GENERATION OF HOMOGENEOUS AND PATTERNED ELECTRON BEAMS USING A MICROLENS ARRAY LASER-SHAPING TECHNIQUE*

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Abstract

In photocathodes the achievable electron-beam parameters are controlled by the laser used to trigger the photoemission process. Non-ideal laser distribution hampers the final beam quality. Laser inhomogeneities, for instance, can be "amplified" by space-charge force and result in fragmented electron beams. To overcome this limitation laser shaping methods are routinely employed. In the present paper we demonstrate the use of simple microlens arrays to dramatically improve the transverse uniformity. We also show that this arrangement can be used to produce transversely-patterned electron beams. Our experiments are carried out at the Argonne Wakefield Accelerator facility.

BACKGROUND ON MLAS

The microlens array (MLA) is a fly's eye type light condenser that is often as an optical homogenizer for various applications [1–3]. The principle of the MLA lies in redistribution of the incoming light intensity across the light beam spot. Typically MLAs are arranged in pairs. After passing through the MLAs, the light rays are collected by a "Fourier" lens, which focuses parallel rays from different beamlets to a single point at the image plane. This process leads to transverse homogenizing of the beam; see Fig. 1. Therefore the MLA homogenization scheme is quite simple and worth investigating in the context of photocathode drive lasers. Alternatively, imaging the object plane of the single microlenses in the MLA with a "Fourier" lens produces a set of optical beamlets arranged as arrays (with a pattern mimicking the microlens spatial distributions). The latter configuration is also relevant to electron sources, as it can lead to the formation of transversely segmented beams that have applications to beam-based alignment, single-shot quantum-efficiency map measurement, and coherent light sources.

We now analyze the typical MLA setup diagrammed in Fig. 1 to derive a few salient features relevant to homogenization using the ABCD formalism [1]. We examine the case when the two MLAs are identical ($f_1 = f_2 = f$), and located

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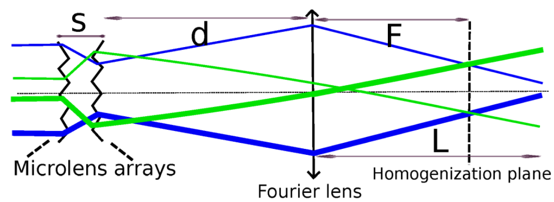

Figure 1: Schematics of the microlens array configuration. Initial incoherence in the beam becomes evenly distributed at the homogenization plane.

in the object plane of the Fourier lens ($L = F$) and $x < p/2$, where x is the distance from the incident ray to the n-th lens axis and p is the pitch (assuming no "cross-talk") [4]. Under these assumptions and assuming a small initial beam divergence (upstream of the MLAs), we find the diameter of the image at the homogenization plane to be

$$D_h \approx \frac{Fp}{f^2}(2f - s). \tag{1}$$

For practical purposes it is also useful to calculate the diameter of the beam at the Fourier lens and therefore estimate the required aperture:

$$A_F \approx \frac{dp}{f^2}(2f - s). \tag{2}$$

Practical implication may sometime result in $L \neq F$; then the following expression is useful to determine the beam size at a given location:

$$D \approx \frac{pL}{f^2}(2f - s) + \frac{dp(2f - s)}{f^2}\frac{F - L}{F}. \tag{3}$$

If the location L is close to the focal plane, the resulting image will stay highly homogenized due to the finite size of the Airy disk. Moving farther away from the focal plane results into slight intensity modulation.

OPTICAL TRANSPORT DESIGN

In photoinjector setups, the laser injection port is relatively far from the photocathode [typically O(m)]. It is therefore necessary to design an appropriate transport line to image

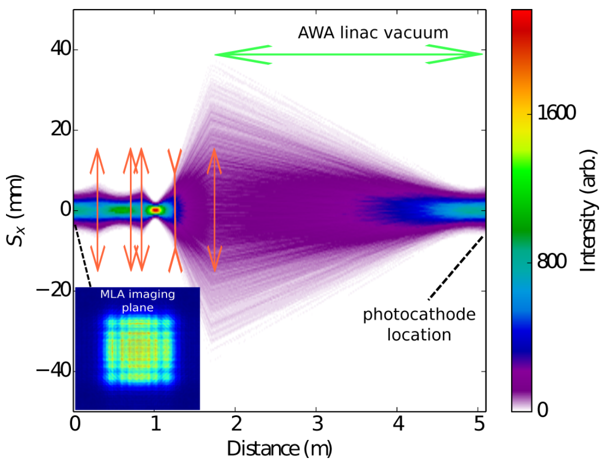

Figure 2: Ray tracing of a five-lens transport capable of imaging the homogenized beam to the photocathode (this system was built at AWA). The inset shows of a 8×8 simulated through the MLA using SRW [6] (bottom left).

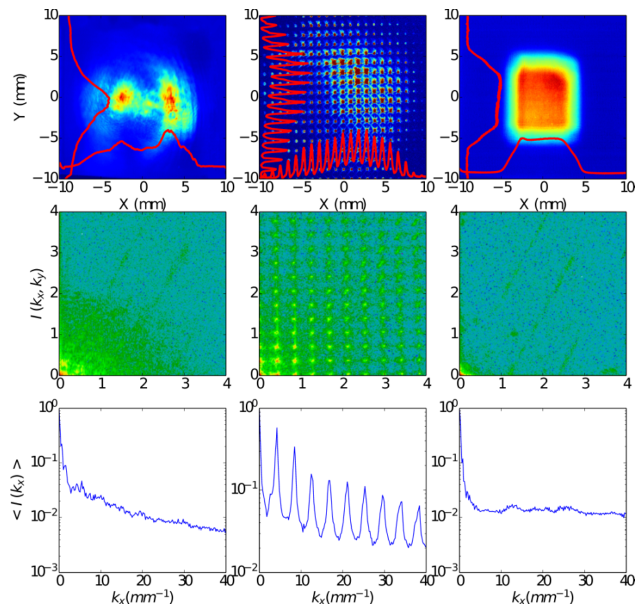

Figure 3: Measured UV laser without MLA (left column) and with MLA setup to produce beamlets (middle column) or as a homogenizer (right column). The upper, middle, and lower rows respectively correspond to the laser transverse density distribution, its 2D FFT, and the projected spectrum along the horizontal frequency k_x.

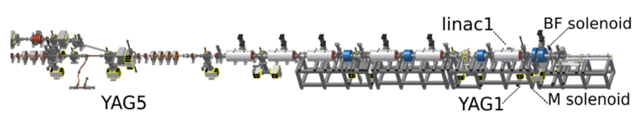

Figure 4: AWA beamline overview. Bucking-focusing (BF) and matching (M) solenoids were adjusted to image the beam on YAG screens. The energy gain of one accelerating cavity (linac) is 10 MeV.

the homogenized laser spot on the photocathode surface. Given these limitations, the commonly-used $4f$-imaging system is not suitable and the "imaging" plane has to be much farther downstream than the "object" plane upstream.

The ray tracing associated to a possible solution consisting of five lenses is shown in Fig. 2. As it can be seen, the final-lens aperture is a limiting factor, as the setup under consideration requires a large beam size (typically a few cm) at the lens before it slowly decreases in the drift up to the photocathode. In addition the mirror inside the evacuated accelerator beamline can be a limiting aperture which would clip the beam.

LASER MEASUREMENTS

To evaluate the performance of the proposed scheme, we use two MLA's on the photocathode drive laser of the Argonne Wakefield Accelerator (AWA) [5]. The input UV (λ = 248 nm) laser pulse is obtained from frequency tripling of an amplified Ti:Sp laser system followed by a two-pass excimer amplifier. After transport from the laser room to the accelerator vault, the laser is collimated and sent to the MLA setup described in Fig. 1 followed by the and optical transport line shown in Fig. 2.

The nominal UV laser pulse is shown in Fig. 3 (left column) and is highly disrupted. This disruption is mainly attributed to filamentation during transport in air up to the accelerator enclosure. The transverse modulation is quantified with the help of spatial 2D Fourier transforms. Fig. 3 summarizes the results of two settings of the MLA setup (middle and right columns). When the MLA is tuned as a homogenizer, spectral components at $k_i < 5$ mm^{-1} on the initial beam (left) are suppressed by a factor ~ 4. On the contrary, when the homogenizer is setup to produce a patterned beam, spectral components are present at the fundamental modulation frequency (here $k_x \simeq 5$ mm^{-1}) and their harmonics. This topic was explored in a great detail in [7, 8].

Finally, we measured the laser power loss in the described setup. The MLA plates did not have a UV coating, hence the power loss was about 5% per surface or 20% per two MLAs. The use of non-coated UV lenses will drop the laser power by additional 10% per lens. Yet in many facilities the power budget of the laser is large so it is affordable to operate at a reasonable charge with the MLA and imaging transport system. The maximum measured laser power was 2.4 mJ.

PRELIMINARY EXPERIMENTS ON E-BEAM GENERATION

The electron beam measurements were performed at the AWA facility linac diagrammed in Fig. 4. For a detailed description of the facility, see Ref. [5]. The manipulated laser pulse impinges a high-quantum efficiency cathode located in a L-band RF gun to produce an electron bunch.

We first produced an electron bunch using a 8×8 laser-beamlet array and accelerated to 8 MeV. The corresponding electron-beam transverse images at the YAG1 for different

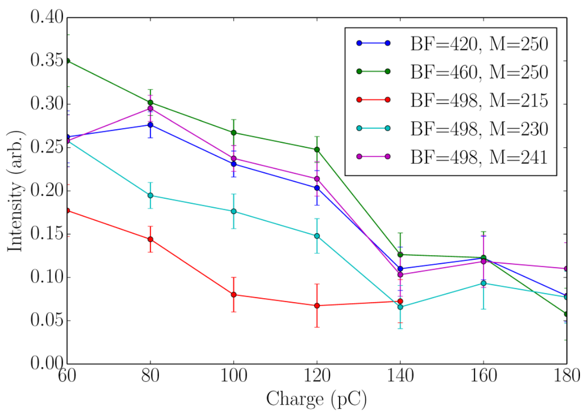

Figure 5: First harmonic amplitude as a function of charge for different solenoid settings at 8 MeV.

settings of the focusing and matching solenoids and different laser intensity. Note, that due to the space charge effect at the emitting surface, there is a critical value of charge that can be produced per beamlet, therefore the total charge of the patterned beam is limited. In our measurement the maximum total charge of the patterned beam was approximately 1.5 nC or ~ 30 pC per beamlet.

The electron beamlets formation is analyzed in the same fashion as MLA laser images. Fig. 5 represents the evolution of the transverse bunching factor vs. charge for different solenoid settings. From Fig. 6 one can see that when the distance between beamlets become small (comparable to beamlet RMS), the modulation is smeared out.

In a second set of experiments, the multi-beamlet beam further propagated along the linac up to an energy of ~ 50 MeV. To this end, an additional solenoid at 50 MeV was used to produce an image of the beamlets at the YAG5 screen. The observed typical beamlet separation is approximately ~ 2 mm; see Fig. 7.

This separation is suitable for the generation of coherent, e.g. transition, radiation enhanced in the THz frequencies, after passing a bunch train through transverse-to-longitudinal phase space exchanger. Such a phase-space exchanger is available at AWA just downstream of YAG5 [10].

Finally, a last experiment attempted to verify the benefits of homogenizing the electron beam by setting up the MLA to produce a homogenized laser spot on the photocathode. A quadrupole scan technique was used to measure the transverse emittance of a 1nC beam produced by the nominal laser spot (upper left image in Fig. 3). The beam was subsequently homogenized (upper right picture in Fig. 3), clipped with a circular aperture to yield the same rms sizes as the nominal laser spot, and its emittance was measured. Our results are consistent with GPT [9] simulations and indicate that the homogenized laser reduced the emittance by a factor ~ 2 compared to the nominal laser distribution (34.8 ±0.8μm vs. 78.4 ±5.5μm). Prior to the experiment no specific procedure was used to minimize the nominal emittances and the emittance values were rather large. Further improvements

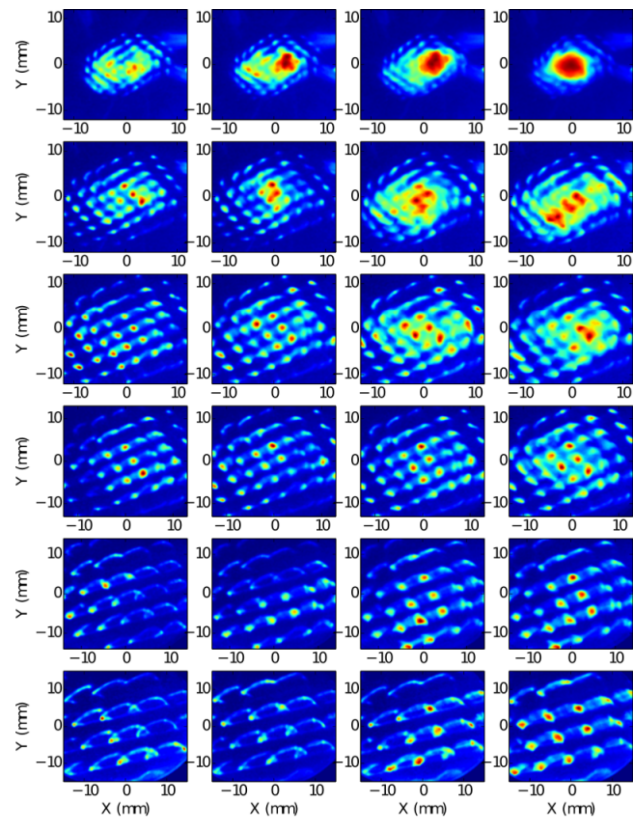

Figure 6: False color 8 MeV electron beam patterns for various matching solenoid current setting and charge. Left to right: Q=60pC, 80pC, 100pC, 120pC. Top to bottom: M=215A, 230A, 241A, 255A, 270A, 290A and BF=498A.

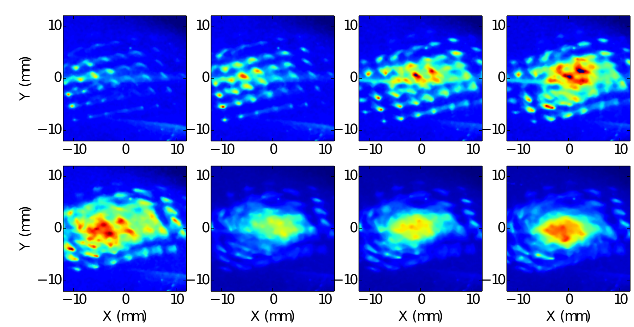

Figure 7: False color 50 MeV electron beam patterns for various charges. From left to right and top to bottom: Q=60pC, 100pC, 200pC, 300pC, 400pC, 500pC, 600pC, 700pC.

of the emittance measurement using a pepper-pot technique are planned.

SUMMARY

We demonstrated the possible use of MLA to control the transverse distribution of a photocathode laser pulse. We particularly showed that homogenization improves the transverse electron-beam emittance and demonstrated the generation of patterned beams consisting of multiple beamlets. The later distribution combined with the emittance exchanger could lead to the formation of bunch trains [10, 11].

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