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Muon Accelerator Program

Design of Muon Collider Lattices

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NAPAC'16 Chicago

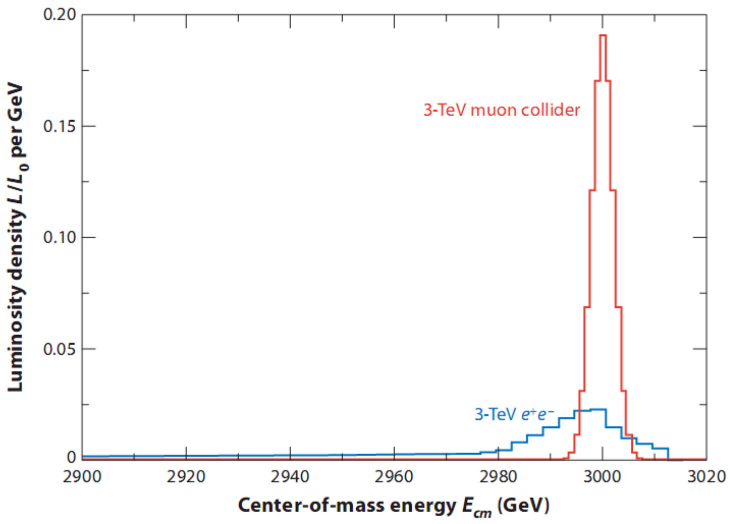
9-14 October 2016

Motivation

Interest in lepton colliders may get a boost from LHC findings.

Compared to e+e- collider the Muon Collider has a number of important advantages, among them:

- Small collision energy spread, <1.e-4 (if needed) - thanks to practical absence of
  - beamstrahlung - radiation in coherent EM field of opposing bunch
  - quantum fluctuations of bremstrahlung in the field of interacting particle
- $(m_\mu / m_e)^2 \sim 4 \cdot 10^4$ times larger cross-section of s-channel production of scalar particles
- Smaller footprint (in size and energy)
- Theorists give a lot of arguments which are far beyond my comprehension!



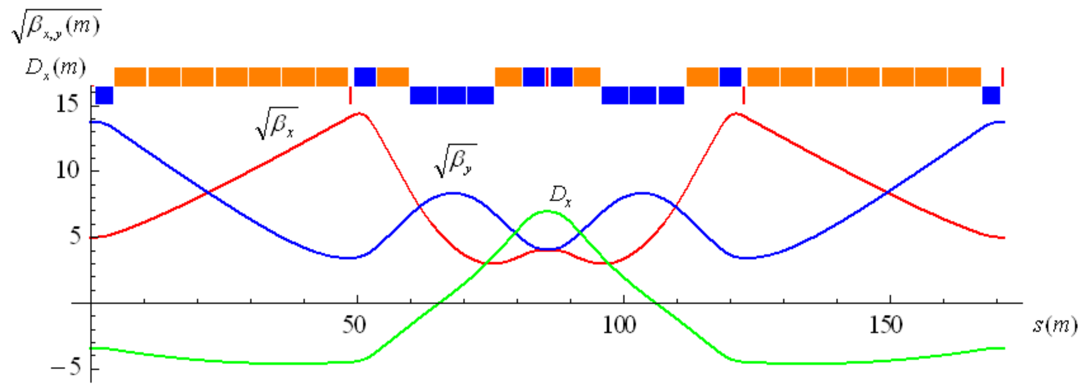
Energy spread in high-luminosity lepton colliders (V. Shiltsev)

Challenges

- Small β^* required for luminosity (3-5mm for high energy MC)
  - $\Rightarrow$ high chromaticity of the Final Focus (FF)
    - $\rightarrow$ beam dynamics issues
  - $\Rightarrow$ high β-function in the FF quads
    - $\rightarrow$ high sensitivity to field errors
    - $\rightarrow$ large quad apertures
      - – engineering issues
      - – detector backgrounds
      - – beam dynamics issues (multipoles, fringe fields)
  - $\Rightarrow$ short bunch length ($\sigma_z \leq \beta^*$ for high energy MC)
    - $\rightarrow$ very small momentum compaction factor
- Large beam-beam tuneshift ~ 0.1
- Neutrino-induced radiation (for $E_{\mathrm{c.o.m.}} \geq$ 3 TeV)
  - $\Rightarrow$ no straights longer than ~0.5 m

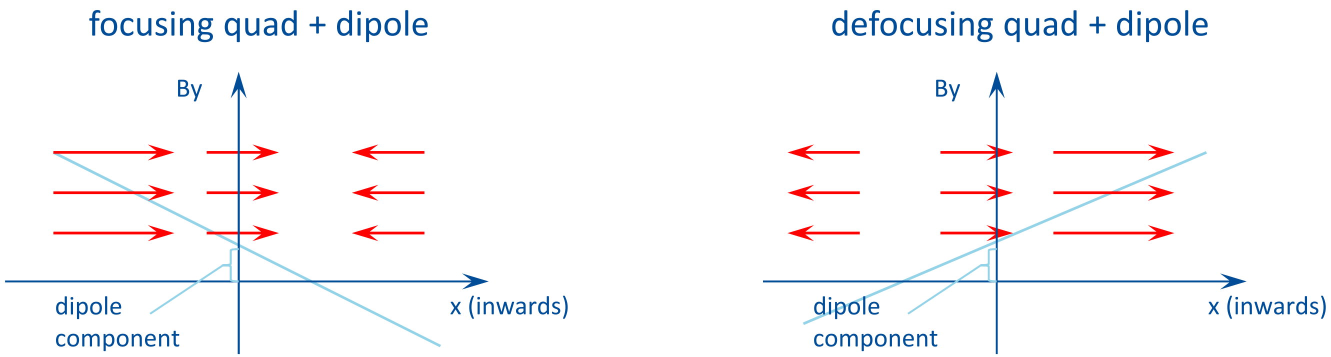
Basic Solutions

- Quadruplet Final Focus
- “Three sextupoles” chromaticity correction
- Flexible Momentum Compaction (FMC) arccell for HE MC
  - with combined-function magnets to spread ν’s



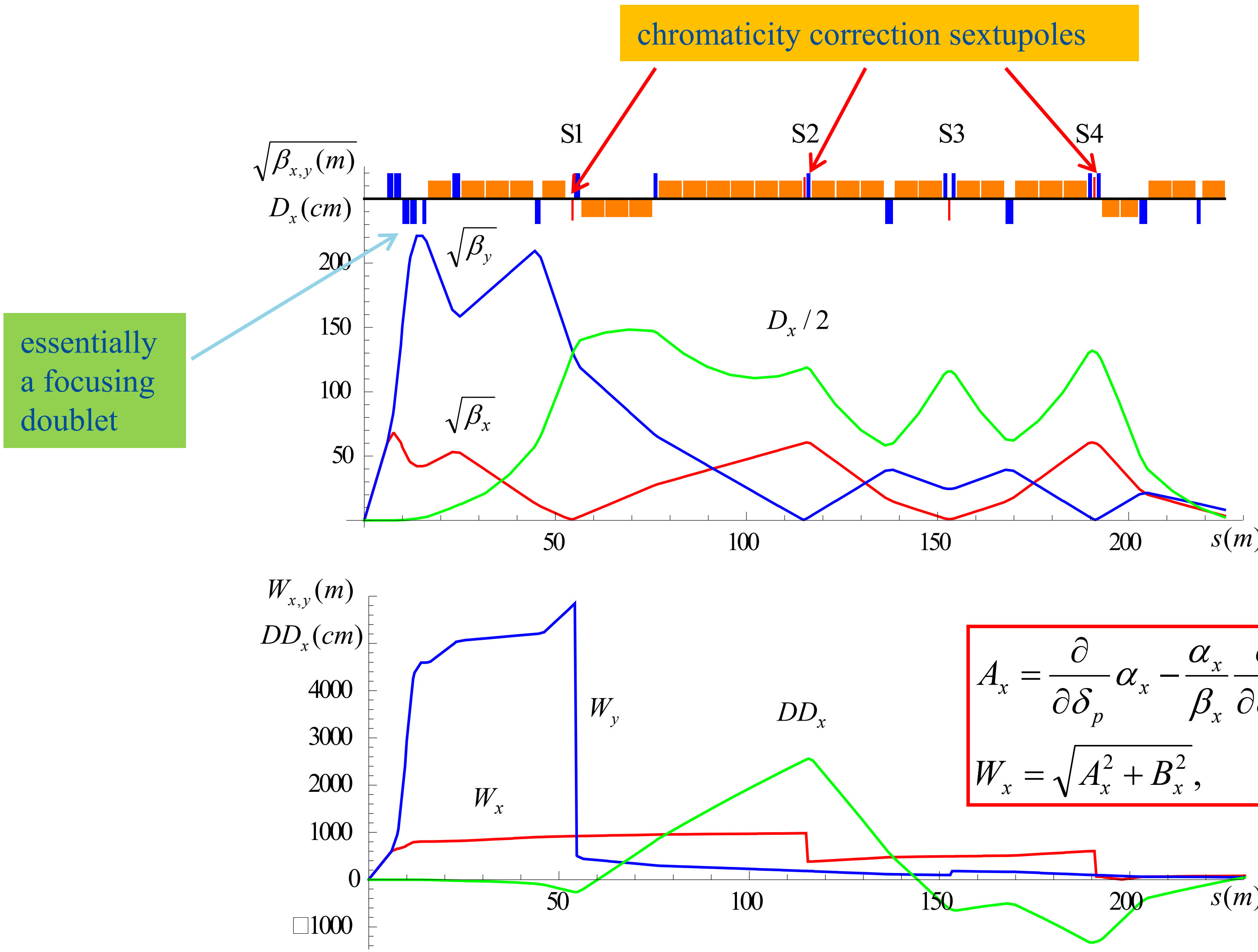
3TeV MC arccell allowing for independent control of tunes, chromaticities, momentum compaction factor and its derivative with momentum

Why Quadruplet Final Focus?



- Dipole component in a defocusing quad is more efficient for cleaning purposes
  - it is beneficial to have the 2nd from IP quad defocusing
- The last quad of the FF "telescope" also must be defocusing to limit the dispersion "invariant" $J_x = \frac{D_x^2 + (\beta_x D_x' + \alpha_x D_x)^2}{\beta_x} \approx \beta_x \phi^2$ generated by the subsequent dipole (generating dispersion for chromatic correction)
- both requirement are met with either doublet or quadruplet FF

“Three sextupole” chromaticity correction (1.5 TeV MC)

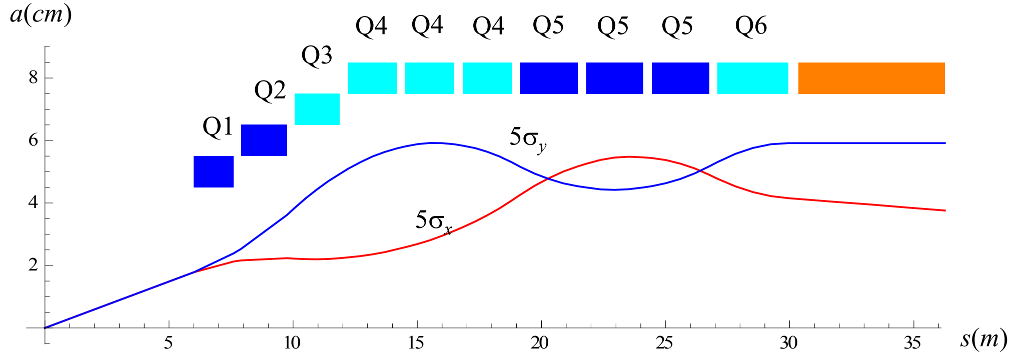


$$A_x = \frac{\partial}{\partial \delta_p}\alpha_x - \frac{\alpha_x}{\beta_x}\frac{\partial}{\partial \delta_p}\beta_x, \quad B_x = \frac{1}{\beta_x}\frac{\partial}{\partial \delta_p}\beta_x,$$

$$W_x = \sqrt{A_x^2 + B_x^2},$$

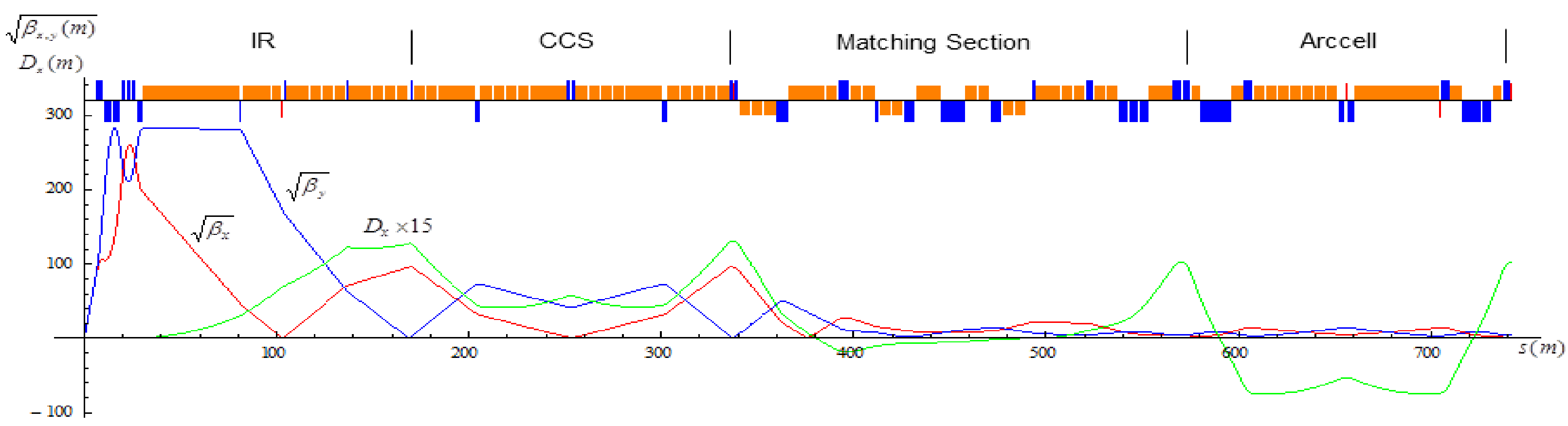
3 TeV MC Lattice with Quadruplet FF

β*=5mm



5 sigma beam sizes and magnet inner radii.

Q3, Q4 and Q6 have 2T dipole component.
$B_{pole\ tip}$= 12T for shown apertures – Nb3Sn is O.K.



Optics functions from IP to the end of the first arc cell (6 such cells / arc) for β*=5mm

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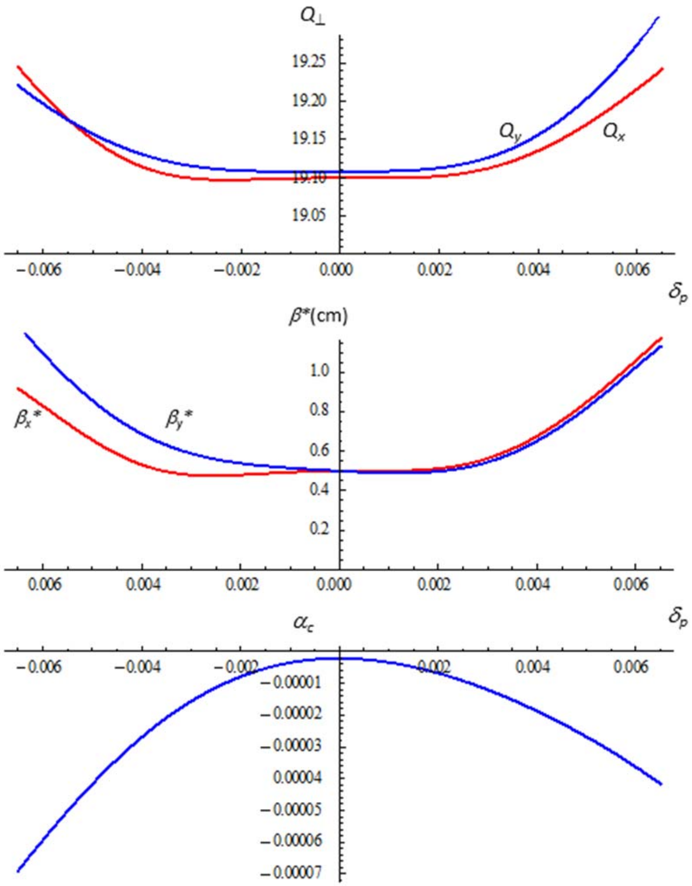
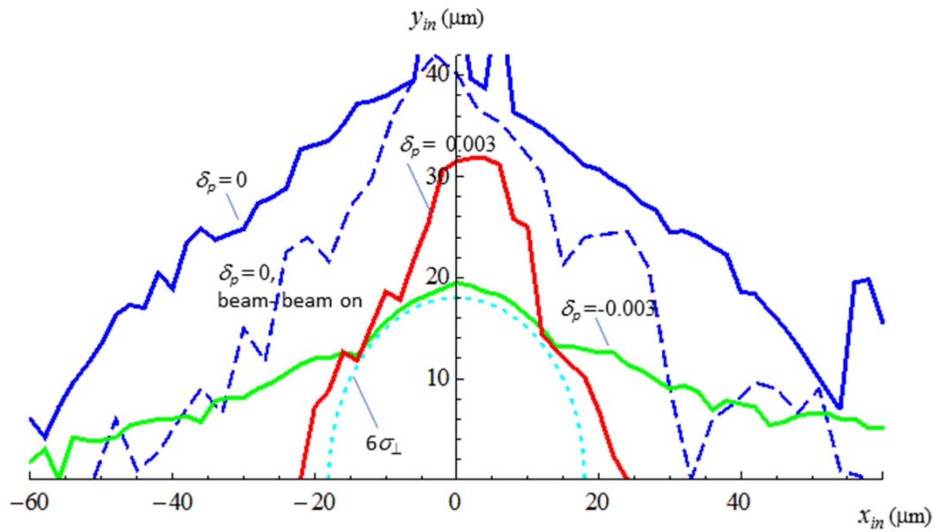
3 TeV MC Lattice Performance



Bare lattice parameters vs. δ_p . Accidentally $\alpha_c(0)$= $-2.15\cdot10^{-6}$ (was shooting for a higher absolute value)



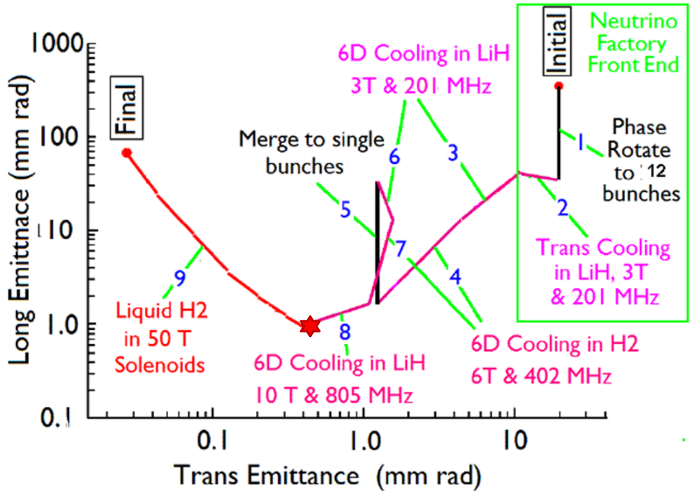
2048 turns dynamic aperture in the plane of initial particle coordinates at IP x_{in}, y_{in} for indicated values of constant δ_p calculated with beam-beam interaction off (solid lines) and on (dashed line) using MADX PTC_TRACK routine and MAD8 TRACK LIE4 option respectively.

With beam-beam on $\beta^*\approx$3mm so that $\sigma_\perp^*\approx$2.3μm. Still, the OFF-momentum DA is barely sufficient, further work is desirable.

Higgs Factory Specifics

The major advantage of a $\mu^+\mu^-$ Higgs Factory – the possibility of direct measurement of the Higgs boson width (Γ~3MeV FWHM expected) $\Rightarrow$ a very small beam energy spread is required, R~0.003%

Dave Neuffer proposed to stop after 6D cooling: $\varepsilon_{\perp N}$ =0.3(π)mm·rad, $\varepsilon_{||N}$ =1(π)mm·rad (σ_s=5.6cm with $\sigma_p/p=3\cdot10^{-5}$)



- Large $\varepsilon_{\perp N}$ $\rightarrow$ small β^* to achieve the required luminosity $\rightarrow$ very large IR magnet apertures (up to ID~50cm).
- Preservation of small σ_E /E ~$3\cdot10^{-5}$ in the presence of strong self-fields (Ipeak ~ 1kA !) $\rightarrow$ LARGE momentum compaction α_c ~ 0.1
- Chromaticity correction is still necessary due to path lengthening effect and operational considerations.

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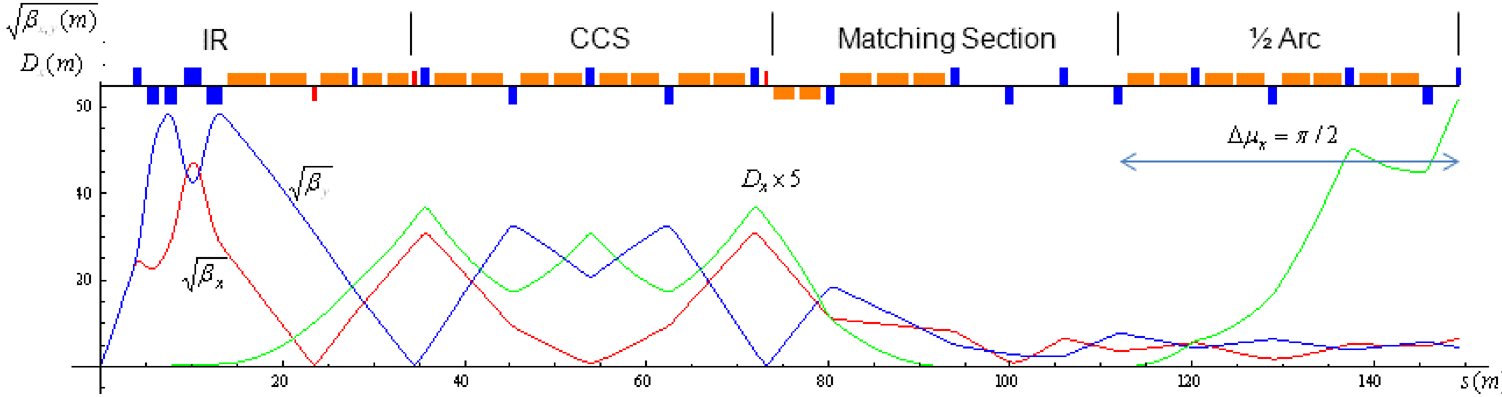
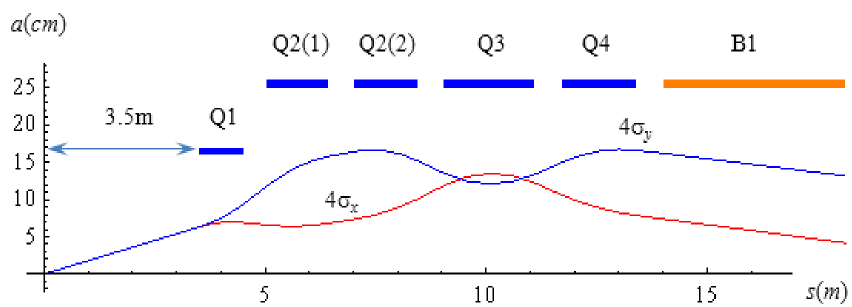
Higgs Factory Preliminary Design

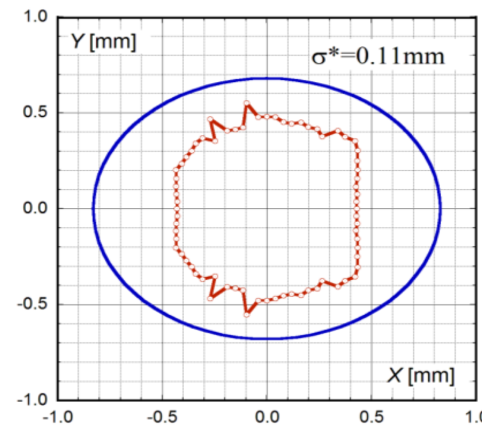


Higgs Factory lattice and optics functions for β*=2.5cm in a half-ring starting from IP



IR quad cold mass inner radii and 4σ beam envelopes for β*=2.5cm. Q2 and Q4 have 2T dipole component

The purpose of this design was to explore the limitations imposed by very large magnet aperture. We can increase β* to 4cm losing <20% in luminosity



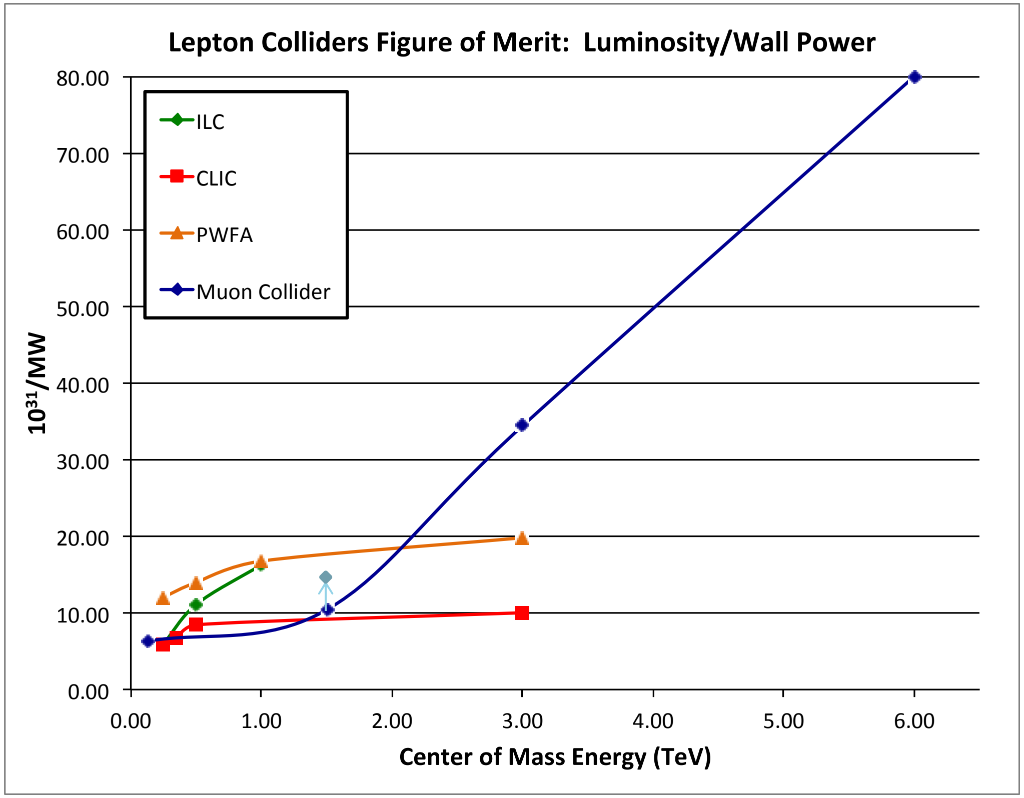
The dynamic aperture (fringe fields + multipoles + correction on) and projection of FF quad aperture (solid ellipse).

Muon Collider Design Parameters

Collision energy, TeV	0.126	1.5	3.0	6.0*
Repetition rate, Hz	15	15	12	6
Average luminosity / IP, 10^{34}/cm^2/s	0.008	1.25	4.6	11
Number of IPs	1	2	2	2
Circumference, km	0.3	2.5	4.34	6
β^*, cm	1.7	1	0.5	0.3
Momentum compaction factor	0.08	$-1.3\cdot10^{-5}$	$-0.5\cdot10^{-5}$	$-0.3\cdot10^{-5}$
Normalized emittance, $\pi\cdot$mm$\cdot$mrad	200	25	25	25
Momentum spread, %	0.004	0.1	0.1	0.083
Bunch length, cm	6.3	1	0.5	0.3
Number of muons / bunch, 10^{12}	4	2	2	2
Number of bunches / beam	1	1	1	1
Beam-beam parameter / IP	0.02	0.09	0.09	0.09
RF frequency, GHz	0.2	1.3	1.3	1.3
RF voltage, MV	0.1	12	50	150
Proton driver power (MW)	4	4	4	2

*) The numbers for 6 TeV case are based on the IR design and projection from 3 TeV MC for the rest of the ring

Luminosity / Wall Power Comparison



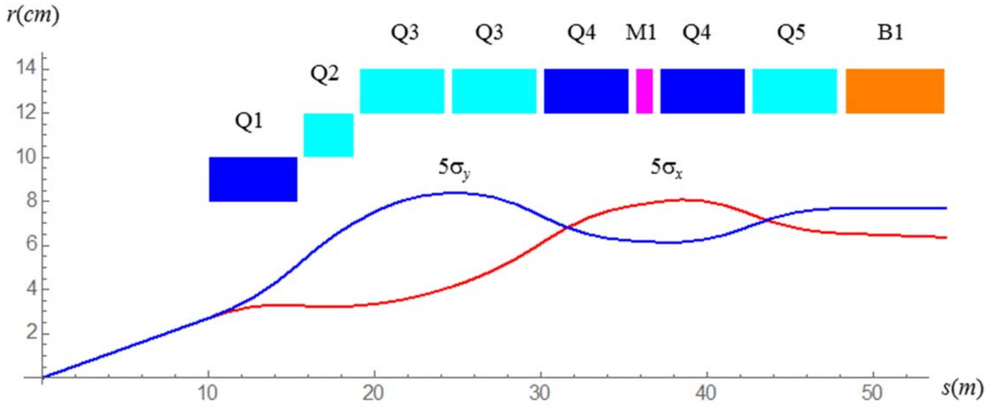
1.5 TeV design used doublet FF, with quadruplet FF β* can be made smaller and luminosity ~50% higher

Summary

- The line of MC designs was developed spanning the collision energy range 0.126 – 6.0 TeV based on the original solutions
  - Quadruplet Final Focus
  - "Three sextupole" chromaticity correction
  - Flexible Momentum Compaction (FMC) arccell of a special type
  - β^*-tuning section with chicane
- New approaches are worth to be studied, e.g. flat beam option – it makes chromaticity correction much easier
- We eagerly wait for the news from LHC – it will undoubtedly renew interest in Muon Collider!

Preliminary Design of the 6 TeV MC FF Multiplet

β^*=3mm



Parameter	Q1	Q2	Q3	Q4	Q5
ID (mm)	160	200	240	240	240
G (T/m)	200	-125	-100	103	-78
B_{dipole} (T)	0	3.5	4.0	3.0	6.0
L (m)	5.3	3.0	5.1	5.1	5.1