Jitter Sensitivity in Photoinjectors*

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Photoinjectors are becoming the electron source of choice for high brightness, high current applications such as very-short wavelength free-electron lasers and electron linear colliders. In both of these applications the electron beam will be bunched to a multi-kiloampère current from its initial value of a few hundred ampères. The performance of such aggressive bunchers is very sensitive to the correlations in the longitudinal phase space. One of the major performance-determining factors is the timing of the injection of the electrons in the gun relative to the rf field. Of particular concern is the jitter of the drive-laser timing and amplitude. We develop a model of the system and use it to study the implications for photoinjector design* .

INTRODUCTION

In the past decade the invention and refinement of the rf photocathode gun has resulted in a dramatic improvement in electron beam brightness over that delivered by conventional injectors [1]. As rf photocathode guns evolve from being laboratory curiosities they are being considered as electron sources for such challenging applications as linear colliders and single-pass x-ray free-electron laser amplifiers.

Previously, the primary beam characteristics of interest have been charge, current, emittance and brightness. Recently, Travier [2] has reported the results of a survey of the photoinjector community where the primary concern of the experimenters has been drive-laser stability. A number of proposed machines, including electron linear colliders and single pass X-ray free-electron lasers, require that the beam be bunched by a factor of ten or more. Consider the Linac Coherent Light Source (LCLS) [3], a proposed single pass X-ray FEL at SLAC, as an example system.

The final specifications of the LCLS are still in flux, however the following design guidelines provide a basis for discussion in this paper. The rf photocathode gun will generate a beam with 3-10 MeV, 1 nC in a 2 ps rms bunch and a normalized rms emittance of 1 π mm-mrad and an rms energy spread of 0.2%. The beam will be accelerated to 7 GeV and compressed by a factor of ten to reach a peak current of 2.5 kA. The compression will occur in two stages: a factor of two at 100 MeV and a further factor of five at 2 GeV. The gain length of the FEL is very sensitive to both the emittance and the peak current of the beam [3]. The transverse emittance required is approximately a factor of two better than has been demonstrated in an rf photocathode gun to date. The bunching is very sensitive to the longitudinal phase space of the bunch and hence to timing and amplitude jitter in the rf gun [4]. The stability required is somewhat better than has been demonstrated in operational photoinjectors.

As indicated above the bunching schemes necessary for the LCLS require precise control of the phase-energy correlations in longitudinal phase space. Phase jitter of the drive laser relative to the gun rf fields impacts both the phase-energy correlation at the gun and the evolution of the correlations in the linac. Current jitter in the gun alters the wakefield induced phase space distortions. Because of phase buffering in the gun, the phase jitter of the beam in the linac is not necessarily equal to that of the drive-laser relative to the rf phase.

JITTER SENSITIVITY

To evaluate the sensitivity of the bunching to drive-laser phase jitter we use a simple model in which we assume that the correlated energy spread is much greater than the uncorrelated energy spread and $\gamma >>1$, where γ is the electron energy divided by its rest energy. Then we may write the bunching ratio (B) i.e. the ratio of the bunch length after (σ_2) and before bunching (σ_1) as:

$$B = \frac{\sigma_2}{\sigma_1} \approx \left|1 - \frac{2\pi f R_{56}}{c\gamma}\frac{\partial\gamma}{\partial\phi_B}\right| \approx \left|1 - \frac{2\pi f R_{56}}{c}\mathrm{Cot}\phi_B\right| \quad (1)$$

where f is the rf frequency, c is the velocity of light, ϕ_B is the asymptotic phase in the linac before the buncher of the bunch centroid relative to zero rf phase, $R_{56} = \frac{\Delta\ell}{\Delta p / p}$ is the bunching parameter of the buncher. The sensitivity of B to injection phase of the drive-laser (ϕ_o) is:

$$\frac{\partial B}{\partial\phi_o} = \frac{\partial B}{\partial\phi_B}\frac{\partial\phi_B}{\partial\phi_o} = \pm\frac{2\pi f R_{56}}{c\sin^2\phi_B}\frac{\partial\phi_B}{\partial\phi_o} \quad (2)$$

where the positive sign corresponds to under compression and the negative to over compression in the buncher. In general in a multi-section linac $\phi_B \neq \phi_G$, the asymptotic phase at the end of the gun. For $\gamma >>1$ at the end of the gun we can write $\frac{\partial\phi_B}{\partial\phi_o} \approx \frac{\partial\phi_G}{\partial\phi_o}$ in Eq. 2.

Our concern is with the sensitivity of ϕ_G to variation in ϕ_0. Travier [5] has shown (using a combination of Kim's theory [6] and simulation) that the asymptotic phase (ϕ_G) of the

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central particle in the bunch at the end of the gun, for $\gamma >> 1$, is given in terms of its injection phase (ϕ_o) at the cathode as:

$$\phi_G = \phi_o + \frac{1}{2\alpha \sin(\phi_o + \frac{\pi}{6\sqrt{\alpha}})} + \frac{\pi}{15\alpha} \quad (3)$$

where $\alpha = eE_o/4\pi fmc$ with e the electronic charge, m its mass, E_o is the peak accelerating electric field. Differentiation of Eq. (1) with respect to ϕ_o gives:

$$\frac{\partial\phi_B}{\partial\phi_o} = \frac{\partial\phi_G}{\partial\phi_o} = 1 - \frac{\cot(\phi_o + \frac{\pi}{6\sqrt{\alpha}})}{2\,\alpha \mathrm{Sin}(\phi_o + \frac{\pi}{6\sqrt{\alpha}})} \quad (4)$$

In Fig. 1 and subsequent figures we compare two common photoinjector cases:

a) f = 2856 MHz and E_o = 100 MV/m, i.e. $\alpha = 1.63$.
b) f = 1300 MHz and E_o = 25 MV/m, i.e. $\alpha = 0.89$.

We see that there can be significant buffering of the phase jitter for small ϕ_o. Therefore sensitivity of the bunching ratio to phase jitter can be significantly reduced by running at small ϕ_o

The asymptotic phase (and hence the bunching ratio) is also sensitive to the accelerating gradient in the gun E_o. Fig. 2 shows a plot of $\frac{\partial\phi_G}{\partial E_o}$ versus injection phase. The sensitivity to fluctuations in E_o is small but may not be negligible. Fluctuations in gun current will result in changes in E_o to an extent dependent on the beam loading and cavity Q of the gun. In contrast to the phase sensitivity, gradient sensitivity is minimized for larger ϕ_o. If we ignore current fluctuations it should be possible to stabilize the accelerating gradient to approximately 0.1%.

The fractional change in the mean energy of the beam at the exit of the gun is given approximately by:

$$\frac{1}{\gamma_G}\frac{\partial\gamma_G}{\partial\phi_o} = \frac{\partial\phi_G}{\partial\phi_o}\cot(\phi_G) \quad (5)$$

For an FEL driven by such a beam the FEL wavelength jitter will be given by $\frac{1}{\lambda}\frac{\partial\lambda}{\partial\phi_o} = 2\frac{\partial\phi_G}{\partial\phi_o}\cot(\phi_G)$. Eqn. (5) is plotted in Fig. 3 for the two cases of interest. Note that that the energy shift becomes negative when $\phi_G > \pi/2$. It is evident that the energy of the beam is most sensitive to phase fluctuations for $\phi_o \ \varepsilon\ [20,30]°$.

The requirement to minimize the transverse emittance generally requires that $\phi_G \approx \pi/2$. [6] This results in the requirement that $\phi_o \approx 30°$ for the 1300 MHz gun and up to 60° for the 2856 MHz gun, however, this may differ from one design to another depending on whether emittance compensation is used on the relative importance of space-charge and rf induced emittance growth. [6, 7]. It is evident from Eq. (2) that sensitivity to jitter may be reduced by having two bunchers one of which over compresses and one of which under compresses so as to cause the jitters to cancel. Simulations [4] with twin bunchers indicate that the tolerance for phase jitter is ± 0.45° (± 0.5 ps) and the gun current jitter tolerance is ± 2.2 %. The choice of injection phase will depend on compromise between bunching stability (governed by achievable drive-laser stability) and transverse emittance considerations.

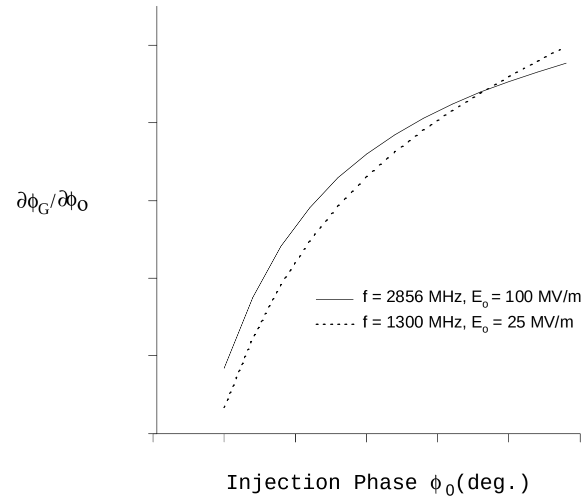

Fig 1. Asymptotic phase jitter sensitivity versus injection phase

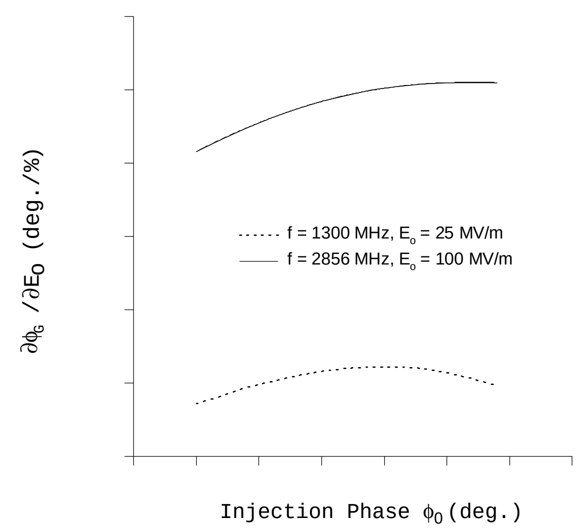

Fig 2 Sensitivity of asymptotic phase to accelerating gradient jitter versus injection phase

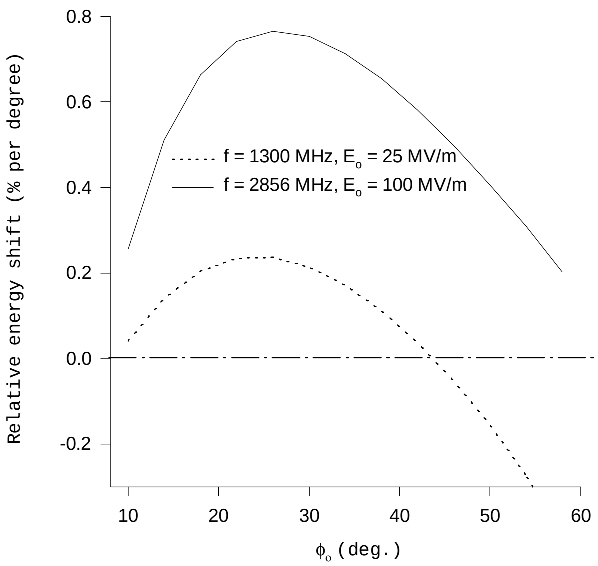

Fig. 3. Fractional energy shift per degree phase change at asymptotic phase for $\gamma >> 1$, versus injection phase.

DRIVE LASER STABILITY

There are currently two types of mode-locked lasers in common use: fourth harmonic Nd:YAG or Nd:YLF [2,8]. Recently 3 rd harmonic Ti:SAF is being studied for producing very short (sub-picosecond) pulse lengths [9]. When operated under ideal conditions, the phase and amplitude jitter of mode-locked lasers can be very small i.e. < 1 ps and 1% peak to peak respectively. The long-term performance of drive lasers has been degraded by some or all of the following conditions: poor temperature control, a non clean-room environment, cavitation in cooling water, and flash-lamp and harmonic crystal aging.

The most extensively studied drive-laser has been that of the second-harmonic Nd:YLF laser at the APEX facility in Los Alamos. The published data for pulse-to-pulse energy stability has been reported to be between 1%-5% peak to peak [10]. Phase jitter with respect to the rf has been reported to the order of 5 ps peak-to peak over short time scales (seconds) with 10 ps per hour long term drifts [10,11].

Unpublished data [24] from APEX show that phase jitters of 2 ps peak to peak (0.5 to 1 ps rms) and long term drifts of 2 ps were achieved using a phase mixing technique to measure the phase of the drive-laser output relative to the rf in conjunction with active feed forward control.

Spatial jitter of the drive laser spot must also be considered. Centroid jitter of the drive-laser spot will result in dipole wakefield modes being excited while mode shape jitter will result in higher-order wakefield modes. Analysis of centroid jitter indicates that a factor of two emittance growth is possible in a 1-nC bunch with a 0.5 mm transverse displacement of 1-mm drive-laser spot in the first six metres of an S-band linac [12]. Simulations for the LCLS indicate that over longer distances emittance growth of 50% is possible with transverse beam displacement of as little as 10 μm [13]. The centroid stability of a 2nd harmonic Nd:YLF drive-laser spot striking the cathode at close to normal incidence has been demonstrated to be approximately 50 μm rms over a few minutes in the APEX photoinjector [11].

The published data show that drive-laser performance will need some improvement for applications such as the LCLS. It should be emphasized that most drive-lasers in operation to date have been one of a kind prototype lasers. The introduction of commercially-produced integrated laser systems along with the use of diode pumped Nd:YLF oscillators and amplifiers offers the possibility of significantly enhanced performance. Preliminary results [14] with such systems indicate sub-picosecond phase stability and less than 50 μm transverse centroid jitter.

CONCLUSION

It is evident that jitter considerations should be taken into account in designing photoinjector systems. For fixed α higher rf frequencies are less desirable. We have not addressed the sensitivity of the transverse emittance. This is of particular importance in cases where compensation for space-charge induced emittance growth is used. [15]

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