Abstract—This work presents an open-source code, FEgen, that generates initial field emission distributions based on the time-dependent Fowler–Nordheim equation. Current in-demand beam tracking software—such as ASTRA, IMPACT-T, and GPT—do not contain native distribution generator functions suitable for field emitted electron tracking and phase space analysis. The intuitive graphical user interface of FEgen generates input files shown to be fully compatible with both ASTRA and GPT. Here, detailed application examples demonstrating a subset of FEgen’s capabilities are given by creating a customized emitter pattern with application to transverse beam shaping and longitudinal beam dynamic experiments.

Index Terms—Beam dynamics, electron emission, field emission, fowler–Nordheim law, radiofrequency injector.

I. INTRODUCTION

As field emitters are poised to become the preferred electron source for next-generation electron accelerators and other vacuum electronics, microphone devices moving up in operating frequency for higher peak power rating and compactness [1], [2], [3], [4], [5] a computational toolbox must be developed to realistically model the particle dynamics. Unlike in photoemission—where an ultrashort high power density laser pulse is synchronized (in other words, phase-matched) with a radio frequency (RF)/microwave drive signal—electrons are generated by and interact with the RF/microwave drive cycle in a much wider phase window, regardless of whether a field emission cathode is operated in an ungated or gated fashion (by means of a physical gate electrode, harmonics mixing, or multicell gun design). An extended interaction phase window is of utmost importance to correctly reveal the longitudinal phase space of the resulting beam, which may promote delayed emission and secondary effects in the injector ultimately leading to beam loading, multipacting, and cathode field screening effects. Another class of important applications are gas discharge and plasma science where field emission physics plays a major role [6], [7], [8].

Compactness of a high-frequency system (and the corresponding small emitting area of an electron source required to emit high charge) poses challenges in regard to correctly tracking and accounting for vacuum space charge effects and beam expansion/explosion. Currently, all in-demand beam tracking software that are capable of accounting for space charge effects—such as ASTRA [9], IMPACT-T [10], or GPT [11]—lack a native particle distribution generator suitable for field emission analysis. There are costly PIC codes—VSim [12] and Michelle [13], for example—that account for the space charge effect yet contain field emission models based on the conventional DC Fowler–Nordheim equation. However, such PIC codes do not incorporate the time dependence necessary for RF modeling. Furthermore, the exact mechanism of how Michelle and VSim determine their field emission distributions is proprietary.

This work is aimed to engineer a distribution generator function using Python by implementing the time dependent Fowler–Nordheim equation, allowing for the observation of temporal/phase (and thus complex longitudinal) beam processes. The incorporation of temporal dynamics based on time-dependent RF emission is of paramount importance and is unlike field emission models used in any existing distribution generators. Furthermore, our generator is available as open source which is advantageous to proprietary PIC codes or custom-made add-ons to existing beam-tracking software. The generated distributions can be directly translated into both ASTRA and GPT, the latter of which was used for our detailed application examples. Of particular note, this work provides the ability to design and simulate transversely inherently shaped beams using array field emission cathodes providing new means for improving wakefield structure or plasma accelerators [14].

The article is laid out as follows. Section II shows the momentum distribution. Section III shows the spatio-temporal distribution, and Section IV shows a GPT application example simulating transverse dynamics for an L-band injector design. Section V provides an additional application example.
demonstrating longitudinal dynamics for an X-band injector. Section VI briefly discusses further developments for FEgen beyond the Fowler–Nordheim equation for future releases.

To download Python software package go to https://github.com/schne525/FEgen.

II. MOMENTUM DISTRIBUTION

The momentum distribution is based off a distribution that arises from the emittance on the cathode surface as the electrons tunnel through the barrier. It is assumed that momentum spread is uniformly distributed over a half sphere, where the base corresponds to particles on the surface of the cathode. This is referred to as an isotropic distribution. The isotropic distribution function \( f(p) \) as a function of momentum \( p \) employed here is defined by [15] as \( f(p) = r(|E - p|) \), where \( f(p) \) can be defined as a radial function whose radius \( r \) is defined by the magnitude of momentum vector and that is centered at \( E \). The momentum vector \( p \) is equal to \( (E_k + E_r)^2 - E_r^2)^{1/2} \), where \( E_k \) is the kinetic energy of the electron and \( E_r \) is the rest electron energy equal to 511 keV. This means that the isotropic distribution intrinsic to FEgen exists on the surface of a half sphere where the sphere is centered in momentum space at \( (0, 0, E) \), i.e., it has a radius of \( E \).

To create the isotropic momentum distributions, the maximum energy of each particle is first calculated. Using NumPy’s random normal distribution function, a 3-D array of values with a normal distribution between -1 and 1 in each dimension is created to serve as unit vectors for each particle’s momentum in the \( x \), \( y \), and \( z \) directions. The \( x \)- and \( y \)-components of the unit vector array are multiplied by the maximum energy for a particle, creating a uniform kinetic energy distribution.

For the initial position distributions, \( x \)- and \( y \)-values are randomly selected for each particle ultimately to form each emitter’s circular distribution within the \( xy \) plane with radius less than (or equal to) that of the cathode radius. The initial position distribution in \( z \) is set to 0 for all particles. The initial direction of electrons is set by their momentum for which all particles have \( p_z \geq 0 \) meaning that electron emission is in the positive \( z \)-direction. As shown in Fig. 1, the absolute value of the \( z \)-dimension of the unit vector array is multiplied by the maximum energy for a particle, given that momentum in the \( z \)-direction must be positive. The magnitude of each particle’s momentum vector is then calculated and used to create an array of each particle’s energy that is then used in Scipy’s statistical Kolmogorov–Smirnov test (kstest). This test generates a \( p \)-value indicative of the uniformity of the energy distribution by testing against Scipy’s statistic uniform distribution function. The given \( p \)-value is then compared to a significance level of 0.01. When the generated momentum arrays meet this significance condition, the momentum values are accepted and stored in the program to later be written into the output file along with the spatio-temporal components.

III. SPATIO-TEMPORAL DISTRIBUTION

FEgen has additional features such that, beyond having a single emitter, one can design a variety of emission patterns to simulate custom emitter arrays. A user can pick not only the radius of the emitter but can also design an emitter grid and a custom pattern of emission points. Each can be simulated using a circular uniform spatial distribution in the \( xy \) plane as seen in Fig. 2. As an additional benefit, if the user knows the total charge of the beam or the total charge over the entire emission pattern region, FEgen can then calculate the charge for each emitter. This is useful in the case of simulating an emission grid of only a few emitters to represent a uniform emission which may have thousands of emitters on the cathode surface to maintain the ratio of emission area to charge and accurately simulate the space charge forces on the beam downstream.

In the RF environment, the Fowler–Nordheim equation is time-dependent. When averaged over an RF cycle, the
The Fowler–Nordheim equation is transformed into a form that reads [16]

\[
I_F(t) = \frac{1.54 \times 10^{-6} \times 10^{4.52 \phi^{0.5}} A_e[\beta E_c(t)]^2}{\phi} \times \exp\left[-\frac{6.53 \times 10^9 \phi^{1.5}}{\beta E_c(t)}\right]
\]  

(1)

here the external electric field is modeled as a time-variant sinusoidal oscillation which is a result of only considering the longitudinal component. Equation (1) is then fit to a Gaussian distribution to determine the mean and standard deviation over the emission phase as specified by the input parameters (exemplified in Fig. 3 for an L-band system operating at 1.3 GHz).

Generally, there is no intrinsic gating in field emission. The current is allowed to emit over 360° of the RF cycle, and only the electric field strength in (1) dictates when the emitting charge quenches. On the other hand, (1) is highly nonlinear, and it is therefore hypothesized that the emission phase window is much shorter than 360°, often assumed [5] to be equal to 60° (±30° around the RF cycle electric field crest). This, of course, not a fundamentally defined threshold. The FEgen interface offers an input to specify the RF phase for the emission to occur thus allowing for finding the best agreement between simulations and experimental data. Other important input parameters include the work function of the cathode material, initial energy spread at the cathode surface, the phase shift, and frequency of the gun, and the local field on the cathode surface (the product of the applied field and the field enhancement factor \( \beta \)). The FEgen code was originally intended for the Argonne Cathode Teststand (ACT) where the default frequency is the L-band operational frequency of 1.3 GHz. The initial energy distribution at the cathode surface has a default value of 0.1 eV; since, for most materials, the initial energy distribution is a fraction of an eV [17]. As this current model uses the Fowler–Nordheim equation, all particles are assumed to emit at \( \zeta = 0 \), which is the location of the
cathode surface in the simulation given that the cathode surface is of a planar geometry. Even so, this planar approximation can be useful when verifying downstream transverse imaging due to the RF’s effect on each beamlet formed by a grid of emitters. The longitudinal effects, where a beam formed from a field emission source, can undergo self-induced micro bunching. Both are illustrated in the following sections for application examples of transverse and longitudinal dynamics.

IV. APPLICATION: TRANSVERSE DYNAMICS

The capability of creating transverse patterned beams is crucial in order to verify that the number of emitters and their uniformity match between field emission simulations and experimental results given that the effective emission area of the cathode from Fowler–Nordheim equations is inaccurate [18], [19]. Due to field emission cathodes having a long emission phase period, each electron beamlet appears on an imaging screen as a streak. One such example can be seen in the experimental results elsewhere in [3]. The transverse profile captured by the yttrium-aluminum garnet (YAG) screen shows the long streaks of each electron beam from the individual emitters on the cathode surface. The following application will demonstrate FEgen’s capability to reproduce experimental results with high fidelity by tracking the distribution created in FEgen using GPT. To simulate the experimental result from [3], emitters are placed in a 5 × 5 pattern with each simulated as a radially uniform emitter of radius 0.1 mm and spaced 1.77 mm apart. To model the temporal distribution of a field emission current, an average work function of 4 eV and maximum local electric field (βEc) of 10 GV/m are used as input parameters with an applied field of 70 MV/m. The full list of adjustable input parameters for the generator can be found Table I. The field map of the RF field in the electron gun and the magnetic field of the solenoids are created in Poisson Superfish [20] and imported into the GPT. Field maps for this case study are described in great detail in [3]. Due to each of the 25 emitters having a different spatial distribution, each of them follows an independent Gaussian distribution for its temporal distribution. Fig. 4(a) shows the initial transverse distribution of the beam at the cathode surface, while Fig. 4(b) illustrates the transverse distribution of the electrons 43 cm down the beamline which corresponds to the location of the YAG1 imaging screen of the ACT beamline [3].

Fig. 4(b) demonstrates the “streak” effect on the imaging screen due to the nature of field emission having a large 180° emission window causing each electron beam to have a long tail. Moreover, the two solenoids in the beamline cause a rotation in the transverse dynamic resulting in a spiraling image at the YAG screen. Comparing the field emission simulation with the experimental YAG image in [3], there is a clear parity between the two showing the capability of the FEgen to recreate complicated transverse dynamics in an RF field emission environment.

V. APPLICATION: LONGITUDINAL DYNAMICS

In both case studies presented here, the injectors operate in TM_{010} mode meaning that the maximal field is on the cathode surface directed on axis away from the cathode to generate and carry away the electrons. The field is the simple sinusoidal function of time and frequency. Therefore, field emission has a 180° emission window when the positive electric field is applied to the cathode surface in a half cycle. This long emission window can cause a complicated longitudinal dynamic of the electron beam since electrons emitted at different phases will be subjected to varying negative and positive RF electric fields before exiting through the gun aperture. This directly results in kinetic energy gain varying within a single beam. One of the interesting consequences of the energy gain dependence on launch phase was experimentally tested on an X-band (~9 GHz) electron gun where two distinct electron bunches were measured from a single RF cycle [2]. The experimental design from [2] uses a diamond cathode with the same work function of 4 eV and maximum local field of 10 GV/m. The emission area was set to 0.5 mm to a single emitter. The applied field is set as 28 MV/m to match the experimental setup, and the field map for the X-band gun was simulated in Superfish and imported into GPT. Field maps for this case study are described in great detail in [2].

Fig. 5 demonstrates how the launch phase dependence of energy gain translates to longitudinal bunching. It is possible for the particles generated later in the emission period to
TABLE I
INPUT FEgen PARAMETERS

| Parameter                  | Details                                                                                                                                                                                                 | Unit   |
|----------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|
| One Emitter                | Select for a single emitter                                                                                                                                                                           |        |
| Emitter Grid               | Select to create a square grid of emitters. See parameters for Size of Grid and Grid Spacing for details on specifying grid size                                                                         |        |
| Custom Emission Pattern    | Select to create a custom pattern of emitters. See parameter for Locations of Emitters for details on specifying emitter locations                                                                      |        |
| Size of Grid               | The length of one side of a square grid of emitters (e.g. Size of Grid = 7 will create a 7x7 grid of 49 total emitters)                                                                                |        |
| Grid Spacing               | The distance between emitters when grid of emitters is selected                                                                                                                                      | mm     |
| Locations of emitters      | The location of each emitter in meters. See note at beginning of Appendix A on how to enter values using scientific notation. Ensure that the number of emitters entered coincides with the number of \((x, y)\) pairs given. To enter locations, separate respective \(x\) and \(y\) with a comma and place a semicolon between \((x, y)\) pairs. Do not place a semicolon after the last \((x, y)\) pair. Straying from this format will result in an error. See Fig. 4 as an example | m      |
| Current                    | For the pulsed power option, current and pulse length are used to calculate charge \(q = I \times \tau_{dc}\) where \(\tau_{dc}\) is the dc pulse length                                                                 | A      |
| Total Charge               | Charge per emitter (e.g. for 1 nC charge over 10 emitters, one would enter 0.1 nC)                                                                                                                   | nC     |
| Charge per rf Cycle        | Select for charge in single rf cycle                                                                                                                                                                  | nC     |
| Charge per Pulse Length    | Select for charge over multiple rf cycles. Pulse length and frequency are used to calculate charge per cycle \(q = \frac{q_{total}}{f \times \tau_f}\) where \(f\) is the operating frequency and \(\tau_f\) is the rf pulse length | nC     |
| Charge per Emitter Radius  | Select to scale the total charge to the emitter radius                                                                                                                                               | nC     |
| Charge per Cathode Radius  | Select to scale the total charge to a smaller cathode radius \(q = q_{total} \left(\frac{r_{emitter}}{r_{cathode}}\right)^3\)                                                                              | nC     |
| Initial Energy             | Initial energy distribution at cathode surface (default is 0.1 eV)                                                                                                                                    | eV     |
| Local Field                | Equal to \(\beta\) times applied field where \(\beta\) is the field enhancement factor                                                                                                              | GV/m   |
| Phase shift                | Accounts for phase shift of the ac field. Default value is 180° due to a 90° phase shift between the cosine and sine field and an additional 90° phase shift such that the reference particle is at the peak field at the time of emission | degree |
| rf Phase                   | Phase window of the rf cycle. Default is 360°, phase window can be specified upon entry                                                                                                               | degree |
| Frequency                  | Default option provided is for the Argonne Cathode Teststand (ACT) for which FEgen was originally intended where the default frequency is the L-band operational frequency of the ACT. Alternate frequencies can be entered by user | Hz     |

Overtake the particles generated earlier in the emission period due to sizable difference in energy. There are electrons that are born at earlier phases, away from the field crest, and therefore gain less energy, and there are electrons that are born on the field crest and therefore gain more energy. Additional dynamics can arise from deceleration when later-in-phase off-crest electrons can be captured by the negative portion of the sine period. Eventually, this phenomenon creates two distinct.
bunches, where one has higher energy than the other and so it becomes possible for electron bunches to overtake each other as they drift down the beamline. Fig. 5 exemplifies this phenomenon for one RF cycle. Typical $L$-band or $X$-band RF pulses contain a few thousand RF cycles (RF pulse time structure and launch phase argument were discussed in great detail elsewhere [2], [21], [22]) and the resulting bunching in field emission systems can be very complex.

With the ability to simulate multiple RF cycles, FEgen and GPT can bring further insight to longitudinal beam dynamics. Fig. 6 further explores the complexity of bunch mixing and splitting by tracking beam dynamics for three consecutive RF cycles. It shows the longitudinal snapshot of three successive RF cycles for which the particles initially emitted in the same RF cycles are enclosed by group of the same shapes (black diamond, white rectangle, and red circle). It can be observed that, in this $X$-band e-gun, the particles from later emission overtake the particles from earlier emission due to the longitudinal bunching caused by the variation in the kinetic energy gain.

VI. CONCLUSION AND OUTLOOK FOR FUTURE RELEASES

The application examples presented here clearly demonstrate the capability of FEgen to simulate and thus further explore the transverse and complex longitudinal beam dynamics of RF field emission. Agreement between simulations and prior experimental results exemplify FEgen’s efficacy as a field emission particle distribution model beyond that of any generators native to popular commercial beam tracking software.

As is indicated by the application examples using synthetic diamond cathodes, the next generation of field emission sources is most likely to be hinged on semiconductor materials, such as those made of carbon nanotubes and diamond materials [21], [23], [24], [25], [26], [27], [28], [29]. Recent results have shown a divergence from the classical Fowler–Nordheim conditions [24], [28], [29], [30], which is attributed to the current model failing to account for an emitter being a semiconductor. Future work will implement the semiconductor effects using the Stratton–Baskin–Lvov–Fursey formalism [29], expanding into the RF environment, temperature, and patchy/varying work function effects. Such implementations will be incorporated for future releases. Additional efforts on incorporating thermionic and thermofield emission [31], [32] are being made. The goal in mind is to modify FEgen to make it versatile to account for these effects and to ultimately understand the new emission physics that is now being seen through experimental studies.

APPENDIX

For all entry of parameters using scientific notation, use notation to prevent errors when inputs are processed (e.g., enter 1.2e3 for 1200, enter 1.2e-6 for 0.0000012). Details on entering parameters are provided in Table I.

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Emily Jevarjian received the B.S. degree in physics from Michigan State University (MSU), East Lansing, MI, USA, in May 2022. While pursuing her degree, she worked with the Materials, Accelerators, and Microscopy Team, MSU College of Engineering. Their work focused on data processing and advanced modeling of field emission, primarily with radio frequency (RF) conditions, with the overarching goal of exploring physics regimes beyond classical Fowler–Nordheim theory. Jevarjian is now pursuing an interdisciplinary career applying their physics and computational experience within the field of conservation, environmental science, and climate action.

Ryo Shinohara received the B.S. degree in physics from the Department of Physics, The Ohio State University (OSU), Columbus, OH, USA, in 2020. He is currently pursuing the dual Ph.D. degree in ECE and physics with Michigan State University (MSU), East Lansing, MI, USA.

The main area of his scientific activity has been in the field of accelerator physics since his time in OSU, and since 2020, he continues his research in the field through computational modeling of electron beam dynamics and accelerator breakthrough dynamic in MSU.

Sergey V. Baryshev received the B.S. degree in applied physics from Polytechnic University, Saint Petersburg, Russia, and the Ph.D. degree in condensed matter physics from the Ioffe Institute, Saint Petersburg, in 2008.

He is currently a Faculty Member with the Department of Electrical and Computer Engineering, Michigan State University (MSU), East Lansing, MI, USA, where he also oversees education and workforce training in radio frequency (RF) power engineering for DOE-MSU Accelerator Science and Engineering Traineeship Program. He has worked extensively in accelerator research and development on creating solutions to enable novel electron emission sources and RF injector and linac designs that can outperform previous generations. This work was further extended to create novel solutions for field emission microscopy, ultrafast time-resolved microscopy, high peak power THz radiation generation, and to obtain new insights into the physics of vacuum breakdown. His research interests also include the use of synthetic diamond for high power RF, microwave, and X-ray devices.

Mitchell Schneider received the B.S. degree in physics from Wright State University, Dayton, OH, USA, and the dual Ph.D. degree in electrical engineering and physics from Michigan State University, East Lansing, MI, USA, in 2022.

He is currently a Post-Doctoral Fellow at SLAC National Accelerator Facility, Menlo Park, CA, USA, where he currently leads the efforts to develop ultrahigh gradient for superconducting radio frequency (SRF) linear accelerating structures as well as developing a high gradient cathode test stand. Building upon his previous work for his Ph.D. thesis understanding the dynamics of radio frequency (RF) field emission cathodes operating in high-frequency high gradient injectors in dynamics beyond classical Fowler–Nordheim and beyond Child Langmuir regimes using synthetic diamond cathodes. His research interests are RF accelerators, SRF high-temperature superconductors, high-frequency injectors, and the underlying physics of the emission physics for a strong thermo-photo-field cathode.