Muon Collider Parameters at different Energies

D. Schulte

Tentative Considerations on Baseline

- Focus on first stage, 1.5 + 1.5 = 3 TeV, L = 1.8 x 10^{34} $cm^{-2}s^{-1}$
  - To come after higgs factory and matching highest CLIC energy
  - Using the high-energy strength of muon colliders
  - Realistic design for implementation at CERN, with cost power and risk scale
  - If successful, feasibility demonstration for CDR

Or less if FCC-ee or ILC are chosen as Higgs factory?

- Explore further step 7+7 TeV, L = = 4 x 10^{35} $cm^{-2}s^{-1}$
  - To match FCC-hh discovery potential
  - Mainly exploration of parameters to guide choices
  - Provide evidence for feasibility, maybe cost frame

Maybe 10 TeV is sufficient?

- Some exploration of lower energies / Higgs factory
  - Scaling from higher energies
  - Not a main focus, except if other projects do not cover lower energies

$$L \gtrsim \frac{5\,\mathrm{years}}{\mathrm{time}} \left(\frac{\sqrt{s}_\mu}{10\,\mathrm{TeV}}\right)^2 2\cdot 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- Open for input

Muon Collider Luminosity Scaling

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High beam power

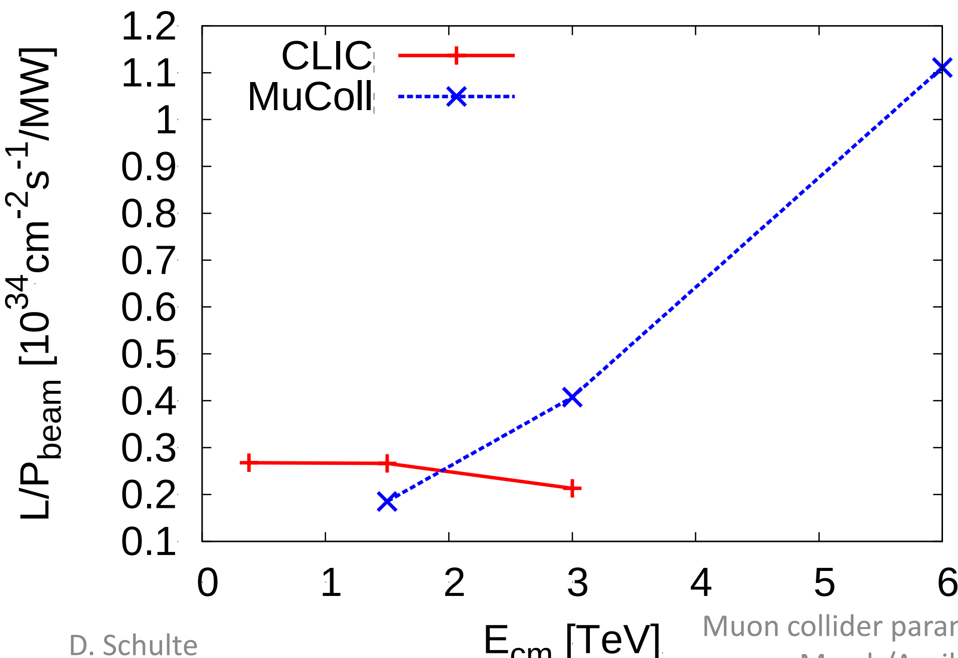
High energy

High field in collider ring

Large energy acceptance

Dense beam

$$L \gtrsim \frac{5\,\mathrm{years}}{\mathrm{time}} \left(\frac{\sqrt{s_\mu}}{10\,\mathrm{TeV}} \right)^2 2 \cdot 10^{35} \mathrm{cm}^{-2} \mathrm{s}^{-1}$$



Basic limitation, need to ensure it can be done!

Luminosity per power proportional to energy

Constant current for required luminosity

Better scaling than linear colliders

MAP Parameters

Parameter	Unit	1.5 TeV	3 TeV	6 TeV
L	10^{34} cm^{-2}s^{-1}	1.25	4.4	12
N	10^{12}	2	2	2
f_r	Hz	15	12	6
P_{beam}	MW	6.75	11.5	11.5
<B>	T	6.3	7	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	10	5	2(.5)
β	mm	10	5	2.5
ε	µm	25	25	25
$\sigma_{x,y}$	µm	5.9	3.0	1.5

From the MAP collaboration:
Proton source

Emittance is constant

$$\sigma_E \sigma_z = \text{const}$$

Collider ring acceptance is constant

$$\frac{\sigma_E}{E} = \text{const}$$

Bunch length decreases

$$\sigma_z \propto \frac{1}{\gamma}$$

Betafunction decreases

Note: should we not rather fix muon beam at source and use different charges at different energies?
(Muons decay while being accelerated)

How Could 10 / 14 TeV Look Like?

Parameter	Unit	1.5 TeV	3 TeV	6 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.25	4.4	12	20	40
N	10^{12}	2	2	2	2	2
f_r	Hz	15	12	6	4	~~3.7~~ 4
P_{beam}	MW	6.75	11.5	11.5	12.8	~~16.8~~ 17.9
$\langle B \rangle$	T	6.3	7	10.5	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1	0.1	0.1
σ_z	mm	10	5	2(.5)	1.5	1.07
β	mm	10	5	2.5	1.5	1.07
ε	µm	25	25	25	25	25
$\sigma_{x,y}$	µm	5.9	3.0	1.5	0.9	0.63

Note: CLIC beam power at 3 TeV is 28 MW

Challenging optics
Maybe hard to make short bunches

And 3 TeV?

Parameter	Unit	1.5 TeV	3 TeV	6 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.25	~~4.4~~ 1.8	12	20	40
N	10^{12}	2	2	2	2	2
f_r	Hz	15	~~12~~ 6	6	4	4
P_{beam}	MW	6.75	~~11.5~~ 5.8	11.5	12.8	17.9
<B>	T	6.3	7	10.5	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1	0.1	0.1
σ_z	mm	10	5	2(.5)	1.5	1.07
β	mm	10	5	2.5	1.5	1.07
ε	µm	25	25	25	25	25
$\sigma_{x,y}$	µm	5.9	3.0	1.5	0.9	0.63

Reduced repetition rate is sufficient
Lower field than at 10 TeV, to be reviewed

Use of LHC Tunnel for Collisions

Average B-field at 14 TeV cm would be about <B> = 5.5 T

- Fixed by beam energy and tunnel circumference
- Well below value of MAP scheme
- Needs about 8 Hz of MAP-type beam to reach luminosity target
- Purpose-built ring would be smaller (15 km?) and needs lower repetition rate

$\Rightarrow$ Seems worth to consider

For 3 TeV cm would only need an average field of <B> < 1.2 T

- Need 36 Hz to reach luminosity target
  - This will be challenging

$\Rightarrow$ Does not seem particularly attractive if source cannot be improved a lot

$\Rightarrow$ But normal conducting magnets in collider might be attractive

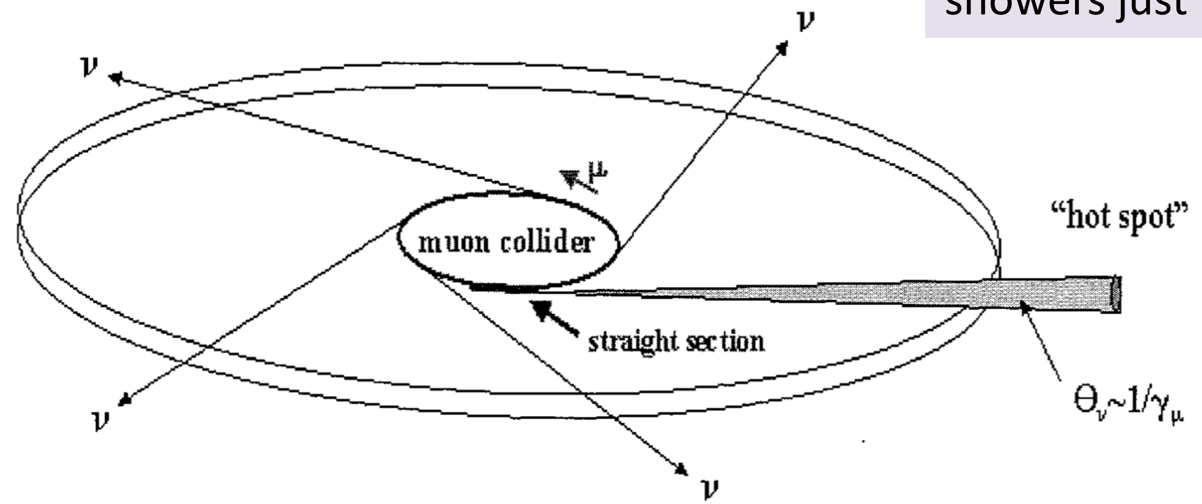
Note: beam power does not depend on energy for the given luminosity scaling

Tentative Target Parameters?

Parameter	Unit	3 TeV	3 TeV*	10 TeV	10 TeV*	14 TeV	14 TeV*
L	10^{34} $cm^{-2}s^{-1}$	1.8	1.8	20	20	40	40
N	10^{12}	2	2	2	2	2	2
f_r	Hz	6	35	4	10	4	7
P_{beam}	MW	5.8	34	12.8	32	17.9	32
C	km	4.5	26.7	10	26.7	14	26.7
<B>	T	7	1.2	10.5	3.9	10.5	5.5
ε_L	MeV m	7.5	7.5	7.5	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1	0.1	0.1	0.1
σ_z	mm	5	5	1.5	1.5	1.07	1.07
β	mm	5	5	1.5	1.5	1.07	1.07
ε	µm	25	25	25	25	25	25
$\sigma_{x,y}$	µm	3.0	3.0	0.9	0.9	0.63	0.63

*Use of LHC tunnel for collider

Neutrino Radiation Hazard



Neutrinos from decaying muons can produce showers just when they exit the earth

Particularly bad in direction of straights
But also an issue in the arcs

Derived combining formulae of B. King

$$D_{gap} \approx 0.41\ \mathrm{mSv}\frac{N_0 f_r T_{operate}}{10^{20}}\left(\frac{E}{\mathrm{TeV}}\right)^3 \frac{\mathrm{m}}{d}\frac{\langle B\rangle}{\mathrm{T}}\left(\frac{\mathrm{T}}{B}+\frac{L}{0.7\ \mathrm{m}}\right)$$

D: radiation dose
E: beam energy
B: Magnetic field
d: depth underground

Radiation to Luminosity Ratio

Based on formulae from B. King

$$D_{gap} \approx 0.41\ \mathrm{mSv}\frac{N_0 f_r T_{operate}}{10^{20}}\left(\frac{E}{\mathrm{TeV}}\right)^3\frac{\mathrm{m}}{d}\frac{\langle B\rangle}{\mathrm{T}}\left(\frac{\mathrm{T}}{B}+\frac{L}{0.7\ \mathrm{m}}\right)$$

$$\mathcal{L} \propto \langle B\rangle \frac{N}{\sqrt{\epsilon_x\epsilon_y\epsilon_L}}\gamma^2\delta N f_r$$

$$\frac{D}{\int\mathcal{L}} \propto aE\left(\frac{\mathrm{T}}{B}+\frac{L}{0.7\,\mathrm{m}}\right)\frac{1}{d}\frac{\epsilon_T\epsilon_L}{N_0}\frac{1}{\sigma_\delta}$$

$$a \approx 4 \times 10^{-4}\frac{mSv}{ab^{-1}}\frac{1}{eV^{-2}m}$$

Reasonable goal could be 0.1 mSv/year

Radiation in Purpose-built Tunnel

Assume MAP-type beam
B = 10.5 T, L = 0.2 m
Deep tunnel d = 500 m

$$\frac{D}{\int \mathcal{L}} \propto aE\left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}}\right)\frac{1}{d}\frac{\epsilon_T \epsilon_L}{N_0}\frac{1}{\sigma_\delta}$$

At 7+7 TeV at target of 4 ab^{-1} radiation would be 0.8 mSv/year

I.e. 8 times too large
⇒ Need to improve

$$\frac{D}{\int \mathcal{L}} = \frac{0.8mSv}{4ab^{-1}}$$

At 3.5+3.5 TeV radiation would be 0.1 mSv/year
(1 ab^{-1} per year)
1.5+1.5 TeV would allow d = 40 m

But need to deal with straights and study exact site

Radiation from Collisions in LHC Tunnel

Radiation at 14 TeV, 4 ab^{-1} per year

- **O(20 mSv/year)** from arcs (B = 6.3 T, L = 0.2 m, d= 23 m)
    - O(7 mSV/year for L=0) mix of magnets would be worse
- **O(3x10^4 mSv/year)** from straights (L = 500 m)

For 5+5 TeV, arcs

- **only factor 2-3 better, straights factor 3**

Arcs could be OK for up to 1+1 TeV, L=0

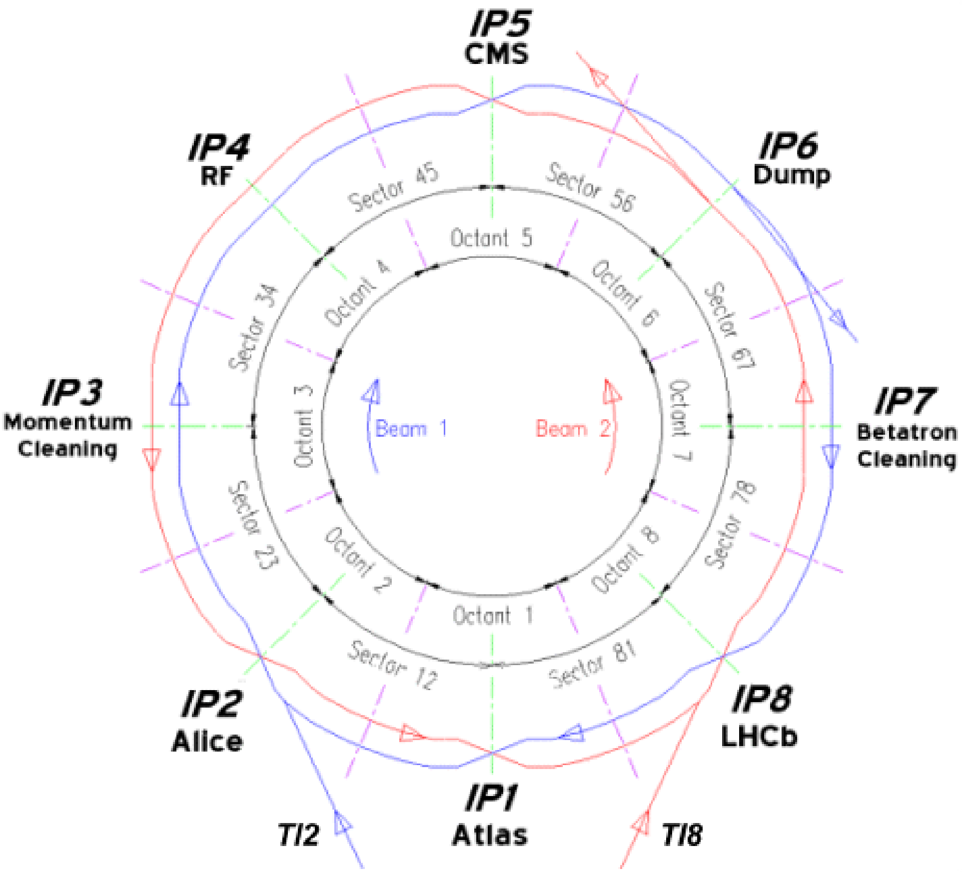
Cannot use LHC tunnel for collider, if we do not find important mitigation

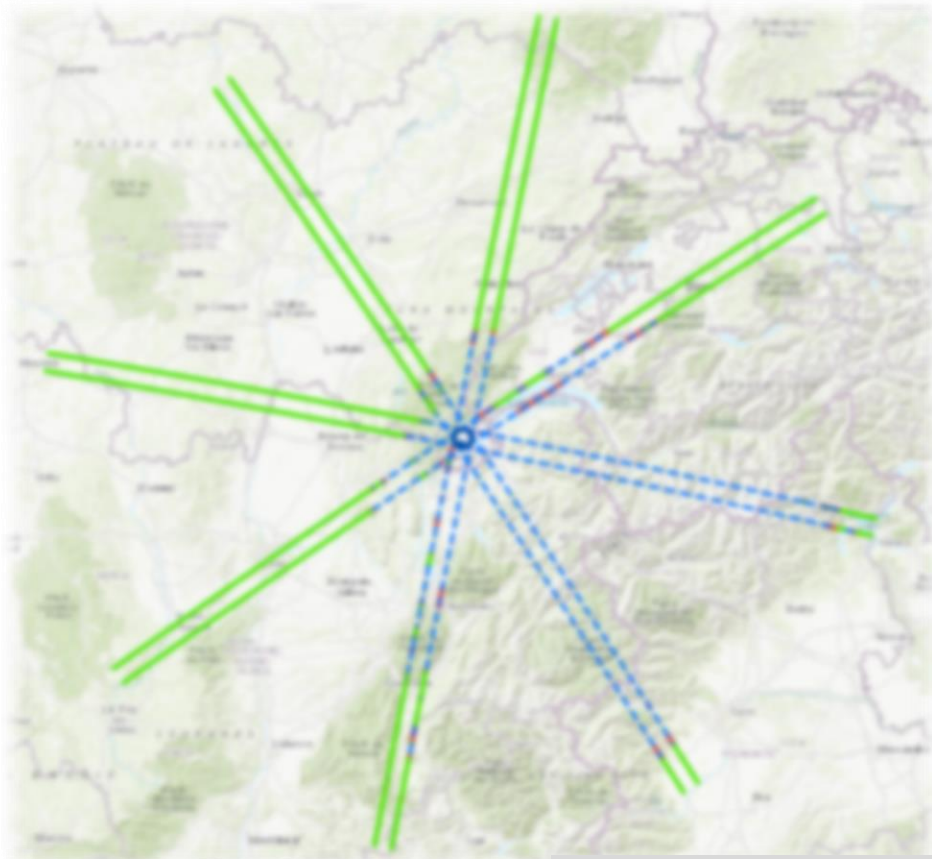
- Provided formula is correct
- Can we wiggle the beam?
- Can we paint it around in the straights?
- Seems an important issue

A much reduced current would help

- LEMMA with 10^{11} muons/s would give factor 80, still problem in straights

Note Effective Depth of LHC





J. Osborn, Y. Robert , …

Minimum distance is 17 km, corresponds to effective depth of d = 23 m
Second shortest is 25 km (d = 50 m), longest is 263 km (d = 5430 m)

Note: Reliability of Estimates

Neuffer / Shiltsev find much smaller radiation for similar proposel of 7+7 TeV in LHC tunnel: 0.15 mSv / year (vs. 19 mSv / year shown)

- Some difference are clear
  - Effective depth 23 m vs. 100 m
  - 20 cm gaps between magnets vs. 0 cm
- But using B. King's formula and their assumption, I find still find 1.4 mSv
- (I find 0.3 mSv / year using the same approach)

Difference may come from translation of dose to effective dose (Gy to Sv) or maybe the spatial distribution of the showers

Need to urgently verify formulae

$\Rightarrow$ Paola's talk

Need to also clarify many points

- What is the integration time for the radiation
  - E.g. if we operate 10^7 s per year can we take dose averaged per year?
- What is the area that needs to be averaged over?

Mitigation Approaches

Tricks
e.g. beam wiggling, dumping the beam, …

$$\frac{D}{\int \mathcal{L}} \propto aE\left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}}\right)\frac{1}{d}\frac{\epsilon_T \epsilon_L}{N_0}\frac{1}{\sigma_\delta}$$

Higher field in collider ring
And shorter gaps

Magnet design

Deeper tunnel

Civil engineering

Denser beam

Source design

Larger energy
spread acceptance

Lattice design work

More efficient physics
More years of running

This is a key for the exploration of 14 TeV
Will benefit also lower energy designs

Performance Consideration

$$\frac{D}{\int \mathcal{L}} \propto aE \left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}} \right) \frac{1}{d} \frac{\epsilon_T \epsilon_L}{N_0} \frac{1}{\sigma_\delta}$$

More efficient physics
More years of running

Note: Integrated luminosity requirement scales with E^2
Hence dose scales with E^3

Obviously, the required energy and luminosity are important
Should make sure that requirements are not exaggerated

- Potentially scenarios with different levels of luminosity
- For some physics trade-of energy vs. luminosity might be considered

Performance Consideration

$$\frac{D}{\int \mathcal{L}} \propto aE \left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}} \right) \frac{1}{d} \frac{\epsilon_T \epsilon_L}{N_0} \frac{1}{\sigma_\delta}$$

Higher field in collider ring
And shorter gaps

Magnet design

This is mainly a question of arc magnet design

Advanced technologies very helpful, can profit from other developments
(HTS for FCC-hh etc.)
But gaps are also critical and have special needs due to remnants of muon decays, so need specific design work

Some beam dynamics questions concerning focusing, i.e. quadrupole content etc.

Performance Consideration

$$\frac{D}{\int \mathcal{L}} \propto aE \left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}} \right) \frac{1}{d} \frac{\epsilon_T \epsilon_L}{N_0} \frac{1}{\sigma_\delta}$$

Deeper tunnel

Civil engineering

This is civil engineering

- In particular: can we find solutions for the straights?
- Can we have a deep tunnel and connect to the existing ones?

Performance Consideration

$$\frac{D}{\int \mathcal{L}} \propto aE\left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}}\right)\frac{1}{d}\frac{\epsilon_T \epsilon_L}{N_0}\frac{1}{\sigma_\delta}$$

Denser beam

Source design

This factor is given by the muon source

- Improve beam quality from source
  - Design of the cooling systems (three stages)
  - Exploration of proton complex and muon combination scheme
- Verify assumption that beam quality is preserved into collider ring
- Important muon losses all along (factor 10), need consistent budgets

Performance Consideration

$$\frac{D}{\int \mathcal{L}} \propto aE \left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}} \right) \frac{1}{d} \frac{\epsilon_T \epsilon_L}{N_0} \frac{1}{\sigma_\delta}$$

Smaller longitudinal emittance or larger energy acceptable of collider ring allow shorter bunches
$\Rightarrow$ Smaller collision betafunction
$\Rightarrow$ Harder optics

Denser beam

Source design

Larger energy spread acceptance

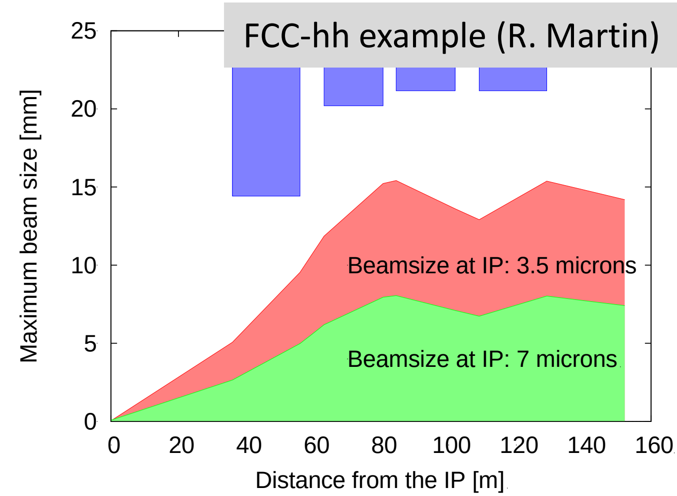
Lattice design work

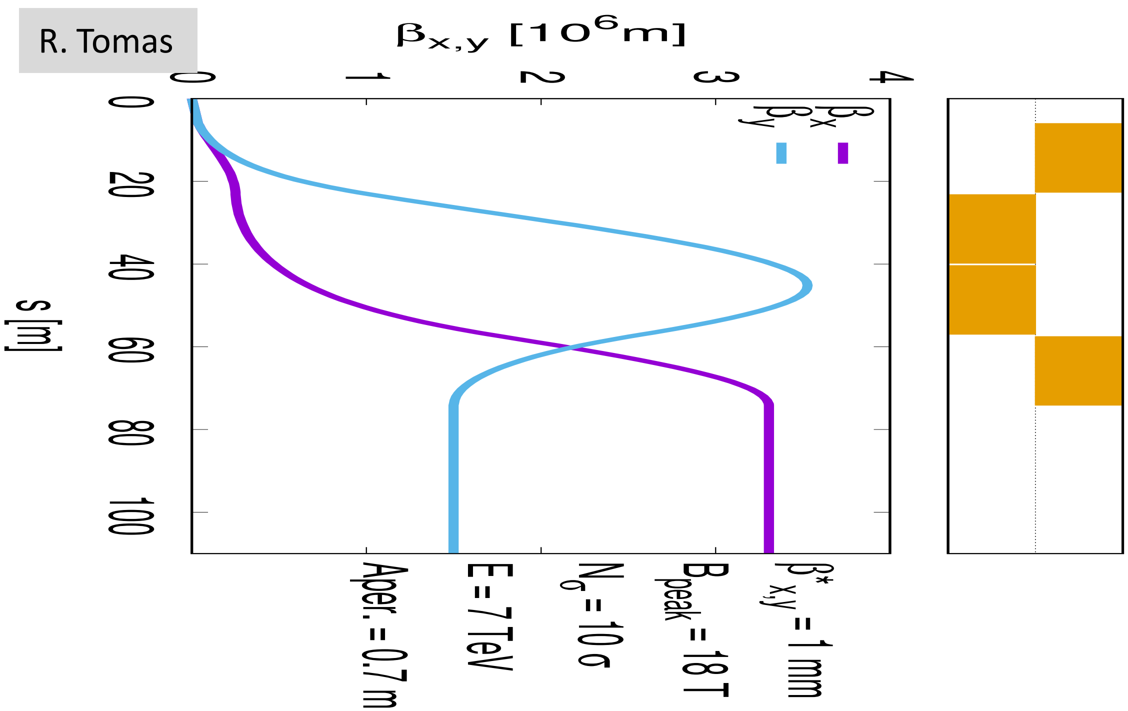
Example Key Question: BDS

Need smaller betafunctions at higher energy
Or smaller longitudinal emittance / larger energy acceptance

$$b^{*} \mu \frac{1}{E}$$

And focusing of higher energy beam is more difficult





First look from Rogelio Tomas on final triplet at 14 TeV (L* = 6 m):

Challenging system
Need to add shielding

Performance Consideration

$$\frac{D}{\int \mathcal{L}} \propto aE \left(\frac{\mathrm{T}}{B} + \frac{L}{0.7\,\mathrm{m}} \right) \frac{1}{d} \frac{\epsilon_T \epsilon_L}{N_0} \frac{1}{\sigma_\delta}$$

Denser beam

Source design

Larger bunch charge or smaller transverse emittance increase luminosity

But also increase beam-beam effect

Note: if limited by the source, faster acceleration can help:
Number from J.-P. Delahaye:
30% of particles survive acceleration

If we push to 50% we gain factor 1.7

$\Rightarrow$ Acceleration design is also important

$$N = N_0 \left(\frac{E}{E_0} \right)^{\frac{m_\mu c^2}{\tau c G}}$$

Example Key Question: Beam-beam

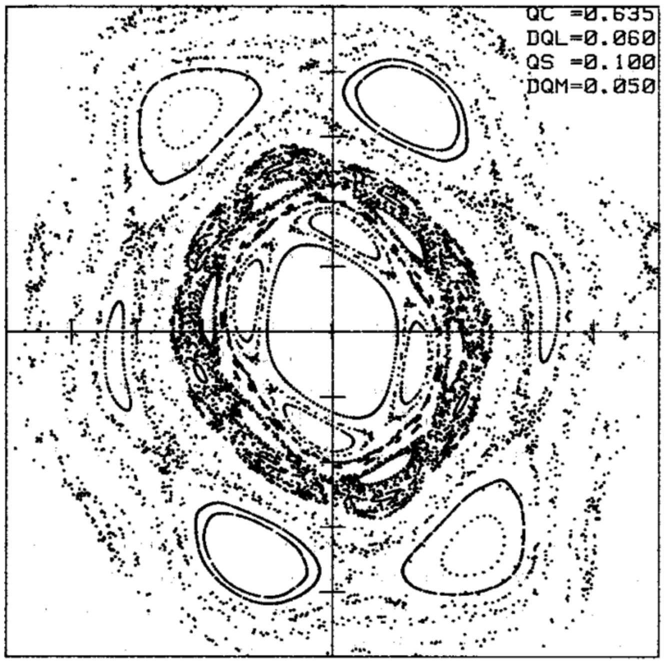


Plate 3b

Beams act as nonlinear lenses
- Can lose particles from tails
- Can blow-up the emittance

MAP parameters are acceptable (D. Neuffer)
But not too much margin

Started first simulations (GUINEA-PIG, linear optics, correction lens) and find similar results

Increase in charge or decrease of transverse emittance will increase beam-beam effects

Need to find ways to push acceptable limit as much as possible
⇒ Detailed studies of beam-beam effect
⇒ Requires also study of impedances in collider ring

Performance Consideration

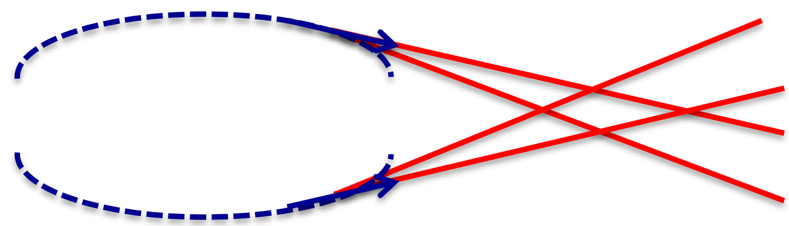
$$\frac{D}{\int \mathcal{L}} \propto aE\left(\frac{\mathrm{T}}{B}+\frac{L}{0.7\,\mathrm{m}}\right)\frac{1}{d}\frac{\epsilon_T\epsilon_L}{N_0}\frac{1}{\sigma_\delta}$$

Tricks
e.g. beam wiggling, dumping the beam, …

Optics and beam dynamics of the collider ring
Needs actual work to understand the consequences of such an approach

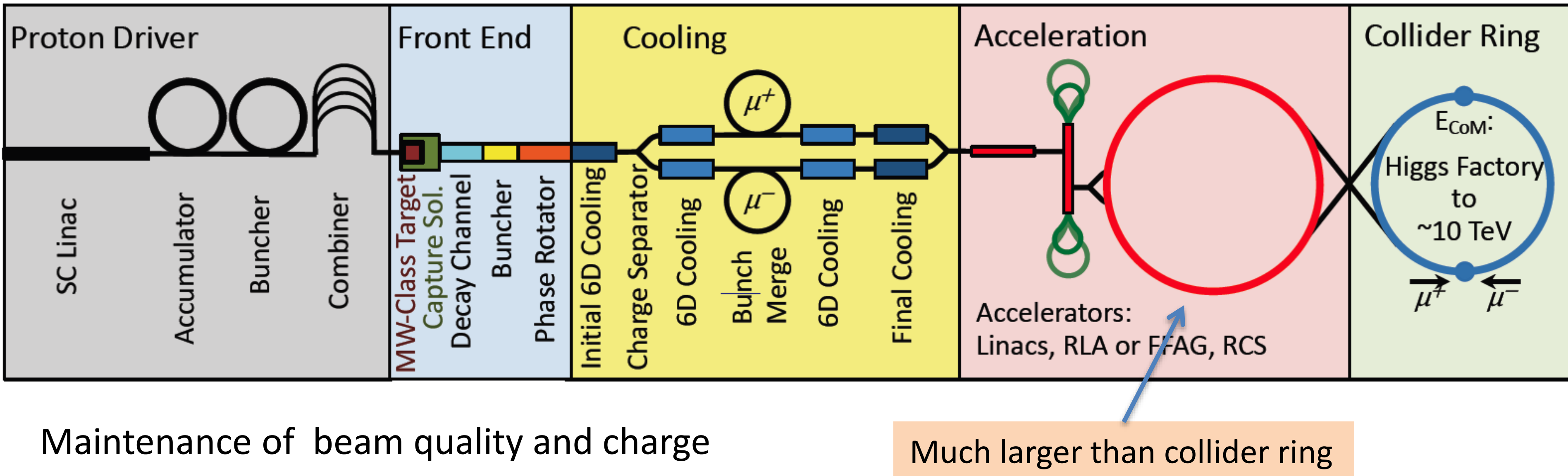
Beam emittance not important in arcs, assume 7 TeV beam, β=100 m gives angle 0.15 / ϒ

Need ± 10/ ϒ, i.e. 15 mm offsets
Can we put elements on movers?



Need to have solution for the straights
- Owning the surface land (area is not so small, O(1km^2))
- What about the accelerator straight parts for acceleration?

Beam Acceleration



Maintenance of beam quality and charge

Important cost driver: RF acceleration, magnets, …

Ambitious superconducting RF field is 20 MV/m in lower frequency cavities

But need to include filling factor (about 2/3 in ILC)

Can we assume

5 MV/m up to 300 GeV (85 %)

1 MV/m to 1.5 TeV (77%)

Would yield 65 % survival, but assume 50% with margin?

Acceleration

Total length L of fast-ramping magnets is (independent of design of rings, ignoring injection energy as approximation)

$$L = 10.5km \frac{E}{B} \frac{T}{TeV}$$

3 TeV case
1.5 TeV beam energy needs 7.9 km of ramping ±2 T magnets
NTi magnets with 8 T, need same integrated field => about 2 km
Need to maybe add at least 10-15 % for RF and 10-5% injection / extraction
(total voltage of 12-24 GV, i.e. 22-12 % loss from 0.3 TeV to 1.5 TeV)
$\Rightarrow$ Total ring circumference about 12 km

Slightly more than dedicated 10 TeV collider ring (10 km) and somewhat less than 14 TeV case (14 km)

Should we build this tunnel and reuse it for the collider later?

Or use the LHC tunnel
About 1.4-1.8 T average field, plenty of reserve, very flexible optimisation
Can maybe install 36 GV in straights

Acceleration

14 TeV case

For 7 TeV beams need a total of 36.8 km of ±2 T magnets
Could be shorter with superconducting, fast-ramping magnets, but is ambitious

Single ring design could use 4.6 km 16 T NSn magnets
Plus RF for 1-2 MV /m (22-40% loss) and injection/extraction
$\Rightarrow$ About 50 km of accelerator ring

10 TeV case

For 5 TeV beams expect to need single ring of about 35 km total

From 1.5 TeV to 5 TeV might be able to live with one new ring in LHC tunnel

- 100% filling of the arcs: 4.3 km of 16 T and 18.4 of ±2 T

7 TeV Acceleration in LHC Tunnel

A bit less than 23 km of arcs (assume 100 % filling of arcs)

14 TeV

Single stage from 1.5 to 7 TeV

- Requires 28.9 km of fast ramping ±2 T magnets, too long

⇒ Have to modify first energy stage ring

⇒ Or higher field in ramping magnets

Two-stage approach

- First ring about 3 km of 16 T and 20 km of ±2 T ramping magnets
    - Up to 4 TeV
- Second ring 7.3 km of 16 T magnets 15.4 km of ±2 T

⇒ Total length of superconducting magnets comparable to collider ring (10km)

Need to review the magnet parameters carefully

- Some may be quite aggressive
- Maybe superconducting ramping magnets can work

Acceleration Radiation Considerations

- Lower radiation than collider ring (fewer turns and mostly lower energy)
  - Depends on the average gradient and magnet ramping speed
  - Typically factor O(10) to O(100), use 30 as example

  $\Rightarrow$ Not so much a problem in the arcs if we avoid field-free gaps
  - But need RF to accelerate the beam

  $\Rightarrow$ This can give short or long straight sections, which amplify the radiation

  $\Rightarrow$ Needs actual design of the accelerator to evaluate this

- For 1.5 TeV beam in LHC (e.g. fast-ramping 1.4-1.8 T magnets, 45 GV RF)
  - Gaps of O(30 m) are still OK
  - Straights would be O(20) too long, requires improvement (helical trajectory?)

- For 3 TeV beam in LHC
  - Gaps of 3 m would be OK
  - O(200) too high in straights, but might still find solutions

- Higher energies likely require advanced solutions for arcs (factor a few improvement)

  $\Rightarrow$ **Important work to use LHC tunnel for the accelerator**

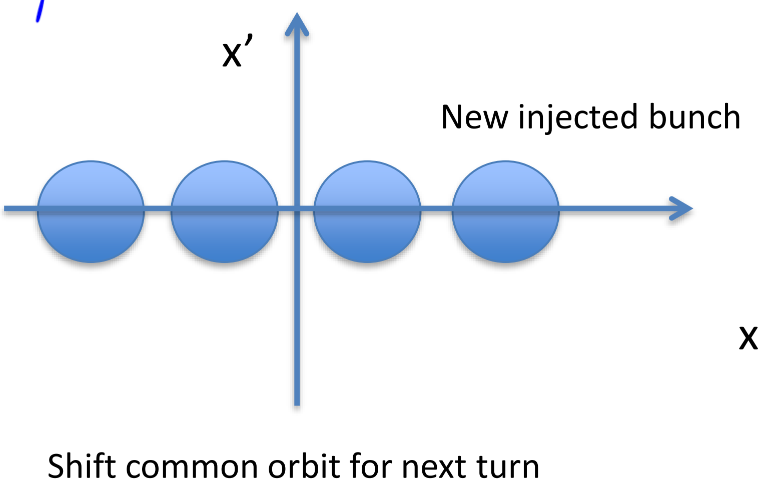
Need to study mitigation of radiation from straights (even for use of FCC tunnel)

Example for Advanced Concept? Stacking

Can increase relevant beam density by stacking n bunches side by side in phase space

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

$$\epsilon = \sqrt{\epsilon_x \epsilon_y}$$



Could combine bunches in transverse phase space

Theoretically, $\varepsilon_x \varepsilon_y$ scales with number of bunches

Charge also scales with number of bunches

Hence

$$\frac{N}{\epsilon} \approx \sqrt{n} \frac{N_0}{\epsilon_0}$$

But difficult to do…

Particularly interesting for LEMMA with high rate of bunches

But only with square root of combination factor

Tentative Target Parameters?

Parameter	Unit	3 TeV	3 TeV*	10 TeV	10 TeV*	14 TeV	14 TeV*
L	10^{34} $cm^{-2}s^{-1}$	1.8	1.8	20	20	40	40
N	10^{12}	~~2~~ 2.2	~~2~~ 2.2	1.8	1.8	1.8	1.8
f_r	Hz	~~6~~ 5	~~35~~ 29	~~4~~ 5	~~10~~ 12	~~4~~ 5	~~7~~ 9
P_{beam}	MW	~~5.8~~ 5.3	~~34~~ 32	~~12.8~~ 14.4	~~32~~ 35	~~18~~ 20	~~32~~ 37
C	km	4.5	26.7	10	26.7	14	26.7
<B>	T	7	1.2	10.5	3.9	10.5	5.5
ε_L	MeV m	7.5	7.5	7.5	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1	0.1	0.1	0.1
σ_z	mm	5	5	1.5	1.5	1.07	1.07
β	mm	5	5	1.5	1.5	1.07	1.07
ε	µm	25	25	25	25	25	25
$\sigma_{x,y}$	µm	3.0	3.0	0.9	0.9	0.63	0.63

Adjust for staging, G = 1 MV from 1.5 to 5 TeV,
Or 1.3 MV from 1.5 TeV to 7 TeV

*Use of LHC tunnel for collider

Conclusion

Important work still required to establish robust parameter sets

- Can define tentative parameters for 3 TeV based on MAP
  - Mainly need to verify and integrate
- But need to find improvements for 10 to 14 TeV for radiation

Key work areas are largely the same for both:

- Radiation mitigation in all parts of the complex
  - Solution for straights, beam wiggling, …
- Limits / improvements of the muon source and cooling
- The collider ring design with its focusing and beam stability
- Exploration and choices of acceleration complex and its parameters
- Need integrated optics and beamdynamics design
  - Exploration / mitigation of bottlenecks
- Technical R&D for
  - Muon source components including integration (construction of model)
  - Collider ring magnets conceptual design
  - Conceptual design of fast ramping / special accelerator magnets, superconducting RF
- Exploration of other technology limitations, e.g. transfer systems, cryogenics, …
- Exploration of alternatives, novel solutions, e.g. LEMMA, …

Many thanks to people who helped
M. Palmer, J.-P. Delahaye, Ch. Carli,
X. Buffat, D. Neuffer, …

Conclusion

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Reserve

Radiation from Arcs

Formula from B. King

$$D_{arc} \approx 0.41\,\mathrm{mSv}\,\frac{N_0 f_r T_{operate}}{10^{20}} \left(\frac{E}{\mathrm{TeV}}\right)^3 \frac{\mathrm{m}}{d}\,\frac{\langle B \rangle}{B}$$

Total number of muons per year

- Neutrino interaction cross section proportional to E
- Energy in shower proportional to E
- Vertical shower size inversely proportional to E

Distance R to surface proportional to sqrt(d)
Irradiated area proportional to R^2

Local rate depends on field compared to average

Radiation from Straights

Formula from B. King

$$D_{straight} \approx 0.59\,\mathrm{mSv}\frac{N_0 f_r T_{operate}}{10^{20}}\left(\frac{E}{\mathrm{TeV}}\right)^3 \frac{\mathrm{m}}{d}\frac{\langle B\rangle}{\mathrm{T}}\frac{L}{\mathrm{m}}$$

Total number of muons per year

- Neutrino interaction cross section proportional to E
- Energy in shower proportional to E
- Vertical shower size inversely proportional to E

Distance R to surface proportional to sqrt(d)
Irradiated area proportional to R^2

Let us check

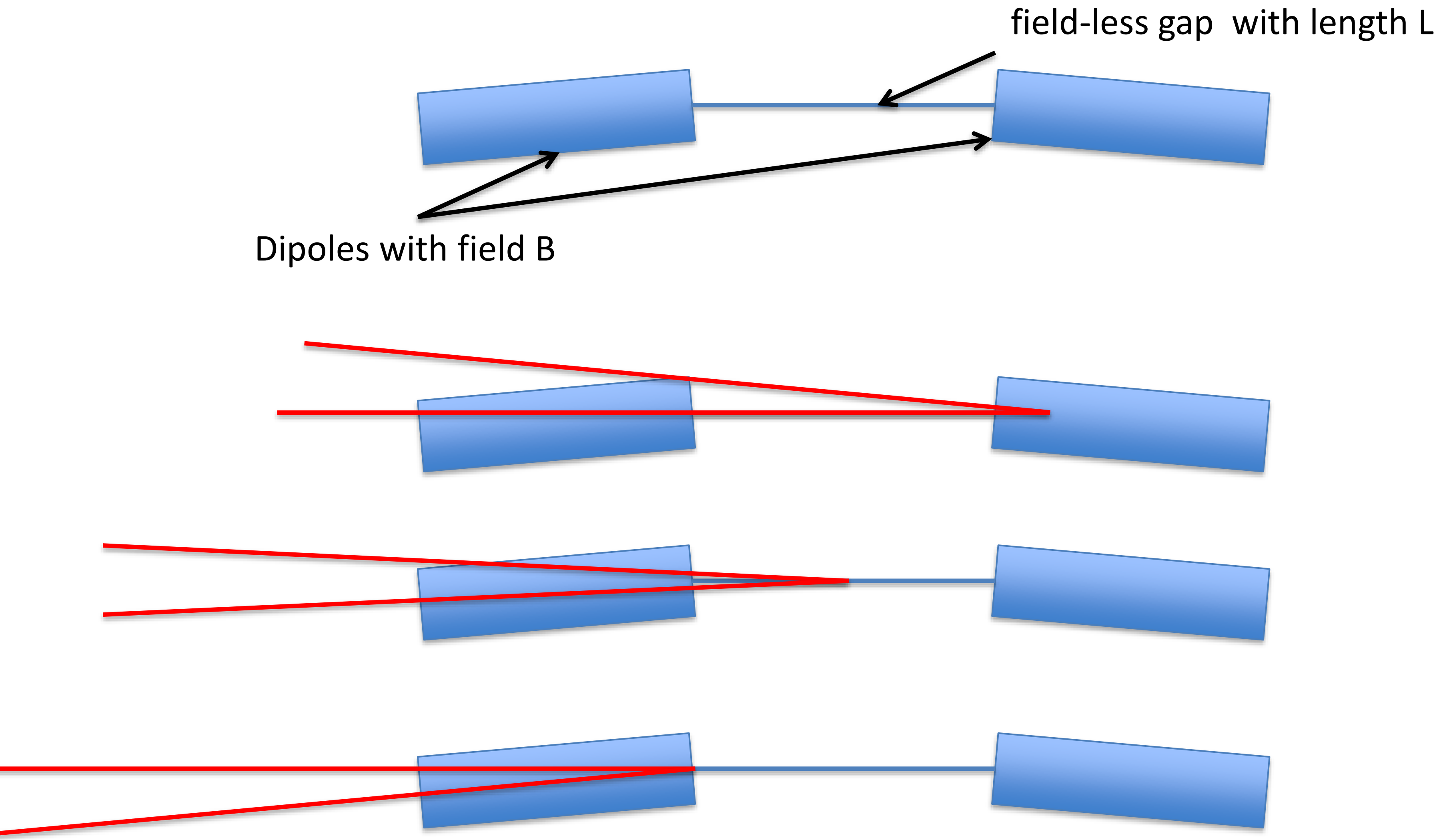
Radiation from Straights

$$D_{straight} \approx 0.59\,\mathrm{mSv}\,\frac{N_0 f_r T_{operate}}{10^{20}}\left(\frac{E}{\mathrm{TeV}}\right)^3 \frac{\mathrm{m}}{d}\frac{\langle B\rangle}{\mathrm{T}}\frac{L}{\mathrm{m}}$$

Fractions of muon lost in straight is L / C
Horizontal width is proportional to R / E
i.e. radiation proportional to L / C x E / R

C is proportional to E / <B>
i.e. L <B> / E x E / R

Radiation from Gaps



Have to add radiation of arc with permanent bending and straight

Collision in FCC Tunnel

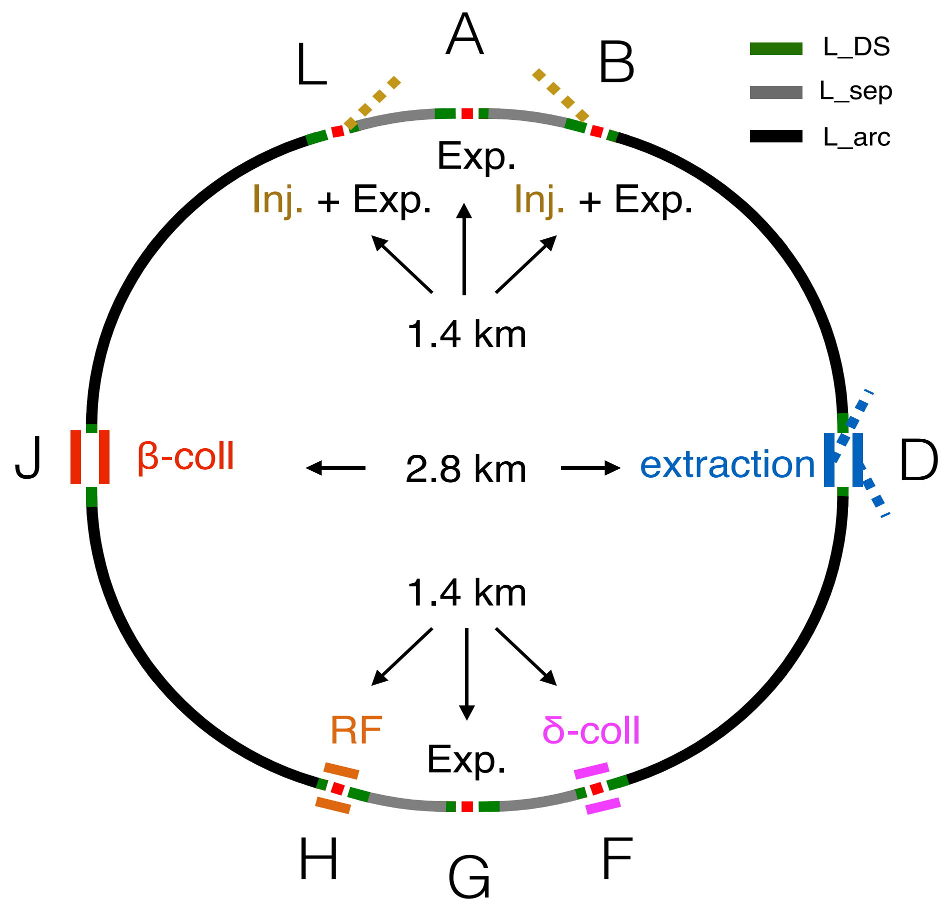
Would be at even higher energies (50 to 100 TeV cm)

- Radiation is much worse
- But can still define layout
  - In particular arrange straights
  - e.g. racetrack design?

Solutions with combined accelerator/collider ring will have even more radiation from arcs since the average field is lower

Low emittance beam would help

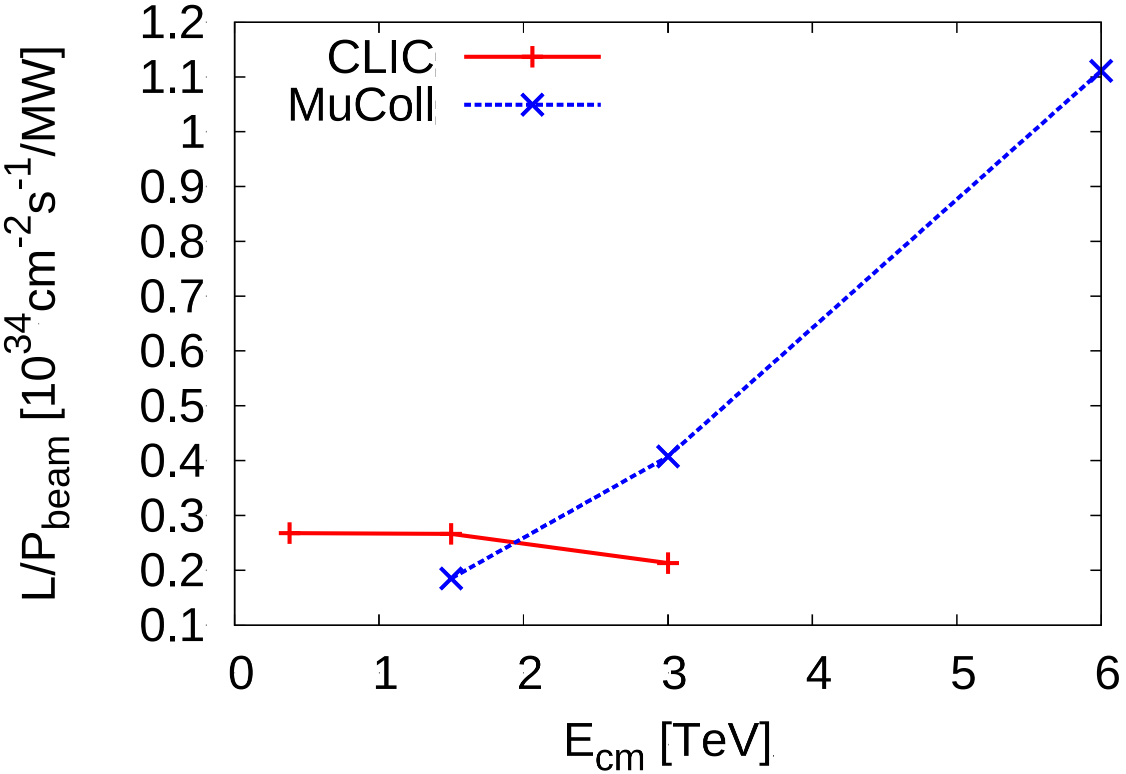
- Need factor 200 less current



Luminosity Comparison

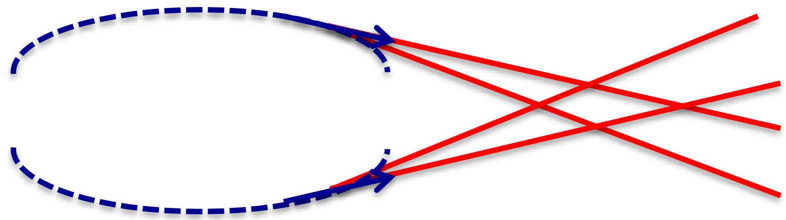
The luminosity per beam power is about constant in linear colliders

- Beam parameters are depending on acceleration technology and beam-beam
- Bunch charge, length normalised emittances and betafunctions remain the same
- Luminosity per current increases (adiabatic damping)
- But power consumption also increases



$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r \propto H_D \frac{N}{\sqrt{\varepsilon_x \varepsilon_y \beta_x \beta_y}} \gamma N n f_r$$

Example Beam Wiggling



Beam angular spread does not help much in arcs

- For 7 TeV beam, β=100 m corresponds to 0.15 / Υ
- Less at lower energies or larger betafunctions

Wiggling of the beam or slow orbit changes requires significant offsets

- Assume factor ten dilution: angle ≈ ± 10/ Υ
- For β=100m need angle of 70 RMS divergences, i.e. equivalent offset at same betafunction of ≈15 mm
- Can we put equipment on movers to vary orbits?

Need to have solution for the straights

- Owning the surface land (area is not so small, O(1km^2))
- What about the accelerator straight parts for acceleration?