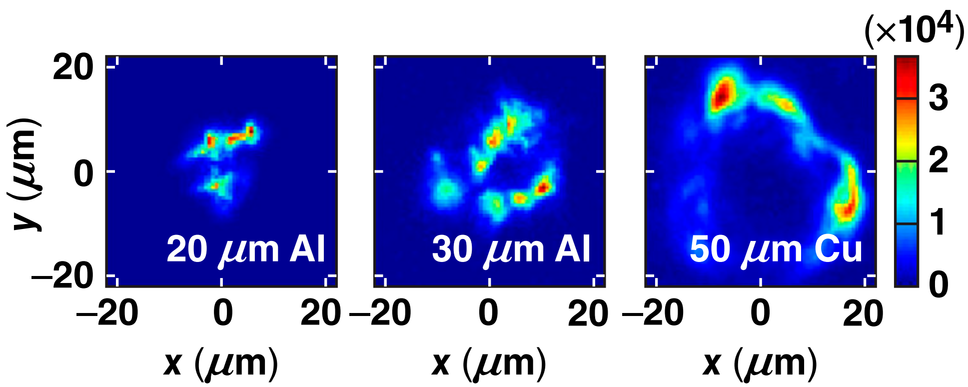
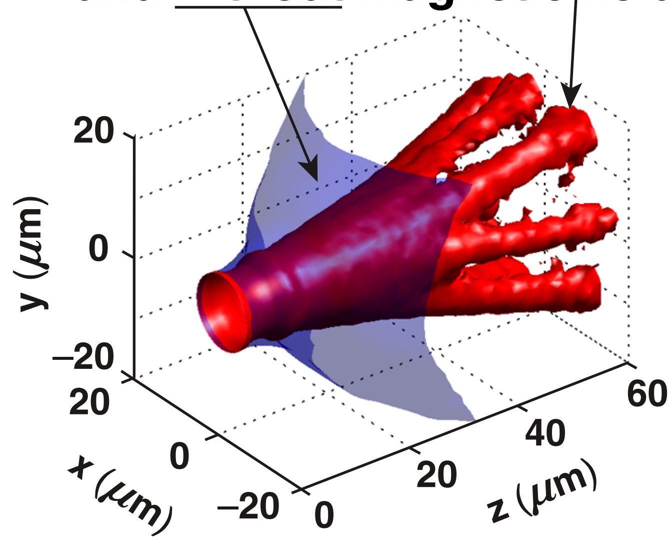
Simulations of Electron-Beam Transport in Solid-Density Targets and the Role of Magnetic Collimation

Experimental images from the coherent transition radiation diagnostics



Hot-electron density isosurface in the simulations with and without magnetic field



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Summary

Observations of fast-electron divergence and filamentation are successfully modeled[1] with *LSP*[2]

- Characteristics of electron transport in high-intensity laser–target interaction have been inferred using Coherent Transition Radiation (CTR)
- Filamentation and divergence of the CTR in solid planar targets with variable thickness was observed
- Self-generated magnetic fields and resistive filamentation are observed in *LSP* simulations and explain the experimental observations
- The hot-electron divergence half-angle of ~16° in the target is reproduced in *LSP* simulations assuming an initial divergence half-angle of 56°, approximately the ponderomotive angle

[1]M. Storm, A. A. Solodov, J. F. Myatt *et al*., Phys. Rev. Lett. 102, 235004 (2009).
[2]D. R. Welch *et al*., Phys. Plasmas 13, 063105 (2006).

TC8555a

Collaborators

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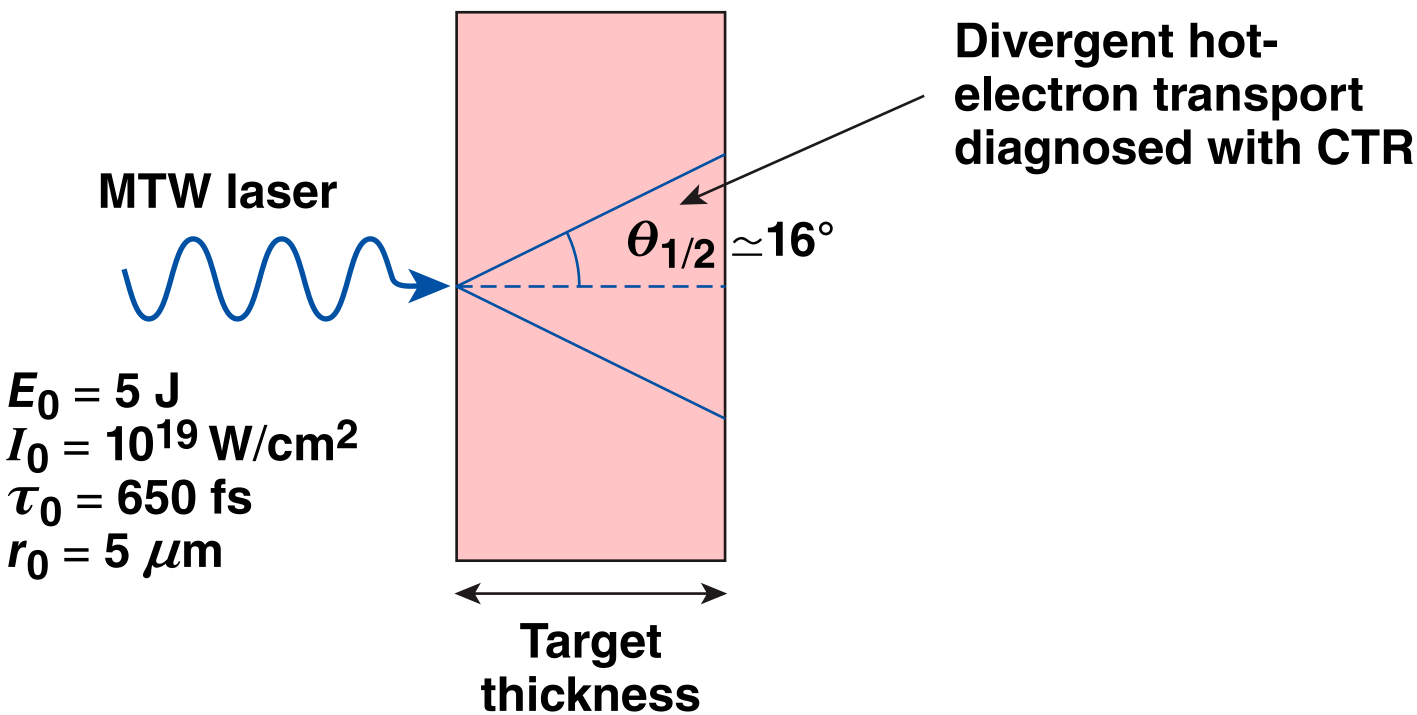
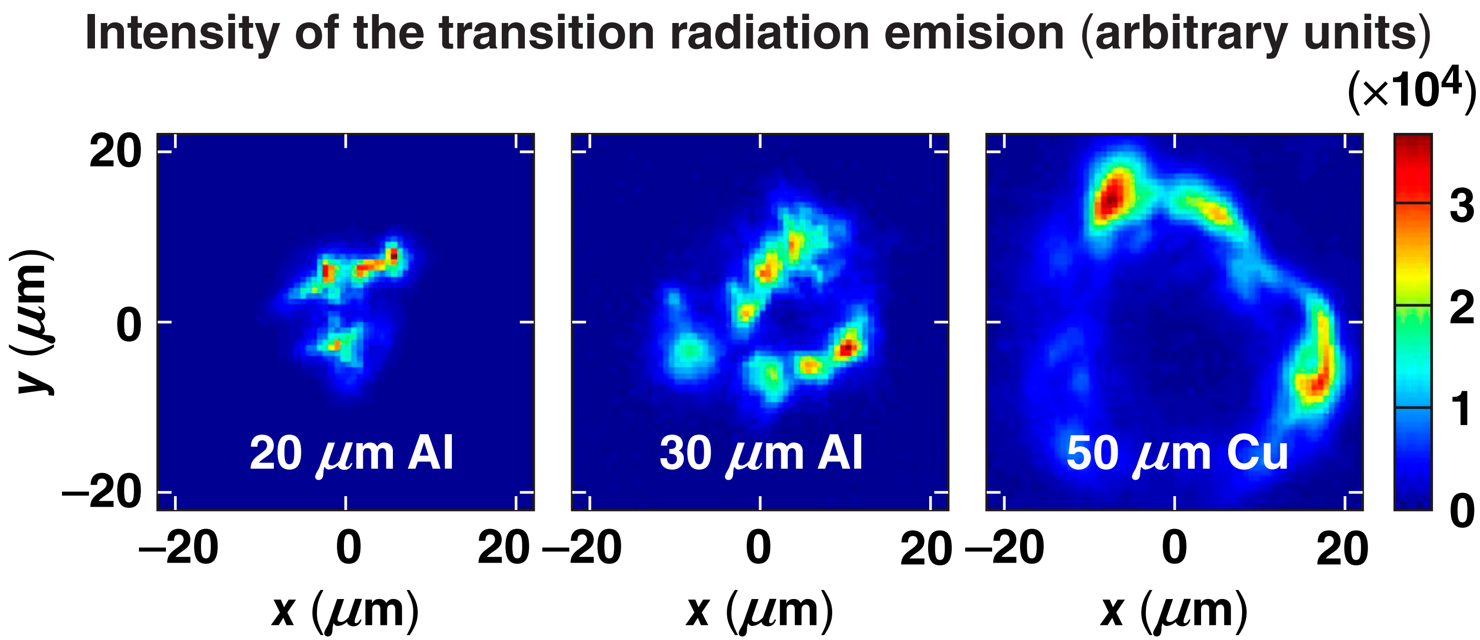
Measurements of coherent transition radiation are used to study fast-electron transport on the Multi-Terawatt (MTW) Laser Facility



- Al, Cu, Sn, and Au foil targets with transverse dimensions of 500 μm and thicknesses ranging from 5 to 100 μm were used

The CTR diagnostic is fielded to acquire images of the rear-side optical emission with a spatial resolution of ~1.4 μm

- Experimental images from the CTR diagnostics



- The CTR images show bright, small-scale structures superimposed on a larger annular structure

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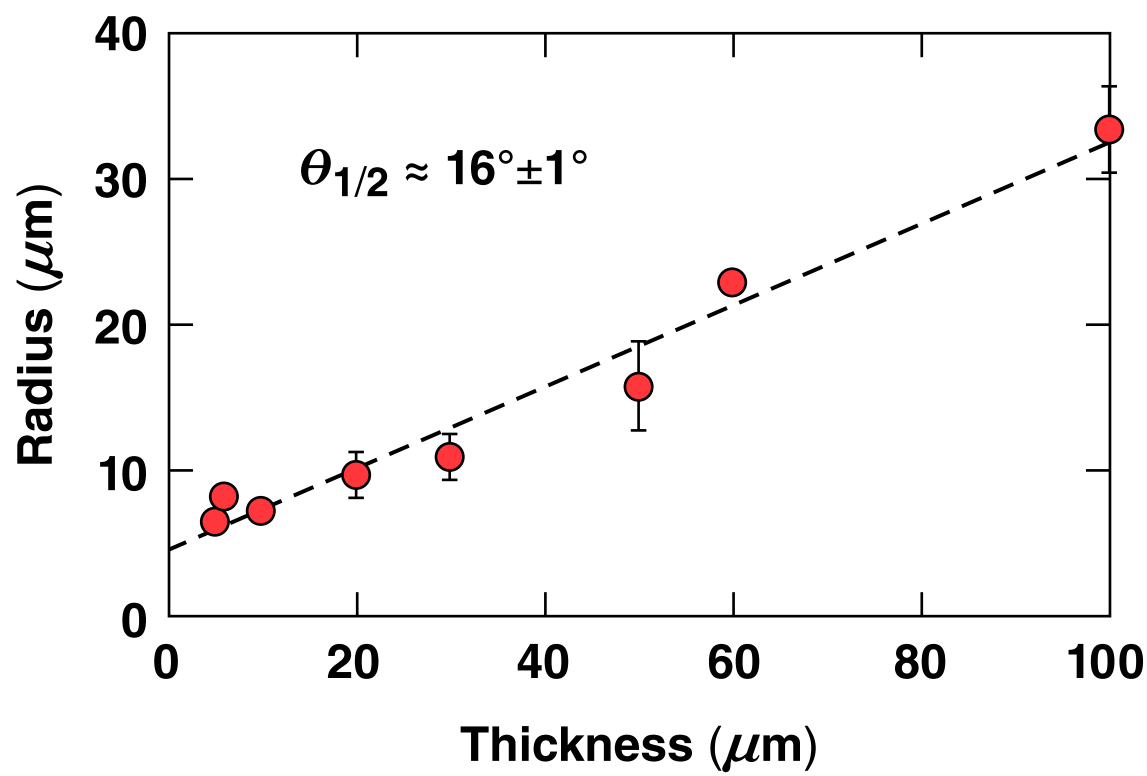
The transverse size of the rear-surface emission grows with the target thickness, indicating a half-angle divergence of 16°



- No dependence on the target material was observed and each experimental point represents the radial size averaged over all materials

The three-dimensional hybrid-PIC code *LSP*[1] is used to model electron transport

- *LSP* uses
  - an implicit solution for the electro-magnetic fields and implicit particle push
  - a hybrid fluid-kinetic description for plasma electrons with dynamic reallocation
  - intra- and interspecies collisions based on Spitzer rates (modified to include relativistic effects[2])
  - the Lee and More[3] resistivity model for the plasma background, the Thomas–Fermi ionization model[4] and equation of state[5]

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[1]D. R. Welch *et al*., Phys. Plasmas 13, 063105 (2006).
[2]A. A. Solodov and R. Betti, Phys. Plasmas 15, 042707 (2008).
[3]Y. T. Lee and R. M. More, Phys. Fluids 27, 1273 (1984).
[4]R. M. More, Adv. At. Mol. Phys. 21, 305 (1985).
[5]A. R. Bell, Rutherford Appleton Laboratory, Report RL-80-091 (1980) (unpublished).

E18418

Simulations of electron transport in Al targets are performed using experimental parameters and a realistic electron source

FSC UR LLE

Electron-beam parameters:

- **Laser intensity:** $I = I_0 \exp\left[-r^2/r_0^2 - (t-t_0)^2/\tau_0^2\right]$
- **Hot-electron distribution function:** $f(E) \sim \exp\left(-E/\langle E_h\rangle\right)$, where

  $\langle E_h\rangle[\text{MeV}] = \max\left\{0.511\left[\left(1+I\lambda_0^2/2.8\times10^{18}\right)^{1/2}-1\right],\ 0.1\left(I\lambda_0^2/10^{17}\right)^{1/3}\right\}$

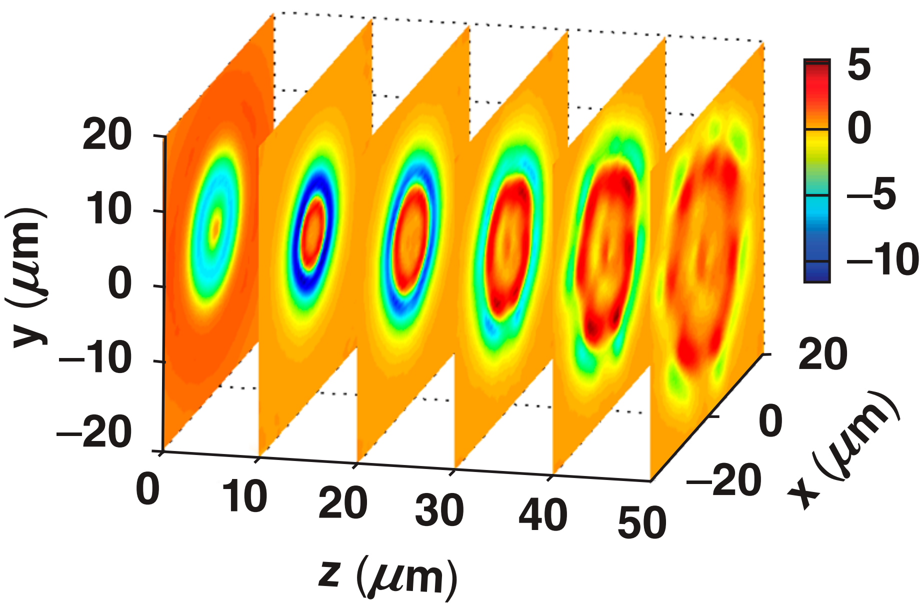
  (ponderomotive and Beg's scalings)
- **Energy-conversion efficiency* = 20%**
- **Initial divergence: electrons with $E_h = (\gamma-1)\,mc^2$ are randomly injected in a cone with half-angle $\theta_{1/2} = \alpha \tan^{-1}\left[\sqrt{2/\gamma-1}\right]$; α = 1–ponderomotive angle.****

* P. M. Nilson *et al.*, Phys. Rev. E 79, 106406 (2009).
** C. I. Moore, J. P. Knauer, and D. D. Meyerhofer, Phys. Rev. Lett. 74, 2439 (1995).

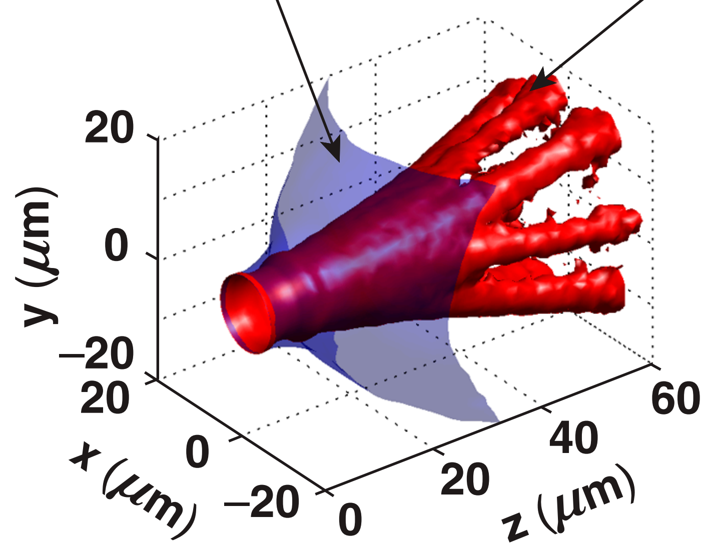
Hot electrons are partially collimated by a self-generated resistive azimuthal magnetic field in *LSP* simulations

$\alpha = 1$ ponderomotive angle,
60-μm-thick target, 350 fs after the peak of the pulse

Azimuthal magnetic field (MG)



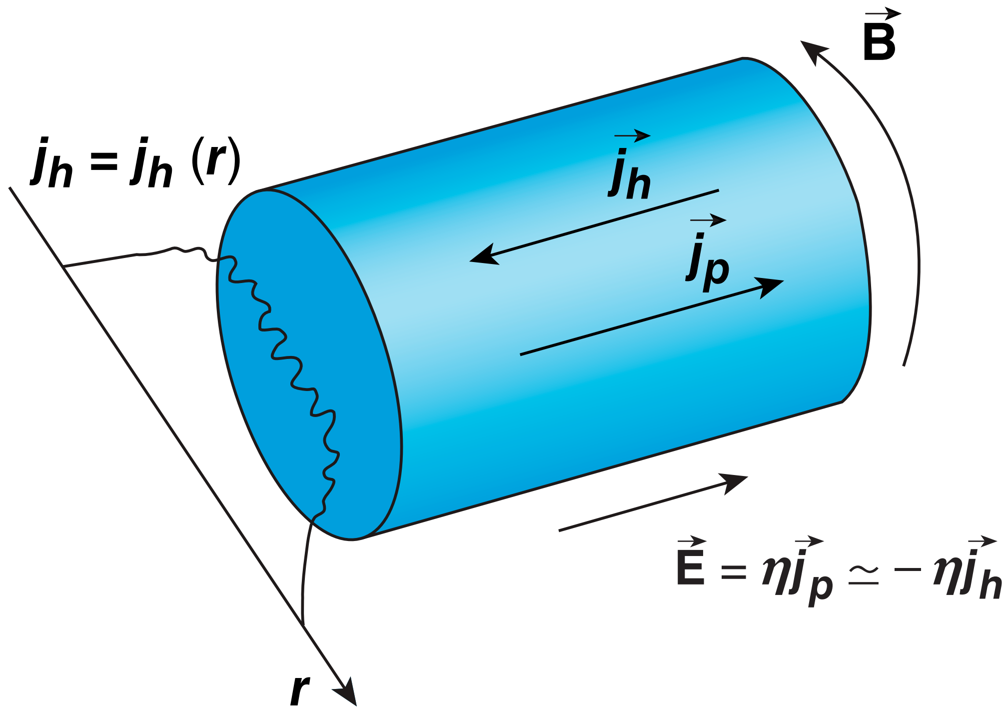
Hot-electron density isosurface at 50% of the peak density in (*x*,*y*) plane with and without magnetic field



- Electron beam develops annular structure and breaks into filaments due to resistive filamentation instability

E17571b

Theoretical models of electron-beam collimation and resistive filamentation have been developed[1,2]



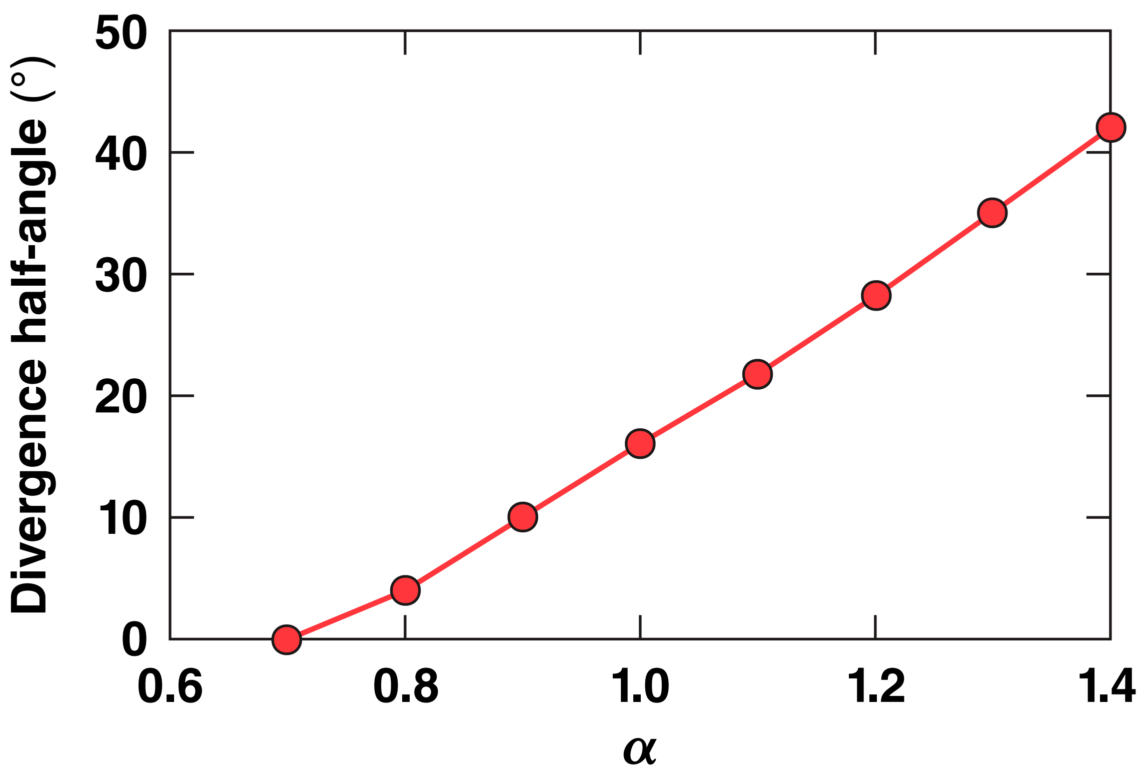
$$\frac{\partial B_\varphi}{\partial t} \sim \frac{\partial E_z}{\partial r}$$

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$$

[1] A. R. Bell and R. J. Kingham, Phys. Rev. Lett. 91, 035003 (2003).
[2] L. Gremillet *et al.*, Phys. Plasmas 9, 914 (2002).

TC8246

The hot-electron divergence half-angle of ~16° is reproduced in *LSP* simulations, assuming an initial divergence half-angle of 56° ($\alpha \simeq 1$)



$$\theta_{1/2} = \alpha \tan^{-1}\left[\sqrt{2/(\gamma - 1)}\right]$$

TC8558a

The simulated size of the rear-surface annular electron-beam density distribution increases with the initial divergence

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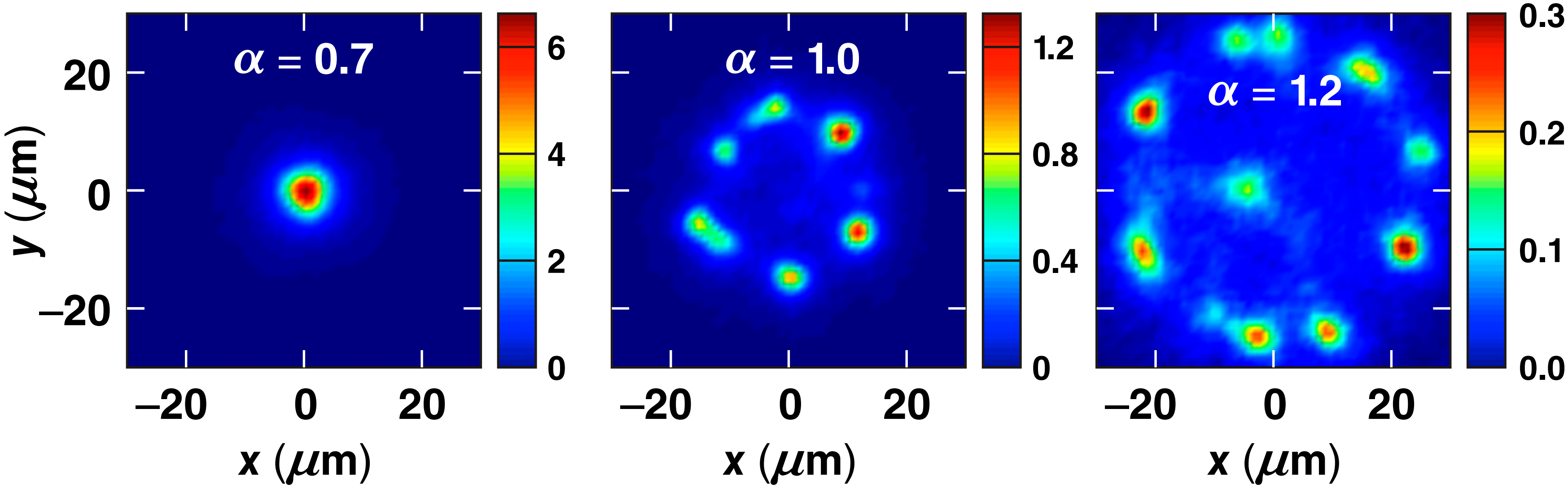
Time-averaged, rear-surface density distributions of electrons with $E > 0.25$ MeV for a 50-μm-thick target (in units of 10^{20} cm^{-3})

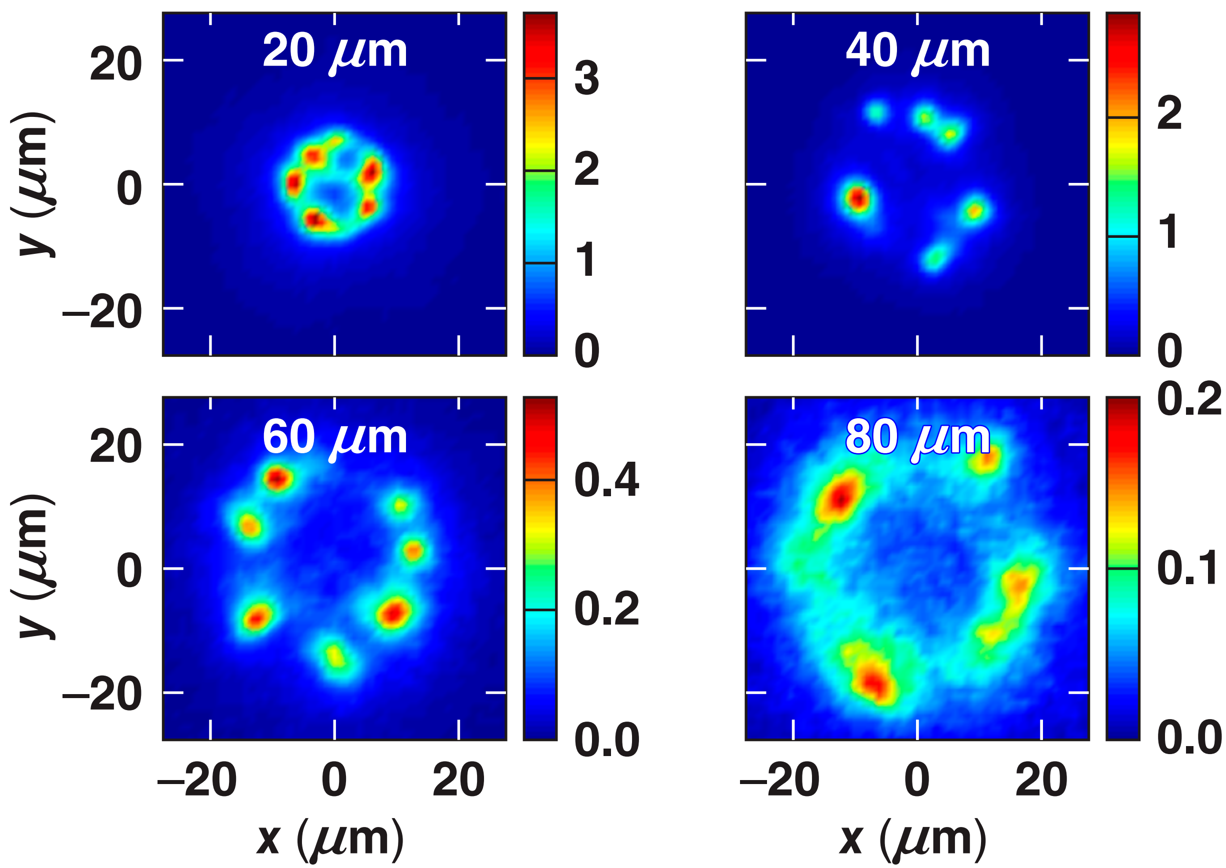


$$\theta_{1/2} = \alpha \tan^{-1}\left[\sqrt{2/(\gamma - 1)}\right]$$

TC8561a

LSP simulations for $\alpha = 1$ predict rear-surface, transverse-density distributions of electrons for different thicknesses of Al, consistent with the measured rear-surface CTR distributions

Time-averaged density of electrons with $E > 0.25$ MeV (in units of 10^{20} cm^{-3})



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