LONGITUDINAL BEAM DYNAMICS OF THE PHOTOINJECTOR BLOWOUT REGIME*

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Abstract

Longitudinal beam dynamics of the photoinjector "blowout" regime are investigated. A two beamlet macroparticle approach is first used to investigate the effects of S-Band RF photogun fields on a picosecond time scale. The beams' longitudinal phase spaces (LPS) are measured via an X-band RF deflecting cavity and dipole spectrometer. Lastly, the LPS of a single subpicosecond beam is investigated as a function of initial charge density at the cathode and compared to simulation.

INTRODUCTION

High brightness electron beams generated by RF photoinjectors have been instrumental in developing important applications such as SASE FEL and relativistic ultrafast electron diffraction. A potentially very high brightness electron source can be obtained by operating RF photoinjectors in the "blowout regime". In this regime, a very short UV laser pulse (50 fs rms) is applied to the photocathode, causing the initial beam to resemble a flat disk with very strong longitudinal space charge forces. These space charge forces cause the beam to expand rapidly, resulting in an ellipsoid with an approximately uniform charge density [1, 2]. Although a "half circle" distribution at the cathode is optimal, the final ellipsoid is robust against variations in the radial profile (as long as azimuthal symmetry is maintained) due to the nature of the expansion [3, 4]. The space charge forces are linear after expansion, resulting in a 3.5 MeV subpicosecond beam with low longitudinal emittance, which promises the possibility of large compression ratios. Such a compressed beam would have very high beam brightness resulting in a high quality electron source for the aforementioned applications. Recent experiments at the UCLA Pegasus photoinjector laboratory have measured the ellipsoid of the blowout regime beam with unprecedented time resolution by use of an X-band RF deflecting cavity [4].

In this paper, we expand upon the discussion of the blowout beam. After a brief discussion of the experimental apparatus, we investigate the blowout beam by use of a two beam "macroparticle" approach [5]. We examine the RF phase compression due to photoinjector gun on the two beams. We then move on to investigate the longitudinal phase spaces of the two time separated beams and lastly we look at the LPS of a single beam as a function of charge.

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EXPERIMENTAL APPARATUS

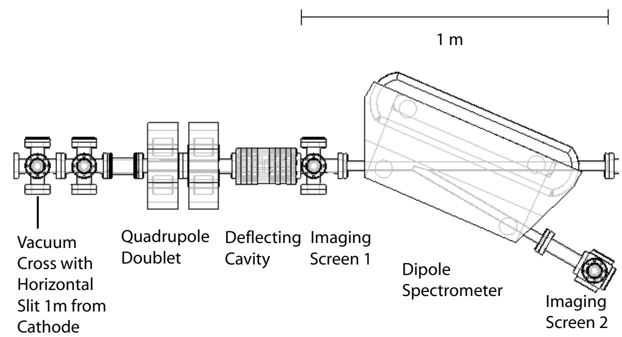

Figure 1: Experimental apparatus used measure the longitudinal profile and longitudinal phase space of the photoinjector blowout beam.

The apparatus to measure the longitudinal profile and the longitudinal phase space of the blowout regime is shown in Fig. 1. The electron beam is accelerated using a 1.6 Cell SLAC/BNL/UCLA S-band (f_{gun} = 2.856 GHz) photoinjector gun using an accelerating field of 70 MV/m. An emittance compensating solenoid is used to guide the beam to a gentle focus 1.5 meters from the cathode. The measurement of the longitudinal profile is achieved by use of a 9 cell RF X-band (f_{def} = 9.959 GHz) deflecting cavity with a maximum deflecting voltage of 500 kV [6]. The electron beam is streaked onto the vertical plane then imaged on a yttrium aluminum garnet (YAG) fluorescent screen labeled as Screen 1 in Fig. 1, located 2 meters from the cathode. The quadrupole doublet is used to minimize the betatron spot size in the vertical direction so that the $x - z$ profile can be time resolved.

The measurement of the longitudinal phase space is more involved. There is an additional energy spread imparted to the beam due to off axis particles in the deflecting cavity as described by the Panofsky-Wenzel Theorem [7]. The fields of the deflecting cavity have a maximum gradient vertically and a minimum gradient horizontally. This allows the use of a horizontal aperture to limit the energy spread induced by the deflecting cavity. A 100 μm horizontal slit is employed 1 meter from the cathode to limit the vertical spot size in the deflecting cavity. The temporal profile is mapped onto the vertical axis while the energy distribution is mapped onto the horizontal axis by a bending magnet that has a design bending radius of .67 m and bend of 45 degrees. The slit reduces the charge to less than 5 percent of its original value, hence the energy distribution evolution beyond the slit is negligible. Therefore the LPS is measured at the deflecting cavity where the tempo-

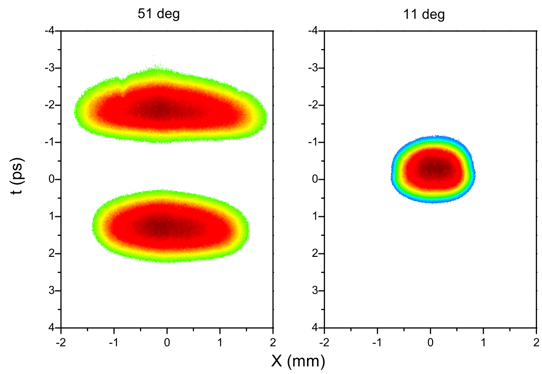

Figure 2: Sample Data of $x - z$ profiles at high and low respective injection phases.

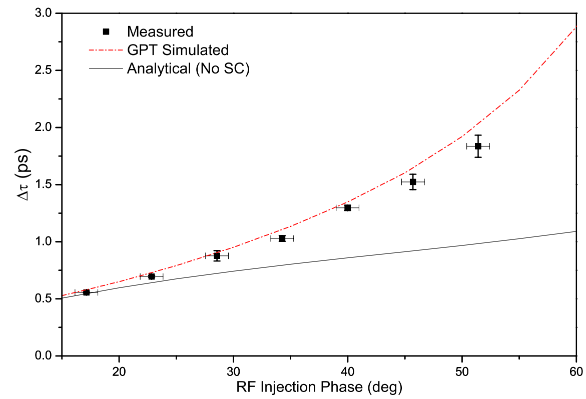

Figure 3: Measured time separation of centroids as a function of RF photogun injection phase.

ral profile is mapped. The quadrupole doublet is used to minimize the betatron spot sizes so that maximum temporal and energy resolution can be achieved.

DOUBLE BEAM STUDIES

The effects of the RF fields in a photoinjector gun on the beam's longitudinal profile are studied by a two bunch "macroparticle" technique [5]. The double beam is produced by shaping the UV laser pulse applied to the cathode. The creation of a double laser pulse consisting 50 fs pulses with a 1.0 ps separation (peak to peak) is accomplished using a Barium Borate crystal (a-BBO), placed in the laser pulse path with optical axis 45 degrees to polarization axis of the beam, generating equal energy pulses. The a-BBO crystal was selected for its large transparency range (190-3500nm) and a large natural birefringence, with refractive indices at our application wavelength (266nm) of the ordinary and extraordinary axes, n_o = 1.76 and n_e = 1.61, respectively. The crystal length, (2.0 +/- .1) mm, was chosen to obtain a 1.0 ps separation.

Sample shots of the $x - z$ profile of the two beams are shown in Fig. 2. The shot shown left is an example of well separated beams. Consequently, the beams' centroids are well defined and they can be used as a diagnostic of the behavior of a section of a beam with a time scale of the separation of the beams. This is contrasted by the shot shown right, where compression has merged the beams, limiting their applicability as a macroparticle diagnostic is minimal. This limit to the macroparticle diagnostic occurs for injection phases below 15 degrees given the length and charge of our initial beams.

A comparison of measured, simulated, and analytical RF phase compression is shown in Fig. 3. The analytical model used for the compression is a curve generated from the solution of following coupled equations [5]:

$$\frac{d\psi}{dz} = k\left(\frac{\gamma}{\sqrt{\gamma^2 - 1}} - 1\right) \qquad (1)$$

$$\frac{d\gamma}{dz} = 2\alpha k E_z sin(\psi + kz) \qquad (2)$$

where $k = \frac{2\pi f}{c}$, γ is the Lorentz factor, $\alpha = \frac{eE_0}{2kmc^2}$ is the normalized accelerating field, and $E_z = cos(kz)$ is the spatial field profile. Simulation performed by General Particle Tracer is in good agreement with the measured data. The analytical model is in good agreement with the measured data at low phase, then diverges as the injection phase increases. This variation from the analytical model is due to space charge effects which are important due to the small time separation between the bunches and relatively low energy.

Although significant compression occurrs on the picosecond scale of the time separation of the macroparticles, there was very little compression of the bunches themselves, indicating that RF phase compression in a 1.6 cell gun is ineffective on subpicosecond timescales [8].

LONGITUDINAL PHASE SPACE

A measurement of the longitudinal phase space of the double bunch is compared with simulation in Fig. 4. The simulated beams' uncorrelated energy spreads appear to be significantly smaller than the measured ones. This is due to the resolution limit of the LPS measurement technique which cannot resolve energy spreads below 1keV [8]. Recent studies at UCLA Pegasus laboratory have shown that a single blowout beam has a very linear longitudinal phase space distribution with a well defined chirp. The first bunch in the double beam appears to have a similarly linear longitudinal phase space while the second bunch has more nonlinearity. This is likely due to the first pulse having a ps to expand without the presence of the fields created by the second bunch, whereas the latter always experiences the fields of the former. As a consequence, the head of the second bunch does not expand as much, and does not achieve the approximately linear self fields normally experienced by the blowout ellipsoid.

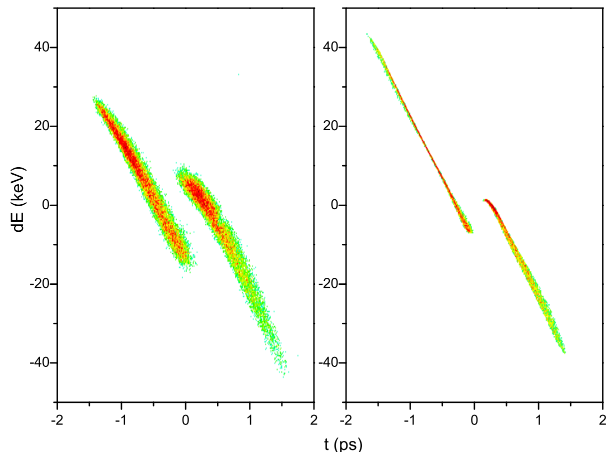

Figure 4: Measured and simulated longitudinal phase space of the double beam. The beams' respective charges were 5.7 and 5.3 pC, RF injection phase was 25 degrees, and the transverse spot size on the cathode was σ_x = 500 μm rms

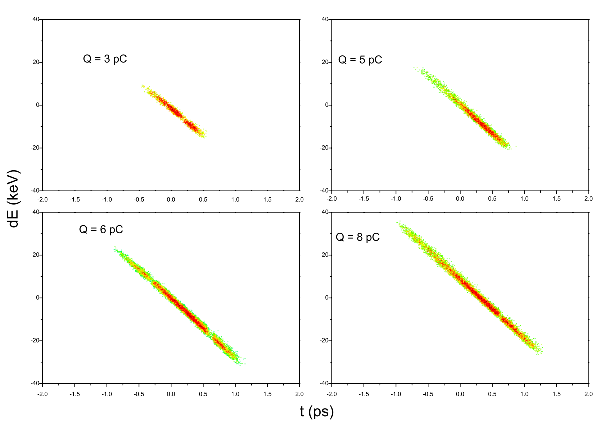

Figure 5: Four LPS's taken for different charges. As the charge is increased the variation in the beam chirp reduces due to the effects of the space charge induced expansion.

Lastly the longitudinal phase space of a single bunch was examined while varying charge at low initial charge. The four shots seen in Fig. 5 show that the blowout beam has a linear longitudinal phase space and a chirp that changes very little over a 200 percent charge increase, becoming more invariant at higher charges. The 3 pC shot has a chirp of (24 $\pm$ 1) keV/ps while the other shots have a chirp of (27 $\pm$ 1) keV/ps. This gives an approximate threshold charge density for variation of the chirp of σ = 12 pC/mm^2.

The reason for the invariance in the chirp is that most of the expansion and energy spread increase occurs while the beam is in the "pancake" regime, where the transverse dimension of the beam is much larger than the longitudinal dimension in its rest frame. In this regime, the energy spread and beam length are both linear functions of the initial surface charge density. The energy spread can be described by $mc^2\Delta\gamma = \frac{e\sigma L_s}{\epsilon_0}$ where σ is the surface charge density, and L_s is the length scale over which the expansion occurs. The bunch length at the measurement point can be described by $\tau = \frac{mc\sigma}{e\epsilon_0 E_0^2} + \frac{\Delta\gamma L_d}{\gamma^3 c}$ where E_0 is the accelerating field on the cathode, and L_d is the drift distance to the measurement point. The beam chirp, which represents the correlated energy spread in the beam is the resultant energy spread over the bunch length at the measurement point. The linear terms in charge density cancel, leaving the chirp invariant with respect to the surface charge density on the cathode. There is a drift to the measurement point, however at very low charge the chirp is more dependent upon the initial charge density. This is due to there being an insufficient amount of charge density to expand the beam into the uniformly filled ellipsoid. Indeed, the 3 pC shot's rms is 250 fs, only a factor of 5 larger than the initial laser pulse.

CONCLUSION

Longitudinal beam dynamics of an RF photoinjector blowout regime beam in a 1.6 Cell photogun were examined using an X-band deflecting cavity and dipole spectrometer. A double beam macroparticle approach was used to show that there are significant space charge effects when considering RF photogun compression for ps scale pC beams. The macroparticles themselves, however experienced little bunching, indicating that subpicosecond S-band RF phase bunching in the gun would be ineffective. Lastly, the chirp of the blowout beam was found to be quasi-constant above an initial charge density of 12 pC/mm^2, but decreases below this value due to a lack of expansion of the beam.

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