ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB129

BEAM DYNAMICS SIMULATIONS IN A HIGH-GRADIENT X-BAND PHOTOINJECTOR*

W. H. Tan†, P. Piot[1], Northern Illinois University, DeKalb, IL, USA
C. Jing[1], S. Kuzikov, G. Chen[2‡], Euclid Techlabs LLC, Bollingbrook, IL, USA
G. Ha, Argonne National Laboratory, Lemont, IL, USA
[1]also at Argonne National Laboratory, Lemont, IL, USA
[2]also at Illinois Institute of Technology, Chicago, IL, USA

Abstract

A high-gradient X-band (11.7-GHz) photoinjector was recently developed by Euclid Techlabs and is in its commissioning phase at the Argonne Wakefield Accelerator (AWA). This contribution discuss the beam-dynamics modeling of the photoinjector system comprising an RF gun and linac section. We especially discuss beam-dynamics optimization of setup for an integrated proof-of-principle experiments. We also discuss the use of such a photoinjector as a witness-bunch source for a future high-gradient collinear-wakefield accelerator experiments at the AWA.

INTRODUCTION

Bright-electron sources are foreseen to enable an array of research opportunities in Basic Energy Sciences. Accelerator-based light sources, e.g., free-electron lasers (FELs), driven bright electron bunches can produce copious amounts of radiation over a broad range of the electromagnetic spectrum. Likewise, directly employing these electron bunches as primary probes, e.g. in ultrafast electron scattering setups, has the potential to yield groundbreaking research in condensed matter and chemistry. A commonly-used figure of merit is the transverse beam brightness $B_\perp = Q/\varepsilon^2$ where Q and ε are respectively the bunch charge and transverse emittance. The brightness scales as $B_\perp \propto E_0^\nu$ where E_0 is the electric field applied at the photocathode surface and ν is a parameter that depends on the initial transverse-to-longitudinal beam-size aspect ratio [1, 2].

Accordingly, a path to generating bright electron beams consists of designing an RF photoinjector capable of supporting a high surface electric field on the photocathode. Electron beams generated from a photocathode will be accelerated to relativistic energies and suppress the impact of space-charge effects on the beam dynamics (emittance growth). The path to producing a high electric field consists of operating the RF-gun cavity at higher frequencies. However, such an approach is ultimately limited by the RF breakdowns where field-emitted due to surface imperfection leads to local RF-induced heating and damage the cavity wall. A phenomenological model indicates that the breakdown rate (BDR) scales as BDR $= AE_a^x \tau_p^y$ where E_a and τ_p are respectively the accelerating gradient and RF pulse duration and A, $x \sim O(10)$, and $y \sim O(1)$ are constants [3]. Therefore decreasing the BDR for a given accelerating field requires a shortening of the RF-pulse duration. Such an approach was recently tested at AWA. In the setup a high-power (~ 300 MW), short (~ 10 ns) RF pulse was generated via deceleration of a relativistic beam using a setup similar to the one used in a two-beam acceleration [4]. In this paper we discuss the use of such short high-power RF pulses to power a compact X-band photoinjector for bright-beam generation.

X-BAND RF GUN

A high-gradient RF gun was designed by Euclid Techlabs [5]. The gun operates at a frequency of 11.7 GHz (the seventh harmonic of 1.3 GHz) selected to match the power extraction and transfer structure (PETS) available at AWA to provide the short RF pulse [6]. The gun geometry consists of a $1 + \frac{1}{2}$ cell cavity and includes a coaxial input-power coupler to minimize field asymmetries; see Fig. 1. The back-plate of of the gun will be used for photoemission (the high surface fields prevent the use of a retractable photocathode). A mechanical tuner located on the back-plate of the gun is used to tune the cavity frequency and/or field balance. The field maps of the RF gun simulated with OMEGA3P appears in Fig. 2 [7]. The short RF pulse produced by the available 11.7-GHz PETS when driven by a train of 8 high-charge (≃ 40 nC) 70-MeV bunches was simulated with CST MICROWAVE-STUDIO to have a ~8 ns (FWHM) duration with trapezoidal envelope as illustrated in Fig. 3. Such an input-power pulse establishes a "transient" field in the RF gun (i.e. the steady-state regime common to standing-wave structures is reached for a brief period of time) as shown in Fig. 3.

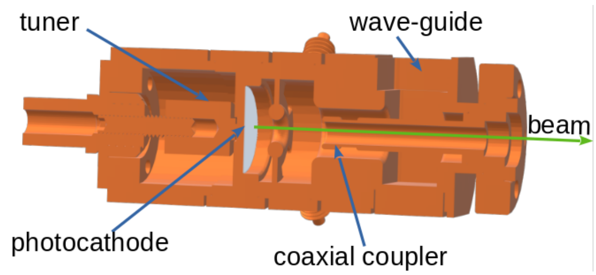

Figure 1: 3D cut-away model of the 11.7-GHz RF gun.The central area of the gun 1/2-cell back plate (colored in white) serves as a photocathode.

* This work is supported by the U.S. DOE, under award No. DE-SC0018656 to NIU, DOE SBIR grant No DE-SC0018709 at Euclid Techlabs LLC, and contract No. DE-AC02-06CH11357 with ANL.
† z1829753@students.niu.edu
‡ Now at Argonne National Laboratory.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB129

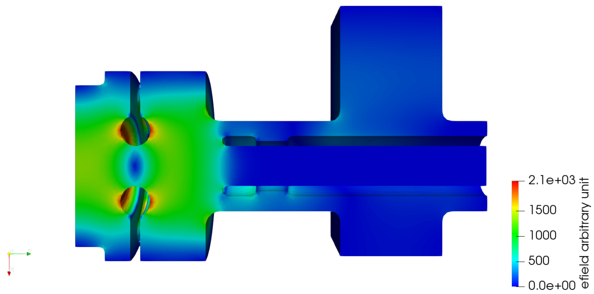

Figure 2: Amplitude of the electric field in the plane $(x, y = 0, z)$ simulated with ACE3P.

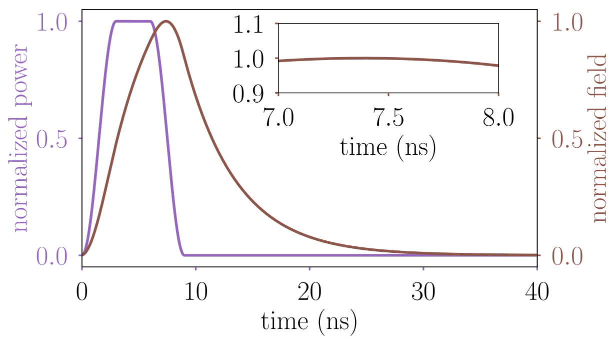

Figure 3: Simulation of RF pulse produced by the available PETS structure (magenta trace) and corresponding time dependence of the electric-field amplitude in the RF gun (brown trace). All traces are normalized to their peak values.

BEAM DYNAMICS STUDIES

Beam dynamics simulations were performed in preparation for a proof-of-principle experiment aimed at generating and characterizing electron bunches produced by the X-band gun. The planned experiment uses the AWA facility as a backbone and will especially use power generated in an X-band PETS along with the available photocathode-laser system. Accordingly, the available laser parameters and RF power were constrained with values available at AWA. The simulations were performed using the ASTRA program.

We modeled the RF gun as a standing-wave structure which is a legitimate assumption given that a bunch photoemitted around the time $t = 7.5$ ns (see Fig. 3) transits through the RF gun in ~0.1 ns) for the nominal peak-field of 350 MV/m. Hence the electron experiences a quasi-steady-state field while traveling in the RF gun. Our modeling focus on an integrated photoinjector composed of the X-band RF gun followed by a X-band linac so to enable a full transverse-emittance compensation process.

Photoinjector Design

The peak field of the RF gun in simulations is set at 350 MV/m, based on early high-power tests of this RF gun prototype in AWA [8]. The beam formed by the RF gun is accelerated by a brazeless 8-cell structure supporting peak accelerating fields of 150 MV/m. Our simulation considers the accelerating structures to be cylindrical-symmetric and the external fields are modeled in ASTRA from the axial on-axis electric field $E_z(r = 0, z)$ shown in Fig. 4. A solenoidal lens is located downstream of the RF gun and can produce peak axial magnetic field up to 0.5 T. The corresponding axial magnetic field appears in in Fig. 5.

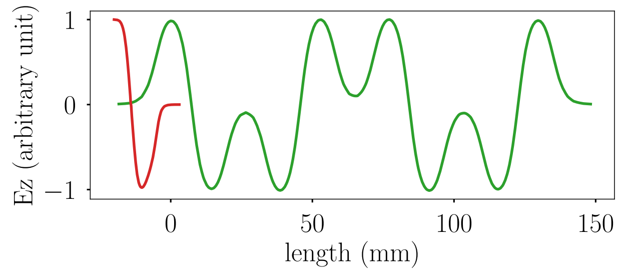

Figure 4: On-axis axial electric field $E_z(r = 0, z)$ associated with the RF gun (red trace) and the 8-cell linac (green trace). The horizontal-axis origin is arbitrary.

A double-cube vacuum-chamber assembly housing the photocathode laser-injection mirror and some diagnostics (a scintillating screen and Faraday cup) is located between the solenoid and linac. Downstream of the linac the beamline incorporates a transverse-emittance measurement and a spectrometer line.

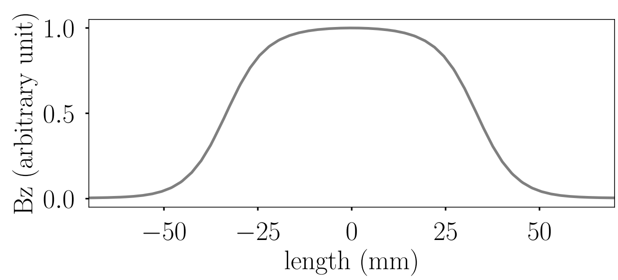

Figure 5: On-axis axial magnetic field associated with the solenoid located downstream of the RF gun.

Beam Distribution

The initial electron-beam distribution is considered to have a 3-ps-duration (FWHM) flattop longitudinal profile. In the planned experiment the same ultraviolet laser will be used to generate the high-charge bunch needed to drive the PETS and to form the electron bunch in the X-band photoinjector. The flat-top distribution is produced via a polarization-splitting pulse stacker comprising four α-BBO crystals to stack 16 300-fs (FWHM) Gaussian pulses. The total charge is set to 100 pC. The transverse beam profile is taken to be radially uniform. The beam distribution has a mean transverse energy (MTE) of 760 meV.

SIMULATION RESULTS AND DISCUSSIONS

Optimizations were performed to investigate the smallest possible emittance achieved in simulations using ASTRA. The

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB129

optimization uses the DEAP toolbox and varied the laser spot size, field amplitude and phase in the RF cavities, along with the solenoidal-lens field amplitude and the location of the solenoidal lens and linac. The system was constrained to allow for beamline component to be inserted between these elements (e.g. laser-injection six-way cross for the photocathode laser and diagnostics, between the solenoidal lens and linac). An example of optimized parameters is summarized in Table 1.

A plot of the evolution of transverse emittance and beam size versus distance is shown in Fig. 6. Our simulations indicate that a normalized emittance as low as 170 nm can be attain downstream of the linac at $z \simeq 1$ m from the photocathode. Figure 7 displays the evolution of beam reference energy and accelerating field experienced by a reference particle along the injector. Figure 8 shows snapshots of the transverse and longitudinal phase spaces at the end of the beamline.

These optimized injector parameters will be used as a reference in our upcoming proof-of-principle experiments at AWA.

Table 1: Optimized Parameters for the Photoinjector and Generated Beam Parameters (The Phase Settings are Relative to Maximum-Energy-Gain Values)

Parameter	**Value**	**Unit**
Laser spot rms size	70	µm
Laser rms duration	4	ps
Beam charge	100	pC
RF gun peak E-field	350	MV/m
RF gun phase	−3.4	deg
Linac peak field	112.7	MV/m
Linac phase	8.7	deg
Linac distance from the cathode	0.62	m
Solenoid B-field	0.38	T
Solenoid distance from the cathode	0.09	m
Photoinjector exit from the cathode	1.06	m
Final beam energy	8.5	MeV
Final beam bunch length	0.36	mm
Final transverse rms size	0.14	mm
Final beam transverse emittance	0.17	µm
Final beam relative energy spread	0.003	-

CONCLUSION

We presented beam dynamics simulation studies of a high gradient X-band photoinjector designed by Euclid Techlabs, where the 11.7 GHz RF gun is being fed with a short ~10 ns RF pulse using power extractors in AWA. Simulation results indicate that a transverse emittance of 170 nm can be achieved in the planned experiment. A full-scale optimization of a photoinjector (without imposing constraints related to an existing setup) is expected to yield lower emittance values and will be the subject of a future investigation

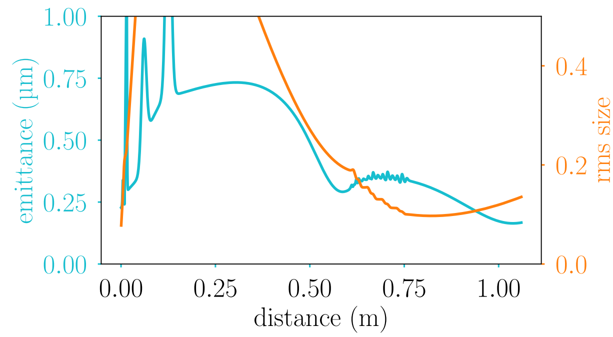

Figure 6: Transverse emittance (turquoise trace) and beam size (orange trace) evolution along the photoinjector.

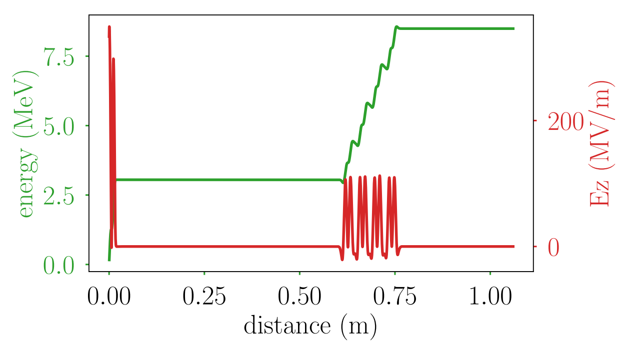

Figure 7: Evolution of the reference-particle energy (green trace) and experienced accelerating field (red trace) along the photoinjector.

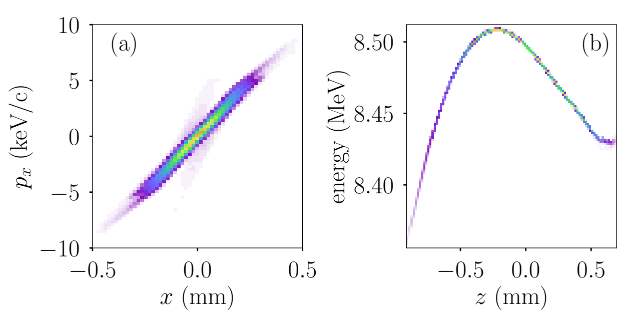

Figure 8: Snapshots of the transverse (a) and longitudinal (b) phase spaces produced at the end of the beamline.

REFERENCES

[1] I. V. Bazarov, B. M. Dunham, and C. K. Sinclair, "Maximum achievable beam brightness from photoinjectors", *Phys. Rev. Lett.*, vol. 102, p. 104 801, Mar. 2009. doi:10.1103/PhysRevLett.102.104801

[2] D. Filippetto, P. Musumeci, M. Zolotorev, and G. Stupakov, "Maximum current density and beam brightness achievable by laser-driven electron sources", *Phys. Rev. ST Accel. Beams*, vol. 17, p. 024 201, Feb. 2014. doi:10.1103/PhysRevSTAB.17.024201

[3] A. Grudiev, S. Calatroni, and W. Wuensch, "New local field quantity describing the high gradient limit of accelerating structures", *Phys. Rev. ST Accel. Beams*, vol. 12, p. 102 001, Oct. 2009. doi:10.1103/PhysRevSTAB.12.102001

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB129

[4] J. H. Shao *et al.*, "Recent Two-Beam Acceleration Activities at Argonne Wakefield Accelerator Facility", in *Proc. Int. Particle Accelerator Conf. (IPAC'17),*, Copenhagen, Denmark, May 2017, pp. 3305–3307. doi:10.18429/JACoW-IPAC2017-WEPVA022

[5] S. Antipov, P. Avrakhov, G. Ha, S. Kuzikov, A. Liu, and J. Power, "Ultra-High Gradient Short RF Pulse Gun", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, Jun. 2019, pp. 2987–2989. doi:10.18429/JACoW-IPAC2019-WEPRB072

[6] J. Shao *et al.*, "Development and high-power testing of an *X*-band dielectric-loaded power extractor", *Phys. Rev. Accel. Beams*, vol. 23, p. 011 301, Jan. 2020. doi:10.1103/PhysRevAccelBeams.23.011301

[7] L. Xiao, L. Ge, Z. Li, and C.-K. Ng, "Advances in multiphysics modeling for parallel finite-element code suite ACE3P", *IEEE Journal on Multiscale and Multiphysics Computational Techniques*, vol. 4, pp. 298–306, 2019. doi:10.1109/JMMCT.2019.2954946

[8] J. H. Shao *et al.*, "High-Power Test of a Highly Over-Coupled X-Band RF Gun Driven by Short RF Pulses", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper THPAB331, this conference.