GENERATION OF ELLIPSOIDAL BEAM THROUGH 3D PULSE SHAPING FOR A PHOTOINJECTOR DRIVE LASER*

Yuelin Li#, ANL, Argonne, IL 60439, U.S.A.
Xiangyun Chang, BNL, Upton, NY 11973, U.S.A.

Abstract

In this paper we present a 3D laser pulse shaping scheme that can be applied for generating ellipsoidal electron bunches from a photoinjector. The 3D shaping is realized through laser phase tailoring in combination with chromatic aberration in a focusing optics. Performance of an electron beam generated from such shaped laser pulses is compared with that of a uniforma ellipsoidal, a uniform cylindrical, and a Gaussian electron beam. PARMELA simulation shows advantage of this shaped beam in both transverse and longitudinal performances..

INTRODUCTION

The emittance of an electron beam is governed by the emittance at its birth and the growth during its propagation. If the beam is only subjected to linear force, the latter can be fully recovered with proper beam compensation. It is well known that an ellipsoidal beam with uniform charge distribution has a linear space-charge force [1-3] and hence the most expected distribution for modern high-brightness beams. Recently, several researchers looked at practical ways of generating such ellipsoidal beams, including self evolving [4], cold electron harvesting [5], and laser pulse manipulations including spectral masking, pulse stacking, and dynamic spatial filtering [6]. In-depth analysis shows that in practical situations, the ellipsoidal beams do generate beam with lower emittance than Gaussian and cylindrical beams [1, 6-8]. Applications for such high-brightness beam include next-generation light sources such as the Linac Coherent Light Source (LCLS), high-energy colliders such as the International Linear Collider (ILC), as well as energy recovery linacs (ERLs).

LASER PULSE SHAPING

To generate an ellipsoidal beam directly from the photocathode, the laser pulse has to be shaped in 3D. It is well known that the longitudinal laser pulse shape can be manipulated by controlling the phase space using techniques such as DAZZLER [9] or SLIM [10]. One essence of this phase modulation is to control the phase and amplitude at certain frequencies at the same time so that the pulse can have a particular phase and amplitude. In the meantime, we notice that the instant frequency of a laser pulse is related to the phase by $\omega(t)=\mathrm{d}\phi(t)/\mathrm{d}t$. This gives a way of actively controlling the focal size of the laser as a function of time using the chromatic aberration of a common lens, of which the focal length can be expressed as [11]

$$\frac{1}{f(\omega)}=\left[n(\omega)-1\right]\left(\frac{1}{R_1}-\frac{1}{R_1}\right), \tag{1}$$

where R_1 and R_2 are the radius of curvature of the first and second surface of the lens, respectively, and n is the frequency-dependent refractive index. Clearly, the time-dependent frequency can then be mapped into a time-dependent focal length. For an observer at the focal plane at a nominal frequency ω_0, this is equivalent to a time-dependent defocusing of the beam of

$$\delta f(t)=-\frac{f_0}{n_0-1}\beta\delta\omega(t), \tag{2}$$

where we assume the frequency range is small and $\beta=dn/d\omega$ is constant. For a Gaussian beam this translates into a time-dependent change of the beam size at the nominal focal plane,

$$w(t)=w_0\left[1+\left(\frac{\lambda_0\delta f(t)}{\pi w_0^2}\right)^2\right]^{1/2}. \tag{3}$$

Here $w_0=N\lambda_0/\pi$ is the beam waist at the nominal wavelength λ_0, and N is the numerical aperture. For $\delta f >> w_0$, we have asymptotically,

$$w(t)\cong\frac{\left|\delta f(t)\right|}{N}. \tag{3a}$$

To generate an ellipsoidal outline, the transverse beam size should be of the form:

$$w(t)=W\left[1-\left(\frac{t}{T}\right)^2\right]^{1/2}. \tag{4}$$

Here W is the maximum transverse beam size at t=0 and $2T$ is the laser pulse duration.

From Eqs. (3-4), we have

$$\left|\delta\omega(t)\right|=\Delta\omega\left[1-\left(\frac{t}{T}\right)^2\right]^{1/2}, \tag{5}$$

where $\Delta\omega=(n_0-1)NW/\beta f_0$ is the bandwidth of the pulse; hence the phase of the pulse is

$$\begin{aligned}\phi(t) &= \int\left[\omega(t)-\omega_0\right]dt \\ &= -\omega_0 t\pm\frac{\Delta\omega}{2}\left[t\left(1-\left(\frac{t}{T}\right)^2\right)+T\sin^{-1}\frac{t}{T}\right].\end{aligned} \tag{6}$$

To make the pulse intensity constant over time, i.e., $|A(t)|^2/w(t)^2$=constant, the amplitude of the pulse is thus

$$A(t)=A_0\left[1-\left(\frac{t}{T}\right)^2\right]^{1/2}. \tag{7}$$

* Work supported by U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Contract No. W-31-109-ENG-38.
# ylli@aps.anl.gov

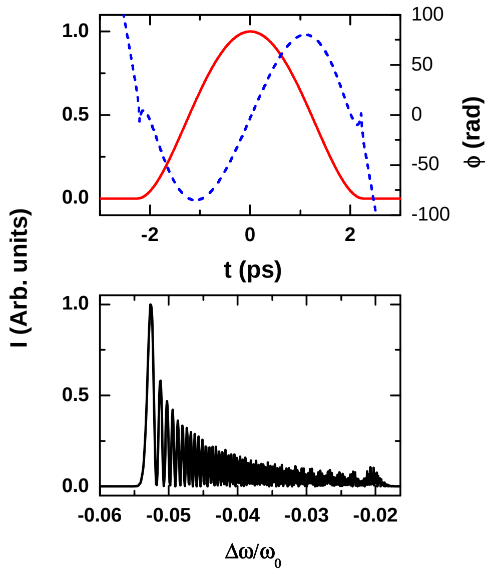

Figure 1: Laser pulse calculated using Eqs. (6) and (7). The intensity and phase in the time domain (top) and its spectrum (bottom).

With a transverse top-hat spatial profile, the field $E(t)=A(t)\exp[i\phi(t)]$ represents a 3D ellipsoidal pulse at the nominal focal plane at λ_0. The time domain representation of the pulse and its spectrum is shown in Fig. 1.

Note that the above model used Gaussian beam geometrical optics, and the effects of group velocity delay (GVDE) and group velocity dispersion (GVDI) due to the varying thickness across the aperture of the lens are not included [11]. It does not take into account the wave property of the light either. To evaluate the effects of GVDE and GVDI, we use the method elaborated by Kempe et al. [12] to calculate the temporal-spatial distribution of the pulse near the focus of a lens. The calculation assumes a collimated beam with top-hat intensity distribution for the input, and was performed in the frequency domain. The final result was Fourier transformed into the time domain to give the laser intensity distribution at the focal plane as a function of time. Figure 2 shows one example of such a shaped pulse and its comparison with the outline of an ideal ellipsoidal pulse.

Clearly this shaped pulse differs from an ideal ellipsoid. First the leading edge shows a recess that is due to the varying group delay as a function of the lens thickness across its aperture. The rays traversing the outer portion of the lens have less material to travel. Consequently, they arrive earlier at the focal plane due to the group velocity delay even when the phase velocity experiences no distortion. This has been studied theoretically and experimentally by a few authors and is an important effect in focusing short duration, short wavelength laser light [12].

We also noticed that, as the input pulse is flat topped, fringes typical of the Fourier transform show up and modulate the spatial distribution of the beam. Most

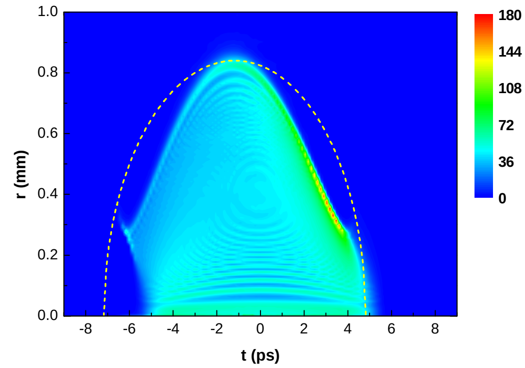

Figure 2: An ellipsoidal laser pulse generated vis laser pulse tailoring and the chromatic aberration at the focal plane of a 1" fused silica lens with a focal length of 150 mm. The contour plot shows the intensity of the beam as a function of time and radius. The dashed line shows a perfect ellipsoidal beam edge.

significant is the high intensity at the trailing edge, which is almost three times more intense than its surrounding field.

BEAM SIMULATION

To evaluate the performance of this shaped laser beam, preliminary simulations using PARMELA were performed and compared with other beam shapes for the following setting.

The simulation followed a setup for the design of the electron cooling ring injector for RHIC [13]. The setup is shown in Figure 3. The gun is a 1.5-cell rf gun at 703.75 MHz with maximum field on axis of 29.5 MV/m and maximum field on surface at 49.3 MV/m. The rf initial phase is set at 40 degrees. Beam distortion due to image charge is considered.

A series of simulations were performed using PARMELA. The simulations compare the performance of

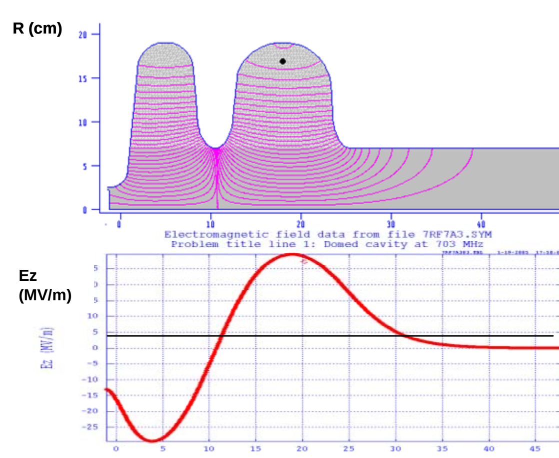

Figure 3: The rf gun system (top) and the field distribution (bottom) used in the beam simulation.

Table 1: Initial Beam Conditions

	Length (ps)	Radius (mm)
a.Shaped, no substructure	17	1.28
b.Shaped, substructure	17	1.28
c. Ideal ellipsoid	18	1.28
d. Ideal cylinder	18	1.13
e. Ideal Gaussian	σ=3.82, truncated at 9	1.13

Table 2: Transverse and Longitudinal Emittance at the Exit of the Gun

	Transverse (mm mrad)	Longitudinal (deg keV)
a.Shaped,no substructure	0.56	1.6
b.Shaped, substructure	0.57	1.5
c. Ideal ellipsoid	0.405	2.6
d. Ideal cylinder	0.73	5.2
e. Ideal Gaussian	1.55	7.7

the 3D laser pulse against three standard cases (see Table 1): c) a perfect ellipsoidal beam, d) a cylindrical beam, and e) a transversely uniform but longitudinally Gaussian beam. For the shaped beam, two cases were tested: a) without considering the substructures and b) with. The simulations use the parameters listed in Table 1. Both the longitudinal and the transverse emittances are compared at the exit of the gun. In total, 46600 particles are used in each simulation, representing 0.15 nC of charge. The low charge is used due to the relatively low rf field in this setup.

The emittances at the gun exit are summarized in Table 2. In general, the performances of the shaped-pulse cases closely trail the performances of the ideal ellipsoidal beam in both longitudinal and transverse emittances. More remarkably, the substructure as shown in Figure 2 has almost no impact on the performance of the beam in this setup. It will be interesting to perform simulations with bending magnets to evaluate the influence of coherence transition radiation, which is detrimental to cylindrical and Gaussian beams but has minimum impact on an ideal ellipsoidal beam. One simulation indicates that after chicane, the ellipsoidal beam shape will be destroyed but the low emittance of the beam remains [8].

DISCUSSION

We note that the scheme is based on the chromatic aberration of a focusing optics due to non-zero $dn/d\omega$. For a conventional lens made of fused silica, this effect is only important for UV radiation and is negligible for radiation in the visible and near IR ranges. To perform such pulse shaping in the visible and IR ranges, a properly designed zone plate can be used, with a reduction of efficiency of 50%.

In comparison with the self-evolving scheme proposed [4], the current scheme has the potential of delivering very high current without causing nonlinear effects during transport. Once set up, the pulse duration can also be adjusted through phase control in the laser system.

However, the pre-request of a flat-topped beam may be difficult to achieve without significant sacrifice of beam energy. In addition, a large bandwidth is needed to perform the phase tailoring, and maintaining the phase from IR into UV maybe a challenge if frequency conversion is needed.

SUMMARY

We described a scheme for generating an ellipsoidal laser pulse and performed preliminary simulations comparing the electron beam generated from this laser beam with an ideal ellipsoidal beam, a cylindrical beam, and a Gaussian beam. It is shown that although the beam generated still defers from an ideal ellipsoidal beam, it has clearly better performance than a cylindrical beam and a Gaussian beam in providing smaller transverse and longitudinal emittance. Further beam simulations are needed to investigate the CSR effect for setup relevant to LCLS and future ERLs.

REFERENCES

[1] F. Sacherer, IEEE Trans. Nucl. Sci. NS-18, 1105 (1971).
[2] I.M. Kapchinskij, V.V. Vladimirskij, Conference on High Energy Accelerators and Instrumentation, CERN, Geneva, 274 (1959).
[3] P.M. Lapostolle, IEEE Trans. Nucl. Sci. NS-18, 1101 (1971).
[4] O.J. Luiten, S.B. van der Geer, M.J. de Loos, F.B. Kiewiet, and M.J. van der Wiel, Phys. Rev. Lett 93, 094802 (2004).
[5] B.J. Claessens, S.B. van der Geer, G.Taban, E.J.D. Vredenbregt, and O.J. Luiten, Phys. Rev. Lett 95, 164801 (2005).
[6] C. Limborg-Deprey and P. Bolton, Nucl. Instrum. Methods A557, 106 (2006).
[7] J.B. Rosenzweig et al., Nucl. Instrum. Methods A557, 87 (2006).
[8] S.B. van der Geer, M.J. de Loos, T. van Oudheusden, W.P.E.M. op't Root, M.J. van der Wiel, and O.J. Luiten, Phys Rev. ST-AB 9, 044203 (2006).
[9] P. Tournois, Opt. Commun. 140, 245 (1997).
[10] A.M. Weiner, D.E. Leaird, J.S. Patel, and J.R. Wullert, Opt. Lett. 15, 326 (1990).
[11] M. Born and E. Wolf, *Principles of Optics*, University Press, Cambridge, UK, 2003.
[12] M. Kempe, U. Stamm, B. Wilhelmi, and W. Rudolph, J. Opt. Soc. Am. B9, 1158 (1992).
[13] I. Ben-Zvi et al., Nucl. Instrum. Methods A557, 28 (2006).