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EMITTANCE GROWTH DUE TO THE LASER NON-UNIFORMITY IN A PHOTOINJECTOR*

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Abstract

For photoinjector, non-uniform laser beams generate non-uniform electron bunch charge density that experiences emittance growth on a time scale of the plasmas period. Experiments were performed at the Brookhaven Accelerator Test Facility (ATF) to investigate the emittance growth due to the non-uniform laser beams in the transverse dimension. Several laser masks were made to generate various laser distributions. Significant emittance growth was observed as the laser distribution seriously deviated from a uniform distribution. For cylindrical symmetric non-uniform lasers, experimental results agree with PARMELA simulations. For non-cylindrical symmetric non-uniform beams, we observe the dependence of the emittance on the laser transmission through the masks, the latter being a measure of the non-uniformity of the laser distribution. Our experimental results provide a valuable guide to the required emission uniformity in high-brightness electron sources.

1 INTRODUCTION

High-brightness electron beams are critical for many applications, from X-ray Free Electron Laser (FEL) to electron cooling for high energy colliders[1-3]. The highest brightness beams are produced by "photoinjectors" [4], that is microwave cavity-based electron guns in which the electrons are generated by photoemission from a cathode illuminated by a laser. The emittance of the electron beam in the photoinjector is mostly affected by three contributions: thermal emittance, Radio Frequency (RF) transverse kick induced emittance and space-charge force induced emittance. Space charge effects, comprising linear and non-linear forces, usually dominate the total beam emittance. While the linear space charge forces can be easily compensated by the solenoid focusing [5,6], this does not hold for the non-linear space charge forces. Non-uniformity of the space charge distribution results in non-linear space charge forces. There are two major sources of non-uniformity: Quantum efficiency variation on the photocathode and laser illumination non-uniformity. In our experimental work, we produce a highly uniform quantum efficiency using a vacuum-based laser cleaning technique [7] and introduce an artificial, controlled non-uniformity of the laser illumination. In this paper we present experimental studies of the dependence of the emittance on uniformity and comparisons to PARMELA simulations and analytical estimations. Two types of non-uniformities are introduced: cylindrically symmetric and non-cylindrically symmetric distributions.

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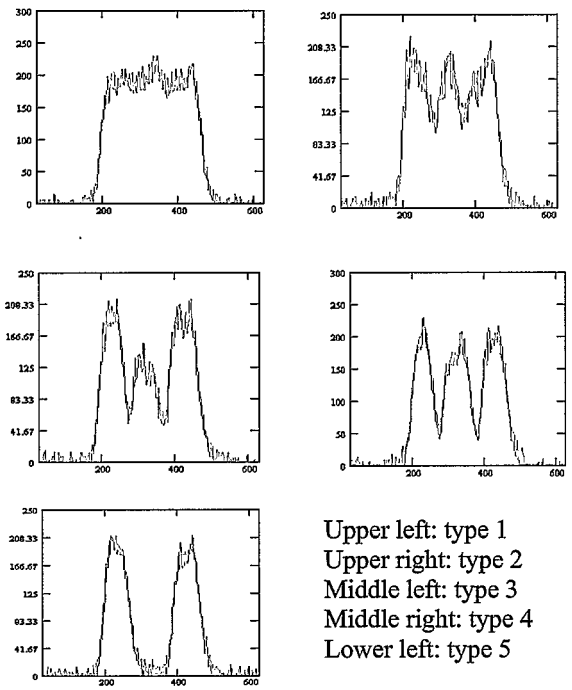
2 EXPERIMENTAL RESULTS AND ANALYSIS

The experimental work was carried out at the Brookhaven Accelerator Test Facility (ATF). The ATF accelerator system consists of a 1.6-cell photocathode RF gun followed by a solenoid magnet, then followed by two S-band (2856 MHz) linac sections. The electrons are produced at the ATF by a photoinjector, whose photocathode is illuminated by a frequency-quadrupled Nd:YAG laser. As mentioned in the introduction, the photocathode's quantum efficiency is uniform because of a careful cleaning procedure. In routine operations, the Nd:YAG laser transverse distribution is nearly uniform. The transverse emittance is measured on a Beam Profile Monitor (BPM), downstream of the linac, where the electron beam energy is tuned to 40 MeV, by scanning a quadrupole. The BPM is composed of a phosphorous screen and a CCD camera with a frame grabber to record data. The detail description for the measurement technique can be found in Ref. 6. The emittance is strongly dependent on the RF gun phase and the minimum emittance can be achieved at the lower RF gun phase [8]. In our measurements, low RF gun phase (30^0) is chosen.

2.1 Cylindrical Symmetric Non-uniform Lasers

The regular laser beam spot size is about 2 mm by 2.3 mm. Its transverse distribution is shown in Figure 1. We observe that the peak-to-peak (p-p) fluctuation relative to the flat top is less than 20%. The non-uniform electron beams are produced by introduction of an artificially non-uniform laser beam by using special laser masks. For simplicity, we denote the various distributions by a "type" number. The original, unperturbed laser distribution is assigned to type 1. We started by producing and measuring cylindrically symmetric, non-uniform beams. This allows us to compare the experimental results with predictions from PARMELA [9] simulations and simple analytical analysis. Using laser masks, four types of cylindrically symmetrical laser beams with different non-uniformities are produced, as shown in Figure 1. Figure 1 shows an intensity profile along the beam diameter. As mentioned above, the unmodified laser beam is designated as type 1. In laser distribution type 2, a 40% p-p variation in laser intensity was introduced. For type 3,

the center's intensity is about 60% of the outer ring. For type 4, we introduce a p-p variation of about 70%. Finally, in type 5, the middle part is blocked and thus the beam is significantly distorted compared with a regular uniform beam. Their normalized transverse emittances, shown in Figure 2, are measured for a bunch charge of 0.48 nC. The emittance grows by about 30% for the 40% p-p variation, and by more than a factor of two for the extreme type 5 distribution. The measured laser profiles and other conditions (e.g., cathode radius, pulse length, etc) are entered into the PARMELA simulations. The resulting measurements agree quite well with these simulations for each type of the non-uniform lasers, as shown in Figure 2.



Upper left: type 1
Upper right: type 2
Middle left: type 3
Middle right: type 4
Lower left: type 5

Figure 1: Uniform and non-uniform laser transverse profiles (horizontal axis scale is in pixels)

Next, the emittance dependence on the bunch charge for regular uniform and non-uniform beams with cylindrical symmetry was investigated. Laser distribution type 5 is taken as an example, being the most distorted distribution. The behavior of the emittance with bunch charge for both the uniform and non-uniform beams is similar, i.e., linear with the bunch charge. In addition to the PARMELA simulation, we provide an analytical estimate for comparison. For the uniform beam, the RF defocusing and space charge induced emittances are derived from a charge cylinder in Ref.10. For the non-uniform beam, its emittance can be described by the free energy between a non-stationary and stationary beams [11, 12]. Using the real parameters, analytical estimates are performed. It is shown that the analytical estimate is underestimate for non-uniform beam while overestimates the emittance for the uniform beam.

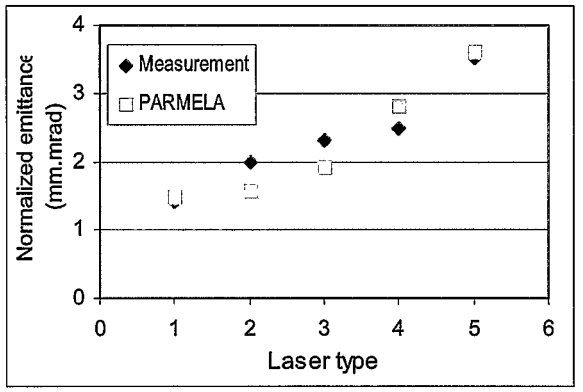


Figure 2: Emittances vs. laser distribution types, arranged by increasing non-uniformity (see text). Type 1 is the unperturbed (most uniform) distribution.

2.2 Non-cylindrical Non-uniform Lasers

In practice, we cannot expect the non-uniformity of the beam distribution to show cylindrical symmetry. In addition, we expect the non-uniformity to be fine-grained and randomly distributed. In order to study the emittance growth we produced masks that create non-uniform laser distributions with non-cylindrical symmetry. Six masks are mounted in one plate. The first mask is simply blank glass with no distortion and defines a 100% laser transmission. The next 5 masks have a rectangular grid pattern in which alternate squares have a reduced transmission. The variable parameter is the degree of attenuation of the reduced transmission. This creates a non-uniformity which is completely characterized by the transmission through the mask, an easily measured quantity. Thus the highest non-uniformity is at 50% transmission, when every other square is totally blanked. Thus we have the following masks: "100%", "90%", "80%", "70%", "60%" and "50%". The laser beam images for these masks are shown in Figure 3.

As these masks are alternated during the measurements, the total laser energy is adjusted in order to keep the bunch charge constant at 0.46 nC. The results are shown in Figure 4. We observe that the emittance is essentially linear with the laser transmissions through the masks. With the mask of "50%" transmission (full modulation of the intensity), the emittance is increased by about a factor of two. For a slight laser modulation, e.g., "90%" transmission, the emittance is increased by about 30%. One must remember that the base uniformity (Type 1) is not perfectly uniform. That means that our best measured emittance has some contribution from non-uniformity. Using the measurements, the measured laser residual non-uniformity (<20%) and quantum efficiency non-uniformity (<10%), we estimate the base emittance (for a perfectly uniform laser) to be about 1 mm.mrad at 0.5 nC, which is close to the recent measurement [13].

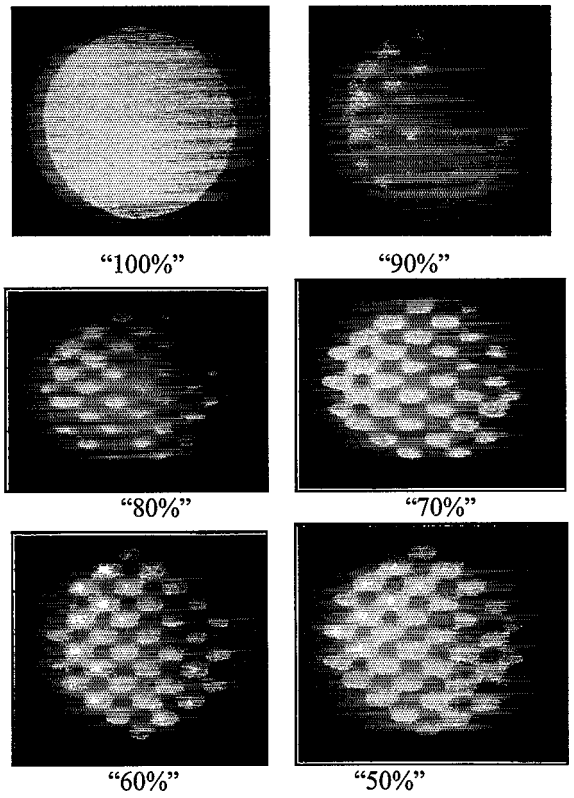


Figure 3: Uniform and non-cylindrical symmetrical laser beam images

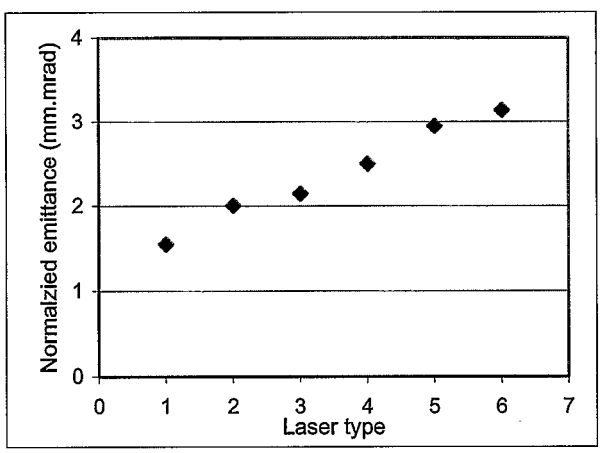


Figure 4: Emittance as a function of laser's non-uniformity. The laser types correspond to increasing attenuation (see text).

3 SUMMARY

We report experimental results and, where practical, comparison to numerical simulation and analytical estimates for the dependence of the transverse emittances of electron beams on non-uniformity of the charge distribution in the transverse plane. For cylindrically symmetrical electron beams, we find a similar dependence on the bunch-charge, which is linear over the charge. The emittance measurements agree well with theory and show the emittance growth by a factor of two for the highest non-uniformity.

For the uniform beam, the emittance measurements agree well with the predictions from PARMELA simulations, but the analytical approach overestimates the measurements and simulations. For non-uniform beam, the predictions from analytical estimates underestimate the measurements and simulations. For non-cylindrically symmetrical, non-uniform beams, the emittance is linear with the laser transmission through laser masks. The emittance is increased by 30% when the laser is slightly modulated by laser mask, i.e., 90% transmission. The emittance is increased by a factor of 2 with 50% laser transmission.

We conclude that the measurements agree with the predictions that emittance grows as a function of non-uniformity. Our results can provide a valuable guide to the estimating the effect of laser non-uniformity in this critical range of very-high brightness electron beams. The results for a non-cylindrical symmetry suggest that a theoretical model of small-grained non-uniformity may be developed but this task is beyond the scope of the present work.

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