A Concept for a Plasma Wakefield Accelerator Driven FEL

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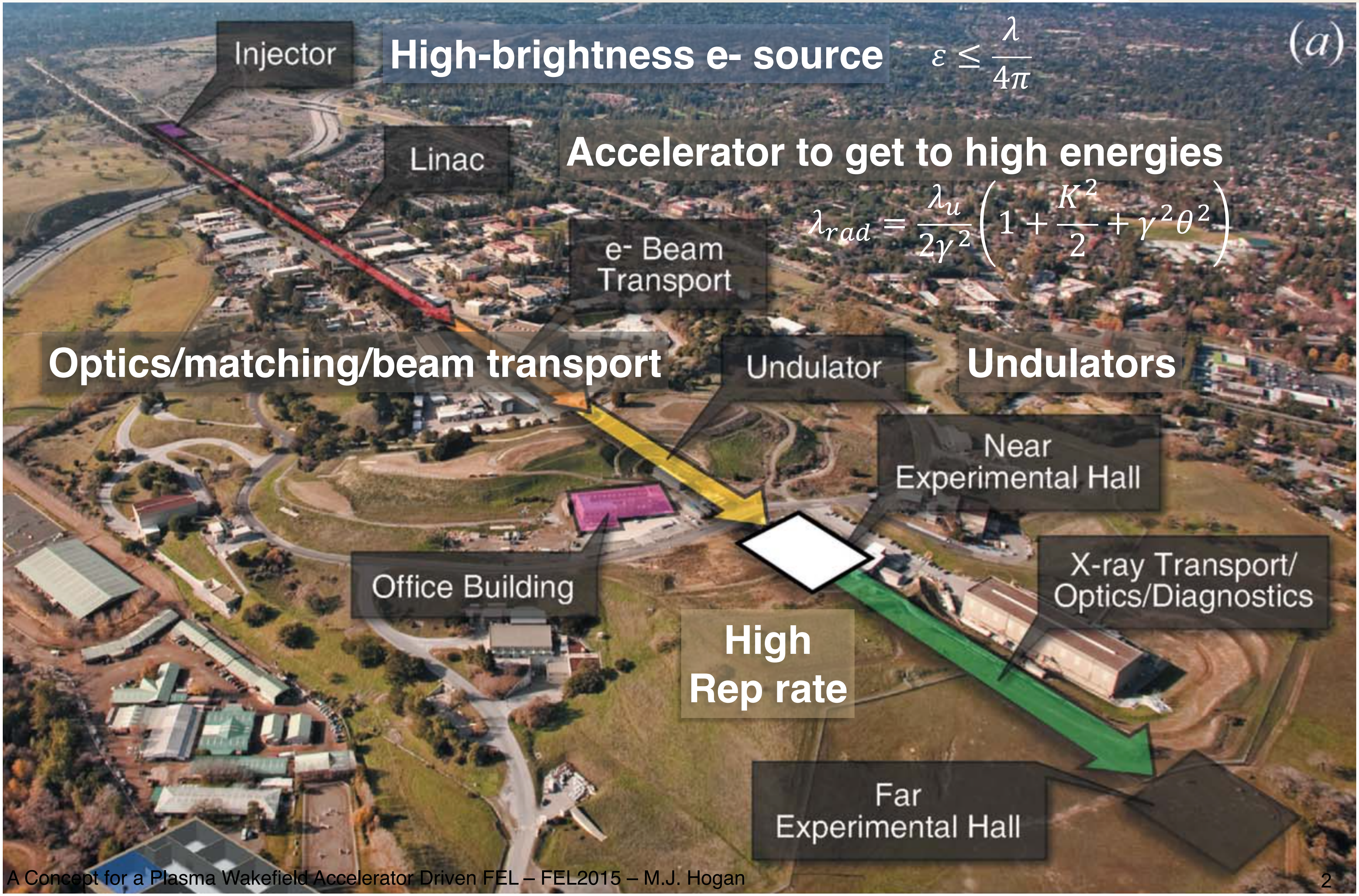
August 26, 2015

U.S. DEPARTMENT OF ENERGY
Office of Science

NATIONAL ACCELERATOR LABORATORY

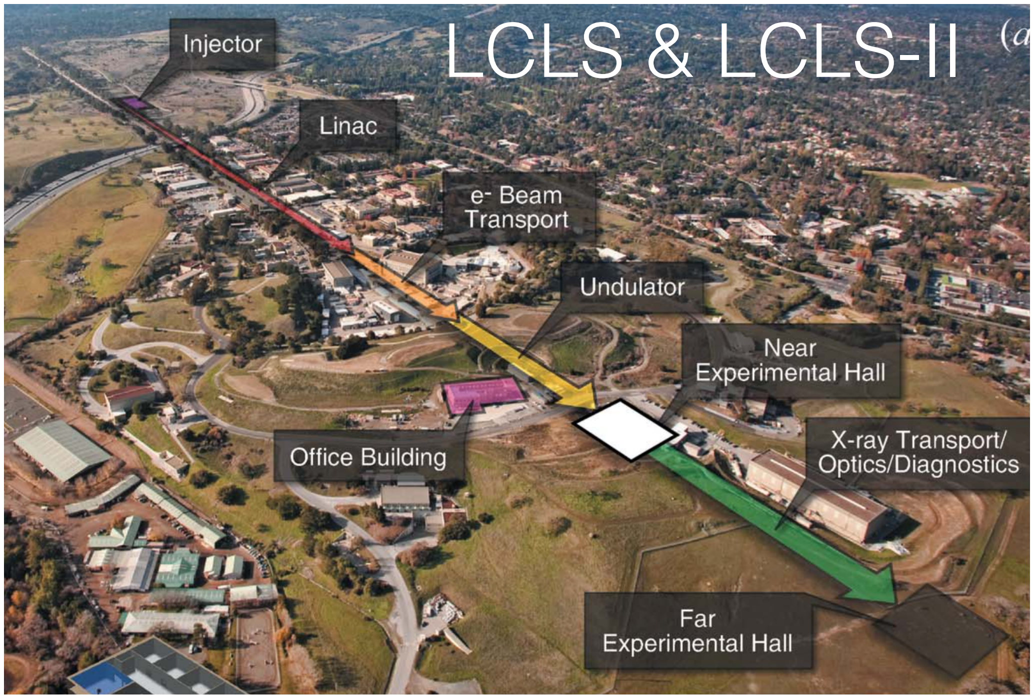
What Do We Need to Make an XFEL?

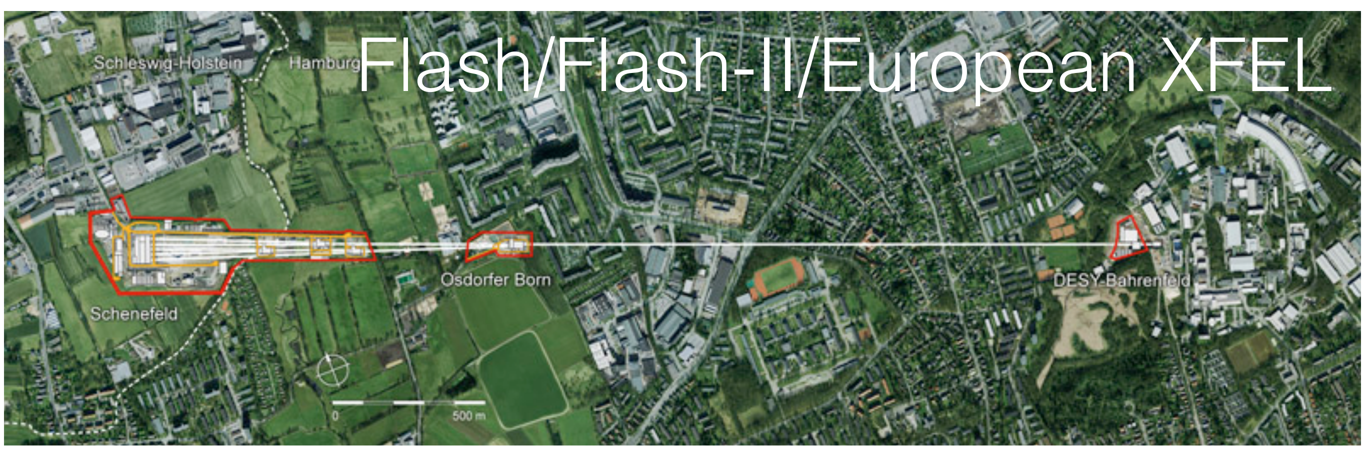
SLAC

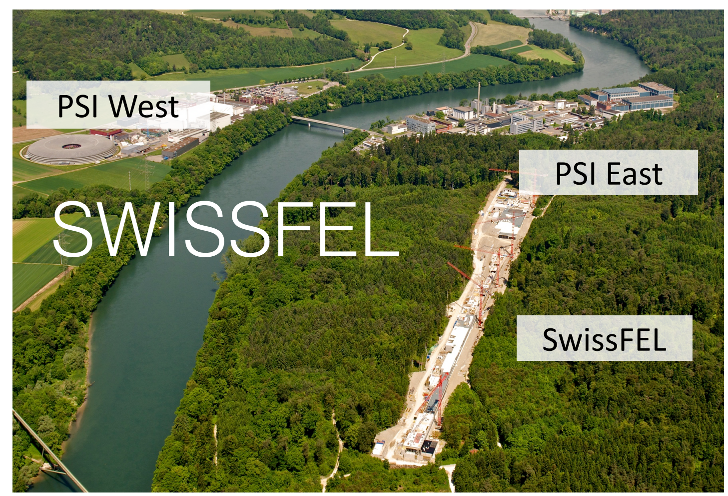


Many XFELs with Large Accelerators Driving Them

SLAC







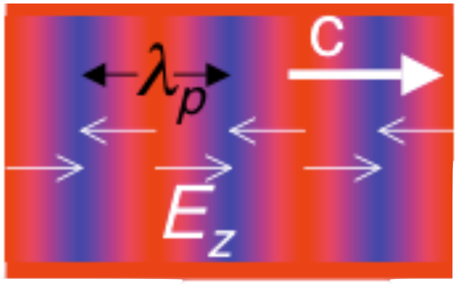
Why Plasmas?

Relativistic plasma wave (electrostatic):

$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\varepsilon_0} \qquad k_p E_z = \frac{\omega_{pe}}{c} E_z = \frac{n_e e}{\varepsilon_0}$$

$$E_z = \left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2} \cong 100\sqrt{n_e(cm^{-3})} = \underline{1GV/m}$$

$n_e = 10^{14}\ cm^{-3}$



Large Collective Response!

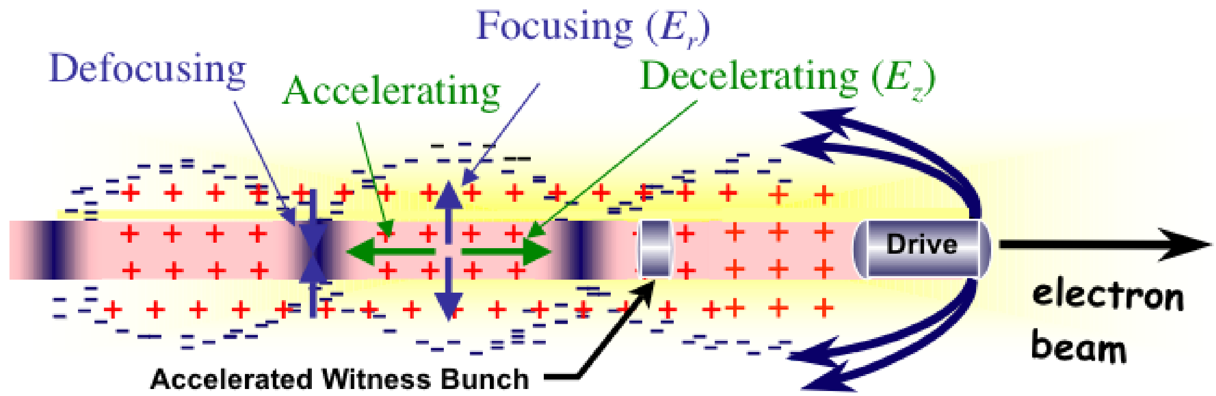
Compare: SLAC linac ~ 20MeV/m

- Plasmas can sustain very large E_z field, acceleration
- Plasmas are already ionized (partially), difficult to break down
- High energy, high gradient acceleration!
- Plasma wave can be driven by:
  - ➡ Intense laser pulse (LWFA)
  - ➡ Short particle bunch (PWFA)

Plasma Wakefield May Be Excited by a Beam or Laser

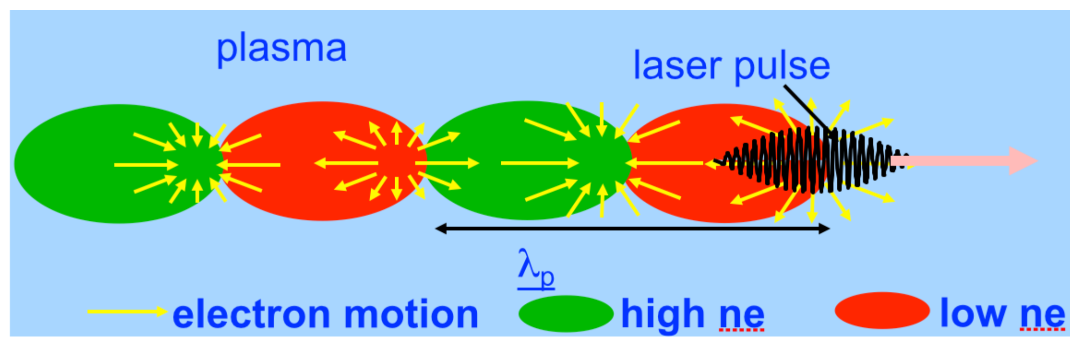
"Blow-out" regime preferred

- For beams when $n_b/n_p \gg 1$
  - Ion channel focussing guides drive beam over meter scale
  - Matched beta (~mm)
  - No phase slippage, non-evolving wake until pump depletion
  - Energy transformer



$$\beta_{matched} = \frac{\sqrt{2\gamma}}{k_p} = \sqrt{2\gamma}\frac{c}{\omega_p}$$

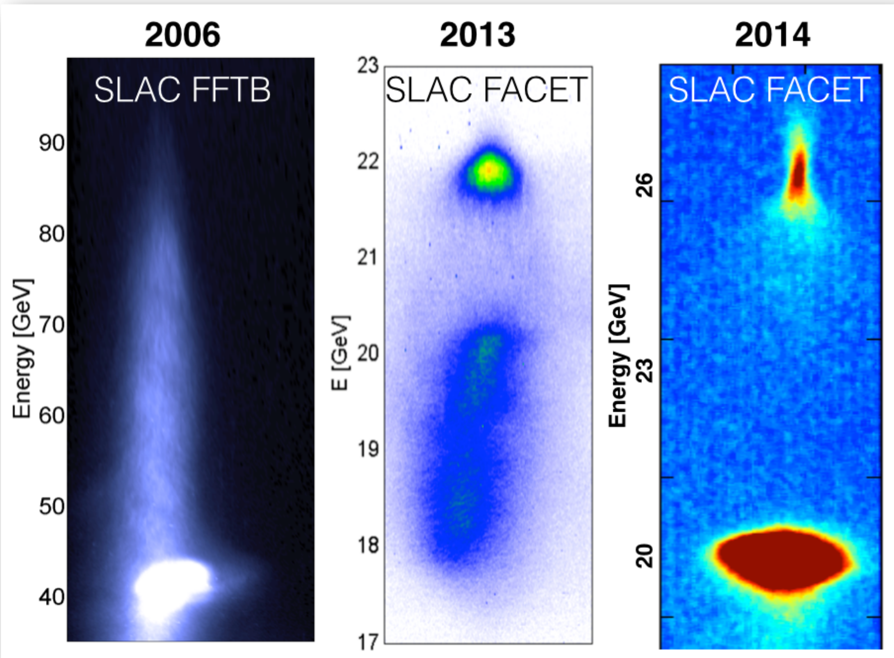
- For lasers when $a_0 > 1$
  - 100's TW, focal spot size < 100µm, Z_R ~ cm
  - Balance three D's: diffraction, de-phasing, depletion
  - Interaction can be extended with channel guiding (<10cm)



$$a_0 = 0.85\times10^{-9}\lambda[\mu m](I_0[W/cm^2])^{1/2}$$

Typical: $n_e \approx 10^{17}$ cm^{-3}, $\lambda_p \approx$ 100µm, G > MT/m, E_z > 10 GV/m

Laser and Beam Driven Acceleration in Plasmas



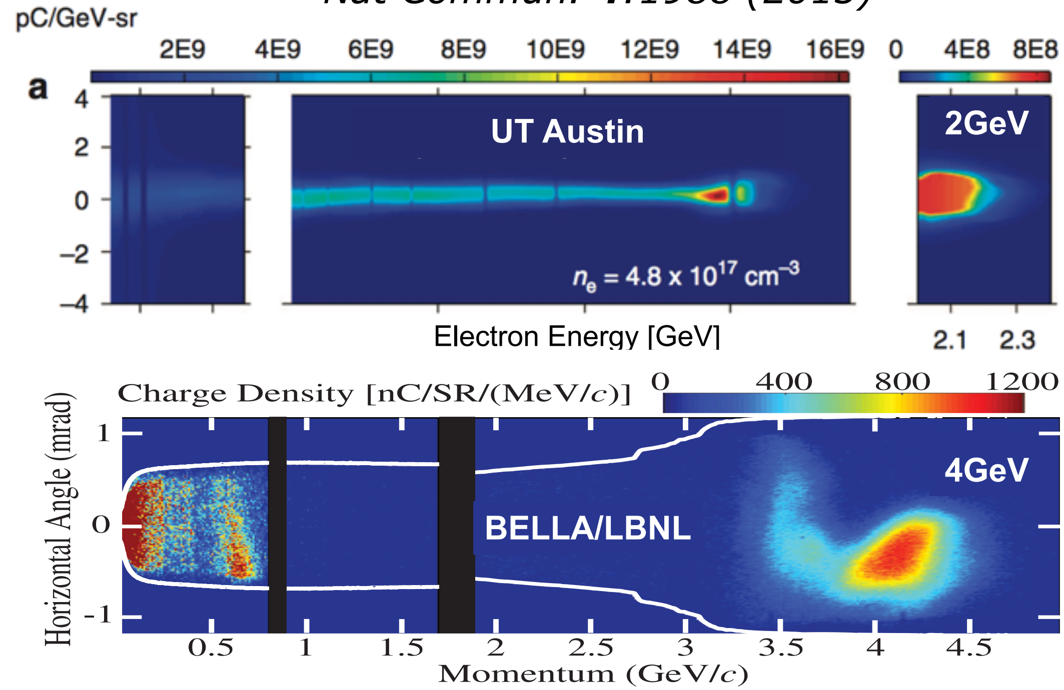
Nature ***445*** *741 (2007)*

Nature ***515****, 92-95 (2014)*

Laser Driven Plasmas:

- 50 GeV/m fields, stable over few cm
- High quality <μm emittance beams created and accelerated in the plasma
- Many groups now > GeV

Nat Commun. ***4****:1988 (2013)*

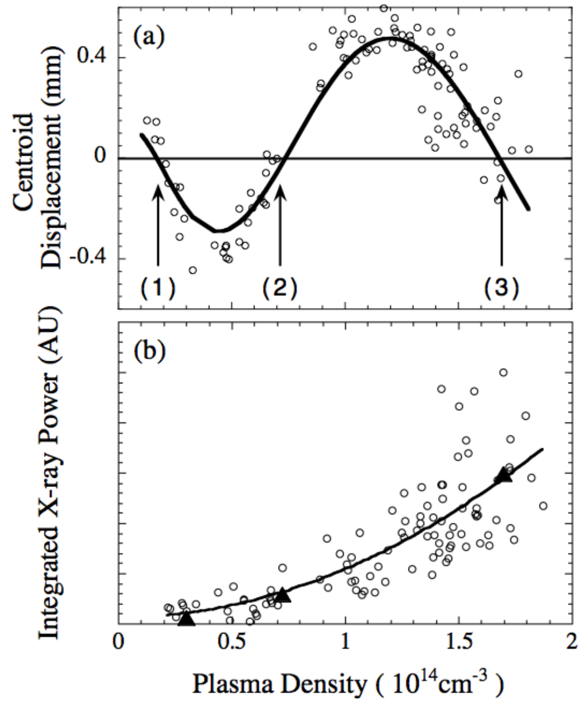


Phys. Rev. Lett. ***113****, 245002 (2014)*

Beam Driven Plasmas:

- 50 GeV/m fields, stable over meter scale
- High-efficiency, low dE/E of externally injected electrons and positrons

X-Ray Emission & Positron Production by X-Rays Emitted by Betatron Motion In A Plasma Wiggler



$$\lambda_\beta \simeq (2\gamma)^{1/2}\lambda_p$$

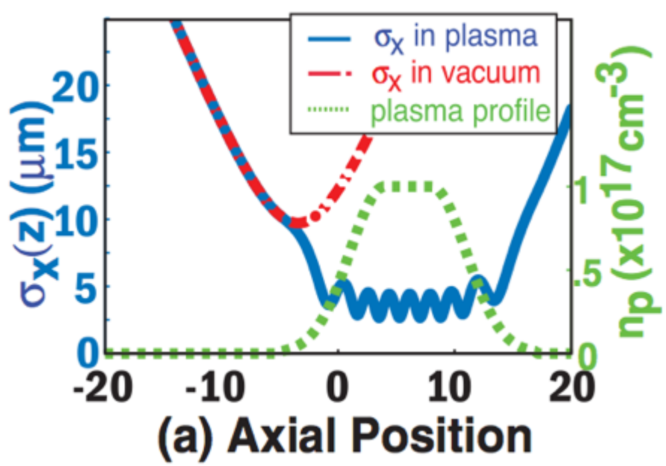
$$a_\beta = \gamma k_\beta r_\beta$$

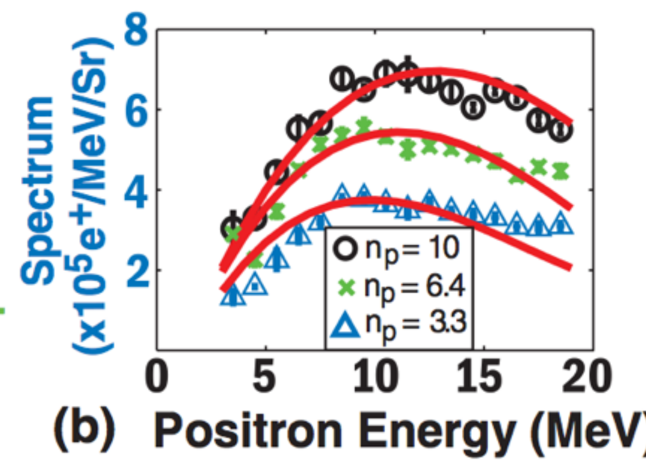
$$a_\beta \approx 0.13\sqrt{\gamma\, n[10^{18}\mathrm{cm}^{-3}]}\, r_\beta[\mu\mathrm{m}]$$

$$\hbar\omega_c[\mathrm{keV}] \approx 10^{-5}\gamma^2 n[10^{18}\mathrm{cm}^{-3}] r_\beta[\mu\mathrm{m}]$$

e.g. 5GeV, 10^{17}/cc, 10μm

MeV critical energy!

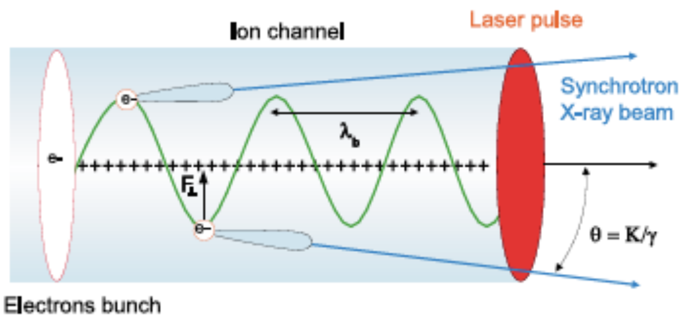


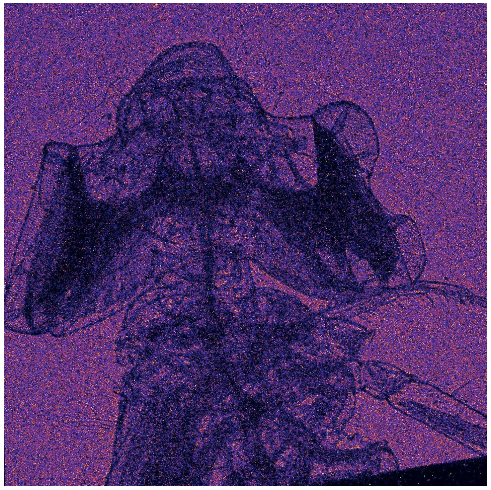


Physical Review Letters ***97***, *175003 (2006)*

Betatron Radiation & Search for First Applications

Femtosecond bursts of x-rays from electron acceleration (up to 800 MeV) can be used for phase contrast imaging





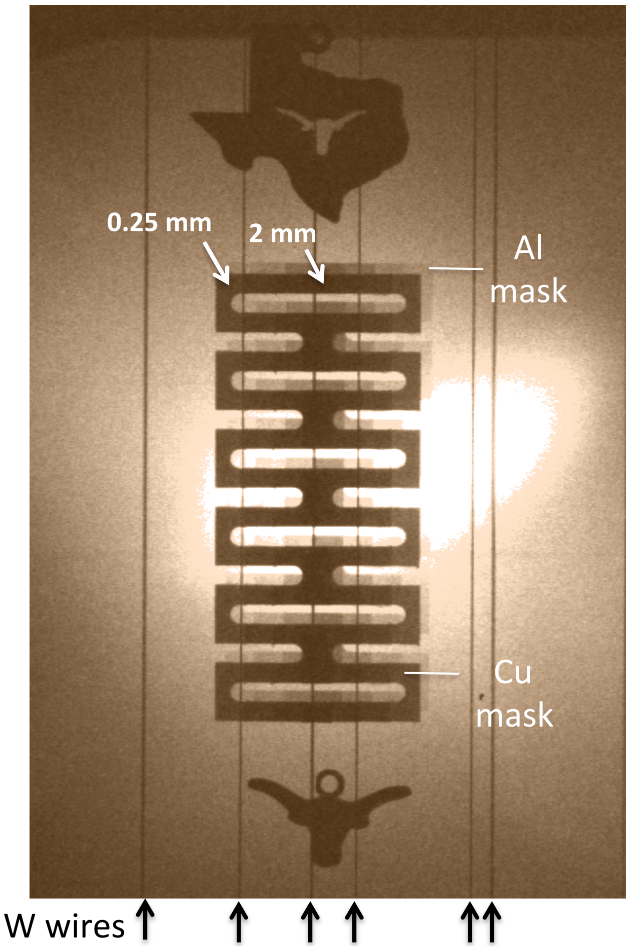
at Michigan:

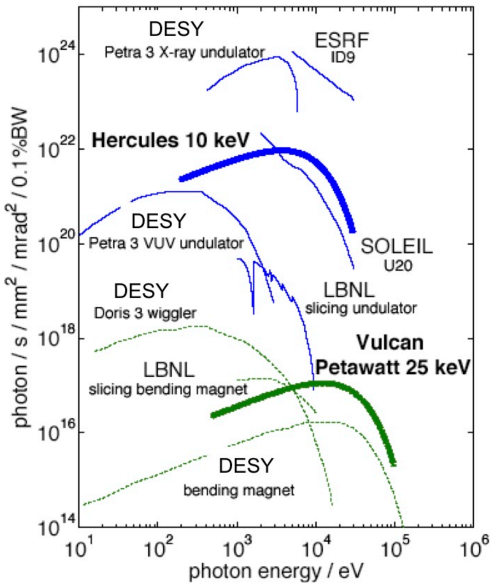
Hercules 100 TW,
S. Kneip, et. al., APL (2011)
. Kneip et al.,, Nature Physics (2010)

Petawatt, kJ laser
S. Kneip, et. al., PRL (2008)

...and elsewhere:

Rousse, *PRL* **93**, 135005 (2004)
Kneip *et al.*, *Nature Phys*. **6**, 980 (2010)
Cipiccia *et al.*, *Nature Phys*. **7**, 867 (2011)

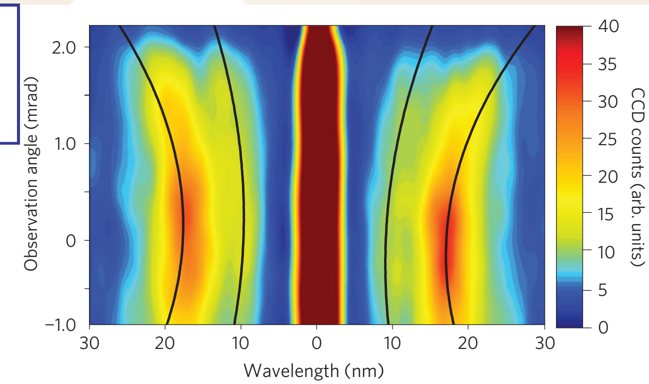




Also Undulator Radiation, ICS...

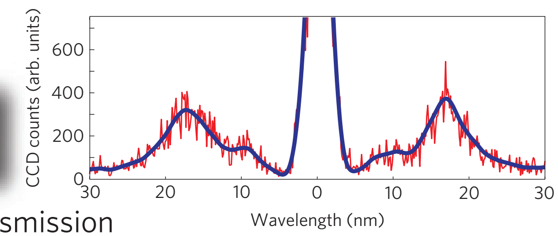
Laser Driven Soft X-ray Undulator Source

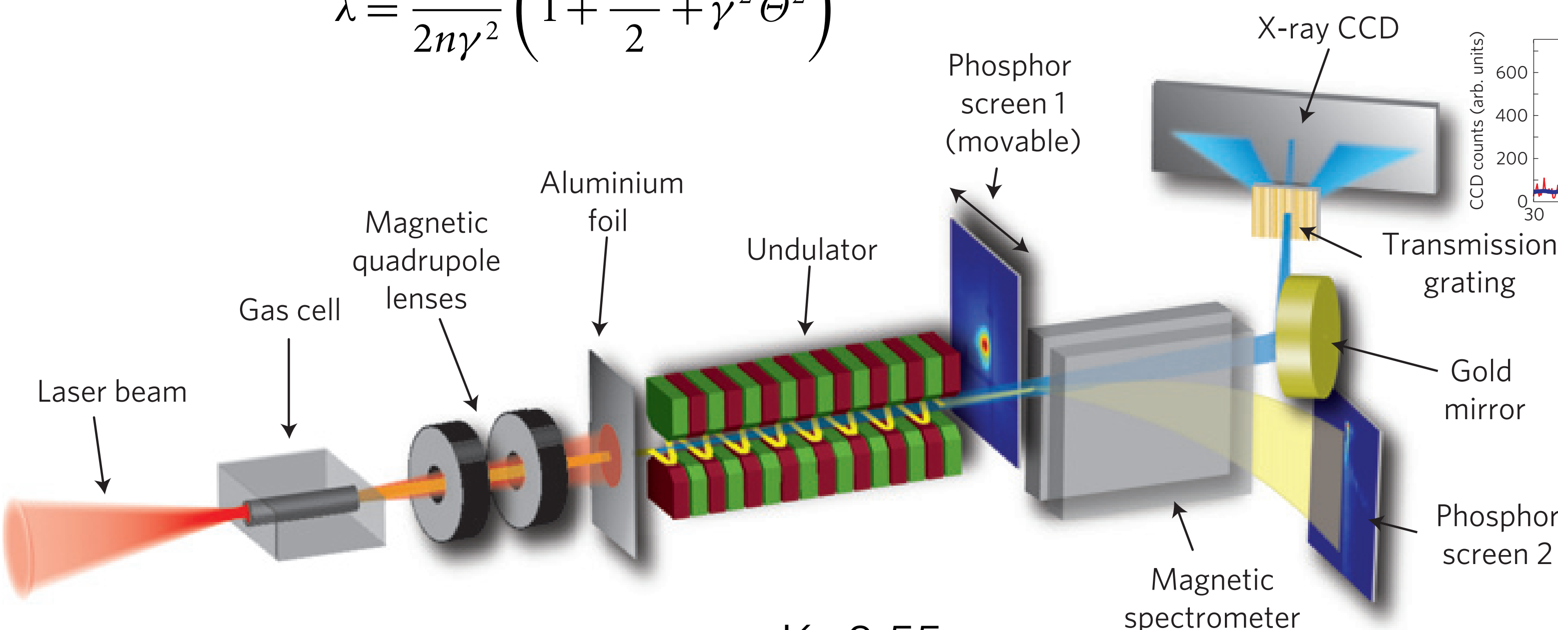
LETTERS M. Fuchs *et al.* nature physics
PUBLISHED ONLINE: 27 SEPTEMBER 2009 | DOI: 10.1038/NPHYS1404



Measure first and second harmonic

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\Theta^2\right)$$

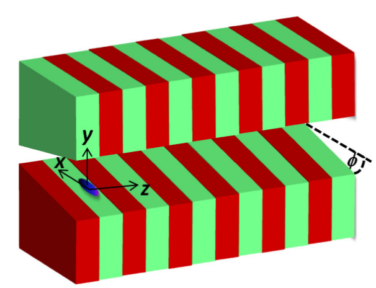




$n_p = 8\text{x}10^{18}$ 10pC, 210MeV K=0.55 λ_u=5mm

Z. Huang *et* al.
PRL 109, 204801 (2012)

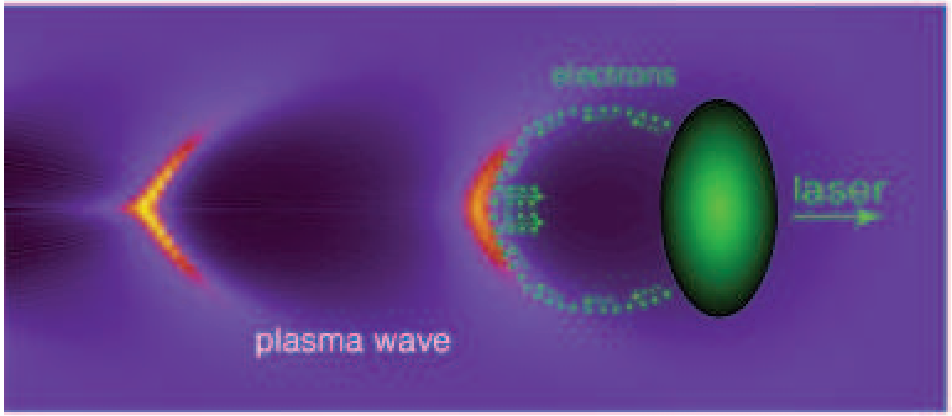
FELs may require novel configurations such as TGU



Controlled Injection for Better Beam Quality & Stability

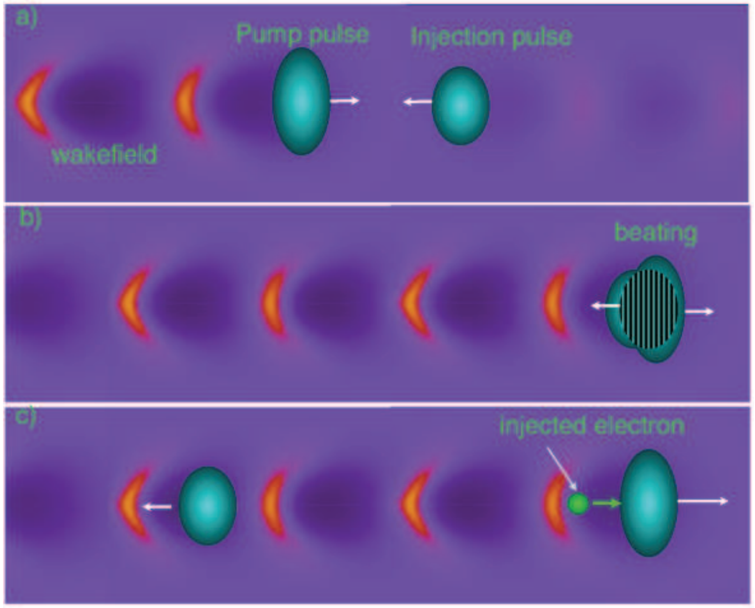
Standard Injection

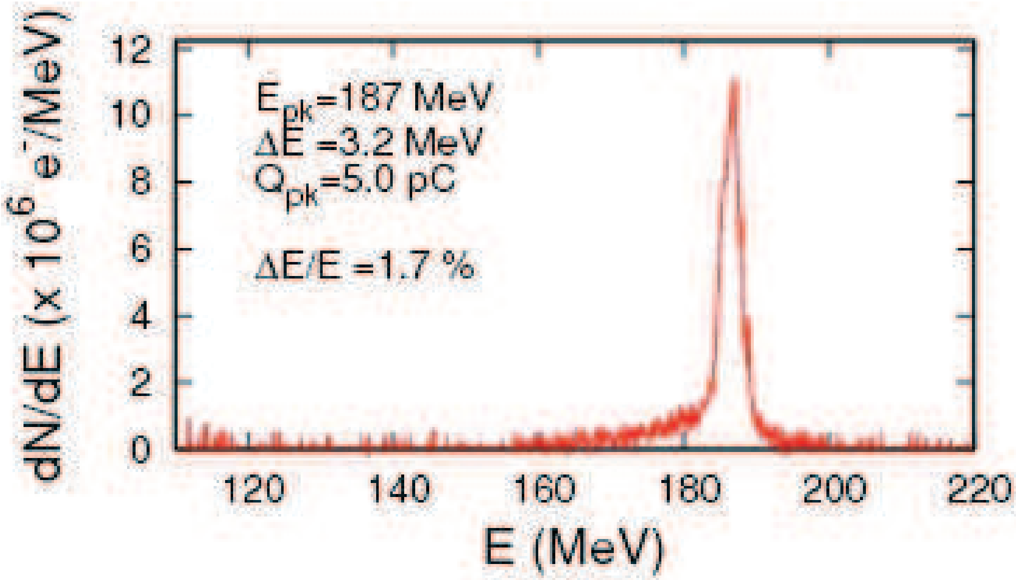
- Electrons circulate around the cavitated region before being trapped and accelerated at the back of the laser pulse



Colliding Pulse Injection

- Beatwave of two counter propagating laser pulses
- Controls injection process/location for higher quality/stability





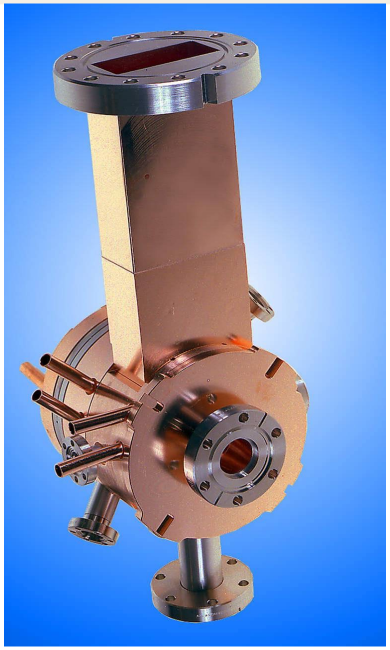
See: Esarey et al, PhysRevLett.79.2682 and Victor Malka (2010). Laser Plasma Accelerators: towards High Quality Electron Beam, Laser Pulse Phenomena and Applications, Dr. F. J. Duarte (Ed.), ISBN: 978-953-307-405-4 and References within

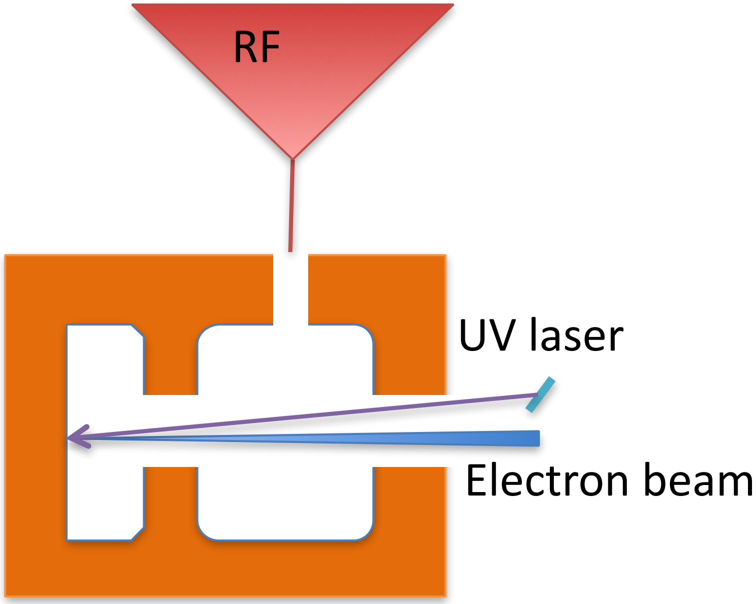
Development of High-Brightness Electron Sources

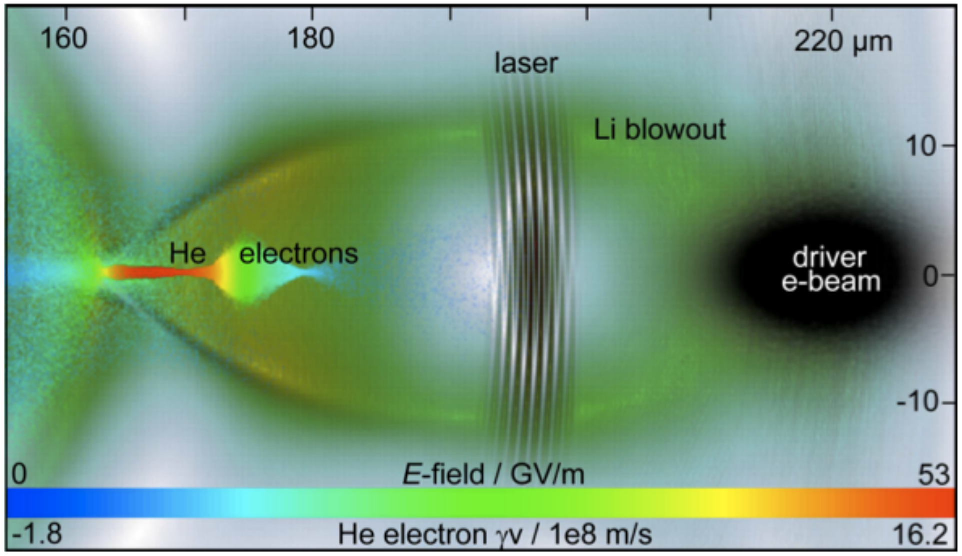
SLAC

LCLS Style Photoinjector

- 100MeV/m field on cathode
- Laser triggered release
- ps beams - multi-stage compressions & acceleration
  - Tricky to maintain beam quality (CSR, microbunching…)





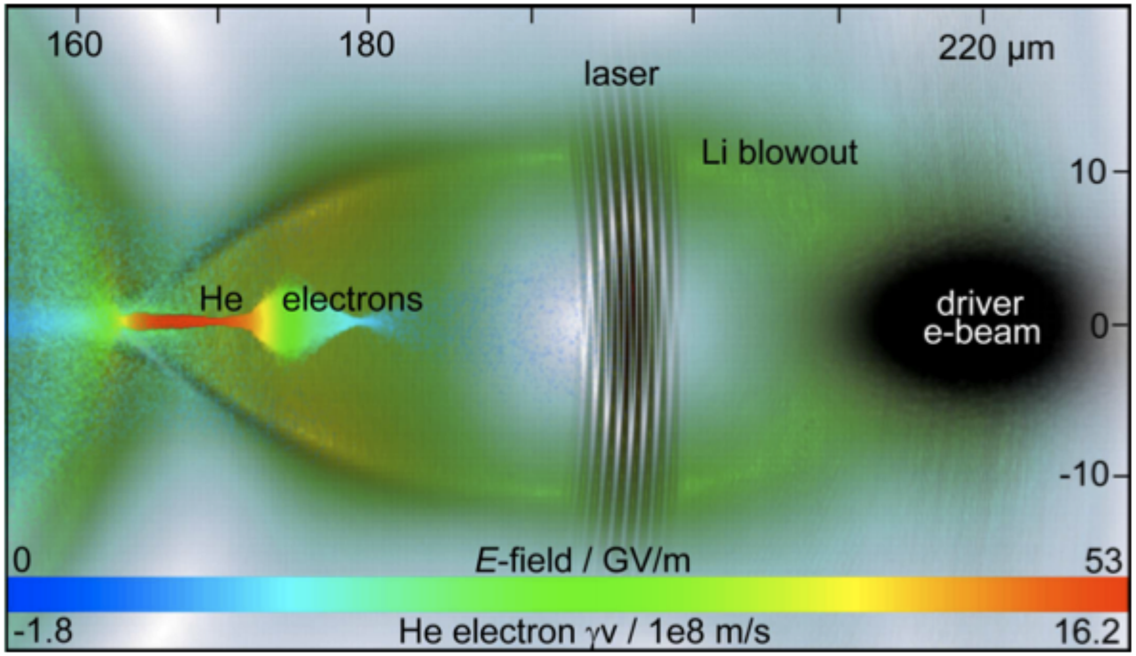


Plasma Photoinjectors

- 100 GeV/m
- fs beams, µm size
- Promise orders of magnitude improvement in emittance
- Injection from: TH, Ionization, DDR, CP…

Underdense Plasma Photocathode a.k.a. the 'Trojan Horse Technique'

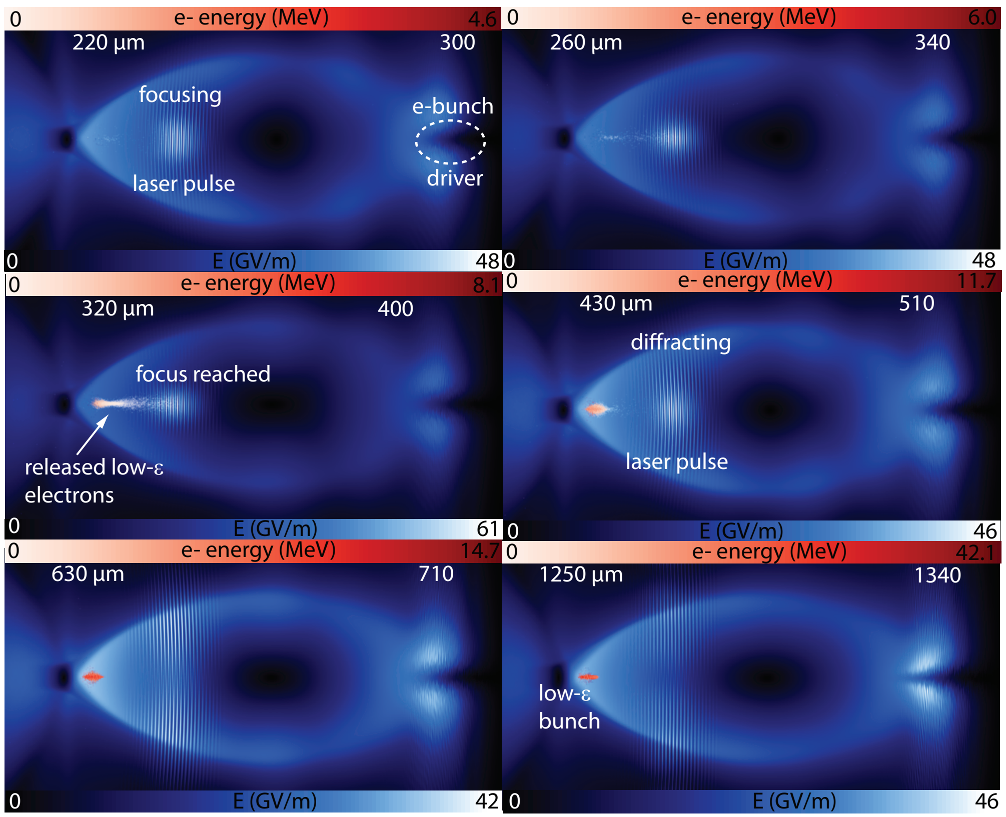
- Plasma bubble (wake) can act as a high-frequency, high-field, high-brightness electron source
- Photoinjector + 100GeV/m fields in the plasma = Ultra-high brightness beams
  - Unprecedented emittance (10^{-8} m-rad)
  - Sub-μm spot size
  - fs pulses
- Two gas species with relatively high & low ionization potential
- Electron beam forms plasma in LIT gas and drives strong wakefield (bubble)
- Injection laser (short pulse, tight focus, fs synchronization) releases HIT electrons in the bubble

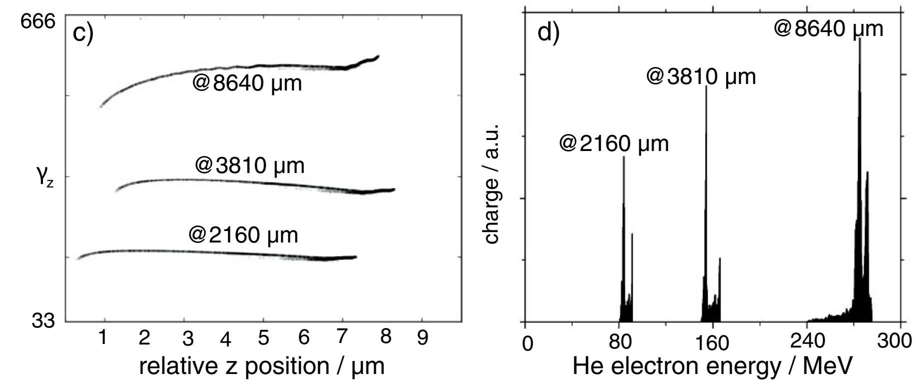


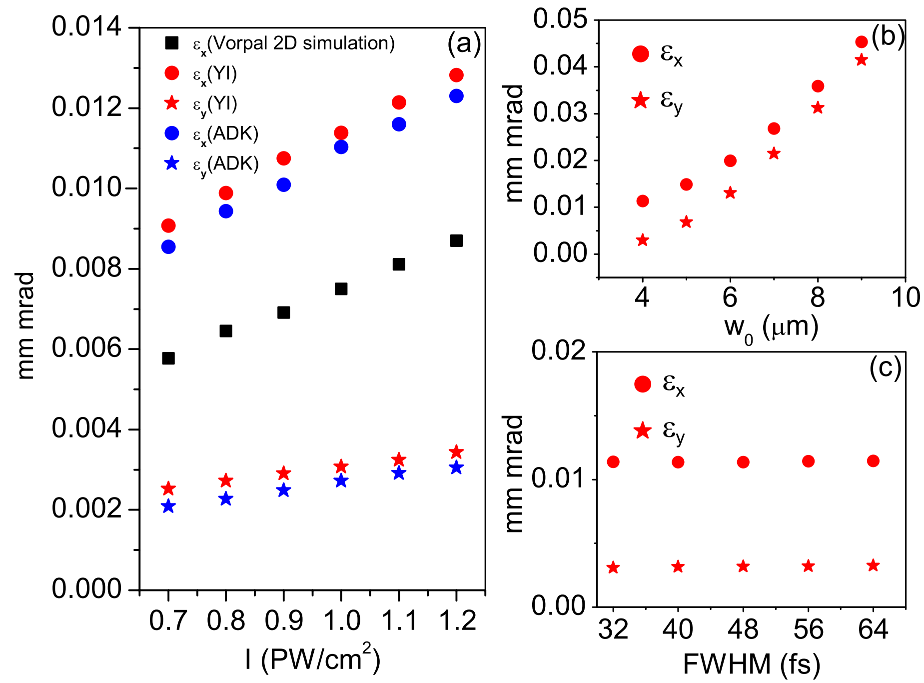
B. Hidding *et al*. Phys. Rev. Lett. 108, 035001 (2012)

Trojan Horse Injection Promises Very Bright Beams

- Parametrically studied in simulations
- E210 collaboration conducting first experiments at FACET







Hybrid Modelling of relativistic underdense plasma photocathode injectors, Y. Xi et al., PRSTAB 2013

Framework for Preserving Emittance After the Plasma

SLAC

Exact phase space matching for staging plasma and traditional accelerator components using longitudinally tailored plasma profiles

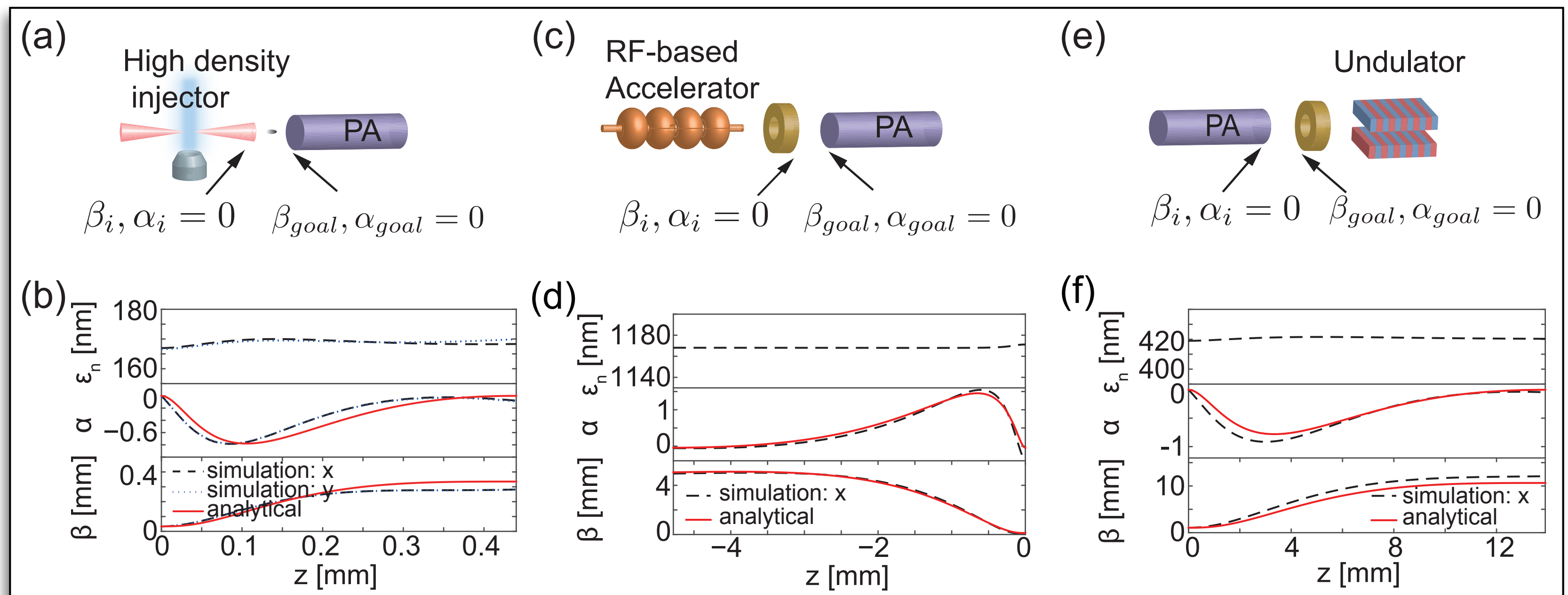
X. L. Xu,[1,2] Y. P. Wu,[1] C. J. Zhang,[1] F. Li,[1] Y. Wan,[1] J. F. Hua,[1] C.-H. Pai,[1] W. Lu,[1,*] W. An,[2] P. Yu,[2] W. B. Mori,[2] M. J. Hogan,[3] and C. Joshi[2]

[1] *Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
[2] *University of California, Los Angeles, California 90095, USA*
[3] *SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*

(Dated: August 21, 2015)

http://arxiv.org/pdf/1411.4386v2

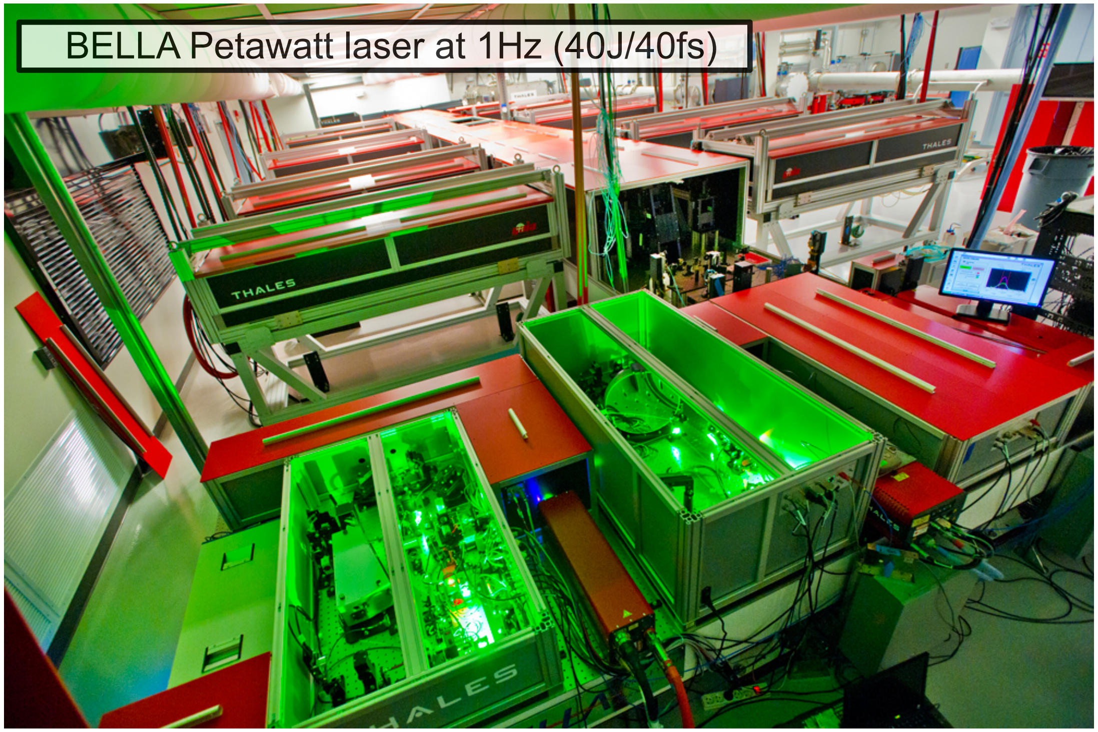
- Match beams with finite energy spread in & out of plasma stages
- Tailored plasma ramps using phase mask & axilens on ionization laser



Want Rep Rate but Want to Limit Size of the Power Source

Now have high energy, higher brightness, but users want rep-rate (they want it all!)

- Beam drivers are great here
- Can make linacs with high efficiency, MHz rep rate like LCLS-II so I'll use this as my power source
- But want to maximize energy boost so accelerator is small

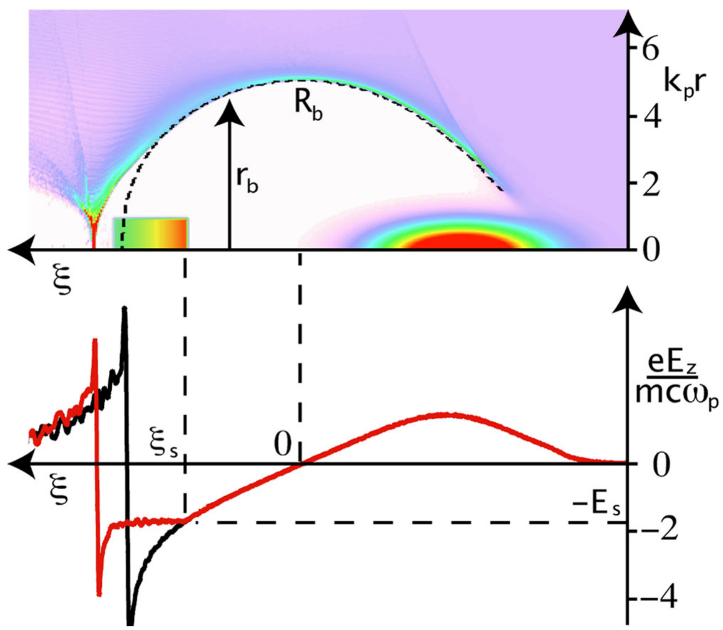


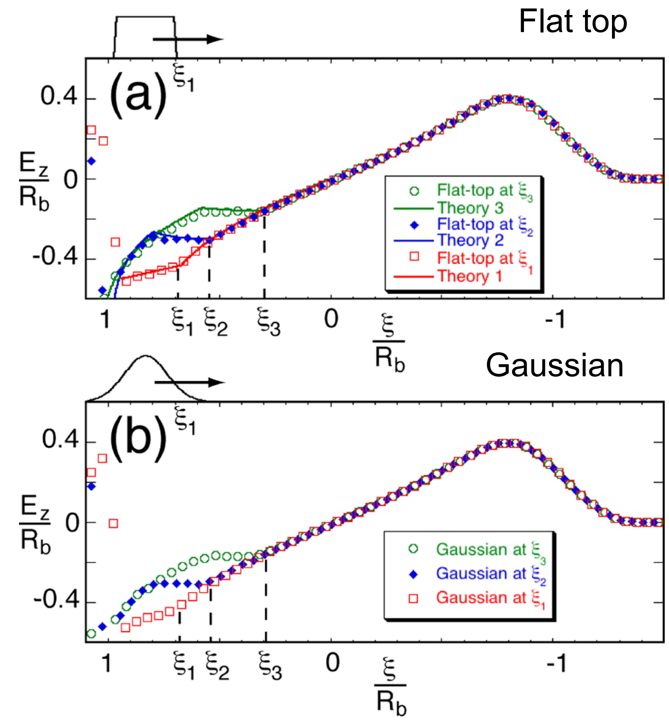
Beam Loading in Non-linear Wakes

Theoretical framework, augmented by simulations

Quasi-static approximation, co-moving frame at v=c, by symmetry find E_{phi}, B_z, B_r = 0 and:

$$E_z = -\frac{1}{c\epsilon_0}\int_r^\infty dr\, j_r$$





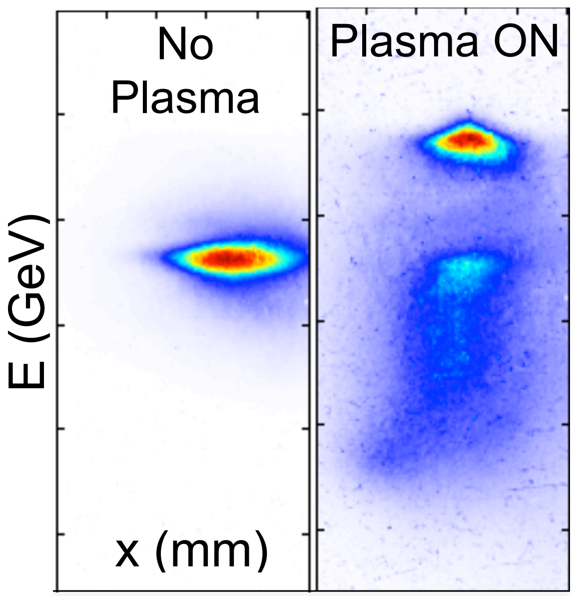
- Possible to nearly flatten accelerating wake – even with Gaussian beams
- Gaussian beams provide a path towards $\Delta E/E \sim 10^{-2} - 10^{-3}$
- Applications requiring narrower energy spread, higher efficiency or larger transformer ratio → Shaped Bunches

$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

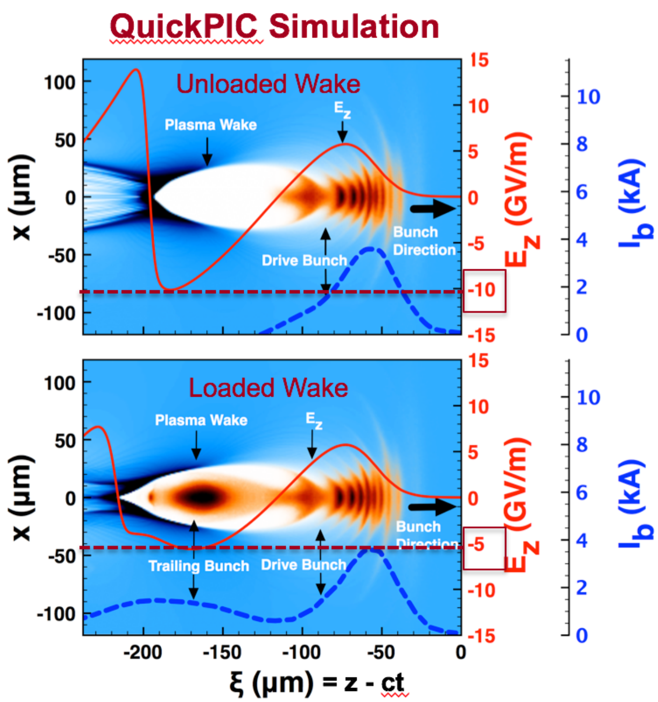
*See: M. Tzoufras et al, Phys. Plasmas **16**, 056705 (2009); M. Tzoufras et al, Phys. Rev. Lett. **101**, 145002 (2008) and References therein*

High-Efficiency Acceleration of an Electron Bunch in a Plasma Wakefield Accelerator

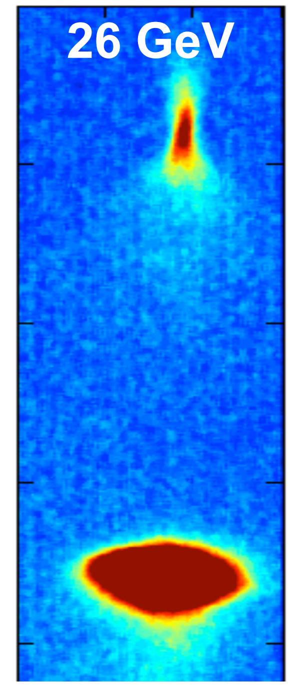
- Inject two beams into the plasma
  - One drives the wake, one samples the wake
- Beam loading is key for:
  - Narrow energy spread & high efficiency



2 GeV Energy Gain
~2% dE/E
~30% efficiency

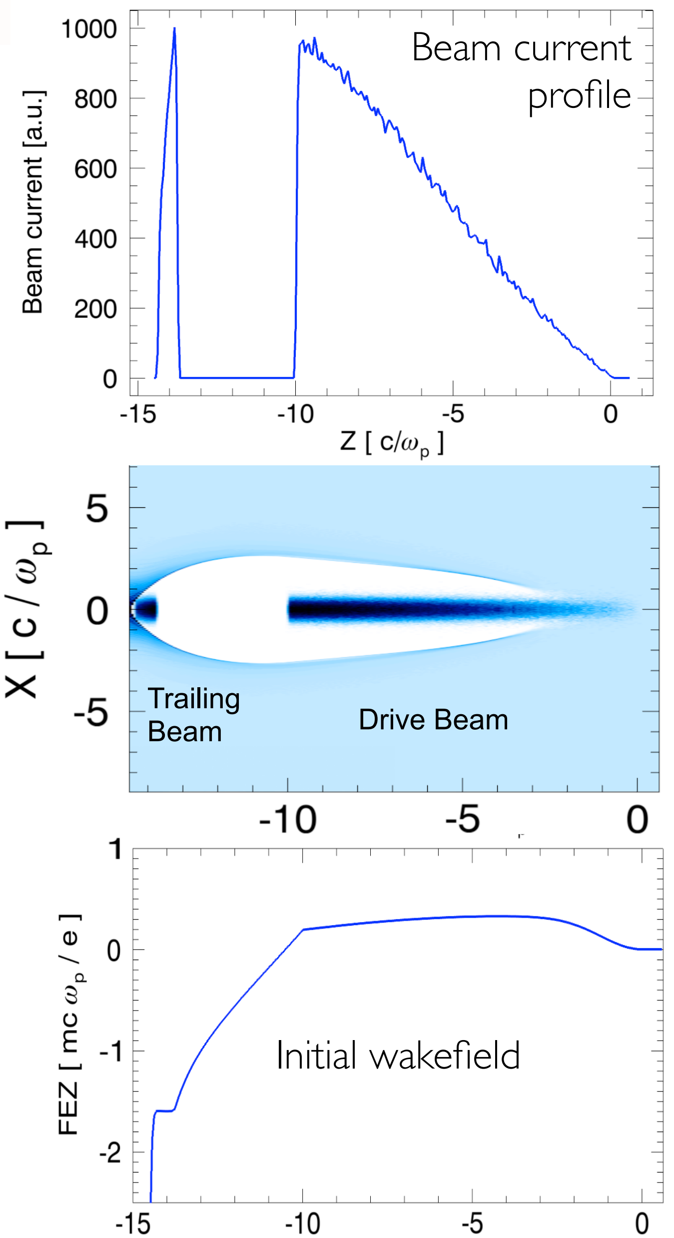


Nature ***515****, 92-95*
(November 2014)



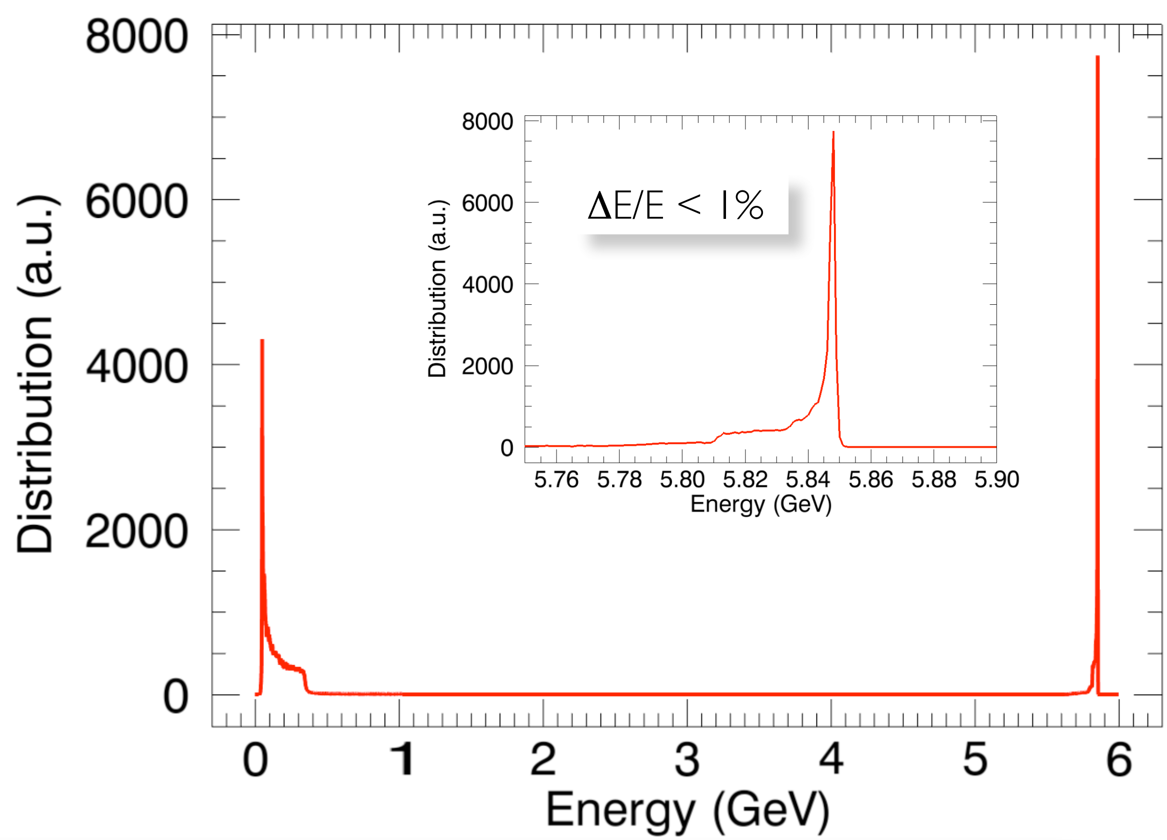
Single shot
6 GeV
Energy Gain

Looking Ahead: Shaped Profile for Transformer Ratio ~ 5



Shaped bunches have many benefits:

- Reduced energy spread
- Maximizes energy boost from a single stage
- Different source & emittance for drive/witness



see W. Lu et al "High Transformer Ratio PWFA for Application on XFELs", PAC2009 Proceedings

Need Undulators to Make Photons (X-rays)

SLAC

PRL **109,** 204801 (2012) PHYSICAL REVIEW LETTERS week ending 16 NOVEMBER 2012

Compact X-ray Free-Electron Laser from a Laser-Plasma Accelerator Using a Transverse-Gradient Undulator

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[2]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Received 13 July 2012; published 12 November 2012)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13,** 070702 (2010)

Short period, high field cryogenic undulator for extreme performance x-ray free electron lasers

F. H. O'Shea,[1,*] G. Marcus,[1] J. B. Rosenzweig,[1,†] M. Scheer,[2] J. Bahrdt,[2] R. Weingartner,[3] A. Gaupp,[2] and F. Grüner[3]
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[3]*Department of Physics, Ludwig-Maximilians-Universität, 85748 Garching, Germany*
(Received 9 March 2010; published 13 July 2010)

Plasma Based Undulators Are Also Being Considered…

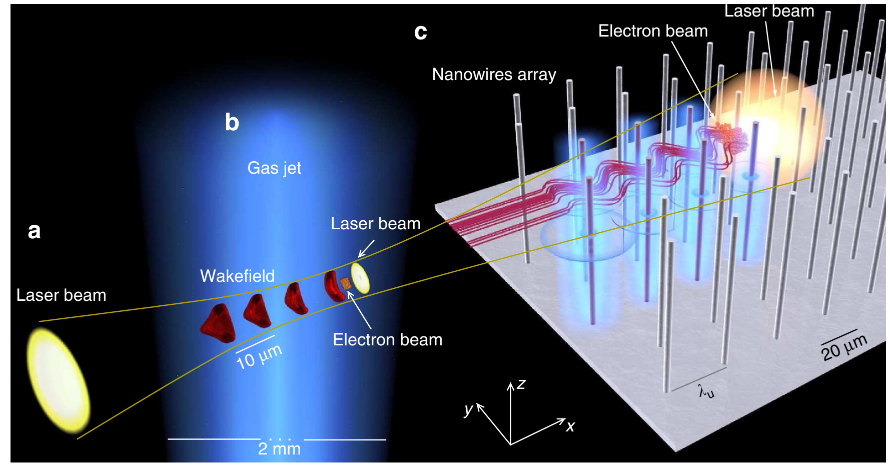
An ultracompact X-ray source based on a laser-plasma undulator

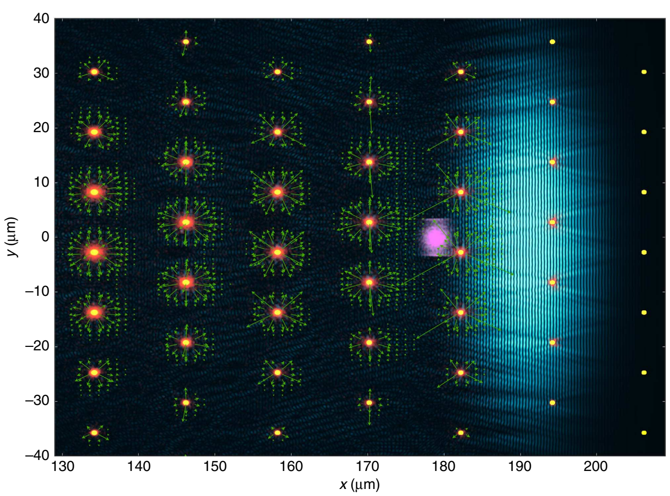
I.A. Andriyash, R. Lehe, A. Lifschitz, C. Thaury, J.-M. Rax, K. Krushelnick & V. Malka

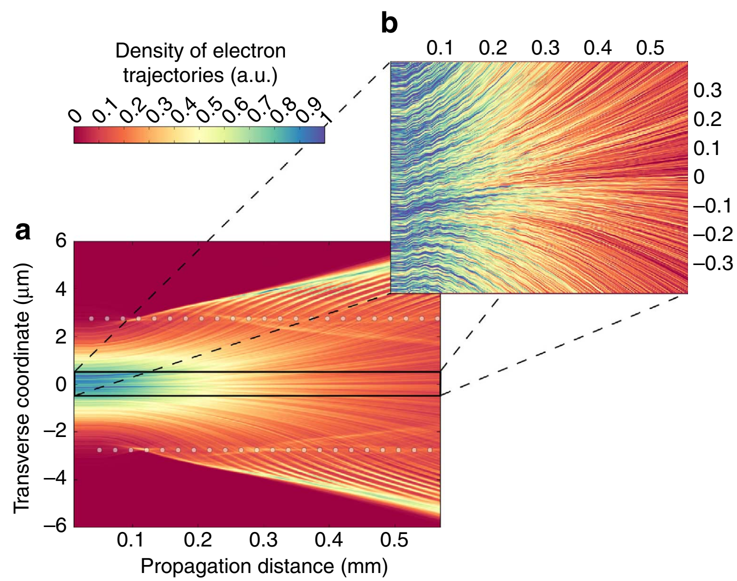
Affiliations | Contributions | Corresponding authors

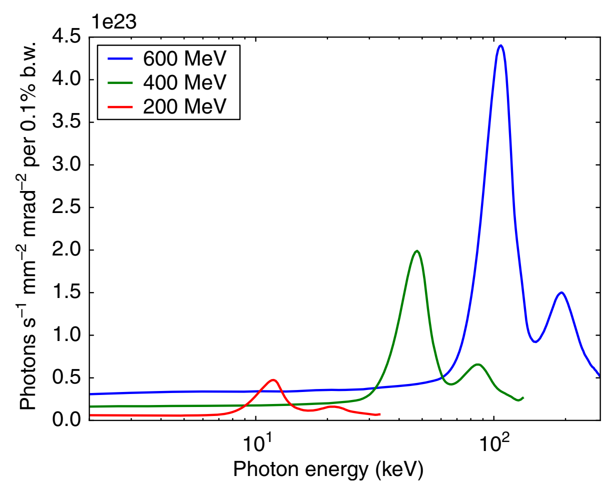
Nature Communications **5**, Article number: 4736 | doi:10.1038/ncomms5736

Received 12 March 2014 | Accepted 18 July 2014 | Published 22 August 2014



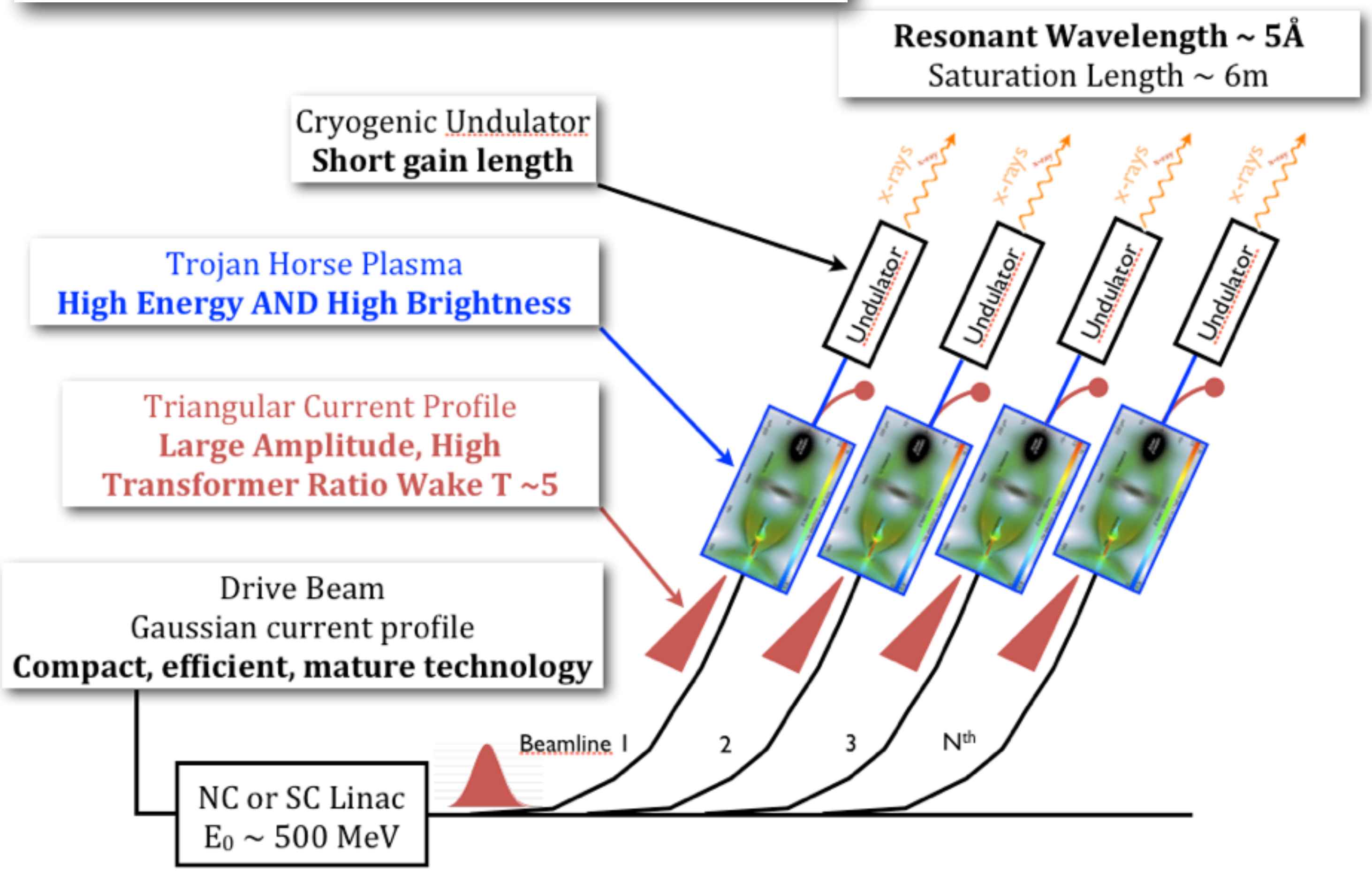






Put These Pieces Together and Imagine a New Generation of Light Sources

Plasma Based FEL Concept



Drive Beam	
Charge	3nC
Energy	500 MeV
Rep Rate	1MHz
Bunch length	210µm, ramped
Peak Current	8.5kA
Normalized Emittance	2.25 mm-mrad
Trojan Horse (plasma)	
Plasma Density	10^{17} e^-/cc
Plasma Length	20 cm
Transformer Ratio	5
Trojan Horse (beam)	
Charge	3 pC
Energy	2.5 GeV
Energy Spread	2×10^{-4}
Normalized Emittance	3×10^{-8} m-rad
Peak Current	300A
Bunch length	12 fs
Brightness	7×10^{17} A/m^2rad^2
Undulator Parameters	
Period	9 mm
K	2
Number of periods (N)	660
Radiation Parameters	
Wavelength	5.4 Å
Single pulse energy	50 µJ
Number of Photons	$>10^{11}$
Peak Power	1.6 GW

Leverage high rep-rate beam drivers with plasma as source of high-brightness high-energy electrons

Summary & Perspective

SLAC

Plasma accelerators offer a compelling chance to create GeV beams with unprecedented brightness and may open the door to a new generation of more compact higher-performing XFELs

- Plasma accelerators are already making GeV beams with brightness comparable to what is used by existing XFELs
  - Stability, reliability won't get you the cover of Nature but they are crucial to a user facility so likely developed close to one (physics & engineering)
- Many groups around the world are studying many techniques for plasma injection (trojan horse, ionization, density down ramp, colliding pulse…)
  - *Potential* for more than an order of magnitude improvement in beam brightness
  - Need to demonstrate these concepts in experiments – have to make *and* to measure these low emittance beams
  - Need to understand tolerances and optimize numerically
- FACET-II Science Opportunities Workshop on Plasma Driven XFELs Thursday October 15, 2015

Thank you to all my colleagues whose collaborations and discussions have contributed material for this talk!

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FACET-II Science Opportunities Workshops

- October 12-16, 2015 @ SLAC
  - Five Days
  - Five Workshops (one per day)
- Dual WG Leaders
  - SLAC & non-SLAC

October 12-16, 2015	Workshop
Monday	Accelerator Physics of Extreme Beams
Tuesday	Material Interactions with Extreme Fields
Wednesday	Plasma Acceleration Based Linear Colliders
Thursday	Plasma Acceleration Based XFELs
Friday	Application of Compton Based Gamma Rays

FACET-II Science Opportunities Workshops
October 12-16, 2015
SLAC National Accelerator Laboratory
Menlo Park, CA

FACET-II is a new user facility that will provide unique capabilities to develop advanced acceleration and coherent radiation techniques with high-energy electron and positron beams. FACET-II provides a major upgrade over current FACET capabilities and the breadth of the potential research program will make it truly unique.

A baseline design for FACET-II has been established that progressively increases capabilities in three distinct stages. Stage one completes a new photoinjector at Sector 10 and re-establishes operations with high-energy high-brightness electron beams. Stage two will add a new positron damping ring system and allow user runs with high-current positron beams. Stage three will upgrade the chicane in sector 20 for simultaneous delivery of positrons and electrons to the experimental area.

By offering bunch charge ranging from pC to nC, emittance from nm to microns, electrons and positrons, single and double bunches, tailored current profiles of up to nearly 100kA and energy up to 10GeV FACET-II provides experimental capabilities unparalleled anywhere in the world. By leveraging the additional infrastructure afforded by SLAC's laser group, the FACET laser systems provide multi-terawatt peak powers with state of the art synchronization approaching 10fs.

The FACET-II team is organizing a series of five separate one day-long workshops to discuss the scientific opportunities of this new facility, and refine the technical requirements to ensure maximum impact during early operations and into the future. Each of the workshops will focus on a different scientific topic: plasma acceleration based colliders, plasma driven X-FELs, accelerator physics of extreme beams, Material interactions with extreme fields and Application of Compton based gamma-rays.

The results of these workshops will feed directly in to the science strategy for FACET-II, and will help guide the design, commissioning and ultimate operation of the upgraded facility, as well as informing the R&D roadmap for instrumentation and machine performance.

We encourage everyone interested in applying FACET-II to his or her scientific problems to attend. Separate registration is required for each of the five workshops. For more information and to register please click on the individual workshop links above.

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