Field electron emission in an external magnetic field parallel to the surface

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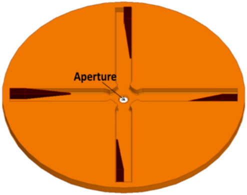
MeVArc Workshop 2019, Padova, 15–19 September 2019
Orto Botanico di Padova

The emission current "switching-off" by means of $\vec{B} \perp \vec{E}$ is a possible way of preventing breakdowns.



Parameters for the Main Linac RF structures
[The CLIC Project Implementation Plan, Geneva, 2018]

	3 *TeV* stage
Number of structures	143,232
Active structure length [mm]	230
Aperture diameter [mm]	6.3-4.7
Accelerating voltage loaded [MV]	100

- The distance which an electron can cover during the elementary act of the acceleration is $\sim$**6 cm**$\gg$ **Aperture** $\rightarrow$ the electric field is constant during the electron motion in the aperture.
- The electron Lorentz factor is $\sim 1 \rightarrow$ it is possible neglects the electron's spin.

- Using the Klein–Gordon equation instead of the Schrődinger equation for wave functions of an electron motion at relativistic speed.
- The Klein–Gordon equation allows consideration of the external uniform magnetic field parallel to the metal surface in the case $cB < E$.

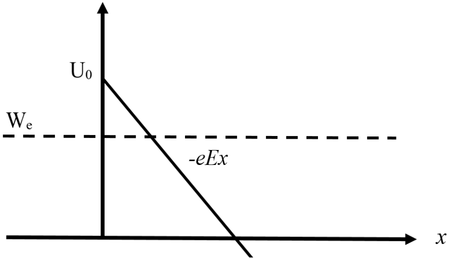


Fig. 1. The potential barrier in presence of an electric field.

$$\left[\frac{\partial^2}{\partial x^2} + \frac{x^2}{4} - 1\right]\psi(x) = 0, \qquad (1)$$

where x is a dimensionless coordinate, $D_\nu(x)$ is a parabolic cylinder function.

This equation is a parabolic cylinder equation. The solution is

$$\psi(x) = D_{-\frac{1}{2}-i}\left(xe^{-\frac{\pi i}{4}}\right).$$

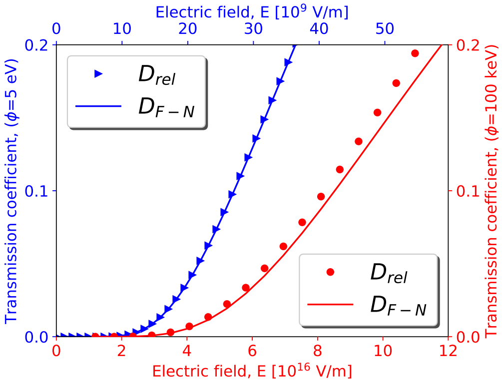


Fig. 2. Fowler-Nordheim D_{F-N} and relativistic generalized D_{rel} transmission coefficients for different work function values. A typical values for laboratory conditions $E \cong 10^9 \frac{V}{m}$, $\phi \cong 5eV$ are in blue color and for the field emission from neutron stars surface $E \cong 10^{16} \frac{V}{m}$, $\phi \cong 100keV$ are in red color.

$$D_{rel} = D_{F-N}\left(1 + \frac{\sqrt{2}}{5}\frac{(U_0 - W_e)^{\frac{5}{2}}}{\sqrt{mc^2}\,eE\hbar} + \frac{\sqrt{2}}{48}\frac{(7U_0 - 12W_e)\,eE\hbar}{U_0\sqrt{m}(U_0 - W_e)^{3/2}} + \frac{37U_0 - 79W_e + 12\frac{W_e^2}{U_0}}{120mc^2} + \frac{\left(49U_0^2 - 216U_0W_e + 192W_e^2\right)e^2E^2\hbar^2}{1536U_0^2m(U_0 - W_e)^3}\right) \quad (2)$$

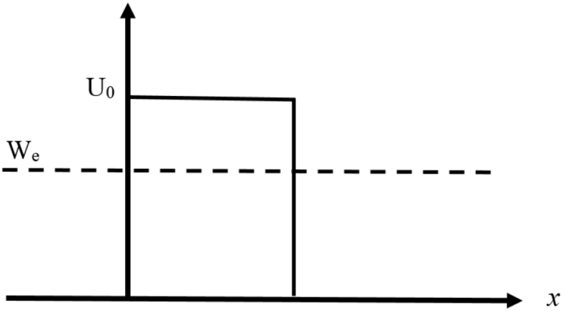


Fig. 3 The potential barrier in absence of an electric field.

The potential barrier width in relativistic case can be written as

$$h_{rel} = h\sqrt{1 - V^2/c^2}, \tag{3}$$

where h is the potential barrier width in non-relativistic case and

$$V^2 = \frac{U_0 - W_e}{2m}$$

.

The transmission coefficient in presence of a magnetic field D_B in the first nonvanishing approximation can be written as

$$D_B = e^{-\frac{4\sqrt{2}\left(E^2 - 2\left(\frac{U_0 - W_e}{mc^2}\right)c^2B^2\right)\sqrt{m}(U_0 - W_e)^{\frac{3}{2}}}{3E^3 eh}} \frac{4\sqrt{U_0 - W_e}\left(E^2 - B^2c^2\right)^{\frac{3}{4}} E^{\frac{3}{2}}\sqrt{W_e}}{W_e E^3 + \left(E^2 - B^2c^2\right)^{\frac{3}{2}}(U_0 - W_e)} \qquad (4)$$

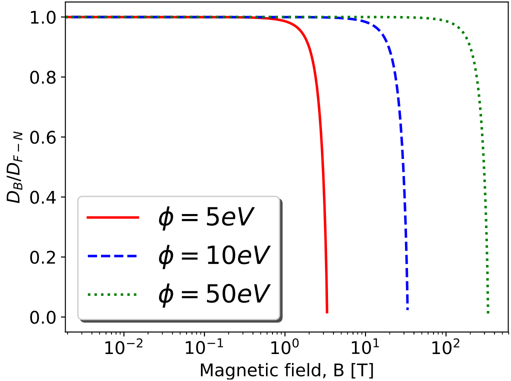


Fig. 4. Dependence of the transmission coefficient upon magnetic field for the different work function values ϕ.

Conclusions

- The Fowler-Nordheim equation for field emission current density has been generalized to the relativistic case.
- The effect of Lorentz contraction of a potential barrier at the metal-vacuum interface was found. This effect results in increasing of the transmission coefficient by 0.015% for field emission in laboratory conditions and by 15% for emission from neutron stars surface.
- An expression for the transmission coefficient was found when the condition $cB < E$ is satisfied. The transmission coefficient decreases by 0.1%, 5% and 50% when cB is equal to 0.1 E, 0.5 E and 0.9 E respectively.
- The magnetic induction is needed for "switching-off" an emission current during the elementary act of the acceleration is $B \geq 0.5\ T$.

The list of publications

- S. O. Lebedynskyi, V. I. Miroshnichenko, R. I. Kholodov, V. A. Baturin, "The effect of a magnetic field on the motion of electrons for the field emission process description", Problems of Atomic Science and Technology, vol. 98, pp. 62-66, 2015.
- S. Lebedynskyi, O. Karpenko, R. Kholodov, V. Baturin, I. Profatilova, N. Shipman, W. Wuensch, "DC vacuum breakdown in an external magnetic field", Nuclear Instruments and Methods in Physics Research Section A, vol. 908, pp. 318-324, 2018.
- S. O. Lebedynskyi, O. O. Pasko, R. I. Kholodov, "Relativistic correction of the field emission current in the Fowler-Nordheim formalism", Journal of nano- and electronic physics, vol. 2, pp. 02022-1–02022-6, 2019.
- S. Lebedynskyi, R. Kholodov, "Field emission with relativistic effects in a magnetic field", Eur. Phys. J. D vol. 73 pp. 190-1–190-5, 2019.

Thank you for attention!