LASERS AND NEW METHODS OF PARTICLE ACCELERATION*
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LASERS AND NEW METHODS OF PARTICLE ACCELERATION

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Abstract

Current progress in the advanced accelerator research, development of revolutionary laser driven accelerators, and requirements of the high energy physics for future accelerators are discussed.

Introduction

There has been a great progress in development of high power laser technology. Harnessing their potential for particle accelerators is a challenge and of great interest for development of future high energy colliders. We discuss some of the advances and new methods of acceleration including plasma-based accelerators. The exponential increase in sophistication and power of all aspects of accelerator development and operation that has been demonstrated has been remarkable. This success has been driven by the inherent interest to gain new and deeper understanding of the universe around us. With the limitations of the conventional technology it may not be possible to meet the requirements of the future accelerators with demands for higher and higher energies and Luminosities. It is believed that using the existing technology one can build a linear collider with about 1 TeV center of mass energy [4,5,7]. However, it would be very difficult (or impossible) to build linear colliders with energies much above one or two Tev without a new method of acceleration. Laser driven high gradient accelerators are becoming more realistic and is expected to provide an alternative, (more compact, and more economical), to conventional accelerators in the future. In the following, we discuss some of the new methods of particle acceleration, including laser and particle beam driven plasma based accelerators, near and far field accelerators. We also discuss our enhanced IFEL (Inverse Free Electron Laser) and NAIBEA (Nonlinear Amplification of Inverse-Beamstrahlung Electron Acceleration) schemes, laser driven photo-injector and the high energy physics requirements.
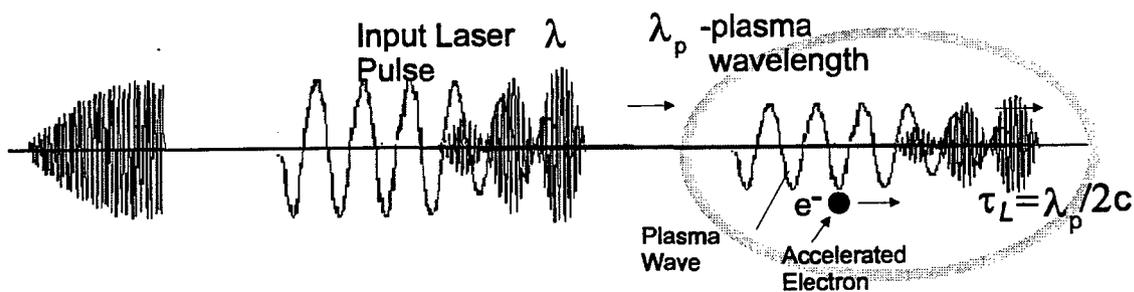
Figure 1: Schematic of Laser-driven Plasma-Wake acceleration

Plasma Acceleration

The concepts of Laser plasma acceleration is not knew; however only with the recent development of compact terawatt laser systems could these concepts be fully investigated in the laboratory. Among a number of laser accelerator concepts, laser wakefield accelerators have great potential for producing ultra-high field gradients of plasma waves excited by intense ultrashort laser pulses. Schematics of a laser driven plasma based accelerator is shown in Figure 1. The Plasma structures have been considered as basis for the future accelerators.The plasma has

no breakdown limits since it is already ionized. Further, the plasma can support large longitudinal waves in which the electrons oscillate with $\omega_p = (4\pi e^2 n/m)^{1/2}$, due to the space charge of the immobile ion background (regardless of the wavelength). One can create a relativistic plasma wave by properly phasing these oscillations such that $v_\phi \cong c$. So that, the electron can reach relativistic energies before dephasing from the wave. The accelerating gradient of a relativistic plasma wave can be expressed as $n^{Purt}\sqrt{n}$ V/cm, where n^{Purt} is the density of the perturbed wave, n is the plasma density in cm^{-3}. Relativistic plasma waves can be generated by propagating intense laser beams or intense particle beams. In the following sections we discuss laser and particle beam-driven acceleration schemes. The laser wake-field acceleration (LWFA), the plasma beat-wave accelerator (PBWA) and the self-modulated laser-wake-field accelerator (SMLWFA) concept are illustrated in Figures 1, 2, and 3 respectively.

LWFA

In the laser wake-field acceleration (LWFA) a single short laser pulse of length L excites a plasma wave of wavelength λ_p. In this scheme $L \simeq \lambda_p$. This method requires short, $\lesssim 1$ pico-second, laser pulses of ultra high intensity $\gtrsim 10^{18}$ W/cm^2 and could not be tested until chirped-pulse amplification (CPA) was used to create Table-Top Terawatt (T^3) lasers. Several papers on progress in T^3 technology based on CPA in solid state lasers were presented at this conference.

PBWA

The plasma beat-wave accelerator (PBWA) was proposed earlier as an alternative to LWFA because short-pulse, high-power lasers were not available. This approach employs two long pulse laser beams of slightly different frequencies w_1 and w_2 such that $w_1 - w_2 \simeq w_p$ the frequency of the plasma wave which is to be resonantly excited. PBWA experiments have been performed in Japan (ILE), the USA (UCLA), Canada (CRL) and France (LULI). The UCLA experiment observed the highest electron energy gain, ~ 28 MeV [Clayton et al.], with an effective accelerating gradient of 2.8 GV/m. They plan to continue with PBWA experiments.
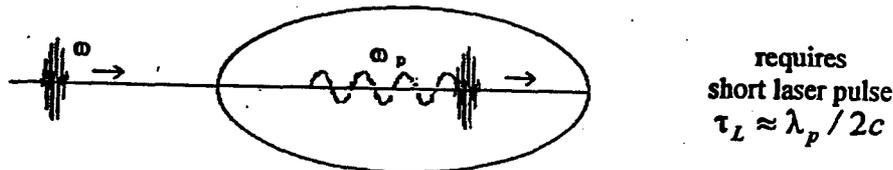

requires
short laser pulse
$\tau_L \approx \lambda_p / 2c$

Figure a Schematic of Laser-driven Plasma-Wake acceleration

requires two
laser beams with
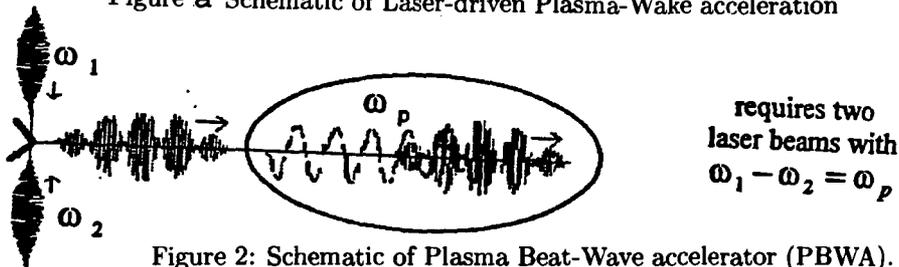$\omega_1 - \omega_2 = \omega_p$

Figure 2: Schematic of Plasma Beat-Wave accelerator (PBWA).

SMLWFA

One of the impressive advances reported is in the area of self-modulated laser wakefield acceleration (SML-WFA). In this method, a laser pulse of length $L > \lambda_p$ is subdivided into a series of shorter pulses of length $\sim \lambda_p/2$ by its interaction with the plasma wave (which it created). This interaction creates a large amplitude (resonantly driven) plasma wave. This process requires a laser power greater than the critical level required for relativistic guiding of the laser field. The phase velocity of the guiding plasma wake can become relativistic for high enough plasma electron densities, for example $n_p \sim 10^{19}$ cm^{-3}.

Experiments on SMLWFA have been performed in Japan (KEK), the US (LLNL, CUOS, NRL) and the UK (RAL). The latter experiment achieved impressive results: electron energy gains of $\gtrsim 44$ MeV and accelerating gradients $\gtrsim 100$ GV/m. Conventional accelerators are capable of accelerating gradients of ~ 100 MV/m. This experiment employed a 2.5 TW, 0.5 picosecond laser, producing an intensity of 10^{19} W/cm^2 and a plasma electron density of $10^{19} cm^{-3}$. The accelerated electrons in this experiment cover a wide range of energies from a few MeV up to the maximum. The theoretical limit for this experiment was ~ 70 MeV. The spectrometer was capable of

requires relativistically
strong and steep laser pulse

$$P > 17\left(\frac{\omega}{\omega_p}\right)^2 [GW]$$

$$\tau_L \approx 10\lambda_p / c$$
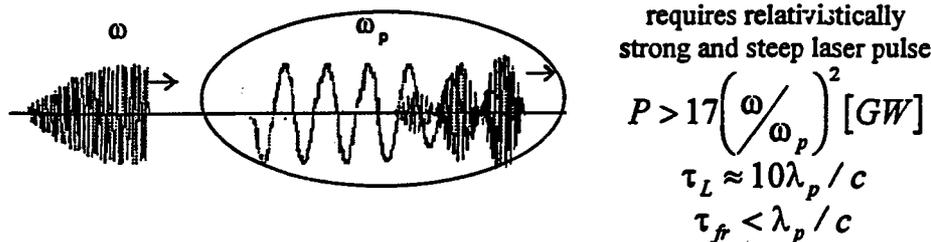
$$\tau_{fr} < \lambda_p / c$$

Figure 3: Schematic of Self-modulated Laser Wakefield Acceleration (SMLWFA).

measuring only up to 44 MeV. The normalized transverse emittance of any particular energy group was about 5π mm-mrad, which is on the order of the emittance of photo injector based linacs. However the measured beam current was 10-100 times lower than that achieved with photoinjectors.

Although the reported accelerating gradients for SMLWFA are spectacular, they are achieved over short distances of the order of 100's of microns to millimeters. The size of the acceleration distance is determined by the diffraction limited Rayleigh length (of the region of minimum focal spot size). Various schemes for getting accelerating lengths greater than a few Rayleigh lengths have been considered. For example, optical guiding can be achieved with preformed lower density plasma channels produced by hydrodynamic expansion of ionized gas generated by another laser focused along the acceleration axis. Other approaches suggested were using laser blow out to create a low density hollow plasma channel or using acoustic wave channel formation. Relativistic focusing can provide optical guiding in the case of SMLWFA for laser power levels $P > P_c = 17(w/w_p)^2$ GW. Other limiting factors on accelerating lengths are electron detuning, (i.e., the length over which the accelerated relativistic electron outruns the plasma wave), and pump depletion,(i.e. is roughly the length over which the laser pulse gives up all its energy to the plasma wake).

All these SMLWFA experiments have accelerated background plasma electrons. Producing and injecting 20-100 femto-second electron bunches is a difficult challenge. Umstadter et al. proposed to solve this problem by using two orthogonally propagating laser pulses, one along the acceleration direction as a plasma wave pump pulse, and an injection pulse at right angles. This scheme is called LILAC, laser injection and laser acceleration. The University of Michigan is building an all optical accelerator to produce femto-second electron pulses with GeV energies.

Particle Beam-driven Plasma Wakefield Accelerator.

Another approach is that of Plasma wakefield accelerators, which are similar to LWFA, except that one or more relativistic electron beams are used to excite the accelerating plasma wave. The electron beam pulse must be shorter than the plasma wavelength in analogy with the situation for the LWFA. This concept was originally proposed by Fainberg in 1956. Enhancing the wakefield by using multiple electron drive bunches spaced at the plasma period was proposed in the original work on PWFA. The first PWFA experiment was performed by Berezin and co-workers in the early 1970's in Ukraine. More recently experiments were performed in the US (e.g.at Argonne Nat. Lab) and in Japan (at KEK).

Skrinsky and co-workers have proposed[25] a system design for a 1TeV PWFA using a pre-ionized hydrogen plasma, which is driven by trains of electron bunches, which are made of 10 micro-bunches of 0.2 mm length. This system would employ a 10 GeV drive beam at 10 kHz rep rate with 2×10^9 electrons/bunch. Challenges involve the energy requirements of maintaining the hydrogen plasma channel. A PWFA test experiment is being proposed at INP, Novosibirsk with a goal to reach more than 0.5 GeV/m over several tens of cm.

Advances in these and other advanced acceleration schemes have been reported at this and earlier meetings[1,5]. Some of these schemes are discussed in more detail below.

Far Field and Near Field Accelerator

An electromagnetic field 'E', expressed as the sum of propagating waves with wave vector k_m, is referred to as: "far field" if k_m are real and "near field" if k_m are imaginary. In the interaction of a charged particle with the far fields (with interaction dimension "d") the distance from the field source R must be much larger than the wavelength of the field (λ), i.e. $R \gg \lambda$ or near field effects may need to be considered.

$$\vec{E}(\vec{x}, t) = \sum_m a_m e^{i(\vec{k}_m \cdot \vec{x}_m - \omega_m t)} \tag{1}$$

Equations of motion of a charged particle of mass m, charge e, in an (E,B) electromagnetic field can be expressed as:

$$mc\frac{d(\gamma\vec{\beta})}{dt} = e\vec{E} + ec\vec{\beta} \times \vec{B} \tag{2}$$

$$mc^2\frac{d\gamma}{dt} = ec\vec{\beta} \cdot \vec{E} \tag{3}$$

Where the relativistic velocity is $\beta = \frac{v}{c}$ and the corresponding relativistic energy factor is γ. As can be seen from the last equation, to increase the energy the particle velocity must have a component along E direction. Further, if the particle interact with one wave, the (first order) process depends on 'e', if the particle interact with 2 waves the (2nd order) process would depend on e^2, etc.

In the far field acceleration the particle travels either in vacuum or a static medium (characterized e.g. by refractive index n), where the radiation source is located far away from the interaction region. For example, if a wave crosses the particle trajectory at an angle θ when a particle is traveling "in vacuum" along the z direction with velocity $v = \beta c$, the wave phase velocity v_{phase} can be expressed as:

$$v_{phase} = \frac{\omega}{k_z} = \frac{c}{cos\theta} > c \tag{4}$$

To obtain continuous interaction in the vacuum the particle velocity and the phase velocity of the wave must be equal, which is not possible in a vacuum. Although we can have synchronism, by using a dielectric medium (which can reduce the wave phase velocity) provided that

$$n\beta cos\theta = 1. \tag{5}$$

then

$$v_{phase} = \frac{\omega}{nk_z} = \frac{c}{ncos\theta} \tag{6}$$

The above relation is the same as Cerenkov radiation and acceleration under the above conditions is called (ICA) Inverse Cerenkov Acceleration, which is the only example of the first order far field acceleration process. All other far field acceleration schemes are second order processes, since to give the particle an oscillating transverse velocity component a second field is used. The synchronism is maintained if the particle slips one radiation wavelength behind the wave each period of particle's motion. Inverse Free Electron Laser Acceleration (IFEL) is an example of this type of acceleration scheme. Some of the others are given in Figure 4 and Table 1 (see e.g. [4,5,12,12b]).

| Accelerator	Fields	couplings	$V_{transverse}$	order
ICA	$1EM$	e	0	1
2-wave IFEL	$2EM$	e^2	v_T	2
IFEL	$1EM + staticB_T$	e^2	v_T	2
Resonance	$1EM + staticB_L$	e^2	v_T	2
Inverse Bremstrahlung	$1EM + staticE_T$	e^2	v_T	2

Enhanced IFEL and NAIBEA

The Nonlinear Amplification of Inverse-Bremsstrahlung Electron Acceleration (NAIBEA) is a scheme of accelerating charged particles that uses a laser coupled to a static applied field structure in which a constant magnetic, or electric, field alternates sign at some appropriately determined positions in such a way that the particle is always accelerated. This may be understood as a kind of the Inverse Free Electron Laser Acceleration (IFEL). In both of these acceleration schemes[13-15], relativistic particles move under the combined action of an electromagnetic traveling wave, the laser field, and a magnetic, or electric, applied static field. Both, the laser radiation and the beam of particles, propagate along the field structure. This static field, usually provided by magnets, acts like a wiggler by producing a small undulation in the particle trajectory. The transverse velocity of this undulation couples in such a way to the electric field of the electromagnetic wave that the energy is transferred from the laser to the beam.

In the standard IFEL this wiggling motion is created by an undulator whose magnetic field varies sinusoidally with the longitudinal distance[13] , while in our new IFEL scheme the wiggling motion is created by a square wave
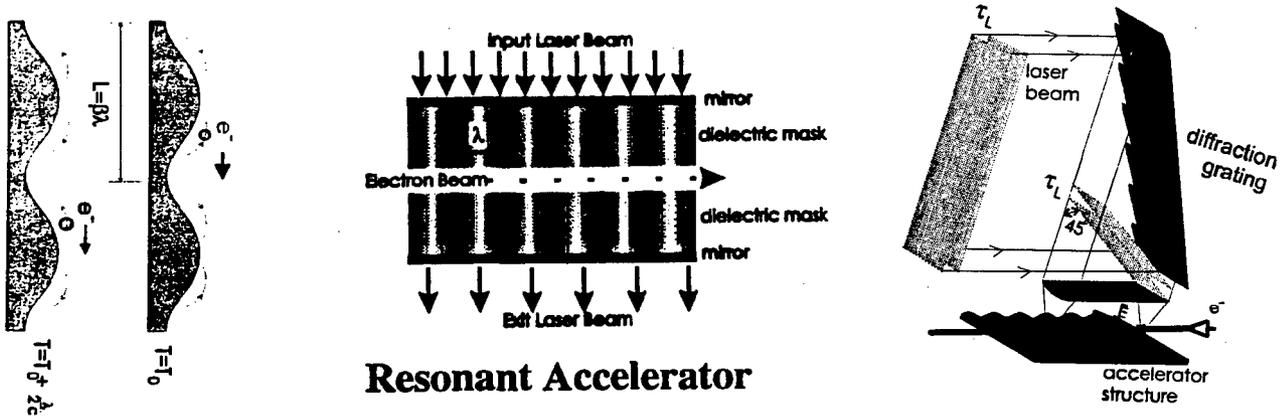
Resonant Accelerator

Figure 4: Schematics of near field acceleration
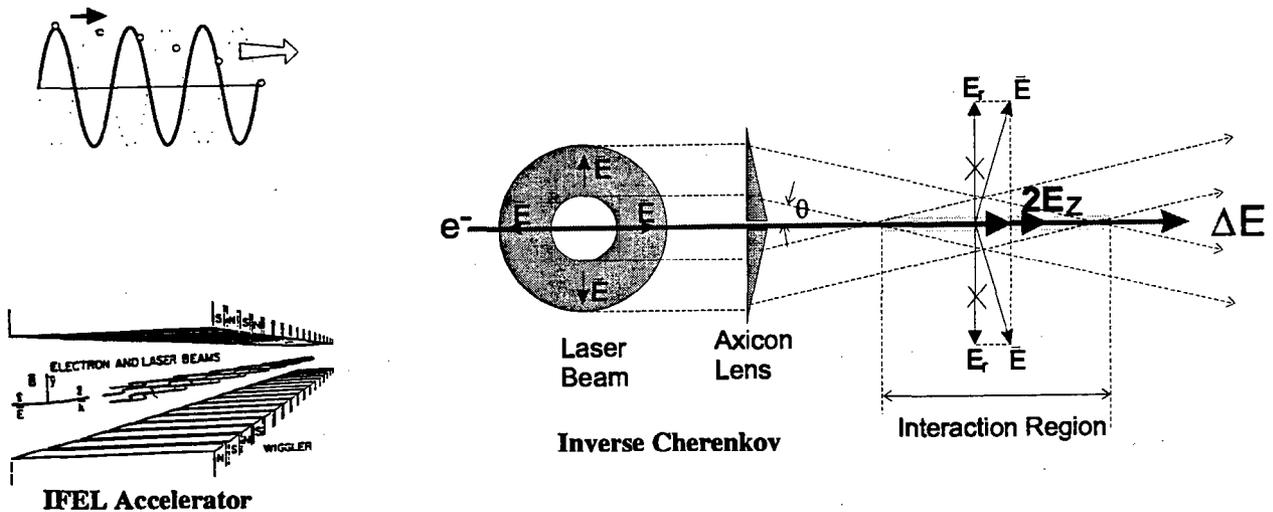
IFEL Accelerator

Inverse Cherenkov

Figure 5: Schematics of far field acceleration

wiggler (IFELSW). Similarly, in our new NAIBEA scheme [15] the applied field is taken as a constant field that changes sign abruptly and therefore it behaves more like a square wave. We have explored the new NAIBEA scheme as an IFEL with a square wave wiggler(IFELSW). To do this we introduced some modifications in the NAIBEA [14] field structure and in the way the electrons enter it. We showed [15] both analytically and numerically how IFEL with a square wave wiggler (and the new NAIBEA) accelerates particles and obtained explicit expressions for the average rate of energy increase. In that we have found a gain in energy of about two times when compared with the standard IFEL with a sinusoidal wiggler. We note that, although Maxwell's equations do not allow an abrupt change of sign of the field, the results we have obtained suggest that the acceleration scheme using laser field turns out to be more efficient as we approach the square wave field patterns[15].

Laser-Driven Photoinjector

In a Photoinjector, short bunches of electrons are generated by laser pulses incident on a photocathode located inside an rf accelerating structure. The structure is operated at a high accelerating field to make the electron bunch relativistic in a short distance. The high surface field on the cathode and the high yield of electrons due to photo emission can produce a very large current density, $e.g.$ $J = 10$ to 100000 A/cm^2 which is much larger than the current produced by thermionic emission ($e.g.$ $about$ $10 A/cm^2$). A Photoinjector can deliver a very high brightness,
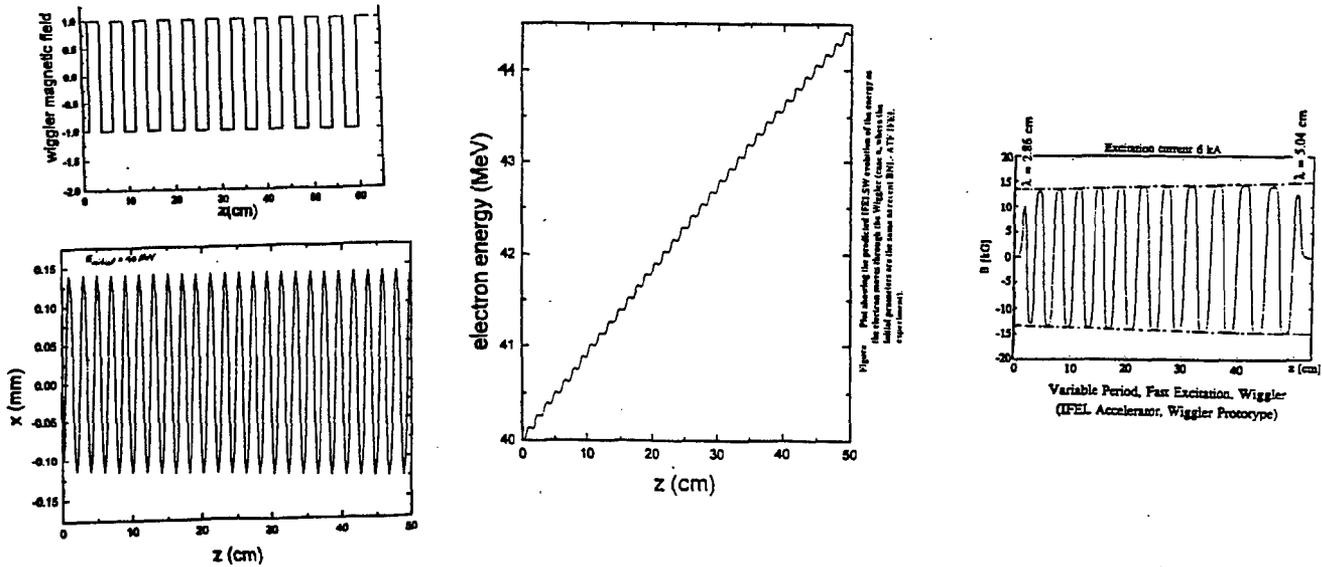
Figure 6: The above figures show the case of recent Brookhaven experiment

since the normalized thermal rms brightness B_N, (for a cathode effective temperature T) is proportional to the current density. Photoinjectors are in operation in many electron accelerator facilities. For example, we have a S-band photoinjector at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory.[12,6,7]
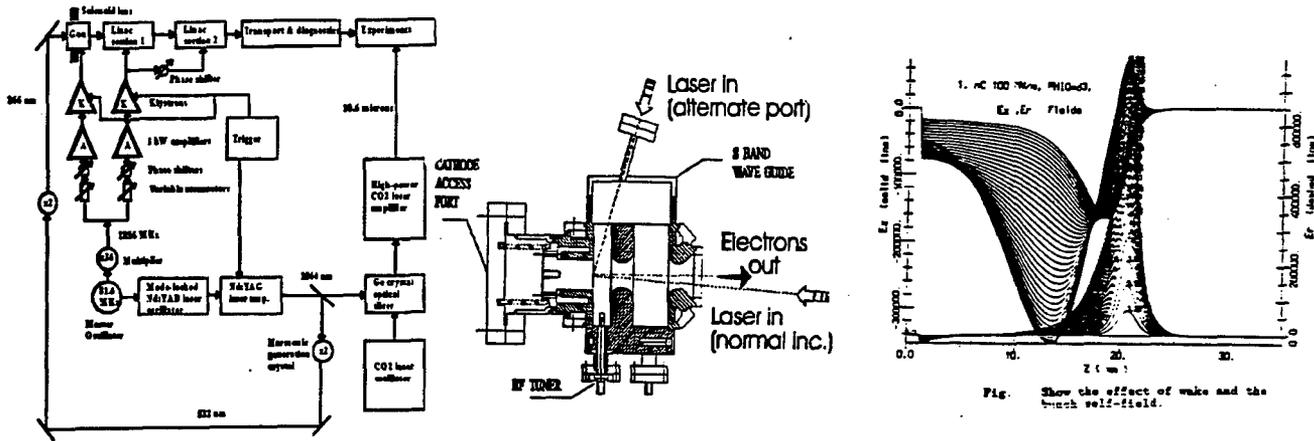

Figure 7: Schematic drawings of BNL- ATF, gun and a gun simulation.

The laser-driven rf gun is a resonant pi-mode $1\frac{1}{2}$ cell cavity operating at 2856 MHz. It uses a metal photocathode that forms part of the wall of the first $\frac{1}{2}$ cell. The 78.75 mm long cavity has 83.08 mm inner diameter with beam aperture diameter of 20 mm. The unloaded Q of 11900 and a shunt impedance of 57 MOhm/m, corresponds to the expected beam energy of 4.65 MeV at a structure peak power of 6.1 MW, with the cathode field of 100 MV/m. These operating conditions is expected to be achiveable after a few days of careful rf conditioning. The parameters that one control are the electric field on the cathode, the laser pulse length and the laser spot size. The remaining parameters are obtained from simulations with various computer codes, (for example see Ref [6,7,5]). The present photoinjector at the ATF uses a solenoid lens for initial focussing of the beam. Figure 7 shows the ATF photoinjector with the solenoid lenses. The solenoid-gun-solenoid photo injector and an example of a laser-driven photoelectron beam - simulation results[16] are also included.

High Energy Physics Requirements

There has been much theoretical and experimental work on the acceleration of particles using lasers, in the last two decades. Application of these new methods in high energy physics continues to be a major interest and a motivating force, for the effort. The high energy physics requirements, can be summarized by the "Luminosity" L, "Beamstrahlung energy spread" δ, the required collider operating "beam power" P_{beam}:

$$L = \frac{fN^2}{4\pi\sigma_x^2 R_{H/V}} \tag{7}$$

$$\delta = \frac{0.88r_e^3 N^2 \gamma}{R_{H/V}^2 \sigma_x^2 \sigma_z} \tag{8}$$

$$P_{beam} = 2\gamma mc^2 Nf = \eta P_{wall} \tag{9}$$

Where N is the number of particles per bunch, f is the frequency of the collider (bunch number times the repetition. rate), σ_x is the transverse rms bunch dimension at intersection, $R_{H/V}$ is the ratio of the horizontal to vertical beam size, r_e is the electron classical radius, E the beam energy, σ_z is the rms longitudinal bunch dimension. the efficiency η is the ratio of the beam power to the wall-plug power. Economic considerations provide us the wall-plug power P_{wall}, the high energy requirements provide us γ, L and δ, and the remaining unknown parameters $R_{H/V}$, N, σ_x, σ_z, can be expressed in terms of the independent variables such that σ_z scale approximately with the acceleration wavelength λ_{accel}. For convenience, the units are inserted in brackets in the following formula:

$$\sigma_x[nm] \approx 126\sqrt{\delta\sigma_z[cm]}\frac{\eta P_{wall}[GW]}{L[10^{35}]E^{3/2}[TeV]} \tag{10}$$

$$\frac{N}{\sigma_z}[cm^{-1}] = 6.4x10^{10}(\frac{\delta P_{wall}[GW]R_{H/V}}{L[10^{35}]E^2[TeV]}) \tag{11}$$

$$f[MHz] = 0.05\frac{L[10^{35}]E[TeV]}{\delta\sigma_z[cm]R_{H/V}} \tag{12}$$

Applying the above requirements for the example of a 1 TeV on 1 TeV high energy linear collider to laser - driven accelerators as we discussed [4], puts very severe requirements on the accelerators. The repetition rates must be very high and the emittance must be very small. The constraints are more severe, if one includes corrections (to the classical calculations) when calculating these parameters. The difficulties for the 1 TeV application makes it unlikely that these requirements can be met for higher energies at this time. Serious work is needed, to use the laser-driven accelerators for collider applications in the future.

Discussion

There have been solid advances in understanding of the laser-plasma processes in accelerating electrons. However, there still remain the need to look into the systems issues. How and if one could make a stageable accelerator? For example, see if the beam from a first gas jet can be focused (with an external solenoid or a quad) onto a second gas jet, and the plasma wave in the second, phased well enough with respect to the first, that e.g. 95% of the electrons make it into the capture bucket of the second stage. Laser accelerators are considered very promising to reach extremely high accelerating gradients greater than 100 GeV/m, but it would be more interesting to pursue a "stageable" concept that promisses e.g. 1 GeV/m, instead of few GeV (or > 100) from a few Rayleigh lengths, if they are to be used as (or part of) future colliders.

High energy accelerators take us to new domains. Such a facility, if feasible, would be a significant technological leap forward. These ideas and technologies should be considered to the degree they will bring revolutionary, not evolutionary changes to accelerators and to the way collisions at ultra high energies can be achieved.

Some of the remaining questions to be studied include: What are the means of injecting electrons with femtosecond precision? What are the means of creating plasma channels many Rayleigh lengths long? Can the electron beam properties be preserved through multiple synchronized accelerating stages? etc.

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