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New Concepts for a Compact 5 TeV Collider*

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NEW CONCEPTS FOR A COMPACT 5 TEV COLLIDER*

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Abstract

We propose new design concepts for a multi-TeV linear collider which provide for a much shorter system length and for higher luminosity at lower beam power than conventional approaches. The new concepts include an active matrix linac, linac energy compensation, sextupole-free final focus, and bunch combination. We present a consistent parameter set for a 5 TeV collider.

1 MOTIVATION

The final focus has been overlooked in advanced accelerator research, yet it dwarfs the linac. While in the 90-GeV Stanford Linear Collider (SLC) the final focus occupies less than 5% of the total length, for a 1-TeV Next Linear Collider (NLC) it is already 4 km long [1]; and this length will increase quadratically as a function of beam energy [2]. At 5 TeV center of mass, the final-focus length would approach 80 km. This unfavorable scaling is a consequence of three constraints: (1) the chromaticity of the final focusing lens increases linearly in energy, as the beta function at the interaction point are decreased to balance reduced cross sections at higher energies; (2) the tolerances on sextupole vibration and beam-orbit stability in the chromatic correction section cannot be pushed much below the nanometer level, which translates into a maximum value for the product of sextupole-field strength and beta function at the sextupole; (3) synchrotron radiation in the bending magnets of the chromatic correction sections becomes more important, and the induced increase in the interaction-point (IP) spot size must be confined by weaker and longer bending, while the required dispersion at the sextupoles increases.

In view of this scaling, we propose to eliminate the chromatic correction section, thereby removing the constraints (2) and (3). The implications for energy-spread compensation in the linac are described below.

A second drawback of the conventional collider scheme is that a large portion of the beam power is not converted into luminosity. Due to transverse and longitudinal wakefields in the linac, the beam charge is split into n_b bunches. These are collided separately at a loss in luminosity by a factor of n_b. We propose to recover some of this luminosity by combining individual bunches into superbunches prior to the collision.

We now proceed backwards from the interaction point through such a TeV collider and highlight important design considerations: IP disruption, synchrotron radiation in the last quadrupoles, beam combining and final-focus optics match, and the linear accelerator (principles of operation, beam break up, and harmonic acceleration). Finally we present a consistent parameter set for a 5-TeV collider.

2 BEAM DELIVERY

We start from the interaction point, where we assume 1.7 nm round beams, of 3 nC each, in collision. To confine the energy spread due to beamstrahlung, such a scenario requires neutral beam collisions (charge compensation by combining equivalent electron and positron bunches) [3], or gamma-gamma conversion prior to the IP [4]. For an IP free length of $l^* = 2$ m and a final quadrupole strength of $K \approx 1$ m^{-2} the effect of synchrotron radiation in the final quadrupoles [5] is still tolerable. According to Monte Carlo simulations, it reduces the ideal theoretical luminosity of 10^{35} cm^{-2}s^{-1} (at a 120 Hz repetition rate) by about 20%.

We consider a linac that provides parallel beams, each of small energy spread, but slewed across an energy full width of 10% (see below). Making use of the energy variation the individual bunches are combined in a half-chicane (see Fig. 1), consisting of two horizontal bending magnets, each of length l_0 and with opposite deflection angles $\pm\theta$ and bending radii $\pm\rho$. Considering the limit $\rho \gg l_0$, bunches are combined if $\Delta x/\Delta\delta = 2\, l_0^2/\rho$, where Δx is the interchannel distance in the linac, and $\Delta\delta$ the bunch-to-bunch energy difference.

Synchrotron radiation in the half chicane induces an rms energy spread of [6] $\delta_{rms}^2 = 55 r_e \lambda\!\!\!^{-}_c/(12\sqrt{3})\gamma^5\theta^3/l_0^2$, with r_e the classical electron radius and $\lambda\!\!\!^{-}_c$ the Compton wavelength. Since there is no chromatic correction downstream, this energy spread increases the IP spot size by interacting with the uncompensated final-focus chromaticity ξ. Requiring $\delta_{rms} \leq 1/\xi$, the minimum half length of the half-chicane combiner is

$$l_0[\mathrm{m}] \geq 3\times 10^{-6}\;\gamma\;\xi^{2/5}\left(\frac{\Delta x[\mathrm{m}]}{\Delta\delta}\right)^{3/5}. \qquad (1)$$

If ξ increases in proportion to γ, and the interchannel spacing Δx decreases as $1/\gamma$ (assuming that the rf wavelength is increased inversely proportional to the beam energy) the length of Eq. (1) increases with energy as the 4/5th power. The length of a 2.5-TeV combiner is about 1 km.

The multi-bunch combination in a half-chicane takes advantage of different bunch energies. The difference in energy implies that the optics for each bunch must be matched individually, to obtain the same IP beta function. This is accomplished by means of quadrupole magnets in the still separated beam lines, and, thus, it differs from conventional

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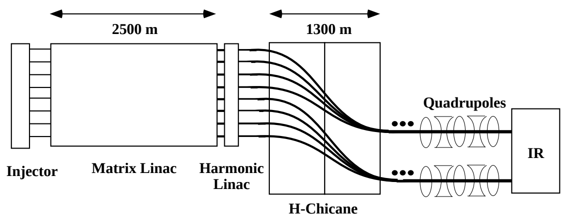

Figure 1: Schematic of a 5 TeV collider with linac energy compensation, bunch combination and sextupole-free final focus.

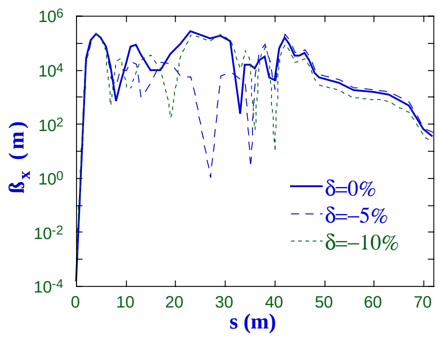

Figure 2: Final-focus beta functions for 10% different beam energies; on the right are linac-like FODO cells with $\beta \approx 20$ m, on the left the IP with $\beta = 150\ \mu$m.

chromatic correction in that it requires neither sextupoles nor bending magnets.

As an illustration, Fig. 2 shows 3 sample beta functions over the last 80 m prior to the IP, spanning a total energy range of 10%. The initial optics is identical to the FODO lattice at the end of the main linac. In Fig. 2 a series of final-focus quadrupoles were adjusted to obtain the same IP beta function for each beam energy. For perfect matching the off-energy optics can be fine-tuned using quadrupoles in the linac, where the bunches are still separated.

Synchrotron radiation in the final-focus quadrupoles is not an issue (except for the final quadrupoles, see above). At a beam energy of 2.5 TeV, each electron radiates about $dN_\gamma/ds \approx 5/(3\sqrt{2})\alpha\gamma K\sigma_{x,y} \approx 6\times10^{-3}K\sqrt{\beta_{x,y}}$ photons per unit length, with K the quadrupole gradient (in m^{-2}), $\sigma_{x,y}$ the rms beam size and $\beta_{x,y}$ the beta function (both in m), and assuming emittances of $\gamma\epsilon_{x,y} \approx 100$ nm. For $K \approx 0.5$ m^{-2}, $\beta_{x,y} \approx 10$ km, and over a length of 60 m, this amounts to $N_\gamma \approx 18$ photons per electron, a sizable number, but the critical relative photon energy is only $\delta_c \approx 1.5\lambda\!\!\!^{-}_c K\sigma_{x,y}\gamma^2 \approx 2\times10^{-8}[\mathrm{m}^{3/2}]\,K\sqrt{\beta_{x,y}} \approx 10^{-6}$, a factor of 10 smaller than the final-focus energy bandwidth.

3 MAIN LINACS

The parallel-beam accelerator we consider has been discussed elsewhere [7], and consists of three components, a primary energy storage line running parallel to the beam axes, secondary lines running roughly orthogonal to the beam axes, and a switch coupling between the lines every 1/3 of a wavelength, all as depicted in Fig. 3. Accelerator operation consists of three steps: (1) charging of the primary line on the 15-ns W-Band fill-time scale (2) laser triggering of the diamond substrate in the H-plane tees comprising the switches and (3) discharge of a 0.3 ns, 200 MW pulse down each secondary line. The beams propagate in parallel channels, separated by 1.4 mm. Two modes of operation are possible, corresponding to temporally coincident beam pulses, or staggered beam pulse arrival.

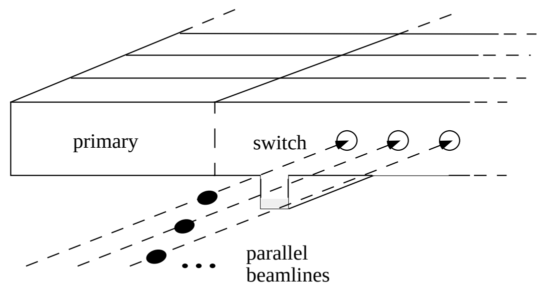

Figure 3: The linac employs a 'primary' storage line, a switch and a series of secondary transmission lines.

In the linac proper, single bunch charge is constrained by beam break up. The motion of a beam-slice centroid takes the form $x(s,z) = \mathrm{Re}(\chi(s,z)B(s))$, where $B = (\beta/\gamma)^{1/2}e^{j\psi}$ describes the machine lattice in terms of the beta function β, Lorentz factor γ and betatron phase ψ. The coordinate s is the position along the linac, and z is the longitudinal distance from the bunch head. The asymptotic solution for a unit initial offset in the presence of a linear (in z) wakefield is

$$\chi \approx \frac{3^{1/4}}{2^{3/2}\pi^{1/2}}\,\frac{e^A}{A^{1/2}}\exp\left\{A\left(1-\frac{j}{3^{1/2}}\right)+j\frac{\pi}{12}\right\} \quad (2)$$

where, for a lattice with $\beta \propto \sqrt{\gamma}$,

$$A = \frac{3^{3/2}}{2^{5/3}}\left(\frac{\beta_0}{GL^2}\right)^{1/3}\left(\sqrt{\frac{\gamma}{\gamma_0}}-1\right)^{1/3}. \quad (3)$$

The characteristic length L measures the strength of the wakefield and is given by $L = (r_e N_b W_x(l_b))^{-1/2}$, where l_b is the (flat-top) bunch length taken to be 30 μm, r_e the classical electron radius and $W_x(l_b)$ the wakefield per unit length at distance l_b. Figure 4 compares the analytical solution with the result of a macroparticle simulation.

We assume $\beta_0 \approx 1.6$ m, accelerating gradient $G \approx 1$ GV/m, and 60 pC charge per bunch. For $L > 3$ cm there is negligible growth in the linac, and this corresponds to $W_x \leq 10^3$ cm^{-3} (or 0.9×10^3 V/pC/cm^2). This β value can be achieved in a thick-quad FODO lattice starting at 10 GeV with a quad length of 0.5 m and a quadrupole gradient of 185 T/m. Such a quadrupole field is consistent with permanent-magnet pole-tip fields and a several millimeter aperture. Scaling for a constant phase advance per period, the quadrupole length increases as $\gamma^{1/2}$, and the

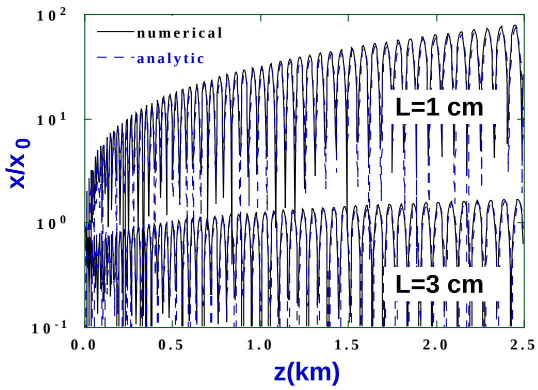

Figure 4: Simulated and analytical beam break up in the linac, without BNS damping.

quadrupole field gradient is constant. In such a linac lattice, a 10% energy difference results in a variation of the periodic beta functions by less than 10%.

Without sextupole correction the control of the chromatic spot size requires a very small energy spread across each bunch, of the order of 10^{-5} or below. We may attain this energy spread by employing rf acceleration sections operated at harmonics of the fundamental. The energy kick imparted by a linac with harmonic acceleration and single-bunch beam loading takes the form $V(t) = \sum_h V_h \cos(h\omega_1 t + \phi_h) - \int^t dt'\, I(t') W_{\|}(t-t')$, with V_h, ϕ_h the voltage and phase for the harmonic h, and ω_1 the angular frequency for the fundamental. The function $W_{\|}$ describes the longitudinal wakefield of the linac and $I > 0$ the bunch current waveform. For the sake of definiteness let us consider a model wakefield, varying with time as $W_{\|} \propto t^{-1/2}$, and a flat-top current profile turning on at $t = 0$ and extending to $t = T$, with total charge Q.

In this case, adding a 2nd ($h = 10$) and a third frequency ($h' \approx 30$), and optimizing five parameters: fundamental mode phase, harmonic phases and harmonic amplitudes, the energy spread can be reduced to 9×10^{-6} excluding the front 5% of the beam. Figure 5 shows the waveform that can be attained in such a three frequency linac for a sharp-edged profile like this. Smoother profiles should make for easier compensation.

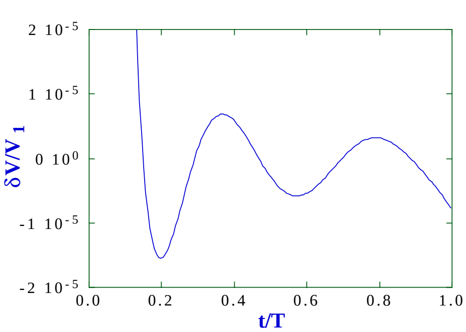

Figure 5: Loaded voltage waveform in a three frequency linac; shown is the difference from the average voltage.

The total rf input energy per pulse for all harmonic sections together as a fraction of that for the fundamental mode rf system is $U_h/U_1 \approx 1/(\rho h^4)$, where ρ is the fractional contribution to the loss factor from the harmonic sections. For $h = 10$ and $\rho = 10\%$, $U_h/U_1 \approx 10^{-3}$. This corresponds to a field of 200 MeV/m at 0.91 THz, and a 5% reduction in average gradient due to the additional length (100 m) of the harmonic sections. The $h' = 30$ section would correspond to a 1-m plasma linac at the linac exit.

4 CONCLUSIONS

A linear collider based on an active matrix accelerator, linac energy compensation, sextupole-free final focus, and bunch combination avoids the problems of more conventional designs and offers an avenue to multi-TeV energies. Table 1 lists sample parameters for a 5 TeV collider.

Table 1: Parameter set for a 5-TeV linear collider with charge compensation, providing a luminosity of 10^{35} cm^{-2}s^{-1}.

parameter	symbol	value
beam energy	E	2.5 TeV
particles per IP bunch	N_b^*	4.5×10^9
charge per linac bunch	Q	60 pC
number of same-charge IP bunches	n_b^*	2
repetition frequency	f_{rep}	120 Hz
average beam power (per side)	P	0.7 MW
rms linac energy spread	δ_{rms}	10^{-5}
transverse emittance	$\gamma\epsilon_{x,y}$	100 nm
IP spot size w/o Oide effect	$\sigma_{x,y}$	1.7 nm
IP beta function	$\beta^*_{x,y}$	150 μm
disruption parameter	$D_{x,y}$	11

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