Advanced Acceleration Techniques*

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I. INTRODUCTION

With the demise of the SSC there is an increased urgency to develop advanced acceleration techniques capable of continuing the progress in high energy accelerator physics beyond the next linear colliders. Of the many alternative accelerator concepts currently being explored, it is impossible to predict whether any will ever meet the incredibly challenging requirements for a collider at 1 TeV and beyond. What is clear, however, is that there has been rapid and dramatic progress in this field, with particularly exciting results coming in the past year. Many of the new techniques may soon be ready for applications in industry, medicine and research that require compact and inexpensive accelerators in the 100 MeV-GeV range. This talk will highlight current research on several advanced acceleration techniques, including two beam, wakefield, laser and plasma accelerators.

To set the stage for the advanced accelerator concepts we are about to discuss, we first briefly review the challenges to building accelerators that can extend the frontier of high energy physics. These challenges are set both by economics and physics. The experience of the SSC has shown us that the capital construction costs of a machine on the 60 km scale are likely more than government and society are willing to bear. Taking 10 km as an arbitrary upper limit on accelerator length dictates that the acceleration gradient of an advanced linear accelerator must be 100 MeV/m to reach 1 TeV and 1 GeV/m to reach 10 TeV. We adopt 100 MeV/m as the first, although not necessarily the most stringent, requirement for any advanced acceleration technique. The accelerator must also be efficient and have reasonable stage lengths to prevent the operating costs and capital costs of the power sources from becoming exorbitant. These requirements and the need for high beam quality become clear from a survey of the physics requirements of the future machines.

The main physics requirement for a future collider is that the luminosity ($L = f N^2/4\pi\sigma_x\sigma_y$, where f is repetition rate, N is the number of particles in each beam, and $\sigma_{x,y}$ are the spot sizes in the x and y directions) exceed a few times 10^{33} cm^{-2} s^{-1} at 1 TeV and increase as the square of the energy at higher energy (in order to keep the physical event rate at a reasonable level). Any design example illustrates the importance of efficiency and beam quality. If $N = 10^{10}$ and the spot area is 10^{-4} μm^2, then $f \approx 10^3$ is required at 1 TeV and the average beam power ($2fN\gamma mc^2$) is 4 MW. Thus an overall wall plug efficiency of more than 1% is required to keep power consumption below, say 250 MW.[1, 2] Implicit in achieving such small focused spot areas is that beam quality (emittance and energy spread) must be jealously guarded (e.g., to reach σ_y= 1 nm with a flat beam requires $\varepsilon_N < 0.1$ mm - mrad). Further requirements arise from the maximum allowable beamstrahlung, pair production and disruption at the collision[3,4]. There have been proposals that relax these latter requirements, each solution with its own cost[5]. These are common to all the proposed accelerator schemes and are not discussed here.

All present and advanced accelerating schemes have in common that the energy they transfer to a particle is given by

$$\frac{d}{dt}\gamma mc^2 = q\,\bar{v}\cdot\bar{E} \tag{1}$$

That is, all require a large electric field that remains in phase with the particle over a long time (or distance), and they require a component of the particle velocity that is in the direction of $\bar{E}$. Each of the following techniques accomplish these simple requirements in a different way.

II. ADVANCED CONVENTIONAL ACCELERATORS

A natural approach to miniaturizing an accelerator is to do simply that -- scale down the dimensions (a) and RF wavelength (λ) of a conventional structure. This turns out to be a good idea for several reasons. First, at fixed peak power per unit length (p) or fixed RF pulse energy (u) one gains in accelerating gradient[6] (E_a):

$$E_a \propto p^{1/2}\,\lambda^{-1/4}$$
$$E_a \propto u^{1/2}\,\lambda^{-1} \tag{2}$$

Second, one increases the limit imposed by electrical breakdown of the structure walls (E_b)[7]:

$$E_b \propto \lambda^{-1/2}\,\tau^{1/4} \propto \lambda^{-7/8} \tag{3}$$

where τ is the filling time ($\leq 1\ \mu$s).

Many designs based on scaling linacs to higher frequency are being pursued for the next linear collider; they include collaborations on DLC (DESY Darmstadt), JLC (KEK, Japan) and SLAC-NLC (USA). (The TESLA collaboration is exploring a superconducting structure at lower frequency and gradient.) [8]

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Two big issues for extending such schemes to the ≥ 100 MeV/m level are (1) developing efficient power sources matched to the structure's requirements on peak power, frequency and pulse length, and (2) avoiding breakdown/dark current. There is a world-wide effort on alternative power sources including klystrons, gyroklystrons, EIK's (extended interaction klystrons), TWT's, twystrons, magnicons, gyrotrons, and FEL's (free electron lasers)[9]. 11.4 GHz klystrons producing > 50 MW for 0.5 μs with 44% efficiency have already been used to generate 100 MeV/m gradients in an unloaded structure at SLAC[10,2]. In order to keep the capital costs of the RF sources to a reasonable level, the number of sources[9] will probably need to be less than about 1000. For a TeV machine this requires that each source provide peak power on the order of 100 MW for of order 1 μs, preferably with efficiency of 50% or more.

There is a limit to the benefits of scaling conventional structures to ever shorter wavelengths due to transverse wakefields[11]. These scale as

$$W_T \propto \frac{1}{a^2\lambda} \sim \frac{1}{\lambda^3} \qquad (4)$$

and increase rapidly as λ is reduced. Since these lead to emittance growth and beam break-up (BBU) instabilities in multi-bunch operation[12] (needed for high efficiency)[8], a major challenge is the design of novel cavity geometries to damp out the long range wakefields.

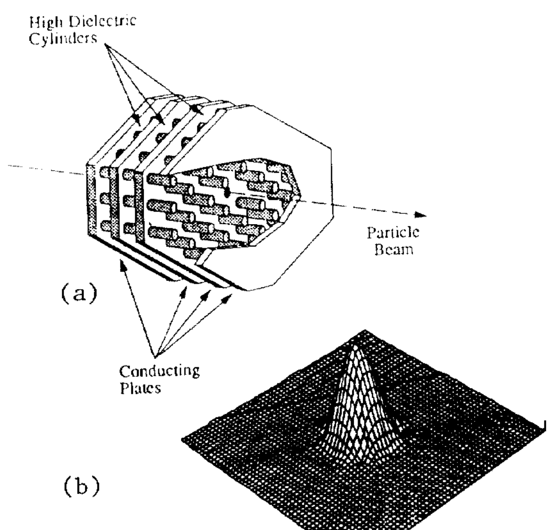

Figure 1. (a) A schematic view of the proposed pbg accelerator unit. In this example the unit consists of three triangular photonic lattices separated by superconducting sheets. Each of the lattices has a cylinder removed to allow the formation of a defect mode with an electric field maximum in the center. Holes drilled through the conducting plates would allow a particle beam to be accelerated through the unit; (b) Defect mode

Approaches that have been investigated include slotted structures that allow the power in higher order modes to couple to outer lossy regions and staggered cell dimensions that detune the wake from one section to the next. A truly revolutionary accelerating structure that has been proposed is called the photonic band gap structure[13]. It is an open structure consisting of a periodic array of dielectric (or metallic) cylinders as shown in Fig. 1. A defect in the lattice allows a localized (trapped) accelerating mode to be supported in a frequency range that would otherwise be in the band gap. Higher order wakefield modes can propagate freely away from the beam axis.

III. TWO BEAM ACCELERATORS (TBA'S)

An alternative power source that would represent a significant simplification is the two beam accelerator (TBA) concept[14]. In this scheme a high-current (drive) beam runs parallel to the accelerated beam in a separate structure. The drive beam produces radiation via a free electron laser mechanism (Lawrence-Berkeley Laboratory, USA approach) or a relativistic klystron interaction (CLIC, CERN and LBL approach)[15]. This radiation is diverted via output couplers to the high-gradient structure as shown in Fig. 2.

The drive beam is periodically re-accelerated (e.g. , via induction accelerator units or superconducting cavities). This scheme takes advantage of the high peak power and efficiency possible with a relativistic driver (e.g., 1000 MW at 34% efficiency were demonstrated in an FEL at LBL[16]). The re-acceleration of the drive beam overcomes the need for thousands of separate power sources.

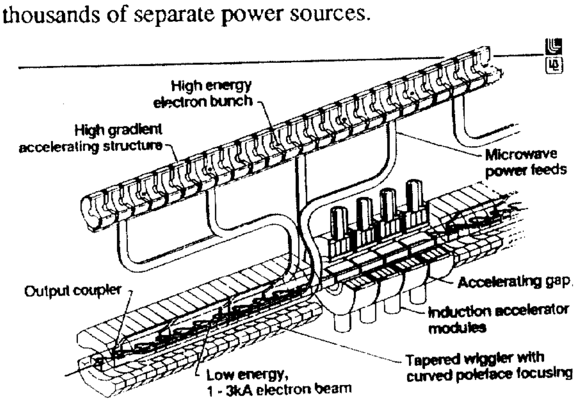

Figure 2. A two beam accelerator consisting of a high power microwave FEL and a high gradient linac.

Recent work on TBA's has included extensive modeling of the tolerance on drive beam quality in order to maintain control of RF phase[17], fabrication of scaled high gradient structures for testing with conventional power sources[18], and development of a new theoretical model that allows comparison of the relativistic klystron and FEL approaches to a TBA[19]. Simulations have shown that an FEL in a standing wave structure enables adequate control of RF phase if the structure is also designed to suppress BBU instabilities. Since the frequency generated by the relativistic klystron interaction is dependent on beam speed rather than energy, it has been shown that the tolerance on energy spread ($\Delta\gamma/\gamma$) is relaxed at high γ compared to the FEL interaction[19]. The final choice will depend on how such advantages trade off against the added difficulty of accelerating a bunched drive beam to high γ. Experiments at the CLIC test facility have already reached a 50 MeV/m gradient with a relativistic klystron TBA.

IV. WAKEFIELD ACCELERATORS

One step simpler than the TBA's, conceptually at least, are the wakefield accelerator schemes. Here the drive beam excites a wakefield in a structure or a medium (e.g., dielectric or plasma), and the high-energy beam is directly accelerated by this wakefield (i.e., without shunting the wakefield off to a separate structure). In order to overcome a fundamental wakefield theorem[20] and obtain a large transformer ratio (ratio of energy gained per trailing particle to energy per driving particle), various geometries have been proposed. These include non-collinear or hollow drive beams[21] and shaped beams with slowly rising and sharply falling current profiles[22].

Various proof-of-principle experiments were performed in the late 80's[21, 23, 24, 25]. At Argonne National Laboratory (ANL, USA) Jim Simpson's group used test particles to successfully confirm theoretical predictions of wakefields in hollow dielectric tubes[23] and in plasmas[24]. A multi-bunch driver experiment at KEK (Japan) led by A. Ogata accelerated trailing particles by 10 MeV over .75 m in a plasma[25]. Currently experiments are planned at ANL and UCLA (USA) to extend the experiments to high-gradients (up to 100 MeV/m) and non-negligible transformer ratio. The early ANL work showed that BBU instability and charging of the walls are critical issues in dielectric tubes. To overcome these, a design has been developed by which the driving and accelerating beams travel through different tubes. This scheme then resembles the TBA's of the previous section.

The plasma experiments may test a new regime recently identified theoretically[26]. This is the blow-out regime and occurs when the drive beam density exceeds the plasma density. In this case the plasma electrons are quickly expelled, leaving a uniform ion channel. The longitudinal and transverse wakefields (W_L, W_T) in the channel have attractive accelerating properties: W_L is very large $\geq \sqrt{n_o}$ eV/cm, where n_o is the plasma density in cm^{-3}), is not strongly sensitive to changes in drive beam radius and is independent of radial position r; and W_T is linear in r. The latter three properties are important for maintaining high beam quality. Methods of controlling electron-hose instabilities[27], achieving high transformer ratios and the acceleration of positrons are topics of current investigation. If the theoretical and experimental work is successful, it is possible to imagine the role of a plasma wakefield accelerator as a booster on a more conventional linac. For example, an appropriately shaped SLAC-type bunch ($N \sim 10^{10}$ at 50 GeV) could be used in principle to accelerate a trailing bunch of order 10^8 electrons to .5 TeV in 10 m of $3 \times 10^{17} cm^{-3}$ density plasma.

V. LASER ACCELERATORS

Several factors make laser drivers attractive for future accelerators, not least of which are the tremendous advances in high-power laser technology in recent years. As discussed earlier, high-gradients favor high peak power and short wavelength power sources. Lasers with peak power exceeding a terawatt (T^3 or table-top terawatt lasers) have become rather commonplace, and petawatt lasers are currently being built[28] using the techniques of chirped-pulse amplification (CPA)[29].

Since the electric field of a focused petawatt laser would be of the order 800 GeV/cm, it is interesting to consider whether the fields of the laser could be used directly to accelerate particles. Many articles have been written "proving" that there is no net acceleration in a focused laser or a plane wave in vacuum[30]; however, these assume the interaction length is infinite. We are not necessarily bound to this assumption in an experiment, and in fact if we remove the particle from the laser beam at the right time (e.g., with a plasma mirror in the laser path), the energy gain from the interaction can be considerable. A particle injected co-linearly with the laser gets a perpendicular velocity component $v_\perp$ from the laser electric field ($E_\perp$); this gives the particle a forward accelerating force $qv_\perp B$ and energy gain at a rate $qv_\perp \cdot E_\perp (\leq q^2E^2/\gamma\,\omega$, where ω is the laser frequency). The maximum energy gain is limited by the dephasing length (the distance for the particle of energy γ_o to fall behind the laser by a quarter of a laser cycle $\approx \gamma_o^2\lambda/2$) or the focal depth of the laser ($\leq 2\pi\sigma^2/\lambda$, where σ is the spot size and λ the laser wavelength):

$$\Delta(\gamma mc^2)^{Max}_{dephasing} \approx 46\,\gamma_o mc^2 \left(\frac{P}{TW}\right)\left(\frac{\lambda}{\sigma}\right)^2 \qquad (5)$$

$$\Delta(\gamma mc^2)^{Max}_{diffraction} \approx E\sigma \leq 20\text{ MeV}\sqrt{\frac{P}{1\text{ TW}}} \qquad (6)$$

where P is the laser power. These predict maximum energy gain of .6 GeV in 2 mm for a 4 MeV electron injected into a petawatt laser focused to $\sigma = 18\mu$.

The rapid progress in table top high-power lasers make vacuum acceleration (appropriately truncated) and the related inverse free electron laser[31] (IFEL) and cyclotron auto-resonant accelerator[32] (CARA) concepts attractive for making very compact (1 mm to 10 cm) 100 MeV accelerators for a variety of applications[33].

To obtain ultra-high energies, however, the $1/\gamma$ scaling of these schemes (as well as synchrotron radiation losses) eventually dictates that linear acceleration and hence a parallel electric field component are needed. A natural approach to achieving this is with miniaturized slow-wave structures on the scale of the laser wavelength. Although new micro-machining technology using lithographic techniques or open structures may make these feasible to build, some novel approach is still required to make the transverse wakefields (scaling as $1/\lambda^3$) small enough to avoid instabilities and degradation of beam quality. Furthermore, electrical breakdown is obviously an issue. Assuming for the moment that these problems could be overcome, R. Byer has described a scenario for a 1 km long TeV accelerator with 10^{10} electrons and a rep rate of 120 Hz[34]. To accommodate the beam load and avoid surface damage requires a rectangular slow wave structure 3 cm wide by 1 μ high. The laser needed to fill a 10 cm length of this structure would have a kW of average power. Byer points out that such a laser could be commercially available for approximately $25K in four years; and diode pumped solid state lasers already operate with wall plug efficiency of 10%.

An alternate approach to coupling particles to a parallel component of laser electric field is the Inverse Cerenkov Accelerator (ICA). In the ICA a parallel component of E is created by tilting the laser at a slight angle Θ to the particle beam direction in a gaseous medium. By choosing Θ to be the Cerenkov angle ($\Theta_c = \cos^{-1}$ [1/n], where n is the refractive index of the gas), the particles remain in phase with the (slowed) laser and can gain energy at a rate $q\,\vec{v} \cdot \vec{E} \approx qcE \sin \Theta_c$. The perpendicular component of E can be nearly canceled (leaving a modest net focusing force) by using a converging laser geometry as shown in Fig. 3[35]. In a recent experiment led by W. Kimura at Brookhaven National Laboratory (USA)[36], this technique was used to accelerate test particles with a .7 GW CO_2 laser (λ = 10.6 μ) in an H_2 gas at 2.2 atm (Θ = 20 mrad). Energy gain from 40 MeV to 43.7 MeV over 12 cm was measured for a gradient of 31 MeV/m in agreement with their theoretical model.

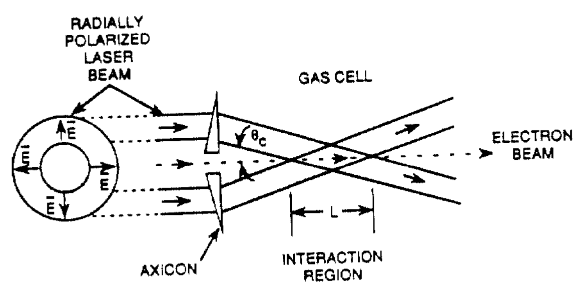

Figure 3. Arrangement for the inverse Cerenkov interaction. The electrons travel parallel to the z axis and the laser beam consists of a radially polarized field that passes through an axicon and converges at an angle Θ_c onto the z axis[35].

Critical issues for this scheme are how to avoid gas ionization by the laser (limiting E), how to maximize n and hence Θ and $E_{\|}$ without increasing gas pressure and consequent particle beam scattering (e.g., by taking advantage of atomic resonances), and how to stage (by re-focusing the laser beam). An interesting twist on the ICA in the geometry of Fig. 3 is to remove the gas[37]. This eliminates the gas ionization and scattering issues, but results in phase slippage between the particles and laser. By choosing the laser spot size to be $\sigma < \lambda/\Theta$ and injecting particles with energies $\gamma_o > 1/\Theta$, it may be possible to limit phase slip to less than λ/2 in a Rayleigh length. In this case the energy gain per stage would be roughly given by Eq. (6) (without suffering the 1/γ scaling of the gradient).

A final approach to utilizing the high peak power of lasers is to use them to drive longitudinal space charge waves in a plasma. Plasma waves are accelerating structures that support large parallel electric fields and are immune from electrical breakdown. The plasma waves can be driven resonantly by the radiation pressure of a train of laser pulses[38, 39] separated approximately by a plasma period ($2\pi/\omega_p$, where $\omega_p = [4\pi n_o e^2/m]^{1/2}$) as in the beat wave accelerator or by a single short ($\approx \pi/\omega_p$) pulse as in the laser wakefield accelerator[38, 40]. In the beat wave scheme the accelerating gradient scales as

$$E_{\|} = \sqrt{n_o}\ \mathrm{V/cm} \cdot \int_0^{\tau} dt\, \alpha_1\ \alpha_2\ \omega_p / 4 \qquad (7)$$

where $\alpha_{1,2} = eE_{1,2} / m\omega_{1,2}c$ is the normalized oscillatory velocity in the laser field, $\omega_1 - \omega_2 = \omega_p$, n_o is in cm^{-3}; and τ is the smaller of the laser pulse length, the relativistic detuning time ($\approx 7\ [\alpha_1\ \alpha_2]^{-2/3}/\omega_p$) and the time scale for ion instabilities (a few times the ion plasma period $\approx 43 \times 2\,\pi/\omega_p$)

Several groups including C. Joshi, et al. at UCLA (USA), A. E. Dangor, et al. at Rutherford (UK), F. Amiranoff, et al. at Ecole Polytechnique (France) and Y. Kitagawa, et al. in Osaka (Japan) have performed beat wave experiments in the last decade, successfully demonstrating the generation of plasma waves with longitudinal fields of 1 - 3 GeV/m and phase velocity ≈ c.[41] Recently UCLA[42], Osaka[43] and a group at National Research Council (Canada)[44] have also reported acceleration of injected particles. In Fig. 4 the set-up and sample results of the UCLA experiment are shown.

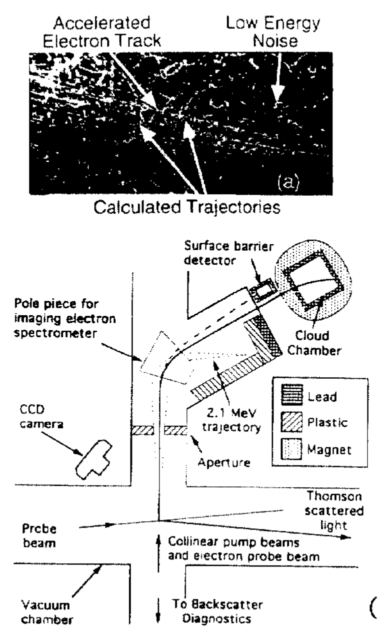

Figure 4. UCLA Beatwave experiment[42]: (a) accelerated electron trajectories at 5.2 MeV in the cloud chamber; (b) setup.

The UCLA group accelerated ~ 10^5 test particles (approximately 1% of the randomly phased injected particles) from 2 MeV to up to 30 MeV over 1 cm in a plasma of density 8 x 10^{15} cm^{-3}. This corresponds to a gradient of 3 GeV/m. The energy gain was limited by the focal depth of their CO_2 lasers. The experiment confirmed earlier simulations and theoretical work predicting that competing instabilities could be avoided by employing short laser pulses (compared to an ion plasma period ≈ 43 x $2\pi/\omega_p$) of sufficient amplitude ($eE/m\omega c \geq .1$). Based on these results it is possible to extrapolate the UCLA design to a 1 GeV experiment over ~ 10 cm using T^3 class lasers beating in a 10^{17} cm^{-3} density plasma. Results of a model of this design are shown in Fig. 5.

The critical issues for laser-plasma accelerators beyond 1GeV include diffraction and staging; long time scale instabilities and pump evolution[45]; dephasing[46]; beam loading; beam quality and efficiency[47]. Pre-formed plasma channels have been explored recently both theoretically[48, 49] and experimentally[50] as a means of confining the laser for many diffraction lengths as well as for creating accelerating and focusing fields that are optimal for high beam quality.

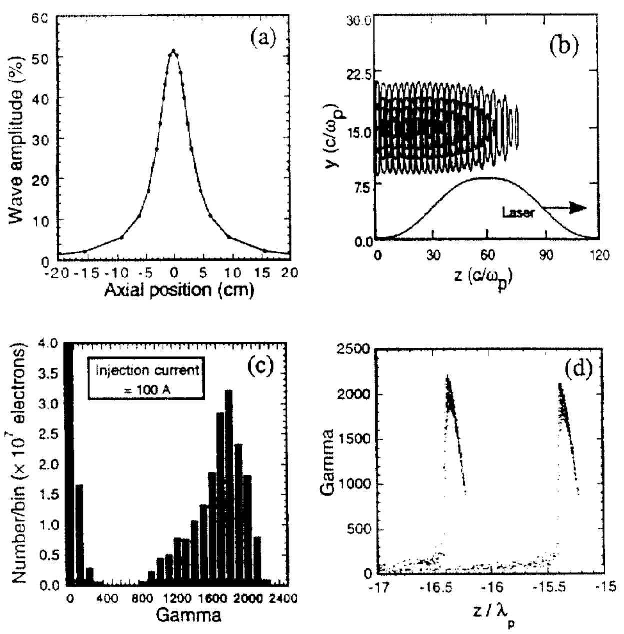

Figure 5. A model of a GeV plasma beatwave experiment (n_o = 10^{17} cm^{-3}, P_{laser} = 14 TW, τ = 2 ps, σ = 100 μ, $\lambda_{1,2}$ = 1.05, 1.06 μ). [51] The plasma wave is shown in a and b and final particle distribution in c and d.

VI. ADVANCED ACCELERATOR RESEARCH

Many of the advanced accelerator schemes just described as candidates for future colliders can play other roles in accelerator technology. They may make compact light sources for applications in industry, medicine and research. For example, the time structure of the microbunches in Fig. 5(d) is such that if these bunches were sent through a wiggler, they would produce bursts of x-rays only 30 fsec long, coming every 300 fsec. Some of the advanced accelerator schemes can be modified to produce strong focusing fields. These focusing fields can be used to make ultra-high strength lenses for low energy anti-protons[52], heavy ion fusion and for the final focus of a collider[53]. For example, the effective magnet strength of a plasma lens can be as high as a Giga Gauss/cm (at a beam density of 3 x 10^{17} cm^{-3}) or higher. Another use for the ultra-strong fields of a plasma lens has recently been suggested; namely, that in a $\gamma - \gamma$ collider they be used to overfocus the electron beams and scatter them away from the interaction point. Experimental results of a thin plasma lens experiment at UCLA this year are shown in Fig. 6[54].

This is an exciting time for advanced accelerator research. Both physical understanding and supporting technologies are improving at a rapid pace. As a result, given reasonable levels of funding, proto-type advanced accelerators at the GeV level are possible within the next five years.

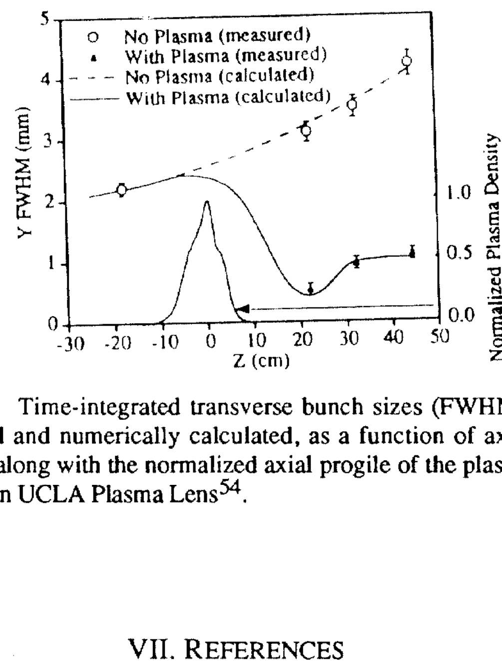

Figure 6. Time-integrated transverse bunch sizes (FWHM), measured and numerically calculated, as a function of axial position along with the normalized axial progile of the plasma density, in UCLA Plasma Lens[54].

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