Statistical Coulomb Forces In Electron Guns

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We show the importance of including the statistical Coulomb forces in electron gun design. We model this for needle emitters with combinations of thermal, field and photo emission. We find that the statistical Coulomb forces can seriously limit probe size at sample by limiting brightness and energy spread see fig(2). However whilst they can not be completely overcome an understanding of the physics and some good rules of thumb can be applied to considerably reduce them.

Reduced brightness Br and energy spread dE are key parameters of electron guns. They are interdependent, so a change in one affects the other (normally adversely). Brightness and energy spread are conserved quantities except under statistical forces. They are extremely important, and ultimately (neglecting diffraction) determine probe size, at a given current. This is demonstrated in fig (1), for details see caption and [1].

Coulomb forces are a major hurdle in transferring the Br and dE of a gun to the source. Often space charge forces are calculated, but not the statistical forces. In microscopy statistical forces dominate, and space charge has mainly a defocusing effect,

Electron guns are particularly prone to Coulomb forces as they usually have a crossover (sometimes virtual) with large current densities, and as the electrons travel at low velocity they have long interaction times.

Jansen and Kruit developed simple analytical formulae and fitted them with Monte Carlo simulations, These can be applied to give an estimate of the Coulomb force [2] for field free regions. These have been extended to gun optics with strong fields using the slice method [3] and ray tracing programs.

In fig (2) we apply this method with our Br and dE calculations of thermal field and thermal–field-photo emitters [4]. We see that the Coulomb forces not only limit Br but also causes dE to rise rapidly. This happens at around Br =1E8 A/m^2/Sr/V which is in line with maximum proven experimental brightnesses such as [4]. When we add photons we find that the situation worsens dramatically, because the current increases without the accelerating field. In both cases the energy spread is very quickly doubled.

Also in fig (2), we show how to maintain the intrinsic Br and dE yet reduce the amount of Coulomb forces by aperturing the beam. This helps to maintain the brightness but does not help the energy spread. To reduce dE we can make the tip radius smaller, however this also has effect on Br so a compromise must be reached.

We will discuss in more detail how to calculate the Coulomb forces and how to reduce them in our paper. We will also discuss cold field(photo) emitters. In particular single atom tips, which represent a fundamental size limit and a maximum practical brightness for needle emitters.

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[1] P Kruit, M Bezuijen, and JE Barth J. Appl. Phys. 99(2) 2006
[2] Jansen & Kruit Chap.7 Handbook of Charged Particle Optics Ed. Orloff CRC press 1997
[3] Van Veen AHV, Hagen CW, Barth JE, and Kruit P. J. Vac. Sci. Technol. B 19 p2038 2001
[4] De Jonge N, lamy Y, Schoots K and Oosterkamp T H *Nature* **420** 393-6 2002
[5] Cook B,Bronsgeest M, Hagen CW, Kruit P, I, Ultramic, 109(5)2008

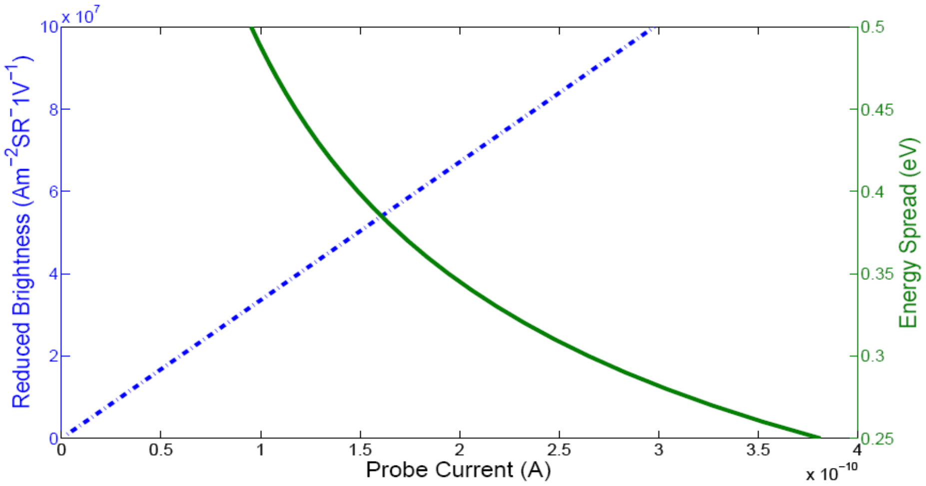

Figure 1. Minimum required brightness and maximum allowable energy spread (FW50) for a 1nm(FW50) probe size, in a system dominated by chromatic aberration, in which the opening angle of the probe forming lens is optimised. Parameters used are electron energy 5keV, chromatic aberration of 0.5mm.

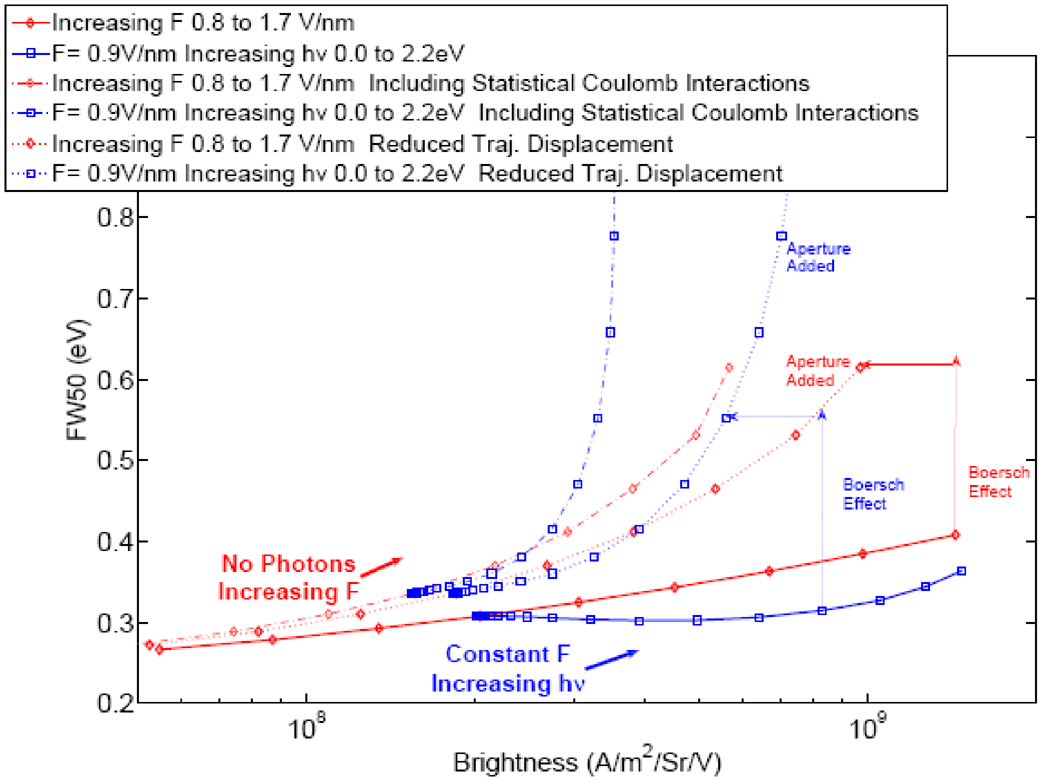

Figure 2. Calculated effect of Coulomb forces on intrinsic energy spread (FW50) and reduced brightness for a thermal field emitter(red) and thermal field photo-emitter (blue). The thermal field-emitter has an increasing field strength and the thermal-field photo emitter has fixed field strength and increasing photon energy. Solid lines are without Coulomb forces. Dotted lines include coulomb forces with the smaller dots. for an adaptation to reduce the amount of brightness loss. The arrows link the same field or photon energies.