Collider Study needs

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Choice of Energy for Study

- Go to highest reasonable Energy: 2 TeV in c of m
- Some parameters (e.g. muons/bunch are easier)
- We need a Frontier Machine for attention

- 3 times SC Linear Collider
  Minimum useful factor
- Stated ’equivalent’ of LHC
- Same as CLIC
- 1/4 the radiation Problem
  e.g. 1/4 the depth
Collider

\[ L \propto n_{\text{turns}} n_{\text{bunches}} \frac{N_{\mu}/\text{bunch}}{\sigma_{\perp}^2} \]

\[ = n_{\text{turns}} n_{\text{bunches}} \frac{N_{\mu}/\text{bunch}}{\left(\frac{\epsilon_{\perp}}{\gamma} \beta_{\perp}\right)} \]

\[ = n_{\text{turns}} \left(\gamma n_{\text{bunches}} N_{\mu}/\text{bunch}\right) \left(\frac{N_{\mu}/\text{bunch}}{\epsilon_{\perp}}\right) \left(\frac{1}{\beta_{\perp}}\right) \]

\[ = n_{\text{turns}} (P_{\text{beam}}) (\Delta \nu_{\text{tune shift}}) \left(\frac{1}{\beta_{\perp}}\right) \]

- \(n_{\text{turns}}\) set by average bending field
- \(\sigma_{\parallel} \leq \beta_{\perp}\) set by final focus design and dp/p
- So \(\epsilon_{\parallel} \propto \gamma \frac{dp}{p} \gamma\) set by final focus design
- \(\epsilon_{\perp}\) does NOT appear in \(L\) formula
- For more Luminosity: allow greater \(\Delta \nu_{\text{tune shift}}\) or smaller \(\beta_{\perp}\)
## Parameter Examples

### Assume

<table>
<thead>
<tr>
<th>Average bending field</th>
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<tbody>
<tr>
<td>Luminosity</td>
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<table>
<thead>
<tr>
<th>E$_{cm}$</th>
<th>N$_{\mu}$</th>
<th>N$_{b} \times$ f</th>
<th>P$_{\mu}$</th>
<th>$\beta_\perp = \sigma_z$</th>
<th>dp/p</th>
<th>emit$_\perp$</th>
<th>$\Delta \nu$</th>
<th>$\epsilon_6$</th>
<th>10$^{-12}$m</th>
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<td>2</td>
<td>$3 \times 15$</td>
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<td>3</td>
<td>0.24</td>
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### Variations

<table>
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<tr>
<th>E$_{cm}$</th>
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<td>a Higher $\epsilon_\perp$</td>
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<td>$1 \times 15$</td>
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<td>d High $\Delta \nu$</td>
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**Hard**  **Easier**

Values inside $N_b \times f$ are given as examples only the product matters here
Notes on Variations

Alternatives keeping same beam power and radiation
a) Higher emittance easy, but requires Larger number of muons per bunch, probably demands single bunch of each sign from phase rotation

b) Lower emittance will require new final cooling method allows lower number of muons/bunch, but demands smaller 6D emittance or larger $\text{dp/p}$

Alternatives lowering beam power and radiation
c) A lower beta requires stronger final focus, and shorter bunch final 6D emittance is less

d) Higher beam beam tune shift may be acceptable or may require some tune shift correction. Problem is larger numbers of muons per bunch and probable single bunch from phase rotation

e) Higher tune shift and smaller emittance gives power reduction without increasing charge per bunch
Beam-beam tune shift correction

- Would increase muons per bunch
- Lower average beam current and radiation
- Lithium at IP background may be problem
- Electron beam correction at another location in the ring
  But not working yet at Fermi
- 4 beam: $\mu^+ + \mu^-$ on $\mu^+ + \mu^-$ transverse instability
Acceleration

- FFAG cost/GeV is falling fast with Energy
- Suggests FFAG’s will be suitable all the way
- But pulsed synchrotron can still be considered

Particle loss for

\[ \varepsilon = 6 \text{ MV/m} \]

\[ \frac{N_{\text{final}}}{N_{\text{initial}}} = \left( \frac{E_{\text{initial}}}{E_{\text{final}}} \right) \left( \frac{m_{\mu}}{\varepsilon \tau_{\mu} c} \right) \approx 0.8 \]

for baseline

\[ N_{\mu}(\text{final}) = 2 \times 10^{12} \]

\[ N_{\mu}(\text{initial}) = 2.5 \times 10^{12} \times 3 \text{ bunches at 15 Hz} \]

Can 6 MV/m average be achieved?
3 Final Cooling

Solenoid

- Lattice with local low Betas
  (Rol calls this PIC)

Problems

- many cells of thin $w \approx \beta_\perp$ absorbers
- Momentum acceptance tends to be small

- Very high field pulsed or HTC small bore solenoids 60T?

Problems

- difficult acceptance match from linac to high field solenoid
- even 60 T not enough
Lithium Lens Ideas

- Need large momentum acceptance match from linac to lens, independent of whether used in ring or linear system.
- Helical Lithium lens for emittance exchange by path length vs energy correlation.

To decrease final beta

- Liquid lithium free ”jets”
  - Wiggled beam might give emittance exchange.
- Liquid Li in ”rubber” tube
- Li with salt blanket
Optical Stochastic cooling

1. Need to revisit parameters and power dependence on initial emittance

2. Note: Recent progress on lasers for RHIC study
Minimum Transverse Emittances

Required $= 50 \times 10^{-6}$ m
Initial $= 20 \times 10^{-3}$ m
Factor $= 1/400^2 = 1/160,000$

- Solenoid barely ok for Alternative a): emit$=150$ mm mrad
- Even Li Lens needs development
- Or use of inverse emittance exchange
- Optical Stochastic cooling could do better by several orders
  but still needs low input emittance
Minimum Longitudinal Emittance

Initial $\epsilon_\parallel = 2$ m
Final $\epsilon_\parallel = 6.8 \times 10^{-2}$ m

Required with dilution: $\epsilon_\parallel = 4 \times 10^{-2}$ m

Factor 1/50  (or 1/15 into 3 bunches)
6D factor $1/6 \times 10^6$ (or $1/(2 \times 10^6)$ into 3 bunches)

For RFOFO Ring:
$\mathcal{E} = 8$ Mv/m, $\lambda = 1.5$ m:
$\sigma_z(\text{min}) = 2.5$ cm, $dp/p(\text{min}) = 3.6$
$\epsilon_\parallel(\text{min}) = 2.7$ mm = Req/15

If f=800 MHz:
$\epsilon_\parallel(\text{min}) = 1.1$ mm = Req/40

- We do not need emittance exchange in final Li Lens cooling
• We can use reverse emittance exchange in final Li Lens cooling
Final reverse emittance exchange

- Use of wedges must be at very low beta or emittance will be blown up
- Consider use of septa (potato slicer)

This can be done at any momentum
4 Intermediate Cooling with emittance Exchange

a) Cooling Ring
   - Severe kicker problem at start
   - Many windows in RFOFO

b) Gugenheim
   - Solves kicker problem but expensive

c) Hydrogen Gas Helix
   - See next transparency

d) LiH Wedge wiggler
   - Longer pitch ok?
   - No good example yet

No system seems ideal
Helical gas channel

For: \( \lambda = 1 \text{ m} \)
\( B_\perp = 0.5 \text{ T} \)

\[ B_r = 2B_o I'_1(x) \sin(\phi - \alpha_s) \]
\[ B_\phi = 2B_o \frac{I_1(x)}{x} \cos(\phi - \alpha_s) \]
\[ B_s = 2B_o I_1(x) \cos(\phi - \alpha_s) \]

Problem: design RF inside 50 cm
Or: increase pitch \( \lambda \)
Possible better solution  (after Balbekov)

- Ring with longer linacs at higher beta
- Alternating with longer liquid hydrogen absorbers at low beta
- Separate LiH wedges for exchange as in Tetra
- Reduce window problem with many short absorbers
- Reduce cost of a solenoid outside the rf.
Particle loss in Cooling

Define \[ Q(z) = \frac{d\epsilon_6/\epsilon_6}{dN/N} \]

If \( Q(z) \) = constant, then \[ \frac{N(n)}{N(o)} = \left( \frac{\epsilon_6(n)}{\epsilon_6(o)} \right)^{1/Q} \]

We require \[ \frac{\epsilon_6(n)}{\epsilon_6(o)} = 10^{-6} \]

Over good part in RFOFO Ring, without windows or Injection/extraction

\[ Q = 15 \]

Then

\[ \frac{N(n)}{N(o)} = \left( \frac{\epsilon_6(n)}{\epsilon_6(o)} \right)^{1/15} = 0.4 \]

For \( 2 \times 10^{12} \) \( \mu \) at end, \( 5 \times 10^{12} \) \( \mu \) at start
**Phase Rotation**

a) Single bunch at low frequency (e.g. 30 MHz)
   - low rf gradients (e.g. 2 MV/m)
   - Cooling/bunch compression is slow
   - large decay losses

b) Multi-bunch as in Studies 2 and 2a, and combine later
   - Combiner not designed
   - Additional cooling
   - More loss

c) Compromise: 2-3 bunches of each sign
   - Moderate frequency (e.g. 80 MHz)
   - Moderate Gradient (e.g. 5 MV/m)

- Use of high pressure gas at low frequencies to increase gradients could be important
- Use of lower frequency (at high gradient) helps beam loading
7 Proton Driver & target

| Survival from decay loss in acceleration | 80% \( (\text{for } \mathcal{E}=6 \text{ MV/m}) \) |
| Survival from all losses in cooling | 40% \( (\text{for } Q=15) \) |
| Muons per proton of each sign before cooling | 0.28 \( (\text{from Study 2a}) \) |

| Muons in collider | \( 2 \, T_\mu \times 3 \) bunches of each sign | at 15 Hz |
| Muons at end of cooling | \( 2.5 \, T_\mu \times 3 \) bunches of each sign | at 15 Hz |
| Muons at start of cooling | \( 6 \, T_\mu \times 3 \) bunches of each sign = 18 \( T_\mu \) of each sign | at 15 Hz |
| Protons on target | \( 18/0.28 = 70 \, \text{Tp} \times 3 \) proton bunches = 200 \( \text{Tp}/\text{fill} \) | at 5 Hz |
| Proton Power | \( 2 \, 10^{14} \times 24 \, 10^9 \) Volts \( \times 1.6 \, 10^{-19} \times 5 \text{ Hz} = 3.8 \text{ MW} \) |

Which equals Snowmass projection

But this remains optimistic because:

- Muons per proton = 0.28 is from Study 2a capture and rotation may not be so good for lower frequency 3 bunch rotation
- An average Q=15 may be hard when including final cooling
- No allowance for matching losses
- It will be harder to get 2 ns bunches of 70 Tp

Current studies were for 16 Tp
Conclusion

- Snowmass parameters still reasonable
- Longitudinal cooling not a problem for 2 TeV machine but could be for Higgs Factory
- Getting required 50 pi mm final trans emittance a main challenge though not required for Higgs factory
  - Need R&D on liquid Li lens
  - Need invention to avoid containment tube shock
  - Allowing larger emittance allows current lens technology but required larger bunches not nice
  - Need to study final reverse emittance exchange
- Loading of cooling RF anyway needs study
- A cooling channel with higher Q would help required charge