Workshop on an e+e- Ring at VLHC
Illinois Institute of Technology
March 9-11, 2001

Sponsored by
The Illinois Consortium for Accelerator Research
and
Illinois Institute of Technology

- **Fermilab** is doing a 5-month feasibility study of a post-LHC hadron collider ("VLHC"), which would be sited in a large (240-km circumference) tunnel. An attractive addition to this plan would include an e+e- ring, with a CM energy in the range of 100 to perhaps 400 GeV. The physics would be limited to low-mass higgs, large-sample Z^0 physics, and possibly a study of physics around the t-bar threshold.

- **The goal** of the Workshop, held on the campus of the Illinois Institute of Technology in Chicago, was to prepare a short document in time to be useful at Snowmass.

- **The Workshop schedule** may be found here, along with links to presentations as they become available.

- **Reference materials** for the Workshop may be found here.

- **A list of participants** in the Workshop may be found here.

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**Organizers**: Tim Morrison, IIT; Alvin Tollestrup, Fermilab; Gerry Dugan, Cornell; and Jim Norel, ANL.

**For further information**, you may contact the Organizers or the Workshop secretariat:

e+e- Workshop Center for Accelerator and Particle Physics
Illinois Institute of Technology
3101 S. Dearborn Street
Chicago, IL 60616

http://capp.lit.edu/~capp/workshops/epem/ee_workshop.html
**Workshop on BESSER in VELC**

**Day 1: Monday, October 23, 2000**

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<td>9:00 AM</td>
<td>Welcome and Goals of Workshop</td>
<td>Andrew Tippett</td>
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<td>9:30 AM</td>
<td>Design Review of Z-Frame Test Panel</td>
<td>Chris Hiltzs</td>
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<td>10:00 AM</td>
<td>VLHC Study and Constraints</td>
<td>Peter Gross</td>
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<td>Lunch at ITB HUB (Catered)</td>
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<td>1:00 PM</td>
<td>Preliminary Design</td>
<td>Jessica Sizemore</td>
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<tr>
<td>2:00 PM</td>
<td>Preliminary Design</td>
<td>Jessica Sizemore</td>
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<td>2:30 PM</td>
<td>Coffee Break – Room 106</td>
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<tr>
<td>3:00 PM</td>
<td>Beam Dynamics</td>
<td>Assaf Comisar-Talman</td>
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<td>4:30 PM</td>
<td>AE Considerations</td>
<td>A. Pepekin</td>
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<tr>
<td>5:30 PM</td>
<td>Magnet System Considerations</td>
<td>O. O. Graham</td>
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<td>6:00 PM</td>
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<td>7:15 PM</td>
<td>Welcome Reception – Room 108</td>
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<td>8:00 AM</td>
<td>Continental Breakfast – Room 108</td>
<td>Carol Johnstone</td>
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<td>8:30 AM</td>
<td>Lattice and B0</td>
<td>Philip Gullikson</td>
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<td>9:30 AM</td>
<td>RF Power Sources</td>
<td>Nabil Assmania</td>
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<tr>
<td>10:30 AM</td>
<td>Lattice Considerations</td>
<td>L. Teng</td>
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<td>11:30 AM</td>
<td>Coffee Break – Room 106</td>
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<tr>
<td>12:30 PM</td>
<td>Magnet Radiation and Absorbers</td>
<td>S. Sharma</td>
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<td>1:30 PM</td>
<td>Magnet Shielding</td>
<td>J. Norme</td>
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<tr>
<td>2:30 PM</td>
<td>Magnet Shielding</td>
<td>C. Beals</td>
</tr>
<tr>
<td>3:30 PM</td>
<td>Lunch – Room 106</td>
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<td>4:30 PM</td>
<td>Working Groups, RF &amp; Cryogenes, Vacuum, Synchrotron Radiation &amp;</td>
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<tr>
<td>5:00 PM</td>
<td>Magnet Induction &amp; Beam Dynamics</td>
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<td>6:00 PM</td>
<td>Coffee Break – Room 106</td>
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<tr>
<td>9:00 PM</td>
<td>End of Session</td>
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</tr>
<tr>
<td>10:00 PM</td>
<td>Conference and Dinner – HUB (Faculty Club)</td>
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[http://capp.lit.edu/~capp/workshops/opem/ee_workshop_schedule.html](http://capp.lit.edu/~capp/workshops/opem/ee_workshop_schedule.html)
Role of a High-Energy $e^+e^-$ Synchrotron:

- First stop on path to a VLHC:
  1. May allow the argument to be made for large tunnel now rather than apres LHC;
  2. Amortization of tunnel costs extends over century;
  3. Program may be cost competitive with LC; Advantageous?
  4. Part of Advanced Accelerator R & D → we must examine all possibilities; possible new concepts?

- 5-point $e^+e^-$ Physics Program:
  1. Giga-Z: $> 10^9$ Z bosons $\rightarrow$ improve measurements of most EW parameters by order of magnitude. (Do we need polarization for $\sin^2\theta_W$ from $A_{LR}$?)
  2. Continuum fermion pair production.
  3. W mass from W threshold studies.
  4. Higgs: “Bj process” $e^+e^- \rightarrow Z^* \rightarrow Z + H$
  5. Top quark threshold: $e^+e^- \rightarrow \gamma^*, Z^* \rightarrow t\bar{t}$

- Enlarged Physics Program Potential:
  1. Is $e + \gamma$ Feasible? $\gamma \gamma$?
  2. Is $e + p$ (Tevatron) Feasible? Desireable?
Conclusions

- The case for an $e^+e^-$ synchrotron seems weakened if we have little or no polarization.

- However, the inherent physics limitations on the utility of polarization-based measurements, e.g., $\delta^2\alpha(M_Z)$, may weaken the case for polarization.

- A rich physics case exists for $> 10^9$ $Z$'s without polarization (IMO).

- It is important to understand if there are inherent advantages in the synchotron to beam energy resolution, and the consequences for the physics program. There may be novel opportunities, e.g., $\delta M_Z$, $\delta \Gamma Z$, etc.

- New opportunities, such as $e+p$, to $Q^2 > 10^6$ strengthen the case.

- As a first stage of the VLHC the ALC program offers a wide range of excellent physics topics.
The Concept

- Take advantage of the space and excellent geology near Fermilab
  - Build a BIG tunnel, the biggest reasonable for the site
  - Fill it with a cheap collider
  - Later, upgrade to a higher-energy collider in the same tunnel
    - This spreads the cost, and, if done right, enables exciting energy-frontier physics at each step
    - It allows more time for the development of cost-reducing technologies and ideas
    - A high-energy full-circumference injector into the high-field machine solves some sticky accelerator issues, like field quality at injection
    - A BIG tunnel is reasonable for a synchrotron radiation-dominated collider, and tunneling can be relatively cheap.
Some Details

- There are many possibilities for staging
- Favored at Fermilab now is an \( \sim 240 \text{ km} \) tunnel
  - This seems possible in the Fermilab area
- Fill it with superferric magnets, \( \sim 2 \text{ T} \), yielding a 35 TeV - 40 TeV (cm) collider (we believe this is least costly, but that remains to be shown - one of the goals of the Study)
- Later, 10 T magnets results in \( E \sim 175 \text{ TeV} \) (cm). It could go higher, but synchrotron radiation or IP radiation and power may limit the energy
  - By the way, a 240 km tunnel will easily support a 300 GeV (cm), \( 10^{34} \text{ e}^+ \text{e}^- \) collider, or a top factory, with an affordable power cost
### Parameters for a Staged VLHC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phase 1</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{cm}$ [TeV]</td>
<td>40</td>
<td>175</td>
</tr>
<tr>
<td>Peak Luminosity $[cm^{-2} s^{-1}]$</td>
<td>$10^{34}$</td>
<td>$2 \times 10^{34}$</td>
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<tr>
<td>$Circ_{total}$ [km]</td>
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<td>233</td>
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<tr>
<td>$B_{dipole}$ [T]</td>
<td>1.9</td>
<td>9.4</td>
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<tr>
<td>Arc packing factor</td>
<td>$\sim 95.0%$</td>
<td>$\sim 83.0%$</td>
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<td>Average $R_{arc}$ [km]</td>
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<td>34.961</td>
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<td>Half-cell length [m]</td>
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<td>Number of half cells</td>
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<tr>
<td>Length of dipoles [m]</td>
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<td>16</td>
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<tr>
<td>Bunch spacing [ns]</td>
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<td>18.8</td>
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</tbody>
</table>

March 9, 2001

VLHC Study $e^+e^-$ Workshop

P. Limon
Parameter Lists at Different Energies

Tanaji Sen

The design is optimized at a luminosity of $10^{33}$ cm$^{-2}$ sec$^{-1}$. At this luminosity, the maximum energy per beam is 185 GeV, assuming that the synchrotron radiation power from both beams is limited to 100 MW. The FODO cell length, dipole and quadrupole lengths are chosen at this energy. These parameters are held fixed as the operating energy is changed.

In the tables that follow, the following parameters are held constant at the values shown in this table.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Circumference [km]</td>
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<td>Revolution frequency [kHz]</td>
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<td>Arc radius [m]</td>
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<td>Bend radius [m]</td>
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<td>$\beta_x, \beta_y$ [cm]</td>
<td>100,000, 5,000</td>
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<td>Ratio of emittances</td>
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<tr>
<td>Number of cells</td>
<td>861</td>
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<tr>
<td>Bend angle in half-cell [mrad]</td>
<td>3.64697</td>
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<td>Length of cell [m]</td>
<td>226.345</td>
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<td>Length of all dipoles in cell [m]</td>
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<tr>
<td>Quadrupole length [m]</td>
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<td>Cell packing fraction</td>
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<td>Harmonic number</td>
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<td>Parameter</td>
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<td>--------------------------------------------------------------------------</td>
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<tr>
<td>Circumference [m]</td>
<td>2665.94</td>
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<tr>
<td>Maximum Energy [GeV]</td>
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<tr>
<td>Luminosity [cm$^{-2}$sec$^{-1}$]</td>
<td>9.73 x 10$^{31}$</td>
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<td>Emittances $\epsilon_\nu$ [nm]</td>
<td>21.1, 0.22</td>
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<td>$\beta_\nu^<em>$, $\beta_\nu^</em>$ [cm]</td>
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<td>RMS Beam size at IP $\sigma_x^<em>$, $\sigma_y^</em>$ [\mu m]</td>
<td>178, 3.3</td>
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<td>Bunch intensity/current [mA]</td>
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<td>Bunch spacing [km]</td>
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<td>Total beam current (both beams) [mA]</td>
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<td>Beam-beam tune shift $\xi_x$, $\xi_y$</td>
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<td>$e^+e^-$ bremsstrahlung lifetime [hrs]</td>
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<td>Dipole field [T]</td>
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<td>Bend Radius [m]</td>
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<td>Phase advance per cell $\mu_x$, $\mu_y$</td>
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<tr>
<td>Arc tune</td>
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<td>Cell Length [m]</td>
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<tr>
<td>Total length of dipoles in a cell [m]</td>
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<td>Quadrupole gradient [T/m]</td>
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<td>Length of a quadrupole [m]</td>
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<td>Arc $\beta_{max}^<em>$, $\beta_{min}^</em>$ [m]</td>
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<tr>
<td>Arc $\sigma_{x}^{max}$, $\sigma_{x}^{min}$ [mm]</td>
<td>1.7, 0.6</td>
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<tr>
<td>Arc dispersion $D_{arc}$ [mm/m]</td>
<td>1.03, 0.45</td>
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<tr>
<td>Bend radius to Machine radius $2\pi\rho/C$</td>
<td>0.71</td>
</tr>
<tr>
<td>Momentum compaction</td>
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</table>

**Table 1:** Parameters of the very large lepton collider with a desired luminosity of 10$^{33}$ cm$^{-2}$sec$^{-1}$ and a circumference of 228km. For comparison the parameters of LEP during 1999 are also shown (taken from [2]).
Intensity Limitations

Bunch intensity limitations

- At top energy, the limit is set by the beam-beam interactions. Limits from the desired collisions are included in the design, there may be additional limits from parasitic collisions.

- At injection energy, the transverse mode coupling instability sets the limit. At the threshold the \( m = 0 \) and \( m = -1 \) modes of the betatron modes \( \omega_\beta + m\omega_s \) become degenerate. Threshold bunch current

\[
I_b^{TMCI} \sim \frac{8f_{rev}\nu_sE}{e \sum_i \beta_i k_{\perp,i}(\sigma_s)} \tag{6}
\]

\( k_{\perp,i} \) is a bunch length dependent transverse mode loss factor. At LEP TMCI limits the bunch current to below 1mA. I assume that similar bunch intensities as in LEP will be stable in the large ring but this may be optimistic...

Beam intensity limitations

- This is primarily determined by the available RF power.

- Cryogenic cooling power.

The dynamic heat load on the cavities includes a contribution from the beam

\[
P_{\text{dynamic}} = 2R_m(\sigma_s)I_bI_e \tag{7}
\]

- HOM power in cavities.
Arc parameters: phase advance and cell length (T. Se..)

Equilibrium emittance

- The emittance decreases as the phase advance increases, reaching a minimum at 135°. In a lattice with FODO cells,

\[ e_x(\mu_C^C) = 4 \frac{C_q \gamma^2 \theta^4}{J_x} \left[ 1 - \frac{3}{4} \sin^2(\mu_x^C/2) + \frac{1}{60} \sin^4(\mu_x^C/2) \right] \frac{\sin^2(\mu_x^C/2) \sin \mu_x^C}{\sin^2(\mu_x^C/2) \sin \mu_x^C} \]  \hspace{1cm} (17)

but

- Stronger focusing increases the chromaticity and the strength of the chromaticity sextupoles which can limit the dynamic aperture.

Typically

\[ 60^\circ \leq \mu_C < 120^\circ \]

For example, LEP has operated with (60°, 60°) at 45GeV, and since then (90°, 60°), (90°, 90°) and (102°, 90°) at higher energies.

TMCI threshold

\[ I_{\text{thresh}}^{TMCI} \propto \frac{\nu_s}{\langle \beta \rangle} \propto \frac{1}{L_c} \cos(\frac{\mu_c}{2}) \]  \hspace{1cm} (18)

The TMCI threshold increases if the cell length \( L_C \) and phase advance per cell \( \mu_C \) decrease.

Emittance control by changing the RF frequency.

\[ \frac{dJ_x}{d\delta} = - \frac{dJ_s}{d\delta} = - \frac{4L_D}{L_Q} \left[ 2 + \frac{1}{2} \sin^2 \mu_C/2 \right] \]  \hspace{1cm} (19)

\( L_D \): length of dipoles in a half cell, \( L_Q \): length of a quadrupole.

Required RF frequency shift is related to the momentum deviation \( \delta \) by

\[ \frac{\Delta f_{RF}}{f_{RF}} = - \frac{\Delta R}{R} = - \alpha_C \delta \]  \hspace{1cm} (20)

Important to keep \( \Delta R \) small to minimize loss in physical aperture and transverse quantum lifetime, i.e. design \( \Delta J_x/\Delta R \) to be large. This requires lower \( \mu_C \) and \( L_Q/L_D \) to be small i.e. weaker focusing.

Example: \( C = 228\text{km}, L_D = 103.7\text{m}, L_Q = 4.1\text{m}, \mu_C = 90^\circ, \alpha_C = 0.28 \times 10^{-4}, \]

\[ \frac{\Delta J_x}{\Delta R} = 0.54 \text{ /[mm]} \]

This is large enough to be useful.
Model of beam-beam parameter versus bunch current:

Dependence of vertical beam-beam tune param. on bunch current $I$ (in the regime of strong synchrotron radiation, K. Cornelis):

$$\xi_y = \sqrt{\frac{1}{A + (B \cdot i)^2}} \cdot i$$

Two fit parameters $A$ and $B$:

$$A = \left( \frac{2\pi e f \gamma}{r_e} \right)^2 \cdot \frac{\beta_x^*}{\beta_y^*} \cdot \varepsilon_x^0 \cdot \varepsilon_y^0$$

$$B = \frac{1}{\xi_y (i \rightarrow \infty)}$$

Knowing all other parameters, $A$ is just given by the unperturbed vertical emittance. Without a beam-beam limit:

$$\xi_y = \sqrt{\frac{1}{A}} \cdot i$$

B gives the asymptotic beam-beam limit of the vertical beam-beam parameter:

- Beta beat due to beam-beam not included.
- Tune dependent resonances are not included.
- Beam-beam tune shift might see other limits.
Use model to predict luminosity:

From model get the luminosity incl BB:

$$L = \left( \frac{n_b \gamma}{2 e r_e \beta_y^*} \right) \cdot \frac{i_b^2}{\sqrt{A + (B \cdot i_b)^2}}$$

In the BB limit:

$$L = \left( \frac{n_b \gamma}{2 e r_e \beta_y^*} \right) \cdot \xi_y^\infty \cdot i_b$$

For a given BB limit, the increase of luminosity with current is proportional to the energy $\gamma$

(el.-magn. field of beam scales as $1/\gamma$)
Figure 3: Three data sets at 94.5 GeV are fitted with the constraint of equal asymptotic beam-beam parameter $\xi_y$. 
Accelerator Physics Challenges

• Combating TMCI

The transverse impedance of the beam pipe alone is close to the threshold impedance. Other major contributions to the impedance from cavities, bellows, ... will likely increase the impedance to beyond threshold.

Possible solutions

– Coalescing bunches at top energy or intermediate energy
– Feedback system
– Raising the injection energy
– Increasing the bunch length and the synchrotron tune. Contrary!
– ...

• If a single ring machine, then long-range beam-beam interactions with many bunches will limit the beam stability. Will likely affect the required physical aperture.

• With many bunches, multi-bunch instabilities may be an issue.

• Avoiding synchro-betatron resonances e.g. those driven by dispersion in the cavities.

• The beam-beam limit may not increase with damping decrement as hoped for. In that case, achievable luminosities will be lower.

• At low energy (45 GeV), the beam current is high (≈ 2 A) and the number of bunches is very large (about 47000). Operation in a single ring machine at these parameters will be extremely difficult if not impossible and will be challenging even in a two ring machine of this circumference.

• ...

!
Horizontal Orbit Offset due to Synchrotron Radiation

\[ \delta x / p c = 0. \]

Table name = TWISS

\[ \times 10^{-3} \]
Wiggler Magnets

- Homogeneous-field dipoles in $- + + -$ arrangement
- In + wigglers field $p_1 u s B \approx 0.3$ T in same direction as in arc dipoles
- Compute total length $p_1 u s L$ of + poles
- Polarization requires field in $-$ wigglers a factor $r a t i o B$ smaller
- Wigglers effective in VLLC with low $B$ in arc dipoles
- Always increase energy spread $\sigma_e$ and bunchlength $\sigma_s$, decrease damping times $\tau$
- Wigglers may be "photon cutters"

- Damping wigglers installed at $D_x = 0$
  - reduce equilibrium emittance $\epsilon_{xn}$, e.g. in collision below nominal current
  - Used at injection with $p_1 u s L \approx 340$ m achieve $\sigma_{e i} \approx \sigma_e \approx 10^{-3}$

- Emittance wigglers installed at $D_x \neq 0$
  - increase equilibrium emittance $\epsilon_{xn}$
  - best in dispersion bumps with $H_w \approx 4H_{arc}$, ratio is called $H_{byhB}$
  - used in VLLC below maximum energy
Collective Effects: Transverse Mode Coupling Instability TMC1

- Bunch current threshold $I_b$ with synchrotron frequency $f_s$, e+ voltage $E/e$,

  $$I_b = \frac{8f_s(E/e)}{\sum \beta_i k_i (\sigma_i)}$$

- Scale RF cavities by number from LEP with $k_\perp = 9.31$ V/pC, $\sigma_\parallel = 10$ mm

- Find $I_b \approx 0.26$ mA at 184 GeV, and $I_b \approx 0.14$ mA at 20 GeV with my arrangement of damping wigglers at injection

- Scale "shielded bellows" from LEP with 10 m spacing and $k_\perp = 0.42$ V/pC at

- Find $I_b \approx 0.136$ mA at 184 GeV, and $I_b \approx 0.0148$ mA at 20 GeV with my arrangement of damping wigglers at injection

- TMCI dominated by bellows and below design current by factor 10
Lattice & Beam Dynamics Working Group Summary

- Lower $\beta^*$ to 1 cm, magnets in detector?
- $\xi_y \leq 0.14$ based on LEP experience
- 2 separate rings very desirable necessary for $\mathcal{L} \Rightarrow 10^{34}$
- Are 2 rf stations needed? (E-sawtooth $>2\%$)
- Instabilities & Impedance control
  - no bellows
  - minimize # of cavities
  - may need bunch gymnastics at intermediate energy
  - may determine vac. aperture
  - may need bunch-by-bunch f/b
- Need a higher-energy injector
Injector

1) $185 \text{ GeV} \leftrightarrow 45 \text{ GeV}

\sim \text{LEP-like}

\sim \text{B-factory-like}

2) $E_{\text{imj}}: 20 \text{ GeV}$ difficult!

($Z_1/m_1$ $10 \times$ better than LEP)

$E_{\text{imj}}: 45 \text{ GeV} + \text{combine imj in with } Z_0 \text{ Factory, allow for } \vec{e}$
2. Proposals

(1) 6 km

\( L = 10^{33} \rightarrow 5 \times 10^{33} \) (\( P = 10^m \))

\( V_{RF} = 400 \text{ MV} \)

\( P_{RF} = \frac{126 \text{ MW}}{21 \text{ kW/m}} \)

\( I_{\text{MIC}} = 0.01 \text{ A/ } \text{m} \) \( \) (20 GeV)

\( \tau_p = 0.04 \) hours.

\( \frac{\Delta P}{P} = 1.6 \times 10^{-3} \) high for \( e^+ e^- \)

(Too high?)

Existing Tevatron may be good
only tunnel OK.
12 km
\[ L = 10^{33} \rightarrow 5 \times 10^{33} \]

\[ V_{RF} = 260 \text{ MV} \]

\[ P_{RF} = 65 \text{ MW} \]

\[ I_{TMAX} = 0.0056 \text{ A/m (At 12 GeV)} \]

\[ z_p = 20 \text{ mm} \]

\[ \frac{\Delta p}{p} = 1.14 \times 10^{-3} \]