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Summary of the Physics Opportunities Working Group*

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ABSTRACT

The Physics Opportunities Working Group was convened with the rather general mandate to explore physics opportunities that may arise as new accelerator technologies and facilities come into play. Five topics were considered during the workshop: QED at critical field strength, novel positron sources, crystal accelerators, suppression of beamstrahlung, and muon colliders. Of particular interest was the sense that a high energy muon collider might be technically feasible and certainly deserves serious study.

INTRODUCTION

A Working Group was convened with the rather general mandate to explore physics opportunities that may arise as new accelerator technologies and facilities come into play. The agenda was set by the interests of the participants,[1] many of whom were inspired to give extemporaneous presentations of ideas they had not expected to discuss, but which ideas had been quietly nurtured awaiting a forum such as this Working Group. The working group considered five topics:

1. QED at critical field strength.
2. Novel positron sources.
3. Crystal accelerators.
4. Suppression of beamstrahlung.
5. Muon colliders.

In the following we attempt to give a flavor of the discussion on each of these topics.

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QED AT CRITICAL FIELD STRENGTH

K. McDonald reviewed how the combination of low-emittance high-energy electron beams with tabletop teraWatt lasers offers the opportunity to explore QED beyond the critical field strength,

$$E_{\rm crit} = \frac{m^2c^3}{e\hbar} \approx 10^{16}\ {\rm V/cm}, \tag{1}$$

at which the vacuum is unstable against pair creation.[2] A speculative possibility is that a QED phase change occurs that could lead to structure in the e^+e^- mass spectrum related to the positron peaks reported in heavy-ion collisions at Darmstadt.

A. Varfolomeev recalled that teraWatt lasers could lead to a demonstration of light-by-light scattering using the technique of four-wave mixing. A note discussing this further appears in these proceedings.[3]

A major theme of the Working Group was the production of high-quality, high-energy lepton-lepton collisions in future accelerators. It is anticipated that it will be difficult to maintain a well-defined center-of-mass energy in e^+e^- collision once the electromagnetic fields of a bunch exceed the QED critical field as observed from the oncoming bunch. The resulting radiation is generally called beamstrahlung.

P. Chen reviewed three aspects of beamstrahlung that will limit the performance of future e^+e^- colliders. First, the bunches on the average radiate a substantial fraction of their energy once the so-called beamstrahlung parameter

$$\Upsilon = \frac{2\gamma E_{\rm bunch}}{E_{\rm crit}} \sim 1. \tag{2}$$

Nevertheless, a good fraction of the bunch particles remain at the initial energy, thanks to the quantum nature of the radiation. For example, with $E_{\rm cm} = 500$ GeV and $\Upsilon = 0.12$ some 70% of the e^+e^- collisions still have more than 98% of the nominal center-of-mass energy, although the average energy loss per beam particle is 10%.[4] However, running with Υ much higher than this value would result in a spread of center-of-mass energies rather like that for quark-quark and gluon-gluon scattering at a hadron collider.

Second, once $\Upsilon \gtrsim 1$ there is copious production of e^+e^- pair by a two-stage process, as discussed earlier.[5] The rates are an extremely rapid function of Υ so the pair creation is negligible for $\Upsilon < 0.2$. Third, the light-by-light scattering processes that lead to e^+e^- pair creation also lead to gluon-gluon and quark-antiquark pair creation. The most annoying feature of this is radiation of soft-gluon jets ('minijets') which spew low-P_t hadrons into the collision region.[6] While only a few percent of the collisions lead to minijets for $\Upsilon \approx 1$, the number of low-P_t particles in such events is large. Any detector must be effectively blind to these particles, which may compromise the capability for low-P_t physics which has been such a rich source in present e^+e^- machines.

NOVEL POSITRON SOURCES

The copious production of positrons at critical field strength might be an excellent source of positrons for future linear colliders in a proposal by P. Chen and R. Palmer.[7] In e-laser collisions the QED strong-field processes become prominent once parameter $\Upsilon \gtrsim 1$ where

$$\Upsilon = \frac{E^\star}{E_{\text{crit}}} = \frac{2\gamma E_{\text{laser}}}{E_{\text{crit}}} \tag{3}$$

($E^\star$ is the laser field strength in the electron's rest frame). Pair creation occurs in a two-step process: laser photons collide with high-energy electrons to produce high-energy backscattered photons; then the high-energy photons collide with laser photons to produce e^+e^- pairs.

For $\Upsilon > 1$ the interaction probability approaches unity, and the created positrons and electrons reinteract with the laser to produce an electromagnetic cascade. There are two important aspects in such an approach: First, there exists a threshold at $\Upsilon \sim 1$ in the coherent pair creation process. This helps to accumulate positrons at a low, but finite, energy with a small energy bite. Second, a remarkable fact is that the angular distribution of the positrons closely follows that of the incident electrons, *i.e.*, geometric emittance is preserved. But since the positrons have much lower energy, their invariant emittance is lower than that of the electrons. That is, 'cooling' automatically occurs!

If an optical laser is to be used, the initial electron energy is optimized at 250 GeV. To use 50-GeV electrons, the laser should have $\approx$ 40-nm wavelength. This is strong motivation for a far-UV free-electron-laser program at SLAC.

P. Channell and D. Cline presented two variations on schemes for production of low-energy positrons in p-nucleus interactions. The mechanism is that the proton is absorbed by the nucleus,

$$p + (Z, N) \rightarrow (Z + 1, N) + \gamma, \tag{4}$$

which then decays via positron emission:

$$(Z + 1, N) \rightarrow (Z, N + 1) + e^+. \tag{5}$$

For 5-MeV protons the capture cross sections are of order 300 mb, and the beta-decay times of order 10-100 sec. The positrons emerge with a few-MeV energy.

For high production rates the target must be dense, but for efficient positron extraction the $(Z+1, N)$ nuclei should be in a diffuse medium. Hence the $(Z+1, N)$ nuclei must be separated from the (Z, N) nuclei via chemical or isotope separation. The $(Z + 1, N)$ nuclei could then be stored in a magnetic bottle until they decay.

Small-scale versions of such a scheme are presently implemented as sources for positron emission tomography. Significant R&D is required to achieve production rates of 10^{14}/sec as desired for high-energy physics.

CRYSTAL ACCELERATORS

W. Gabella reviewed suggestions for plasma accelerators in crystals.[8] Here the plasma consists of the conduction electrons of the crystal. In one scheme a acoustic standing wave established by a transducer induces a spatial periodicity to the electron density. Then a pump laser whose wavelength is the same as that of the acoustic wave excites electrons into a plasma oscillation.[9] The crystal must be largely transparent to the laser, so the plasma frequency of the crystal electrons must be less than the laser frequency. A (properly phased) charged-particle beam passing through the crystal can then extract energy from the plasma oscillations.

The use of a crystal is of interest because of channeling, which works best for positively charged particles. In principle very good emittance preservation can be maintained during acceleration.

It appeared that a demonstration of this technique might be possible at the BNL Accelerator Test Facility with 50-MeV electrons and the 10.6-μm CO_2 laser. While negatively charged particles suffer Coulomb collisions after some distance in a crystal, acceleration over a short distance should be feasible. The channeling capture angle was calculated to be 1 mrad at 50 MeV, which is well matched to the emittance of the ATF electron beam. The frequency of the CO_2 laser is $\omega \sim 2 \times 10^{14}$ Hz, so the electron density in the crystal must be $\sim 10^{19}/\text{cm}^3$ ($\Rightarrow$ arsenic??). The frequency of the acoustic wave would be about 300 MHz. For a laser intensity near the damage limit, $\sim 10^{13}$ Watts/cm^2 the accelerating gradient would be a few MeV/cm.

Another scheme was presented by S. Bogacz[11] in which a crystal has a periodic strain to form a kind of undulator. Such a crystal could be then used in FEL and inverse FEL configurations, but with characteristic wavelengths much shorter than by other means.

BEAMSTRAHLUNG SUPPRESSION

In this context any additional mechanisms that could suppress the beamstrahlung would be most welcome. A. Sessler reviewed a proposal for beamstrahlung suppression using a plasma at the interaction point.[12] According to Lenz' law we expect charge separation and return currents to be induced in the plasma so as to cancel the **E** and **B** fields of the colliding bunches. For good cancellation the bunch radius must be much smaller than the plasma wavelength, which leads to the condition that the plasma charge density must be much larger than that in the e^+e^- bunches. For example, at a Next Linear Collider operating at 500 GeV with bunches of 10^{10} particles each 1 mm long and 100 nm in radius, the electron density is of order $10^{21}/\text{cm}^3$. Hence plasma density of order $10^{22}/\text{cm}^3$ are needed. This is a high number, but perhaps achievable. If so, calculation suggests that 90% of the beamstrahlung could be suppressed.

W. Barletta reviewed the possibility of generating such plasma densities by laser excitation.

However, as the energy of the e^+e^- collider rises, the luminosity must increase as s to maintain constant event rates, so the bunch size is likely to shrink. This would require ever higher plasma densities for beamstrahlung suppression, and the scheme becomes difficult for energies of a few TeV or more. In addition, the use of high density plasmas at the interaction point would introduce its own kind of backgrounds such as high energy photons from bremsstrahlung.

J. Rosenzweig reviewed the issue of instabilities in plasma compensation schemes and compared these to alternatives based on 4-beam collisions (two pairs of comoving e^+e^- bunches).[13] The conclusion is that plasma compensation is more stable against dipole (kink) and quadrupole instabilities than 4-beam schemes. The stability of the latter can be improved by tailoring the longitudinal charge-density profile of the bunches.

P. Channell presented a rather speculative "e^+e^- plasma" compensation scheme in which plasma densities exceeding $10^{24}/\mathrm{cm}^3$ might be obtained by beamstrahlung e^+e^- pairs from auxiliary accelerators.

P. Chen reviewed the Landau-Pomeranchuk-Migdal mechanism and other LPM-like effects for suppression of radiation effects in beams. He noted that while the LPM effect is not sufficient in suppressing these raidations, the strong EM field of the opposing beam does help to suppress bremsstrahlung.[14]

It appears that beamstrahlung remains a fundamental limit to performance of e^+e^- colliders in the multi-TeV regime.

MUON COLLIDERS

The limiting effect of beamstrahlung on future colliders makes it timely to reconsider the merits of muon colliders.[15,16] From the definition (2) of the beamstrahlung parameter we see that for muons beams of the same energy and bunch parameters as electrons, Υ will be only 1/205 that for electrons. Without the disruptive effects of beamstrahlung, a muon collider would enjoy all the advantages of a well-defined purely leptonic initial states that has made experimentation at electron colliders crisper than that a hadron colliders.

D. Cline, and also D. Neuffer[16] reviewed the physics potential of muon colliders at the Higgs energy scale, 200 Gev-1 Tev. While production cross sections for quarks, leptons and vector gauge bosons are the same for electron and muon beams, a muon collider has a major advantage over either electrons or hadrons for production of Higgs bosons. Since the latter couple to the mass of the spin-1/2 beam particles, production of Higgs by muons is $(m_\mu/m_e)^2 = 4 \times 10^4$ larger than by electrons. Luminosities of only 10^{30} cm^{-2}sec^{-1} would make a muon collider very competitive for Higgs production.

R. Noble reviewed the prospects for high flux muons sources based on proton accelerators in the 50-200 GeV range.[17] A rapid-cycling proton accelerator, such as that considered for the TRIUMF II upgrade, could provide 10^{15} protons/sec. This would yield some 10^{13} pions/sec into a 1% momentum bite. As the pions decay some 10^{12} muons/sec could be collected into an normalized emittance of $\epsilon_N \approx 10^{-3}$ m-rad. These muons have a total momentum spread of about 40%, so if the muon-momentum spread is limited to 1%, the yield would be 2.5×10^{10} muons/sec, *etc.*

Various participants debated the option of muon production by stopping pions, with the conclusion that further studies are needed. In particular, there are substantial differences between positive- and negative-muon production from stopping pions.

Once a source exists, the muons must be accelerated, cooled, and brought into collision before they decay. Of course, the muons live longer at higher energy according to $\tau = \gamma \times 2.2 \times 10^{-6}$ sec. A useful result is that the lifetime of muons moving in circles under the influence of a fixed magnetic field is independent of the muon energy. In particular, the lifetimes is conveniently expressed in the number of complete revolutions, or 'turns' as

$$\text{muon lifetime in turns} = 300B[\text{Telsa}]. \tag{6}$$

For example, if 3.3-Tesla magnets are used throughout the accelerator, the muon lifetime is 1000 turns.

D. Neuffer[16] and A. Ruggerio[18] reviewed the luminosity requirements for a muon collider, using 1 TeV × 1 Tev as an example:

$$\mathcal{L} = \frac{N^+ N^- f}{4\pi \beta^\star \epsilon} \approx 10^{30}\ \text{cm}^{-2}\text{s}^{-1}, \tag{7}$$

where N is the number of muons per bunch, f is the bunch-collision frequency, $\beta^\star *$ is the focusing strength, and $\epsilon = \epsilon_N/\gamma$ is the geometric emittance. At 1 TeV the muons have $\gamma = 10^4$, so their lifetime is 20 ms. This suggests the source should cycle at about $\approx$ 50 Hz. The collision region might be either single pass, or multiple pass in a storage ring.

Muon accelerators that include a storage ring to take advantage of the potential 1000 turns of muon lifetime must face a new technical challenge. As the muons decay roughly 1/3 of their energy is dumped into material close to the ring in the form of electromagnetic showers. For example, with 10^{11} 1-TeV muons/sec in the ring, some 10^4 Watts must be dissipated. For a ring of 1000 superconducting magnets, this is 10 Watts per magnet deposited in a localized region of the coil unless precautions are taken.

Possible parameters for a muon accelerator are then:

Single pass: $f = 50$ Hz; $\beta^\star = 5\ \mu$m.

Multiple pass: $f = 50 \times 1000$ turns $= 4 \times 10^4$; $\beta^\star = 5$ mm.

$N^+ = N^- = 10^9$ per cycle.

which leads to a requirement that the geometric emittance be 10^{-10} m-rad, and the normalized emittance be $\epsilon_N = 10^{-6}$ m-rad. This is three orders of magnitude smaller than that expected out of the muon source, so cooling is required, which must be accomplished in approximately 1 msec.

Two possible schemes for muon cooling were presented. D. Neuffer[16] reviewed the method of 'ionization cooling' in which muons pass through an absorber and lose both transverse and longitudinal momentum to ionization, followed by accelerating sections in which the longitudinal momentum only is restored.

A. Ruggerio presented a new scheme based on stochastic cooling, conceived during the Workshop.[18] In this the muon beam is bunched into perhaps 10^9 bunches of 100 particles each. These bunches are transmitted through a series of (≈ 10) arcs separated by accelerating sections. In the arcs stochastic cooling is to be accomplished with very high frequency pickups and kickers. The luminosity is achieved in single pass collisions of each bunch. The invariant emittance of each bunch must be very small ($\lesssim 10^{-16}$ m-rad) in this scheme.

While the ionization-cooling scheme is relatively conservative, the stochastic-cooling scheme provoked lively discussions that continue after the Workshop. There remained very considerable enthusiasm to understand the feasibility of muon accelerators in greater detail, which led to the formation of a new Workshop for that purpose.[19]

HIGHLIGHTS

The major themes developed in each of the five topics explored by the Working Group were:

1. A proposed demonstration of induced light-by-light scattering with a three-beam configuration of a tabletop teraWatt laser.
2. A proposed low-emittance high-yield positron source at SLAC via pair creation by light from a 50-nm free electron laser.
3. A proposed demonstration of a crystal accelerator at the BNL Accelerator Test Facility.
4. Reaffirmation that beamstrahlung is a severe limit to the performance of e^+e^- colliders for $E_{\mathrm{cm}} \gtrsim 1$ TeV.
5. A muon collider based on an aggressive cooling scheme that might provide the cleanest high-luminosity source for future high-energy physics.

REFERENCES

1. B. Barletta, A. Bogacz, P. Channell, P. Chen, D. Cline, P. Debenham, B. Gabella, A. Jackson, G. Jackson, K. Kim, N. Kurnit, A. Lebedev, K. McDonald, F. Mills, D. Neuffer, R. Noble, R. Palmer, I. Pogorelsky, J. Rosenzweig, A. Ruggerio, A. Sessler, G. Shuets, J. Simpson, D. Sutter, A. Varfolomeev, X. Wang, J. Wurtele.
2. K.T. McDonald *et al.*, *Study of QED at Critical Field Strength*, in *Workshop on beam-Beam and Beam-Radiation Interactions: High Intensity and Nonlinear Effects*, ed. by C. Pelligrini, T. Katsouleas and J. Rosenzweig (World Scientific, Singapore, 1992) p. 127.
3. K.T. McDonald, *Induced Scattering of Light by Light*, these Proceedings.
4. P. Chen, *Differential Luminosity under Multiphoton Beamstrahlung*, *Phys. Rev.* **D46** (1992) 1186.
5. P. Chen and V.L. Telnov, *Coherent Pair Creation in Linear Colliders*, *Phys. Rev. Lett.* **63** (1989) 1796.
6. M. Drees and R. M. Godbole, *Minijets and Large Hadronic Backgrounds at* e^+e^- *Supercolliders*, *Phys. Rev. Lett.* **67** (1991) 1189; J. R. Forshaw and J. K. Storrow, *The Minijet contribution to the Total* e^+e^- *Cross Section*, *Phys. Lett.* **B278** (1992) 193; P. Chen, T. Barklow and M.E. Peskin, *Hadronic Production in* $\gamma\gamma$ *Collisions as a Background for* e^+e^- *Linear Colliders*, SLAC-PUB/5873 (1992); submitted to *Phys. Rev.* **D**.
7. P. Chen and R. B. Palmer, *Coherent Pair Creation as a Positron Source for Linear Colliders*, these Proceedings.
8. P. Chen and R. J. Noble, *Channeled Particle Acceleration by Plasma Waves in Metals*, NATO ASI Series **B165** (1987) 517.
9. T. Katsouleas *et al.*, *A Side-Injected Plasma Accelerator*, *IEEE Trans. Nucl. Sci.* **NS-32** (1985) 3554.
10. P. Chen, D. B. Cline, and W. E. Gabella, *Issues Regarding Acceleration in Crystals*, these proceedings.
11. S. A. Bogacz, *Inverse FEL Proton Accelerator via Periodically Modulated Crystal Structure*, these Proceedings.
12. D.H. Whittum *et al.*, *Plasma Suppression of Beamstrahlung*, *Part. Accel.* **34** (1990) 89.
13. J.B. Rosenzweig, B. Autin and P. Chen, *Instability of Compensated Beam-Beam Collisions*, AIP Conf. Proc. **193** (1989) 324.
14. P. Chen and S. Klein, *The Landau-Pomeranchuk-Migdal Effect and Suppression of Beamstrahlung and Bremsstrahlung in Linear Colliders*, these Proceedings.
15. A. N. Skrinsky, *Accelerator and Instrumentation Prospects of Elementary Particle Physics*, *AIP Conf. Proc.* **68** (1980) 1056.

16. D. Neuffer, *Principles and Applications of Muon Cooling*, *Part. Accel.* **14** (1983) 75; *Multi-TeV Muon Colliders*, *AIP Conf. Proc.* **156** (1987) 201.

17. R.J. Noble, *Particle Production and Survival in Muon Acceleration*, these Proceedings.

18. A.G. Ruggerio, *The Muon Collider*, these Proceedings.

19. Worshop on *Muon Colliders: Particle Physics and Design* (Napa Valley, Dec. 9-11, 1992).