Magnetic Field and Radiation Production in Laser-Driven Electron Beams

SSGF/LRGF Program Review 2023

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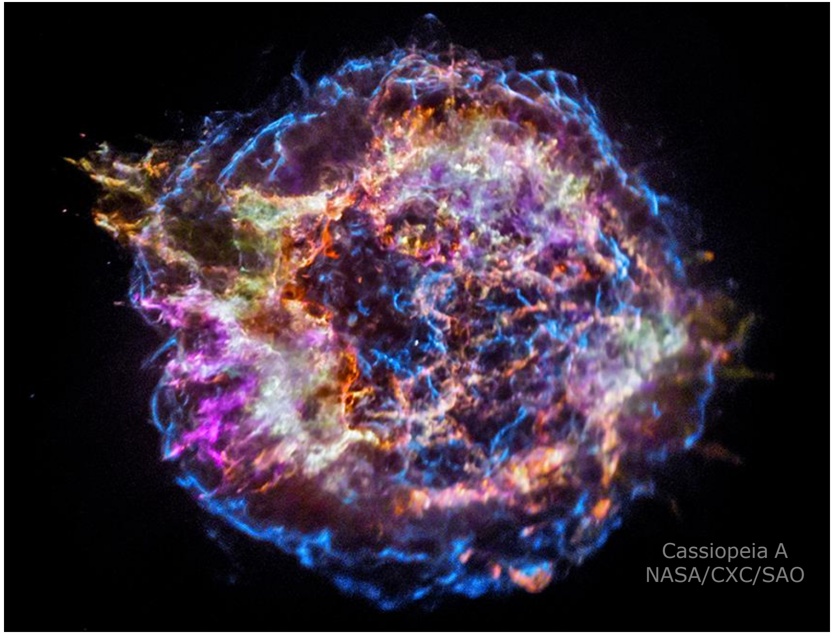
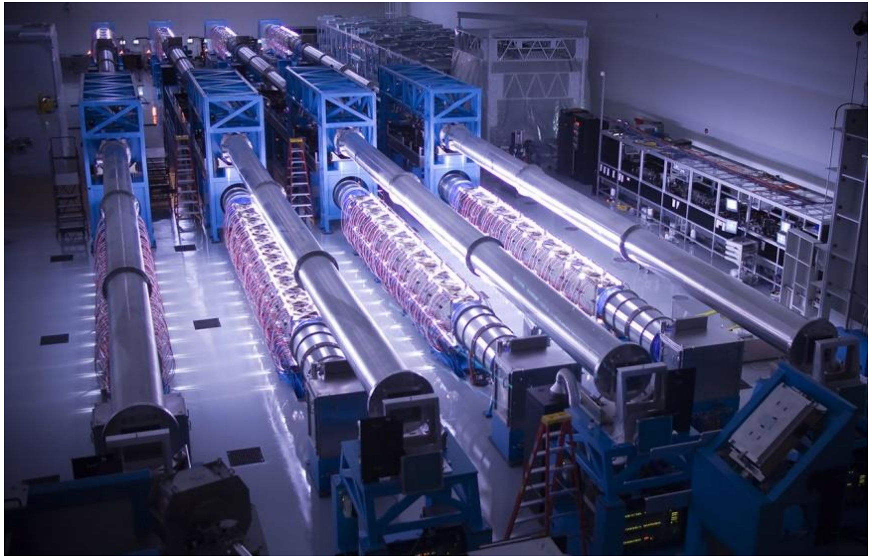
- Cori (NERSC)
- Ruby (LLNL)

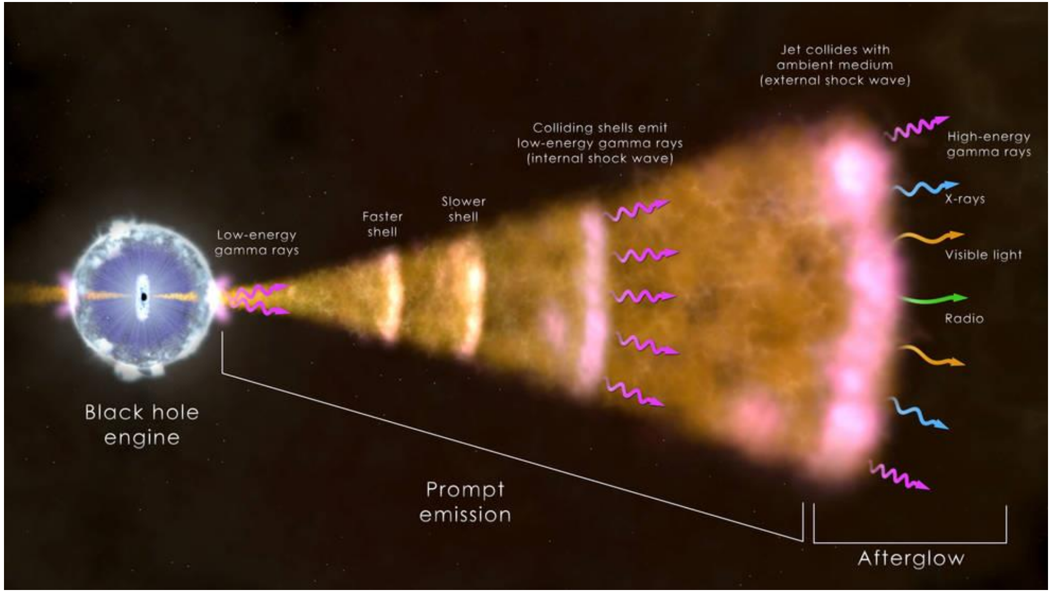
Particle acceleration in astrophysical and laboratory plasmas



Cassiopeia A
NASA/CXC/SAO

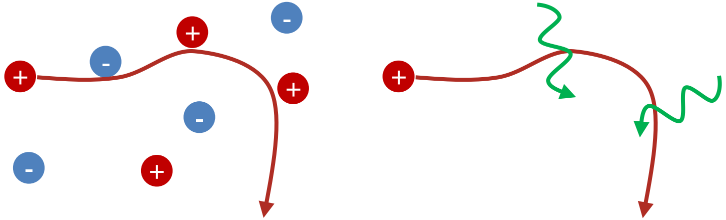


Gamma-ray bursts: the most powerful explosions in the universe

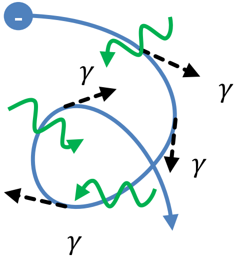


NASA Goddard Space Flight Center

Particle collisions are rare; plasmas interact via self-generated electromagnetic fields



Particles emit intense x-ray and γ-ray synchrotron radiation in self-generated fields

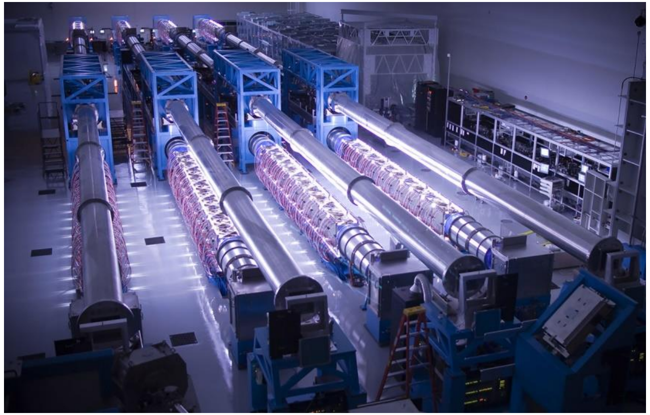


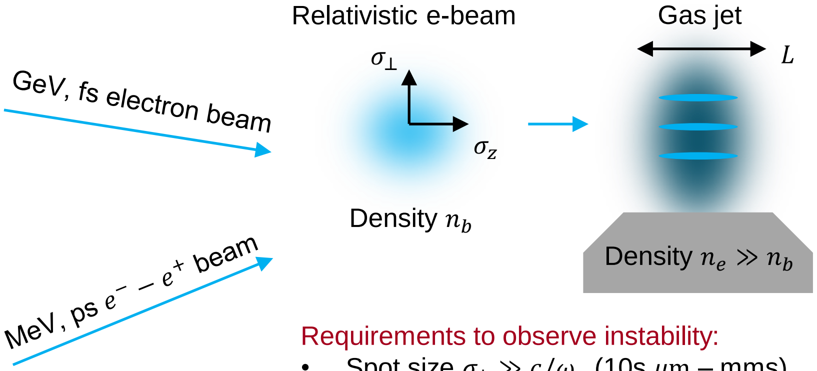
Plasma waves are too small to observe directly. We need to use simulations to understand their behavior.

Laboratory studies of GRB conditions are now possible

Linear accelerators
(SLAC FACET-II)

High-power
lasers
(OMEGA-EP)





GeV, fs electron beam

MeV, ps $e^- - e^+$ beam

Relativistic e-beam

$\sigma_\perp$

σ_z

Density n_b

Gas jet

L

Density $n_e \gg n_b$

Requirements to observe instability:

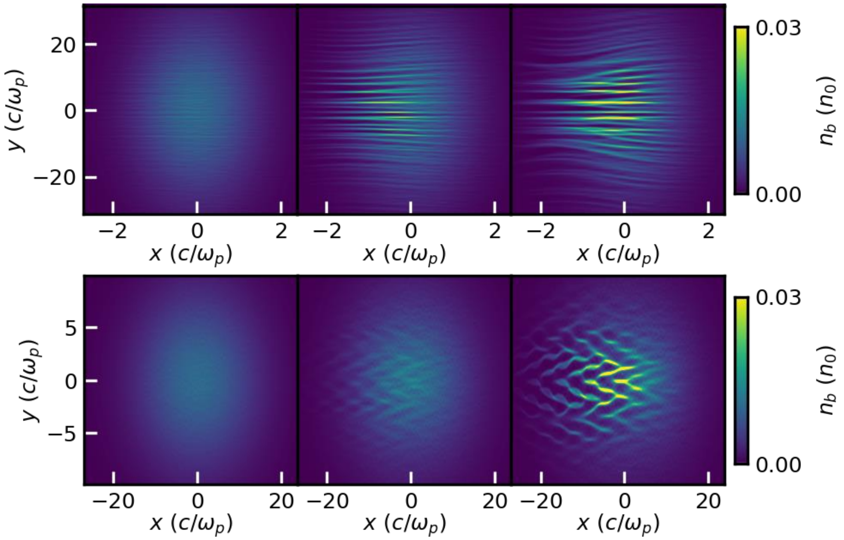
- Spot size $\sigma_\perp \gg c/\omega_p$ (10s μm – mms)
- Beam duration $\sigma_z \gtrsim \mu$m
- Target length $L \gtrsim 100$s μm
- Total charge $\gtrsim$ nC

We need to understand the impact of finite beam size

Finite-size beams can probe plasma instabilities

Narrow beam
Weibel/filamentation
instability

Wide beam
OTSI (oblique)
instability



Beam duration affects instability growth rate

Growth rate depends on duration: $\Gamma \propto \sqrt{\sigma_z}$

[Claveria, Davoine, Peterson et al., PRR 4, 023085 (2022)]

Beam width and duration affect self-focusing

[Keinigs and Jones. PhFl 30:252, 1987]

$$\partial_r W_\perp \approx \alpha m_e \omega_p^2 \min\left[\frac{\omega_p}{\sqrt{2}c}, \frac{1}{\sigma_\perp}\right]^2 \min\left[\frac{c}{\omega_p}, \sigma_x\right]^2$$

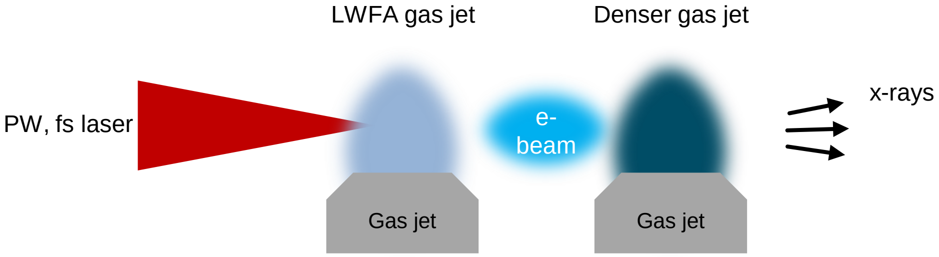
Electron beam shape needs to satisfy

$$\sigma_\perp \gtrsim 10\sqrt{\frac{c}{\omega_p \sigma_x}}\,\frac{c}{\omega_p}$$

for plasma instabiltiies to outrun self-focusing

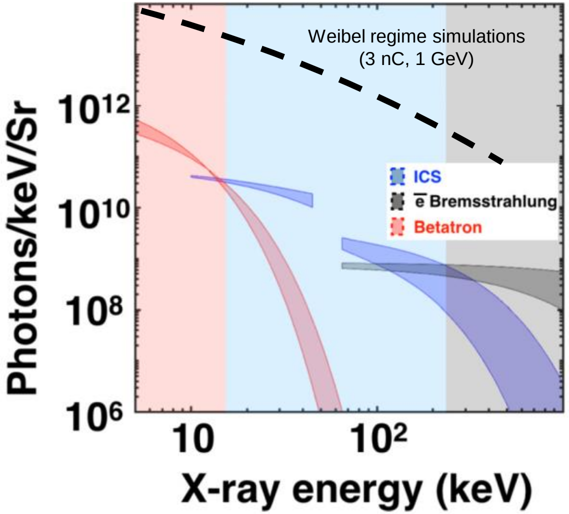
Weibel instability can mediate intense x-ray emission

Laser-driven e-beams could enable compact x-ray source


LWFA gas jet
Denser gas jet
PW, fs laser
e-beam
x-rays
Gas jet
Gas jet

Benedetti et al., Nat. Phot. 12, 319 (2018)

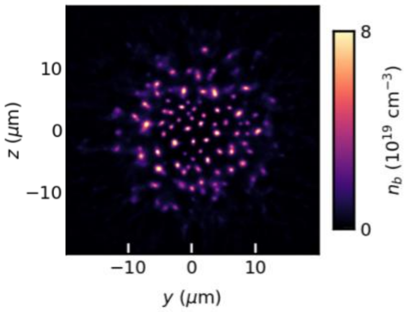
Unprecedented 100+ keV flux possible

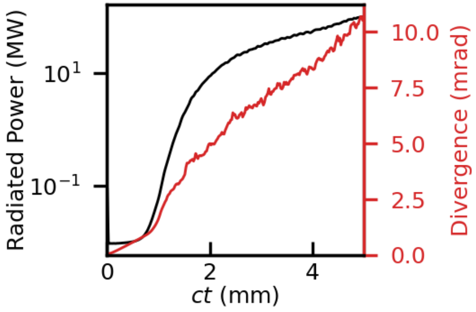


Adapted from Lemos et al.,
Phys. Plasmas 26, 083110 (2019)

Simulations predict nearly-collimated x-rays

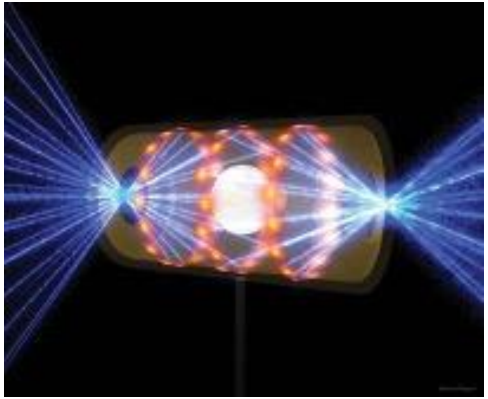
Beam profile at $ct = 5$ mm





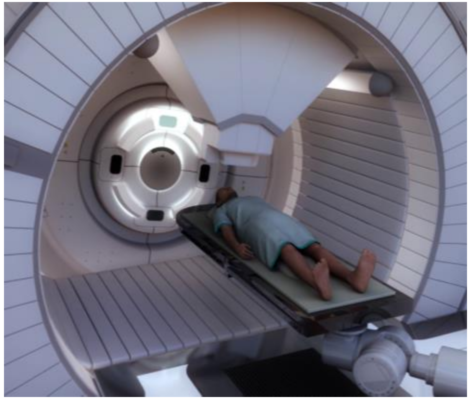
Laser-driven ions are urgently needed in several fields

Fusion Energy Science



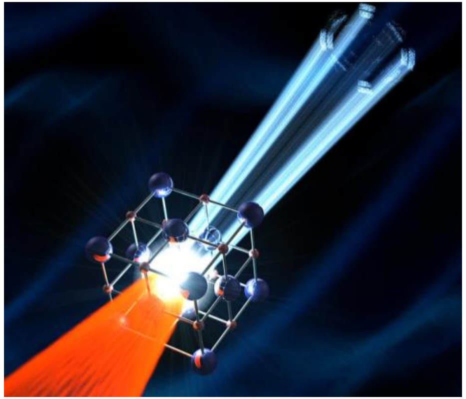
- Radiography of quickly-evolving phenomena
- Ion stopping power measurements

Accelerator Physics



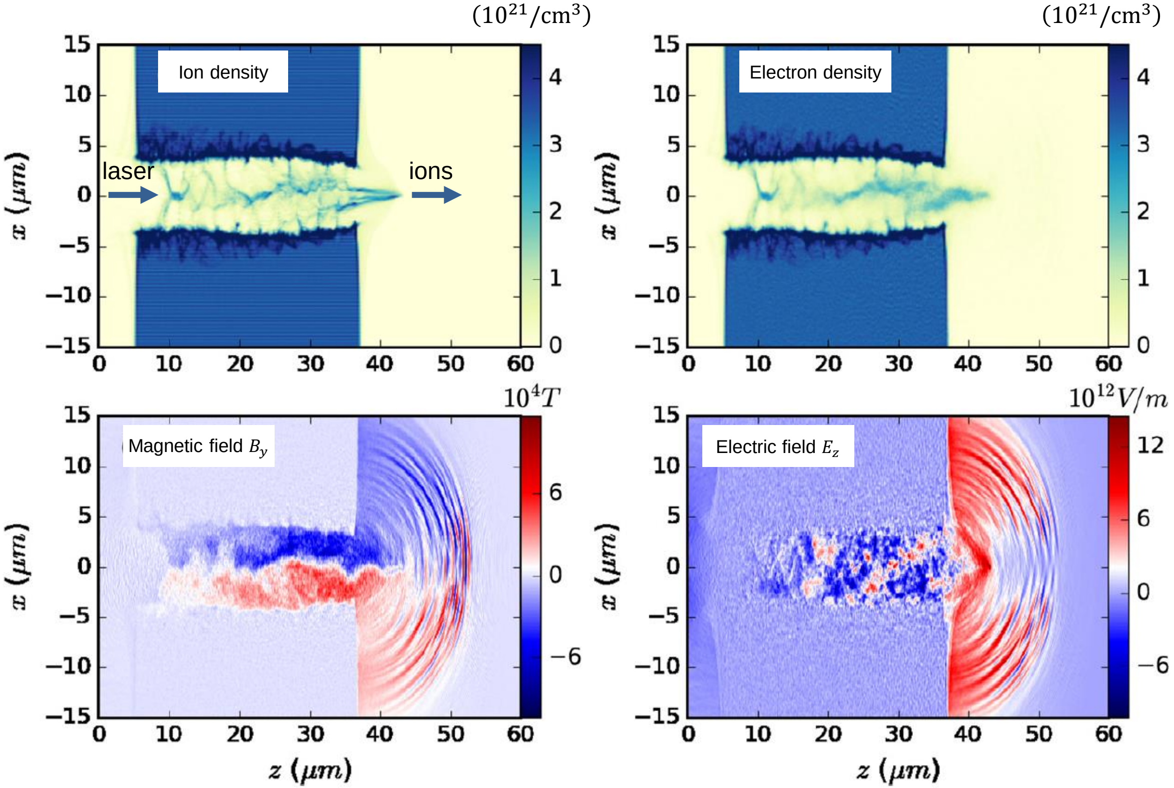
- Hybrid accelerator development
- Compact cancer care facilities

Materials Science

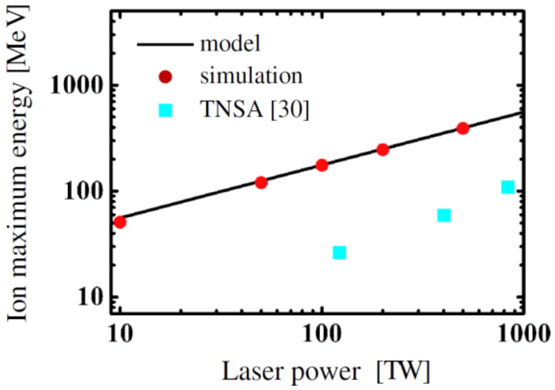


- Ion damage studies
- Next-generation fusion material development

Magnetic vortex acceleration scheme promises high ion energies



Park et al., POP 103108 (2019)

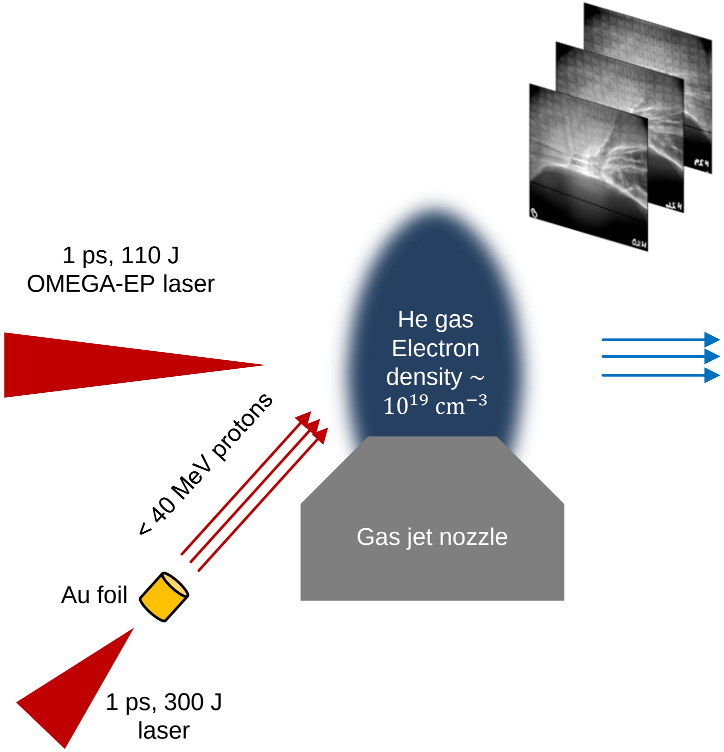


Nakamura et al., PRL 105, 135002 (2010)

No experiment has conclusively observed magnetic vortex acceleration.

- Targets are difficult to manufacture
- Electromagnetic fields are too strong and short-lived to see

Low-density gas jets allow us to study magnetic vortex formation with larger, longer-lasting fields



Radiochromatic film

Lower energies arrive later,
providing time series

1 ps, 110 J
OMEGA-EP laser

He gas
Electron density ~ $10^{19}\ \mathrm{cm}^{-3}$

μC electron beam
energies up to 100 MeV

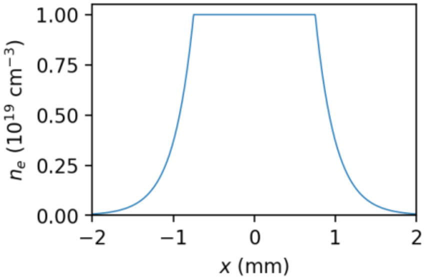
< 40 MeV protons

Gas jet nozzle

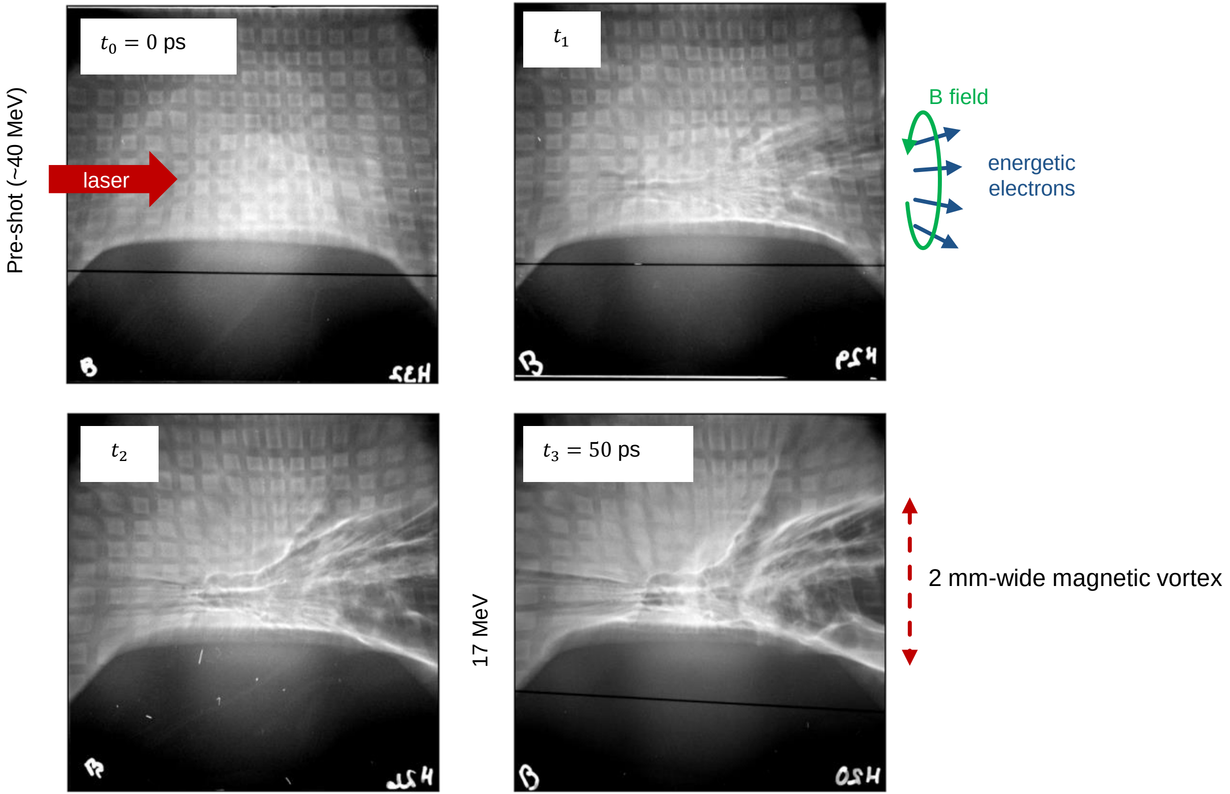
Au foil

1 ps, 300 J
laser

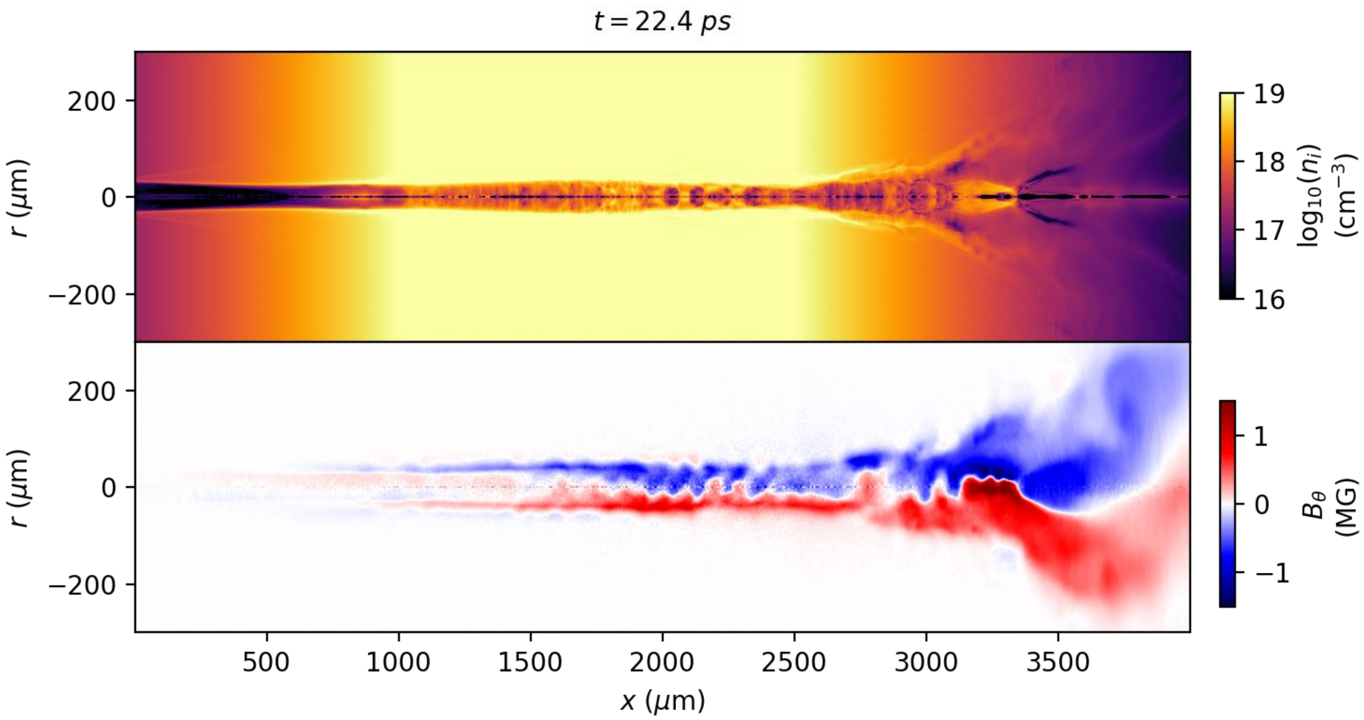
Gas jet density profile



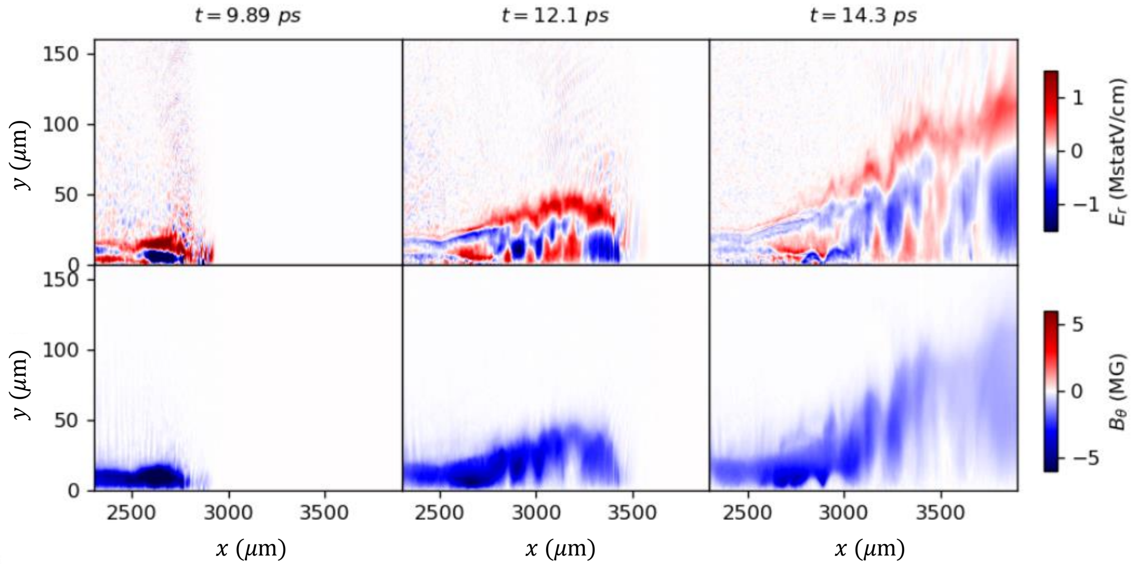
Proton radiography captures field evolution over 10s of picoseconds



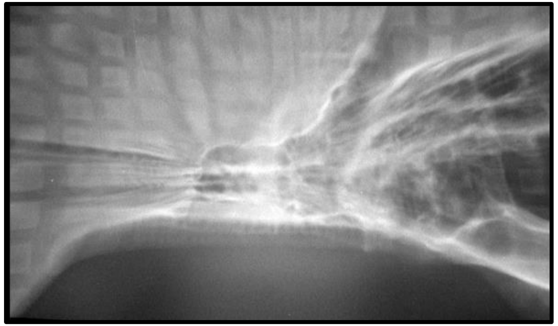
Simulations qualitatively reproduce behavior from experiments



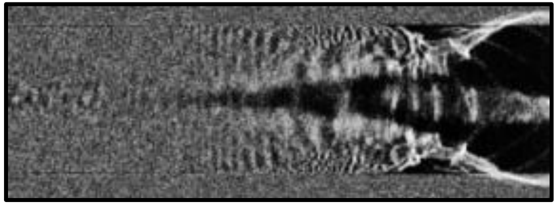
Simulations show caustic structures related to sheath E-field



Experimental radiograph



Simulated radiograph



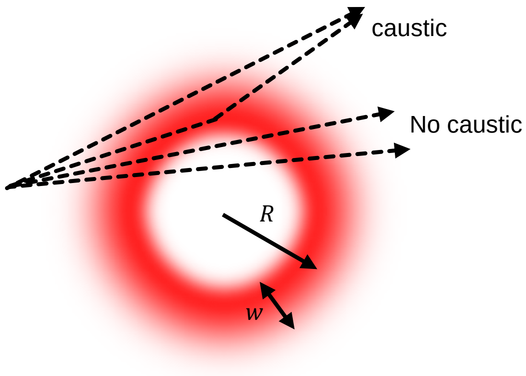
Electric field directly couples magnetic pressure to the ions:

$$Q \times E = \frac{B^2}{8\pi} \times A \quad \text{(for wall area } A \text{ and charge } Q\text{)}$$

As long as $B > E$, this reduces to

$$\boxed{B = \sqrt{E \times \frac{2\omega_p m_e c}{e}}}$$

We analytically calculate electric field caustic threshold



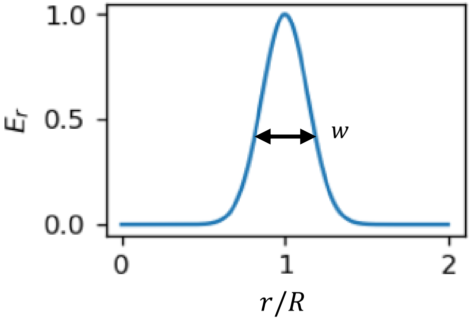
With cylindrical symmetry, caustics form when
[Kuland et al., Rev. Sci. Instrum. 83, 101301 (2012)]

$$\frac{dr_i}{dr_0} = 0,$$

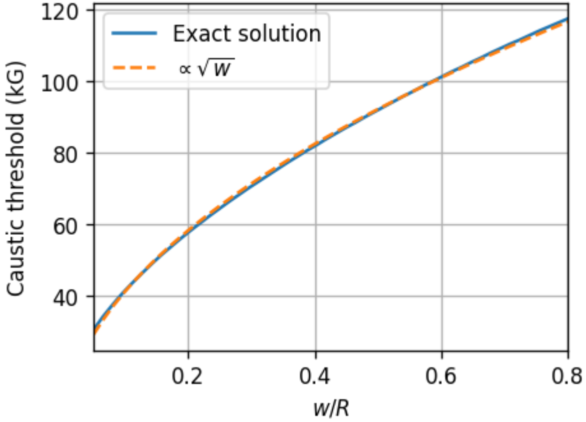
where

$$r_i = L\left(\frac{r_o}{l} + \alpha(r_0)\right), \qquad \alpha(r_0) = -\frac{e r_0}{W}\int_{r_0}^{\infty} \frac{dr'}{\sqrt{r'^2 - r_0^2}} E_r(r')$$

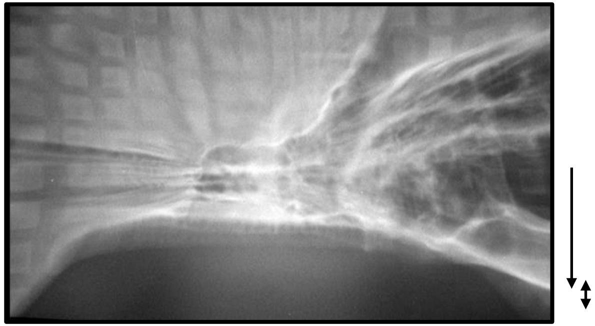
Approximate electric field as a gaussian ring



Caustic formation threshold for 40 MeV protons

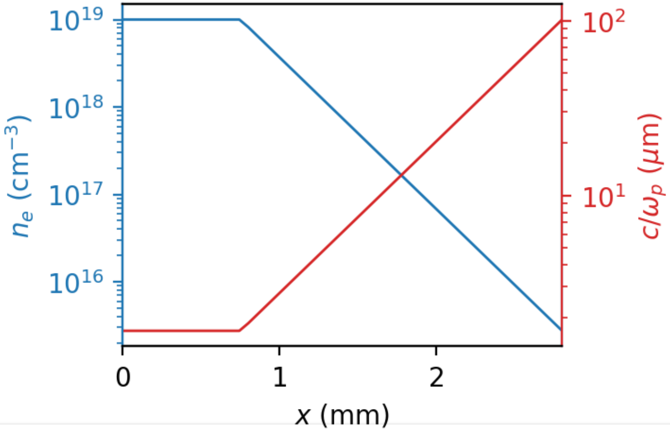


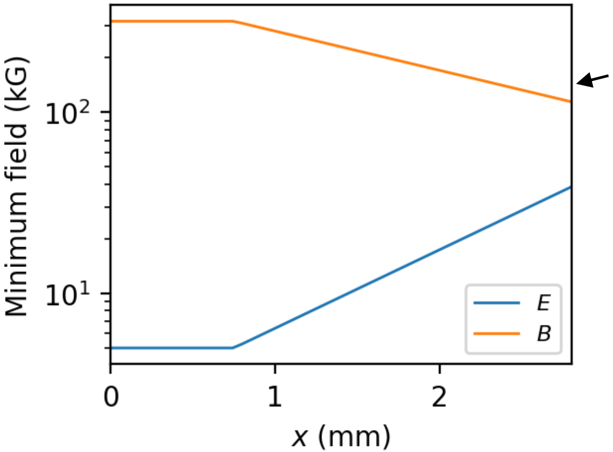
Inferred magnetic fields agree well with theoretical expectations



$R \sim 1.1$ mm

$w \sim c/\omega_p$





Radiograph indicates ~**120 kG** fields at end of jet

	Theory	Electron spectrum
Peak current	$I \sim ecn_e\pi R_{laser}^2 \sim 97\text{ kA}$	70 nC in 1 ps ~ 70 kA
Peak B	$B \sim \frac{2I}{Rc} \sim 167\text{ kG}$	$B \sim 120\text{ kG}$

Field strength calculated from radiographs agrees with theory and the measured electron spectrum

Conclusions

- High-current laboratory electron beams can drive and study plasma instabilities relevant to gamma-ray bursts
- Plasma instabilities can enable bright, energetic compact x-ray sources
- Studying laser-plasma interaction at low densities enables clear measurements of the electromagnetic field evolution
- We report the first measurement of the magnetic fields in a laser-driven magnetic vortex and confirm that it agrees well with theory