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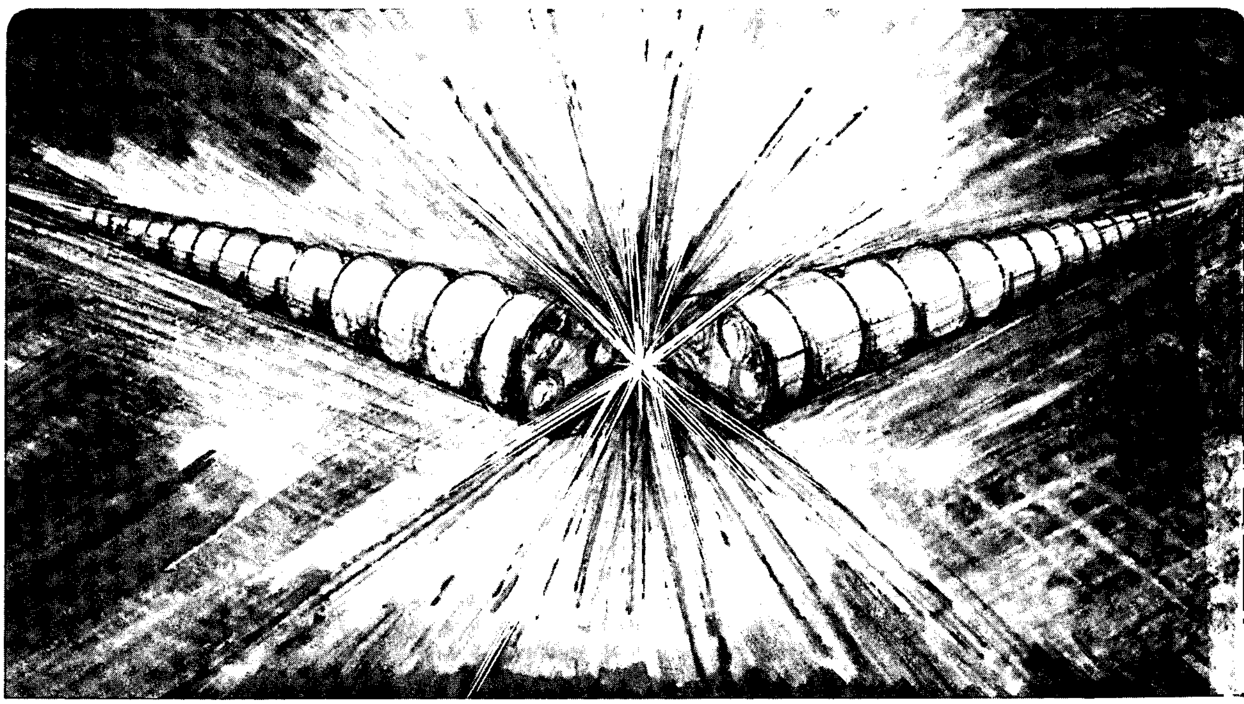

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Exotic Colliders*

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Abstract: The motivation, feasibility and potential for two unconventional collider concepts — the Gamma-Gamma Collider and the Muon Collider — are described. The importance of the development of associated technologies such as high average power, high repetition rate lasers and ultrafast phase-space cooling techniques are outlined.

1. INTRODUCTION

In spite of some personal reservations about the title of this article, I will keep to it since it was presented as such at the Advanced Accelerator Concepts Workshop in The Abbey at Lake Geneva, Wisconsin in June, 1994. Indeed, the topic under discussion revolves around two rather unusual high energy collider concepts that surfaced in the community about a decade ago and have been receiving increasing attention lately as the related concepts, technologies and their limitations go through progressive scrutiny. These colliders — unconventional by present day practice — are the Gamma-Gamma Collider and the Muon Collider. The former refers to high energy collision of two real (as opposed to 'virtual') hard photons (i.e., gamma rays) while the latter refers to high energy collision of oppositely charged muons — rare and unstable particles (leptons) similar to but heavier than electrons and positrons. I will motivate and describe these colliders in the following. However, before proceeding, it is worth making two statements regarding these colliders at the very outset: the Gamma-Gamma Collider will provide interesting physics and prototype technology even at low energy and modest cost, but most importantly, it provides yet another raison d'être for development of "high average power, high repetition rate lasers"; the Muon Collider will probably be very difficult to implement, but it provides a platform for the development of "ultrafast phase-space cooling techniques" useful for many applications beyond muon colliders (e.g., damping rings, femtosecond radiation sources, etc.).

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2. GAMMA-GAMMA COLLIDERS

2.1 A Bit of History

The physics of gamma-gamma collisions and its potential utility was exposed in a series of pioneering articles by Ginzburg, et al. (1) slightly more than a decade ago. Sporadic articles appeared in the literature throughout the 1980's culminating in a detailed exposition of a possible gamma-gamma collider scenario by Telnov (2) in 1990. Motivated by the growing interest and literature on the subject, a special topical and international workshop on Gamma-Gamma Colliders was held at the Lawrence Berkeley Laboratory in March 1994, where several working groups focused on the physics of photon-photon and electron-photon collisions, detectors, conventional and free electron lasers and accelerators (including interaction regions). I base this article on the conclusions reached at that workshop as expressed in its proceedings (3,4).

2.2 Why photon-photon collisions?

The collision of hard photons is believed to provide unique access to some fundamental physics (5,6) e.g., study of the Photon Structure Function, spectroscopy of bound-states such as toponium and its supersymmetric counterpart, study of Quartic Gauge Anomalies, supersymmetric Higgs particle, width of Higgs resonance from gamma-gamma, etc. In addition, collisions of hard photons provide complementarity and some welcome redundancy with respect to the physics from electron-positron collisions. The photon beams have the potential of being customized as well in terms of spectral bandwidth and polarization (broad/narrow band, circular/linear polarization). All these point to the fact that photon-photon collisions are equally valuable tools as electron-positron collisions in advancing the frontier of high energy physics.

2.3 Production of Hard Gammas

There are four methods explored so far for the production of hard photons (2). They are:

(i) Bremsstrahlung: electrons impinging on a target.
(ii) Coherent Bremsstrahlung on Crystals: electrons interacting collectively with atoms in a crystal leading to higher radiation intensity.
(ii) Beamsstrahlung: hard beam-beam impingement of colliding electron-positron beams.
(iv) Compton Scattering of Laser Light off a Relativistic Electron Beam:

$$\gamma_{\text{soft}} + e^{-} \rightarrow \gamma_{\text{hard}} + \text{recoil electron}$$

The kinematics of Compton Scattering is illustrated in Fig. 1. This last method i.e., Compton scattering is acknowledged to be the best method suitable for implementing directed and focused gamma-gamma collisions for the following reasons:

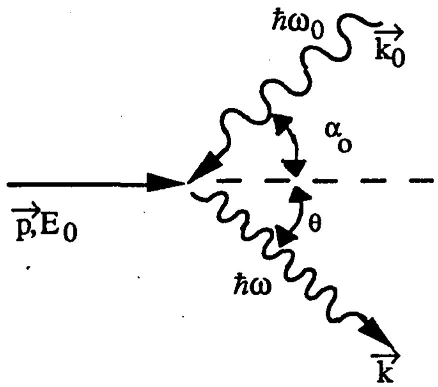
(a) Directivity: the hard gammas are predominantly produced in the direction of the relativistic electron beam ($\vec{k} \parallel \vec{p}$ in Fig. 1);

(b) At a 1 Joule/pulse of laser energy, the conversion efficiency $k = N_\gamma / N_e$ is close to 1 leading to instantaneous gamma-gamma collision luminosities $L_{\gamma\gamma}$ comparable to instantaneous electron-positron collision luminosities L_{ee}, due to absence of other charged particle collision effects (e.g., disruption, etc.);

(c) Expected low background of clean e-γ scattering compared to electron-on-target or beam-beam interactions;

(d) Relative probability of the scattered photons carrying away most of the energy of the relativistic electrons ($\hbar\omega \sim E_0$) and

(e) Relative ease of polarization control of the colliding photon beams (plane and circular polarization, etc.).



$$x = 4E_0\omega_0 \cos^2\left(\frac{\alpha_0}{2}\right) \Big/ m^2c^4$$

$$\theta_0 = \frac{mc^2}{E_0}\sqrt{x+1}$$

$$\omega_m = \frac{x}{x+1}E_0$$

$$\omega = \frac{\omega_m}{1+\left(\theta/\theta_0\right)^2}$$

FIGURE1. Kinematics of Compton Scattering from ref. (2).

2.4 Collider Configuration

A gamma-gamma collider presupposes the existence of high energy electrons or positrons as available from a conventional linear collider. The modification due to gamma-gamma collisions all take place close to the interaction region, where lasers would scatter off and siphon energy from high energy electron beams generating hard gamma rays that may collide and spawn massive particles. A generic gamma-gamma collider arm attached to a linear collider, as envisioned today, would look like as shown in Fig. 2. A blow up of the interaction region is shown conceptually in two views in Fig. 3(a) and (b) where the electron beams are removed from each other via crossing at an angle rather than being swept away magnetically, for example.

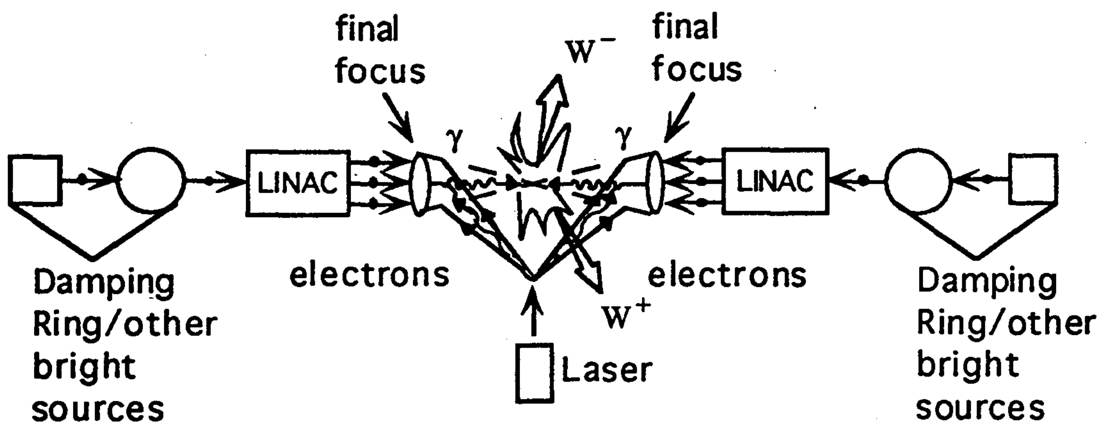


FIGURE. 2 A generic gamma-gamma collider configuration.

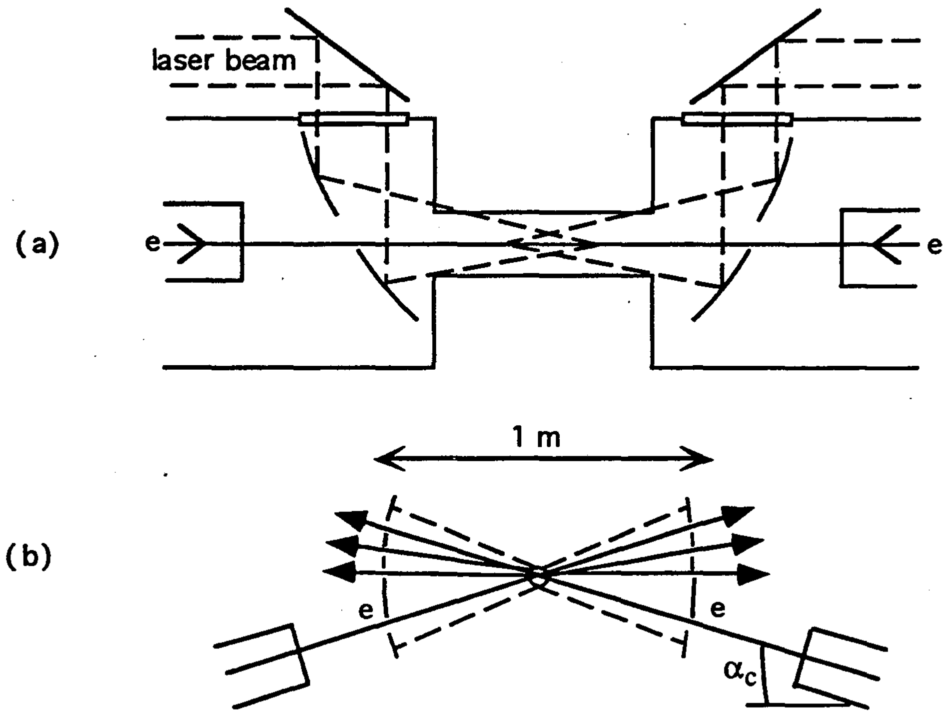


FIGURE. 3 Laser and electron beams at the IP of a gamma-gamma collider (from Ref. (3)).

2.5 Laser Parameters and Systems

There are various constraints on the laser parameters and other systems such as wavelength, pulse energy, repetition rate etc., put by the gamma-gamma collider configuration. We outline them briefly here.

2.5.1 Choice of Laser Wavelength

The maximum energy of scattered photons and the monochromaticity of the spectrum can be improved (increased) by raising the energy of the incident laser photons. However, the incident laser photon energy cannot be raised indefinitely, being limited by other secondary processes at the conversion region, the most important of which is the creation of electron-positron pairs in the collision of the primary laser photon (γ_0) and the high energy scattered photon (γ):

$$\gamma_0 + \gamma \rightarrow e^+ + e^-$$

The threshold for this reaction is (2,3): $\omega_m \omega_0 > m^2 c^4$ i.e., $x \gtrsim 4.8$ (in Fig. 1). Above this threshold, the two photon cross-section exceeds the Compton cross-section by a factor of 1.5 - 2. Accordingly, the wavelength and energy of the incident laser photons are limited to:

$$\lambda \gtrsim 4.2\, E_{0[\mathrm{TeV}]}\ [\mu\mathrm{m}] \quad ;$$

$$\omega_0 \lesssim 0.3/E_{0[\mathrm{TeV}]}\ [\mathrm{eV}] \quad .$$

2.5.2 Laser Pulse Energy and Conversion Coefficient

The conversion coefficient of electrons into photons depends on the laser pulse energy A as (2,3):

$$k = \frac{N_\gamma}{N_e} \approx 1 - \exp\left(\frac{A}{A_0}\right) (\sim A/A_0 \text{ at } A < A_0) \quad .$$

At the conversion region, let us assume that the laser beam has the typical configuration of a focused gaussian beam (see Fig. 4). The laser beam radius (r.m.s.) depends on the distance 'z' to the focus along the beam as:

$$r_\gamma^2(z) = a_\gamma^2\left(1 + \frac{z^2}{\beta_\gamma^2}\right)$$

where a_γ is the r.m.s. focal spot radius, $\beta_\gamma = 2\pi\, a_\gamma^2 / \lambda$ and λ is the laser wavelength, for a diffraction-limited Gaussian beam. The probability of electron-photon Compton collision (cross-section σ_c) in an interaction region of length 'l' is:

$$p \sim n_\gamma \sigma_c l$$

where n_γ is the photon density at the laser focus given by:

$$n_\gamma \sim A / \left[\hbar\, \omega_0 \left(\pi\, a_\gamma^2\, l_\gamma\right)\right] \quad .$$

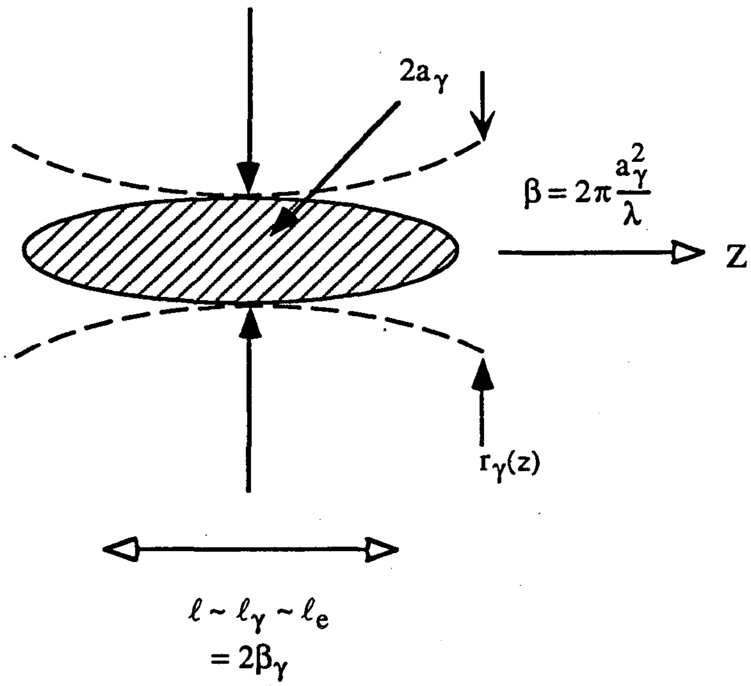


FIGURE. 4. Focused Gaussian Laser Beam Profile

The probability reaches close to '1' then at a critical laser pulse energy of:

$$A_0 \sim \frac{\pi \hbar c l_e}{2\sigma_c} \quad .$$

Using the value of Compton cross-section $\sigma_c = 1.9 \times 10^{-25}$ cm^2 at x = 4.8 leads to the critical laser pulse energy of :

$$A_0 \sim 25\, l_e[\mathrm{cm}] \quad \text{Joules} \quad .$$

For most practical purposes, this implies incident laser pulses with instantaneous peak powers of the order of a Terawatt.

[Note: electrons feel only one photon at a time when the nonlinearity parameter: $\xi = (eF\hbar / m\omega_0 c) << 1$ where F = (E, B) is the strength of the electromagnetic field. For high photon density, F ~ (E, B) is large and $\xi >> 1$ and multiphoton processes become important, leading to different limiting values (2) of the laser pulse energy and interaction length.]

2.5.3 Laser and Collider Systems for Electron-Positron Colliders in Existence or Under Design

The laser parameters required for a respectable gamma-gamma collider based on the present designs of the Next Linear Collider (NLC), TESLA and the existing SLC are summarized in Table I. The table is based on laser characteristics determined by diffraction-limited angular divergence and wavelength and flash energy limited by mechanisms as described above and repetition rate determined by the pulse format and repetition rate of the collider, given a certain luminosity, which is taken to be of the order of 10^{33} cm^{-2} sec^{-1} for gamma-gamma collision (7,8).

TABLE 1. Laser Parameters for a NLC-, TESLA-, and SLC-based Gamma-Gamma Collider

	NLC	TESLA	SLC
λ_γ	1μm	1 μm	0.25 μm - 20 μm
N_{train}	30	800	10
$\Delta\tau_{sep}$	4 ns	1 μs	25 ns
L_{train}	120 ns	.80 ms	250 ns
W/pulse	1 J	1 J	1 J
τ_γ	1 ps	1 ps	1 ps
Rep. Rate	180 H_3	10 H_3	180 H_3
<u>Optical Power</u>			
peak	1 TW	1 TW	1 TW
macro average	250 MW	1 MW	40 MW
long term average	5.4 kW	8 kW	1.8 kW

The terawatt level peak power required is already available from conventional table-top terawatt lasers that exist today. The repetition rate needed for high average power requires research and development on conventional lasers (9) (both materials e.g., Ti-Sapphire, Alexandrite, etc. and geometry e.g., slab vs. rod etc.). With Free Electron Lasers, the required repetition rate is relatively easy to obtain. However the high peak power needed to raise the average power needs demonstration.

The most optimal and optimistic choice of the FEL configuration is a two-stage FEL system consisting of a tunable FEL oscillator (output power~ 1-10MW) with subsequent amplification of the master signal in a FEL amplifier up to the power level of approximately 300 GW (MOPA configuration). The scheme is discussed in more detail in reference (10) and is shown schematically in Fig. 5. Table-2 summarizes the FEL amplifier parameters for a photon collider based on a 2 X 0.25 TeV, 2 x 0.5 TeV and 2 x 1 TeV linear electron-positron collider respectively. The respective photon collider parameters are shown in Table-3.

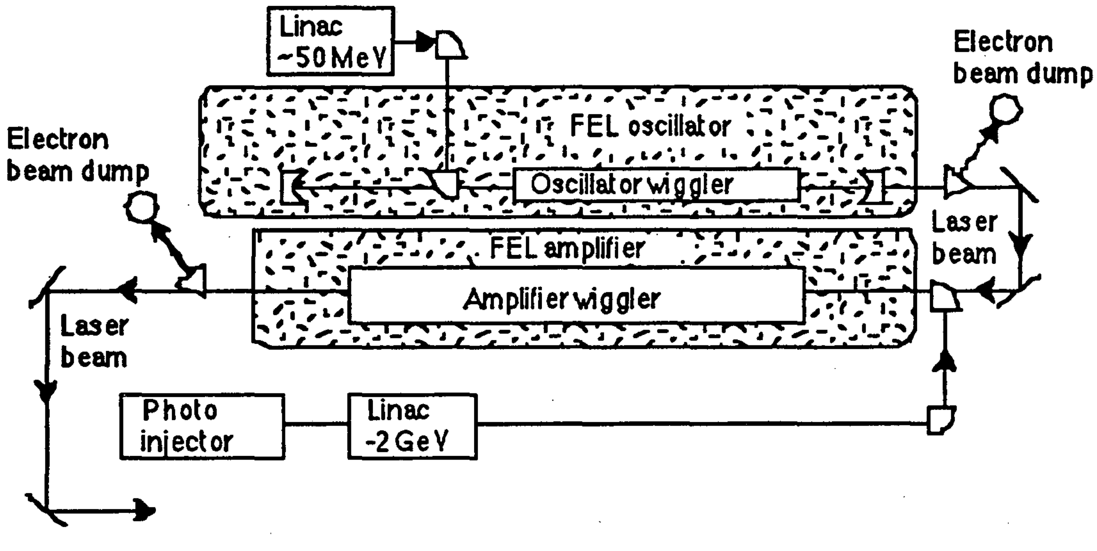


FIGURE. 5 Two-stage FEL scheme (MOPA Configuration) for a Photon Collider.

TABLE 2. FEL Amplifier Parameters for the PLC

	2x0.25 TeV	2x0.5 TeV	2x1 TeV
Electron beam			
Electron energy, GeV	2	2	2
Beam current I, kA	2.5	2.5	2.5
Energy spread σ_E/E, %	0.3	0.3	0.3
Normalized emittance ε_n, cm-rad	1.3×10^{-2}	2.6×10^{-2}	5×10^{-2}
Undulator			
Undulator period λ_w, cm (entr./exit)	15/12.9	20/17.2	20/17.1
Undulator field H_w, kG (entr./exit)	10.2/11.9	9.34/10.9	13.2/15.44
Length of untapered section, m	11.7	15.6	14.0
Total undulator length, m	37.5	46.9	43.7
Radiation			
Radiation wavelength λ, µm	1	2	4
Input power, MW	10	10	10
Output power, TW	0.3	0.3	0.3
Efficiency η, %	6	6	6
Reduced parameters			
Gain parameter Γ, cm^{-1}	5.1×10^{-3}	3.84×10^{-3}	3.84×10^{-3}
Saturation parameter $\beta = \lambda_w\Gamma/4\pi$	0.006	0.006	0.006

TABLE 3. Photon Linear Colliders of TeV Energy Range

	2x0.25 TeV	2x0.5 TeV	2x1 TeV
Main Linear Accelerator			
Electron energy, TeV	0.25	0.5	1
Number of electrons in the bunch, N_e	2×10^{11}	2×10^{11}	2×10^{11}
Repetition rate f, Hz	150	150	150
Normalized emittance ε_n, cm-rad	$\pi\times10^{-3}$	$\pi\times10^{-3}$	$\pi\times10^{-3}$
Electron bunch length σ_z, cm	0.1	0.1	0.1
β-function at the interaction point β_o, cm	0.1	0.1	0.1
Luminosity L_{ee}, $cm^{-2}s^{-1}$	9.3×10^{32}	1.9×10^{33}	3.7×10^{33}
Optical System			
Laser Power, TW	0.3	0.3	0.3
Laser ligth wavelength λ, µm	1	2	4
Laser beam spot size at the mirror a_o, cm	2	2	2
Focus distance of the mirror F, cm	30	20	15
Conversion & Interaction Region			
χ parameter	4.75	4.75	4.75
Maximal energy of γ-quantums, GeV	206	413	826
Conversion efficiency $\eta_{e\gamma}$	0.7	0.7	0.7
Distance between CP and IP, cm	3	5	8
Luminosity $L_{\gamma\gamma}$, $cm^{-2}s^{-1}$	4.6×10^{32}	9.2×10^{32}	1.8×10^{33}

In the FEL oscillator scenarios, one considers putting the entire macropulse within a long cavity and then switching out the laser pulses by "cavity-dump" techniques. The scheme is illustrated in Fig. 6 and for it to work, the length of the pulse train must be less than or equal to the round trip time of the optical resonator, so that the whole pulse train is in the cavity. While this will work for the NLC parameters, it poses special difficulties for TESLA, with a pulse train 0.8 ms long, demanding unrealistically long cavities. Hence, for TESLA we take a single pulse of photon, circulating 50 times in the oscillator and interacting with 50 consecutive electron bunches, for a total time of 1 μsec. Table-4 summarizes FEL oscillator parameters for the NLC and TESLA, with a cavity round trip time of 20 ns and charge per bunch of 4 nC chosen for the latter. For the SLC, one would have to consider a 200 MeV beam with 2 nC per bunch and a pulse compression scenario for the photon beams (from 18 ps to 1 ps) utilizing the injection chirp signal. All oscillator based scenarios need significant R&D.

Intra-cavity conversion of laser protons into gamma rays offer the possibility of high peak power. However, cavities, even when considered to be compact, will probably be too close to the detector for comfort.

Finally, although we picked three types of colliders: NLC, TESLA and SLC in the most generic sense to design the FELs, with three collision energy ranges for the first two (2x0.25 TeV, 2x0.5 TeV and 2x1 TeV), exciting possibilities need to be explored with the existing SLC and NLCTA. These are presented in reference (11).

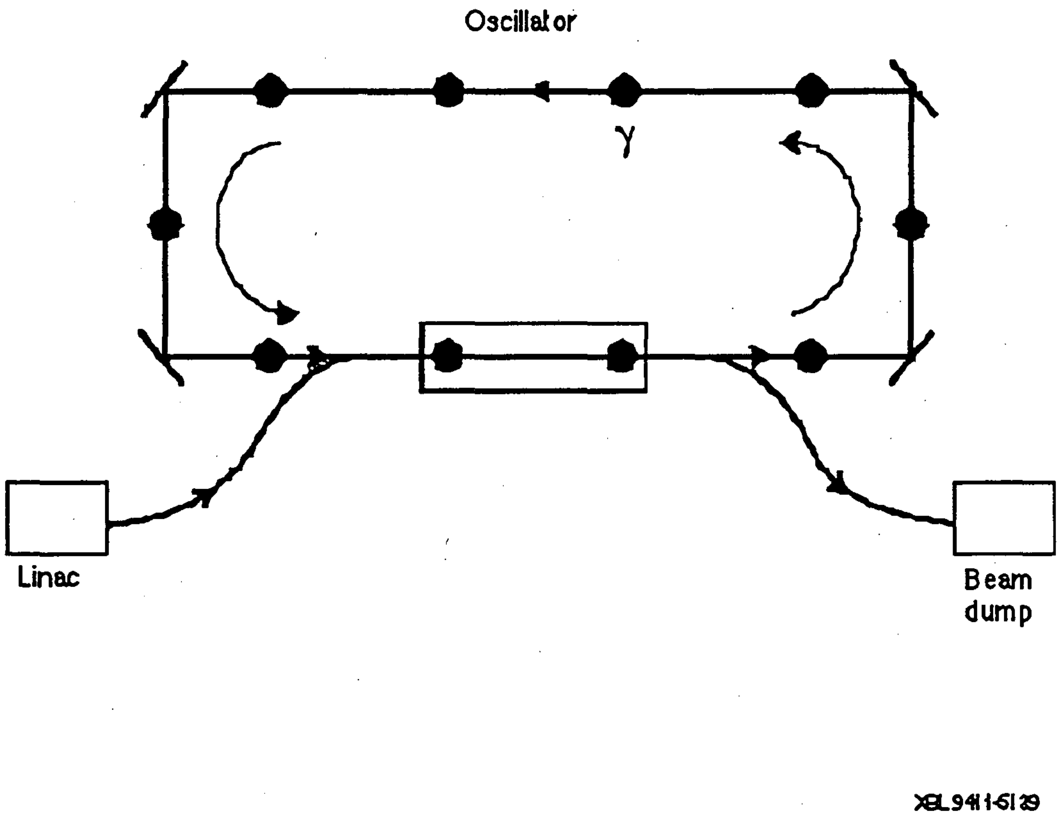


FIGURE. 6 FEL oscillator configuration with the entire pulse train within the cavity.

TABLE 4. FEL Oscillator Parameters for NLC and TESLA

	NLC	TESLA
Pulse Frequency	250 MHz	50 MHz
e^--beam Energy	100 MeV	100 MeV
Charge/bunch	4 nC	4 nC
No. of Passes	≥ 50	50
e^--bunch Length	18 ps	18 ps
Energy/pulse	1.6 J	1.6 J
Peak Current, $\hat{I}$	222 A	222 A
Macro-average, $\bar{I}$	1 A	0.2 A
Long term average, I	2.7 mA	16 mA
Linac Duty Factor	2×10^{-3}	8×10^{-2}
Macro-Power	100 MW	20 MW
Average Power	200 kW	1.6 MW

2.6 Outlook on Gamma-Gamma Colliders

We are at an early stage of conceptualizing the Gamma-Gamma Collider in all its three major aspects: particle physics, detector physics and accelerator physics. We believe that the physics of gamma-gamma collisions is just as fundamental as electron-positron collisions and that the required research and development are comparable in both cases, gamma-gamma collisions being no more difficult to implement than electron-positron collisions aside from the development of high average power, high repetition rate lasers (both conventional and free electron lasers) which will be promoted by the gamma-gamma colliders. Such lasers will find other applications e.g., in novel techniques of acceleration, among many others.

Clearly an electron-positron/photon-photon/electron-photon collider complex would be a significant extension of a rather conventional electron-positron Linear Collider at a moderately low incremental cost. It is then most natural to integrate photon-photon and electron-photon collision Interaction Regions (IRs) into any Linear Collider design right from the start. At least two separate Interaction Points could be easily conceived.

Lastly significant opportunities already exist in physics and collider development at the Stanford Linear Collider — the only existing electron-positron collider to date. The community simply cannot afford to miss such an opportunity.

3.0 MUON COLLIDERS

3.1 Motivation and Challenges

It is well known that multi-TeV e^+-e^- colliders are constrained in energy, luminosity and resolution, being limited by "radiative effects" which scale inversely as the fourth power of the lepton mass ($(E/m_e)^4$). Thus collisions using heavier leptons such as muons offer a potentially easier extension to higher energies (12). It is also believed that the muons have a much greater direct coupling into the mass-generating "Higgs-sector", which is the acknowledged next frontier to be explored in particle physics. This leads us to the consideration of TeV-scale μ^+-μ^- colliders. However, with the experimental determination of the top quark being heavier than the Z boson, there is increasing possibility of the existence of a 'light' Higgs particle with a mass value bracketed by the Z-boson mass and twice that value. This makes a 100 GeV $\mu^+ \otimes$ 100 GeV μ^- collider as a "Higgs Factory" an attractive option (13). The required average luminosity is determined to be 10^{30} $cm^{-2}s^{-1}$ (13). We note that the required luminosity for the same 'physics reach' scales inversely as the square of the lepton mass and implies a significantly higher luminosity required of a similar energy e^+-e^- collider, in order to reach the same physics goals.

The challenges associated with developing a muon collider were discussed at the Port Jefferson workshop (12,14), subsequent mini-workshops at Napa (13), Los Alamos (15) and at the workshop (16) on "Beam Cooling and Related Topics," in Montreux, Switzerland in 1993. Basically, the two inter-related fundamental aspects about muons that critically determine and limit the design and development of a muon collider are that muons are secondary particles and that they have a rather short lifetime in the rest frame. The muon lifetime is about 2.2 μsec at rest and is dilated to about 2.2 msec at 100 GeV in the laboratory frame by the relativistic effect. The dilated lifetime is short enough to pose significant challenges to fast beam manipulation and control. Being secondary particles with short lifetime, muons are not to be found in abundance in nature, but rather have to be created in collisions with heavy nuclear targets. Muon beams produced from such heavy targets have spot size and divergence-limited intrinsic phase-space density which is rather low. To achieve the require luminosity, one needs to cool the beams in phase-space by several orders of magnitude. And all these processes — production, cooling, other bunch manipulations, acceleration and eventual transport to collision point — will have to be completed quickly, in 1-2 ms, and there in lies the challenge. Bunch manipulation and cooling of phase space are some of the primary concerns. In the following section, we describe the two scenarios, and associated parameters being considered at present for muon colliders.

3.2 Scenarios, Parameters and Comments

Basically, there are two scenarios that have been considered to date for muon colliders. These two scenarios start with very different approaches to the production of the secondary muon beam from a primary beam hitting a heavy target. The subsequent acceleration, cooling, stacking, bunching and colliding gymnastics are all dictated and differentiated by these production schemes, which are very different. We consider them in sequence in the following.

The first approach considers production of the muons starting from a primary 'proton' beam hitting a heavy target according to the following reaction:

$$p + N \longrightarrow \pi + X, \quad \pi \to \mu\nu$$

Since proton bunches are typically long (few ns), one basically obtains long bunches of low phase-space density unless further phase-space manipulations are done to bunch and cool the beams. The situation is similar to the use of the Proton Ring as a pion source in the Los Alamos Meson Physics Facility (LAMPF-II) or conventionally considered kaon factory sources, for example. In order to reduce the length of the produced muon beam bunches, considerable gymnastics is required of the proton ring rf system. Ultimately, of course, a bunch rotation in the longitudinal phase space to reduce bunch length comes at the expense of the relative momentum spread, $(\Delta p/p)$, which could be as high as 5%. The produced muon bunches will need to be cooled longitudinally from $(\Delta p/p)$ of 5% to about 0.1% in order to have acceptable spectral purity at the collision point. In addition, the muon bunches will have to be cooled in the transverse phase space by a significant amount in order to meet the luminosity demand at the collision point. The cooled muons are subsequently accelerated and injected into a 100 GeV μ^+-μ^- collider where the bunches collide in at most a few hundred to a thousand turns (the number of turns, $n \simeq 300\,\bar{B}\,[\text{Tesla}]$). Clearly the constraint of short muon lifetime puts a premium at every stage on minimizing the time for production, cooling, acceleration and bunch processing, so as to still leave a few hundred turns in the collider to produce luminosity. Thus, it is clear that high field magnets play a crucial role in the collider. Details of this scenario have been considered by D. Neuffer (13,16) and R. Palmer (17). In Fig. 7, we depict schematically the scenario of a muon collider based on production via protons (16).

A second approach considers production of the muons starting from a primary 'electron' beam hitting a heavy target according to the following reaction:

$$e + N \longrightarrow e + N + \gamma, \quad \gamma \to \mu^+\mu^-$$

In this electro-production scenario, one obtains short bunches most naturally, since it is compatible with the normal mode of operation of high energy linacs. Although one obtains the 'optimum bunch format' naturally, one has to consider unprecedently high power and high repetition rate electron linacs, not explored before in order to meet the required collision luminosity. This is so because of the rather low yield of muons per electron, even at the optimum energy of incident electrons of 60 GeV, and the difficulty of packing more electrons per bunch in the linac. The low transverse phase-space density of the muons will require significant improvement via cooling, similar to the proton production scenario, and, in addition, calls for a nontrivial beam stacking scheme before collision (described in Ref. 18). Details of this scenario have been considered by Barletta and Sessler (13,18). In Fig. 8, we depict schematically the scenario of a muon collider based on electro-production (18).

Table 5 presents a comparison of parameters for the above two scenarios for a 100 GeV $\mu^+ \otimes$ 100 GeV μ^- collider, with an average luminosity of 10^{30} $cm^{-2}s^{-1}$. We assume a collider scenario with a low beta at the collision point of 1 cm, about 1000 bunches colliding in the ring and muon production limited by a 5 MW power at the target. It is clear that while powerful pion sources, bunch compression and cooling are essential for the proton-production scenario, high current electron linacs, cooling and stacking are essential for the electro-production scenario. It is fair to say from an inspection of Table I that, fundamentally, both scenarios are equally amenable to a muon collider configuration with comparable luminosities, given the fact that in both cases equally difficult and challenging technological problems will have to be addressed and solved.

The most difficult and challenging of these technological problems is probably that of 'ultra-rapid' phase space cooling of 'intense' bunches. One can consider radiation cooling via synchrotron radiation, which is independent of the bunch intensity. However, it is too slow for our purposes. The stochastic cooling rate, on the other hand, depends on the number of particles per bunch and, although too slow usually, can be made significantly faster by going to an extreme scenario of a few particles per bunch with ultra-fast phase mixing or an ultra-high bandwidth (~10^{14} Hz) cooling feedback loop. Both the latter cases will require significant technological inventions. A promising scheme that is both 'fast' and 'intensity-independent' is that of 'Ionization Cooling' (16,17), which looks feasible in principle. We have assumed Ionization Cooling in arriving at the parameters of Table 5. We discuss cooling considerations briefly in the next section.

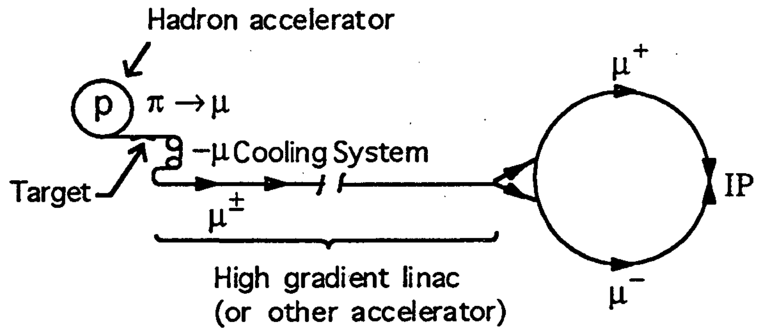


FIGURE 7. Overview of a μ^+-μ^- collider, showing a hadronic accelerator, which produces p's on a target, followed by a μ-decay channel (p → mv) and μ-cooling system, followed by a μ-accelerating linac (or recirculating linac or rapid-cycling synchrotron), feeding into a high-energy storage ring for μ^+-μ^- collisions (from Ref. 16).

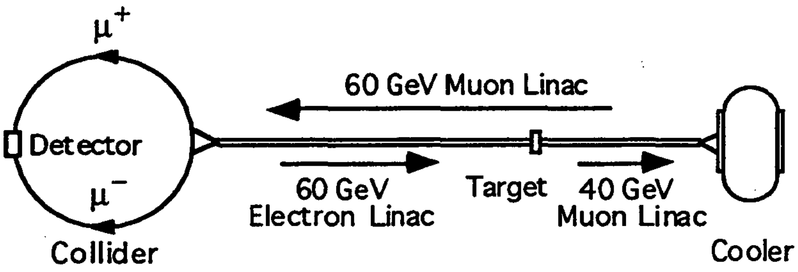


FIGURE 8. A muon collider scenario with electro-production of muons (from Ref. 18).

TABLE 5. Parameters for a Muon Collider

100 GeV ⊗ 100 GeV

$$L = M \frac{N_+ N_- f}{4\pi \varepsilon_N \beta^*} \gamma \sim 10^{30} cm^{-2} s^{-1}$$

M = 1,000; γ = 1,000; β^* = 1 cm; P = 5 MW @ target

	Production via Electrons	Production via Protons
$E_{e\ or\ p}$ (GeV)	60	30
Intensity	5×10^{11}/pulse	10^{14}/pulse
# pulses	100 (stacked later)	1
Rep. Rate	10 Hz	10 Hz
E_μ (GeV)	40	1.5
ε_N (π m-rad)	2×10^{-3}	2×10^{-2}
$\Delta p/p$	± 3%	± 3%
(μ/e) <u>or</u> (μ/p)	4×10^{-3}	10^{-3}
Ionization Cooling	$\varepsilon_n^f = 2 \times 10^{-5} \pi$ m–rad	$\varepsilon_n^f = 2 \times 10^{-5} \pi$ m–rad
Bunch Rotation Factor	None	100

3.3 Cooling of Muons

The cooling of the transverse phase-space assumed in Table 5 is of the kind known as "Ionization Cooling." In this scheme the beam transverse and longitudinal energy losses in passing through a material medium are followed by coherent reacceleration, resulting in beam phase-space cooling (13,16,19). The cooling rate achievable is much faster than, although similar conceptually to, radiation damping in a storage ring in which energy losses in synchrotron radiation followed by rf acceleration result in beam phase-space cooling in all dimensions. Ionization Cooling is described in great detail in Ref. 13, 16 and 17. It seems that the time is ripe to make a serious design of an Ionization Cooling channel, including the associated magnetic optics and rf aspects, and put it to real test at some laboratory.

Exploration of the alternate cooling scheme of stochastic cooling takes us to a totally different regime of operation of the collider, determined by the very different nature and mechanism of cooling by an electronic feedback system. Here, the muon lifetime and the required low emittance demanded by the luminosity requirements determine the necessary stochastic cooling rate of the phase space. This rate scales directly as the bandwidth (W) of the feedback system and inversely as the number of particles (N) in the beam (stochastic cooling rate $\propto$ W/N). If we limit our consideration to practically achievable conventional feedback electronics, amplifiers, etc., with bandwidth not exceeding 10 GHz, the number of particles per bunch must be less than a thousand (1,000) in order to meet the desired rate. This then would imply a very different pulse format. This alone drives all the parameters back to the source and issues of "targetry" and "muon source", etc., are not critical. The critical issues for stochastic cooling are: (1) large bandwidth, (2) ultra-low noise, as the cooled emittance reaches the thermal limit of the electronics, (3) rapid mixing and (4) bunch recombination techniques.

Critical issues in the stochastic cooling scenario are discussed by Ruggiero (13,20), where he also explores a conventional cooling scheme with modest bandwidth but with a special nonlinear (magnetic) device that stirs up the phase space rapidly and provides "ultra-fast mixing". It is clear that we need new technical inventions in stochastic cooling for application in a muon collider. Another novel scheme (21,22) being explored currently is that of 'optical cooling' where one detects the granularity of phase space down to a micron scale by carefully monitoring the incoherent radiation from the beam, which is a measure of its Schottky noise, then amplifying this radiation via a laser amplifier of high gain and bandwidth (10^7, 100 THz) and applying it back to the beam. Various issues regarding quantum noise and effective pickup and kicker mechanisms will have to be understood before it can be considered for a serious design.

3.4 Outlook on Muon Collider

As we have seen, both scenarios — production of muons from protons and electro-production of muons — are competitive but very ambitious and challenging. Production of muons from protons will clearly require nontrivial and sophisticated target design and configuration. In addition, in order to match the bunch length of the colliding (but secondarily produced) muon beams to the low beta function at the collision point, the primary proton beams must be bunched by a large factor (~ 100). The complicated bunch rotation and rf manipulations are cumbersome and must be done at the low energy proton end before the target, which implies an associated increase in the relative momentum spread, ($\Delta p/p$). On a positive note, however, targetry with protons and rf gymnastics with proton beams are relatively familiar affairs at hadron and kaon facilities, albeit at a lower level of power and rf manipulation of the bunches. Electro-production of muons, on the other hand, requires, high peak current, high repetition rate linacs, so far unexplored, in order to meet the luminosity demand. Besides, "stacking" of many electron bunches from a linac into a single bunch poses a nontrivial problem. The significant and most attractive feature of the electro-production scenario, however, is that the 'optimal pulse format' is produced directly at the target by electrons from a linac, without complex bunch compression schemes in a ring.

No matter what the optimal scenario would turn out to be, should the muon collider concept turn into reality, further consideration of such a collider at 200 GeV center-of-mass energy with an average luminosity of ~ 10^{30} $cm^{-2}s^{-1}$ would have to assume major advances in, and eventual operation of, (1) megawatt muon targets, (2) multi-kiloampere peak current electron linacs, (3) efficient transfer, compression and stacking schemes for charged particle beams, (4) high field magnets and (5) most importantly, feasible phase-space cooling technologies with low noise and large bandwidth. While 'Ionization Cooling' looks promising, it needs experimental demonstration. A possible feasibility test of muon production and ionization cooling at existing facilities, e.g., CERN or FNAL, would be highly desirable. The 'Stochastic Cooling' approach, however, would need fundamental invention of a new technique, as elaborated earlier. The emerging new ideas of 'Optical Stochastic Cooling', 'Ultra-rapid Phase-Mixer', etc., are ambitious, but may hold the key to the success of such high frequency stochastic cooling. Plans are already underway (23) at the Center for Beam Physics at LBL to launch R&D, feasibility and proof-of-principle experimental tests of optical stochastic cooling. Finally, the synchrotron radiation and muon decay in the collider ring vacuum chamber and detector area pose issues that cannot be overlooked.

4.0 CONCLUSION

There is no question that the Gamma-Gamma Collider and the Muon Collider are quite unconventional. But as we weigh the value, utility and eventual realizability of such colliders in the future, the necessary conceptual and technological explorations forced upon us by these considerations are extremely valuable, going beyond the narrow domain of high energy physics. Development of high power and high repetition rate lasers has application in compact high gradient acceleration schemes, fusion, etc. Development of ultrafast cooling schemes will surely be useful in the production of short pulses of particles and radiation, valuable for research in ultrafast processes. Taken together, all these sum up to exciting opportunities in advanced studies, research, experimental tools and facilities.

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