Optically controlled laser-plasma electron accelerators for compact γ - ray sources

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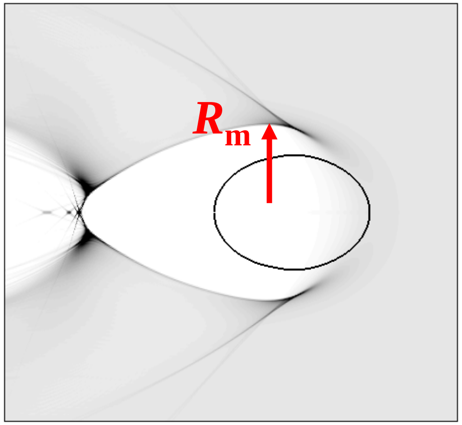
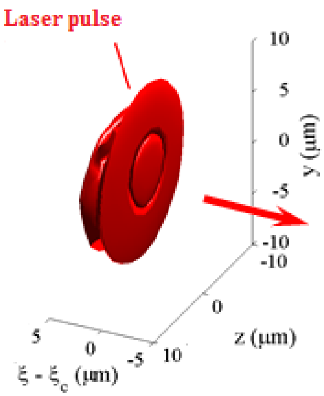


Laser-plasma acceleration – transverse matching provides partial control



Controlling transverse effects:

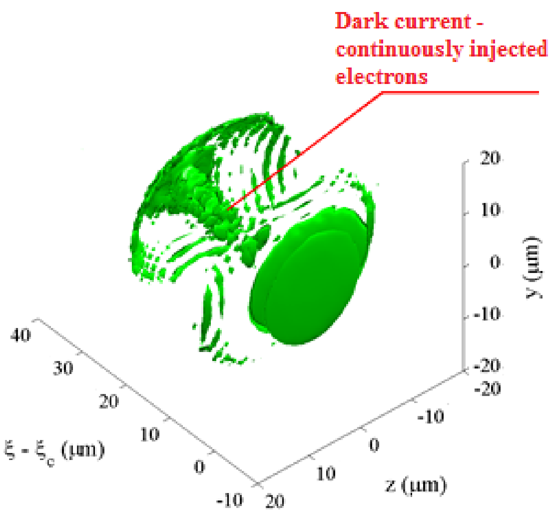
Match the pulse spot size to $R_m = 2^{3/2} k_p^{-1} (P/P_{cr})^{1/6} >> k_p^{-1}$

⇒ **Stable self-guiding & Full electron cavitation**

Longitudinal effects

– red-shift of the pulse leading edge & self-compression due to negative GVD of radiation in plasma –

remain uncontrolled



⇒ Reduced phase velocity of the bubble

⇒ Early electron dephasing, limited energy gain

⇒ **Massive continuous self-injection**

W. Lu *et al.*, *Phys. Rev Accel. Beams* **10**, 061301 (2007)

Matching strategy leads to unfavorable energy scaling

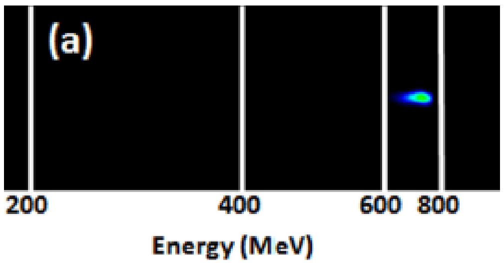
Match pulse length and spot size to make electrons dephase as the pulse depletes:

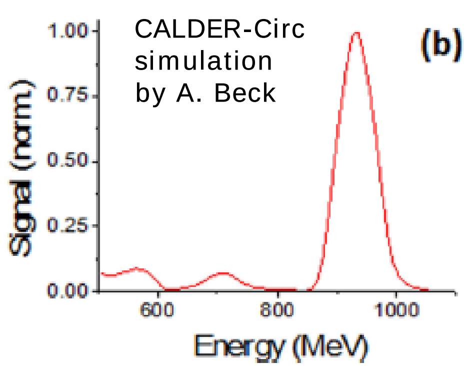
$$\tau_L = 2R_m / (3c)$$

Energy gain at dephasing/depletion: ΔE [GeV] = $0.125\,(P[\mathrm{PW}])^{1/3}\,(n_{20}\,\lambda_{\mu m}^2)^{-2/3}$

Robust self-guiding & self-injection: $P/P_{cr} > 10 \;\Rightarrow\; n_{20}\,\lambda_{\mu m}^2 > 1.8 \times 10^{-3}\,(P[\mathrm{PW}])^{-1}$

056703-7 Banerjee *et al.* Phys. Plasmas **19**, 056703 (2012)





Stringent scaling of the energy gain:

$$\Delta E\ (\mathrm{GeV}) < 8.6\, P[\mathrm{PW}]$$

$\Delta E \approx 1$ GeV $\Rightarrow$ $P \approx 120$ TW

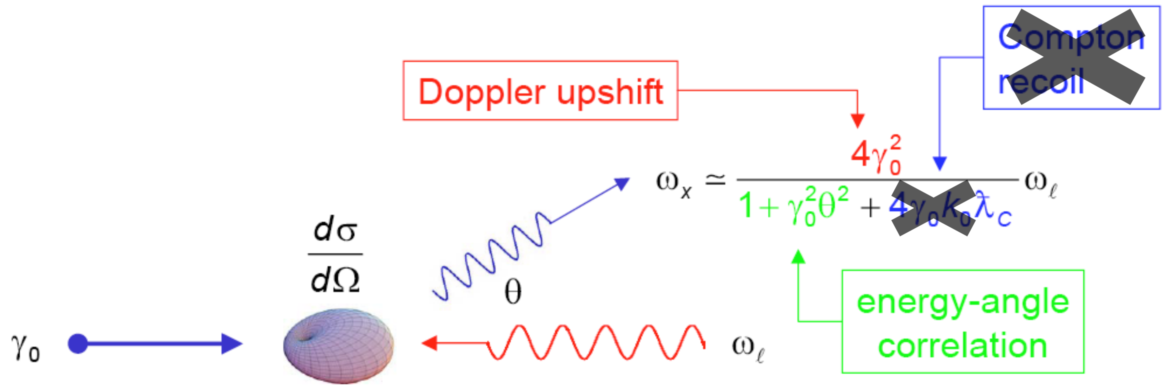
$\tau_L \approx 32$ fs

$L_{\mathrm{dephasing}} \approx 0.7$ cm

Regime is accessible, but

the repetition rate is <<< 10 Hz

Inverse Compton (Thomson) scattering and its requirements for e-beams



From: C. P. J. Barty, LLNL Proposal for the ELI-NP γ-Source, ELI-NP Gamma Source Meeting, 04/18/2011

- Photon flux > 10^6/shot/full bandwidth

  E-beam 5-D brightness >10^{16} A/m^2 [A. Cianchi *et al*., *NIM A* **829**, 343 (2016)]

  Sub-% energy spread in the e-beam

- Photon energy 10-20 MeV – challenge

  GeV e-beams needed – scaling suggests using PW-/kJ-scale pulses

- Repetition rate in kHz to raise the dosage – major challenge

  MW-class average-power laser amplifiers are not going to be available soon

Raising the repetition rate: GeV LPA with sub-Joule (10-TW-scale) pulses

Moderate average power:

1. Enables *high repetition rate* needed by applications that require high dosage (medicine, nuclear fluorescence studies *etc*.)

   1J @1 kHz = 1 kW — a hard, yet manageable laser engineering problem.

2. Helps *reduce the size and cost of facilities*.

3. *Lifts the barriers for first-principle modeling*.

4. Enables *real-time control* of the laser pulse phase (using genetic algorithms) for optimization of the acceleration process

   [Z.-H. He *et al.*, Coherent control of plasma dynamics, *Nat. Comm.* **6**, 7156 (2015)]

Transform-limited, 10-TW-class pulse rapidly destroys itself *and* e-beam ☹

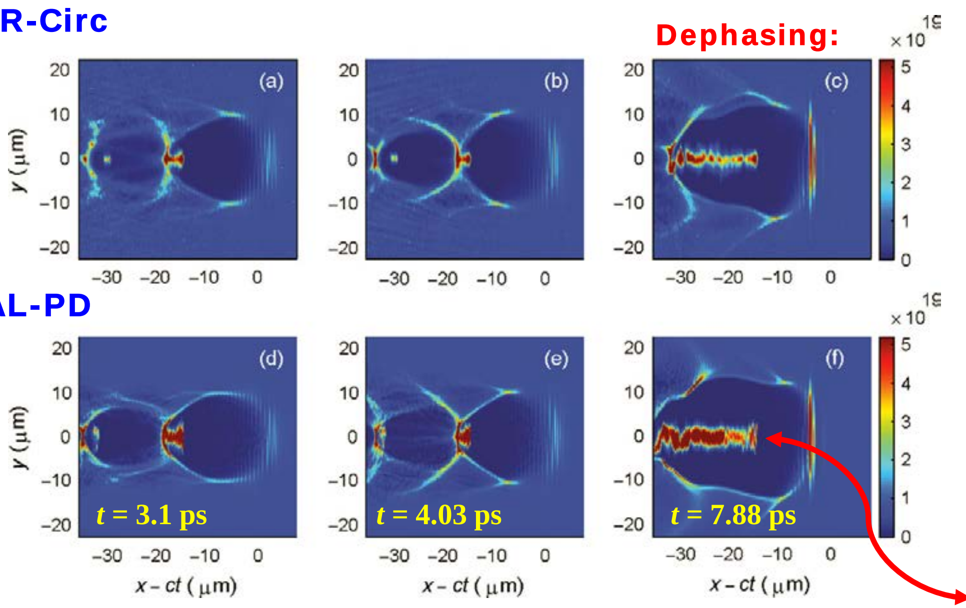
1. Self-guiding needs a dense, highly dispersive plasma ($\sim 10^{19}$ cm^{-3})
2. Self-compression of the pulse

   (a) keeps the energy gain below half-GeV

   (b) forces expansion of the bubble, hence massive dark current

CALDER-Circ code:

VORPAL-PD code:



Power / energy / length	70 TW / 2.1 J /30 fs
Plasma density, n_0	6.5×10^{18} cm^{-3}
$P/P_{cr} \approx 16$	

B. M. Cowan *et al.*, *J. Plasma Phys.* **78**, 469 (2012)

E ≈ 420 MeV + huge tail

Large bandwidth ($\Delta\lambda \sim \lambda_0$) and negative chirp solve the problem ☺

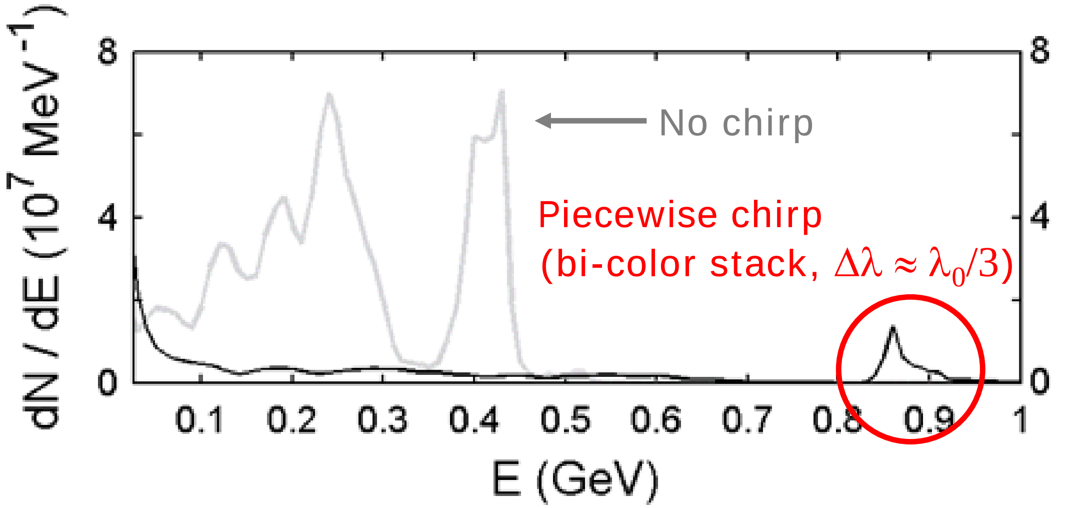
These features:

- ➢ mitigate the frequency red-shift
- ➢ slow down pulse self-compression in dense plasmas ($\sim 10^{19}$ cm^{-3})
- ➢ extend the dephasing length, boosting the energy gain to GeV level
- ➢ strongly reduce the energy tail.

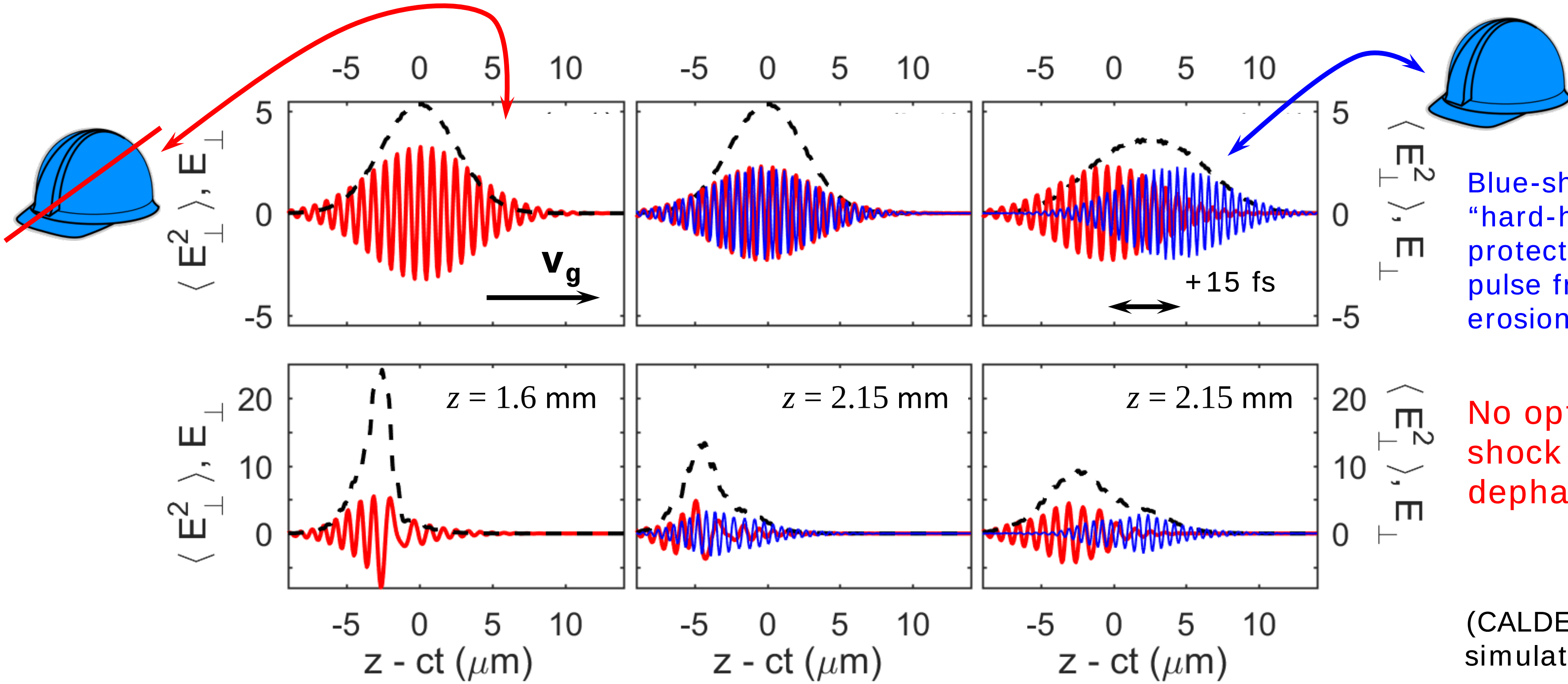
HIGH EXPECTATIONS: Background-”free” near-GeV acceleration with 1.4J laser energy

20–30 fs pulse

$n_0 = 6.5 \times 10^{18}$ cm^{-3}



Temporally advanced blue-shifted "head" protects the optical driver from nonlinear erosion



Blue-shifted "hard-hat" protects the pulse from erosion

No optical shock at dephasing

(CALDER-Circ simulations)

Head: 20 fs, 0.7 J, $\lambda_{tail} = 0.8$ μm
Tail: 20 fs, 0.7 J, $\lambda_{head} \approx 0.53$ μm

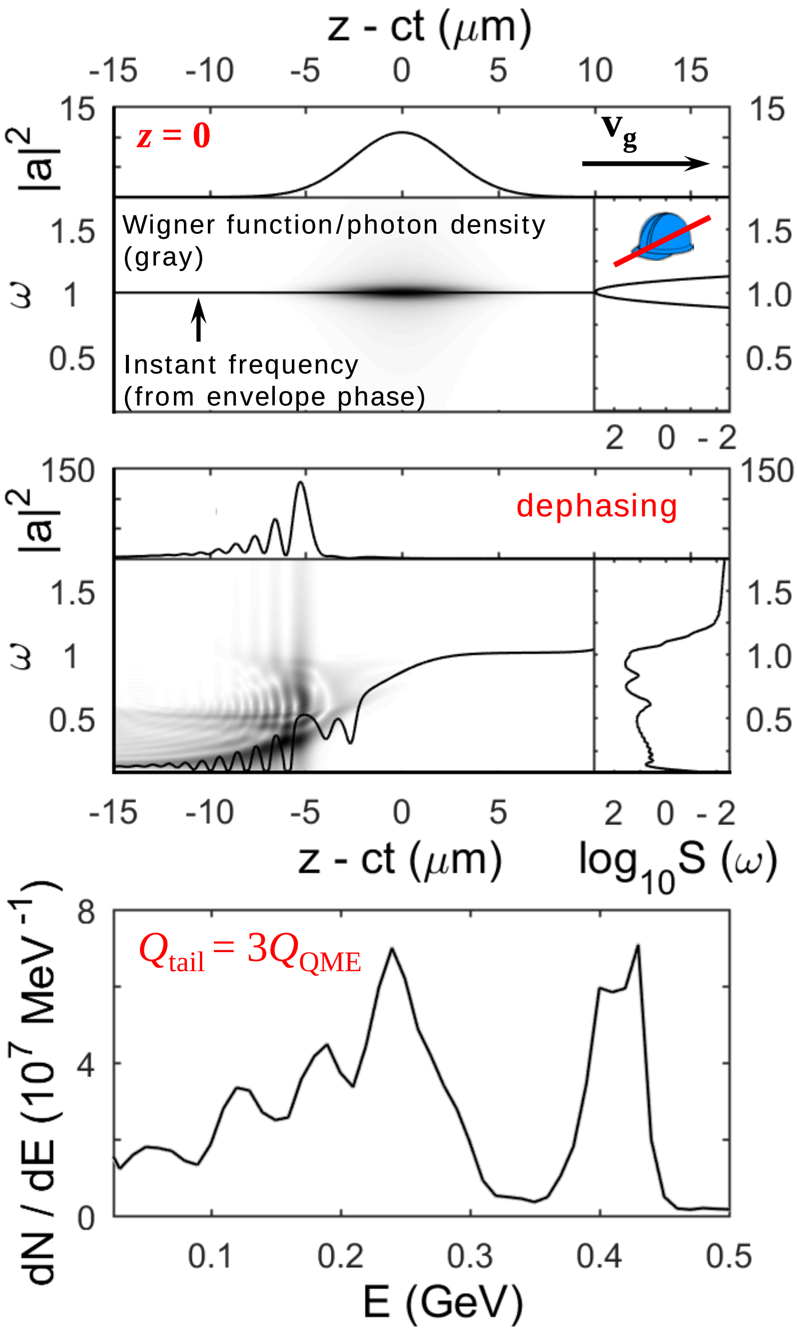
} orthogonally polarized (**incoherent mixing**)

- Frequency shift in Raman cells with subsequent conventional CPA

[F. B. Grigsby *et al.*, *JOSA B* **25**, 346 (2008)]

- Energy-efficient methods of 2nd harmonic pulse generation.

Acceleration with a single TLP: Electron beam ruined



Pulse at dephasing:

Compressed to a single cycle and 60%-depleted

"Photon phase-space rotation": mid-IR photons slide into the bubble

QME bunch:

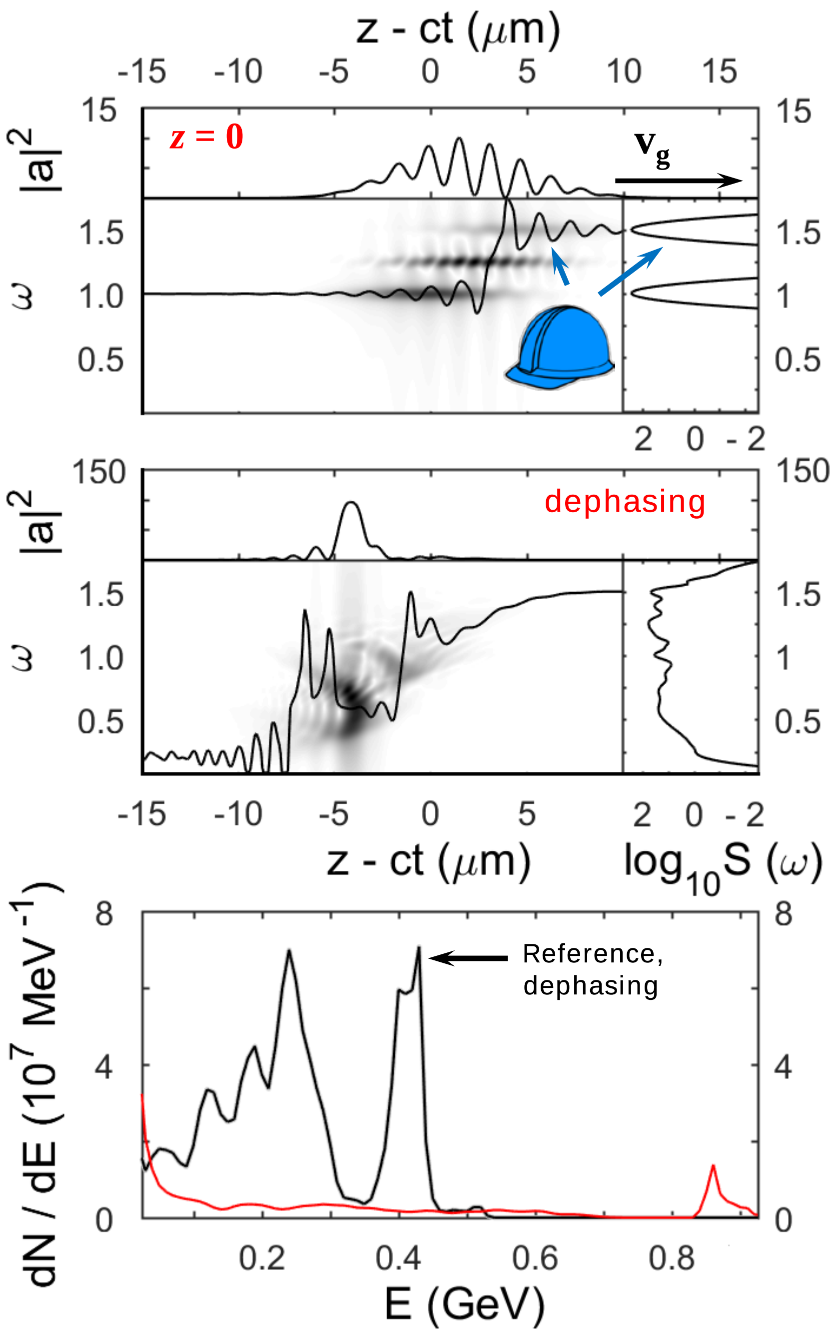
$\langle E \rangle$	427 MeV
$\sigma_E / \langle E \rangle$	6%
$\varepsilon_{\text{norm}, \perp}$	0.7 mm mrad
Charge	0.495 nC
RMS current	90 kA
RMS divergence	2.9 mrad

5-D brightness:

$2\langle I \rangle (\pi \varepsilon_{\text{norm}, \perp})^{-2} = 3.8 \times 10^{16}$ A/m²

Simulation codes: WAKE and CALDER-Circ (energy spectra)

Bi-color stack: Doubling electron energy



QME e-beam at dephasing ($L_{dephasing} \times 1.8$):

$\langle E \rangle$	882 MeV	(×2 of reference)
$\sigma_E / \langle E \rangle$	3.2%	
$\varepsilon_{norm, \perp}$	0.4 mm mrad	(×1/2 of reference)
Charge	73 nC	
RMS current	88 kA	(same as reference)
RMS divergence	1.35 mrad	
5-D brightness	1.1×10^{17} A/m^2	(×3 of reference)

Tail at dephasing:

Reduction by a factor 6 in charge, by a factor 20 in average flux

S. Y. Kalmykov *et al.*, Phys. Plasmas **22**, 056701 (2015)

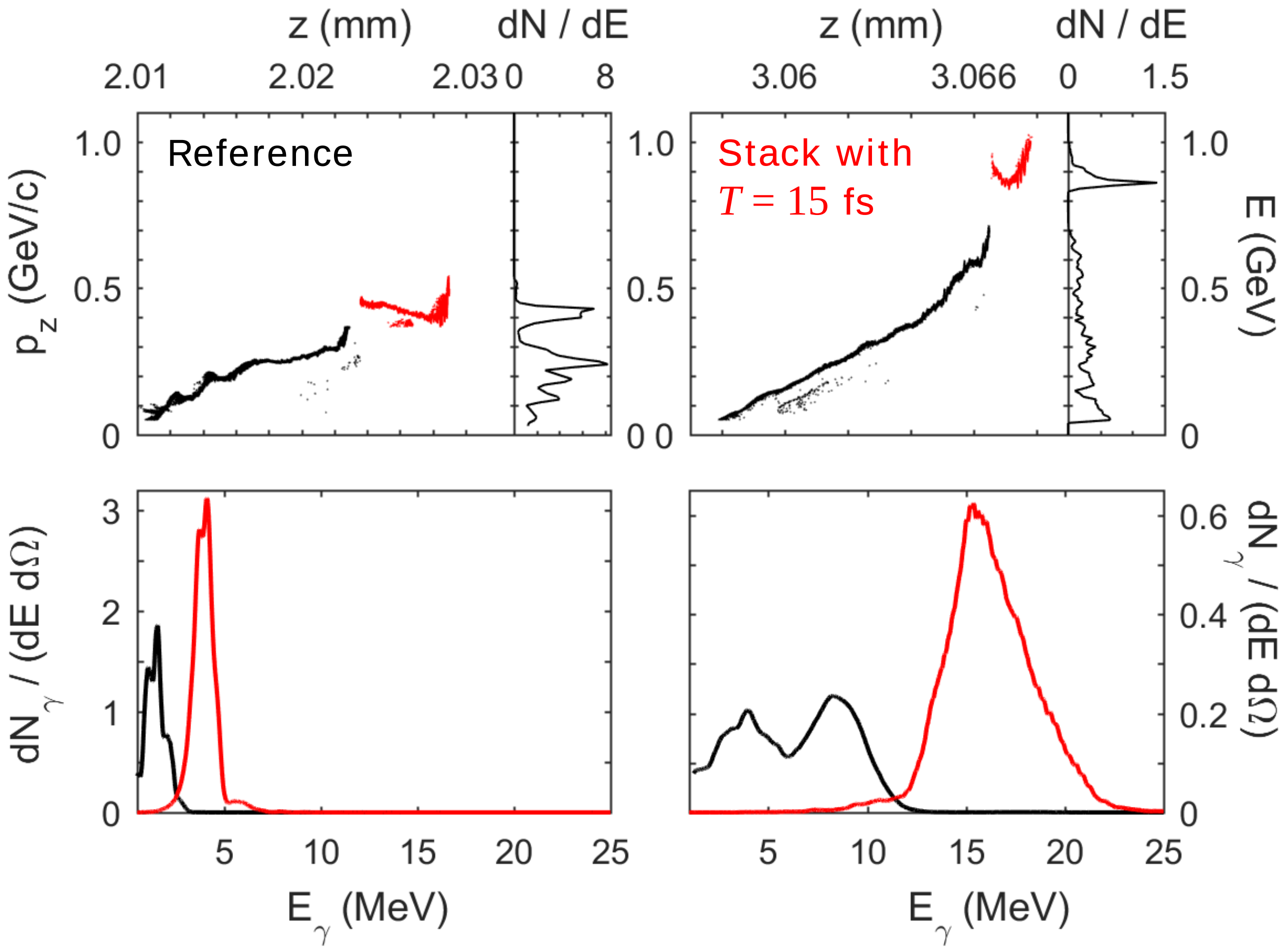
Improvement in Thomson scattering signal

E-beam phase space and flux (in 10^7 MeV^{-1}) at dephasing

Photon flux (in 10^{12} MeV $^{-1}$ sr $^{-1}$) in the e-beam propagation direction

– head-on collision

– on-axis observation



- Photon energy boost by a factor 4.2 (to 16 MeV)
- Increase in the signal to background ratio, from 2:1 to 4:1

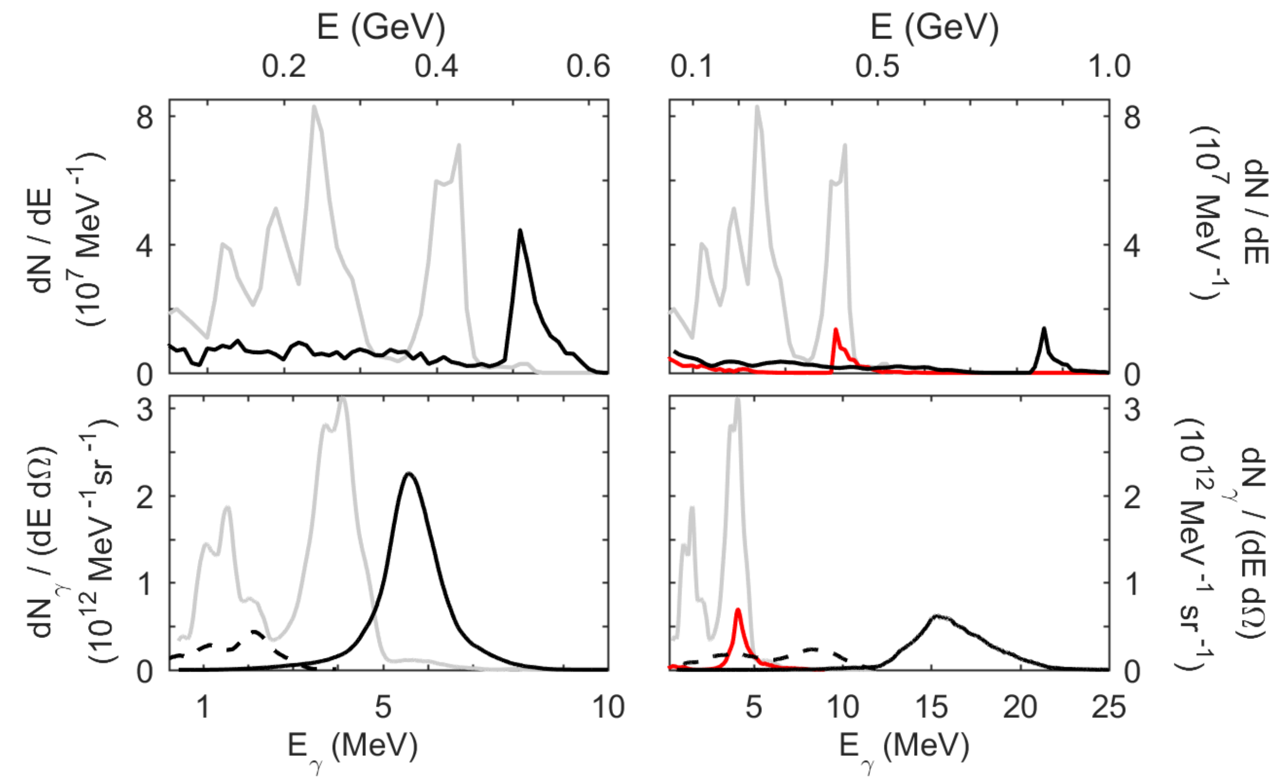
Thomson back-scattering (almost linear regime, quasi-planar-wave interaction):
Interaction laser pulse: Linearly polarized, $r_0 = 16.8\ \mu$m; $a_0 = 0.1$; $\lambda = 0.8\ \mu$m; FWHM 250 fs

Time delay in the stack controls γ-photon flux and energy

Stack with a full overlap | Stack with a delay ($T = 15$ fs)

Electron energy spectra at dephasing

γ-ray flux in the direction of e-beam propagation

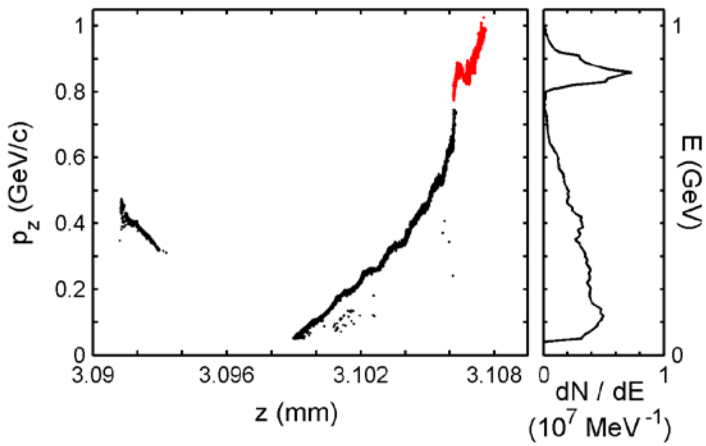


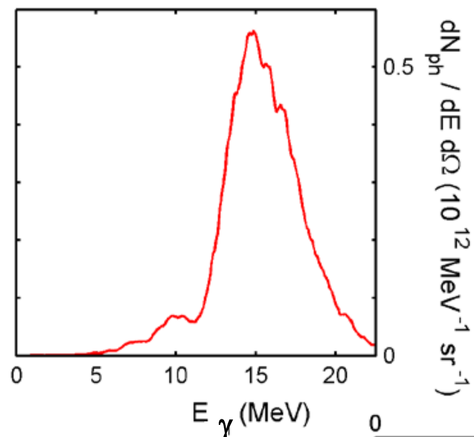
QME γ-ray signals	Reference	Stack wit full overlap ($T = 0$)	Stack with $T = 15$ fs	
			$z = 1.47$ mm	Dephasing (3.07 mm)
$\langle E_\gamma \rangle$ (MeV)	3.85	5.67	4.35	16
$\sigma_E / \langle E_\gamma \rangle$, %	18.7	17.1	21.3	15.5
N_γ per Ω_d	8.95×10^6	5.08×10^6	1.52×10^6	1.58×10^6
Energy (μJ)/power in Ω_d	5.5 (1 GW)	4.6 (1.2 GW)	1.1 (1.3 GW)	4 (4.7 GW)

Few-% energy spread of e-beam imparts 15–20% bandwidth into the Thomson signal

Full phase space of e-beam: $\langle p_z \rangle = 1726\, m_e c$, $\sigma_{pz} = 56\, m_e c$ (3.25% energy spread)

$\langle p_r \rangle = 0$, $\sigma_{pr} = 2.3\, m_e c$ (1.35 mrad divergence)





$\langle E_\gamma \rangle = 16$ MeV

$\sigma_E = 2.5$ MeV

(15.5% spread)

Reduced phase space I:

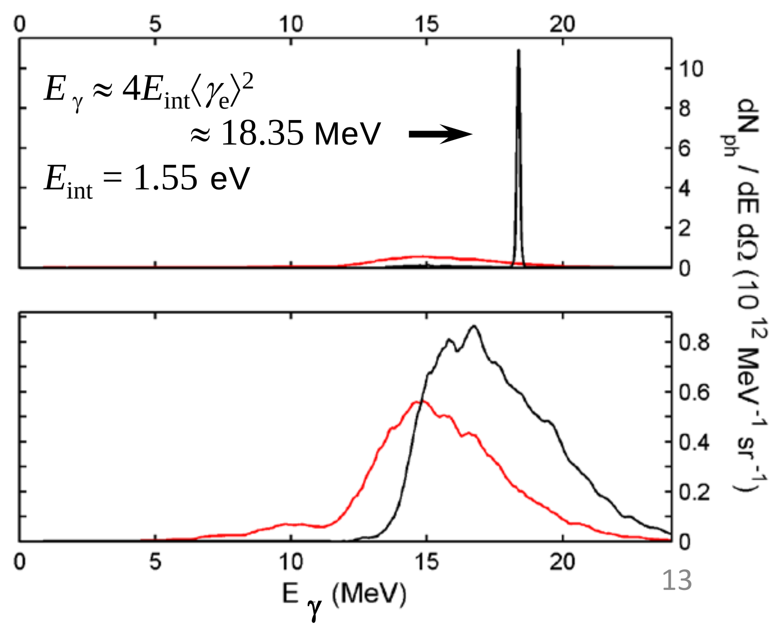
$\langle p_z \rangle = 1726\, m_e c$, **$\sigma_{pz} = 0$** (**≈ 0% energy spread**)

$\langle p_r \rangle = 0$, $\sigma_{pr} = 2.3\, m_e c$ (1.35 mrad divergence)

Reduced phase space II:

$\langle p_z \rangle = 1726\, m_e c$, $\sigma_{pz} = 56\, m_e c$ (3.25% energy spread)

$\langle p_r \rangle = 0$, **$\sigma_{pr} = 0$** (**zero divergence**)

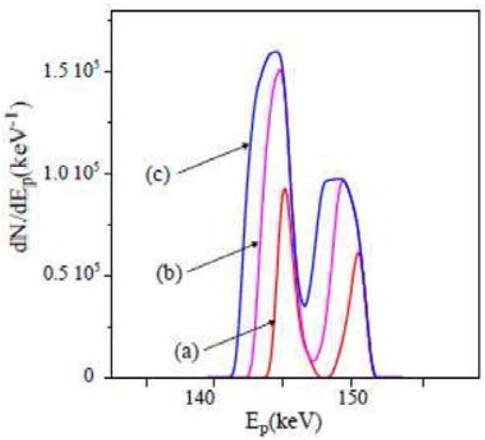


Electrons from stack-driven LPA for quasi-monochromatic Thomson sources

- High-power (1–5 GW), fs-length γ-ray pulses contain $> 10^6$ photons in the sub-μsr observation solid angle
- This flux corresponds to the full bandwidth (1–2.5 MeV) imparted by a few-% energy spread in the e-beam
- Mean photon energy is tunable between 4 and 16 MeV without losing photons in the μsr observation solid angle $\Omega_d = (\pi/2)\langle\gamma_e\rangle^{-2}$
- Signal to background ratio is better than 4:1
- Changing time delay in the stack permits accurate tuning e/γ energy and flux, with the same laser energy and frequency ratio in the stack
- Sub-Joule energy in stack components affords kHz repetition rate at the affordable average power
- Expectation of 10^{10} ph/s flux (good for NRF applications).

Trains of multi-color X/γ-ray pulses: What are they good for?

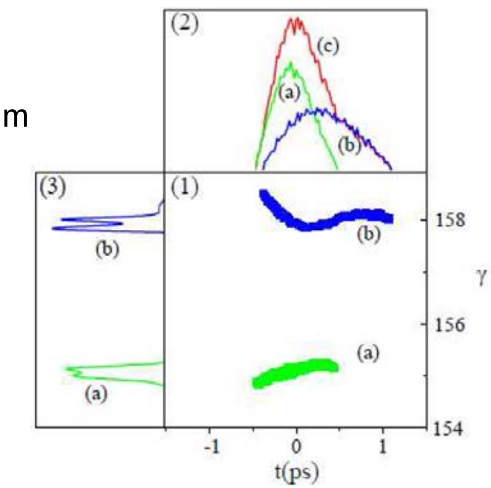
Comb-like X/γ - ray beam: Train of wave packets with an adjustable frequencies and time delays



A bi-color X-ray beam @ SPARC-LAB

Source: a comb-like e-beam – a train of bunches with adjustable energies and time delays

Bi-color e–beam from SPARC-LAB:



Images:

V. Petrillo *et al.*, Dual-color X-rays from Thomson or Compton sources, *Proc. SPIE* **9512**, 95121E (2015)

Generation mechanism: bi-color FEL or inverse Compton (Thomson) scattering

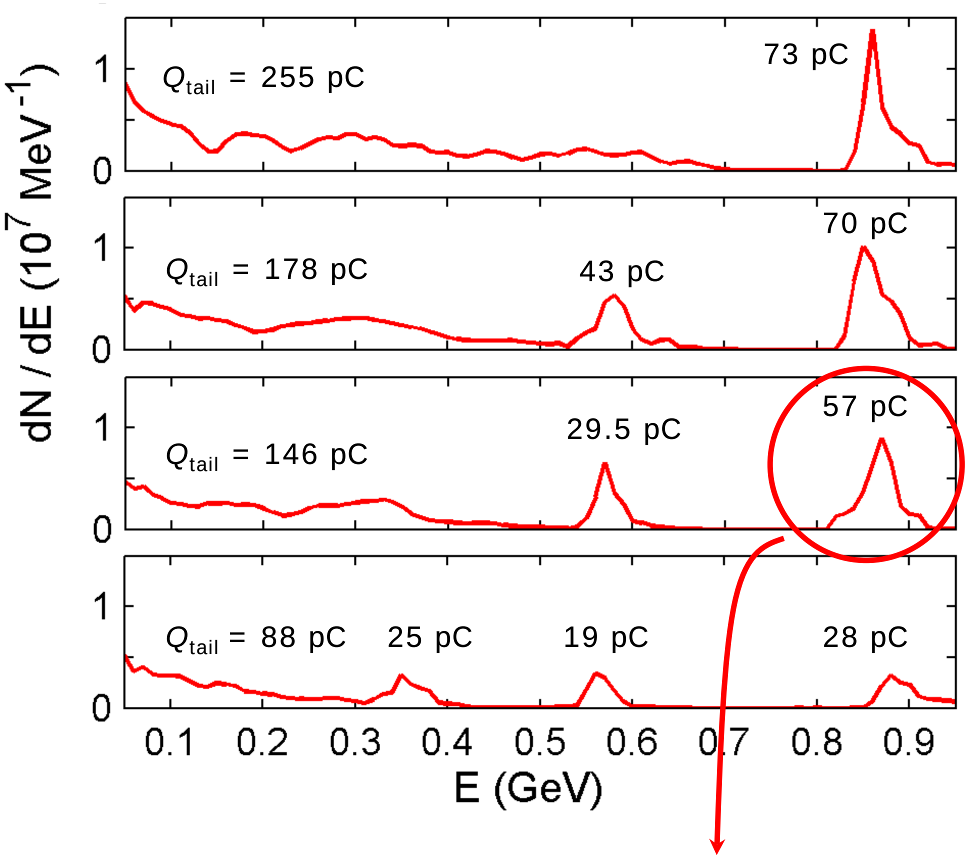
Applications:

- Ultrafast (on a fs- to ps-scale) pump-probe experiments in AMO or HEDP
- Time-domain spectroscopy [J. F. Cahoon *et al.*, *Science* **319**, 1820 (2008)]
- Screening/diagnostic mammography: Color components help discriminate chemical composition of absorbing tissues [I. Willekens *et al.*, *Eur. Soc. Radiography*, 2011]
- Nuclear photonics [S. Chen *et al.*, *Phys. Rev. Lett.* **110**, 155003 (2013)]

Generating comb-like e-beams in stack-driven LPA

Stack (with $T = 15$ fs) permits focusing head and tail differently.

Weak focusing of the tail ($R_{\text{tail}} \geq R_{\text{head}}$) destabilizes the bubble.
Periodic injection generates a polychromatic train of bunches.



$R_{\text{tail}} = R_{\text{head}} = 13.6\ \mu\text{m}$

$R_{\text{tail}} = (3/2)^{1/2} R_{\text{head}}$

$R_{\text{tail}} = 2^{1/2} R_{\text{head}}$

$R_{\text{tail}} = 3^{1/2} R_{\text{head}}$

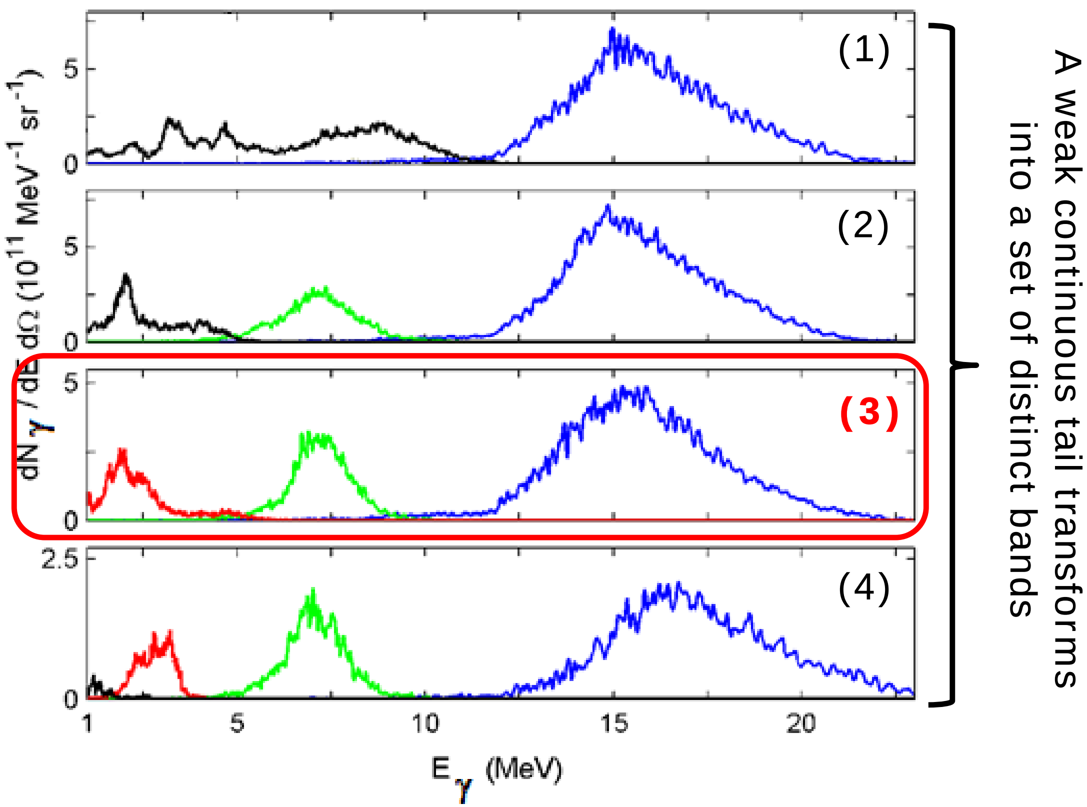
— too weak focusing makes injection ineffective

Brightness (10^{17} A/m^2): (1) 0.44 (2) 0.96

$\sigma_E / \langle E \rangle$: (1) 3.2% (2) 2.4%

[S. Y. Kalmykov *et al.*, *AIP Conf. Proc.* **1872**, 100001 (2017)]

Generating X/γ-ray pulse trains using comb-like e-beams from stack-driven LPA



Characteristics of γ-ray energy bands (QME pulses):

$\sigma_E / \langle E_\gamma \rangle$: 14.7 to 19.5%

N_γ per Ω_d : 0.4 to 1.6×10^6

Total energy per band,

in detector solid angle,

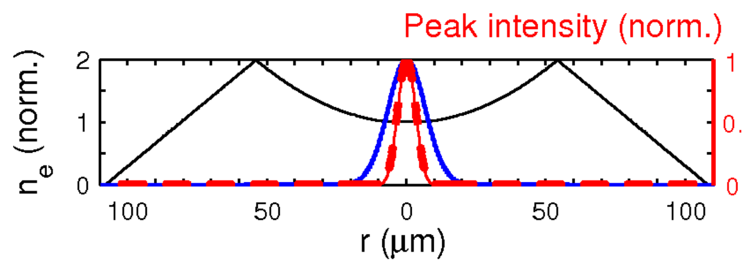
$\Omega_d = (\pi/2)\langle \gamma_e \rangle^{-2}$: 0.17 to 4 μJ

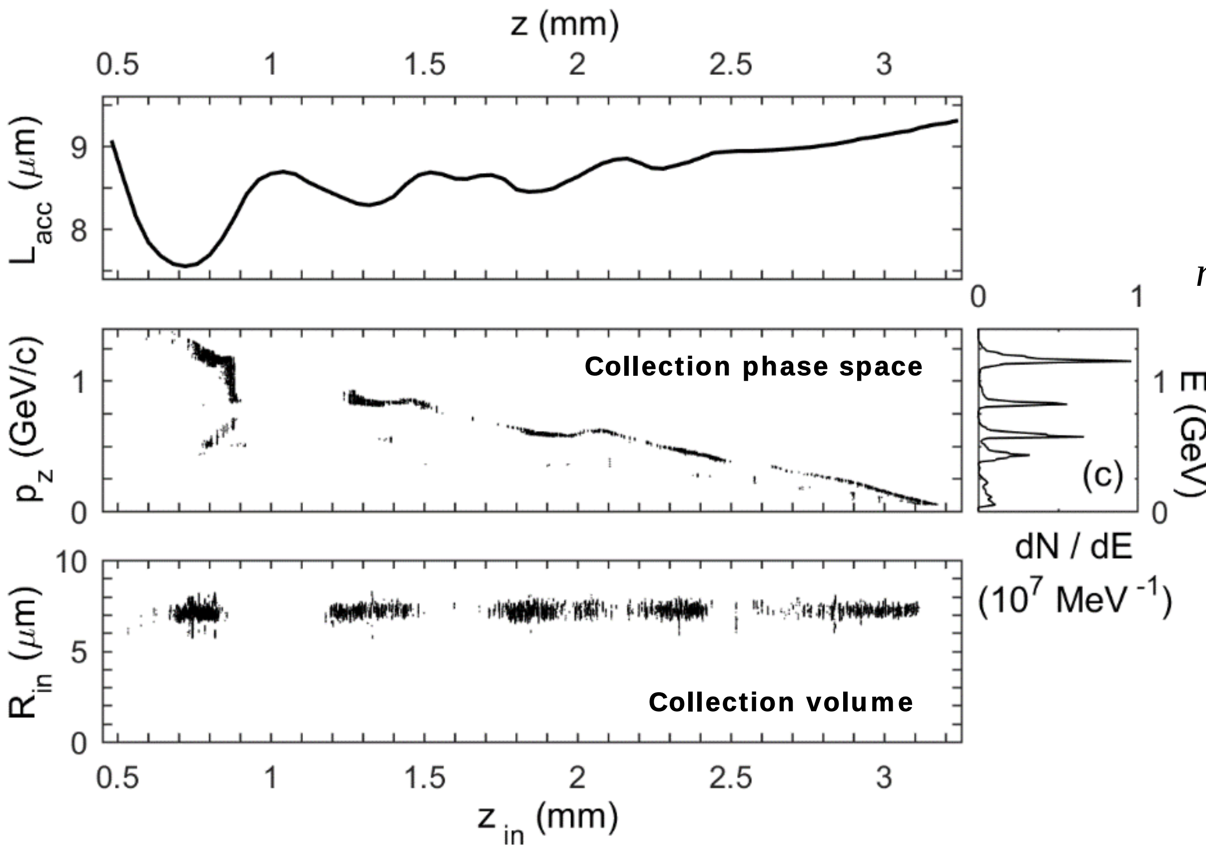
Case 3	1	2	3
$\langle E_\gamma \rangle$ (MeV)	2.8	7.25	15.8
$\sigma_E / \langle E_\gamma \rangle$, %	19.4	14.7	15.7
N_γ per Ω_d	0.91×10^6	0.62×10^6	1.25×10^6
Energy/power per Ω_d (μJ)	0.4 (0.17 GW)	0.72 (0.75 GW)	3.16 (4.27 GW)

Propagating the stack in a channel (a) adds more control, (b) further boosts electron energy

Same stack as before, with a $T = 15$ fs delay.

Stack head and tail have the same spot sizes, matched to the single-mode channel.





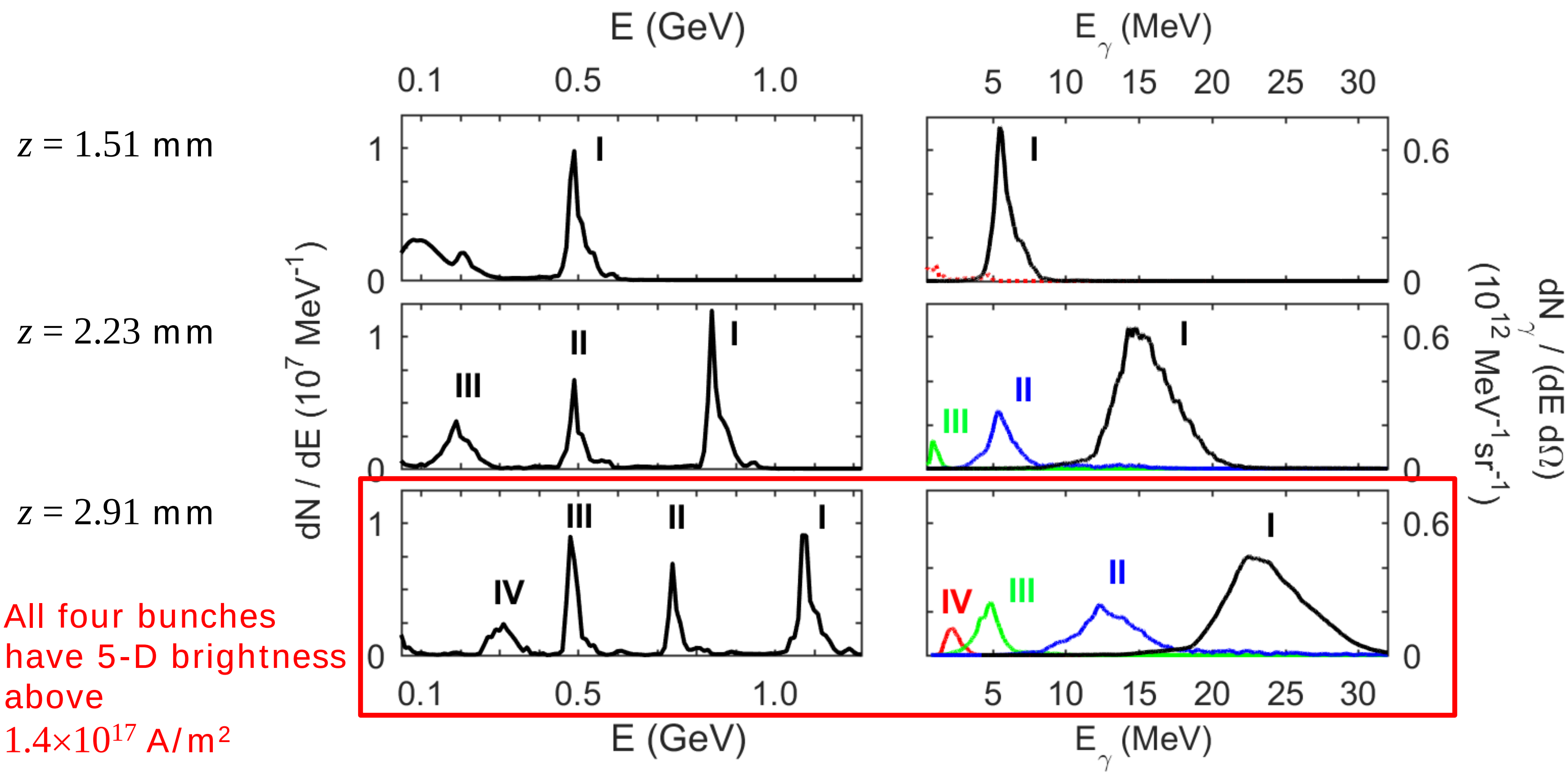
$$
n_e(r) = \begin{cases} n_0\left(1+\dfrac{r^2}{r_{ch}^2}\right), & \text{for } r \le r_{ch} \\ 2n_0\left(2-\dfrac{r}{r_{ch}}\right), & \text{for } r_{ch} < r \le 2r_{ch} \\ 0 & \text{for } r > 2r_{ch} \end{cases}
$$

The e-comb absorbs 10% of laser energy

The peak energy 1.2 GeV (vs ~ 430 MeV of the reference case)

S. Y. Kalmykov *et al*., Phys. Plasmas **22**, 056701 (2015)

Progress of comb-like e-beam through dephasing and generation of multi-color γ-ray beams



4-color γ-ray signal	1	2	3	4
$\langle E_\gamma \rangle$ (MeV)	24.1	12.6	4.67	2.27
$\sigma_E / \langle E_\gamma \rangle$, %	15	18.4	20	22.6
N_γ per Ω_d	1.64×10^6	0.66×10^6	0.585×10^6	0.595×10^6
Energy/power per Ω_d (μJ)	6.5 (10.3 GW)	1.34 (1.8 GW)	0.46 (0.39 GW)	0.22 (0.34 GW)

Summary

Designing the LPA drive pulse as an incoherent stack of independent sub-Joule, transform-limited pulses with a large difference frequency ($\Delta\omega \sim \omega_0$) permits an *unprecedented freedom in e-beam phase space control*, suppressing the background and increasing 5-D brightness of individual bunches above $\sim 10^{17}$ A/m^2.

Stack-driven LPAs promise generation of fs-length, ultra-bright, near-GeV electron bunches at a kHz repetition rate, with affordable average power.

These bunches (or trains of bunches) promise to drive quasi-monochromatic (or comb-like) Thomson-scattering γ–ray sources, tunable into 10's of MeVs, while keeping the γ–ray pulse length extremely short (100's of as) and the number of photons high ($> 10^6$).

ACKNOWLEDGEMENTS

Inverse Thomson scattering simulations were completed by S.Y.K. utilizing the Holland Computing Center of the University of Nebraska.

SYK cordially thanks Natasha Pavlovikj of HCC for assistance.

Addenda

Simulation tools: fully relativistic PIC codes & particle tracker for radiation calculation

- Exploring optical pulse evolution in the plasma and beam loading effects: **WAKE** (extended-paraxial, ponderomotive guiding center, quasi-static)

  [P. Mora and T. M. Antonsen, Jr., *Phys. Plasmas* **4**, 217 (1997)]

- Accurate simulation of self-injection and acceleration: **CALDER-Circ** (quasi-cylindrical, fully explicit; poloidal mode decomposition of fields and currents)

  [A. F. Lifschitz *et al*., *J. Comp. Phys*. **228**, 1803 (2009)]

  Also: numerical Cherenkov-free EM solver; 2nd or 3rd order macro-particles

  [R. Lehe, A. F. Lifschitz et al., PR-STAB Beams 16, 021301 (2013)]

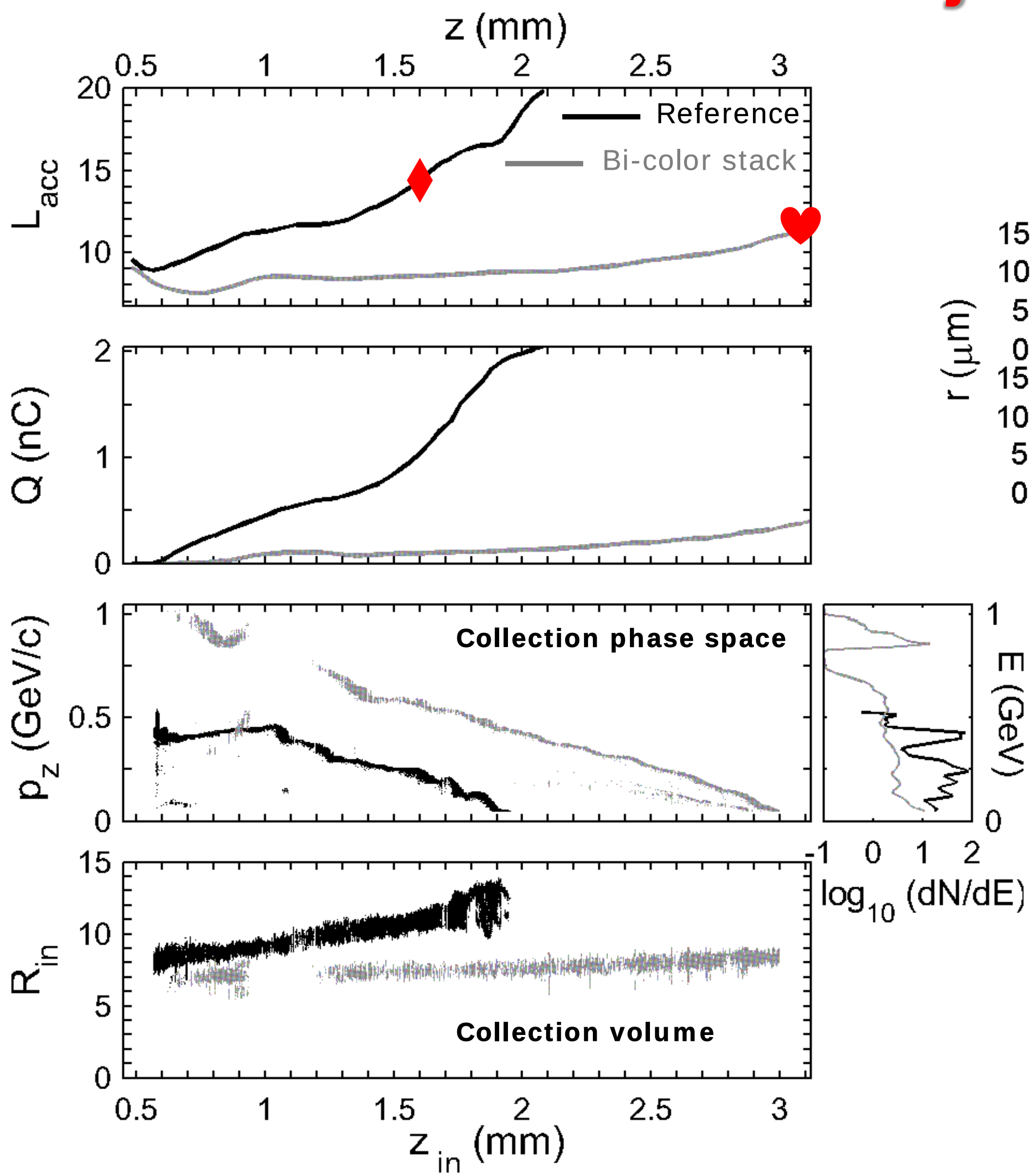
- Inverse Thomson scattering code

  [I. Ghebregziabher *et al., Phys. Rev. Accel. Beams* **16**, 030705 (2013)]

  fully relativistic particle tracker; laser beam is paraxial; radiation calculation using classical formula

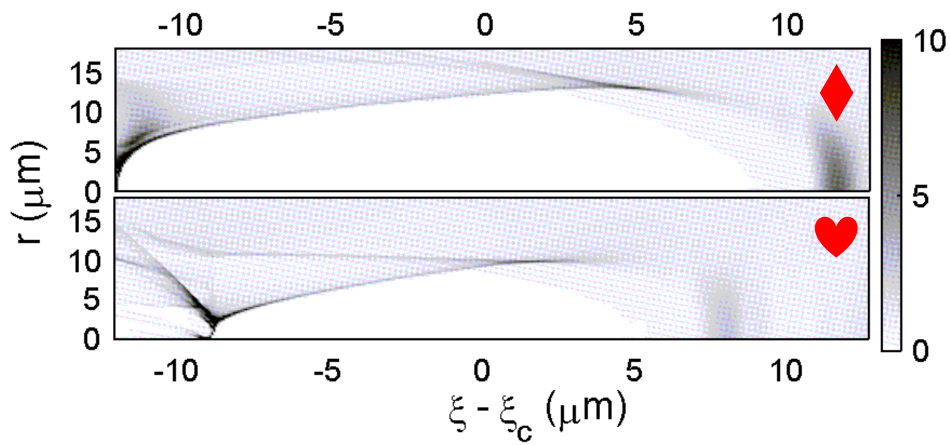
$$\frac{d^2 I}{d\omega d\Omega} = 2|\mathbf{A}(\omega)|^2, \qquad \mathbf{A}(\omega) = \left(\frac{e^2}{8\pi^2 c}\right)^{1/2} \int_{-\infty}^{\infty} e^{i\omega t}\left[\frac{\mathbf{n}\times[(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}]}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3}\right]dt, \qquad \frac{d^2 I_e}{d\omega d\Omega} = \frac{1}{N_s}\sum_{i=1}^{N_s}\frac{d^2 I_i}{d\omega d\Omega}.$$

Stack vs. reference: Suppressing continuous injection



(CALDER-Circ simulations)

Quasi-static bubble (WAKE simulations):



Due to much slower self-compression of the stack

- ➢ bubble expands slowly
- ➢ *continuous injection insignificant (hence the weak energy tail)*