An Inverse-Compton-Scattering Source via Self-Guiding in a Plasma

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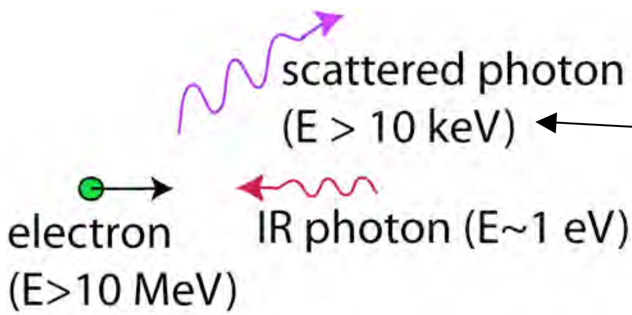
Compton (Thomson) Scattering as an X-ray Source

- mechanism well-studied since 1960s
- large cross-section (600 mb)



photon energy upshift from Doppler factor

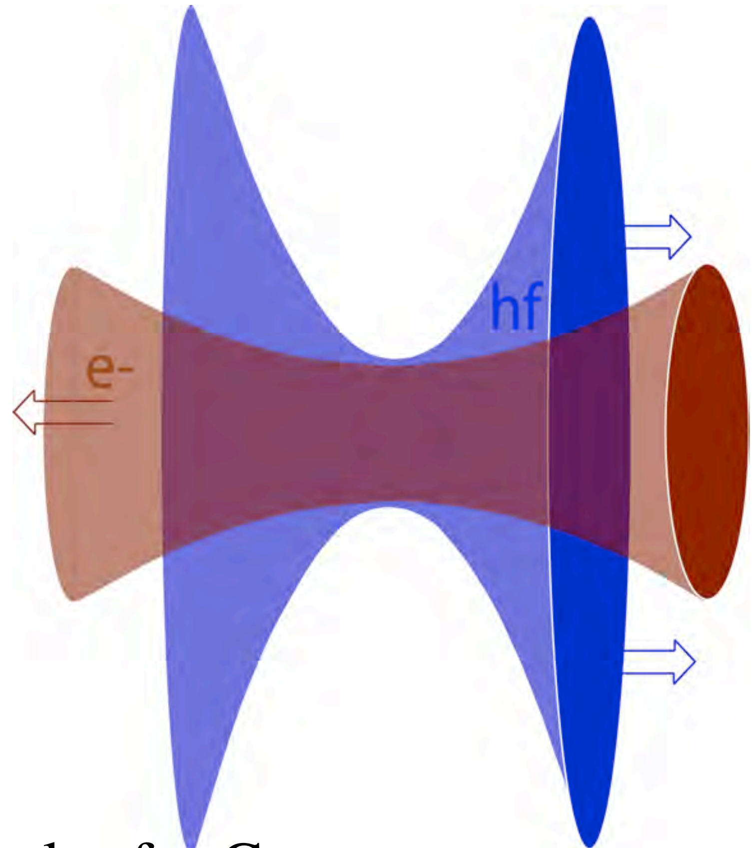
$$\lambda' = \lambda_0 / 4\gamma^2$$

- radiation opening angle ~ $1/\gamma$
- considered for short-pulse x-ray and gamma ray sources

(synchrotron light sources are broadband, long-pulse)

Obstacle to high brightness: Spatial overlap problem

- Photon production ~ $\sigma_T \frac{N_b N_\gamma}{Area} \frac{\sigma_{t,\gamma}}{\sigma_{z,b}}$
- Want high photon density, but tight focus gives **strong diffraction**
- Beam limited by emittance
  $\beta = \sigma_r^2 / \varepsilon \leq 0.5 - 1\ \text{cm}$
- Laser limited by diffraction
  $Z_R = \pi r_0^2 / \lambda_0 \leq 1 - 2\ \text{mm}$



- Result: **basic limitation** on photons/pulse for Compton sources: must have beam lengths ≤ diffraction length;
- large laser fields and beam space charge effects

Emittance, field are limiting factors

Particle beam has (approximately) $\varepsilon_n = \gamma\, \sigma_x\, \sigma_{x'}$ = constant
Brightness comes at expense of divergence

Laser has wavelength-limited product of σ_r and θ
Can't simply add more energy to short pulse without increasing
$a_L = eE_L/mc\omega$
If $a_L \geq 1$, transverse relativistic motion becomes important and e-beam disruption is an issue
Only solution is to increase interaction **volume**

Guiding Channel: beat the diffraction limit

- **Plasma channels**: region of plasma with low electron density, positive ion background
- Created by intense laser pulses or electron beams
- Laser guiding over many Rayleigh ranges has been demonstrated
- Matched electron beam can be transmitted over many β
- Full beam length available for interaction even for small spot size

- Can do this using a **pre-formed** channel

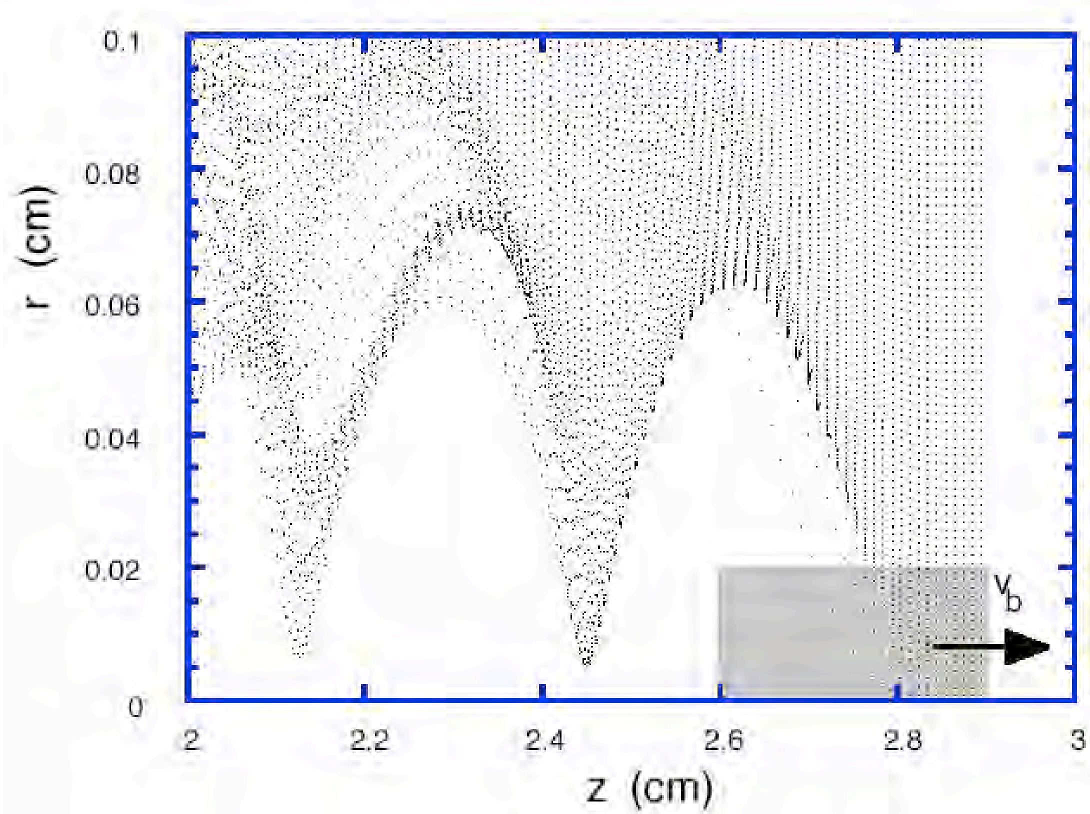
  (BNL-ATF, current work using capillary discharge tubes)

… but potentially easier to exploit **self-guiding**:

- both laser and e-beam will self-guide under correct conditions
- no need for timing 2 laser pulses or spark devices

Beam Self-Guiding: PWFA in blowout

- Field of beam pushes plasma electrons away from axis
- Rarefaction forms behind beam
- Long beam needed: the head erodes as the channel forms
- Middle/tail of beam is focused and guided
- Very high axial fields created in rarefaction

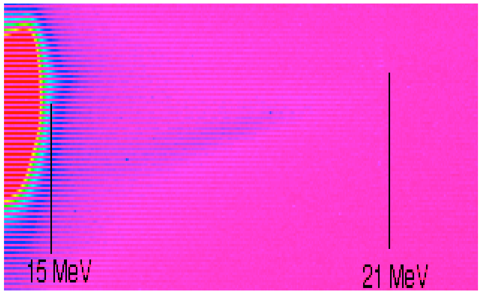


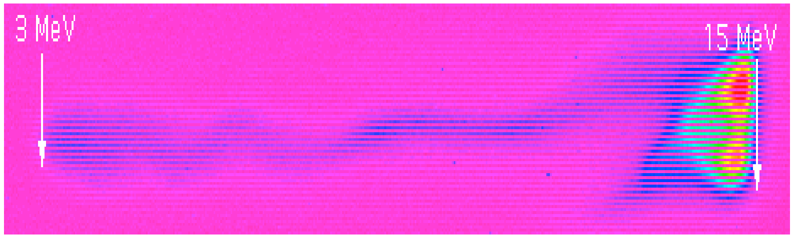
Self-Guiding Results

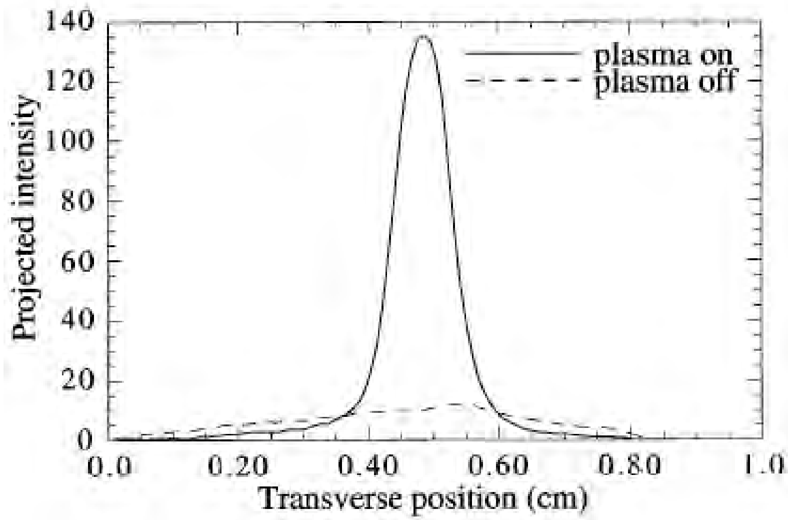
Recent demonstrations include

• Argonne AWA: 70% of 14 MeV, 25 ps, 10 nC beam transmitted intact through 12 cm plasma (= 8β) forming 280 μm channel

• SLAC FFTB: Beam tail propagation through 1.4 m plasma (overfocused). using 28 GeV, 2 ps, 3 nC beam — observed steering







Plasma Blowout: Theory

- Blowout efficiency depends on the ratio n_b/n_p as long as beam is relativistic (must be > 1 for blowout; usually ~ 5 to 10)
- but density decrease still observed for $n_b/n_p < 1$
- Focusing strength of channel is fixed: this sets the depth of focus for the e-beam

$$\beta_{\mathrm{eq}} = \sqrt{\gamma / 2\pi r_e n_0}$$

- Match the beam to this gradient to avoid overfocusing
  - set $\sigma_r^2/\varepsilon = \beta$; then focus onto plasma boundary
- Assume $\sigma_z k_p >> 1$, so plasma matches beam
- Beam distribution near head expands radially; the head electrons are focused less due to finite plasma response time
- Beam body transverse size is near stationary

Laser Guiding:

- Need plasma refractive index to be lowered off-axis
- Decrease plasma density on-axis, *n* is modified:

("optical fiber")

$$n^2 = 1 - \frac{1}{\gamma}\left(\frac{\omega_p}{\omega}\right)^2$$

Self-guiding: if $a_0^2 >> 1$, high efficiency
requires $P > 17.4\ (\lambda_p/\lambda_w)^2$ [GW]

Pre-formed channel: careful plasma manipulation

or Electron beam blowout ….

Once channel forms, propagation is very efficient:
e.g. guiding 10^{14} W/cm^2 over 25 to 70 Rayleigh lengths with pre-formed channel! (*Durfee et al., Maryland, 1995*)

Relativistic Laser Self-Guiding: not a likely prospect

- Guiding doesn't work well for $L \leq \lambda_p$
  (no plasma collective response)

⇨ Only long pulses can be considered

- Self-modulation can occur due to wakefield formation
- There is a wavelength-independent
  critical density: $n_{\rm crit} = 1/(r_e\, \pi\, w_0^{\,2}) \geq 10^{19}\ \text{cm}^{-3}$
  for 10 μm laser (better focus for 800 nm)

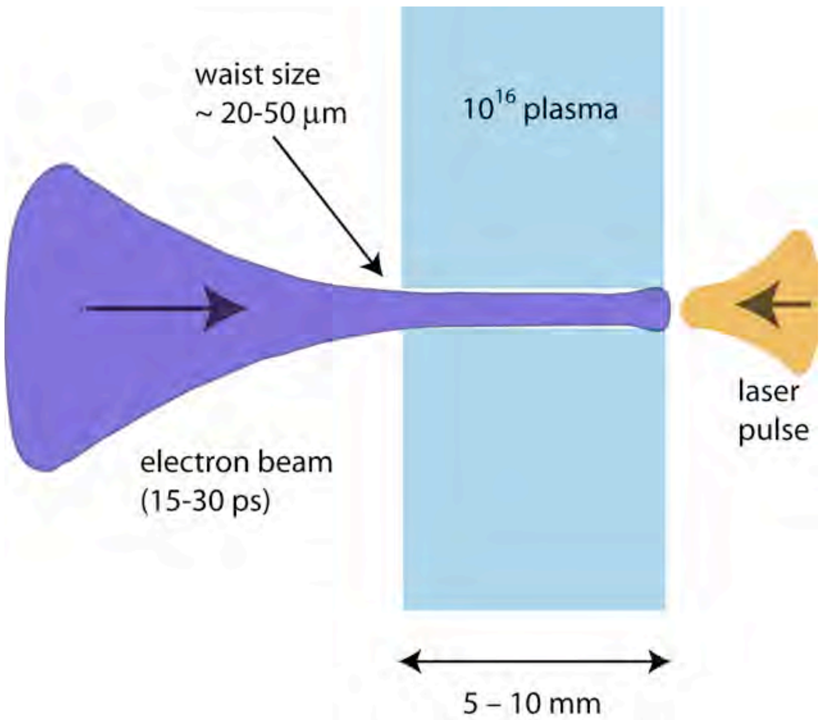
Laser constraints
(critical power)

• Choose long wavelength (10 μm), achievable power levels (~20 TW?) ⇨ very dense plasma ($n_p = 10^{17}/\mathrm{cm}^3$), $\lambda_p = 48\ \mu$m

• To beta-match into this requires $\sigma_r = 2.3\mu$m with low-emittance beam (4 mm mrad) at 80 MeV ⇨ $n_b \sim n_p$ even with this focusing

Thus: don't try to match laser at critical density, instead use beam to prepare channel for **both**, with $P_{laser} < P_{crit}$

Beam-driven channel scenario



- long electron beam (3–4 mm), high charge (~10-100 nC)
- laser pulse arrives when beam head exits plasma
- laser guiding over 5–10 Z_R through plasma-formed channel

Design method

(λ = 800 nm, E = 1.6 GeV)

Free parameters:

plasma density n_0

e-beam emittance ε, population N_b, length σ_z

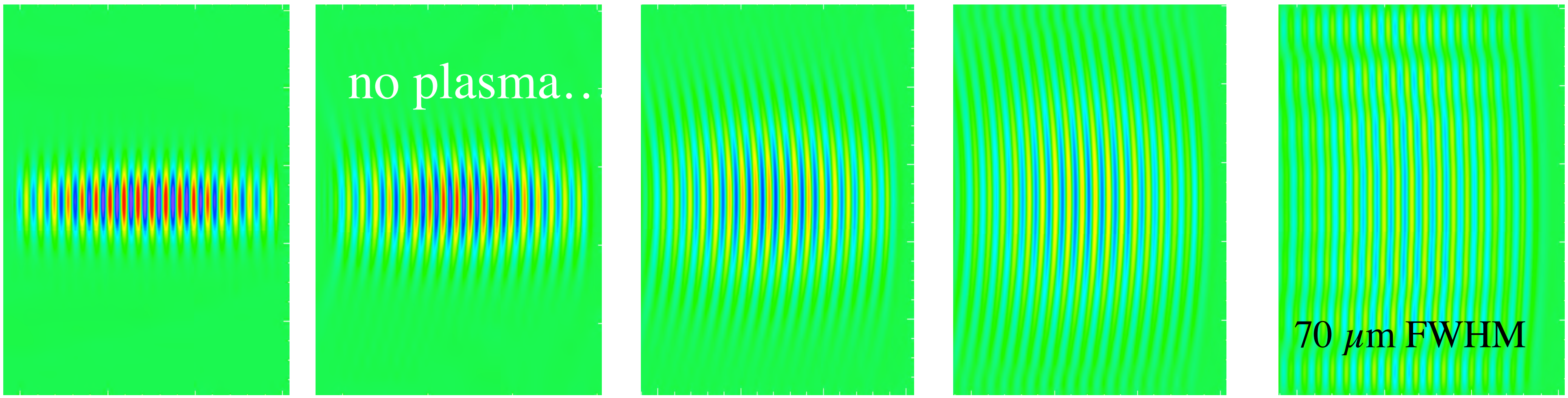
Beam guiding requirement fixes β and σ_r

$$\beta_{\mathrm{eq}} = \sqrt{\gamma / 2\pi r_e n_0}$$

$$\sigma_r = \left(\varepsilon_n^2 / 2\pi\gamma r_e n_0\right)^{1/4}$$

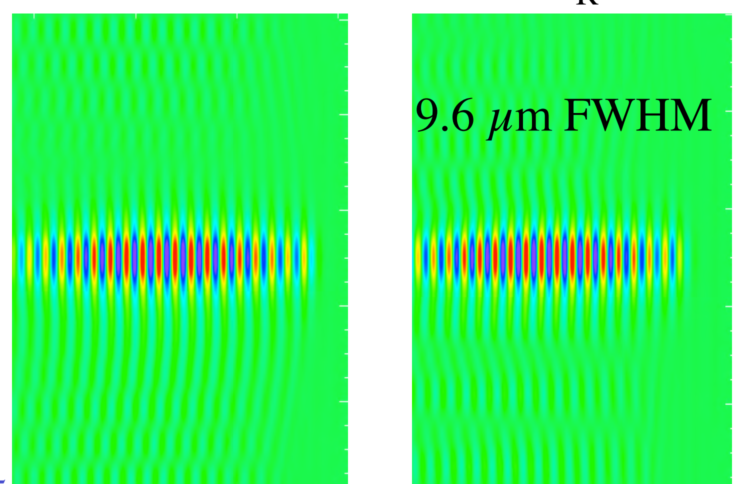
Set laser σ_r to match the channel, focus

Laser guiding: 2D simulation
800 nm, 50 fs pulse

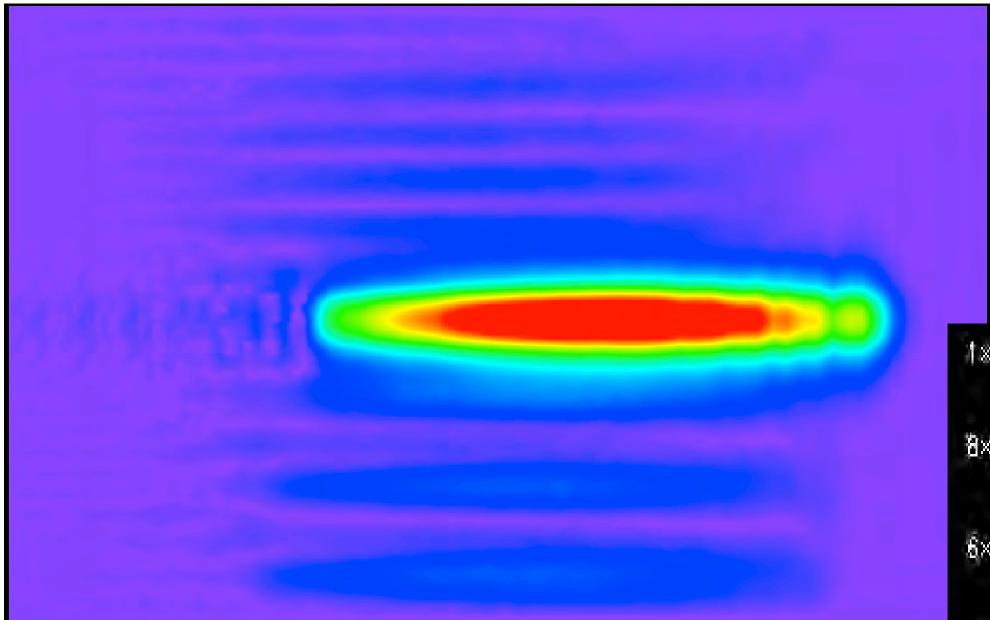


6.6 Z_R

3×10^{18} cm^{-3} plasma
8 μm pre-formed channel
(= w_0)
Z_R = 250 μm

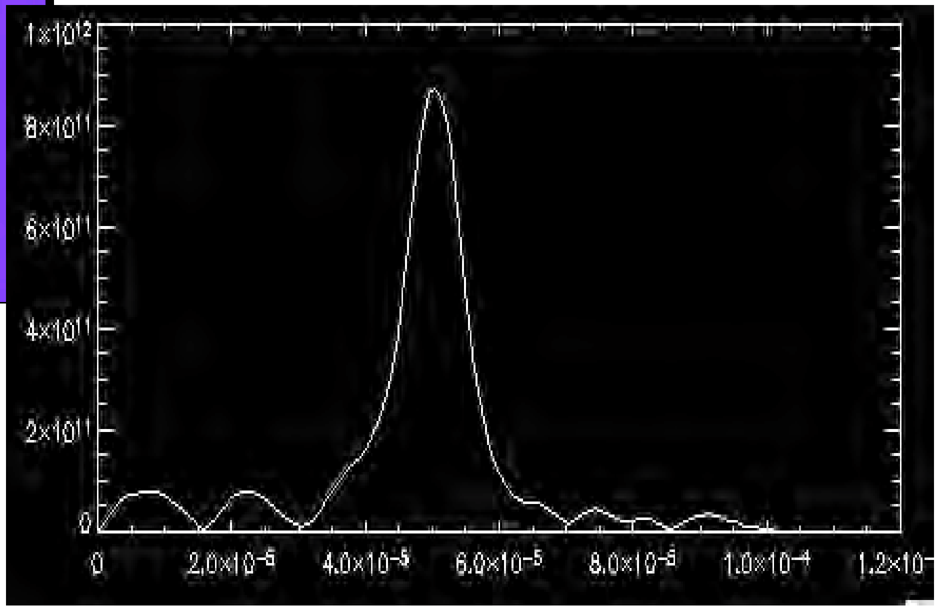


Pulse quality is still reasonable



Envelope function
($\sigma_z = 15\ \mu$m, $\sigma_y = 9\ \mu$m)

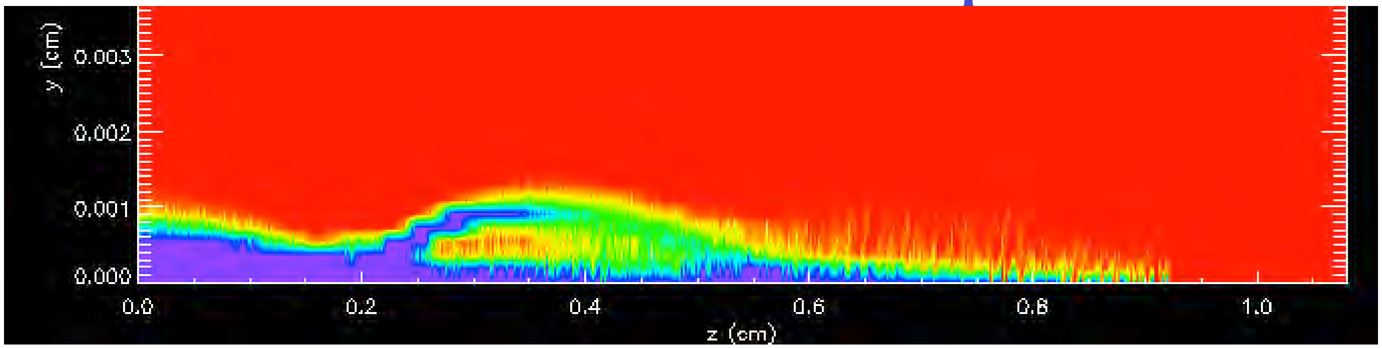
Intensity profile



y (m)

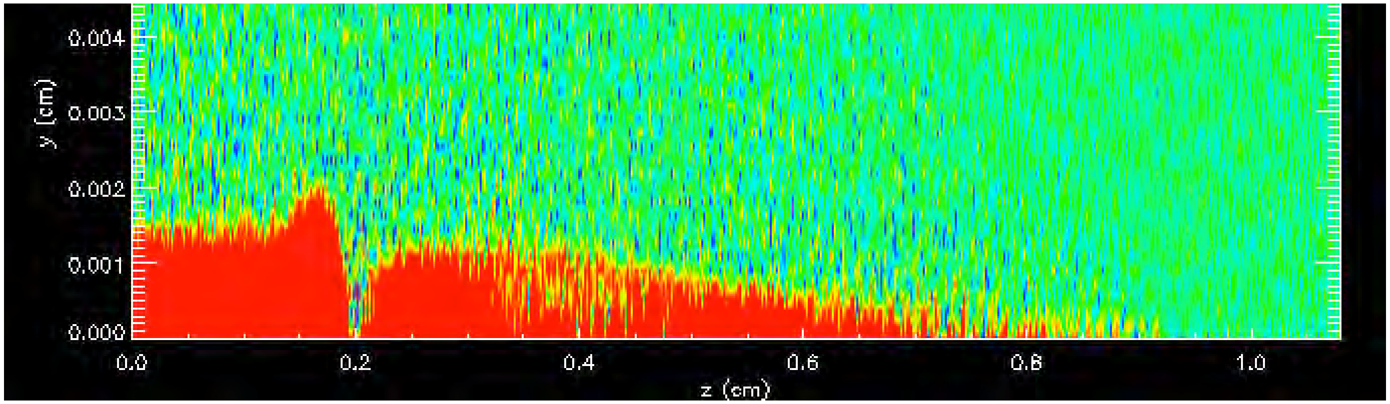
Plasma channel formation
t = 300 ps

n_b



self-pinching (overfocusing)

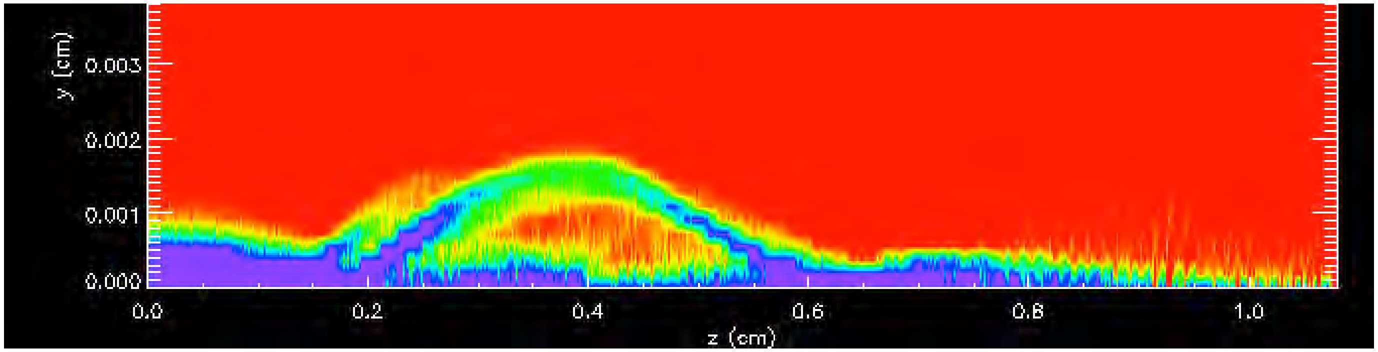
n_p



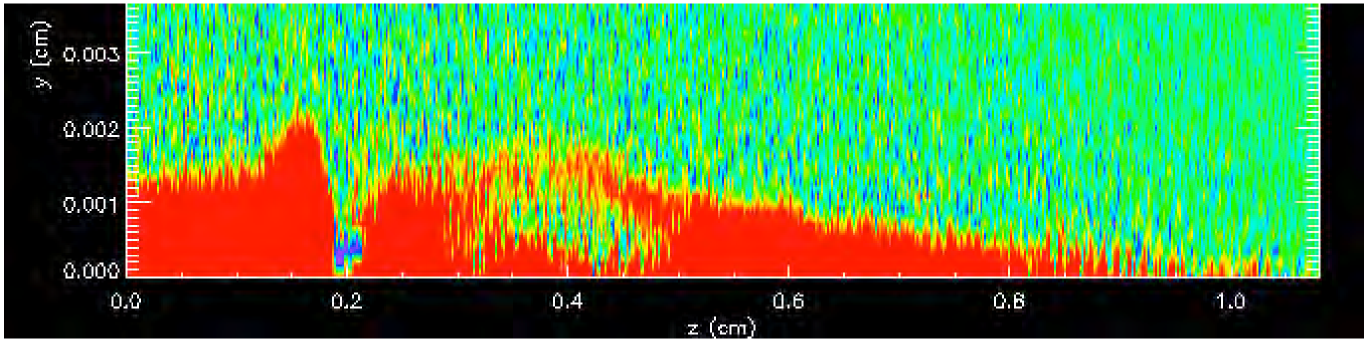
10 nC beam
1.6 GeV
5 μm σ_r
3 mm σ_z
27 mm mrad ε_n

Spectral order; red = 0

t = 360 ps

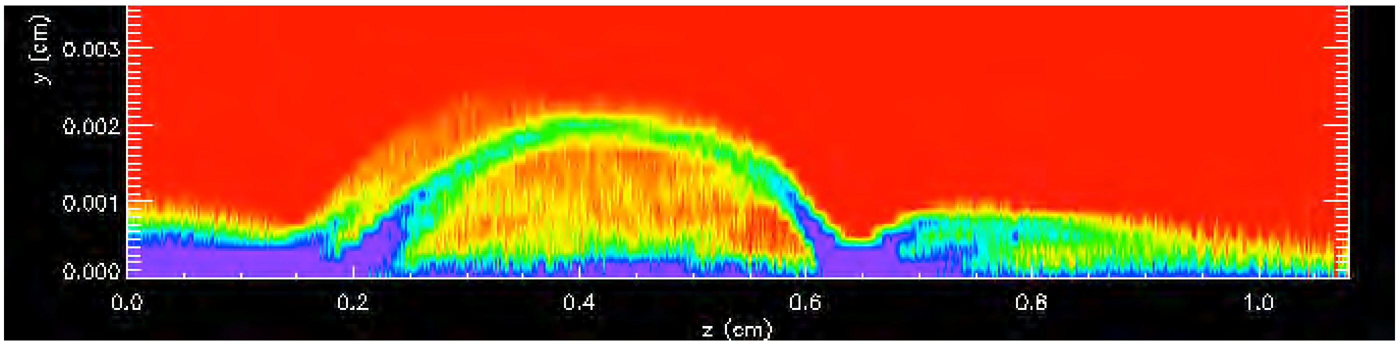


y (cm)
0.003
0.002
0.001
0.000
0.0
0.2
0.4
0.6
0.8
1.0
z (cm)



y (cm)
0.003
0.002
0.001
0.000
0.0
0.2
0.4
0.6
0.8
1.0
z (cm)

t =410 ps


y (cm)
0.003
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0.0
0.2
0.4
0.6
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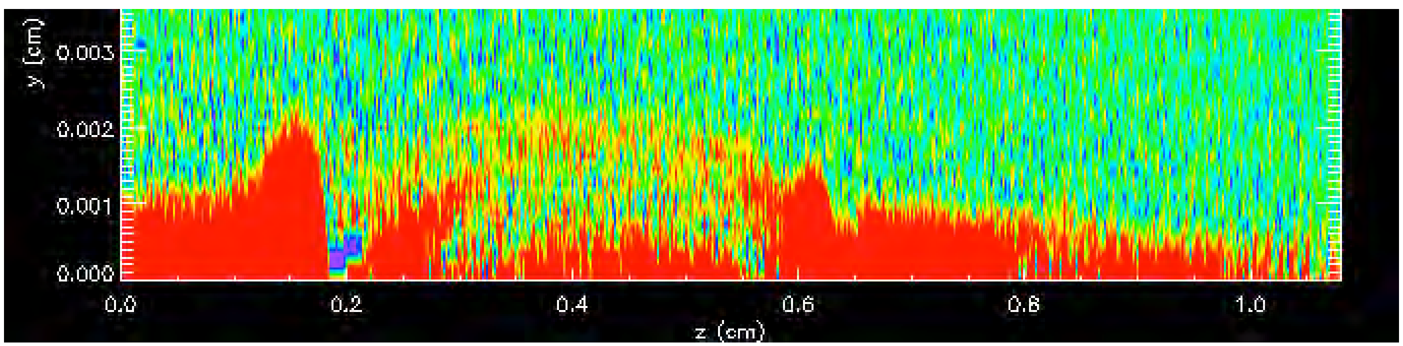
1.0
z (cm)


y (cm)
0.003
0.002
0.001
0.000
0.0
0.2
0.4
0.6
0.8
1.0
z (cm)

Projected Photon Flux

Approximately: $$N_x = \sigma_T \frac{N_b N_\gamma}{A} f$$

A is transverse overlap area; *f* is ratio of lengths (≤1);
$\sigma_T = 0.6$ barn

Assume 800 nm laser, 1 TW, 500 fs, 20 μm spot:
- $N_\gamma \sim 10^{18}$, $N_b = 6 \times 10^{11}$, entire laser pulse is usable energy, $a_L < 0.1$

⇨ photon yield roughly 10^9– 10^{10} / pulse

With 10.6 μm, N_γ goes up, but $a_L \sim 0.5$–1

Very challenging simulation problem!

- resolve laser wavelength over ~ $10Z_R = 3000\ \lambda$
- symmetry problem: e-beam cylindrical, laser Cartesian

An Application?

- Compton scattering has been proposed for high-flux γ-ray source for e+/e- collider (multiple laser beams)
- Requires only high-energy e-beam (~ 2 GeV)
- Plasma-assisted Compton source could greatly simplify this idea by extending useful pulse lengths
- Obtain small-angle, bright, polarized positron beam with only one laser?

γ-ray source

- 800 nm YAG laser, 10 ps, 1.5 J/pulse, 60 MeV scattered photons
- 100 nC e-beam, 1.6 GeV, 20 ps length, in 10^{17} plasma
- Matched beam, $\beta = 800\ \mu$m, $\sigma_x = 2.3\ \mu$m, $n_b/n_0 \sim 5$ (like SLC)
- Laser guided over 7 Z_R
- $\geq 10^{11}$ scattered photons/pulse, with $a_L \sim 0.1$ (low is good)
- Average brightness ~ 10^{22} photons/sec

Competitive with proposed polarized positron sources, with much simpler laser setup!

10.6 μm laser has higher photon number, but

- need much higher n_p to guide, then beam is difficult
- much higher $a_L \sim 0.5 - 1$ ⇨ nonlinear effects, distortion

Conclusion

• Self-guiding in plasma by electron beam has potential to create a high-brightness, long-pulse x-ray source through inverse Compton scattering

- *conceptually simple*
- *easy to time*
- *high photon number output*

• Output looks competitive with other x-ray and γ-ray generation methods involving pre-formed channels or multiple lasers

• **Not** necessary to use 10.6 μm laser!

- increase in photon number offset by high a_L
- similar performance from 800nm systems

• Simulation of yield is tough — ongoing project