Optimization of a thermionic microwave electron gun

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An electron beam with low normalized emittance, 2π mm mrad, has been achieved using a microwave electron gun as the injector for a rf linac. However, cathode heating caused by back-bombarding electrons limits the macropulse length and repetition rate. A transverse magnetic field has been applied across the gun cavity to reduce cathode heating by deflecting the back-bombarding electrons. This article presents the results of computer simulations to determine a magnetic field configuration that will allow lengthening of the macropulse and raising the repetition rate to the desired levels. The simulations predict a 75% drop in the cathode heating with negligible loss of beam current if the applied transverse magnetic field decays rapidly down the cavity axis. The effect of the deflection field on the beam’s emittance will also be discussed.

1. Emittance and the gamma factor

Electron beam emittance growth in a rf linac can be minimized by using a microwave electron gun instead of a traditional dc gun as the injector. While practical dc surface fields are limited to 8 MV/m, surface fields within resonant rf cavities can reach several hundred megavolts per meter [1]. The increased fields quickly accelerate the electrons to relativistic velocities, thereby minimizing space charge forces and preserving the original emittance.

For simple distributions, the effect of γ on the emittance is easily illustrated. Assuming magnetostatics,

\[ E = \int \hat{d}^3x' \rho(x') \frac{(x - x')}{|x - x'|^3}, \]

and

\[ B = \frac{1}{c} \hat{\int} \hat{d}^3x' J(x') \times \frac{(x - x')}{|x - x'|^3}. \]

Now, let the velocities of the particles be independent of time and space, \( J(x) = c\beta \rho(x) \). The force on a particle in the beam due to the rest of the beam is

\[ F = q \left( E + \beta \times B \right). \]

\[ F = q \int \hat{d}^3x' \rho(x') \frac{(x - x')}{|x - x'|^3} + q \int \hat{d}^3x' \rho(x') \beta \]

\[ \times \left[ \beta \times \frac{(x - x')}{|x - x'|^3} \right]. \]

\[ F = q \int \hat{d}^3x' \rho(x') \frac{(x - x')}{|x - x'|^3} \left( 1 - \beta^2 \right). \]

\[ F = \frac{q}{\gamma^2} E. \]

By reducing the magnitude of the nonlinear space-charge forces experienced by the electrons following emission from the cathode, rapid acceleration to relativistic velocities substantially reduces the emittance growth due to these forces.

2. The microwave electron gun

Westenskow, Madey, Vintro and Benson [2] designed and demonstrated a microwave electron gun for the Mark III FEL in which electrons were accelerated within the gun to kinetic energies up to 1000 keV. Electrons exit typical dc guns at 100 keV. Thus, the space-charge forces in the microwave gun are less than one-fifth the space-charge forces in a traditional dc gun.

The Mark III microwave electron gun consists of a LaB₆ cathode at one end of a single-cell s-band cavity that is cylindrically symmetric about the cathode–anode axis [3] (see fig. 1). Since the cavity oscillates in the TM₀₁₀ mode, the electric field is parallel to the cathode–anode axis. Nosepieces extend into the cavity to achieve a higher field about the cavity axis for a given input power (see fig. 2). The peak field on axis is 53 MV/m, the field at the cathode is 40 MV/m, and the peak surface field is 100 MV/m.

Other elements of the microwave electron gun system include the momentum filter and power supply. Since the electric fields vary sinusoidally, the electron beam exits the gun with a large energy spread. To decrease this spread, the beam passes through a momentum filter. The momentum filter is an alpha magnet with slits that absorb the electrons with energies outside the desired range, usually 780 to 1000 keV. In the Mark III FEL system, the same klystron powers both the gun and the linac, facilitating phasing between...
the two components. The system operates at a micro-
pulse frequency of 2.857 GHz with a rf pulse length
from 1.5 to 10 μs and a 1–60 Hz repetition rate. No
prebuncher is required since the current is pulsed at the
linac frequency.

Using the gun as the injector, the Mark III rf linac
achieved a normalized emittance of 2π mm mrad and a
peak brightness of $3 \times 10^8$ A/cm$^2$. The total average
current out of the gun during a macropulse is 530 mA.
The typical average current after the momentum filter is
220 mA.

3. Back-bombardment and cathode heating

Because the cavity fields oscillate in time, electrons
that are emitted late in the rf period do not cross the
cavity before the accelerating field reverses direction.
The reversed rf field stops the low energy electrons in
the cavity and accelerates them back towards the
cathode (see fig. 3). If an electron hits the cathode, its
kinetic energy is transferred to the cathode. Computer
simulations, described later, predict that the total en-
ergy of the back-bombarding electrons is $2.4 \times 10^{11}$ keV
per micropulse. The power impacting on the cathode
during the macropulses is 110 kW and the typical time

![Fig. 2. Schematic drawing of the gun cavity and fields](image)

![Fig. 3. Computer simulation data: the energy of electrons that exit the gun and that hit the cathode vs the phase at which the electrons were emitted.](image)
average power is 4.1 W (2.5 μs pulse length at 15 Hz repetition rate).

This predicted back-bombarding power of 4.1 W agrees with the estimates of the power needed for steady-state operation. Since the cathode housing unit is at a higher temperature than its surroundings, it will lose thermal energy through conduction and black-body radiation. Thermal losses through electron emission are minimal. Assuming a linear temperature gradient along the housing unit, the unit loses around 9 W [5]. For steady-state operation, the cathode must then be supplied with 9 W of power. With zero deflection field, the cathode heating element supplies about 5 W to the housing unit [2]. The only other source of energy to the cathode is back-bombarding electrons. Therefore, experimental data suggests 4 W of time average back-heating power. The computer simulations calculate 4.1 W.

While the effects of the average back-bombarding power are easily corrected for by reducing the cathode heater power, the extremely high peak power creates a temperature ramp during the macropulse. The increasing cathode temperature causes a ramp in the macropulse current (see fig. 4). Since the performance of the FEL degrades if the macropulse current varies, the ramping limits the useable length of the macropulse at full current to around 2.0 μs.

In addition, the back-heating energy forms a positive feedback system with the cathode. If the temperature of the cathode increases, the back-heating energy increases. This increase in energy increases the temperature of the cathode and can result in thermal runaway. To avoid thermal runaway, it is necessary to limit the macropulse frequency to 15 Hz when operating at full current and with the present cathode mounting.

4. Dc transverse magnetic field

A transverse magnetic field was applied across the cavity of the Mark III gun to reduce cathode heating by deflecting the back-bombarding electrons. If the deflection is large enough, the back-bombarding electrons hit the cavity walls instead of the cathode. This method has successfully worked on the gun to increase the pulse length to 9 μs and to raise the threshold for thermal runaway [6].

To quantitatively determine the effect of the transverse magnetic field, the cathode heater power needed to maintain a constant output current for various applied magnetic field strengths was experimentally measured on the Mark III gun [2] (see fig. 5). As the applied field increases, it deflects the back-bombarding electrons a greater distance, and fewer electrons hit the cathode. Since the back-bombarding power decreases with the increase in deflection strength, the cathode heater power must be increased to keep the cathode temperature and thus the output current constant.

The data shows a total increase in the cathode heater power of 7 W, while the computer simulations predict that the time average power of the back-bombarding electrons is only 4.1 W. This apparent discrepancy is due to the difference in the heating efficiencies of the sources. While the back-bombarding electrons directly heat the front of the cathode, the cathode heater filament heats the back of the cathode and the entire housing unit. Since back-bombarding heats the cathode more efficiently, the increase in cathode heater power must be greater than the decrease in the back-bombarding power.

![Fig. 4. Experimentally measured effects of back-heating on the emission current in the first generation cavity. The rf macropulse power from the klystron is also shown [2].](image-url)
5. Computer simulations and results

The desire to further lengthen the macropulse and to increase the repetition rate resulted in computer simulations to determine the optimum magnetic field to apply. In our search for the optimum field, we sought to maximize the deflection of the back-bombarding electrons while minimizing the effect on the current and the emittance of the electrons injected into the linac. Both the strength and functional form of the field varied in the search consistent with the constraints imposed by magnetostatics, device geometry, and the properties of the materials.

5.1. Gun cavity fields calculations

The calculation of the gun cavity fields requires the following assumptions:
1. The electron beam is a negligible perturbation to the cavity fields.
2. The fields oscillate at a single microwave frequency \( \omega \).
3. The cavity has cylindrical symmetry.
4. Only the \( \text{TM}_{010} \) mode is excited.

From the above assumptions, \( E_\rho = B_\phi = B_z = 0 \) and \( \partial E_\rho / \partial \rho = \partial E_\phi / \partial \phi = \partial B_\phi / \partial \phi = 0 \). Thus \( E_z, E_\rho, \) and \( B_\phi \) satisfy

\[
\left( \frac{\partial^2}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial}{\partial \rho} + \frac{\partial^2}{\partial z^2} + \frac{\omega^2}{c^2} \right) \psi = 0.
\]

The LALA code was used initially to calculate the electric field on the cavity axis given the dimensions of the cavity [2]. Using the field on axis predicted by LALA, we then solved the above wave equation for \( E_\rho \) off axis. \( E_\rho \) and \( B_\phi \) were then calculated by integrating Maxwell’s equations,

\[
E_\rho(\rho, z) = \left. \frac{-1}{\rho} \int_0^\rho \rho' \frac{\partial E_z}{\partial z} \right|_{\rho'},
\]

and

\[
B_\phi(\rho, z) = \left. \frac{-i \omega}{\rho c^2} \int_0^\rho \rho' E_z(\rho', z) \right|_{\rho'}.
\]

The consistency of the calculations was checked using Ampère’s law. In the regions of interest, the difference between \( (\partial / \partial z)B_\phi \) and \( (i \omega / c^2)E_\rho \) is less than 10% of the average value.

5.2. Trajectories

The covariant Lorentz force law is \( \partial p^\mu / \partial \tau = q u^\nu F^{\mu \nu}(x) \). This law can be rewritten as a system of eight equations:

\[
\frac{\partial u^\mu}{\partial \tau} = \frac{q}{m} \mu, \quad \frac{\partial x^\mu}{\partial \tau} = u^\mu.
\]

These equations are solvable using standard numerical techniques.

While the forces on an electron due to the cavity fields are straightforward to calculate, the forces due to space charge are not. However, by treating the space-charge forces as a perturbation, the change in momentum of a single particle due to space-charge forces of the rest of the beam can be estimated. An electron distribution is modeled assuming the charge distribution of an unperturbed electron beam. The change in momentum of an electron is calculated assuming an unperturbed trajectory using

\[
p_x(t) - p_x(0) = \int_{t=0}^{t} \text{d} t' E_x(r, t'),
\]

and

\[
F = \frac{q}{\gamma^2} \int \text{d}^3 x' \rho(x') \frac{(x - x')}{|x - x'|^3}.
\]

The largest possible change in momentum due to space charge is \( \Delta p_x/m = 2.3 \times 10^6 \text{ m/s} \), while the unperturbed momentum is \( p_x/m = 2.9 \times 10^7 \text{ m/s} \). Thus the upper limit on the perturbation is less than 10% of the total transverse momentum. Space-charge forces in this system therefore appear to be negligible.

5.3. Applied magnetic fields

The functional form of the applied magnetic field must be consistent with the following assumptions. First, since the electrons are traveling along the cavity axis, \( k \), and the deflection perpendicular to that axis is desired,
the field needs only to be transverse to the cavity axis, 
\[ B = B_j. \] \nSecond, since the electrons are relatively close to the axis compared to the dimensions of the cavity, the field can be assumed only to depend on \( z \), 
\[ B(z) = B(z) j. \] \nto systematically explore all fields consistent with our assumptions, the field was expanded in a second-order Taylor series, 
\[ B(z) = B_0 + B_1 z + B_2 z^2. \] \nThe parameter space, \( B_0, B_1, \) and \( B_2, \) was thoroughly searched [7].

An axially constant magnetic field is a reasonable representation for the initial deflection system [2]. The results of the computer simulations for such a field are presented in fig. 6. The present cathode current feedback control system requires a constant total output current. This constraint limits the maximum constant deflection field to 63 G. At this value, the back-heating energy is reduced by 50%. Assuming a linear relation between the back-bombarding power and the maximum pulse length, the macropulse could be doubled to around 5 \( \mu s \). Both the deflection strength and maximum pulse length match the experimental parameters of the first Westenskow gun [2,8].

5.4 C-magnet

The fields that give the best results, high current and low back-heating energy, have high initial values near the cathode and decline rapidly with \( z \). Electrons moving through such a field are given a large initial transverse deflection, then drift transversely through the rest of the cavity. If the initial deflection is large, the back-heating electrons drift far enough to miss the cathode. Since the desired electrons (kinetic energy > 780 keV) spend less time in the cavity, their transverse drift is smaller than that of the electrons responsible for back-heating.

A C-magnet provides an almost ideal field. The magnet is aligned such that the cathode is an equal distance from each pole and the cavity axis is perpendicular to the plane of the poles. In this configuration, the magnetic field along the cavity axis is perpendicular to the axis and declines rapidly with the distance from the poles (see fig. 7). Several physical considerations affect the design and placement of the C-magnet. To achieve a rapid decline, the poles must be relatively close together. For a given field at the cathode, placing the poles as close as possible to the cathode reduces the peak field between the poles. Reducing the peak field reduces the A turn requirement and thus the size of the C-magnet. The present design requires 1000 A turns. Further reduction is not possible since the cavity walls must be at least 2 mm thick for vacuum and support. The poles will extend across the cavity so that the applied field is unidirectional. In addition, the poles will be vanadium permendur to avoid saturation.

Using a C-magnet with a peak field of 630 G, simulations indicate that the back-heating energy will be reduced by 75% with no loss of usable current. Further reduction is limited by the feedback system (see fig. 8).

6. Emittance calculations

The microwave electron gun was designed to provide a low emittance electron beam. Therefore, it is unacceptable for the deflecting magnet to drastically increase
the beam’s emittance. The simulations calculate the rms emittance as defined by Penner [9]:

\[ \epsilon_{x - \text{rms}} = \left( \langle x^2 \rangle \left(\frac{\partial x}{\partial z}\right)^2 \right)^{1/2} - \left( \langle x^2 \rangle \left(\frac{\partial x}{\partial z}\right)^2 \right)^{1/2} \]

with \( \langle x \rangle = \left( \frac{\partial x}{\partial z} \right) = 0. \)

Without any deflection field, the computer calculated emittance at the anode is \( \epsilon_{x - \text{rms}} = \epsilon_{y - \text{rms}} = 0.14 \text{ mm mrad}. \) With the C-magnet set at 620 G peak, the emittance increases to \( \epsilon_{x - \text{rms}} = 0.18 \text{ mm mrad} \) and \( \epsilon_{y - \text{rms}} = 0.14 \text{ mm mrad}. \) Although the deflection fields increase the emittance, it is still substantially lower than that of traditional dc guns.

7. Conclusion

The microwave electron gun described by Westenskow et al. lowers beam emittance by quickly accelerating the electrons to relativistic velocities. However, the time varying accelerating field causes some electrons to hit the cathode. These back-bombarding electrons heat the cathode and cause thermal instabilities. Computer simulations predict that a C-magnet will reduce the back-heating energy by 75% with no loss of forward current, but with a slight increase in emittance. Presently, the third-generation gun with the C-magnet is under construction. Future development depends on the experimental performance of the new gun.

References