Current Distribution Across the Target of Field-Emission Probing Systems.

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Rapid advancement of nanotechnology calls for both perfection of instruments currently used in microelectronics and development of new nanometer-resolution tools. Widely used in science and technology, electron and ion probing systems are among such instruments. Their basic parameters – current and resolution – are fully determined by current distribution in the target plane. If we know how to control current density across the target, then we know basic factors that define extreme abilities of this kind of systems. Moreover, the focal-spot current density distribution is spread function that determines image contrast and helps solve inverse problems such as lithographic data preparation and image recognition.
It is a common opinion that current distribution across the target is a kind of Gaussian distribution whose variance is proportional to the sum of squared system aberration coefficients. It suggests that the resolution of probing systems is governed by the full width at half maximum (FWHM), which is assumed to be the mean square of spherical and chromatic aberrations. However, experiments showed that at least probing systems using field-emission sources exhibit target-plane current density distribution that differs from the Gaussian curve. For example, an unusually long ranging tail was detected in current density distribution in experiments with liquid-metal ion source [1]. With the overall dispersion radius of 800 nm, half the current concentrated in a 18-nm spot. The authors of the paper used Holtzmaker distribution to approximate it, assuming that it involves Coulomb interactions in the beam.
The paper will show that this unusual kind of distribution relates to spherical aberration, which gives rise to formation of caustic surface – bright axial spot. The caustic radius as function of target position and system parameters is found. How shifts of the focal plane change current distribution across the spot is considered for two particular ion and electron probing systems. Though the paper deals with field-emission sources, the results of research are applicable to other sorts of sources that are used in probing systems and have small virtual size.
The dispersion function of the system is supposed known in the interval from the output of the immersion lens of the accelerating electrode to the focal plane. Computation of the dispersion function of the immersion lens of the field-emission source poses much difficulty because of heavily irregular field near the emitter. What is more, usual equations of charged particles trajectories are not applicable in this region. That is why we use the dispersion function of the standard source – a spherical capacitor. This function takes into consideration major factors that determine dispersion of a real immersion lens of such sources.

As the radius of curvature of the emitter surface is much greater than the distance to the drawing electrode and the accelerating potential is much larger than the initial energy of particles, the asymptotic solution to equation of motion in the central field is used to find the dispersion function. In view of law of conservation of energy and angular momentum in the central field, the dispersion function is to a first approximation

$$r_p = \rho u \qquad r_p^{/} = \psi + u \tag{1}$$

where $u = v_\tau \Big/ \sqrt{\frac{2e}{m} U_p}$

Since the dispersion function of axially symmetrical systems is usually computed in the meridian plane, we assume that angles of departure, normal and tangent velocities of the source in the meridian plane are described by a standard function

$$f(\psi, v_\tau v_n) = C|\psi| |v_\tau| \exp\left(-\frac{m v_\tau^2}{2kT_\tau}\right) v_n \exp\left(-\frac{m v_n^2}{2kT_n}\right) \tag{2}$$

with normalization requirement

$$\int_0^\infty dv_n \int_{-\infty}^\infty dv_\tau \int_{-\pi/2}^{\pi/2} f(\psi, v_\tau v_n) = 1 \tag{3}$$

We suppose that the dispersion function in the target plane takes the form

$$r_i = Mr_0 + Gzr_0' + a_s r_0'^3 + a_{ch} r_0' v^2 \qquad (4)$$

where M, G are linear and angular magnification coefficients, a_s, a_{ch} are spherical and chromatic aberration coefficients, and $v = v_n \Big/ \frac{2e}{m} U_p$.

Taking into account both Liouville's theorem, which asserts that the phase-state distribution function in the flow of non-interacting particles keeps constant, and expressions (1, 2), and using the general method of calculating integral characteristics [2], we can write the radial current distribution function $J(r)$ as

$$J(r) = \int_0^\infty v_n dv_n \int_{-\infty}^{\infty} dv_\tau \int_{-\pi/2}^{\pi/2} d\psi f(\psi \cdot v_\tau, v_n) \delta\{r - r_i[r_p(v_\tau), r_p'(v_\tau, \psi), v_{n,} z]\} \varepsilon(\psi, v_\tau) \qquad (5)$$

where δ is the Dirac delta-function, and $\varepsilon(\psi, v_\tau)$ is the condition of particle passing through the cutting diaphragm. Since r_i is cubic dependent on r_p' in (4), the delta-function in the caustic area divided the integration region in three simply connected fragments. The boundary of the caustic area is determined by the relation

$$r_c = -2a_s \gamma_m^3 \left(\frac{Gz + a_{ch}}{3a_s \gamma_m^2} \right)^{3/2} \qquad (6)$$

where φ_m- is the angular aperture of the beam.
Below you can see the computed target-plane current distribution (Fig. 1) as function of the target position in the ion system.

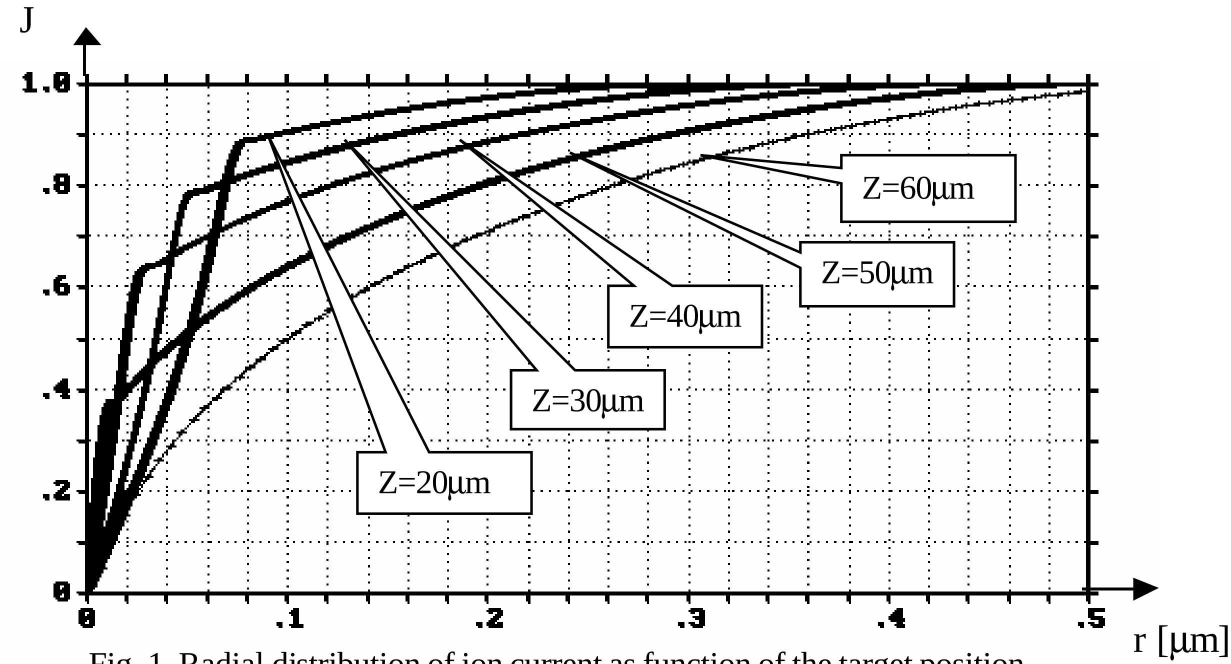

Fig. 1. Radial distribution of ion current as function of the target position

We see that the method that helps compute current distribution across the target of probing systems has been developed. The method does not allow for diffraction effect and is not applicable when the coherence length across the beam is smaller than the caustic extent.

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