DEPENDENCE OF VACUUM ARC INITIATION DYNAMICS ON THE APPLICATION OF A STATIC MAGNETIC FIELD

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INTRODUCTION

Vacuum arcing presents technical challenges in applications where high electric fields are used, such as electron sources, particle accelerators and vacuum interrupters. New accelerator technologies such as the proposed **muon collider** can give rise to different arcing behavior compared to what has been observed previously.

The presence of a **magnetic field** can cause **focusing** of electron beams, which can lead to **heating** (figure 1). The ratio of the beam radius r and beam radius without magnetic field r_0 can be obtained from theory:

$$\frac{r}{r_0} = \rho \left|\sin\left(\rho^{-1}\right)\right|, \quad \rho = \frac{a}{B}\sqrt{\frac{E}{y}}, \qquad (1)$$

where $a = 3.39 \times 10^{-3}$ V T^{-1} nm^{-1}, E is electric field, B is magnetic field and y is position. By assuming the emitter shape, we can get an estimate for the beam radius $r_0 = \sqrt{4\eta h y}$, where h is the height of the emitter and η is the spreading factor. In figures 2a and 2b, we show the predicted beam radius and anode heat flux.

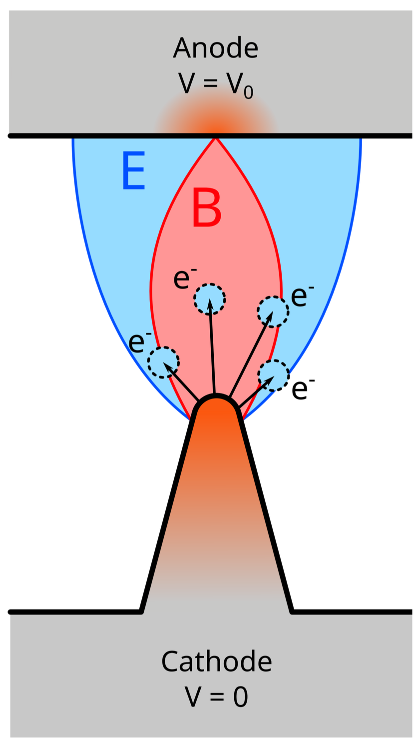
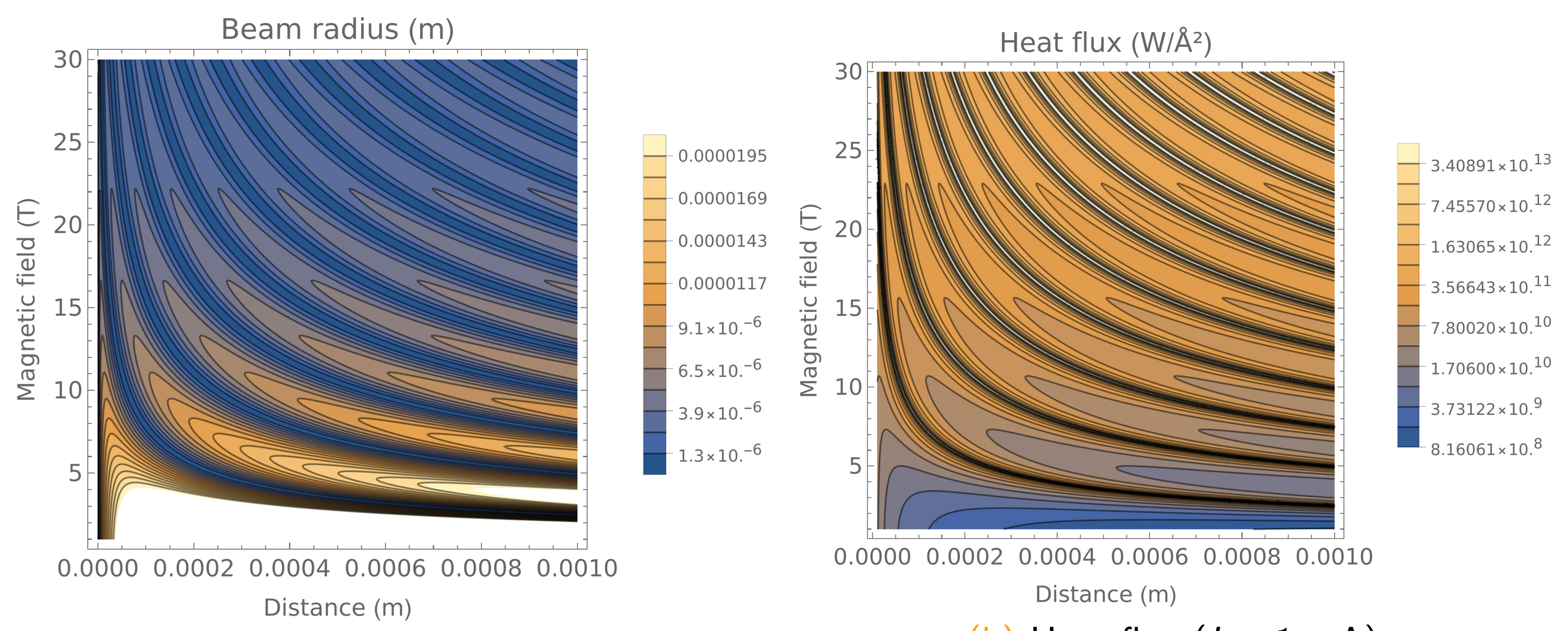


Figure 1: Beam with vs. without B.



(a) Beam radius. (b) Heat flux ($I = 1$ mA).

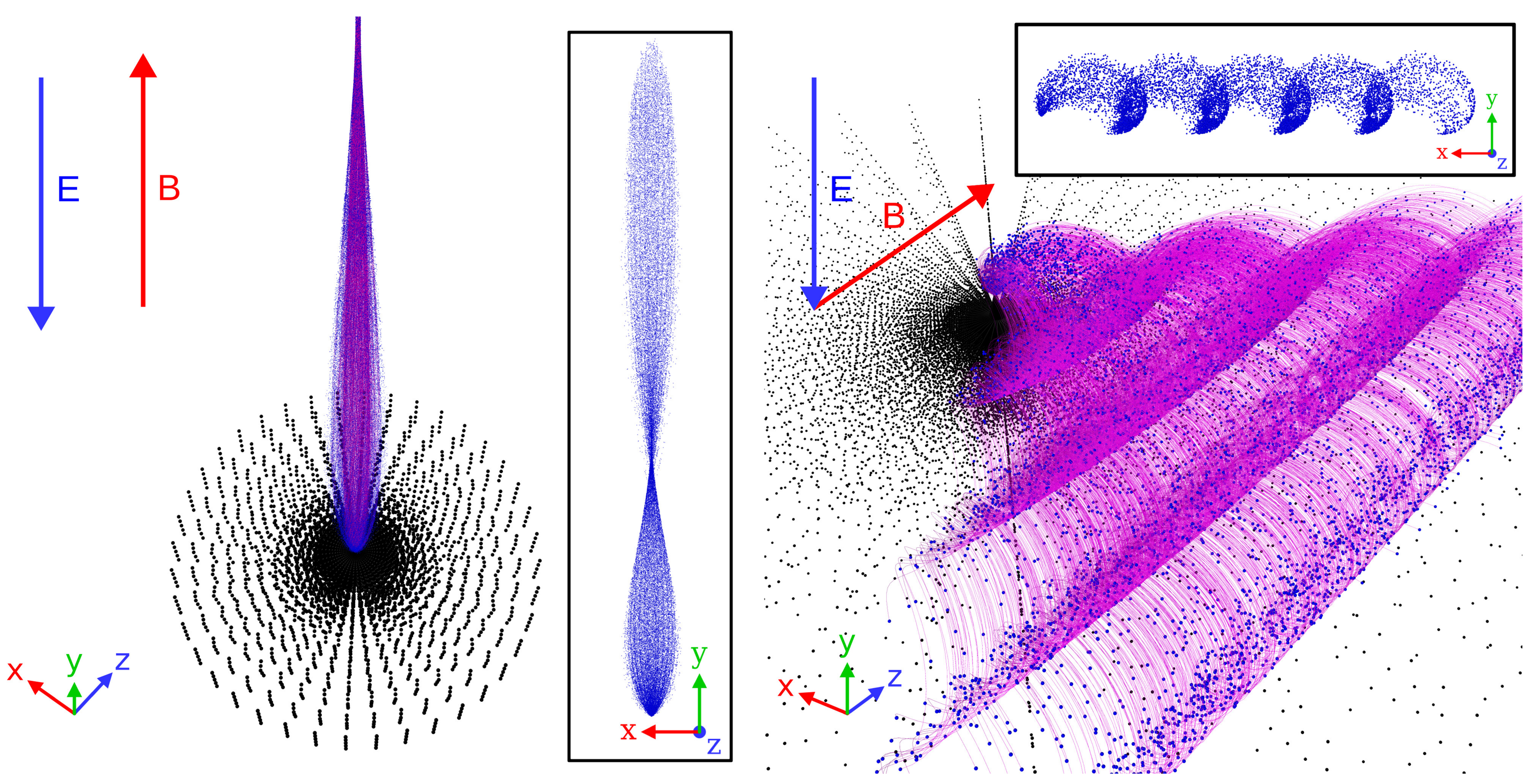
Figure 2: Theory predictions as a function of distance y and magnetic field B.

METHODS

We use the *particle-in-cell* method to calculate trajectories of emitted electrons while including electron-electron interactions. The electrons experience acceleration due to the *Lorentz force* $F = q_e(E + v \times B)$. We use the FEMOCS code to perform these simulations in 3D. The applied voltage between the Cu cathode and anode is $V_0 = 16$ kV, with a gap distance of 300 μm. The macroscopic field is 53 MV/m, while the local field is 9 GV/m.

Current density at the anode is used to calculate heating, performed using COMSOL. In this model, we calculate a heat rate in the anode as $P = V_0 j / z_d$, where j is current density, V_0 is the applied voltage and z_d is the electron CSDA depth in Cu. The top of the anode is assumed to be at a temperature of $T_0 = 300$ K.

RESULTS

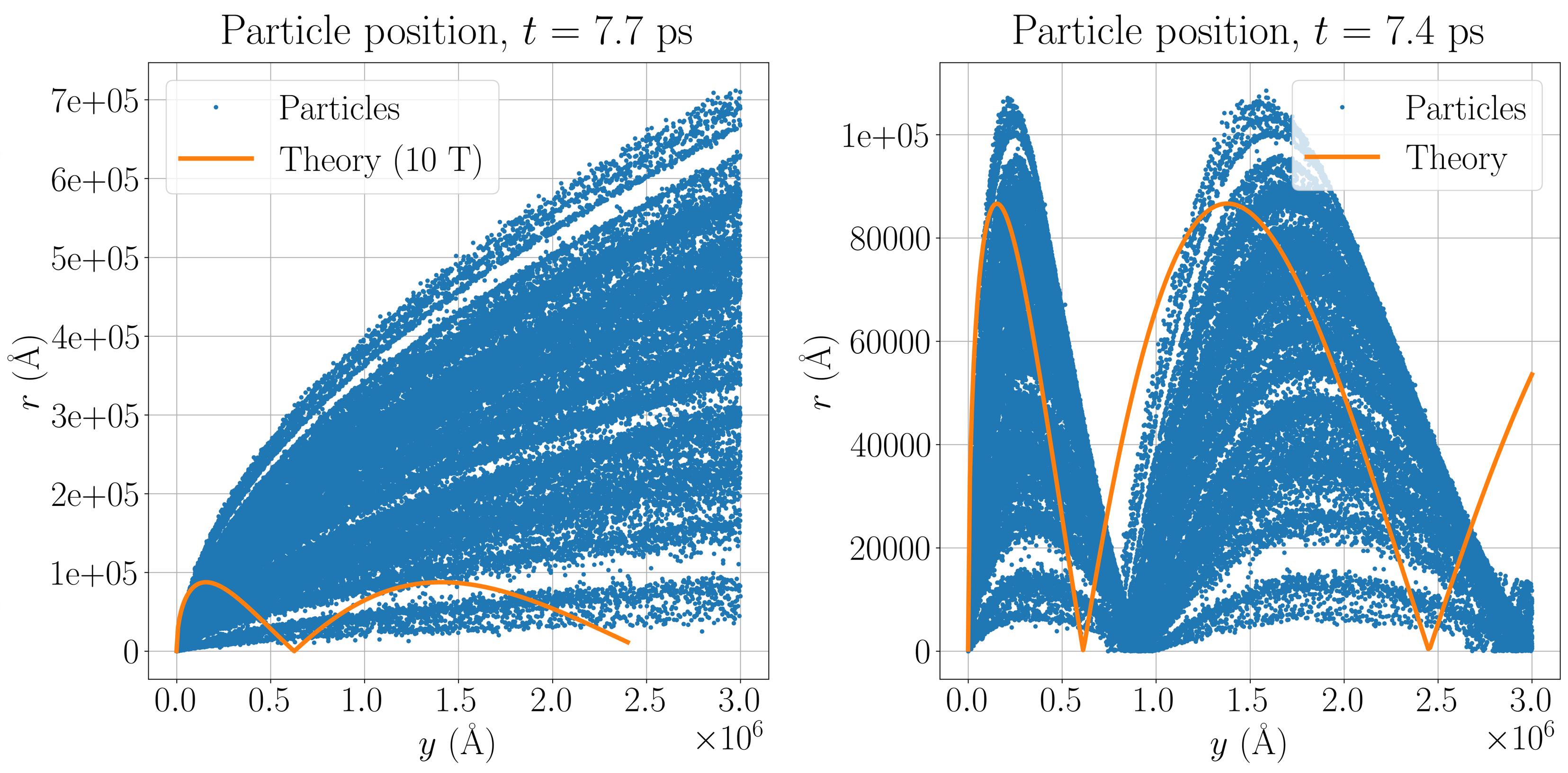


(a) $B_y = 10$ T. (b) $B_z = 30$ T.

Figure 3: Electron paths in magnetic field.

We simulated two cases:

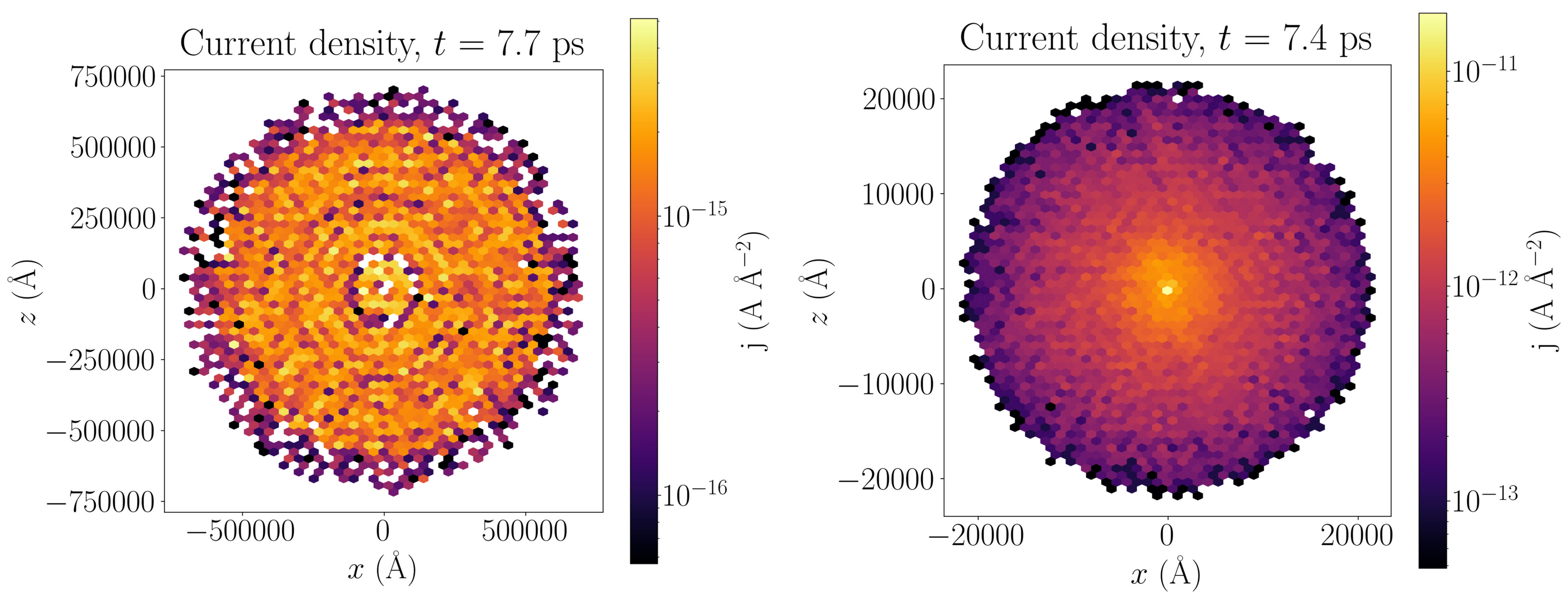
1. Magnetic field **parallel** with electric field $B \parallel E$ (figure 3a)
2. Magnetic field **perpendicular** to electric field $B \perp E$ (figure 3b)



(a) $B_y = 0$ T. (b) $B_y = 10$ T.

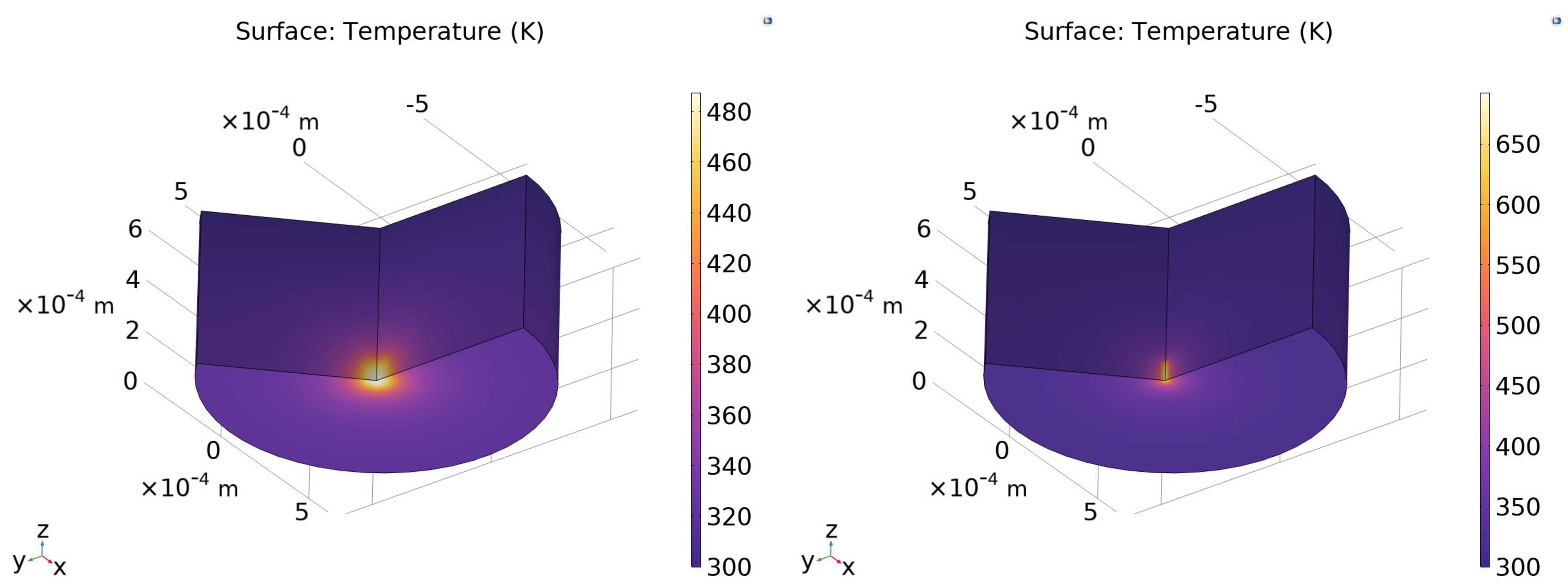
Figure 4: Electron beam shape.

The electron beam shape is plotted with the theoretical prediction at $B_y = 10$ T (equation 1) in figures 4a–4b.



(a) $B_y = 0$ T. (b) $B_y = 10$ T.

Figure 5: Current density on anode surface.



(a) $B_y = 0$ T. (b) $B_y = 10$ T.

Figure 6: Anode temperature.

Based on the simulated current density (figures 5a–5b), we calculate the steady-state temperature distribution in the anode. This is done for the 0 T (figure 6a) and 10 T (figure 6b) cases.

We run additional simulations with varying anode spot size assuming a current of 1 mA. In figure 7, we can see that the average temperature at the anode spot reaches over 1000 K for a spot size of 10 μm.

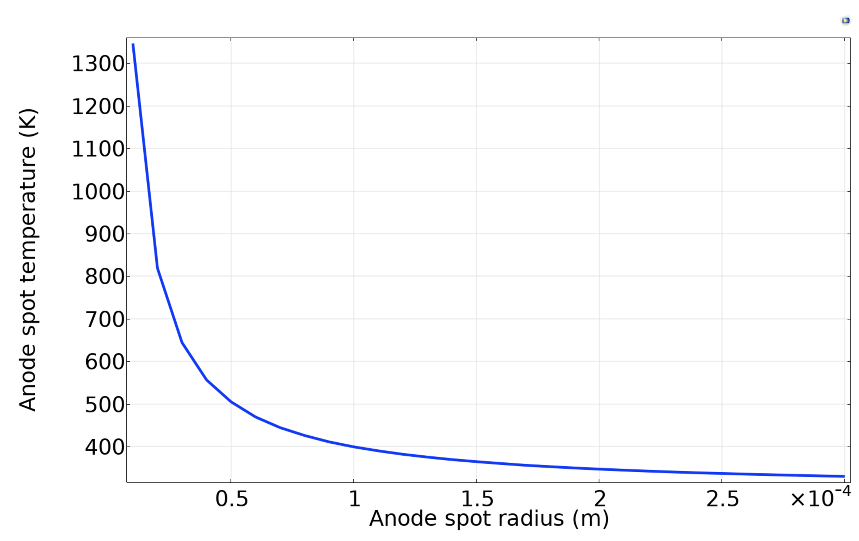


Figure 7: Dependence of anode temperature on heat spot radius, $I = 1$ mA.

CONCLUSIONS

The presence of **magnetic fields** (10 T–30 T) can significantly **focus** emitted electron beams and lead to **heating**. The temperature at the anode can reach as high as 1000 K or more, depending on the **current density** and **voltage**. This opens the possibility for anode-initiated vacuum arcs, as plasma could start forming on the anode side.

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