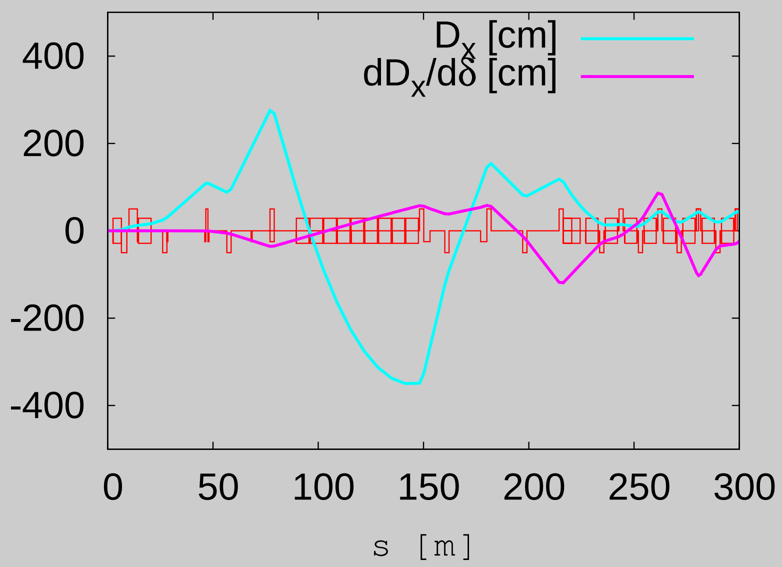
To make use of the local chromaticity correction w/o introducing the "nasty" (?) bending magnet near the IP and keeping $\boldsymbol{D_x}$=0 at the IP, it must be $\boldsymbol{D'_x \neq 0}$ at IP.
Thus the kick from the first sextupole *adds* up to the kick of its twin on the other side of the IP. Likely it is not a good alternative.

[a] https://mctf.fnal.gov/databases/lattice-repository

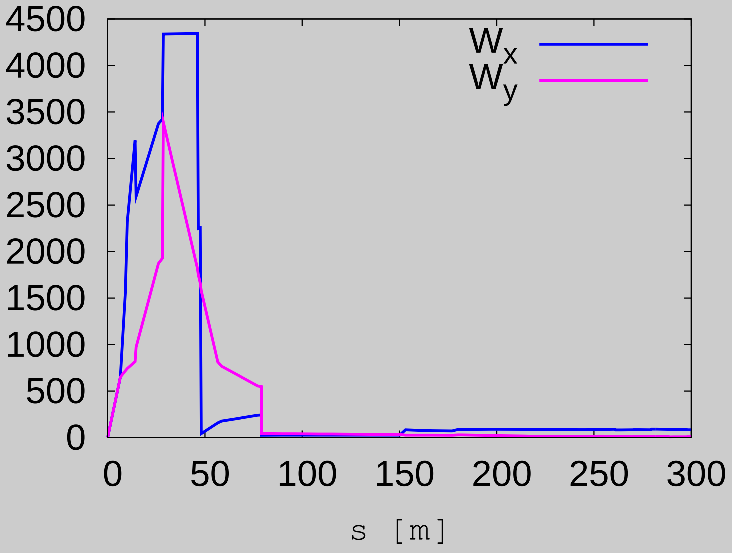
Dipole First Optics



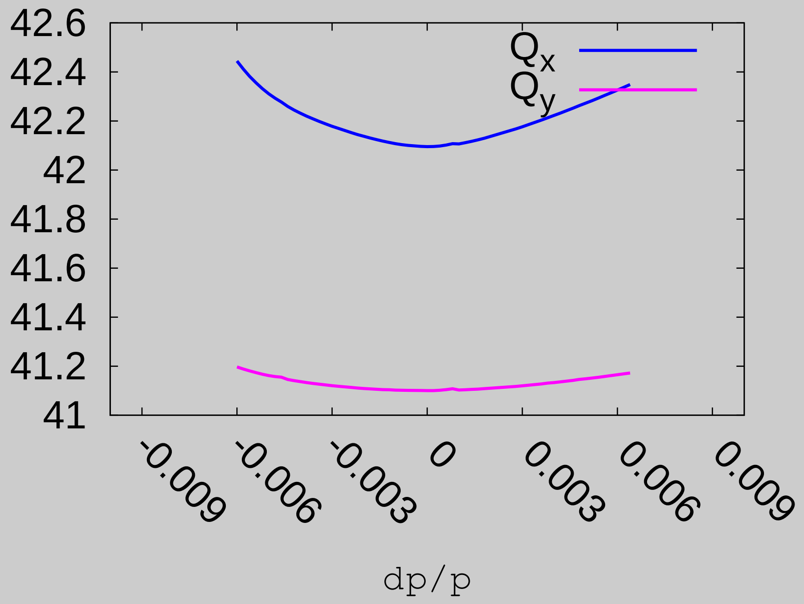
IR Twiss functions



IR Dispersion

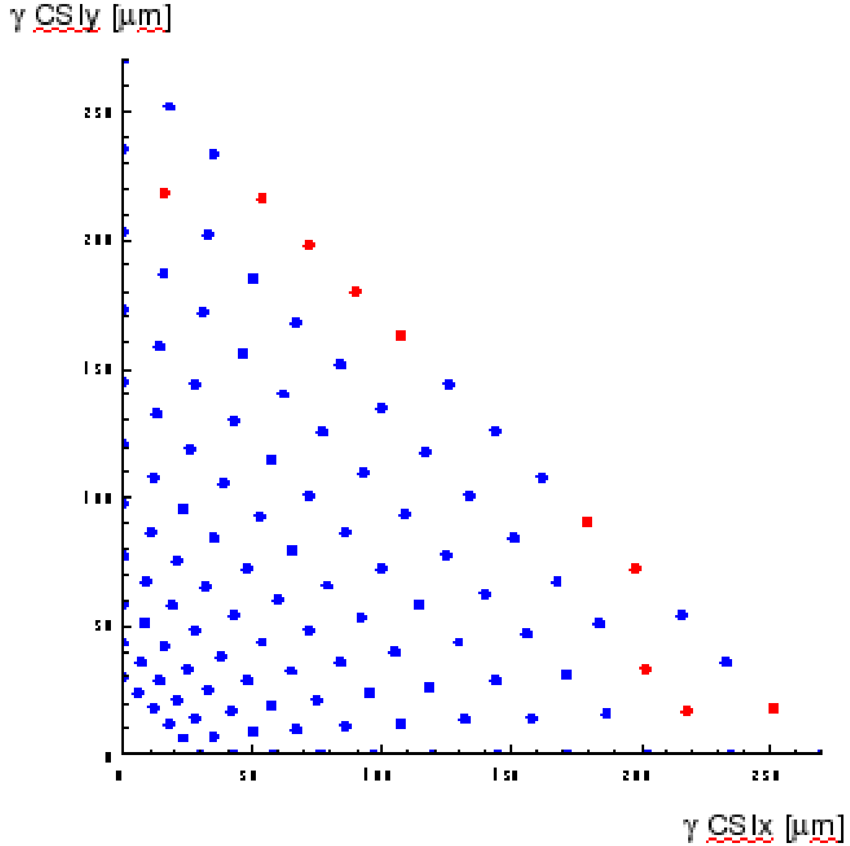


MAD chromatic functions



Tunes vs. dp/p

Yuri updated version (Y. Alexahin, MCDW, JLAB Dec 2008) shows large improvement of DA wrt NFMCC07 version.




```
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
```

One would expect

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

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

Likely it could be improved further by more systematic optimization of multipoles

IR on-interleaved sextupoles optics

Trying combining best of both IR chromaticities correction:

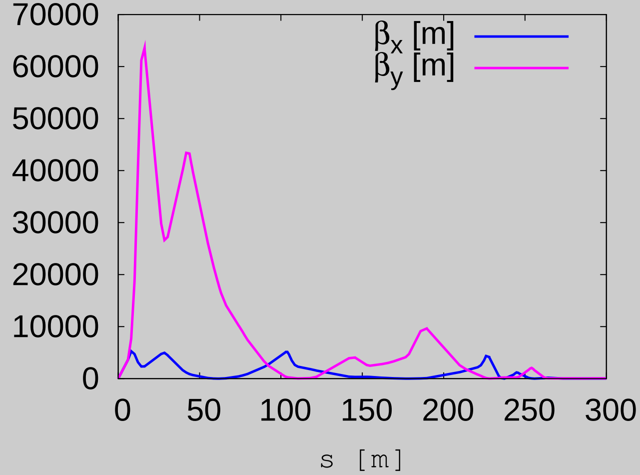
- re-design the IR, keeping the Oide "asymmetry": allow the β in the plane which chromaticity is *first* corrected to grow larger than the other one
- use non-interleaved scheme for correcting IR chromaticity, but place first sextupole at $\Delta\mu$=0 from IR quads the fact that the phase advance across the IP is π allows to spare its *twin* sextupole and relative $-I$ section

Trying shortening arc:

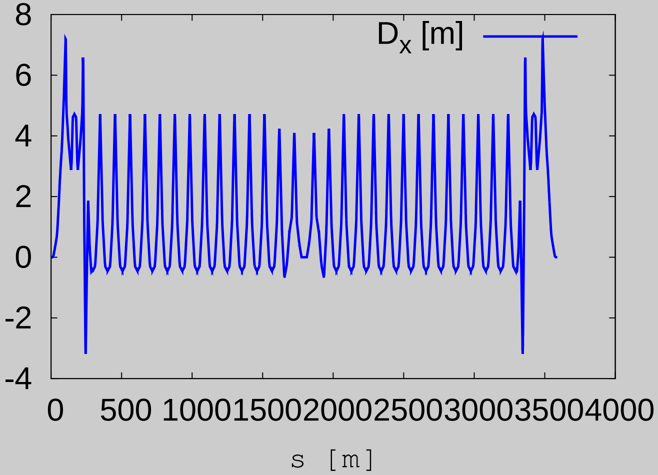
- 2.5 π cells replaced by 90 degree FODO cells
- more compact arcs ($\mathcal{L}$ =3588 including a "tuning/RF" section, one IP) obtained by increasing the bending angle ($\ell_B \simeq 14$ m) and decreasing the number of cells
- interleaved chromaticity correction in arcs: likely the small arc chromaticity does not require a non-interleaved chomaticity correction scheme
- bending structure modified by *reversing* the bending magnet polarity of one over 6 FODO cells to get small α_p[a]

[a]of course this makes the ring longer...

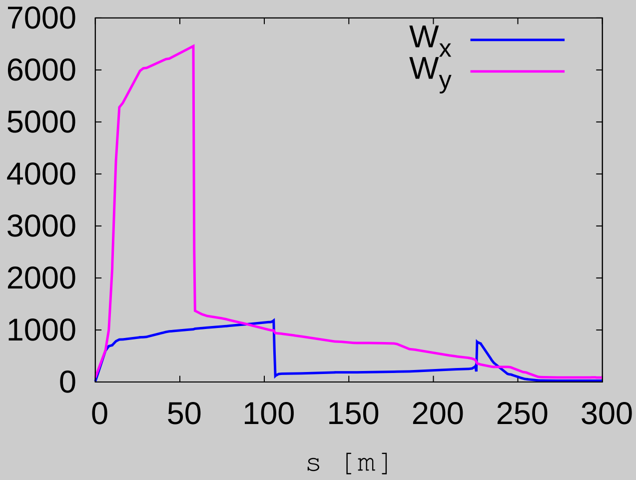
IR Twiss functions



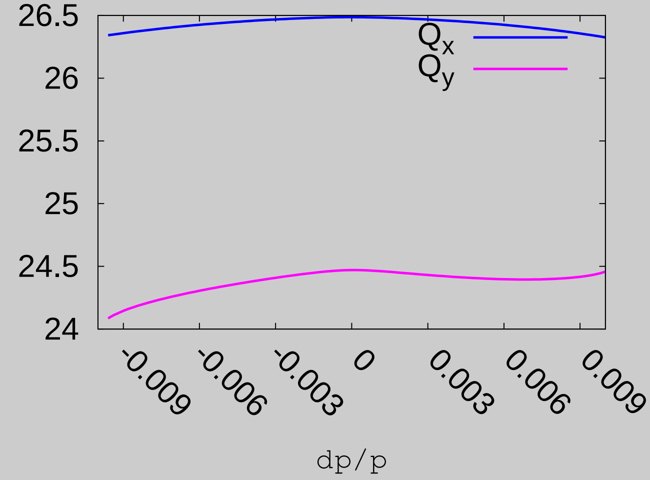
Dispersion



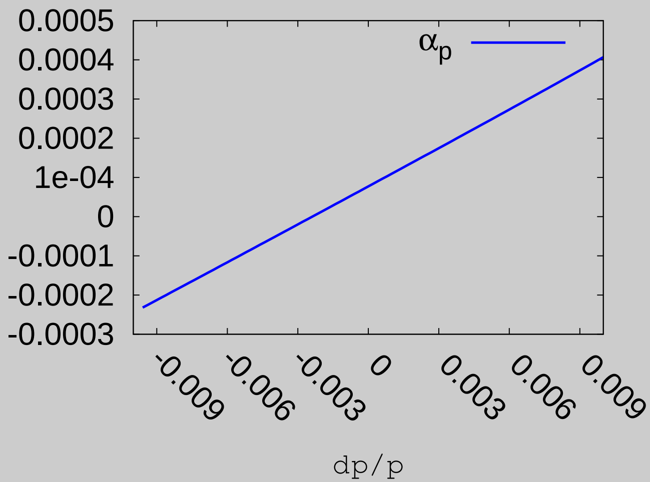
MAD chromatic functions



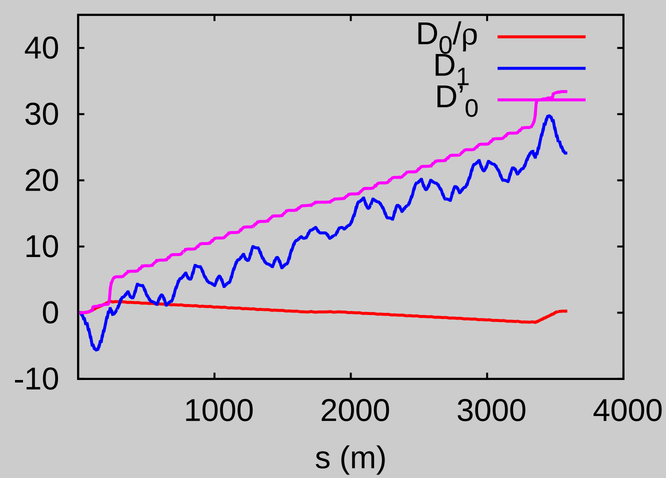
Tunes vs. dp/p



α_p vs. dp/p: it crosses 0!



Contributions to α_p

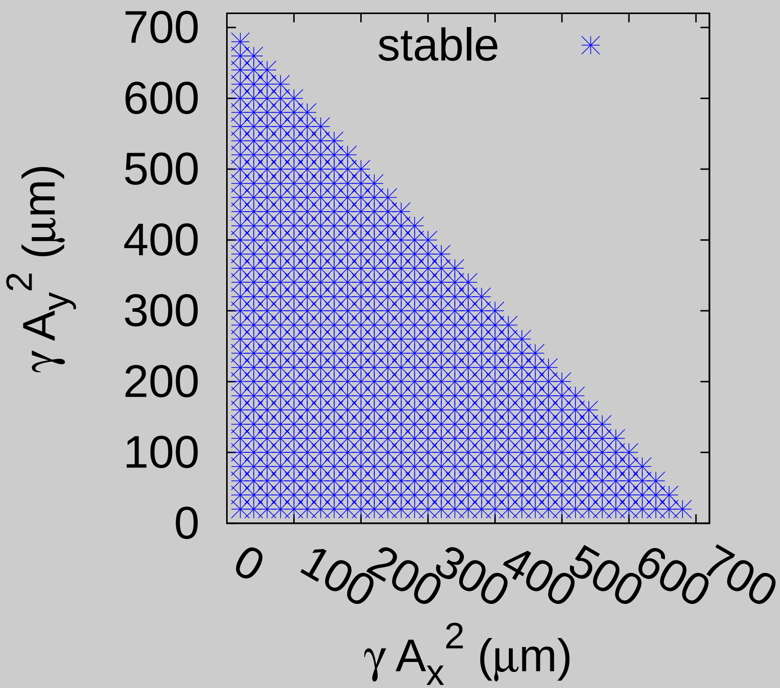


Dynamic Aperture

Tune Dependence on Amplitude (with two octupoles) *(MAD8 STATIC)*	
dQ_1/dE_1	0.60×10^4
dQ_1/dE_2	0.20×10^2
dQ_2/dE_2	-0.5×10^4

Dynamic Aperture (on energy)

(MAD-X PTC)

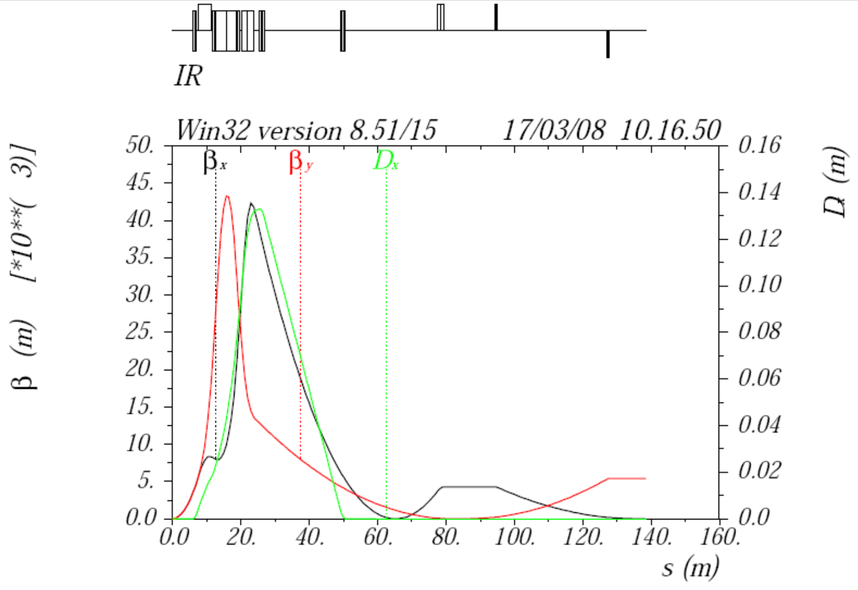


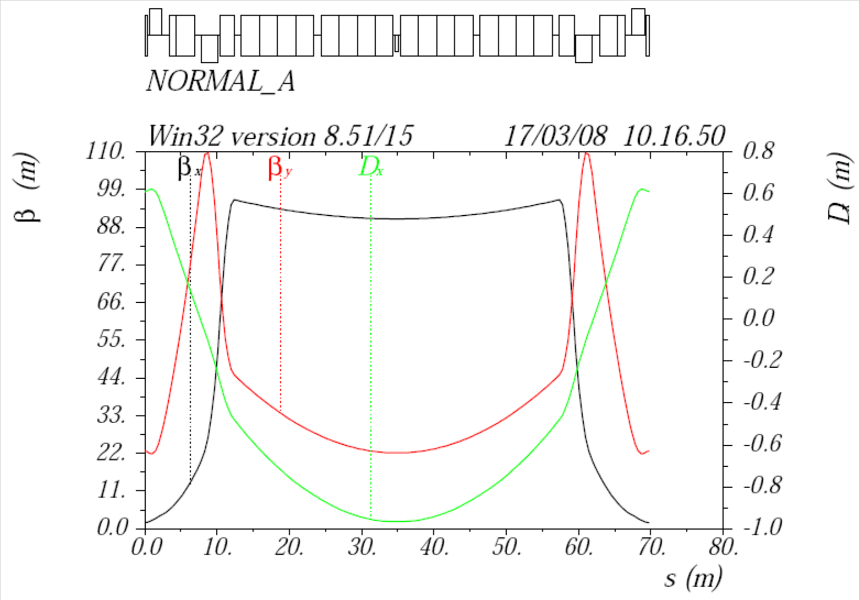
at least 5 sigma's (ϵ_N=25 μm) !

$\Rightarrow$ Suppressing the twin of the first couple of sextupoles and the interleaved chromaticity correction in the arcs did *not* affect negatively the DA !

P. Snopok (NFMCC, FNAL March 08):

- 6 Km long ring
- COSY used for multipole optimization
- isochronous up to $3^{t}h$ order, very flexible arcs
- but DA problematic





Summary and Outlook

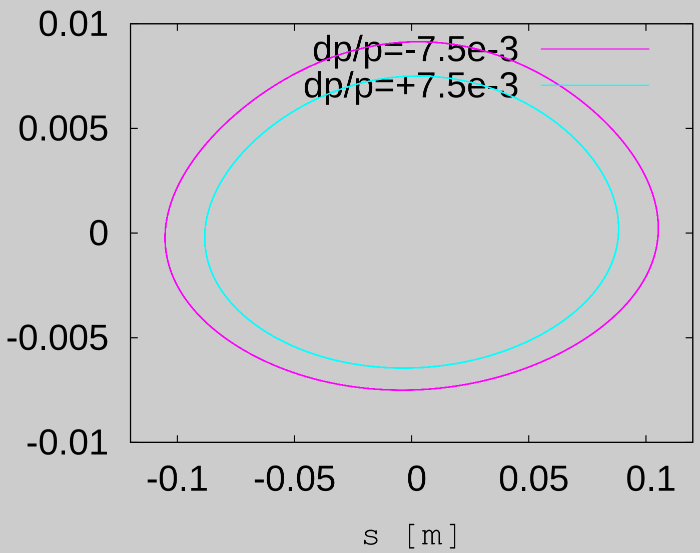
- new ideas for the IR layout and chromaticity correction have been investigated
- it is difficult to meet all requirements at once
- progress have been done on "dipole first" DA
- the "best fit" of all constraints is offered at the moment by the "dipole first" optics
- energy deposition group is going to look into the impact of the dipole close to the IP; all designs are likely to profit from its presence.

Additional slides:

The longitudinal phase space

The fact that $\boldsymbol{\alpha_p^0}$ is small makes higher order terms important:
trajectories in longitudinal phase space are *deformed* and the stable region is *asymmetric*!

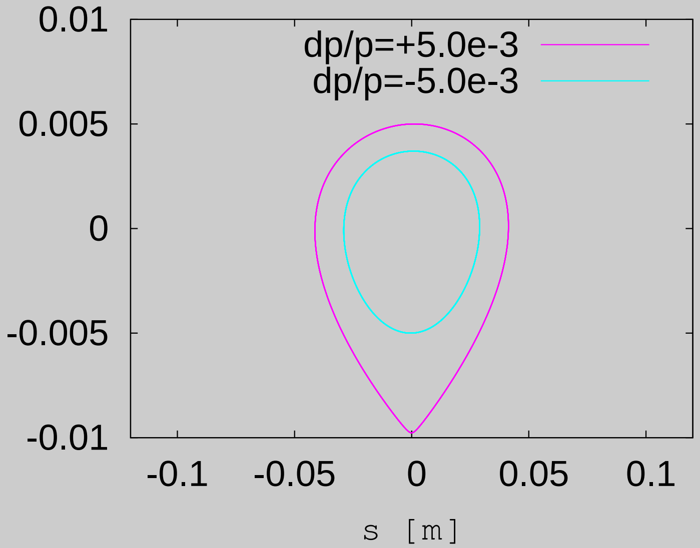
360 MV @ 600 MHz



a particle starting with (0,-7.5e-3) reaches $\boldsymbol{\Delta p/p}$=+9e-3 after half synchrotron period and is lost if the ring is not stable!

This effect *may reduce* further the energy range of the machine!

360 MV @ 600 MHz



The effect is more evident for the “dipole first” optics, version with α_p= 9.7e-5. The $(dp/p)_{t=0}$=+5e-3 trajectory is obtained in 2th order approximation.