Preliminary Design of the $\mu^+\mu^-$ Higgs Factory Ring Lattice

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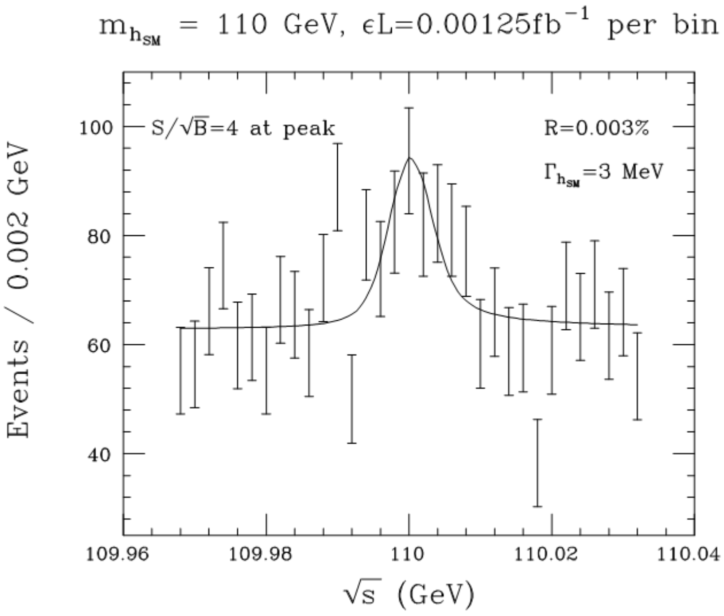
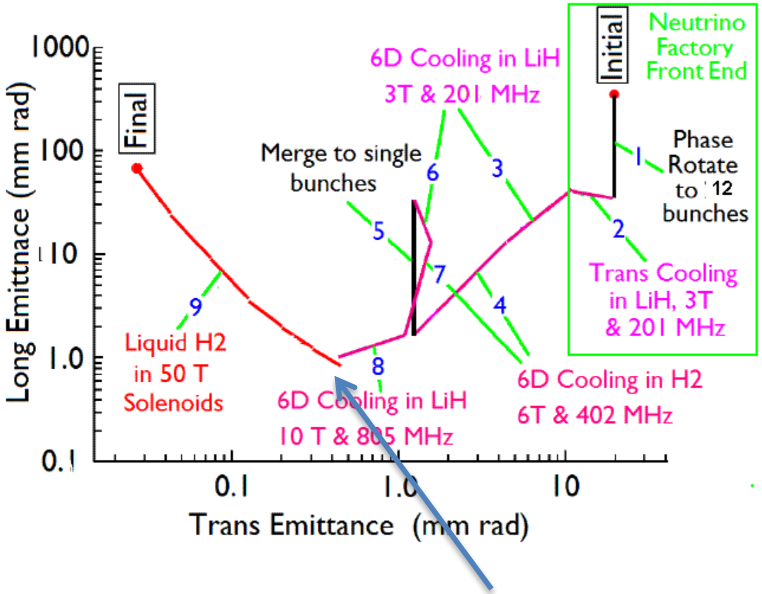
125 GeV Higgs Factory (D.Neuffer)

The major advantage of a $\mu^+\mu^-$ Higgs Factory – the possibility of direct measurement of the Higgs boson width (Γ~3MeV FWHM expected):

a very small beam energy spread is required, R~0.003%



Number of events and statistical errors in the final state $b\bar{b}$ as a function of $\sqrt{s}$ (M.Berger, 2008)



Dave's proposal: stop cooling here:

$\varepsilon_{\perp N}$ =0.3π·mm·rad, $\varepsilon_{||N}$ =1π·mm·rad

The machine must be able to digest even higher emittances (at the price of larger β^*)

Input Parameters

Parameter	Unit	Value
Beam energy	GeV	62.5
Number of IPs	-	1
Number of bunches / beam	-	1
Number of muons / bunch	10^{12}	1.5 → 2
Normalized emittance, $\varepsilon_{\perp N}$	π·mm·rad	0.3
Long. emittance, $\varepsilon_{\|\|N}$	π·mm·rad	1.0
Beam energy spread	%	0.003*
Bunch length, σ_s	cm	5.64
Repetition rate	Hz	10 → 30
p-driver power	MW	1 → 4

*) For initial scan a factor of 3-5 higher energy spread is needed, the machine must handle it.

The goal for the ring circumference is C=300m

HF Lattice Design Issues

- Large $\varepsilon_{\perp N}$ → small β^* to achieve the required luminosity → very large IR magnet apertures
- Detector protection from backgrounds → it's desirable that longest & strongest IR quad was defocusing → quadruplet FF (also good for smaller βmax)
- β^* variation in wide range (2cm – 10cm)
- Preservation of small σ_E in the presence of strong self-fields (Ipeak ~ 500A !) → requirements on RF and momentum compaction
- Do we need chromaticity correction for σ_E/E as low as $3\cdot10^{-5}$? – There are effects which may require it

  - Let us start with the last two items

Momentum Compaction Factor

To obtain small σ_E with high $\varepsilon_{||} \rightarrow$ high $\beta_{||}$ is required:

$$\sigma_E / E = \sqrt{\varepsilon_{||} / \beta_{||}} = 3 \cdot 10^{-5} \rightarrow \beta_{||} \approx 1880\, m, \;\; \beta_{||} = \frac{\alpha_c C}{2\pi Q_s} = C\sqrt{\frac{\alpha_c E}{2\pi h V_{RF} \cos\varphi_s}}$$

→ low V_{RF} and/or high momentum compaction α_c is required.

But V_{RF} should be high enough to minimize the effect of strong self-fields (~50kV for $Z_{||}/n$~0.1Ω in the GHz range*). For V_{RF} =100kV and f_{RF} =200MHz

$$\alpha_c = \frac{2\pi h e V_{RF} \cos\varphi_s}{E}\left(\frac{\beta_{||}}{C}\right)^2 \approx 0.08 \cos\varphi_s$$

Another way to look at this is to use the Keil-Schnell criterion (+ Boussard conjecture)

$$\left|\frac{Z_{||}}{n}\right| \le \frac{2\pi E\,|\alpha_c|}{eI_{peak}}\left(\frac{\sigma_E}{E}\right)^2 \rightarrow |\alpha_c| \ge 0.13$$

Obviously we have to limit $Z_{||}/n$ to well below 0.1Ω and make α_c as large as possible (I set the goal at $\alpha_c > 0.05$)

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*) Characteristic bunch frequency is $c/4\sigma_s$ ~1GHz whereas the rotational frequency is ~1MHz → n~10^3

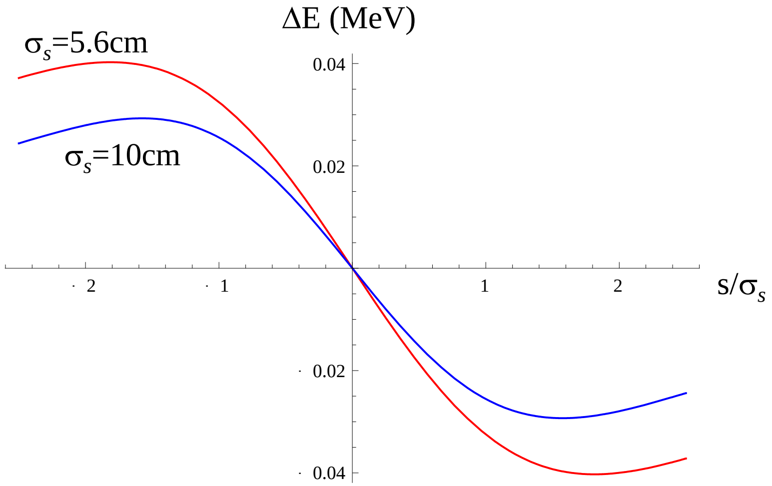
Longitudinal Beam-Beam Effect (Derbenev & Skrinsky, 1972)

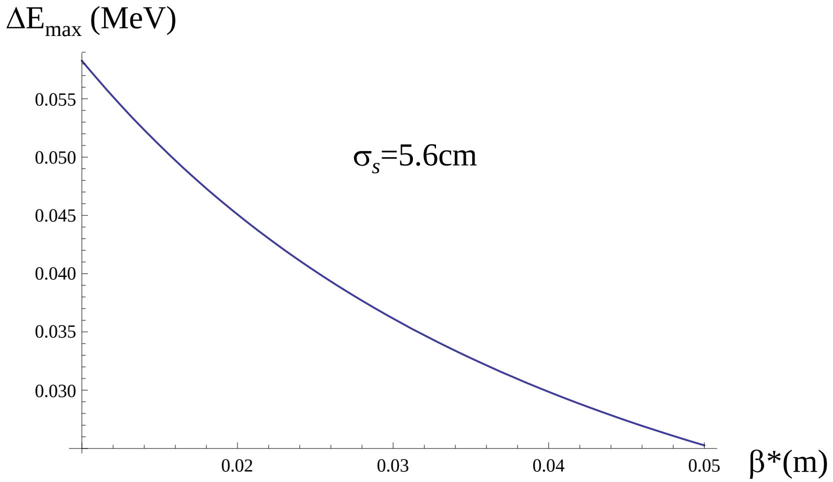
Collision with a thin slice of Ns particles leads to energy change

$$\Delta E = \frac{eN_s}{2\beta_\perp}\frac{d\beta_\perp}{ds}\bigg|_{\text{collision point}}, \quad \Delta E_{\max} = \frac{eN_s}{2\beta^*} \sim 58\text{kV} \ \text{ for } \ N_s = 2\cdot 10^{12} \ \text{ and } \ \beta^* = 2.5cm$$

For $\alpha_c > 0$ the effect is defocusing (good), but it is strongly nonlinear (not so good).

The finite bunch length reduces it somewhat:





Thanks to $\alpha_c > 0$, β^*=1.5cm is probably still admissible

Chromaticity Correction?

Thanks to small $\sigma_E/E \sim 3 \cdot 10^{-5}$ the chromaticity by itself is not a problem (though may be such for larger σ_E/E needed for initial scan).

But there are other effects which require chromaticity correction, most notably the path length dependence on betatron amplitude which translates into additional energy spread:

$$\frac{\Delta E}{E} \approx -\frac{1}{2\alpha_c R}(Q'_x I_x + Q'_y I_y) \;\rightarrow\; \left\langle \frac{\Delta E}{E} \right\rangle_{r.m.s.} = \frac{|Q'_\perp|\varepsilon_\perp}{\sqrt{2}\alpha_c R}, \quad \varepsilon_x = \langle I_x \rangle$$

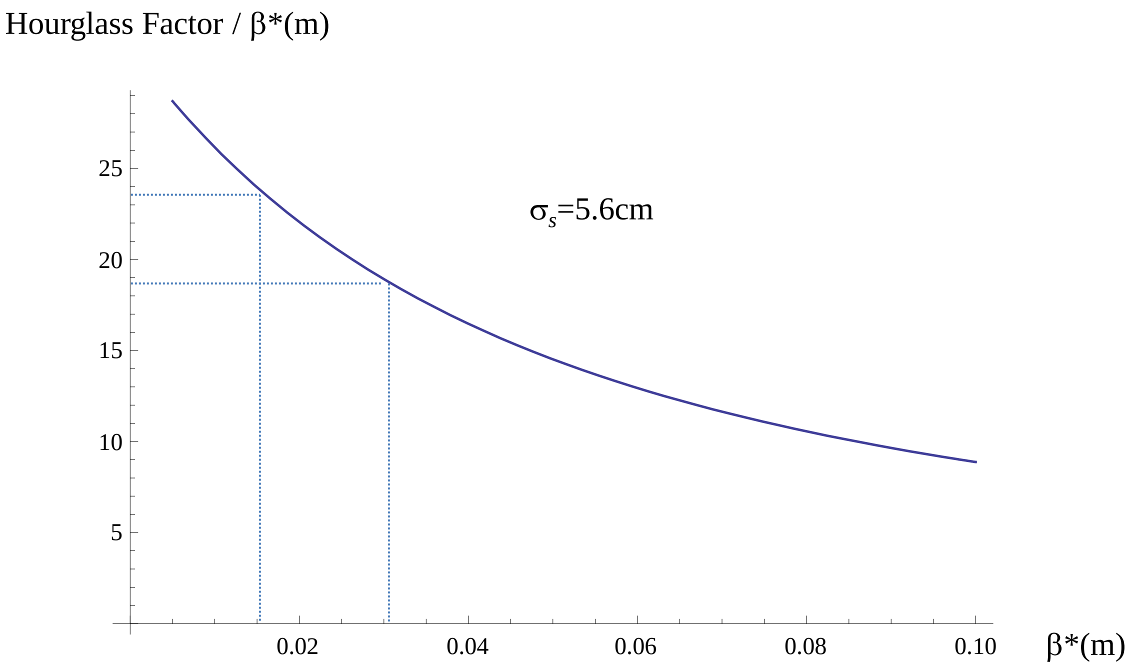
With uncorrected $Q'_\perp \sim -100$ and $\alpha_c = 0.05$ we would have

$$\left\langle \frac{\Delta E}{E} \right\rangle \sim 2 \cdot 10^{-5}$$

→ we need chromaticity correction! - But in a way that will not compromise the dynamic aperture.

Chromaticity correction is also needed from operational considerations.

Optimum β*

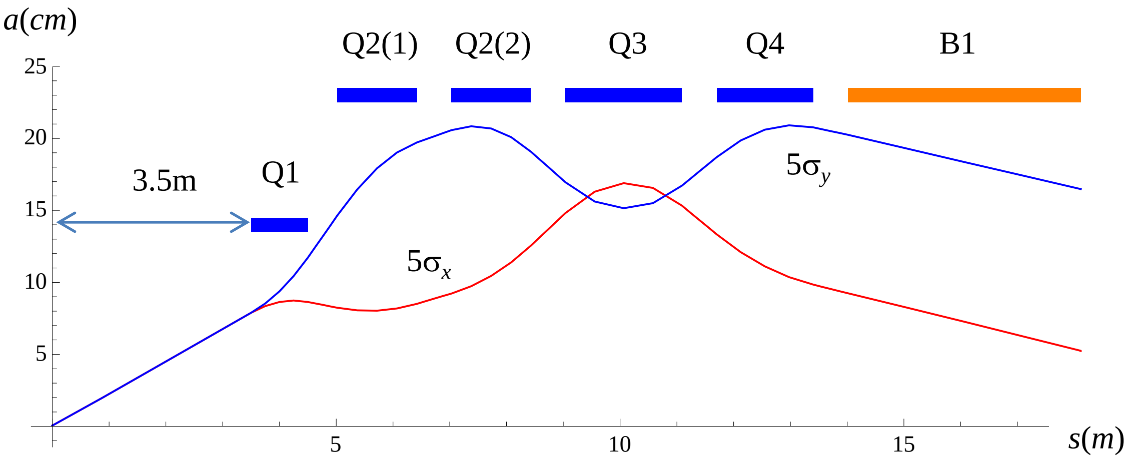


At β*=2.5cm the hourglass factor = 0.5, the gain in luminosity with β*→1.5cm is just 17% - still can be worthwhile.

The main limitation on β* is imposed by aperture of the FF quads, our engineers are confident that the pole tip field of 10T is possible with ID=50cm, but requires additional R&D.

Quadruplet Final Focus

$\beta^*=2.5\text{cm}, \ \varepsilon_{\perp N}=0.3\text{mm}$

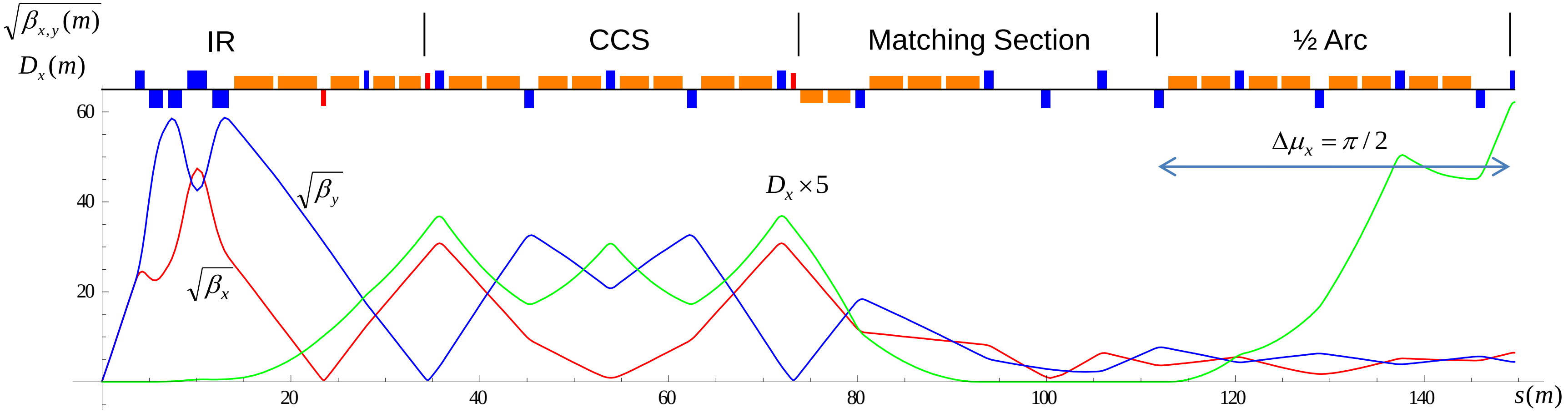


	Q1	Q2	Q3	Q4
aperture (cm)	27	45	45	45
gradient (T/m)	74	-36	44	-25
dipole field (T)	0	2	0	2
length (m)	1.0	1.4	2.05	1.7

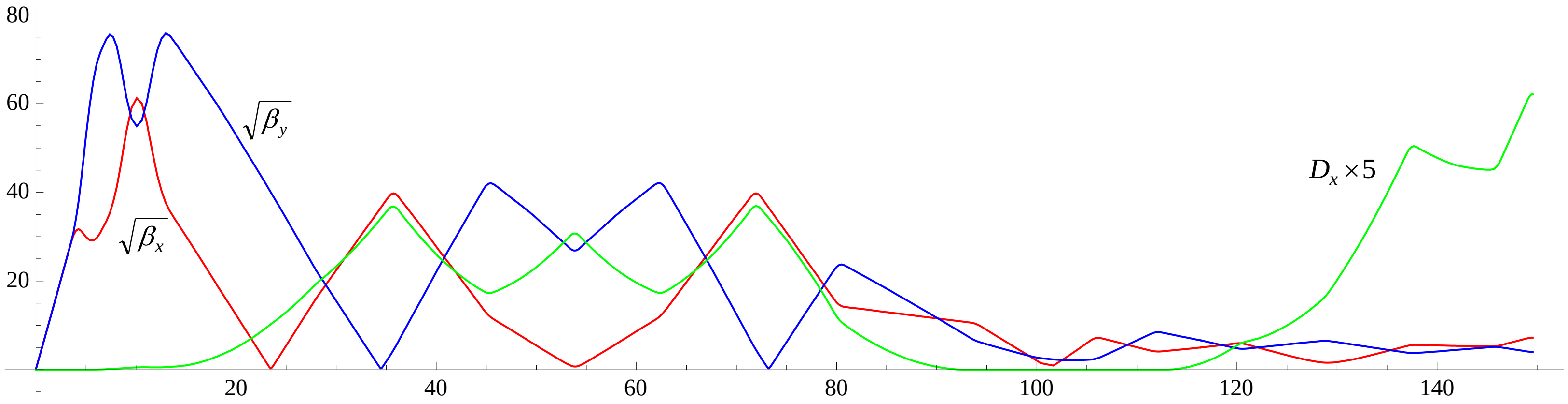
Obviously the design can be improved: βy_max can be reduced to match βx_max

Optics Functions (from IP to SP)

β*=2.5cm



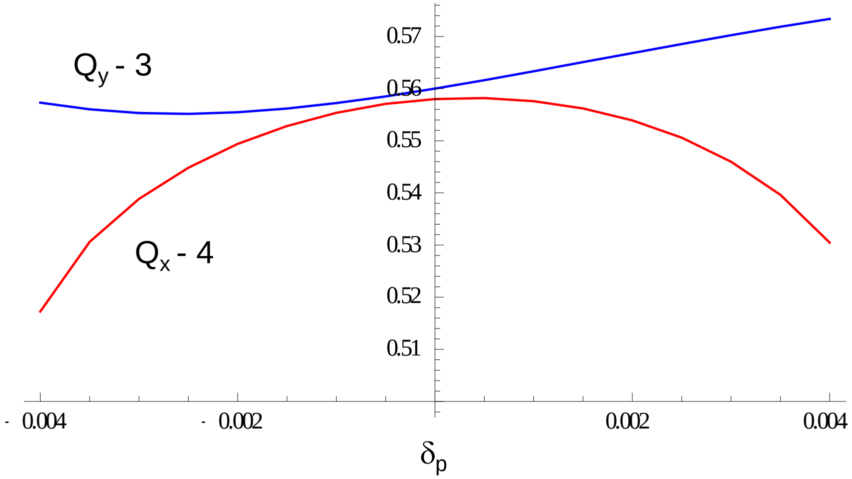
β*=1.5cm



β* can be increased up to 10 cm by changing quad gradients in the matching section

Momentum Acceptance

β^*=1.5cm

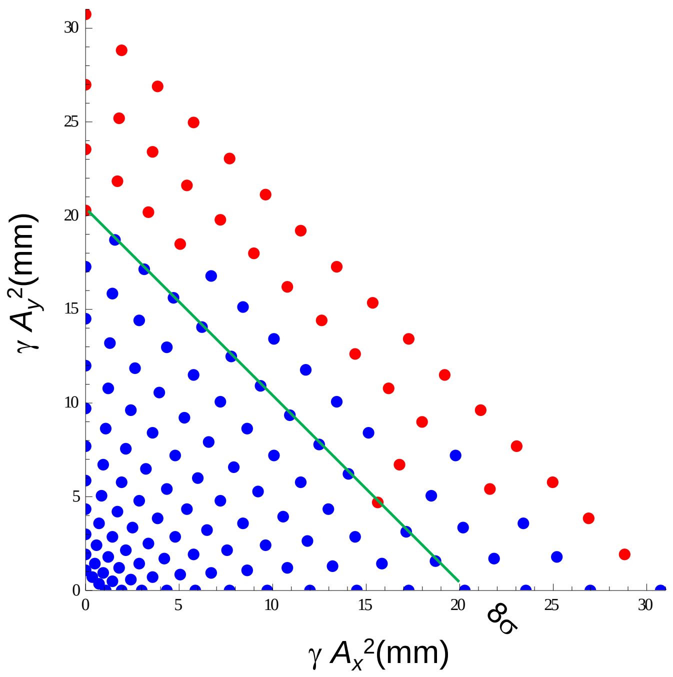


No attempt to correct nonlinear chromaticity has been made (should not be a problem).
Acceptance at β^*=2.5cm exceeds ±0.5%

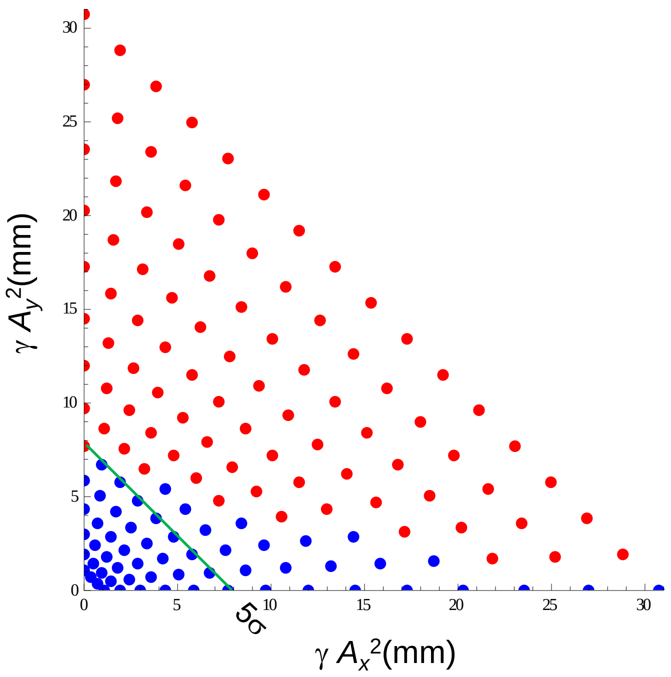
N.B. Chromaticity computed with MAD8 TWISS command are completely wrong!

Dynamic Aperture

β*=2.5cm



β*=1.5cm



2048 turns Dynamic Aperture (DA) computed with MAD8 LIE4 method. Octupole correctors were used to correct vertical detuning with amplitude.
In both cases the DA significantly exceeds the physical aperture (5σ and 4σ respectively)

Parameters of the Present Design

Parameter	Unit	Value
Circumference, C	m	299
β^*	cm	2.5 (1.5-10)
Momentum compaction, α_p	-	0.0793
Betatron tunes	-	4.56 / 3.56
Bare lattice chromaticity	-	-124 / -197
Synchrotron tune (100kV, 200MHz)	-	0.002
Number of muons / bunch	10^{12}	1.5 → 2
Normalized emittance, $\varepsilon_{\perp N}$	π·mm·rad	0.3
Long. emittance, $\varepsilon_{\|\|N}$	π·mm·rad	1.0
Beam energy spread	%	0.003
Bunch length, σ_s	cm	5.64
Beam-beam parameter	-	0.0054 → 0.0072
Repetition rate	Hz	10 → 30
Average luminosity	10^{31}/cm^2/s	0.46 → 2.5