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Muon Accelerator Program

Muon Collider Ring - Status & Outlook

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Outline

- Major differences with circular colliders of other species
- Solutions for Interaction Region
- Chromaticity Correction Scheme
- Arcs
- β*-tuning Section
- Higgs Factory Specifics
- Lineup of Muon Collider Designs
- Remaining Questions
- Flat Beam Option?

Differences with Hadron Colliders

What we would like to achieve compared to other machines:

	MC	Tevatron	LHC
Beam energy (TeV)	0.75	0.98	7
β* (cm)	1	28	55
Momentum spread (%)	0.1	<0.01	0.0113
Bunch length (cm)	1	50	15
Momentum compaction factor (10^-3)	0.01	2.3	0.322
Geometric r.m.s. emittance (nm)	3.5	3	0.5
Particles / bunch (10^11)	20	2.7	1.15
Beam-beam parameter, ξ	0.1	0.025	0.01

Muon collider is by far more challenging:

- much smaller β* while the required momentum acceptance is much larger
- ~ as large Dynamic Aperture (DA) with much stronger beam-beam effect
- protection of detector (and magnets!) from muon decay products
- very small momentum compaction factor

- New ideas for lattice, magnets and MDI were needed!

IR Choice

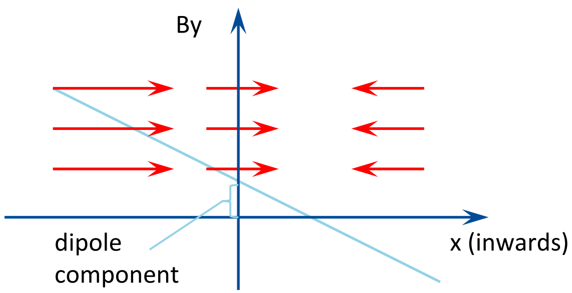
- For local chromaticity compensation the dispersion must be generated as close to the IP as possible.

Then the last quad of the FF "telescope" should be defocusing to minimize the dispersion "invariant" generated by the subsequent dipole,

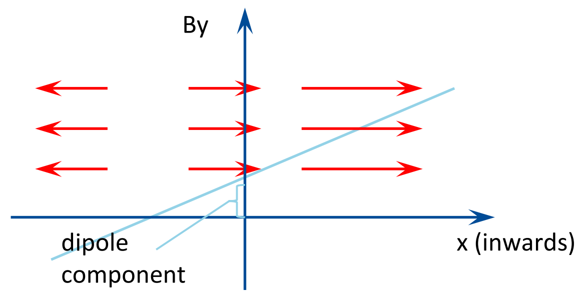
$$J_x = \frac{D_x^2 + (\beta_x D_x' + \alpha_x D_x)^2}{\beta_x} \approx \beta_x \phi^2$$

- Dipole component in a defocusing quad is more efficient for sweeping away secondary particles – therefore it is beneficial to have the 2nd from IP quad also defocusing

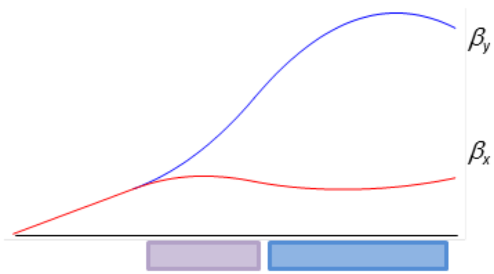
focusing quad + dipole

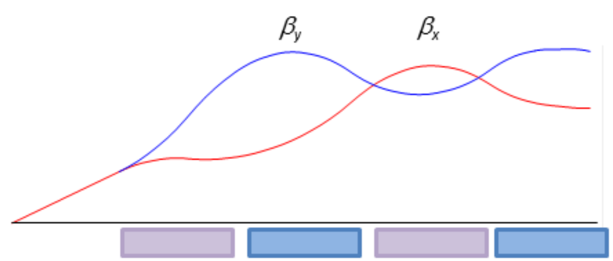


defocusing quad + dipole



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

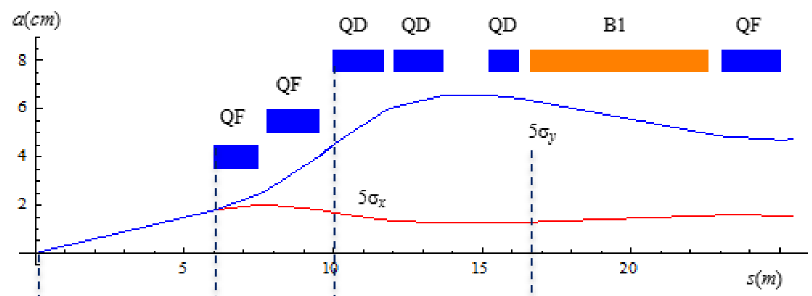


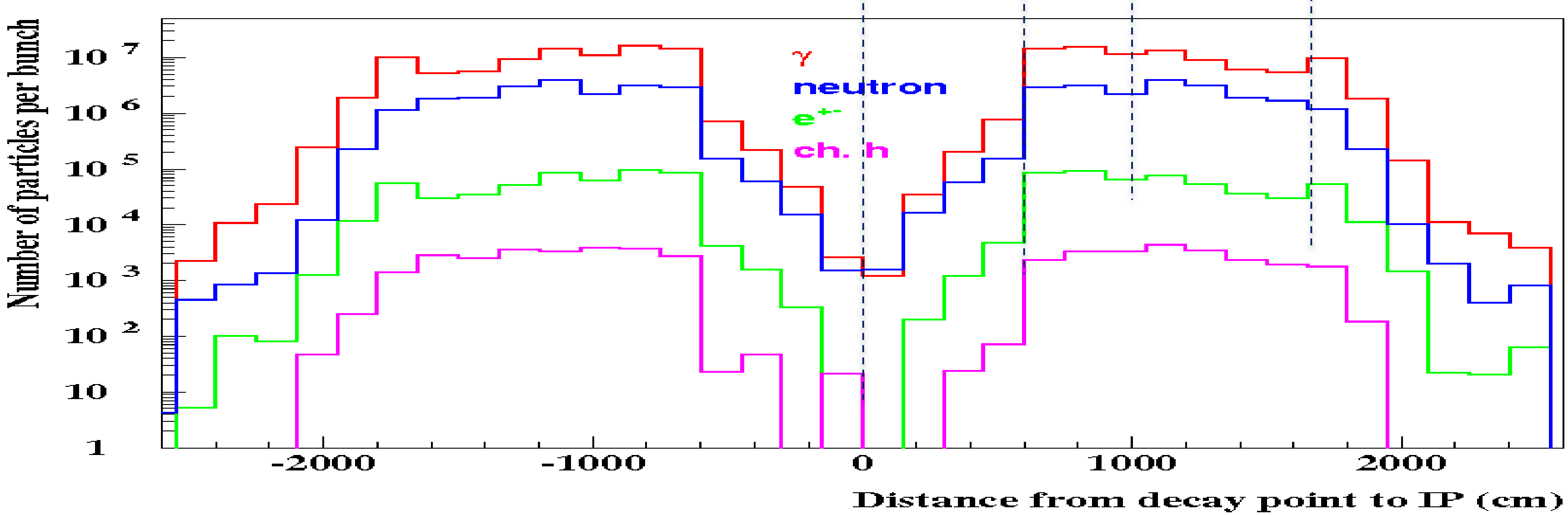


1.5 TeV MC Doublet FF

Parameter	Unit	Q1	Q2	Q3
Coil aperture	mm	80	110	160
Nominal gradient	T/m	250	187	-130
Quench gradient @ 4.5 K	T/m	281.5	209.0	146.0
Quench gradient @ 1.9 K	T/m	307.6	228.4	159.5
Magnetic length	m	1.5	1.7	1.7

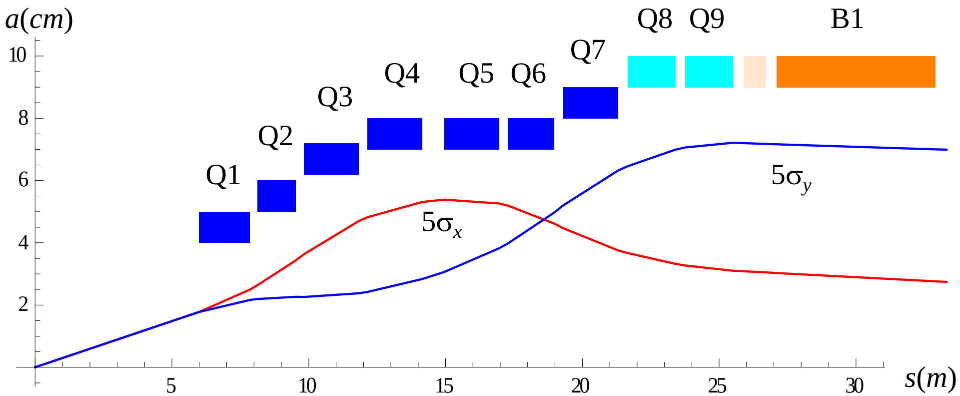
β^*=1cm





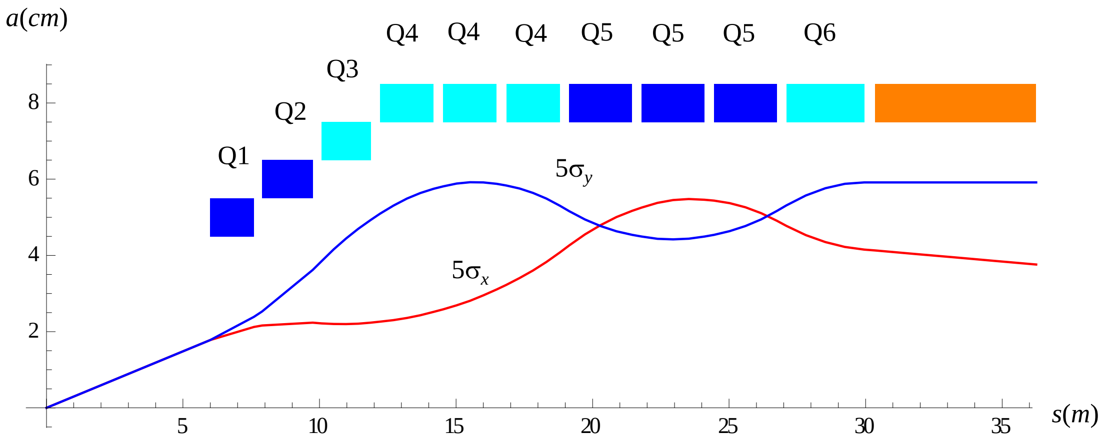
Very little background comes from B1 dipole. Dipole component (2T in both QDs and QFs here) was also shown to be effective.

3 TeV MC Triplet & Quadruplet FF



$B_{\text{pole tip}}$= 10T

β^*=5mm

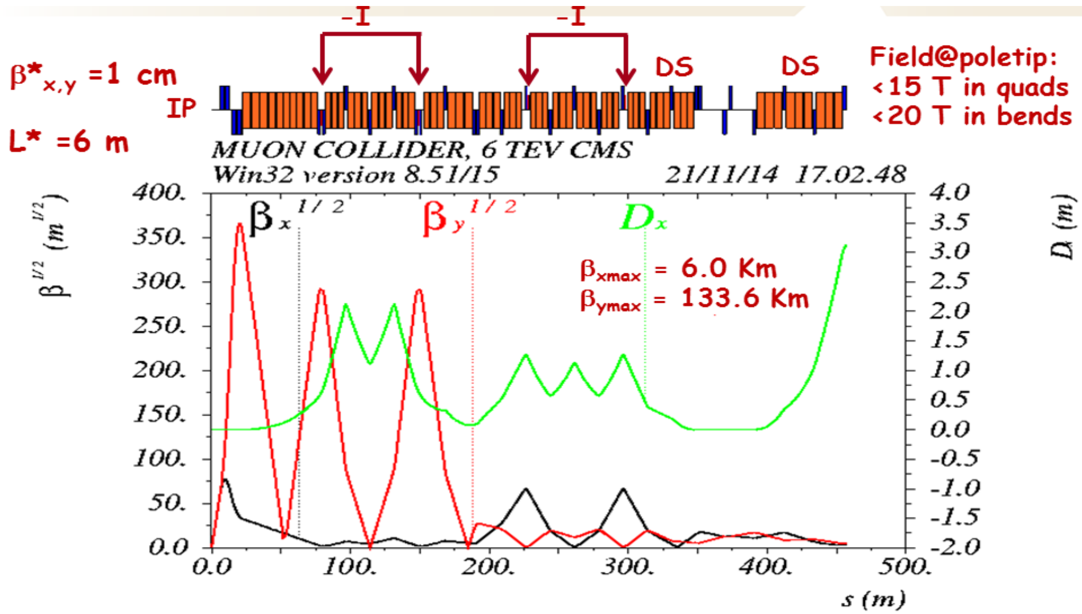


$B_{\text{pole tip}}$= 12T

Quads with 2TeV dipole component are shown in cyan.
In the case of quadruplet FF the first strong dipole is ~4m farther from IP despite higher $B_{\text{pole tip}}$.
Is a quadruplet FF really better for high energy MC? – Background simulations are necessary

Chromaticity Correction

Very popular (but not yet realized) is the scheme with two –*I* blocks (J.Irwin et al., 1991). It can be called “4-sextupole scheme”.
The latest example: 6TeV MC design developed at SLAC (M.-H. Wang et al.)



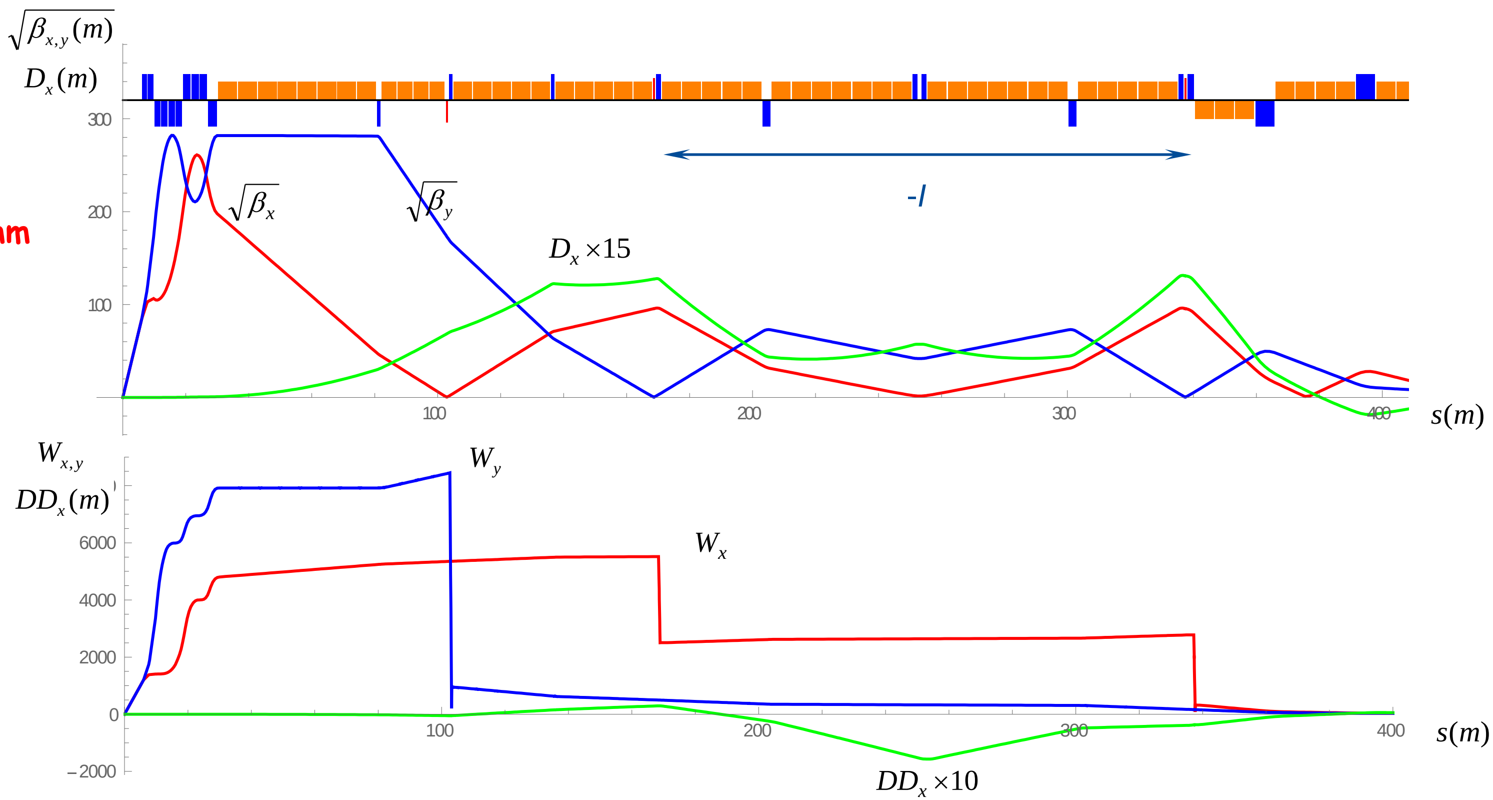
Issues with the 4-sextupole scheme:

- –*I* blocks themselves produce significant contribution to chromaticity
- There is a strong uncompensated nonlinearity in centrifugal force → adverse effect on DA
- Many elements at high-beta locations → high sensitivity to errors
- Large positive contribution to the momentum compaction factor → a strain on the arc lattice which must compensate it

Chromaticity Correction Scheme

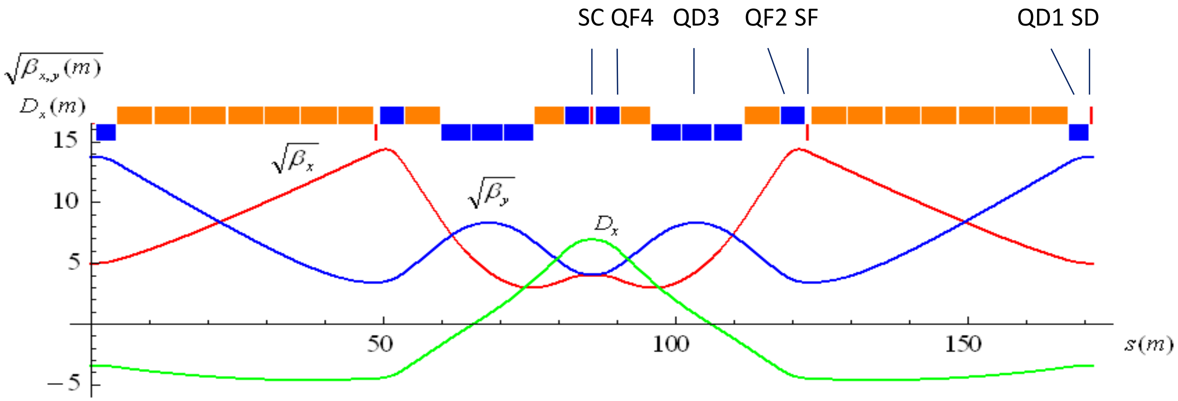
To address the above-mentioned issues a “3-sextupole scheme” was developed at FNAL.
It uses just one sextupole (at each side of IP) for vertical chromaticity correction relying on small β_x for aberration suppression.

β*=5mm



Optical (top) and chromatic (bottom) functions at IR and chromaticity correction section of 3 TeV MC

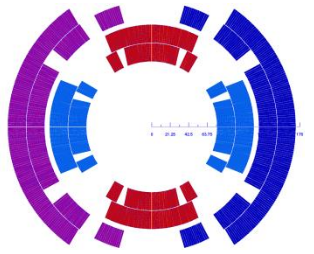
3 TeV MC Arc Cell with Combined Function Magnets



Motivation:

- Spread decay ν's
- Sweep away decay electrons before they depart from median plane – allows for azimuthally tapered absorber

- Central quad (QF4) and sextupole SC control the momentum compaction factor and its derivative (via Dx and DDx) w/o significant effect on chromaticity
- Large β -functions ratios at SF and SD sextupole locations simplify chromaticity correction
- Phase advance 300°/ cell ⇒ spherical aberrations cancelled in groups of 6 cells



Parameter (4.5K)	QDA1/3	QFA2/4
Maximum field in coil (T)	16.5/17.5	
Maximum field / gradient in aperture (T or T/m)	12.0/72.5	
Operating field or gradient (T or T/m)	9.0/35.0	8.0/85.0
Aperture (mm)	150	

- Quad/Dipole design appears superior
- Preliminary analysis shows heat deposition in coils < 1.5 mW/g with only 2cm thick absorbers. However a thicker absorber can be required to keep the heat load below 10W/m

β*-tuning Section

Requirements to the IR-to-Arc matching section design :

a) allows for β* variation in wide range (3mm – 3cm) – important from operational point of view, but also for high energy resolution mode (see later)

b) has enough space with low β's and Dx for RF

c) has no straights w/o bending field to spread ν's – all quads are combined-function magnets

d) has a place with high βx and low Dx for halo extraction (we can put special insertions in the arcs but this will increase C – higher costs, lower Lumi)

Conditions a) and c) are difficult to reconcile:

– if βx changes at a bend then Dx will change all over the ring.

– if we try to adjust the bending angles we will change the orbit.

Possible solution: a chicane with variable B-field – no net bending angle, negligible variation in circumference (hopefully)

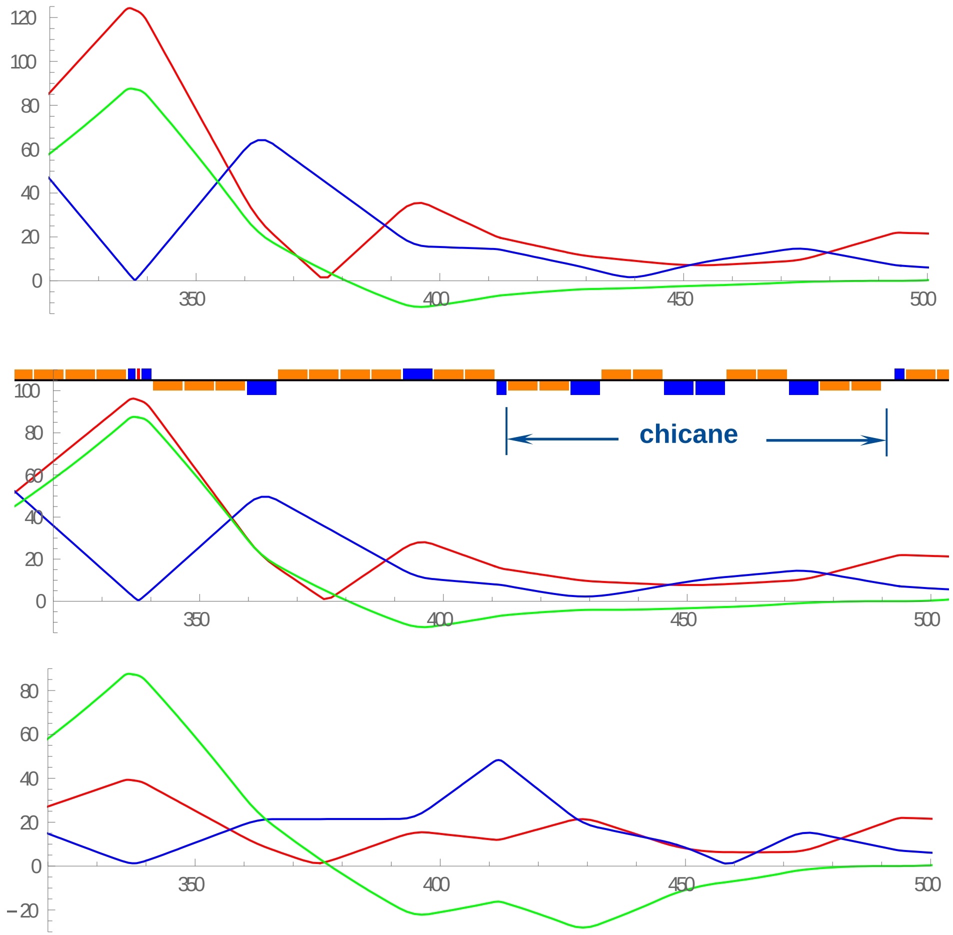
3 TeV MC β*-tuning Section

β*=3mm — B_{chic}=2.23T

IR & CCS ← → arc

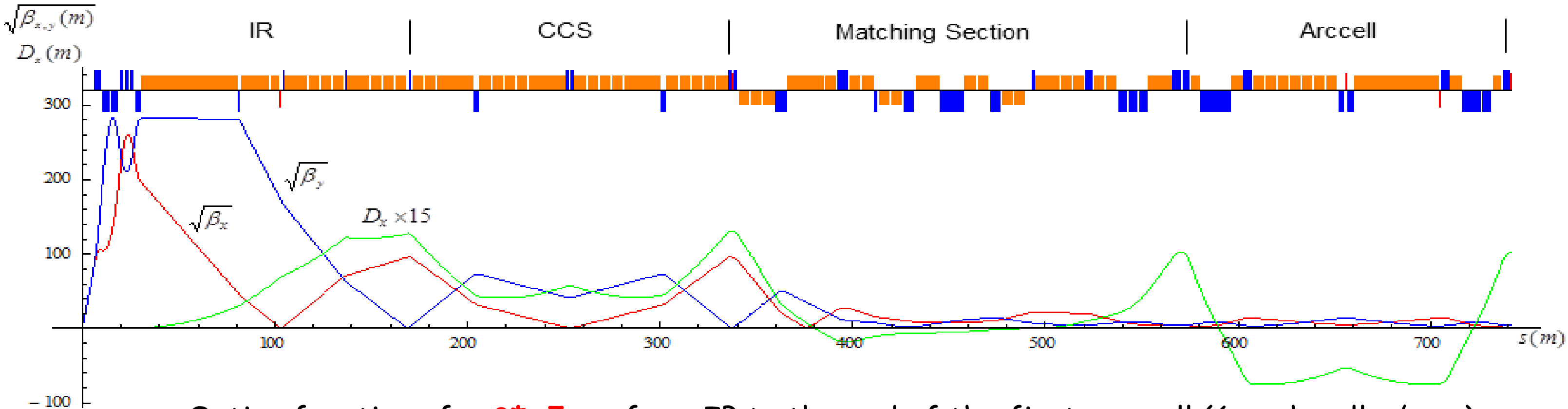
β*=5mm — B_{chic}=3.33T

β*=3cm — B_{chic}=6.92T

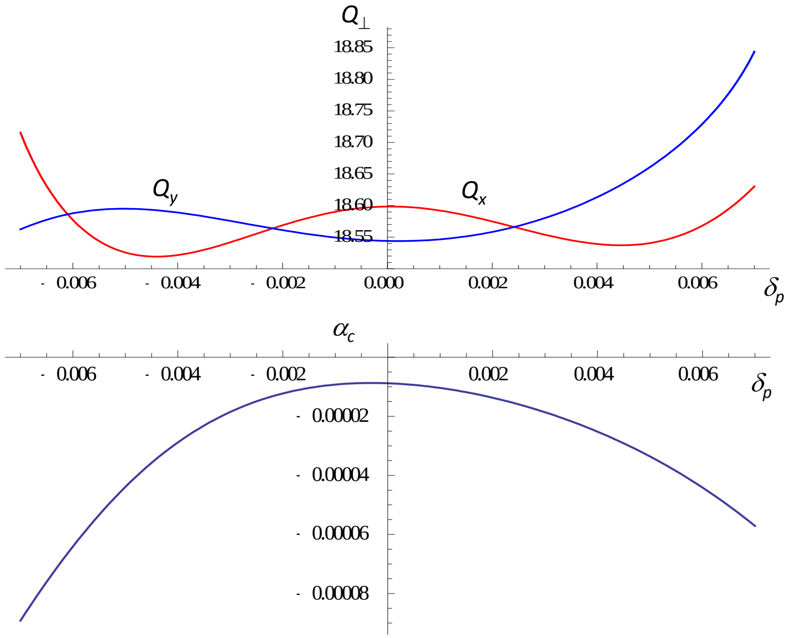


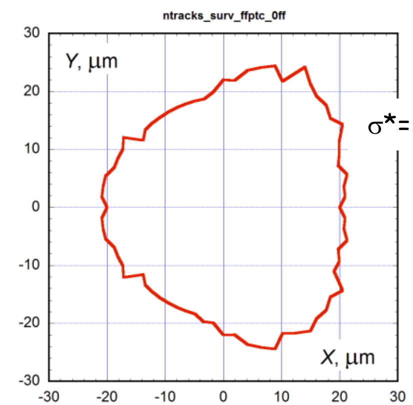
B-field in chicane is rather low, still it will require mechanical movement of the magnets when changing β*
Optics functions at large β* look ugly (resulting in larger beam size) – further work is necessary!

3 TeV MC Lattice Performance



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





σ*=3μm

The dynamic aperture w/o field errors ≈6σ.
The stable momentum range ±0.7%

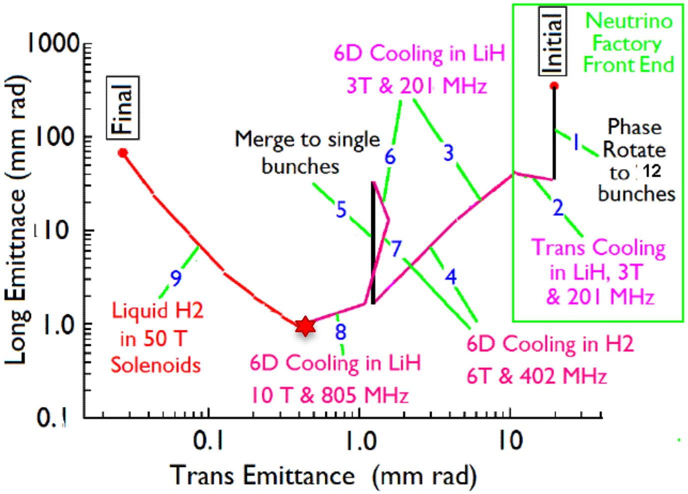
Higgs Factory Specifics

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's 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 **σ_p/p=3·10^{-5}**)

W/o final cooling the muons losses are reduced ~ by half:

N_μ=2·10^{12} @ f_{rep}=30Hz for 4MW p-driver power

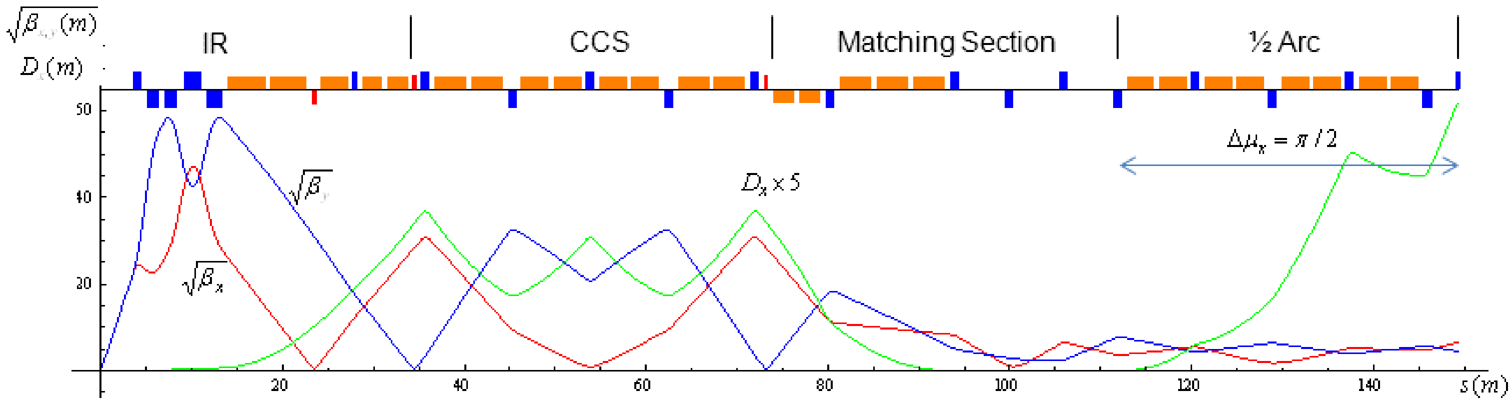


- Large $\varepsilon_{\perp N}$ $\rightarrow$ small β^* to achieve the required luminosity $\rightarrow$ very large IR magnet apertures (up to ID~50cm).

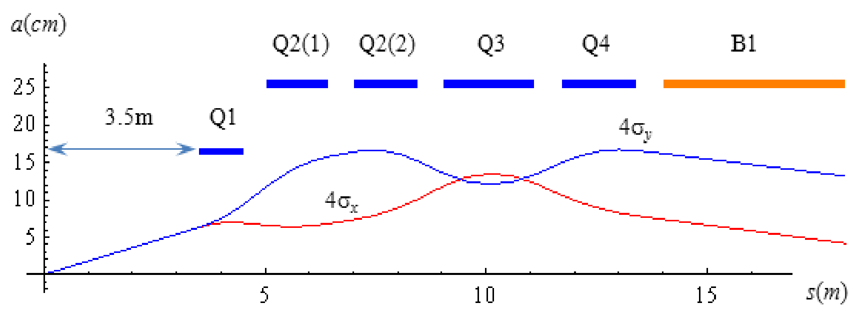
- Preservation of small σ_E /E ~3·10^{-5} in the presence of strong self-fields (Ipeak ~ 1kA !) $\rightarrow$ LARGE momentum compaction α_c ~ 0.1

- Chromaticity correction is still necessary due to path lengthening effect and operational considerations.

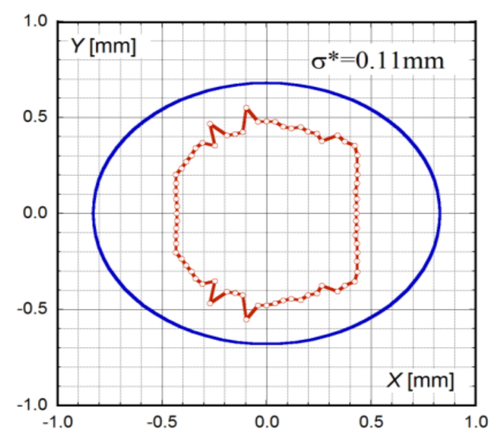
Higgs Factory Preliminary Design



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



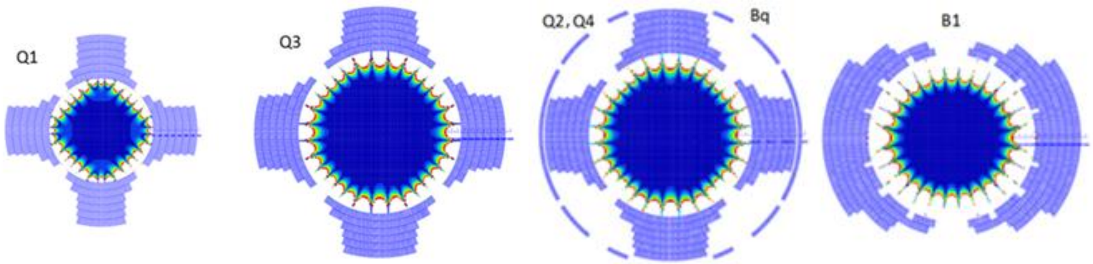
IR quad cold mass inner radii and 4σ beam envelopes for β*=2.5cm.
Q2 and Q4 have 2T dipole component (need higher?)



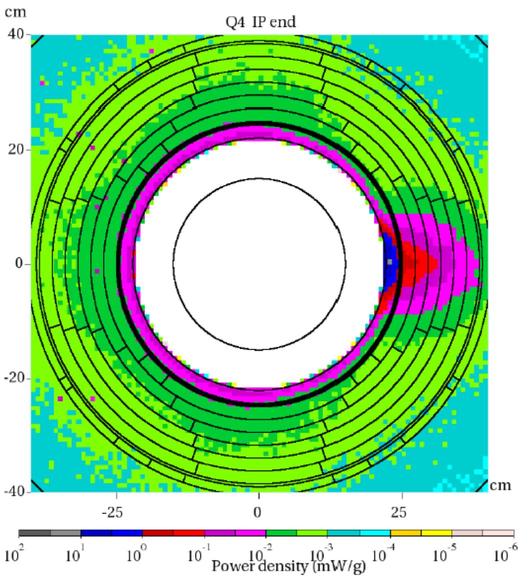
The dynamic aperture (fringe fields + multipoles + correction on) and projection of FF quad aperture (solid ellipse).

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

Large Aperture Magnet Design



	Q1	Q2	Q3	Q4
aperture (cm)	32	50	50	50
gradient (T/m)	74	-36	44	-25
dipole field (T)	0	2	0	2
length (m)	1.0	1.4	2.05	1.7
B_{coil} (T)	16.4	17.2	16.9	(17.2)
Margin @ 4.5°K	0.78	0.62	0.70	(0.62)



- 6-layer, shell-type coil design achieves the design goals with sufficient margin
- Good field quality region (deep blue) ~0.7 of the aperture determines the DA

- Masks between the quads at 4σ and inner absorbers reduced heat loads from 100-150mW/g to <1.5mW/g

The required magnet aperture is feasible from the point of magnet technology. The remaining issue is the detector backgrounds addressed in next talks

Muon Collider Design Parameters

Collision energy, TeV	0.126	1.5	3.0	6.0*
Repetition rate, Hz	30	15	12	6
Average luminosity / IP, $10^{34}/cm^2/s$	0.0025	1.25	4.6	13
Number of IPs	1	2	2	2
Circumference, km	0.3	2.5	4.34	6
β^*, cm	2.5	1	0.5	0.25
Momentum compaction factor	0.08	$-1.3 \cdot 10^{-5}$	$-0.9 \cdot 10^{-5}$	$-0.5 \cdot 10^{-5}$
Normalized emittance, $\pi \cdot$mm$\cdot$mrad	300	25	25	25
Momentum spread, %	0.003	0.1	0.1	0.1
Bunch length, cm	5.6	1	0.5	0.25
Number of muons / bunch, 10^{12}	2	2	2	2
Number of bunches / beam	1	1	1	1
Beam-beam parameter / IP	0.007	0.09	0.09	0.09
RF frequency, GHz	0.2	1.3	1.3	1.3
RF voltage, MV	0.1	12	85	530
Proton driver power (MW)	4	4	4	2

*) The numbers for 6 TeV case are just a projection from lower energy designs

Design Status – Unchanged since December Meeting

E_{com}(TeV)	Lattice design	Magnet design	Heat deposit.	MDI design	Magnet error corr.	Beam-beam & coherent
0.126	✓	✓	✓	✓	✓	✓
1.5	✓	✓	✓	✓	✓	✓
3.0	✓	✓	✓	–	–	–
6.0*	(✓)	–	–	–	–	–

*) There is 6 TeV MC design by the SLAC group (M.-H. Wang et al., IPAC15 TUPTY081) which is not finalized yet (e.g. the momentum compaction factor is by two orders of magnitude higher than required)

The following questions – left unanswered by previous studies but of general interest – can be addressed in the framework of "Fundamental Aspects of Muon Beams":

- Tolerances on random field errors and misalignments, strategy of their correction – of general importance for understanding the real constraints on βmax, momentum compaction factor etc.
- Collimation (halo extraction) - the hope is that with pre-collimated beam bent crystals will be enough.
- Detector backgrounds with quadruplet vs triplet FF in high-energy MC.
- Possible increase in the high-energy MC energy resolution up to $R \sim 10^{-5}$ (next slide)
- Design of new types of lattices, e.g. for beams with large $\varepsilon_y/\varepsilon_x$ ratio as proposed by Dave Neuffer (see support slides)

High Energy Resolution Mode

Final cooling is mostly emittance exchange: $\varepsilon_{6D} = \varepsilon_\perp^2 \varepsilon_L \approx \text{const} \quad \Rightarrow \quad \varepsilon_\perp \sim 1/\sqrt{\varepsilon_L}$

To keep the beam size in FF quads constant: $\varepsilon_\perp \beta_{\max} \sim \varepsilon_\perp / \beta^* = \text{const} \quad \Rightarrow \quad \beta^* \sim \varepsilon_\perp \sim 1/\sqrt{\varepsilon_L}$

To keep the "hour glass" factor constant: $\sigma_s / \beta^* = \text{const} \quad \Rightarrow \quad \sigma_s \sim \beta^* \sim 1/\sqrt{\varepsilon_L}$

Beam relative energy spread:

$$\sigma_E = \varepsilon_L / \sigma_s \sim \varepsilon_L^{3/2}$$

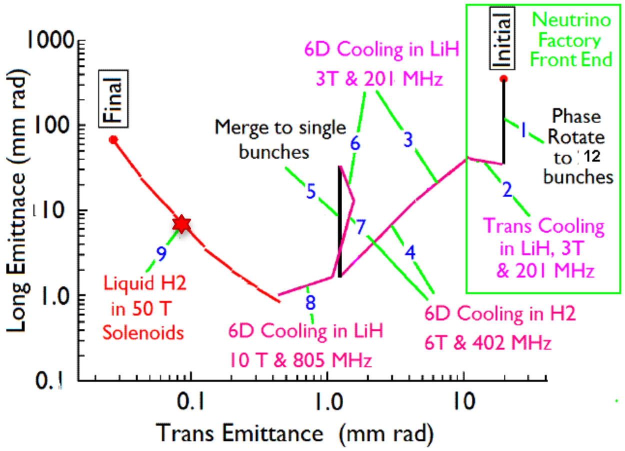
The luminosity will go down, $\mathcal{L} \sim \dfrac{N_\mu^2}{\varepsilon_\perp \beta^*} \sim N_\mu^2 \varepsilon_L$, but not too much thanks to higher Nμ,

whereas the production rate of narrow resonances will go up as

$$\text{PR} \sim \mathcal{L} / \sigma_E \sim N_\mu^2 / \sqrt{\varepsilon_L}$$

Example:

Stop final cooling at ε_{LN}=7mm (instead of 7cm), then the beam relative energy spread will be $\sigma_E \approx 3 \cdot 10^{-5}$ (instead of 10^{-3}) and the production rate of narrow resonances will increase by at least a factor of 3.



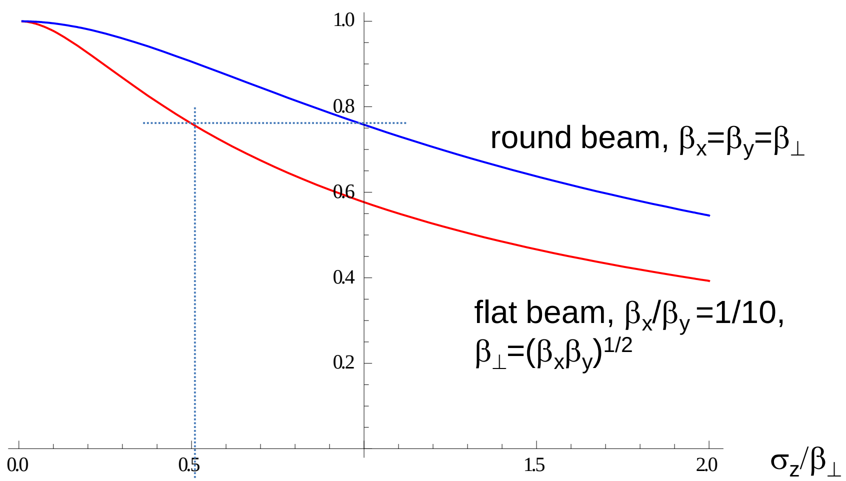
The possibility of high energy resolution is a major advantage of a μ⁺μ⁻ colliders in general (not only of the Higgs Factory) which must not be forgotten.

Flat Beam Proposal (D. Neuffer, D. Summers)

- **1. Cool bunch to ~10^{-4}m ε_T**
  - ~3×10^{-3} ε_L
- **2. Transverse slice to 10 bunches:**
  - $10^{-4}\varepsilon_x \times 10^{-5}$m ε_y
  - Separated longitudinally
- **3. Accelerate as bunch train; recombine longitudinally**
  - 10^{-4}m $\varepsilon_x \times 10^{-5}$m ε_y
  - ~3×10^{-2} ε_L
- **Collide as flat beams;**
  - luminosity ~ same as ε_t= ~3×10^{-5}
- **Flat beam lattice easier to design**
  - **Chromatic correction easier**
    - **10/1 emittance aspect ratio ?**
- **Flat beam (with y as wide dimension) has greatly reduced "neutrino radiation" problem**
    - **Bonus feature**
- **Some disadvantages**
    - hourglass effect (factor) is less
- **Beam-beam parameter ~ twice larger (added by Y.A.)**

Hour-Glass Factor for Flat Beams

For equal beam-beam tuneshifts $\beta_x/\beta_y = \sigma_x/\sigma_y \Rightarrow \beta_x/\beta_y = \varepsilon_x/\varepsilon_y$ (=1/10 in Dave's proposal)



With the same ratio $\sigma_s/\beta_\perp = 1$ the drop in luminosity will be ~ 24% (can stronger beam-beam help?)

The disadvantages with stronger beam-beam effect and lower luminosity can be overshadowed by the possibility to use a doublet FF to minimize the backgrounds – for this we need β_x/β_y<<1 so that the 2nd quad was defocusing