Collider Ring Designs

Muon Collider – Preparatory Meeting, April 10-11, 2019

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- Magnet concepts – A. Zlobin (FNAL)

Key Design Targets

- β^* ~ few millimeters
- Minimize the circumference to provide maximum luminosity
- n_b ~ 2 x 10^{12}
  - Possibly higher
- Large bunch charge requires protection of magnets from heat deposition and detectors from backgrounds produced by secondary particles
- With choice of dipole field (~10T), optimum circumference at each energy results in ~2000 turns in the collider ring before the muons decay

High Energy Collider Comments – p. 1

- Designs require large momentum acceptance
  ⇨ combined with the small β^* leads to challenging IR chromaticity correction!!
  - Local sextupole correction in the IR required
  - Sextupole correction requires significant dispersion so dipoles are an integral part of the IR design
  - Additional benefit of the dipoles is to help sweep away charged particles from muon decays!
- Limited number of turns, has benefits:
  - Impact of high order resonances minimized
  - IBS and residual gas scattering are too weak to produce a beam halo
  - Pre-collimated beams will not grow significantly
    ⇨ collimation in collider ring not necessary
- Bunch length requirements:
  - Need $\sigma_z \leq \beta^*$ to preserve luminosity in presence of the hour-glass effect
  - High energy designs have $\sigma_p/p \sim 10^{-3}$ [Note ~10x Tevatron or LHC values]
    ⇨ large momentum acceptance necessary
    ⇨ small momentum compaction factor required ($\alpha_c \sim 10^{-5}$) to maintain short bunch length with manageable RF voltage

High Energy Collider Comments – p. 2

- Large beam-beam effect: ~0.1/IP
  - Due to large single-bunch charge
  - Stability impacts
  - Aperture impacts in combination with the dynamic β effect
- Neutrino Radiation
  - Limit straight sections to L ≤ 0.5 m
  - Introduce dipole component in all quads
    - Complicates β^* tuning sections
- MAP 1.5 TeV and 3 TeV CoM energy designs utilize Nb_3Sn magnets
- At 6 TeV, preliminary design requires HTS magnets in the IR!

Parameter Summary

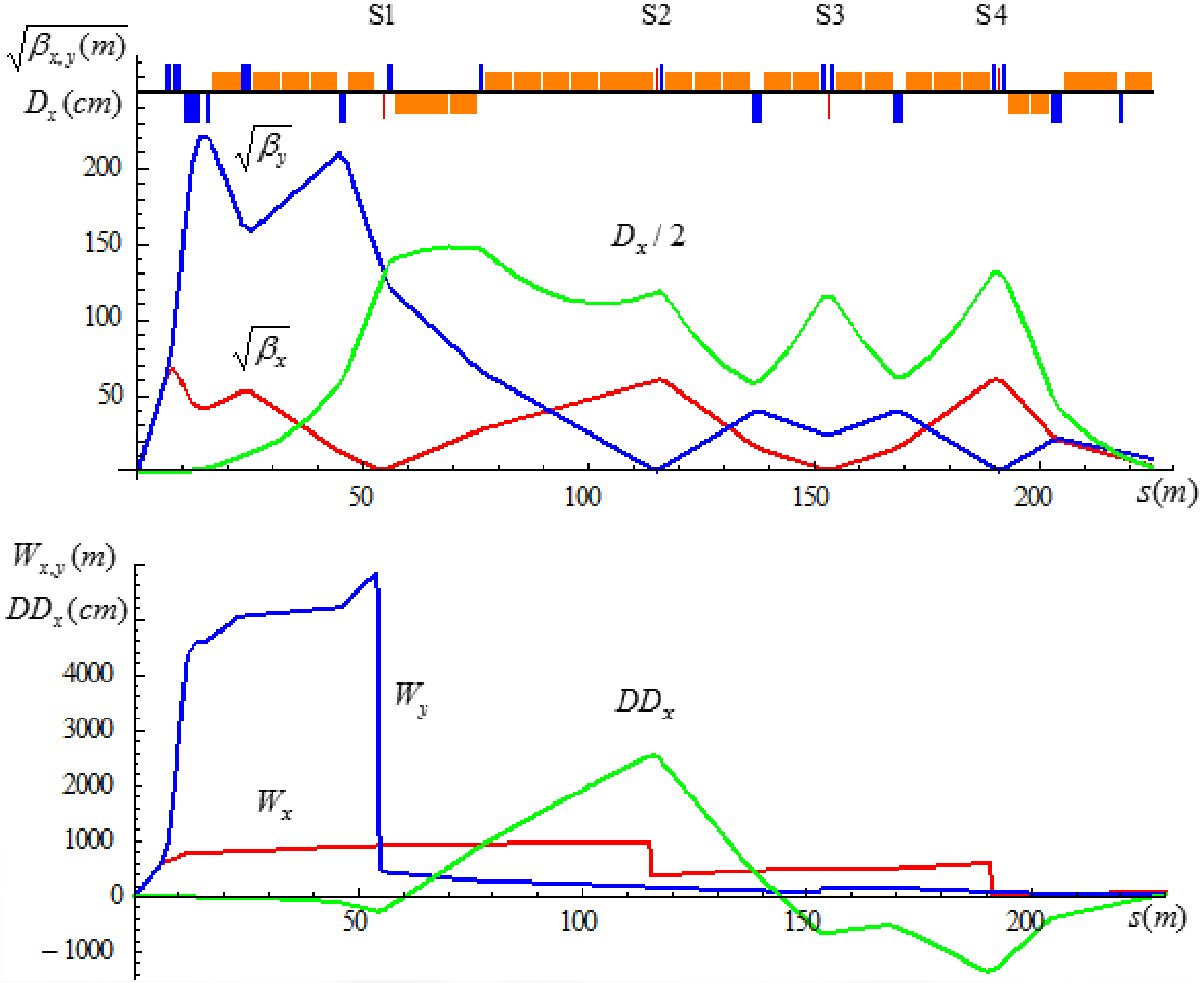
- Detailed designs have been completed for
  - Higgs Factory
  - 1.5 TeV
  - 3.0 TeV
- Including magnet and shielding requirements
- 6.0 TeV design requires more work to finalize IR design and validate projected performance

Parameter	Higgs Factory		High Energy Muon Colliders		
Collision energy, TeV	$0.126^{\text{a)}}$	$0.126^{\text{b)}}$	1.5	3.0	6.0[*]
Repetition rate, Hz	30	15	15	12	6
Average luminosity / IP, $10^{34}/\text{cm}^2/\text{s}$	0.0017	0.008	1.25	4.6	11
Number of IPs	1	1	2	2	2
Circumference, km	0.3	0.3	2.5	4.34	6
β^*, cm	3.3	1.7	1	0.5	0.3
Momentum compaction factor α_c	0.079	0.079	$-1.3 \cdot 10^{-5}$	$-0.5 \cdot 10^{-5}$	$-0.3 \cdot 10^{-5}$
Normalized emittance, π·mm·mrad	400	200	25	25	25
Momentum spread, %	0.003	0.004	0.1	0.1	0.083
Bunch length, cm	5.6	6.3	1	0.5	0.3
Number of muons / bunch, 10^{12}	2	4	2	2	2
Number of bunches / beam	1	1	1	1	1
Beam-beam parameter / IP	0.005	0.02	0.09	0.09	0.09
RF frequency, GHz	0.2	0.2	1.3	1.3	1.3
RF voltage, MV	0.1	0.1	12	50	150

[*] The 6 TeV ring design is not completed yet, the numbers are a projection.

1.5 TeV Design

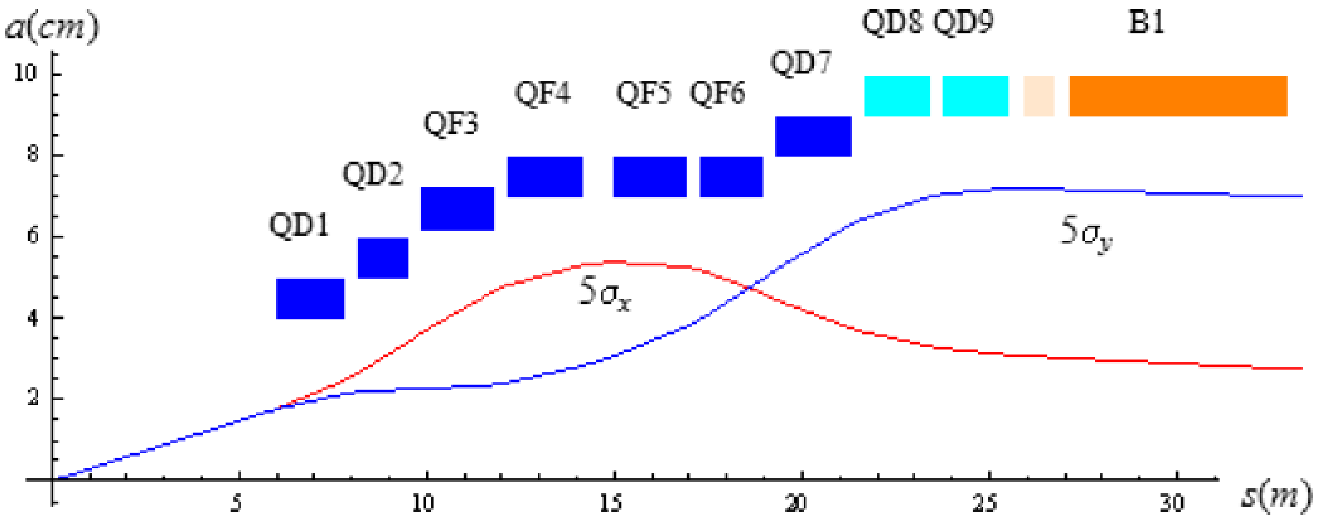
- IR and Chromaticity Correction Section (CCS)
- Utilizes final focus doublet with Nb_3Sn Dipoles
- $\beta^* = 1$ cm
  - Note: smaller β^* or higher energy drives the final focus strengths up rapidly

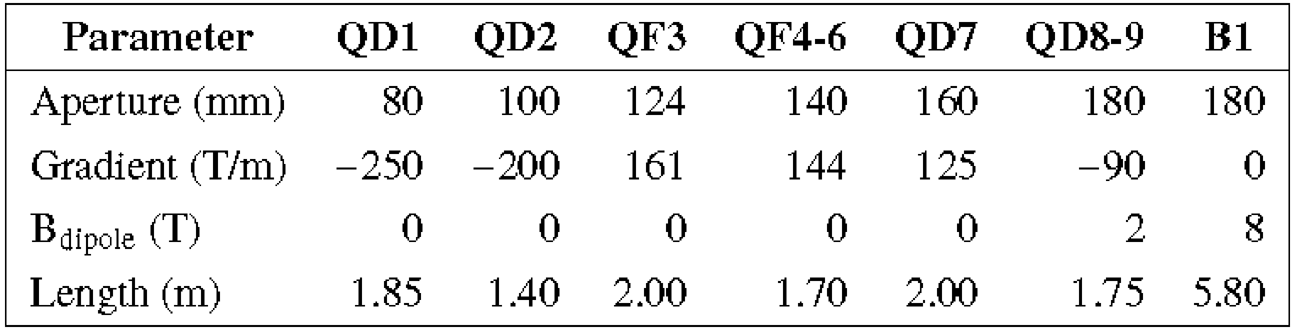


3 TeV Design – p. 1

- IR Triplet Design
  - $\beta^* = 5$ mm
  - Magnet Apertures: $R > 5\ \sigma_{max} + 2$ cm
  - $B_{pole\text{-}tip} < 10$ T

- Challenge
  - Dipole sweeping of decay products not effective in this design
  - Quad nearest IP is focusing



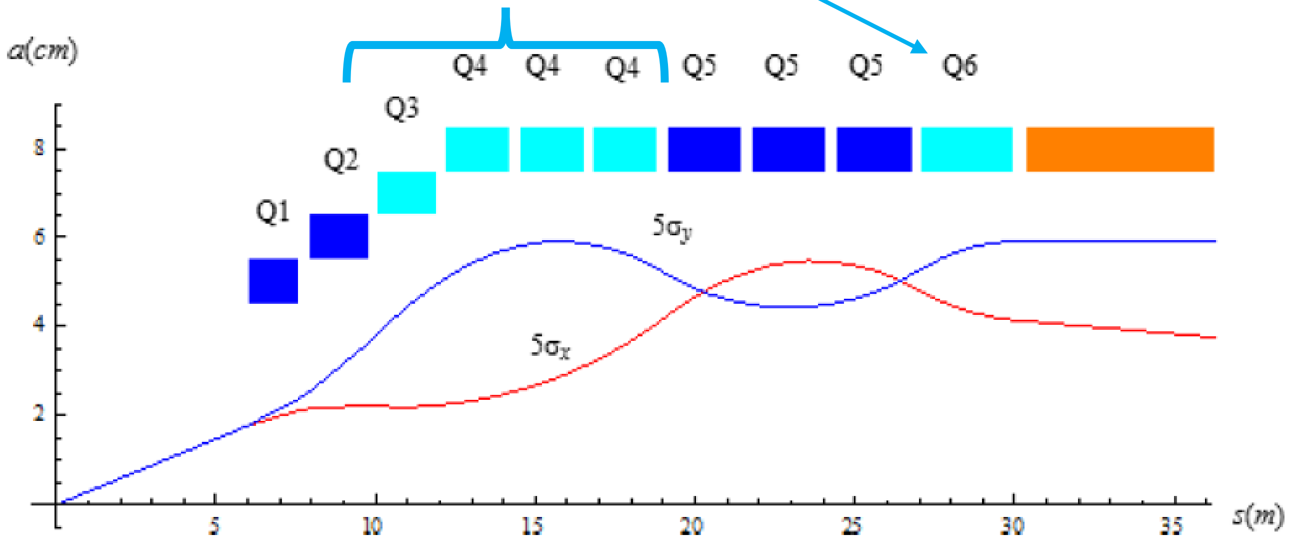


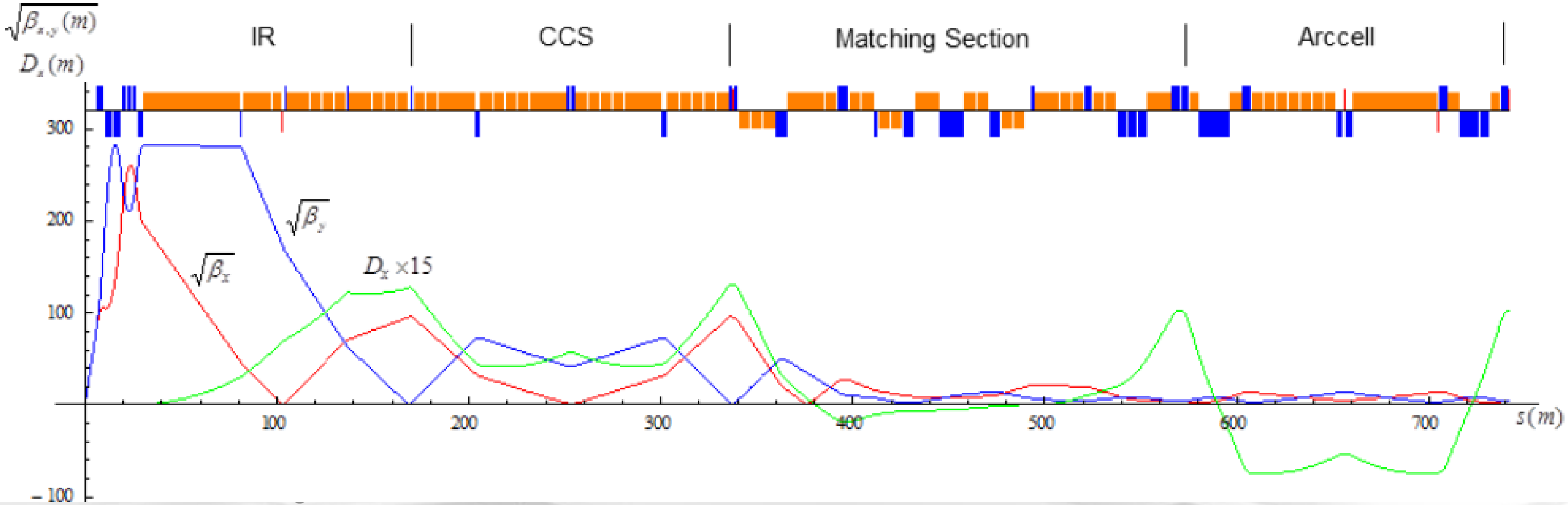
Parameter	QD1	QD2	QF3	QF4-6	QD7	QD8-9	B1
Aperture (mm)	80	100	124	140	160	180	180
Gradient (T/m)	−250	−200	161	144	125	−90	0
B_{dipole} (T)	0	0	0	0	0	2	8
Length (m)	1.85	1.40	2.00	1.70	2.00	1.75	5.80

3 TeV Design – p. 2

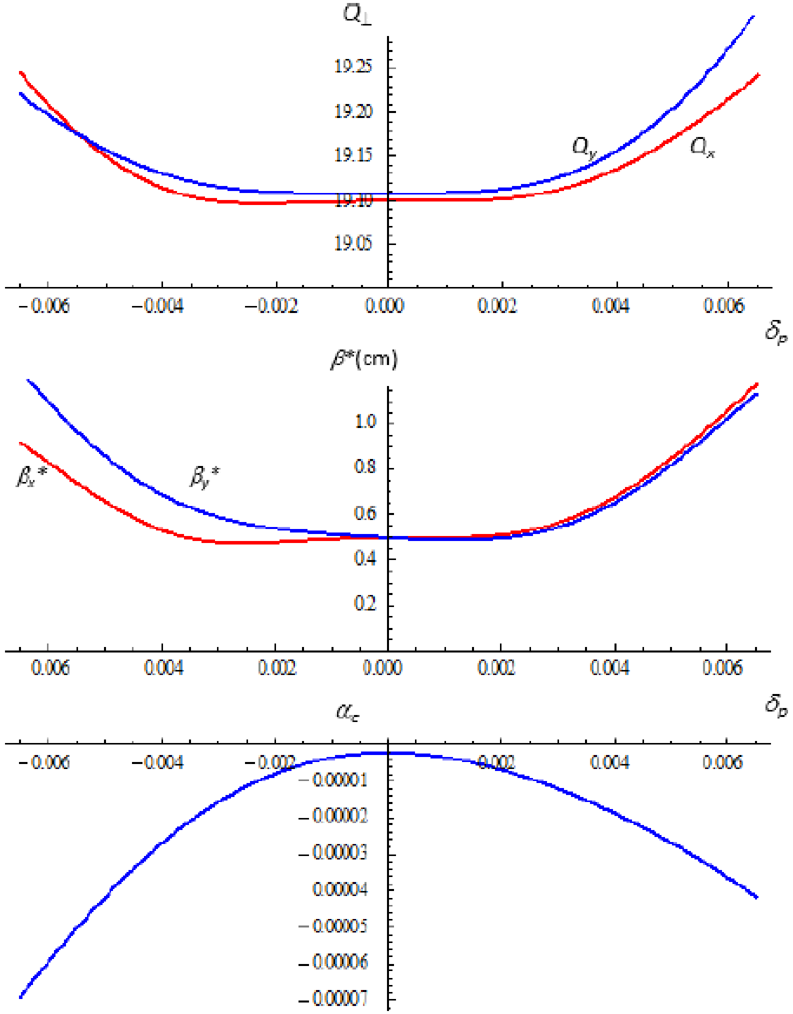
- IR Quadruplet Design
  - $\beta^* = 5$ mm
  - $B_{\text{pole-tip}} < 12$ T
  - Quadruplet design utilized for 3 TeV Baseline parameters
  - Matching sections provide
    - β^* control: 3 mm – 3 cm
    - Low β and dispersion sections for RF bunch-length control
  - Detailed characterization with magnet errors still required

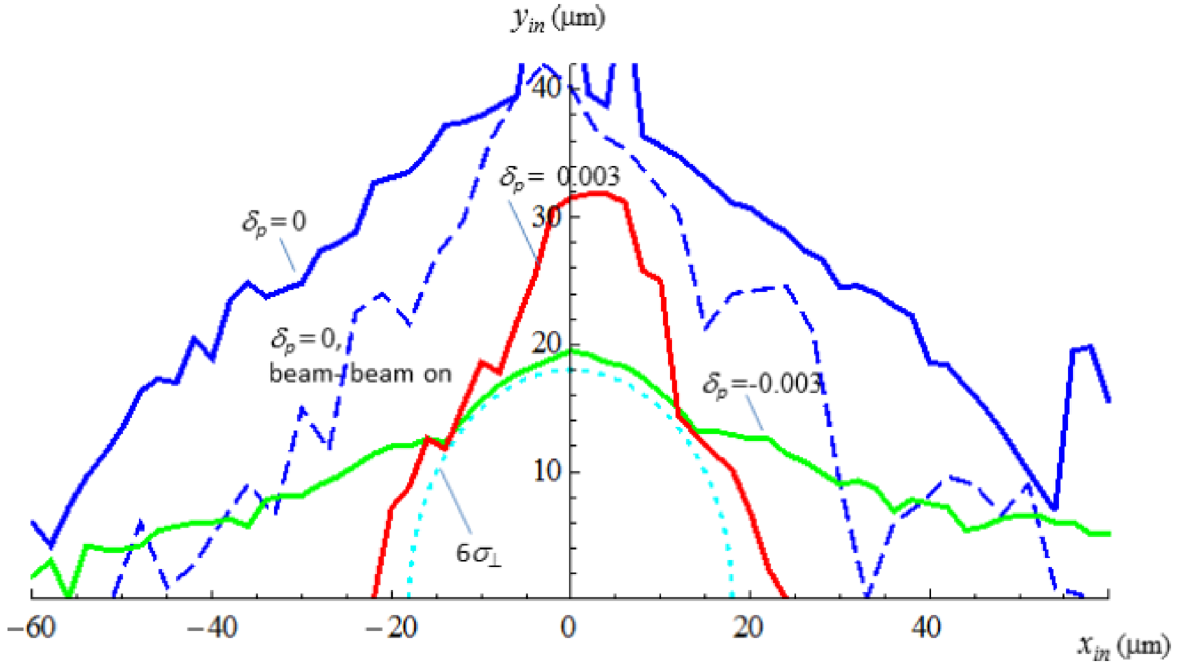
Quads with 2T dipole "sweeping" field





Lattice Performance @ 3 TeV



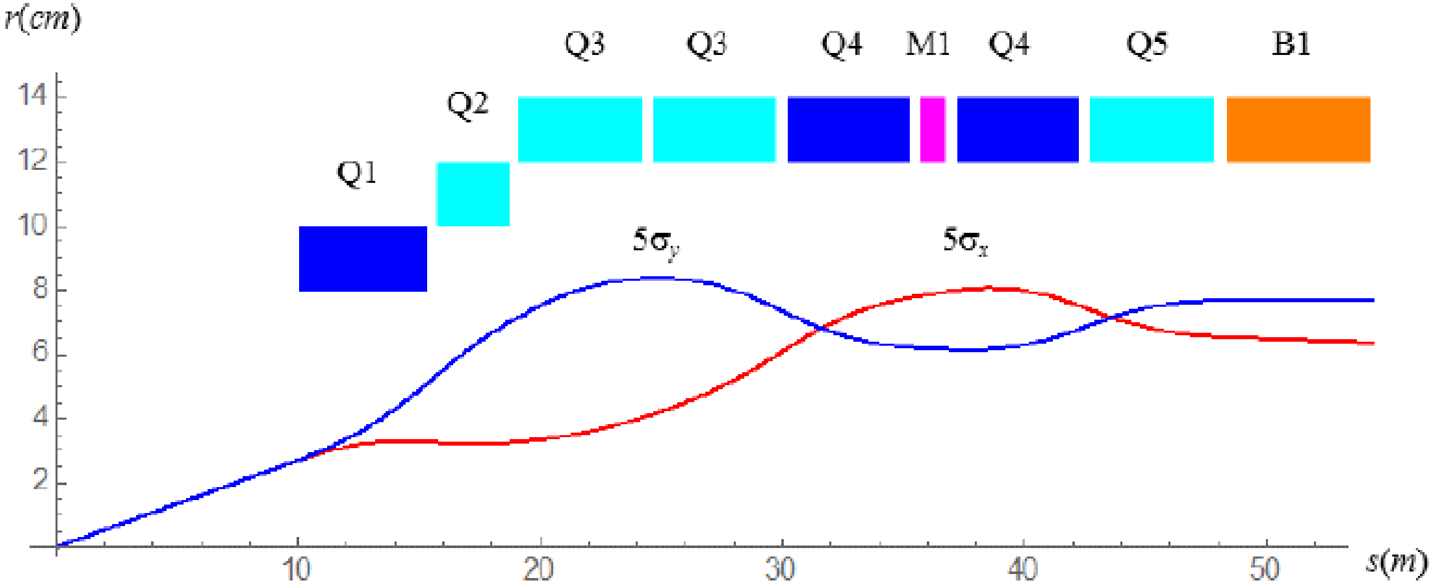


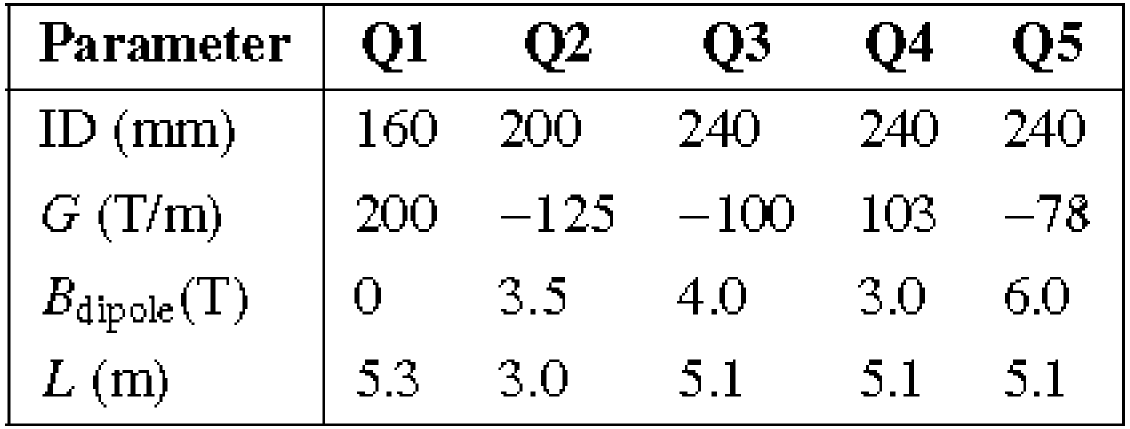
Dynamic aperture (2048 turns) - dashed line includes beam-beam effects.

Off-momentum performance:
Good to ±6σ

6 TeV IR

- $\beta^* = 3$ mm
- Magnet Apertures:
  $R > 5\,\sigma_{max} + 3$ cm
- $B_{pole\text{-}tip} < 16$ T (quads)
  - Now in the HTS regime
  - Is this potentially the real limit on E_{CoM}???

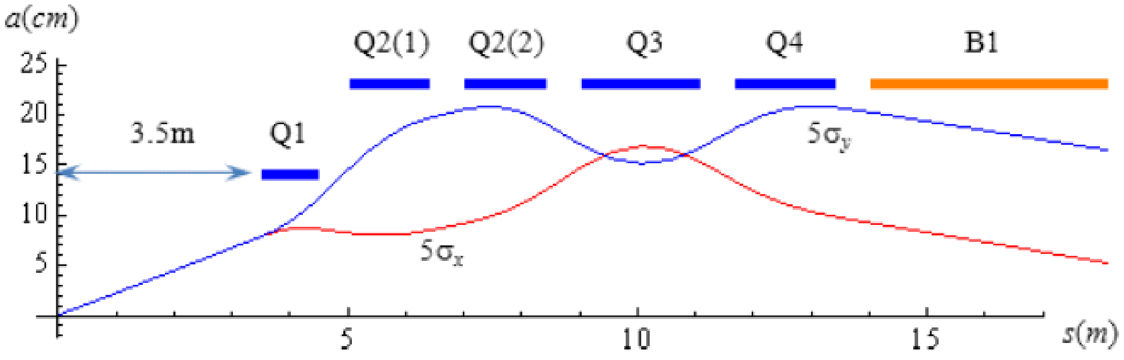




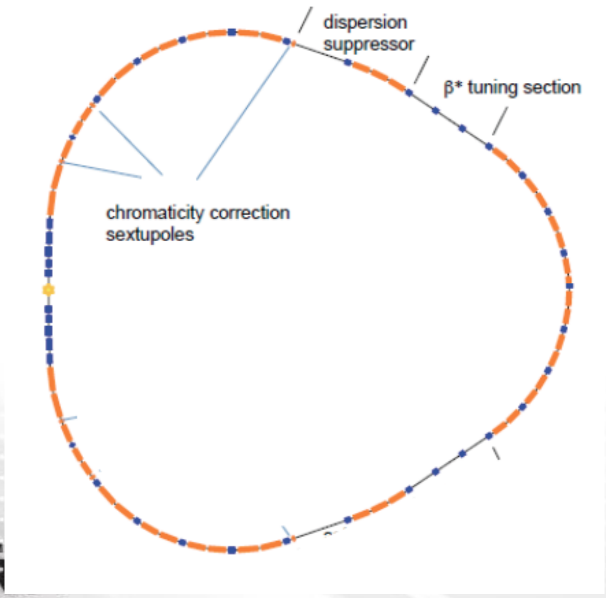
Parameter	Q1	Q2	Q3	Q4	Q5
ID (mm)	160	200	240	240	240
G (T/m)	200	−125	−100	103	−78
B_{dipole}(T)	0	3.5	4.0	3.0	6.0
L (m)	5.3	3.0	5.1	5.1	5.1

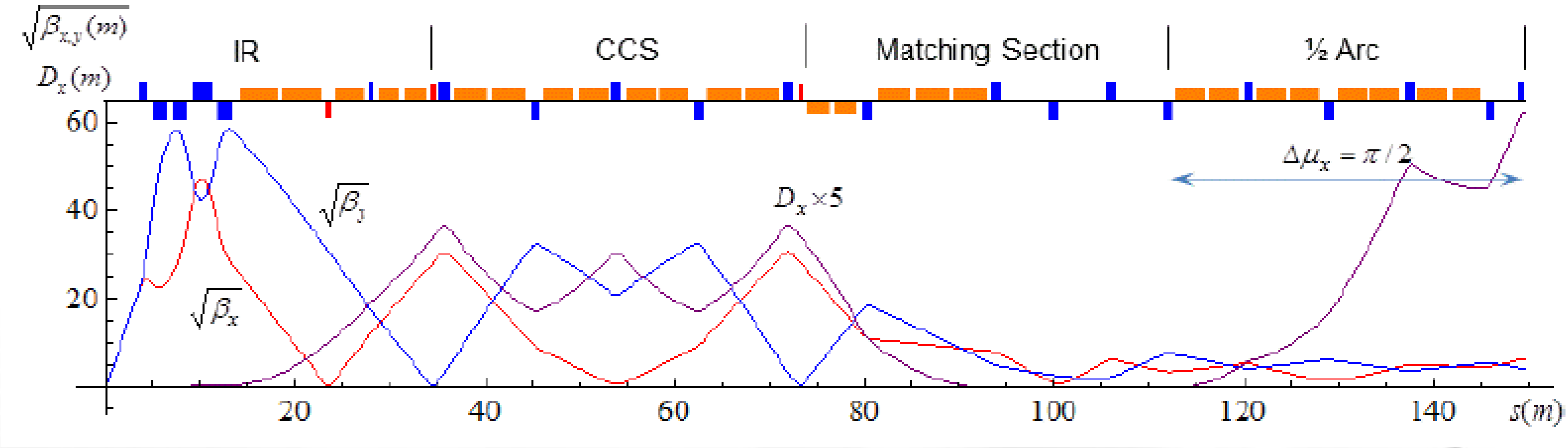
Higgs Factory Design

- Substantively different design given optimization for small energy spread
- Strong sensitivity to machine errors (particularly in the IR) are observed
- Only 1 IR is feasible



Parameter	Q1	Q2	Q3	Q4	B1
Aperture (mm)	270	450	450	450	450
Gradient (T/m)	74	−36	44	−25	0
Dipole field (T)	0	2	0	2	8
Magnetic length (m)	1.00	1.40	2.05	1.70	4.10





7+7 TeV in the LHC Tunnel? (Neuffer, Shiltsev)

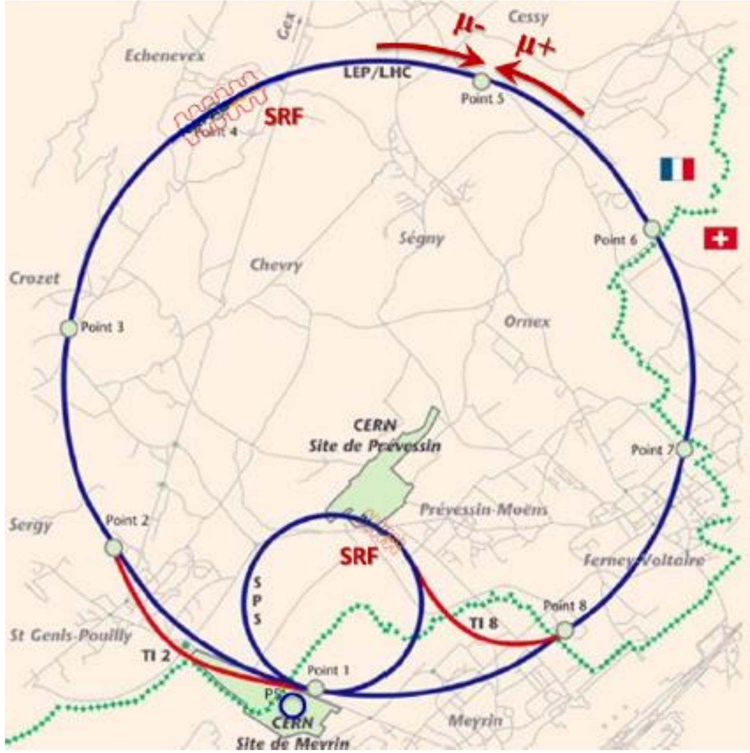
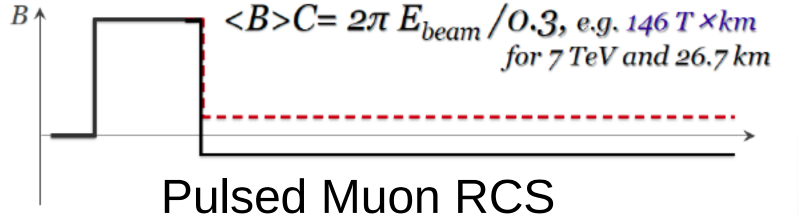


Table 2. Options for a 14 TeV μ^+-μ^- Collider.

Parameter	"PS"	"MAP"	"LEMC"
Avg. luminosity	$1.2 \cdot 10^{33}$	$3.3 \cdot 10^{35}$	$2.4 \cdot 10^{32}$
Beam $\delta E/E$	0.1%	0.1%	0.2%
Rep rate, Hz	5	5	2200
N_μ/bunch	$1.2 \cdot 10^{11}$	$2 \cdot 10^{12}$	4.5×10^7
n_b	1	1	1
$\varepsilon_{t,N}$ mm-mrad	25	25	0.04
β^* , mm	1	1	0.2
σ^*(IR), μm	0.6	0.6	0.011
Bunch length, m	0.001	0.001	0.0002
μ production source	24 GeV p	8 GeV p	45 GeV e^+
p or e/pulse	$6 \cdot 10^{12}$	$2 \cdot 10^{14}$	$3 \cdot 10^{13}$
Driver beam power	0.17 MW	1.6 MW	40 MW
Acceleration, GeV	1–3.5, 3.5–7 RCS	1–3.5, 3.5–7 RCS	40 GV, RLA 20 turn
ν radiation, mSv/yr	0.05	0.8	0.008



$\langle B \rangle C = 2\pi E_{beam} / 0.3$, e.g. 146 T×km for 7 TeV and 26.7 km

Pulsed Muon RCS

Summary

- Detailed concepts are available for Higgs, 1.5 TeV, and 3 TeV
- Study of the 3 TeV design would provide:
  - Comparisons with CLIC
  - Chance to work with a reasonably mature lattice
  - A good next step evaluation
  - Thrusts:
    - Further IR optimization
    - Detector optimization
    - Shielding optimization
- Further design effort needed to:
  - Optimize general IR options
  - Determine realistic limits on max. pole-tip field as a function of collider energy