Muon Collider Design

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Design Goals

• High Luminosity (Higgs Factory $L \sim 10^{32}\text{cm}^{-2}\text{s}^{-1}$, 3TeV MC $L > 4 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$)
  ⇒ round beams (to minimize beam-beam effect)
  ⇒ small $\beta^*$ (Higgs Factory $\beta^* \sim 2\div 3$ cm, 3TeV MC $\beta^* \sim 3\div 5$ mm)
  ⇒ small circumference
  ⇒ small bunch length $\sigma_s \leq \beta^*$ (high-energy MC)
    → momentum compaction factor $\sim 10^{-5}$

• Acceptable detector backgrounds
  ⇒ tight apertures in W absorbers (resistive wall instability?)
  ⇒ dipole component in FF quads
  ⇒ halo extraction (bent crystals?)

• Manageable heat loads in magnets
  ⇒ enough space for W absorbers, shorter distance between masks

• $\beta^*$ variation in wide range (w/o breaking dispersion closure)

• Small collision energy spread $\sigma_E/E \leq 4 \cdot 10^{-5}$ (for Higgs Factory)
  ⇒ instabilities? longitudinal beam-beam effect?

• Safe levels of $\nu$-induced radiation (for $E \geq 3$ TeV)
  ⇒ no long straights (except for IRs)
  ⇒ combined-function magnets to spread $\nu$’s
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 1$^{\text{st}}$ sextupole correcting vertical chromaticity while 2$^{\text{nd}}$ and 3$^{\text{rd}}$ sextupoles form -/+ separated pair for horizontal correction                                    | PRSTAB 14, 061001 (2011)           |
| IR-to-Arc Matching    | $\beta^*$-tuning section with a chicane$^*$ allowing for $\beta^*$ variation in a wide range and having bending field everywhere to spread $\nu$’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 2\textsuperscript{nd} 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):

\[ J_x = \frac{D_x^2 + (\beta_x D'_x + \alpha_x D_x)^2}{\beta_x} \approx \beta_x \beta^2 \]

– both requirement are met with either doublet or quadrupole FF:
Higgs Factory Interaction Region (IR) and Chromaticity Correction Section (CCS), $\beta^* = 2.5\text{cm}$

IR quad cold mass inner radii and $4\sigma$ beam envelopes for $\beta^* = 2.5\text{cm}$

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.
Dispersion suppressor and $\beta^*$ tuning section noticeably increase the ring circumference, but they are probably indispensable.

Flexibility of the optics ($\beta^*=1.5\text{-}10\text{cm}$) allows for adjustments depending on the parameters of the muon beam.

Arcs are very short and do not allow for wide-range tune adjustment.
Modified Higgs Factory Lattice

No reverse bends $\rightarrow$ circumference reduced to 283m (from 300m).

Difficulty in adjustment of the horizontal tune (now $Q_x=5.16$, $Q_y=4.56$).

Some unexpected problem with vertical dynamic aperture is encountered.

Optics functions in half ring for $\beta^*=2.5\text{cm}$
## Higgs Factory Parameters

| Parameter                          | Startup | Design | Baseline |
|-----------------------------------|---------|--------|----------|
| Beam energy, GeV                  | 63      | 63     | 63       |
| Average luminosity, 10^{31}/cm²/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 $\beta^* = 3\text{ cm}$ is 19.6cm – small effect on the total circumference

This concept will be used in the new design but with combined-function magnets.
Momentum compaction factor for a stand-alone cell is $\alpha_p = -0.004$, betatron phase advance is $300^\circ$ 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

$\beta_x, \beta_y$ 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

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

The momentum acceptance for $\beta^* = 5$ mm is $\pm 0.45\%$ and $\pm 0.4\%$ for $\beta^* = 3$ mm
| High Energy MC parameters                  | 1.5 | 3.0 | 6.0* |
|-------------------------------------------|-----|-----|------|
| Collision energy, TeV                    |     |     |      |
| Repetition rate, Hz                      | 15  | 12  | 6    |
| Average luminosity / IP, $10^{34}$/cm²/s | 1.25| 4.4 | 12   |
| Number of IPs                            | 2   | 2   | 2    |
| Circumference, km                        | 2.5 | 4.5 | 6    |
| $\beta^*$, cm                            | 1   | 0.5 | 0.25 |
| Momentum compaction factor, $10^{-5}$    | -1.3| -1  | -0.5 |
| Normalized emittance, $\pi \cdot$ 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)

| Plan Description                                                                 | Person-months |
|----------------------------------------------------------------------------------|---------------|
| 3 TeV MC lattice with quadruplet FF                                               | 6             |
| **Halo extraction scheme for high energy MC**                                     |               |
| Electrostatic separator – too long (~25m for 3 TeV)                               | 3             |
| RF or pulsed septum?                                                              |               |
| Bent crystals? – First look quite encouraging                                     |               |
| 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
Support Slide - Higgs Factory Specifics

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

• Preservation of small $\sigma_E/E \sim 3 \cdot 10^{-5}$ in the presence of strong self-fields ($I_{\text{peak}} \sim 1\text{kA}$!) → LARGE momentum compaction $\alpha_c \sim 0.1$

• 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*:

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

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

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

$$A_x / \sigma = \sqrt{2 I_x / \varepsilon_x}$$
Collision with a thin slice of $N_s$ particles leads to energy change

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

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?