Development of a low-emittance high-current continuous electron source

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ABSTRACT

The Advanced Continuous-wave Electron injector aims to provide accelerator-based light sources with a high repetition rate and high average current electron beam. The injector consists of a DC thermionic gun generating a continuous electron beam, after which a radio-frequency (rf) cavity operating in dual mode at 1.5 and 3 GHz deflects the beam onto a knife-edge, creating a pulsed beam. A final rf cavity, also operating at 1.5 and 3 GHz, compresses the electron bunches for injection into a booster linac. The DC thermionic gun is fully operational and this paper presents the first results, demonstrating a continuous beam with a transverse emittance of 49 ± 2 nm rad at 9.6 mA.

1. Introduction

There is an increasing demand for high-brightness, high current continuous wave (CW) electron beams for the use in X-ray light sources [1–3]. Next generation Energy Recovery Linac light sources require average CW currents of ~100 mA with an emittance of only a few microns [4–6], while X-ray Free Electron Lasers require tens to hundreds of pC per bunch with a sub-micron emittance [3,7]. Over the past years, new injector concepts and designs have been developed [8], including DC photoinjectors [9–11], superconducting radio-frequency photoinjectors [12] and normal conducting photoinjectors [13]. An issue faced by all photoinjectors is the choice of cathode material, with factors such as beam quality, quantum efficiency and cathode lifetime [14]. With user facilities operating 24 h per day and seven days per week, the downtime is a crucial aspect, leading to research in cathode materials with longer lifetimes, as well as load-lock designs to allow for cathode replacement without breaking the vacuum [15].

Alternatively, thermionic electron sources have been suggested as they are capable of providing high currents for long lifetimes [16]. Several designs of low-emittance high current thermionic guns have shown these guns to be viable candidates for both CW [17,18] and pulsed [19] beam applications. Furthermore, developments in electron-impact X-ray sources allow for greater electron power densities [20,21]. Low-emittance high-current DC thermionic sources could thus increase the brightness of these types of X-ray sources.

The concept of the Advanced Continuous-wave Electron (ACE) injector is explained in detail in [22]. In short, it is a thermionic electron source designed to provide a 100 keV high-average current pulsed electron beam to a radio-frequency (rf) accelerator structure [23] and strives to meet the requirements of future light sources. The ACE injector consists of three stages: a thermionic emitter housed in a custom design 100 kV DC accelerator, an rf cavity for beam chopping and an rf cavity for beam compression.

For proof-of-principle, the injector will initially operate at a continuous current of 10 mA, which is projected to deliver 2–3 pC bunches at a 1.5 GHz repetition rate, corresponding to a chopping duty cycle of 30–45%. The first stage has been completed and this paper will report on the continuous electron beam characteristics.

2. Gun Design & Beam characteristics

The DC accelerator, operating at 100 keV, is designed to generate a high-current continuous electron beam while also maintaining a low emittance. Shown in Fig. 1, the outwardly tapered cathode and anode ensure the peak electric field remains as low as possible to prevent breakdown, while reaching ~10 MV/m near the emitter. With the electric field lines running parallel in the negative z-direction, a higher electric field will increase the acceleration of the electrons, thereby decreasing space charge effects. Furthermore, a high electric field also increases the emission current through the Schottky effect, without increasing the beam emittance [24]. Accordingly, the ultimate transverse brightness of an electron source is limited by the electric field at the cathode [25,26], and a higher electric field such as those achieved by RF photoinjectors [13] is favorable. For this design, a DC gun was chosen to reduce the complexity of the injector. Operating at 10 MV/m then allows for both good performance and robust operation.
During the emission and acceleration of the electrons, space charge forces push to expand the beam. With the electric field becoming increasingly nonlinear further from the beam axis, the beam is confined using a solenoid magnetic lens placed directly behind the anode. While the residual magnetic field on the cathode can increase the final emittance, the current density follows the modified Richardson equation [31]

\[ J = A_s T^2 \exp\left(-\frac{(W - \Delta W)}{k_b T}\right), \]

with \( k_b \) the Boltzmann constant, \( A_s \) the material-dependent Richardson constant, \( T \) and \( W \) respectively the filament temperature and work function, and the electric field \( E \)-dependent lowering of the work function \( \Delta W \) given by

\[ \Delta W = \frac{e^4 E}{4\varepsilon_0 c^2}. \]

where \( e \) is the electron charge and \( \varepsilon_0 \) is the vacuum permittivity. The material constants for the two types of filament tested, CeB\(_6\) and LaB\(_6\), are detailed in Table 1. The filament temperature not only governs the emission current, but determines the initial normalized rms emittance as well. The latter is given by

\[ \varepsilon_{n,rms} = \frac{r}{2} \sqrt{\frac{k_b T}{m_e c^2}}, \]

where \( r = 150 \mu m \) is the filament radius, \( m_e \) is the electron mass and \( c \) is the speed of light. Due to the mechanical design of the filament, its temperature may not exceed 1800 K to prevent structural failure. As such, the maximum operational temperature will be approximately 1760 K, at which the projected beam properties are listed in Table 2.

### 3. Emittance measurement & analysis

Several techniques exist to measure the beam emittance, including waist scans, wire scans, double-slit scans and pepperpots [32]. The main limitation of our beam with respect to measurement techniques is the continuous beam power of 1 kW, which will melt conventional detection screens. To circumvent this problem, an electrostatic beam blanker is used to separate a pulse of 1 µs or longer from the beam for diagnostics. Having to separate a pulse for a measurement means that scan methods will take significantly longer, as well as suffer from shot-to-shot noise. Additionally, the beam needs to be emittance-dominated rather than space-charge-dominated to achieve accurate results, ruling out waist scans. The pepperpot method, which is single shot while also reducing the beam charge, avoids both these issues and is therefore the method of choice. Shown in Fig. 2 is the 30 × 40 mm\(^2\) beam blanker with a plate spacing of 10 mm. Charging the blanker with a fast square wave delivers a slice of the continuous beam to the pepperpot mask downstream. The fast square wave is generated with a push–pull pulser with a 10–90% rise and fall time of <20 ns, such that the contribution of the flanks is negligible.

The pepperpot mask is a tantalum sheet with a 15 × 15 square grid of circular holes with diameter \( d = 5 \mu m \), spaced evenly with a pitch of 200 µm. As the beam passes through it, it is cut into several beamlets which drift for \( L = 149 \) mm towards a P43 phosphor screen. The screen is imaged one-to-one on a camera outside the setup, which is triggered at a variable delay to the beam blanker. An example is shown in Fig. 3.

In general, the 4D beam matrix is given by

\[ \Sigma^{4D} = \begin{pmatrix} \langle x^2 \rangle & \langle xy \rangle & \langle x'y' \rangle \\ \langle yx \rangle & \langle y^2 \rangle & \langle y'y' \rangle \\ \langle x'y' \rangle & \langle y'y' \rangle & \langle y'' \rangle \end{pmatrix}, \]

with \( x \) and \( y \) the transverse coordinates and \( x' \) and \( y' \) their respective derivatives to the longitudinal coordinate \( z \). The apparent emittance in the \( x \)-plane is expressed by

\[ \varepsilon_x = \sqrt{\det \Sigma_{xx}} = \sqrt{\langle x^2 \rangle - (\langle xy \rangle)^2}, \]

and equivalently for the \( y \)-plane, whereas \( \Sigma_{yy} \) describes the correlation between the two planes. Similarly to how the \( x \)-emittance is equal to the area of the \((x, x')\)-phase space divided by \( x \), a 4D emittance

\[ \varepsilon_{4D} = \sqrt{\det \Sigma^{4D}} \leq \varepsilon_x \varepsilon_y, \]

where \( r = 150 \mu m \) is the filament radius, \( m_e \) is the electron mass and \( c \) is the speed of light. Due to the mechanical design of the filament, its temperature may not exceed 1800 K to prevent structural failure. As such, the maximum operational temperature will be approximately 1760 K, at which the projected beam properties are listed in Table 2.
is related to the 4-volume of the 4D phase space [34]. A normalized emittance

\[ \epsilon_n = \gamma \beta \epsilon \]  

(7)
can then be obtained, with \( \gamma \) the relativistic Lorentz factor and \( \beta \) the velocity normalized by the speed of light. From here on, every emittance is normalized.

All elements in the 4D beam matrix can be rewritten in terms of measurable beamlet properties. As shown schematically in Fig. 4, each hole center \( n \) in the pepperpot mask has transverse coordinates \( (X_n, Y_n) \) and creates a spot on the detector screen with a mean position \( (\bar{x}_n, \bar{y}_n) \), a mean angular spread \( (\sigma_{x_n}', \sigma_{y_n}') \) and an rms divergence \( (\sigma'_{x_n}, \sigma'_{y_n}) \). The latter two pairs are, similarly for \( x \) and \( y \), given by

\[ \bar{x}_n = \frac{x_n - X_n}{L} \]  

(8)
and

\[ \sigma_{x_n}' = \frac{\sigma_{x_n}}{L}. \]  

(9)
where \( \sigma_{x_n} \) is the rms beamlet size at the screen. Note that Eq. (8) takes the paraxial approximation and Eq. (9) assumes a hole size \( d_n \ll \sigma_{x_n} \).

Finally, each spot has an intensity \( I_n \), which is proportional to the charge passing through hole \( n \).

As shown by Zhang [33], the final emittance does not depend on the coordinate alignment. Each coordinate is therefore taken with respect to the center of mass of its respective distribution, weighted by \( I_n \). The matrix elements from \( \Sigma_{x,y} \) are then calculated with

\[ \langle x y \rangle = \frac{\sum_n I_n x_n y_n}{\sum_n I_n}, \]  

(10)
\[ \langle x y' \rangle = \frac{\sum_n I_n x_n y_n'}{\sum_n I_n}, \]  

(11)
\[ \langle x' y \rangle = \frac{\sum_n I_n x_n' y_n}{\sum_n I_n}, \]  

(12)
and

\[ \langle x' y' \rangle = \frac{\sum_n I_n (x_n' y_n' + \text{cov}(x_n', y_n'))}{\sum_n I_n}. \]  

(13)
where \( \text{cov}(x_n', y_n') = \rho \sigma'_{x_n} \sigma'_{y_n} \) is the covariance and \(-1 \leq \rho \leq 1\) is the correlation coefficient between the angular spreads. The calculations for \( \Sigma_{x', y'} \) and \( \Sigma_{y', x'} \) are analogous, where the covariances simplify to the variances \( \sigma^2_{x_n} \) and \( \sigma^2_{y_n} \) respectively.

4. Results

The emission current is controlled by changing the heating current through the filament and is measured both by the 100 kV power supply and by the beam block at the end of the beam line. The latter giving an underestimation of < 2% due to the loss of secondary electrons. Operating at 99 kV, pepperpot images such as Fig. 3 are taken for varying emission currents. As each beamlet carries some information on all transverse dimensions \( (x, x', y, y') \), the full 4D phase space can be reconstructed from a single image [35], allowing for inspection of the beam divergence and aberrations. For example, Fig. 5 shows the \((x, x')\)-phase space taken by slicing the 4D phase space generated from Fig. 3 along the \( y = 0 \) and \( y' = 0 \) hyperplanes and interpolating the result. Some phase space filamentation in the converging beam is visible, which can be attributed to nonlinear space-charge forces during focusing.

Fig. 6 shows the transverse emittances for a CeB₆ and LaB₆ filament, where the latter has a higher average current primarily due to the higher Richardson constant. In order to resolve the emittance from an image, it is preferable to have the beamlet spots as large as possible without overlapping. This is done by changing the current through the solenoid lens directly behind the gun. However, doing so rotates the beam w.r.t. the chosen transverse coordinates, appearing as an exchange in emittance between the \( xx' \) and \( yy' \)-planes.

Fig. 4. 1D schematic of the pepperpot method. The incoming electron beam (green) is split up into beamlets, creating an array of intensity distributions (red) on the detector. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Source: Adapted from [33].

Fig. 3. Pepperpot image from the CeB₆ filament at 0.68 mA. The red dots and lines indicate where the analysis software was able to find and successfully fit a peak.

Fig. 5. The \((x, x')\)-subspace from the center of the reconstructed 4D phase space of Fig. 3.

Fig. 6 shows the transverse emittances for a CeB₆ and LaB₆ filament, where the latter has a higher average current primarily due to the higher Richardson constant.
emission current of the gun increases, the solenoid current should also increase to compensate for the growing space-charge forces, leading to a similar exchange of apparent emittance, which is indicated in Fig. 6 for LaB$_6$ by the arrows. Conversely, $\varepsilon_{4D}$ takes into account the full 4D phase space and therefore does not suffer from this apparent exchange. Additionally, increasing the solenoid current also increases the residual magnetic field on the cathode and thereby its consequent emittance growth. However, such an increase would be sub-0.5 nm rad over the entire range of emission currents.

Several sources of error are present in the measurement technique. First, both the mean angular spread and the rms divergence of a beamlet are inversely proportional to the drift distance. As such, the error made in measuring $L$ translates almost directly into an error in the final emittance, e.g., a deviation in $L$ of 3 mm would result in the entire graph shifting by approximately 1 nm rad.

Secondly, the beam blanker adds some dispersion to the beam, leading to an increase in $\gamma$-emittance of up to a few tenths of nm rad. Thirdly, imperfect alignment of the solenoid causes the beam to shift position slightly. Realignment of the beam then results in shot-to-shot fluctuations. This can be somewhat mitigated by taking many pepperpot images, 83 for the CeB$_6$ filament and 343 for the LaB$_6$ filament, and averaging the results.

Finally, the peak fitting procedure also introduces an error. While a smaller intensity of a peak leads to a larger relative uncertainty in the fit parameters, its contribution to the emittance decreases as well. Consequently, its contribution to the overall error is relatively small.

At an emission current of 9.6 mA, a final transverse emittance of $\sqrt{\varepsilon_{4D}} = 49 \pm 2$ nm rad is achieved; slightly higher than the projected value of 40 nm rad. While the solenoid magnetic field on the cathode should give rise to $\sim 2.3$ nm rad, imperfect alignment of the solenoid or the optics may increase this further. Additionally, a difference in the material properties listed in Table 1 can alter the emittance as well.

5. Conclusion and future plans

With the 100 kV DC thermionic gun in operation, the first stage of the ACE injector is completed. The diagnostics module, including beam blanker, pepperpot and detector, provides feedback on beam quality during operation, demonstrating a sub-50 nm rad transverse emittance for a continuous beam. With the LaB$_6$ filament, the gun is capable of reliably operating up to an emission current of 10 mA. At that current and emittance, the DC thermionic gun can provide an interesting option for electron-impact X-ray sources.

The next stage involves implementing the dual mode cavity for pulsed beam operation. With a high duty cycle of $\sim 30\%$, the diagnostics module will be able to characterize the transverse phase space of the pulsed beam to a similar degree of accuracy as the continuous beam.

CRediT authorship contribution statement

W.F. Toonen: Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Visualization. A. Rajabi: Methodology, Validation, Writing - review & editing. R.G.W. van den Berg: Software, Validation, Investigation. X.F.D. Stragier: Conceptualization, Methodology, Writing - review & editing. P.H.A. Mutsaers: Conceptualization, Project administration, Writing - review & editing, Supervision. P.W. Smorenburg: Resources, Writing - review & editing. O.J. Luiten: Conceptualization, Writing - review & editing, Supervision, Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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