Dependence of vacuum arc initiation dynamics on the application of a static magnetic field

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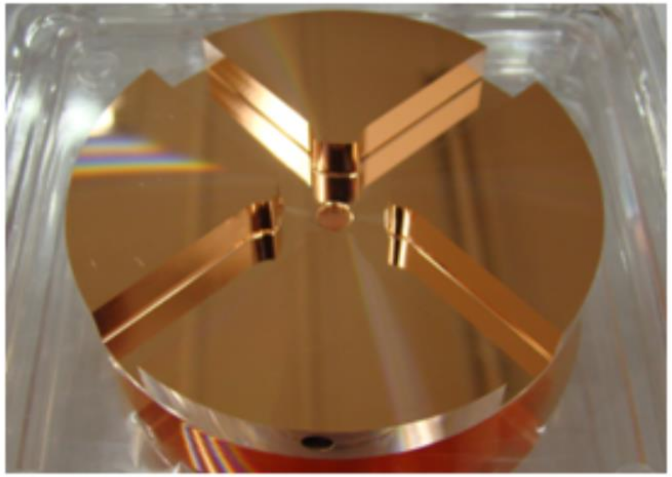
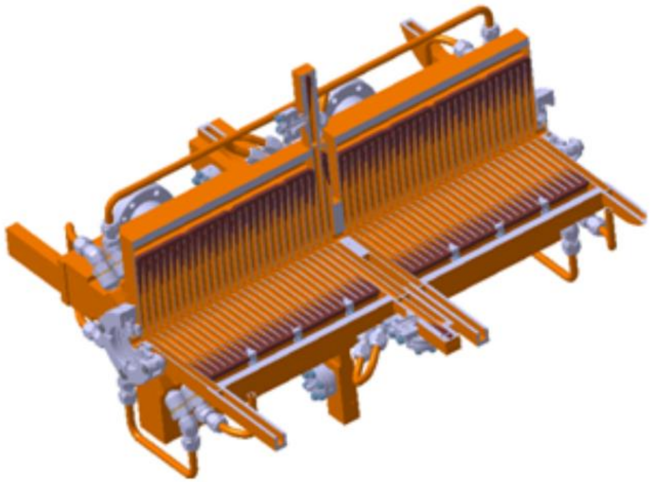
Vacuum arcing

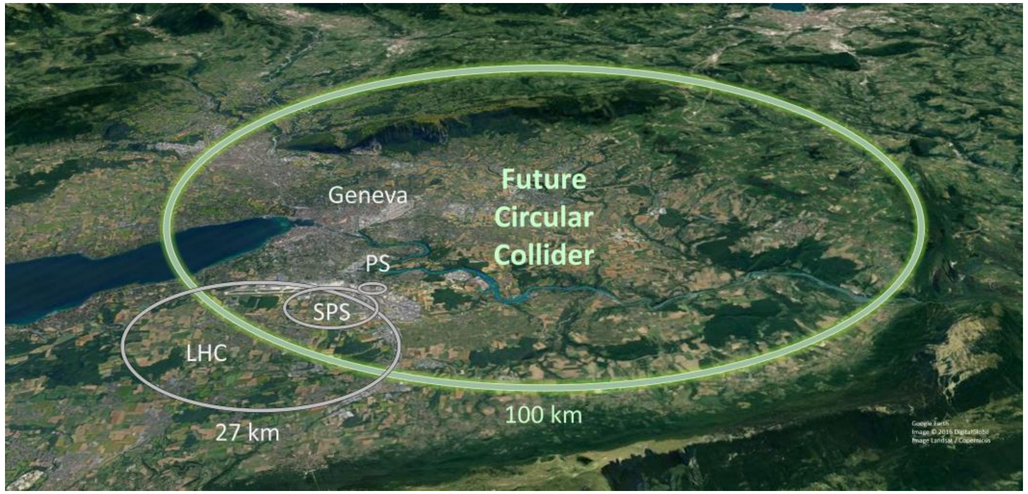
- Vacuum arcing i.e. vacuum breakdown (VBD): electrical arcing in a vacuum
- In lighting, air ionizes to form a conducting pathway, but what happens in a vacuum?
- Problem in high electric field gradient devices: X-ray sources, vacuum switches, particle accelerators, ...





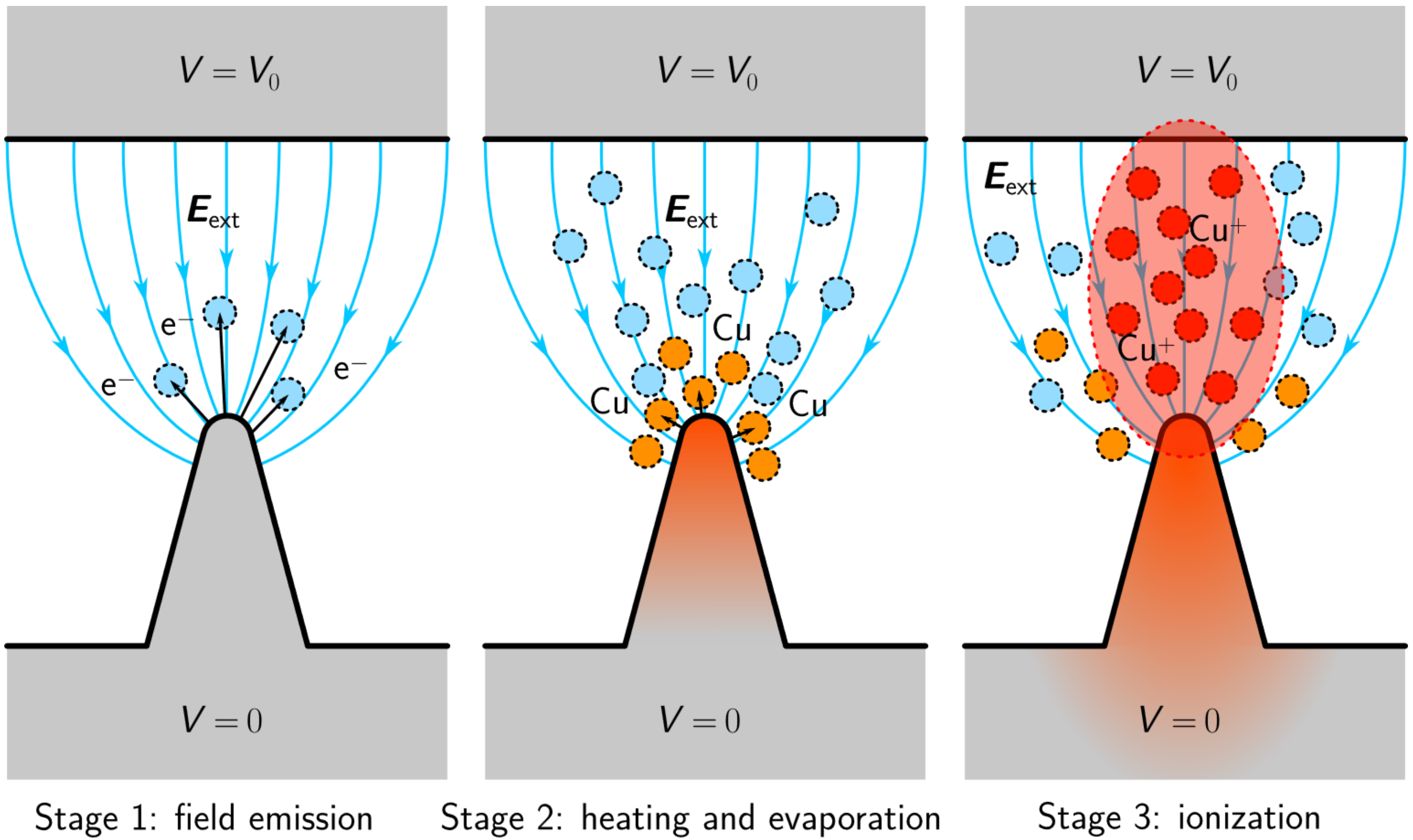
Vacuum arcing in accelerators

- Vacuum arcing one limiting factor for accelerator projects
- New physics requires higher energies → more problems with arcing
- Future accelerators discussed after Large Hadron Collider (LHC), e^+e^- 200 GeV, 27 km
  - Future Circular Collider (FCC), 350 GeV, 100 km
  - Compact linear collider (CLIC), 3 TeV, 50 km
  - **Muon collider, 10 TeV, 27 km**



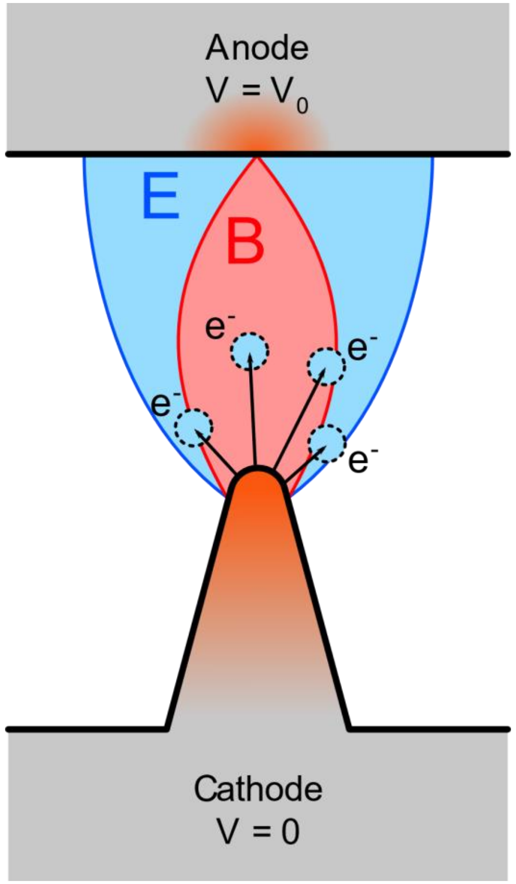
International MUON Collider Collaboration

Cathodic vacuum arc initiation



Anodic vacuum arcing in magnetic field

- Muon collider uses extremely large magnetic fields B ~ 30 T
- Presence of a magnetic field can potentially change the nature of vacuum arcing (cathodic vs. anodic)
- Magnetic field focuses electron beam → anode heating → arc initiation?



Beam radius

- Theoretical beam radius in magnetic field:

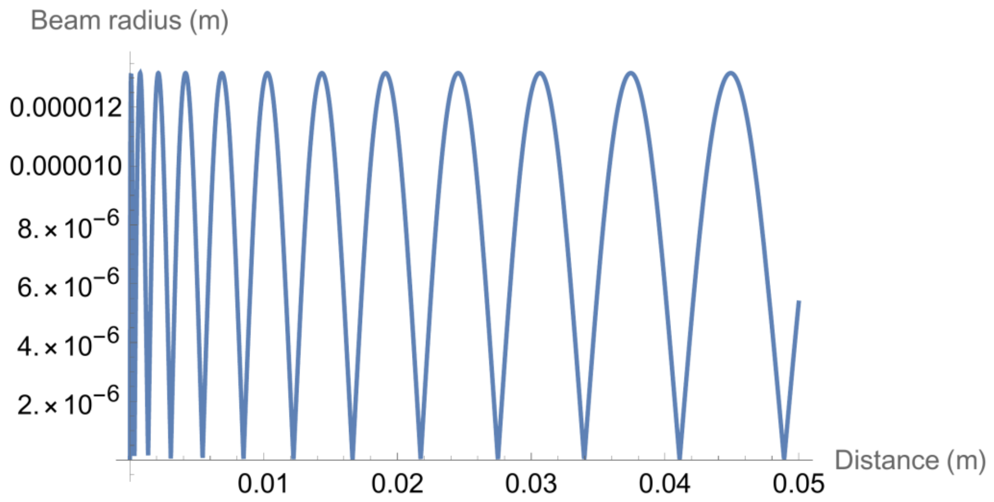
$$\frac{r}{r_0} = \rho|\sin(\rho^{-1})|, \qquad \rho = \frac{a}{B}\sqrt{\frac{E}{y}},$$

where r is beam radius, y is distance, E is electric field and B is magnetic field.

- In magnetic field, beam amplitude is constant
- Without magnetic field the beam opens as the square root:

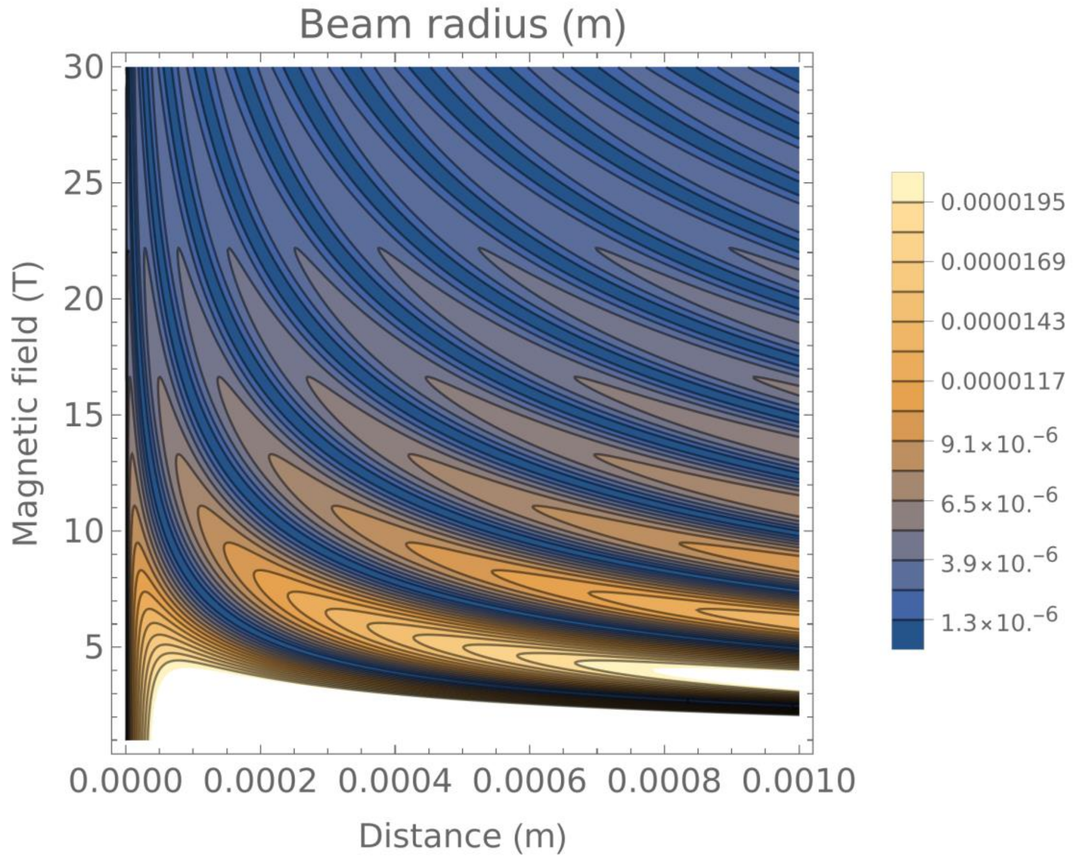
$$r_0 = \sqrt{4\eta h y},$$

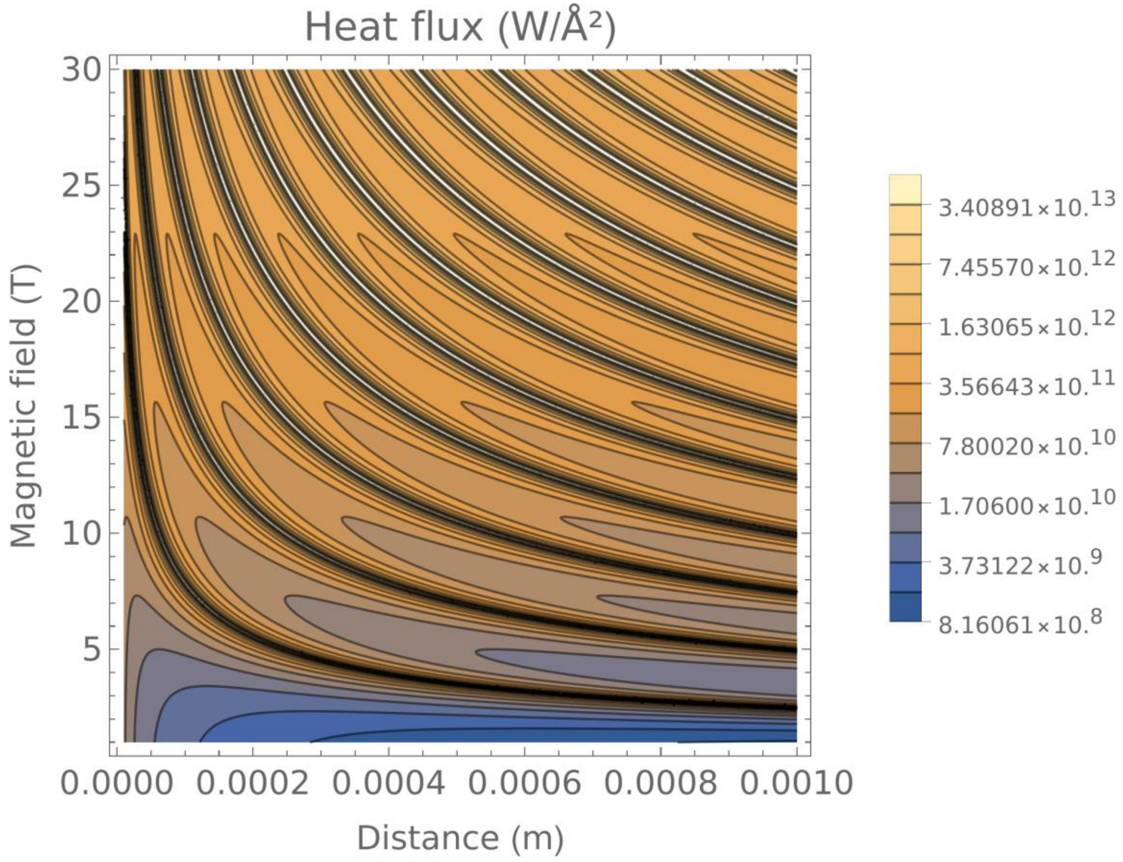
where η is the spreading factor and h is tip height.



Anode heating

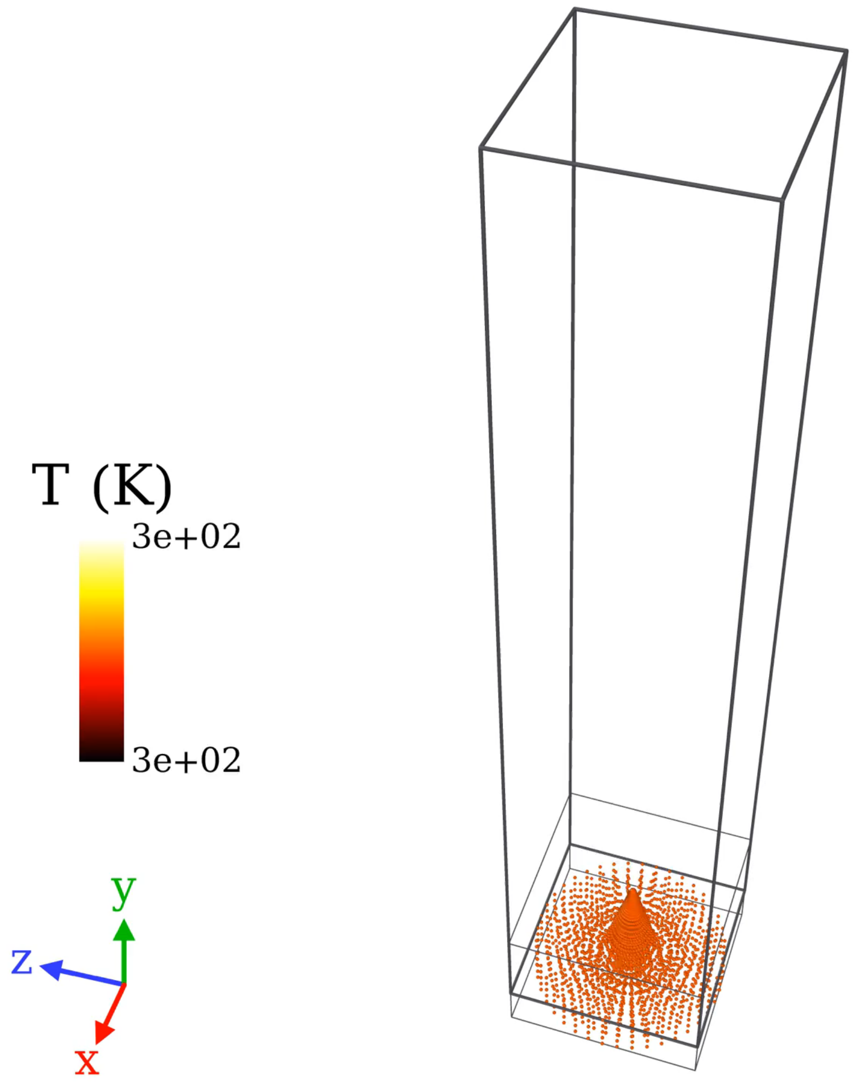
- Heat flux at anode: $P = \frac{VI}{\pi r^2} = Ejd$, where j is current density and d is gap size.



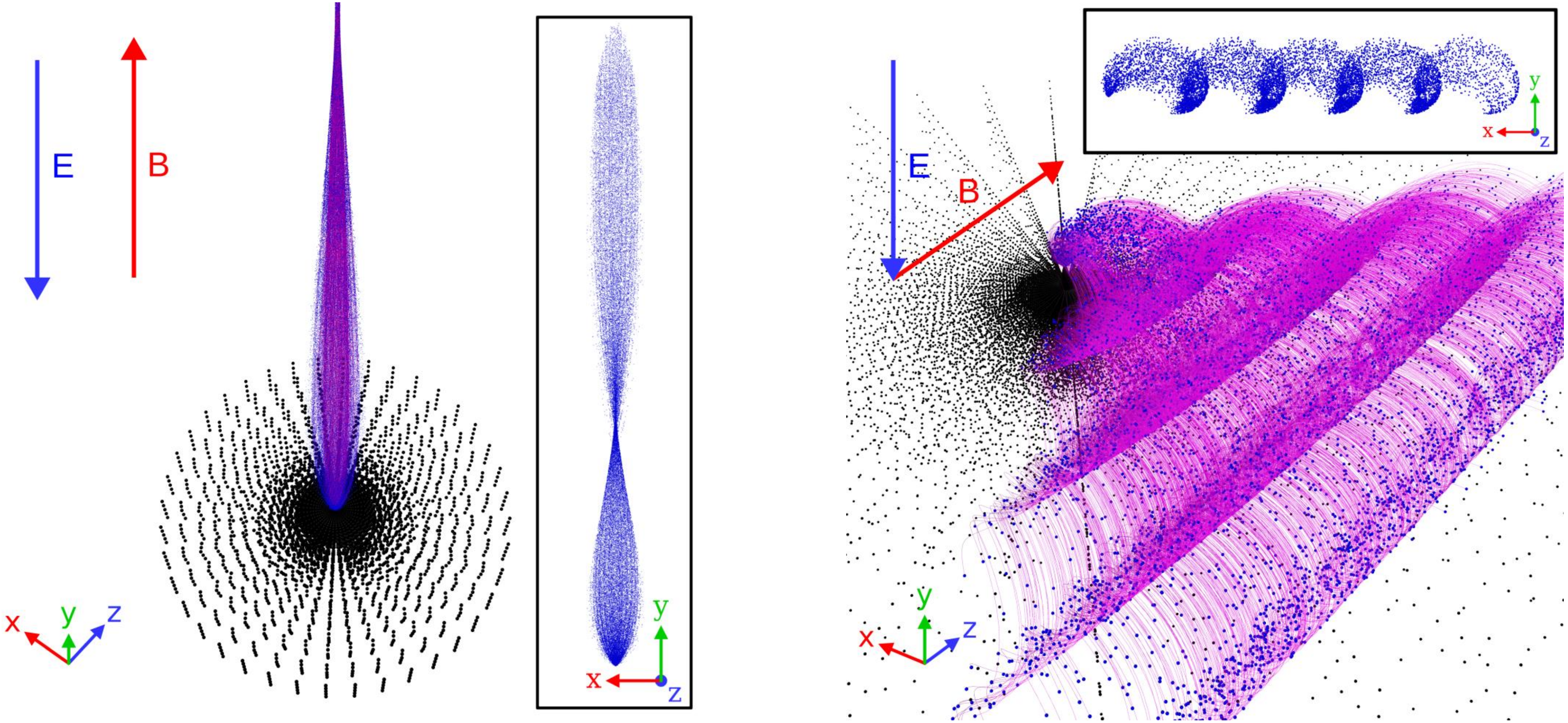


Simulations of emitted beam

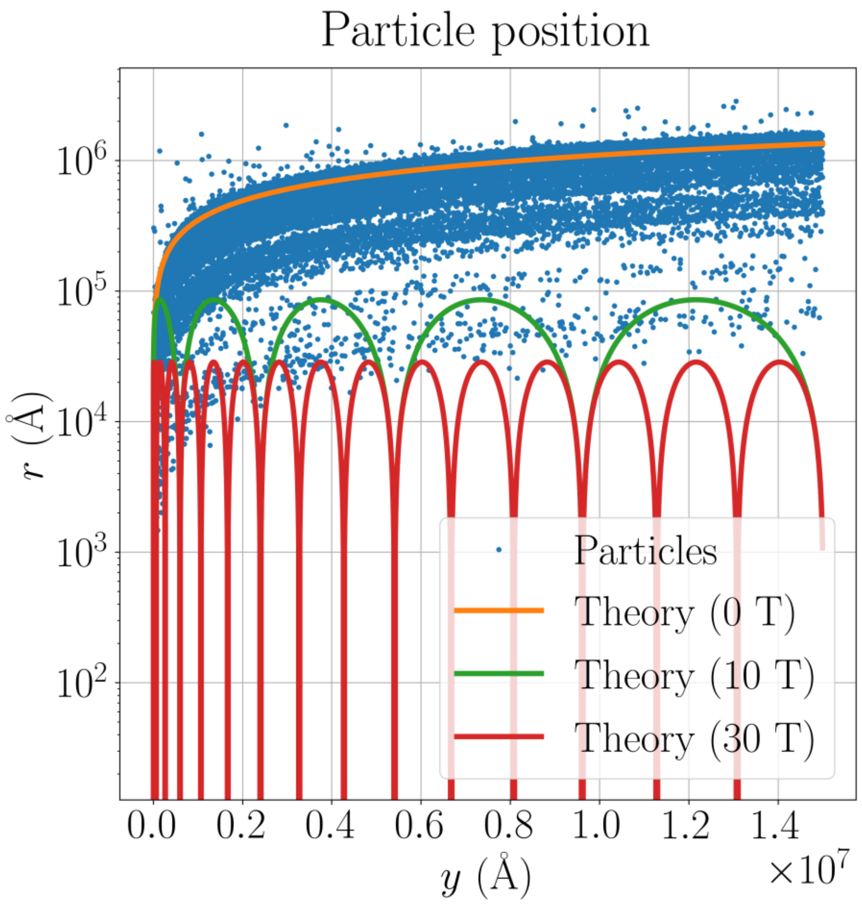
- Simulation of electron beam can give insight into beam dynamics
  - FEMOCS: particle-in-cell, finite element method
  - GETELEC: electron emission
- Apply static magnetic field, calculate Lorentz force $F = q_e E + q_e v \times B$ for particles
- Coulomb collisions between electrons



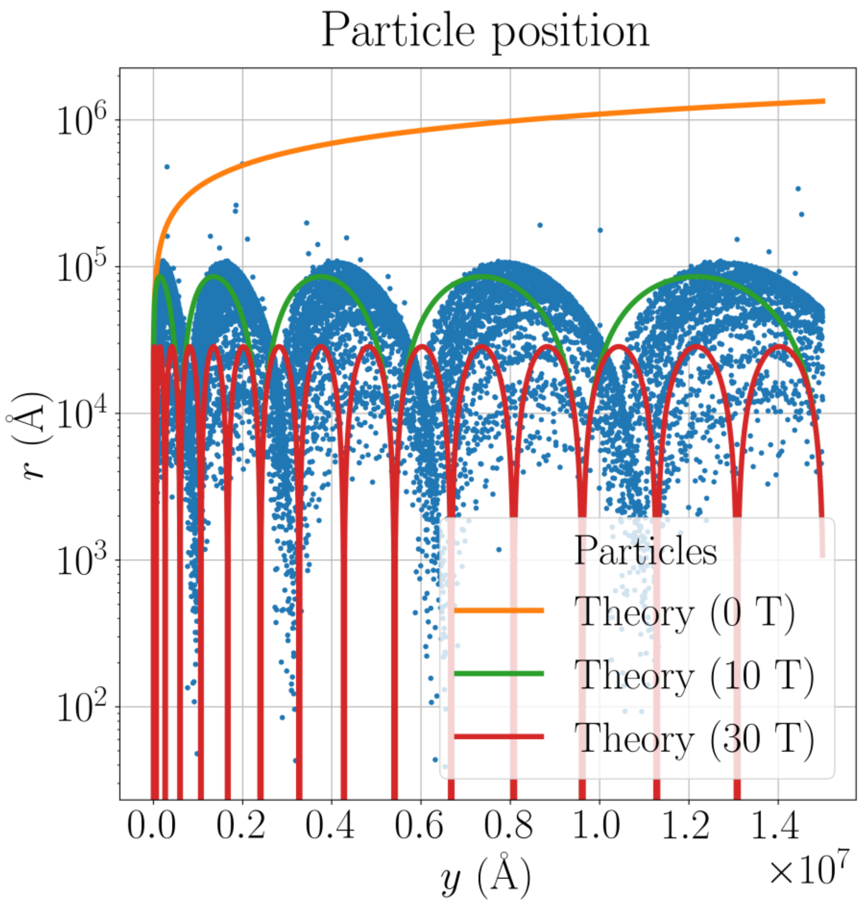
Simulation: Magnetic field direction



Simulation: Beam focusing

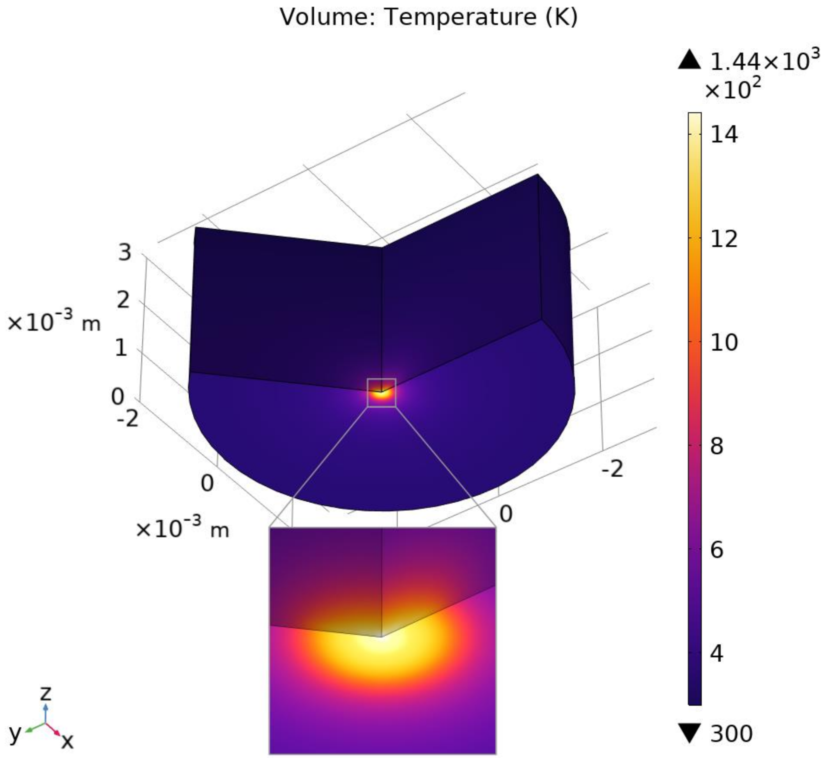


$B_y = 0$ T

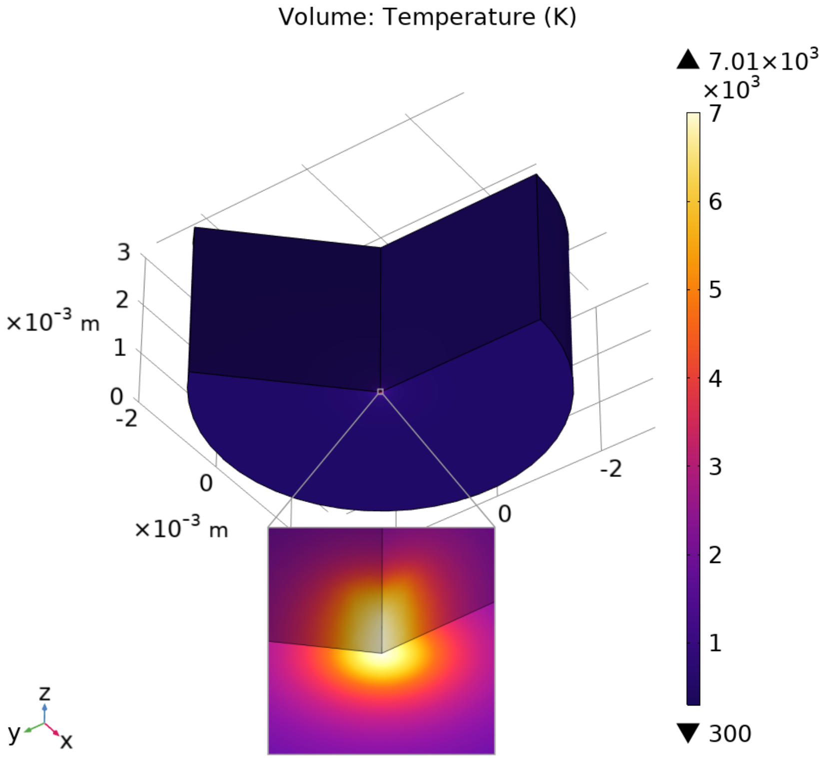


$B_y = 10$ T

Simulation: Anode heating



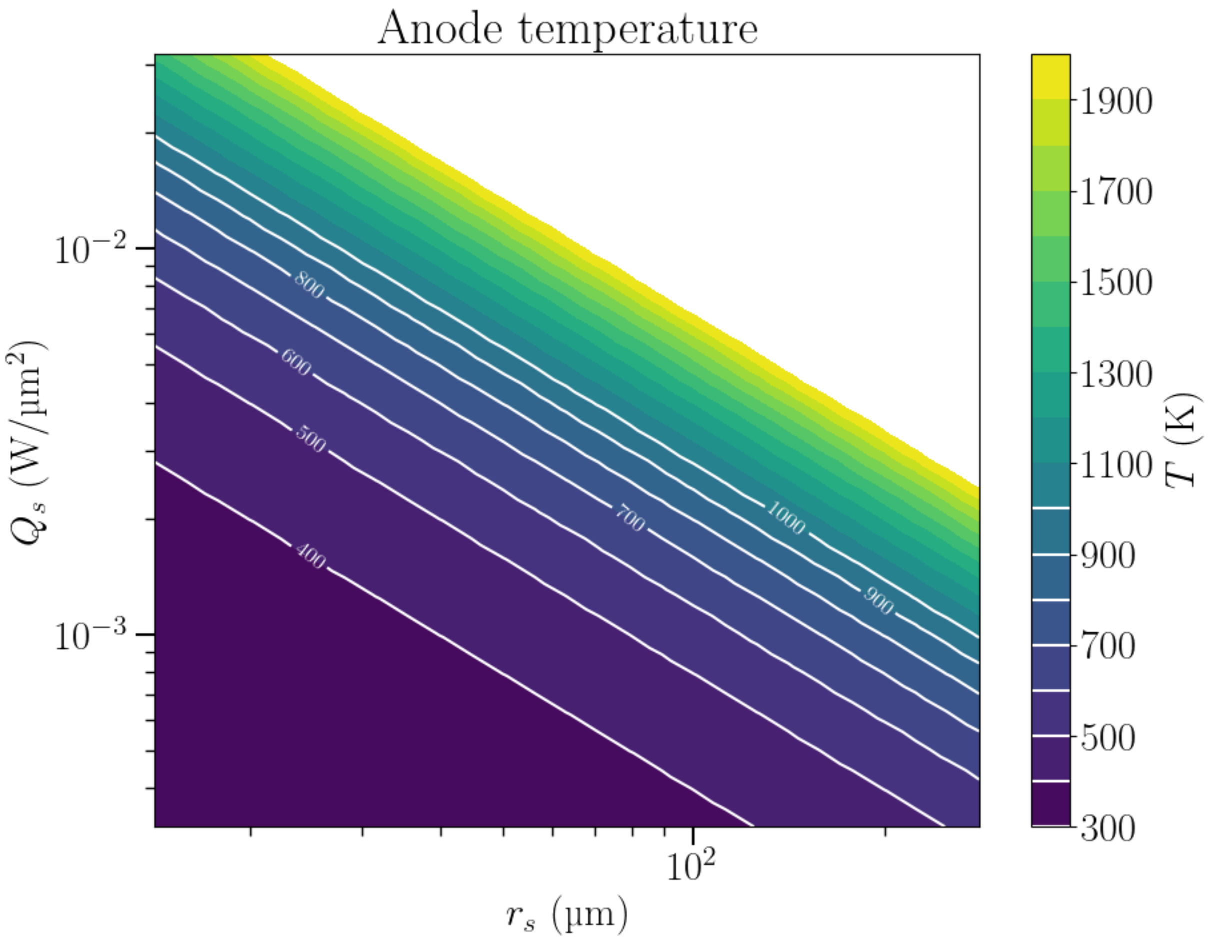
$B_y = 0$ T



$B_y = 10$ T

Simulation: Anode heating

- Simulate anode heating due to electron beam using COMSOL
  - Heat rate at anode: $P = Vj/z_d$, where z_d is the electron CSDA depth in Cu (from ESTAR database).
- Anode temperature highly dependent on spot size
  - For a spot size of 10 µm, anode temperature can reach over 1000 K



Conclusions

- Presence of a magnetic field can focus emitted electron beams and cause anodic heating, potentially leading to vacuum arcing
  - At large distances, heat flux at a given field will be much higher when magnetic field is present
- High temperatures can be observed at fields on the order of 10 T
- Future work: coupled simulations, plasma formation in magnetic field?

Thank you!