RING-CATHODE FOCUSED ELECTRON BEAM COLUMNS

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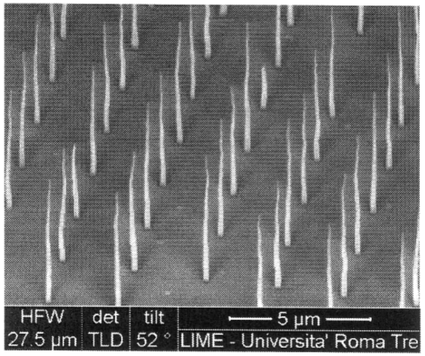
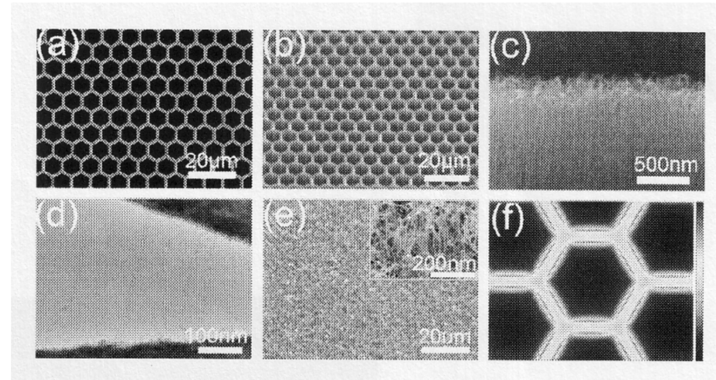
Nano-resolution high current focused electron beam columns

The goal of creating a focused electron beam column that has both high probe current (> 1 μA) and high probe resolution (< 20 *nm*) is important for many applications such as Electron Beam Lithography, Auger Electron Spectroscopy, and Electron X-Ray Microanalysis. The main challenges that need to be overcome stem primarily from present-day electron source limitations.

Large area field emitter tips



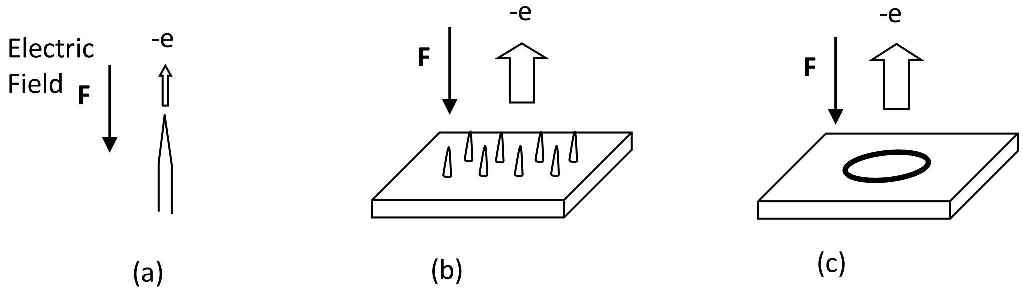
Vertically aligned carbon nano-tube (CNT) array
S. Lacobucci *et al*, Appl. Phys. Letters **100**, 053116 (2012)



Various grid shapes of CNT arrays
Chi Li *et al*, Appl. Phys. Letters 97, 113107 (2010)

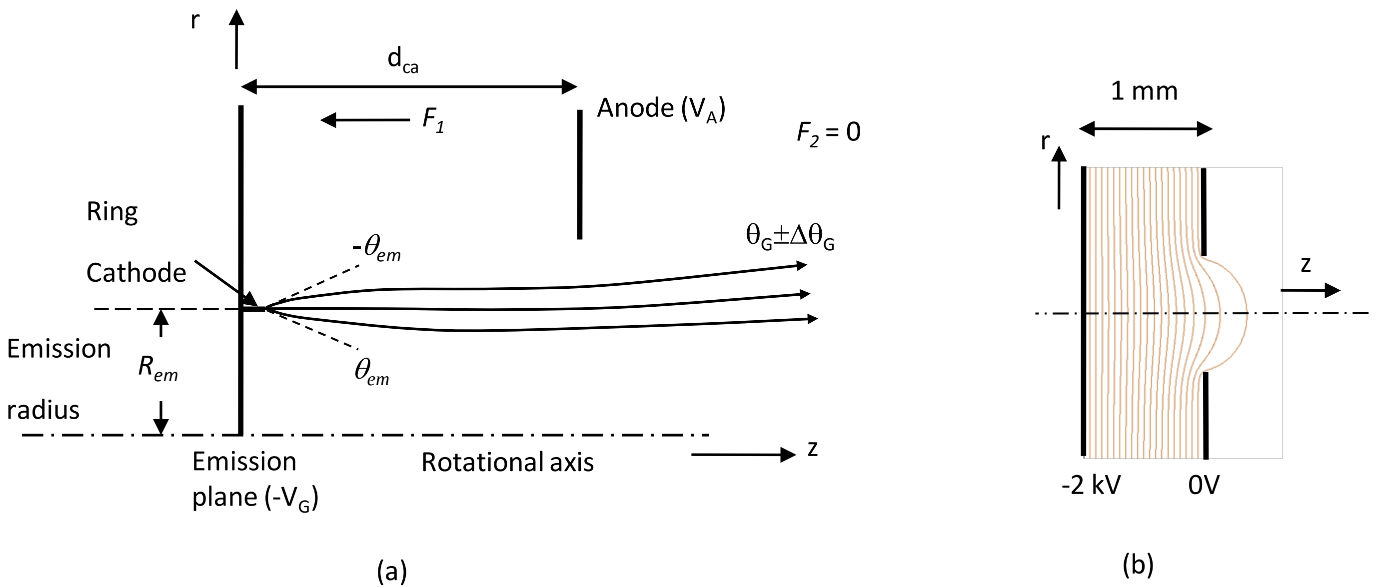
- Pattern nickel catalyst on silicon substrate, CNTs a few nanometers in diameter
- CNT fibre 5 μm high, 2.5 μm spacing, diameter 100 nm at base, 50 nm at tip
- Current is approximately between 0.3 nA to 30 nA per tip (depending on field strength), around 300 μA measured from 100 by 100 array at around 10 kV/mm
- Usual application is for Field Emission Displays and X-ray tubes

Types of cold field emitters



(a) Single-tip emitter with disadvantages of large current fluctuations, low total current, difficulty of manufacture, high vacuum.
(b) Large area emitters, currents up to 1A/cm^2 , for large-scale projection such as display devices, not for focused electron beams
(c) Propose to make a ring emitter, consists of a single circular ring block. For a 200 μm radius ring (1,256.8 μm circumference), the emission area of the ring edge is over 1000 times greater than the emission area of a single tip (diameter say below 50 nm), so at least one to two orders increase in total probe current can be expected

Ring-cathode gun layout

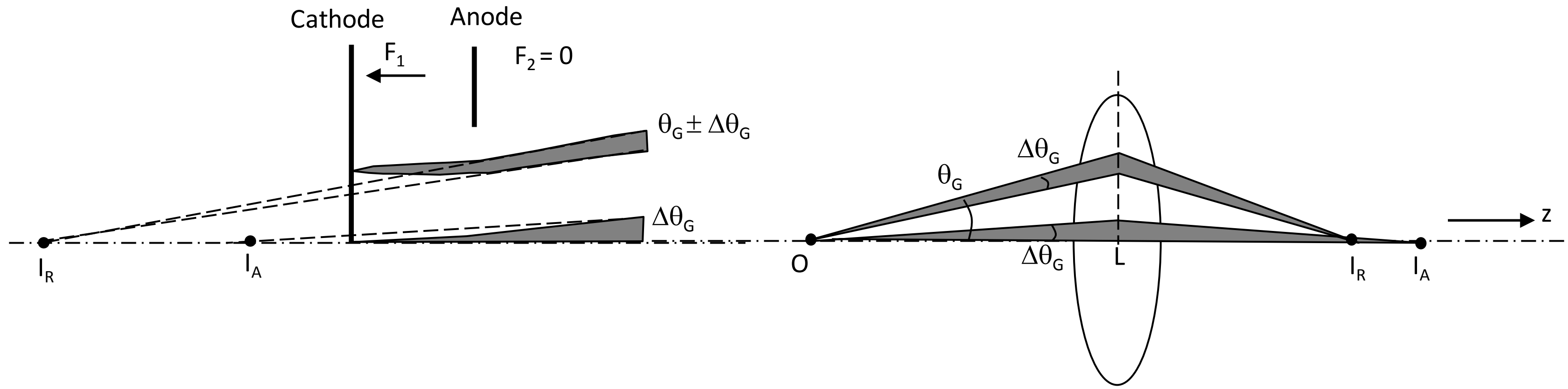


Assumptions about the source:

1) Emission only in the r-z plane, that is, electrons travelling either radially towards or away from the rotational axis

2) Cathode-tip can be approximated to be a point on the emission plane, ignore nano-scale geometry of the tip and cathode height (several microns)

Ring transmission



In terms of on-axis and chromatic and spherical aberration coefficients, C_C, and C_S respectively

$$On-axis$$

$$\Delta z_A \approx C_C \frac{\Delta E}{E} - C_S(\Delta\theta_G^2)$$

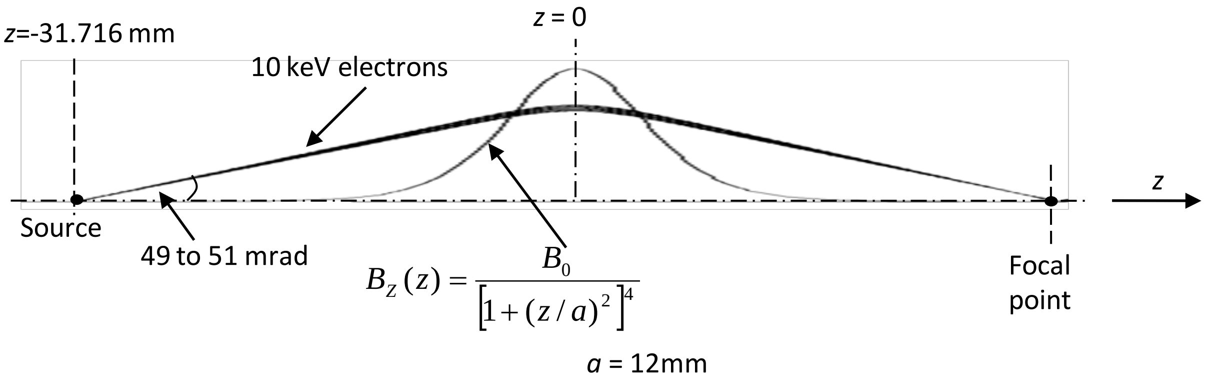
$$\Delta r_{SA} \approx C_S(\Delta\theta_G^3), \quad \Delta r_{CA} \approx \Delta\theta_G C_C \frac{\Delta E}{E}$$

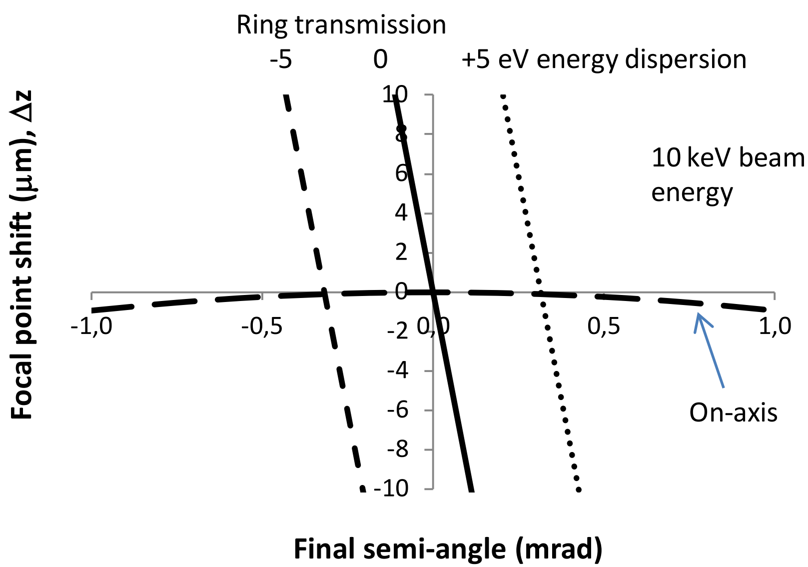
$$Ring-transm.$$

$$\Delta z_R \approx C_C \frac{\Delta E}{E} - C_S(\theta_G + \Delta\theta_G)^2 - C_S\theta_G^2 = C_C \frac{\Delta E}{E} - 2C_S\theta_G\Delta\theta_G - C_S(\Delta\theta_G^2)$$

$$\Delta r_{SR} \approx -2C_S\theta_G^2\Delta\theta_G - C_S\theta_G(\Delta\theta_G^2), \quad \Delta r_{CR} \approx C_C \frac{\Delta E}{E}\theta_G$$

Simple magnetic lens example





In the ring emission column, the aberrations for the final probe radius, r_P, can therefore be simply expressed in terms of a probe axial spread Δz_P, final semi-angle, θ_P, and final semi-angle spread, $\Delta\theta_P$, as

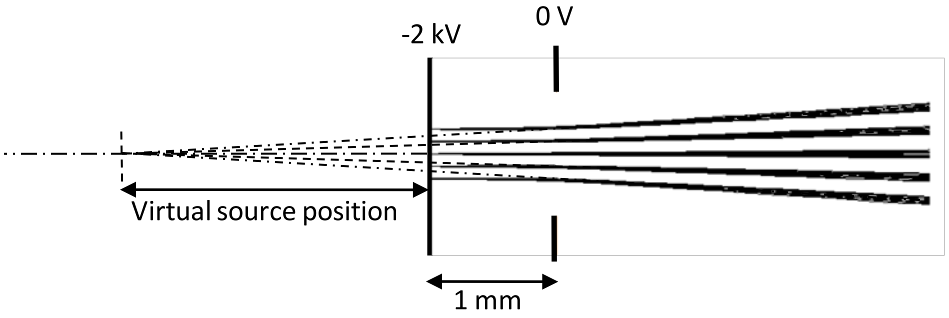
$$r_P = \theta_P \Delta z_P = \theta_P [A_0 + A_1 \Delta\theta_P + A_2 \Delta\theta_P^2 + A_3 \Delta\theta_P^3 + ...]$$

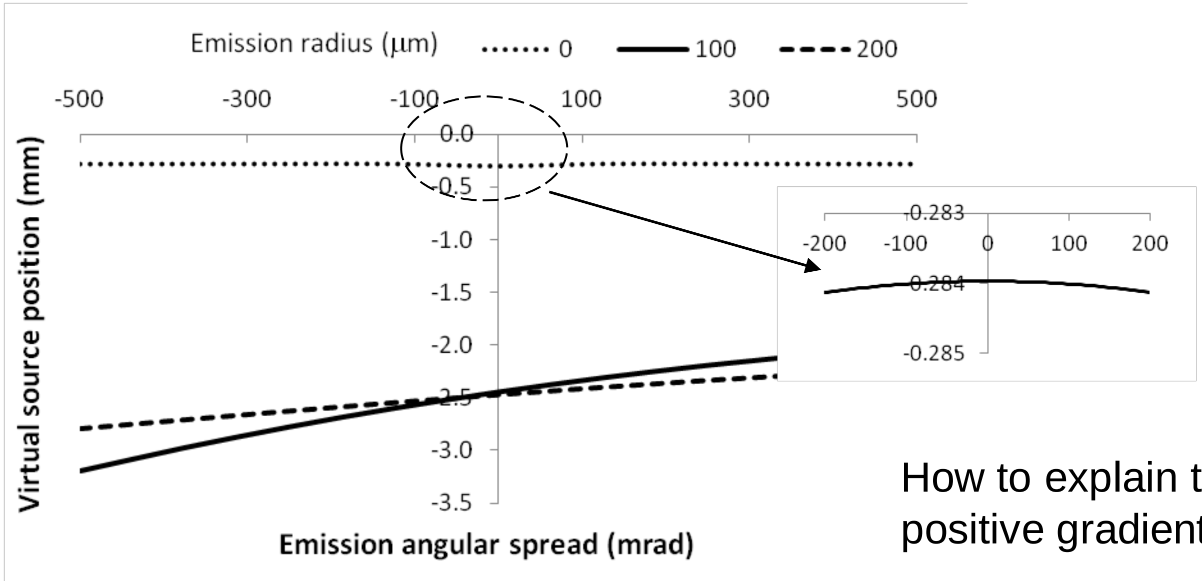
where A_0, A_1, A_2, A_3….. are aberration coefficients.

For on-axis emission, A_0 is related to the axial chromatic term, $A_0 = (\Delta E/E)C_C$, and $A_2 = C_S$, the usual third-order spherical aberration coefficient.

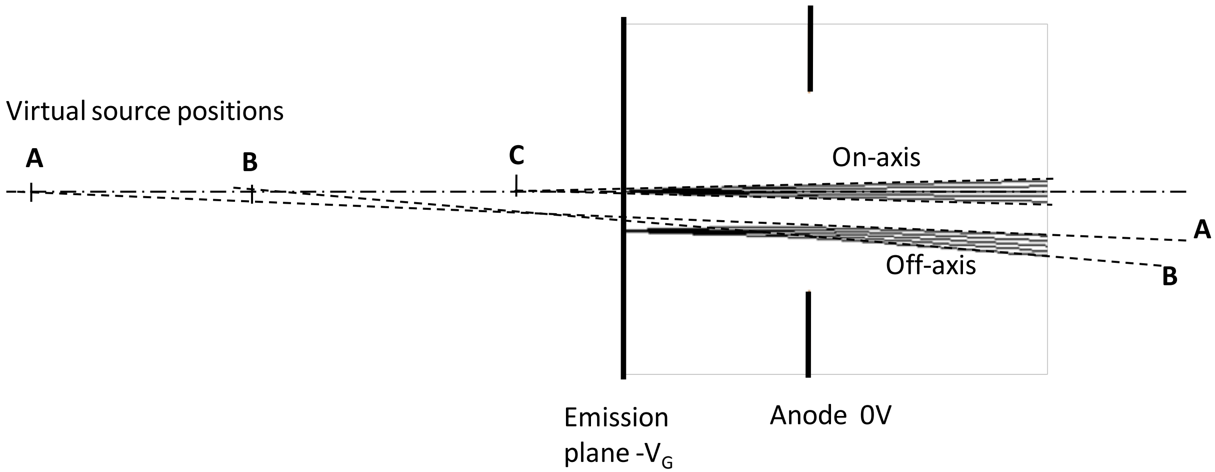
This equation is similar to the one for on-axis aberrations, only it includes more terms such as A_1 which are generated from the mixing of the final semi-angle θ_P with the final semi-angle spread, $\Delta\theta_P$. In the case of on-axis emission, these two angles are identical.

Simple ring-cathode gun unit simulation

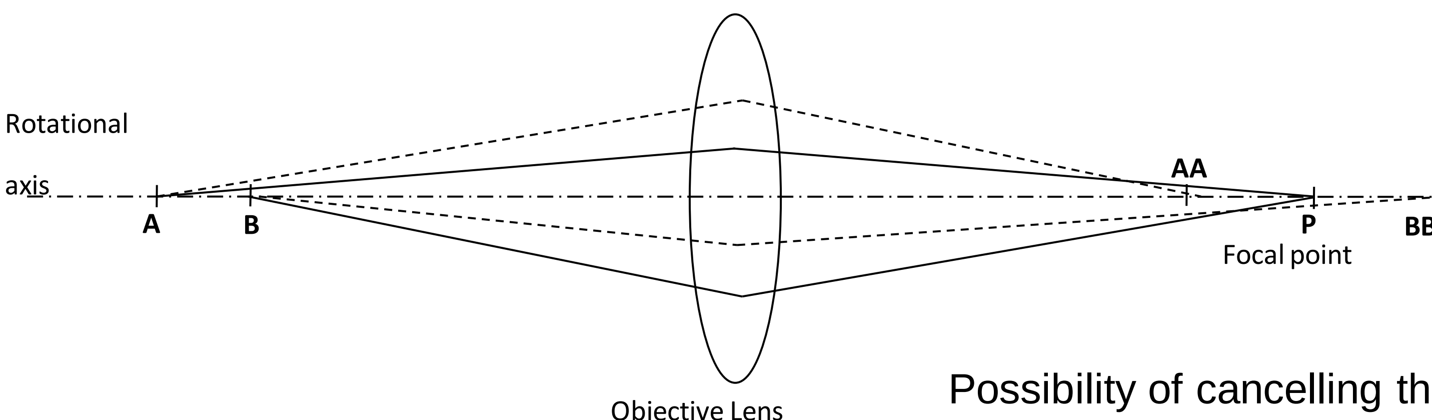




How to explain the positive gradient?

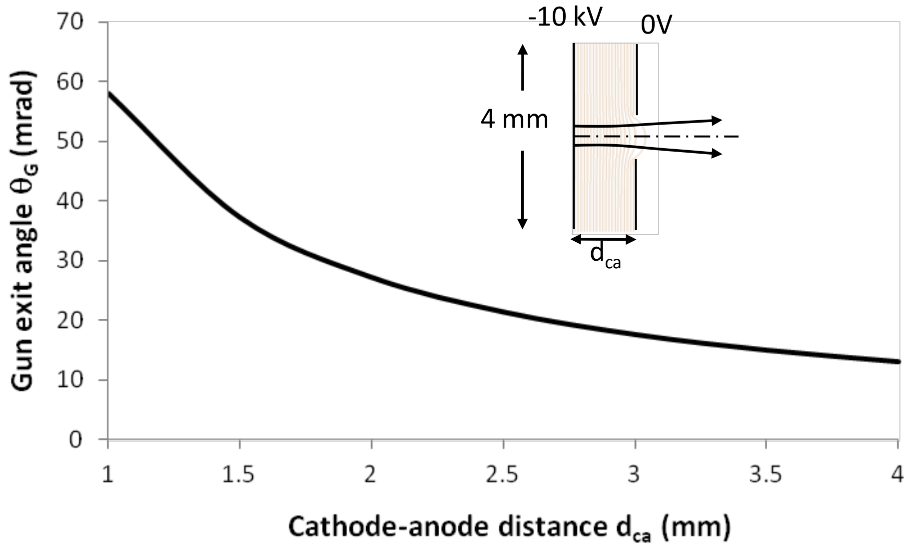


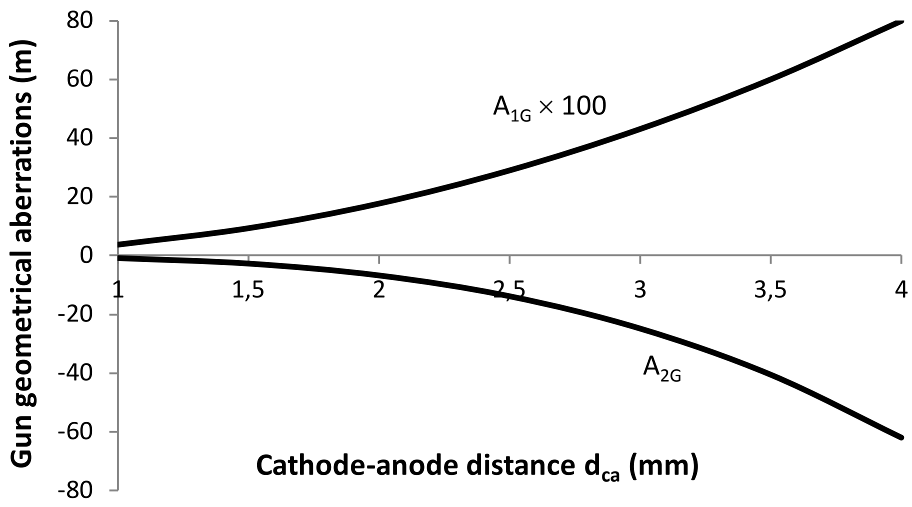
(a)



(b)

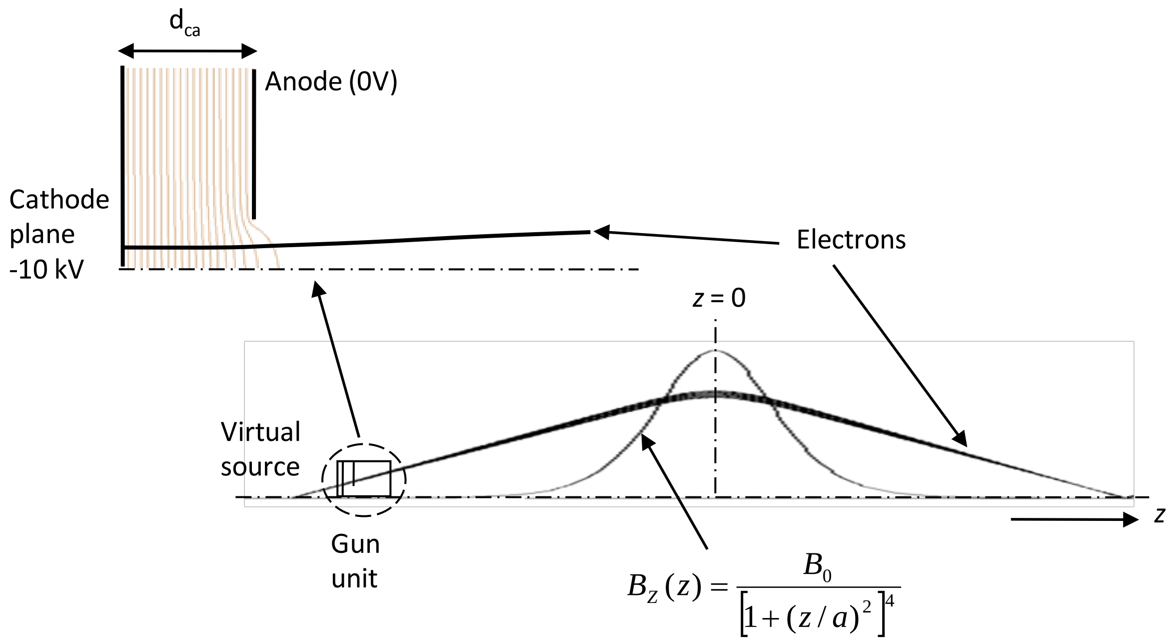
Possibility of cancelling the 1st-order geometric aberration term



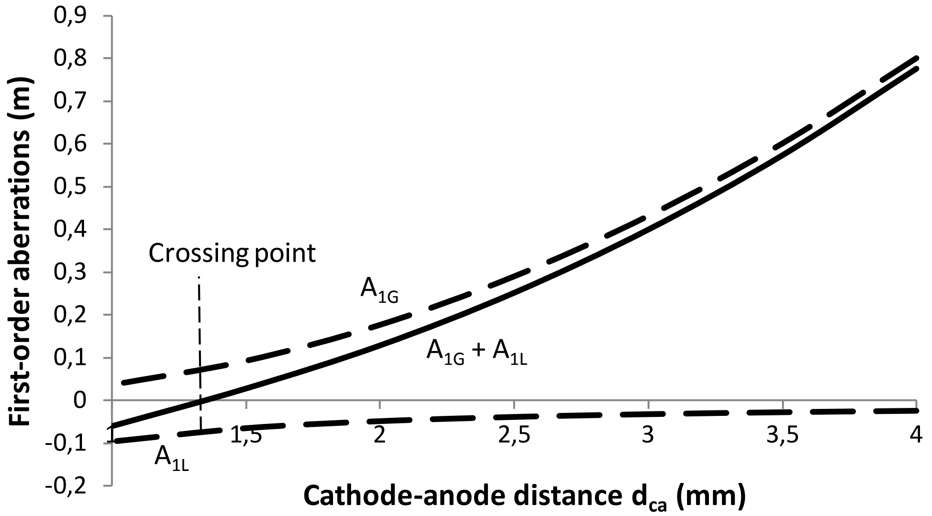


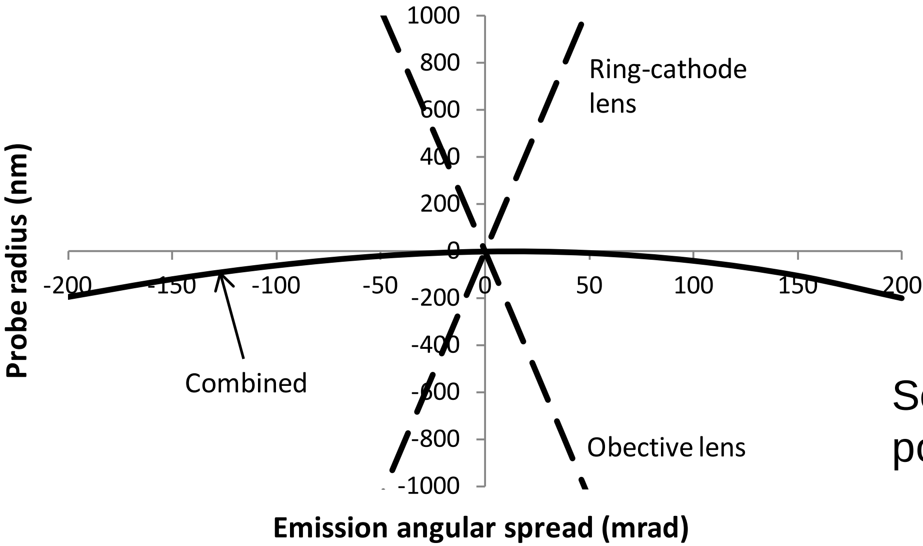
Can use the cathode-anode distance as a free parameter for aberration cancellation

Ring-cathode gun combined with a single magnetic lens



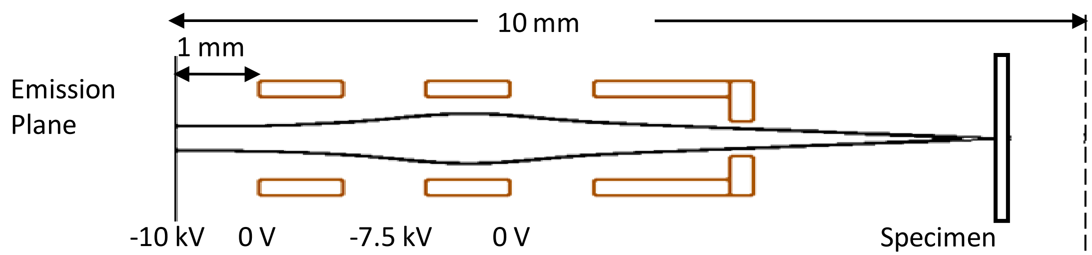
Cancellation of first-order geometric aberration

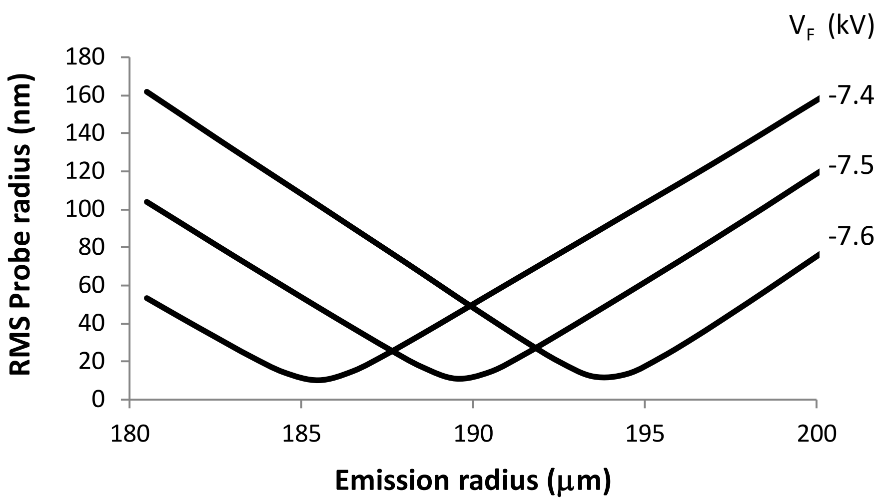




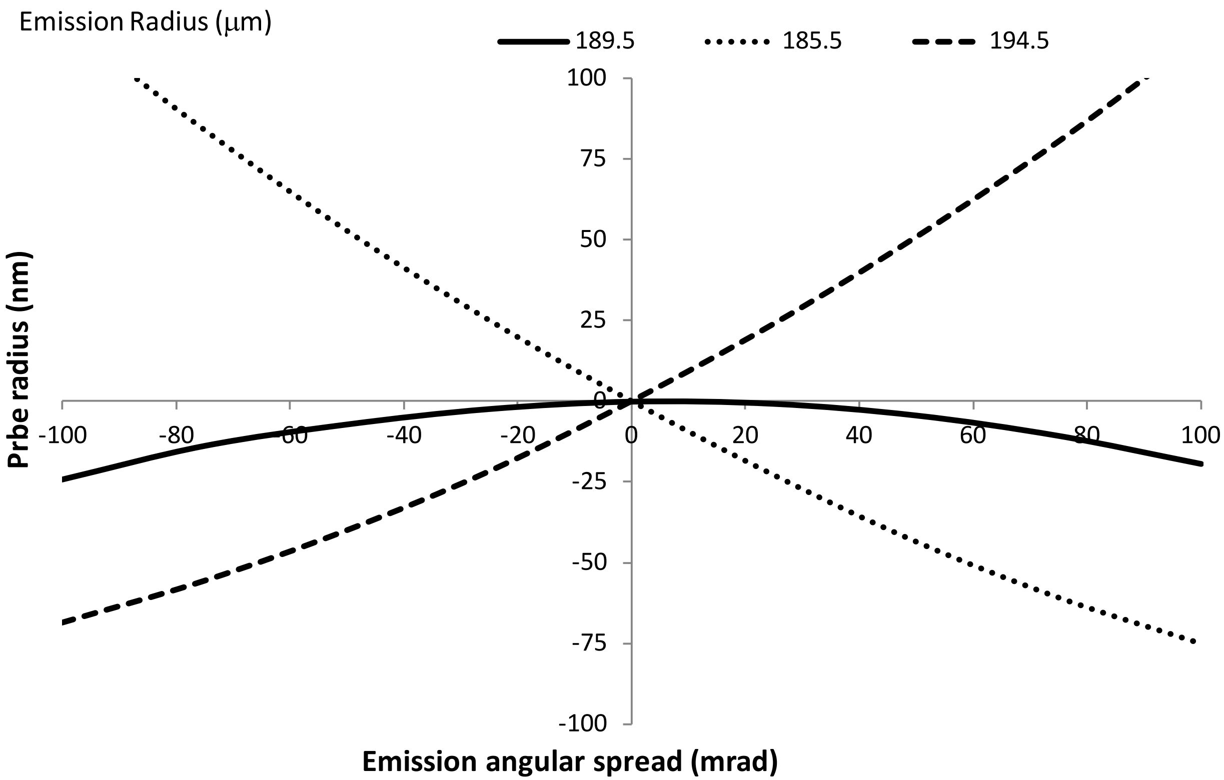
Select d_{ca} for crossing point

Single miniature electric column





Simulated probe radius as a function of emission angle close to critical emission radius

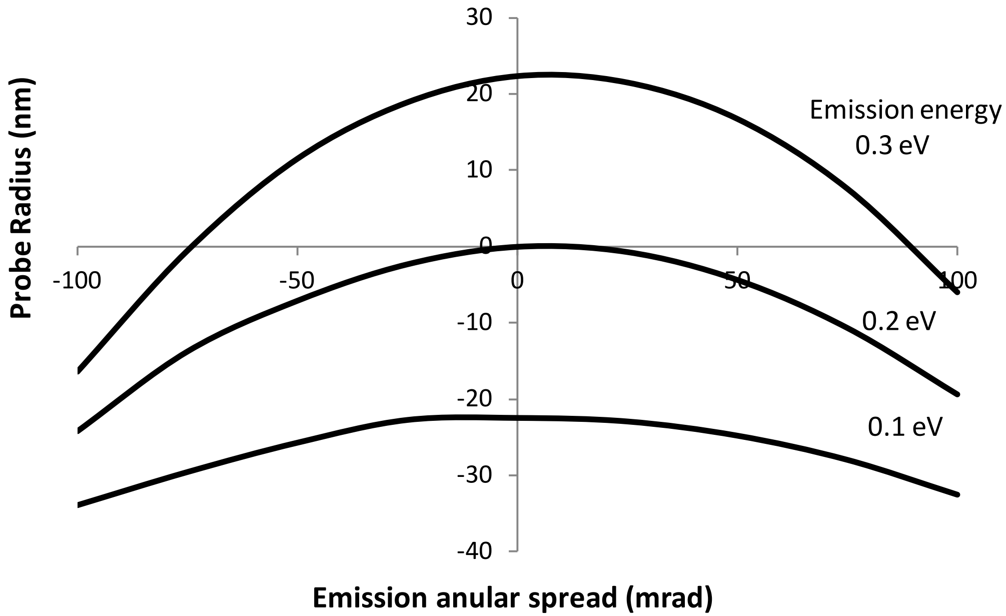


Indicates that there is a cancellation of field curvature and astigmatism aberrations, leaving residual coma.

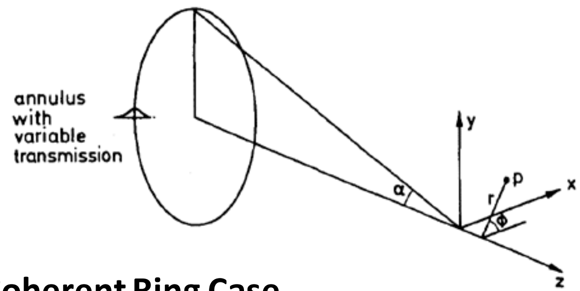
Cancellation comes from the fact that field curvature/astigmatism aberrations have opposite sign in acceleration and focusing regions of the column

Chromatic aberration

Probe size due to both axial and transverse chromatic aberration also limit spot size



Diffraction



Coherent Ring Case

$$\psi = J_0(v)\exp(-v^2 a^2/2)$$

$$d_d = \frac{1.2\lambda}{\pi \sin(\alpha_i)}$$

where *v* is normalized coordinate in radial direction, *a* is a constant related to the thickness of the ring (C. J. Sheppard and T. Wilson, Microwaves, optics and acoustics, Vol. 2, No. 4, (1978) pp 105-112)

Coherent case means that coherence around the ring, we know that a field emission source has coherence from a single tip. Full coherence around the ring is unlikely at room temperature, but may be possible with single block emitters at low temperatures.

If ring is fully coherent around the ring , diffraction spot is dependent mainly on the final semi-angle (over 50 mrad in this case), not on the angular spread, and is predicted to be very small for present column, 0.044 nm. This brings out an interesting challenge about ring emitters, the challenge to achieve ring coherence, if can be achieved, diffraction effects become are likely to be negligibly small.

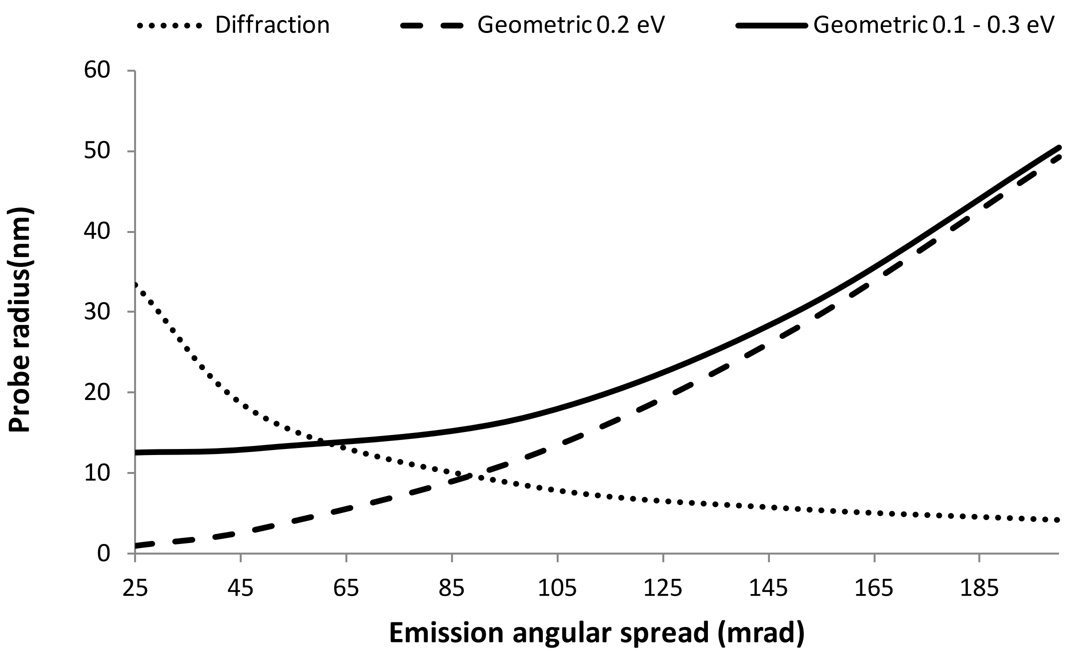
Diffraction (fully incoherent)

The usual Airy diffraction pattern, characterized by a first-order Bessel function solution, and its diameter (full-width half-maximum FWHM), d_d, is given by,

$$d_d = \frac{0.61}{\Delta\alpha}\lambda$$

where λ is the De Broglie wavelength, and $\Delta\alpha$ is the angular spread at the specimen [9]. At 10 keV, the electron wavelength is 12.26 pm, an emission angular spread of $\pm$ 100 mrad is translated into an angular spread of $\pm$ 0.44 mrad at the specimen, which gives a diffraction spot radius of 8.35 nm

Total effect of aberrations on Probe Radius



Incoherence around the ring is assumed