

EXPERIMENTAL GENERATION AND CHARACTERIZATION OF UNIFORMLY FILLED ELLIPSOIDAL BEAM DISTRIBUTION

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Abstract

Recently, a scheme for producing ideal uniformly filled ellipsoidal beam distributions, which depends on the strong longitudinal expansion of an initially very short beam under its own space charge forces, has been demonstrated at the UCLA Pegasus Laboratory. Here we present further work on the characterization of this novel regime of operation of a photoinjector. In particular we study the sensitivity of the generation of the uniformly filled ellipsoidal distribution from the initial transverse laser profile. The ultra-high brightness of the beam created operating in this ‘blow-out’ regime is verified obtaining high quality relativistic electron diffraction patterns from thin Al foils.

INTRODUCTION

For forty years, uniformly filled ellipsoidal beam distributions have been studied theoretically, as they have had the promise of generating self-fields that produce forces linear in the coordinate offset in all three directions [1]. In the last few years, a scheme for producing such distributions, which depends on the strong longitudinal expansion of an initially very short beam under its own space charge forces, has been proposed[2,3] and more recently demonstrated[4]. At the Pegasus Laboratory in UCLA we successfully created a uniformly filled distribution by illuminating the cathode with a sub-50 fs laser pulse and letting the beam evolve under the action of its own space charge forces into a final nearly ideal ellipsoidal distribution.

In order to operate the photoinjector in the blow-out regime there are no requirements on the laser pulse length other than be much shorter than the final electron bunch length. However, in the original proposal [3] the radial shape of the initial transverse laser profile is deemed critical for creating the ellipsoidal beam. In the next section, we make an attempt to quantify this sensitivity, which has been at times indicated as a weak point of this scheme, by measuring how the ellipsoidal distribution changes under the effect of different initial conditions.

In the third section of this paper, we show the preliminary results on the longitudinal phase space of the dynamically self-optimized beam. The linearity of the phase space together with the very low longitudinal emittance confirms the linearity of the beam self field also in the z -direction opening the possibility of large compression factors and suggesting this regime as the

optimum one for creation of low-charge ultrashort electron bunches for single-spike FEL operation.

Finally, one of the ambitious goals of the UCLA Pegasus Laboratory is to implement the ultrafast relativistic electron diffraction technique to enable material studies at atomic length scale with sub-100 fs time resolution[6]. The high brightness of the uniformly filled ellipsoidal beam was exploited to obtain a diffraction pattern from thin Aluminum foils.

Table 1: Parameters of Pegasus photoinjector for operation in ‘blow-out’ regime.

Parameter	Value
Laser pulse length	35 fs (rms)
Laser spot size on cathode	400 μm (rms)
Peak field on the cathode	80 MV/m
Beam energy	3.75 MeV
Beam charge	15 pC
Injection phase	25°

In Table 1 we report the parameter of the Pegasus photoinjector for operation in the ‘blow-out’ regime. For more details we refer to our previous publications on the subject [4,5].

TRANSVERSE LASER PROFILE

In our measurements the initial laser transverse profile has been shaped by simply imaging onto the cathode an iris of aperture r_a illuminated with a larger gaussian laser spot of measure σ_g . Properly adjusting an upstream telescope on the uv transport line we were able to vary the initial gaussian laser dimension σ_g and hence the shape of the laser spot on the cathode.

The main observation from these studies is that the t -dependent beam streaks that the shape of the final beam distribution is not particularly sensitive to the initial transverse profile, as long as this one has sharp edges. Only when the laser transverse profile presents long tails, i.e. when the laser is apertured at a radius $r_a > 1.5 \sigma_g$ does the beam lose its characteristic sharp ellipsoidal boundary.

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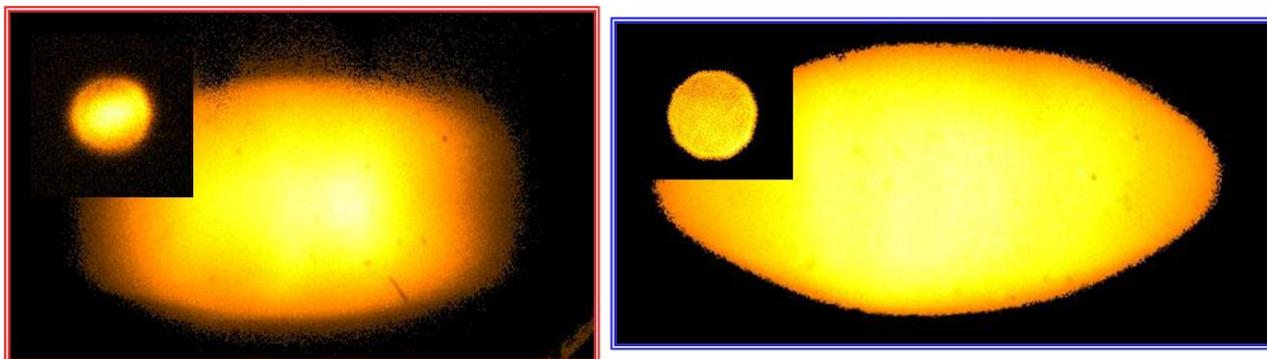


Figure 1: Projected x-t beam distribution and corresponding initial laser transverse profiles.

To be more quantitative, in Fig. 1 we report the streak images representing the beam distribution projected onto the $x-t$ plane obtained for two different laser transverse profiles. In the upper left insets we show the virtual cathode images of the laser spot. The electron beam charge is kept constant.

of relativistic dilation the beam rest-frame aspect ratio -- the ratio between the transverse and longitudinal beam sizes-- grows very quickly to be of order unity. Hence the space charge driven expansion and distribution rearrangement take place both radially and longitudinally, leading to an ellipsoidal boundary that is not critically dependent on the details of the initial conditions.

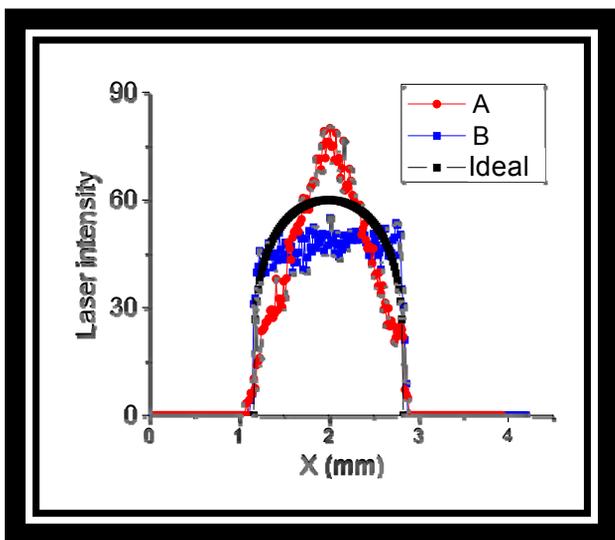


Figure 2: Line-out of transverse laser profile at the cathode for the cases corresponding to Fig.1. The ideal half-circle shape is also represented.

In Fig. 2 we show the transverse laser profiles at the cathode corresponding to the experimental cases of Fig.1 and the ideal half-circle profile for comparison. Looking at Fig.1, a clearly defined ellipsoidal boundary is obtained with the transverse laser profile B corresponding to a cut $r_a=0.4 \sigma_g$, that is an almost flat-top profile. On the other hand, for the situation of profile A corresponding to a cut at $r_a=1.8\sigma_g$ the $x-t$ beam distribution has a very different shape.

The relative mild dependence (profile B is quite different than the ideal transverse half-circle distribution) on the initial laser transverse shape is in good agreement with particle tracking simulations. It originates in the details of the dynamics of the beam rearrangement. A half-circle initial distribution would be required if the beam expansion were entirely longitudinal. However, because

LONGITUDINAL PHASE SPACE

A uniformly filled ellipsoidal beam distribution has the unique characteristics of generating space charge fields linear in the offset in all three directions. In presence of linear external forces, the beam distribution should be characterized by fully linear phase spaces. The transverse phase space does in fact show a high degree of linearity and the emittance of the beam (at least for the conditions where the effects of the symmetry-breaking image charge field can be neglected) is at the thermal emittance level. Using the RF deflector in conjunction with an horizontally dispersing dipole we report here a direct longitudinal phase space measurement.

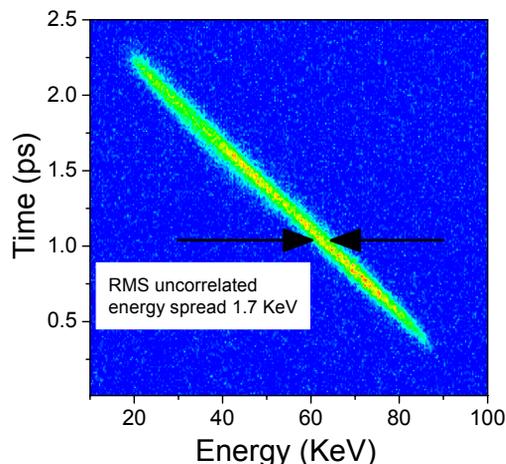


Figure 3: Longitudinal phase space of the beam out of the photoinjector in 'blow-out' regime.

The betatron beam sizes at the measurement screen define the energy resolution both in the energy and in the temporal dimension. By a carefully choice of the electron optic (quadrupole magnets) and screen position we were

able to obtain a resolution of 50 fs in the temporal direction and 1-2 KeV in the horizontal (energy) dimension.

A preliminary picture of the beam longitudinal phase space is shown in Fig. 3. The phase of the deflecting cavity is chosen so that the head of the beam is deflected towards the negative vertical direction. The left side of the picture corresponds to particles which have deviated more in the field of the dipole and so to lower energy particles.

It is evident a strong linear chirp in the beam longitudinal phase space with higher energy particles at the head of the beam. The total rms energy spread and bunch length are respectively 0.9 % and 600 fs. We also measure a slice, uncorrelated energy spread of < 1.7 KeV. While this measurement is dominated by the resolution of the spectrometer, the reported value is one of the best estimates on this parameter to our knowledge. For many applications, like for example driving free-electron laser amplifiers, the uncorrelated energy spread is a key-parameter to assess how sensitive the beam dynamics is to phase space instabilities like longitudinal space charge or CSR and to determine the injector performance. Further work is going on to obtain better measurement of this important parameter and its dependence on the other photoinjector parameters.

The thickness of the beam distribution gives a measure of the longitudinal emittance. Calculating the second order moments of the distribution we obtain on the longitudinal emittance is ~ 0.3 mm-KeV in good agreement with the result from particle simulations.

APPLICATIONS

The electron beam from the Pegasus photoinjector operating in the ‘blow-out’ regime was used to generate static diffraction pattern off free standing thin polycrystalline aluminum foils (200 nm thickness). The samples were inserted in the beam path at a 80 cm distance from the cathode. After diffraction the electrons go through a 1 m long drift region before being focused onto the detection screen by two magnetic quadrupole lenses. The raw image data collected on the screen downstream of the quadrupoles is shown in Fig. 4.

The ellipticity of the diffraction pattern is due to the different magnification of the magnetic quadrupole lenses used to focus the beam angular distribution on the screen. A software algorithm was used to integrate and average the pixel intensities on the elliptical contours. The scattering angles distribution is shown in the Fig. 4 inset together with the expected results from a simple start-to-end simulation model. The model integrates a particle tracking code like Astra[7] with a Monte Carlo model of the scattering in the foil.

The use of the rf photoinjector as a source for ultrafast relativistic electron diffraction is a new application of high brightness electron beams being developed at the

UCLA Pegasus laboratory. This promising new approach takes advantage of the strong suppression of the space charge forces at relativistic energies. Sub-100 fs long probe e-beams with more than 10^7 particles per bunch can be created. These parameters correspond to an electron flux -- and hence a diffraction signal -- at least two order of magnitude larger than what is available in conventional (non relativistic) electron diffraction setups. A time-resolved diffraction study using an rf photoinjector generated relativistic electron beam is the ambitious next goal of our laboratory. Such a result would open the way to study a variety of irreversible ultrafast processes with time resolution sub-100 fs which are out-of-reach of the present UED capabilities.

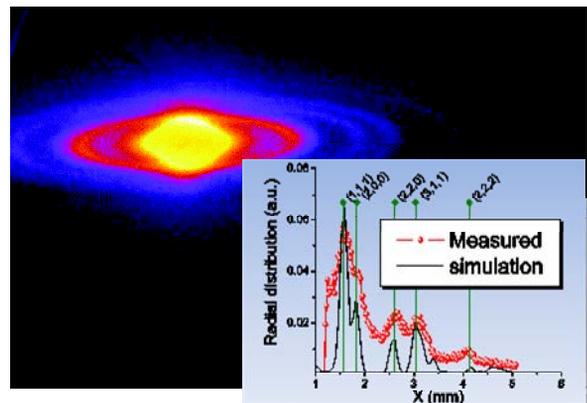


Figure 4: Diffraction pattern of a 200 nm thick Al foil recorded using the relativistic electron beam from the Pegasus photoinjector. In the inset the radially averaged intensity distribution and the results from the start-to-end simulation model are reported.

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