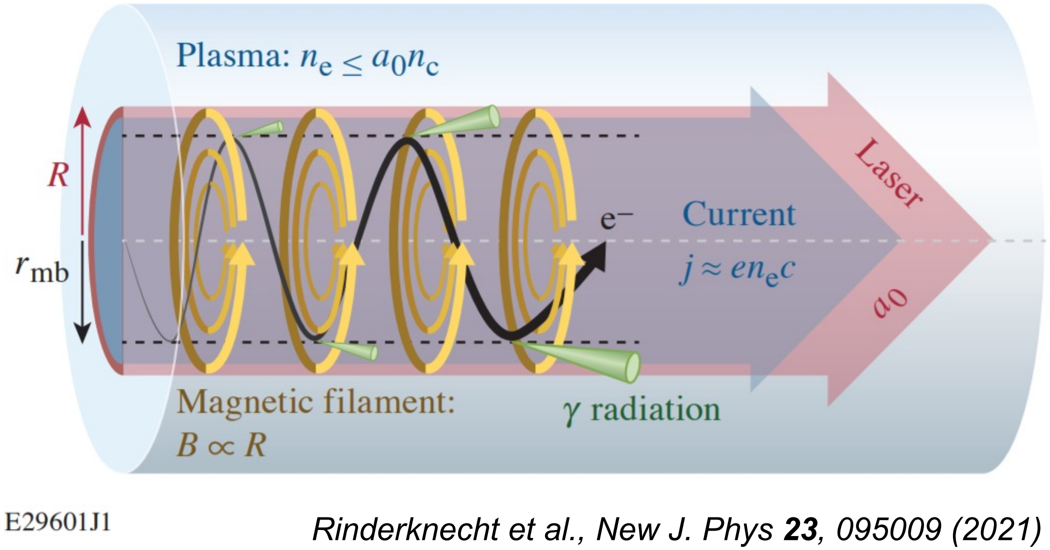
Relativistically Transparent Magnetic Filaments:
a short-pulse path to megaTesla fields and efficient gamma radiation

Schematic of a magnetic filament



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

Hans Rinderknecht
University of Rochester
Laboratory for Laser Energetics

Anomalous Absorption Conference
11:00 AM, Tuesday June 7th 2022

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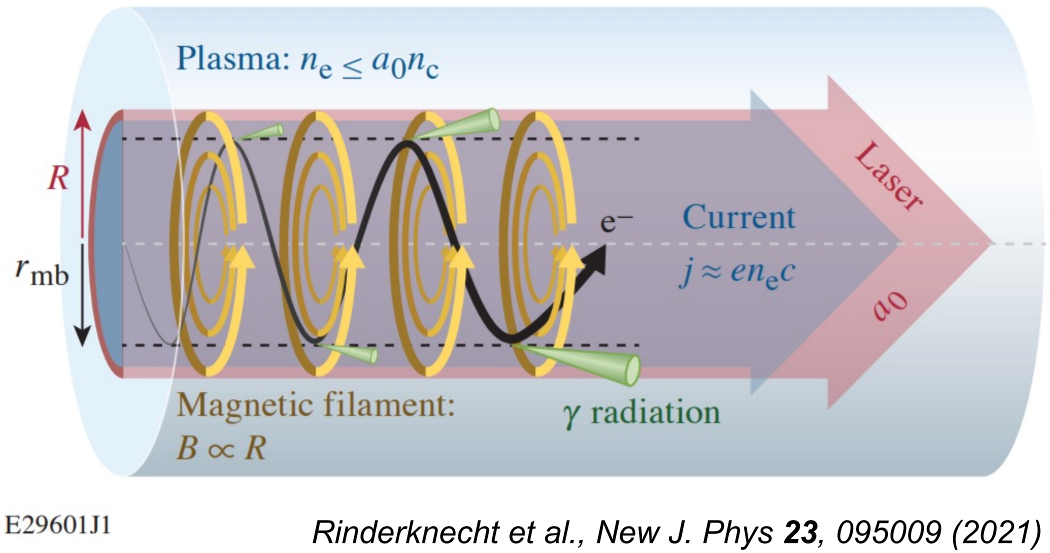
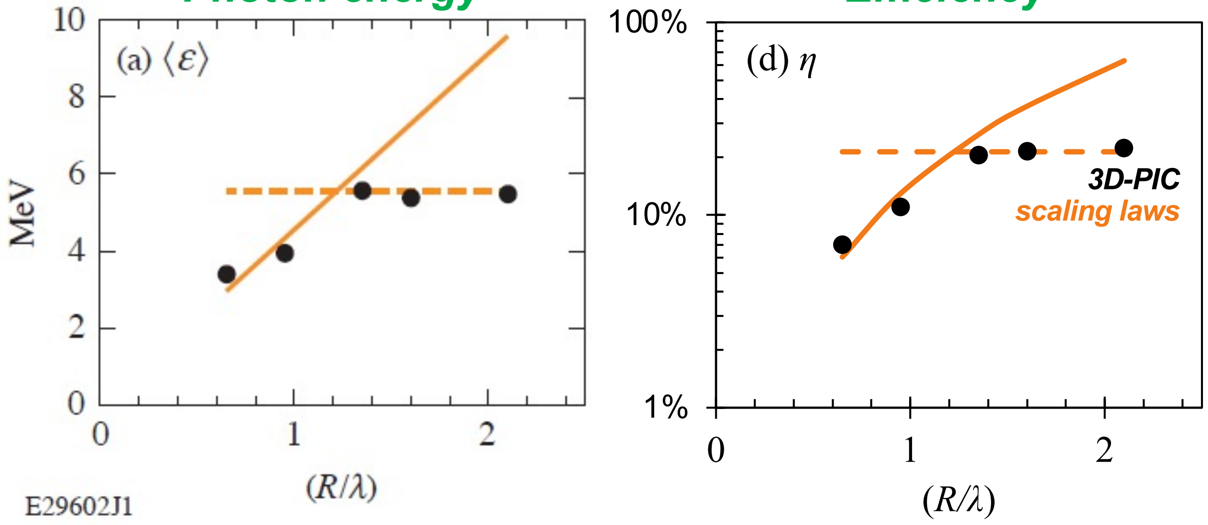


Rinderknecht et al., New J. Phys ***23****, 095009 (2021)*

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



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Magnetic filaments promise a repeatable and efficient laser-driven source of MT fields, 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 6×10^{21} W/cm^2

- **Experiments have been performed on Texas Petawatt and OMEGA-EP to test these predictions**
  – The predicted electron and photon signatures were observed in a subset of experiments

Collaborators

LLE/UR:
- Hans Rinderknecht
- Gerrit Bruhaug
- Kathleen Weichman
- Matthew Van Dusen-Gross
- John Palastro
- Mingsheng Wei

UCSD:
- Alexey Arefiev
- Tao Wang

HZDR:
- Toma Toncian
- Alejandro Laso Garcia

ELI-NP:
- Domenico Doria
- Klaus Spohr

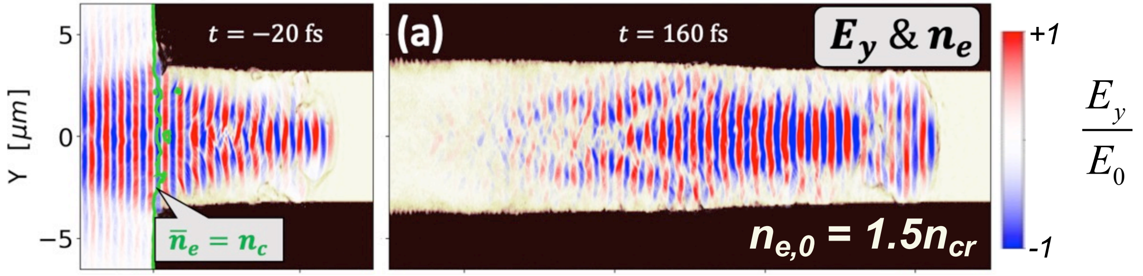
Texas Pettawatt (TPW)/UT Austin:
- Hernan J. Quevedo
- Todd Ditmire

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

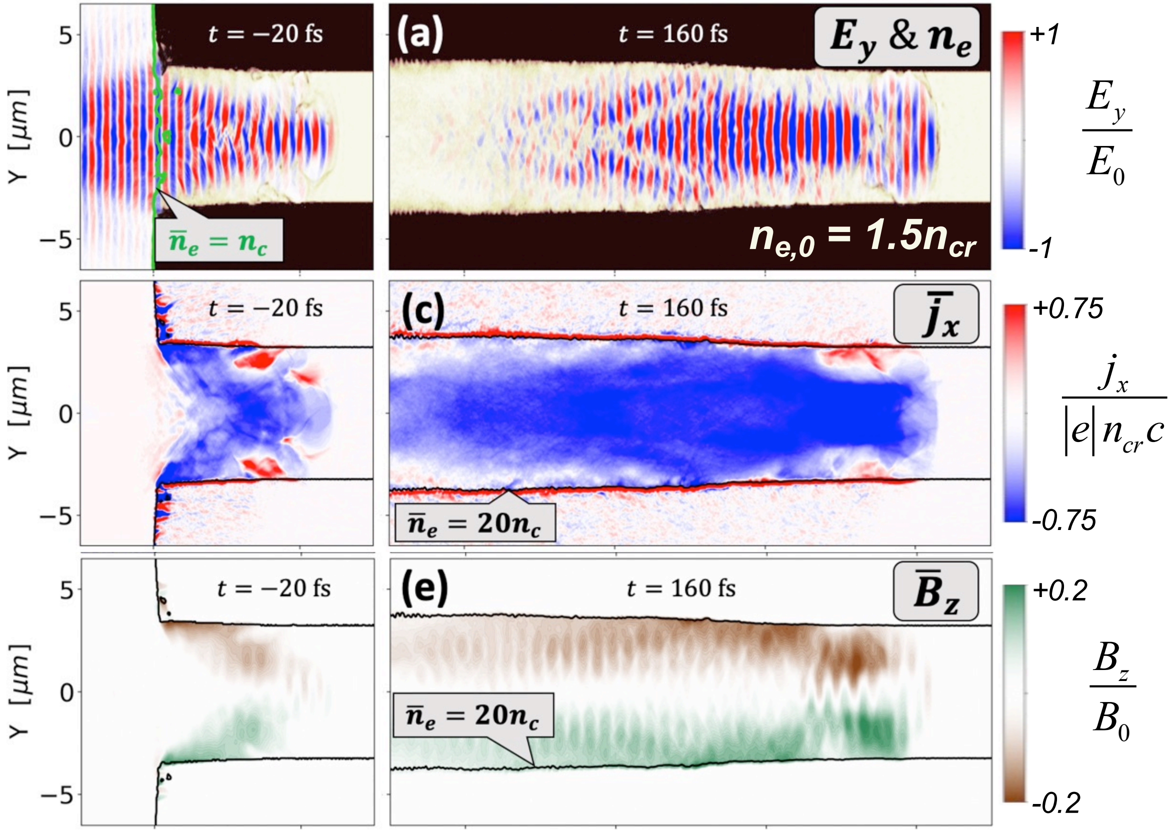
$a_0 > 1 \rightarrow$ Relativistic Transparency:

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

[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:

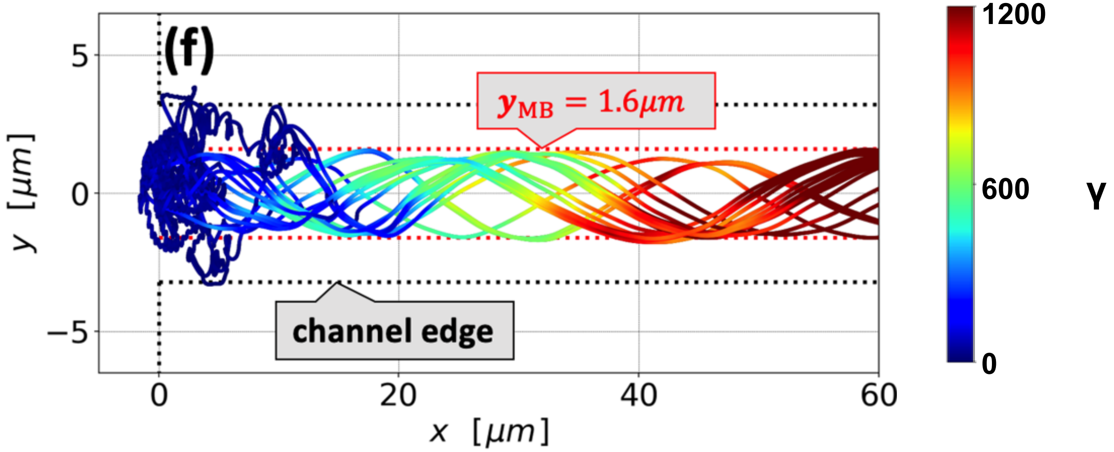
$$\frac{B_j}{B_0} = \left(\frac{\mu_0 j r}{2}\right) \Big/ \left(\frac{2\pi a_0 mc}{e\lambda}\right) = \pi\left(\frac{r}{\lambda}\right)\left(\frac{n_e\beta}{n_{cr}a_0}\right) \equiv \pi r_\lambda S_\alpha$$

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)

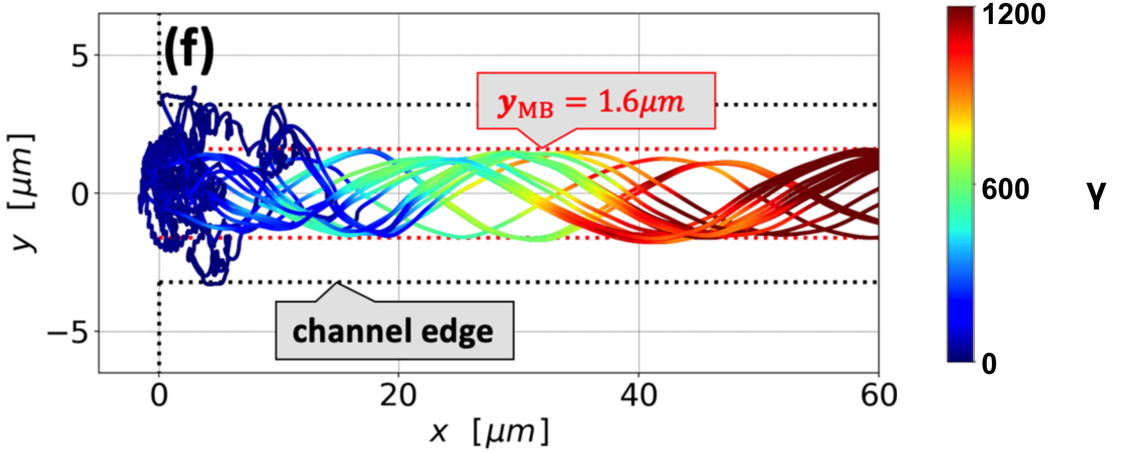
Electrons oscillate within the filament: those in phase with the laser are rapidly accelerated,

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

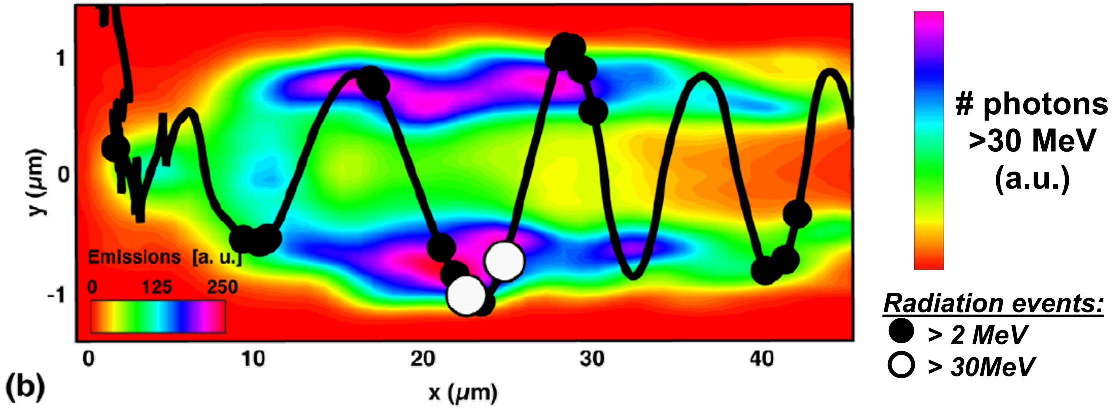


Electrons oscillate within the filament: those in phase with the laser are rapidly accelerated, and radiate in the strong magnetic field.

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



Photon radiation ($a_0 = 190$)[2]

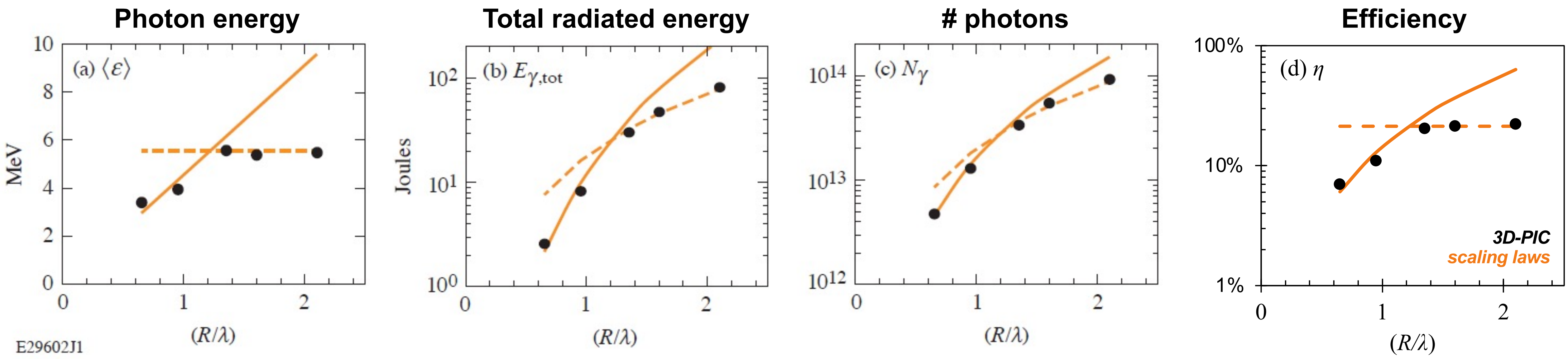


$$\hbar\omega_{rad} \propto \gamma^2 B, \qquad P_{rad} \propto \gamma^2 B^2$$

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

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

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

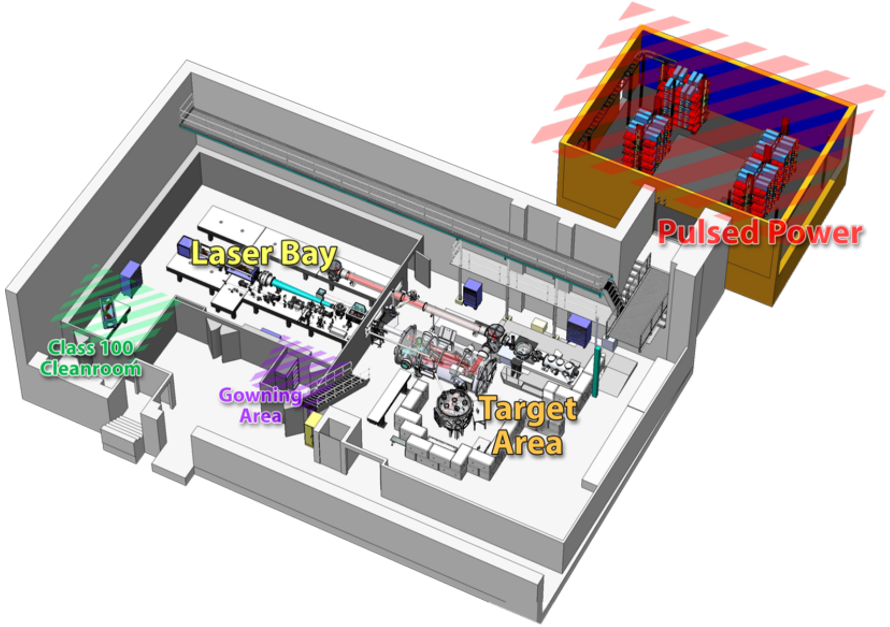


Parameters: a_0 = 190 (5×10^{22} W/cm^2)
S_α = 0.105 (n_e = 20n_{cr})
R_λ = [0.65, 2.1]
τ_V = 10.5 (35 fs)

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

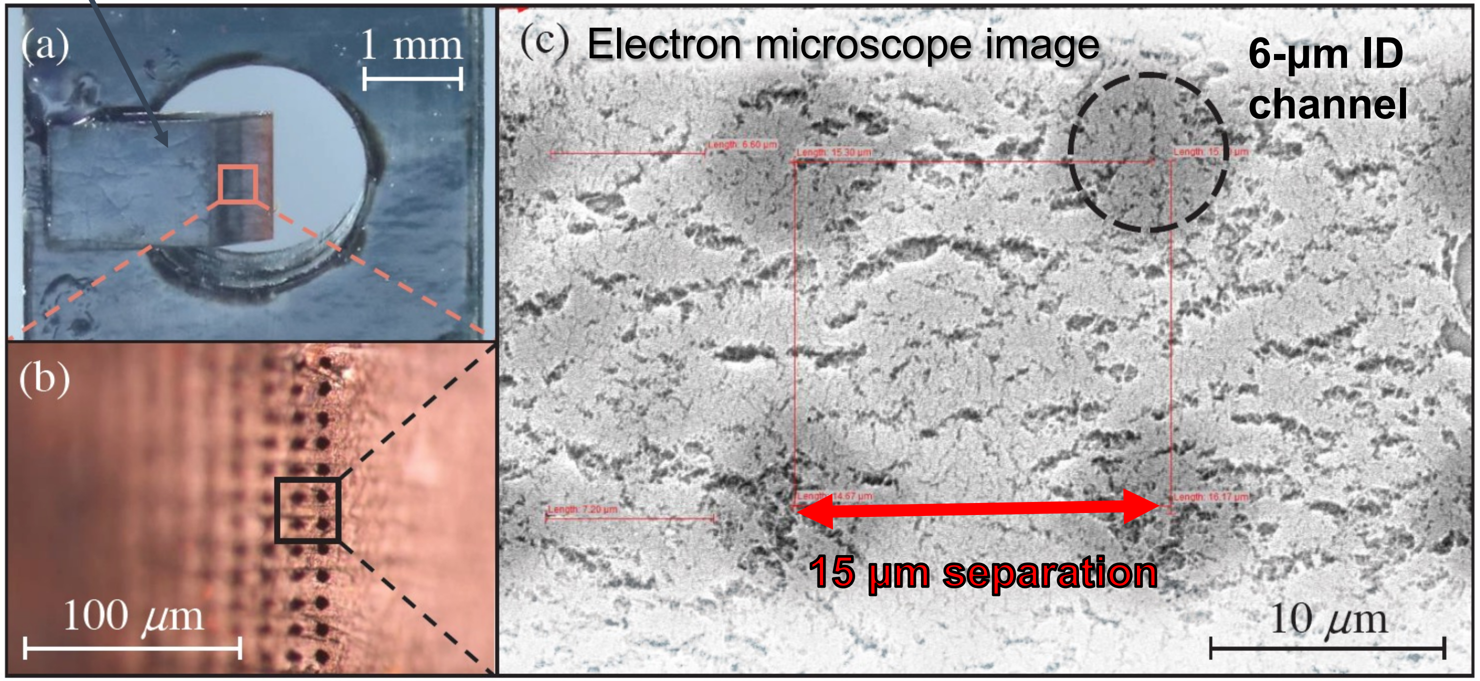
- Intensity: [1.09 ± 0.07]×10^{21} W/cm^2 (a_0 = 29.9 ± 1.0)
- Radius: 2.6 ± 0.12 µm (at 50% peak intensity)
- Pointing: 8-µrad rms → 5-µm rms on target

- **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



E29603J1

laser-drilled channel array

Channels filled with low-density CH foam: 15 or 30 mg/cm^3

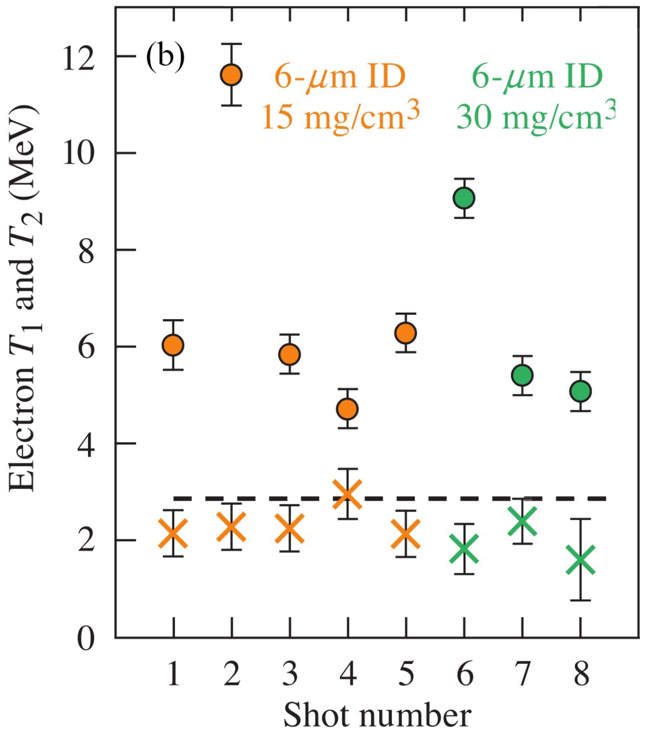
11 shots were performed with good laser-target alignment:

- [×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}

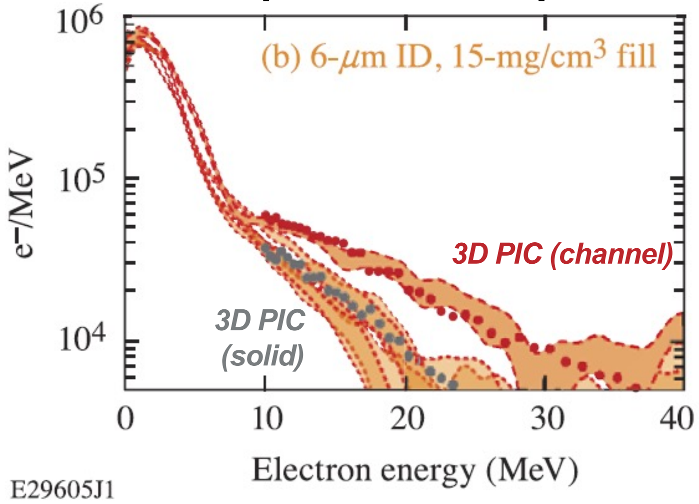
Given the pointing stability (5-μm rms), we did not expect channel interactions on every shot.

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

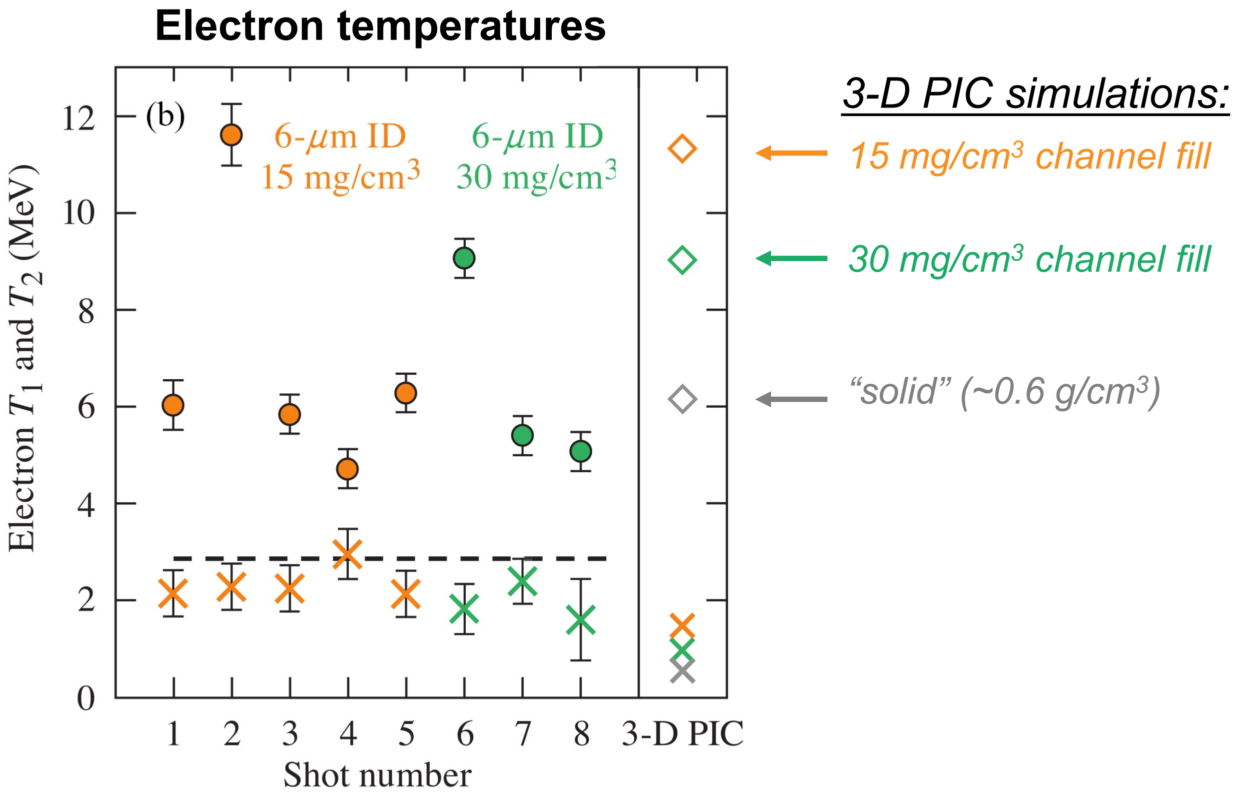
Electron temperatures



Example electron spectra



The ‘hot’ electron temperature was elevated on 2 of 8 microchannel shots, consistent with the predicted magnetic filament behavior



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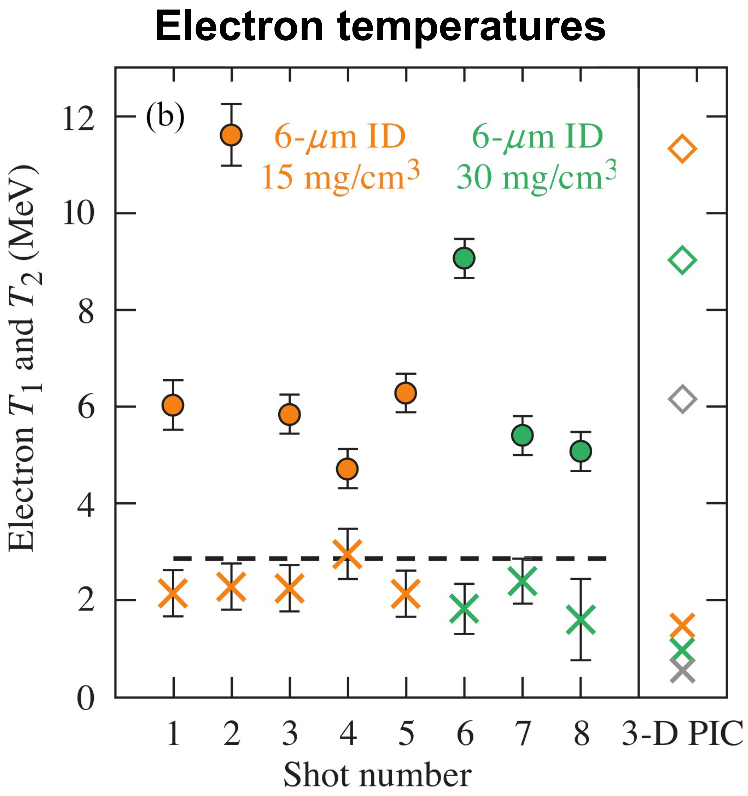


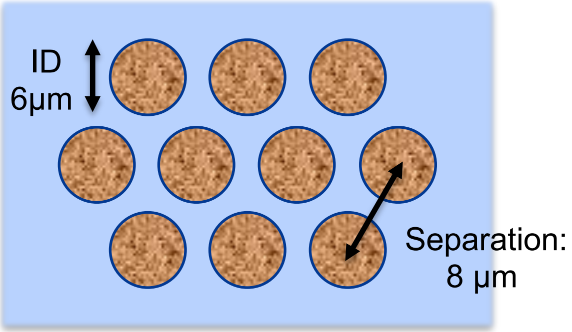
Given the pointing stability and channel size, the probability of observing N interactions is:

N	Probability
0	0.21
1	0.36
2	**0.27**
3	0.12
4	0.03
5+	< 0.01

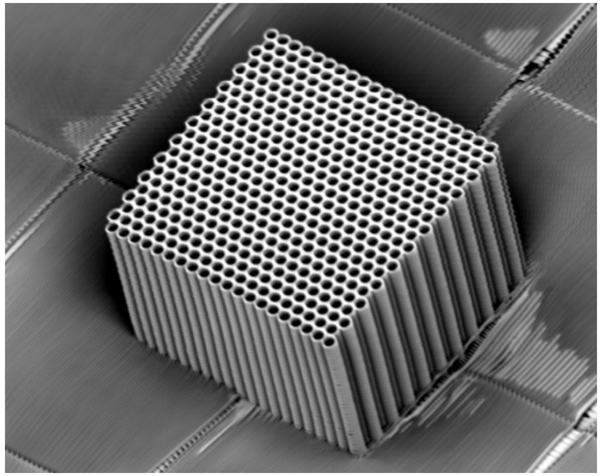
We conclude that the predicted electron acceleration was observed in a subset of these experiments.

A follow-on campaign on OMEGA-EP (Dec 2022) used a new target engineering technique to improve laser-target coupling: 3-D printing *inside* foam

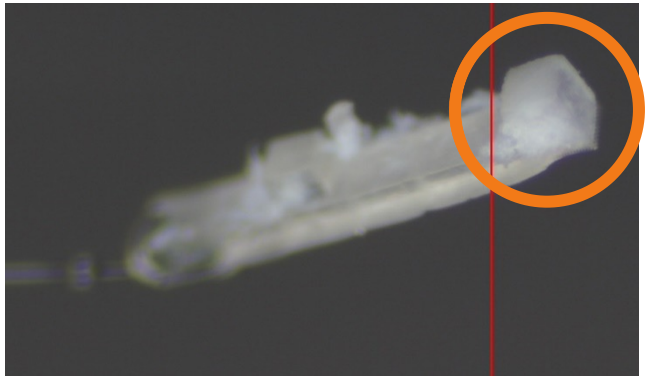
Target Geometry

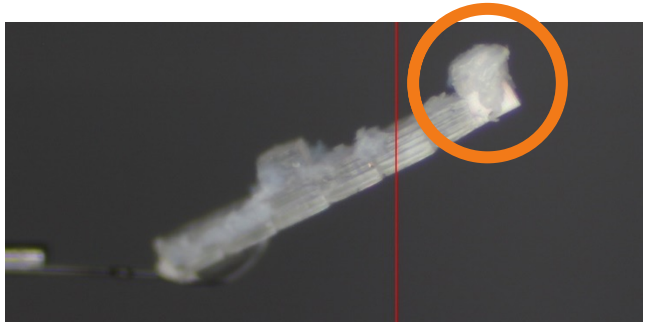


Electron radiograph (empty channels)



Foam-filled channel targets:





Shot #	Beam	Peak I ×10^{20}	a_0 max	Target ρ
35891	BL	3.49	16.8	Empty channels
35892	SL	1.42	10.7	Empty channels
35893	BL	10.1	28.6	3 mg/cc (1 n_{cr})
35894	SL	3.84	17.6	3 mg/cc (1 n_{cr})
35895	BL	7.69	25.0	3 mg/cc (1 n_{cr})
35896	SL	3.01	15.6	3 mg/cc (1 n_{cr})
35897	BL	9.64	28.0	5 mg/cc (1.6 n_{cr})
35898	SL	3.08	15.8	3 mg/cc (1 n_{cr})
35899	BL	6.76	23.4	5 mg/cc (1.6 n_{cr})
35900	SL	2.74	14.9	5 mg/cc (1.6 n_{cr})
35901	BL	6.56	23.1	5 mg/cc (1.6 n_{cr})
35902	SL	4.49	19.1	5 mg/cc (1.6 n_{cr})
35903	BL	6.80	23.5	Empty channels
35904	SL	1.55	11.2	5 mg/cc (1.6 n_{cr})

This technique increases the density of channel openings and guarantees the foam fully fills the channel.

The first OMEGA-EP experiments show electron acceleration on all target types: No significant difference was observed between target types**

EPPS data:

electron spectra:

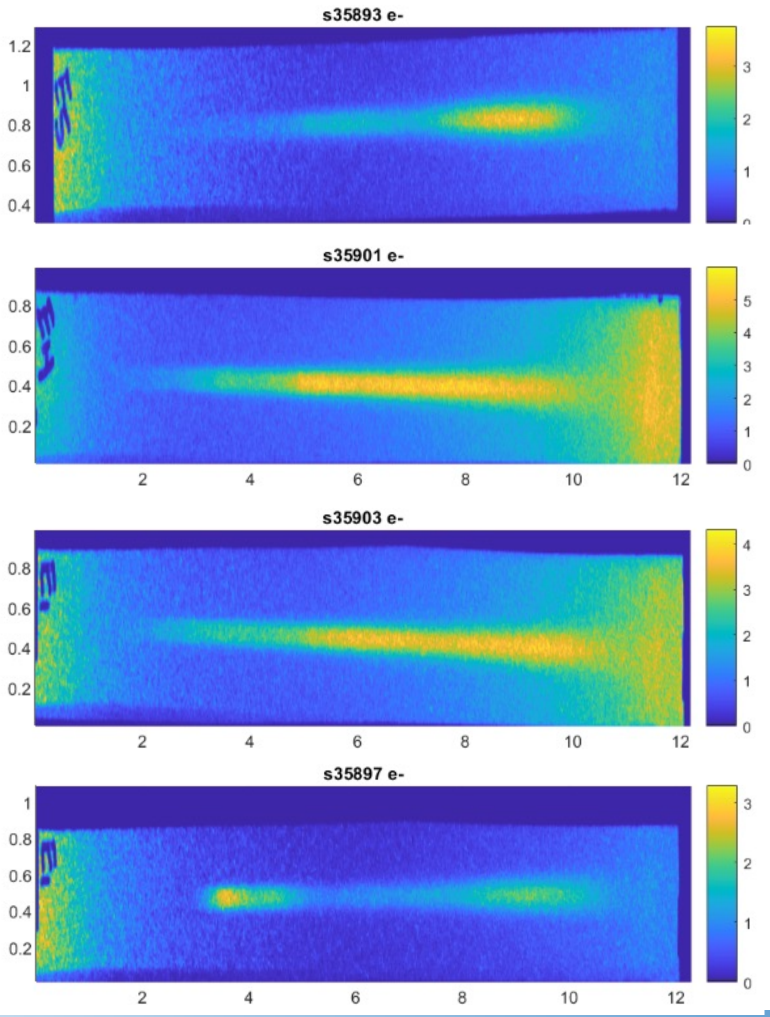
Shot 35893: BL, **3 mg/cc**

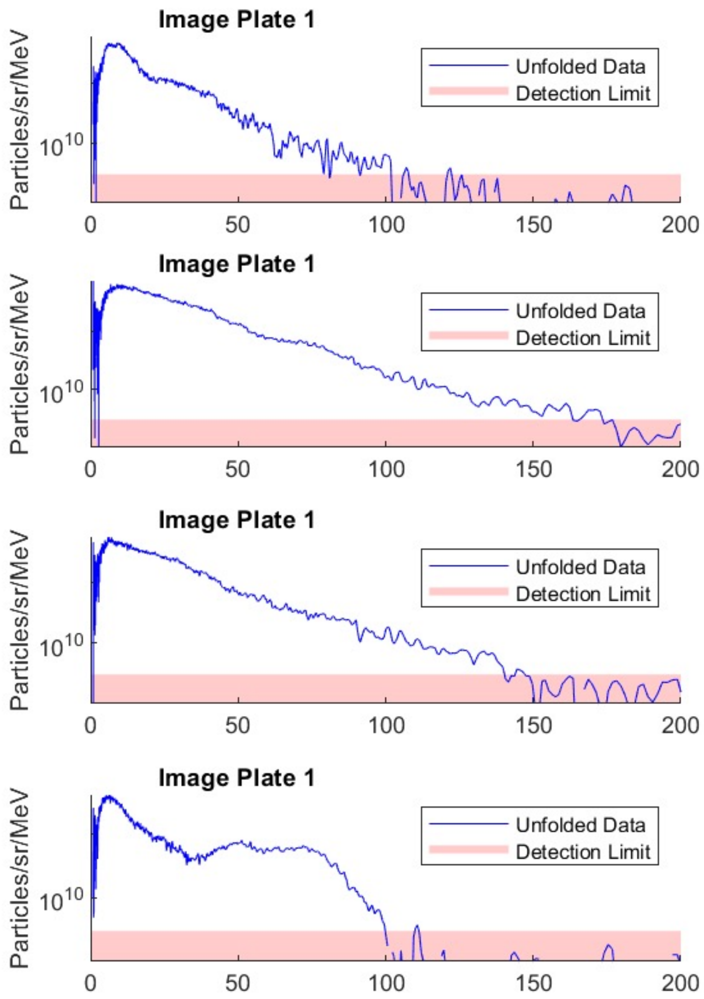
Shot 35901: BL, **5 mg/cc**

Shot 35903: BL, **empty**

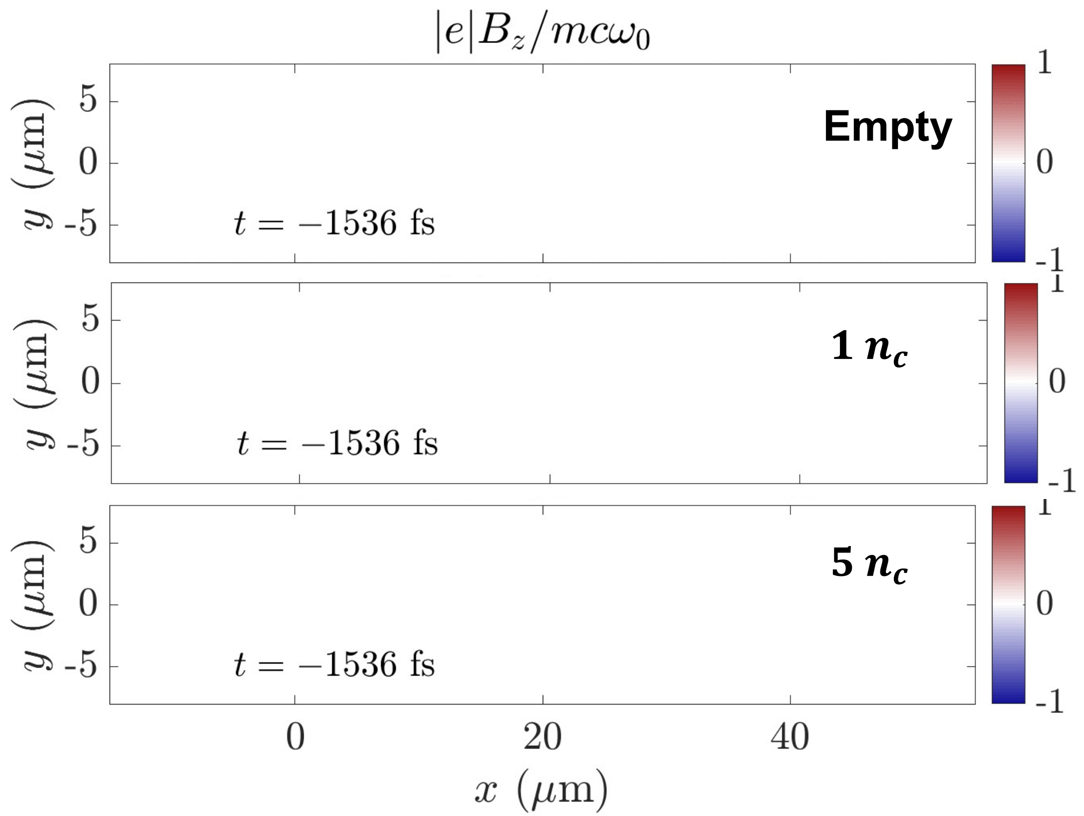
***possible exception*

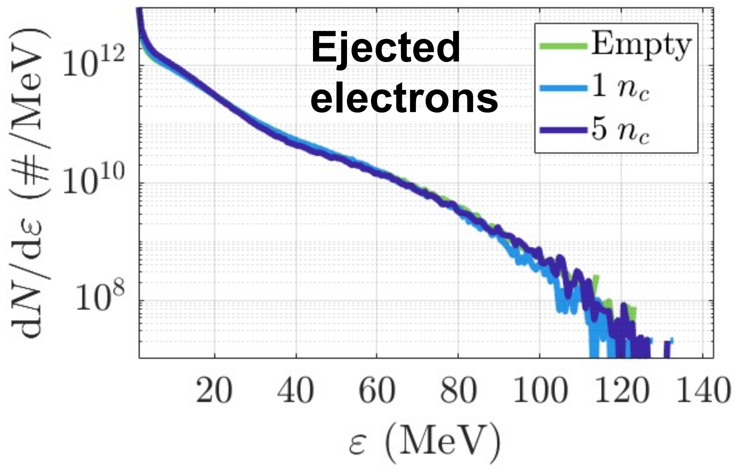
Shot 35897: BL, **5 mg/cc**

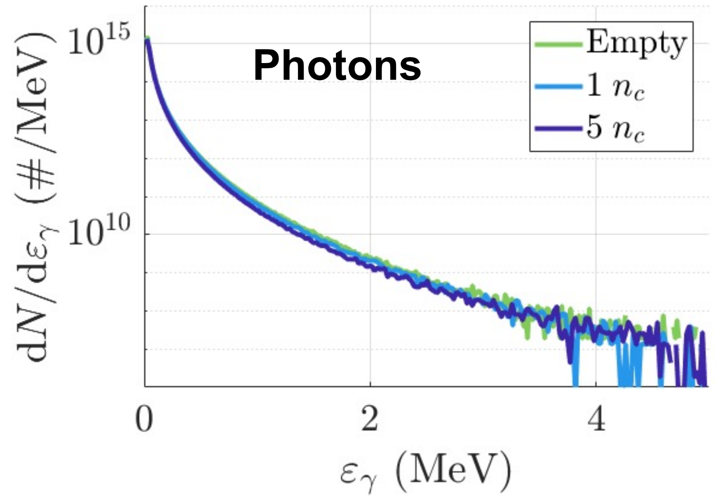




Subsequent 3-D PIC simulations predict that, for 0.7 ps pulses, the magnetic field amplitude and electron and x-ray spectra are independent of fill density





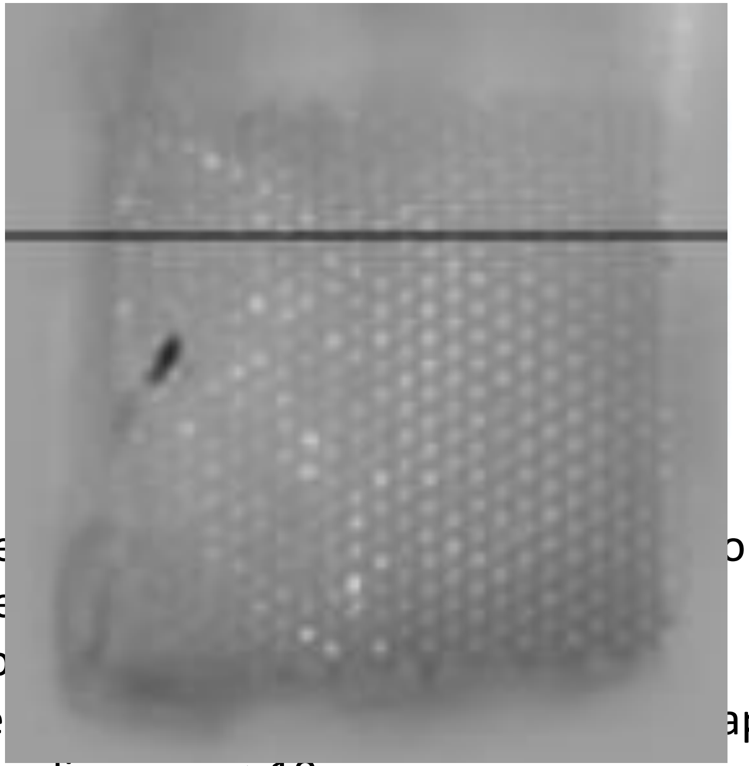


All cases essentially behave the same as the empty channel

Slide courtesy of: Kathleen Weichman

For future EP experiments, we will continue to test out advanced targets for improved laser-channel coupling and “long-pulse” coupling physics

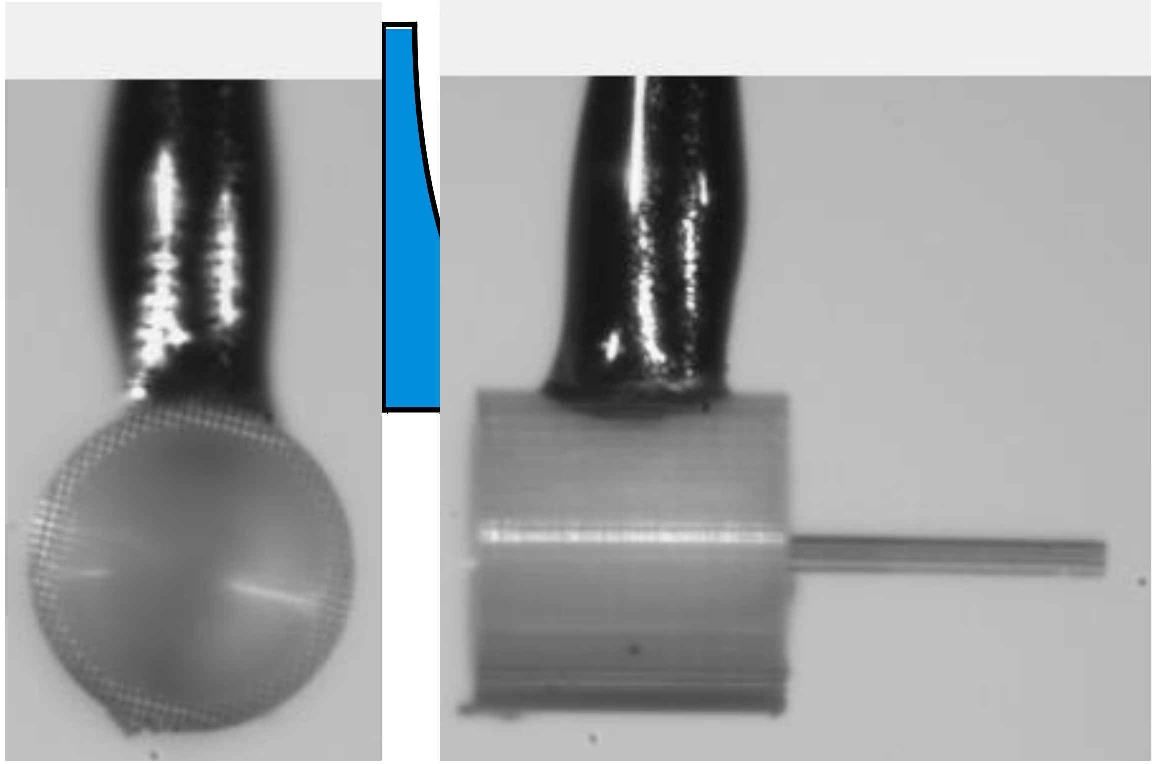
Improved target arrays (June 15, 2022)



Channe … ond foam.
Channe …

- reso …
- At e … apering to 6 µm diam over >10 µm
- Tan(Angle) < (1.5) / (10) → $\phi < 9°$

Contentrator targets (Matt Van-Dusen Gross (GS), FY23)



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

Laser	**ELI-NP†**		**ELI-Beamlines L4‡**	
λ	0.8 μm		1.057 μm	
τ	23 fs		150 fs	
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:	**$S_\alpha = 0.01$**	**$S_\alpha = 0.05$**	**$S_\alpha = 0.01$**	**$S_\alpha = 0.05$**
Photon energy $\langle\varepsilon_*\rangle$	**68 MeV**	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*

Magnetic filaments promise a repeatable and efficient laser-driven source for MT fields, 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
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  - Efficiency of >10% is predicted for intensity above ~10^{22} W/cm^2
- **Experiments have been performed on Texas Petawatt and OMEGA-EP to test these predictions**
  - The predicted electron and photon signatures were observed in a subset of experiments

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.

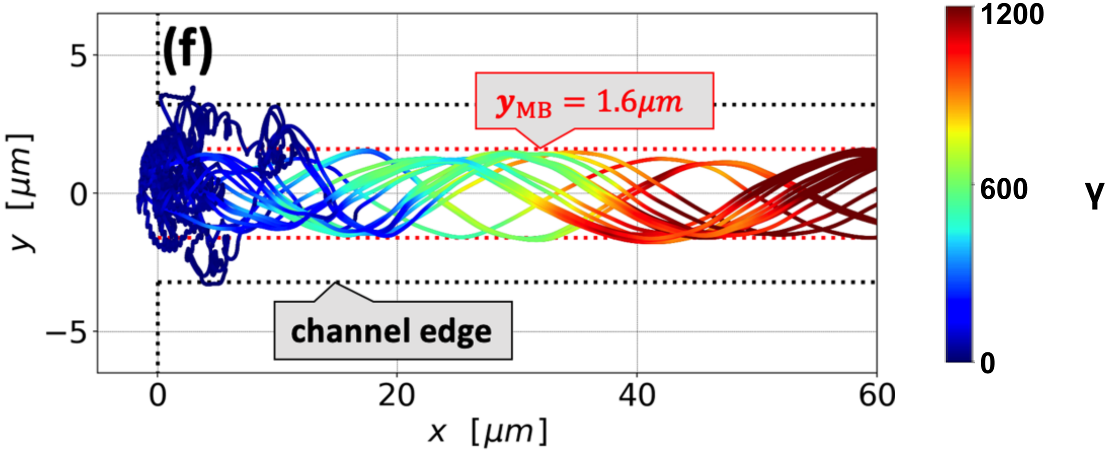
Magnetic boundary[1]:

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

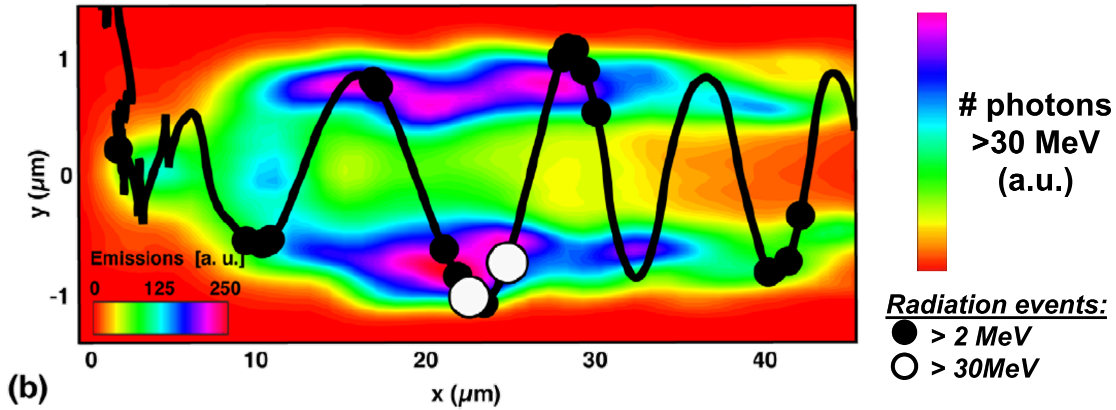
$$\left(f_i \equiv \frac{\gamma_i}{a_0}\right)$$

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]



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

UR LLE

0: Electrons are thermal

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

1: Electron acceleration is linear in time

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

2: Radiation is synchrotron-like

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

3: The laser depletes by heating electrons

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

These assumptions have four constants: f_i, f_t, f_r, C_T and four design parameters: a_0, S_α, R/λ, $c\tau/\lambda$

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	$\langle \acute{U} \rangle_{tot} \approx 1.38\times10^{-6}\ f_t^2 a_0^3 S_\alpha^{-1} R_\lambda \lambda_{\mu m}^{-1}\, m_e c^2$	$\langle \acute{U} \rangle_{tot} \approx 4.40\times10^{-7}\sqrt{f_i}\, f_t^2 a_0^3 S_\alpha^{-3/2} \lambda_{\mu m}^{-1}\, m_e c^2$
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)
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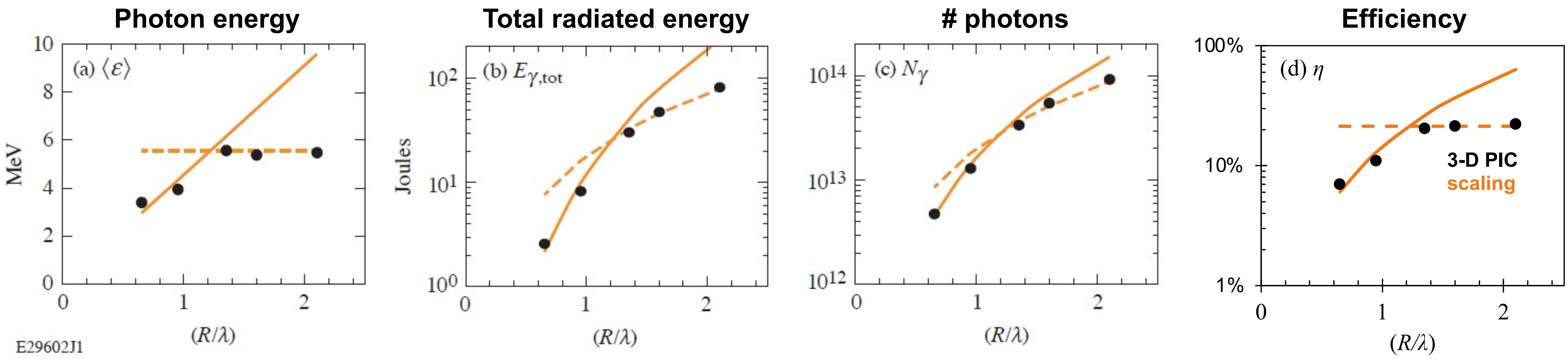
The scaling laws show good agreement with 3-D PIC simulations that varied the focal radius, with reasonable constants



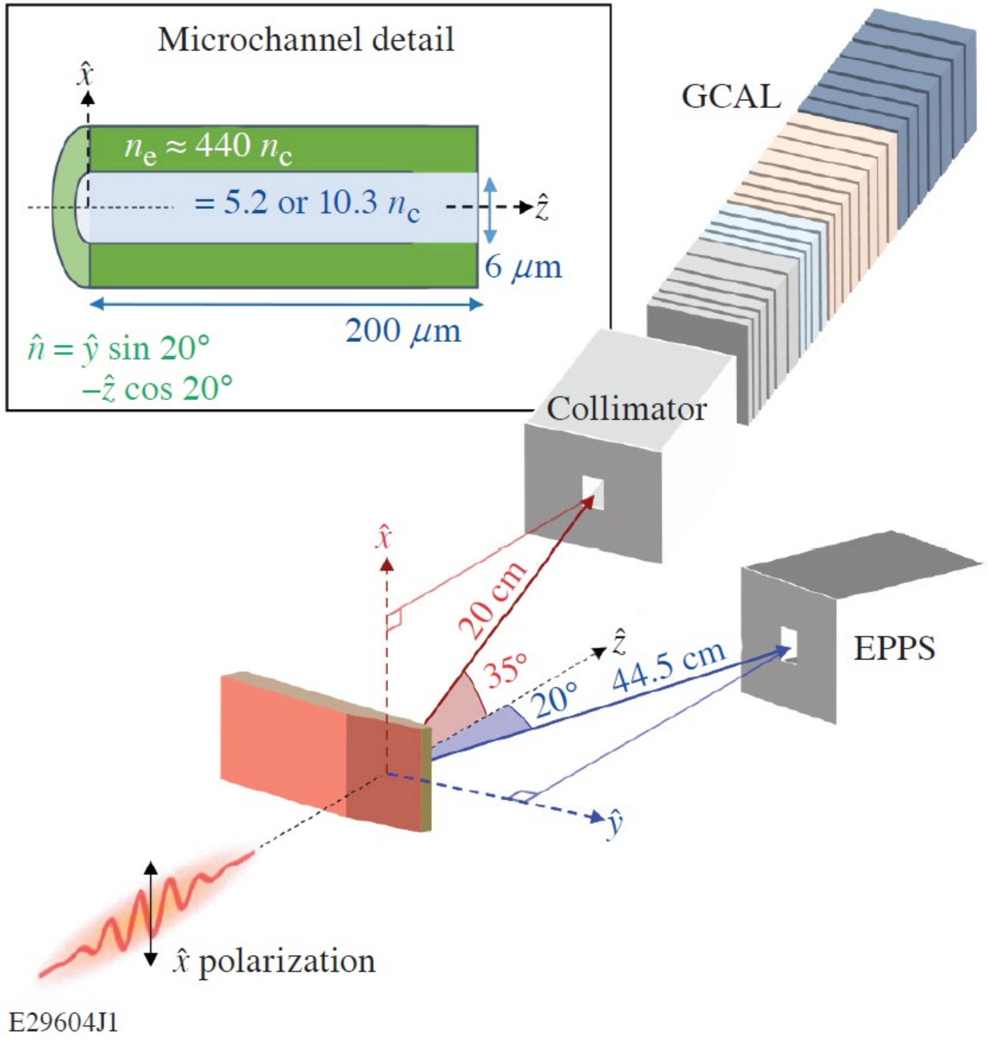
Parameters: a_0 = 190 (5×10^{22} W/cm^2)
S_α = 0.105 (n_e = 20n_{cr})
R_λ = [0.65, 2.1]
τ_v = 10.5 (35 fs)

Constants:

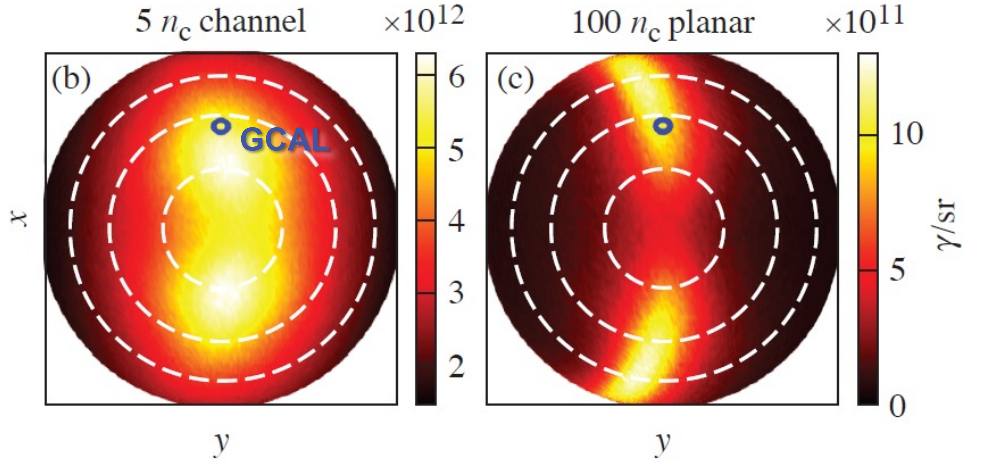
f_i = 1.533,	initial electron momentum scalar,	$\gamma_i \equiv f_i a_0$
f_t = 0.311,	cutoff time scalar,	$t_{\nu,cut} \equiv f_t t_{\nu,max}$
f_r = 0.189,	radiation duty cycle,	$P \equiv f_r P_{synch}$

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

Primary diagnostics were an electron spectrometer (EPPS) and a gamma calorimeter (GCAL) in the expected radiation direction



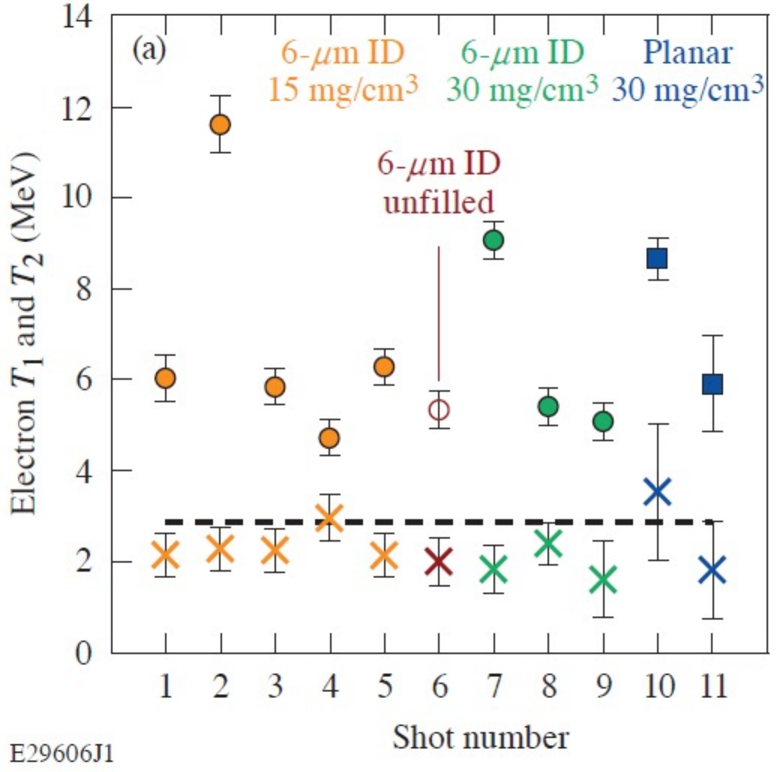
Simulated x-ray profiles (> 10 keV)



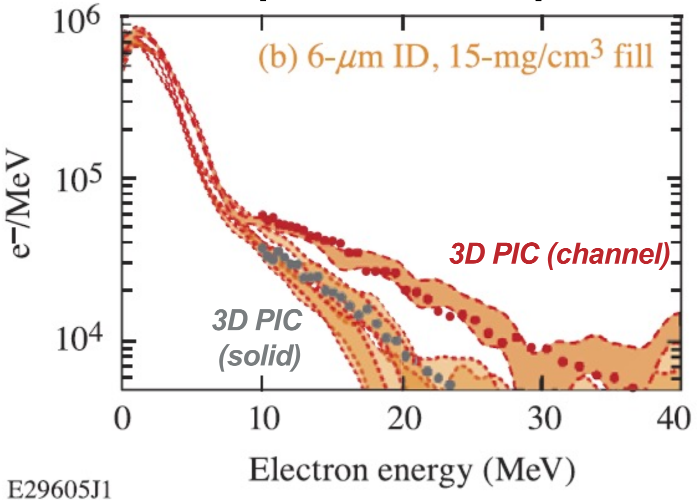
A factor of 5 difference in photon brightness is predicted between microchannel and 'solid' targets.

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

Electron temperatures



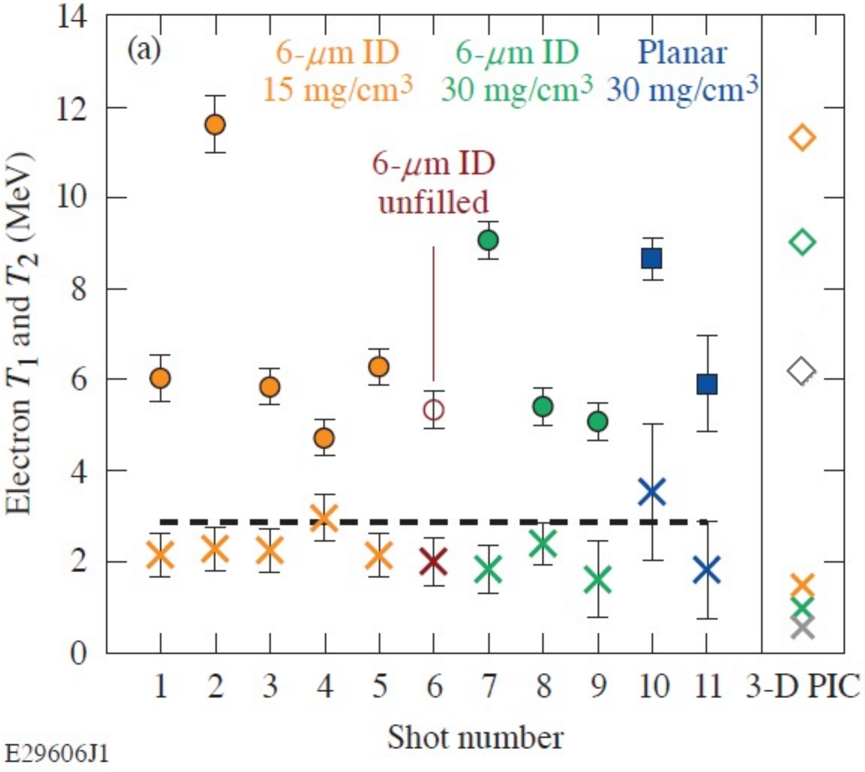
Example electron spectra



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

The 'hot' electron temperature was elevated on 2 of 8 microchannel shots, consistent with the predicted magnetic filament behavior

Electron temperatures



3-D PIC simulations:

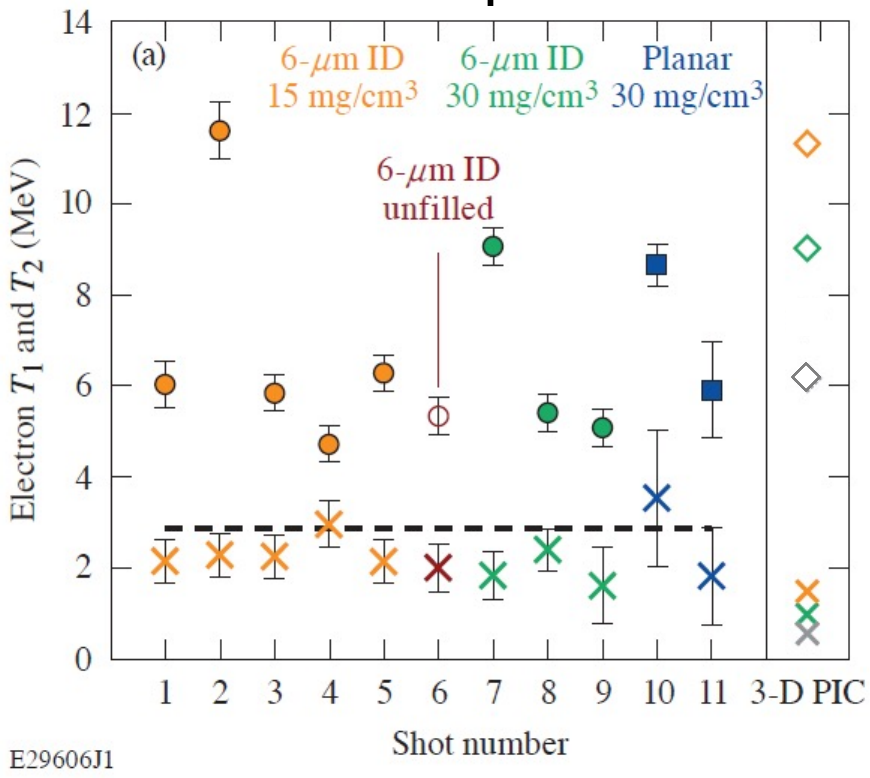
15 mg/cm³ channel fill

30 mg/cm³ channel fill

"solid" (~0.6 g/cm³)

The 'hot' electron temperature was elevated on 2 of 8 microchannel shots, consistent with the predicted magnetic filament behavior

Electron temperatures



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

N	Probability
0	0.21
1	0.36
2	**0.27**
3	0.12
4	0.03
5+	< 0.01

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

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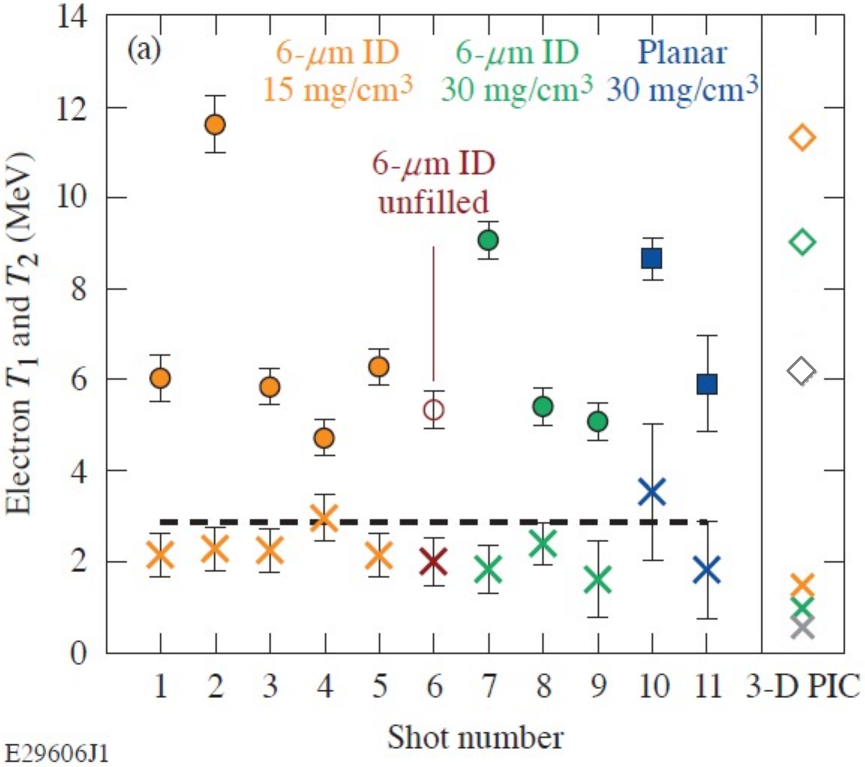
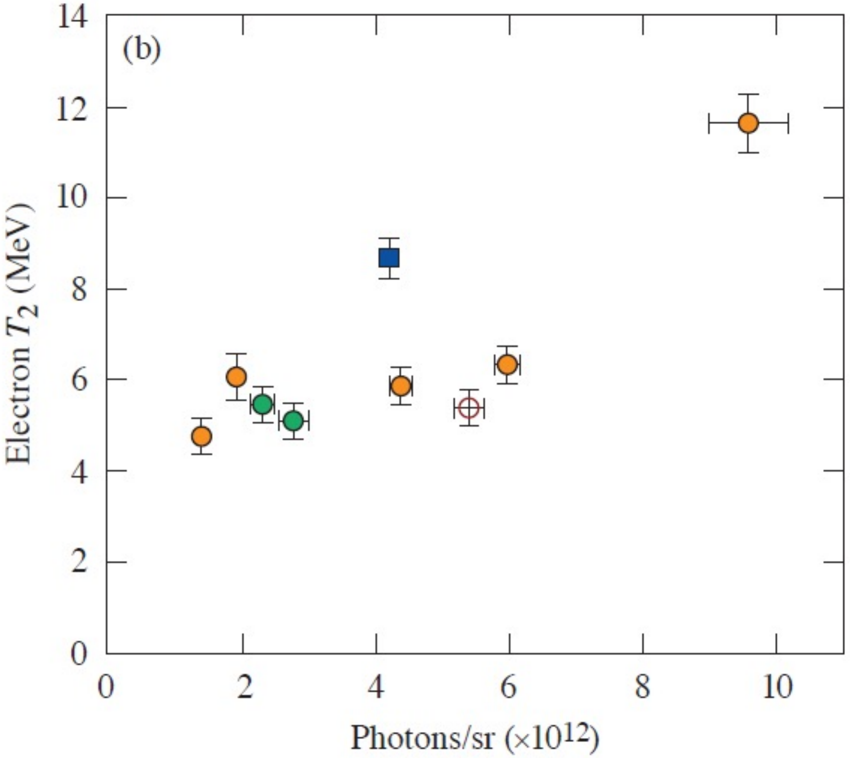


Electron T_{hot} vs # photons



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

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