GENERATION OF TRANSVERSELY SEGMENTED BEAM USING A NANO-PATTERNED PHOTOCATHODE

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Abstract

Plasmonic photocathodes – nano-patterned photocathodes with periodicity comparable to the excitation laser – have demonstrated enhanced quantum efficiency. In the present paper we present numerical simulations of the beam dynamics associated to the emission process from this type of cathodes and to the subsequent acceleration to relativistic energies by combining WARP and IMPACT-T programs. We especially consider the possibility to transversely image the cathode surface at high energy and enable the generation of transversely segment beams.

INTRODUCTION

Photocathodes are widely used to generate electron beams for applications in fundamental-science research, as a part of compact-light source and ultra-fast electron-diffraction systems. Novel photocathodes such as plasmonic photocathodes have been demonstrated and considered for next level of the applications.

The plasmonic photocathode employs a surface engineered at the nanometer scale with periodicity matching with the excitation laser wavelength. For instance, the periodic structure can be a two-dimensional pattern or array of tips or holes, or a series of tranches organized as a grating. Throughout this paper we consider a nanohole with geometry similar to the one investigated in Ref. [1]. Such nano-patterned photocathode have demonstrated enhanced quantum efficiency, owing to both higher laser field absorption and field enhancement at sharp edges of each nano-structures.

The nanoscale pattern controls the beam initial distribution and could form density-modulated beams. The transversely-modulated beams could be directly applied to a variety of applications or further manipulated, e.g., using transverse-to-longitudinal phase-space exchangers to yield temporally-modulated electron bunches [2,3].

The numerical simulations of the beam dynamics, is performed piecewise by combining the WARP [4] simulation framework with the IMPACT-T [5] beam dynamics program. WARP is employed to investigate the beam dynamic in the vicinity of the cathode while IMPACT-T tracked the emitted electrons through an RF-gun for acceleration to relativistic energies. A crucial question we wish to address is the possible preservation of information related to the initial

patterned distribution (on the cathode surface) for the subsequent imaging after acceleration to relativistic energies.

EMISSION PROCESS

The emission process and early beam dynamics were simulated using a finite-difference time-domain (FDTD) particle-in-cell (PIC) electromagnetic model based on WARP. This program was used to study the beam dynamics close to the cathode surface with interaction with the emission-triggering laser pulse [6].

The simulations are set up for a single emitter (or nano-structure) in a cathode-anode configuration, in which a potential between the anode and cathode imitates the RF field experienced by the cathode when located on the back plate of the typical S-band RF gun. A laser pulse propagates from the anode to the cathode and triggers the electron emission. Nano-structures patterned as periodic arrays manifest resonance effects: as the pattern's periodicity matches the applied electromagnetic field wavelength a stronger coupling occurs. For example, a Titanium-Sapphire laser $\lambda \in [600, 1100]$ nm triggers the plasmonic excitation on the cathode with periodic arrays the order of 1 μm; see Ref. [7]. The single-emitter simulations are performed with proper boundary condition to reflect the periodicity of the problem (assuming an infinitely large array). In our simulations the cathode is modeled as a perfect electric conductor (infinite conductivity). The spatial period (or periodicity) of the cathode array is defined as the center-to-center distance between nanoholes. The cathode
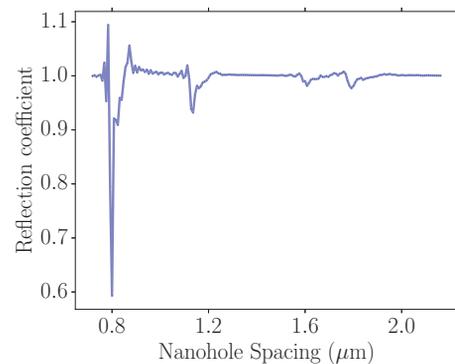
Figure 1: Laser reflection coefficient for study of periodicity.

periodicity is nominal set to 800-nm however in an effort to explore possible configurations with larger periodicities (for

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Table 1: Settings of RF-gun and photocathode-laser parameters used for in the presented simulations.

parameter	symbol	nominal	unit
laser launch phase	ϕ_l	65	deg
laser rms spot size	σ_c	1	μm
laser rms duration	σ_t	3.5	ps
cathode periodicity	Λ	1.6	μm
RF gun peak field	E_0	120	MV/m
# of $e-$ per holes	$N_{1\times1}$	1000	–

better imaging) we investigated the plasmonic properties of the cathode as function of the periodicity of the cathode array was investigated by simulations of a vertically-polarized laser pulse (duration of σ_l = 10 fs) with a fixed wavelength of λ = 800 nm. The pulse injected from the z=30 μm travels along the $-\hat{z}$ direction and reflects on the nanoholes (profiled as a surface of revolution of a Gaussian function with depth of -264 nm and RMS width of 93.4 nm) with its base located at $z = 0$. The laser-pulse electromagnetic fields are recorded on a 41×41 grid positioned at $z = 15$ μm from the cathode surface. The average FFT (over the 41×41 grid) of the Poynting vectors associated to the incident and reflected pulses is computed and provide the absorption at the wavelength of λ = 800 nm. Some absorption occurs at periodicities $\simeq$ 800, 1136, 1608, and1792 nm; see Fig. 1.

ACCELERATION TO RELATIVISTIC ENERGIES

Although space-charge effects are expected to be small, it is anticipated that they will predominantly impact the emission process [due to the $O(\gamma^{-2})$ scaling]. Given the small emission area, it is expected that binary Coulomb collisions may play a crucial role in the early-stage beam dynamics. To quantify such a possibility we first explore the dynamics using IMPACT-T as it includes a point-to-point N-body space charge solver. The simulations uses an idealized distribution with parameters consistent with the distribution simulation with WARP. The cathode is located on the back plate of a standard $1 + \frac{1}{2}$-cell RF gun of BNL/SLAC/UCLA type operating at the S-band frequency 2.856-GHz. In our simulations no external focusing is applied so that the beam expands during acceleration. Figure 2 presents the evolution of the beam size, transverse emittance, bunch length and energy from the cathode up to the gun exit (0.2 m) for a single hole and a 3×3-hole array. The single-hole beam emittance are below 2 nm while the emittance of the 3×3-hole array is three fold higher as expected. The simulation ends at 0.2-m from the cathode. At the latter location the beamlets are no more transversely separated due to the large correlated divergence they acquired during acceleration in the RF gun. However the information is preserved in the phase space where the beamlets keep apart; see Fig. 3.
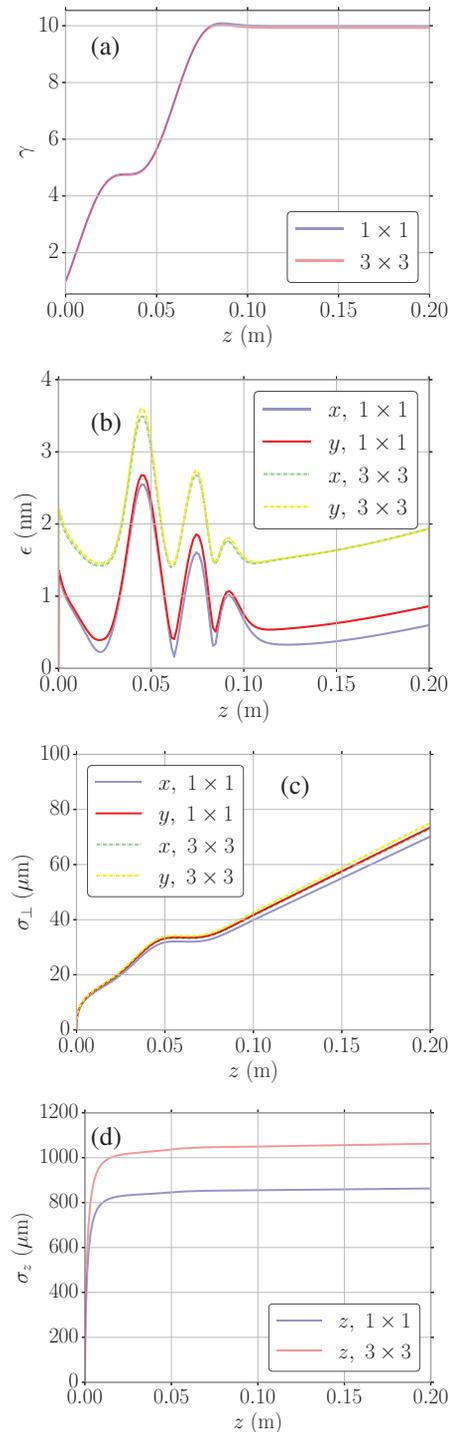
Figure 2: Evolution of (a) the relativistic gamma, (b) transverse emittance, (c) transverse beam size, and (d) longitudinal beam size from the cathode up to the gun exit (0.2 m), for a single (1×1 array) hole and the 3×3-hole array emitter.

IMAGING AT ~ 5 MEV

The beam distributions simulated with IMPACT-T at $z =$ 0.2 m downstream from the cathode surface were used as an input into ELEGANT. A set of quadrupole magnets can be used to implement the transverse-matching conditions derived
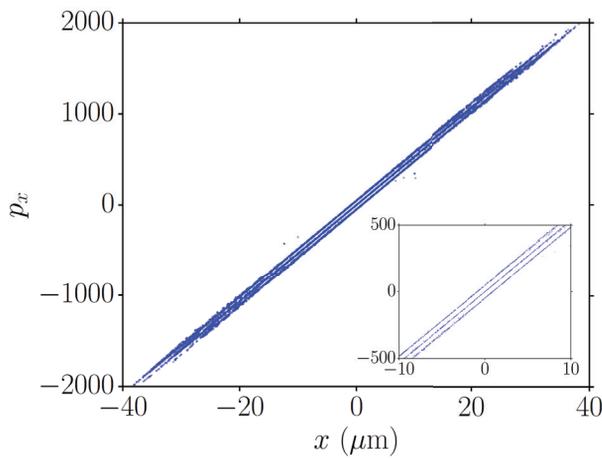
Figure 3: Transverse phase space associated to the 3×3-hole array emitter downstream of the Rf gun at $z = 0.2$ m from the cathode surface.

in Ref. [6]. As a simple test we used a single quadrupole magnet and tune its strength to provide an image in the (x, x') phase space at 0.3 m downstream of the cathode; see Fig. 4. There is a significant smearing of the density modulation due to the fan-like trace-space distribution associated to each beamlet. In the latter example, a 10-cm long quadrupole with field gradient of 67.13 T/m was used − such a setup could be easily implemented with permanent-magnet quadrupole(s). We also note that the requirement on the quadrupole magnet could be further relaxed by adding a solenoidal lens around the RF gun.

FUTURE PLANS

The presented setup will be expanded to also include a short S-band traveling-wave accelerating section thereby boosting the beam energy to < 50 MeV. Applications of this compact accelerator to produce X-ray via inverse-Compton scattering will be explored. Further beam dynamics studies with larger nanohole arrays will also be conducted.

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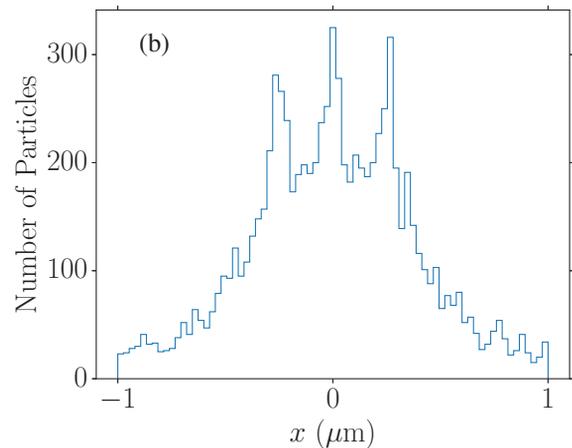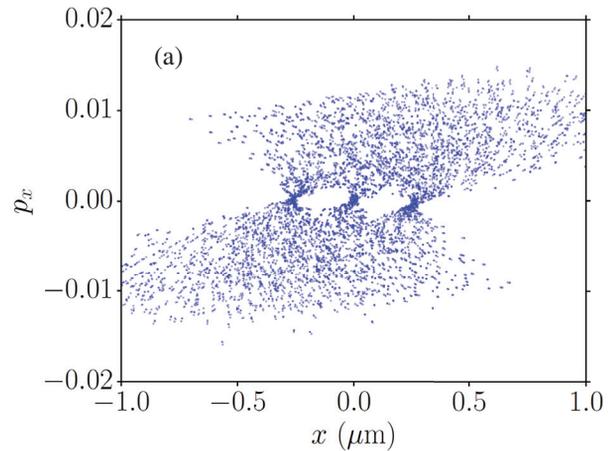
Figure 4: Transverse phase space (a) and its projections (b) at $z = 0.3$ m after a single quadrupole magnet tuned to image the cathode distribution.

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