Northern Illinois University

Transverse Density Pileup in Dense Ultracold Electron Beamlets Under Coulomb Expansion

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24 May 2021

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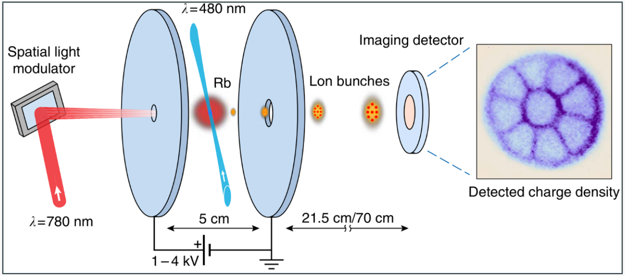
Introduction

An Unexpected Pattern

Dynamics of Ultracold Ion Beamlets [Murphy (2014)]

Rather than smoothly overlapping, the evolving beamlets formed a pattern which retains a distinct impression from each beamlet

- Structured nonuniformities in density and energy present limitations for beam applications
  - Loss of resolution in imaging techniques
  - Decoherence of the radiation in a FEL

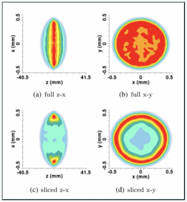


Murphy et al., Nat. Commun. 5, 4489 (2014)

Challenges and Applications

A related phenomenon was modeled for a pancake electron bunch [Zerbe (2018)]

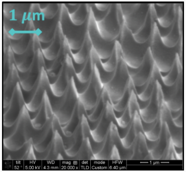
- The bunch density hollowed out in the transverse dimensions
- Not yet observed experimentally for electrons
  - Evolution dynamics occur on the scale of the plasma frequency



Zerbe et al., Phys. Rev. Accel. Beams 21, 064201 (2018)

A relevant application is the nanotip array cold electron cathodes

- Beams from each nanotip will interact to form a single beam
  - Similar density pileup and structures may form for these cathodes



Silicon Nanotip Array Fabricated at NIU

Simulation Methods

Creating the Initial Beamlet Distibutions

Structure the Array Similar to [Murphy (2014)]

Generate an array of 8 beamlets surrounding a central beamlet

- Outer Beamlet Ring Radius: 0.5 mm

Beamlet Parameters

- Radius: 0.1 mm
- Length: 5 μm
- Charge: 1.6 fC
- Transverse Profile: Gaussian
- Longitudinal Profile: Uniform

Halo Parameters

- Radius: 1 mm
- Length: 5 μm
- Charge: 3.2 fC
- Transverse Profile: Uniform
- Longitudinal Profile: Uniform

The particle velocity is sampled from the Maxwell-Boltzmann distribution for a given temperature T

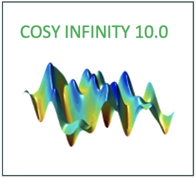
$$f(\mathbf{v}) = \left(\frac{m}{2\pi k_B T}\right)^{3/2} \exp\left(-\frac{m||\mathbf{v}||^2}{2k_B T}\right),$$

Accurate Simulation Of Electron Dynamics

Collisional *N*-body Code PHAD (particles' high-order adaptive dynamics)

Divide domain equations into *near* and *far* regions

- Compute far forces via the FMM (fast multipole method)
- Capture near interactions with the collisional Simó integrator
- All scripts written for COSY Infinity
  - A general purpose nonlinear-dynamics scripting language



M. Berz and K. Makino, MSU (2017).

Performing Simulations

Simulations performed on the Gaea Cluster at NIU

- A hybrid CPU/GPU cluster
- 60 Infiniband connected nodes
  - Two Intel Xeon X5650 2.66 GHz 6-core processors
  - Total of 72 GB of RAM

Center for Research and Computing and Data

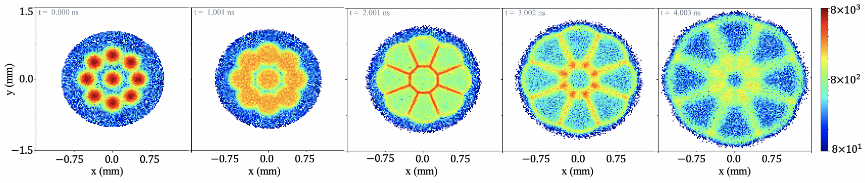
Temperature and Density Dependencies

Initial Evaluation Of Electron Beamlets

Observation of Pattern Formation for Electrons

Set the initial beamlet and halo temperatures to 1 K and 10 K

- High density spokes form at 2 ns, but outer wheel is less dense
  - At 4 ns, the full wheel-and-spokes pattern is seen
  - Interaction between beamlets pushes density higher than the interaction with the halo alone

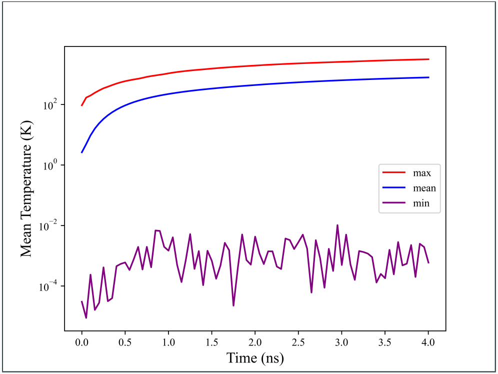


Electron charge density ($\mu C/m^3$) at time $t = 0$ ns, 1 ns, 2 ns, 3 ns, and 4 ns from left to right

Evolution of the Electron Temperature

Coulomb explosion leads to a rapid increase in max transverse temperature

- Mean temperature shows same trend but order of magnitude lower
- After a short increase, the minimum temperature remains consistent
  - Cold temperature is preserved for a subset of particles

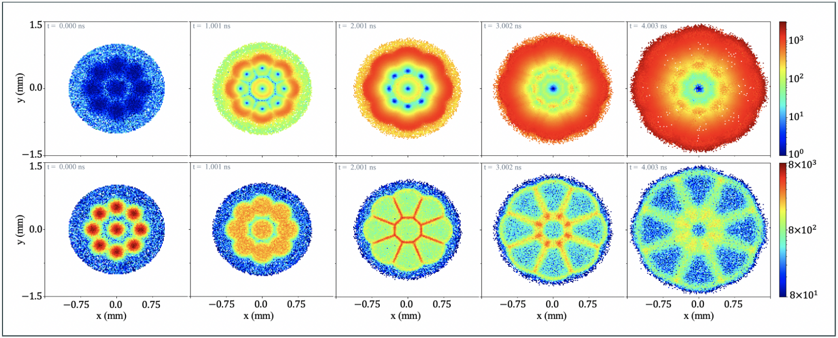


Initial Evaluation Of Electron Beamlets

Evolution of the Electron Temperature

Initial temperature explosion is concentrated to the exterior of the ring

- Beamlet interactions have a transverse cooling effect
  - They are buffered by halo electrons
- Core of the final beam remains relatively cool



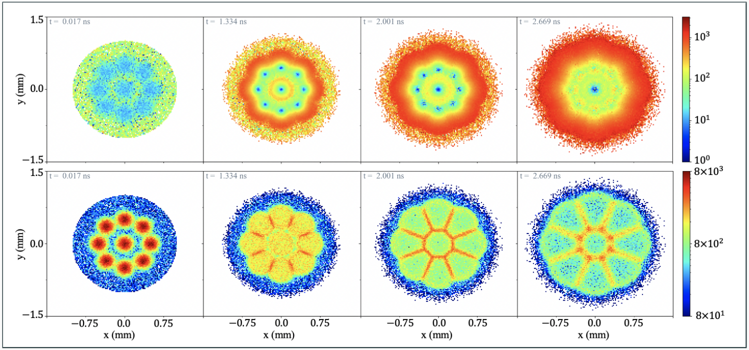
Electron temperature (K) above and charge density ($\mu C/m^3$) below at time $t = 0$ ns, 1 ns, 2 ns, 3 ns, and 4 ns from left to right

Varying The Initial Temperatures

Beamlet: 10 **K**, **Halo:** 100 **K**

Increasing beamlet and halo temperatures leads to a decrease in resolution

- High density spokes form at 2 ns, but outer wheel is less dense
  - Inherent thermal noise reduces the cooling effect of neighboring beamlets and of the halo
  - Halo density decreases via diffusion



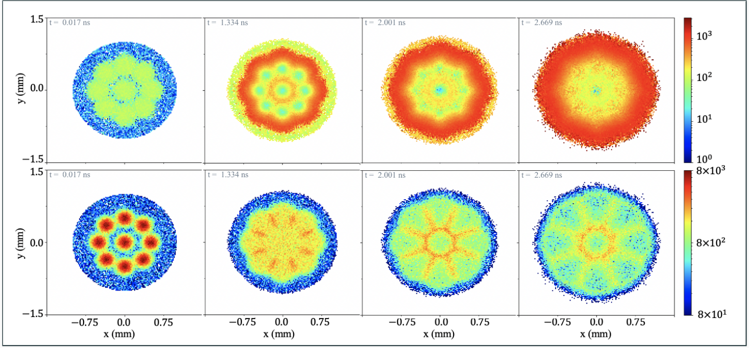
Electron temperature (K) above and charge density ($\mu C/m^3$) below at time $t = 0$ ns, 1.3 ns, 2.0 ns, 2.7 ns

Varying The Initial Temperatures

Beamlet: 100 **K**, **Halo:** 10 **K**

Heating up the beamlet temperatures nearly eliminates the patterns entirely

- Hints of high density spokes are visible at 2 ns
  - Large thermal noise impairs the symmetry cooling benefits
  - The wheel-and-spokes pattern vanishes entirely for $T > 100$ K

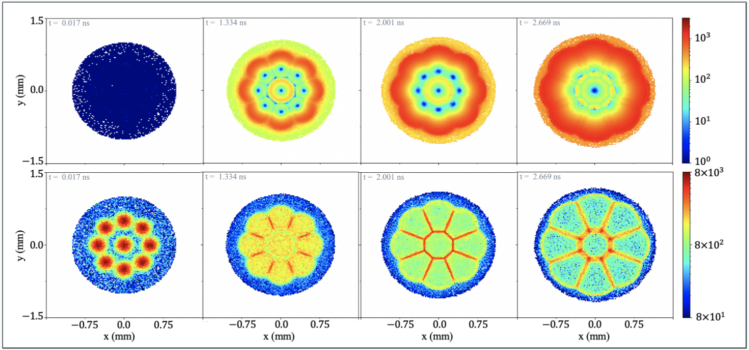


Electron temperature (K) above and charge density ($\mu C/m^3$) below at time $t = 0$ ns, 1.3 ns, 2.0 ns, 2.7 ns

Beamlet: 0.2 **mK**, **Halo:** 0.2 **mK**

Cooling the temperature leads to a long-term increase in the pattern clarity

- High density spokes form at 2 ns and outer wheel is visible by 2.7 ns
  - Temperature distribution retains much more spatial structure than for previous cases



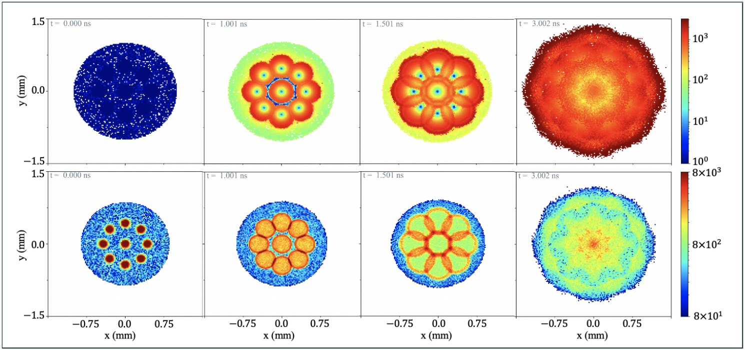
Electron temperature (K) above and charge density ($\mu C/m^3$) below at time $t = 0$ ns, 1.3 ns, 2.0 ns, 2.7 ns

Varying The Initial Densities

Beamlet Radius: 0.05 **mm (**50% **of previous case)**

Decreasing beamlet radius only leads to cross-over at the interaction points

- High density fringes cross around 2 ns
  - Coulomb explosion provides sufficient energy to overcome the beam-beam cooling
  - Final thermal profile of the beam is much warmer



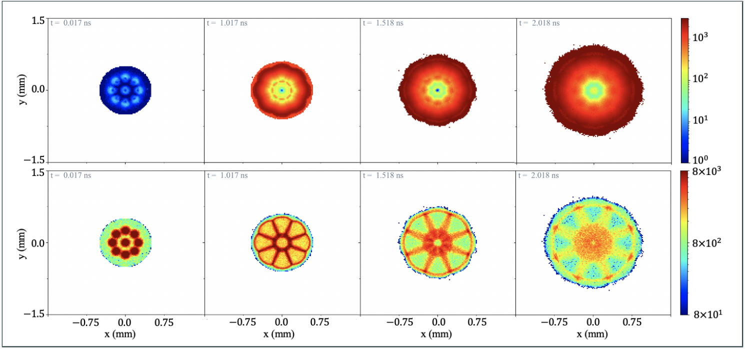
Electron temperature (K) above and charge density ($\mu C/m^3$) below at time $t = 0$ ns, 1.0 ns, 1.5 ns, 3.0 ns

Varying The Initial Densities

Beamlet Radius: 0.05 **mm, Halo Radius:** 0.5 **mm, Ring:** 0.25 **mm**

Scaling the geometric arrangement with the increase in density leads to faster pattern formation

- High density spokes and wheel are visible at 1 ns
  - Faster increase in beam temperature as well
  - Rapid heating leads to a blurring of the final pattern over time



Electron temperature (K) above and charge density ($\mu C/m^3$) below at time $t = 0$ ns, 1.0 ns, 1.5 ns, 2.0 ns

Concluding Remarks

Conclusions

Cold Electron Beamlets will Interact to Form Complex Patterns

The overall results are similar to those for the rubidium ions

- Formation occurs in $\mathcal{O}(1 \text{ ns})$

Initial Temperature and Density of Beamlets Effects Quality of Patterns

- Increasing temperature decreases resolution
  - Disappears above initial temperature of 100 K
- Increasing beamlet density leads to shock-wave formations
  - Instead of pileup at the boundary, dense regions cross over
- Increasing beamlet density and decreasing the radius commensurately leads to faster pattern formations
  - Overall temperature increases more substantially

Conclusions

Practical Impacts of these Studies

Based on thermal plots, core beam temperature can be limited if geometric parameters are optimized

- Optimal proximity has a damping effect on Coulomb explosion
  - Disappears above initial temperature of 100 K
- High energy electrons are concentrated at the extremity of the beamlet array
  - Can be selectively removed (ie. via collimation)
  - Efficiently cools the beam with a minimal loss of particles

Provides a possible tool for emittance/temperature measurement in the ultracold regime

- Characterization of initial beam properties based on the observed spatial distribution
  - Beam structures can persist over longer timeframes

Research Sponsors

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Thanks for Your Attention!

Beam Physics Code Repository

https://www.niu.edu/beam-physics-code/projects/index.shtml