Uli Wienands

Workshop on an e+e- Ring at VLHC

Illinois Institute of Technology
March 9 -11, 2001

Sponsored by
The Illinois Consortium for Accelerator Research
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- **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-tbar* 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 particpants** in the Workshop may be found here.

- **Organizers** : Tim Morrison , IIT; Alvin Tollestrup , Fermilab; Gerry Dugan , Cornell; and Jim Norem, 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

Workshop on an e+e- Storage Ring at VLHC
March 9 - 11, 2001

Note: You may follow active links on speakers' names to their workshop presentations.

	Topic	Speaker
Friday		
9:00 AM	Registration – Room 166	
10:00 AM	Welcome & Goals of Workshop	Alvin Tollestrup
10:15 AM	Physics Reach – Z^0, Higgs, t tbar	Chris Hill
11:30 AM	VLHC Study and Constraints	Peter Limon
12:00 PM	Lunch at IIT HUB (Cafeteria)	
1:30 PM	Preliminary Design	Tanaji Sen
2:15 PM	Preliminary Design	Eberhard Keil
2:45 PM	Coffee Break – Room 108	
3:00 PM	Beam Dynamics	Assmann/Cornelis/Talman
4:30 PM	RF Considerations	S. Belomestnykh
5:15 PM	Vacuum System Considerations	O. Grobner
6:00 PM	End of Session	
6:15 PM	Cocktail Reception – Room 108	
Saturday		
8:30 AM	Continental Breakfast – Room 108	
9:00 AM	Lattice and IR	Carol Johnstone
9:20 AM	RF Power Sources	Phillipe Guidee
9:50 AM	Is Polarization Possible?	Ralph Assmann
10:10 AM	Injection Considerations	L. Teng
10:30 AM	Coffee Break – Room 108	
11:00 AM	Synchrotron Radiation and Absorbers	S. Sharma
11:30 AM	Magnet Shielding	J. Norem
11:50 AM	Magnet Steel	C. Belanger
12:20 PM	Lunch – Room 108	
1:30 PM	Working Groups: RF & Cryogenics; Vacuum, Synchrotron Radiation & Magnets; Injection & Beam Dynamics	
3:30 PM	Coffee Break – Room 108	
4:00 PM	Working Groups: RF & Cryogenics; Vacuum, Synchrotron Radiation & Magnets; Injection & Beam Dynamics	
6:00 PM	End of Session	
6:30 PM 7:30 PM	Cocktails and Dinner – HUB (Faculty Club)	

http://capp.iit.edu/~capp/workshops/epem/ee_workshop_schedule.html

C. Hill

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: $\gtrsim 10^9$ Z bosons → improve measurements of most EW parameters by order of magnitude. **(Do we need polarization for $\sin^2\theta_W$ from A_{LR}?)** "Z-factory"
  2. Continuum fermion pair production.
  3. W mass from W threshold studies.
  4. Higgs: "Bj process" $e^+e^- \to Z^* \to Z + H$
  5. Top quark threshold: $e^+e^- \to \gamma^*, Z^* \to t\bar{t}$
- Enlarged Physics Program Potential:
  1. Is $e + \gamma$ Feasible? $\gamma\gamma$?
  2. Is $e + p$(Tevatron) Feasible? Desireable?
  3. Future: Is $e + p$(VLHC) Feasible? Desireable?

C. 15.4

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 opportunites, e.g., δM_Z, $\delta\Gamma_Z$, etc. !
- New opportunites, 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.

P. Limon

The Concept

- Take advantage of the space and excellent geology near Fermilab
  - Build a <u>BIG</u> 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 <u>synchrotron radiation-dominated collider</u>, and tunneling can be relatively cheap.

P. Limon

Some Details

- There are many possibilities for staging
- Favored at Fermilab now is an ~240 km tunnel
  - This seems possible in the Fermilab area
- Fill it with superferric magnets, ~2 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 ~ 175 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} e^+e^- collider, or a top factory, with an affordable power cost

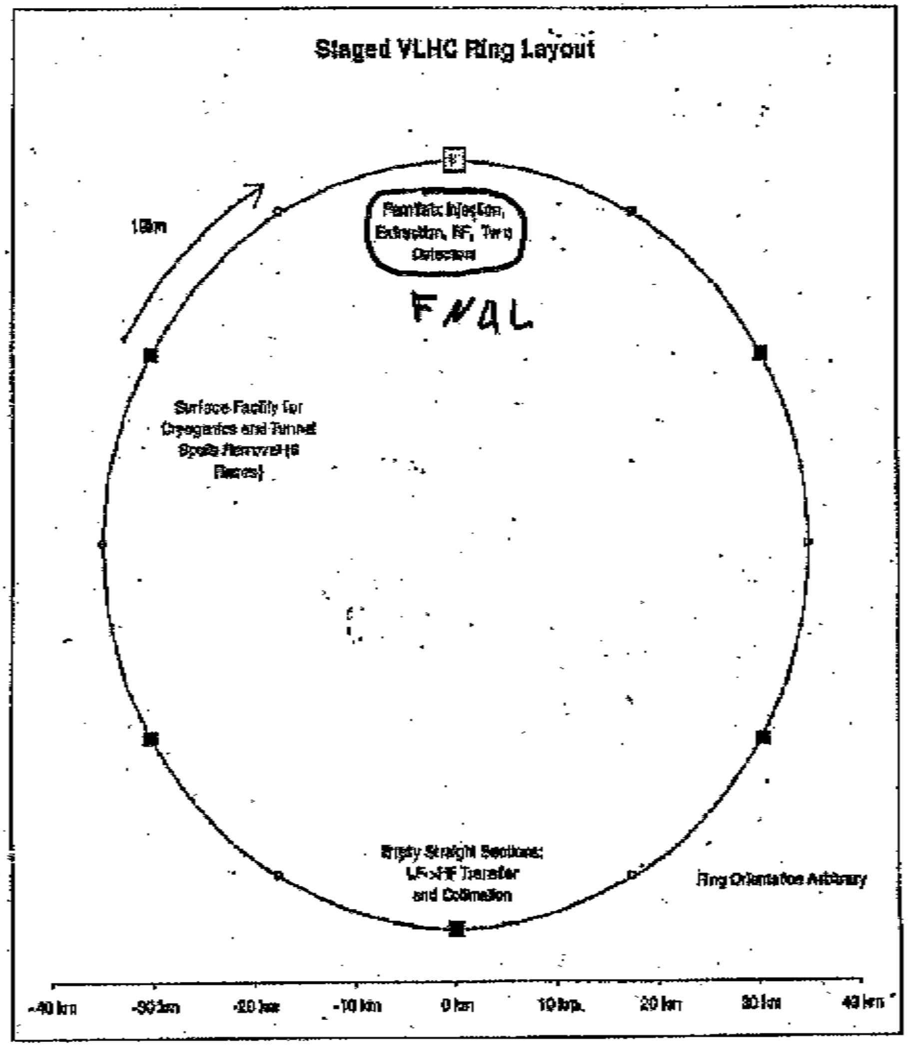
P. Limon

Parameters for a Staged VLHC

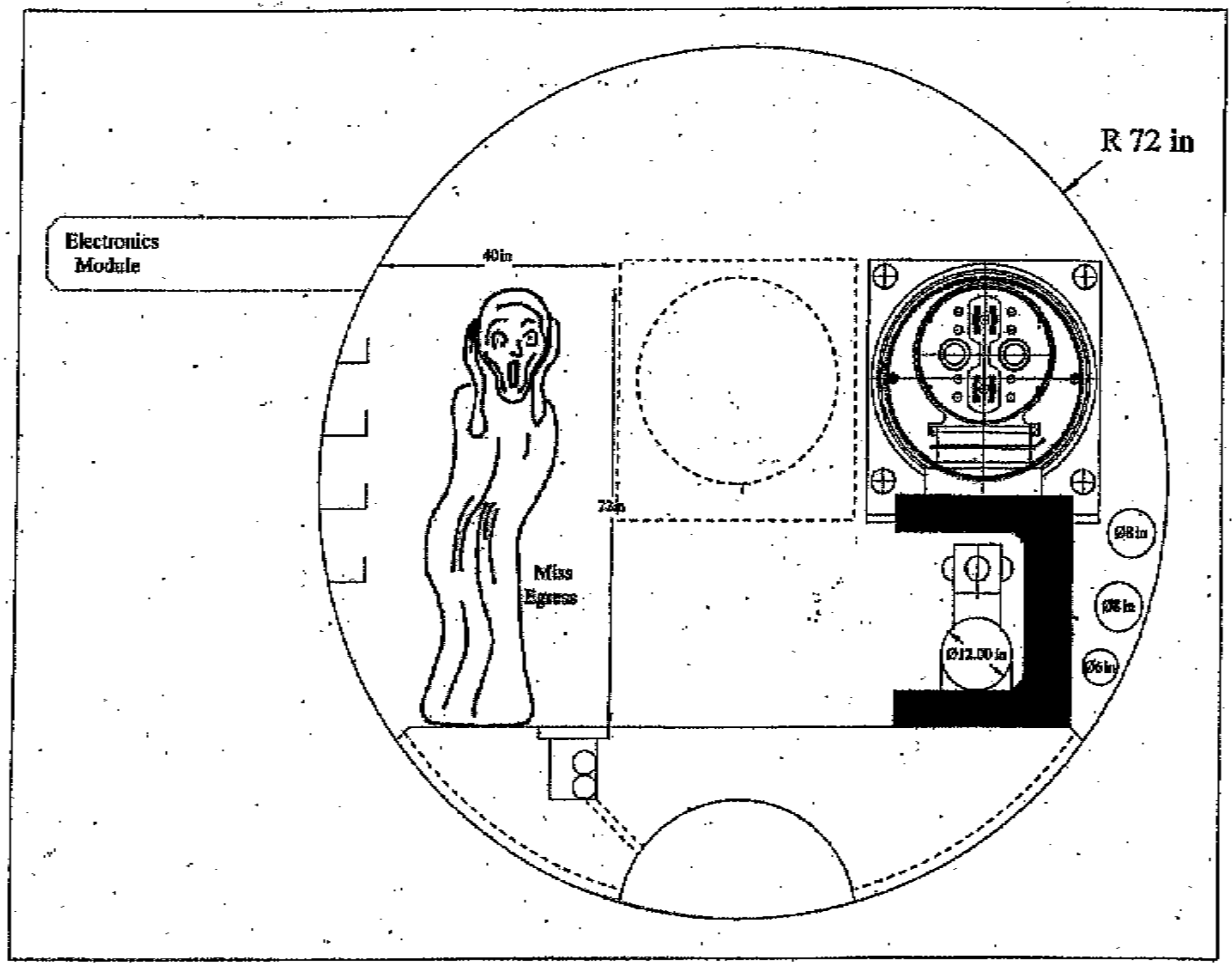
	Phase 1	Phase 2
E_{cm} [TeV]	40	175
Peak Luminosity [cm^{-2} s^{-1}]	10^{34}	2×10^{34}
$Circ_{total}$ [km]	233	
B_{dipole} [T]	1.9	9.4
Arc packing factor	~95.0%	~83.0%
Average R_{arc} [km]	34.961	
Half-cell length [m]	135.486	
Number of half cells	1720	
Number of dipoles	3440	9728
Length of dipoles [m]	65	16
Bunch spacing [ns]	18.8	

P. Limon

Very Large Hadron Collider


Staged VLHC Ring Layout

P. Limon


R 72 in
Electronics Module
40in
72in
Miss Egress
Ø8 in
Ø8 in
Ø6 in
Ø12.00 in

March 8, 2001

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 185GeV, assuming that the synchrotron radiation power from both beams is limited to 100MW. 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.

Circumference [km]	233.00
Revolution frequency [kHz]	1.2867
Arc radius [m]	31031.880
Bend radius [m]	25968.098
β_x^*, β_y^* [cm]	100.000, 5.000
Ratio of emittances	0.050
Number of cells	861
Bend angle in half-cell [mrad]	3.64697
Length of cell [m]	226.345
Length of all dipoles in cell [m]	189.410
Quadrupole length [m]	0.494
Cell packing fraction	0.189
Harmonic number	310882

Wg reco.

$e^+ - e^-$ Collider Parameters

Parameter	LEP 1999	VLLC33	
Circumference [m]	26658.9	228000	
Maximum Energy [GeV]	**97.8**	**184**	
Luminosity [$cm^{-2}sec^{-1}$]	9.73×10^{31}	1×10^{33} ●	→ 10^{34}
Emittances ϵ_x, ϵ_y [nm]	21.1, 0.22	8.3, 0.415	
β_x^*, β_y^* [cm]	150, 5	100, 5 ●	→ x, 1
RMS Beam size at IP σ_x^*, σ_y^* [μm]	178, 3.3	91, 4.6	
Bunch intensity/current [/mA]	$4.01\times10^{11}/0.72$	$6.7\times10^{11}/0.14$	
Number of bunches per beam	4	89	
Bunch spacing [km]	6.66	2.56	
Total beam current (both beams) [mA]	5.76	25.04	
Beam-beam tune shift ξ_x, ξ_y	0.043, 0.079	**0.1, 0.1** ●	→ 0.14 (!?)
e^+e^- bremmstrahlung lifetime [hrs]	6	23	
Dipole field [T]	0.11	0.024 ●	240g !
Bend Radius [m]	3026.42	25411	
Phase advance per cell μ_x, μ_y [degrees]	102, 90	90, μ_y	
Arc tune	70.3, 62	193, Q_{yC}	
Cell Length [m]	79.11	248	
Total length of dipoles in a cell [m]	69	207	
Quadrupole gradient [T/m]	9.5	28	
Length of a quadrupole [m]	1.6	4.1	
Arc β^{max}, β^{min} [m]	144, 18	423, 73	
Arc $\sigma_x^{max}, \sigma_x^{min}$ [mm]	1.7, 0.6	1.9, 0.8	
Arc dispersion D^{max}, D^{min} [m]	1.03, 0.45	1.37, 0.65	
Bend radius to Machine radius $2\pi\rho/C$	0.71	0.70	
Momentum compaction	1.6×10^{-4}	2.8×10^{-5}	
Energy loss per particle per turn [GeV]	2.67	3.99	
Critical energy [keV]	686	455	
Longitudinal damping time [turns/msec]	73/6.5	46/35	
RMS relative energy spread	1.52×10^{-3}	1.0×10^{-3} ●	?
Bunch length [mm]	11	7.5	
Synchrotron tune	0.116	0.133	
RF Voltage [MV]	**3050**	**4660** ●	
RF frequency [MHz]	352.209	400.0 ●	→ 350
Revolution frequency [kHz]	11.245	1.315	
Synchrotron radiation power - both beams [MW]	14.5	100 ●	
Available RF power [MW]	34.1		
Power load from both beams [kW/m]	0.82	0.52	
Photon flux/length from both beams [/m/sec]	2.4×10^{16}	2.3×10^{16}	

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 (T. Sen)

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

$$I_b^{TMCI} \simeq \frac{8 f_{rev} \nu_s E}{e \sum_i \beta_i k_{\perp\, i}(\sigma_s)} \tag{6}$$

  $k_{\perp\, i}$ 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

$$P_{dynamic}^{beam} = 2R_m(\sigma_s) I_b I_e \tag{7}$$

- HOM power in cavities.

Arc parameters: phase advance and cell length (T. Sen)

Equilibrium emittance

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

$$\epsilon_x(\mu_x^C) = 4\frac{C_q\gamma^2}{J_x}\theta^3\frac{1-\frac{3}{4}\sin^2(\mu_x^C/2)+\frac{1}{60}\sin^4(\mu_x^C/2)}{\sin^2(\mu_x^C/2)\sin\mu_x^C}. \tag{17}$$

but

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

Typically

$$60^\circ \le \mu_c < 120^\circ$$

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

TMCI threshold

$$I_{thresh}^{TMCI} \propto \frac{\nu_s}{\langle\beta\rangle} \propto \frac{1}{L_c}\cos(\frac{\mu_c}{2}) \tag{18}$$

The TMCI threshold *increases* if the cell length L_C and phase advance per cell μ_C *decrease*.

Emittance control by changing the RF frequency.

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

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 δ by

$$\frac{\Delta f_{RF}}{f_{RF}} = -\frac{\Delta R}{R} = -\alpha_C\delta \tag{20}$$

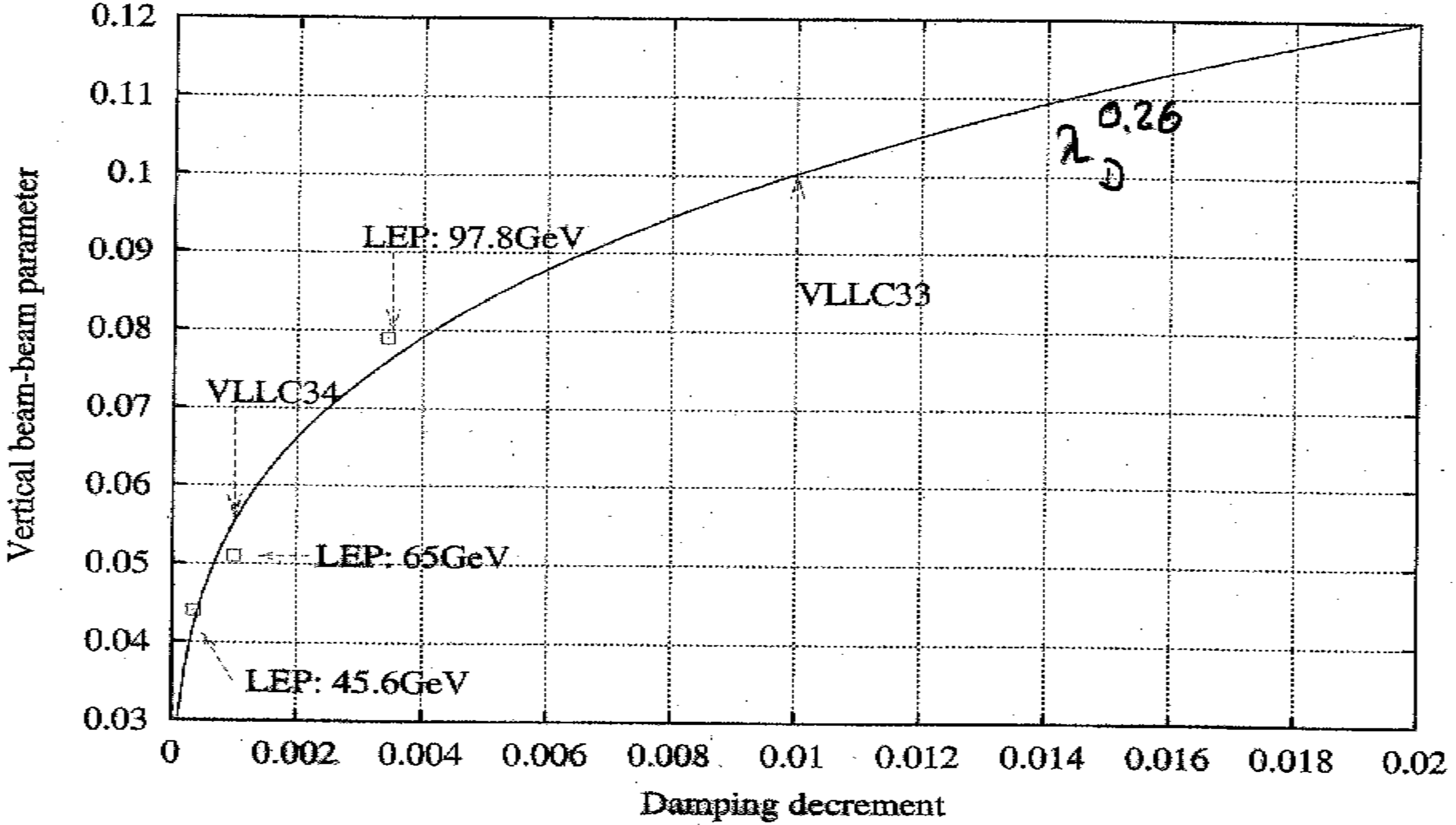
Important to keep ΔR small to minimize loss in physical aperture and transverse quantum lifetime, i.e. design $\Delta J_x/\Delta R$ to be large. This requires lower μ_C and L_Q/L_D to be small i.e. *weaker focusing*.

Example: $C = 228$km, $L_D = 103.7$m, $L_Q = 4.1$m, $\mu_C = 90^\circ$, $\alpha_C = 0.28\times10^{-4}$,

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

This is large enough to be useful.

Scaling of the beam-beam parameter (Sen)



R. Assmann

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

R. Assmann

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 γ
(el.-magn. field of beam scales as 1/γ)

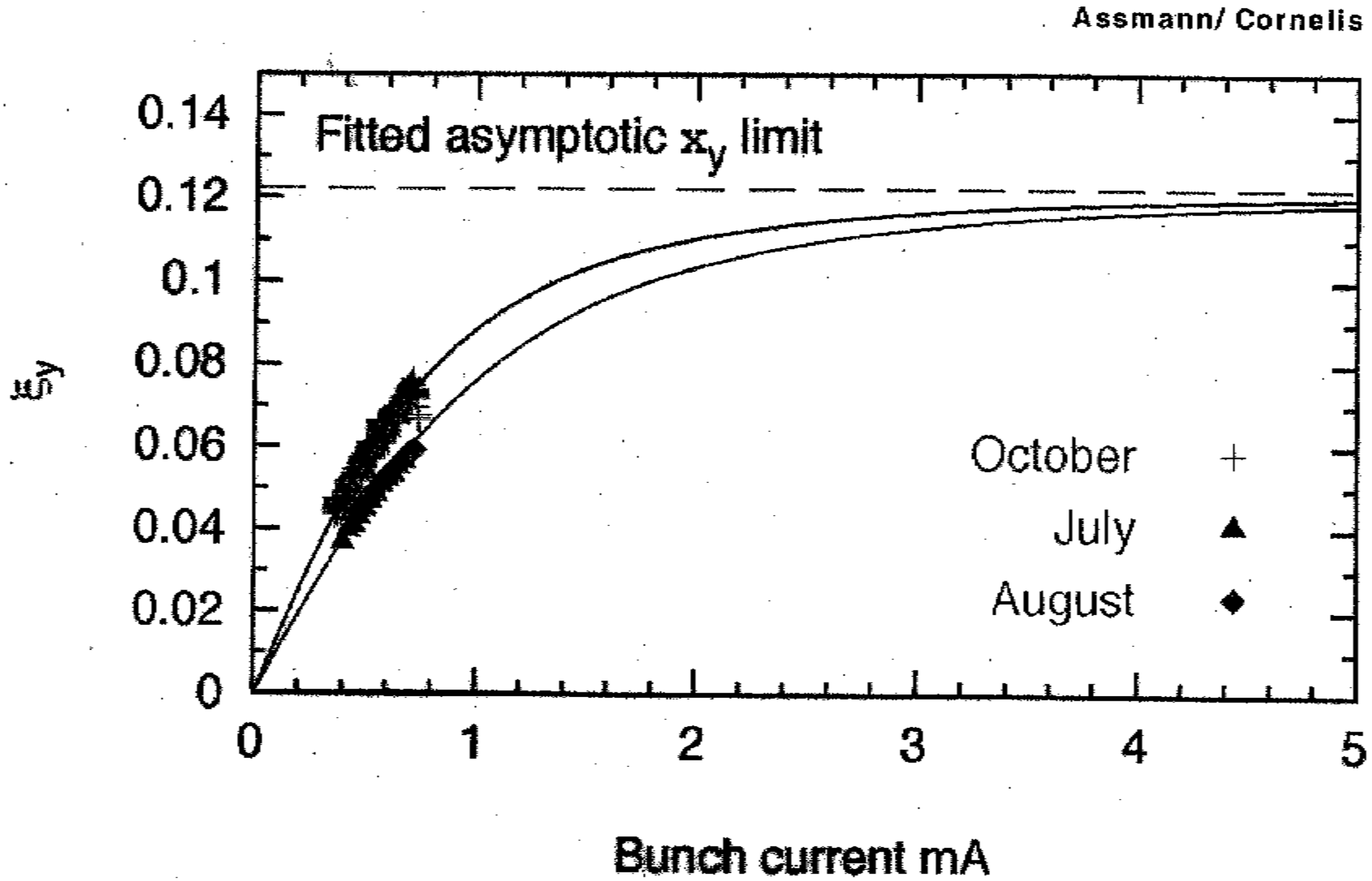


Figure 3: Three data sets at 94.5 GeV are fitted with the constraint of equal asymptotic beam-beam parameter ξ_y

T. Sen

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. contradictory!
  - ...

- 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.

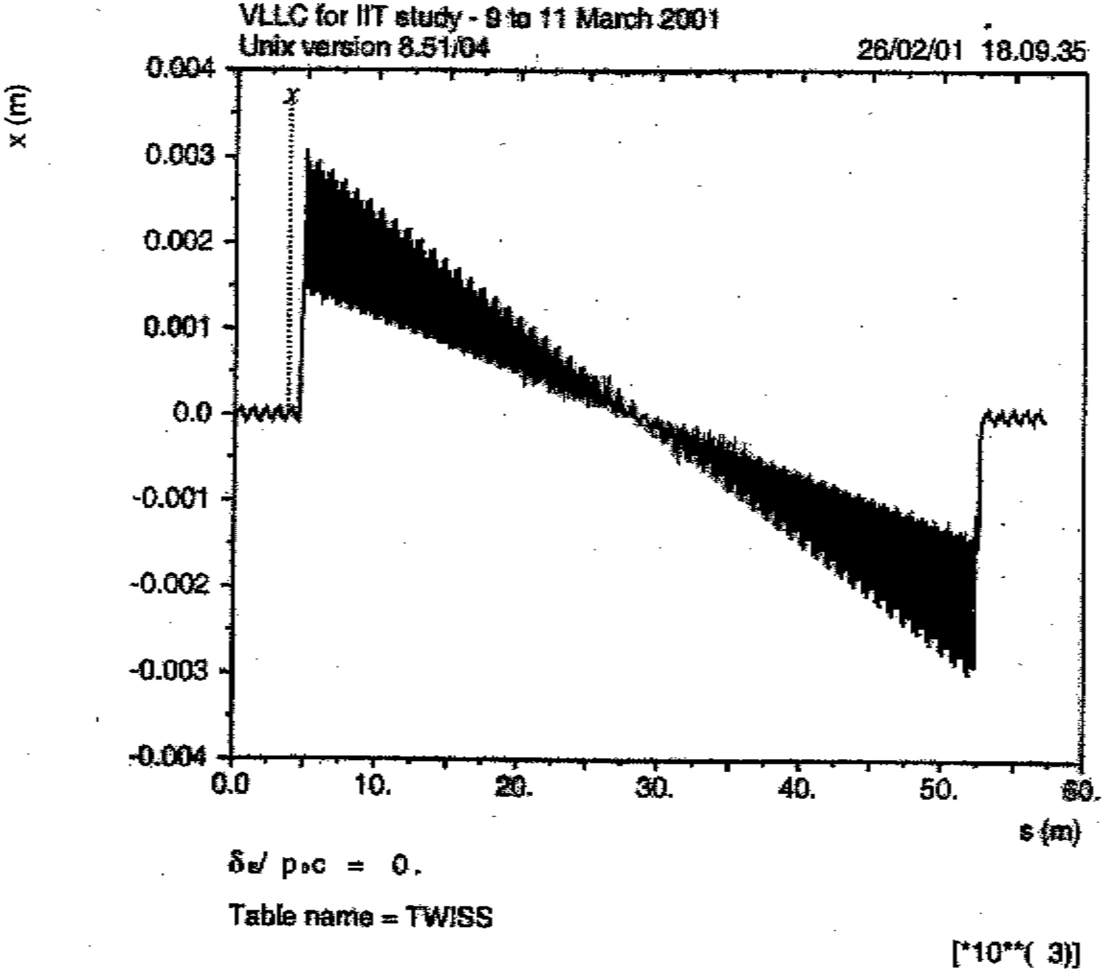
- The beam-beam limit may not increase with damping decrement as hoped for. In that case, achievable luminosities will be lower.

- ! 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.

- ...

E. Keil

Horizontal Orbit Offset due to Synchrotron Radiation



E. Keil

Wiggler Magnets

- Homogeneous-field dipoles in $-++-$ arrangement
- In $+$ wigglers field `plusB` ≈ 0.3 T in same direction as in arc dipoles
- Compute total length `plusL` of $+$ poles
- Polarization requires field in $-$ wigglers a factor `ratioB` smaller
- Wigglers effective in VLLC with low B in arc dipoles
- **Always** increase energy spread σ_e and bunchlength σ_s, decrease damping times τ
- Wigglers may be "photon cutters"
- **Damping wigglers** installed at $D_x = 0$
  - reduce equilibrium emittance ϵ_{xn}, e.g. in collision below nominal current
  - Used at injection with `plusL` ≈ 340 m achieve $\sigma_{ei} \approx \sigma_e \approx 10^{-3}$
- **Emittance wigglers** installed at $D_x \neq 0$
  - increase equilibrium emittance ϵ_{xn}
  - best in dispersion bumps with $\mathcal{H}_{\mathrm{w}} \approx 4\mathcal{H}_{\mathrm{arc}}$, ratio is called `hWbyhB`
  - used in VLLC below maximum energy

E. Keil

Collective Effects: Transverse Mode Coupling Instability TMCI

- Bunch current threshold I_b with synchrotron frequency f_s, $e^{\pm}$ voltage E/e, transverse β and transverse loss factors $k_\perp(\sigma_s)$

$$I_b = \frac{8 f_s (E/e)}{\sum_i \beta_i k_\perp(\sigma_s)_i}$$

- Scale RF cavities by number from LEP with $k_\perp = 9.31$ V/pC at $\sigma_s = 10$ mm
- Find $I_b \approx 1.26$ 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 $\sigma_s = 10$ mm
- 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 β^* to 1 cm, magnets in detector ?
- $\xi_y \leq 0.14$ based on LEP experience
- 2 separate rings very desirable
  necessary for $\mathcal{L}$ => 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

T. Sen
WG Summary

① 185 GeV ⟺ 45 GeV

185 GeV ⇓ LEP-like

45 GeV ⇘ B-factory like

② E_{inj} : 20 GeV difficult!
($Z_{\perp}/m$ 10 x better than LEP)

E_{inj} : 45 GeV + combine injector with Z_0 Factory, allow for $\vec{e}$

2 PROPOSALS.

T. Sen
WG Summary

① 6 km

$\mathcal{L} = 10^{33} \rightarrow 5\ 10^{33}$ ($\beta^* = 10$cm

$V_{RF} =$ ~~400~~ MV

$P_{RF} = \underline{126\ \text{MW}}$ 21 kW/m

$I_{TMCI} = 0{,}01$ A/b (20 GeV)

$\tau_p = 0.04$ hours.

$\frac{\Delta p}{p} = \underline{1.6\ 10^{-3}}$, high for $\vec{e}$ (too high?)

Existing Tevatron __no__ good
only tunnel ok.

②

T. Sen
WS Summary

12 km

$\mathcal{L} = 10^{33} \longrightarrow 5\ 10^{33}$

$V_{RF} = \overset{400}{\cancel{[illegible]}}$ MV

$P_{RF} = \overset{50}{\cancel{63}}$ MW $\qquad \overset{5}{\cancel{[illegible]}}$ kW/m

$I_{TMCI} = 0.0056$ A/b (At 12 GeV

$Z_p = 20$ mm

$\frac{\Delta p}{p} = 1.14\ 10^{-3}$

} about best compromise for $\vec{e}$