# BEAM SLICING WITH LASERS AND PLASMAS FOR HIGH-TRANSFORMER-RATIO PLASMA WAKEFIELD ACCELERATION

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*Abstract*

A novel method of "slicing" electron beams – Laser-Plasma Scissors (LPS) is suggested. Generation of the sharp-edged beams for high-transformer-ratio plasma wakefield acceleration (PWA) is considered numerically and analytically. Slicing, high-transformer-ratio acceleration, and beam loading are studied numerically, using a one-dimensional code which treats plasma as a linear medium and electron beams as a collection of macroparticles. A tentative design of a multi-stage PWA with laser slicing is presented. Other applications of LPS include generation of ultra-short bunches for sychrotron radiation.

## 1 INTRODUCTION

Because of the very high electric field it can sustain, plasma has been proposed [1] as a medium for high-gradient particle acceleration. Plasma waves can be excited by relativistic electron bunches [2, 3] in a plasma wakefield accelerator (PWA) or by intense laser pulses [1] in a laser wakefield accelerator (LWA). In this paper we describe the possibility of shaping the driving electron bunch (in the PWA scheme) by the laser pulse, in presense of the plasma. This shaping may lead to high ratio of energy transfer between from the driving to the accelerating beam. A straw-man design of a high-efficiency, multi-stage TeV electron-positron collider, based on this scheme, is presented.

Electron drivers offer several advantages over laser drivers, including (i) long interaction distance due to low emittance (ii) high repetition rates (a megahertz or higher) of rf photocathode guns (iii) possibility of recovering the unused beam energy by sending the beam through an rf cavity.

Unfortunately, the fundamental wake theorem [2, 4] limits the transformer ratio – the peak accelerating field $E_+$ experienced by the accelerated electrons over the average decelerating field $\langle E_- \rangle$ acting on the driving electron bunch – to less than 2 for symmetric bunches. This makes the total length of the conventional acceleration necessary to produce the driving beams very large. The transformer ratio might be increased by utilizing shaped driver bunches [3] with a slow rise in density and an abrupt termination over a distance smaller than a collisionless skin depth of the plasma $k_p = \omega_p / c = \sqrt{4\pi e^2 n_0 / m}$. Novel approaches to beam slicing have to be used to produce such an abrupt termination. In this paper we propose to use an ultra-short intense laser pulse, co-propagating with the electron beam through the plasma, to induce energy variation in a small slice of the electron beam. A magnetic chicane (or simply a magnetic bend) can then be used to scrape off the affected slice, thereby creating a sharp edge in the beam density, and splitting it into two bunches.

A novel configuration of PWA is suggested, in which the leading driving bunch excites the wake; it is followed by the accelerating ( witness) bunch, which is accelerated with high transformer ratio; the trailing driving bunch "cleans up" the wake, left behind the leading driving bunch and the accelerating bunch. Limits on per-stage acceleration, acceleration efficiency, and the transformer ratio of this scheme are studied analytically and numerically. Tentative parameters for a multi-stage high transformer-ratio PWA, with energy gain of about $400$MeV per stage, are presented.

High transformer ratio in a PWA can be achieved by shaping the driving e-beam. For example, if the beam density is a Gaussian, with a sharp termination at the peak density, i.e. $n_b(\zeta) = n_{b0} \exp\left(-\zeta^2/2\sigma_z^2\right)$ for $\zeta < 0$ and $n_b(\zeta) = 0$ for $\zeta > 0$, the ratio between the peak *accelerating* field behind the bunch and the peak *decelerating* field at $\zeta = -\sigma_z$ is approximately equal to $T \approx 11.0\sigma_z/\lambda_p$. To slice the beam we consider a laser-plasma scissors (LPS) configuration. For simplicity, consider a short flat-top laser pulse, of duration exactly equal to the plasma period $2\pi/\omega_p$,.co-propagating through the plasma with a longitudinally Gaussian electron beam of duration $\sigma_z \gg \lambda_p$. Such a laser pulse has an important property of leaving no plasma wake behind it. While in practice flat- top laser pulses may not be obtainable, a combination of, two Gaussian pulses separated by half of a plasma wavelength, may be utilized to reduce the wake behind the pulses.

Neglecting the electron self-wakes, find that electrons at $\xi < 0$ and $\xi > \lambda_p$ are unaffected by the wake, while the electrons at $0 < \xi < \lambda_p$ are modulated in energy. Assuming linear response of the plasma, i.e. $a_0^2/2 \ll 1$, the peak longitudinal field of the wake is estimated as $eE_z = a_0^2/2[\mathrm{GeV/m}]\sqrt{n_p/10^{14}\mathrm{cm}^{-3}}$. Assuming that the interaction length is limited by laser diffraction to twice the Rayleigh length, the energy change of the beam electron at the wake phase $\phi = \omega_p(t - z/c)$ is given by $\Delta E = 2\pi e E_z \sin\phi w^2/\lambda_0$. In practical units,

$$\Delta E\ [MeV] \approx \frac{14.0 \sin\phi U_L\ [\mathrm{J}]\lambda_0\ [\mu]}{n_p/(4\times 10^{17}\mathrm{cm}^{-3})}, \qquad (1)$$

where $U_L$ is the laser energy. After the plasma section, electron beam can be passed through a magnetic bend with a scraper, thereby removing beam electrons which were subjected to the wake. The final result of these manipulations is an electron beam consisting of two half- Gaussian parts, with a $\lambda_p$-long hole between them.

To verify these ideas numerically, a one-dimensional code was developed. The philosophy behind the code is

Table 1: Parameters for a $0.4$ GeV per stage high-transformer-ratio PWA with laser-plasma slicing

| | | |
|---|---|---|
| Drive beam energy | $\gamma mc^2$ | 100 MeV |
| Laser Energy | $U_L$ | 1.0 J |
| Pulse duration | $\tau_L$ | 160 fs |
| E-beam current | $I_b$ | 2.0 kAmp |
| E-beam radius | $r_b$ | 50 $\mu$ |
| E-beam emittance | $\epsilon_n$ | 2 $\pi$mm mrad |
| E-beam density | $n_b$ | $6.0 \times 10^{15}$ cm$^{-3}$ |
| Bunch length | $\sigma_z$ | 1.0 psec |
| Plasma density | $n_p$ | $4 \cdot 10^{17}$ cm$^{-3}$ |
| Accelerating gradient | $W_z$ | 1.0 GeV/m |
| Final energy | $\gamma_f mc^2$ | 0.5 GeV |
| Length of slicer | $L_{sl}$ | 50.0 cm |
| Length of accelerator | $L_{acc}$ | 0.25 cm |
| Rayleigh length | $Z_r$ | 0.75 cm |
| Beam divergence length | $Z_D$ | 25.0 cm |
| Dephasing length | $Z_{deph}$ | 200 cm |
| Peak EER | $\eta$ | 0.2 |

that in a viable plasma-based accelerator plasma dynamics should remain linear. However, the full nonlinear dynamics of the driving beam needs to be modeled. Laser pulse is asumed non- evolving in the code. This is justified by our assumption that the interaction distance does not exceed a Rayleigh length. Thus, every beam particle excites a sinusoidal plasma wave and moves in a combined wake field of (i) laser pulse and (ii) all other beam electrons ahead of it.

We simulated propagation of electron beam+laser pulse through $2.5$mm of plasma using parameters from Table 1. Electron phase space is shown in Fig. 1.

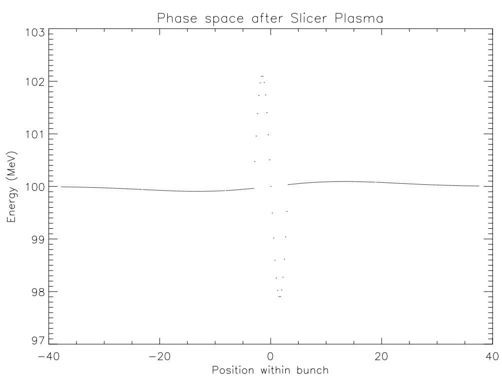


Figure 1: Electron phase space at the end of the laser-plasma scissors.

To simulate the effect of the magnetic chicane we removed all the beam electrons with energies differing from the initial energy ($100$MeV) by at least twice the energy change of an electron at $\zeta = \pm\sigma_z$. As a result, a split-beam driver is generated, which can now be injected into the plasma for high transformer ratio high efficiency plasma wakefield acceleration.

With the possibility of beam-slicing established, one can envision a multi-stage Tev-scale accelerator, based on a concept of plasma wakefield acceleration. A single stage of such an accelerator consists of 5 sections: (1) RF photocathode gun (2) laser-plasma scissors (3) magnetic chicane (4) plasma-wakefield accelerator (5) energy recovery rf cavity. Sections (1) and (5) can be combined so that the same RF cavity performs the functions of energy recovery from stage $N$ and rf injector into stage $N + 1$.

Below we calculate how much energy accelerating electrons gain inside section (4). Assume that the overall length of the plasma is approximately equal to twice the distance over which the cross-section of an unfocused beam doubles, $z_D = \gamma r_b^2/\epsilon_n$ (thereby neglecting plasma focusing). The peak accelerating gradient in *overdense* plasma $n_p > n_b$ can be estimated as

$$W_z[\mathrm{GeV/m}] \approx \frac{(n_b/10^{14}\mathrm{cm}^{-3})}{(n_p/10^{14}\mathrm{cm}^{-3})^{1/2}}. \quad (2)$$

Simple scaling can be derived for the total gained energy:

$$\frac{\Delta E_{acc}}{E_{drive}} \approx \frac{12Q[\mathrm{nC}]}{\epsilon_n[\mathrm{mm\ mrad}]}\frac{\lambda_p}{\sigma_z}, \quad (3)$$

where $\Delta E_{acc}$ is the energy gained by the accelerating electron, $E_{drive}$ is the energy of the driving beam electron, $Q$ is the total charge of the driving beam.

As Eq.(3) indicates, the single-stage energy gain of accelerating electrons *decreases* as the the bunch length increases. On the other hand, the transformer ratio *increases* as the bunch length increases, according to

$$\frac{\Delta E_{acc}}{\Delta E_{drive}} \approx \frac{3.3\pi\sigma_z}{\lambda_p}. \quad (4)$$

Beam length (in units of $\lambda_p$) determines the peak energy extraction ratio $\eta = \Delta E_{drive}/E_{drive}$, thereby fixing the transformer ratio $T$ and fractional energy extraction per stage $\eta$:

$$T \approx \frac{11.0}{\eta^{1/2}}\left(\frac{Q[\mathrm{nC}]}{\epsilon_n[\mathrm{mm\ mrad}]}\right)^{1/2}, \quad (5)$$

$$\frac{\Delta E_{acc}}{\Delta E_{drive}} \approx 11.0\eta^{1/2}\left(\frac{Q[\mathrm{nC}]}{\epsilon_n[\mathrm{mm\ mrad}]}\right)^{1/2} \quad (6)$$

Note that the fraction of energy the driver beam loses on average is $\bar{\eta} \approx 0.5\eta$. Extracting a large fraction of the driver beam energy per stage increases the energy gain per stage, but has a disadvantage of decreasing the transformer ratio. Present day emittance compensated photoinjectors are, in principle, capable of delivering electron beams with $Q[\mathrm{nC}]/\epsilon_n[\mathrm{mm\ mrad}]$ of order unity [5]. If, for example, a $100$ MeV drive beam is used, and $\eta = 1/4$ of its energy is spent on exciting the plasma wake, transformer ratio $T = 22$ can be achieved, with single-stage acceleration $\Delta E_{acc} \approx 0.4\mathrm{GeV}$. This is confirmed by the numerical simulation. The phase space of the driver and test electrons after the accelerator stage are shown in Fig. 2, where $2.0$

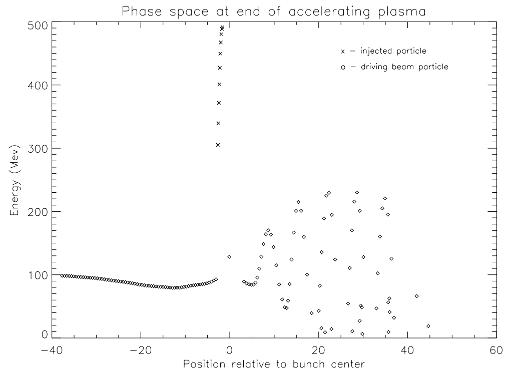


Figure 2: Electron phase space at the end of the laser-plasma scissors.

nC of driver beam are used to accelerate about $2.0$ pC of injected electrons from $100$ MeV to $500$ MeV. An important feature of the proposed split-beam PWA configuration (two half-Gaussian beams, separated by a plasma wavelength) is that the second half of the drive beam picks up some of the wake energy, left behind by the first half of the drive beam. To compare such a configuration with a more conventional one, utilizing a single shaped electron bunch, in Fig. 3 we plotted the fraction of the energy remaining in the first half of the driver beam (diamonds) and in the entire beam (triangles) as a function of the distance along the accelerator. The advantage of using a split beam is evident: more beam energy can be recovered in section (5) (less than a percent of the initial beam energy is left behind the bunches).

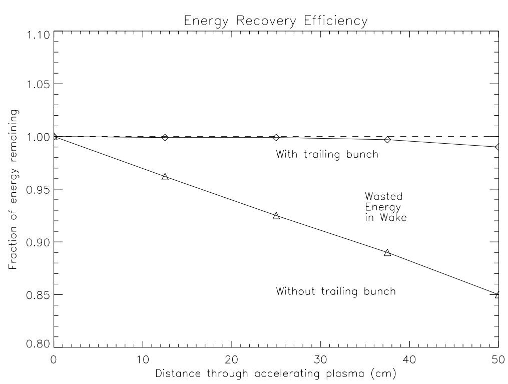


Figure 3: Fraction of energy remaining in leading half of driver bunch (diamonds) and in both halves (triangles) as a function of acceleration distance.

To investigate the efficiency of particle acceleration and the effect of beam loading we simulated the accelerating section (4) using witness beams of five different charges. The acceleration efficiency defined as

$$\eta_{acc} = \frac{\sum_{j=1}^{N_{inj}} \Delta\gamma_j mc^2}{\sum_{i=1}^{N_{drive}} -\Delta\gamma_i mc^2} \tag{7}$$

is shown in Fig. 4, which indicates that an optimal beam loading exists for which the acceleration efficiency can be as high as $70\%$. Incidentally, the energy recovery deteriorates with the increased beam loading, and about $2.8\%$ of the total drive beam energy is wasted in the wakes left behind (for the optimal beam loading case). At the same time, energy spread of the trailing half of the drive beam increases, making efficient energy recovery in an RF cavity problematic.

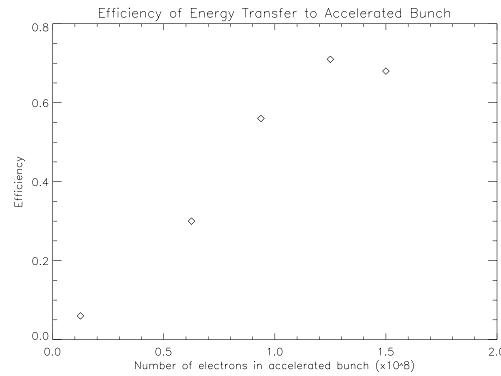


Figure 4: Acceleration efficiency $\eta_{acc}$ as a function of beam loading.

In conclusion, we suggested and numerically demonstrated the possibility of beam slicing with ultra-short laser pulses and plasmas (laser-plasma scissors). One of the applications of this beam slicing technique is a high-transformer-ratio, high-efficiency multi-stage particle accelerator. The high transformer ratio is achieved by slicing a long beam on a scale shorter than plasma wavelength while the high efficiency is achieved by splitting the beam into two bunches, separated by a plasma wavelength. Future work will extend the present one-dimensional analysis to three dimensions.

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