AN ELECTRON SOURCE FOR A LASER ACCELERATOR*

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Abstract

Laser accelerators offer the promise of producing attosecond electron bunches from a compact accelerator. Electron source requirements for laser accelerators are challenging in several respects, but are achievable. We discuss these requirements, and propose an injector design. Simulation and design work for essential components for a laser accelerator electron source suitable for a high energy physics machine will be presented. Near-term plans to test key technical components of the laser injector will also be discussed.

INTRODUCTION

Laser performance has improved markedly in recent years, bringing the possibility of using lasers to accelerate charged particles closer to reality. Advances in power output though optical parametric chirped-pulse amplification, the mass production of inexpensive, highly efficient diode bars for laser pumping, and the production of very low quantum defect materials has already raised the wall-plug-to-light power efficiencies of high-power solid state lasers beyond 10% with theoretical limiting efficiencies of 30-40% possible. Advanced mode-locking and dispersion control techniques have led to lasers that are mode-locked and phase-locked at the optical carrier frequency, an essential step towards synchronizing many lasers to power a high energy accelerator.

Many laser acceleration mechanisms proposed for linear colliders rely on dielectric or metallic structures with beam tube apertures on the order of the accelerating wavelength, of the order of micrometers for laser-powered accelerators. Producing the required luminosity for high-energy physics applications will therefore require that high power beams be produced in spite of these tiny apertures. We offer an example here of how the demands for a linear collider can be met, and outline future experiments to test some of the key technical components.

A number of candidate structures with sufficiently high shunt impedance to give reasonable power efficiency for a laser linear collider have been proposed, and share in common accelerator apertures of order of the accelerating field wavelength. The example here is based on a structure proposed by Lin[1], and analyzed by Siemann[2].

The optimal beam loading bunch charge for the Lin photonic band gap structure (PBG) powered at a gradient of 1 GeV/m corresponds to ~1.5x10^5 electrons per laser pulse. Producing 10 MW of beam power at 0.5 TeV requires ~1.2x10^{14} electrons per second, or a bunch repetition rate of ~830 MHz at this population.

Obtaining this high repetition rate will require that the laser accelerator structures be embedded in resonant rings[3] with the driving laser amplifiers, together with suitable phase and dispersion control. Resonant recirculation of the laser power will not only reduce the average power required from the drive lasers by recycling the remaining laser power, but practical resonant ring dimensions (~1 m) will quite naturally lead to pulse spacings in the hundreds of megahertz.

Figure 1 illustrates the resonant enhancement of power coupling efficiency (power transferred to the beam in ratio to the total power input to the structure) against the recirculation Q of the resonant ring. The first curve at left corresponds to the η=5% power coupling efficiency of the Lin PBG structure, successive curves correspond to successively lower single-pass power efficiencies. It is clear that for very modest recirculation Q values (<10) the PBG structure power coupling efficiency approaches the power coupling efficiency of the NLC structures.

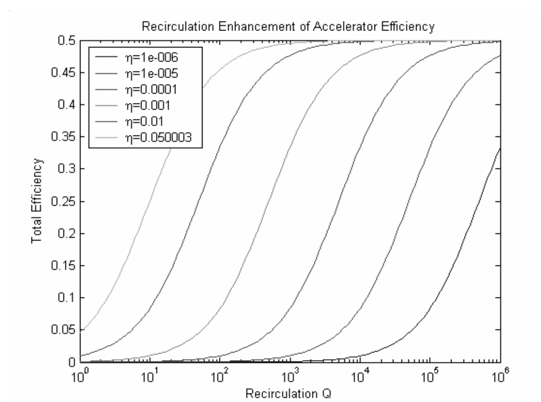

Figure 1: Enhancement of power efficiency through power recirculation.

Recirculation of the laser pulse offers a means to both increase power efficiency and to naturally obtain the high repetition rates needed to produce useful luminosities.

The micrometer-scale accelerator apertures naturally require very small normalized emittances for unintercepted beam transport. If the beam must maintain an n=5σ clearance from the accelerator (assumed to operate at 2 μm wavelength), which has an aperture a=1.2λ=2.4 μm, and focusing is carried out with permanent magnet quadrupoles of length L_q=1 cm with 0.1 mm apertures, K_q=2.5 kT/m gradients (2.5 kG pole tips fields), and a $\phi=\pi/4$ phase advance lattice is used, then the maximum normalized emittance is:

$$\varepsilon_N = \frac{a^2}{n^2}\frac{eK_qL_q}{2mc}\frac{\cos(\varphi)}{1+\sin(\varphi)} = 7\times10^{-4}\pi \text{ mm-mr}$$

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Although this is a very small normalized emittance, it is at very low charge ($5x10^5$ e/bunch or 80 fC/bunch). The transverse phase space density for this case is just $D=Q/e_N$~0.12 nC/π mm-mr, which is nearly an order of magnitude lower than the density sought for linac-based FELs, D~1 nC/π mm-mr, and is well within the current performance capabilities of rf guns.

INJECTOR CONCEPTUAL DESIGN

Obtaining very small transverse emittances from an rf gun requires aggressive control of the space charge and rf emittance growth. Space charge driven growth is naturally low given the small bunch charge. RF emittance growth is given by $\varepsilon_N=\alpha\ k_{rf}^3\ \sigma_x^2\sigma_z^2 2^{1/2}$, with α the dimensionless accelerating gradient, k_{rf} the rf wavenumber, σ_x the spot size, and σ_z the bunch length[4]. Suppressing transverse rf emittance growth therefore favors using the smallest possible bunch dimensions in a low gradient, low frequency rf gun. Further reduction in spot size, and hence transverse emittances, is possible by focusing the electron beam early on. A normal conducting rf gun, permitting a solenoid field to be introduced for focusing purposes, is therefore desirable. Additionally, thermal emittance contributions grow linearly with initial spot size, further motivating very small initial spot sizes.

Obtaining the required high repetition rate means the rf gun and booster accelerator must run CW with a bunch containing ~$5x10^5e^-$ in every rf cycle. A normal conducting gun is required to permit solenoid focusing to keep the bunch (and hence the transverse emittances) small. Heat removal from a normal conducting rf gun operating CW is a daunting challenge, but one which has been largely met.

The Boeing APLE injector, built and operated in the early 1990s, demonstrated several essential aspects of the required technology[5]. The rf gun was a room-temperature, 433 MHz, 1.5 cell, solenoid-focused rf gun which demonstrated operation at 25% duty cycle, and used a high quantum-efficiency bi-alkali photocathode that could be rejuvenated in an attached preparation chamber. We have taken the frequency and operating gradient of this gun as our starting point for the following demonstration calculation.

Path length and collective effects would rapidly wash out optical bunching at low energies, so a booster linac must be used to accelerate the beam prior to optical bunching. For the example here, four TESLA-type 1.3 GHz, 9-cell superconducting cavities operating CW at 18 MeV/m gradient raise the beam energy to 61 MeV. It may prove advantageous to perform the optical bunching at still higher energies, an optimization that will be studied in the future. Since only one linac rf bucket in three is loaded, adding two more 433 MHz guns and interleaving the pulses would triple the current, and provide both for better gun failure tolerance and for continuous beam operation with two injectors while the third (for example) has its cathode reprocessed.

An IFEL buncher operating at the accelerator wavelength is used to produce the required optical bunching. Like the downstream laser accelerator structures, the IFEL will most likely be embedded in a resonant ring to reduce the average power required from the drive laser.

Plots of the transverse envelope and emittance evolution were calculated with Parmela through to the exit of the microwave injector and are shown in Figure 2. Evolution of the bunch length and energy spread are shown in Figure 3. Final electron bunch properties at the exit of the microwave linac are summarized in Table 1.

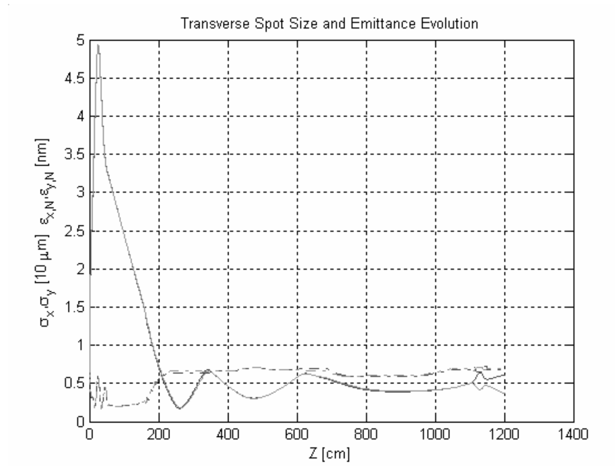

Figure 2. Transverse RMS beam sizes (solid curves, in units of 10 μm) and normalized (one-sigma) emittances (dashed curves, in units of nm) through the injector.

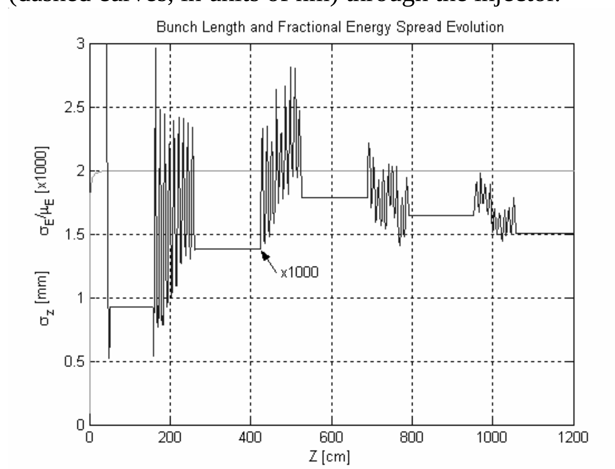

Figure 3. RMS bunch length and fraction energy spread (x1000) through the injector.

Optimization of the transverse emittance has been accomplished at the expense of significant increase in the longitudinal emittance, as can be seen in Table 1. The longitudinal emittance value (70 deg-keV), although for an 80 fC bunch, is more typical of an optimized 1 nC bunch. As the IFEL bunching process will induce significant energy spread beyond this value, this is not a serious issue.

Table 1: Beam Properties at Microwave Accelerator Exit

Property	**Value**	**Units**
Bunch Charge	5.8×10^{5}	e^{-}
Bunch Rep Rate	433	MHz
Energy	61.5	MeV
Transverse emittance	7.7×10^{-10}	m
Transverse emittance (65% collimated away)	3.6×10^{-10}	m
Transverse P.S. Density	0.12	nC/mm-mr
Bunch Length (rms)	6.7	ps
Fractional Energy Spread	0.0015	
Longitudinal Emittance	70	Deg-keV

Optical bunching of the resultant beam has been studied via numerical simulations in some detail, and will be tested experimentally at an optical wavelength of 800 nm in future experiments at SLAC.

LASER ACCELERATION AT THE NLCTA

Demonstration of optical bunch formation, capture, and subsequent acceleration at 10.6 μm wavelengths has already been demonstrated experimentally by the STELLA collaboration[6]. We are in the process of designing and constructing a facility at SLAC to produce pulse trains bunched at 0.8 μm for acceleration and wakefield experiments. This effort is part of experiment E-163, “Laser Acceleration at the NLCTA”, approved in the summer of 2002. Facilities construction is underway now.

The NLCTA accelerator injector will be used to supply 60 MeV bunched beam similar to that simulated above, but at significantly higher charge and emittance. An rf gun will be installed at the position of the current thermionic gun, and 60 MeV beam extracted into a separate shielding enclosure. Simulations[7] show that very cold $\delta=2\times10^{-4}$, short σ_t=1-2ps, low charge q=50 pC beam can be produced for laser acceleration experiments. Detailed simulations of an IFEL optical buncher with magnetic chicane compressor using Genesis and Elegant are shown in Figure 4.

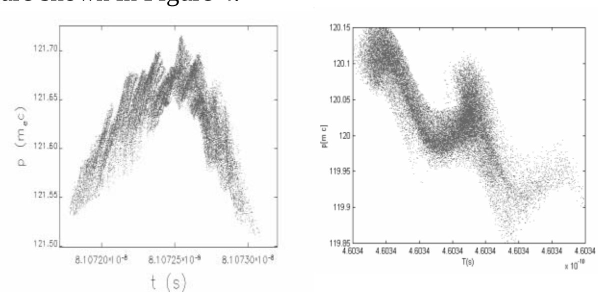

Figure 4. Unbunched (left) and optically bunched (right) longitudinal phase spaces. Entire time scale on left spans 1.5 psec, on the right: 3.3 fsec (one optical cycle).

The phase space plot on the right shows all ~450 optical pulses plotted one atop the other to show the degree of optical bunching over the entire ~1.2 psec long pulse.

The IFEL is a 3-period, 1.8 cm period, variable-gap permanent-magnet undulator (a_w=0.45) with half-period matching and mirror plates at the ends. NeFeB permanent magnets and vanadium permendur pole tips are employed. The chicane is a standard magnetic chicane, with $\theta=0.8^{o}$ rectangular bends of a hybrid permanent-magnet and coil excitation design. At optimal bunching, the correlated energy modulation induced for bunching is just 0.1 %. In principle, an IFEL alone could be used to bunch the electrons, however for the E163 experiment, a very small final energy spread is desired so that small energy gains (or losses) from short prototype laser accelerator structures can be clearly observed.

Once the IFEL and magnetic compressor are commissioned at the NLCTA, trains of optical bunches will be available for testing acceleration and wakefield properties of candidate laser accelerator structures.

CONCLUSION

We have presented a conceptual design for an electron injector, built from conventional technologies, which is a solution to the challenge of producing beam properties suitable for a laser-driven linear collider. Additional work to optimize the design, and explore options, such as the introduction of additional harmonic bunching stages to improve capture efficiency, will be explored in the future.

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