Muon Collider Design

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Design Goals

- High Luminosity (Higgs Factory $L \sim 10^{32}$cm^{-2}s^{-1}, 3TeV MC $L > 4\cdot10^{34}$cm^{-2}s^{-1})
  - $\Rightarrow$ round beams (to minimize beam-beam effect)
  - $\Rightarrow$ small β^* (Higgs Factory $\beta^* \sim 2\div3$ cm, 3TeV MC $\beta^* \sim 3\div5$ mm)
  - $\Rightarrow$ small circumference
  - $\Rightarrow$ small bunch length $\sigma_s \leq \beta^*$ (high-energy MC)
    - $\rightarrow$ momentum compaction factor ~ 10^{-5}
- Acceptable detector backgrounds
  - $\Rightarrow$ tight apertures in W absorbers (resistive wall instability?)
  - $\Rightarrow$ dipole component in FF quads
  - $\Rightarrow$ halo extraction (bent crystals?)
- Manageable heat loads in magnets
  - $\Rightarrow$ enough space for W absorbers, shorter distance between masks
- β^* variation in wide range (w/o breaking dispersion closure)
- Small collision energy spread $\sigma_E/E \leq 4\cdot10^{-5}$ (for Higgs Factory)
  - $\Rightarrow$ instabilities? longitudinal beam-beam effect?
- Safe levels of ν-induced radiation (for $E \geq 3$ TeV)
  - $\Rightarrow$ no long straights (except for IRs)
  - $\Rightarrow$ combined-function magnets to spread ν's

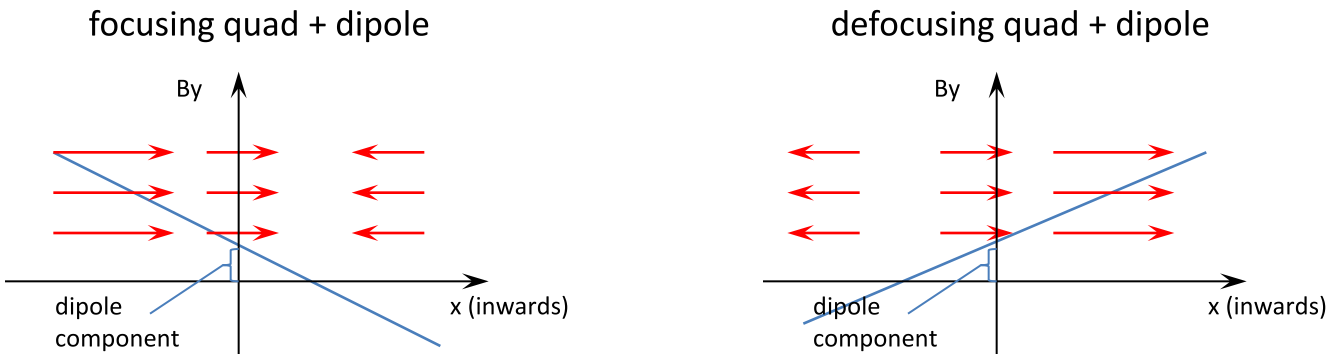
Basic Concepts (from 2014 DOE review)

New concepts were developed in the course of muon collider design:

Section	Description	Report
Interaction Region (IR)	Quadruplet Final Focus (see support slide for explanation, implemented only in the Higgs Factory lattice thus far)	IPAC13 TUPFI061, NAPAC13 THPBA19
Chromatic correction	3 sextupole scheme with 1st sextupole correcting vertical chromaticity while 2nd and 3rd sextupoles form -*I* separated pair for horizontal correction	PRSTAB 14, 061001 (2011)
IR-to-Arc Matching	β^*-tuning section with a chicane♣ allowing for β^* variation in a wide range and having bending field everywhere to spread ν's	IPAC12 TUPPC041
Arc	Flexible Momentum Compaction arccell♣ allowing for independent control of tunes, chromaticities, momentum compaction factor and its derivative with momentum	PRSTAB 14, 061001 (2011)

♣) for High-Energy MC

Why Quadruplet Final Focus?



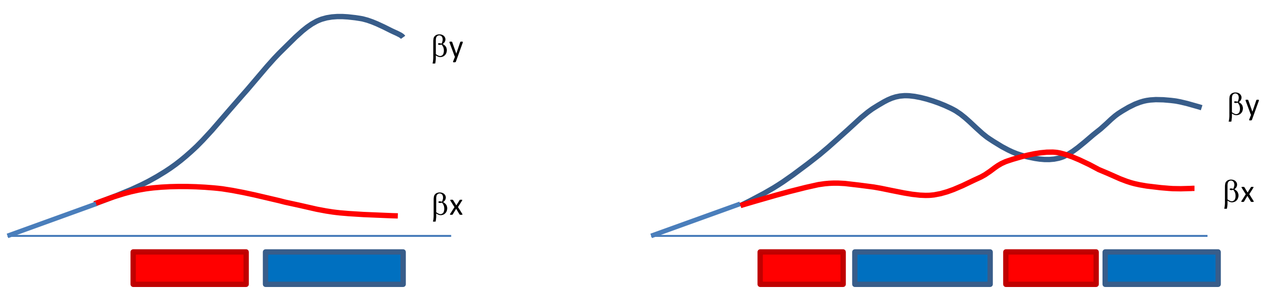
- Dipole component in a defocusing quad is more efficient for cleaning purposes

– it is beneficial to have the 2nd from IP quad defocusing

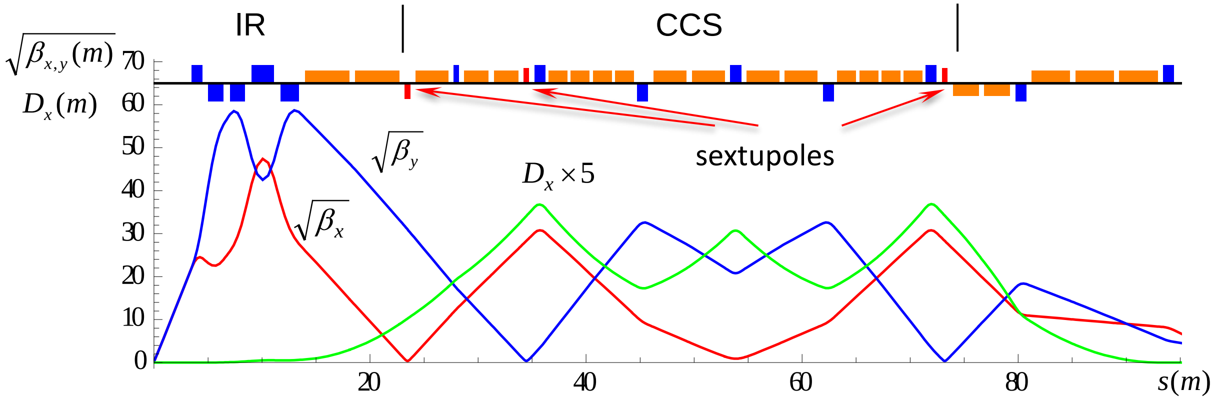
- The last quad of the FF “telescope” also must be defocusing to limit the dispersion “invariant” generated by the subsequent dipole (not shown)

$$J_x = \frac{D_x^2 + (\beta_x D'_x + \alpha_x D_x)^2}{\beta_x} \approx \beta_x \phi^2$$

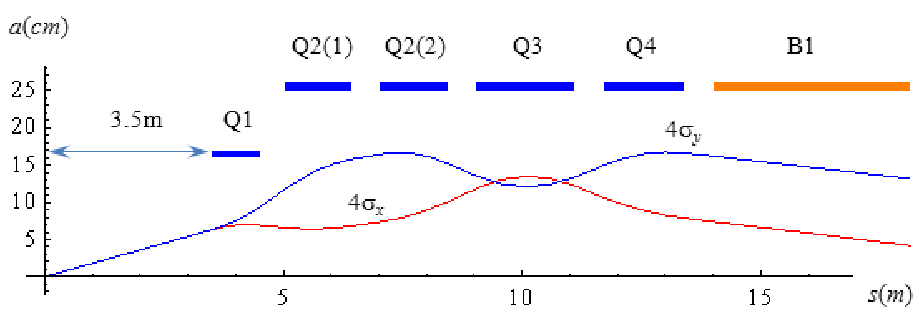
– both requirement are met with either doublet or quadrupole FF:



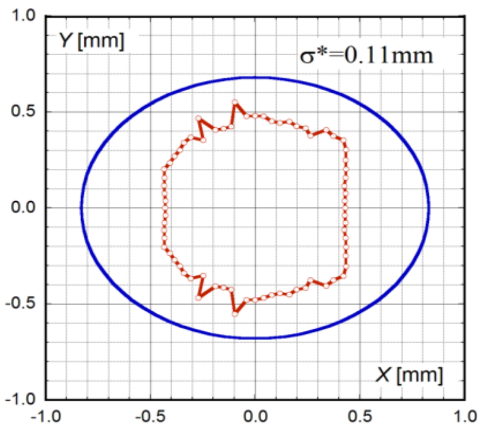
Higgs Factory Lattice



Higgs Factory Interaction Region (IR) and Chromaticity Correction Section (CCS), β*=2.5cm



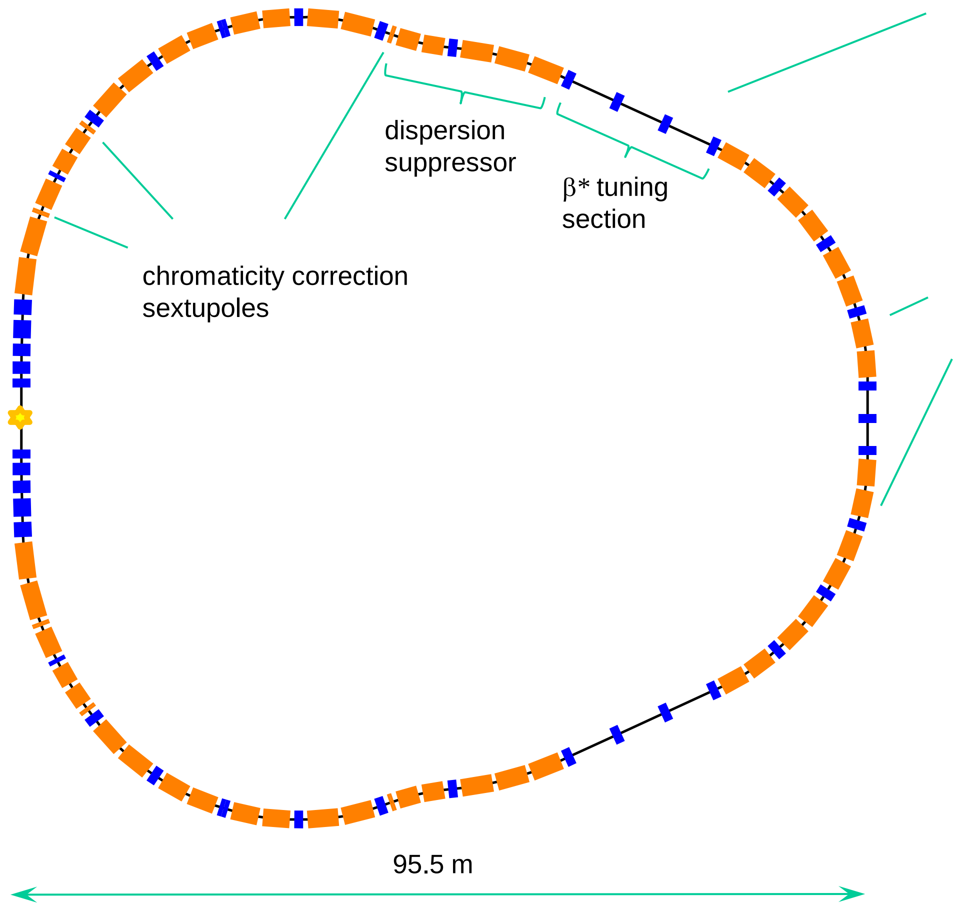
IR quad cold mass inner radii and 4σ beam envelopes for β*=2.5cm



The dynamic aperture at IP and projection of FF quad aperture (solid ellipse).

Specifics of the Higgs Factory lattice are discussed in a support slide

Higgs Factory Layout

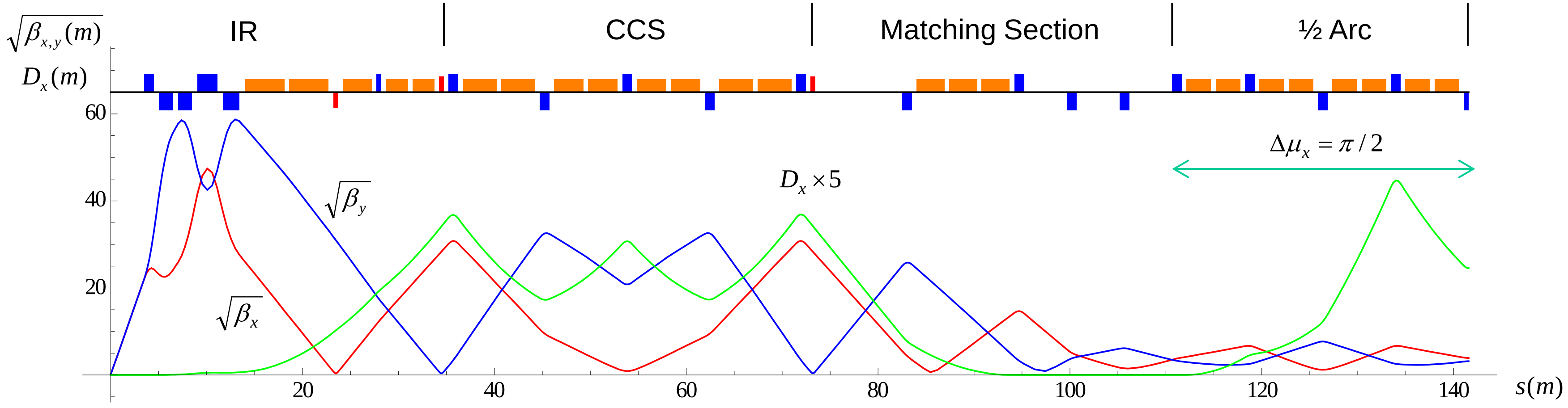


Flexibility of the optics (β^*=1.5-10cm) allows for adjustments depending on the parameters of the muon beam

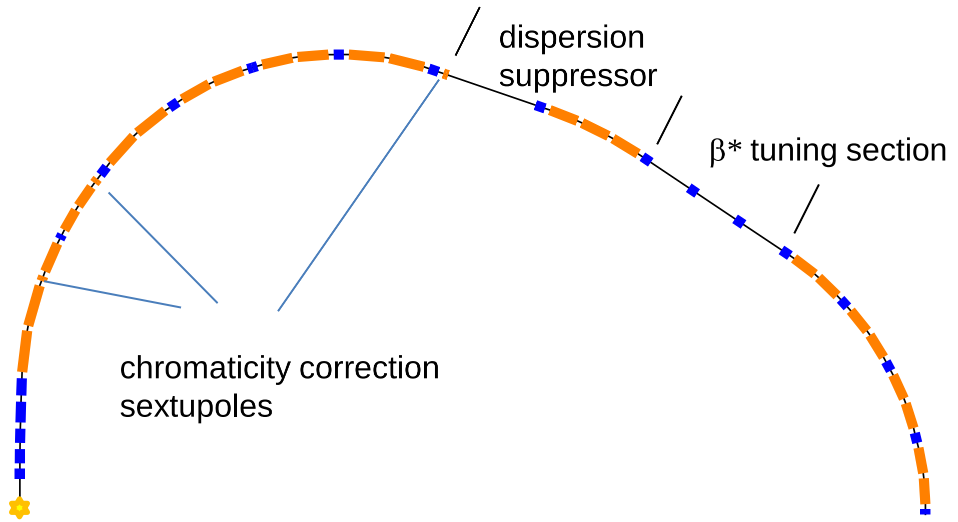
Arcs are very short and do not allow for wide-range tune adjustment

Dispersion suppressor and β^* tuning section noticeably increase the ring circumference, but they are probably indispensable

Modified Higgs Factory Lattice



Optics functions in half ring for β*=2.5cm



Half ring layout

No reverse bends → circumference reduced to 283m (from 300m).

Difficulty in adjustment of the horizontal tune (now Qx=5.16, Qy=4.56).

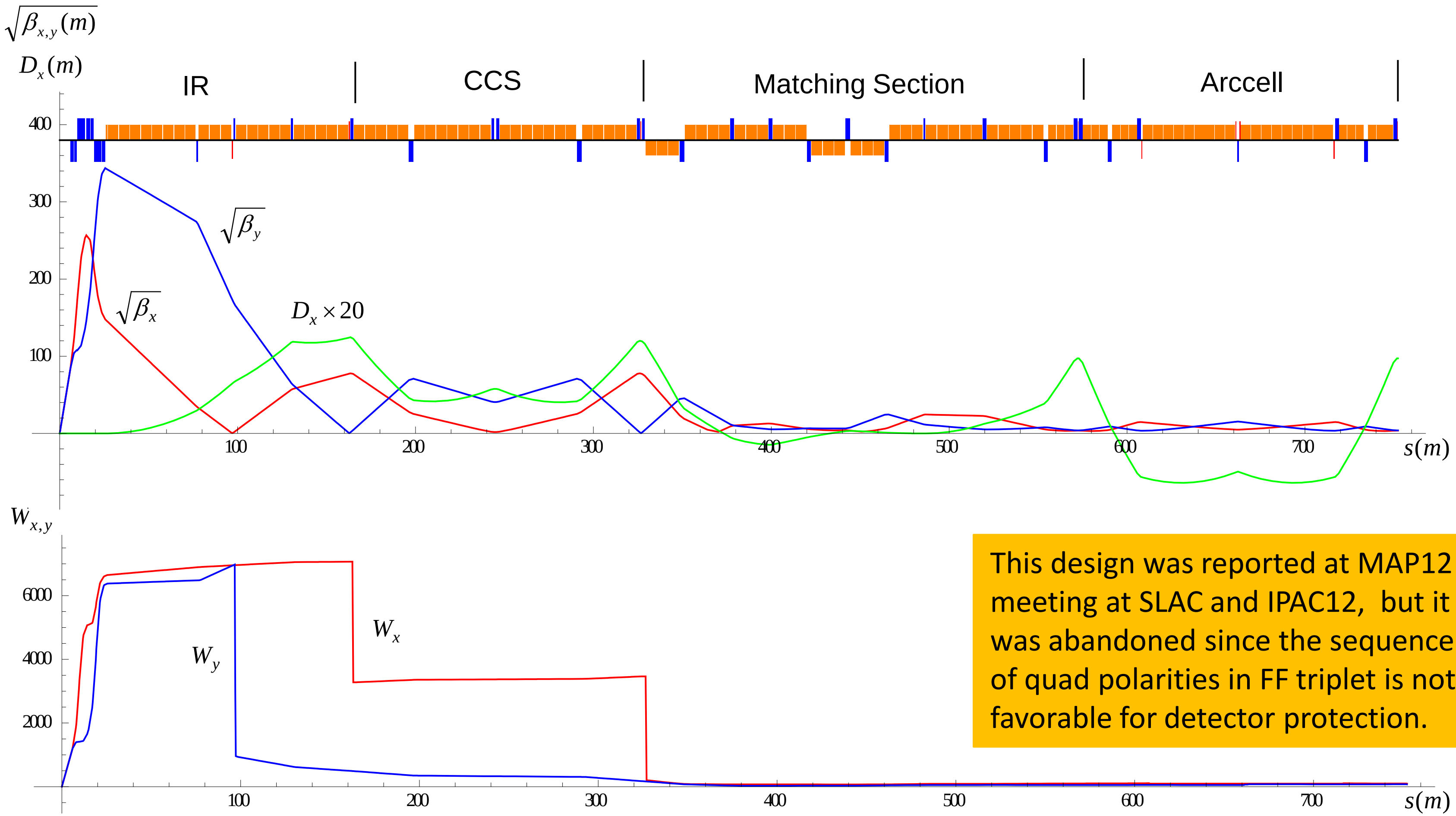
Some unexpected problem with vertical dynamic aperture is encountered.

Higgs Factory Parameters

Parameter	Startup	Design	Baseline
Beam energy, GeV	63	63	63
Average luminosity, 10^{31}/cm^2/s	1.7	2.5	8.0
Collision energy spread, MeV	3	3	4
Circumference, m	300	300	300
Number of IPs	1	1	1
β^*, cm	3.3	2.5	1.7
Number of muons / bunch, 10^{12}	2	2	4
Number of bunches / beam	1	1	1
Beam energy spread, %	0.003	0.003	0.004
Normalized emittance, π·mm·rad	0.4	0.3	0.2
Longitudinal emittance, π·mm	1.0	1.0	1.5
R.m.s. bunch length, cm	5.6	5.6	6.3
R.m.s. beam size at IP, mm	0.15	0.11	0.075
Beam-beam parameter	0.005	0.007	0.02
Momentum compaction factor	0.079	0.079	0.079
Repetition rate (Hz)	30	30	15
Proton driver power (MW)	4	4	4

> 13k h-bosons/year at this luminosity

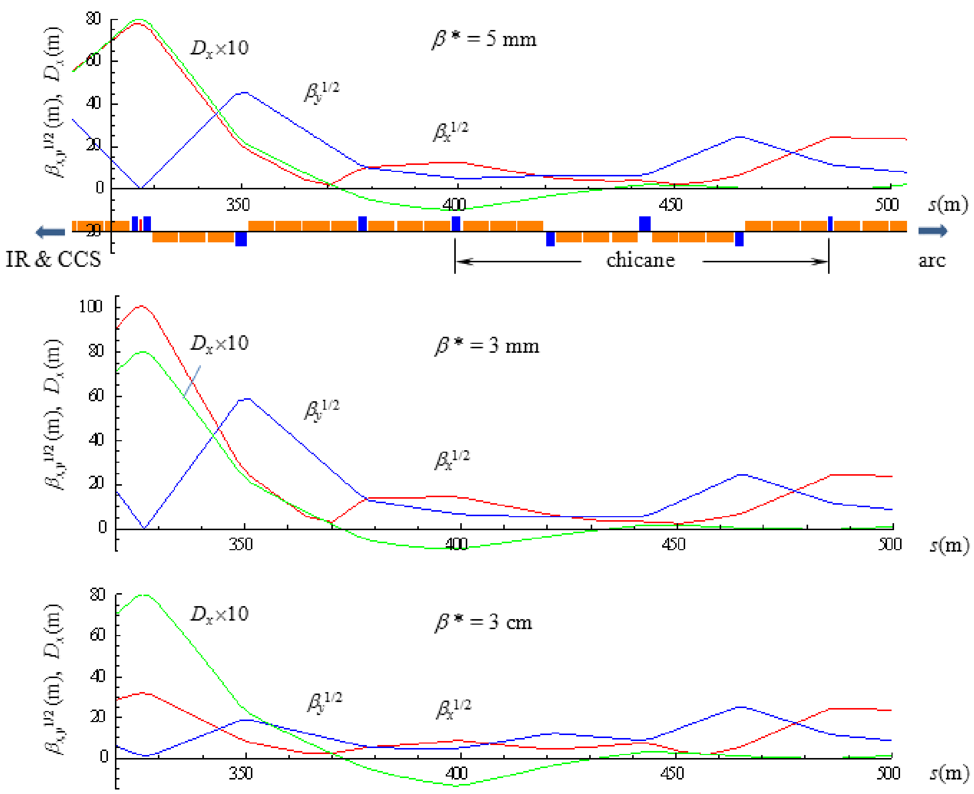
3 TeV MC Preliminary Design (Triplet FF)

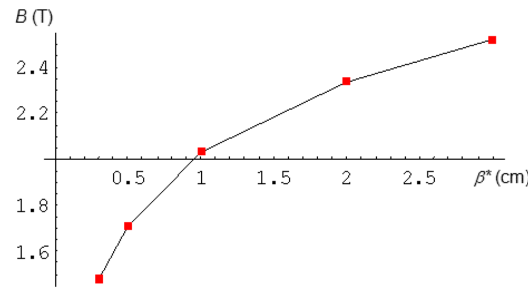


This design was reported at MAP12 meeting at SLAC and IPAC12, but it was abandoned since the sequence of quad polarities in FF triplet is not favorable for detector protection.

Optics and chromatic functions in IR, horizontal Chromatic Correction Section (CCS), Matching Section and the first arc cell (out of 6 per arc)

Matching Section with Chicane

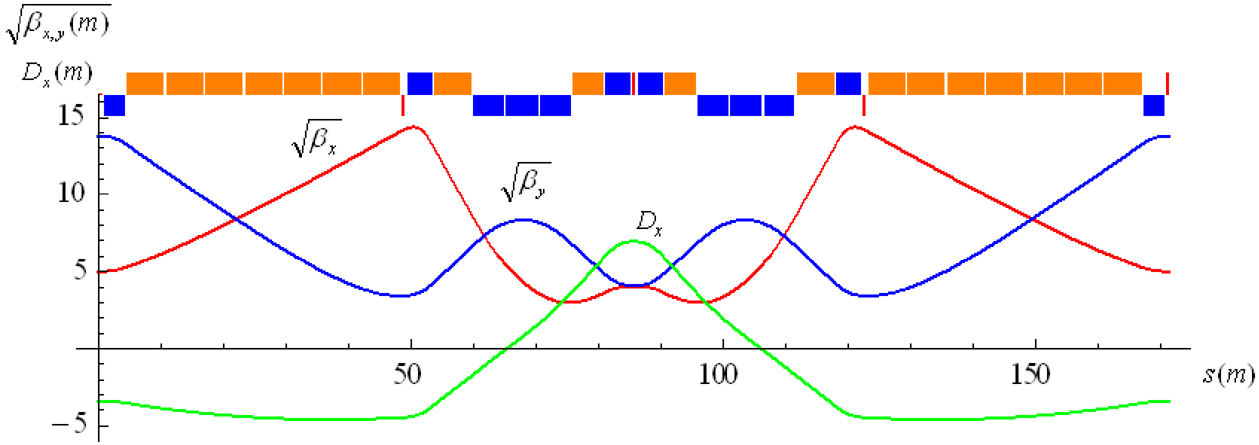




- The required B-field in chicane is quite low – magnets can be shorter to free space for RF cavities or pulsed halo deflectors.
- Chicane length is 84.5m, depth at β*=3cm is 19.6cm – small effect on the total circumference

This concept will be used in the new design but with combined-function magnets.

3TeV MC Arc Cell with Combined-Function Magnets

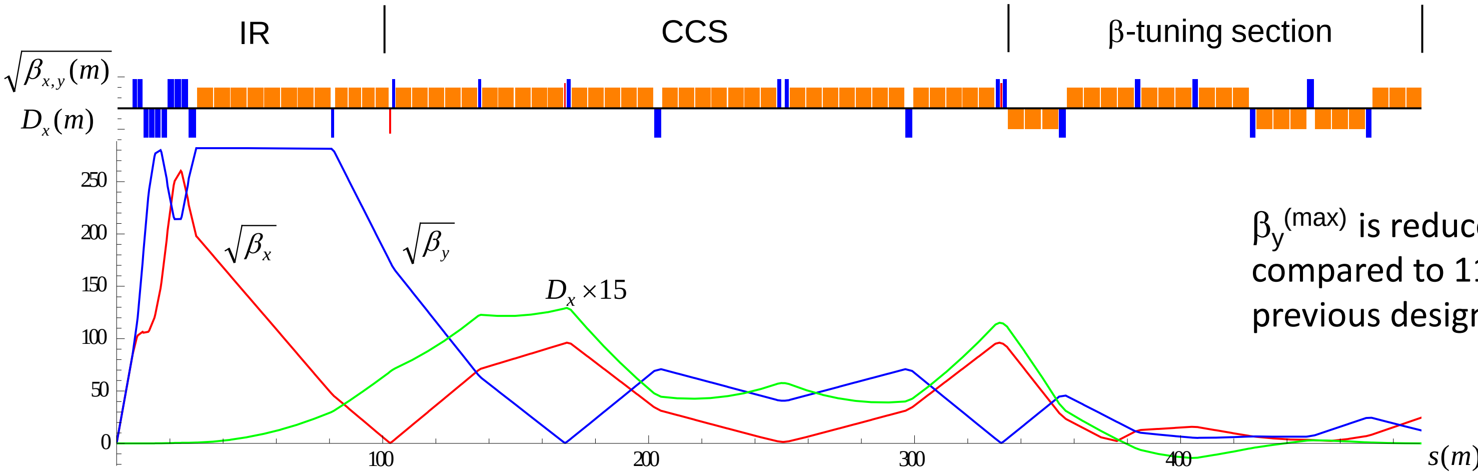


Momentum compaction factor for a stand-alone cell is
α_p = -0.004,
betatron phase advance is 300° in both planes.

Each arc consists of six such cells and two dispersion suppressors

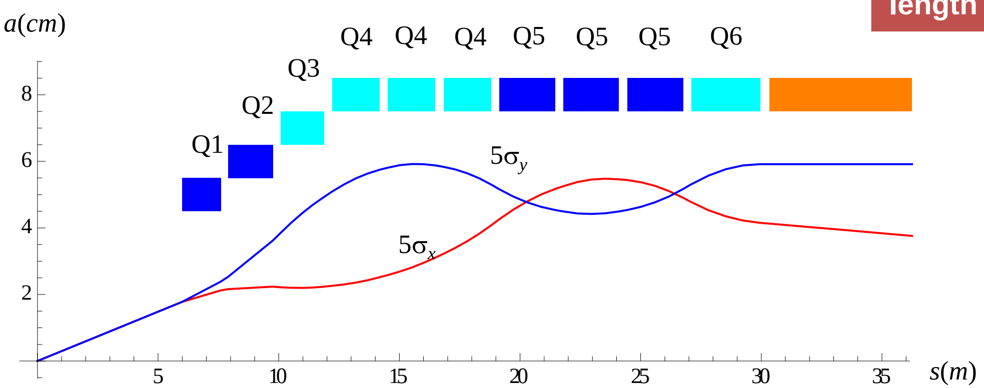
name	L (m)	B (T)	G (T/m)
QD	5	9	-35
QF	4	8	85

3 TeV MC Design with Quadruplet FF



$\beta_y^{(max)}$ is reduced to 80km compared to 118km in the previous design with triplet FF.

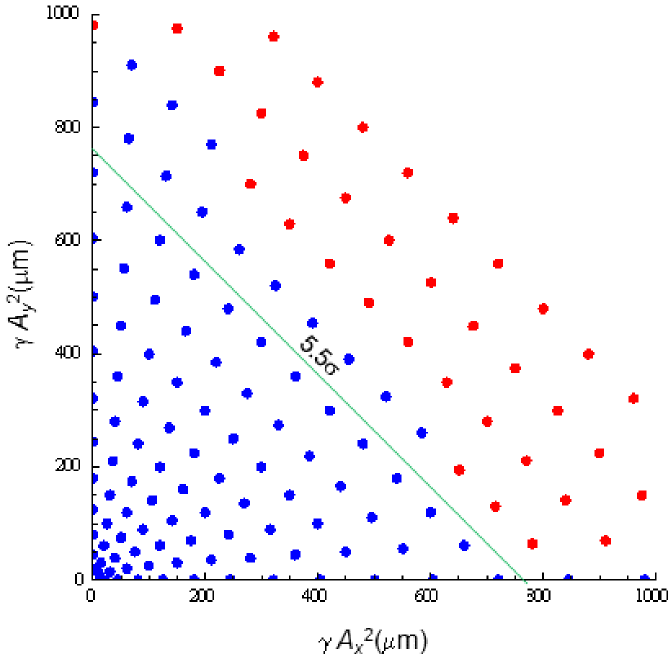
	Q1	Q2	Q3	Q4	Q5	Q6
aperture (mm)	90	110	130	150	150	150
G (T/m)	267	218	-154	-133	129	-128
B (T)	0	0	2	2	0	2
length (m)	1.6	1.85	1.8	1.96	2.3	2.85



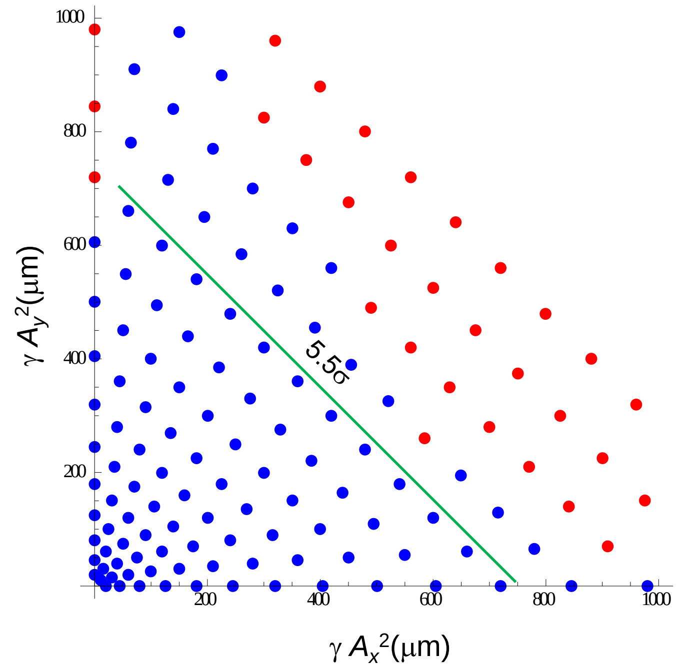
Now 12T pole tip field is assumed

3TeV MC Dynamic Aperture

triplet FF



quadruplet FF



1024 turns on-momentum dynamic aperture at β^* =5 mm for two versions of 3TeV MC lattice

The momentum acceptance for β^* = 5 mm is ±0.45% and ±0.4% for β^* = 3 mm

High Energy MC Parameters

High Energy MC parameters			
Collision energy, TeV	1.5	3.0	6.0*
Repetition rate, Hz	15	12	6
Average luminosity / IP, 10^{34}/cm^2/s	1.25	4.4	12
Number of IPs	2	2	2
Circumference, km	2.5	4.5	6
β^*, cm	1	0.5	0.25
Momentum compaction factor, 10^{-5}	-1.3	-1	-0.5
Normalized emittance, π·mm·mrad	25	25	25
Momentum spread, %	0.1	0.1	0.1
Bunch length, cm	1	0.5	0.25
Number of muons / bunch, 10^{12}	2	2	2
Number of bunches / beam	1	1	1
Beam-beam parameter / IP	0.09	0.09	0.09
RF voltage at 1.3 GHz, MV	12	150	600
Proton driver power (MW)	4	4	2

*) based on extrapolation, not a real design yet

Lattice Design Plans(from 2014 DOE review)

	person-months
• 3 TeV MC lattice with quadruplet FF	6
• Halo extraction scheme for high energy MC electrostatic separator – too long (~25m for 3TeV) RF or pulsed septum ? bent crystals ? – First look quite encouraging	3
• Tolerances on field errors and misalignments	3
• Longitudinal dynamics in HF with wakes and beam-beam	6
• Update of the HF lattice	3
• 6 TeV lattice design	6
• 1.5 TeV MC lattice with quadruplet FF (?)	3
Total (rough estimate)	30*

Most Urgent Items

- Finish of the 3TeV MC lattice with quadruplet FF (will be done no matter what by end of July)
- Study tolerances on field errors and misalignments – very important for understanding the real constrains on beta-functions, momentum compaction factor etc. (will be done only if sanctioned)
- First look at 6TeV lattice (?)

Other items can be put on a slow burner

Collider Ring	Concept Specification	Lattice Files & Performace Eval	Lattice Sign-off	Interface Params	Technology Specification	Technology Sign-Off	IBS Review Ready Date	IBS Initial Review (where needed)	IBS Review	IB Specifications (Dependent on results from previous system)
Higgs Factory	10/1/2013	3/30/2014	4/29/2014	5/29/2014	9/26/2014	10/26/2014	1/27/2015	2/26/2015	1/27/2016	8/29/2016
1.5 TeV (2 & 4 MW Source)	10/1/2013	3/30/2014	4/29/2014	5/29/2014	9/26/2014	10/26/2014	1/27/2015			
3 TeV (2 & 4 MW Source)	10/1/2013	7/28/2014	8/27/2014	9/26/2014	1/24/2015	2/23/2015	5/27/2015			
>5 TeV (<2 MW Source)	10/1/2014	2/28/2015	3/30/2015	4/29/2015	8/27/2015	9/26/2015	12/28/2015			
Ring-MDI Interface Parameters	10/1/2014			4/29/2015						8/29/2016

Support Slide - Higgs Factory Specifics

- 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 ~$3\cdot 10^{-5}$ 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.

Path length dependence on betatron amplitude (L. Emery, HEACC'92, Hamburg) translates into additional energy spread*:

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

$$A_x / \sigma = \sqrt{2 I_x / \varepsilon_x}$$

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

$$\left\langle \frac{\Delta E}{E} \right\rangle \sim 6\cdot 10^{-5}$$

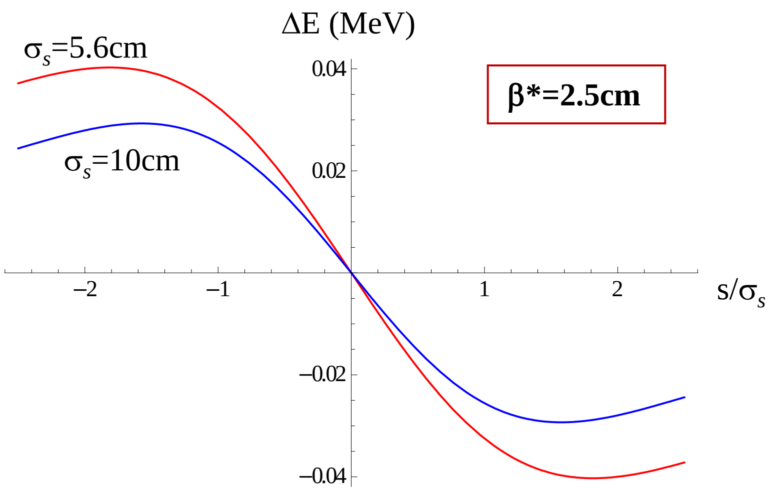
Longitudinal Beam-Beam Effect (Derbenev & Skrinsky, 1972)

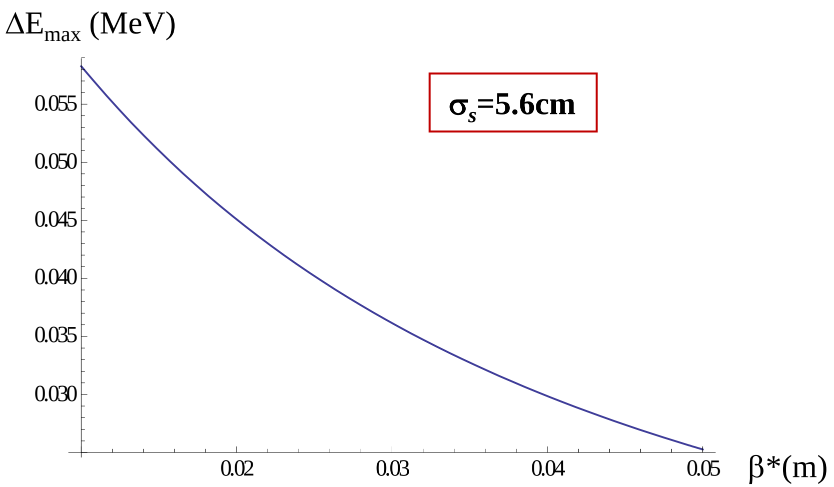
Collision with a thin slice of Ns particles leads to energy change

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

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

The finite bunch length reduces it somewhat:





Effective gradient is ~0.7 MV/m for cited parameters, can exceed 2 MV/m for the upgrade.

Higher-frequency (500MHz) RF for compensation?