Laser-accelerated comb-like electron beams for generation of pulsed polychromatic γ-rays

Serge Kalmykov[1], Xavier Davoine[2], Isaac Ghebregziabher[3]

[1] Department of Physics & Astronomy, University of Nebraska – Lincoln, USA

[2] CEA, DAM, DIF, Arpajon, France

[3] Department of Mechanical & Nuclear Engineering, Pennsylvania State University, USA

Erice – Trends in Free Electron Lasers, May 19, 2016

Trains of multi-color X/γ-ray pulses: Why do we need them?

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

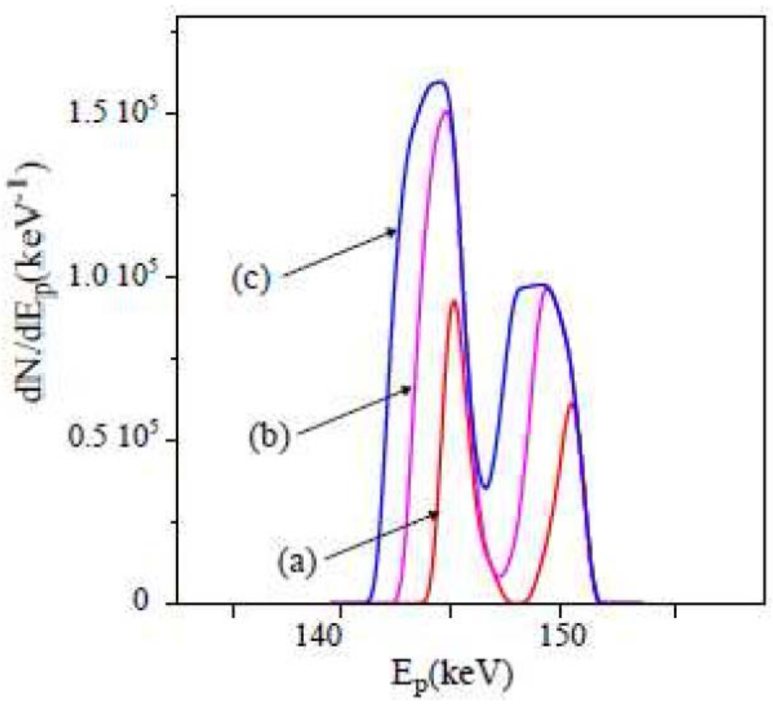
- Pump-probe experiments to monitor ultrafast changes (on a fs- to ps-scale) in atomic, electronic, magnetic structures (or in HEDP)
- Time-domain spectroscopy

  [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: Activation of different levels of suspect nuclear species in a long-distance interrogation

  [S. Chen *et al*., PRL 110, 155003 (2013)]

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



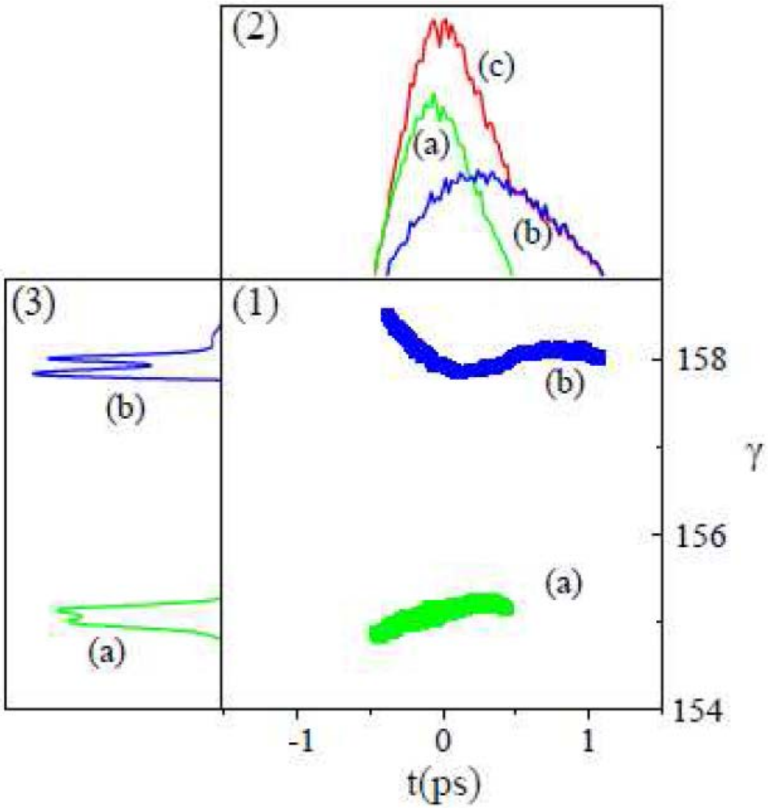
The image from:

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

Trains of multi-color X/γ-ray pulses: How do we get them?

First, we need a comb-like e-beam – a train of bunches with adjustable energies and time delays

A bi-color e–beam from SPARC-LAB:



The image from:

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

<u>Conventional way to generate electron comb</u>:

Illuminate a photocathode with a UV comb laser pulse and rotate e-phase space during acceleration in a linac

[A. Cianchi *et al*., PR-STAB 18, 082804 (2015); Zh. Zhang *et al*., PR-STAB 18, 090701 (2015)]

<u>Less conventional way (**subject of this talk**)</u>:

Laser wakefield acceleration with optically controlled periodic self-injection

<u>Producing X/γ-ray pulse trains</u>:

- Bi-color XFEL [V. Petrillo, *et al*., PRL 111, 114802 (2013); A. Martinelli *et al*., Nat. Commun. 6, 6369 (2015)] – (pros) extra-high brilliance, coherence; (cons) extremely hard to do; multi-ps pulse duration.
- Inverse Thomson scattering (ITS) (**another subject of this talk**) – (pros) less technically demanding, high transverse coherence & tunability, fs pulse duration; (cons) lower brilliance

All-optical generation of X/γ-ray energy combs - I

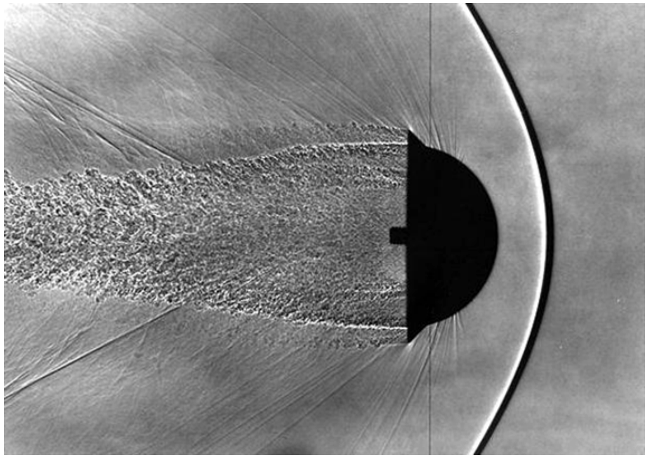
Match the drive pulse parameters for self-guiding in the blowout regime:

- Select the drive pulse power $P/P_{cr} > 10$ [$P_{cr} = 16.2(n_c/n_0)$ GW – critical power for relativistic self-focusing]

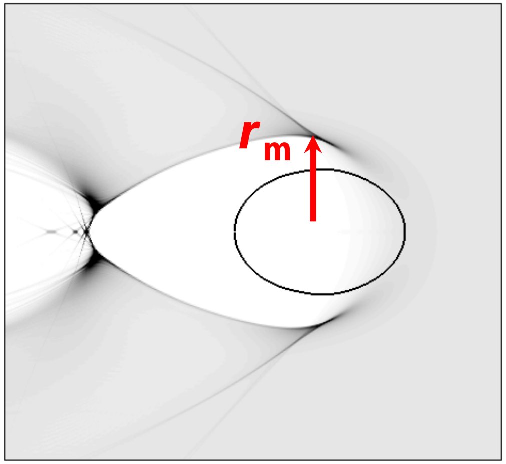
- Select the matched focal spot size $r_m = (c/\omega_{pe})2^{3/2}(P/P_{cr})^{1/6}$ [hence the peak vector potential $a_m = 2(P/P_{cr})^{1/3} >> 1$]

r_m is also close to the radius of the accelerating cavity – *a bubble of electron density encompassing the pulse*

Ultrasonic projectile:
Cavitation in a gas



Laser pulse in a plasma:
Cavitation of electron fluid



All-optical generation of X/γ-ray energy combs - II

Destabilize self-focusing by choosing pulse duration $\tau_L > r_m / c$

⇓

Size of the bubble starts to oscillate

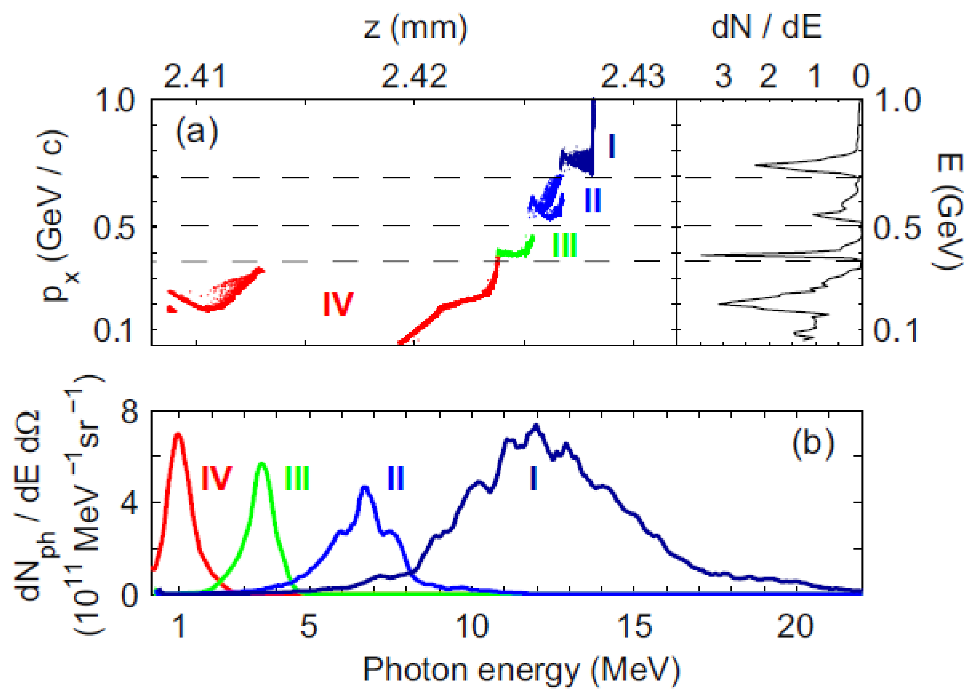
⇓

Electrons are injected periodically, rapid phase space rotation makes every bunch quasi-monoenergetic

⇓

Thus forms a train of fs-length bunches with a fs delay,
controllable energy difference,
and $10^{15} - 10^{16}$ A/m^2 brightness

γ-rays flashes from ITS contain $10^6 - 10^7$ photons within a solid angle $\Omega_{scat} \sim \pi \langle \gamma_e \rangle^{-2}$



Electron and γ-ray combs from LPA with a periodic self-injection
[S. Y. Kalmykov *et al.*, NIMA (2016)]

PHYSICAL OBSTACLES:

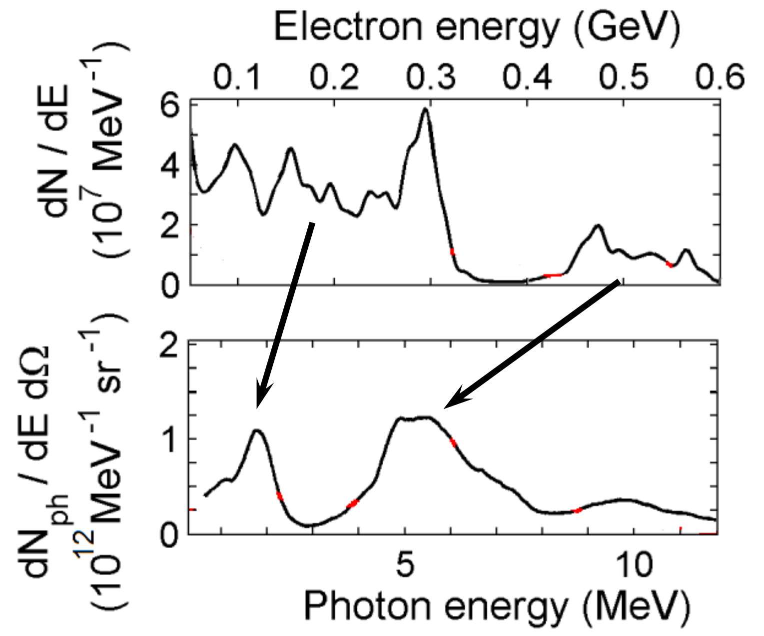
In the radially uniform plasma, oscillations in the bubble size may subside too soon, making periodic injection inefficient

MORE OBSTACLES:

laser pulse self-compresses into an optical shock

⇒ bubble constantly expands

⇒ continuous injection (a.k.a. dark current) creates massive electron energy tail, washing out the results of periodic injection



Electron spectrum at dephasing and ITS γ-ray signal (<u>on axis</u>) with a *transform-limited pulse* accelerating electrons through dephasing in the uniform plasma
[S. Y. Kalmykov *et al*., NIMA (2016)]

Solution #1:

Propagating the pulse in a channel

- enhances & controls periodic injection
- reduces the pulse self-compression; hence, increases phase velocity of the bubble and somewhat reduces the dark current

Solution #2:

Eliminating the dark current by driving the wake with a broadband negatively chirped pulse

Remainder of the talk:

1. Basics of all-optical control of dark current and production of comb-like electron beams: A case study of a drive pulse with a linear frequency chirp

2. Photon engineering for acceleration control: Designing the negative chirp through pulse stacking

3. Comb-like e-beams from uniform plasmas

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

- Exploring optical beam 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, X. Davoine 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. A. Ghebregziabher, B. A. Shadwick et al., PR-STAB 16, 030705 (2013)]

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

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

A case study: Linearly chirped pulse in a plasma channel

$\lambda_0 = 2\pi c/\omega_0$	Power/energy	τ_L	r_0	$n_e\ (r = 0)$
0.8 μm	70 TW / 2.1 J	30 fs	13.6 μm	6.5×10^{18} cm^{-3}

Laser vector potential:

$$a(r, z=0, t) = a_0 \exp\left[-\left(\frac{r}{r_0}\right)^2 - 2\ln 2\left(\frac{t}{\tau_L}\right)^2 + i\varphi(t)\right]$$

$$\omega(t) = -\frac{d\varphi}{dt} = \omega_0 - 4\ln 2\left(\frac{\kappa}{\tau_L}\right)^2 t$$

Longitudinally uniform, leaky parabolic plasma channel:

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

Reference case

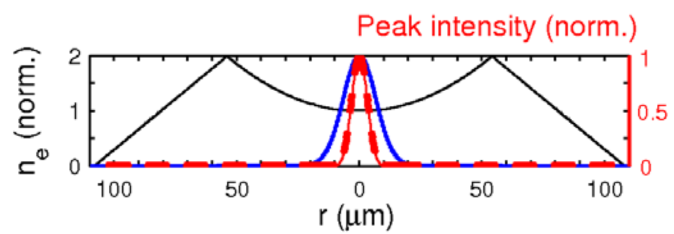
Transform-limited pulse, $\kappa = 0$:

$\Delta\lambda_{FWHM} = 26.7$ nm

Negatively chirped pulse

$\kappa = 2.4323$: $\Delta\lambda_{FWHM} = 160$ nm

(eq. $\tau_L = 5$ fs when fully compressed!)



Channel:

Matched to the self-guided spot size,

$r_{ch} = 38$ μm

or

$r_{ch} = \infty$ (flat plasma)

Inverse Thomson back-scattering:

Interaction pulse: linearly polarized, $r_0 = 20$ μm; $a_0 = 0.1$; $\lambda = 0.8$ μm; FWHM 250 fs.

Detector: on axis, scattering angle = π.

Joule-energy, broadband OPA for cycle-length pulses

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Third-generation femtosecond technology

Hanieh Fattahi,[1,2] . . . ,[3 - 10] and Ferenc Krausz[1,2,*]

[1]Max-Planck Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany

[2]Department für Physik, Ludwig-Maximilians-Universität München, Am Coulombwall 1, D-85748 Garching, Germany

[3]Physics and Astronomy Department, King Saud University, Riyadh 11451, Saudi Arabia

[4]Current address: Electrical Engineering, Computer, Electrical and Mathematical Sciences and Engineering Division, Building 1, 4700 King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia

[5]TRUMPF Scientific Lasers GmbH + Co. KG, Feringastr. 10, 85774 München-Unterföhring, Germany

[6]Wigner Research Center for Physics, Konkoly-Thege Miklós út 29-33, H-1121 Budapest, Hungary

[7]Physics Department, POSTECH, San 31 Hyoja-Dong, Namku, Pohang, Kyungbuk 790-784, South Korea

[8]FFI (Norwegian Defence Research Establishment), Postboks 25, NO-2027 Kjeller, Norway

[9]Current address: Center for Nano-Optics (CeNO), Georgia State University, Atlanta, Georgia 30303, USA

[10]TRUMPF Laser GmbH + Co. KG, Aichhalder Str. 39, 78713 Schramberg, Germany

*Corresponding author: krausz@lmu.de

… Diode-pumped ytterbium-doped solid-state lasers … are able to deliver 1 ps scale pulses at kilowatt-scale average power levels, which, in thin-disk lasers, may come in combination with terawatt-scale peak powers. Broadband OPAs pumped by these sources hold promise for … the third-generation femtosecond technology (3FST) < that > offers the potential for femtosecond … multi-terawatt few-cycle pulses …

http://dx.doi.org/10.1364/OPTICA.1.000045

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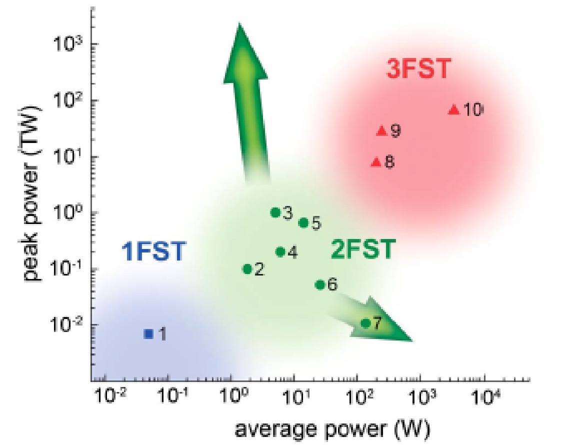


	τ_{pulse}	E_{pulse}	P_{peak}	$P_{average}$
system 8	5 fs	40 mJ	7.5 TW	200 W
system 9	1.7 fs	49 mJ	27 TW	245 W
system 10	5 fs	345 mJ	65 TW	3450 W

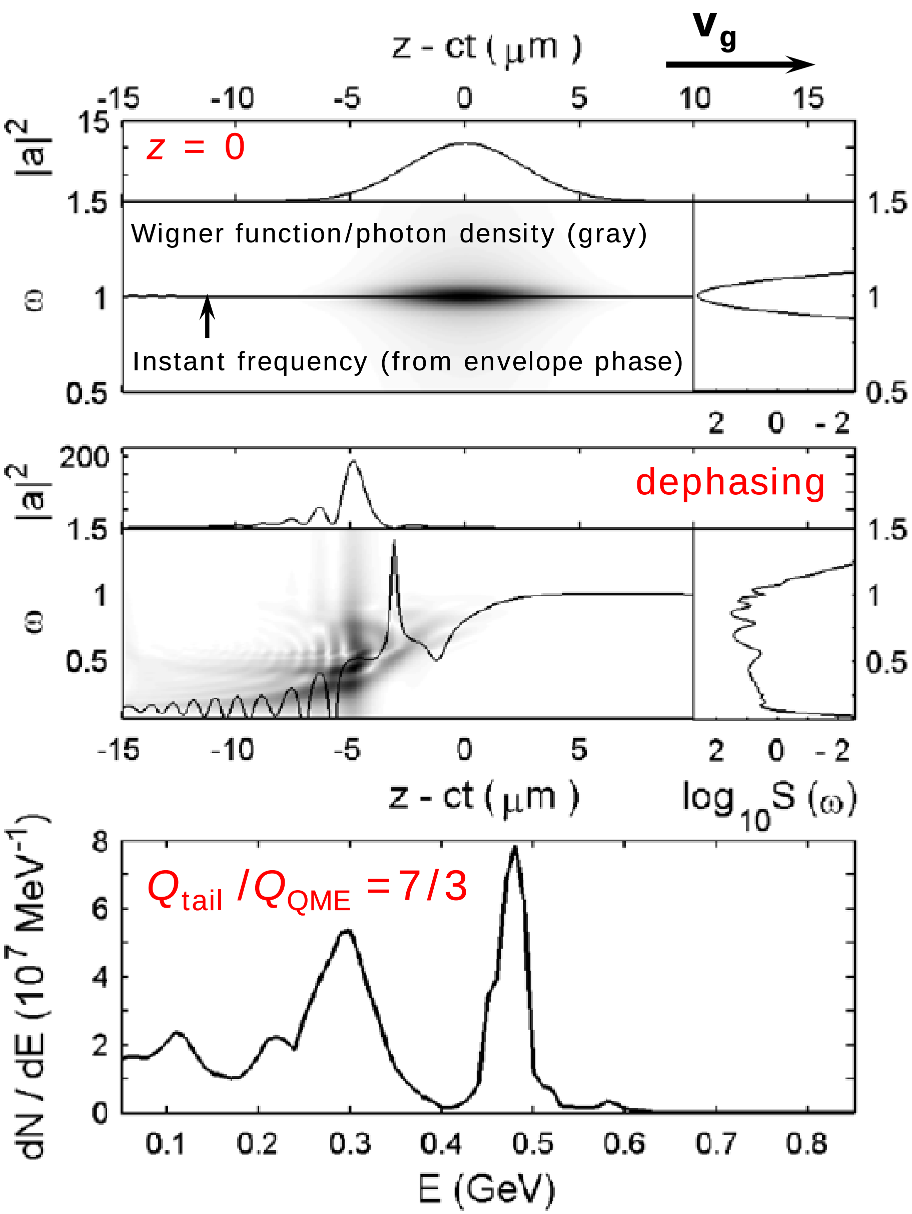
Fig. 1. Summary of recorded performances of 1FST and 2FST and the expected performance of 3FST, in terms of average and peak powers. … The blue square represents the best performance achieved by dye-laser technology (1, corresponding to Ref. [9]), the green dots show femtosecond CPA solid-state technology (2–7, corresponding to Refs. [60,71,66,18,67], and [25], respectively), and the red triangles represent the simulated results for OPCPA based on pump sources under development (8 and 9, pumped by a 1 ps, 5 kHz, 200 mJ Yb:YAG thin-disk laser) and envisioned (10, based on a future 1 ps, 10 kHz, 2 J Yb:YAG thin-disk laser system). …

NB: 5-10 kHz repetition rates!!

System 10 for parameters of the case study:

Pulse energy ×7 (2.1 J, ~ 1 kHz rep. rate), pulse stretched to 30 fs, negatively chirped

Transform-limited pulse in a channel turns into optical shock



Massive dark current follows

Pulse at dephasing:

RMS frequency bandwidth ×10 (≡ a single-cycle pulse)

Average frequency ≈ $0.4\omega_0$

RMS length ×0.4 (while FWHM ~ 1 cycle)

Pulse energy ×0.4

QME component at dephasing:

Charge	0.55 nC
RMS current	92 kA
RMS divergence	3.3 mrad

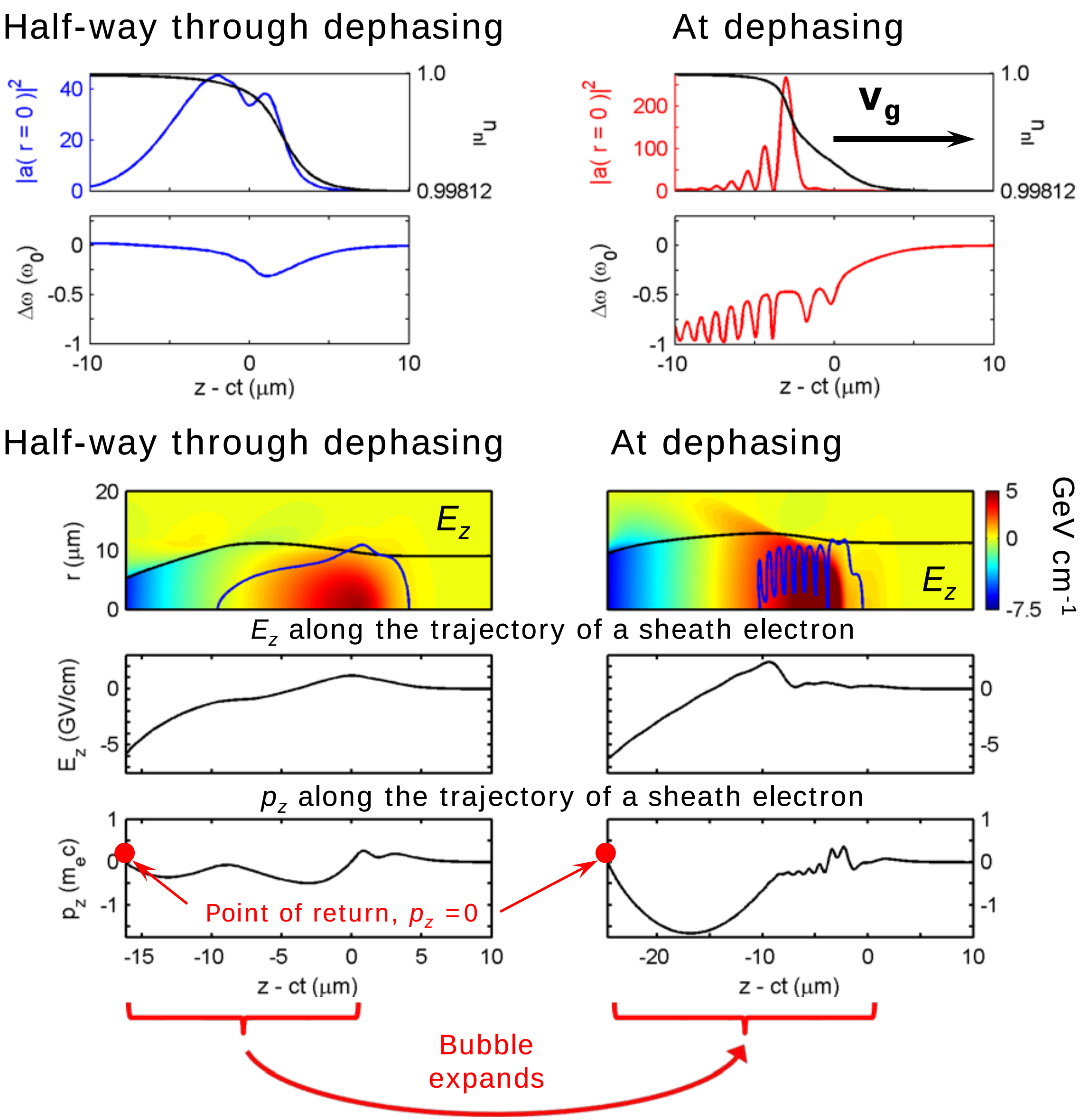
RMS norm. transverse emittance 0.91 μm

Brightness = $2I(\pi\varepsilon_{\perp,N})^{-2}$ = 2.25×10^{16} A/m^2

Yet, channel alone does not help suppress the dark current

WAKE (pulse) and CALDER-Circ (e-spectrum) simulation:
S. Y. Kalmykov *et al*., Plasma Phys. Control. Fusion 58, 034006 (2016)

Physics of dark current



Formation of optical shock (OS) begins long before dephasing

Snow-plowing by the OS *piles up negative charge inside the shock*

Longitudinal electric field acting upon sheath electrons – injection candidates – increases multi-fold

Sheath electrons receiving stronger backward push at once become relativistic

- ⇒ their return to axis is delayed
- ⇒ bubble expands

Corollaries:

- ➢ Expansion of the bubble is a purely quasistatic phenomenon – plasma response to the drive pulse self-compression
- ➢ Mitigating self-compression eliminates the dark current.

Figures borrowed from S. Y. Kalmykov *et al.*, NJP 14, 033025 (2012)
Simulation code: WAKE ⇒ PLASMA IS QUASISTATIC

Preventing pulse self-compression should take the energy tail down.

Task: compensate for the nonlinear frequency red-shift imparted by the plasma wake at the pulse leading edge

What is needed:

- large bandwidth of the drive pulse ($\Delta\lambda \sim \lambda_0$)
- temporal advancement of high frequencies (***negative chirp***).

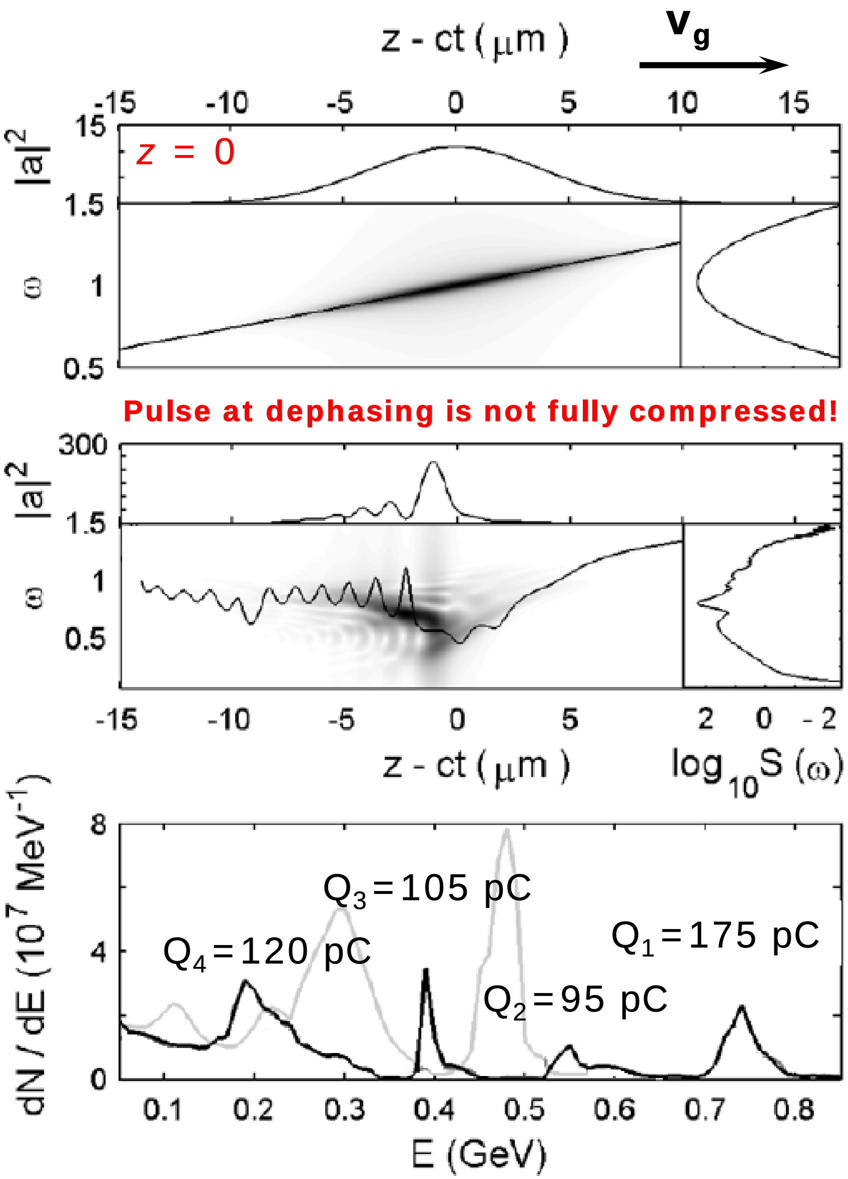
Added benefit of the chirp:

Slower self-compression of the pulse extends the dephasing length, increasing the energy gain far beyond predictions of accepted scaling (to the GeV level)

Added benefit of a channel:

The channel turns residual dark current into a periodic injection, creating the e-bunch train!

Negatively chirped pulse in a channel: Creating electron energy comb



Electron energy comb (absorbs 12.5% of laser energy):

I (kA): (1) **120** (2) 83 (3) 70 (4) 40

$\varepsilon_{\perp,N}$ (μm): (1) 1.27 (2) 1.43 (3) 0.75 (4) 2.73

RMS length (fs):

(1) 1.45 (2) 1.15 (3) 1.5 (4) 3.0

Brightness (10^{16} A/m^2):

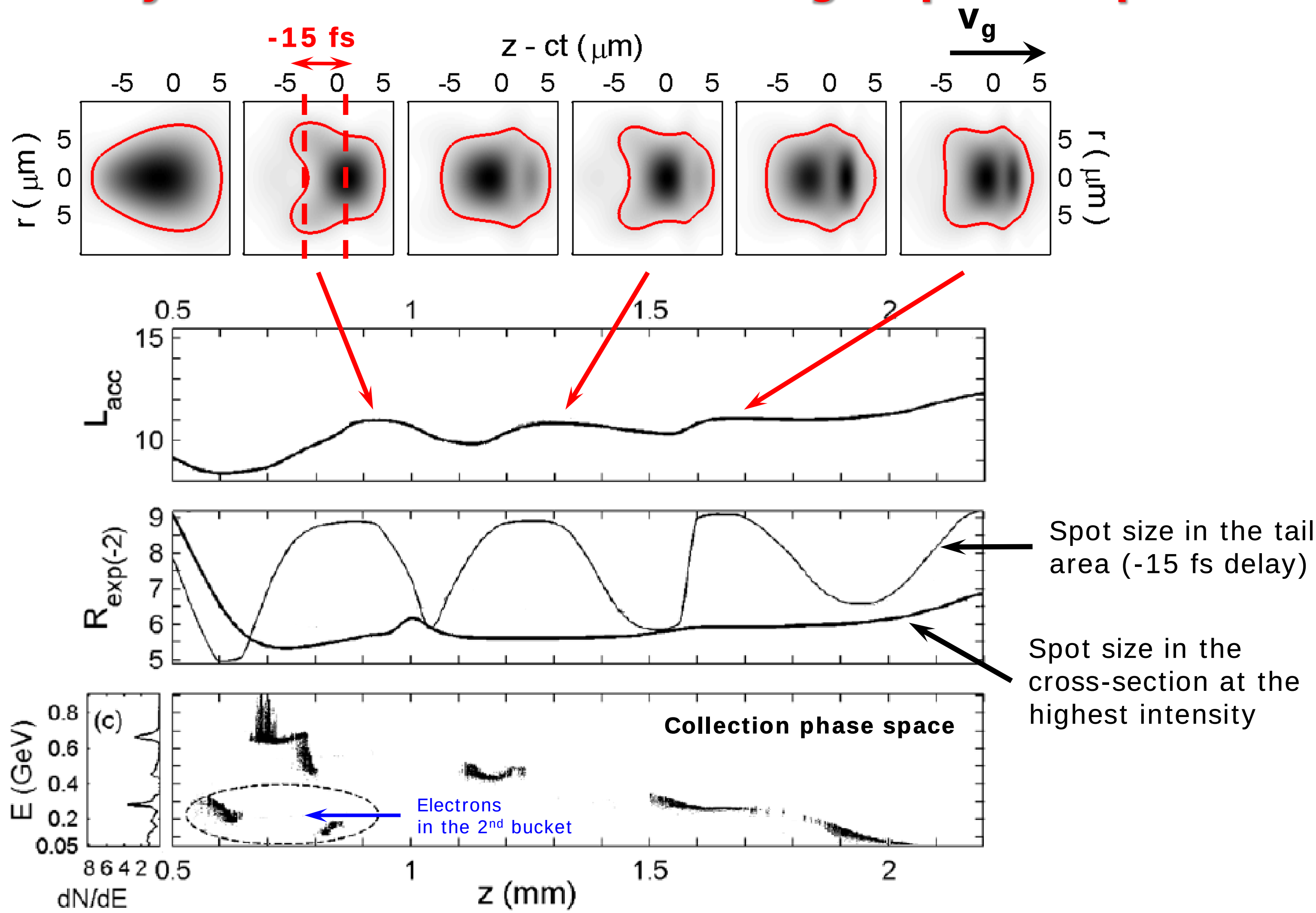
(1) 1.5 (2) 0.82 (3) 2.5 (4) 0.11

Remnant of the tail: E < 150 MeV, $Q \approx 100$ pC

Chirp and channel delay dephasing, boost electron energy by 60%, and eliminate the tail almost completely.

S. Y. Kalmykov *et al*., Plasma Phys. Control. Fusion 58, 034006 (2016)

Periodic injection and multi-bunching in phase space

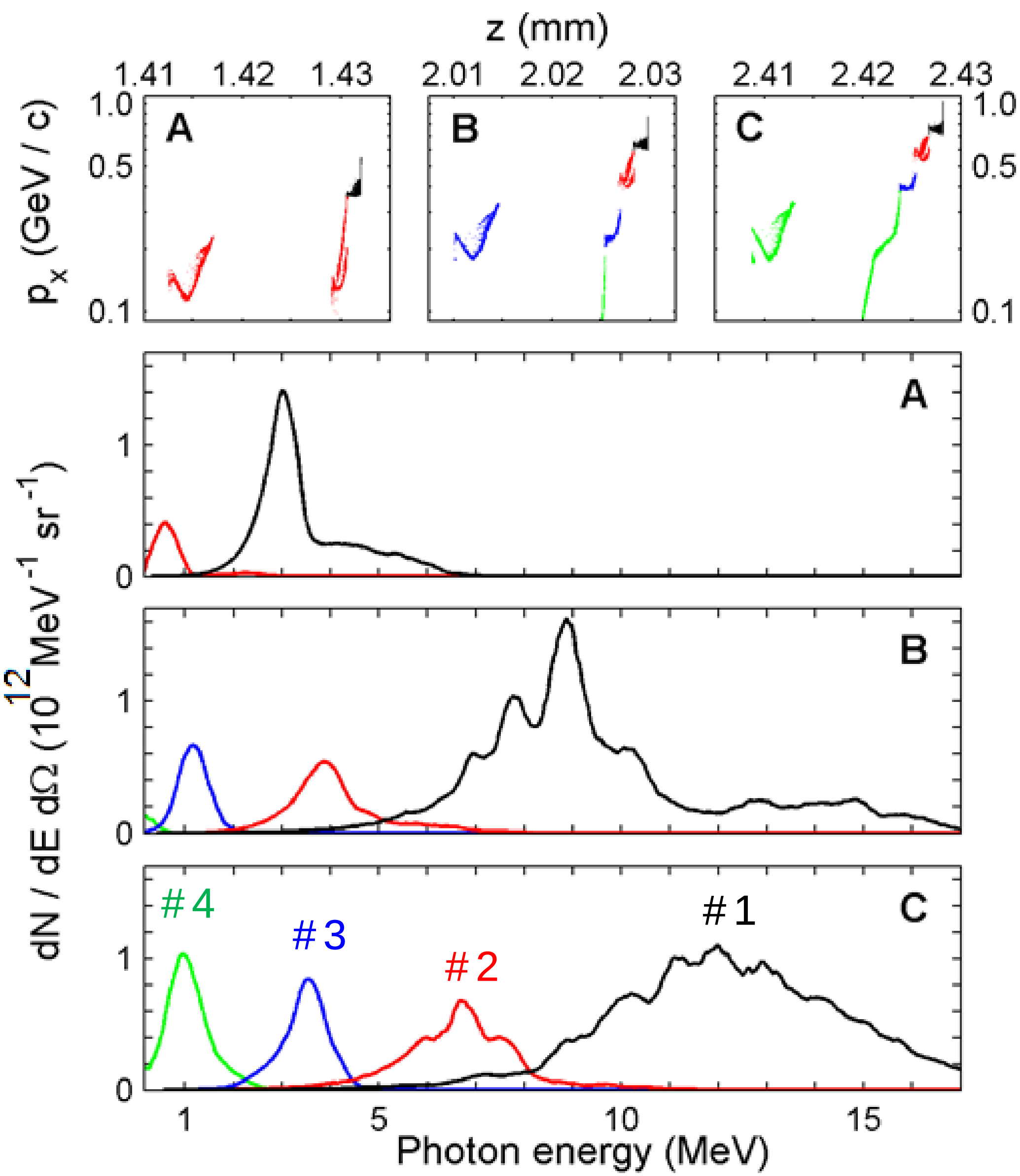


Pulse “head” (the most intense segment) self-guides with a weakly varying spot. Channel upsets the balance between the radiation pressure and charge separation force in the pulse tail area.

The unmatched tail flaps; oscillations in the pulse spot size in the tail area are phase-locked with the oscillations in the bubble radius and the events of electron injection.

It is thus essential that the pulse tail extends deeply into the bubble (i.e. $\tau_L > r_m /c$)!

Multi-color ITS γ-rays from comb-like beams

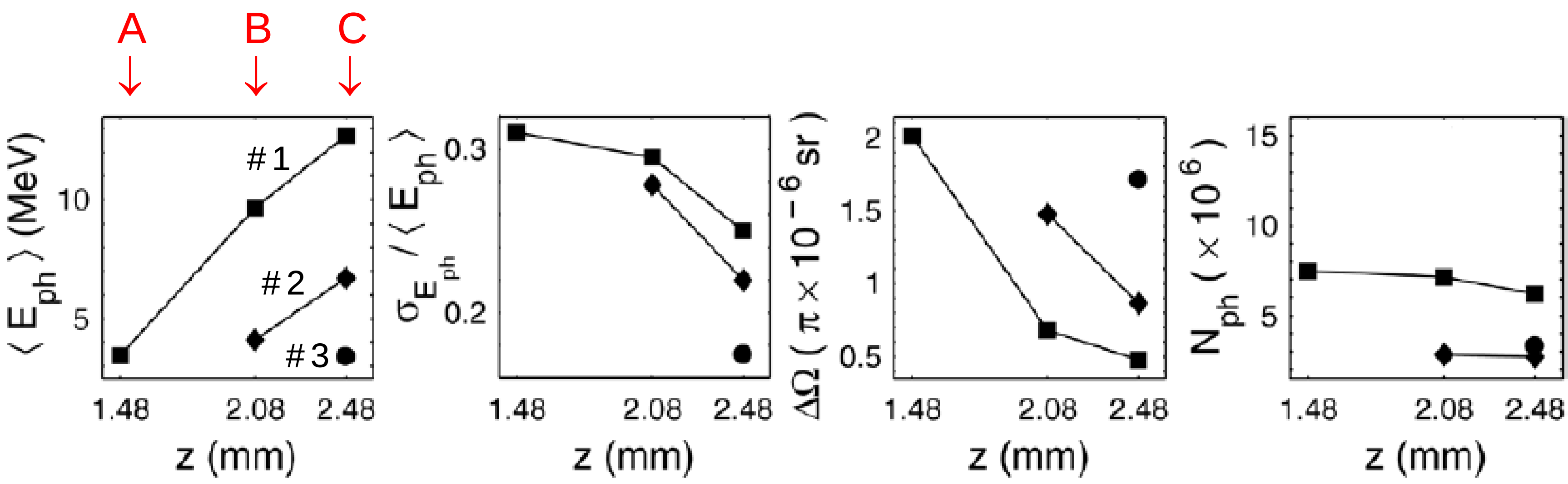


In the course of acceleration, transverse emittance of individual e-bunches (~1 μm) varies in the third digit – benefit of the numerical Cherenkov-free EM solver in CALDER-Circ.

Extracting comb-like beams from plasma at the points (A)–(C) provides drivers for bi-, tri-, four-color pulsed ITS γ-ray source (background free).

Separating fs-length components of the comb using magnets and using delay lines may help synchronize them (and γ-ray flashes) at various pre-selected delays.

Statistics of γ-ray combs



S. Y. Kalmykov *et al*., Plasma Phys. Control. Fusion 58, 034006 (2016)

Mrad divergence of electron bunches dictates 20 – 30% width of γ-ray energy bands.

The number of photons, per band, in the observation angle $\Delta\Omega \approx \pi\langle\gamma_e\rangle^{-2}$, is preserved: 11, 3.4, 2.7, 6.2×10^6 (from low to high energy)

When electrons are extracted at dephasing ($z \approx 2.5$ mm):

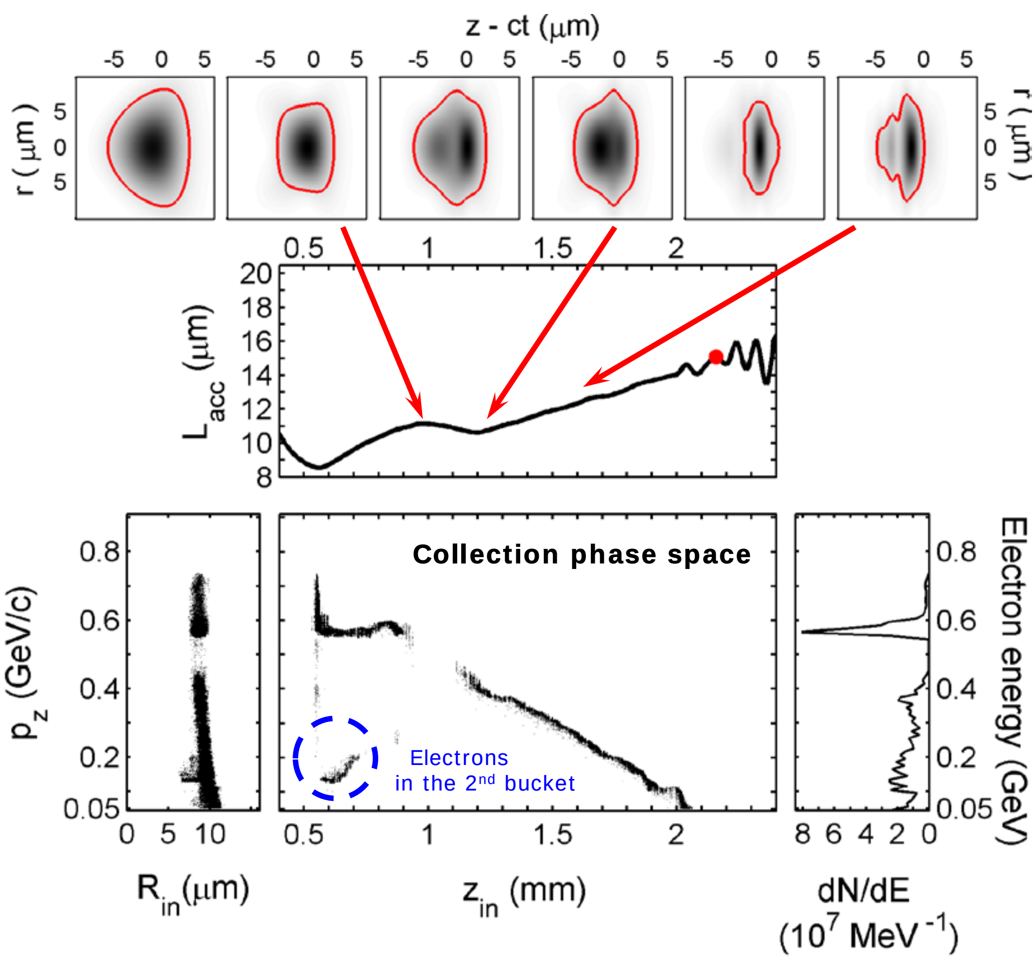
- central energies of the γ-ray bands: $\langle E_{ph}\rangle \approx 4\pi\langle\gamma_e\rangle^2 E_{int} \approx 1, 3.75, 6.8, 12$ MeV
- conversion efficiency from the LPA drive pulse to the γ-ray signal: 10^{-5}
- length of γ-ray beamlets: 1 – 3 fs.

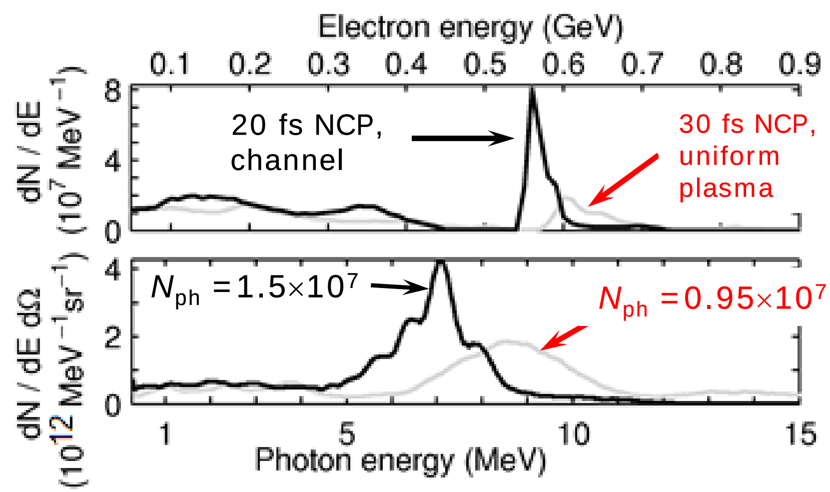
Clipping the pulse tail reduces e-comb to a single bunch

Physical solution: Reduce the amount of radiation confined in the bubble

Practical approach: Compress the pulse (as permitted by the large bandwidth)

Results are shown for 20 fs (rather than 30 fs), 70 TW negatively chirped pulse





Shortening the drive pulse:

- restores the QME signal (absorbing 16% of laser energy)
- increases electron and γ-ray flux
- keeps the background low (same as in the uniform plasma).

Photon engineering for e-beam control:

Near term-perspectives

Synthesizing the negative chirp with pulse stacking

Linearly chirped, 100-TW scale optical pulses with the bandwidth $\Delta\lambda \sim \lambda_0$ are not immediately available.

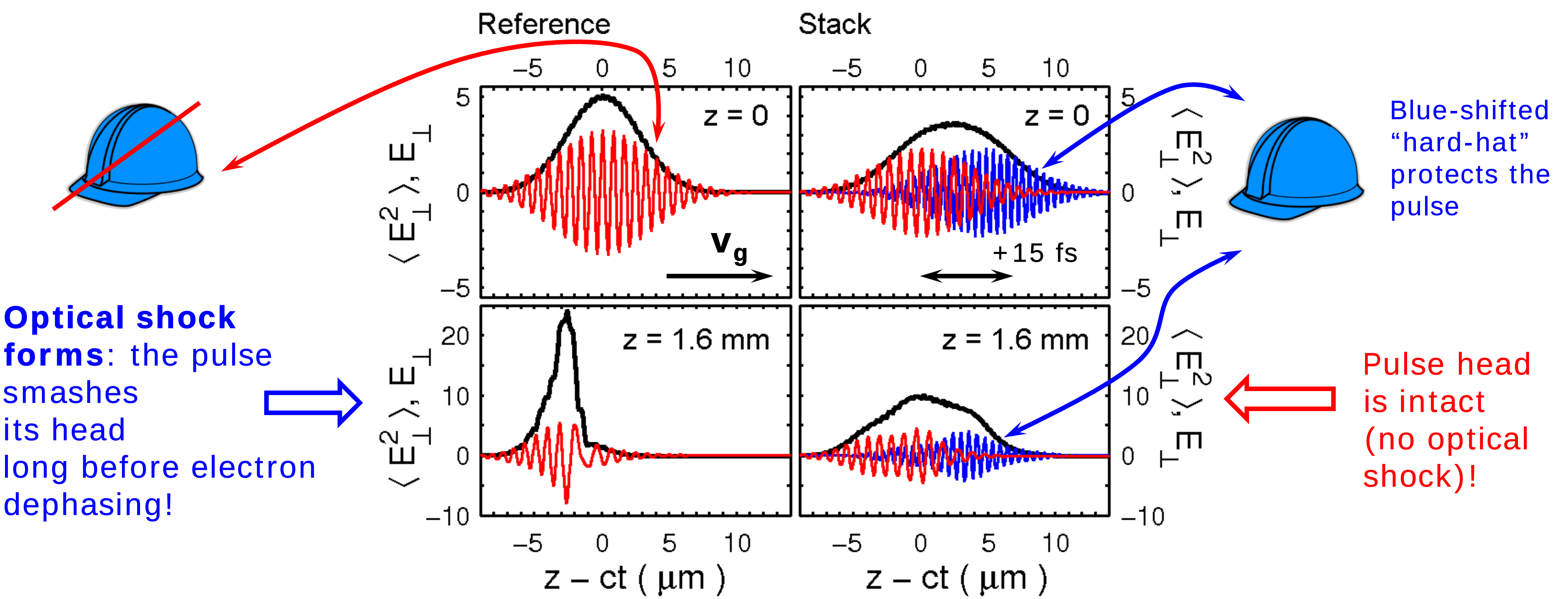
Fortunately, the exact shape of the chirp is not an issue.

Technological options available in the near-term afford synthesizing a large-bandwidth pulse (with a step-wise negative chirp) by stacking collinearly propagating pulses from conventional CPA.

Pulses must be frequency-shifted, with the amount of frequency blue-shift (comparable with ω_0) dictated by the LPA optimization routine and availability of technological options:

- Frequency shift in Raman cells with subsequent conventional CPA
  [F. B. Grigsby, P. Dong, and M. C. Downer, JOSA B 25, 346 (2008)]
- Energy-efficient methods of 2nd harmonic pulse generation.

Stacking protects the pulse from nonlinear erosion

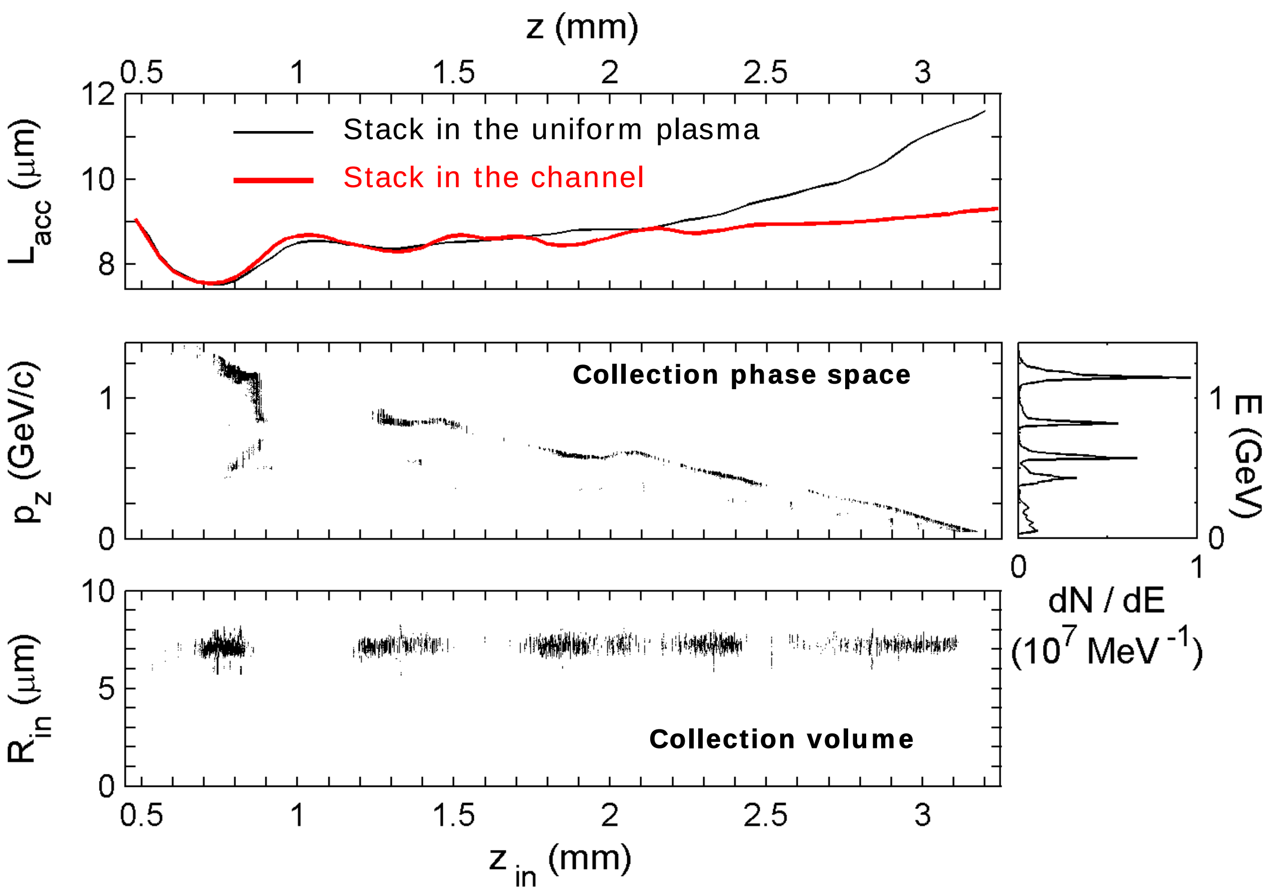


Pulse 1: 20 fs, 2.1 J, $\lambda_1 = 0.8$ μm
Pulse 2: 20 fs, 0.7 J, $\lambda_2 \approx 0.5$ μm
} orthogonally polarized (incoherent mixing)

No need in the extreme frequency up-shift: Reducing λ_2 by 20% is sufficient!

(CALDER-Circ simulation)

Generating comb-like e-beam with a stack in a channel



Stack with

+15 fs delay,

$\lambda_2 = 2/3\ \lambda_1 = 0.53\ \mu m$,

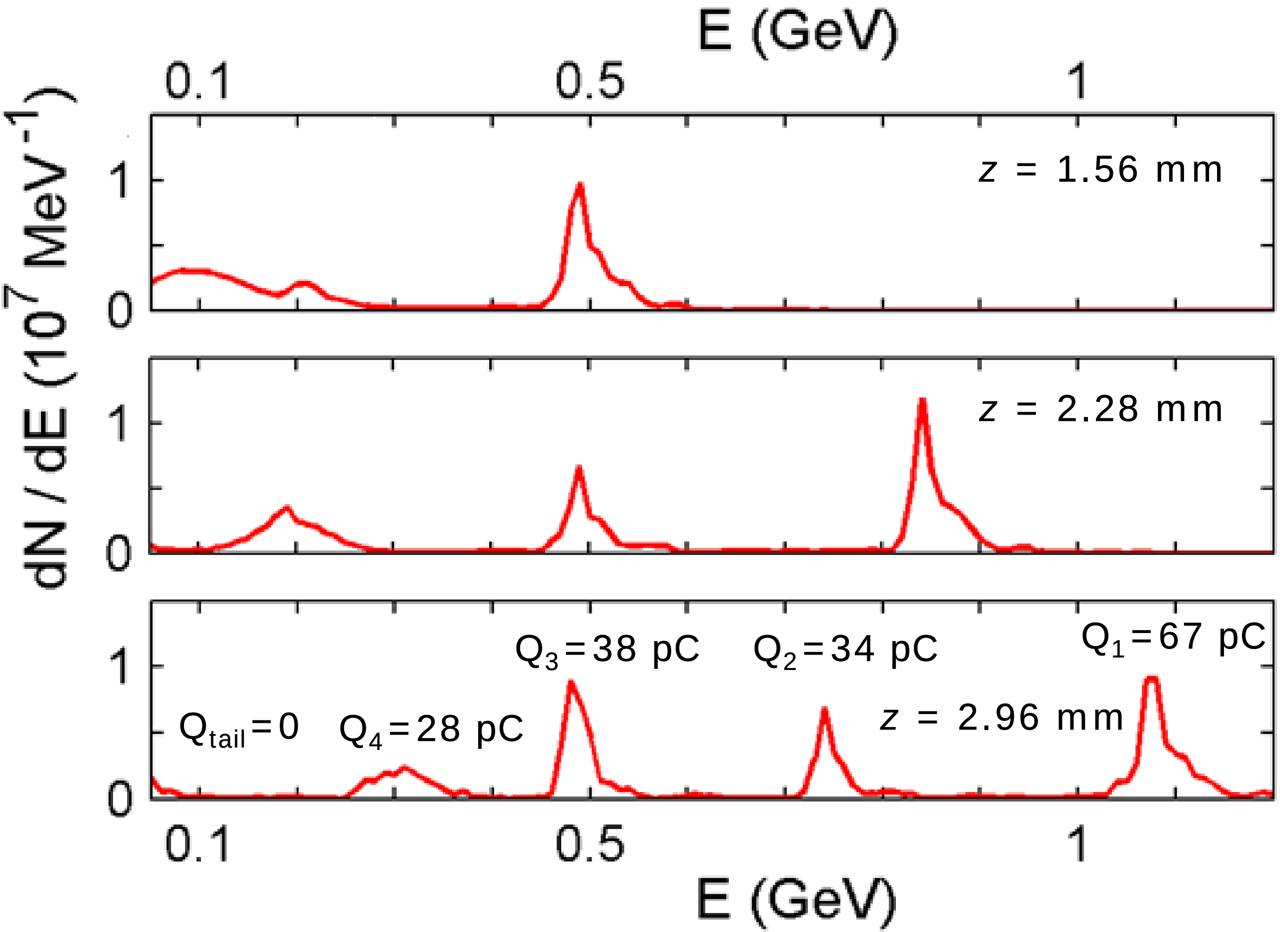
$E_1 = E_2 = 0.7$ J,

in a channel matched to the incident pulse waist

The e-comb absorbs 10% of laser energy

The peak energy is ~ 1.2 GeV (vs ~ 420 MeV from accepted scaling)

Progress of comb-like e-beam through dephasing

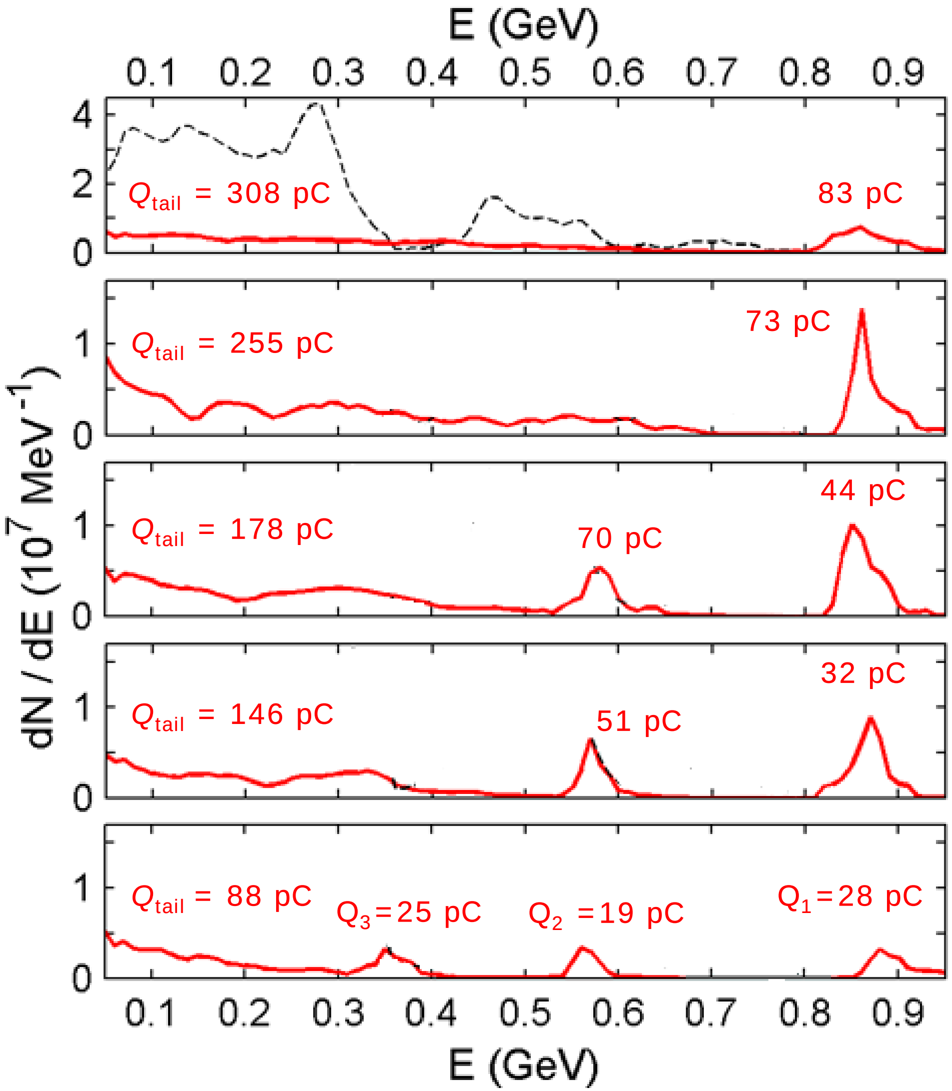


Varying the channel length controls the number of components in the comb, their energy and energy difference without compromising their quality

I (kA):	(1) 97	(2) 47	(3) 35	(4) 42
$\varepsilon_{\perp,N}$ (μm):	(1) 0.38	(2) 0.27	(3) 0.57	(4) 0.27
RMS length (fs):	(1) 0.7	(2) 0.73	(3) 1.1	(4) 0.66
Brightness (10^{16} A/m^2):	(1) **13.6**	(2) **13.1**	(3) 2.2	(4) **11.7**

Channel is not a pre-requisite for controlled generation of e-combs: weak focusing of the tail enforces accordion effect in the uniform plasma.

Same stack, but in a uniform plasma, and with the tail and head focused differently.



Radius of the pulse head: R_h = 13.6 μm

Radius of the tail:

R_t =

$R_h / 2^{1/2} \approx 9.6$ μm

$R_h = 13.6$ μm

Tight focusing of the tail ($R_1 \leq R_2$) keeps the bubble stable, preserving the single electron bunch

$(3/2)^{1/2} R_h \approx 16.7$ μm

$2^{1/2} R_h \approx 19.2$ μm

$3^{1/2} R_h \approx 19.2$ μm

Weak focusing of the tail destabilizes the bubble, generating a comb-like beam

Brightness (10^{16} A/m^2): (1) 5.9 (2) 3.4 (3) 0.75

Summary and outlook

Comb-like e-beams produce trains of pulsed (fs to ps) X/γ–ray pulses of different colors via mechanism of inverse Thomson scattering.

ITS permits extending the photon energy into the range of interest of nuclear photonics (10's of MeVs), while keeping the pulse length extremely short (100's of as) and the number of photons high.

High-repetition-rate, GeV-scale LPAs permit generating fs, multi-kA electron bunch trains to be used as drivers of the ITS γ–ray sources.

Building the drive pulse of independent sub-Joule, transform-limited pulses with large (up to ω_0) difference frequency permits an *unprecedented degree of electron beam phase space control*, suppressing the background and increasing brightness of individual e-bunches to ~10^{17} A/m^2.

This photon engineering helps control the current, the number, the energy partition, the time delay of e-bunches in the comb, while boosting their energy far beyond the predictions of the accepted scaling.

Addendum

Energy spread of γ-ray beams

$$\omega_{ph} = \frac{4\omega_{ph}\gamma_e^2}{1+\left(\gamma_e\tilde{\theta}\right)^2}$$

$$\tilde{\theta}^2 = \theta^2 + \alpha^2 - 2\alpha\theta\cos\varphi$$

Recoil is negligible:

$$\Delta = \frac{4\langle\gamma_e\rangle\hbar\omega_{ph}}{m_e c^2} \approx 0.02$$

Electron travels at an angle to the scattering axis α (which represents the electron beam divergence)

θ - observation angle (θ = 0: scattering in the direction of electron beam propagation)

φ - azimuthal angle (φ = 0: scattering in the plane of laser polarization)

If the electron beam has a small energy spread $\sigma_E << \langle E\rangle$ and arbitrary divergence,

$$\frac{\Delta E_{ph}}{\left\langle E_{ph}\right\rangle} = \frac{\Delta\omega_{ph}}{\omega_{ph}} = \frac{2(\Delta\gamma_e/\gamma_e)}{1+\gamma_e^2\alpha^2}$$

$$\frac{|\Delta\gamma_e|}{\gamma_e} \sim \frac{\sigma_E}{\langle E\rangle}$$

$\alpha \sim \sigma_\alpha$ – e-beam divergence

$$\frac{\Delta E_{ph}}{\left\langle E_{ph}\right\rangle} = \frac{2\,\sigma_E/\langle E\rangle}{1+\langle\gamma_e\rangle^2\sigma_\alpha^2}$$

For our beams, $\langle\gamma_e\rangle\sigma_\alpha$ ~ 2.5 to 4.3 and $\sigma_E/\langle E\rangle$ ~ 3.7 to 20%

This energy spread of the e-bunch thus contributes merely ~1% to the energy spread! Remaining 20 to 30% are due to the beam divergence.

For small observation angles ($\theta << 1$) and "large" divergence, $\langle\gamma_e\rangle\sigma_\alpha > 1$, the photon energy changes with the observation angle as

$$\frac{|\Delta E_{\text{ph}}|}{E_{\text{ph}}} \approx 2|\cos\varphi| \frac{\Delta\theta}{\sigma_\alpha} \frac{\langle\gamma_e\rangle^2 \sigma_\alpha^2}{1 + \langle\gamma_e\rangle^2 \sigma_\alpha^2} \approx 2|\cos\varphi| \frac{\Delta\theta}{\sigma_\alpha}$$

Averaging over the azimuthal angle yields

$$\boxed{\frac{\langle |E_{\text{ph}}| \rangle_\varphi}{E_{\text{ph}}} \approx \frac{4}{\pi} \frac{\Delta\theta}{\sigma_\alpha}}$$

Photon energy reduction due to reduction in the observation angle is small!

To estimate the photon number in the solid angle of the cone with an apex angle $2\theta \approx 2\langle\gamma_e\rangle^{-1}$, i.e. $\Omega \sim \pi\langle\gamma_e\rangle^{-2}$, one may neglect variation of the photon flux with an observation angle, and use the flux corresponding to the direct backscattering ($\theta = 0$).