Relativistically Transparent Magnetic Filaments:
A Laser-Plasma Platform for Efficient Electron Acceleration & MeV Photon Radiation

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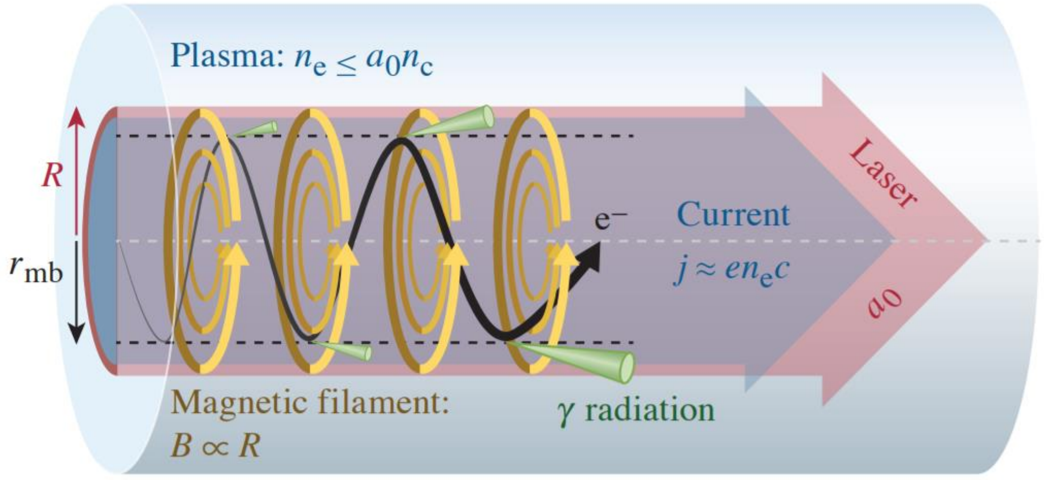
Schematic of a magnetic filament



E29601J1

Rinderknecht et al., New J. Phys. ***23****, 095009 (2021)*

Hans Rinderknecht
University of Rochester
Laboratory for Laser Energetics

APS Division of Plasma Physics
November 9, 2021 | Pittsburgh, PA
GO5.12

UNIVERSITY of ROCHESTER

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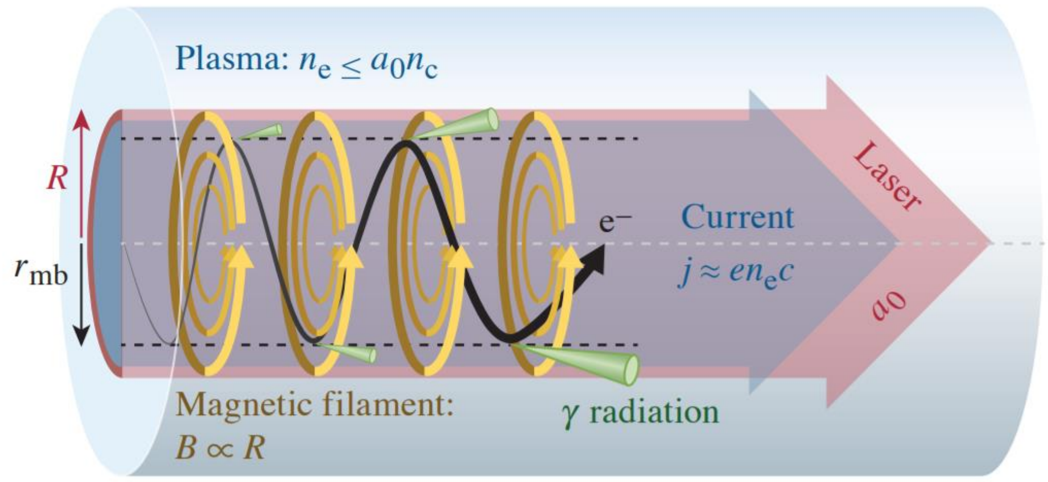

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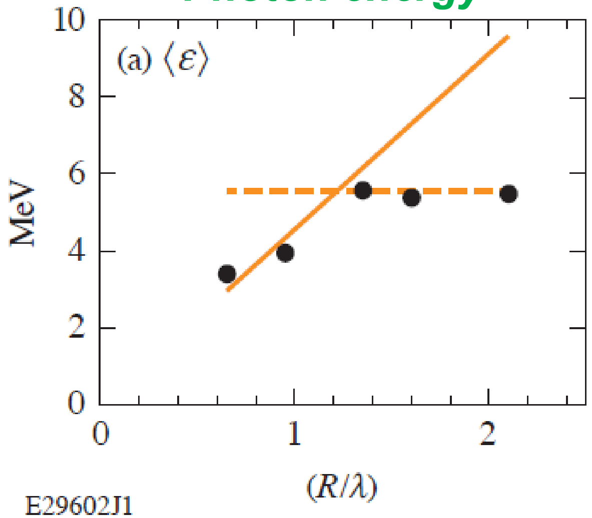
Rinderknecht et al., New J. Phys. ***23****, 095009 (2021)*

Predicted radiation (I = 5×10^{22} W/cm^2)

Photon energy



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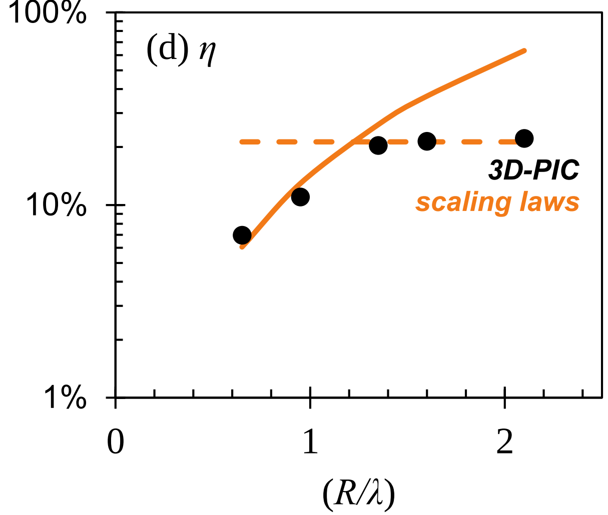
Efficiency



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Magnetic filaments promise a repeatable and efficient laser-driven source for relativistic electrons and MeV photons

- **Intense lasers in relativistically-transparent plasmas generate ultra-strong magnetic filaments**
  - Electrons are trapped and accelerated, efficiently radiating MeV-scale photons
- **Scaling laws were derived for magnetic filament radiation and validated with 3-D PIC simulations**
  - Efficiency of >10% is predicted for intensity above ~10^{22} W/cm^2
- **Experiments on the Texas Petawatt laser were performed to test these predictions**
  - The predicted electron and photon signatures were observed in a subset of experiments

Collaborators

LLE/UR:
- Hans Rinderknecht
- Mingsheng Wei
- Gerrit Bruhaug
- Kathleen Weichmann
- John Palastro
- Jon Zuegel

UCSD:
- Alexey Arefiev
- Tao Wang

HZDR:
- Toma Toncian
- Alejandro Laso Garcia

ELI-NP:
- Domenico Doria
- Klaus Spohr

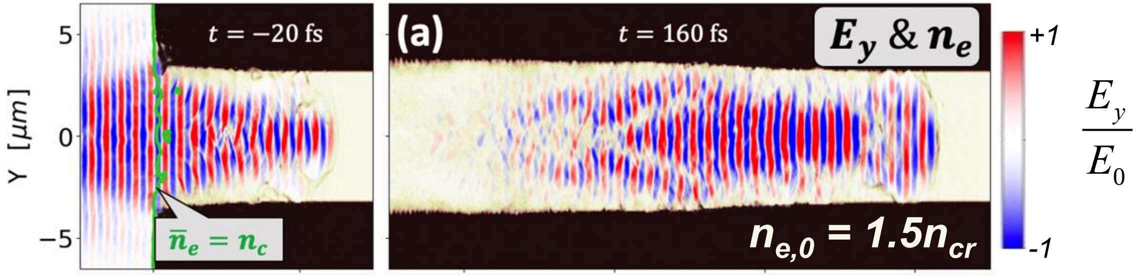
Texas Pettawatt (TPW)/UT Austin:
- Hernan J. Quevedo
- Todd Ditmire

General Atomics (GA):
- Jarrod Williams
- Alex Haid

Johns Hopkins University:
- Dan Stutman

Relativistic transparency allows an intense laser to interact with a plasma above the classical critical density (n_{cr})

3-D PIC simulations (a_0 = 50 ~ 3e21 W/cm^2)[1]:



$$a_0 \equiv \frac{|e|E_0}{m_e \omega c} \propto \sqrt{Intensity}$$

> 1 → *relativistic electrons*

$$n_{cr} = \frac{\epsilon_0 m_e}{e^2}\omega_L^2$$

= critical plasma density limit for a laser of frequency ω_L

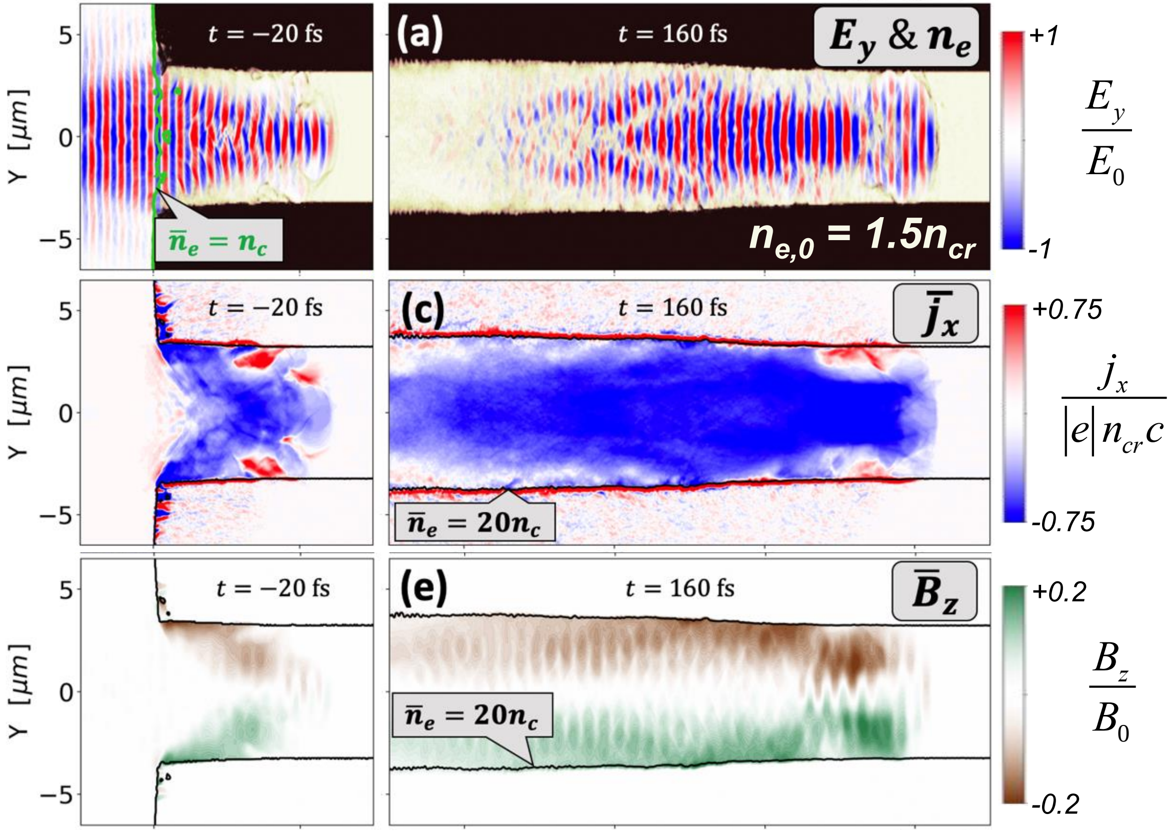
$a_0 > 1 \rightarrow$ **Relativistic Transparency:**

$$n_e \le n_{cr}\langle\gamma\rangle \approx n_{cr} a_0$$

[1]Z. Gong, et al., Phys. Rev. E 102, 013206 (2020)

The ponderomotive force drives a relativistic current, producing a strong azimuthal magnetic field: a magnetic filament

3-D PIC simulations (a_0 = 50)[1]:



Magnetic field of current normalized to laser field:

$$\frac{B_j}{B_0} = \left(\frac{\mu_0 j r}{2}\right) \Big/ \left(\frac{2\pi a_0 mc}{e\lambda}\right)$$

$$= \pi \left(\frac{r}{\lambda}\right)\left(\frac{n_e \beta}{n_{cr} a_0}\right)$$

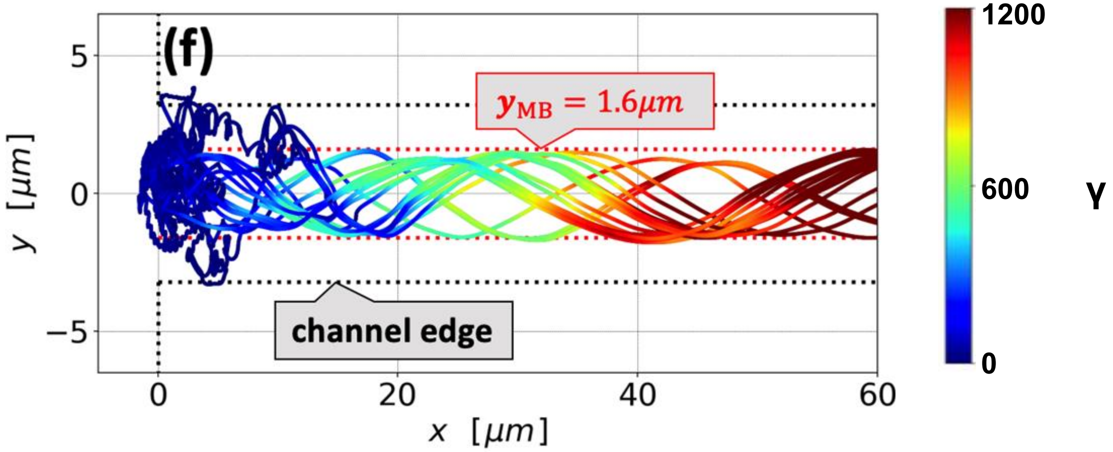
$$\equiv \pi r_\lambda S_\alpha$$

Quasi-static magnetic fields of the order of the oscillating laser field are produced.

[1]Z. Gong, et al., Phys. Rev. E 102, 013206 (2020)

Electrons oscillate within the filament: those in phase with the laser are rapidly accelerated,

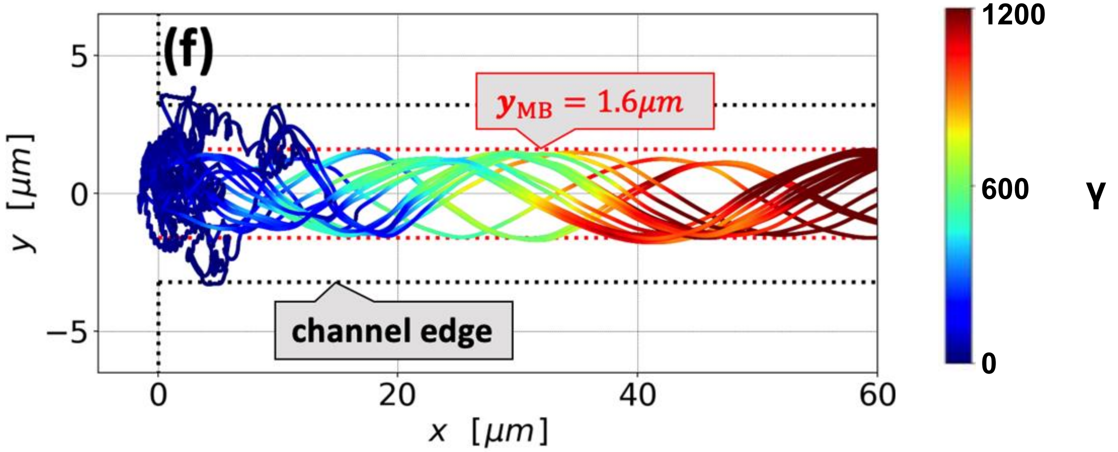
Electron orbits & acceleration (a_0 = 50)[1]



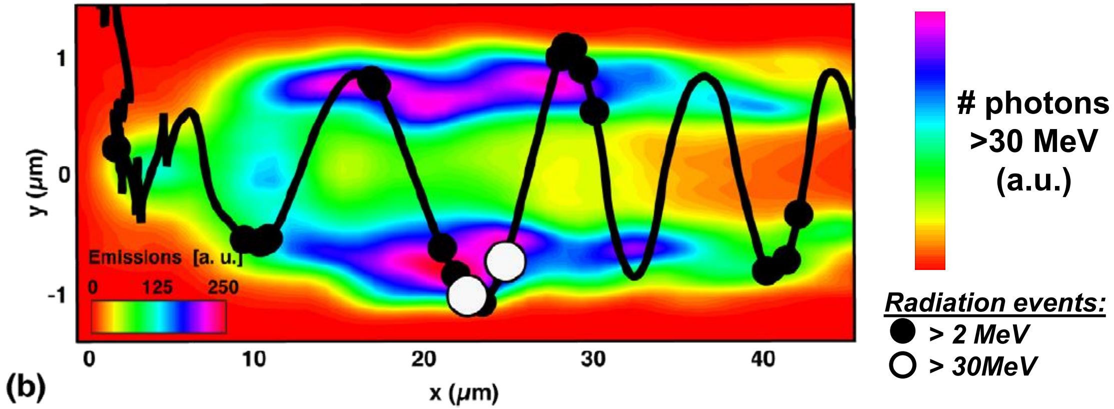
[1]Z. Gong, et al., Phys. Rev. E 102, 013206 (2020);

Electrons oscillate within the filament: those in phase with the laser are rapidly accelerated, and radiate in the strong magnetic field.

Electron orbits & acceleration (a_0 = 50)[1]



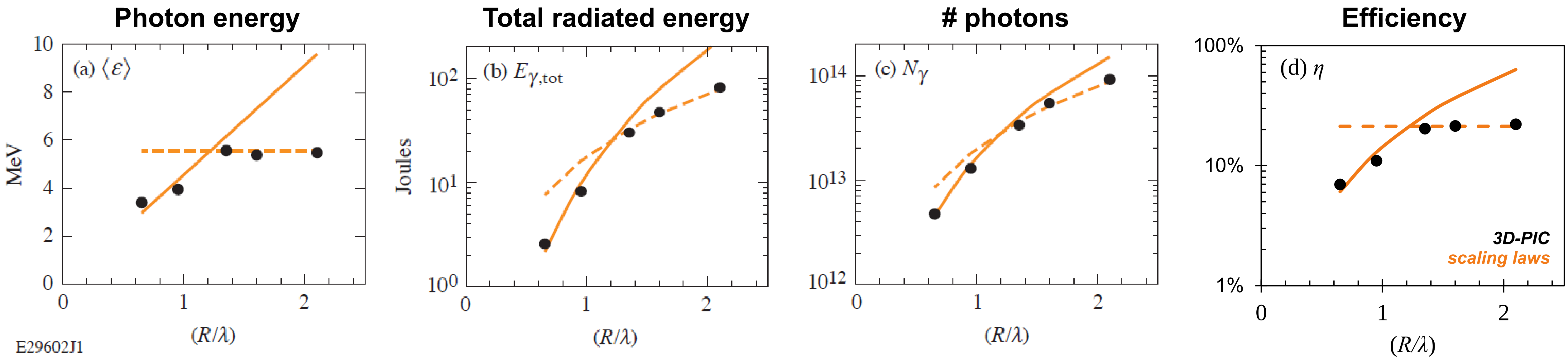
Photon radiation (a_0 = 190)[2]



$\hbar\omega_{rad} \propto \gamma^2 B, \qquad P_{rad} \propto \gamma^2 B^2$

The maximum magnetic field seen by electrons depends on the laser focal radius and the initial transverse momentum.

Analytical scaling laws and 3-D PIC simulations of magnetic filaments predict > 10% radiation efficiency of MeV photons from sufficiently intense lasers

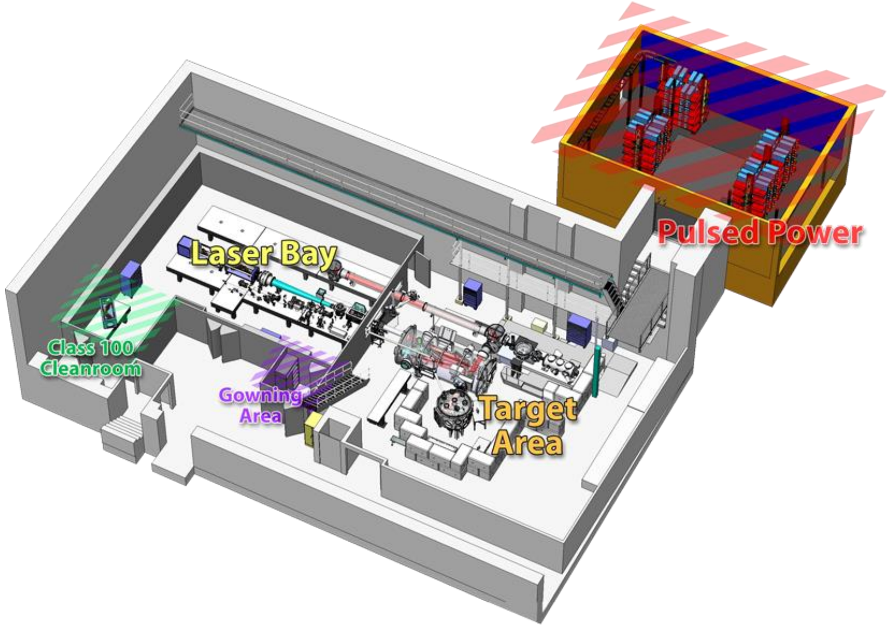


Parameters: a_0 = 190 (5×10^{22} W/cm^2)
S_α = 0.105 (n_e = 20n_{cr})
R_λ = [0.65, 2.1]
τ_V = 10.5 (35 fs)

Photon energy and radiation efficiency ∝ a_0^3 ∝ $I^{3/2}$

For more details, please see:
H.G. Rinderknecht, et al., New J. Phys. 23, 095009 (2021)
doi:10.1088/1367-2630/ac22e7

Initial experiments to study relativistically transparent magnetic filaments were performed at the Texas Petawatt Laser (TPW)[1]



- Wavelength: 1057 nm
- Energy: 98.8 ± 6.0 Joules
- Duration: 140 fs
- Power: 694 ± 38 TW

- Intensity: $[1.09 \pm 0.07]\times10^{21}$ W/cm^2 ($a_0 = 29.9 \pm 1.0$)
- Radius: 2.6 ± 0.12 µm (at 50% peak intensity)
- Pointing: 8-µrad rms → 5-µm rms on target

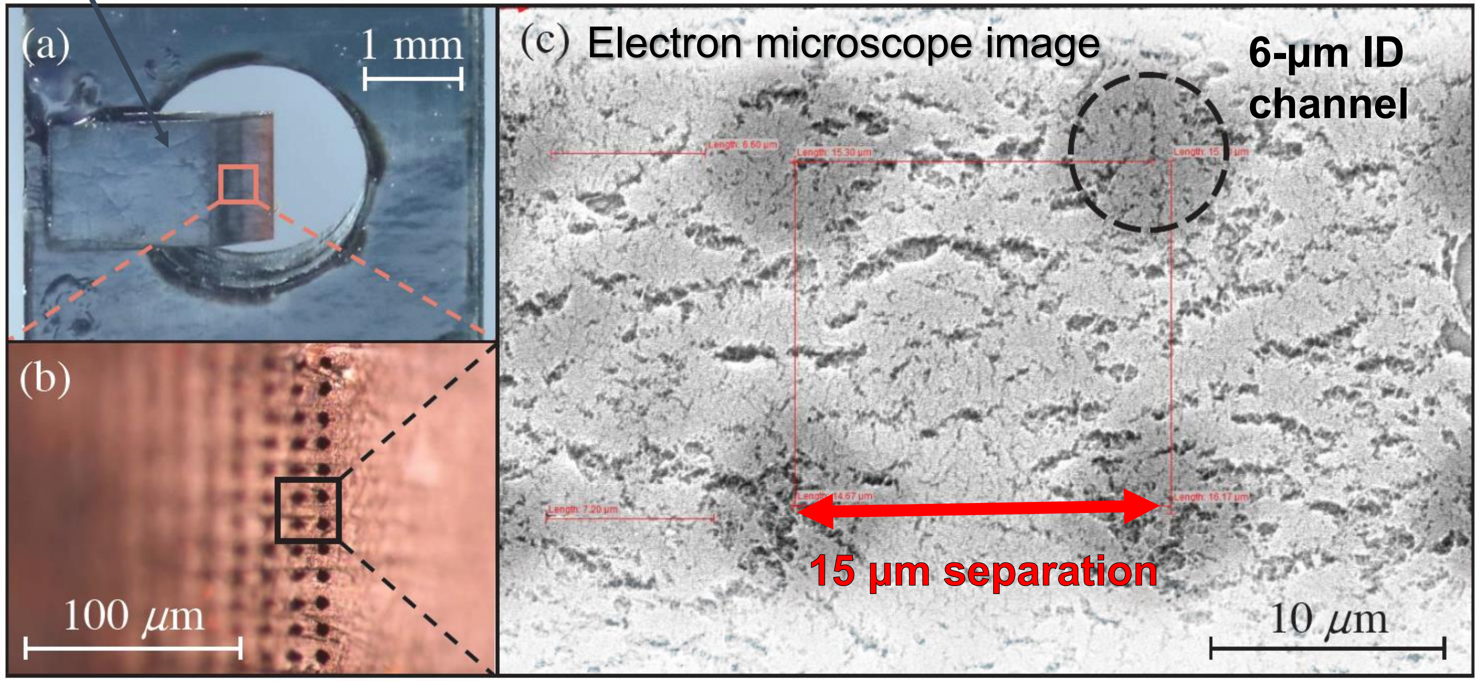
- **Primary diagnostics:** EPPS electron spectrometer[2]
  Gamma calorimeter

[1]See http://texaspetawatt.ph.utexas.edu/

[2]H. Chen et al., RSI 79, 10E533 (2008)

Microchannel targets filled with low-density foam (n_e = 5 or 10 n_{cr}) were developed for this campaign

Kapton wedge



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laser-drilled channel array

Channels filled with low-density CH foam: 15 or 30 mg/cm³

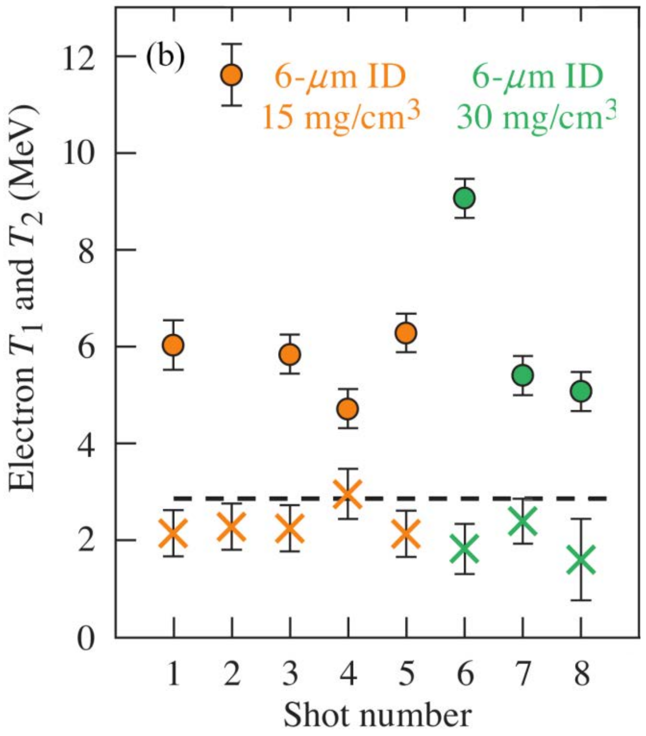
11 shots were performed with good laser-target alignment:

- [×5] 6-μm channels, 5-n_{cr} fill
- [×3] 6-μm channels, 10-n_{cr} fill
- [×1] 6-μm channels, unfilled
- [×2] Planar foam, 10-n_{cr}

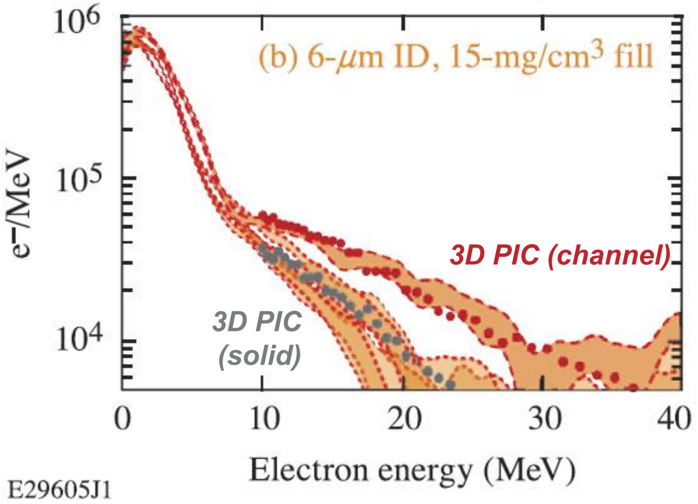
Given the pointing stability (5-μm rms), we did not expect channel interactions on every shot.

The ‘hot’ electron temperature was elevated on 2 of 8 microchannel shots

Electron temperatures



Example electron spectra



H.G. Rinderknecht, et al., New J. Phys. **23**, 095009 (2021) doi: 10.1088/1367-2630/ac22e7

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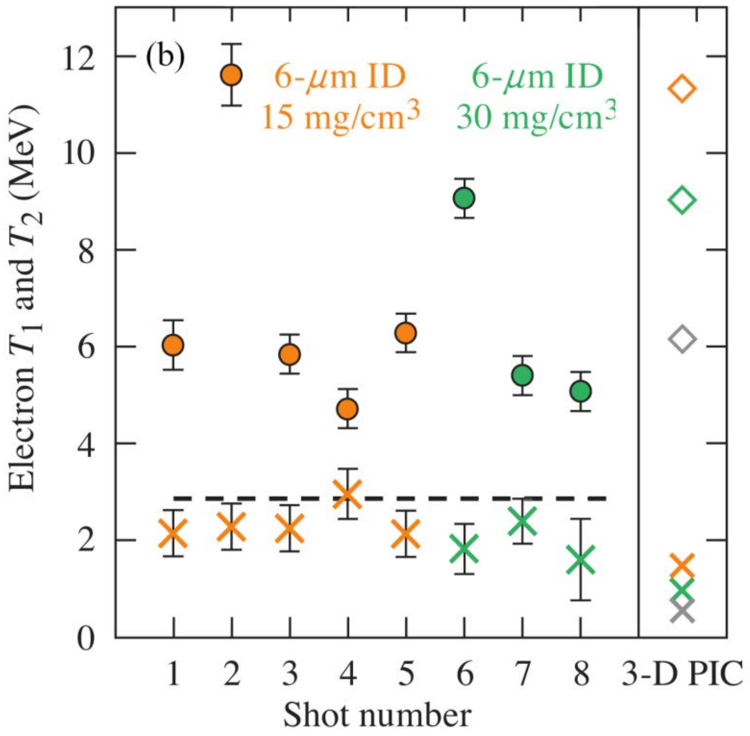

3-D PIC simulations:

15 mg/cm³ channel fill

30 mg/cm³ channel fill

"solid" (~0.6 g/cm³)

H.G. Rinderknecht, et al., New J. Phys. **23**, 095009 (2021) doi: 10.1088/1367-2630/ac22e7

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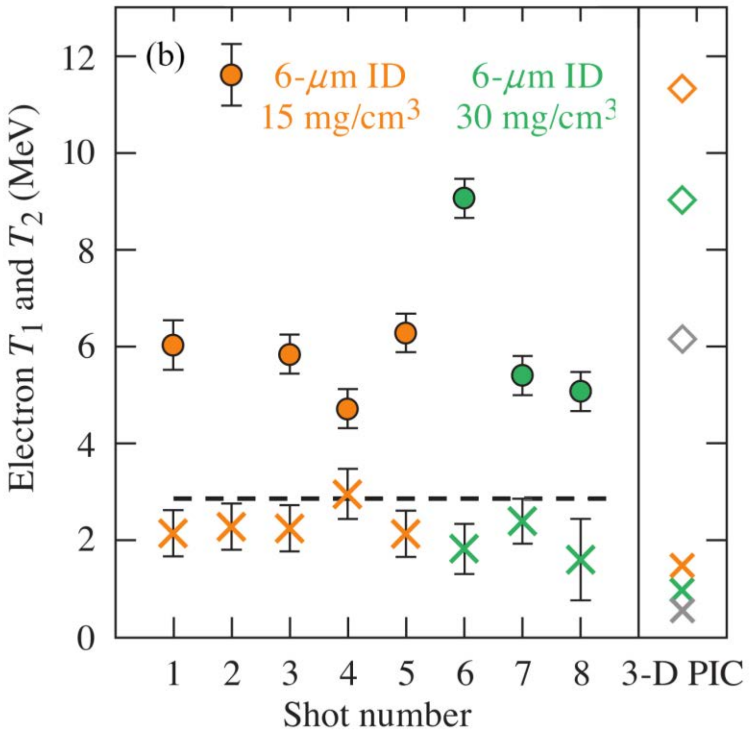


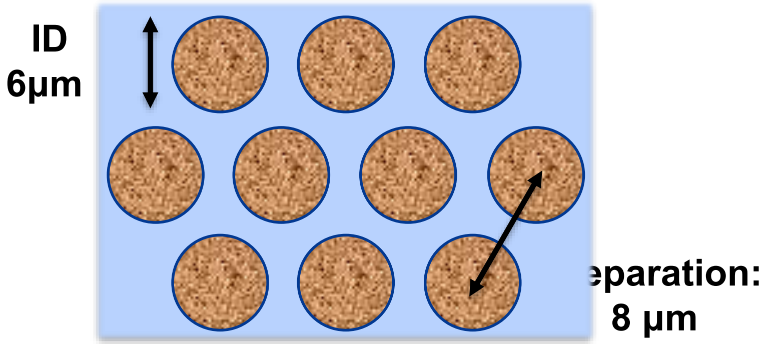
Given the pointing stability and channel size, the probability of observing N interactions is:

We conclude that the predicted electron acceleration was observed in a subset of these experiments.

For future experiments, closely packed channel arrays will be used to improve repeatability and control over channel properties

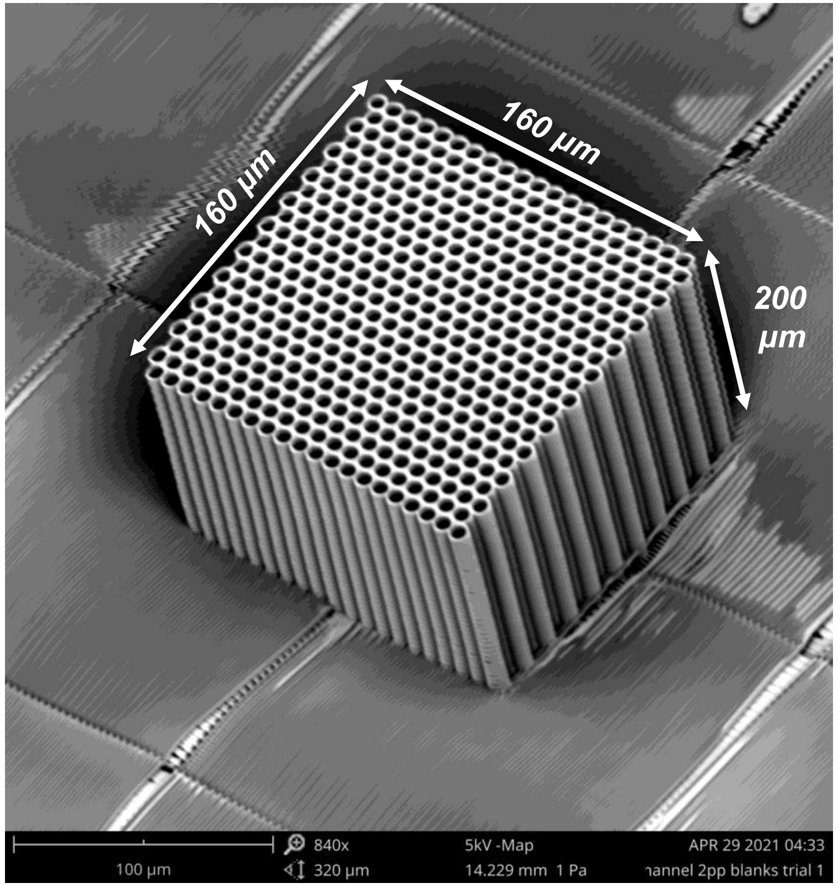
Microchannel arrays in development

Top view:



- Hexagonal close-packed array (20 by 20)
- Channel length: 100 µm minimum
- Foam density: 1—5 n_{crit} (ρ ~ 3—15 mg/cm^3)

Photo of array produced by 2-photon polymerization:



A. Haid, GA

With 10-PW lasers now becoming available, magnetic filaments promise exciting opportunities for high-flux gamma-ray sources

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T				
Peak power	10 PW		10 PW	
Intensity (a_0)	5×10^{22} W/cm^2 (153)		5×10^{22} W/cm^2 (202)	
Design choice:	**S_α = 0.01**	**S_α = 0.05**	**S_α = 0.01**	**S_α = 0.05**
Photon energy <ε_*>		9.2 MeV	**96 MeV**	19 MeV
Total energy $E_{\gamma,tot}$	111 J	51 J	797 J	727 J
# photons N_γ	1.0×10^{13}	**3.5×10^{13}**	5.2×10^{13}	**2.5×10^{14}**
Efficiency η	48%*	22%*	53%*	48%*

By varying the channel design, the photon spectrum and flux may be optimized.

† D. Ursescu, et al., Romanian Reports in Physics 68, S11 (2016)
‡ S. Weber, et al., Matter and Radiation at Extremes 2, 149 (2017)

**model limited by radiation depletion*

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Please also visit these related posters:

PP11.112 (Wed 2pm) I. Yeh, *"Strong interplay between superluminosity and radiation friction within a magnetic filament"*

PP11.113 (Wed 2pm) M. Van Dusen-Gross, *"Design of experiments to study magnetic filaments using OMEGA-EP"*

Appendix

* First reference
** Second reference
† Third reference
‡ Fourth reference

Electrons orbit within a magnetic boundary. Those in phase with the laser are accelerated, and radiate by deflecting in the strong magnetic field.

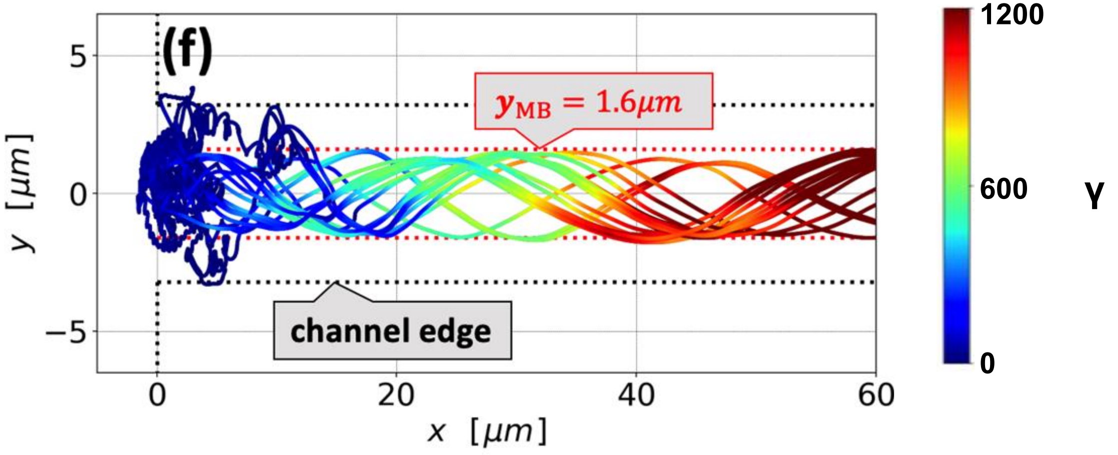
Magnetic boundary[1]:

$$\frac{r_{mb}}{\lambda} \approx \frac{1}{\pi}\sqrt{\frac{\gamma_i n_{cr}}{n_e}} \approx \frac{1}{\pi}\sqrt{\frac{f_i}{S_\alpha}}$$

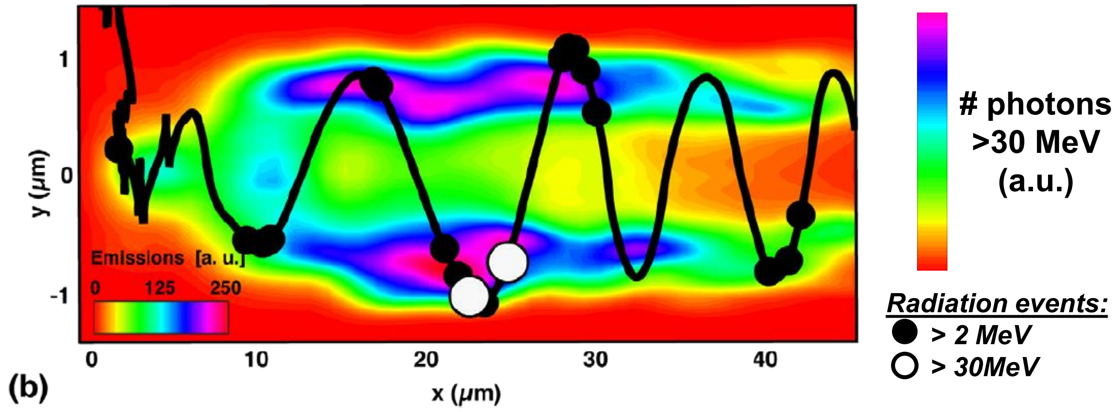
$$\left(f_i \equiv \frac{\gamma_i}{a_0} \right)$$

The maximum magnetic field seen by electrons is limited by the *smaller* of focal radius and magnetic boundary.

Electron orbits & acceleration (a_0 = 50)[1]



Photon radiation (a_0 = 190)[2]



[1]Z. Gong, et al., Phys. Rev. E 102, 013206 (2020); [2]D. J. Stark, et al., Phys. Rev. Lett. 116, 185003 (2016)

Using simple assumptions for the electron acceleration and orbits, we derive scaling laws for the radiation from magnetic filaments

0: Electrons are thermal

$$f_e(\epsilon_e, t) = \frac{N_e}{T_e}\exp\left[-\frac{\epsilon_e}{T_e}\right], \quad \text{where} \quad N_e = n_e(\pi R^2)(c\tau)$$

1: Electron acceleration is linear in time

$$T_e(t) = C_T a_0 \left(\frac{ct}{\lambda}\right) mc^2 \equiv C_T a_0 t_v mc^2$$

2: Radiation is synchrotron-like

$$\frac{dP}{d\epsilon_*} = f_r \frac{4}{9}\alpha_{fsc}\frac{mc^2}{\hbar}\left(\frac{B}{B_{cr}}\right)F\left[\frac{\epsilon_*}{\epsilon_c}\right], \quad \text{where} \quad \epsilon_c = \frac{3}{2}\chi\gamma mc^2, \quad F[x] \equiv \frac{9\sqrt{3}}{8\pi}x\int_x^\infty K_{5/3}(z)\,dz \quad \left[\int_0^\infty F(y)dy = 1\right]$$

3: The laser depletes by heating electrons

$$\frac{E_e}{E_{Laser}} \le 1 \quad \rightarrow \quad t_{v,\max} \le \frac{\sqrt{\pi}}{4(\ln 2)^{3/2}}\frac{1}{C_T S_\alpha}. \qquad \text{We define:} \quad t_{v,cut} \equiv f_t t_{v,max} \approx 0.768\frac{f_t}{C_T S_\alpha}$$

These assumptions have four constants: f_i, f_t, f_r, C_T and four design parameters: a_0, S_α, R/λ, cτ/λ

H.G. Rinderknecht, et al., New J. Phys. **23**, 095009 (2021)
doi: 10.1088/1367-2630/ac22e7

Using simple assumptions for the electron acceleration and orbits, we derived scaling laws for the radiation from magnetic filaments

Radiation property:	…if focal radius R < r_{mb}:	…if focal radius R > r_{mb}:
Photon energy	$\langle \epsilon_* \rangle_{tot} \approx 1.38\times10^{-6}\ f_t^2 a_0^3 S_\alpha^{-1} R_\lambda \lambda_{\mu m}^{-1}\ m_e c^2$	$\langle \epsilon_* \rangle_{tot} \approx 4.40\times10^{-7} \sqrt{f_i}\, f_t^2 a_0^3 S_\alpha^{-3/2} \lambda_{\mu m}^{-1}\ m_e c^2$
Radiated energy	$E_{\gamma,tot} \approx 7.74\times10^{2}\ f_r f_t^3 C_T^{-1} a_0^5 R_\lambda^4 \tau_\nu\ m_e c^2$	$E_{\gamma,tot} \approx 7.84\times10^{1}\ f_i f_r f_t^3 C_T^{-1} a_0^5 S_\alpha^{-1} R_\lambda^2 \tau_\nu\ m_e c^2$
# photons	$N_{\gamma,tot} = 5.59\times10^{8}\ f_r f_t C_T^{-1} a_0^2 S_\alpha R_\lambda^3 \tau_\nu \lambda_{\mu m}$	$N_{\gamma,tot} = 1.78\times10^{8} \sqrt{f_i}\, f_r f_t C_T^{-1} a_0^2 S_\alpha^{1/2} R_\lambda^2 \tau_\nu \lambda_{\mu m}$
Radiation efficiency	$\eta_\gamma = 2.88\times10^{-7}\ f_r f_t^3 C_T^{-1} a_0^3 R_\lambda^2 \lambda_{\mu m}^{-1}$	$\eta_\gamma = 2.92\times10^{-8}\ f_r f_t^3 f_i C_T^{-1} a_0^3 S_\alpha^{-1} \lambda_{\mu m}^{-1}$

→ **4 Parameters:** *Intensity (a_0), Relativistic transparency ($S_\alpha = n_e/n_{cr}a_0$), Focal radius (R_λ), Pulse duration (τ_ν)*

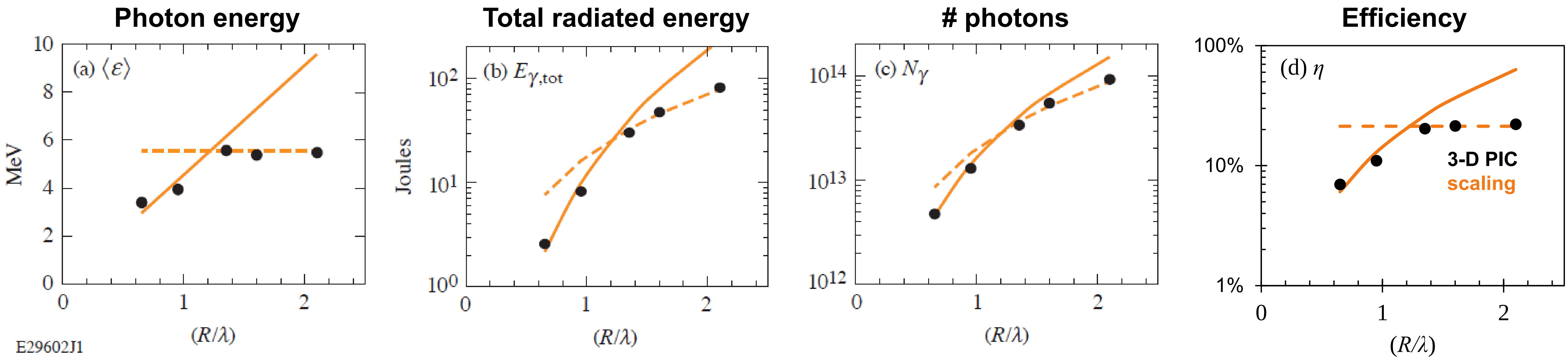
→ **3 Constants:** *Initial e- momentum scalar (f_i ~ 1), cutoff scalar (f_t < 1), radiation duty cycle (f_r < 1)*

For more details, please see:

H.G. Rinderknecht, et al., New J. Phys. 23, 095009 (2021)

doi:10.1088/1367-2630/ac22e7

The scaling laws show good agreement with 3-D PIC simulations that varied the focal radius, with reasonable constants



Parameters: a_0 = 190 (5×10^{22} W/cm^2)
S_α = 0.105 (n_e = 20n_{cr})
R_λ = [0.65, 2.1]
τ_v = 10.5 (35 fs)

Constants:

f_i = **1.533,**	initial electron momentum scalar,	$\gamma_i \equiv f_i a_0$
f_t = **0.311,**	cutoff time scalar,	$t_{v,cut} \equiv f_t t_{v,max}$
f_r = **0.189,**	radiation duty cycle,	$P \equiv f_r P_{synch}$

H.G. Rinderknecht, et al., New J. Phys. 23, 095009 (2021)
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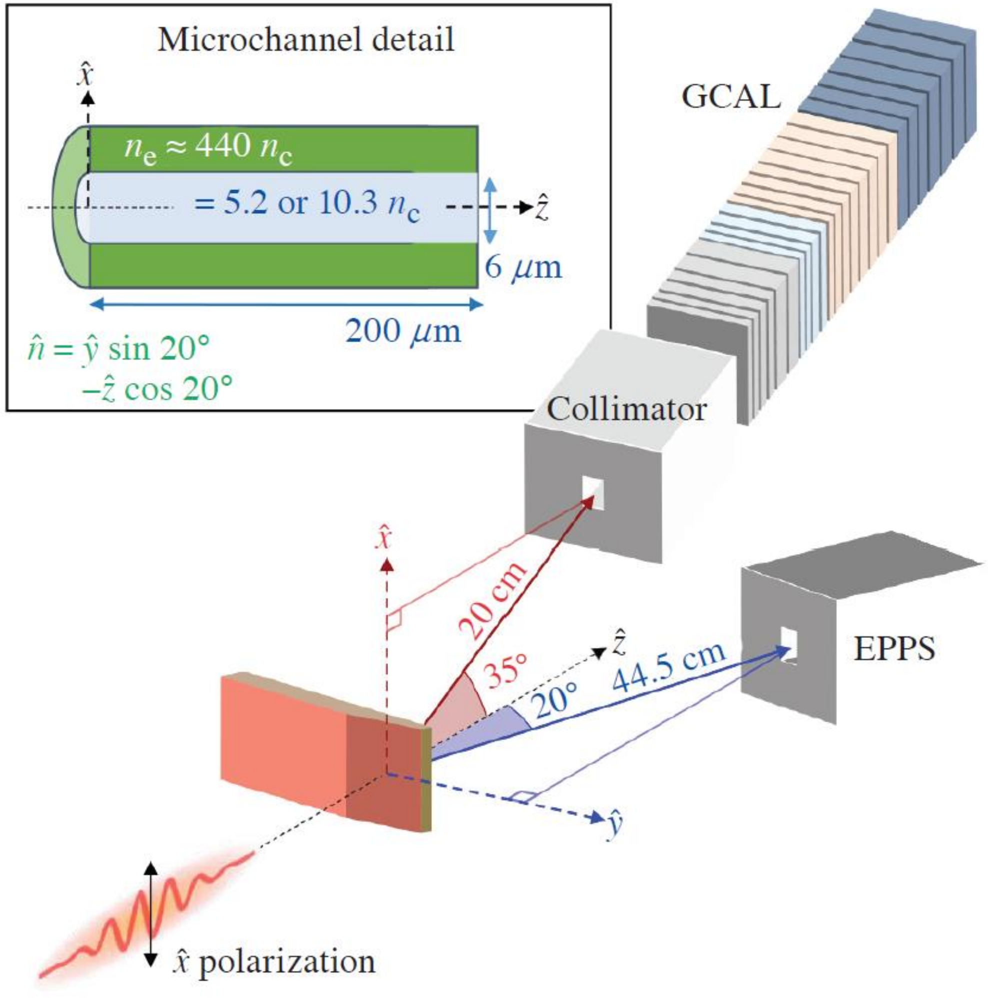
Primary diagnostics were an electron spectrometer (EPPS) and a gamma calorimeter (GCAL) in the expected radiation direction



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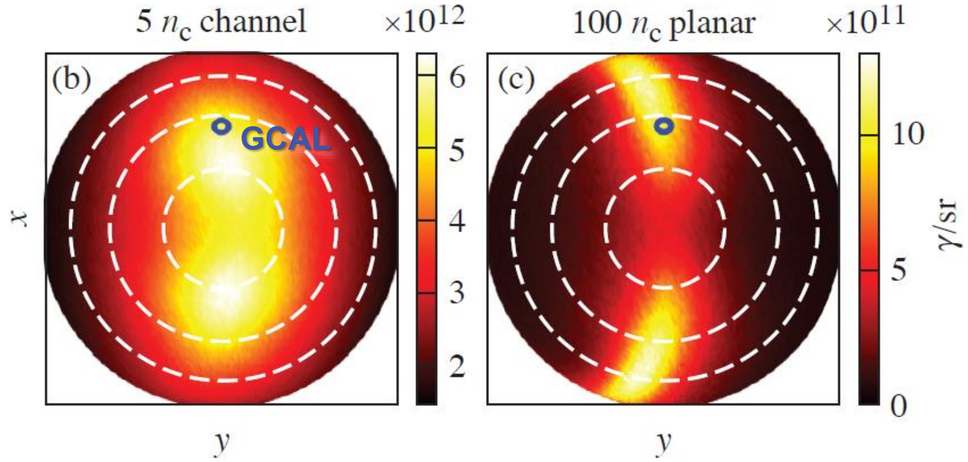
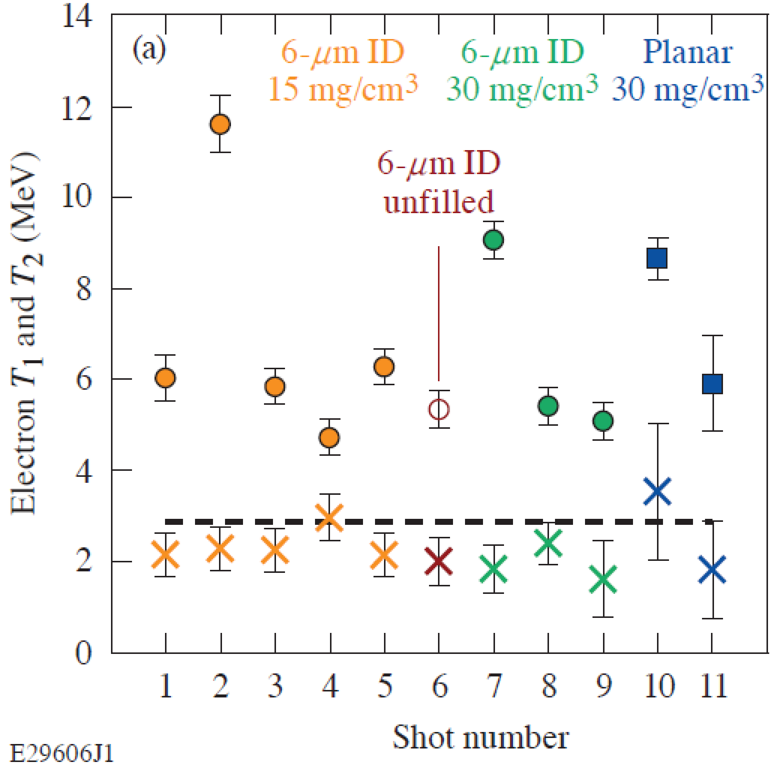
Simulated x-ray profiles (> 10 keV)



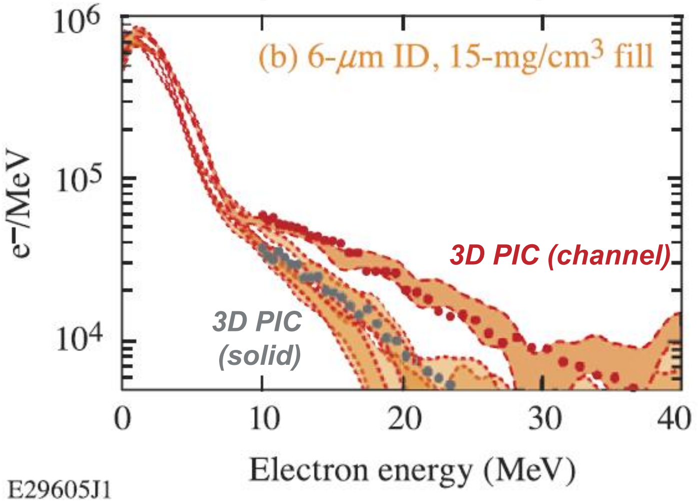
A factor of 5 difference in photon brightness is predicted between microchannel and 'solid' targets.

The ‘hot’ electron temperature was elevated on 2 of 8 microchannel shots

Electron temperatures



Example electron spectra



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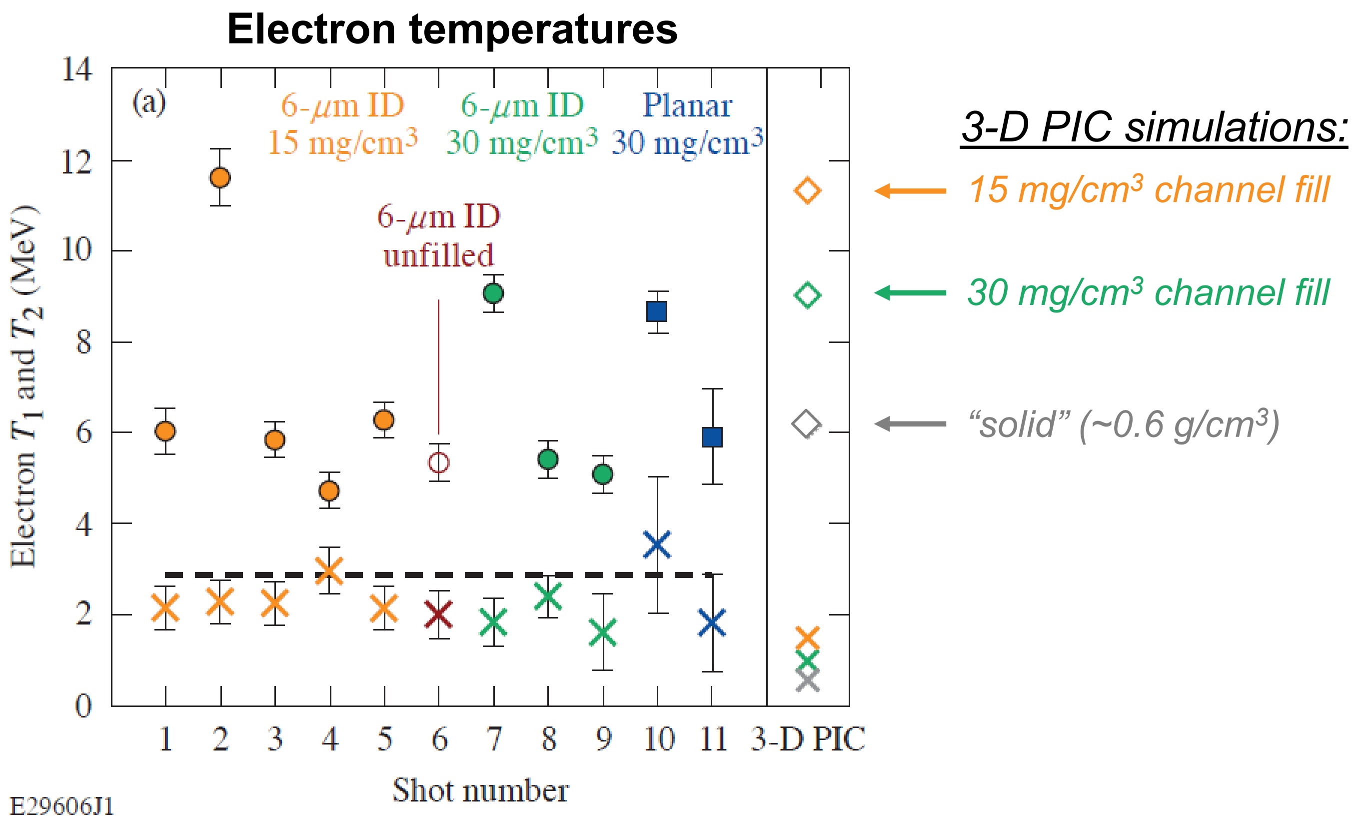

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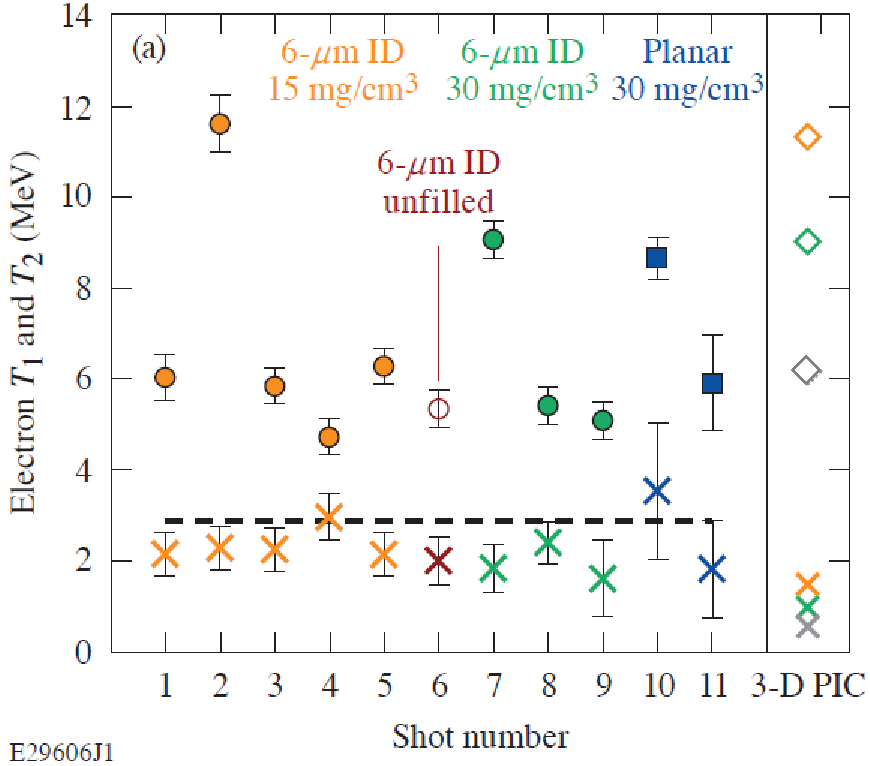

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We conclude that the predicted electron acceleration was observed in a subset of these experiments.

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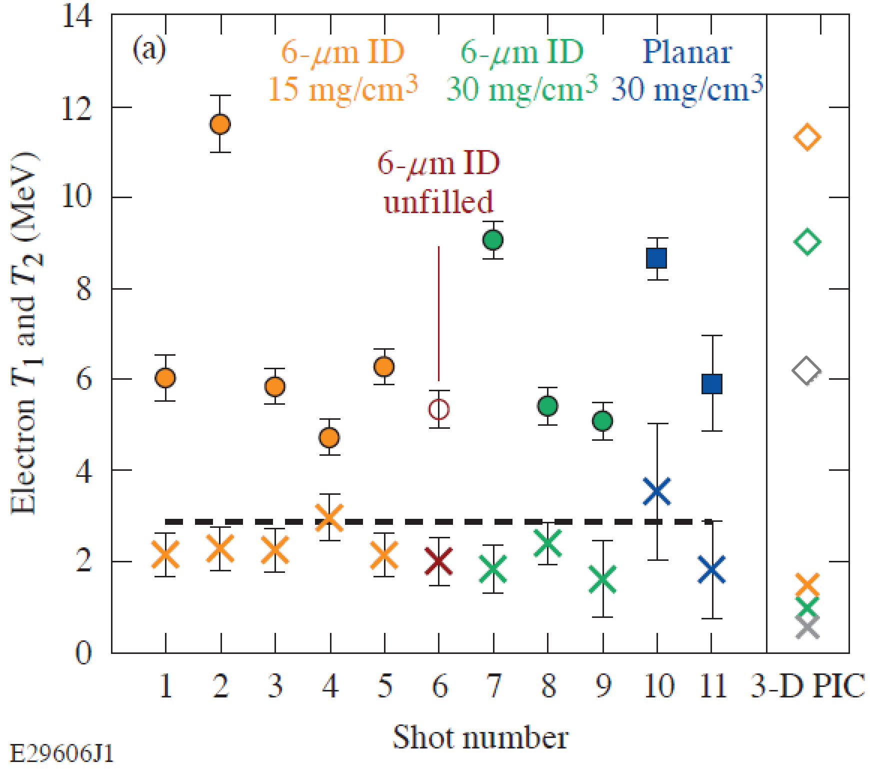
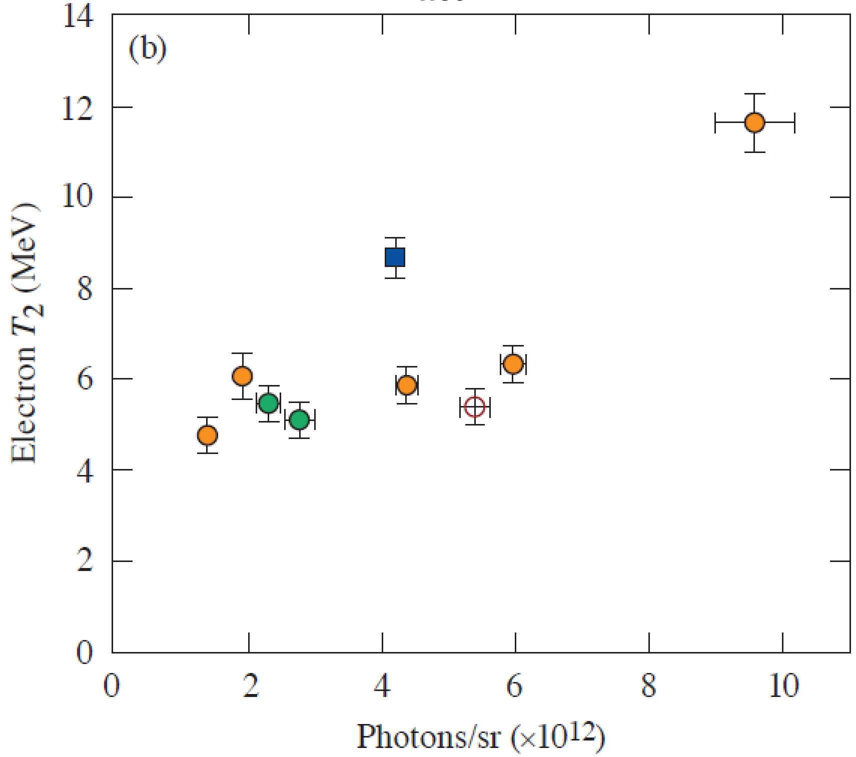


Electron T_{hot} vs # photons



The number of photons > 10 keV also scaled with hot electron temperature as expected.

H.G. Rinderknecht, et al., New J. Phys. **23**, 095009 (2021) doi: 10.1088/1367-2630/ac22e7