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Advances in Beam Physics and Technology: Colliders of the Future

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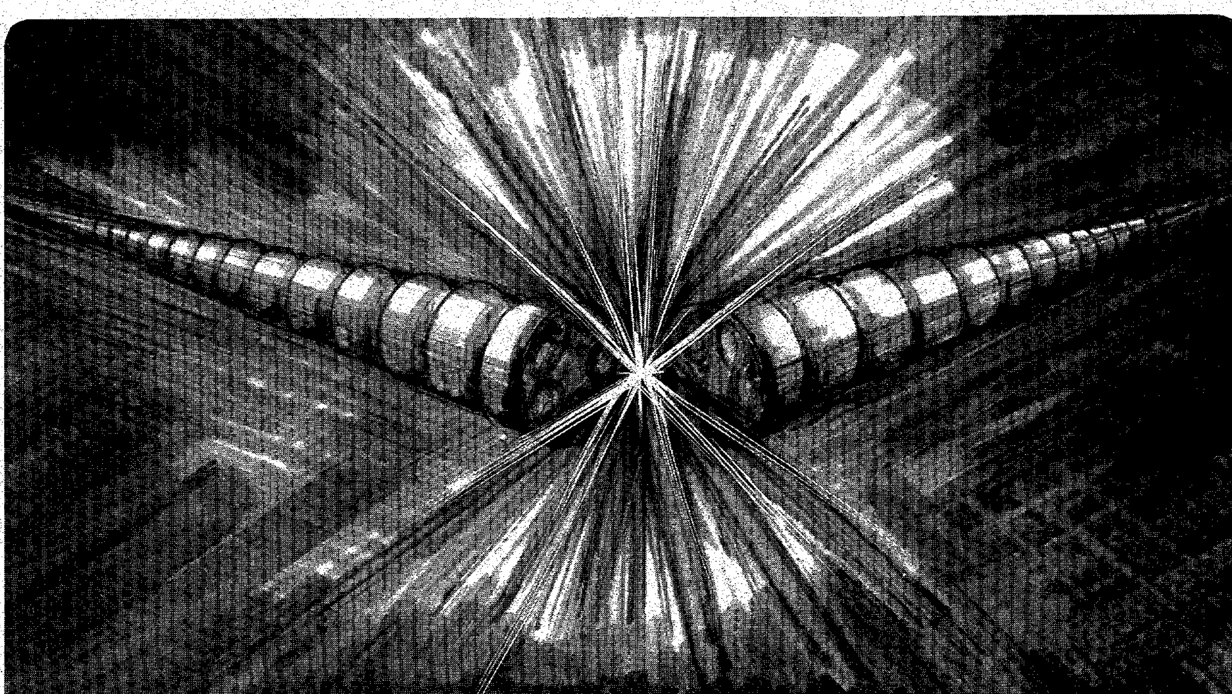
November 1994



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Advances in Beam Physics and Technology: Colliders of the Future

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" Here I would like to make an analogy. There are three kinds of physicists, as we know, namely the machine builders, the experimental physicists, and the theoretical physicists. If we compare those three classes, we find that the machine builders are the most important ones, because if they were not there, we would not get into this small-scale region. If we compare this with the discovery of America, then, I would say, the machine builders correspond to captains and ship builders who really developed the techniques at that time. The experimentalists were those fellows on the ships that sailed to the other side of the world and jumped upon the new islands and just wrote down what they saw. The theoretical physicists are those fellows who stayed back in Madrid and told Columbus that he was going to land in India."

Victor F. Weisskopf in
The development of the concept of an elementary particle.

ADVANCES IN BEAM PHYSICS AND TECHNOLOGY: COLLIDERS OF THE FUTURE

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Abstract - Beams may be viewed as directed and focussed flow of energy and information, carried by particles and electromagnetic radiation fields (i. e. photons). Often, they are brought into interaction with each other (e.g. in high energy colliders) or with other forms of matter (e.g. in fixed target physics, synchrotron radiation sciences, neutron scattering experiments, laser chemistry and physics, medical therapy, etc.). The whole art and science of beams revolve around the fundamental quest for, and ultimate implementation of, mechanisms of production, storage, control and observation of beams — always directed towards studies of the basic structures and processes of the natural world and various practical applications. Tremendous progress has been made in all aspects of beam physics and technology in the last decades — nonlinear dynamics, superconducting magnets and radio frequency cavities, beam instrumentation and control, novel concepts and collider paradigms, to name a few. We will illustrate this progress via a few examples and remark on the emergence of new collider scenarios where some of these progress might come to use — the Gamma-Gamma Collider, the Muon Collider, laser acceleration, etc. We will close with an outline of future opportunities and outlook.

1. Introduction

The two major frontiers of high energy accelerator research and development today are: the 'energy' frontier and the 'luminosity' frontier. The energy frontier is presented in the form of today's multiple TeV-scale high energy hadron colliders (either in operation — as the 2 TeV center-of-mass Tevatron at FNAL, or under construction — as the 15 TeV center-of-mass Large Hadron Collider at CERN, or under conceptual development — as the 100 TeV center-of-mass Eloisatron) and electron-positron colliders (either in operation — as today's Stanford Linear Collider at SLAC or LEP at CERN, or future TeV - scale electron-positron colliders envisioned around the world today). The primary thrust of research and technology development in this frontier is on many aspects — high field superconducting magnets (to assure confinement of high energy heavy hadrons in reasonable albeit large circular orbits), complicated nonlinear particle dynamics and phase-space acceptance of the confining storage rings (to minimize the transverse aperture requirements of the rings in order to reduce cost and still assure particle stability over many turns and hours of luminosity lifetime), various sources of spatial and temporal perturbations over large distances and long time-scales such as ground motion and noise, more efficient radio-frequency power sources, mechanisms of generating higher electric fields over shorter distances, control and stability of nanometer focal spots in ultrafine collisions and fundamentals of the physics of acceleration. As the collider energy goes up, so does the required luminosity: this demands more detailed and innovative solutions to the high current collective phenomena such as coherent instabilities involving multiple bunches, beam feedback systems, incoherent and coherent effects of one beam on the other, radio-frequency systems with special spectral purity properties and highly constrained interaction regions. In addition to applications to the highest energy colliders, the luminosity frontier is particularly relevant today to the relatively lower energy but ultra-high luminosity Meson Factories for studies of rare and exotic phenomena such as the CP violation in B-factories. We should also note the potential of the luminosity upgraded Tevatron — the TeV* — in the FNAL for studies of the 'top' quark and low mass 'Higgs' phenomena, etc. The typical configurations of high energy colliders, as we know them today, are sketched in Figs. 1 and 2 for the circular and linear versions respectively. The critical components and systems requiring special physics, engineering and technological solutions are outlined in the figures as well.

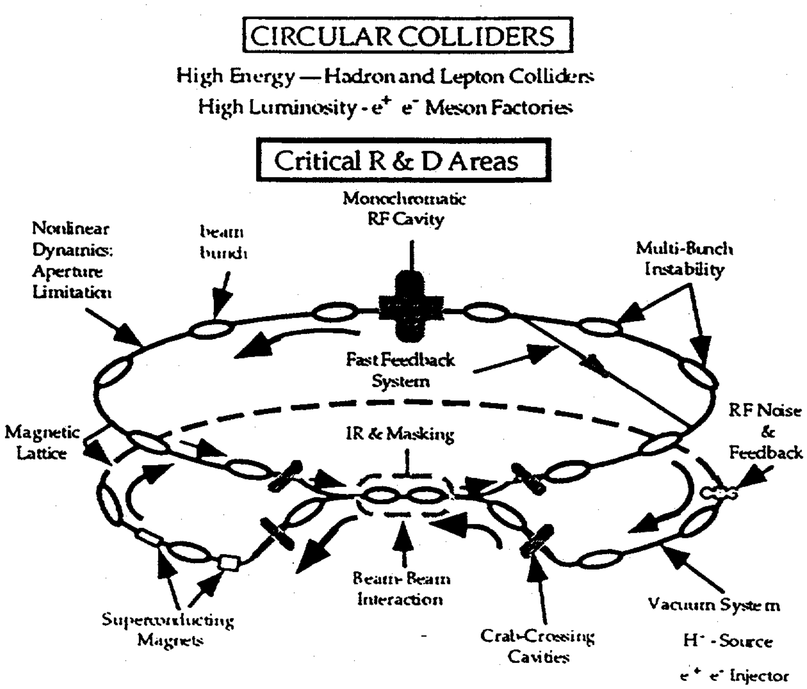


Figure 1 - Generic configuration and critical areas of circular colliders.

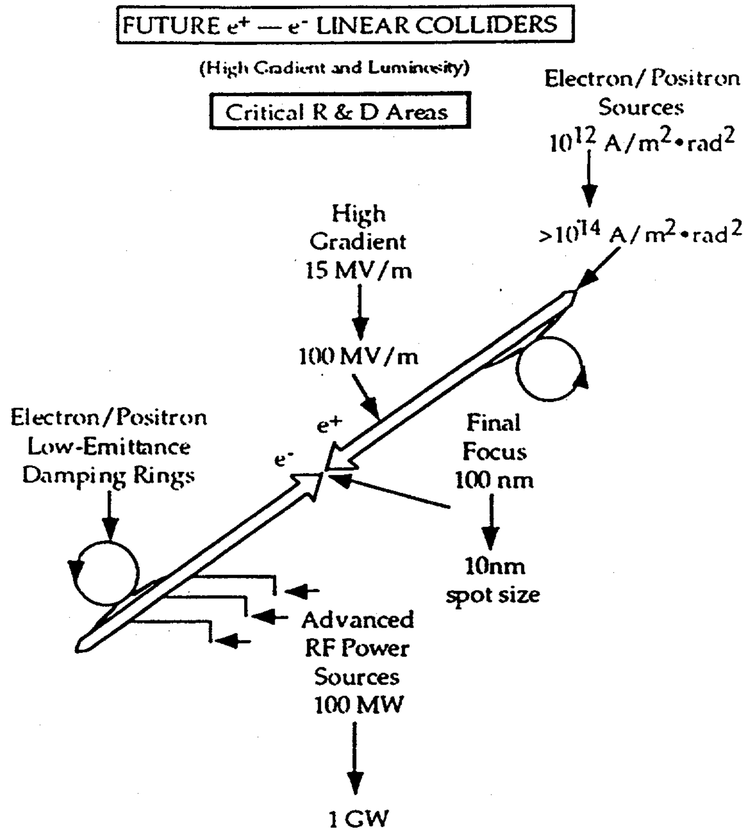


Figure 2- Generic configuration and critial areas of linear colliders.

As we appreciate the complexity in design, construction and operation of these colliders, it is particularly reassuring and important today — in view of the current general depression in the field — to recount and remind ourselves of some of the most outstanding and notable achievements in the field so far.

2. Achievements

A few critical areas have progressed significantly in the last few decades, thanks to the advent of various high energy colliders: high field superconducting magnets, nonlinear partcle dynamics, radio-frequency power and cavity technology, superconducting RF technology, beam monitoring and control, development of new collider paradigms such as the asymmetric energy colliders etc. are a few examples. Let us review a few notable ones briefly.

2.1 Superconducting Magnets

The possibility of high energy hadron colliders, such as the Large Hadron Collider (LHC) and the now-terminated SSC would be non-existent today without tremendous progress in the capability of designing and fabricating high-field superconducting magnets. It all started with the superconducting magnets that made the Fermilab Energy Doubler possible in the early '80's. However, I would like to stress that today we have actually gone far beyond even the LHC and SSC-type magnets. Today, we can boast of not only the design but existence of prototype superconducting magnets exceeding a field of 10 Tesla (the D19 magnet at LBNL and the Nb-Ti model at CERN)[1]. In addition, a prototype magnet of an advanced Nb_3Sn design, called the D20, with a promise of a 13 Tesla field is already designed and under construction at LBNL[2].

The training curve for the LBNL D19 magnet is shown in Fig. 3 which depicts the new world record field for an accelerator magnet, just over 10 Tesla (10.06 Tesla for the D19). Advanced magnets of this type are made of ductile cable materials such as NbTi or NbTaTi and pretty much reach a limit around 10 Tesla field.

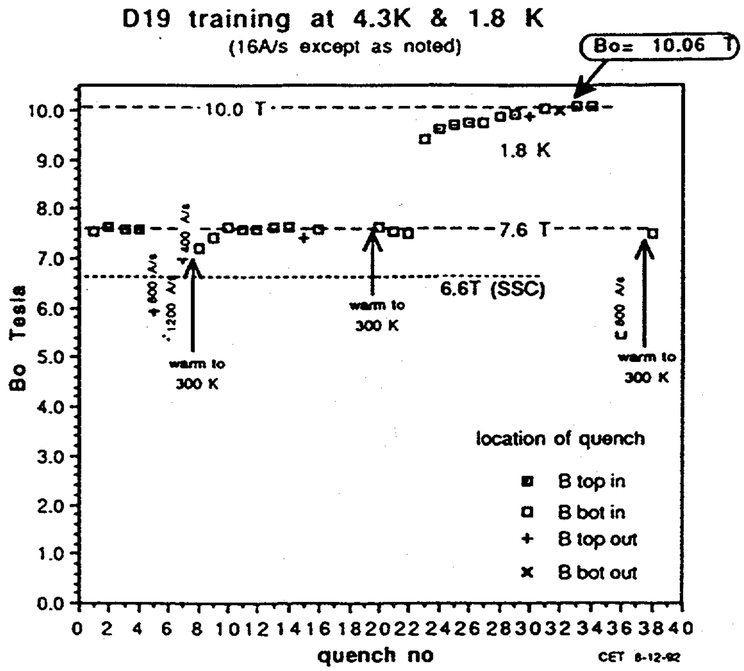


Figure 3- The training curve of the LBNL D19 Magnet.

The challenges are efficient magnet designs, achieving higher critical currents, higher fields and lower conductor costs by improved cable designs, Artificial Pinning Center (APC) techniques, etc. — and all that using "commercial" materials. For fields higher than 10 Tesla, one has very little choice but to consider brittle materials such as Nb_3Sn or other high T_c materials. The challenges there are to have improved cable and mechanical structure designs (to be able to withstand the stress) in order to have higher critical currents and fields. The overall cross-section and detail of coil configuration for the LBNL D20 Nb_3Sn dipole (50 mm bore), designed to achieve 13 Tesla and under construction at present is shown in Fig. 4. A sophisticated ANSYS computation output showing the mechanical stress on such a structure (reaching upto 130 Mega Pascals) at a field of 13 Tesla is shown in Fig. 5. It is worth noting that one can imagine such a magnet as almost enabling the doubling of the energy of the SSC, had it been built, to an energy of 40 TeV X 40 TeV proton on proton — not an insignificant feat!

2.2 Nonlinear Dynamics in Colliders

Pioneering work in nonlinear dynamics in circular storage ring systems as well as linear spectroscopic and Final Focus transport systems have been advanced thanks to the dedicated and persistent efforts of a few key individuals in the field. These have led to radical perspectives and advances in beam dynamics of which

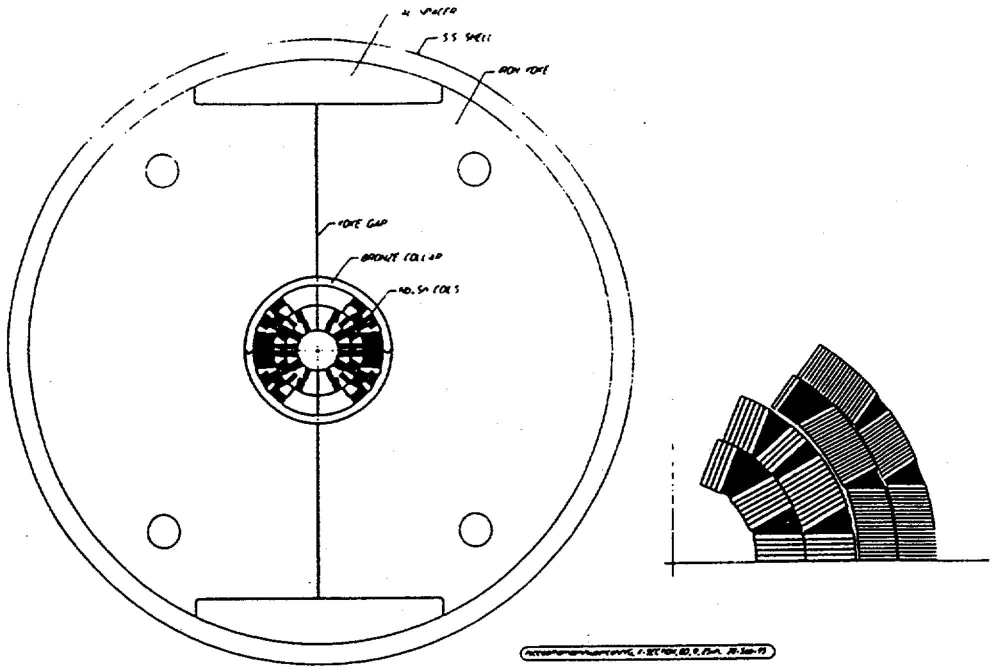


Figure 4 - Cross-section and coil configuration detail of 13T D20 magnet at LBNL.

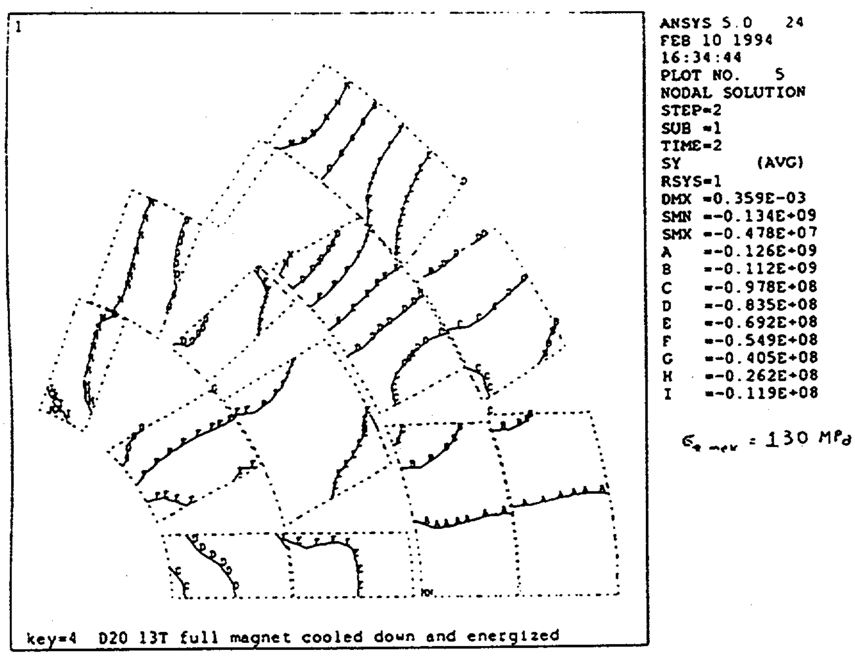


Figure 5 - ANSYS plot of mechanical stress on D20.

we can only mention a few: Lie-algebraic formulation and normal form analysis (A. Dragt, E. Forest and J. Irwin), symplectic integration (R. Ruth and P. Channel), Differential-algebraic tools for computation of high order maps (M. Berz), novel numerical tracking algorithms (R. Talman and Y. Yan), frequency map analysis of a spectacularly high degree of accuracy in phase space (J. Laskar), study of phase space invariants and long-term stability (R. Warnock and R. Ruth) and finally implementation of dynamic systems in the object-oriented language of C++ (J. Bengtsson). I hope much of this progress transpires via the talk later on by Dr. Yiton Yan.

One of the most difficult feats achieved by all this progress in nonlinear dynamics is our ability to compute frequencies ('tunes' in the accelerator jargon), invariants (nonlinear 'emittances'), full six-dimensional one-turn map of an arbitrarily complex accelerator ring to arbitrarily high order in nonlinearity and long-term tracking and stability at large amplitudes of motion close to the separatrix that marks the border of single particle stability. As an illustration, we show in Fig. 6, for the ALS storage ring at Berkeley, the region of horizontal and vertical 'tune'-space or frequency plane, accessible to any trajectory starting on an initial distribution after 10^7 turns (Fig. 6 (a)), after 10^8 turns (Fig. 6 (b)), after 10^9 turns (Fig. 6 (c)) and after 10^{10} turns (Fig. 6 (d)) respectively as a result of transport and diffusion along and across numerous nonlinear resonances in the action-frequency space[3]. Such plots are the result of complicated frequency analysis using sophisticated nonlinear dynamic mathematical tools and modern day high-speed and-accuracy computers. Such computational capability in nonlinear particle dynamics is crucial to the design and operation of today's and future colliders. As we stretch the limits of electromagnetic fields in high energy colliders — either in the form of high magnetic fields to have finite and reasonably sized particle orbits, or to have ultra-small and tight focal spots at the collision point to have high luminosity, etc. — we introduce extremely high orders of nonlinearity in the fields in the form of higher order multipoles, aberrations, chromatic effects, etc. that threaten the quality, integrity and indeed, in the case of circular hadron colliders, the very survivability of the beam over long times. The precise knowledge and computed properties of the expected particle trajectories over extended space-time domains are critical elements in the success of any high energy collider.

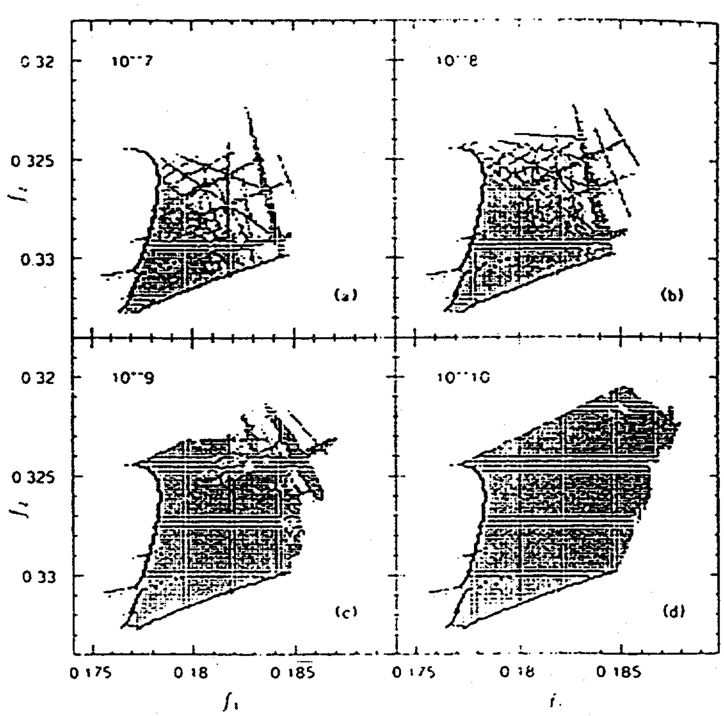


Figure 6 - Phase space of a storage ring in the transverse tune-plane accessible to a particle trajectory after (a) 10^7 turns, (b) 10^8 turns (c) 10^9 turns and (d) 10^{10} turn respectively.

2. 3 Concept of the Asymmetric Energy Collider

One of the major paradigm shifts for high energy colliders has been achieved in the last few years with the advent of the idea of low energy electron-positron colliders of asymmetric energies in the two beams (9 GeV electrons X 3.1 GeV positrons for example) for CP violation studies[4,5,6]. This should indeed be recognized as a pioneering idea of the decade, resulting in the first few asymmetric colliders to be built in the next few years such as: PEP-II (a tri-laboratory SLAC-LBNL-LLNL collaboration)[6], CESR-B (Cornell Univ.) and TRISTAN-B (Japan).

The primary purpose of all these asymmetric B-factories is to answer the fundamental question: "Where has all the Antimatter gone?". As we know from the CPT theorem, for every particle, there is an antiparticle. Whatever and however the origin of the universe, all we see today is MATTER that is relatively 'stable' having outlived all 'unstable' matter that have decayed away, as illustrated in Fig. 7. But Antimatter is stable! Antiproton, discovered in 1955, has a long lifetime similar to a proton! It is believed today that the violation of the CP symmetry is responsible for this state-of-affairs. Simply stated, the CP violation asserts that particle and antiparticle behave like each other on rare occassions and that there exist "mixed" patterns.

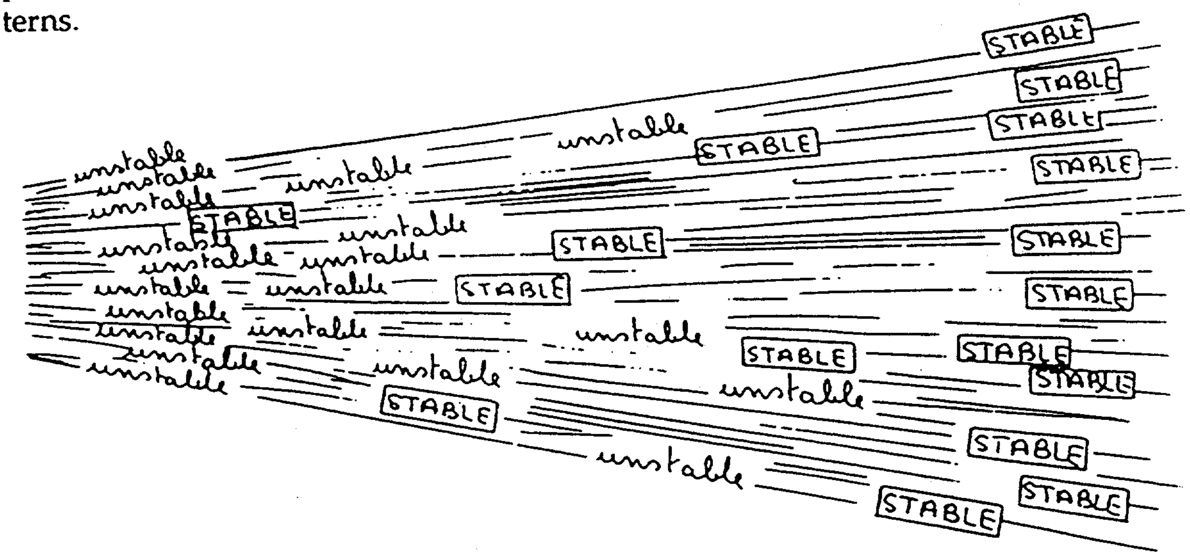


Figure 7 - Persistence of stable matter.

In a 'symmetric' collision of equal energy but oppositely directed electron and positron beams, as in Fig. 8 (a), the B- and Anti B-mesons are produced almost at rest in the laboratory. The separation of their decay vertices cannot be resolved by state-of-the-art detectors. In the 'asymmetric' collision scenario, as in Fig. 8 (b), the idea is to get the center-of-mass moving in the laboratory frame. The Lorentz boost ensures that the decay vertices are separated enough to be resolved by today's detectors. This allows measurement of the time-evolution of the "mixed" wave packets as a function of separation between decay vertices, leading to detailed CP violation studies.

Figure 8 (a) - Symmetric electron-positron collision

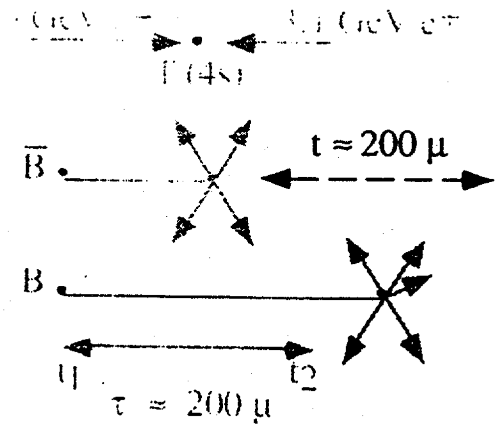


Figure 8 (b) - Asymmetric electron-positron collision.

The SLAC-LBNL-LLNL asymmetric B-factory, known as the PEP-II and under construction at present, is shown schematically in Fig. 9, superimposed on a potential Linac Coherent Light Source (LCLS) at the SLAC linac, proposed by various institutions. The LCLS would be an one Angstrom coherent radiation source based on the Self-Amplified Spontaneous Emission (SASE) principle in Free Electron Lasers (FELs).

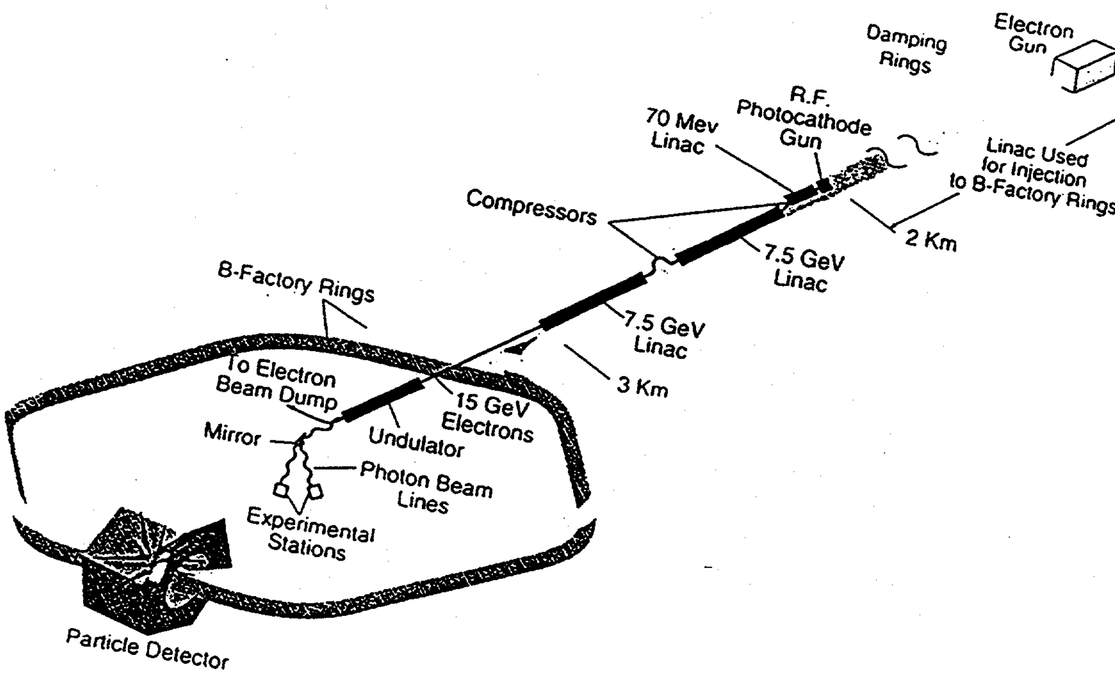
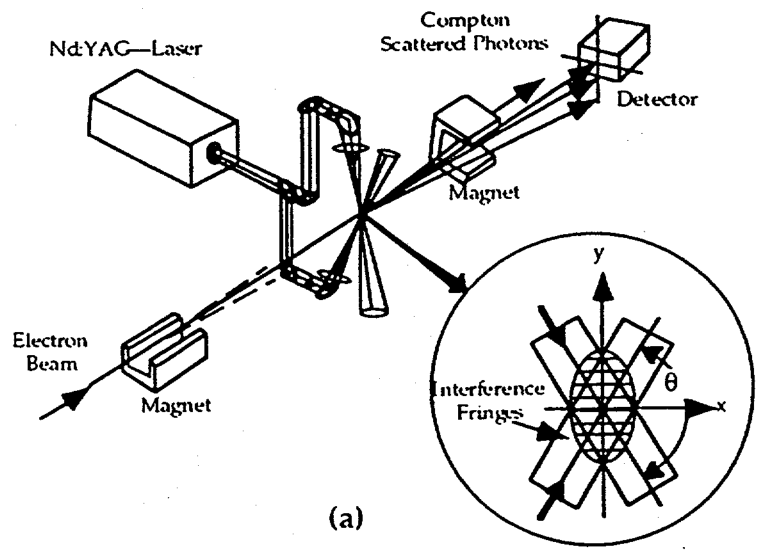


Figure 9 - The SLAC-LBNL-LLNL asymmetric B-Factory PEP-II and the proposed LCLS.

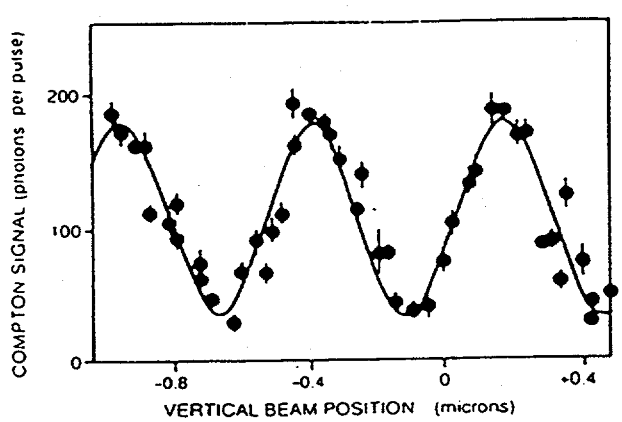
2. 4 Beam Monitoring in Ultrashort Dimensions

In today's vision of TeV-scale electron-positron linear colliders one requires beam spot sizes at the final focal region of collision of a few to a few tens of nanometers. The ability to monitor and measure such ultra-small spot sizes is crucial to controlling the collision and maintaining the luminosity. The progress made in this task at a lower energy but otherwise a prototype linear collider, namely the SLC at Stanford, is astounding.

Fig. 10 (a) below illustrates the principle of small spot size measurement at the SLC by scanning the relativistic electron beam across an interference fringe or standing wave pattern at its waist created by direct and reflected visible or near-infrared laser beams orthogonal to the electron beam and studying the pattern created by the Compton scattered photons at a detector along the beam forward direction. The intensity oscillations of the scattered photons as a function of beam scanning contains information about the beam size and is shown in Fig. 10 (b) for the SLC, resulting in a measured spot size of 70nm ![7]



(a)



(b)

Figure 10 (a) and 10 (b) - Final spot size measurement at the SLC via Compton Scattering across laser interference fringes.

2. 5 Phase Space Cooling of Antiprotons

One of the most notable and outstanding achievements in accelerator physics has been the invention of methods to cool the phase space of heavy secondary charged particles such as antiprotons. Aside from the Electron Cooling method invented by G. I. Budker of Novosibirsk, Russia in 1966 , the most noteworthy is the invention of the Stochastic Cooling technique by S. van der Meer of CERN, Geneva, Switzerland in 1968. Stochastic cooling made it possible to pack sufficient number of antiprotons in a bunch and allowed the possibility of proton-antiproton collisions with sufficient luminosity for the discovery of the Intermediate Vector Bosons, $W^{\pm}$ and Z^0 in 1983 at CERN. It has also finally made it possible, via the antiproton source and proton-antiproton collider program at Fermilab, to establish the existence of the Top Quark.

The motivation for cooling antiprotons is obvious. The average temperature of antiprotons produced by proton beams impinging on a target is about 5 MeV (the corresponding transverse momentum being 300 MeV/c). The typical transverse temperature accepted by a high energy storage ring's dynamically available phase-space is about 12 keV. Hence the need for phase space cooling by many orders of magnitude.

The idea of stochastic cooling was slow in being accepted since we are all used to thinking in terms of incompressible Liouvillian flow in the phase space of a conservative dynamical system. To S. van der Meer, however, phase space is mostly empty and where particles live, they cluster together leaving space in between. This leads to the possibility of employing a Maxwell's Demon to herd the particle clumps into a tight bunch, as illustrated in Fig. 11, if only one could see the phase space clutter! Today, we know that with high frequency microwave pickups (more than a GHz of bandwidth) one can listen to the internal 'tune' of individual particles in a bunch (known as the Schottky signal of a beam), modify and amplify the theme by high power amplifiers and teach the particles to stay and sing close together, as illustrated in Fig. 12. For a proton beam containing 10^8 particles, one is considering a total Schottky signal of only 10 picoWatts with a signal-to-noise ratio of a nV to a μV, a cooling feedback system of a GHz bandwidth, a gain of 260 dB and a cooling power of 100 Watts to achieve the required antiproton stacking rate for useful lumonosity.

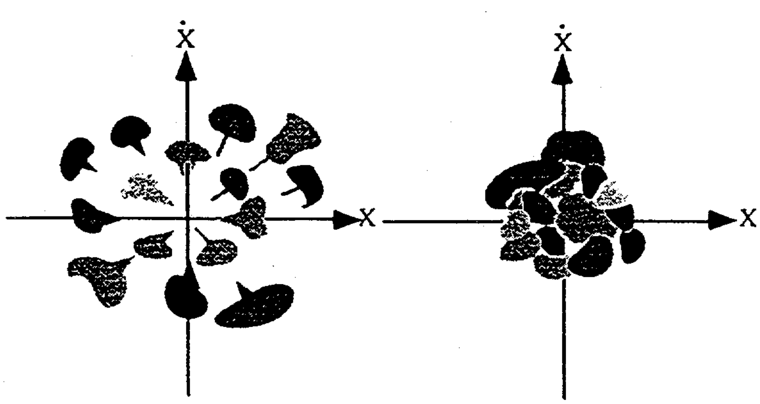


Figure 11 - Principle of Phase Space Cooling

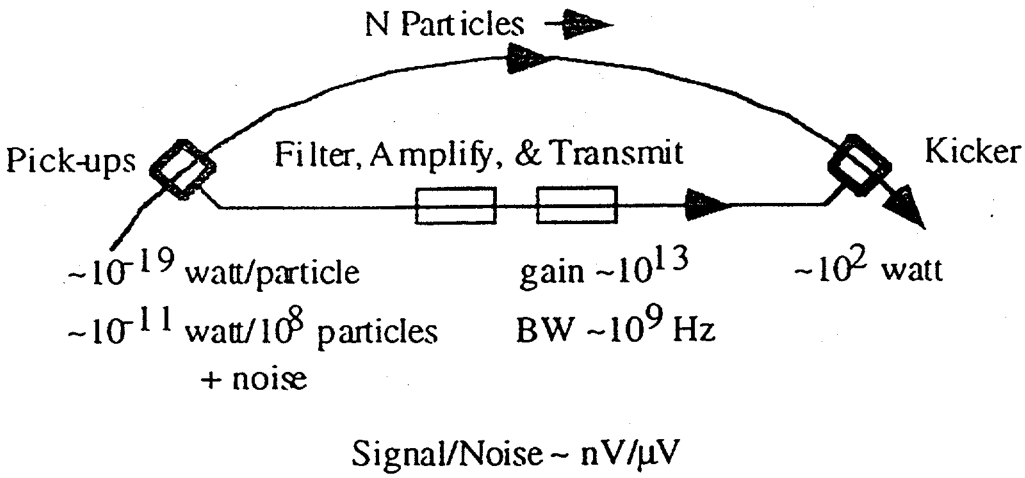


Figure 12- Typical stochastic colling feedback loop.

The CERN and FNAL proton- antiproton Colliders as they looked in the '80's are shown in Figs. 13 and 14 respectively. The FNAL proton-antiproton complex, as it looks in 1995 with the new Main Injector and the proposed recycler and stacking rings, is shown in Fig. 15. This facility, known as the TeV*, promises to find the Low Mass Higgs particle if it exists and to rule out Supersymmetry via 'no SUSY discoveries' with an integrated lumonosity of $10fb^{-1}$.

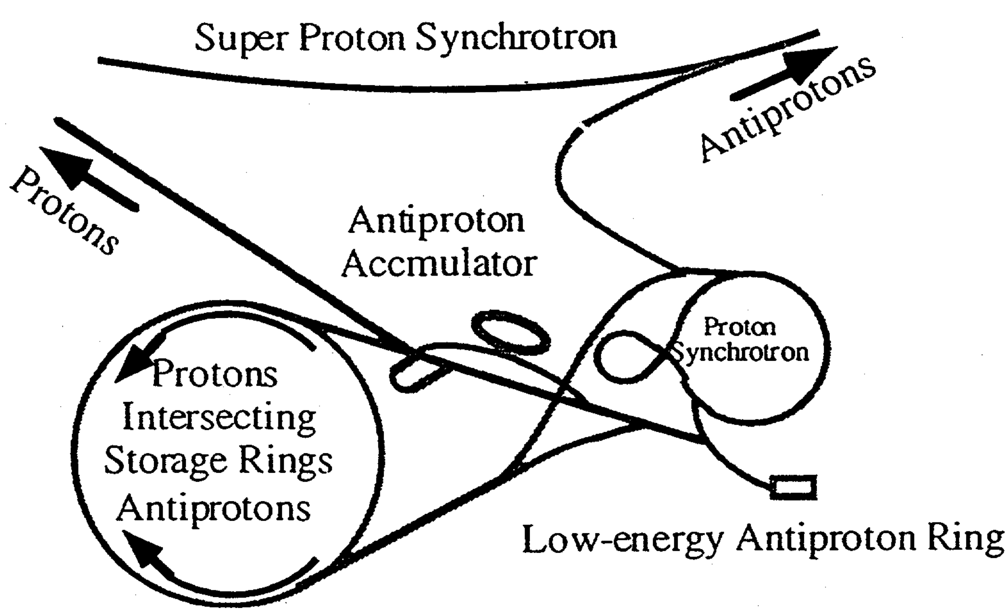


Figure 13 - CERN $p\bar{p}$ complex in 1982.

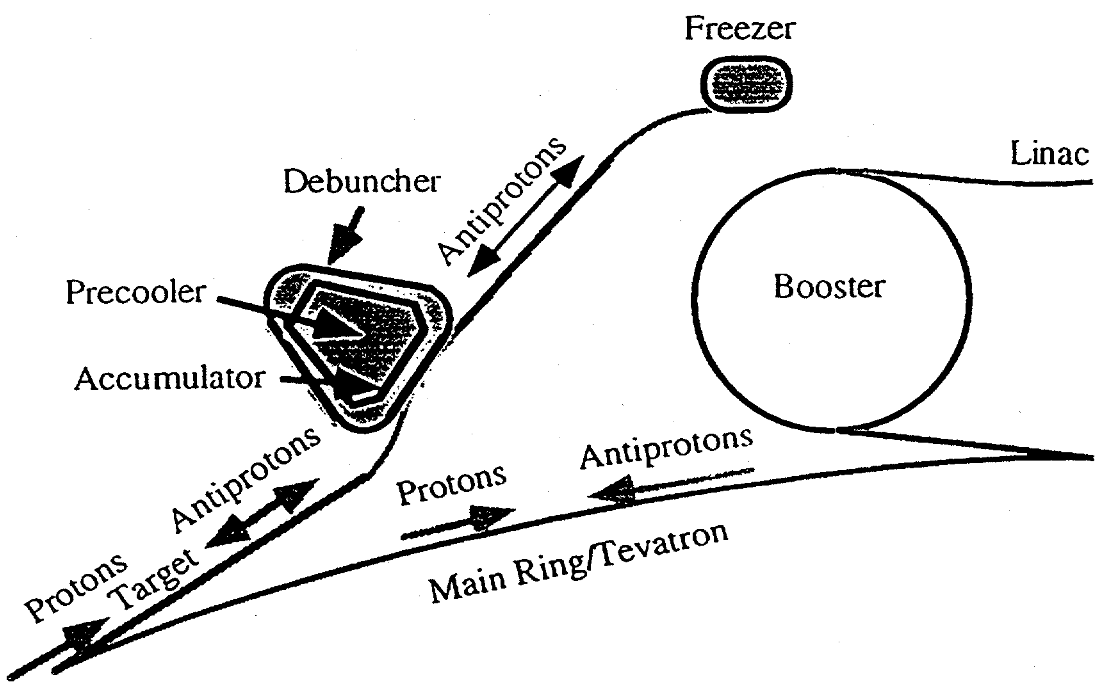


Figure 14 - FNAL $p\bar{p}$ complex in the '80's.

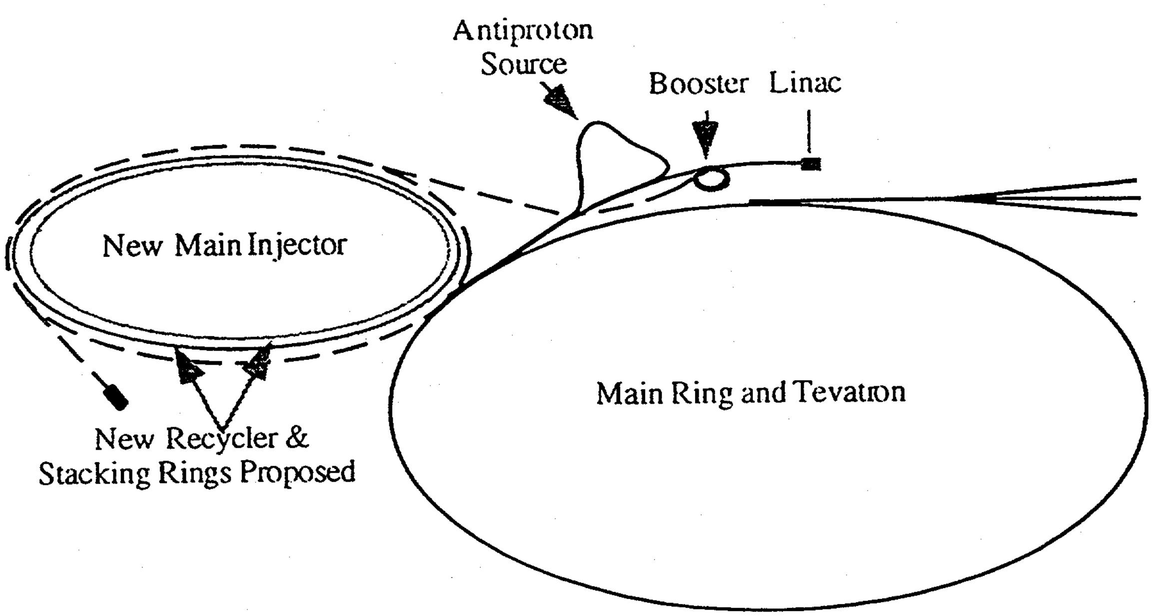


Figure 15 - Proposed TeV* upgrade of FNAL.

2.6 Radio-Frequency Power and Cavity Technology

The microwave technology at frequencies between a few MHz and a few GHz has been the work horse for particle accelerators since World War I and II. Powerful radio frequency power sources — such as cw tetrodes and pulsed klystrons, with a great deal of flexibility in amplitude, phase and frequency control — have been the drivers of particle storage and acceleration in circular and linear accelerators. Along with such versatile power sources, came the necessity to control and manipulate particle beams via radio-frequency electromagnetic fields to a high degree of precision. The RF and beam feedback systems, bunch rotators and Landau cavities, etc. all have been employed successfully to benefit collider operation. As the science and technology of RF progressed, the demands on the spectral purity of RF components for accelerator applications rose unprecedently. One particular area where the demands are stringent is the design and fabrication of radio-frequency storage and acceleration cavities capable of sustaining high electromagnetic fields at very precisely determined and desired frequencies and almost no fields or electromagnetic response at any other frequencies. This is so in order to assure a high degree of stability and control of the beam.

The development of superconducting RF technology leading to RF cavities with fields reaching upto 10 MV/meter and Quality Factors (unloaded by beam) reaching up to 10^{10} have been advanced by various laboratories such as Cornell, DESY, CEBAF, CERN, Saclay and KEK. Such cavities have already been employed at KEK to increase the energy of TRISTAN in the 1980s and are now being employed in LEP at CERN to increase the energy of the stored leptons. The development of superconducting cavity mechanical and electrical design, surface properties and purity, design of cryogenics in an accelerator environment and most importantly the mechanical, electrical and cryogenic design of the primary power input coupler and Higher Order Mode (HOM) couplers to get rid of unwanted modes have been most remarkable. These state-of-the-art Superconducting RF cavities ranging from 350 MHz to 3 GHz in frequency, input power capabilities of up to a 100 kW and HOM Quality Factors reduced to room temperature values while still maintaining a fundamental at a 'Q' of 10^9 — are in use today at various accelerators world wide e.g. in CESR at Cornell, CEBAF, DESY, CERN, etc.

In parallel, there has been tremendous progress in room temperature normal-conducting RF cavities for various meson factories and synchrotron radiation sources that are almost free, practically speaking, of any higher order modes. Examples are cavities built for the PEP-II, DAPHNE ring, etc. These cavities are designed to provide the desired level of power only at a fundamental frequency and provide almost zero cross-talk between beam bunches by suppressing cavity response at all other higher frequencies. A typical 500 MHz cavity designed for the PEP-II and its HOM frequency spectrum is shown in Fig. 16 (a) and (b) respectively[6].

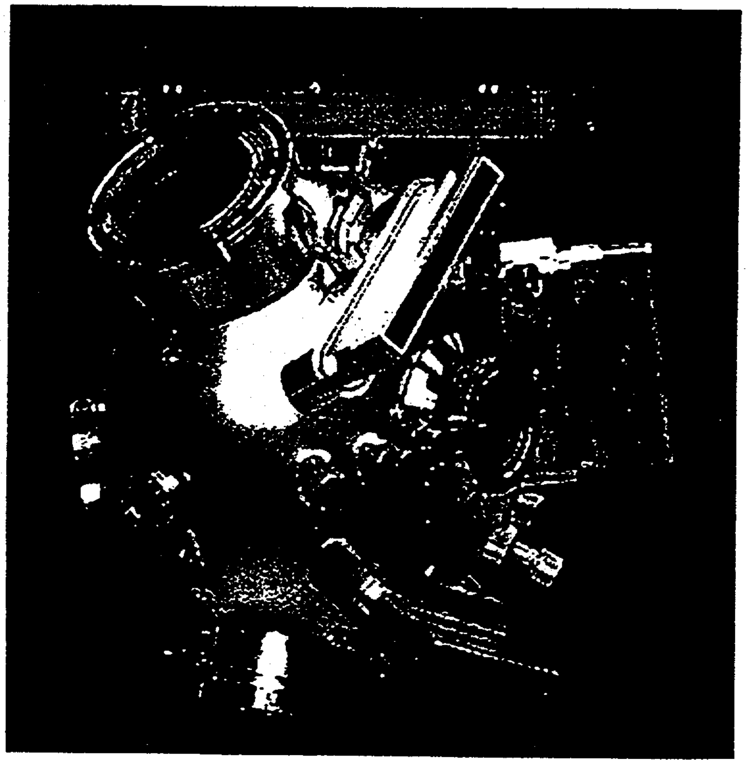


Figure 16 (a) - PEP-II cavity.

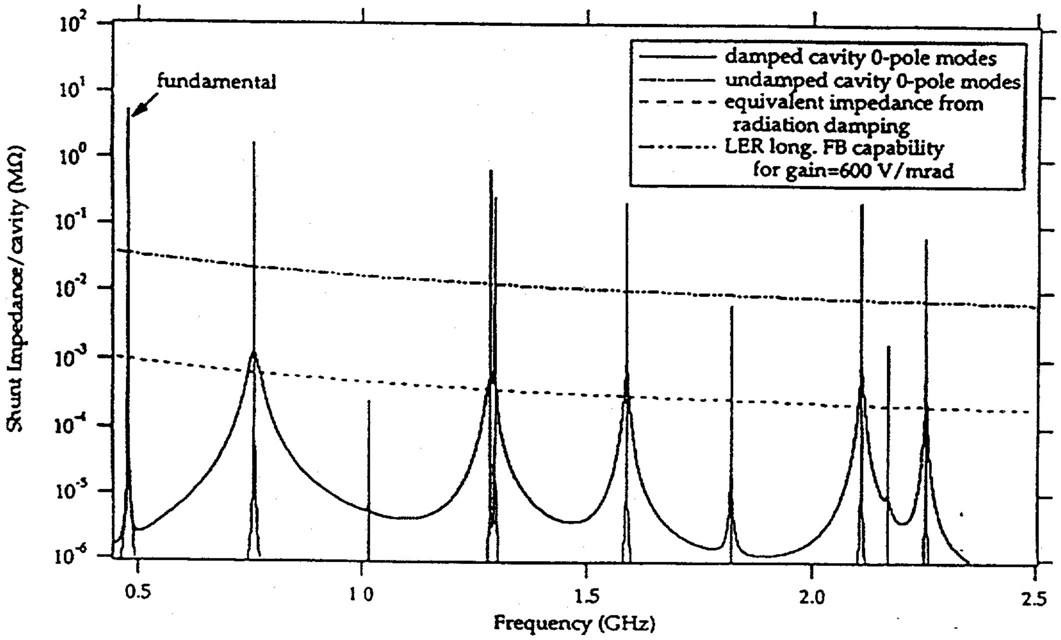


Figure 16 (b) - The suppression of its longitudinal higher-order-mode (HOM) response.

3. Future Opportunities

Future opportunities in the field of collider physics and technology are plenty and fascinating! To speak of a few: the electron-positron energy frontier, the muon colliders, possibilities of high energy electron-photon and photon-photon collisions, the promise of ultra-high gradient acceleration reached via various mechanisms involving high power short pulse lasers in free space and in plasmas, high frequency THz beam manipulation techniques such as Optical Stochastic Cooling, etc. Let us discuss a few notable ones briefly here.

3.1 Electron-Positron, Electron-Photon and Photon-Photon Colliders

With the success of the LEP and the SLC in doing precise spectroscopy of the $W^{\pm}$ and Z^0 and an understanding of the technical and fiscal unaffordability of large circular lepton colliders owing to limits imposed by the synchrotron radiation, there is increasing interest world-wide in TeV scale linear colliders involving electrons and positrons. Such colliders are seen as complementing the multi-ten TeV hadron colliders of the future.

However, it has also 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[8]. High energy photons i.e. gamma rays for these collisions are most effectively produced via Compton backscattering of focussed 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.

A preliminary but rapidly evolving conception of such a composite and integrated linear collider complex is shown in Fig. 17. Such a configuration, in various forms and variations, is being considered by the international linear collider community at present. 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 Table-Top Terawatt lasers based on the Chirped Pulse Amplification technique. And there is significant promise of enhanced repetition rate operation of these lasers to match the particle beam collision frequency for luminosity considerations. The peak power and repetition rate characteristics of available and potentially available lasers are shown in Fig. 18[9]. There exists also the possibility of using a Free Electron Laser (FEL) for this purpose. Investigations on both conventional lasers and FELs towards this goal are underway at present.

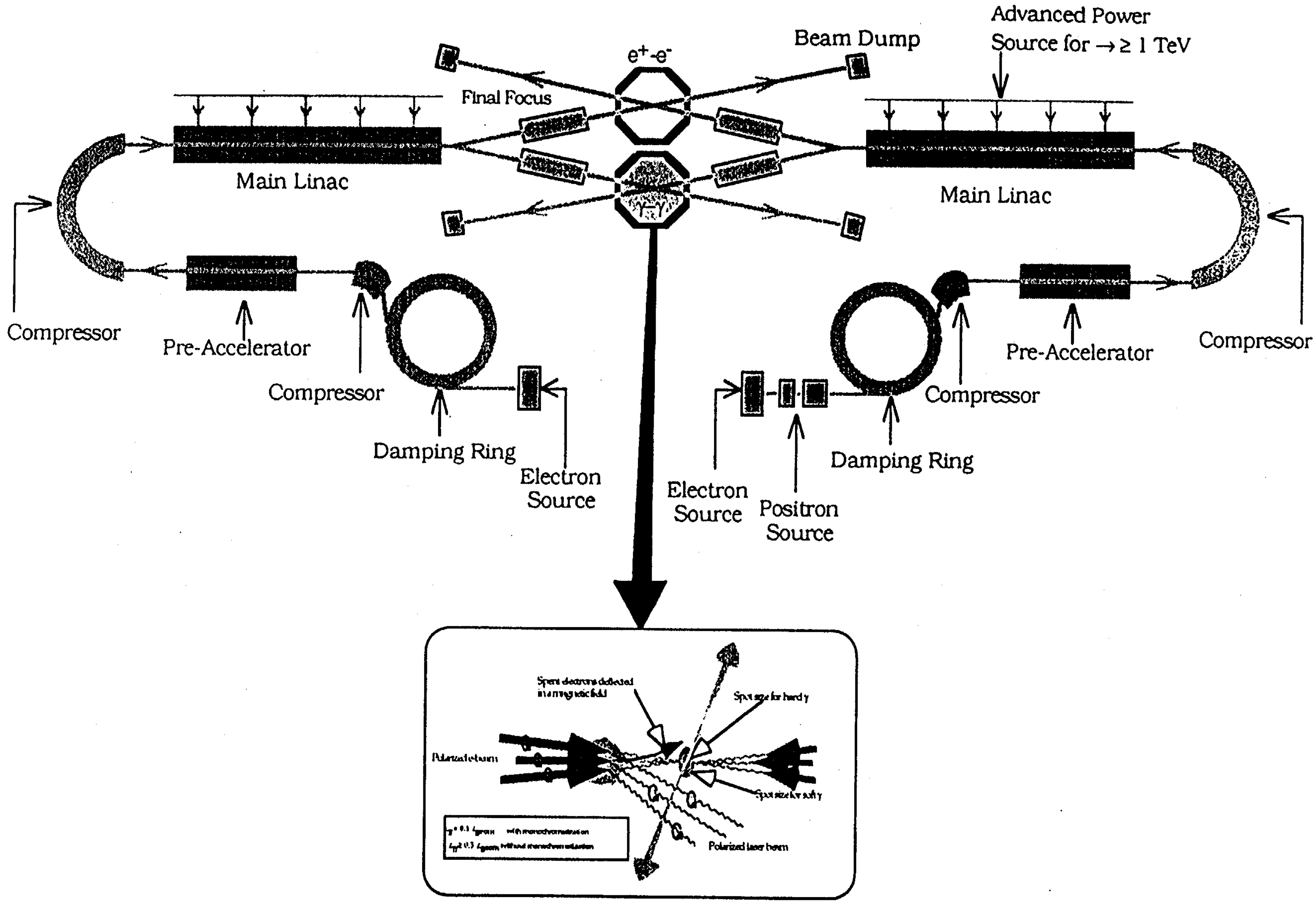


Figure 17 - A linear collider configuration with electron-positron, photon-photon, electron-photon, and electron-electron collisions.

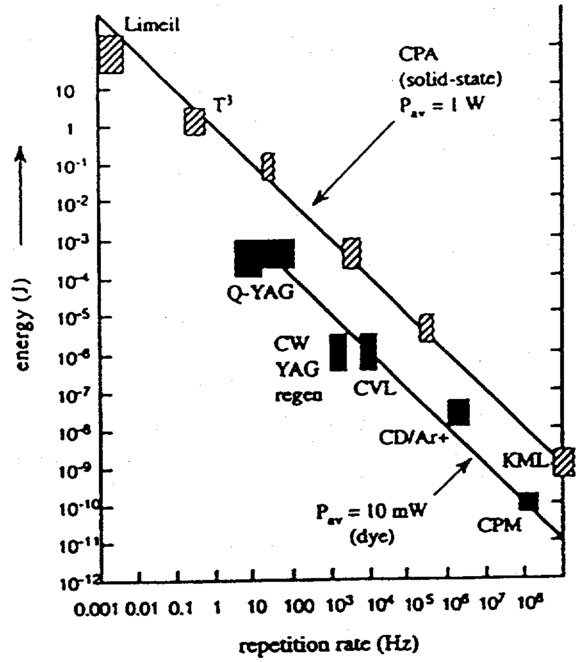


Figure 18 - State-of-the-art laser pulse energy and repetition rates.

3.2 Muon Colliders

It is well known that multi-TeV electron-positron 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 involving heavier, but still fundamental, leptons such as muons offer a potentially easier extension to higher energies. It is also believed that muons have a much greater direct coupling into the mass-generating "Higgs-sector". The Physics of the Higgs is acknowledged to be the next frontier to be explored in particle physics. This leads us to consider a TeV-scale muon collider. 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 electron-positron collider, in order to reach the same physics goals.

The challenges associated with a high energy muon collider are , however, many. 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 elementary but secondary particles and that they have a rather short lifetime in the rest frame. The muon lifetime is about 2.2 microseconds at rest and is dilated to milliseconds and longer by the relativistic dilation effect at higher energies. The dilated lifetime is still short enough to pose significant challenges to fast beam manipulation and control. Being secondary particles with short lifetimes, muons are not to be found in abundance in nature, but rather have to be created in collisions with heavy nuclear targets. Muons beams produced from such heavy targets have spot-size-and divergence-limited intrinsic phase-space density which is rather low. To achieve the required luminosity, one needs to cool the beams in phase space by several orders of magnitude. And all these processes — production, cooling, other beam manipulations, acceleration and eventual transport and storage to the collision point — will have to be completed fast in a few milliseconds! And there lies the challenge of muon colliders. High power targetry, bunch manipulation, phase space cooling, etc. are some of the primary concerns.

A schematic of a high energy muon collider is shown in Fig. 19. More details can be found in another article by Neuffer and Palmer in these proceedings[10].

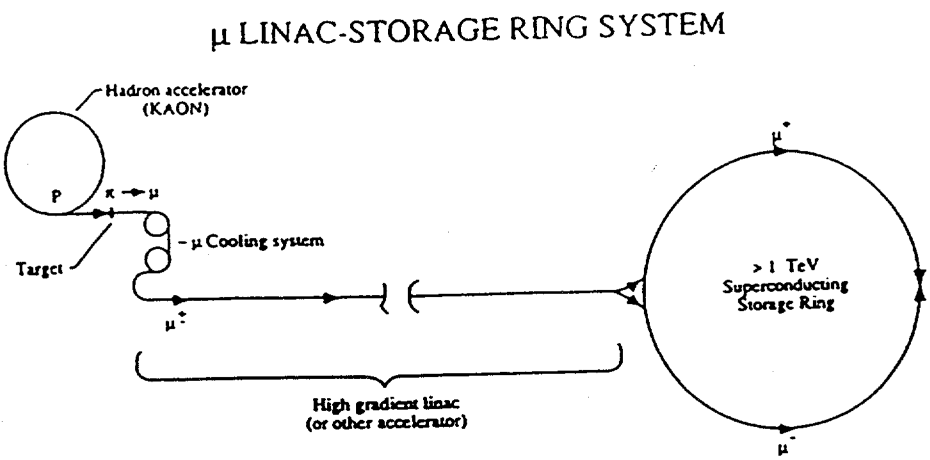


Figure 19 - A TeV muon collider configuration.

The cooling technique envisioned to date for ultrafast cooling of muons is based on the principle of Ionization Cooling, suggested by A. Skrinsky of Novosibirsk. In this scheme , illustrated in Fig. 20, the muon beam passes through a material medium and loses both transverse and longitudinal energy. Such energy loss in all dimensions is then followed by energy gain by coherent reacceleration preferentially in one direction only, namely along the longitudinal direction. This results in overall beam phase-space cooling in the transverse plane. The cooling rate achievable is much faster than, although similar conceptually to, radiation damping in a storage ring in which energy losses to synchrotron radiation followed by rf acceleration result in beam phase space cooling in all dimensions. I believe 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 test at some laboratory.

Yet another fascinating approach to ultrafast phase space cooling is offered by the advent of broadband high power compact laser amplifiers, which can be used in an Optical (as opposed to microwave) Stochastical Cooling scheme[11,12] utilizing undulator radiation. We will discuss this in the context of the next section.

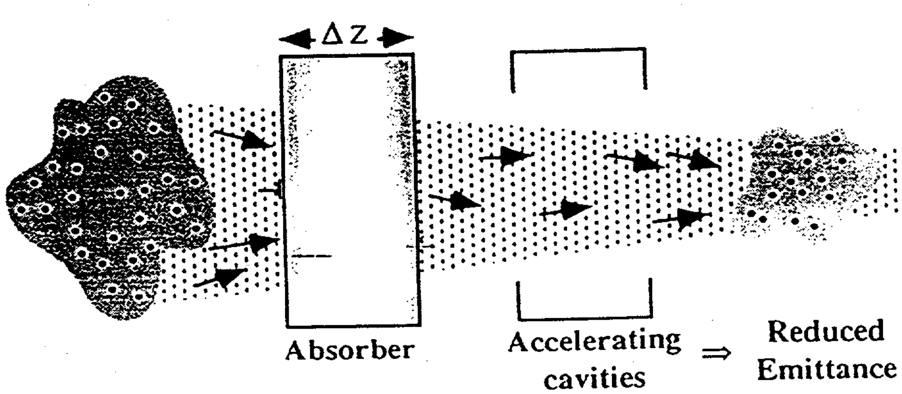


Figure 20 - Principle of Ionization Cooling.

3.3 Femtosecond (THz) Control and Optical Stochastic Cooling

Today we are almost ready to replace the GHz microwave rf technology by state-of-the-art short pulse high power compact lasers as work horses for particle accelerators. Indeed, as we will hint in the next section, there exist possibilities of generating ultrahigh electromagnetic fields by coupling today's lasers either to a suitably formed plasma or to a channel in free space with suitable boundaries. However, just as in today's microwave technology involving beam manipulation over fractions of mms in time-scales of picoseconds at frequencies of GHz, one would have to learn to manipulate and control signals and particles at optical wavelengths of microns, in time-scales of femtoseconds at frequencies of THz and higher in order to take advantage of today's lasers. For example, the development of Femtosecond kickers, choppers, bunch rotators etc., as thematically illustrated in Fig. 21, will be one of the most challenging jobs for beam scientists, but needs to be accomplished for further progress.

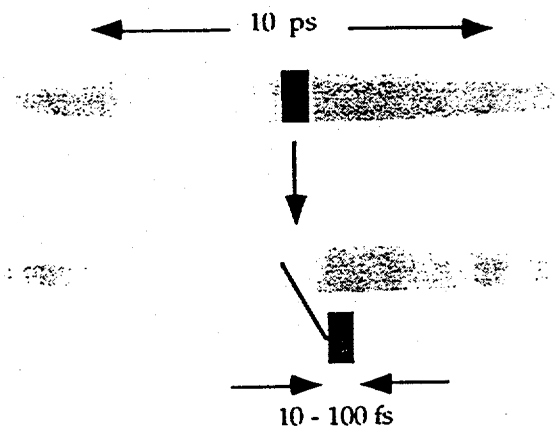


Figure 21 - Femtosecond chopping of a beam slice out of a picosecond beam.

It is important to explore optical control of charged particle beams in all possible forms. For example in the scheme of Optical Stochastic Cooling[11,12] illustrated in Fig. 22, one strives to extract beam granularity in phase space, (i.e discrete Schottky noise) in a length scale of a micron (i.e at a frequency of 300 THz or so) via spontaneous emission in a periodic magnetic field (wiggler or undulator), amplifying the radiation by a Laser Amplifier with a 100 THz bandwidth and large gain and making the particle beam interact with the amplified radiation in presence of a suitable periodic magnetic field again leading to phase space cooling. The number of photons emitted per single charged particle is approximately given by $\sim \alpha N_w K^2$, where K is the undulator parameter. In the limit of a weak undulator with $K \sim 0.1$, the no. of photons/electron is of the order of the fine structure constant $\alpha \sim 1/137$: very 'noisy' in the quantum sense. In the limit of a strong undulator, $K \sim 1$, the no. of photons/electron is of the order of 1. Thus the issues of quantum noise, signal-to-noise ratio, coherent radiation etc. —all will have to be understood properly for beam control to such fine levels.

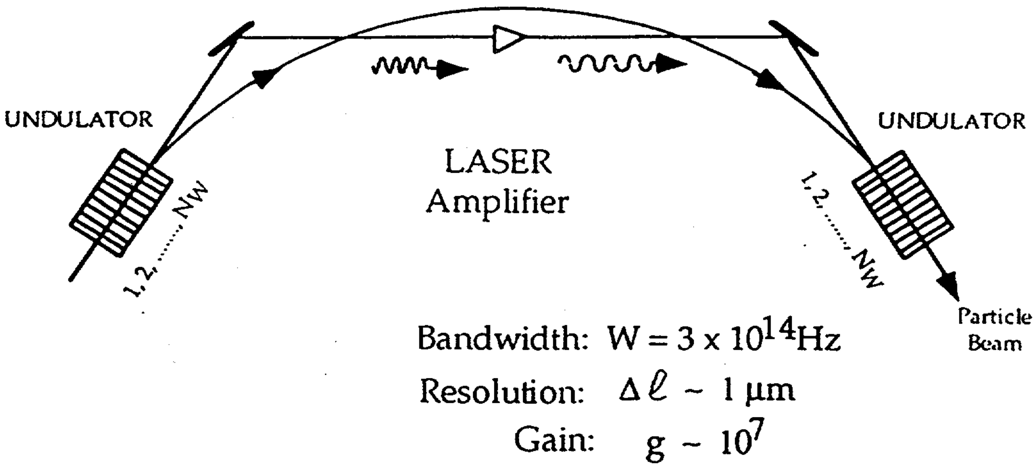


Figure 22 - Optical Stochastic Cooling.

3.4 Laser Acceleration

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. While there may be debate about the feasibility of acceleration in free space by the field of a laser or crossed lasers or whatever, nobody debates the possibility of acceleration in free space via lasers in presence of suitable boundaries or via non-linear higher order mechanisms or via direct coupling of lasers to a plasma-like medium. I would like to remind the readers of two important aspects that will critically determine the success of the laser acceleration scheme. 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 guide simultaneously 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.

Much progress is being made in the second topic in the context of pulse train generation and control in today's table-top terawatt lasers for applications in coherent wavepacket control for studies in chemistry etc.[9] One has the capability today of tailoring a sequence of up to eight or ten pulses, varying in strength, phase and width from a short pulse laser. In the domain of optical guiding much progress needs to be made. However I would like to mention here the important results obtained at Maryland[13], albeit at low power, in propagating and guiding laser pulses in hollow plasma channels. It is crucial that such experiments be repeated at high powers to assess their robustness.

Should the focussing, guiding and controllability issues be worked out, there remains little doubt 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[14] available today, as shown in Fig. 23 (a) and (b). In Fig 23 (a), one sees the laser intensity profile after propagating two diffraction lengths in a hollow plasma channel. In Fig. 23 (b) we see the electric field of the surface modes excited by the laser in the plasma. Such simulational capability exists today to give us confidence in proper laser wakefield design computations. However the crucial issue of the dynamical stability and phase-space acceptance of the laser wakefield acceleration channel should be investigated in detail experimentally.

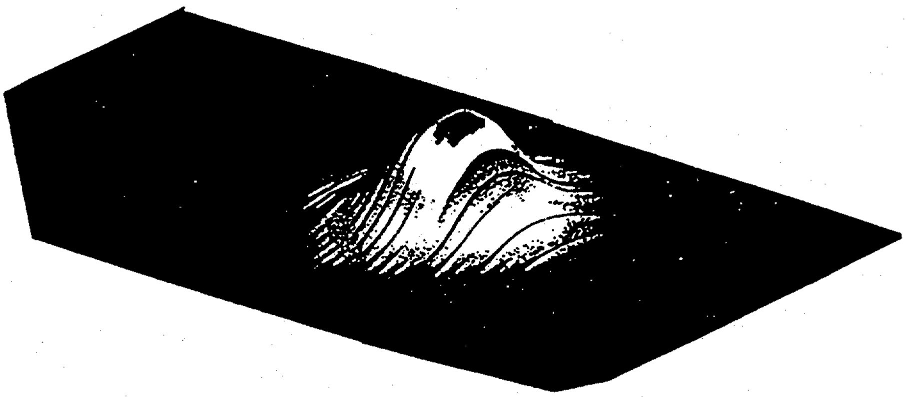


Figure 23 (a) - Propagation of a laser pulse.

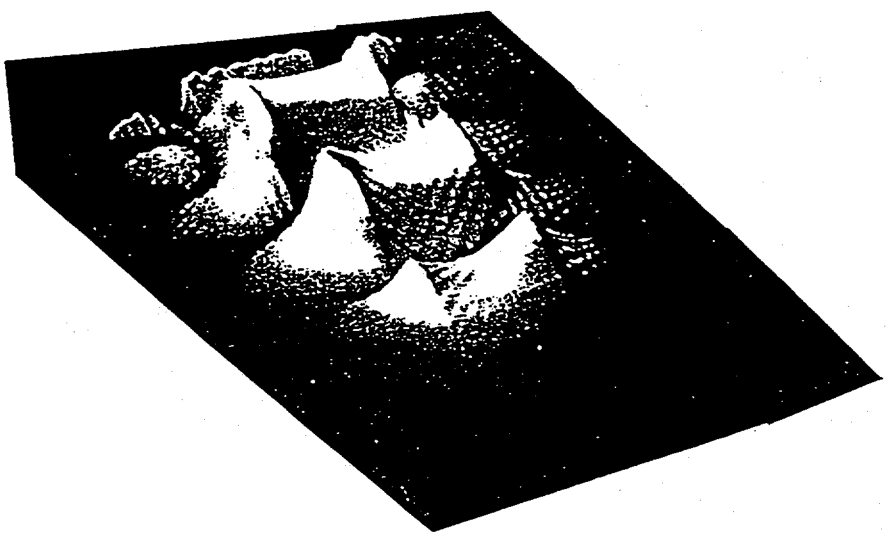


Figure 23 (b) - Generated surface mode electric fields in a hollow channel.

3.5 A New Paradigm for Colliders

As one reflects upon the status of today's laser and particle beam technology, the necessity of femtosecond control of beams, etc. in the context of potential future accelerators, be it laser-based or some other novel power source based, be it based on plasmas or on some other exotic channelling medium such as crystals, —— it slowly becomes apparent that perhaps a new paradigm is about to dawn on us — a paradigm based on utilizing the limit of zero-emittance, high repetition rate and low no. of particles per bunch that circumvents many of the problems of low laser efficiency, beamstrahlung, ultimate spot-size etc. Due to the inherently low wallplug-to-electromagnetic fields efficiency of lasers, and other anticipated power sources, one would have to consider scenarios where the number of particles packed per bunch would have to be low in order to conserve the wallplug power. In order to have the same event rate and hence luminosity for useful physics, the high repition rate and low, almost zero-emittance (and hence zero spot-size) limit is not a choice but a necessity demanded by the technology constraints and physics. One thus enters into a rather new paradigm of collider physics where one considers a series of microbunches containing 10^8 or 10^9 particles, arriving at a rather high repetion rate of hundreds of THz and ultra-small emittance and focal spot size of sub-Angstrom domain. Even if such beams could be supported in a novel accelerator channel of tomorrow, are there injectors capable of producing them? And what about the physics at the collision point? Can we calculate luminosity by simple overlap of geometric areas? What about radiative effects such as beamstrahlung? Are they still relevant? Note that conventional ideas of beamstrahlung, classical cross-section and luminosity, etc.—all will have to be revisited to assess the feasibility and viability of such a scenario. The contrast between today's RF-based collider scenario and a potential laser-based scenario of tomorrow, if it is technologically feasible at all, is demonstrated in a provocative style in Fig. 24.

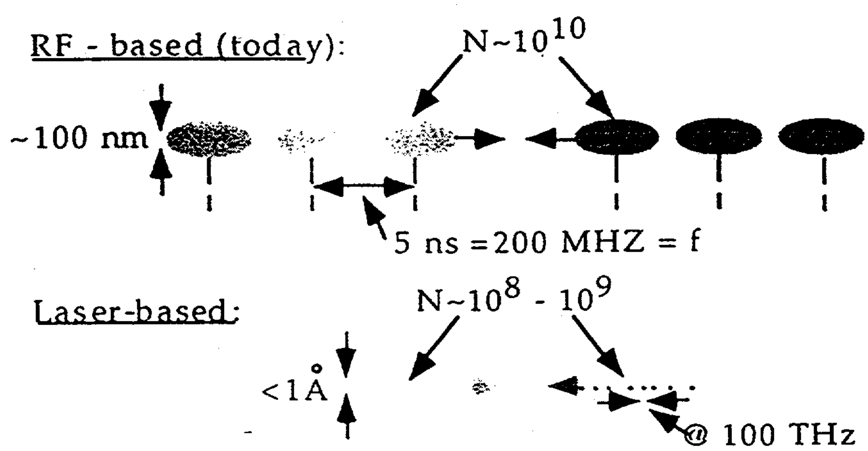


Figure 24 - A new paradigm of colliders?

4. Outlook

In conclusion, I would like to remark that we should look at the past as an era of outstanding accomplishments and jobs superbly done on the technical front. And I hope that I have given you reasons to look at the future as opportunity: some very exciting opportunities in beam physics and technology. I believe that empowered with these, we should be able to ride the rather hurtful present, felt throughout the community as a result of the termination of the Superconducting SuperCollider. We have more to look forward to than ever. And we should always remember that 'naiveté' (i.e. questioning the 'unquestionable' and believing in the 'impossible') and 'internationalism' are the cornerstones of success in all research and development efforts, especially so in the field of high energy physics. We should all take a lesson on international collaboration in our field, which is a 'must' with the problems and resources of today.

Acknowledgment

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