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ATTAINING HIGH LUMINOSITY IN LINEAR e^+e^- COLLIDERS*

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INTRODUCTION

The attainment of high luminosity in linear colliders is a complex problem because of the interdependence of the critical parameters. The situation is complex and has been discussed in more detail in Ref. (1) and in Ref. (2). For instance, changing the number of particles per bunch affects the damping ring design and thus the emittance; it affects the wakefields in the linac and thus the momentum spread; the momentum spread affects the final focus design and thus the final β^*; but the emittance change also affects 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. One can only maximize the luminosity by a process of search and iteration.

The process can be facilitated with the aid of a computer program, using the approximate formulae given in Ref. (2). Examples can then be optimized for maximum luminosity, and compared to the optimized solutions with different approaches.

ASSUMPTIONS

1. RATIO OF HORIZONTAL TO VERTICAL EMITTANCES

I have assumed relatively large ratios of horizontal to vertical emittances in the damping rings. An asymmetric emittance is natural in a damping ring and comes with essentially no price. It easily allows the generation of a flat beam profile to minimize beamstrahlung, without loss of luminosity.

2. RATIO OF HORIZONTAL TO VERTICAL BETAS

Greater luminosity is obtained with smaller ratios of the betas. However, the beamstrahlung rises, and has, in these examples, been limited to a value of $\delta \leq 0.3$. This ratio can also be used to control the beamstrahlung Υ parameter, and to allow finite angle crossing without luminosity loss.

3. DAMPING RING

Wiggler damping rings are assumed. The energies are chosen to make the contributions from intrabeam scattering and quantum fluctuations the same. The ring diameters are then chosen to give a longitudinal impedance requirement of $Z/n = 0.5\ \Omega$. The wiggler fields are, in most cases, 2 T, but are raised to 4 T (superconducting) for the 10 TeV case. The quadrupole apertures are 12 mm and pole tip fields, 1.4 T. The partition functions are normal in most cases, $\beta y/\beta x = 4$, and the phase advance per cell is 65°.

4. QUADRUPOLE DOUBLET FINAL FOCUS

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 $S = 0.04 \times dp/p$ (scaling law from Brown). The maximum pole tip field, in most cases, is assumed to be 1.4 T. The aperture is taken to be ten times the rms beam size.

5. ACCELERATING STRUCTURE

Conventional iris-loaded accelerating structures are assumed. The iris radius, in most cases, 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). For the 5 and 10 TeV examples, it is raised to 0.25 and 0.3, respectively, to ease wakefields and resulting tolerances. The fill time for the structure is usually taken to be 0.45 times the attenuation time. In the 5 and 10 TeV cases, it is lowered to 0.3 for maximum efficiency.

6. LINAC FOCUSING

Five percent of the linac length is assumed to be taken up with quadrupoles whose apertures are 1.26 times the structure irises and whose pole tip fields are 1.4 T.

7. NUMBER OF BUNCHES

In all but the multi-TeV examples, a limit is set on the number of bunches such that not more than 25% of the total stored energy is extracted. This is consistent with the conventional traveling wave design.

In the 5 and 10 TeV examples, this percentage is raised to 75%, on the assumption that a resonant ring design is adopted.

8. DILUTION

No machine is perfect; so in designing it, one must make allowances for the imperfections, whose effect will be to dilute various parameters. 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 xy in final focus:	1.2
$\beta^* xy$ in final focus:	1.2

9. LONGITUDINAL EMITTANCE

The longitudinal emittance is constrained by the need to restrict the momentum spread in the linac, and thus the range of phase advances and resultant alignment requirement. It is also restricted by rf voltage considerations in the damping ring. In some multibunch cases, it is further restricted in order to keep a sufficiently small ratio of bunch length to bunch spacing in the damping ring.

10. ACCELERATING FIELDS

From the machine physics point of view, there seems no disadvantage in high accelerating fields. The optimized luminosity is affected very little, the tolerances are easier and, of course, the length is less. The fields used are thus the highest possible consistent with expected breakdown.

0.5 TeV COLLIDERS USING DIFFERENT PHILOSOPHIES

Depending on one's philosophy, one can come up with quite different collider designs, and attain different luminosities. In order to illustrate this, I give (in Table 1, columns A–H) eight different designs of a 0.5 TeV center-of-mass energy collider. Each is constrained to use the same wall power (70 MW) and the same rf source efficiency (20%). The designs vary in their having:

(a) single or multiple bunches,

(b) head-on or finite angle collisions,

(c) crab crossing or no crab crossing,

(d) conventional (1.4 T pole tip field) final focus quadrupoles or exotic focusing (5 T), and

(e) 11.4 GHz rf or 30 GHz rf.

SINGLE BUNCH DESIGNS

In all the single bunch cases, it is found that maximum luminosity is obtained when the number of particles per bunch is maximized. The loading (i.e., the fraction of the stored rf energy that is transferred to a bunch) η can be allowed to rise to between 8% and 12%, but great care must be exercised to correct the momentum spread that comes from the longitudinal wakes. The transverse wakes are severe and BNS damping is essential and strong (the required momentum or focusing strength variation $dk/k = 3\%$). This might best be applied by modulating the focusing strength rather than the momentum, but in either case, the differences in phase advances in the linac are large and the alignment tolerances severe (below 2 μm) unless autophasing is employed. The luminosities obtainable vary with the assumptions, but in no case can the aimed-for 2.5×10^{33} cm^{-2} sec^{-1} be achieved.

In the following, the letters refer to the columns in Table 1.

(A) Head-on, conventional quadrupole, 11 GHz:

In this case, the quadrupole apertures have to accept the disrupted beam, and have, as a result, limited strength ($\beta^* = 4.3$ mm). The maximum luminosity is only 0.24×10^{33}.

(B) Head-on, high field quadrupole, 11 GHz:

If an exotic quadrupole (pole tip field = 5 T) is employed, the focus strength can be increased ($\beta^* = 1.9$ mm) and the luminosity is increased in proportion, to 0.6×10^{33}.

(C) Flat beam, finite angle crossing, conventional quadrupole, 11 GHz:

This is the philosophy, but not the particular parameters, that has been pursued at Novosibirsk (3). A finite crossing angle is employed that is much greater (by a factor of 25) than the disruption angles. The disrupted beam, instead of passing through the quadrupole aperture, now passes to one side of the quadrupole, and, as a result, the quadrupole's aperture is limited only by the incoming beam dimensions, which are far smaller. The apertures can be very small (0.6 mm), and the focusing strong ($\beta_y^* = 0.13$ mm).

In order not to lose luminosity from this large crossing angle, a very wide flat beam (180 : 1) must be employed. The luminosity is increased, compared to case (A); but, because of the need for this very wide beam, the increase is not large (50%, to 0.34×10^{33}). An advantage, however, is that the beamstrahlung is now relatively small ($\delta = 8\%$) .

We may note that, in this case, the vertical β^*, or "depth of focus," is already of the same order as the bunch length σ_z ($\sigma_z/\beta_y^* = 0.7$). Further reduction in β^*, by the use of higher field quadrupoles, will thus not increase the luminosity.

(D) Crab crossing, conventional quadrupole, 11 GHz:

With crab crossing (4) (see Figure 1), rf-driven deflecting structures are introduced just before or after the final focusing magnets of each beam. The phasing of the rf is such that the center of each bunch is undeflected, the front shifted to one side, and the back to the other, in order to introduce a tilt of $\theta_c/2$ in the bunch with respect to its direction of motion (the bunches moves in a partially "crab"-like way). The sign of the tilts are such that the two bunches are "in line" as they cross. In their own center of mass, they interact with zero crossing angle and suffer no luminosity loss.

In this case, the constraint on the width of the beam is removed, while the advantage that the quadrupole does not have to contain the disrupted beam is retained. One is free to reduce the bunch width until the beamstrahlung δ becomes unacceptable. With $\delta = 0.3$ (obtained with a horizontal to vertical ratio of 39) one obtains a luminosity of 1.2×10^{33}, which seems the highest value obtainable with single bunches at this radio frequency.

(E) Crab crossing, conventional quadrupole, 30 GHz:

This would be a possible philosophy for the CERN CLIC (5). The choice of the high operating frequency is dictated by the desire for a very low total rf energy (18 J, compared to 120 J for the 11 GHz cases).

Surprisingly, as the frequency is raised, the luminosity does not change much. The lower number of particles per bunch (1.7×10^{10} instead of $\approx 10^{11}$) is compensated for by the lower emittance (1.9 mm mrad, instead of $\approx$10 mm mrad) that the damping ring can now provide. As the number of particles per bunch falls, the beamstrahlung is suppressed, rounder beams can be employed, and the required ratio of emittances is not so severe (37 : 1, instead of 100 : 1). When all this is taken into account, a somewhat higher luminosity is obtained (1.8×10^{33}).

But the alignment tolerance is tighter (0.9 μm, compared to 2 μm for the 11 GHz cases). The tighter tolerance arises because the lower emittance, combined with the stronger focusing, gives a smaller beam size in the linac.

MULTIPLE BUNCH DESIGNS

If the problems with beam breakup can be solved by the use of damped cavities, then the whole optimization of the collider is changed. Instead of employing a few large bunches, greater luminosity is obtained using a larger number of small bunches. Not only is greater luminosity obtained, but one finds that the momentum correction is now trivial, the BNS damping is weak, the differences in phase advance in the linac are less than 1.5 rad, and the alignment tolerances are much easier (20–3. μm, instead of 1–2 μm). I will consider four cases (the letters refer to the columns in Table 1):

(F) Flat beam finite angle crossing, conventional quadrupole, 11 GHz:

> This is the philosophy discussed in Ref. (1). As in example (C), the crossing angle is chosen to be 25 times the disruption angles, so that the used beam can pass outside the quadrupole aperture. A very flat beam (aspect ratio 180 : 1) is needed to avoid luminosity loss from the finite angle crossing. The finite crossing angle allows the multiple bunches to interact strongly only at the intersection point, but the long-range interactions do excite a kink instability resulting in an amplification of misalignments by the factor C_n of 1.4.
>
> A luminosity of 1.4×10^{33} is obtained (four times that obtained in the single bunch case), and the beamstrahlung energy loss δ is only 3.9%. A possible problem with this design would come from the electrons pairs produced at the intersection. Since the crossing angle is constrained, some of the electrons from the pairs may hit the opposite quadrupole and generate an unacceptable experimental background.

(G) Crab crossing, conventional quadrupole, 11 GHz:

> This is the philosophy now considered at SLAC. The crab crossing allows a large enough crossing angle to avoid background problems from electron pairs, and it allows any desired aspect ratio to be used. For maximum luminosity consistent with the requirement of beamstrahlung $\delta < 0.3$, the aspect ratio is 25 : 1, and a luminosity of 5.8×10^{33} is obtained (five times that obtained with the single bunch, and over twice that required). If other aspect ratios are

chosen, both beamstrahlung and luminosity vary as shown in Figure 2. One must note, however, that points on this figure represent different damping ring and final focus designs. With a fixed design optimized at one particular aspect ratio, the other aspect ratios will yield somewhat less luminosity.

From Figure 3, we see that very high luminosity appears possible for very high values of the beamstrahlung parameter δ. Since δ represents the fractional energy of loss of the beams, values above one need interpretation. They imply almost total conversion of the electron beams to real high-energy photons. The electron-positron luminosity is suppressed, but there remains a significant and interesting cross section for photon-photon interactions (6).

For the $\delta = 0.3$ case, the bunch length is significantly less than the β_y^* ($\sigma_z/\beta_y^* = 0.32$), so one might expect that the luminosity could be significantly improved by the use of higher field quadrupoles. This turns out not to be the case. As the focusing strength is increased, the beamstrahlung is also increased, and a wider beam must be employed to control it. The net luminosity increase from the use of a 5 T (instead of 1.4 T) quadrupole is only 25%, which hardly seems worth it.

(II) Crab crossing, conventional quadrupole, 30 GHz:

This would be a possible philosophy for CERN to follow, if they wished to raise the luminosity and ease the tolerances, yet maintain the high frequency, and consequent low total rf energy. In order to keep the range of phase advances below 1.5 rad (so that the tolerances can be eased), one finds it necessary to use very small bunches (1.8×10^9 electrons). Twenty bunches can then be used, and a luminosity of 4.1×10^{33} is obtained. But the bunches are now spaced by only three cycles and the bunch-length-to-spacing ratio in the damping ring is 0.6, which would not be acceptable. Some scheme for compressing the bunches together, prior to extraction, would have to be used. Another problem is that the damping time is rather long (4 msec) compared to the high repetition rate (900 Hz). A predamping ring would be essential.

It is clear that this case has not been fully optimized, but it illustrates the basic insensitivity of the luminosity to the wavelength used. However, tolerance and damping ring problems get worse for shorter wavelengths. Luminosity is also insensitive to the accelerating gradient. Tolerance and damping ring problems improve with higher gradients.

The above discussion can be shown graphically in Figure 3. It is seen how for the single bunch designs the luminosity rises with η. Whereas for the multiple bunch machines the luminosity is maximized for many bunches, each of which has a low η. In the single bunch cases, the upper limit on η, and thus maximum luminosity, is set by beamstrahlung, tolerance, and momentum spread considerations at around 20%. For multibunch machines, the useful lower limit on η is set when the problems of designing the lower emittance damping rings and final focus systems become such that the gains that should be expected from the lower charge are no longer realized.

Figure 4 shows how the achievable emittance rises with the loading, and how the differences in betatron phase (due to the needed momentum spread in the beam) also rises with η. If these differences in phase advance are small compared to $\pi/2$, then alignment tolerances are not a problem. If they are large, then the required alignment must be better than the beam size, which is of the order of a micron– a hard requirement to meet. Autophasing, which was not assumed here, can reduce the phase differences, but introduces new tolerances on the bunch intensity and shape.

It is a pleasant observation that the highest luminosity is obtained (assuming multiple bunch operation is achieved) with the lowest η, which gives an easy tolerance, without the need for autophasing or other sophisticated correction.

DESIGNS AS A FUNCTION OF ENERGY

At higher center-of-mass energies, for the same event rates, we require luminosities that rise as the square of the energy. For 10,000 events per year per unit of R, the required luminosity is given approximately by $L \approx 10^{34}\,[E\,(\mathrm{TeV})]^2$ cm^{-2} sec^{-1}. In Table 1, examples are given for four energies up to 10 TeV. These examples achieve the required energies and luminosities by using progressively higher gradients, lower wavelengths, higher wall power and increasing damping ring sophistication. In all cases, multiple bunches and crab crossing are assumed. In column (I), for comparison, the approximate parameters for the SLC, calculated in the same way, are also given.

The letters below refer to columns in Table 1.

(J) ILC, an intermediate 0.5 TeV linear collider:

This is essentially the same as example (G) above, except that a flatter beam (100 : 1), easier crab crossing requirements, and lower beamstrahlung (0.07), has been chosen.

(K) TLC, a 1 TeV collider:

It is assumed that a more advanced power source will allow the gradient to be raised to 150 MeV/m. No change in wavelength is assumed, and the repetition rate remains the same (120 Hz).

The four-times-higher luminosity (1×10^{34}) is obtained from:

(a) an assumed improvement in the power source efficiency (from 20% to 40%);

(b) a 40% increase in wall power (from 70 to 100 MW); and

(c) by allowing the beamstrahlung δ to rise to 0.3.

(L) 5 TLC--A 5 TeV collider:

In order to avoid an excessive rise in the total rf stored energy, the wavelength is reduced to 12 mm. At this frequency, breakdown and dark current should be less of a problem, so the accelerating field can be raised to 200 MeV/m.

The required 25-fold increase in luminosity (to 2.5×10^{35}) is obtained by:

(a) a further increase in assumed rf power source efficiency to 60%;

(b) assuming the use of a standing wave, or resonant ring structure, with a bunch train running for 75% of the fill time; and

(c) assuming a damping ring with Robinson Wigglers, so that the horizontal partition function is raised to 2.5 (and the longitudinal partition function lowered to 0.5).

One may note that in this example the vertical size of the beam at the intersection (0.2 nm) is essentially equal to the Oide limit [a minimum spot size consistent with the effects of synchrotron radiation in the final focus quadrupoles (7)]. No further reduction in size is possible without a further reduction in vertical emittance or some other trick. Stronger quadrupoles will not help.

(M) 10 TLC--A 10 TeV collider:

Once again the wavelength has been reduced (to 10 mm), and the accelerating gradient increased (to 300 MeV/m). A more drastic reduction of wavelength would lower the now very large stored energy (1.2 kJ), but the bunch spacing then becomes small compared to the bunch length in the damping ring (now only a factor of 5, already requiring the use of higher harmonic rf). The possibility of compression of the bunch train before extraction would relieve this constraint, and needs to be studied.

The required luminosity is now 1×10^{36} cm^{-2} sec^{-1}. No further improvement in rf efficiency or number of bunches seems realistic, so the required increase in luminosity can only come from a reduction in spot size. This, since one is at the Oide Limit, can only come from a reduction in the emittance or by finding a way around the limit.

To lower the emittance, one needs a further improvement in the damping ring. In the example given, this is achieved by raising the wiggler magnetic fields (to 4 T) by the use of superconducting magnets. Whether this is really practical is not clear. The wigglers have quite a short period, and must have strong field gradients to obtain the still-needed modification of the partition functions.

This 10 TeV parameter set is clearly very speculative, but it is significant, nevertheless. The luminosity calculated in a self-consistent way, with possible dilutions included, is nearly six orders of magnitude higher than that of the SLC [see column (I)]. And there are other ideas for improvement, as mentioned below.

ENERGIES ABOVE 10 TeV

To build colliders at yet higher energies, one must find ways to obtain the yet higher needed luminosities. As before, high efficiency is essential. In addition, one will have to find solutions to the apparent limit implied by the Oide limit combined with the emittances limits (both transverse and longitudinal) imposed by current damping ring designs. There are some ideas:

1. A possibility for improvement in damping ring performance has been raised by Pellegrini, who has suggested the use of isochronous rings whose bunches would be intrinsically unstable, but in which the growth time of that instability would be longer than that required to damp the bunch.
2. The Oide limit can be avoided if the final focus is performed by an adiabatic focusing channel (8). It is, however, difficult to conceive of a mechanism to provide the required strength of focusing. The density of plasma that could do it is far too high and would essentially stop the beam. It could, in principle, be provided by the disruption from a long-graded bunch in the opposite beam. But if two long-graded bunches are collided to give mutual adiabatic focusing, then the bunches suffer a kink instability (9) and no gain in luminosity is obtained.
3. Another way to go beyond the Oide limit is to employ very short precursor bunches to focus the opposite beams [Super Disruption (10)]. The limit is modified in this case because the synchrotron radiation is in the quantum regime and is much suppressed. But another problem is then encountered. The focusing can give a β^* as small as a micron, but the longitudinal emittance of the bunches from the damping rings do not allow such short bunches. Again, Pellegrini's isochronous rings would help.
4. The very small longitudinal emittance required for Super Disruption might, but only in the case of electrons, be obtained from a high current photocathode. This could lead one to consider a Hybrid Disruption scheme in which a long-graded positron bunch is collided with a very short cathode-generated electron bunch; the latter being preceded by a focusing precursor bunch. The electron

bunches would be adiabatically focused by the long positron bunch, and the positrons strongly focused by the precursor onto the super-short electron bunch. The kink instability is avoided when only one of the bunches is long.

5. Clearly, one must continue to search for novel ways to obtain super low emittance positrons.

In addition, there will be many problems associated with the higher energies. Higher gradients are clearly desirable; shorter wavelengths will be needed to keep the stored energy down and the repetition rate up. One must learn to handle the electron pair background. One must learn to meet the ever-tighter tolerance requirements. And there will be many other problems.

We cannot hope to attain the energies beyond 10 TeV, and the required corresponding luminosities, easily or soon. We must build a long sequence of colliders with reasonable steps along the way. It is, however, encouraging that there seems to be no single problem that would be insoluble.

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Table 1 Parameters of colliders based on different design philosophies

			A	B	C	D	E	F	G	H	I	J	K	L	M
c-of-m energy	TeV		0.5								0.1	0.5	1	5	10
bunches			Single					Multiple			single	Multiple			
crossing			head	head	flat	crab	crab	flat	crab	crab	head	crab			
focus pole field	T		1.4	5	1.4	1.4	1.4	1.4			1	1.4			
rf wavelength	cm		2.6				1	2.6		1	10	2.6	2.6	1.7	1
General															
luminosity	10^{33} cm^{-2} s^{-1}	$\mathcal{L}$	0.74	0.50	0.34	1.2	1.8	1.37	5.85	4.12	0.002	2.54	11.1	278	1130
wall power	MW	W	70.0	70.0	70.0	70.0	70.0	70	70	70	26	70	100	200	300
length overall	km	l	6.87	6.87	7.07	6.87	6.87	6.58	6.58	6.29	3.0	6.6	8.5	27.3	36.2
vertical spot size	nm	σ_y	44.7	29.3	7.0	15.7	8.5	3.4	6.5	5.6	1463	4.0	3.1	0.2	0.1
aspect ratio		σ_x/σ_y	25.5	25.5	180	38.7	15.5	180	25.5	3.6	1	109	62	136	265
horiz emittance	mm mrad	ϵ_x	13.4	13.4	9.67	13.4	1.91	3.77	3.77	0.19	30.0	3.77	3.41	0.29	0.16
emittance ratio		ϵ_x/ϵ_y	100	100	100	100	37	100	100	2	1	100	100	200	300
pulse frequency	Hz	f	115	115	110	115	794	130	130	913	120	130	128	169	148
particles/bunch	10^{10}	N	11.6	11.6	7.7	11.6	1.7	2.41	2.41	0.18	5.00	2.41	2.13	0.31	0.40
loading	%	η	12	12	8	12	12	2.50	2.50	1.25	3.23	2.50	1.47	0.60	0.60
number of bunches		N_b	1	1	1	1	1	10	10	20	1	10	17	125	125
total loading	%	η_t	—	—	—	—	—	25	25	25	3.23	25	25	75	75
rf source efficiency	%	η_{rf}	20	20	20	20	20	20	20	20	12	20	40	40	60
Intersection															
bunch length	mm	σ_z	0.32	0.32	0.11	0.32	0.12	0.11	0.11	0.04	1.05	0.11	0.12	0.02	0.015
disruption		D_y	5.5	12.8	7.3	29.7	13.5	9.6	17.8	3.9	0.7	11.4	16.9	7.3	11.0
disruption enhancement		H_D	2.33	2.20	1.08	2.22	2.60	1.56	2.25	2.23	1.94	1.74	1.89	2.07	2.21
crossing angle	mrad	θ_c	0	0	10	50	50	5.7	50	50	0	50	50	100	100
Oide factor		σ_y/σ	9.6	6.3	1.9	3.4	3.6	1.8	3.5	1.6	9.8	2.1	1.8	1.1	1.0
σ_z/β_y^*		A	0.07	0.17	0.71	0.59	0.29	1.17	0.31	0.41	0.15	0.84	0.73	0.21	0.19
bunch separation	m	Δs	—	—	—	—	—	0.29	0.29	0.03	—	0.29	0.17	0.03	0.02
multibunch instability		C_n	—	—	—	—	—	1.4	1	1	—	1	1	1	1
quantum E/E_{crit}		Υ	0.10	0.15	0.19	0.20	0.40	0.12	0.45	0.75	0.002	0.17	0.60	21	70
beamstrahlung loss	dE/E	δ	0.09	0.18	0.08	0.29	0.29	0.04	0.30	0.23	0.001	0.07	0.26	0.27	0.30

			A	B	C	D	E	F	G	H	I	J	K	L	M
c-of-m energy	TeV		0.5								0.1	0.5	1	5	10
bunches			Single					Multiple			single	Multiple			
crossing			head	head	flat	crab	crab	flat	crab	crab	head	crab			
focus pole field	T		1.4	5	1.4	1.4	1.4	1.4			1	1.4			
rf wavelength	cm		2.6				1	2.6		1	10	2.6	2.6	1.7	1
Final focus															
vertical focus	mm	β_y^*	4.35	1.66	0.15	0.54	0.41	0.09	0.33	0.10	7.00	0.13	0.16	0.08	0.08
β^* ratio		β_x^*/β_y^*	6.5	6.5	324	15.0	6.5	324	6.5	6.5	1	120	38	96	265
dp/p for focus	%	δ_f	0.22	0.22	0.20	0.22	0.24	0.17	0.17	0.12	0.45	0.17	0.09	0.07	0.07
quad aperture	mm	R_q	297	191	0.5	4.5	1.9	0.4	4.7	0.8	49.1	0.7	1.5	0.10	0.03
free length	m	l_1	14.5	6.20	0.63	1.60	1.38	0.50	1.85	0.76	3.16	0.70	1.47	0.86	0.81
pole field	T	B_q	1.40	5.00	1.40	1.40	1.40	1.4	1.4	1.4	1.4	1.4	1.4	1.4	0.94
Wakes															
uncorr emit gain		C_W	14.9	14.9	4.4	14.9	23.5	2.1	2.1	2.4	6.8	2.1	2.0	1.3	1.3
dp/p BNS	%	δ_{BNS}	3.33	3.33	0.82	3.33	3.33	0.26	0.26	0.32	2.26	0.26	0.25	0.03	0.04
phase advance	deg	$\Delta\Phi$	10.5	10.5	2.8	10.5	17.0	1.41	1.41	1.46	4.46	1.41	0.91	1.44	1.33
tolerance due to dp/p	μm	dx_δ	1.8	1.8	1.5	1.8	0.9	33.6	33.6	52.1	77.0	34	41	5	2.7
vibration tolerance	nm	dx_v	62.8	41.7	55.9	8.4	14.7	23.0	12.5	46.6	2052	27.1	11.5	2.64	1.1
phase for BNS	deg	Φ_{BNS}	5.0	5.0	27.3	5.0	5.0	14.3	14.3	3.1	−3.8	14.3	5.5	11.2	8.5
Rf															
wavelength	mm	λ	26.2	26.2	26.2	26.2	10.0	26.2	26.2	10.0	105	26.2	26.2	12.0	10.0
max acc gradient	MeV/m	G_{max}	100	100	100	100	100	100	100	100	20	100	150	200	300
iris/wavelength		a/λ	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.11	0.20	0.20	0.25	0.30
rf pulse length	ns	t	82.1	82.1	82.1	82.1	19.3	82.1	82.1	19.3	919	82.1	82.1	16.4	12.1
peak power/length	GW/m	P/l	0.24	0.24	0.24	0.24	0.15	0.24	0.24	0.15	0.10	0.24	0.54	1.12	2.93
total rf energy	kJ	J	121	121	128	121	17.6	107	107	15.3	26	107	312	474	1218
Damping															
wiggler field	T	B_D	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	4.0
partition function		J_x	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.5	2.5
E of ring	GeV	E	0.86	0.86	0.89	0.86	0.86	1.00	1.00	0.59	1.20	1.00	1.01	2.45	1.77
bunch length	mm	σ_z	3.7	3.7	3.5	3.7	3.7	3.0	3.0	2.3	1.1	3.0	2.9	0.2	0.4
bunch length/sep		$\sigma_z/\Delta s$	—	—	—	—	—	0.10	0.10	0.66	--	0.10	0.17	0.08	0.71
cooling time	msec	t_d	2.68	2.68	2.58	2.68	2.69	2.31	2.31	3.88	2.45	2.31	2.26	0.94	0.37
horizontal tune		Q_x	8.6	8.6	10.6	8.6	27.5	19.5	19.5	37.7	5.7	19.5	20.9	137	175

FIGURE CAPTIONS

1) Crab crossing.

2) Luminosity for different aspect ratios, plotted against the beamstrahlung parameter δ, for a 0.5 TeV, crab crossing, multibunch collider.

3) The luminosity of colliders as a function of the loading η for various philosophies.

4) The damping ring emittance, and differences in betatron phase advance due to BNS momentum spread in a bunch, as a function of beam loading η.

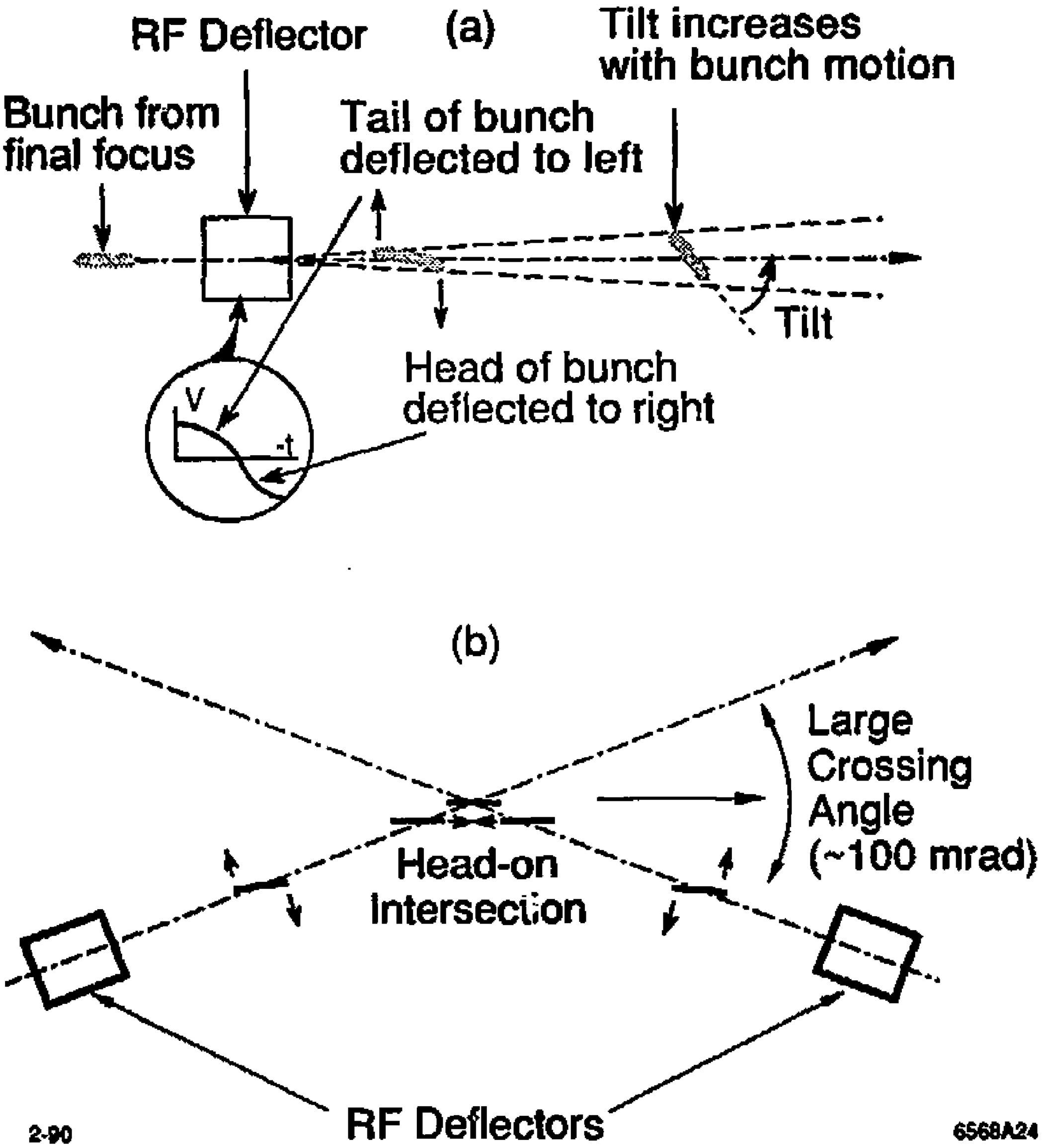
(a)
RF Deflector
Tilt increases with bunch motion
Bunch from final focus
Tail of bunch deflected to left
Tilt
V
-t
Head of bunch deflected to right
(b)
Large Crossing Angle (~100 mrad)
Head-on Intersection
RF Deflectors
2-90
6568A24

Fig. 1

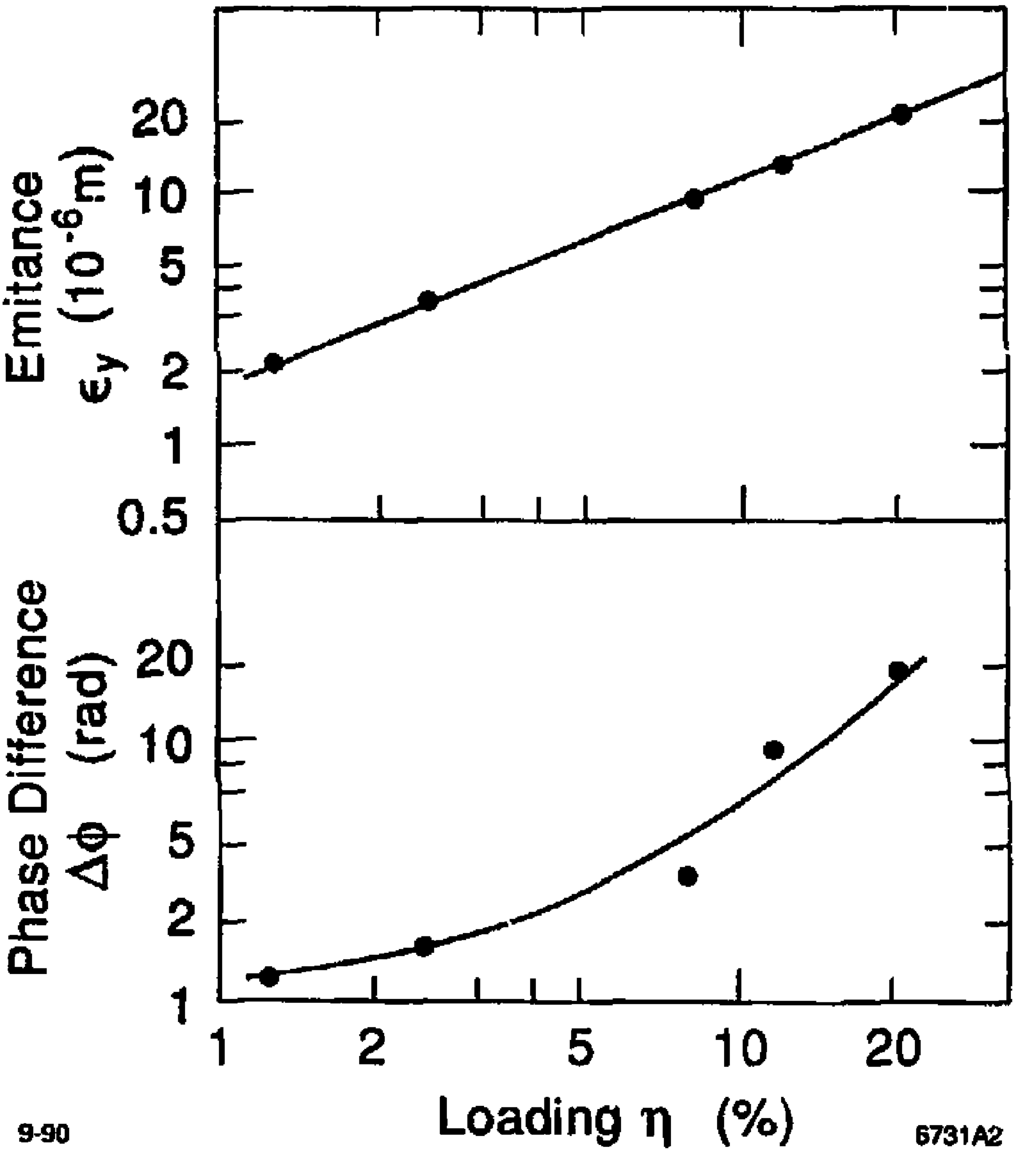
Emitance
ϵ_y (10^{-6}m)
20
10
5
2
1
0.5
Phase Difference
$\Delta\phi$ (rad)
20
10
5
2
1
1
2
5
10
20
Loading η (%)
9-90
6731A2

Fig. 2

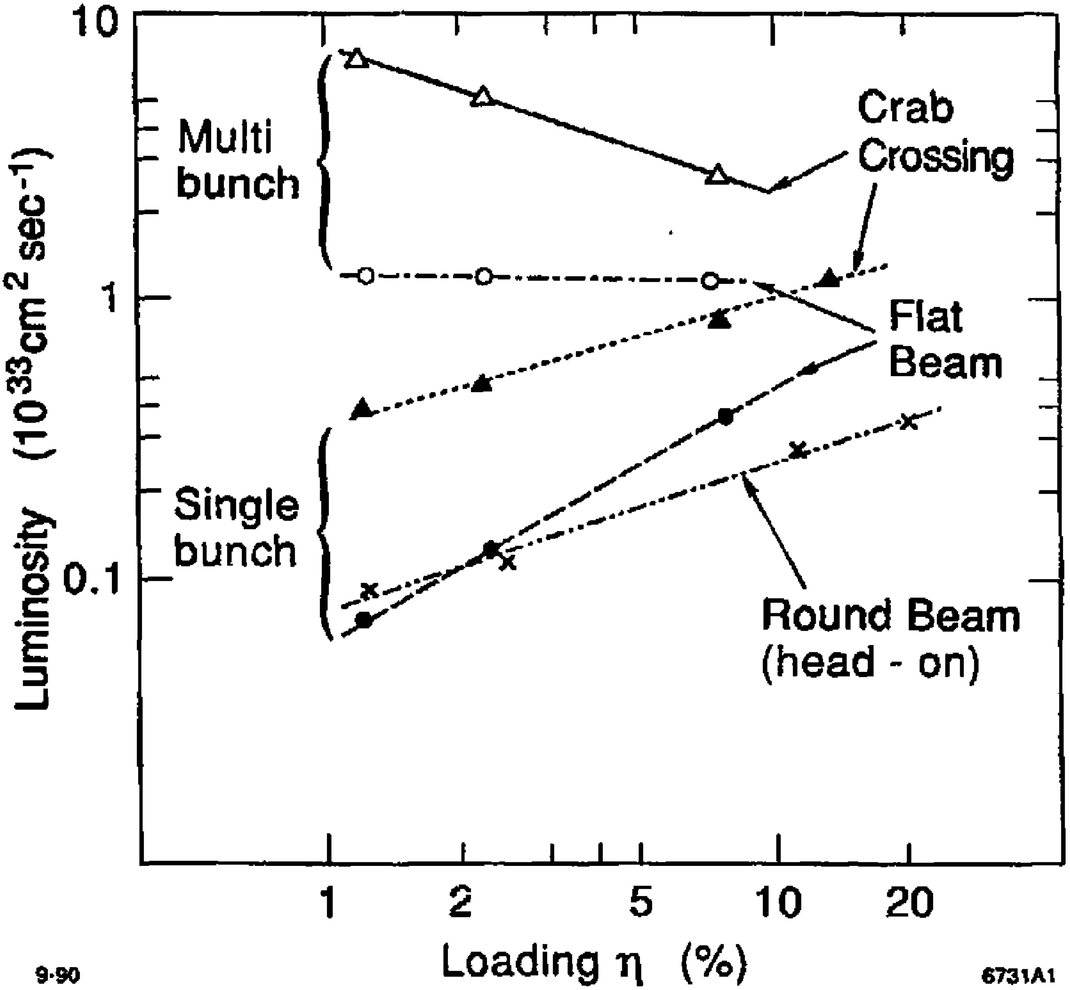
10
1
0.1
Luminosity (10^33 cm^2 sec^-1)
Multi bunch
Single bunch
Crab Crossing
Flat Beam
Round Beam (head - on)
1
2
5
10
20
Loading η (%)
9-90
6731A1

Fig. 3

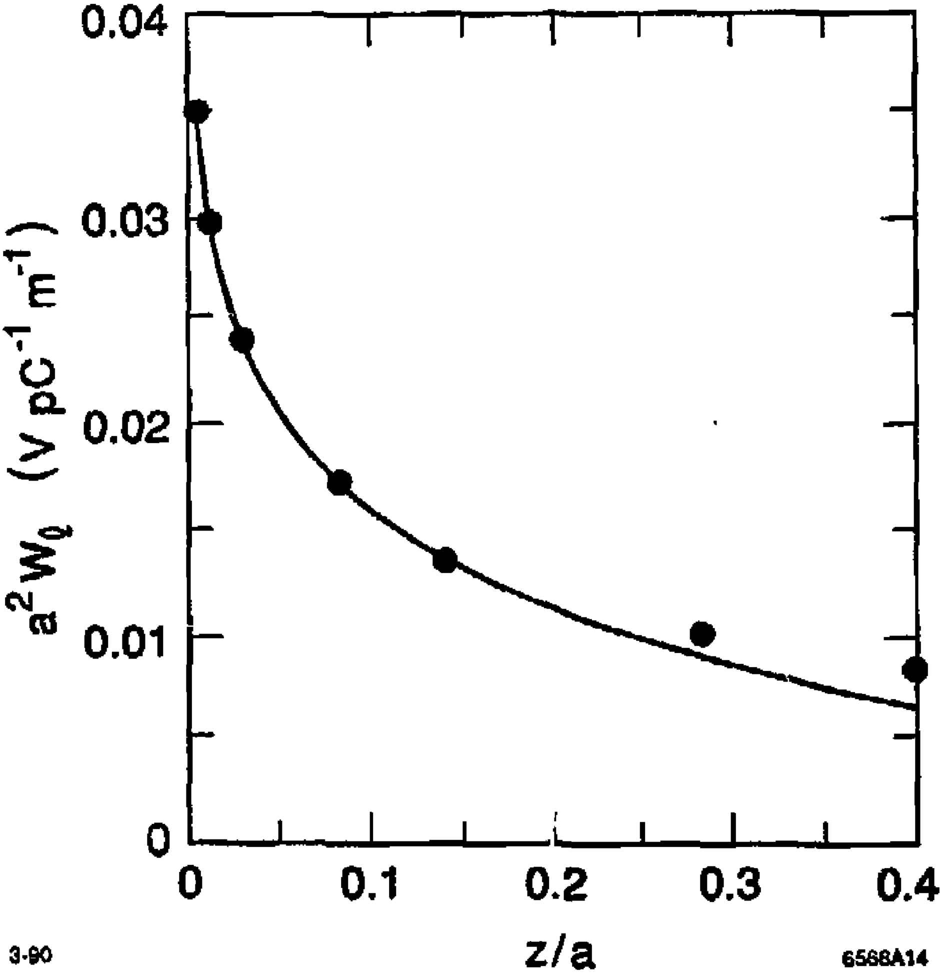

Fig. 4