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COMPARISON OF TWO APPROACHES TO LINEAR COLLIDER DESIGN*

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1. INTRODUCTION

This paper contains yet another review of linear collider parameters. It offers nothing basically new but aims at analyzing two specific design approaches - the ones for CLIC at CERN and for a TeV linear collider at SLAC - which appear to lead into remarkably different directions although they start from the same premises and try to respect the same boundary conditions.

Short lists of parameters are given in an Appendix. The SLAC parameters are R. B. Palmer's, set [1] for 26 mm wavelength. The CLIC parameters [2,3] (for which I am to be held responsible) were meant to be a consistent set at their creation in early 1986. They have been adjusted again, here, to be formally consistent but contain several obvious flaws, such as excessive bunch length for good energy spread, an embarrassingly large power input and a strictly round beam making it very difficult to dispose of the disrupted beam in a classical final focus system.

In any case, since neither of the two sets is meant to represent an immediate proposal for a feasible machine I shall not comment on any details at all but refer to the two approaches as the high-rep. (CERN) and low-rep. (SLAC) cases. Indeed, almost two orders of magnitude difference in repetition frequency is the most conspicuous distinction. It may have been just as fair (and quite equivalent, as it will turn out) to call them round-beam and flat-beam approaches. But the

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advocates of the CLIC parameters are quite ready to accept some measure of flatness in the final beam spot, without wanting to go to as high an aspect ratio as SLAC. Both design approaches make use of copper, disc-loaded, travelling-wave linac sections of identical aperture to wavelength ratio and fill efficiency and both are based on the same accumulated knowledge [4] concerning beam-induced wakefields, disruption by electromagnetic beam-beam interaction and radiation. A fractional radiation loss of about 30% is accepted in both cases as the ultimate limit to luminosity, a limit which an efficient design should, in fact, reach.

Both approaches aim at luminosities at or slightly above $10^{33} \text{cm}^{-2} \text{s}^{-1}$ with a single bunch per rf pulse. Multibunching is universally considered very desirable - and studies of suitable rf structures are in progress at BNL and CERN - but both designs reserve this possibility for future developments.

Palmer's parameter study [1] includes scaling considerations of injector damping rings and of the final focus. This part of the parameter set does not yet have its equivalent at CERN where it is considered preferable to develop specific designs rather than extrapolate existing ones to very un-familiar parameters. Therefore, damping ring performance will not be discussed here and the final focus will be merely introduced by a focal length and a global improvement factor for reduction of raw energy spread and chromaticity correction.

The method followed below is the usual one of manipulating known and accepted design formulae until inescapable constraints show up. I have tried to present complete equations, in mks units, including numerical constants and apparently insignificant parameters, applying the necessary broad brush to the interpretation of these equations rather than their presentation. Unavoidably the brush broadens as the arguments develop. The conclusions, nevertheless, seem clear enough.

2. RADIATION LOSS AND REPETITION RATE

Following ref. [1] the luminosity can be written as

$$L = \frac{N^2 f H_z H_y}{4\pi\sigma_y^2 R} \quad (1)$$

where N is the bunch population, f the repetition rate, σ_y is the rms beam height $R = \sigma_z/\sigma_y$ the beam's aspect ratio (all at the final focus) and H_z , H_y are pinch enhancement factors. At sufficiently large disruption the enhancement equals $H_z H_y \approx 5.6$ in a round beam and $H_z H_y \sim H_y \sim 2.4$ in a flat one. Loss of

luminosity due to a crossing angle or to the bunch length approaching the beta function is ignored here.

The fractional energy loss due to beam-beam radiation ("beamstrahlung") can be written as

$$\delta = 1.8 \frac{r_e^2}{\lambda_c} (H_T \Upsilon) \sqrt{\frac{L}{f} \left[\frac{2\sqrt{RH_x H_y}}{H_x + RH_y} \right]} \quad (2)$$

where $r_e = 2.82 \times 10^{-15} \text{ m}$, $\lambda_c = 3.86 \times 10^{-13} \text{ m}$ and H_T is the reduction factor for quantum effects [5] depending solely on the parameter Υ (the fractional average critical photon energy in the classical regime).

The product $H_T \Upsilon$ goes through an extremely flat maximum [6] (the peak value being 0.20) for all values of Υ that may possibly be encountered around one or two TeV center of mass energy.* It can, therefore, be considered as practically constant in scaling considerations. The maximum tolerable value of δ is generally taken as one third so that $\delta/(H_T \Upsilon) \approx 1.6$ in first approximation.

It follows, that for a round beam, where $R = 1$ and $H_x = H_y$ nature determines the maximum luminosity per bunch and, thus, inescapably imposes a repetition rate given by

$$f = 1.4 \times 10^{-33} \left[\frac{H_T \Upsilon}{\delta} \right]^2 L \quad (3)$$

This happens to be of the order of ten kilohertz for $L = 10^{37} \text{ m}^{-2} \text{ s}^{-1}$. The high-rep. approach accepts this. The scheme proposed [7] at CERN for powering the main linac is adapted to the multi-kilohertz repetition rate due to the superconducting drive cavities. Suitable injectors and drive-beam generators have yet to be developed, however.

For a flat beam with $R \gg 1$ eq. (2) results in

$$f = 1.4 \times 10^{-33} \left[\frac{H_T \Upsilon}{\delta} \right]^2 L \frac{4}{RH_y} \quad (4)$$

with $H_y = 2.37$ for sufficiently high disruption. Now the radiation loss is decoupled [1,4,6] from the luminosity per bunch and the repetition rate can be reduced

* The formula $H_T \Upsilon = \Upsilon / (1 + 1.33 \Upsilon^{2/3})^2$ has been shown [1] to be in excellent agreement with computations [5].

accordingly. However, to bring f down to the order of 100 Hz generally considered suitable for rf power sources not employing superconducting cavities the aspect ratio R must be made very large, as indeed it has been in the SLAC design. It follows from this and eq.(1) that N/σ_y must be increased from the round-beam case by roughly two orders of magnitude in order to secure the luminosity per bunch which is now required as much as it is permitted by radiation. Indeed eqs. (1) and (4) imply that

$$\frac{N}{\sigma_y} = 4.8 \times 10^{16} \frac{\delta}{H_T \gamma} R \quad (5)$$

is the condition for reaching the radiation loss δ in a flat beam with large R (for a round beam R is to be replaced by $2/H_0$ in this formula, $H_0 = H_x H_y$ being the actual pinch enhancement).

It would appear natural to consider N/σ_y as one of the measures of potential difficulties with the final focus. Note that eq. (5) does not even contain the pinch enhancement.

3. REPETITION RATE AND RF WAVELENGTH

The beam power is given by

$$P_b = eNfU \quad (6)$$

where eU is the particle energy. The total average rf power, P_{rf} , per linac is given by

$$P_b = P_{rf} \eta_r \eta_e \quad (7)$$

Here η_r is the filling efficiency of the travelling wave accelerating sections (i.e. $1 - \eta_r$ is the fraction of energy dissipated before the beam arrives) and the fractional energy extraction by the beam is given by

$$\eta_e = \frac{\omega^2 e N Z}{2\pi \epsilon E_0} (1 - \xi) \quad (8)$$

where $\omega/2\pi$ is the rf frequency, E_0 the zero beam accelerating gradient and $(1 - \xi)E_0$ the actual gradient. In practice $(1 - \xi)$ will be close to unity (in fact

$\xi \approx \eta/2$) and η_r - a compromise between peak and average power - will be chosen well above 0.5, the value of 0.78 being adopted in both designs considered here.

The quantity Z is the shunt impedance over Q factor per rf wavelength, a frequency-independent geometrical quantity with 377Ω as the scale factor. It is related to the more familiar quantities of shunt impedance per unit length (r'), fundamental frequency loss factor per unit length (k'_0) and elastance per unit length (s) via

$$\omega r' = 4k'_0 = s = \frac{\omega Z}{\lambda} = \frac{\omega^2 Z}{2\pi c}. \quad (9)$$

The value of Z equals 660Ω for a $2\pi/3$ mode string of pillboxes, 460Ω for an average SLAC cell and 290Ω for the structure with $a/\lambda = 0.2$ (iris radius) adopted for both designs.

Combining eqs. (6) to (8) yields

$$\frac{\omega^2}{E_0} = f \frac{2\pi c U}{P_{rf} Z \eta_r (1 - \xi)}. \quad (10)$$

Once the aspect ratio R (and thus f) is chosen the desired top energy, available length and affordable rf power practically determine the rf frequency. It scales with $\sqrt{f}$ and is independent of luminosity; in fact, besides the insignificant factor $1 - \xi$, eq. (10) is concerned with dissipation only. Three tactical considerations follow from this. Firstly, the dissipation of any given linac always decreases in direct proportion to f and hence to R^{-1} for large R . Secondly, however, a long-wave linac, built on the basis of large R , cannot later be run at increased repetition rate and full gradient without excessive power. Thirdly, a short-wave linac, once successfully built, might later be run at reduced power if an improved final focus with increased R were to permit a smaller repetition rate.

Instead of scaling at given structure geometry (and hence constant Z) it may be preferable to scale at constant iris radius a , since this would much reduce the frequency dependence of the wake fields [8]. Since Z is roughly proportional to a^{-1} for not too small a/λ (but tending towards the pillbox value for vanishing a) this procedure would tend to increase the final choice of frequency. However, the two designs compared here feature the same value of $a/\lambda = 0.2$.

4. DISRUPTION AND BUNCH POPULATION

Equations (4) and (5) show that the choice of R determines f and N/σ_y with hardly any freedom. However, N or σ_y can still be chosen so far. One constraint on this choice is the disruption parameter D given by

$$D_y = \frac{r_c \sigma_z}{\gamma \sigma_y^2} \frac{2N}{(1 + R)} \quad (11)$$

where σ_z is the rms bunchlength. Because of eq. (1) this means

$$D_y = \frac{\sigma_z}{N f} \frac{4\pi r_c L}{\gamma H_T H_y} \left[\frac{2R}{1 + R} \right] \quad (12)$$

or, for $R \gg 1$ and because of eq. (4)

$$N \approx 1.3 \times 10^{19} \left[\frac{\delta}{H_T \gamma} \right]^2 \frac{\sigma_z R}{\gamma D_y} \quad (13)$$

leaving σ_z as the only free parameter once R and D are chosen. It is true that the choice of D is not very critical; values much above ten are considered dangerous for stability and values below unity lead to the loss of pinch enhancement. It is nevertheless clear that large R require very small σ_z to keep D from becoming embarrassingly large while round beams need the longest bunches compatible with λ to maintain a measure of pinch enhancement. Note that for a design close to the radiation limit ($\delta \sim 0.3$) and for large R the disruption is inversely proportional to the longitudinal charge density N/σ_z and proportional to R . For $R = 180$, $\gamma = 10^6$, $\delta = 0.33$, $H_T \gamma = 0.2$ and $D = 14$ the internal current ecN/σ_z becomes 22 kA.

5. ENERGY SPREAD AND BUNCH POPULATION

It seems logic and very convenient to take the total longitudinal loss factor per unit length, k'_H , as the measure of the raw, uncorrected energy spread within the bunch* This fractional spread is, thus, given by

$$\Delta = \frac{e N k'_H}{E_0(1 - \xi)} \quad (14)$$

Consideration of the spread due to the cosine shape of the rf and the possibility of partial cancellation with the wake-induced Δ of eq. (14) is deferred to the qualitative discussion of an "improvement factor" at the end. With the help of eq. (9) eq. (14) may be written as

$$\Delta = \frac{B}{4} \eta \frac{1}{(1 - \xi)^2} = \left[\frac{B}{4} \right] \frac{\omega^2 e N Z}{2 \pi c E_0 (1 - \xi)} \quad (15)$$

where $B = k'_H/k'_0$ is the beam loading enhancement factor. Equation (15) expresses the old rule of thumb that $\Delta \sim \eta/2$ but, in reality, B depends on σ_s/λ . Available computational data [9,10] agree well with

$$B = \sqrt{\frac{c}{2 \omega \sigma_s}} \quad (16)$$

Explicitly this makes (cf. eq. (10))

$$\Delta = \frac{N f}{8 P_{rf} \eta r} \frac{e U}{(1 - \xi)^2} \sqrt{\frac{\lambda}{\pi \sigma_s}} \quad (17)$$

Eliminating $N f$ between this and eq. (12) shows that $D_y \Delta \propto L \sqrt{\lambda \sigma_s}$. Thus, small energy spread and long wavelength unavoidably require very short bunches to limit disruption.

In order to advance further it is now necessary to make sweeping assumptions about the final focus system. It is assumed that it has an effective focal length F and that the variation of F over the bunch is given by

* Taking the peak longitudinal wake per unit length $\hat{w}'_H$, would perhaps be more logic and slightly more pessimistic since $\hat{w}'_H/k'_H \approx 1.3$.

$$\frac{\delta F}{F} = \frac{\Delta}{G} \quad (18)$$

where G is an overall improvement factor including partial compensation of Δ (balancing wakes against the rf cosine) and chromaticity correction. Since δF can, at most, approach the amplitude function β^* and $\sigma^2 = \epsilon_n \beta^* / \gamma$, where ϵ_n is the normalized emittance, one may write

$$\sigma_y^2 = \epsilon_{ny} \Delta \frac{F}{\gamma G} \quad (19)$$

where F/G are now assumed to contain all imperfections and represent a global description of the best possible final focus. Substituting eqs. (17) and (1) for Δ and σ_y^2 respectively yields

$$\frac{N}{\epsilon_{ny}} = R \frac{F L \pi m c^2}{G H_x H_y P_f \eta_r (1 - \xi)^2} \sqrt{\frac{\lambda}{4 \pi \sigma_x}} \quad (20)$$

This shows that the vertical phase plane density which has to be generated in the damping rings and maintained throughout the linacs increases at least in proportion with R . The increase is faster in fact because of the influence of small σ_x (eq. (13)) and long λ once R is pushed beyond the point where the final focus performance (expressed by F/G) can profit from the beam's flatness.

Superficially eq. (20) suggests that N (and hence ϵ_{ny}) could be increased to whatever limit is imposed by transverse wakefields. In reality G is likely to depend on Δ . The least that can be said is that Δ cannot be allowed to increase above a few per cent, but chromaticity correction may become impossible if the actual energy spread at the linac output - including partial correction by wake version rf compensation - exceeds a few tenths of a percent.

Linear wake versus rf compensation of the energy variation within the bunch appears to work best for small values of σ_x / λ . Second order compensation, on the other hand, might be attempted if the bunches can be made long enough to fulfill the approximate condition

$$\frac{\sigma_x}{\lambda} = (1.2 \times 10^{-3} \eta)^{0.4} \quad (21)$$

For very large R excessive disruption will prevent such a choice of σ_x (eq. (13)) but for moderate R it looks promising.

Two more conditions have to be observed concerning the final focus system. One condition is that σ_z be smaller than β^* . Combining eqs. (1) and (12) this can be expressed as

$$\frac{\beta^*}{\sigma_z} = \frac{Nr_c}{\epsilon_n R D} \left[\frac{2R}{1+R} \right]. \quad (22)$$

As might be expected from eq. (20) the term $Nr_c/\epsilon_n R$ does not differ much in the two cases but the unavoidably large D of the low rep. case leads to a barely tolerable $\beta^*/\sigma_z = 1.2$ as compared with a comfortable 6.0 for the high rep. case. The second condition favours large R . It is that a certain aspect ratio is required to permit a large enough crossing angle so as to save the front-end quadrupole from the spray of the opposite disrupted beam. This has been analyzed by Palmer [1]. It may well be a problem for moderate R , and one I have not analyzed.

6. TRANSVERSE WAKE FIELDS

The maximum slope of the transverse wake within a bunch may be approximated by [1]

$$\frac{\partial W_{\perp}'}{\partial z} = W_{\perp}' = \frac{Z_w c}{\lambda^4} \left(\frac{\lambda}{a} \right)^{3.5} \quad (23)$$

with $Z_w \approx 220\Omega$. The dimension of $W_{\perp}'$ is $VA^{-1}s^{-1}m^{-3}$ i.e. transverse energy gain in volt per Asm of inducing dipole moment, per distance z within the bunch (from head to tail) and per distance s travelled down the linac. (The value $cZ_w = 6.6 \times 10^{10} As/Vm$ is in fact given in reference [1] for $z \ll a$ while $Z_w \approx 350\Omega$ can be inferred from reference [10] for an infinitely short bunch dropping to half that value at $\sigma_z/\lambda = 2.5\%$ and ref. [11] implies 275Ω for a 1 mm bunch in a SLAC cell at $\lambda = 10.5$ cm). The ratio a/λ (aperture radius over wavelength) may be expressed in terms of Z of eq. (9) if so desired.

Assuming that Landau damping is required in any case an approximate criterion of stability against avalanching self deflection can be written as [12,13,14]

$$\sigma_z c N W_{\perp}' \approx 2U_s k_{os}^2 d \quad (24)$$

for the case that energy spread is employed to generate the necessary spread in transverse wave number. In eq. (24) k_{os} is the wave number (approximately

equal to the inverse β -function) at the bunch center and at location s along the linac where U_s is the energy and $\pm d$ is the fractional energy spread at $\pm\sigma_z$. Constant quadrupole strength means constant $k_{0s}^2 U_s$ and strongest possible focusing for given pole-tip-field implies $k_{0s}^2 U_s \propto \lambda^{-1}$, as shorter wavelength means smaller aperture quadrupoles. All this tends to make

$$N \propto \lambda^2 \left(\frac{\lambda}{\sigma_z} \right) \left(\frac{a}{\lambda} \right)^{3.5} d \quad (25)$$

but this relation only confirms the acknowledged fact that transverse wakes can just barely be stabilized by means of energy spread at $\lambda = 10$ mm while they do not present a practical limit for N at $\lambda = 26$ mm.

Much more powerful Landau damping can be obtained by microwave focussing [15]. In this case energy spread is not required and the criterion (24) is to be replaced by

$$eNW_{\perp}^{*'} \approx \eta_a \eta_Q \frac{\pi^2 \mu_0}{\cos \frac{\mu_0}{2}} \cos \phi_0 \frac{E_0(1 - \xi)}{\lambda^2} \quad (26)$$

where μ_0 is the phase advance per alternating gradient period, ϕ_0 the rf phase (both at the bunch center), η_Q the filling factor with rf focusing sections. The coefficient η_a accounts for the decrease of rf quadrupole moment expected to set in for large aperture. So far the only known result from computations done at CERN [16] indicates $\eta_a \approx 0.85$ for a slit aperture with 0.25λ width. Combining eqs. (8), (23), (26) yields

$$\eta = \eta_a \eta_Q \frac{Z}{Z_w} \left(\frac{a}{\lambda} \right)^{3.5} \frac{2\pi^3 \mu_0}{\cos \frac{\mu_0}{2}} \cos \phi_0 (1 - \xi)^2 \quad (27)$$

for the maximum possible energy extraction compatible with wake-stability under microwave focussing conditions. This relation looks extremely interesting as it contains neither N nor ω (for given a/λ) or even E_0 and σ_z and appears to give a final verdict as to the maximum possible energy extraction per bunch. With $\mu_0 = 90^\circ$, $\phi_0 = 20^\circ$, $(1 - \xi) = 0.95$, $\eta_Q = 0.3$, $\eta_a = 0.8$ and $a/\lambda = 0.2$ (and, thus, $Z = 290 \Omega$), $Z_w = 220 \Omega$ as discussed above one finds $\eta = 13\%$ confirming the impression gained from computational studies [17] that the CLIC parameters as given in the Appendix still hold a small margin of safety.

For long wavelength eq. (27) becomes irrelevant – even if microwave focussing were in fact employed – not only because single bunch energy extraction will be

low anyway at long wavelength but also because the contribution of energy spread to the Landau damping - ignored in eq. (27) - is likely to be important.

Since $Z \propto \lambda/a$ for large a/λ eq. (27) suggests that one keeps gaining with $\lambda^{-2.5}$ by going to shorter wavelength at constant aperture. This possibility cannot be explored, however, so long as η_a is not known for large aperture to wavelength ratios in the focussing sections.

A serious objection to strong Landau damping is the observation that the rapid decoherence of any transverse oscillation and concomitant transformation to irreparable emittance growth leads to very tight tolerances for quadrupole misalignment along the linac. For the small spread in transverse wave number associated with Landau damping by energy spread in a long wave linac it is found [18] that the rms alignment tolerance is given by

$$\delta y_{rms} = \sigma_s \frac{1}{\mu_s d_s} \sqrt{\frac{2}{N_q}} \quad (28)$$

where the phase advance per period is μ_s , the beam size σ_s and the fractional energy spread d_s while N_q is the number of quadrupoles in the linac. In a short-wave linac with microwave focussing where the spread of phase advances within $\pm 2\sigma_s$ may easily reach two to one the alignment tolerance might be expected to be a fraction of σ_s and, therefore, of the order of $1 \mu\text{m}$ in the high rep. case shown in the Appendix.

Even this might well be achievable by automatic alignment correction which might be made quite rapid taking advantage of the high repetition rate. Recent computer simulations done for CLIC parameters [17] show however, that with proper choice of Landau damping by microwave focussing the central part and tail of the bunch is kept coherent by the very action of the wakefields. These results indicate that even a random alignment jitter of 10 to 20 μm rms can be tolerated without serious blow up of the (relatively large) emittance associated with the high-rep. short-wave case. It is true that this is a provisional result requiring further study but it is one of the elements encouraging us at CERN to pursue the high-rep. short-wave approach.

7. CONCLUSIONS

It appears that the first and foremost choice to be made in designing a linear collider is the beam's aspect ratio at the final focus. Apart from an insignificant margin in the maximum possible value of $\delta/(H_T Y)$ the aspect ratio $R = \sigma_x/\sigma_y$ is the only parameter which separates beam-beam radiation loss from luminosity per bunch. Therefore, for given luminosity and a single bunch per rf pulse the aspect ratio inescapably determines the repetition rate f . For large R it is found that $f \propto R^{-1}$ [eq. (4)].

Since the power dissipation of any normal conducting linac, run at a given gradient, always increases in proportion with the repetition rate the linac's efficiency has to be increased with increasing f by rising the rf frequency $\omega/2\pi$. It found that $\omega^2 \propto f E_0$ and that there is little choice for the rf frequency once R - and thus f - has been chosen and the final energy, total available length and affordable rf power are known [eq.(10)]. As the difficulties of linac construction and of dealing with transverse wakefields rapidly increase with rf frequency a large aspect ratio, leading to a slow long-wave linac, is very desirable in this respect.

However, in order to generate in fact the luminosity per bunch permitted by beam-beam radiation the ratio of bunch population to vertical beam size, N/σ_y , must be increased in proportion with R . Again there is nothing left to choose besides $\delta/(H_T Y)$, as is shown by eq. (5) for large R . While it does seem to be possible to increase N with R such an increase cannot be anything like proportional so that σ_y becomes very small indeed for very large R - 1.3 nm in fact in the low-rep. case considered here. This appears to present a severe alignment problem for the final focus, if nothing else.

Moreover, eq. (13) shows that the longitudinal linear density in the bunch, N/σ_z , has to be increased in proportion with R if the disruption is to be kept from growing much above ten, and again there is little choice.

Finally, as shown by eq. (20), the required normalized vertical phase plane density tends to increase in proportion with R . Equation (20) is less conclusive as it contains an "equivalent uncorrected final focus length" F/G (i.e. the actual focal length divided by whatever degree of chromaticity correction and energy correction may be achieved) and this degree of correction might take advantage of the smaller wake-induced raw energy spread at lower rf frequency. But the actual parameters given do show a ratio of 270 in N/ϵ_{ny} admittedly at 6.7 times the rf power in the round beam case.

If the rf power source envisaged makes repetition rates much above 100 Hz unacceptable a final focus aspect ratio at or above one hundred - thus requiring

that $\epsilon_{nz}/\epsilon_{ny}$ and β_z^*/β_y^* be both of that order - becomes unavoidable. But if higher repetition rates are considered technically feasible a solution between the extremes of $R = 180$ and $R = 1$ would seem to deserve consideration. That these are indeed extremes is suggested by the extremely small values of σ_y (and to a lesser extend of ϵ_{ny} , β_y^* and σ_z) on the one hand and the need of pushing a new method of Landau damping close to the extreme limit implied by eq. (27) on the other.

It seems noteworthy that the rf wavelengths pertaining to solutions as extreme as this differ by only a ratio of 2.5. One might conclude from this that the wavelength should not be chosen a priori.

The general situation is certainly difficult enough to make multiple bunches per rf pulse very desirable. At given rf repetition rate multiple bunches multiply the luminosity while having only a small influence on linac dissipation. The main obstacle is beam break up due to long range wakefields and R. B. Palmer's [19] suggestion to damp transverse resonant modes by propagating slits in the cavity walls is being pursued in at least two laboratories. It would seem very desirable, however, to reserve this - if and when it is proved practicable - to an increase of luminosity beyond $10^{33} \text{cm}^{-2}\text{s}^{-1}$.

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DISCLAIMER

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APPENDIX TYPICAL PARAMETERS FOR ONE LINAC

Case		High rep. CERN [2]	Low rep. SLAC [1]	
Energy	eU	1.0	0.5	TeV
Luminosity	L	1.1×10^{33}	1.7×10^{33}	cm^2s^{-1}
Accelerating Gradient	E_0	80	186	MV/m
Final Focus Aspect Ratio	R	1	180	
Final Focus Beam Height	σ_y	65	1.3	nm
Fractional Energy Loss by Beam Radiation	δ	0.19	0.33	
Fractional Average critical energy	T	0.28	1.8	
Pinch Enhancement	$H_z H_y = H_0$	3.5	2.37	
Repetition rate	f	5.8	0.1	kHz
Number of bunches per pulse		1	1	
Bunch population	N	0.54	1.8	$\times 10^{10}$
Beam power	P_b	5	0.144	MW
Iris aperture over wavelength	a/λ	0.2	0.2	
Fill efficiency	η_r	0.78	0.78	
RF frequency	$\omega/2\pi$	29	11.4	GHz
RF power (average)	P_{rf}	120	18	MW
Bunch length	σ_z	500	40	μm
Disruption	D	0.91	14	
Vertical emittance (normalized)	ϵ_{ny}	2.8×10^{-6}	3.5×10^{-8}	rad m
Emittance ratio	$\epsilon_{nz}/\epsilon_{ny}$	1	100	
Vertical amplitude function	β_y^*	3000	47	μm
Ratio of amplitude functions	β_z^*/β_y^*	1	320	

* Luminosity corrected for $\beta^* \approx \sigma_z$ and crossing angle; would be $2.0 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ without that.