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LOW EMITTANCE THERMIONIC ELECTRON GUNS*

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1. SELF FIELDS

The beam emitted from the cathode of a "well-designed" electron gun is born with uniform current density. Almost by definition, this "well-designed" gun is a Pierce[1] design with the focusing electrode carefully matched to the edge of the cathode.

The advantage of the Pierce design is that the focusing fields at the edge of the beam exactly cancel the defocusing fields from space charge. Thus there are no transverse forces on the edge of the beam. This "Pierce condition , as it is sometimes called, cannot be maintained for very long, however. Using, for example, Child's Law for space-charge limited flow in a plane parallel diode:

$$j = \frac{4}{9}\sqrt{2e/m}\;\epsilon_0\frac{V^{3/2}}{x^2} \quad , \tag{1}$$

it is readily found that, for a given current density, j, the voltage V varies as the 4/3 power of distance x, from the cathode. Because of the limitation on high voltage, the space between cathode and anode is typically between 1 and 3 times the radius of the cathode. Since the Pierce condition can only be maintained as far as the anode, space charge spreading of the beam will begin as the beam approaches the hole in the anode.

Space charge spreading does not necessarily cause emittance growth. So long as the beam maintains uniform current density, the transverse electric field, due to space charge, is given by

$$E_r = \frac{r}{2\epsilon_0 c}\left(\frac{j}{\beta}\right) \quad , \tag{2}$$

where r is the distance from the axis within a uniform beam and βc is the (assumed uniform) axial velocity. Particles which are focussed only by forces that vary linearly with the displacement variable can always be transported without emittance growth.

The above condition on a uniform beam of course does not include the familiar idea of a Gaussian beam profile. Thus, the Gaussian beam will encounter nonlinear transverse fields. The designer of a low emittance gun wants to delay the onset of this condition as long as possible. The greater the kinetic energy of the beam when it encounters nonlinear forces, the less damaging these nonlinearities will be.

There is a lower limit to the emittance of an emitted beam, resulting from the temperature of the cathode. Using the Lapostolle[2] definition of rms emittance for a uniform beam

$$\epsilon_n = 4\left[\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2\right]^{1/2} \tag{3}$$

and the condition that $\langle xx'\rangle = 0$ on the cathode, Lawson[3] has noted that for a thermionic emitter of radius r_c at a uniform temperature T,

$$\epsilon_n = 2r_c\left(kT/m_0c^2\right)^{1/2} \ \mathrm{m-rad} \tag{4}$$

The practical lower limit for emittance as pointed out by Fraser,[4] is found by substituting for r_c in (4) from $I = \pi r_c^2 j$. Noting that kT is 0.1 eV for 1160K, which is a typical cathode temperature, the lower limit on rms emittance is

$$\epsilon_n = 5.0\times 10^{-6}\,(I/j)^{1/2} \ \mathrm{m-rad} \ \text{ with } j \text{ in } A/cm^2 \tag{5}$$

A typical cathode area for a linac injector is of order 1 cm^2. Since the nominal current density from dispenser cathodes is 5–10 A/cm^2, the ratio I/j is of order unity, and the minimum practical emittance is about 5×10^{-6} m-rad.

The rms divergence $\langle\theta\rangle$, implied by this emittance, for a cathode radius of 0.5 cm, is 1 m-rad. Normally such a low divergence does not significantly affect the beam profile; the beam would have to drift for one meter to cause a 1 mm rounding-off of the profile. However, if it is desired to significantly compress a beam transversely, then by the conservation of transverse emittance, the divergence increases inversely to beam radius. A beam thus compressed from a few millimeters diameter to about one millimeter, will almost immediately assume a Gaussian profile, with its attendant nonlinearities.

The above treatment completes our discussion of self-field effects in the gun region. We have deliberately ignored self magnetic fields because,

(1) They are not significant until the beam achieves semi-relativistic velocities, ($\beta > 0.5$), which usually does not happen within the gun region, and

(2) The self-magnetic fields, act only to partially neutralize the space charge forces. As such, the self-magnetic fields depend on radial uniformity of the beam in exactly the same way as do space charge forces.

The only consideration should be that, if it is desired to avoid the nonlinear self fields altogether, then it is only necessary to maintain a uniform beam profile until the beam has relativistic velocity.

2. EXTERNAL FIELDS

By definition, the first order radial fields, from external electric and magnetic structures, are all linear. The scale, by which one determines if first order considerations are adequate, is the ratio of beam radius to electrode or pole piece radius. As a rule of thumb, if this ratio is less than one-half, the significant nonlinear forces have been avoided.

Since the above criterion, i.e., keeping the beam radius small, argues precisely against the conclusions for self fields, it is apparent that there is a preferred dependence of radius as a function of axial position, for the best beam conditions. However, there are usually other criteria for transverse matching of a beam to a subsequent transport system that preempt trying to rigidly apply the above considerations.

There is, in addition, the option of attempting to avoid nonlinear fields in the design of the electrodes and pole pieces. Peter and Jones[5] have devised a formalism for designing electrodes that result only in linear fields in the acceleration cavity. Similarly, one can shape magnetic pole pieces to reduce saturation and nonlinear fields. Both applications have the added advantage of minimizing peak fields. The cost is frequently some increase in size.

In many cases, the current desired in a beam is much greater than a cathode can emit in an area similar to that of the desired beam profile. In these cases, it is usual to use a spherical cathode with a focus electrode inclined to the edge of the beam at the Pierce angle, defined by $4/3\tan^{-1}(y/x) = \pi/2$, i.e., the slope of the electrode at the edge of the beam, relative to the edge of the beam, is 67.5°. A general treatment of the Pierce structure for different beam profiles including hollow beams and curved paths, was given by Sar-El.[6]

3. THERMAL-EMITTANCE-LIMITED GUNS

Most electron gun applications do not allow for a gun designed according to the foregoing discussion. The most frequent additional requirement is for the control of pulse length. In the limit of an injector to an accelerator, pulse length is ultimately determined by a bunching system that will increase the emittance far beyond thermal limits. This subject is treated by T. Smith in another chapter in this volume.

The next level of pulse length control is that from about 1 to 1000 ns, that can be controlled by a pulsed grid. Since such guns are frequently used in accelerator injectors, the subsequent bunching process will dominate over emittance induced by the grid.

There are however, applications for which the very best possible emittance is required and in which it is possible to avoid grids and rf bunching. Two of these are:

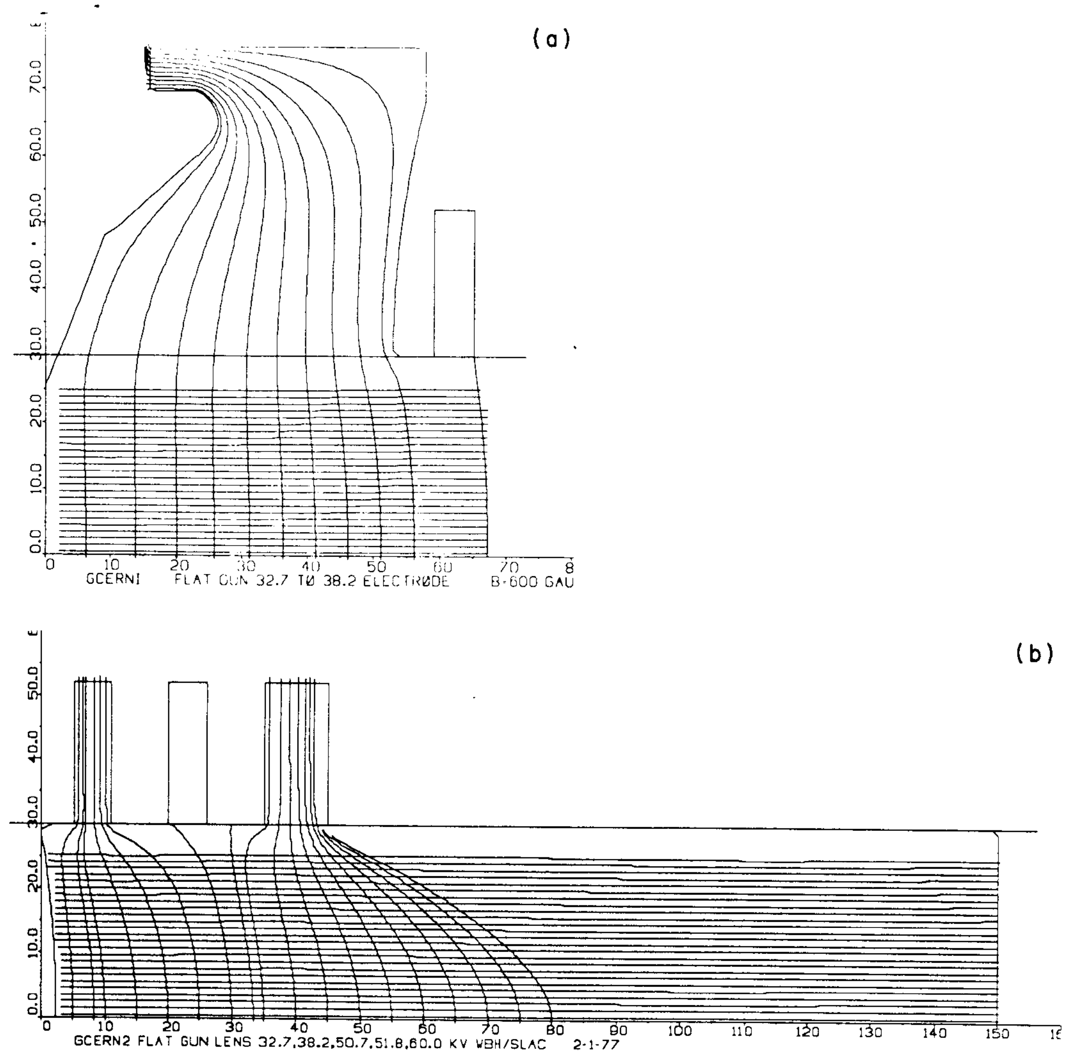
1) A gun for an electron cooling system, and

2) An injector for an electrostatic free electron laser (FEL).

Electron cooling is a process in which a low emittance ("cold") electron beam is made to mix with a circulating beam of ions to improve the emittance of the ion beams. The process was suggested by Budker[7] and has been implemented at several laboratories world wide. The most typical application is to cool a beam of anti protons in a storage ring. To provide adequate dc current at reasonable power, the gun and collector are both operated at the same high voltage (except for a small bias). The beam power can be, for example, 20A $\times$ 120 kV = 2.4 MW with only a few kilowatts of beam energy lost to heat.

The specific problem in the design of an electron gun for electron cooling is to avoid any type of transverse motion. A uniform magnetic field is employed in the interaction area to keep the beam from spreading. There is an unavoidable, but quite small azimuthal motion induced by the $\vec{E} \times \vec{B}$ drift from space charge forces and this magnetic field. The design problem then is reduced to matching the beam into the magnetic field in the drift region. The method that was devised to do this was used by guns for both CERN[8] and Fermilab.[9] The technique is illustrated in Fig. 1 which is a computer simulation of the flat cathode gun used for the CERN ICE experiment. The gun region is shown in Fig. 1A and the matching section is shown in Fig. 1B. The boundary conditions for the two segments are matched so that 1B is a continuation of 1A.

Counting the gap at the end of Fig. 1A, there are four gaps which can have more or less arbitrary voltages across them. The system is constrained by the voltage between cathode and first anode, which determines the current, and by the overall cathode-to-drift-tube voltage, which determines the total kinetic energy. The kinetic energy is chosen to give the electrons the same velocity as the orbiting proton or antiproton beam. There are thus three free parameters for voltages that can be adjusted to minimize transverse velocity in the beam. An empirical approach to minimizing the transverse energy can be shown to succeed to within about 1 eV. If these voltages are not properly adjusted, or if the "resonant lenses" as these electrodes are called, are not used, the beam is found to continue with quite large scallops representing unacceptable transverse energy. In the Fermilab experiment,[9] a spherical cathode and fully immersed flow (meaning the same total magnetic flux in the beam as through the cathode) was used to obtain higher current density. The same technique of resonant lenses was employed. In both devices, the best residual transverse motion was similar to the transverse thermal velocity.



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tial cooling experiment (ICE). Fig. 1B. Continuation of the simulation of Fig. 1A showing the resonant lens configuration.

The SLAC Electron Trajectory Program, known as EGUN[10] was used for the design of both of the above electron cooling guns and also for the FEL injector described below. The use of computer programs to design electron guns and beam transport systems was described by Herrmannsfeldt[11] and others at the Beam Optics Codes Workshop.

Free Electron Laser (FEL) injectors must provide a beam with emittance

$$\epsilon = \langle x \rangle \langle \theta \rangle \approx \lambda$$

in order for there to be adequate coupling between the electron and the photon distributions.[12] Note that this is the laboratory emittance, not the "normalized" or invariant emittance $\epsilon_n = \beta\gamma\epsilon$. Thus, ϵ is inversely proportional to the momentum $\beta\gamma$. In most FEL's, an electron accelerator is used to achieve a high γ, typically 200 (for a 100 MeV beam) yielding sufficient "adiabatic" damping to permit the FEL to operate.

In one case, however, using an electrostatic accelerator, the achievable energy is only a few MeV. Then it is necessary to achieve the best possible emittance from the electron gun. The gun designed for the UCSB FEL project was described by Elias and Ramian.[13] The design of this gun is shown in Fig. 2. The first electrode is known as a "mod anode" and is used to gate the beam on and off. At the design voltage, the fields in front and behind the plane of the mod anode still obey the Child's Law criterion, so that there is no defocusing of the beam. In order to smoothly maintain this field, the mod anode is made as thin as possible, tapering to a sharp edge at the inner ring.

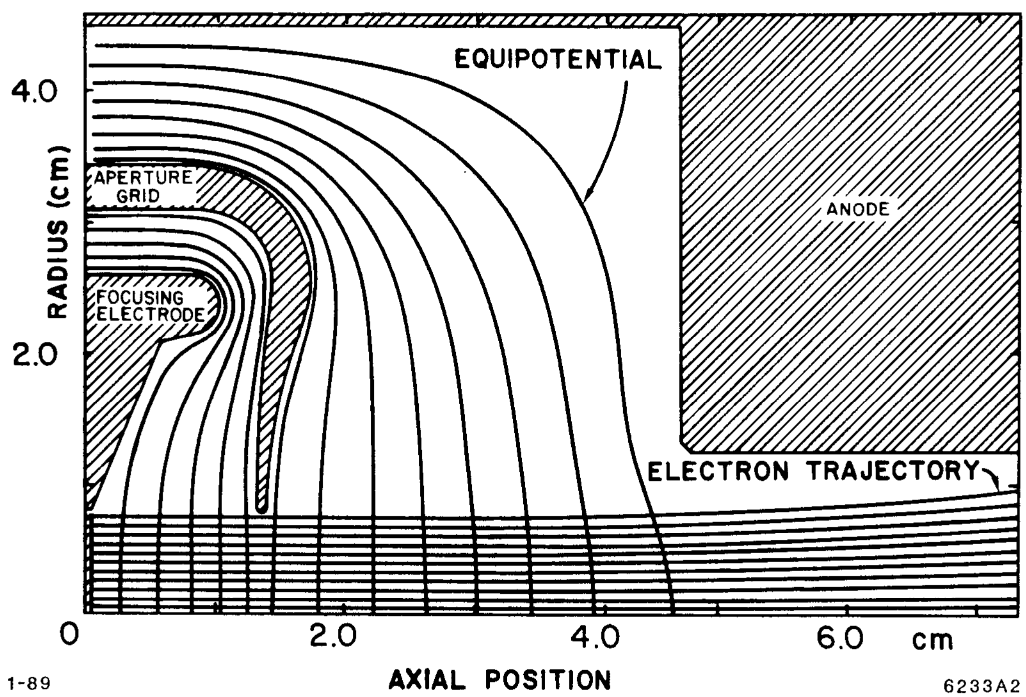

Fig. 2. Design of the electron gun for the UCSB electrostatic accelerator FEL.

A section view of the hardware design of the UCSB gun is shown in Fig. 3. As the beam enters the accelerator column, the field becomes quasi-constant so that there can be some space charge spreading. However, the velocity is now so great that the residual forces are very weak. There is, in addition, a sort of "weak strong focusing" effect caused by the presence of the system of rings and gaps in the electrostatic accelerator column. Cline et. al.[14] made measurements of this gun, evaluating it for a recirculating electron cooling system. They found the emittance to be very near the thermal limit as defined above.

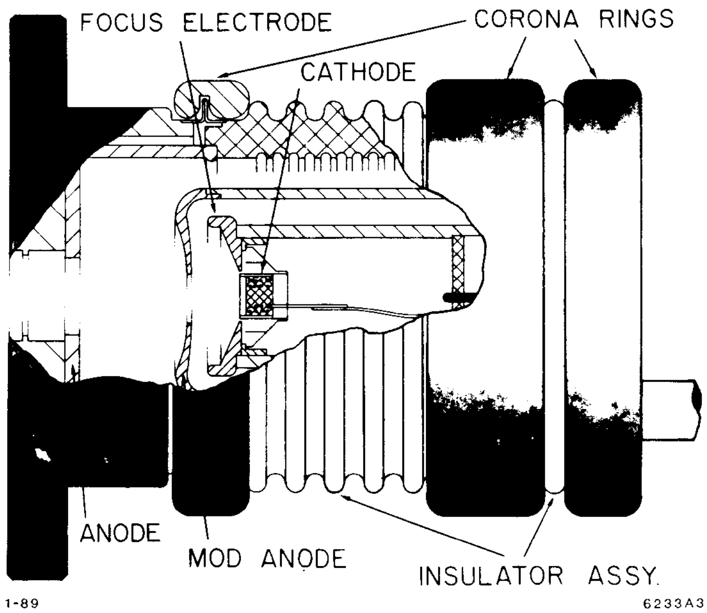

Fig. 3. Mechanical configuration of the UCSB FEL gun.

Note that the configuration for an electron cooling system is essentially the same as for an FEL, i.e., the collector must operate at the same voltage as the gun, usually slightly positive relative to the cathode, but much less than the high voltage of the electrostatic column. In this mode, all of the power that is available to the optical process of the FEL comes from the power supplied to the gun, and not from the electrostatic power system for the accelerator column. The limit to duty cycle usually occurs when the laser process causes some beam current loss which then must be replaced. Thus improving the collection efficiency and eliminating transport losses allow approaching cw operation with a very high efficiency FEL.

4. GUNS FOR ELECTRON LINACS

A criterion, known as the "Lawson-Penner Relation" has been used by several authors to compare emittance of different linacs. Although Lawson and Penner[15] have stated that it is not a "law" and better injectors probably can be built, it is still useful to examine the implications. In the form studied by Roberson[16], the Lawson-Penner relation is

$$\epsilon_n(\mathrm{m-rad}) = S\sqrt{I(A)} \tag{6}$$

where S is an empirical constant found by comparing existing accelerator systems. Usually this comparison should be made within the same general category of accelerators, i.e., rf bunching or induction linac, etc. Penner found $S = 160 \times 10^{-6}$, in the units used for this paper. Roberson made a better fit to the data he used with $S = 95 \times 10^{-6}$. Both numbers are much greater than the thermionic limit of Eq. 5, thus seemingly confirming the statements earlier that bunching and/or pulse transients dominate the emittance.

If, as these authors have supposed, better injectors can be built, it is worthwhile to speculate what techniques need to be used. If, as seems to be the case, the gun does not limit the emittance, then it follows that it must be the transient fields introduced by the bunching and/or gating devices. Since this discussion quickly leads into the subject areas covered by Sheffield and Smith in their respective chapters in this volume, it may be sufficient to point out that while nonlinear fields may cause emittance growth, other nonlinear fields can cancel the effect. Usually this approach only works if done quickly, as in the case of the electron cooling guns discussed earlier. In the particular case of interest here, Sheffield and Carlsten[17,18] have used the nonlinear space charge fields themselves to correct the damage done to the emittance by the beam expanding earlier due to those same nonlinear fields. This approach is analagous to the use of properly spaced sextupole and octupole lenses in a beam transport line. Numerical simulations of space charge spreading and refocusing, with attention to the effects of nonlinear forces, are the subject of work by Hanerfeld et al.[19]

Before leaving the subject of electron guns for linear accelerators, it is important to note the significant number of gun assemblies that have been supplied commercially by Ron Koontz.[20] For short pulse, high current applications, these guns use cathode grid assemblies supplied by the Eimac Corporation. Grid-to-cathode spacings of under 0.1 mm are employed to reduce the grid voltage that must be pulsed. This is especially important for very short pulses.

Although grids are a necessary evil in many guns, it is possible to design the grid so that it is electrically invisible to the beam. There will still be some percentage interception, given by the opacity of the grid, but if a grid is placed on an equipotential line for a diode, and is then pulsed to the potential of that equipotential line, there will be no electric field deflection of the beam particles by the grid.

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