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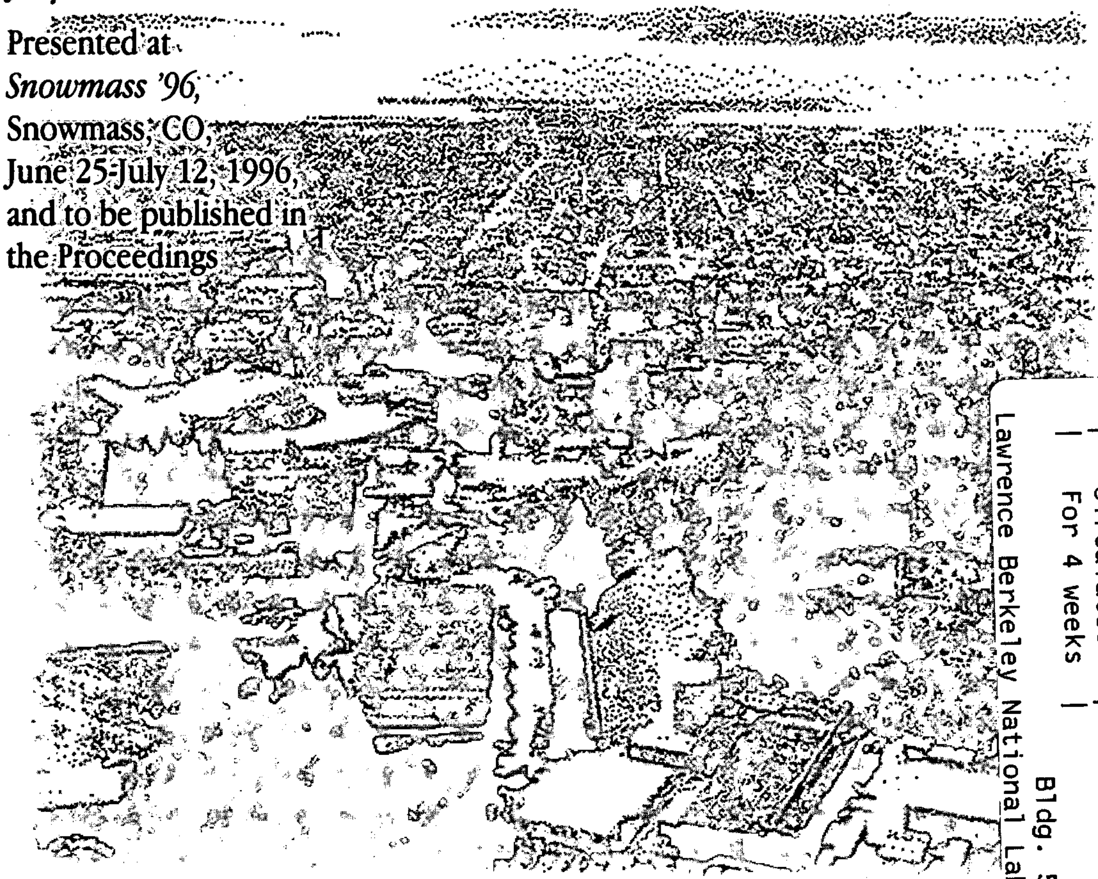
and Jonathan Wurtele

**Accelerator and Fusion
Research Division**

July 1996



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ABSTRACT

We address the collider physics issues, concepts and technologies of ($e^+e^-\gamma$) colliders at a cm. energy of 5 TeV and a luminosity of 10^{35} cm^{-2}s^{-1}.

I. INTRODUCTION

The Advanced Accelerator Technologies subgroup at Snowmass'96[1] provided the platform to discuss and evaluate concepts as well as technologies for achieving ($e^+e^-\gamma$) collisions at a center-of-mass energy of 5 TeV with a luminosity of 10^{35} cm^{-2}s^{-1}. The collider parameters were grounded to the key issues of achievable acceleration gradient, beam emittance, beam stability and overall power efficiency: they had direct implications on the length (compactness), beam quality (luminosity), average luminosity (physics reach) and wall-plug power (operating cost) of the collider. One of the primary goals of the group was also to identify promising research and development directions in potential electromagnetic power sources, acceleration schemes, accelerating structures and instrumentation relevant to such high energy, high luminosity colliders.

The agenda and participation in the Advanced Accelerator Technologies subgroup are described in Appendix A and B, respectively. The discussions and talks covered a broad range of topics: lasers; laser wakefields; THz radiation; klystrons and gyrotrons; mm-wave technology; microfabrication (via LIGA process); plasma-based devices; metals, dielectrics, semiconductors and superconductors; short bunch wakefields and its instrumentation; beam dynamics; plasma physics; microwaves; $\gamma\gamma$ colliders and new concepts. The frequencies considered for the elctromagnetic power source of the collider ranged from a few GHz (tens of cm.s in wavelength) to a hundred THz (a μm in wavelength) with traditional stop-bands at L-band (~1.3 GHz), S-band (~3 GHz), X-band (~11 GHz), W-band (~30 GHz, ~90 GHz), 1 THz and 100 THz. The THz source explored was based on solid-state microstrip lines irradiated by short pulse lasers and the 100 THz sources were the modern short pulse, high peak power T^3 lasers themselves.

Starting out with discussions on collider scalings in the highly radiative environment of collisions at 5 TeV with a luninosity of 10^{35}cm^{-2}s^{-1}, the group explored ideas of transcending the radiative limitations via gamm-gamma collisions, neutralized beams, etc. The scalings indicate a significant trend towards higher accelerating frequencies in order to achieve high gradients and luminosity. This led to discussions on accelerating structure research which included topics such as: state-of-the-art damped detuned structures (DDS) being explored for the future linear colliders; mm-wave structures; dielectric structures for laser linac and plasma channel guiding structures for laser wakefield acceleration. Structures at high frequencies and with small dimensions raise obvious concerns regarding wakefields and their harmful effects on beams. The idea of 'planar' structures as a way of overcoming wakefield limitations arising from 'cylindrial' ones were explored. The typical problem of wakefields from the short bunches expected in high frequency accelerating structures were discussed at length. These discussions were also grounded to the facts about and experience with the SLC collimator wakefields. Yet another vital topic concerned the power sources that drive these structures at high frequencies. Sheet beam klystrons, two-beam acclerator drivers, gyrotrons and lasers were all discussed in this context. Finally, the progress in mm-wave structure design and fabrication at ANL, the gamma-gamma interaction point design at Berkeley and Livermore, 30 GHz klystron thoughts at SLAC and laser wakefield acceleration of electrons to relativistic energies approaching 100 MeV in laboratory settings at various institutions - were all noted.

This summary report is organized as follows. In Section II, we review the classical collider design scalings, taking into account the radiative effects at the interaction point (IP). In Section III, we expose and demonstrate the failure of this classical design paradigm to provide a credible collider scenario, unless we reconsider and re-interpret the radiative constraints at the IP via a shift of paradigm which we discuss in Section IV. Section V gives a brief synopsis and status of the current concepts of and research on colliders with a 5 TeV reach, broken into broad categories of wavelengths, gradients and technologies, but all based on the new paradigm expounded in Section IV. Section VI to IX further elaborate on the collider categories of Section V. Section X outlines the possible next steps in 5 TeV collider explorations. We conclude with an outlook for the future in Section XI.

II. CLASSICAL COLLIDER DESIGN SCALINGS

A typical collider configuration at the IP is shown in Figure 1 (a). The goal is to ensure the highest probability of collisions (and hence rate of events) without being compromised by the severe electromagnetic environment at the IP. The radiative effects at the IP affect the charged particle beam phase-space (and hence luminosity and collision kinematics) and gen-

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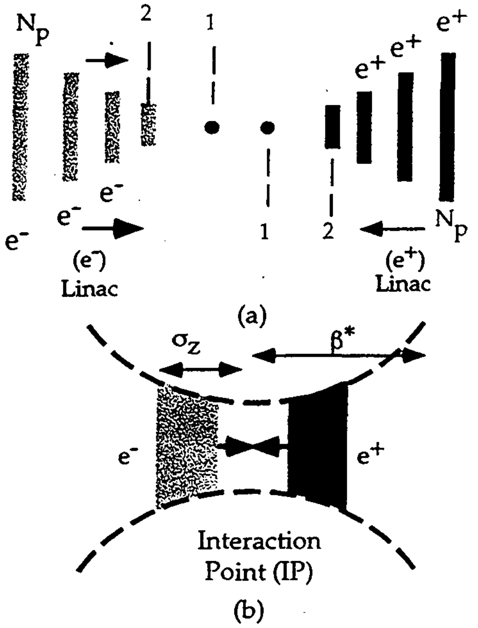

Figure 1.

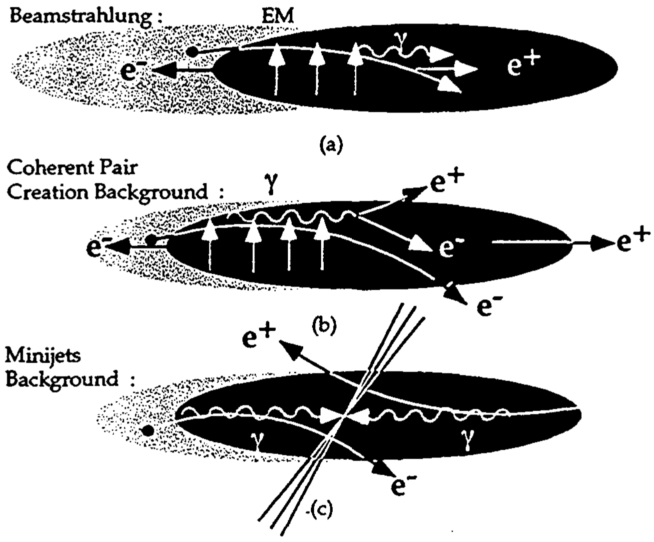

Figure 2.

erate undesirable backgrounds in the surrounding detector. To achieve high probability of collision, one attempts at as high a charge density in the bunch as possible: packing a large number (N) of electrons in a single bunch and squeezing them into a tight focus at the IP (vertical and horizontal spot sizes of σ_y^* and $\sigma_x^* = R\sigma_y^*$). In addition, one tries to collide as frequently as possible (at a rate $f = N_p f_{rep}$, with a string of N_p colliding bunches, repeated at a rate f_{rep}). The luminosity in this configuration is given by:

$$L = \frac{fN^2}{4\pi\sigma_y^{*2}R} H \tag{1}$$

where H is a luminosity enhancement factor[2] due to the electromagnetic pinching of one beam against another dependent on the bunch length σ_z and focusing beta function β^* at the IP (Figure 1 (b)). This luminosity comes at the price of a high average power P_b in the colliding beams (two of them) of energy γmc^2 and given a certain wallplug-to-beam efficiency η, at a certain cost of the wall-plug power, P_w:

$$P_b = 2\left(\gamma mc^2\right)(Nf) = \eta P_w. \tag{2}$$

A charged particle in one of the colliding beams, feels a strong electromagnetic field arising from the macroscopic motion at relativistic speed of the opposing intense beam at collision.The transverse acceleration (or bending) of charged particles in this field leads to emission of energetic photons, known as 'Beamstrahlung photons' as depicted in Figure 2 (a)[3].

The first parameter to characterize the radiative effects due to macroscopic beam electromagnetic fields is known as the Upsilon paramter Υ, which is a measure of the average beamstrahlung photon energy in units of the beam particle energy in collision, in the classical sense.

The severe radiative effects at the IP lead to significant energy loss of an individual colliding particle, measured in terms of the statistical beamstrahlung energy spread parameter, δ_B: average energy loss of a beam particle to beamstrahlung in units of its own full energy.

If the number of particles per bunch is too large, the macroscopic fields are strong, the beamstrahlung photons are higher in energy and can produce coherent (e^+e^-) pairs, as depicted in Figure 2 (b)[4]. In addition, some of these hard beamstrahlung photons from opposing beams will collide and interact through the hadronic QCD sector to give rise to mini-jets, as depicted in Figure 2 (c)[5]. The electromagnetic and hadronic background is characterized by the parameter n_γ, which when multiplied by the hadronic cross-section, gives us the hadronic background. Typical beamstrahlung concerns for a collider designer revolve around issues of a large number of coherent pairs produced, a large beam energy spread, significant electromagnetic and hadronic background in the detector, etc. Typical flags for large radiative energy spread and backgrounds are:

$$\Upsilon >> 0.3$$
$$\delta_B > 0.1$$
$$n_\gamma >> 1 \ .$$

Although there are many sources to the background, conventional collider designs primarily focus on the rate of coherent pair production per particle given by:

$$\Upsilon = \frac{0.43 r_e^2}{\alpha}\left(\frac{\gamma N}{\sigma_z \sigma_y^*}\right)\left(\frac{2}{1+R}\right). \tag{3}$$

The "conventional wisdom" in collider designs to date has been to operate in the regime of $\Upsilon \le 0.3$.

III. IMPLICATIONS OF CLASSICAL SCALING FOR A 5 TeV COLLIDER

To explore implications of classical collider scalings for a 5 TeV collider, let us introduce the "scaled" natural variables as follows:

$$\beta^*_{x,y} = \sigma_z \, \hat{\beta}_{x,y}$$
$$\sigma_z = (\lambda/100) \, \hat{\sigma}_z$$
$$\gamma = 5\text{x}10^6 \, \hat{\gamma}$$
$$L = \left(10^{35}\text{cm}^{-2}\text{s}^{-1}\right) \hat{L}$$
$$\varepsilon_{N,x,y} = \left(10^{-6}\text{mrad}\right)\hat{\varepsilon}_{N,x,y}$$
$$R = \left(\sigma^*_x / \sigma^*_y\right)$$
$$\lambda(\text{cm}) = \left(\hat{\gamma} / \hat{\sigma}_z\right)\hat{\lambda} \; .$$

In terms of these fundamental beam and acceleration parameters, one can write the following scaling relations between the number of particles per bunch, beamstrahlung energy spread, collision frequency, beam power, vertical disruption parameter and the scaled variables as follows[6]:

$$N \sim 10^8\left(\hat{\varepsilon}_x\hat{\beta}_x\right)^{1/2}\left(\frac{1+R}{R}\right)\hat{\lambda}^{3/2}\Upsilon \tag{4}$$

$$\delta_B \sim 0.5\frac{\hat{\lambda}\Upsilon^2}{\left[1+(1.5\Upsilon)^{2/3}\right]^2} \tag{5}$$

$$f \sim 2.6\text{x}10^7 \frac{R}{(1+R)^2}\frac{1}{\hat{\lambda}^2}\frac{1}{\Upsilon^2}\hat{L} \tag{6}$$

$$P_b \sim 2\text{x}10^9 \; \frac{\hat{\gamma}\;\hat{L}}{(1+R)}\;\frac{1}{\Upsilon}\;\frac{1}{\hat{\lambda}^{1/2}}\left(\hat{\varepsilon}_x\hat{\beta}_x\right)^{1/2} \tag{7}$$

$$D_Y \sim 0.6 \; \Upsilon \, R\hat{\lambda}^{3/2}\left(\hat{\varepsilon}_x\hat{\beta}_x\right)^{-1/2} \; . \tag{8}$$

Figure 3 demonstrates the scaling and variation of these scaled variables as a function of the 'beamstrahlung' parameter Υ for a 5 TeV c.m. collider at a luminosity of $10^{35}\text{cm}^{-2}\text{s}^{-1}$. We have assumed the colliding beams to be round (R=1) with a state-of-the-art normalized rms horizontal emittance of 10^{-6} mrad and a beamstrahlung energy spread parameter δ_B of 10%.

As we clearly recognize from the scaled parameter variations (and Figure 3 could be re-examined with different values of δ_B,R, and $\varepsilon_{N,x}$with similar conclusions), at a 5 TeV center-of-mass energy with a luminosity of $10^{35}\text{cm}^{-2}\text{s}^{-1}$, conventional collider design choices for the radiative parameters (e.g. Υ~0.3) lead to unrealisitc values for critical collider parameters e.g. total site power well above a gigawatt (highlighted by the curve "d" in Figure 3), etc. A detailed examination of the collider scalings leads to the conclusion that any approach to the 5 TeV collider (that uses a "realistic" emittance and average beam power) pushes the IP parameters towards high Υ and the accelerator towards short wavelength.

We are thus forced to consider colliders with radiative parameters in the nonconventional regime, Υ>>1 and δ_B>>.1, to achieve pragmatic collider scenarios.

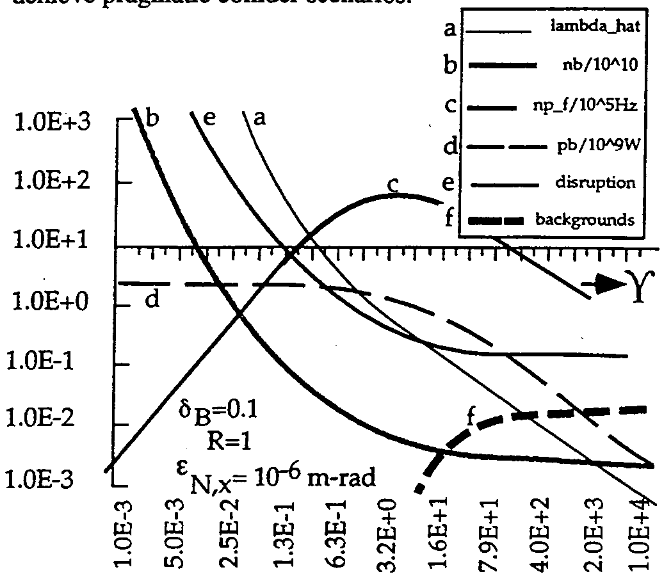

Figure 3.

IV. SHIFT OF COLLIDER SCALING PARADIGM

The previous section suggests that we would have to think about future multiple TeV-scale e⁺e⁻ colliders rather differently. In fact, this shift of paradigm can be achieved based on some nonconventional, albeit not new, ideas. There are many ways of circumventing <u>or</u> living with the rather high radiative effects at the IP. We enumerate a few of them below.

A. Photon-Photon Collisions.

Instead of direct e⁺e⁻ collisions, one could consider the " γ–γ collisions" via Compton conversion as shown in Figure 4[7].

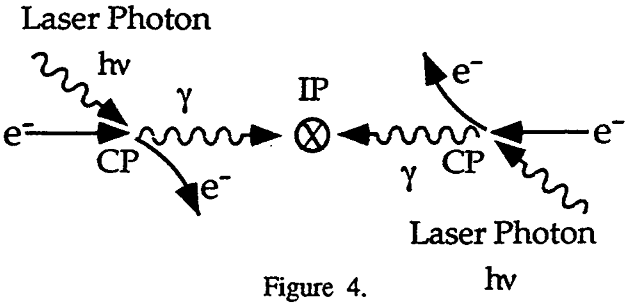

Figure 4.

In photon-photon collisions, there are no issues of beamstrahlung (δ_B) or coherent pair (Υ) limitation as in direct e⁺e⁻ collisions. Rather the relevant issues here would be: (i) does the laser technology exist to allow us to reach physically interesting γγ collision regime? (ii) is the photon-photon collision physics really complementary to (e⁺e⁻) collision physics? and (iii) the technical feasibility of (γγ) IP geometry, given the proximity of the IP to the Compton Conversion Point (CP) and other mechanical constraints imposed by the detector, for example.

B. Neutralized Beams

One could conceive a colliding scenario, as shown in Figure 5 (a), where both the total charge and current is neutralized at the IP. There are no macroscopic electromagnetic fields expected in this configuration and hence no severe radiative effects and limitations from Υ and δ_B.

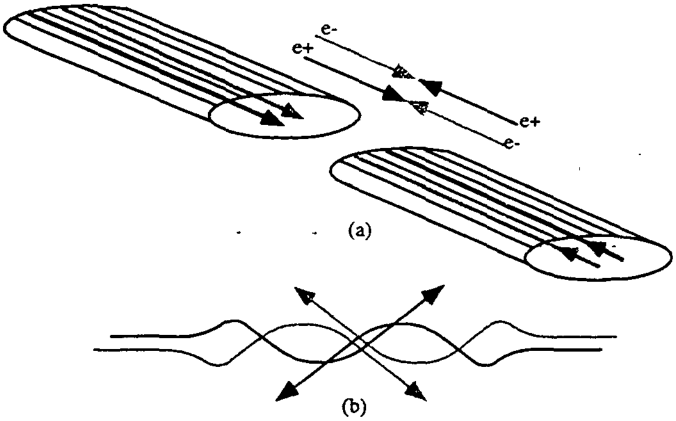

Figure 5

The relevant issues here are: (i) size and cost of the resulting collider; (ii) complicated (although 'systematic' and 'tunable') collision kinematics with uncertain initial states and, (iii) coherent stability of the four beams against each other's electromagnetic fields which leads to beam disruption as shown in Fig. 5 (b), driven by uncompensated total charge dipole moments of the colliding beams. This scenerio is also amenable to enhancing the luminosity by scaling it as $N^2N_p^2$ as opposed to N^2N_p as in eq. (1). This could be achieved by relaxing the final focus which could then employ a larger β^*. That would allow coherent collisions of many bunches within the focal region as shown in Fig. 6. To reduce the site power, however, such a scenario could envision a beam combining scenario in a multiple bunch "matrixed" linac as shown in Fig. 7[6]. It is obvious here that the beam combining scale length L_C is bounded below due to emittance growth from synchrotron radiation from the hard bends. The criticality of beam alignment in this neutrialized four-beam and beam-combiner scenario is obvious. Such beam combining schemes can also ameliorate loading and wakefield constraints by distributing the colliding charges into many weaker bunches into multiple linac channels, before combining them as in Fig. 7.

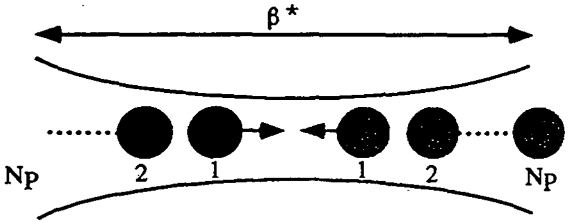

Figure 6

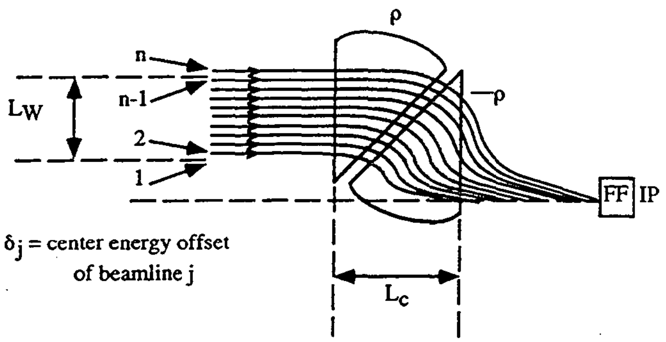

Figure 7

C. Other Options

There are some other options to bypass the large Υ issue: one could consider a 'plasma lens compensation' scheme at the IP[8]. However, the background generated by the plasma itself needs to be studied. One can also contemplate a lower luminosity initially (with modest δ_B and Υ to "DISCOVERY ONLY"), but the question of an upgrade path begs an answer.

D. Accept Large Υ and δ_B

A final option would be simply to live with the high radiative environment and ignore high Υ and δ_B. Flirting with such large Υ and δ_B implies that we will have to live with collisions potentially not as "clean" as lower energy (e^+e^-) colliders, but maybe it will inspire new schemes for detectors and data filtering. It should be noted however that it is important and even possible to limit the hadronic background to n_γ~1 even with large Υ and δ_B, as is the case with all collider scenarios in this report.

V. CURRENT RESEARCH AND STATUS OF 5 TeV COLLIDER CONCEPTS

Current research on collider components, parameters and basic schemes splits naturally into two broad categories:

(1) One that is based on relatively low (albeit augmented from present day designs) gradients of hundreds of MV/m and low frequencies of GHz to tens of GHz; and (2) One that is based on high gradients of 1 GV/m or higher and high frequencies from mm-waves to 100 THz.

The status of current research is summarized in Table I. It is important to note that all colliders based on any of these technologies would still have one common theme that is relevant at the IP: they will all have a high Υ (>1), high δ_B (>>10%) and/or would contemplate a gamma-gamma collider arm or neutralized four-beam scheme to overcome radiative effects. They all will also come with the associated particle physics implications: high backgrounds and/or uncertain initial states due to four beams. We now discuss the categories in Table I in turn.

Table I - CURRENT STATUS OF 5 TeV COLLIDER RESEARCH

Technology	*Wave-length λ*	*Potential Gradient*	*Collider Length*	*R & D*	*Technology Details*
SCRF	>10 cm	100 MV/m	60 km	Superconducting materials research; new superconductor; site	'Bismuthate' materials
RF	1 cm	200 MV/m	30 km	Power sources prototype, drive beam dynamics, site	30 GHz TBA
				sheet beam klystron research, site	30 GHz Tube Driven
mm-wave and THz	<3 mm	1 GV/m	< 10 km	pwr source invention, structure invention, fabrication tech.	90 GHz Dielectric 90 GHz Conducting 1 THz
Lasers & beams in plasmas & structures	<300 μm	>10 GV/m	~ km	module prototype, rep. rating guiding, staging, beam dynamics	laser structure-based laser plasma-based beam structure-based beam plasma-based
$\gamma\gamma$	relevant to all the above			~10 kHz rep. rate, TW peak power lasers, IR mechanical configuration	

VI. A 5 TeV e^+e^- LINEAR COLLIDER BASED ON SUPERCONDUCTING (SC) CAVITIES

Possibilities of a 5 TeV e^+e^- linear collider on the "TESLA" site based on superconducting cavities were discussed and explored[9]. Major parameters for such a collider are shown in Table II. Such a collider would be based on:

(1) an installed 300 MW wall-plug power with 37% efficiency for conversion to beam;
(2) 1-3 GHz klystrons rated at 10 MW over 10 ns each;
(3) 5,000 such klystrons filling 40 km active linac length;
(4) Loaded gradient of 120 MV/m in sc cavities; and
(5) $Nb_3Sn \rightarrow BaKBi0_3$ superconducting cavity upgrades using high T_c 'bismuthate' materials.

We note that none of the above have been achieved yet. The maximum achieved gradient today in a 9-cell TESLA Niobium Cavity at DESY is limited to 25 MV/m[10].

If TESLA were built with a large site measuring upto 58 km facility length to allow upgrades and up to 40 km active structure length, the envisioned evolution path to 4.8 TeV is as in Table III[9], based on a series of technology upgrades involving initial Nb cavities later coated with Nb_3Sn in situ to raise gradients to 80 MV/m and eventual replacement by 'bismuthate' cavities with potential gradient of 120 MV/m.

Table II

$L \sim 10^{35} cm^{-2} s^{-1}$	$N \sim 2.7 \times 10^{10}$
f ~ 4.7 kHz	$N_p \sim 20{,}000$
Spot Size :	1.3 nm x 505 nm
Normalized Emittance :	10^{-8} m-rad x 10^{-8} m-rad
$\Upsilon \sim 2.3$	$\delta_B \sim 23\%$

Table III - Evolution Path

Active Length	*Gradient*	*Material*	T_c	E_{max}	*CM Energy*	*Luminosity*
km	MV/m		°K	MV/m	GeV	$cm^{-2}s^{-1}$
20	25	Nb	9.2	60	500	5×10^{33}
20	40	Nb	9.2	60	800	10^{34}
40	40	Nb	9.2	60	1600	2×10^{34}
40	80	Nb_3Sn	18	100	3200	6×10^{34}
40	120	$BaKBi0_3$	30	160?	4800	10^{35}

The essential R&D areas required to go with this envisioned evolution are as follows:
Near Term:
(i) Evaluate RF critical field of Nb_3Sn;
(ii) Develop 1-cell Nb_3Sn cavities at E_{acc} = 80 MV/m and
(iii) Develop method to covert multi-cell Nb cavities to Nb_3Sn in situ.

Medium Term:
(i) 10 MW, 10 msec klystrons;
(ii) SMES based modulator and
(iii) Input power couplers at1 MW.

Long Term:
Evaluate potential of bismuthate $BaKBi0_3$ at T_c=30 °K for higher gradients.

VII. A 5 TeV ($e^+e^-\gamma$) LINEAR COLLIDER BASED ON 34 GHz NORMAL CONDUCTING RF

Possibilities of a 5 TeV ($e^+e^-\gamma$) collider on a possible NLC site based on advanced higher frequency RF sources driving normal conducting structures were discussed and presented at the Workshop[11]. The parameters of such a collider are presented in Table IV.

Table IV

$L \sim 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$	$N \sim 2.4 \times 10^9$
$f \sim 120$ Hz	$N_P \sim 225$
Spot Size :	0.5 nm x 40 nm
Normalized Emittance :	10^{-8} m-rad x 10^{-6} m-rad
$\Upsilon \sim 2.7$	$\delta_B \sim 27\%$

Such a collider would be based on the following:

(1) an installed 300 MW wall plug power with 20% efficiency for coversion to beam;
(2) 34 GHz "clustered" or "sheet beam" klystrons rated at 130 MW each;
(3) 12,500 such klystrons filling 30 km active linac length;
(4) 16 ⊗ Binary Pulse Compression scheme;
(5) an acceleration gradient of 260 MV/m, loaded down to 190 MV/m with beam, and
(6) a C-band injector and Damping Ring.

We note again that none of these are achieved today. We have 50-70 MW klystrons @ 11.4 GHz, an 8 ⊗ Binary Pulse Compression Scheme and a 10% wall-plug to beam efficiency today. The corresponding gamma-gamma luminosity would be optimized to[12]:

$$L_{\gamma\gamma} \sim 1.4 - 7 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

requiring:

(1) laser at 10 μm, 1 J per pulse and 27 kW average power and
(2) photoinjector with five times better brightness than state-of-the-art.

These do not exist today, without further R & D.

VIII. LIMITS OF METALLIC STRUCTURES

It is evident from Section VI and VII, that even with significant R&D on superconducting material technology, power sources up to 30 GHz, etc., it is going to be difficult to attain significant economy in the size or cost of these colliders based on achievable gradients. The fields would probably saturate out at a few hundred MV/m and the lengths would have to be at least few tens of kilometers. Probably this is an indication that one should take a leap to a totally different technology (in analogy to the transition from "propellar-driven" to "jet propulsion" aviation technology) that would allow us to reach 1 GV/m and higher electric field gradients, with potential for colliders at TeV energy range within a few kilometers of site length.

However, before contemplating such a transition, we would like to pose and answer the following question: "What are the ultimate limits of metallic structures?". In particular, what is the ultimate "gradient" achievable in Copper or some such structure? What are the thermal and electrical limits? Can existing power sources be exploited and improved? Can new power sources be designed and built?

The surface breakdown gradient limit is given by[6]:

$$G_{BD} \sim \left(\frac{1}{4}\right)\frac{1.3(\mathrm{GV/m})}{\tau^{1/4}\lambda_{(\mathrm{cm.})}^{7/8}} \sim \lambda^{-7/8} \qquad (9)$$

while the background electron capture limit is given by[6]:

$$G_{\mathrm{capture}}\lambda \sim 2\mathrm{MV} \rightarrow G_{\mathrm{capture}} \sim \lambda^{-1} \ . \qquad (10)$$

The "pulsed heating" limit on gradient, G_{PH}, for a temperature rise of ΔT in a metal with electrical and thermal conductivites of σ and K pulsed by radio-frequency power at a wavelength of λ (cm.) is given by[6]:

$$G_{PH} \sim 0.3\left(\frac{\mathrm{GV}}{\mathrm{m}}\right)\left[\frac{\Delta T}{50^\circ\mathrm{C}}\right]^{1/2}\lambda_{(\mathrm{cm.})}^{-1/8}\tau^{-1/4}\left[\frac{\sigma K C}{(\sigma K C)_{Cu}}\right]^{1/4} \qquad (11)$$

In Figure 8, we have plotted the three gradient limits from eqs. (9), (10) and (11) vs. wavelength for a τ=0.5 long radio frequency pulse with 40°C, 80°C and 120°C temperature rises respectively. It is evident that metallic structures are limited by breakdown and capture at long wavelengths, before being limited by pulsed heating, whose threshold is an order of magnitude higher in gradient. This limit is around 100 MV/m at around 1 cm. wavelength, the primary cause behind the gradient and length limitations at long wavelengths. As we go to shorter wavelengths approaching mm-waves, metallic structures are limited primarily by pulsed heating, whose threshold is significantly lower than breakdown or capture limits, but still a respectable ~1GV/m. Thus the experimental question of the effect of pulsed heating at short wavelengths should be studied at various temperature rises ΔT vs. pulse lengths and number of pulses per second, etc. It is clear that the thrust would be towards shorter wavelengths approaching mm-waves (~90 GHz) to push conventional metallic structure and power source technology to its limit. The questions of fabrication, wakefields, rf sources, etc. at such short dimensions should be studied.

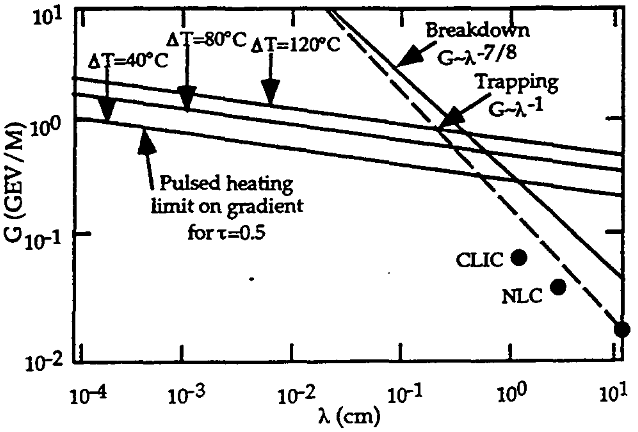

Figure 8

IX. POTENTIAL OF LASERS

Modern short pulse lasers can be focused to generate intense fields exceeding 10 GV/m. These lasers can be used either directly to generate accelerating fields in presence of boundaries or indirectly to drive a density and electromagnetic wave in a plasma for purposes of acceleration. They can also be used as fast triggers to switch and release enormous energy densities in the THz frequency that can be stored in semiconductor striplines biased with high pulsed voltages. This energy, when focused to small spot sizes can also yield high gradients. We discuss this last process in the following Section A, followed by possibilities with lasers in free-space in B and possibilities with laser in plasmas in C. Finally, we discuss progress on $\gamma\gamma$ colliders briefly in D.

A. Possibilities in the THz

For frequencies higher than 100 GHz, it becomes difficult to conceive metal waveguides as structures. However, one may contemplate propagation of waves in “open” or “dielectric” structures. We ask the questions: (a) can freely propagating THz or optical pulses be coupled to an electron beam by some structure with boundaries ? and (b) what are the ultimate possibilities of THz or optical sources?

High intensity THz pulses at 1 kHz repetition rate has already been produced by Budiarto et al.[13] They report generation of terahertz pulses with 0.4 μJ pulse energy at 1 kHz repetition rate using a large aperture GaAs photoconductor with 3 cm. gap aluminum electrodes, biased at voltages up to 45 kV, irradiated with short pulse lasers with fluences of the order of 40 μJ/cm^2. By focusing the THz beam with a 9" parabolic mirror to a FWHM of 2.8 mm, peak electric fields of 15 MV/m were obtained. Bias fields significantly higher than 15 kV/cm. can be obtained by utilizing pulsed voltage switches (as opposed to DC bias voltage). The radiated fields could be potentially focused to hundreds of MV/m. Such higher intensity THz pulses could be explored for applications to electron guns with high brightness in phase space[14].

B. Possibilities with Lasers in Free Space

There exists the possibility of acceleration via lasers in free space in presence of suitable boundaries. These boundaries provide proper termination of electromagnetic fields, resulting in net acceleration of particles. They could be either metallic or dielectric boundaries. The laser-induced surface damage in terms of damage fluence (J/cm^2) and maximum acceleration gradient (GV/m) vs. laser pulse length are shown in Figs. 9 (a) and (b) respectively[15]. Both the damage threshold and surface field are a good fraction of an order of magnitude higher for dielectrics than for metallic structures. There is, ongoing research[15] on Inverse Cherenkow acceleration using a dielectric channelled 10-100 THz waveguide structure, as shown in Fig. 10. Here a radially polarized laser pulse is guided by a dielectric fiber with potential axial electric fields upto a 1 GV/m.

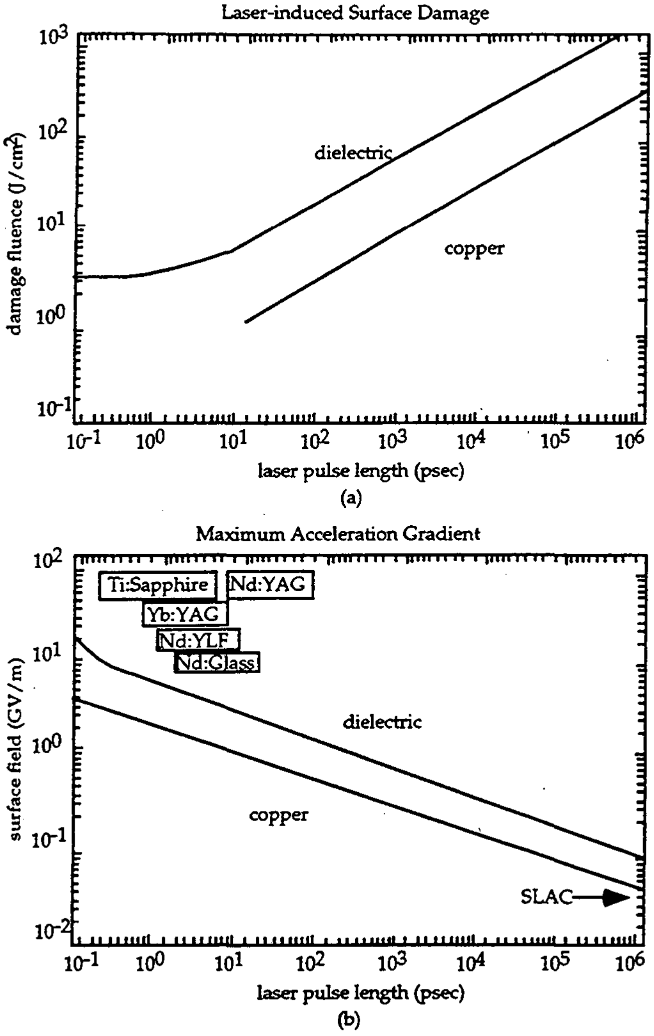

Figure 9

Finally a dielectric micro-accelerator using cylindrical laser focusing has been proposed by Huang and Byer[16] based on an accelerating electromagnetic mode created by two crossed laser beams as shown in Fig. 11. The net energy loss to coherent Cherenkov ratiation at mode-restricting apertures will compete with the energy gains from crossed fields in this configuration. Gradients of a 1 GV/m and acceleration of upto a million particle per bunch are expected.

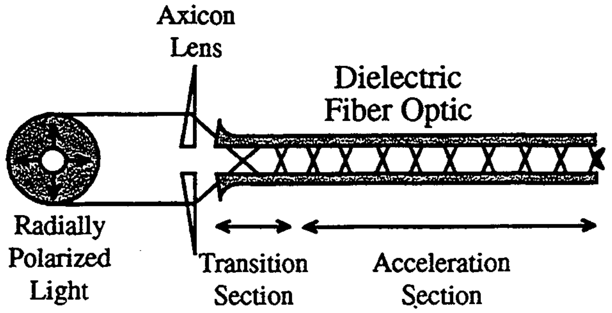

Figure 10

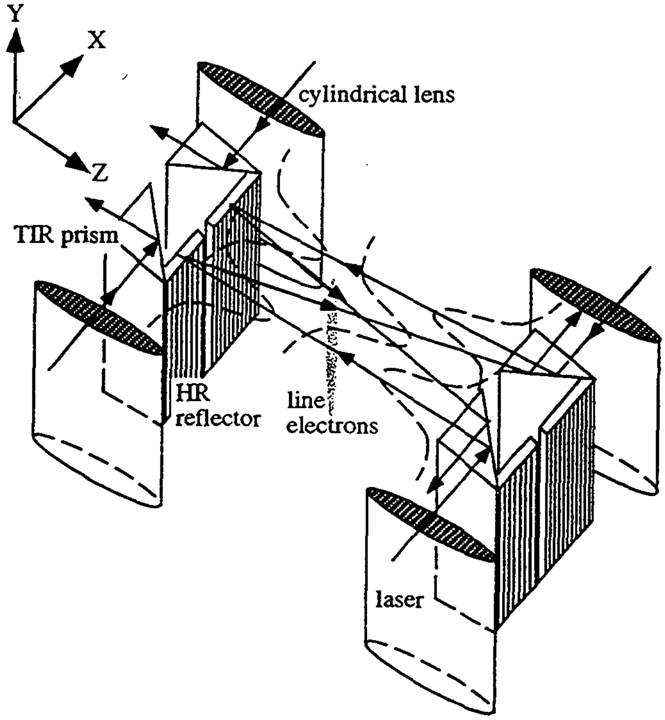

Figure 11

C. Laser in Plasmas

Lasers can be used to drive large amplitude waves in high density plasmas with associated fields reaching 10-100 GV/m. However focused lasers tend to diffract away and it is one of the ongoing research and development programs to channel or guide lasers focused to high energy densities over many Raleigh ranges[17]. Such plasma channels not only over come diffraction, but decouple transverse gradient of laser field from that of the accelerating wake. There are may similarities between linac structures and hollow plasma channels. These need to be quantified and better understood.

An example laser wakefield acceleration (LWFA) scheme is worked out in Appendix C with associated parameters listed there. Even if a 10 GV/m module as exemplified in Appendix C would work out, there are many issues in staging of such modules for a collider: (i) synchronization of laser and electron pulse from stage-to-stage requiring a sub-picosecond laser synchronization clock; (ii) range of plasma densities, laser energies and laser spot sizes from injection to collision and (iii) injection schemes. The required R&D for laser acceleration, as identified today are:

(i) Laser channelling in a plasma at 10^{18} W/cm^2;
(ii) Injection and locking in laser plasma;
(iii)Wakefield diagnostics and instrumentation: emittance preservation and stability;
(iv) Laser development and control, and
(v) A 1 GeV in 1 m demonstration experiment.

D. Photon-Photon Colliders

It has been recognized that in order to maximize the reach to accessible high energy physics frontier, it is important and reasonable to explore the technical possibility of at least two interaction points (IPs) at these colliders: one for normal electron-positron collisions and a second one for collisions of hard photons on hard photons, electrons on hard photons and electrons on electrons. This second IP is commonly referred to as the Gamma-Gamma Collider arm of a linear collider - a term dubbed after an international workshop on the topic in Berkeley in 1994[7]. High energy photons i.e. gamma rays for these collisions are most effectively produced via Compton backscattering of focused laser beams by the high energy electron beams of the linear collider. The high energy photon beams are then brought into collision with opposing electron or photon beams. Since one does not need positrons for the Compton conversion, the possibility of electron-electron collision exist as well. With suitable laser and electron beam parameters, a luminosity of electron-photon and photon-photon collisions comparable to that of the electron-positron collisions can be achieved. In addition, the polarization of the high energy photons can be controlled via polarization of the laser and the electron beams. With high luminosity and variable polarization, the photon-photon and electron-photon collisions at TeV energies will significantly enhance the discovery potential and analytic power of a TeV linear collider complex.

Yet another important reason to consider photon-photon collisions is the limitations imposed by radiative effects of the macroscopic beam electromagnetic fields, as discussed in Section II-IV. Charged particles get bent severely by the macroscopic electromagnetic field of the opposing colliding beam, leading to copious emission of what is known as 'beamstrahlung' photons, characterized by the Υ parameter - a classical measure of average radiated photon energy in units of beam particle energy. The effect also leads to a large energy spread, δ_B, in the colliding beams. If the number of particles per colliding bunch is too large, the beamstrahlung photons can produce coherent pairs, causing concern about electromagnetic and hadronic backgrounds in the detector.

The "γ-γ" collisions (instead of direct e^+e^- collisions) via Compton conversion offer an alternative paradigm to collider physics, with no limitation from beamstrahlung or coherent pair production.

A preliminary but rapidly evolving conception of such a composite and integrated linear collider complex is being considered by the international linear collider community at present and is shown in Figure 12. The required laser peak powers - about a Joule in a picosecond or a 100 mJ in 100 femtoseconds - have already been achieved in today's state-of-the-art T^3 lasers. And there is significant promise of enhanced repetition rate operation of these lasers to match the particle beam collision frequency for luminosity considerations. Investigations on both conventional lasers and Free Electron Lasers (FELs) towards this goal are underway at present[17].

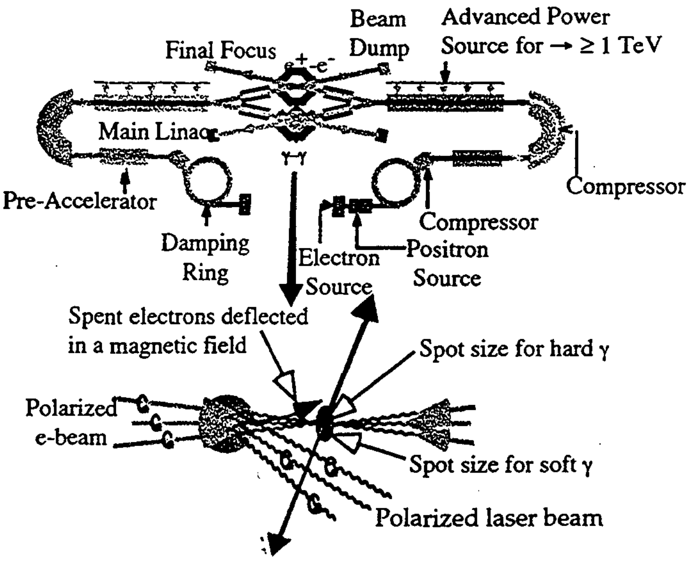

Figure 12

X. WHAT NEXT ?

A credible collider design involves concerns and optimization in a multidimensional space that is bound to vary in its mutual relative weights among the various concepts and technologies. Each parameter requiring optimization raises concerns that demand vigorous research and devleopment. The small spot size at the IP required to maximize luminosity, for example, raises questions of optical and beamstrahlung limitations. Any new structure being comtemplated would have to be examined in terms of beam dynamics implied by its wakefields. Any power source in the wavelength range $10\ \mu m < \lambda < 2$ cm would have to be judged based on its peak and average power and overall efficiency. High gradient mechanisms in the $G>1$ GV/m regime should be examined for their efficiency in coupling power from the accelerating wave to the particle. Finally any collider scenario will imply an 'acceptance' for the total beam phase space volume or 'emittance' that is compatible with collider parameters at the IP. This acceptance will typically demand 'ultralow emittance' or ultracold beams at injection, begging research and development of ultracold particle sources and their beam dynamics.

To get a concrete and clearer picture of the required R&D for any collider concept, scenario or technology, one should attempt at a reasonable parameter set for each collider scenario at $\lambda=1$ cm., 3 mm., 1 mm and those based on Laser Wake Field Acceleration (LWFA), Plasma Wakefield Acceleration, etc.. In Appendix C, we provide a preliminary outline of such an exercise for a possible LWFA. Such an exercise would be useful for all scenarios. The site power, minimum required normalized emittance and beam dynamics are common concerns. In addition, pulsed peak power level, minimum pulsed heating, ultimate electric field gradient in metal, power feed scheme, etc. would be important issues for higher frequency power tubes and structures such as in the W-band, say. Finally, emittance growth, minimum length, instabilities, disruption and final focus are common concerns, especially for schemes using beam combiners and neutralized beams.

XI. OUTLOOK

It is clear that the various concepts are at a different level of development and have a different set of near and medium term problems to address. For example, the high-frequency rf schemes have to study fabrication, breakdown and heating limits, while the laser wakefield schemes, which have acheived high field gradients in a plasma, must demonstrate the ability to accelerate a low emittance beam, to excite wakes in plasma channels over distances much longer than diffraction lengths, to couple efficiently to the plasma, etc. The power sources, rf and laser, also need substantial development to reach the simultaneous requirements of power, repetition rate and efficiency.

It should be emphasized that the purpose of the group was to study the state of the field and discuss research directions and requirements. The level of maturity of the concepts and associated technologies varied greatly. None of the schemes was presented as, nor considered to be, at present, a candidate for colliders. Another goal of the group was to provide the opportunity for workers in the advanced accelerator areas to gain an appreciation of the requirements and concerns for the high energy collider, and, of course, for the more mainstream accelerator scientists to become aquainted with the exciting developments in the advnaced accelerator field. We believe a sound basis for futher collaborations between these groups was established.

The key physics issues of collider design are acceleration gradient, low-emittance particle sources and beam stability. The key engineering issue is that of wallplug-to-beam power efficiency. At the end of the Snowmass'96, many in the AAT subgroup believed in the following:

By the year 2000 AD, critical experiments on the feasibility of generating a 1 GeV beam of electrons compatible with a 5 TeV collider module — e.g. 10^6 *to* 10^8 *electrons of 1 GeV energy within a normalized transverse emittance of* 10^{-6} *to* 10^{-7} *m-rad, shorter than 1 ps in length and produced in a distance under a meter — will be performed at many laboratories worldwide based on many of the schemes discussed in this report — acceleration by wakefield or guide fields generated in plasmas or structures (metal or dielectric) by lasers, particle beams or microwave power sources.*

The subsequent R&D focus will be on the beam quality, control, staging and engineering. Such an outlook begs the question: what has changed lately that allows us to be so optimistic? There have been many new results and achievements that give us confidence in this prognosis:

(i) Feasibility and operation of compact high power, short pulse, lasers have already been demonstrated. The Table Top Terawatt (T^3) solid state lasers based on the Chirped Pulse Amplification (CPA) technique is a fast moving technology. Sufficient peak powers relevant to colliders (>1-10 TW) have already been achieved. Current research is focused on achievement of high repetition rates exceeding 1 kHz;

(ii) The necessary phase, amplitude and jitter control of T^3 lasers have also been demonstrated. Here we benefit from laser developments driven by demands of coherent control needed to study ultrafast chemistry. A phase noise of less than 200 fs rms for single pulses has been achieved. The current research is focussed on multipule pulses;

(iii) Guiding of laser pulses at power densities in excess of 10^{15} watts/cm^2 over a cm. (~70 Raleigh lengths) of macroscopic distance in a plasma channel (or fiber) has been demonstrated[18]. Current research is on channelling power densities at the 10^{18} watt/cm^2 levels promising an electric field gradient in excess of 10 GV/m in the laser channel;

(iv) Much visible progress has been made in the technology of microfabrication at the 10 nm feature size level via the LIGA process at existing synchrotron radiation sources[19];

(v) There has been remarkable progress - at existing colliders at SLAC, DESY, KEK, etc.- in the precision instrumentation for diagnosis and cure of wakefields generated in high frequency structures by the passage of particle beams. Such instrumentation is key to preserving the ultimate quality of the colliding beams required for high luminosity. At the same time, new optical interferometric techniques are being developed for monitoring wakefields induced in plasmas by lasers or particle beams at the μm wavelength scale[20];

(vi) And finally, new ideas have come up that show much promise towards alternative collider scenarios based on a shifted collider paradigm that utitizes: (a) Compton-scattered laser photons in a $\gamma\gamma$ collider thus avoiding radiative constraints of e^+e^- collisions[7]; (b) beam combining before final focus to capitalize on coherent luminosity enhancement and reduce site power; (c) Neutralized four beam collisions to suppress beamstrahlung limitations; (d) the idea of a matrixed linac where the radiofrequency power and the particle beam travel in mutually orthogonal directions (as opposed to travelling together in a conventional linac) thus overcoming the pulse heating and field-gradient limitation of conventional linacs[6].

The three primary and generic issues regarding high energy linear colliders that are ready for intense study in the coming years are: (i) the limits of the beam-beam electromagnetic interaction; (ii) establishing the limits of metallic and dielectric structures and finally, (iii) using the enormous potential of the laser.

Much theoretical and experimental work is in progress at many universities, laboratories, institutes and industries throughtout the world. It promises to be an exciting decade of bold and advanced R&D indeed !!!

Acknowledgements

The authors acknowledge "Sam" Vanecek of Berkeley Lab's Center for Beam Physics for the preparation of this entire manuscript and the participants of the Snowmass'96 AAT subgroup for valuable input.

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22. T. Katsouleas, talk at this Workshop. See Appendix A.
23. The authors acknowledge Toshi Tajima for promoting and sharing the vision of laser accelerators as depicted in Fig.C1.
24. The authors acknowledge Eric Esarey and Chris Clayton for help in the design and envisioning of the 10 GeV/m module in Fig. C2 in Appendix C.

Appendix A

Advanced Accelerator Technologies Subgroup
Agenda

The AAT subgroup had a full menu for the entire three week period including 36 speakers on 39 different topics and a total of 26 other participants. The topics covered by the speakers were pre-selected by the AAT chairpersons and convenor (authors of this summary) as follows:

A Menu of 5 TeV Colliders	June 27, Thursday, 1996
Structures	June 28, Friday, 1996
Low Emittance Beams	July 1, Monday, 1996
Wakefields	July 1, Monday, 1996
Power Sources	July 2, Tuesday, 1996
$\gamma\gamma$ at 5 TeV c.m.	July 2, Tuesday, 1996
Laser Acceleration	July 5, Friday, 1996
Directions for Research	July 8, Monday, 1996
Ad Hoc Discussions	

The details of the speakers and topics are given below.

June 27, Thursday : 1996 - A Menu of 5 TeV Colliders

Prof. Jonathan Wurtele, UC Berkeley,
“Constraints on Laser-Driven Accelerators for a High-Energy Linear Collider”.

Prof. Hasan Padamsee, Cornell University
“A scheme for a 5 TeV cm at 10^{35} luminosity linear collider (with a parameter set) for a linear collider based on SC cavities”.

Dr. Glen Westenskow, LLNL,
“5TeV Linear Collider Based on a Two-Beam Accelerator at <30 GHz”.

Prof. David Whittum, SLAC,
“5 TeV Linear Collider at 91 GHz”.

Prof. Tom Katsouleas, USC,
“Plasma and Laser 5 TeV Colliders”.

June 28, Friday: 1996 - Structures

Prof. Hasan Padamsee, Cornell University,
“Promise of and R&D directions for Nb$_3$Sn and high T$_c$ SC cavities”.

Dr. David Yu, Duly Research Inc.,
mm-Wave Structures”.

Dr. Yoon Wan Kang, ANL,
“RF, Thermal & Dynamics Considerations for mm-Wave Structures”.

Dr. Wei Gai, ANL,
“100 GHz Traveling Wave Dielectric Acceleration Structures”.

Dr. Yen-Chieh Huang, Stanford University,
“Dielectric-Based Structures for Laser-Driven Accelerators”.

Dr. Gennady Shvets, Princeton University,
“Creating Guiding Structures in Plasmas: Beam-Channeled Laser-Wakefield Accelerators”.

July 1, Monday : 1996
Part 1 - New Approaches to Low-Emittance Beams

Dr. Max Zolotorev, LBNL,
“Laser-Based High-Brightness Sources & Optical Manipulation of Beams”.

Dr. Pisin Chen, SLAC, (Zhirong Huang),
“Considerations for Channeling & Damping”.

Dr. Alex Bogacz, UCLA,
“Development of Crystal-Based Components for Future Accelerators: Experience from the Bent Crystal Extraction Experiment at Fermilab (E853)”.

Dr. Jie Wei, BNL,
“Cooling & Crystalline Beams”.

July 1, Monday : 1996 - Part II - Wakefields

Dr. John Irwin, SLAC,
“NLC Collimator Wakefields”.

Dr. Karl Bane, SLAC,
“The Bane-Morton Model”.

Prof. Jaime Rosenzweig, UCLA,
“Wakefields in Planar Slow-Wave Structures”.

Mr. Peter Stoltz, University of Colorado,
“Nonlinear Theory of Beam Bunching and Deceleration Due to Cavity Damping”.

Prof. Alex Chao, SLAC,
“General Planar Wake Conditions”.

Dr. Frank Zimmermann, SLAC,
“Diffraction Model with Image Currents”.

Dr. Franz-Josef Decker, SLAC,.
"SLC Collimator Experience".

July 2, Tuesday : 1996
Part I - **Power Sources**

Prof. Perry Wilson, SLAC,
"A 5 TeV Linear Collider Based on 34 GHz Technology".

Dr. Simon Yu, LBNL,
"Two-Beam Accelerator for a 5 TeV Collider".

Prof. Victor Granatstein, University fo Maryland,
"Gyrotron Amplifiers for Driving Multi-TeV Colliders in the Frequency Range 20 GHz to 100 Ghz".

Prof. Martin A. Gundersen, USC,
"Research Issues in Power Conditioning".

Prof. Toshi Tajima, UT Asutin,
"T^3 Laser Initiatives in the US & Japan".

July 2, Tuesday : 1996
Part II - **$\gamma\gamma$ at 5 TeV**

Dr. Ming Xie, LBNL,
"Parameter Optimization and IP Simulation of Electron and Photon Colliders at 5 TeV".

µ-TESLA

Dr. David Neuffer, FNAL,
"Upgrade from 500 GeV TESLA to a 10+ TeV $\mu^+\mu^-$ Collider".

July 5, Friday : 1996
Laser Acceleration

Dr. Eric Esarey, NRL,
"Laser Acceleration of Electrons in Vacuum, Gases and Plasmas".

Prof. Toshi Tajima, UT Austin,
"5 TeV Laser-Based Collider".

Prof. Jaime Rosenzweig, UCLA,
"A Straw-man Design of a $\gamma\gamma$ Collider based on PWFA".

Prof. Donald Umstadter, Center for Ultrafast Optical Science, University of Michigan, Ann Arbor,
"Laser Acceleration".

Dr. Chris Clayton, UCLA,
"Plasma Beat-Wave Accelerator".

Prof. Martin A. Gundersen, USC,
"Development of Practical Devices for Implementation of Plasma-Based Concepts".

July 8, Monday : 1996 - **Directions for Research**

Dr. Joshua Song, ANL,
"Fabrication of mm-Wave Structures via Deep X-Ray Lithography".

Dr. Wei Gai, ANL,
"Inverse Cherenkov Acceleration using a Dielectric Channeled Waveguide".

July 9, Tuesday : 1996

Dr. John Irwin, SLAC,
"5 TeV Linear Collider on the NLC Site".

Dr. Kwang-Je Kim, LBNL,
"5 TeV $e{+}e_-\gamma$ Collider Parameters".

Appendix B
List of Snowmass'96 AAT Subgroup Participants

Other than the 36 speakers as listed in Appendix A and the authors of this summary report (who chaired and convened the group), there were 26 other participants to the AAT Subgroup at Snowmass'96 as listed below:

LBNL - Wen-Hao Cheng, Andy Sessler, Brad Shadwick
FNAL - Pat Colestock, David Finley, Fred Mills, Robert Noble
LLNL - Dan Klem
ANL - Jim Norem
UCLA - David Cline, Claudio Pellegrini
U. Michigan, Ann Arbor - Lawrence Jones
BNL - Harold Kirk, Q.S. Shu
US DOE - David Sutter
Cornell U. - James Welch
UC San Diego - Norman Kroll
SLAC - Chris Adolphsen, Ralph Aβmann, Keith Jobe, Tor Raubenheimer, Bob Siemann, Kathy Thompson, Juwen Wang, Dian Yeremian, Michiko Minty.

Appendix C
Channelled LWFA Parameter Set for a 5 TeV Collider

It is well known that lasers have inherently high electric and magnetic fields, that can potentially be harnessed for compact ultra-high gradient linear accelerators. There exists the possibility of acceleration via lasers in free space in presence of suitable boundaries or via nonlinear higher order mechanisms or via direct coupling of lasers to a plasma-like medium[21]. Among experimental results to date on laser-driven acceleration of electrons in a plasma, the UK (RAL) experiment is the most recent (1996). It has demonstrated the highest gradient (100 GV/m) and produced beam-like properties in the accelerated electrons with 10^7 electrons @ 40 MeV ± 10% with a normalized emittance of $\varepsilon_N < 5\pi$ mm-mrad[22].

We would like to remind the readers of two important aspects that will critically determine the future of laser acceleration schemes. First, just as today's microwaves from klystrons are suitably guided by linac waveguide structures without diffraction for efficient coupling to a charged particle beam, we will have to learn how to focus strongly (in order to achieve high electric field intensities) and simultaneously guide short pulse high energy lasers over long macroscopic distances of cms without diffraction in order to use them for particle acceleration. Second, one would have to master the relative amplitude, phase and frequency control of lasers similar to that exhibited by today's rf control level, but scaled to laser frequencies.

An artist's impression of a staged and modular laser wakefield accelerator, compared and contrasted to its present-day microwave linac analog, is depicted in Figure C1[23].

Such a scheme depends on the success of propagating and guiding intense laser pulses in hollow plasma channels at high power densities of the order of 10^{18} W/cm^2 over several hundred Rayleigh lengths. I would like to mention here the important results obtained at Maryland[18] where lasers focussed to 10^{15} Watts/cm^2, have been propagated up to 70 Rayleigh lengths. Much progress has also been made in the context of pulse train generation and control in today's table-top terawatt lasers, thanks to applications in coherent wavepacket control for studies in ultrafast chemistry. One has the capability today of tailoring a sequences of up to eight or ten pulses, varying in strength, phase and width from a short pulse laser.

A state-of-the-art T^3 - laser with improved repetition rate (10TW, 300 fs, 10 kHz) will provide 3 J of laser energy per pulse at a wavelength of 1 μm. If one aims at a 1 meter stage with energy gain of 10 GeV, one needs a plasma 1 meter long, with a density of 10^{17}cm^{-3} accommodating 300 Rayleigh lengths. The accelerating wakefield wavelength will be 100 μm, the channel radius 30 μm, the acceleration gradient of 10 GV/m, with channel density variation of a 50% from center to the edge. In this scenario, one laser creates the necessary plasma acceleration structure via guiding, the other creates the wakefield for acceleration. A typical 10 GeV module is shown in Figure C2[24].

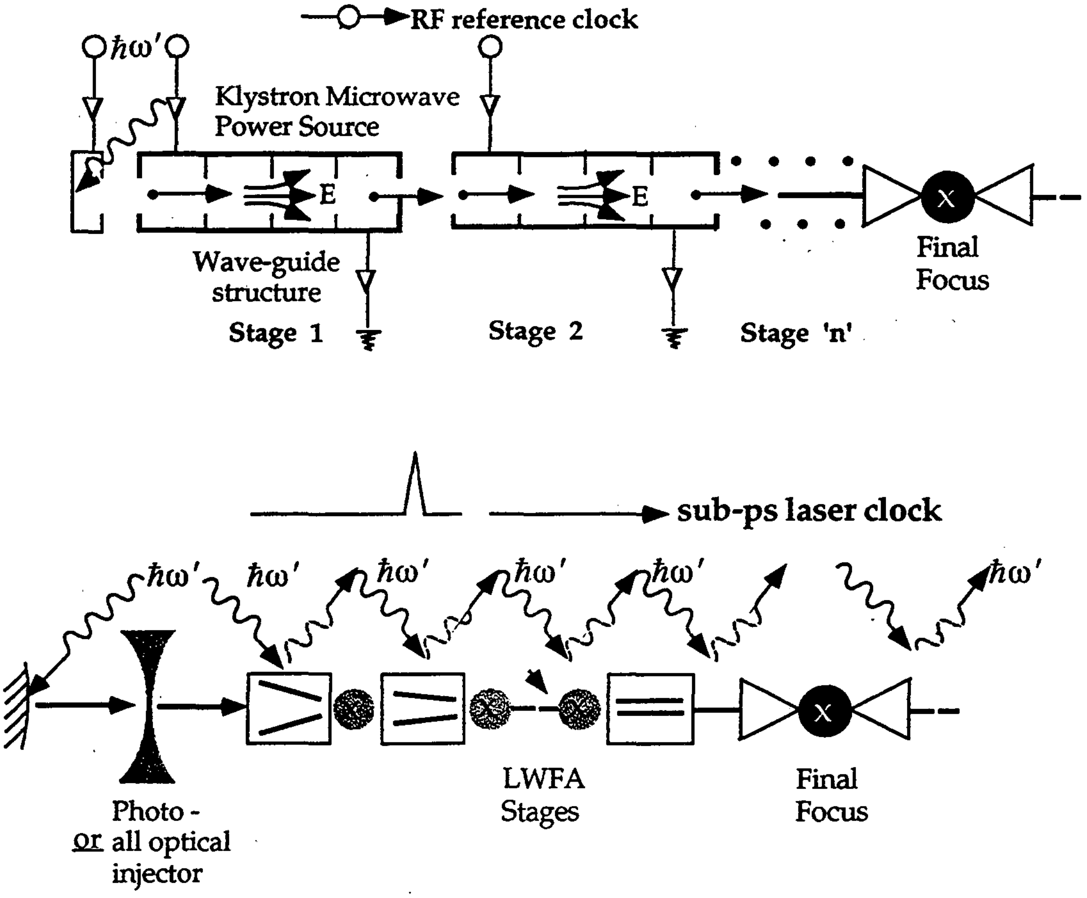

Figure C1

The required plasma channels need further study in order to overcome diffraction and to decouple the transverse gradient from that of the accelerating wake. Many similarities exist between linac structures and hollow plasma guides. These need to be quantified and better understood. Synchronization of laser and electron pulse from stage-to-stage in Figure C2 demands sub-ps laser synchronization scheme. There are various injection and synchronization schemes under study at present.

Should the guiding, staging and controllability issues be worked out, there is hope that wakefields excited in plasmas by a suitably shaped laser pulse will have the necessary characteristics for particle acceleration to ultrahigh energies, based on rather reliable simulations available today.

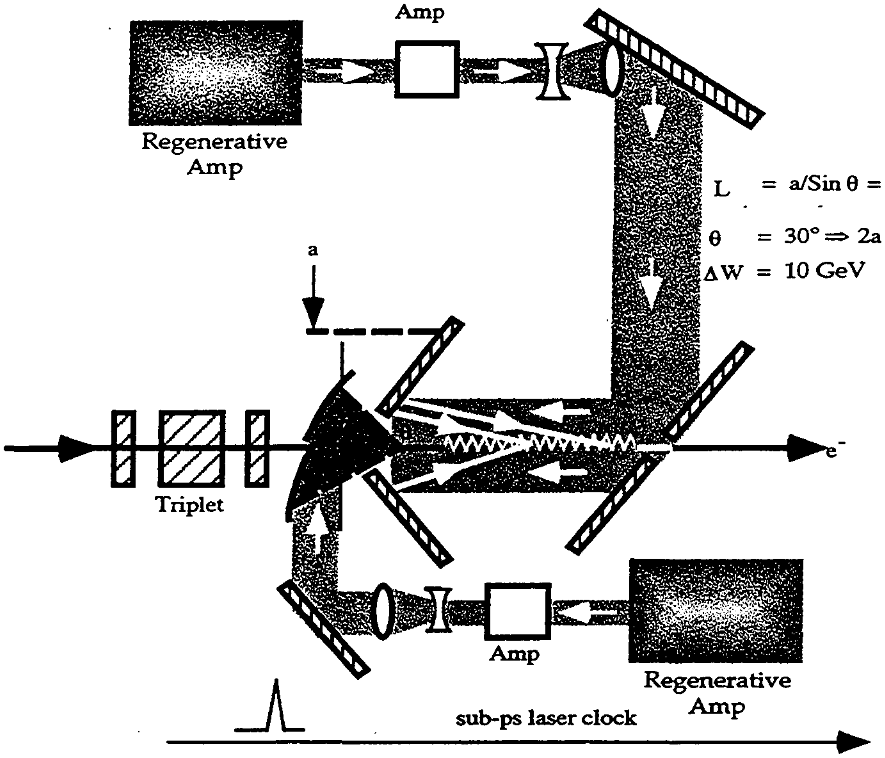

Figure C2

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