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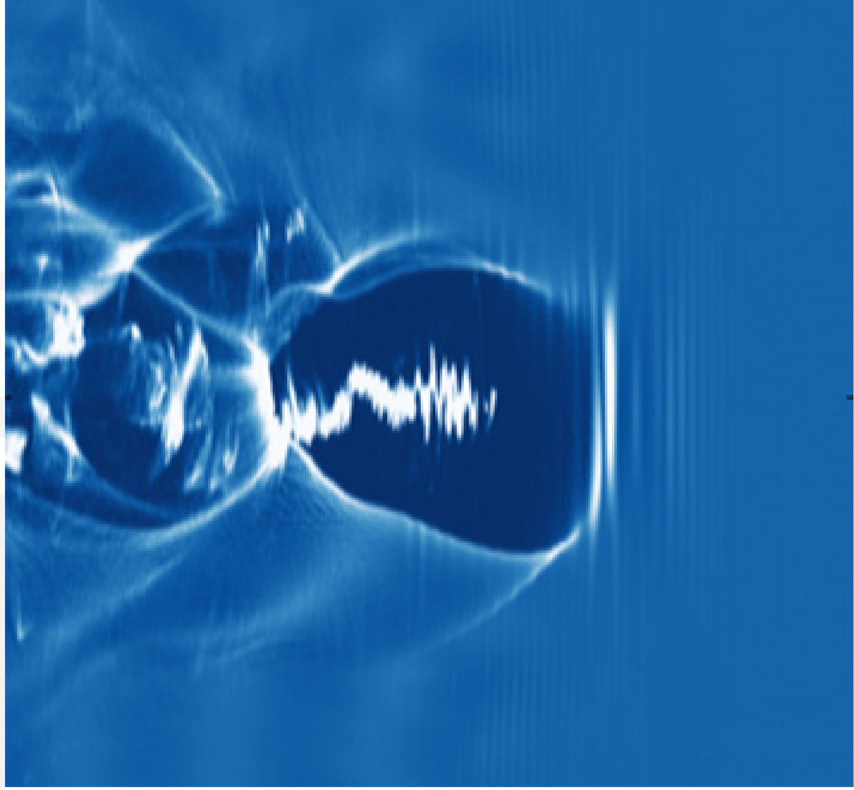


Betatron Radiation as a Dual Diagnostic for Electrons and Photons in Plasma Accelerators

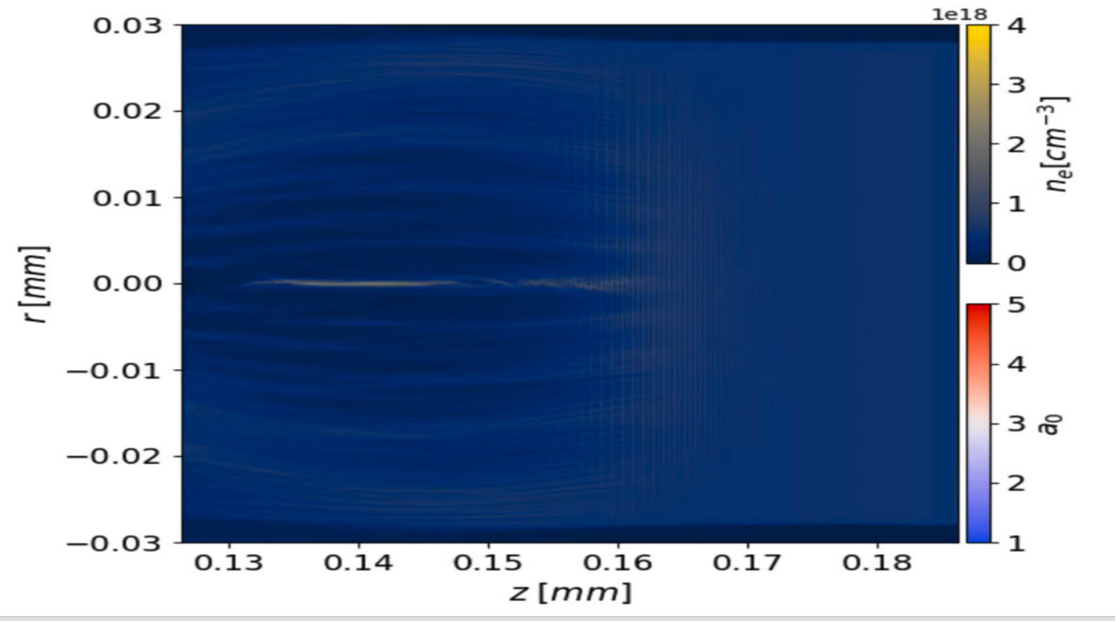
A. Curcio on behalf of many authors

International Beam Instrumentation Conference (IBIC'26)

Layout of the talk

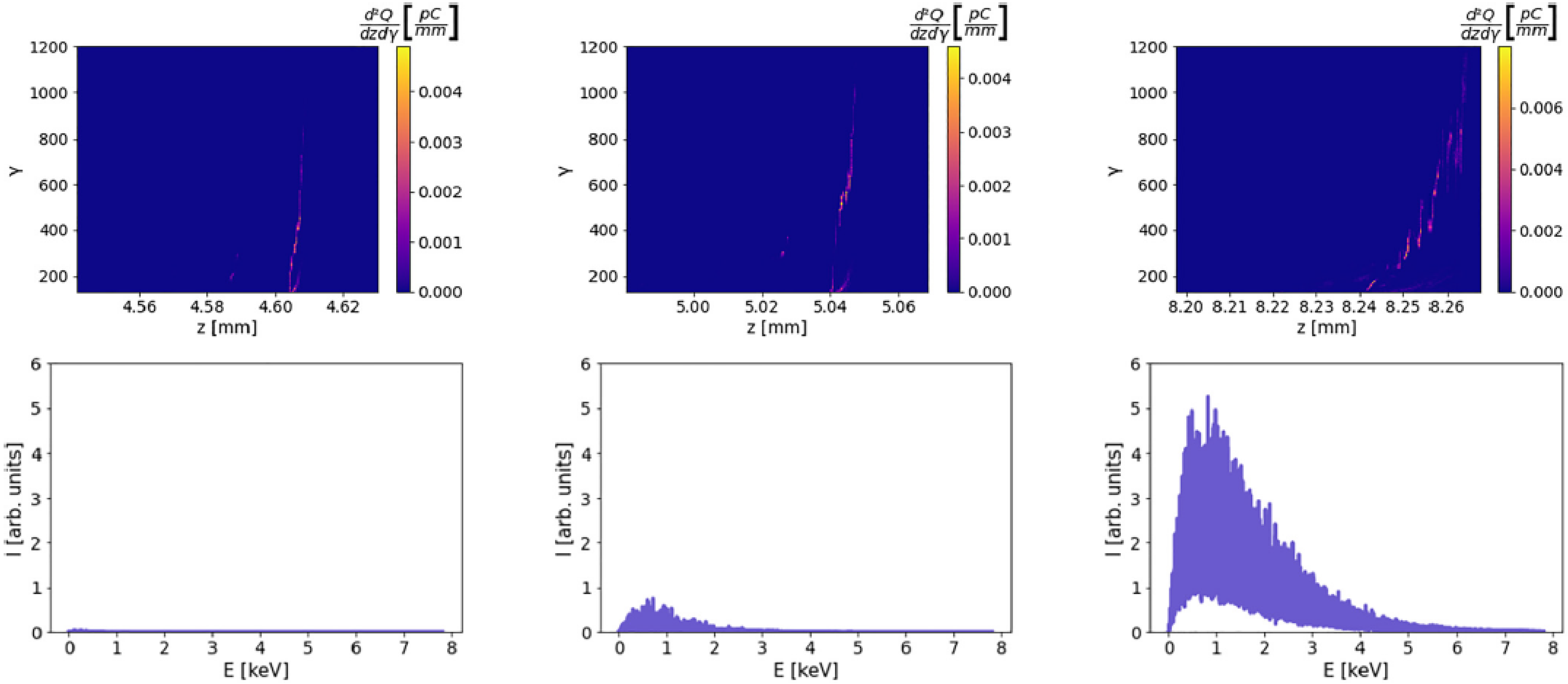
- Brief introduction to betatron radiation
- Review of experiments using betatron radiation as electron and photon diagnostics, with a particular focus on diagnostics
- Conclusions

Formation of the cavity and particle dynamics



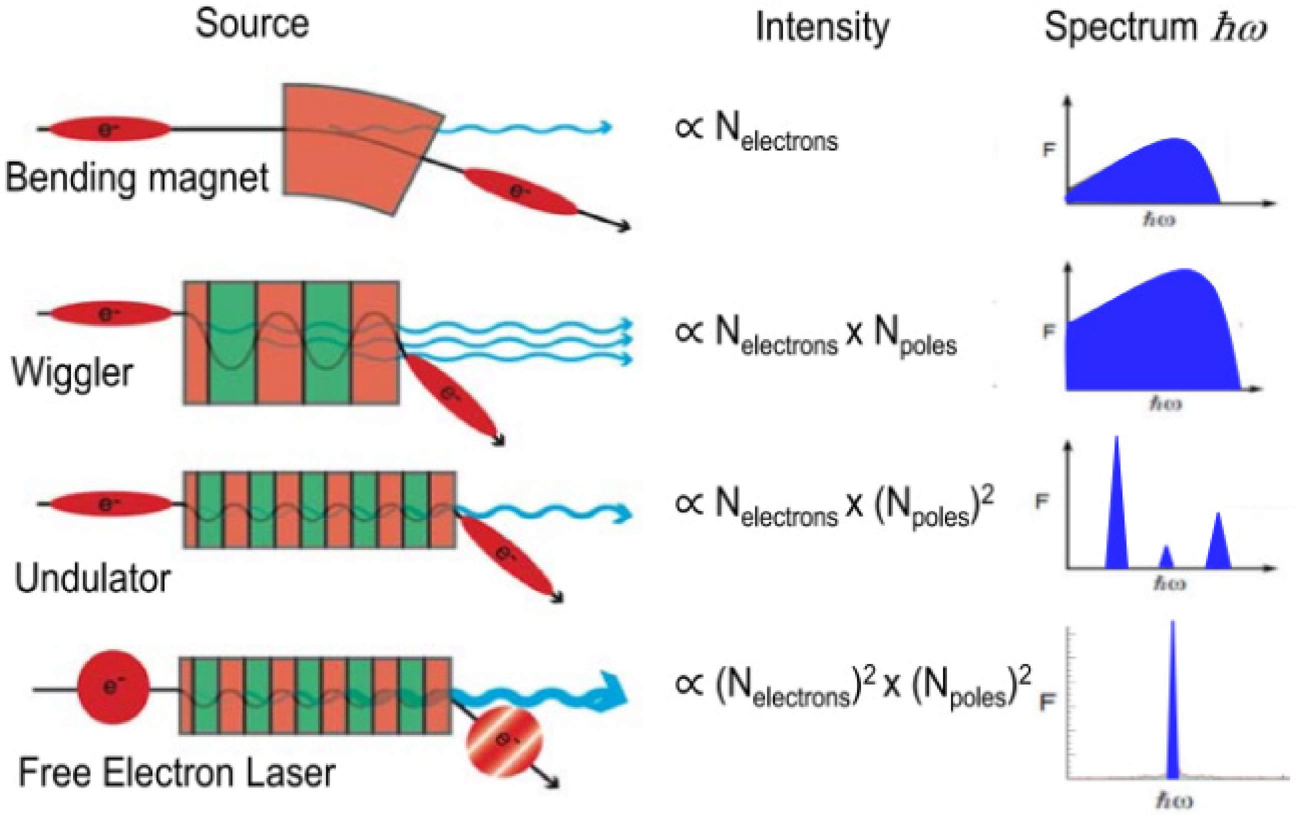
Thanks to Alessio Del Dotto for the simulation

Injection, acceleration and betatron radiation

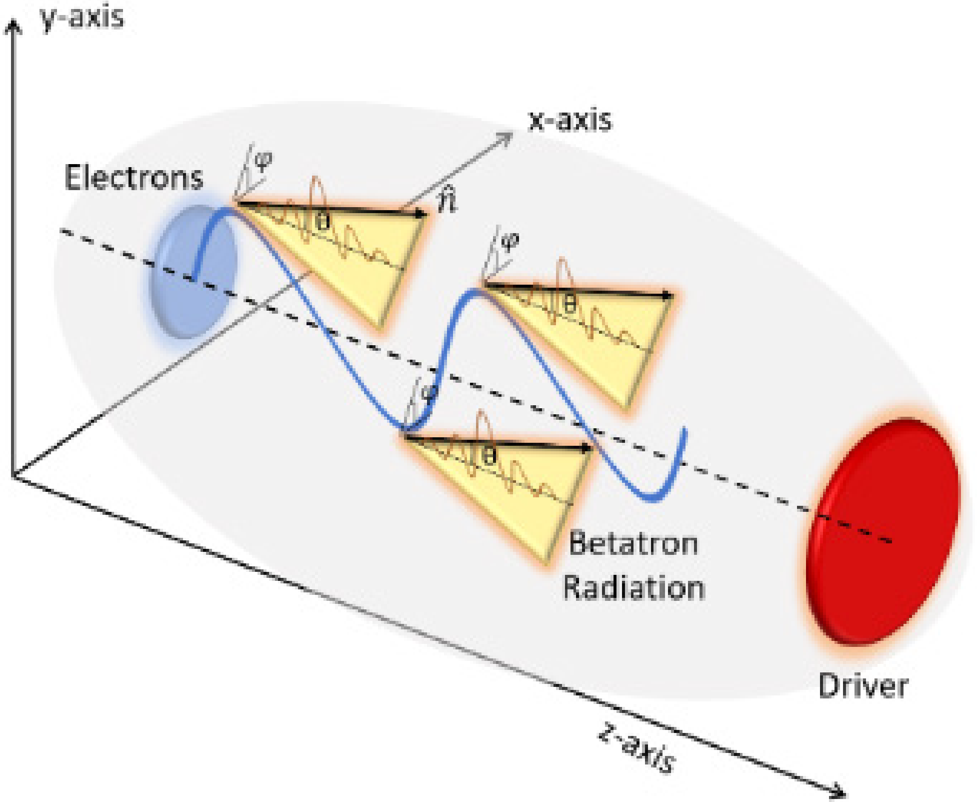


The figure shows the evolution of electron injection and acceleration in a plasma cavity over time (t = 2, 4, and 14 ps), where the longitudinal phase space reveals increasing electron trapping and energy gain. Correspondingly, the emitted radiation spectrum, integrated up to the same time instants, grows in intensity as both the electron charge and energy increase during the process.

Comparison to other radiation mechanisms



Betatron radiation is similar to wiggler radiation…



Why a dual diagnostic?

- Betatron radiation carries information on both the electron beam and the emitted photons.
- Electron dynamics are encoded in spectral and angular features → divergence, oscillation amplitude, emittance, energy(-spread).
- Photon properties are encoded in radiation statistics and coherence →pulse duration and beam quality.
- One non-invasive measurement provides simultaneous electron and photon diagnostics.

VOLUME 93, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 24 SEPTEMBER 2004

Production of a keV X-Ray Beam from Synchrotron Radiation in Relativistic Laser-Plasma Interaction

Antoine Rousse,[1] Kim Ta Phuoc,[1,2,*] Rahul Shah,[2] Alexander Pukhov,[3] Eric Lefebvre,[4] Victor Malka,[1] Sergey Kiselev,[3] Fréderic Burgy,[1] Jean-Philippe Rousseau,[1] Donald Umstadter,[2] and Daniéle Hulin[1]
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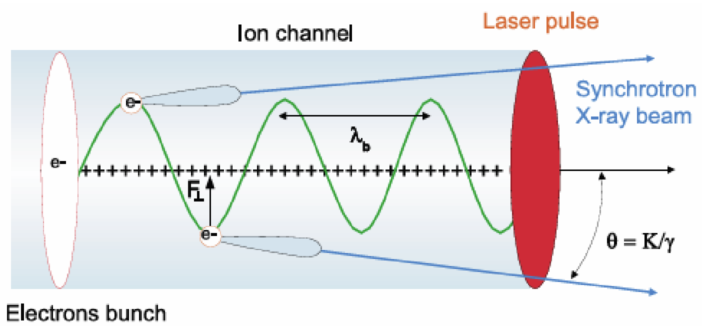
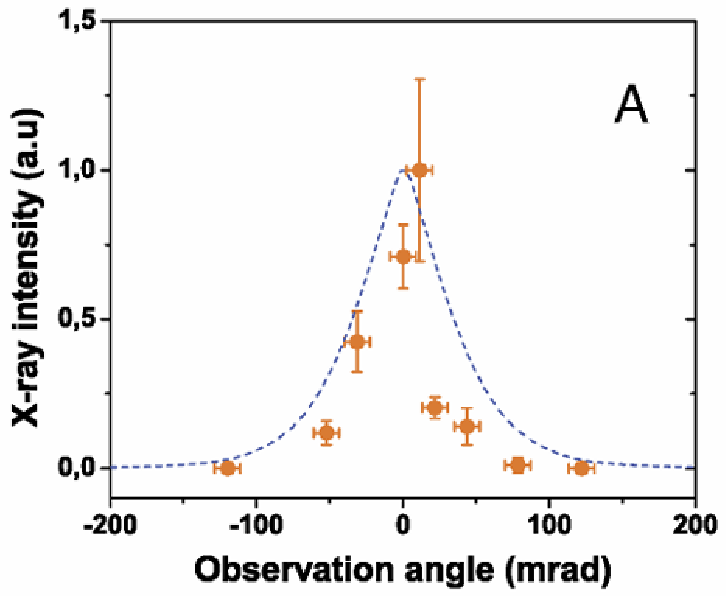
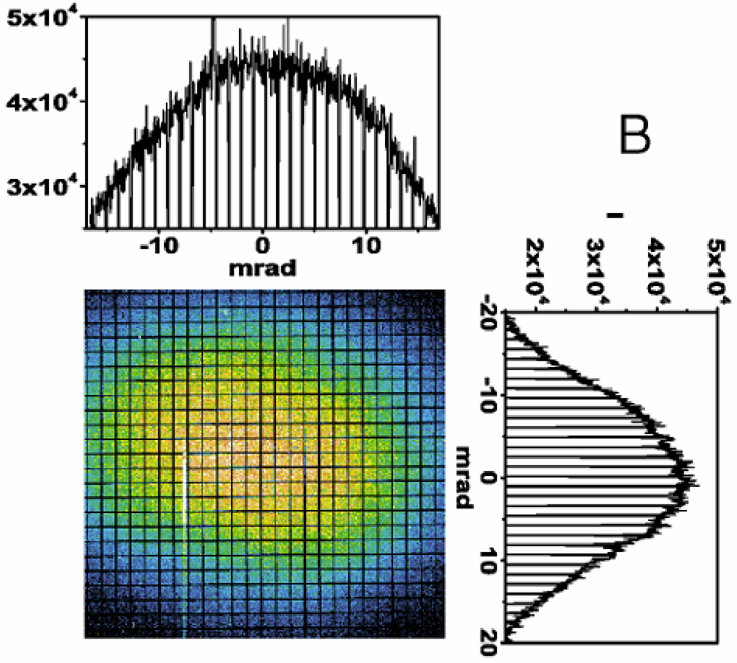






Angular distribution of the radiation for x-ray energies beyond 1 keV. (A) The measurement is made for ne 10^19 cm^-3 in the horizontal plane. Each point corresponds to an average value over ten shots. The dotted line represents the result obtained from the 3D PIC simulation. (B) Spatial profile of the x-ray beam at ne 8*10^18 cm^-3. The corresponding lineout graphics, where the shadow of a nickel grid placed in the beam appears, provides the radiation source size in the transverse directions. The obtained source size is 20 um x 20 um.

PRL 97, 225002 (2006) PHYSICAL REVIEW LETTERS week ending 1 DECEMBER 2006

Imaging Electron Trajectories in a Laser-Wakefield Cavity Using Betatron X-Ray Radiation

Kim Ta Phuoc,* Sebastien Corde, Rahul Shah, Felicie Albert, Romuald Fitour, Jean-Philippe Rousseau, Fréderic Burgy, Brigitte Mercier, and Antoine Rousse

Laboratoire d'Optique Appliquée, ENSTA, CNRS UMR7639, Ecole Polytechnique, Chemin de la Hunière, 91761 Palaiseau, France

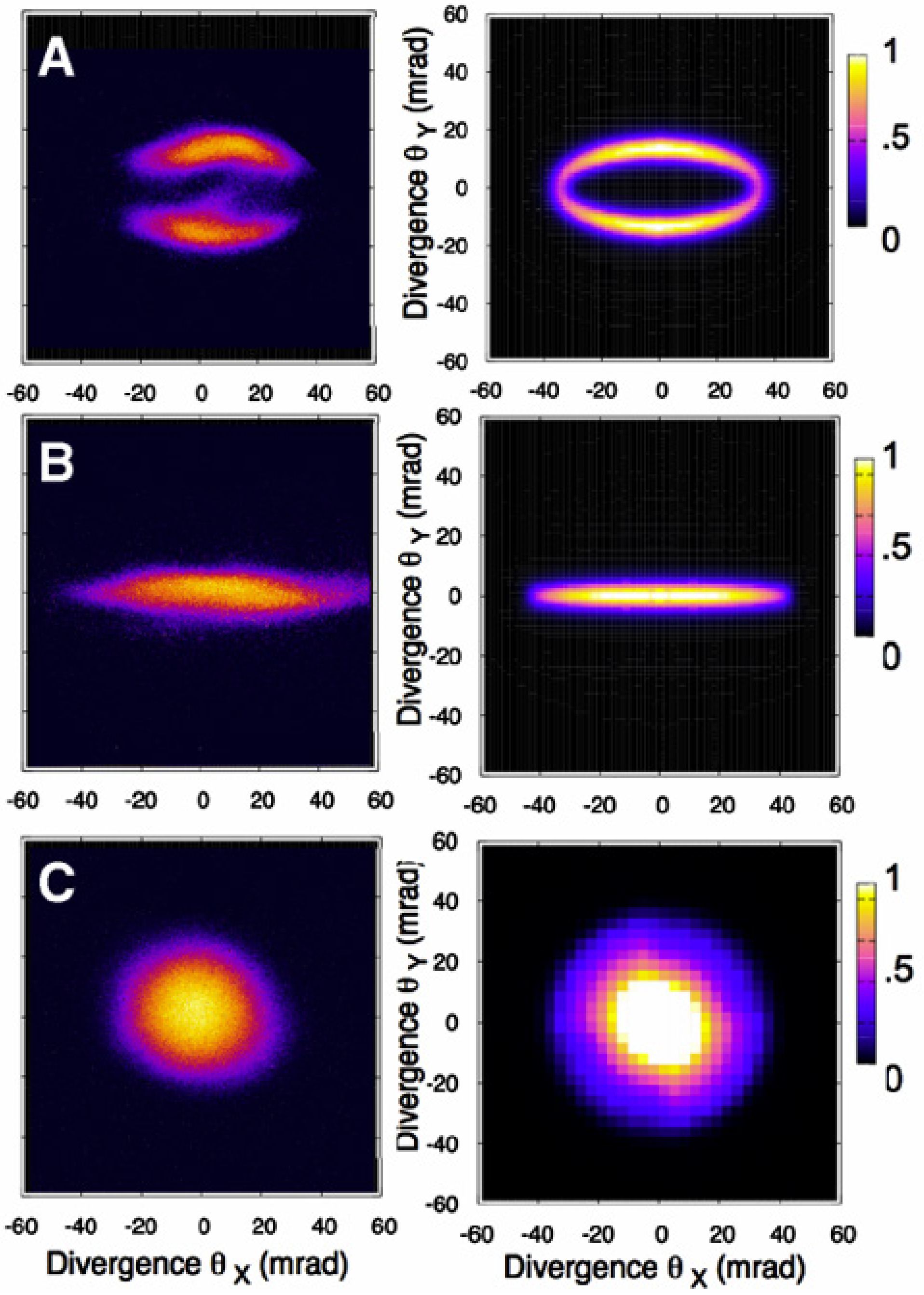
Left: Experimental X-ray beam profiles recorded on an X-ray CCD for energies > 2 keV.

Right: Numerical simulation of the X-ray beam profiles for (n_e = 10^19 cm^-3, p_z = 200 m c , with:

(a) X_0 = 1.2 um, (p_y = 2.7 m c);

(b) X_0 = 1.5 um, (p_y = 0);

(c) Integration over 12 electron trajectories with (p_y = 0) and electrons initially distributed on a circle of radius 1.2 um.



nature COMMUNICATIONS

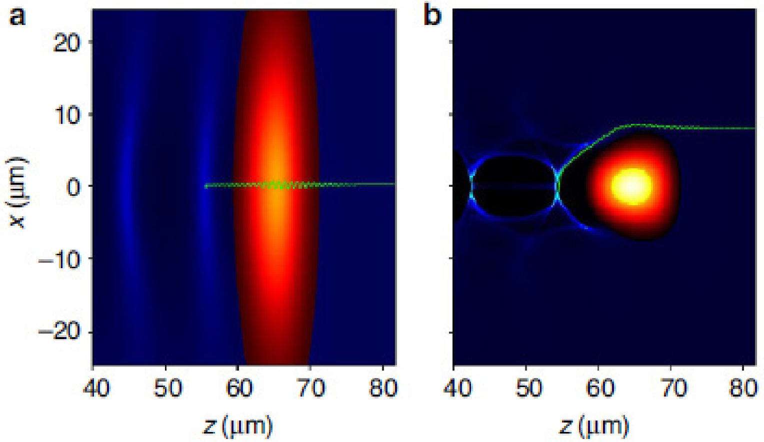
ARTICLE

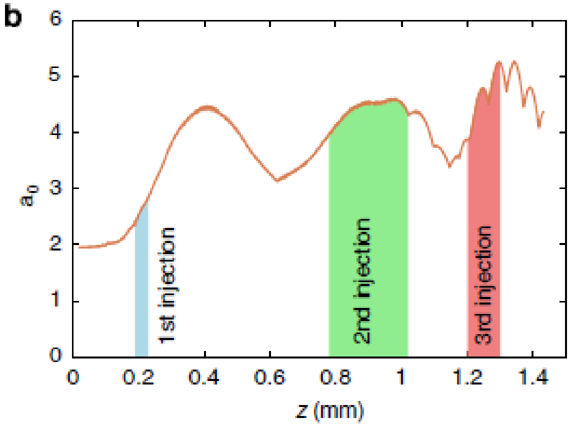
Received 16 Nov 2012 | Accepted 21 Jan 2013 | Published 19 Feb 2013

DOI: 10.1038/ncomms2528

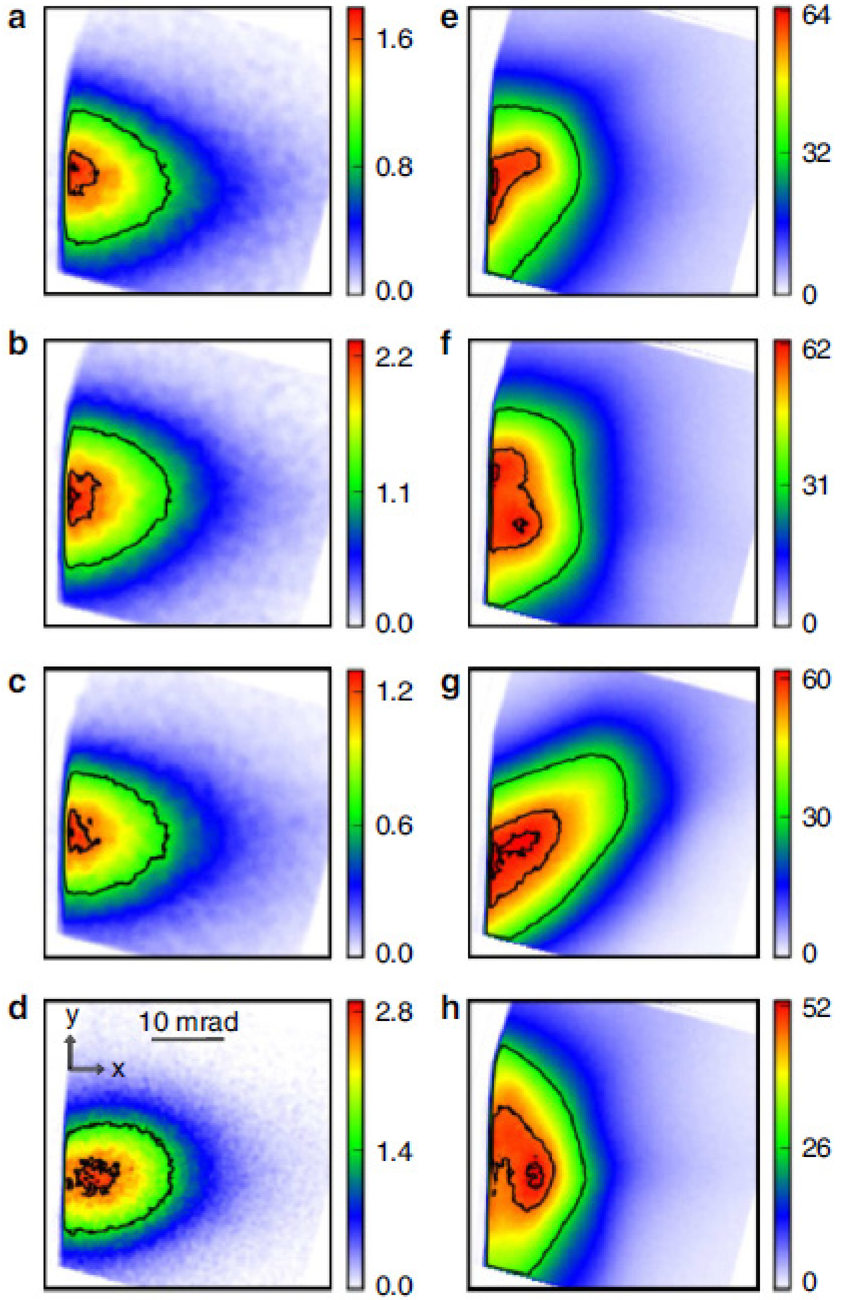
Observation of longitudinal and transverse self-injections in laser-plasma accelerators

S. Corde[1,*], C. Thaury[1,*], A. Lifschitz[1], G. Lambert[1], K. Ta Phuoc[1], X. Davoine[2], R. Lehe[1], D. Douillet[1], A. Rousse[1] & V. Malka[1]





Both experiment and simulation show two electron injection stages. The first, due to longitudinal self-injection early in the laser propagation, produces a few pC with a symmetric and stable electron distribution. The second, caused by transverse self-injection after strong laser self-focusing, yields about 100 pC and leads to an asymmetric, shot-to-shot varying distribution because it depends on the laser intensity profile at injection.



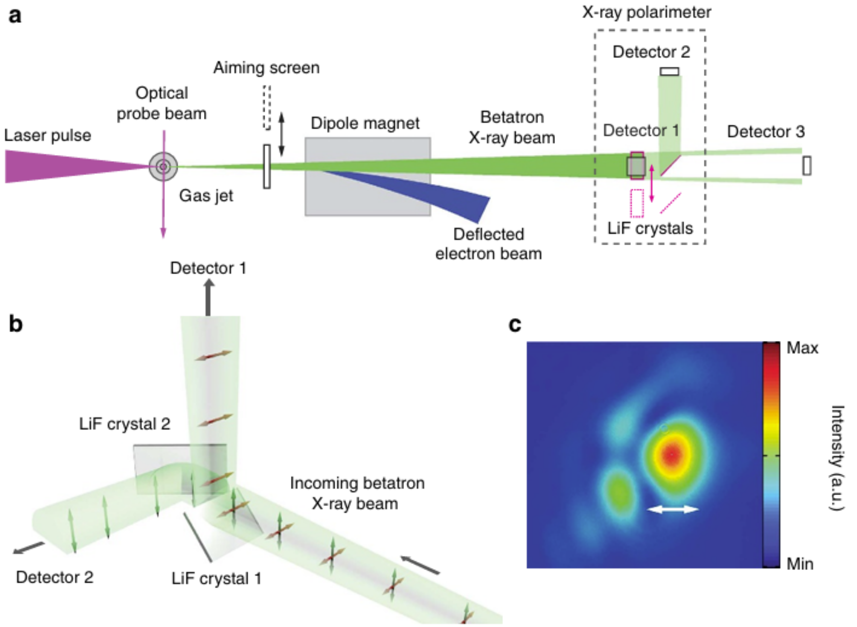
nature COMMUNICATIONS

ARTICLE

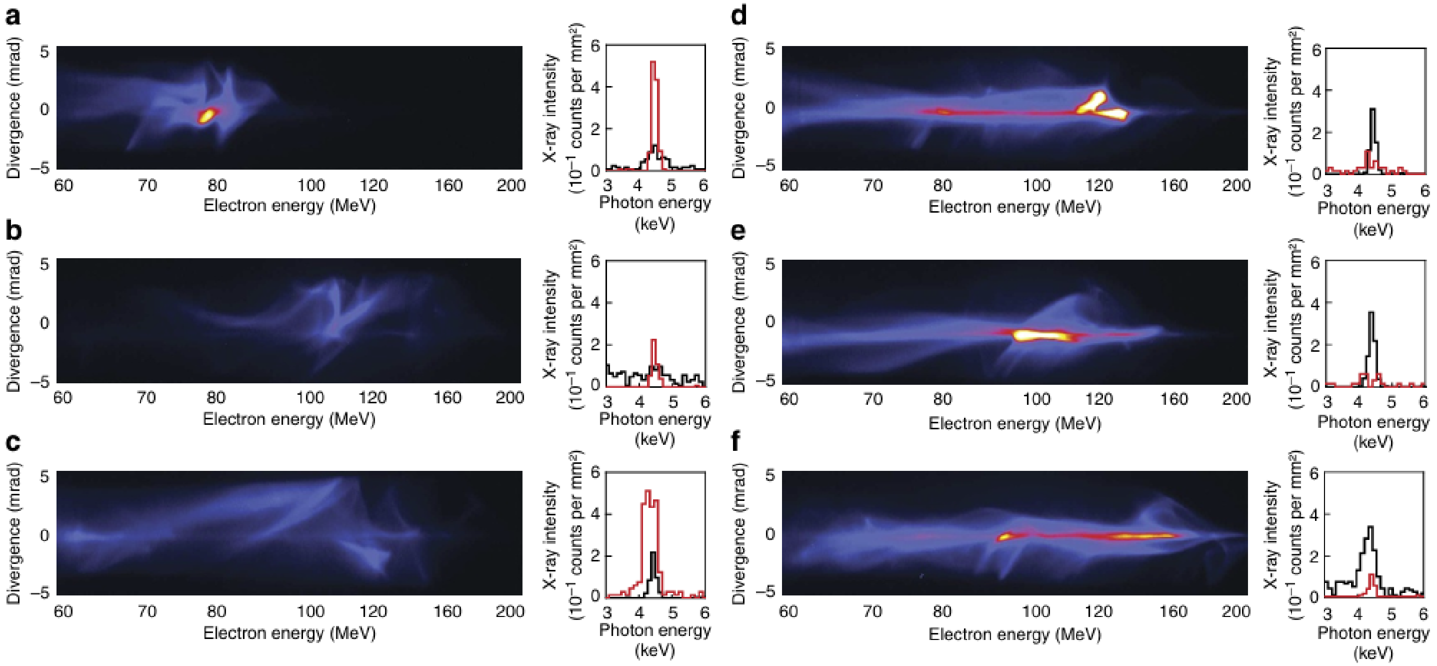
Received 2 May 2013 | Accepted 8 Aug 2013 | Published 12 Sep 2013 DOI: 10.1038/ncomms3421 OPEN

Optical control of hard X-ray polarization by electron injection in a laser wakefield accelerator

Michael Schnell[1], Alexander Sävert[1,2], Ingo Uschmann[1,2], Maria Reuter[1,2], Maria Nicolai[1,2], Tino Kämpfer[2], Björn Landgraf[1,2], Oliver Jäckel[1,2], Oliver Jansen[3], Alexander Pukhov[3], Malte Christoph Kaluza[1,2] & Christian Spielmann[1,2]

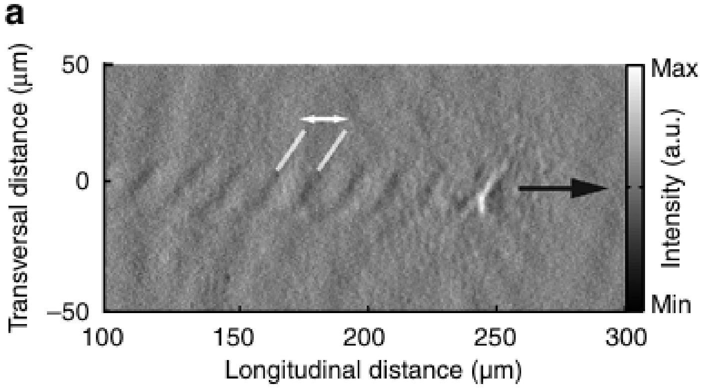


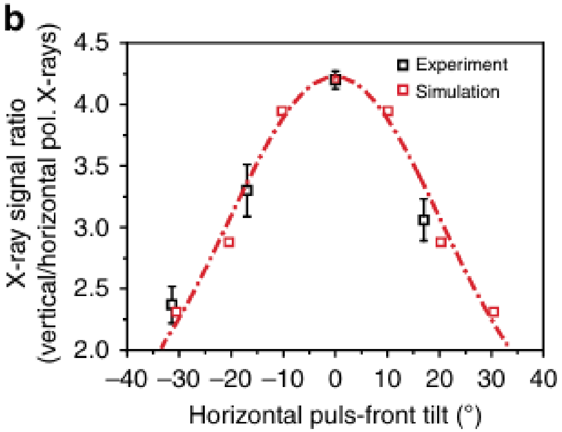
Polarization-sensitive reflection is realized by fulfilling the Bragg condition at Brewster's angle. Only sigma-polarized X-rays at 4.35 keV are reflected (extinction ratio 3%) and detected with an X-ray CCD camera.



Typical single-shot electron spectra on the high-energy scintillating screen. For the vertically confined electron traces (d–f) the horizontally polarized component dominates.

Snapshot of the electron density gradient taken with a 6-fs duration probe pulse for zero horizontal angular dispersion.





PHYSICAL REVIEW LETTERS **132,** 225001 (2024)

Single-Shot Diagnosis of Electron Energy Evolution via Streaked Betatron X Rays in a Curved Laser Wakefield Accelerator

Y. Ma,[1,*] J. A. Cardarelli,[1] P. T. Campbell,[1] S. Fourmaux,[2] R. Fitzgarrald,[1] M. D. Balcazar,[1] A. F. Antoine,[1] N. F. Beier,[3] Q. Qian,[1] A. E. Hussein,[3] B. Kettle,[4] S. R. Klein,[1] K. Krushelnick,[1] Y. F. Li,[5] S. P. D. Mangles,[4] G. Sarri,[6] D. Seipt,[7,8] V. Senthilkumaran,[3] M. J. V. Streeter,[6] L. Willingale,[1] and A. G. R. Thomas[1]

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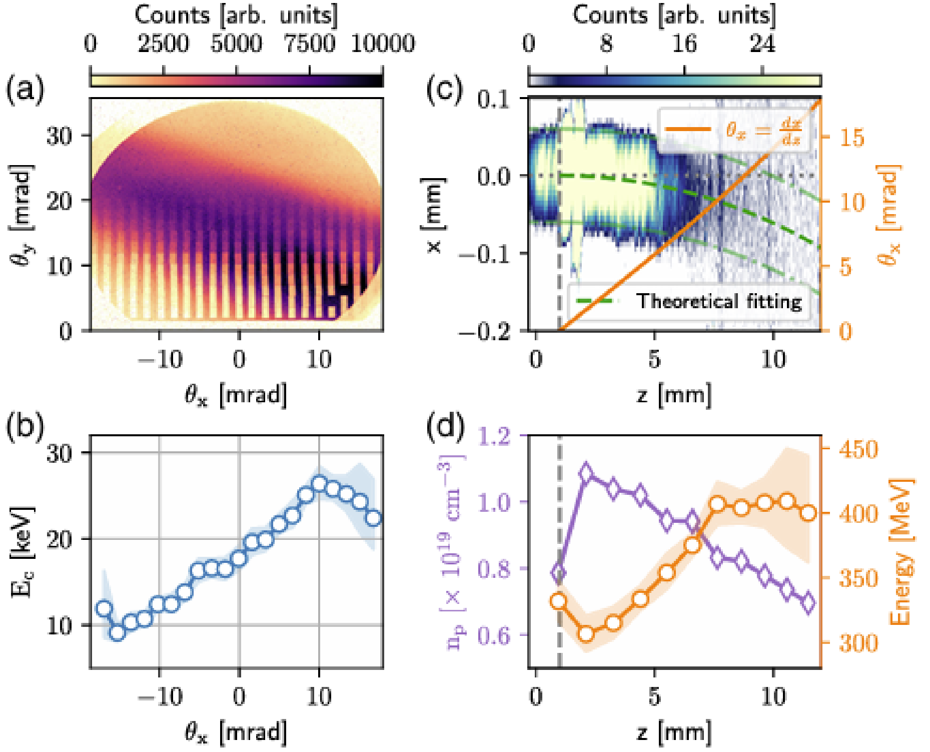
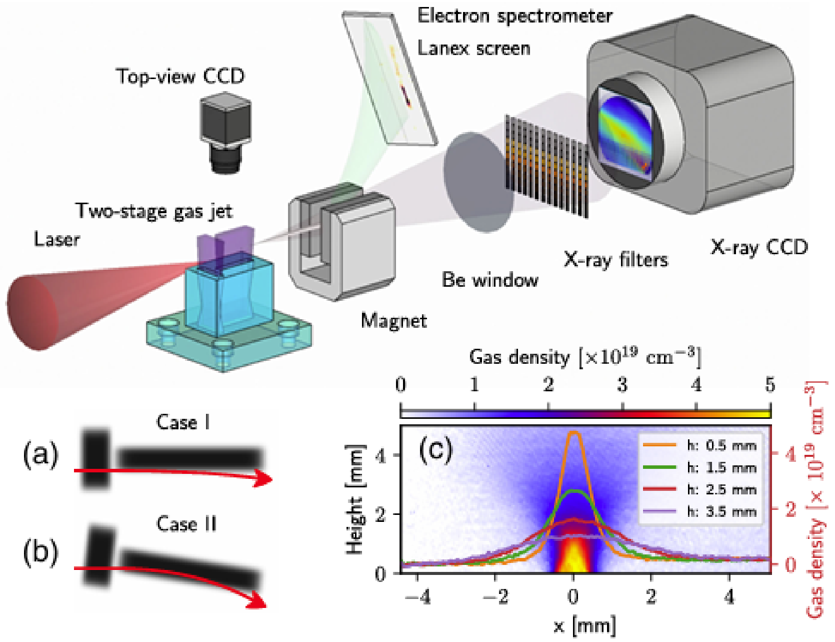


The X-ray filters were designed as a 25×11 matrix, for which each column consists of 11 different thicknesses of aluminum and copper. The angularly resolved X-ray spectrum was retrieved using a forward least-squares fitting method.



$$\gamma(z) = \left[\frac{E_c(\theta(z))}{E_{c1}}\right]^{4/7} \left[\frac{n_{p1}}{n_p(z)}\right]^{3/7} \gamma_1$$

Using the initial condition, i.e., the final electron energy and the betatron X-ray critical energy at the corresponding angle as well as the measured plasma density distribution, the evolution of the electron energy can be reconstructed

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 15, 021302 (2012)

Characterization of transverse beam emittance of electrons from a laser-plasma wakefield accelerator in the bubble regime using betatron x-ray radiation

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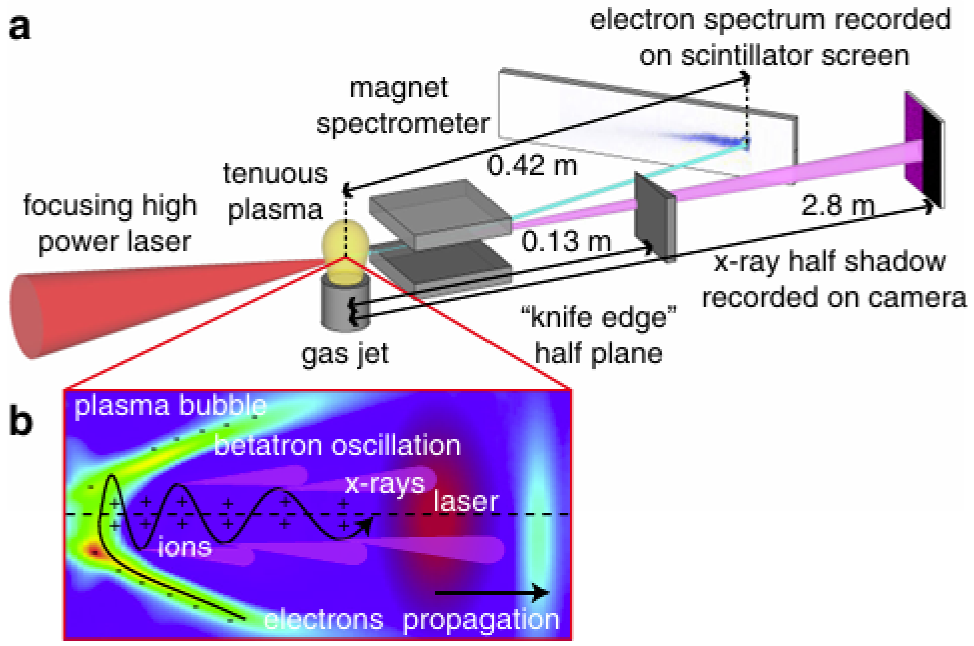
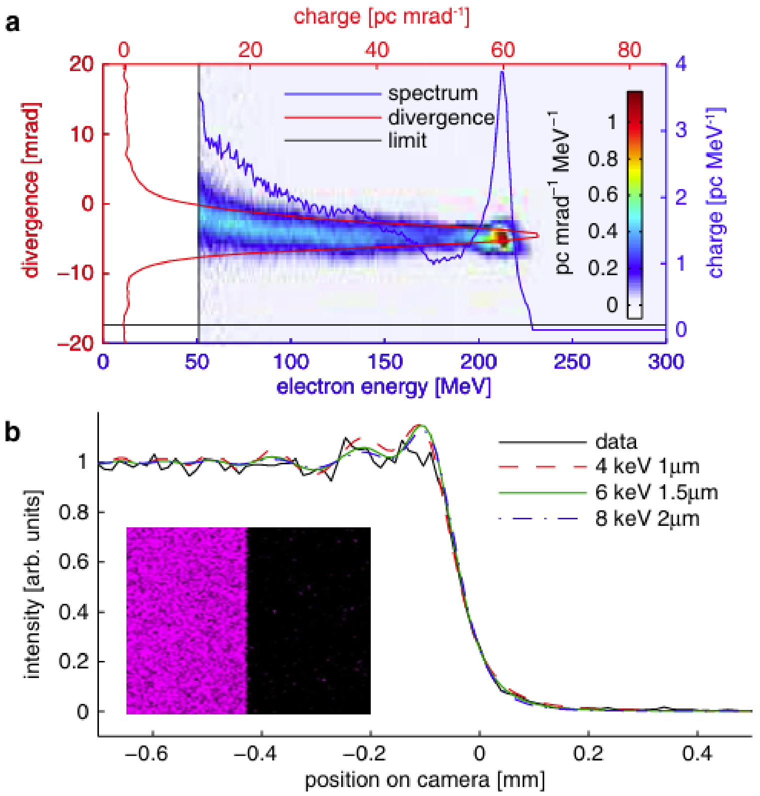
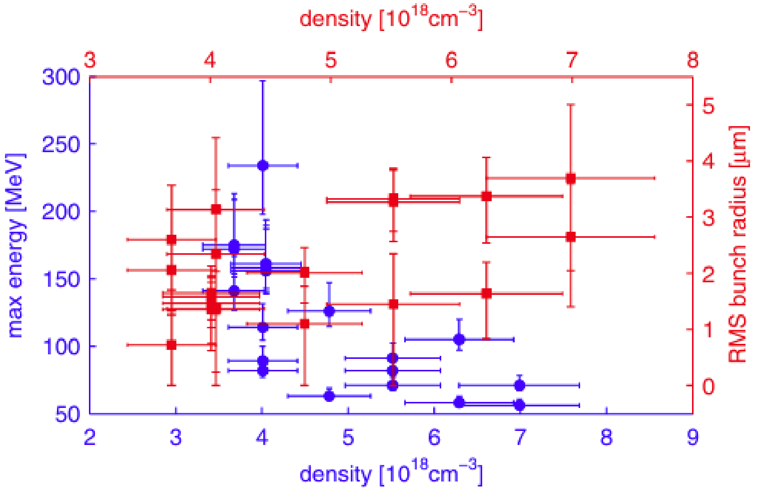




Penumbral imaging is used to determine the betatron X-ray source size by placing a half-plane crystal after the source to cast a shadow on the detector. The measured intensity profile is modeled with Fresnel diffraction theory to extract the X-ray spectrum and source size. A least-squares fit provides the rms source radius with a 95% confidence interval. The upper limit (uncorrelated emittance) is retrieved:

$$\epsilon_n^\perp = \epsilon^\perp \gamma \beta_z = 0.1\pi \text{ mm mrad}$$



PRL 109, 064802 (2012) PHYSICAL REVIEW LETTERS week ending 10 AUGUST 2012

Low-Emittance Electron Bunches from a Laser-Plasma Accelerator Measured using Single-Shot X-Ray Spectroscopy

G. R. Plateau,[1,*] C. G. R. Geddes,[1] D. B. Thorn,[2,†] M. Chen,[1] C. Benedetti,[1] E. Esarey,[1] A. J. Gonsalves,[1] N. H. Matlis,[1] K. Nakamura,[1] C. B. Schroeder,[1] S. Shiraishi,[1] T. Sokollik,[1] J. van Tilborg,[1] Cs. Toth,[1] S. Trotsenko,[3,†] T. S. Kim,[1] M. Battaglia,[1,‡] Th. Stöhlker,[2,3,†] and W. P. Leemans[1,§]

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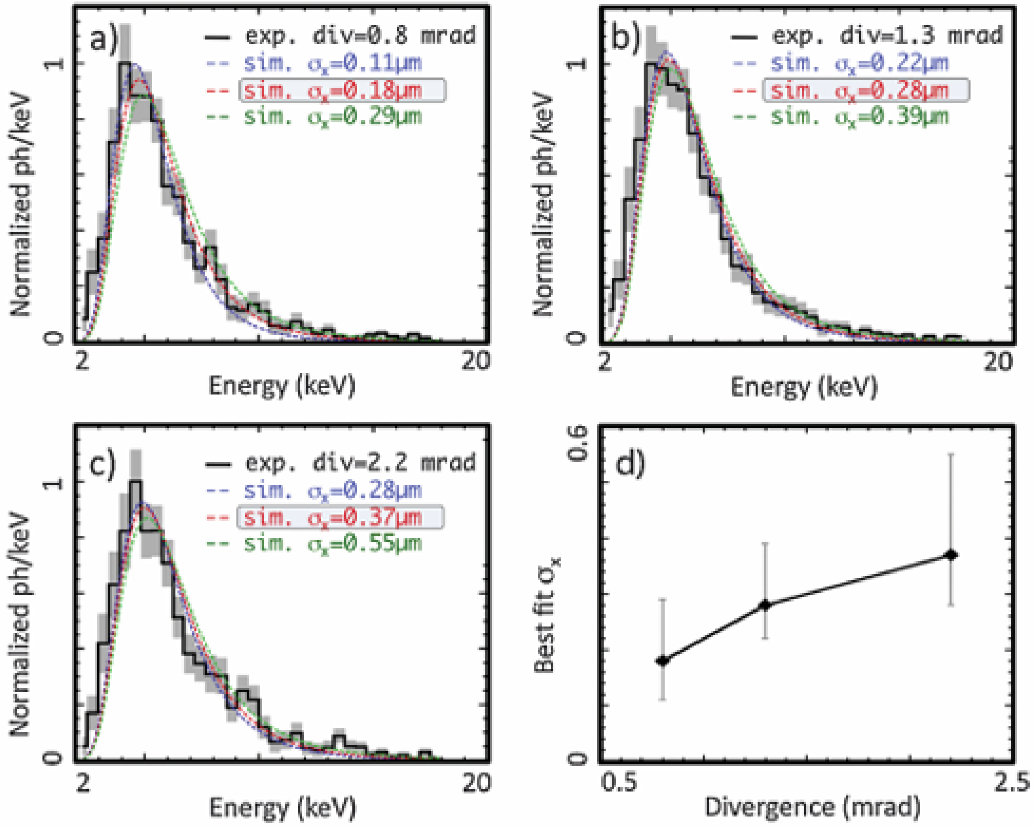
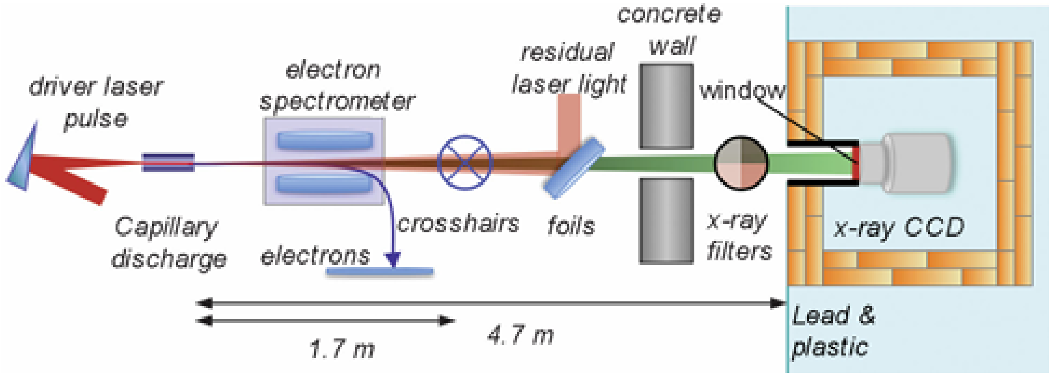
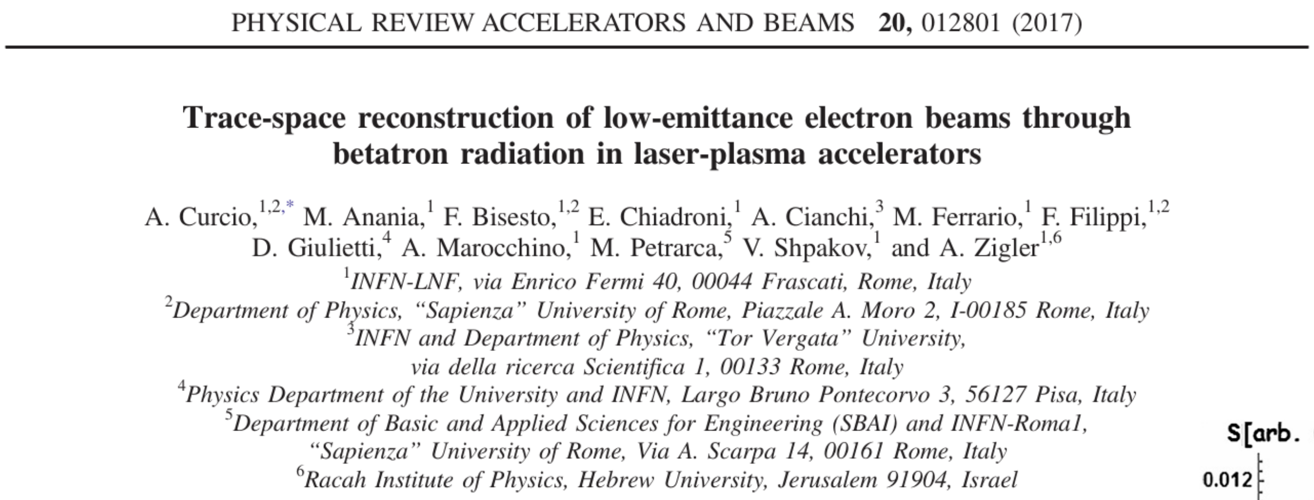




Single-shot spectra (2–20 keV) measured with a photon-counting CCD were compared to betatron radiation models, indicating an electron bunch radius of ~0.1 μm. Combined with divergence measurements, this yielded a normalized transverse emittance as low as 0.1 mm·mrad for a 460 MeV electron bunch

$$\epsilon_x \approx \gamma \sigma_x \sigma_\theta \sim 0.1 \text{ mm mrad}$$



PHYSICAL REVIEW ACCELERATORS AND BEAMS **20**, 012801 (2017)

Trace-space reconstruction of low-emittance electron beams through betatron radiation in laser-plasma accelerators

A. Curcio,[1,2,*] M. Anania,[1] F. Bisesto,[1,2] E. Chiadroni,[1] A. Cianchi,[3] M. Ferrario,[1] F. Filippi,[1,2] D. Giulietti,[4] A. Marocchino,[1] M. Petrarca,[5] V. Shpakov,[1] and A. Zigler[1,6]

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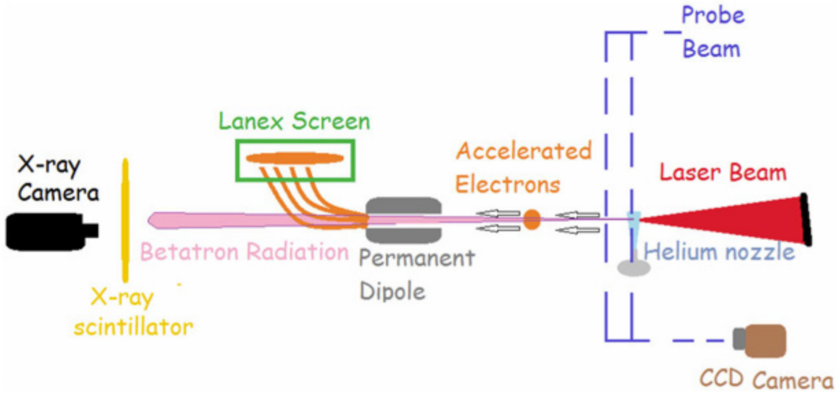
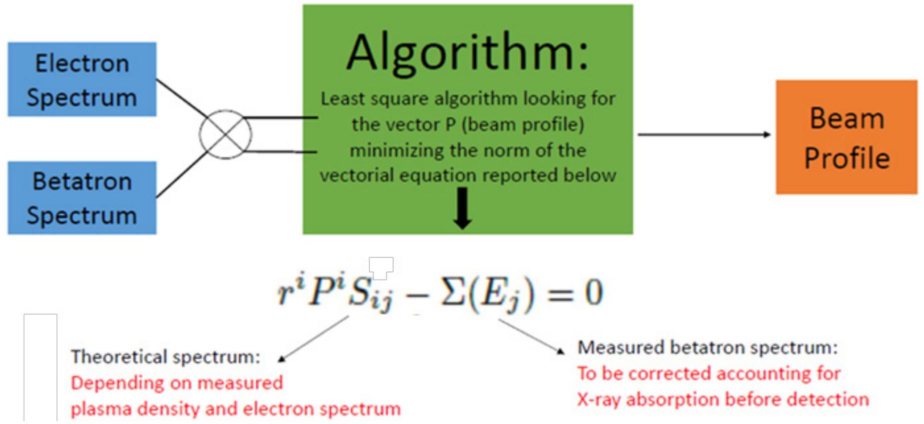
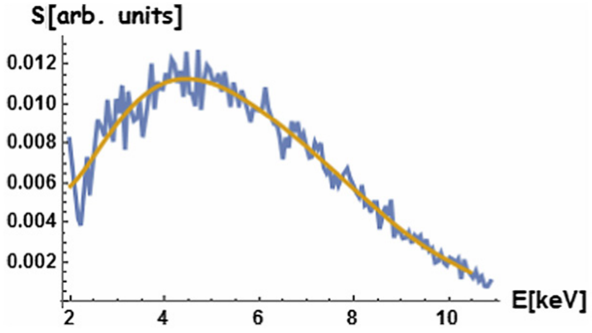
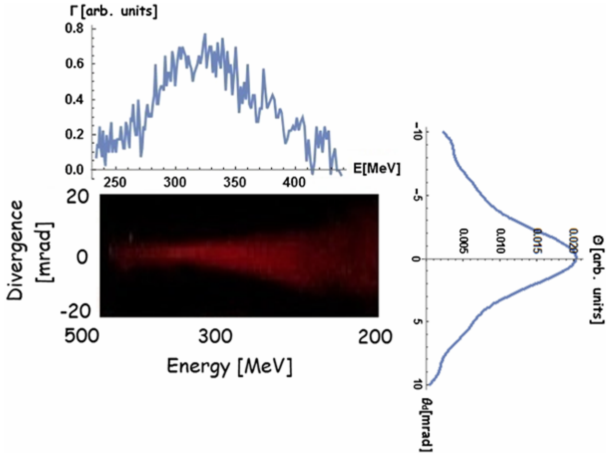
[6]*Racah Institute of Physics, Hebrew University, Jerusalem 91904, Israel*





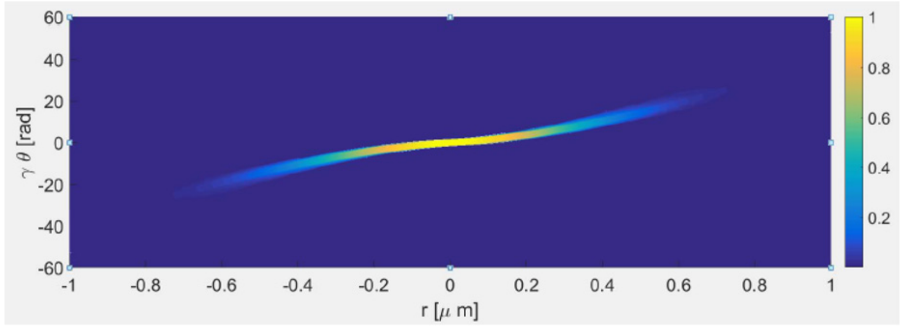
$$r^i P^i S_{ij} - \Sigma(E_j) = 0$$





$$\theta_d = \sqrt{\frac{\sqrt{1+\frac{1}{2}\gamma_0^2 r_\beta^2 k_{\beta 0}^2}}{4\gamma_0} r_\beta k_p}$$

$$\Theta(\theta_d) \propto P[r(\theta_d)]$$



$$\epsilon_{r_\beta N} = \gamma_0 \sqrt{(\sigma_\gamma/\gamma_0)^2 \sigma_r^2 \sigma_\theta^2 + \epsilon_{r_\beta}^2} = (0.6 \pm 0.1)\,\text{mmmrad}$$

From the study of electron transverse dynamics inside the plasma bubble, a nonlinear correlation between betatron amplitude and divergence is found. The angular distribution of the electron beam inside the bubble is then retrieved. Knowledge of the trace-space density enables an indirect measurement of the correlated transverse emittance.

PRL 111, 235004 (2013) PHYSICAL REVIEW LETTERS week ending 6 DECEMBER 2013

Angular Dependence of Betatron X-Ray Spectra from a Laser-Wakefield Accelerator

F. Albert,[1,*] B. B. Pollock,[1] J. L. Shaw,[2] K. A. Marsh,[2] J. E. Ralph,[1] Y.-H. Chen,[1] D. Alessi,[1] A. Pak,[1] C. E. Clayton,[2] S. H. Glenzer,[3] and C. Joshi[2]
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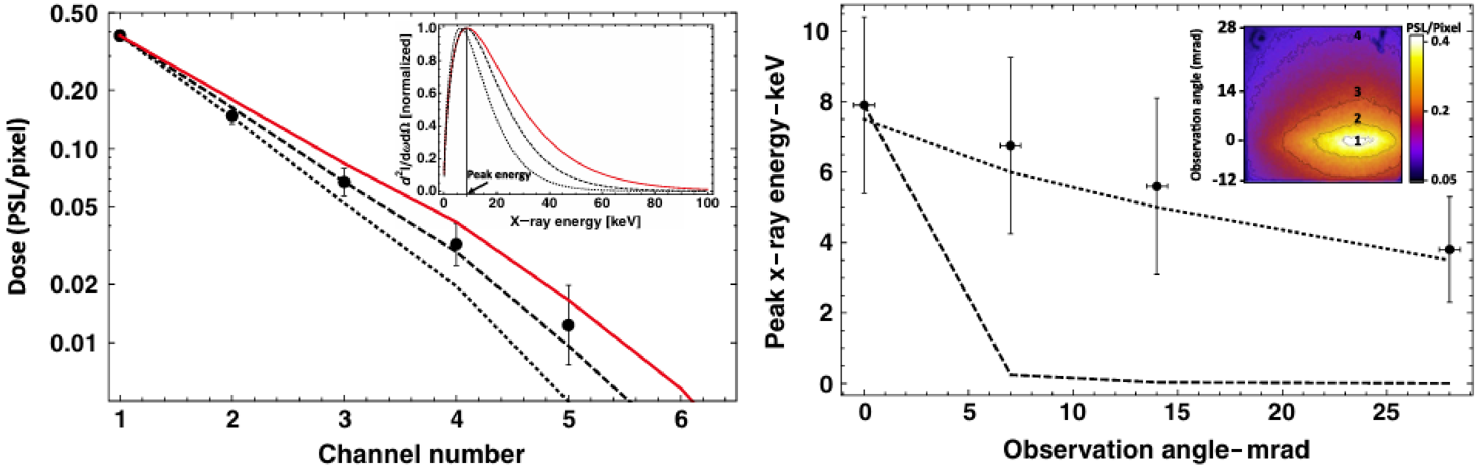
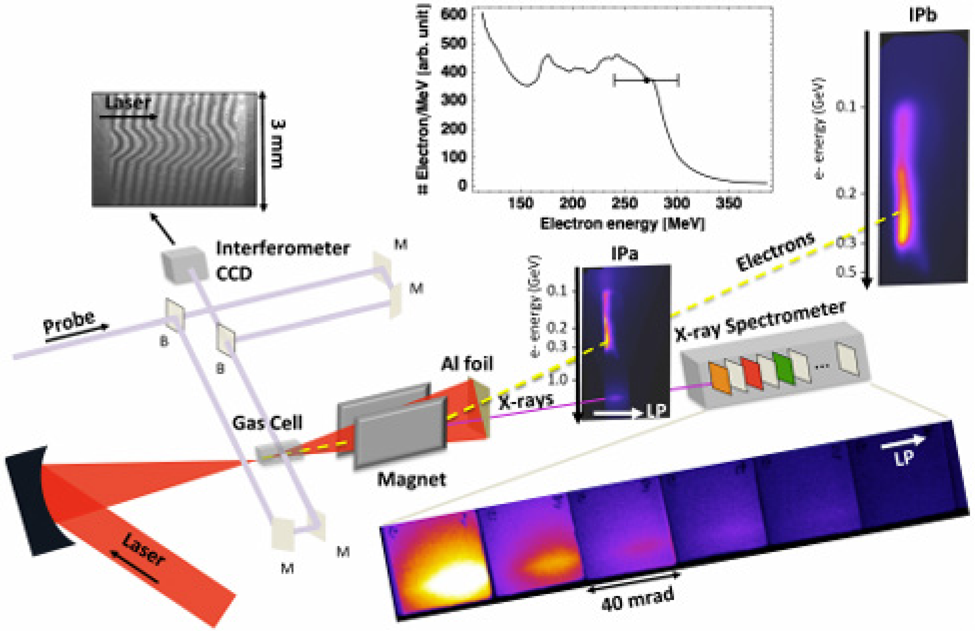


Peak experimental betatron X-ray energy is measured versus observation angle (on-axis, 7, 14, and 28 mrad), with positions indicated on the beam profile. The results are compared to theoretical predictions from Eq. (3) and full electron trajectory simulations. For each angle, the dose measured in detector channels 1–6 is fitted with a synchrotron-like spectral function to extract the peak energy.



Schematic of the experimental setup: an f = 8 off-axis parabola focuses the laser pulse onto a gas cell target.
Electrons (dashed line) are dispersed in energy by a magnet located 3.5 cm from the source and recorded on image plates (IPa and IPb) at 37.2 cm and 111.1 cm.
X-rays (solid line) are measured by a 15-channel spectrometer. LP indicates the laser polarization direction on the image plates.

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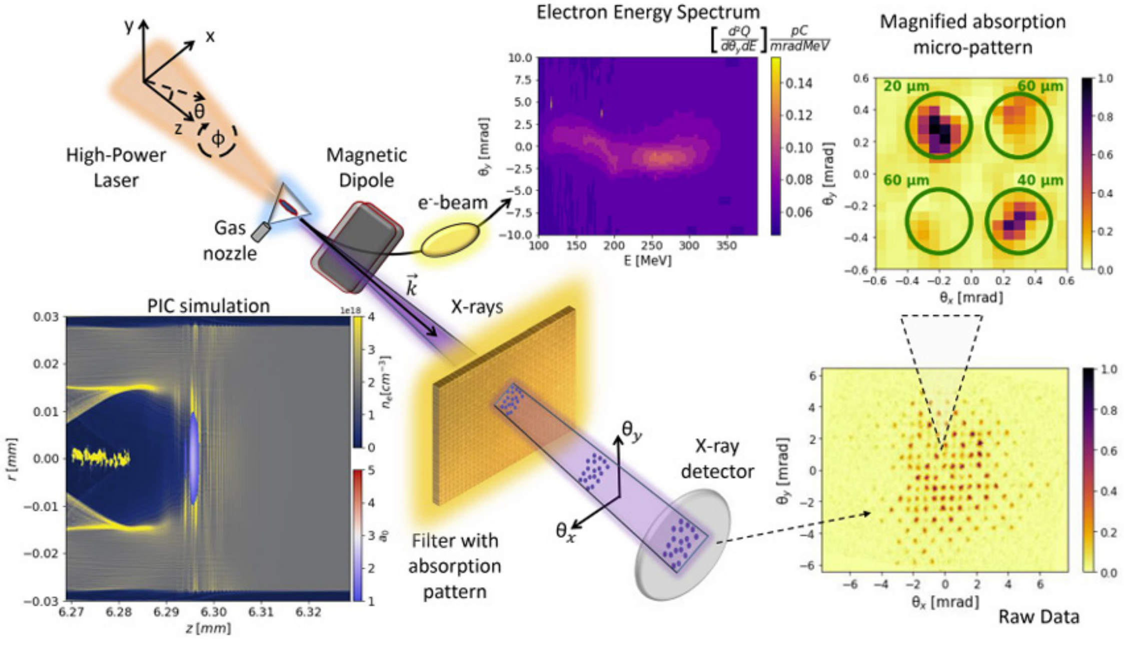
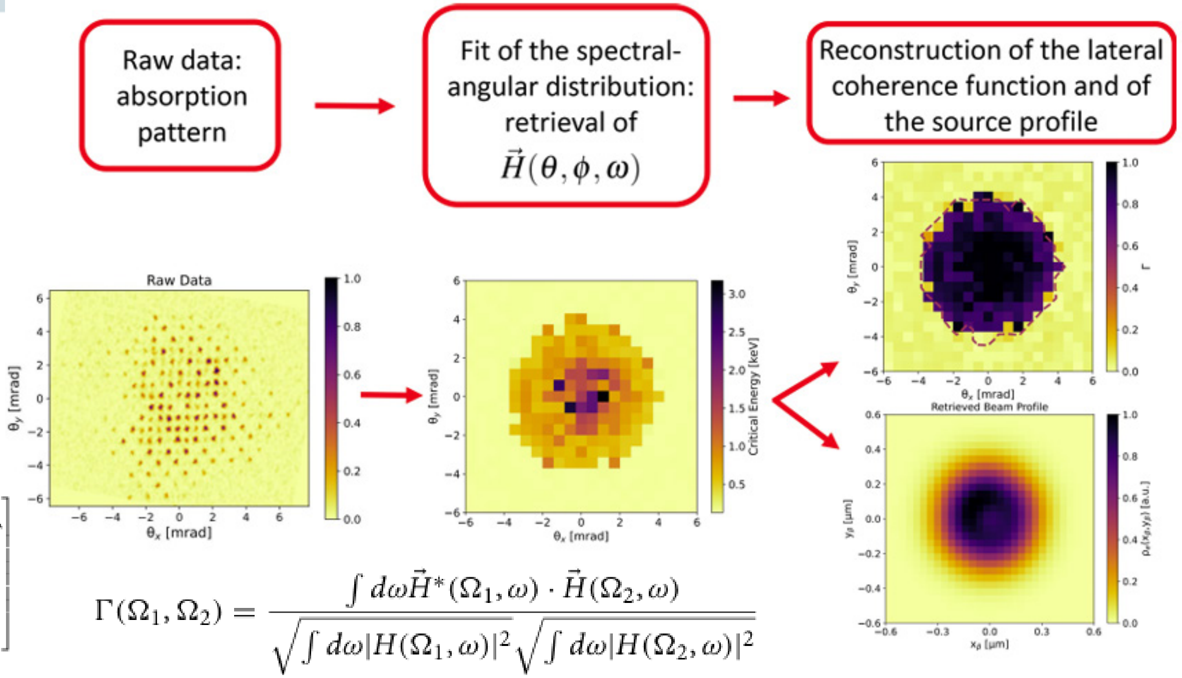
Reconstruction of lateral coherence and 2D emittance in plasma betatron X-ray sources

Alessandro Curcio[1], Alessandro Cianchi[2,3,4], Gemma Costa[1], Alessio Del Dotto[1], Francesco Demurtas[1], Massimo Ferrario[1], Maria Dolores Rodríguez Frías[5,6], Mario Galletti[2,3,4], José Antonio Pérez-Hernández[5] & Giancarlo Gatti[5]

$$\vec{H}(\theta,\phi,t) \propto e^{i\omega t\left[\overbrace{1-\frac{1}{c}\frac{dz}{dt}\cos\theta}^{\text{On-Axis Doppler Effect}} + \overbrace{\frac{\omega_\beta}{c}\sin\theta\,(x_\beta\cos\phi\sin\psi_x + y_\beta\sin\phi\sin\psi_y) - \frac{\omega_\beta^2}{4c^2}\sin\theta\left(x_\beta^2\cos 2\psi_x + y_\beta^2\cos 2\psi_y\right)}^{\text{Betatron Phase Modulation}}\right]}$$



$$\varepsilon_x = (0.29 \pm 0.06)\ \mu\text{m and } \varepsilon_y = (0.29 \pm 0.06)\ \mu\text{m}$$



$$\Gamma(\Omega_1,\Omega_2) = \frac{\int d\omega \vec{H}^*(\Omega_1,\omega)\cdot\vec{H}(\Omega_2,\omega)}{\sqrt{\int d\omega|H(\Omega_1,\omega)|^2}\sqrt{\int d\omega|H(\Omega_2,\omega)|^2}}$$

The raw data (left figure) show an absorption pattern. For each observation angle (identified by a repeating micropattern in the absorption mask), a radiation field is calculated with spectral properties that locally fit the measured absorption. The best-fitting radiation field provides the spectral-angular distribution of the X-ray source (central figure). From this distribution, the lateral coherence function is retrieved (top-right figure) using its definition in terms of the radiation field. Since the spectral-angular distribution is related to the transverse profile of the source, the latter can also be reconstructed (bottom-right figure).

PHYSICAL REVIEW E **111**, L013201 (2025)

Letter

Measurement of femtosecond incoherent XUV pulses using shot-noise-driven fluctuations in plasma betatron sources

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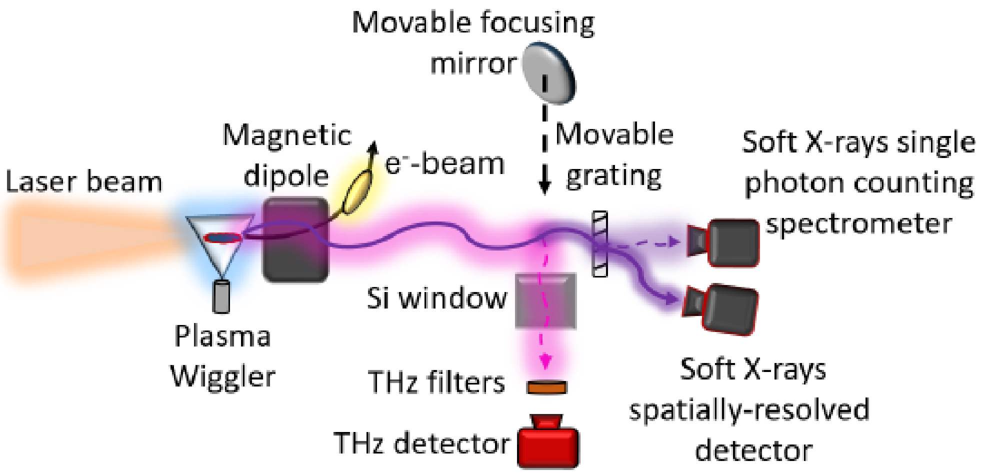
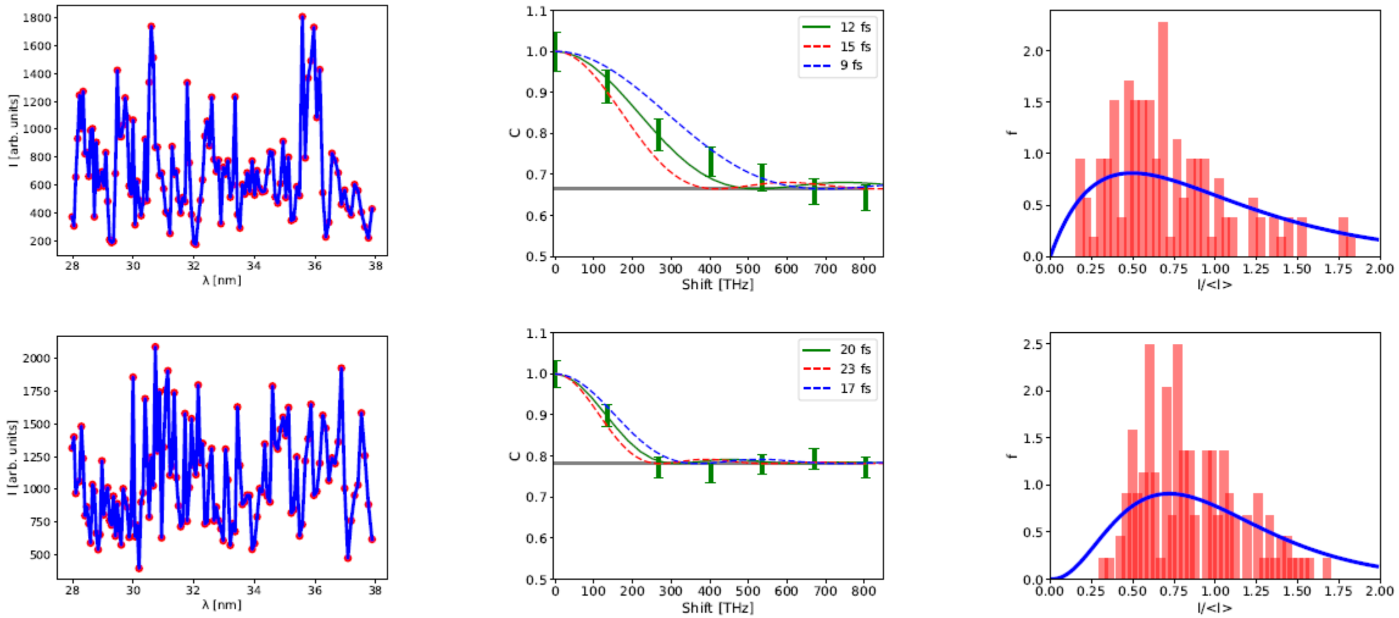


$$C(n) = \frac{1}{1+k}\frac{\rho^2(\omega_n)\star S(\omega_n)}{\rho^2(\omega_0)\star S(\omega_0)} + \frac{k}{1+k}$$

$$f\left(\frac{I}{<I>}, k\right) = \frac{\left(\frac{I}{<I>}\right)^{k-1} k^k}{\Gamma(k)} e^{-k\frac{I}{<I>}}$$



Top left: raw spectral data for a short pulse of betatron radiation (around 3% of critical energy).
Top middle: the spectral intensity correlation function, with a best fit corresponding to a (12 ± 3) fs rectangular pulse. The asymptotic line C = 0.66 is also shown (corresponding to k = 2).
Top right: normalized intensity distribution (red) together with a Gamma distribution fit (blue) for k = 2.
Bottom row: analogous to the top line in the case of a longer pulse [(20 ± 3) fs], corresponding to a k = 3.6 fit.

Conclusions

- A selection of studies on betatron radiation diagnostics in plasma accelerators has been reviewed.

- Over the years, both established and innovative (to some extent) techniques have enabled spatial, angular, spectral, and temporal characterization of betatron radiation.

- Betatron radiation provides simultaneous insight into the properties of the emitting electron beams and the characterization of the radiation source itself.

PHYSICS OF PLASMAS **14**, 080701 (2007)

Demonstration of the ultrafast nature of laser produced betatron radiation

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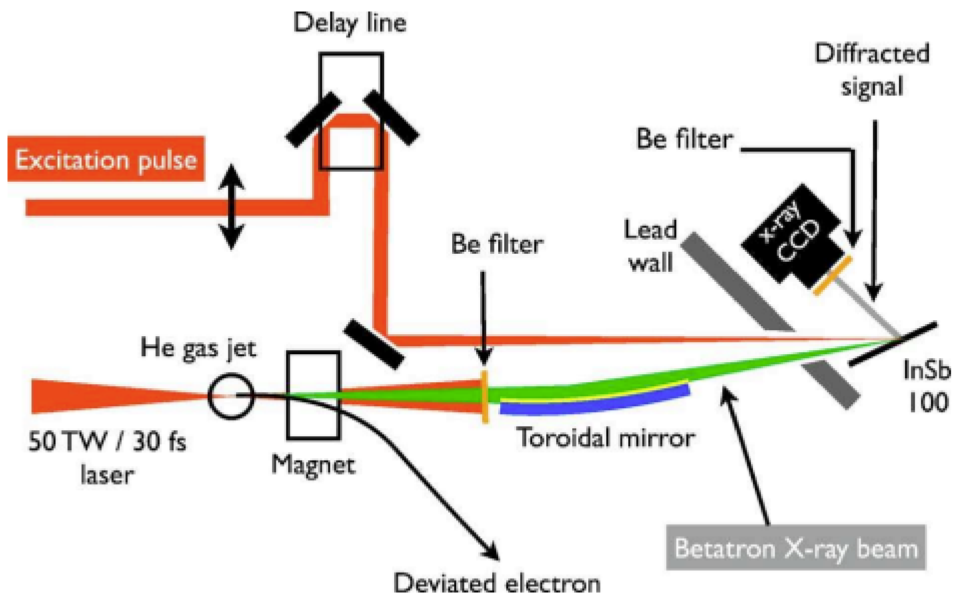

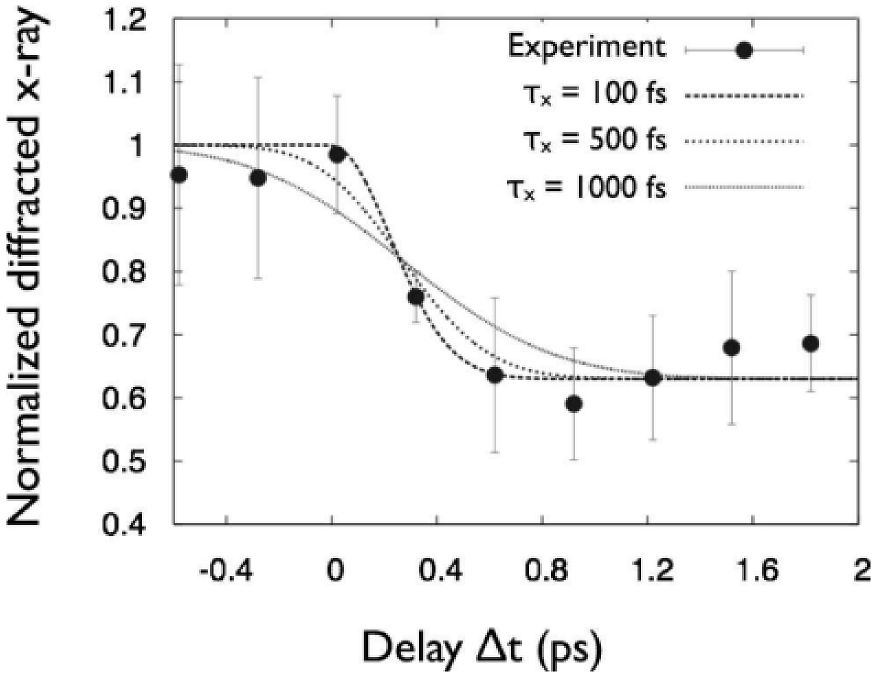

Visible pump, X-ray probe experimental setup. A 30-cm-long toroidal mirror is used to collect and focus the X-ray beam onto an asymmetrically cut (100) InSb sample. The phase transition is triggered using a synchronized 30 fs laser pulse at 820 nm.

X-ray intensity diffracted by the excited InSb sample, normalized to the incident x-ray intensity, as a function of the visible pump, x-ray probedelay t. The fits represent I(Delta t)/ I0 for Tx = 100, 500, and 1000 fs.