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ENERGY SCALING, CRAB CROSSING AND THE PAIR PROBLEM*

R. B. PALMER

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
and
Brookhaven National Laboratory, Upton, New York 11973

ABSTRACT

Making reasonable assumptions, the luminosities of linear colliders are calculated for center-of-mass energies of 10 GeV, 100 GeV and 1 TeV. A calculation is also mode for a 1/2 TeV collider that could be upgraded to 1 TeV later. The improvements possible using "crab-like" crossing are also given.

1. INTRODUCTION

The design of linear colliders is a complex problem because of the interdependence of the critical parameters.$^{1)}$ Changing the number of particles per bunch effects the damping ring design and thus the emittance; it effects the wakefields in the linac and thus the momentum spread; the momentum spread effects the final focus design and thus the final β^*; but the emittance change also effects the final focus design; and all these come together to determine the luminosity, disruption and beamstrahlung at the intersection. Changing the bunch length, or almost any other parameter, has a similar chain reaction. Dealing with this problem by simple scaling laws is very difficult because one does not know which parameter is going to be critical and thus which should be held constant. In the face of this problem, I have written a PC program that—given various assumptions—simultaneously calculates:

- Emittances, damping rate and impedance requirements in the damping ring.
- RF properties of the accelerating structure.
- Longitudinal wakes in the linac.
- Transverse wakes in the linac.
- Focusing requirements for BNS damping and tolerances in the linac.
- Required final focus chromatic correction.
- Required pole tip fields in the final focus quadrupoles.
- Disruption and beamstrahlung at the intersection.
- Multibunch instabilities at the crossing.

Most of the calculations are done using analytic expressions. Inevitably, many approximations have been used. It is not the intent of the program to actually design a machine. It is the object to explore the parameter space and get a feeling for what is and is not possible.

In an earlier paper,$^{1)}$ I used the program to select reasonable parameters for a .5 on .5 TeV Collider. In this paper, the emphasis is on discovering the scaling to lower energies. There are, however, a number of changes in the assumptions and calculations since Ref. 1:

1. It is assumed that damped acceleration cavities$^{2)}$ can be used, and thus multiple bunches can be accelerated without buildup of transverse wakes.
2. The longitudinal wakes are correctly integrated, assuming a Gaussian bunch profile (a four-bunch approximation had been used in Ref. 1).
3. Dilutions are introduced: (a) between damping ring and linac, (b) in the linac and (c) in the final focus. Dilutions are specified for emittances in all three directions and for β.
4. The Oide limit on spot size from synchrotron radiation in the final quads is calculated and applied.

2. ASSUMPTIONS

2.1 Ratio of Horizontal to Vertical Emittances

Assume the ratio of horizontal to vertical emittances in the damping ring to be less than or equal to 100:1. An asymmetric emittance is natural in a damping ring and comes with essentially no price. It allows the generation of a flat beam profile. The original motive for using such a flat beam was to minimize the beamstrahlung without loss of luminosity. It also allows the use of a finite angle crossing, so that the disrupted beam does not have to pass through the opposite quadrupole. I find that the best luminosity always requires the maximum ratio of emittances.

2.2 Ratio of Horizontal to Vertical Betas

With conventional crossing, I assume the undiluted ratio of horizontal to vertical betas at the intersection to be 3.24 times the ratio of emittances. When this condition is satisfied, the beam size in the final quads is approximately the same horizontally and vertically, and maximum luminosity is achieved. With 100:1 emittance ratio and this assumption, the beam will have an aspect ratio of 180:1.

With crab crossing (see Sec. 3.3), greater luminosity is obtained with smaller ratios of the betas; but the beamstrahlung rises, and has been limited to a value of $\delta \leq .3$

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in this study. The maximum luminosity is reached for a β ratio of 3.2.

2.3 Crossing Angle

In order to avoid excessive luminosity loss, a finite crossing angle is selected that is 0.7 times the bunch diagonal angle (*i.e.*, $0.7 \times \sigma x/\sigma z$). The bunch length is then selected to give a crossing angle sufficiently large, compared with the maximum disruption angle, to avoid collisions of the disrupted beam with the poles of the quadrupole. A larger factor is required at the higher energies because of assumed quantum fluctuations in the disrupted beam (this is yet to be calculated). The required ratios were: crossing/disruption = 24 (1 TeV), = 19 (.1 TeV) and = 14 (10 GeV).

2.4 Damping Ring

A wiggler damping ring is assumed. The energy is chosen to make the contributions from intrabeam scattering and quantum fluctuations the same. The ring diameter is then chosen to give a longitudinal impedance requirement of Z/n = 0.5 Ω. The wiggler fields are 2 T, the quadrupole apertures 12 mm radius and pole tip fields 1.4 T, the partition functions were normal, $\beta y/\beta x = 4$, and phase advance per cell 65°.

2.5 Quadrupole Doublet Final Focus

A conventional, chromatically-corrected quadrupole-doublet final focus is assumed. The ratio of the assumed corrected β to a calculated uncorrected value is taken to be $S = .04 \times dp/p$ (scaling law from K. Brown). The maximum pole tip field is assumed to be 1.4 T. The aperture is taken to be ten times the rms beam size.

2.6 Accelerating Structure

A conventional iris loaded accelerating structure is assumed. The iris radius is taken to be 0.2 times the wavelength. This gives a relatively high group velocity (0.08) and lower wakefields than for a SLAC–like structure (radius 0.1 times the wavelength). The fill time for the structure is usually taken to be 0.3 times the attenuation time. But in the case when the wavelength is 17 mm (1 TeV example), then the fill time is taken to be 0.6 times the attenuation length to avoid using pulses of less than 45 ns.

2.7 BNS Damping

Transverse wakes are assumed to be controlled by BNS damping. Focusing in the linac is taken to give a β that rises with the square root of the energy. Five percent of the linac length is assumed taken up with quadrupoles whose apertures are 1.26 times the structure irises and whose pole tip fields are 1.4 T.

2.8 Number of Bunches

It is assumed that transversely damped accelerating structures are used and that multiple bunches can be used without beam breakup. A limit is set on the number of bunches such that not more than 25% of the total stored energy is extracted. This limit is consistent with considerations of energy constancy.

2.9 Repetition Rate

The repetition rate is set to keep the wall power to 200 MW. A klystron efficiency of 36% is assumed.

2.10 Dilution

The following dilutions are assumed:

Emittance z in buncher: 1.4
Emittance x from kicker: 1.4
Particle transmission through buncher: 1/1.2
Emittance y in linac: 1.4
Particle transmission through final focus: 1/1.2
Emittance x y in final focus: 1.2
β^* x y in final focus: 1.2

2.11 Longitudinal Emittance

At high energies the contribution of the longitudinal emittance in the damping ring to the momentum spread at the intersection is negligible. In this case the longitudinal emittance is constrained by considerations of the bunch length in the damping ring to be less than 0.04 m $\times dp/p$ at $\gamma = 1$.

At low energies the longitudinal emittance is constrained only by considerations of momentum spread in the linac and for physics.

2.12 Bunch Length

The bunch length is selected to maximize the final luminosity. In general, a longer bunch length will allow a larger longitudinal emittance and thus, from the damping ring, smaller transverse emittances and higher luminosity. The primary constraint on the bunch length is the loss of luminosity that arises when the diagonal angle becomes less than the finite crossing angle. Another constraint arises when luminosity is lost because the bunch length has become much longer than the β^* at the intersection.

2.13 Accelerating Fields

From the machine physics point of view there seems no disadvantage in high accelerating fields. The optimized luminosity is little effected, the tolerances are easier and of course the length is less. The field used should thus be the highest possible consistent with breakdown and dark current considerations. I have assumed that these limits are wavelength dependent and used: G = 46.5 MV/m for f = 2 GHz, G = 93 MV/m for f = 6 GHz and G = 186 MV/m for f = 17 GHz.

2.14 Wavelength

The wavelength, like the acceleration gradient, has little effect on the optimized luminosity (for the same loading and average power consumption, the larger wavelength collider will have more luminosity per cycle, but a lower repetition rate). At higher energies a lower wavelength is preferred because it will have the lower stored RF energy, lower peak power requirements and thus a cheaper power source; and lower wavelength solutions are also found to have lower beamstrahlung. However, as the wavelength falls the power source becomes harder to build and the linac tolerances become tighter (both alignment and jitter). I selected 17 GHz as the maximum RF frequency.

At lower energies, if the wavelength is reduced, the repetition rate (for fixed wall power and luminosity) becomes excessive, and it would be very hard to design a damping ring (or rings) to provide the low emittance positrons. But, at lower energies beamstrahlung is less of a consideration; also, the accelerator is shorter so the cost of the power supply is less of a consideration. It is then reasonable to use a larger wavelength. Rather arbitrarily I used for:

10 GeV c.m.: f(rep) = 1.7 kHz at P(wall) = 200 MW,
giving f(rf) = 2 GHz ;
100 GeV (rep) = 1.0 kHz at P(wall) = 200 MW,
giving f(rf) = 6 GHz ;
1 TeV f(rep) = 0.4 kHz at P(wall) = 200 MW,
giving f(rf) = 17 GHz .

2.15 Loading (η)

At high energies, when the longitudinal emittance is held to a constant maximum practical value, the loading has a negligible effect on the momentum spread at the final focus. In this case, the luminosity per bunch is found to be nearly independent of the loading. (A higher loading, and thus higher N, would naturally increase the luminosity, but this is offset by the higher emittance from the damping ring and by the higher β^* because of the greater difficulty in correcting the higher momentum spread from higher wakes.) With multibunching, however, the number of bunches is inversely proportional to the loading, and thus the total luminosity turns out to be inverse with the loading. There are various limits to this: when the momentum spread gets too low, the chromatic correction scaling will break down, or the tolerances will get too tight. I limit the chromatic correction factor to 30, which results in the luminosity reaching its maximum for a loading of about 2.5%.

At lower energies the longitudinal emittance dominates the momentum spread at the final focus, and in this case the luminosity per bunch increases with loading. With multibunching the luminosity now becomes independent of the loading. The choice of loading is now rather arbitrary, providing it is not so large as to give an excessive momentum spread. When in doubt, I have used 2.5%.

3. RESULTS

3.1 Conventional Finite Angle Crossing

With these assumptions I have generated the parameter lists for machines at center-of-mass energies of 10 GeV, 100 GeV and 1 TeV [see Table 1 and Fig. 1 (dots)]. For the 10 GeV case, the momentum spread was restricted to less than 0.2% in order to be not larger than the width of the $\Upsilon(4s)$ state.

Note that far more thought has been given to the 1 TeV case than the lower energy examples, so it is not clear that these lower energy examples are fully optimized. In addition, some of the parameters for the B factory case are unreasonable or unphysical (they are indicated by ***). The damping ring design is unphysical and unreasonably small, but the performance indicated is not unreasonable and can, almost certainly, be obtained in a real design. The accelerator section lengths are also too long, but these could be lowered by adding some magnetic coupling between cells.

The exact performances given should not be taken too seriously. Nevertheless we note that the luminosity seems to fall from a value close to 10^{34} at 1 TeV, to only a little above 10^{33} at 10 GeV: falling about as the root of the energy. This conclusion is reached assuming constant wall power (200 MW). In practice it is hard to believe one would consider a collider at 10 GeV using so much power, so the realistic luminosity of such a B-factory would be even lower.

Table 1. Parameters of optimized colliders at three energies.

		B factory	Z factory	TLC
General				
c.m. energy	TeV	.01	.1	1
RF wavelength	cm	15	5	1.7
repetition rate	kHz	1.7	1.0	.36
accel gradient	MV/m	46	93	186
number bunches		10	10	10
particles/bunch	10^{10}	37	6	1.4
wall power	MW	200	200	200
Damping				
emittance x/y		100	100	100
emittance y (ϵ_n)	μm	4.2	.4	.06
emittance z	m dp/p γ	.005	.014	.04
bunch spacing	m	2.4	.5	.2
ring Energy	GeV	.6	.8	1
ring radius	m	.7***	4	15
(avg B)/(peak B)		3***	.7	.24
damping time	msec	3.8	2.8	2.3
RF				
pulse length	ns	680	150	60
peak power/length	MW/m	260	380	580
total RF energy	KJ	40	67	210
Linac				
loading η	%	2.5	2.5	2.5
iris radius a	mm	44	10	3.5
section length	m	57***	4	1.6
dp/p for BNS	%	.04	.17	.4
dp/p from wakes	%	.09	.11	.12
dp/p incl emit	%	.18	.16	.08
RF phase for BNS	deg	20	22	15
Linac tolerances				
alignment	μm	—	300	30
vibration	μm	1.9	.12	.012
Final focus				
β_y^*	mm	.11	.10	.08
crossing angle	mrad	59	14	3.8
disruption angle	mrad	6.7	.72	.25
chrom corr factor		22	24	28
quad radius	mm	19	2.1	.32
free length	m	.53	.56	.68
Intersection				
σ_y	nm	220	21	2.2
Oide min σ_y	nm	43	8	1.7
σ_x/σ_y		180	170	177
σ_z	μm	460	180	70
disruption D		12	8	6.5
lum enhance H		1.3	1.4	1.6
beamstrahlung δ	%	.004	.27	11
dp/p physics	%	.18	.18	3.2
luminosity 10^{33}	$\text{cm}^{-2}\ \text{sec}^{-1}$	1.0	3.1	7.8

*** See text.

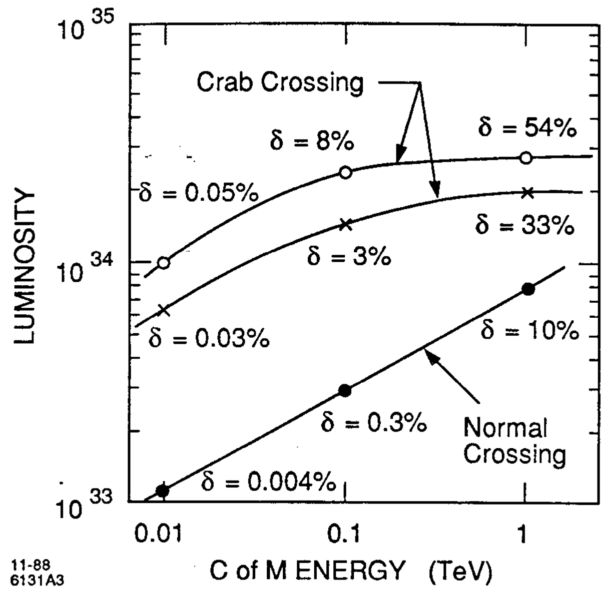

Fig. 1. Luminosity of linear collider designs as a function of energy.

3.2 An Intermediate Linear Collider

Instead of completely redesigning the machine as the energy is lowered, we can consider the performance of a collider with wavelength and repetition rate chosen for the 1 TeV case, but operating at a reduced energy, e.g., at one half energy. Two options are considered: (a) keep the gradient the same and half the length and (b) keep the length the same and half the gradient. In both cases, the final focus and damping rings have been reoptimized. The resulting parameters are shown in Table 2. The higher gradient version gives twice the luminosity and has a less severe vibration tolerance, both of which would be preferred. However, the dark currents and breakdown problems will be less in the low gradient case, and the stored energy is lower by a factor of two, so the power supply will be easier and cheaper.

3.3 Crab-Wise Finite Angle Crossing

The situation can be improved if "crab-wise" crossings are allowed. Such crossings would employ an RF deflector near the end of each linac to deflect the front of the bunches one way and the back the other way (so they now move somewhat crab-wise). If the angle of tilt of each bunch is correctly chosen, then the bunches pass through each other head on—even when the beams have a finite crossing angle (see Fig. 2). This technique removes the constraint on the width of the bunches that is normally present with finite angle crossing and allows a smaller aspect ratio.

Using this crab-wise crossing, machines were redesigned at the three energies [see Fig. 1 (crosses) and Table 3]. For the 10 GeV case, the total momentum spread is again kept below 0.2%; for the 100 GeV case, it is kept to 1% for Z production, and for 1 TeV it is kept to $\delta \leq .3$; *i.e.*, an rms momentum spread of 10%.

Figure 1 (circles) also shows designs with no restriction on momentum spread.

Table 2. Two designs for an intermediate energy collider.

		Low grad ILC	High grad ILC	TLC
General				
c.m. energy	TeV	.5	.5	1
RF wavelength	cm	1.75	1.75	1.75
repetition rate	kHz	.36	.36	.36
accel gradient	MV/m	93	186	186
number bunches		10	10	10
particles/bunch	10^{10}	.7	1.4	1.4
wall power	MW	52	103	210
Damping				
emittance x/y		100	100	100
emittance y (ϵ_n)	μm	.035	.06	.07
emittance z	m dp/p γ	.04	.04	.04
bunch spacing	m	.2	.2	.2
ring energy	GeV	1.1	1.0	1.0
ring radius	m	23	15	15
(avg B)/(peak B)		.17	.24	.24
damping time	msec	2.1	2.3	2.3
RF				
pulse length	ns	60	60	60
peak power/length	MW/m	146	580	580
total RF energy	KJ	51	103	210
Linac				
loading η	%	2.5	2.5	2.5
iris radius a	mm	3.5	3.5	3.5
section length	m	1.6	1.6	1.6
dp/p for BNS	%	.2	.4	.4
dp/p from wakes	%	.11	.11	.11
dp/p incl emit	%	.14	.14	.14
RF phase for BNS	deg	19	15	15
Linac tolerances				
alignment	μm	20	35	30
vibration	μm	.009	.017	.012
Final focus				
β_y^*	mm	.1	.12	.11
crossing angle	mrad	4.2	6.1	3.8
disruption angle	mrad	.23	.31	.25
chrom corr factor		29	29	29
quad radius	mm	.17	.25	.32
free length	m	.36	.43	.7
Intersection				
σ_y	nm	2.7	3.9	2.8
Oide max σ_y	nm	1.3	1.9	1.9
σ_x/σ_y		132	132	132
σ_z	μm	70	70	70
disruption D		5	5	5
lum enhance H		1.6	1.6	1.6
beamstrahlung δ	%	2	4	11
dp/p physics	%	.7	1.1	3.2
luminosity 10^{33}	cm^{-2} sec^{-1}	1.5	2.9	6.2

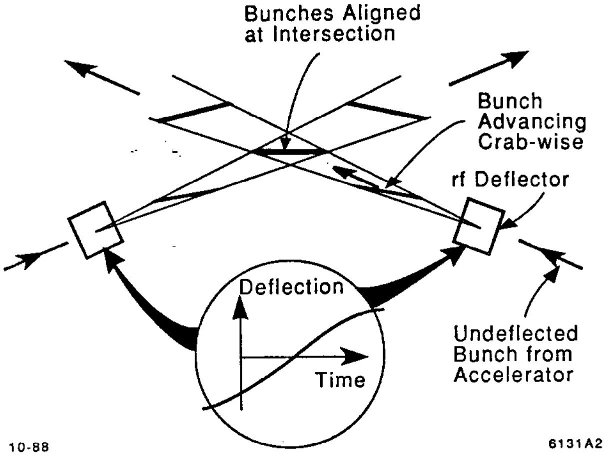

Fig. 2. Crab-wise crossing.

As in the case in Section 3.1, less effort has been spent on the low energy examples than on the TeV case, and there are the same problems in the B factory case. Nevertheless, the general trend is probably correct: a significant gain in luminosity is obtained in all cases, with the larger gain being realized in the lower energy examples.

4. POSSIBLE IMPROVEMENTS

1. Some improvements in the damping ring performance are probably possible. In the examples considered I used a wiggler ring but did not consider a combined function lattice that could alter the partition functions. If a combined function wiggler lattice is possible, we might gain a factor of two in the final luminosity.
2. I have assumed that not more than 25% of the energy stored in the cavities can be extracted with multiple bunches. This may be true for a traveling wave structure, but need not be so in a standing wave structure. A factor of two increase in efficiency, and thus luminosity, might be possible.
3. I assumed only 36% efficiency for the power source. Clusters of low perveance mini-klystrons might have much better efficiency. Another factor of two?
4. One can always hope that the dilutions that have been assumed are overly pessemistic. A maximum gain of about three is possible.
5. One can consider asymmetric arrangements in which a higher electron than positron current is employed. If electrons are available from a high brightness gun whose brightness is higher than that available from a damping ring then some gain in luminosity might be possible. For the low energy machines, one could also consider asymmetric energies with the same possible advantage.

At best there might be another order of magnitude to be won, but it will not be easy. Maybe there are other ideas!

Table 3. Parameters for colliders with crab-wise crossing.

		B factory	*Z* factory	TLC
General				
c.m. energy	TeV	.01	.1	1.0
RF wavelength	cm	15	5	1.75
repetition rate	kHz	1.8	1.0	.36
accel gradient	MV/m	46	93	186
number bunches		20	10	10
particles/bunch	10^{10}	19	6	1.4
wall power	MW	200	200	200
damping				
emittance x/y		100	100	100
emittance y	μm	2.7	.36	.05
emittance z (ϵ_n)	m dp/p γ	.004	.016	.04
bunch spacing	m	1.2	.5	.2
ring Energy	GeV	.64	.8	1.0
ring radius	m	1 ***	4	15
(avg B)/(peak B)		2 ***	.7	.24
damping time	msec	3.5	2.8	2.3
RF				
pulse length	ns	680	150	60
peak power/length	MW/m	260	380	580
total RF energy	KJ	40	70	210
Linac				
loading η	%	1.25	2.5	2.5
iris radius a	mm	44	10	3.5
section length	m	57 ***	4	1.6
dp/p for BNS	%	.02	.15	.4
dp/p from wakes	%	.07	.07	.12
dp/p incl emit	%	.19	.15	.08
RF phase for BNS	deg	14	28	15
Linac tolerances				
alignment	μm	8000	340	30
vibration	μm	3.8	.16	.012
Final focus				
β_y^*	mm	.34	.27	.2
crossing angle	mrad	150	45	9.2
Δz tolerance	μm	50	24	18
disruption angle	mrad	17	2.3	.58
chrom corr factor		26	23	28
quad rad	mm	200	18	1.8
free length	m	1.7	1.6	1.6
Intersection				
σ_y	nm	300	32	3.3
Oide min σ_y	nm	28	7	1.7
σ_x/σ_y (R)		24	35	49
σ_z	μm	340	150	70
disruption	D	15	14	10
lum enhance H		1.7	1.9	2
beamstrahlung δ	%	.03	2.7	33
dp/p physics	%	.2	.8	10
luminosity 10^{33}	cm^{-2} sec^{-1}	6	14	20

*** See text.

5. ADDENDUM–THE PAIR PROBLEM

Since the Snowmass meeting and since writing the above, we have become aware of the serious nature of the backgrounds due to electron positron pairs generated by beamstrahlung photons. These photons can be converted by at least two mechanisms. They can make pairs incoherently on the individual electrons in the oncoming beam.[2] They can also be converted in the coherent electromagnetic field of the entire oncoming beam.[3] There has not been time to give a thorough study of these backgrounds, and thus what follows is preliminary, and concerns only the 1 TeV cases discussed above.

5.1 Pair Production Cross Section

The cross section for the incoherent pair production[3] is relatively energy independent and has a value of the order of 6×10^{-26} cm^2. For the TLC parameters given above, approximately 10^6 electron positron pairs are generated per multibunch crossing.

The coherent production is negligible provided the beamstrahlung remains in the classical regime. Defining Υ as 2/3 times the critical energy divided by the beam energy, then

$$\Upsilon = \frac{.86 R_e \lambda\!\!\!^{-}_e \gamma N}{\sigma_z \sigma_x} \qquad (1)$$

where R_e (2.82×10^{-15}) is the classical electron radius, $\lambda\!\!\!^{-}_e$ is the classical electron wavelength (3.86×10^{-13}), γ is of the beam, N is the particles per bunch, and σ_z and σ_x are the rms length and width of the bunch.

The coherent production remains negligible compared to the incoherent effect provided Υ is less than 0.6.[3] If Υ is above that value the production rises very rapidly until the number of pairs is equal or even larger than the initial number of electrons. In the normal crossing TLC case given above the Υ is only 0.35 and the coherent production would not be a problem. But in the higher luminosity "crab crossing" case Υ is 1.1 and we would have massive coherent pair production.

5.2 Energy and Angular Distribution

Reflecting the bremstahlung spectrum of the photons, the number spectra of the pair electrons falls as the 2/3rd power of the energy. Their angles of production are of order $1/\gamma$, and therefore very much forward, but the magnetic fields at the bunch crossing deflect them to larger angles.

The maximum transverse momentum given to the pair electrons is, in our TLC examples, of the order of 160 MeV, but that is only given to relatively high energy electrons (approximately 50 GeV), and these emerge at relatively small angles (of the order of 2 mrad). With the finite angle crossings, discussed above, such high energy pair electrons would pass by the opposite quadrupole without causing trouble. For lower energy pair electrons, however, the situation is more serious and now depends on their charge.

In the case of the pair electron with the same charge as the beam from which it came, then the fields deflect it in towards the axis, and if its energy is low, trap it along the axis. When such a trapped electron leaves the bunch it emerges in a relatively forward direction, as do the beam electrons themselves when they have lost a large fraction of their energy.[4] The angles in our case are of the order of 1 mrad vertically, but 10 mrad horizontally, which would already be a problem. But the situation for the other sign is much worse.

For the pair electron with the opposite charge to its beam, then, the deflection is away from the axis and the final angle can be much larger. For low energy electrons (in our case less than approximately 50 GeV) the maximum angle can be expressed for flat beams (but I think only approximately) by

$$\Theta = 1.5 \left(\frac{R_e N}{\gamma \sigma_z} \right)^{1/2} \qquad (2)$$

where R_e is the classical electron radius, N is the number of electrons in the oncoming bunch, γ is the γ of the pair electron and σ_z is the rms bunch length. In the TLC cases above, for a pair electron energy of 250 MeV the angle is 70 mrad. And there are approximately 100,000 electrons with energy less than 250 MeV!

5.3 Proposed Solution

I will assume that we should avoid operating in the quantum regime where massive coherent pair production is present. I will also assume that a number of electrons of the order of 100,000, of any energy, colliding with the face of an opposite quadrupole is unacceptable. They will either melt the magnet or at least give an albido that will be intolerable to the detector.

I then propose :

1. *Use crab crossing* to allow a crossing angle of the order of 80 mrad. At 1.6 m this corresponds to a distance of 13 cm. I will assume that we can make a quadrupole with a radius not larger than 4 cm, surrounded by a bucking coil (to shield the quadrupole from the experiments solenoidal field) of thickness not more than 3 cm. In this way only particles at angles greater than 40 mrad can hit the quad or bucking coil.
2. *Reduce the pair electron deflection angles* (Θ) by increasing σ_z and decreasing N. σ_z is increased until the momentum spread from the curvature of the sin wave of the rf is significant. I halve N and, at the same time, double the number of bunches, so as to keep the same total efficiency. The increase in transverse wakes caused by the bunch lengthening is compensated by the lower number of particles per bunch, so the alignment tolerances are the same. Despite the energy spread caused by the long bunch, the lower number of particles per bunch produces a smaller energy spread, and thus the same β can be obtained at the final focus.
3. *Reduce the bunch aspect ratio* $R = \sigma_x/\sigma_y$, and thus increase the luminosity, until the Υ reaches a still safe value of 0.32. The aspect ratio is then 60. The amplitude tolerance on the crab crossing rf separators

$$\frac{dA}{A} = \frac{\sigma_x}{\sigma_z \Theta_c} = 1.6\% \qquad (3)$$

where Θ_c is the crossing angle. The position tolerance on the separators is

$$dz = 2\frac{\sigma_x}{\Theta_c} = 4\ \mu \quad . \qquad (4)$$

Note that this position error is equivalent to a horizontal beam shift of 0.16 μ, and that the beams horizontal position will in any case have to be servoed. The 4 μ tolerance is a jitter tolerance and is not severe.

With these new parameters the luminosity is 10^{34} cm^{-2} sec^{-1}, as required, and other parameters quite reasonable. The maximum angle of pair electrons at 250 MeV is now 40 mrad, and we have chosen a crossing angle and magnet dimensions so that these will not hit the quad or bucking coil. But we must still do something to stop the lower momentum tracks from hitting these magnets.

4. *Use a kinked solenoidal field* to confine the low momentum tracks. If a solenoidal field can be obtained that is aligned along the outgoing beam axes, then low energy electrons will be guided along those axes. Electrons with 250 MeV or less will have transverse momenta of only 10 MeV or less. If the solenoidal field were 3 T then all such electrons would be constrained within a helix of 1 cm radius, *i.e.*, well away from the quadrupole and bucking coils. This maximum extent of the trapped electrons rises linearly with energy, while the maximum extent of untrapped electrons falls as the root of energy from Eq. (2). The maximum distance (Fig. 3) that any electron reaches from the outgoing axis is now 4 cm (at 500 MeV), which is over 2 cm from the bucking coil.

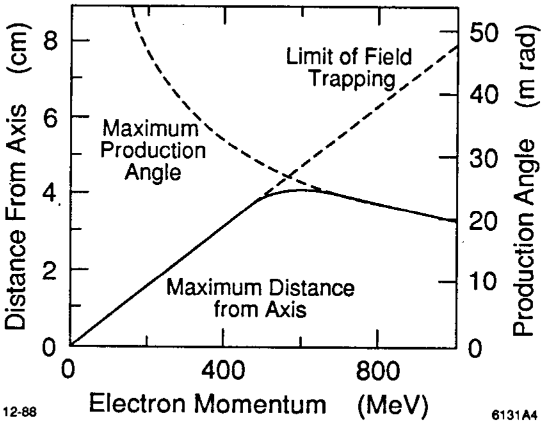

Fig. 3. Maximum radial extent of electrons from their axis at the entrace to the first quadrupole, plotted against their energy. At low energy the extent is limited by field trapping, at high energy by the production angles.

The problem remains as to how to make a solenoidal field that points along both outgoing beam directions; *i.e.*, how to make a solenoidal field with a kink of 80 mrad at the intersection. Such a field would be obtained with a current sheet in the mid plane of the detector, but that would be undesirable. Luckily it seems that the field that inevitably results when bucking coils are placed about the final quadrupoles has, at least to some approximation, the required kink [see Fig. 4(a)]. As shown in the figure, the bucking coils have been extended inward towards the intersection so as to improve the field shape. Further improvements could be made by the addition of horizontal low field (0.12 T) coils between the end of the bucking coils and the intersection. In the absence of bucking coils (e.g., if pure permanent magnet quads were used) such horizontal low field coils, but now much longer, could be used [Fig. 4(b)].

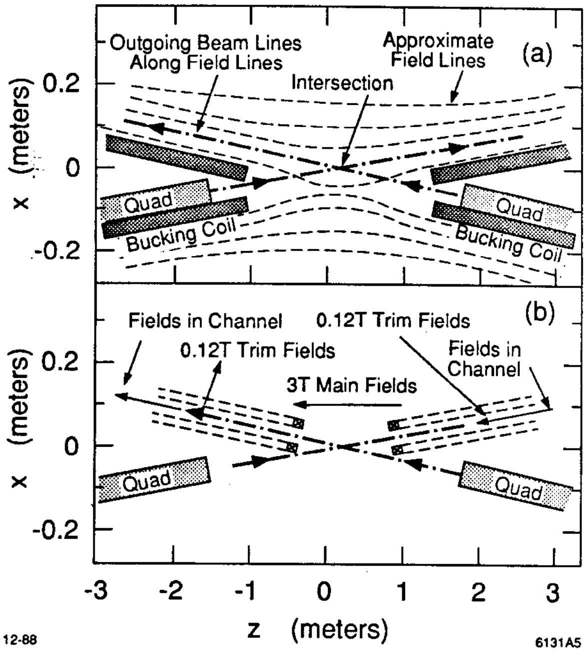

Fig. 4. Possible intersection region geometries in a large experimental solenoid; (a) with bucking coils to shield conventional quadrupoles; and (b) with permenant magnet quadrupoles and transverse trim coils. It is seen that in both cases the resulting fields have the qualitatively correct shape to guide low energy pair electrons away from the quadrupoles.

5.4 Conclusion

It appears that the pair production problem can be overcome, at least at 1 TeV, by a combination of modifications to the previously defined TLC. Crab crossing seems essential to allow a crossing angle of the order of 80 mrad. The high momentum pair electrons now pass well clear of the quadrupoles. The production angles of low momentum pair electrons can be reduced by halving the number of electrons per bunch and doubling the bunch length. Then, with the help of a solenoidal field, these too can be kept clear of the magnets.

A bunch aspect ratio of 60 keeps the beamstrahlung Υ to about 0.3, and the coherent pair production is supressed. Using these new parameters, and by increasing the number of bunches to 20, the luminosity can be maintained at 10^{34} cm^{-2} sec^{-1}.

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