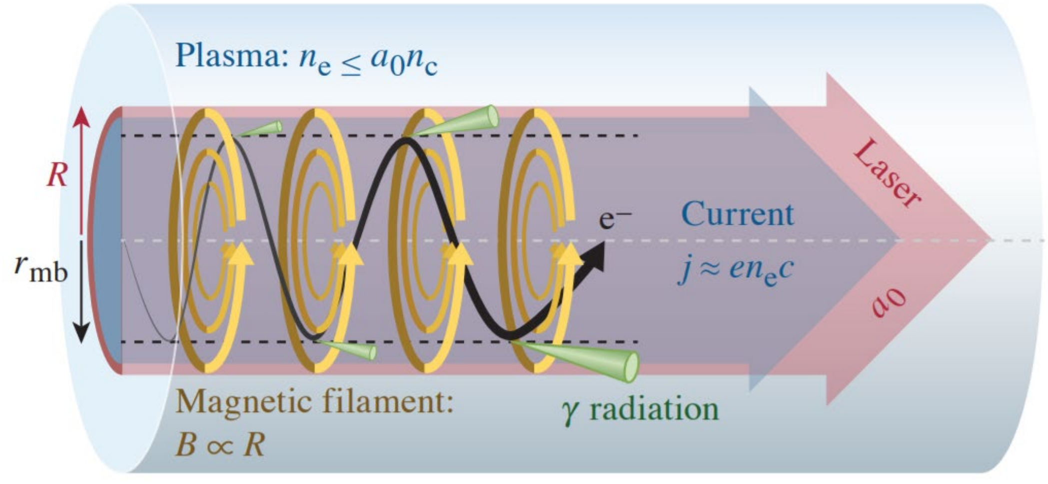
Initial Experimental Results on Relativistically Transparent Magnetic Filaments

Schematic of a magnetic filament



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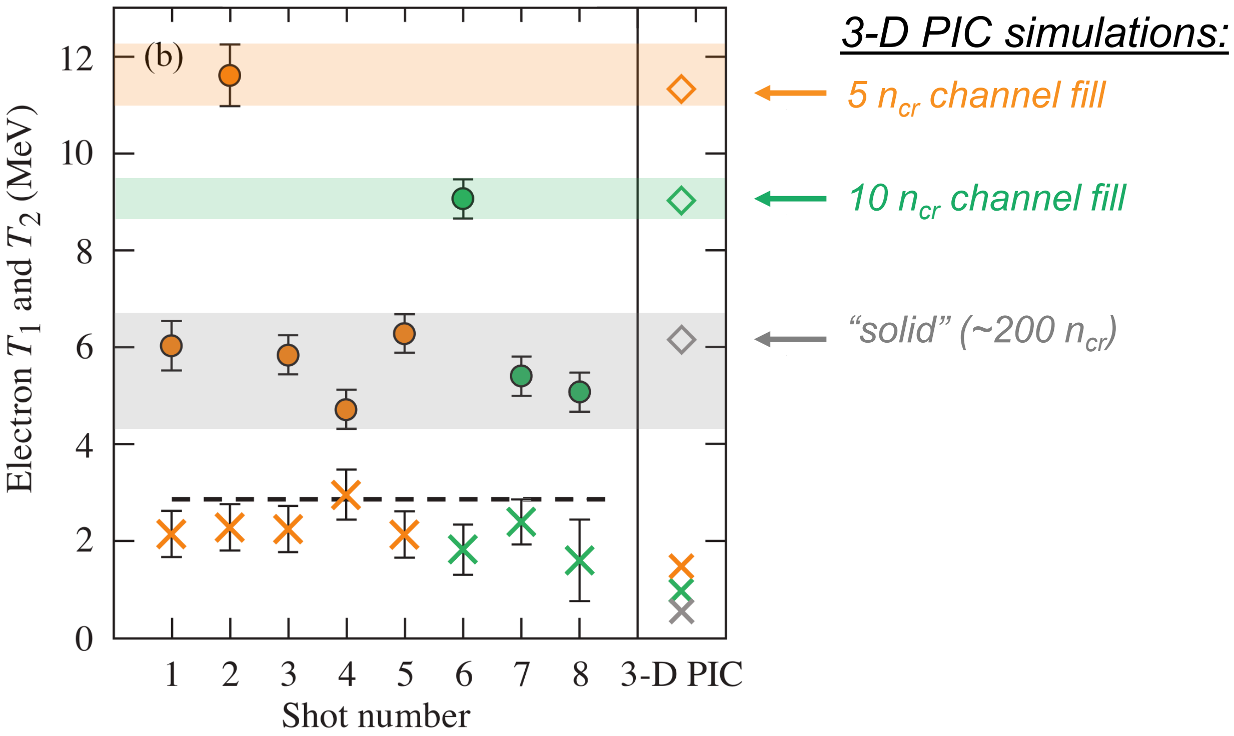
Rinderknecht et al., New J. Phys ***23****, 095009 (2021)*

Electron temperatures (TPW)



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University of Rochester
Laboratory for Laser Energetics

64th annual APS-DPP meeting
Spokane, WA
11:42 AM, Monday Oct 17th 2022

Summary

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
- **Short-pulse (140 fs) experiments at TPW demonstrated magnetic filament radiation**
  - The predicted electron and photon signatures were observed in a subset of experiments
- **Longer pulse (700 fs) experiments on OMEGA-EP show different behavior**
  - Electron acceleration does not appear to depend on initial channel density

Collaborators

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

UCSD:
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HZDR:
- Toma Toncian
- Alejandro Laso Garcia

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

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- Jarrod Williams
- Alex Haid

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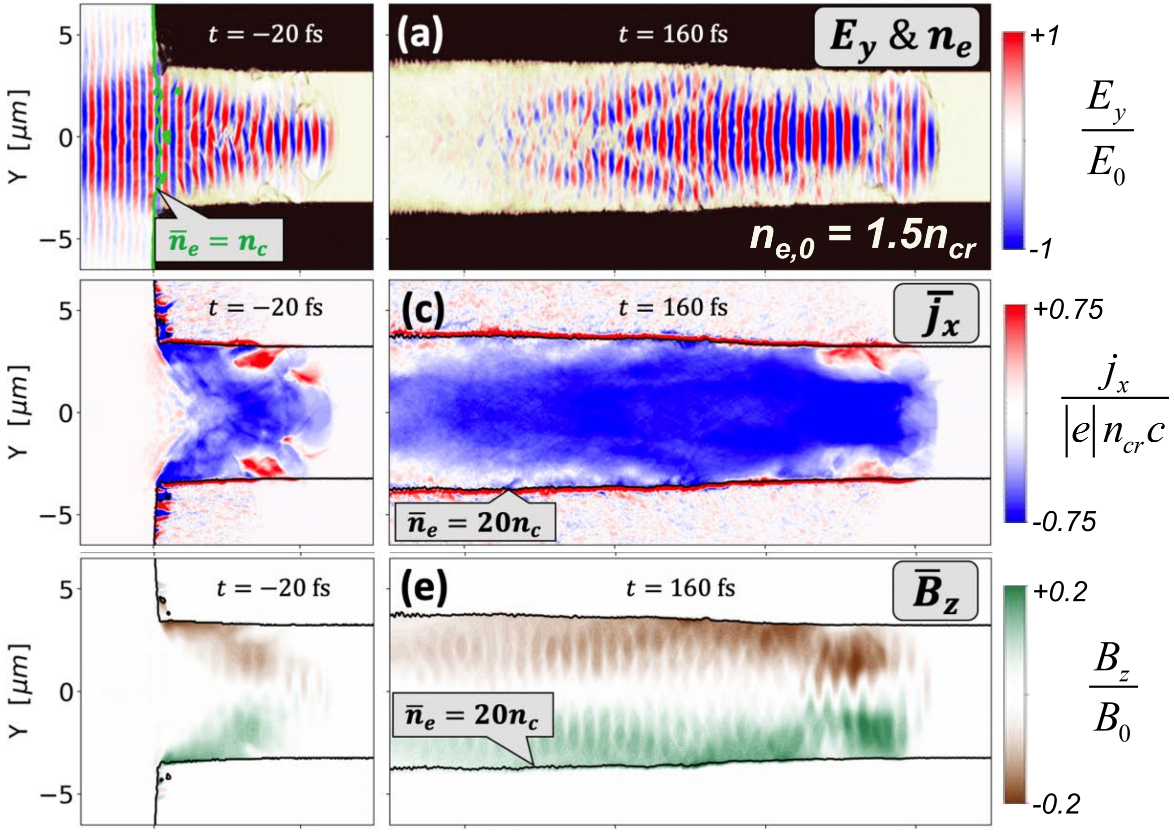
- Dan Stutman

A relativistically-transparent laser pulse drives a relativistic current in a plasma channel, with a strong azimuthal magnetic field: a magnetic filament

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



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

Magnetic field of current normalized to laser field:

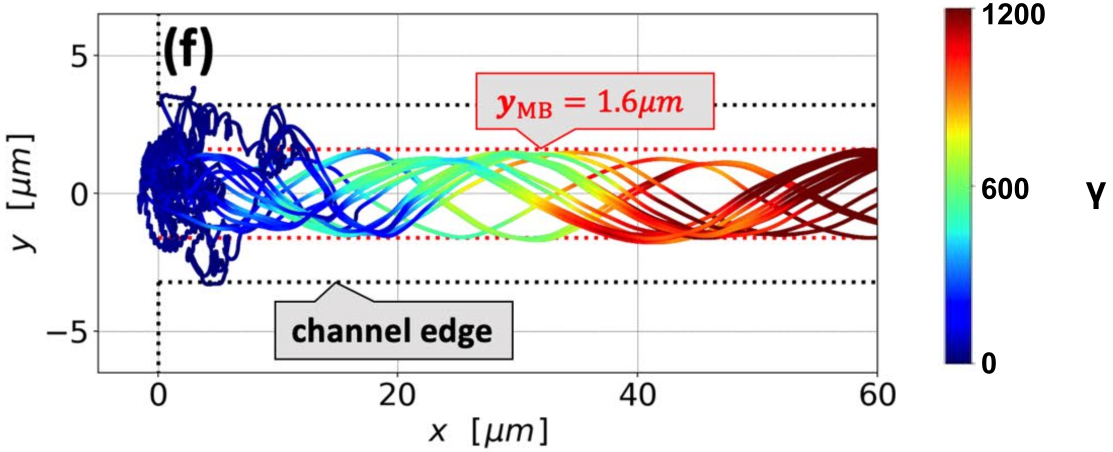
$$\frac{B_j}{B_0} = \left(\frac{\mu_0 j r}{2}\right) \Big/ \left(\frac{2\pi a_0 mc}{e\lambda}\right) = \pi\left(\frac{r}{\lambda}\right)\left(\frac{n_e \beta}{n_{cr} a_0}\right)$$

Quasi-static magnetic fields with amplitude of the order of the 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,

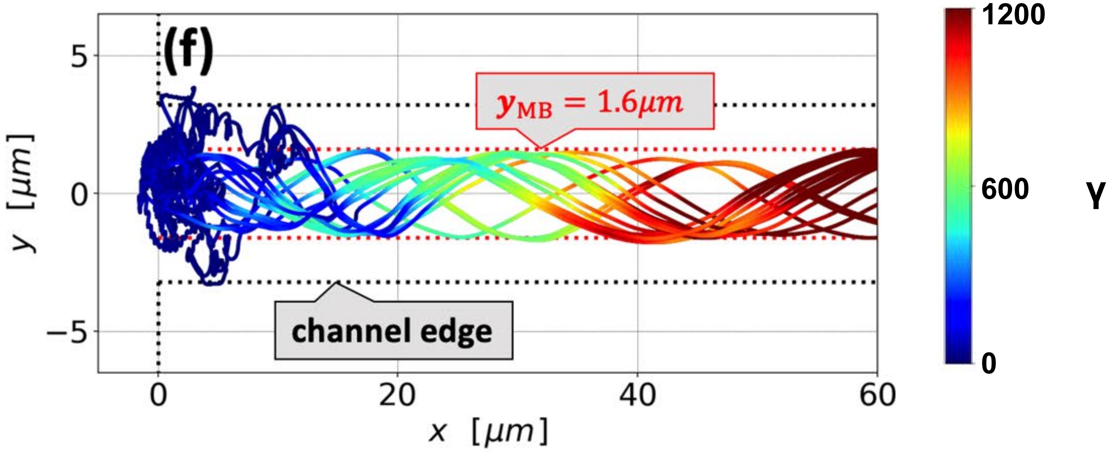
Electron orbits & acceleration (a_0 = 50)[1]



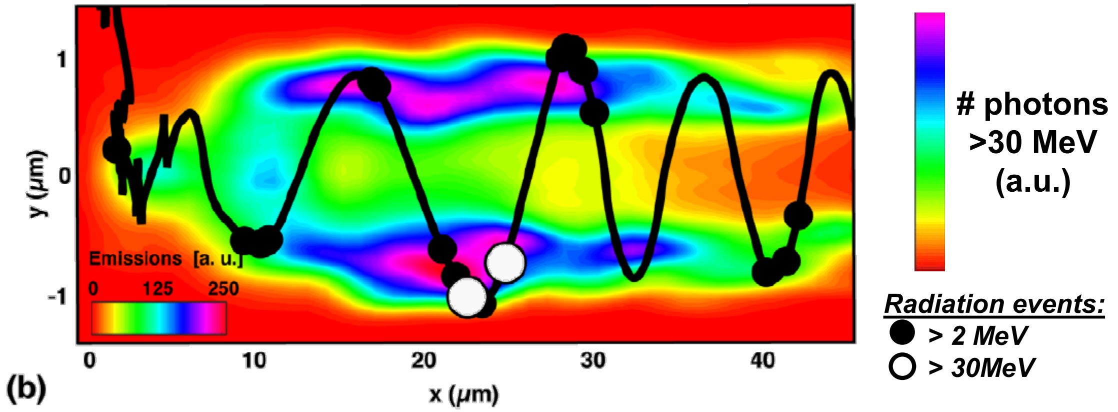
[1]Z. Gong, et al., Phys. Rev. E 102, 013206 (2020);

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]



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

At ultrahigh intensities, magnetic filaments are predicted to radiate MeV photons with > 10% efficiency

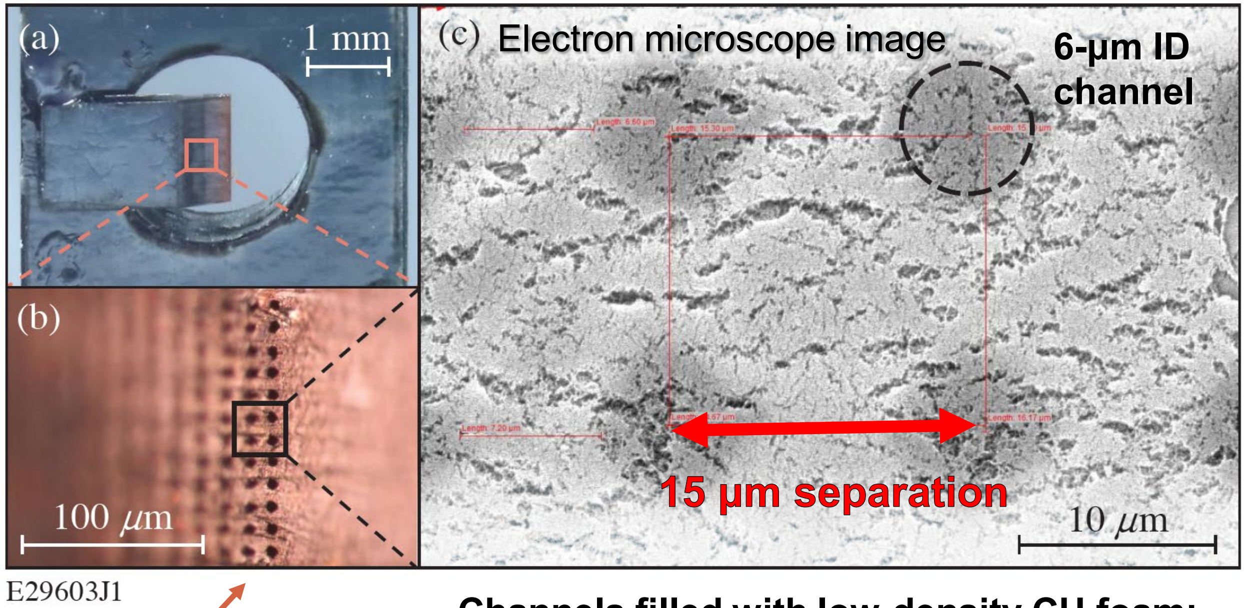
[1]Z. Gong, et al., Phys. Rev. E 102, 013206 (2020); [2]D. J. Stark, et al., Phys. Rev. Lett. 116, 185003 (2016)

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

Laser:

- **Wavelength:** 1057 nm
- **Duration:** 140 fs
- **Intensity:** [1.09 ± 0.07]×10^{21} W/cm^2; a_0 = 29.9 ± 1.0
- **Pointing:** 8-μrad rms → 5-μm on target
- **Primary diagnostic:** EPPS electron spectrometer

Targets:



laser-drilled channel array

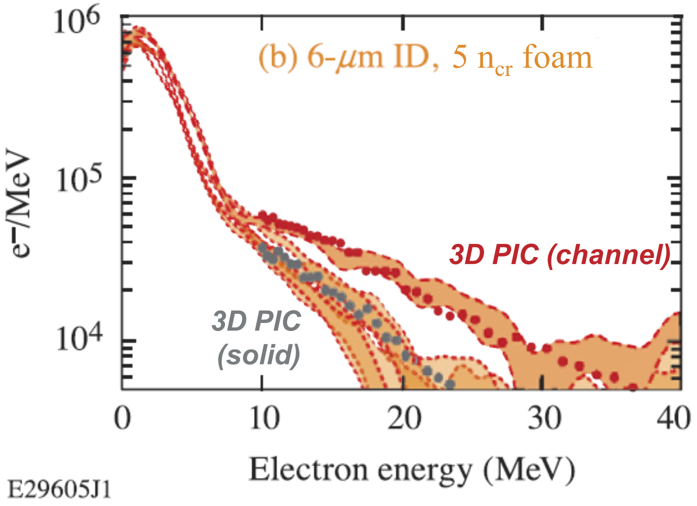
Channels filled with low-density CH foam: 15 or 30 mg/cm^3

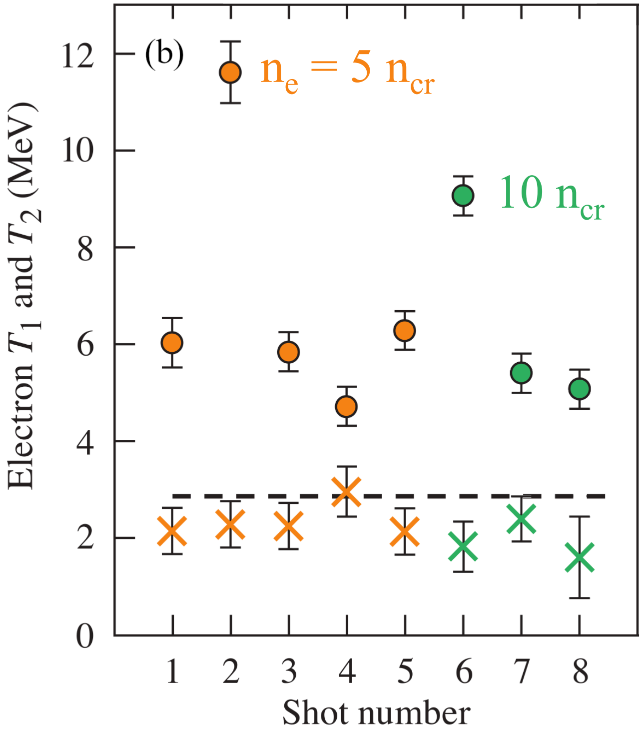
Given the pointing stability (5-μm rms), we did not expect channel interactions on every shot.

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

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

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

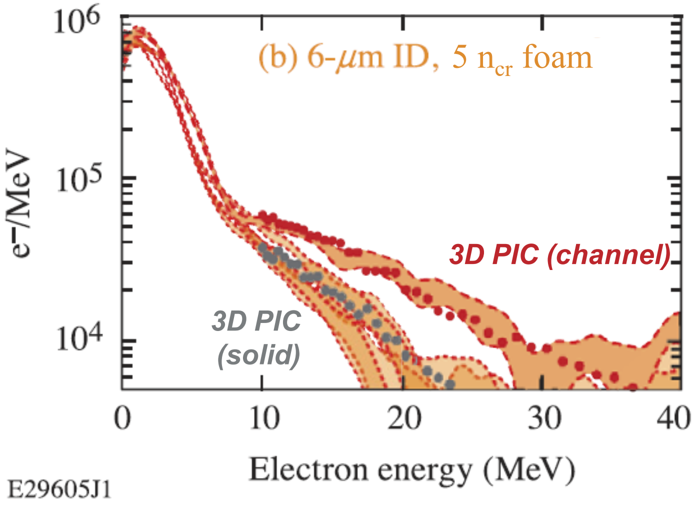




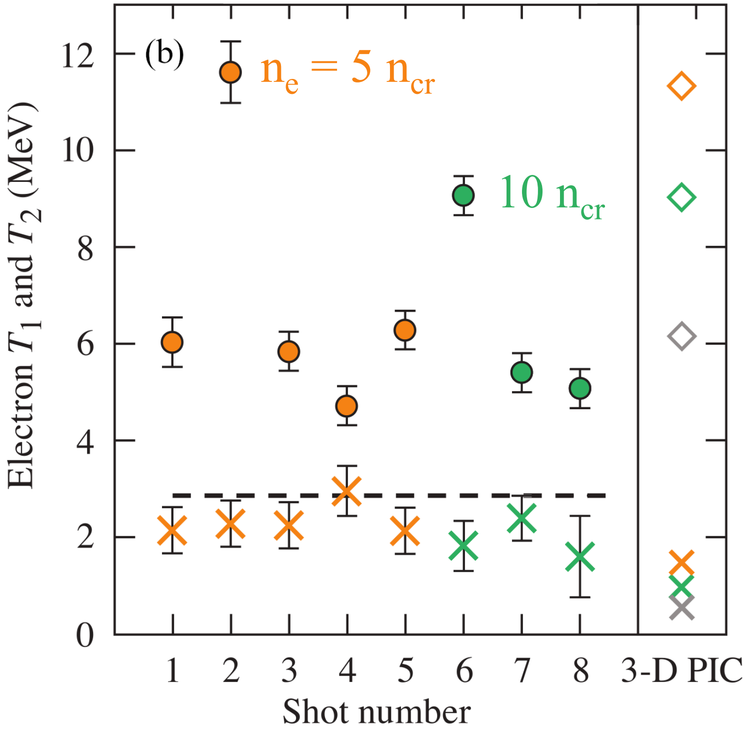
H.G. Rinderknecht, et al., New J. Phys. **23**, 095009 (2021)

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

Example electron spectra



Electron temperatures



3-D PIC simulations:

15 mg/cm³ channel fill

30 mg/cm³ channel fill

"solid" (~0.6 g/cm³)

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A follow-on campaign on OMEGA-EP (Dec 2021) used a new target engineering technique to improve laser-target coupling

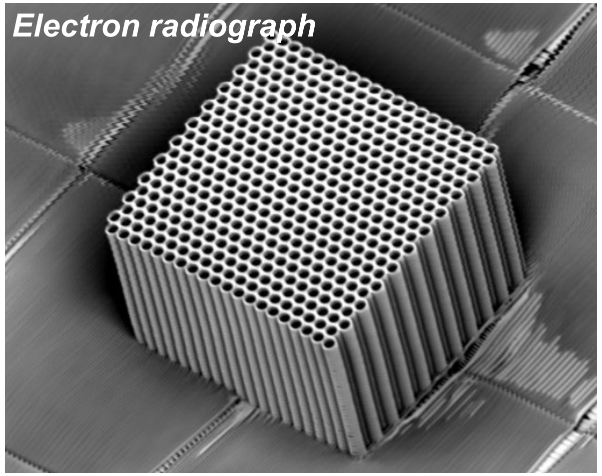
OMEGA-EP Laser:

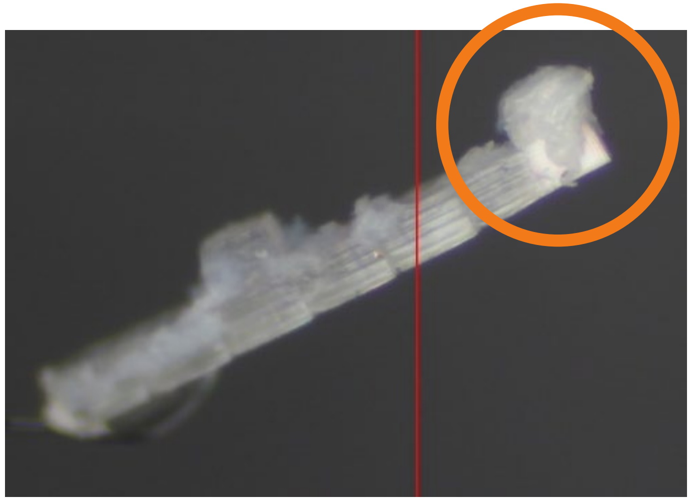
- **Wavelength:** **1054 nm**
- **Duration:** **700 fs**
- **Intensity:** **[0.79 ± 0.14]×10^{21} W/cm^2**
  a_0 = 25.2 ± 2.2

Target shots:

- [×5] 6-μm channels, 1-n_{cr} fill
- [×6] 6-μm channels, 1.6-n_{cr} fill
- [×3] 6-μm channels, unfilled

Foam-filled channel targets:





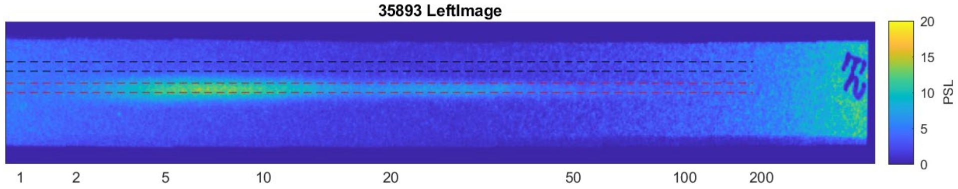
Channel ID: **6 μm**
Separation: **8 μm**
Wall thickness: **2 μm**

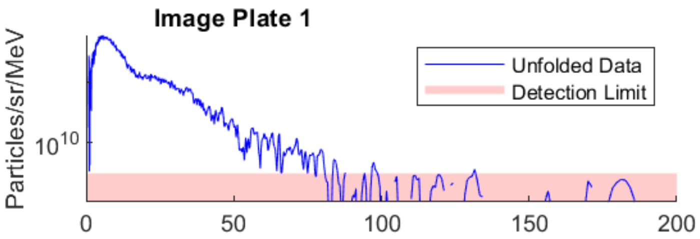
The microchannel structure is 3-D printed inside a low-density foam slab

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

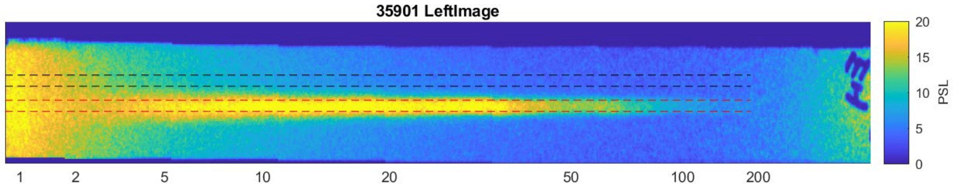
EPPS data: *electron spectra:*

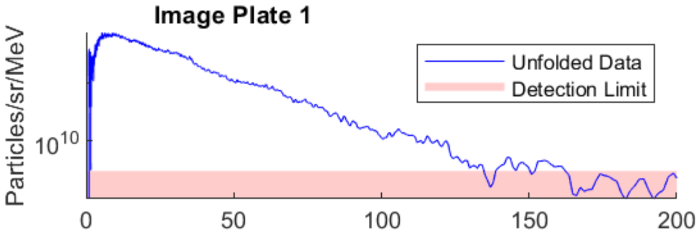
Shot 35893: BL, **1 n_{cr}**



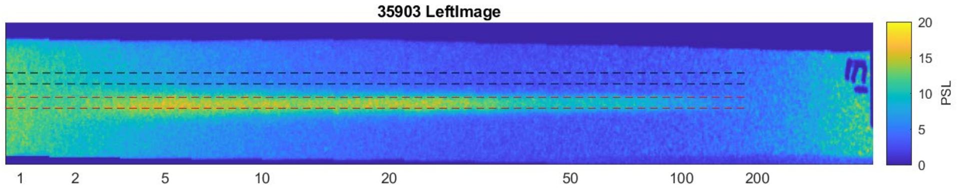


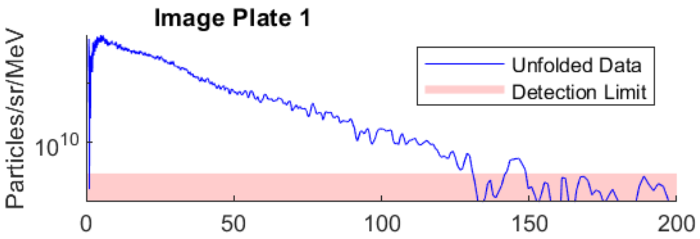
Shot 35901: BL, **1.6 n_{cr}**





Shot 35903: BL, **empty**



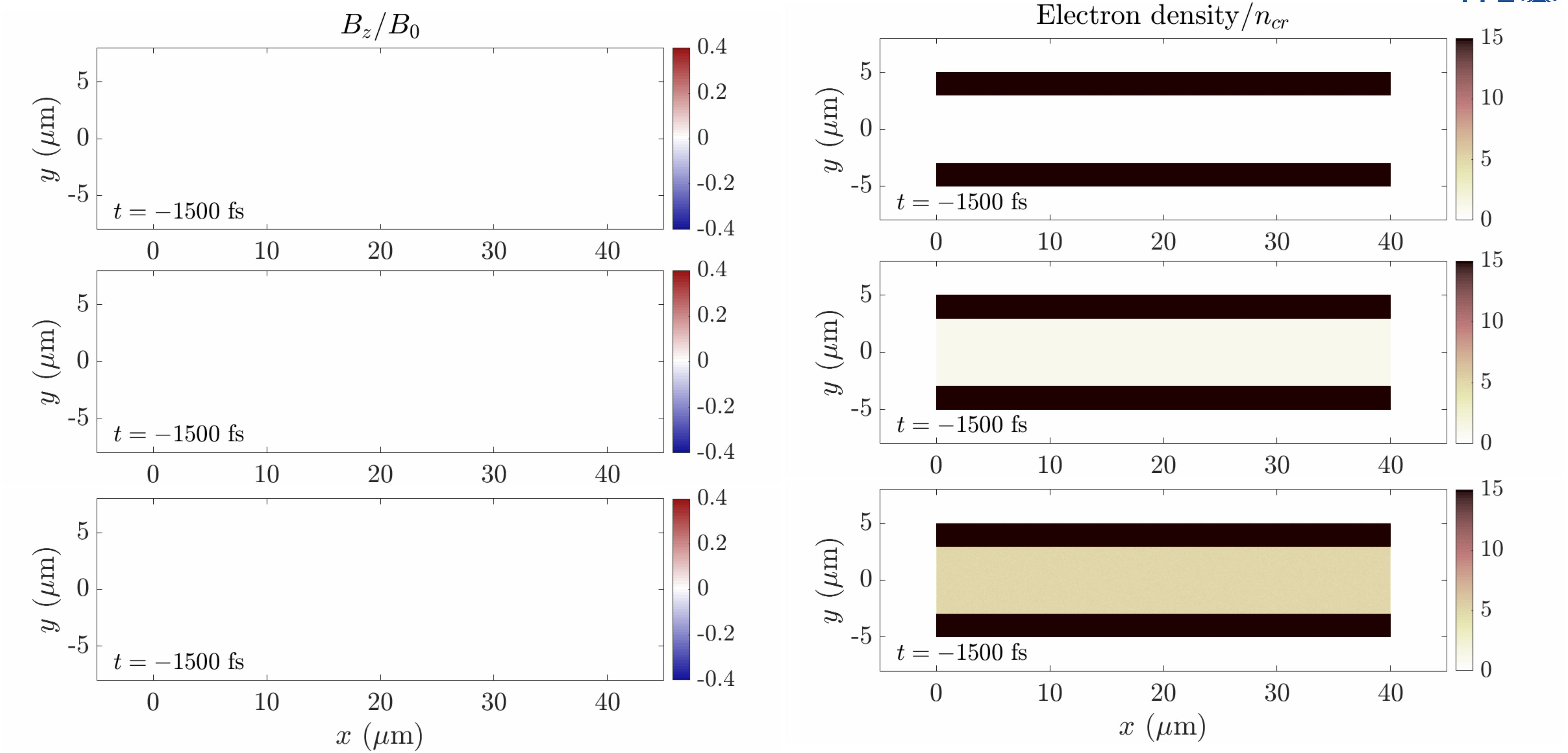


Subsequent 3-D PIC simulations predict that, for 0.7 ps pulses, the magnetic filament properties are independent of initial fill density

Empty

1 n_c

5 n_c



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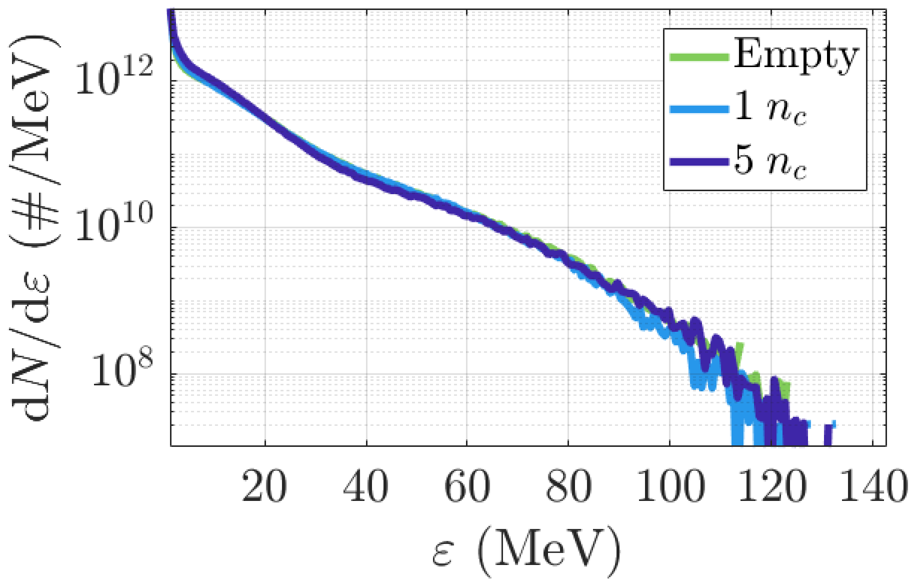
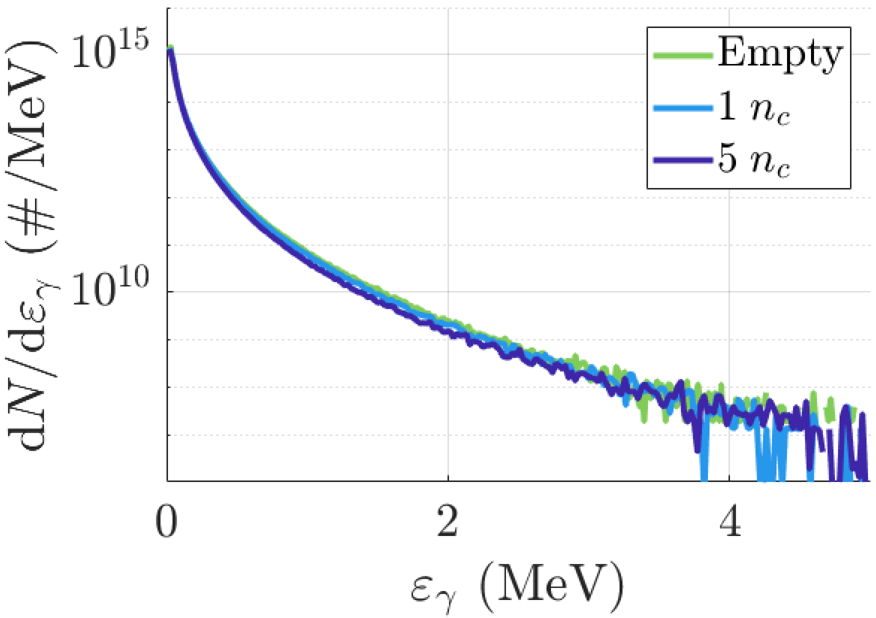
Ejected electrons



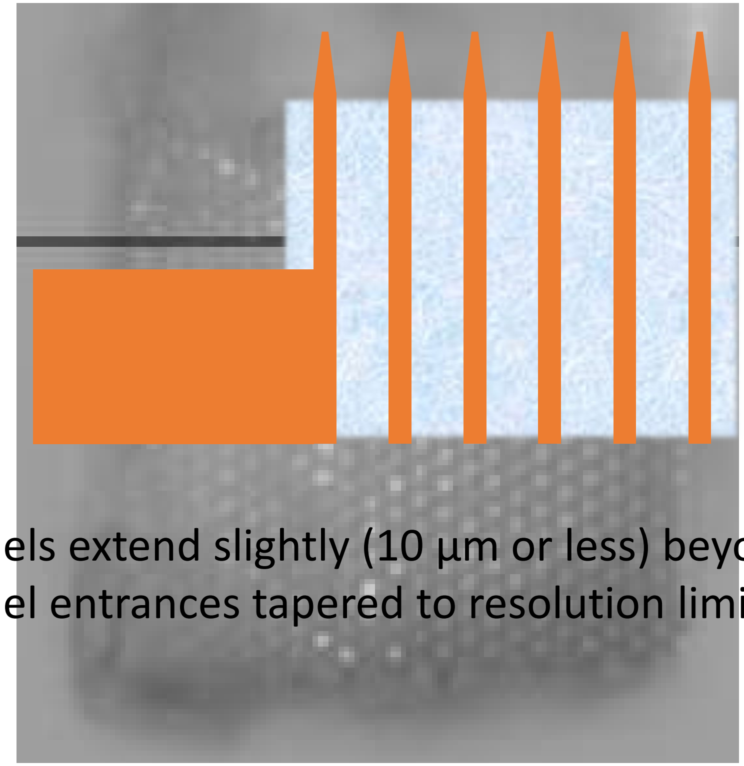
Photon emission



The simulated electron acceleration and photon radiation do not vary with fill density at 0.7 ps.

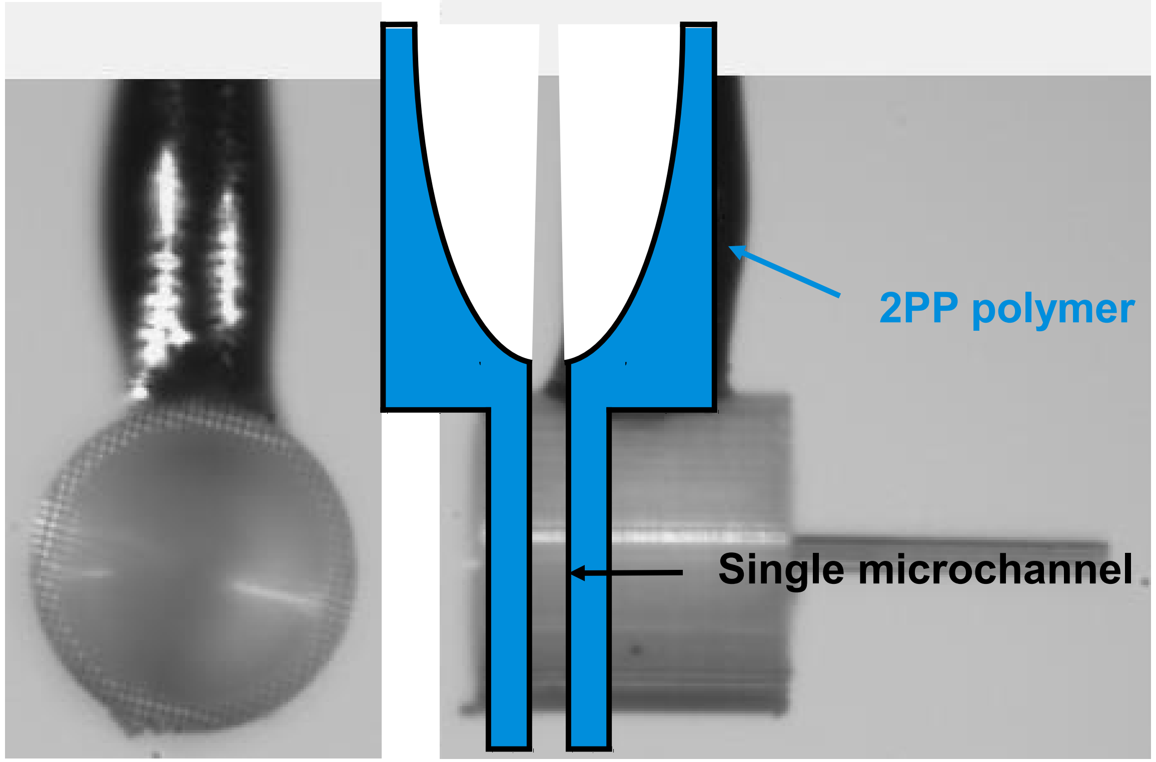
For future experiments, we will continue to test out advanced targets for improved laser-channel coupling and "long-pulse" coupling physics

Improved target arrays
(EP 2022; TPW in 2023)



Channels extend slightly (10 μm or less) beyond foam.
Channel entrances tapered to resolution limit (0.5 μm)

Concentrator targets
(EP in 2023)



See Matt VanDusen-Gross' poster: "Designing Optical Concentrator Targets for High-Intensity Lasers" (JP11.19, Tues 2—5pm)

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Appendix

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

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_α = 0.01**	**S_α = 0.05**	**S_α = 0.01**	**S_α = 0.05**
Photon energy $<\varepsilon_*>$	**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*

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)*

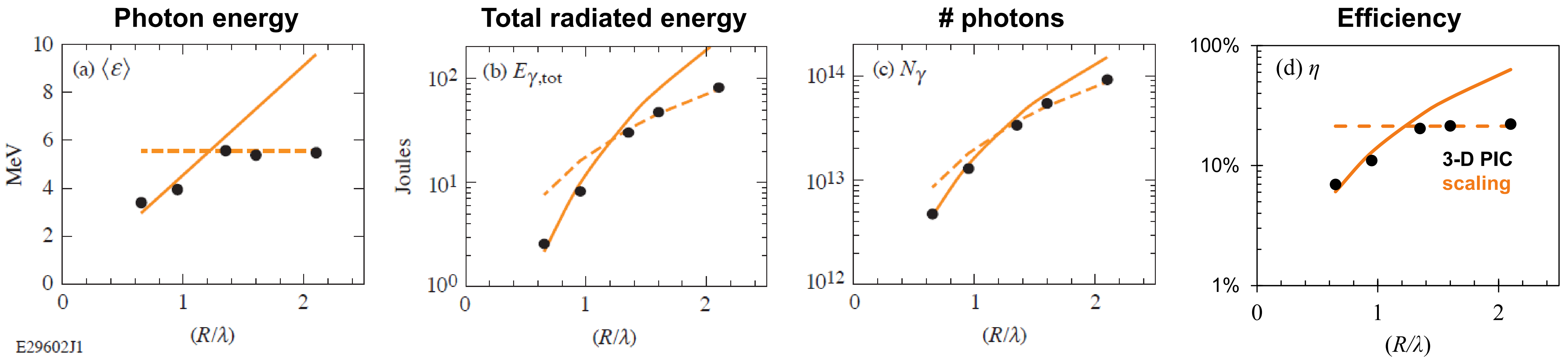
→ **3 Constants:** *Initial e- momentum scalar ($f_i \sim 1$), cutoff scalar ($f_t < 1$), radiation duty cycle ($f_r < 1$)*

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,	$P \equiv f_r P_{synch}$

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