Advanced and Novel Accelerators
for High Energy Physics Research (ANAR),
CERN, April 25-28, 2017

Overview of LWFA science

Mike Downer
University of Texas at Austin

"...speaker should provide a broad introduction of the domain, indicating the **status of the field**, in particular current performance in **electron bunch properties**, **existing projects worldwide** and **current challenges**.

1) **Current status of LWFA electron bunch properties**
2) **Selective survey of major experimental LWFA projects world-wide**
3) **Current LWFA challenges**

Published LWFA reviews:
Esarey *et al*., "Physics of laser-driven plasma-based electron accelerators," *Rev. Mod. Phys*. **81**, 1229 (2009)
Leemans & Esarey, "Laser-driven plasma-wave electron accelerators," *Physics Today* **62**, 44 (2009)

... but a lot has happened since 2009!

Current Status of LWFA Electron Bunch Properties

Property	State of Art*	Reference	Remarks
Energy	**2 GeV** (± 5%, 0.1 nC) **3 GeV** (±15%, ~0.05 nC) **4 GeV** (±5%, 0.006 nC)	Wang (2013) - Texas Kim (2013) – GIST Leemans (2014) - LBNL	Accelerates from E ≈ 0
Energy Spread	**1%** (@ .01 nC, 0.2 GeV) **5-10%**	Rechatin (2009a) – LOA more typical, many results	0.1% desirable for FELs & colliders
Normalized Trans-verse emittance	**~ 0.1 π mm-mrad**	Geddes (2008) - LBNL Brunetti (2010) - Strathclyde Plateau (2012) - LBNL	Measurements at resolution limit
Bunch Duration	**~ few fs**	Kaluza (2010) – Jena (**Faraday**) Lundh (2011) – LOA; Heigoldt (2015) – MPQ/Oxford (**OTR**) Zhang (2016) – Tsinghua	Measurements at resolution limit
Charge	**0.02 nC** @ 0.19 GeV ±5% **0.5 nC** @ 0.25 GeV ±14%	Rechatin (2009b) – LOA Couperus (2017) - HZDR	Beam-loading achieved. FOM: **Q/ΔE** ?
Repetition Rate & Repeatability	~ **1 Hz** @ > 1 GeV **1 kHz** @ ~ 1 MeV	Leemans (2014) - LBNL He – UMIch ('15); Salehi ('17) – UMd; Guénot ('17) -- LOA	Limited by lasers & gas targets

*** No one achieves all of these simultaneously!**

- Brunetti, *PRL* **105**, 215007 ('10)
- Couperus, *submitted* ('17)
- Geddes, *PRL* **100**, 215004 ('08)
- He, *Nat. Comms* **6**, 7156 (2015)
- Heigoldt, PR-STAB **18**, 121302 ('15)
- Kaluza, *PRL* **105**, 115002 ('10)
- Kim, *PRL* **111**, 165002 (2013)
- Leemans, *PRL* **113**, 245002 (2014)
- Lundh, *Nat. Phys*. **7**, 219 (2011)
- Rechatin, *PRL* **102**, 164801 (2009)
- Rechatin, *PRL* **103**, 194804 ('09b)
- Salehi, *Opt. Lettt.* **42**, 215 ('17)
- Wang, *Nat. Comms* **4**, 1988 (2013)
- Zhang, *PRST-AB* **19**, 062802 (2016)

Current Status of LWFA Positron Properties: no results yet

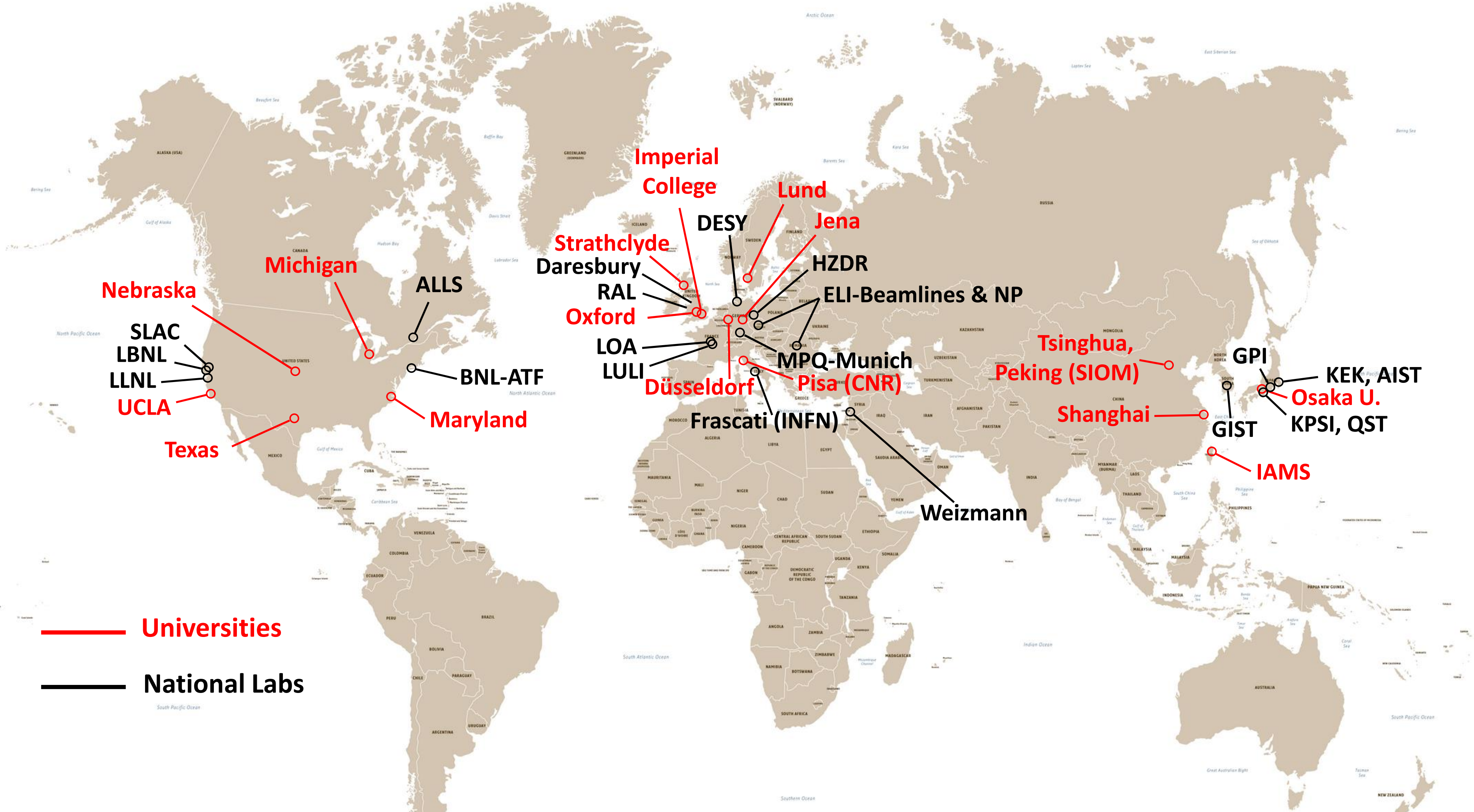
LWFA and PWFA/DWA/DLA: Comparisons & Contrasts*

Property	**LWFA**	**PWFA**	**DWA**	**DLA**
Stand-alone? (*i.e.* no RF accelerator)	YES	NO	NO	NO
Energy Gain Achieved	0 → 4.25 GeV	20 → 30 GeV 40 → 80 GeV	smaller	much smaller
Accelerating Gradient	~1 GeV/cm	~ 0.1 GeV/cm	smaller	smaller
Dephasing Limited?	YES	NO		YES
Positrons accelerated?	NOT YET	YES	NO	NO
Wall-plug efficiency	10^{-5} (@ 1GeV ± 10%) 10^{-7} (@ GeV ± 0.1%)			

* Intended to highlight areas where the approaches differ, not to promote one approach over another.

A sampling of existing LWFA experimental projects worldwide*

** Because of its stand-alone nature, LWFA research has proliferated in small laboratories world-wide, making a complete list of existing projects difficult to compile accurately. Apologies in advance for any omissions. This list is NOT comprehensive.*



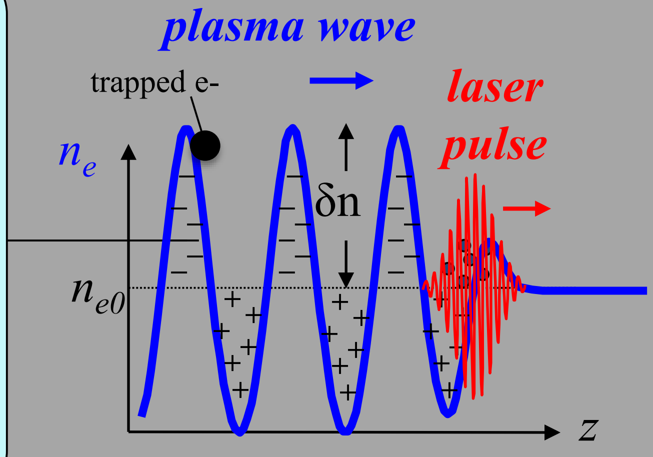
Selected examples from this list will comprise the bulk of the presentation.

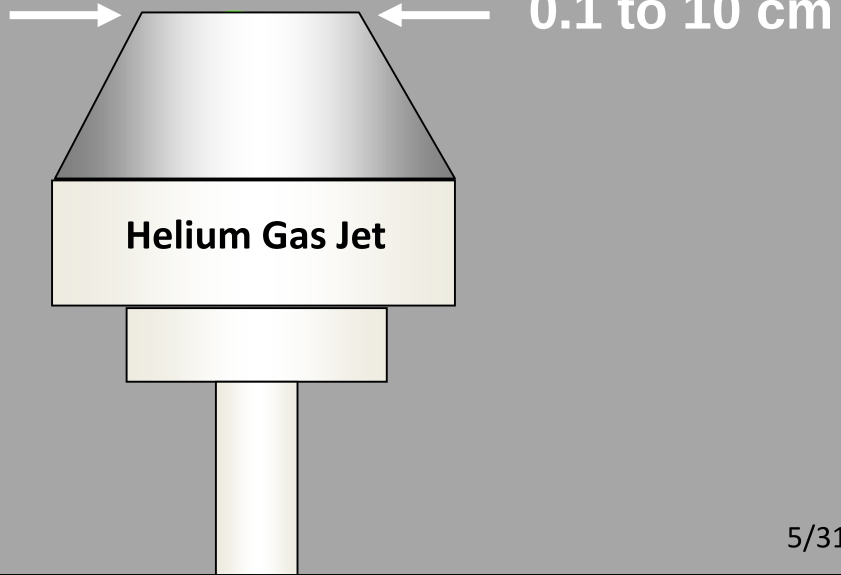
Electrons Surfing on a Laser-Driven Plasma Wave

Tajima & Dawson, Phys. Rev. Lett. ***43,*** *267 (1979)*

T

Dawson



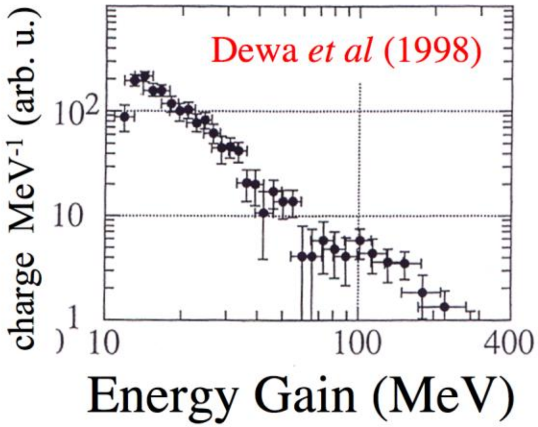


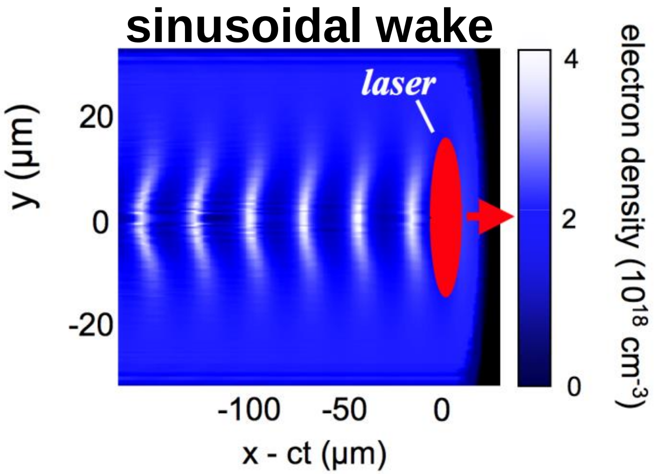
Today, most LPAs operate in the “bubble” regime…

Pukhov and Meyer-ter-Vehn, *Appl. Phys. B* **74**, 355 (2002)

Review: Esarey, *Rev. Mod. Phys*. **81**, 1229 (2009)

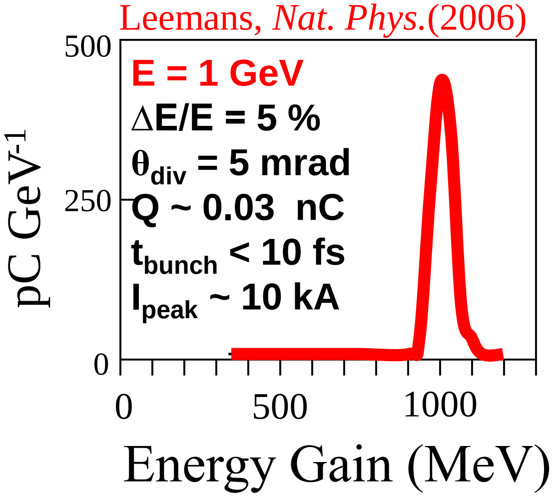
Before 2004:

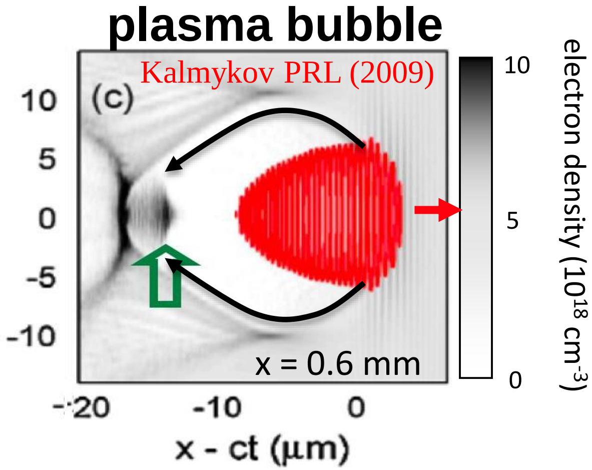




After 2004:

Geddes, *Nature* (2004)
Faure, *Nature* (2004)
Mangles, *Nature* (2004)





... because point-like injection enables quasi-monoenergetic acceleration

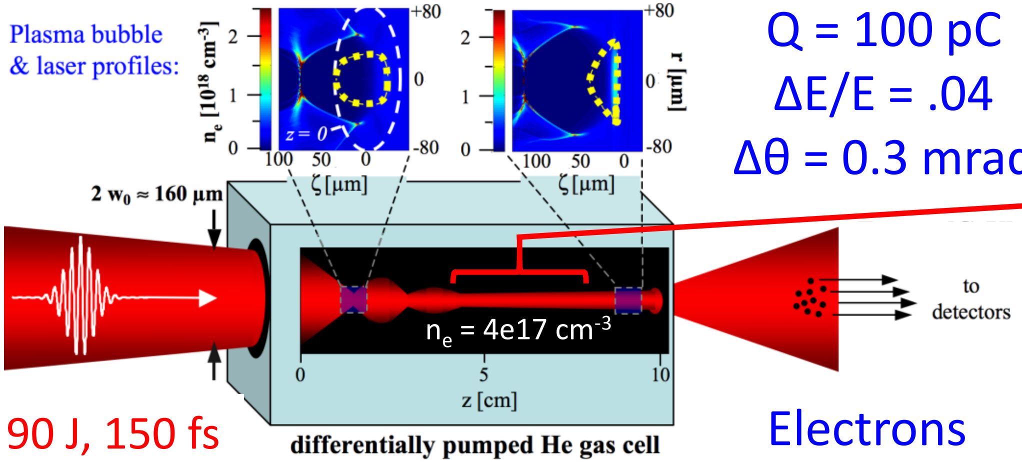
nature COMMUNICATIONS

2013

Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV

Xiaoming Wang[1], Rafal Zgadzaj[1], Neil Fazel[1], Zhengyan Li[1], S. A. Yi[1], Xi Zhang[1], Watson Henderson[1], Y.-Y. Chang[1], R. Korzekwa[1], H.-E. Tsai[1], C.-H. Pai[1], H. Quevedo[1], G. Dyer[1], E. Gaul[1], M. Martinez[1], A. C. Bernstein[1], T. Borger[1], M. Spinks[1], M. Donovan[1], V. Khudik[1], G. Shvets[1], T. Ditmire[1] & M. C. Downer[1]

Electron Energy [GeV]



90 J, 150 fs

Electrons

Q = 100 pC

$\Delta E/E = .04$

$\Delta\theta = 0.3$ mrad

Drive pulse self-guided via nonlinear laser-plasma interactions for L_{eff} ~3 cm

90 J (laser) → 0.2 J (e^-):

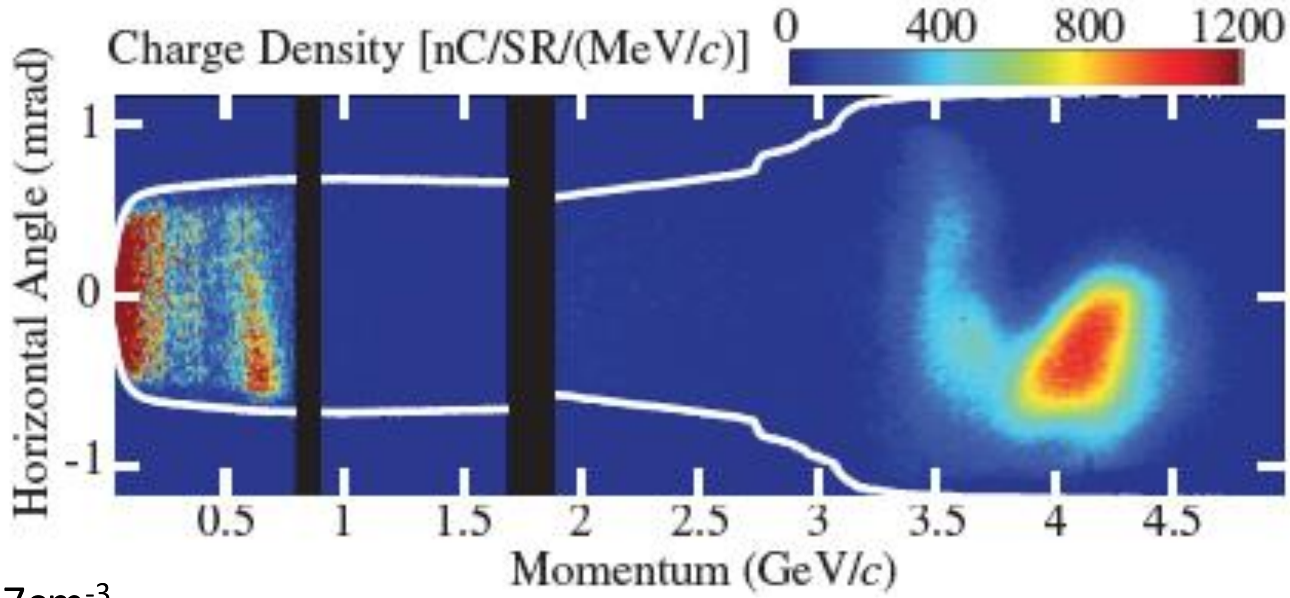
0.2% efficiency

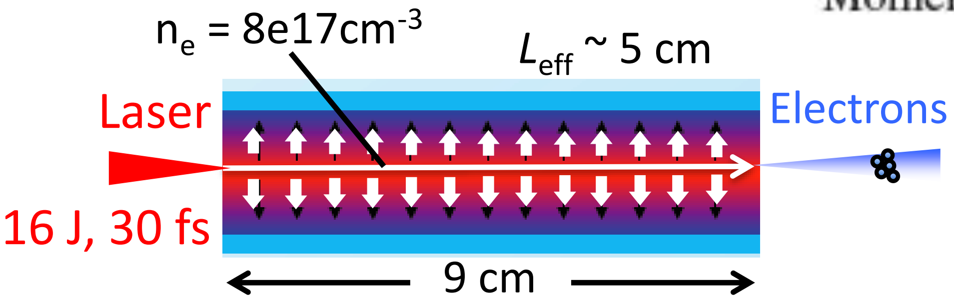
PRL 113, 245002 (2014) PHYSICAL REVIEW LETTERS

2014

Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime

W. P. Leemans,[1,2,*] A. J. Gonsalves,[1] H.-S. Mao,[1] K. Nakamura,[1] C. Benedetti,[1] C. B. Schroeder,[1] Cs. Tóth,[1] J. Daniels,[1] D. E. Mittelberger,[2,1] S. S. Bulanov,[2,1] J.-L. Vay,[1] C. G. R. Geddes,[1] and E. Esarey[1]
[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*





Q = 6 pC

ΔE/E = .06

Δθ = 0.3 mrad

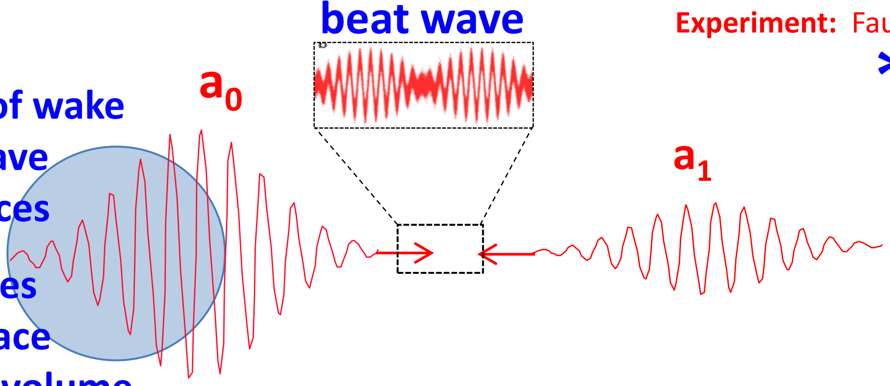
16 J (laser) → .024 J (e$^-$):

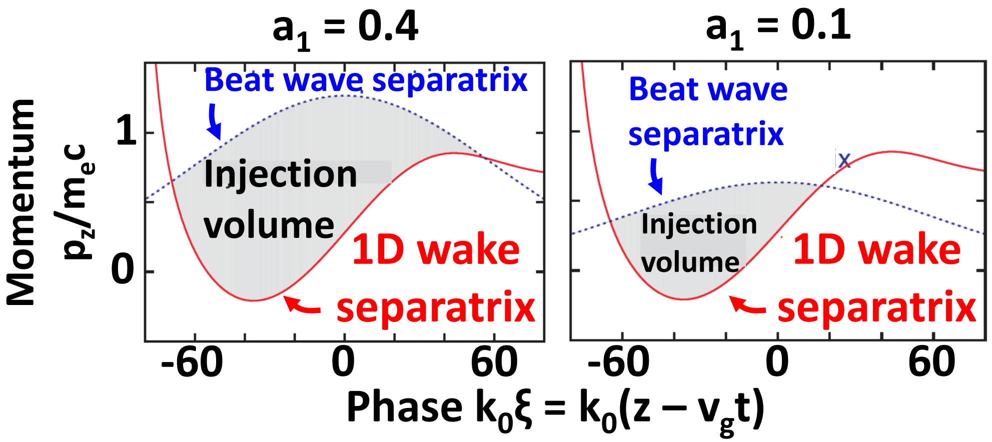
0.15% efficiency

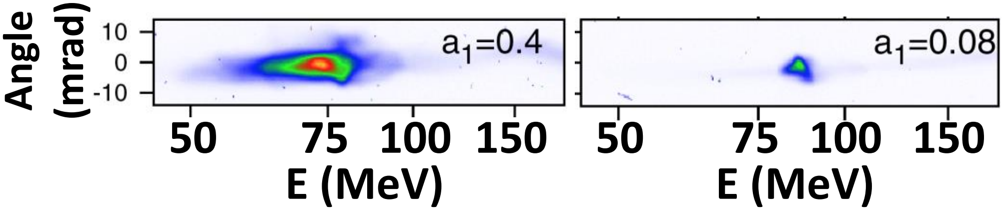
Energy spread as small as 1% has been achieved using precision injection techniques *

Theory: Esarey, *PRL* **79**, 2682 (1997); Fubiani, *Phys. Rev. E* **70**, 016402 (2004)
Experiment: Faure, *Nature* **444**, 737 (2006); Rechatin, *PRL* **102**, 164801 (2009)

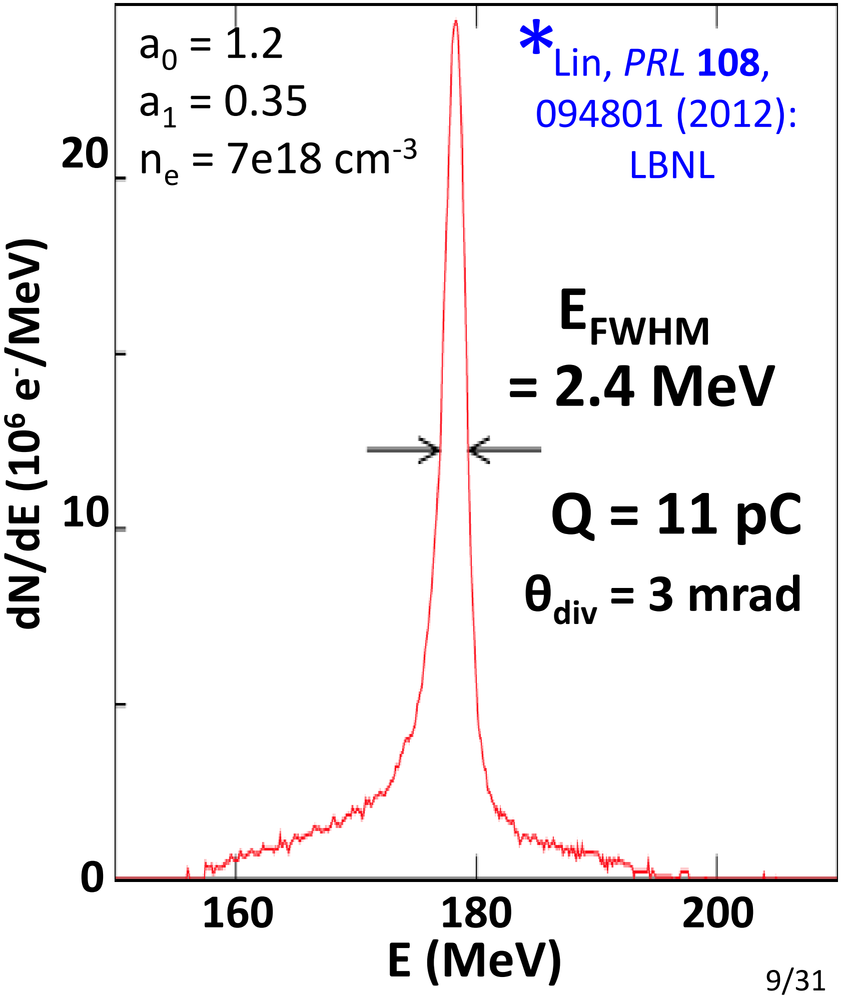
Overlap of wake & beatwave separatrices determines phase space injection volume







***LWFA "slice" energy spread can be < 1%**



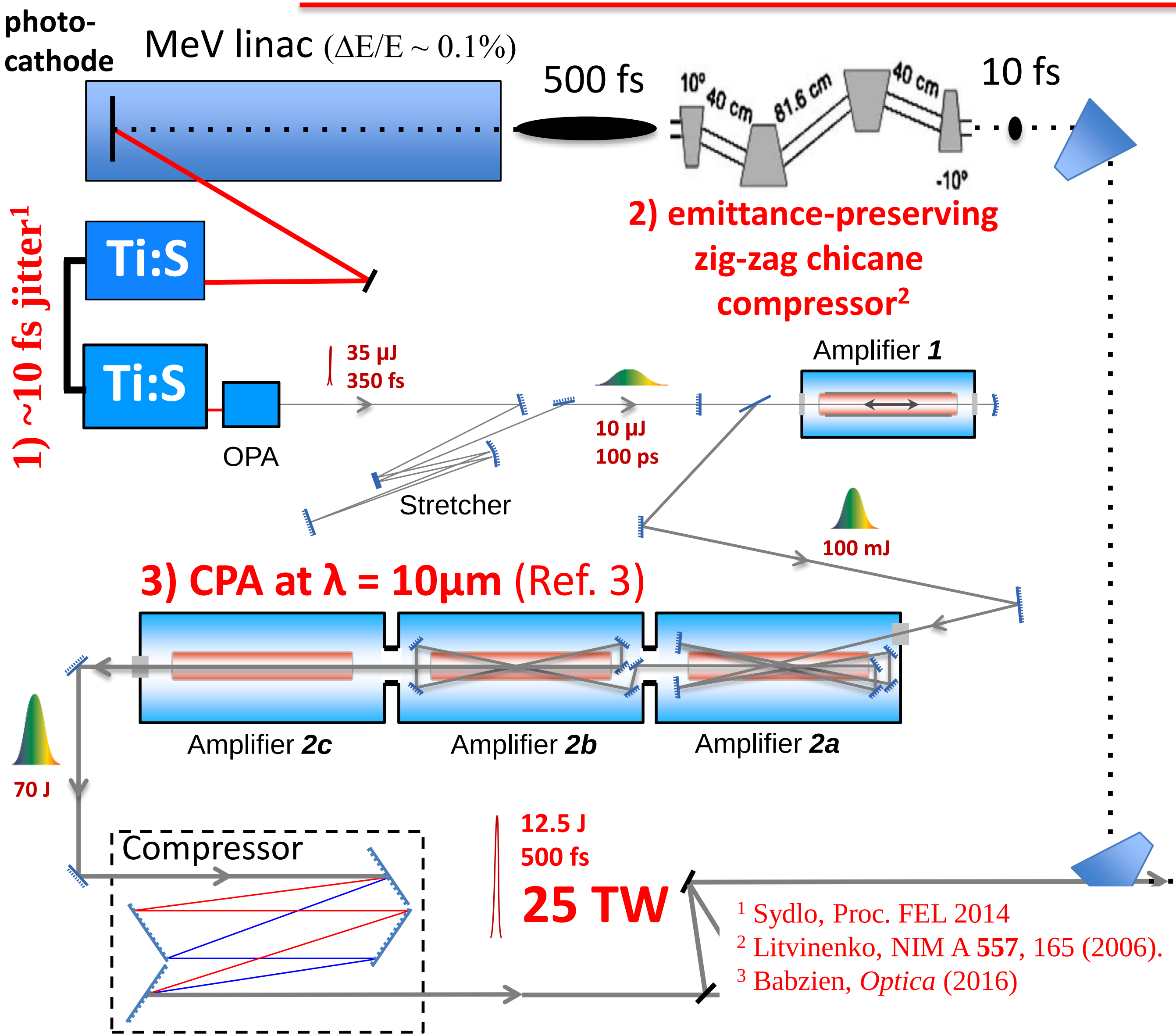
*Lin, *PRL* **108**, 094801 (2012): LBNL

E_{FWHM} = 2.4 MeV

Q = 11 pC

θ_{div} = 3 mrad

Multi-TW CO$_2$ lasers, due to large Iλ^2, drive huge bubbles in tenuous plasma, enabling injection of low ΔE/E beams



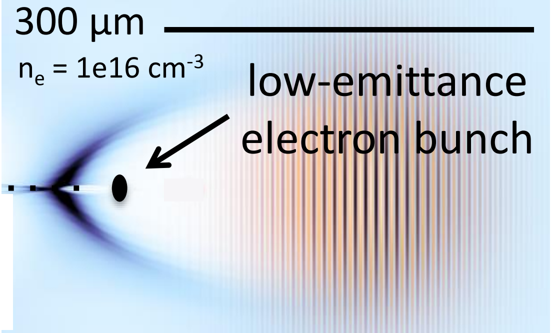
1) ~10 fs jitter[1]

2) emittance-preserving zig-zag chicane compressor[2]

3) CPA at λ = 10μm (Ref. 3)

CO$_2$ laser at BNL's Accelerator Test Facility

Large plasma bubbles
→ easy external injection,
→ high-resolution diagnostics



Bubble driven by 1μm, 25 TW laser in n_e = 1e19 cm^{-3} plasma:

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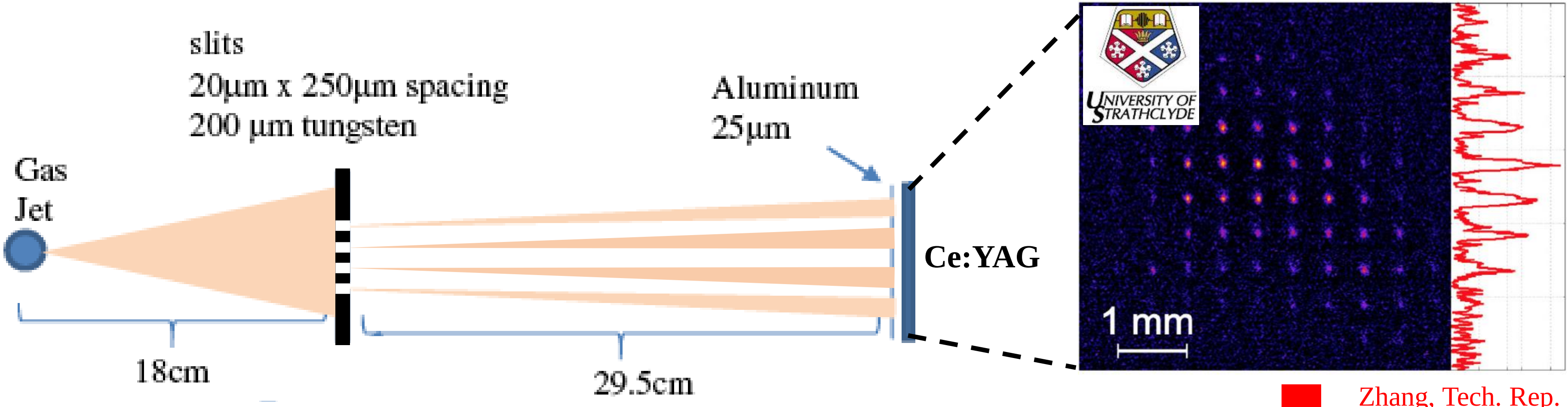
[1] Sydlo, Proc. FEL 2014
[2] Litvinenko, NIM A **557**, 165 (2006).
[3] Babzien, *Optica* (2016)

1. Energy E
2. Spread ΔE/E
3. Emittance ε_n
4. Bunch length σ_z

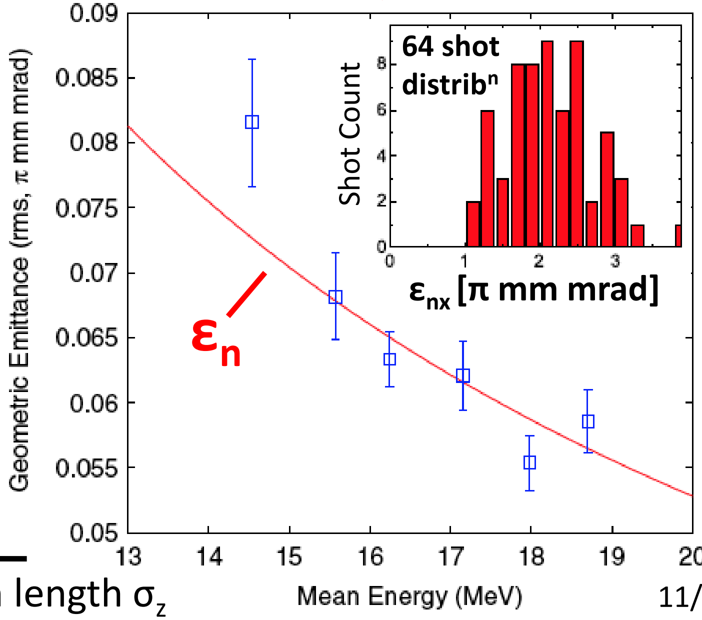
Early measurements of normalized transverse emittance ε_N of PA* electrons used the "pepper-pot" method

Fritzler, *PRL* **92**, 165006 (2004); Sears, *PR ST-AB* **13**, 092803 (2010); Brunetti, *PRL* **105**, 215007 (2010)

**plasma-accelerated*



Zhang, Tech. Rep. No. FERMILAB-TM-1988



Results showed $1 < \varepsilon_N < 3\pi$ mm-mrad, comparable with e-beams from conventional electron accelerators.

PROs

- single shot
- compact

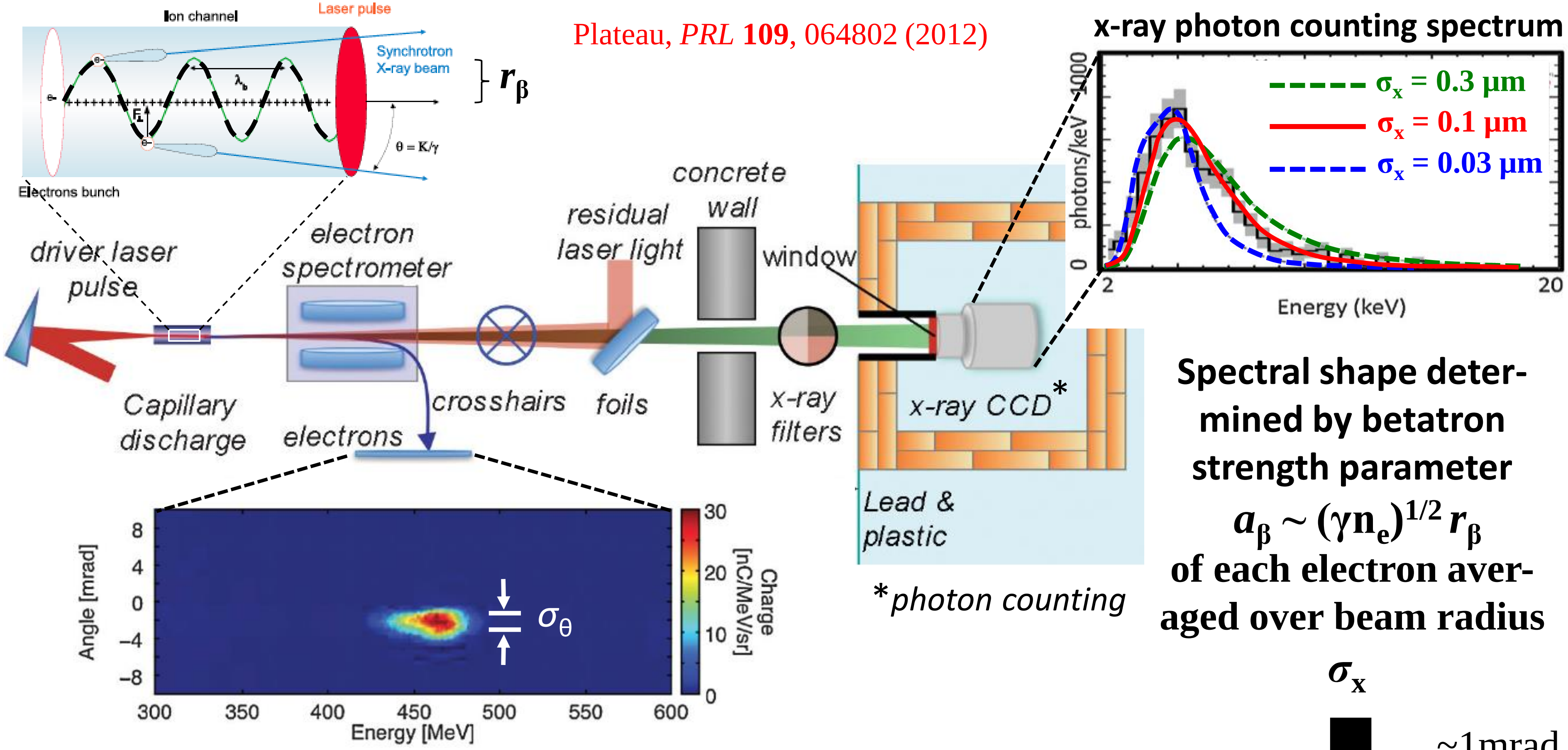
CONs

- invasive
- limited to e^- energy < 500 MeV;*
  (LPA measurements only up 125 MeV)
- resolution limit $\varepsilon_N \sim 1\pi$ mm-mrad

*Delerue, Proc. PAC-09

Betatron x-ray spectroscopy estimated $\varepsilon_n \sim 0.1\pi$ mm mrad for low-divergence, ~500 MeV PA e- beams

Plateau, *PRL* **109**, 064802 (2012)



Spectral shape determined by betatron strength parameter $a_\beta \sim (\gamma n_e)^{1/2} r_\beta$ of each electron averaged over beam radius σ_x

$$\varepsilon_n \approx \underset{\sim 1000}{\gamma}\,\underset{0.1\,\mu\mathrm{m}}{\sigma_x}\,\overset{\sim 1\,\mathrm{mrad}}{\sigma_\theta}$$

PRO

- single-shot
- non-invasive
- high ε_n resolution
- compatible with low GeV e-

CON

- relies on betatron modeling
- measures ε_n *inside* wake; could change outside
- only *estimates* ε_n using $\gamma\sigma_x\sigma_\theta$

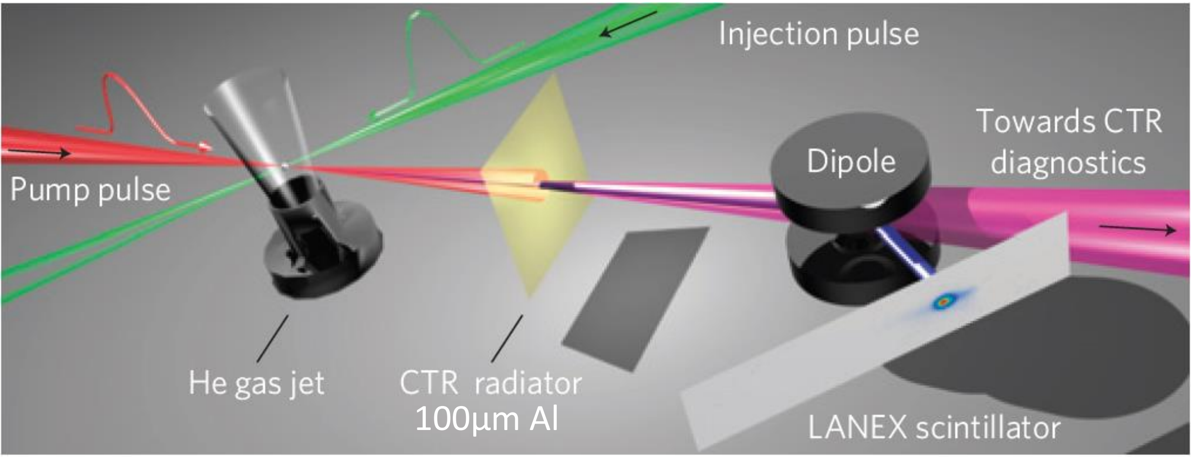
Plasma accelerators can produce electron bunches of few fs duration,* presenting a diagnostic challenge

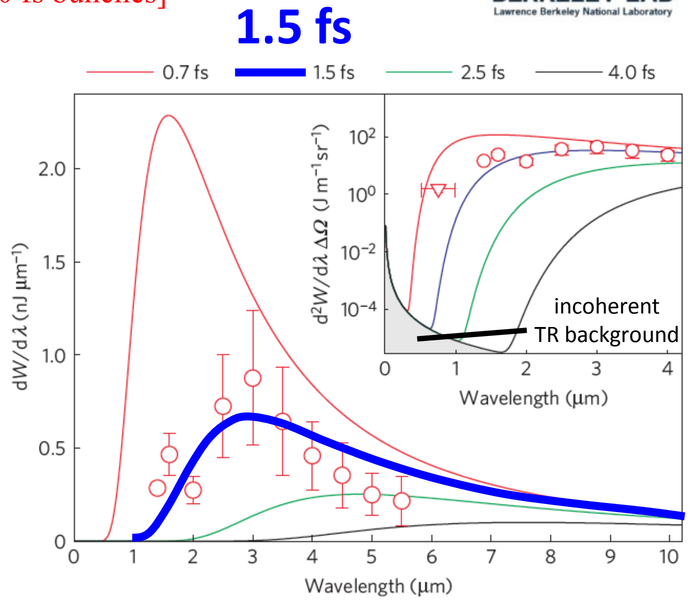
IR CTR results below: Lundh, *Nat. Phys.* **7**, 219 (2011) - LOA

* minimizes beam-strahlung, saves power

THz CTR: van Tilborg, *PRL* **96**, 014801 (2006); Debus, *PRL* **104**, 084802 (2010) [≥30 fs bunches]

Infrared Transition Radiation (TR) bunch length σ_z diagnostic





TR becomes coherent when $\sigma_z \le \lambda_{TR}$:

$$\underbrace{\frac{d^2W}{d\omega\, d\Omega}}_{\substack{N\text{-electron}\\ \text{TR spectrum}}} = \Big[\overbrace{N}^{\text{incoherent}} + \overbrace{N^2 \underbrace{F(\omega,q)}}^{\text{coherent}}\Big] \underbrace{\frac{d^2 w}{d\omega\, d\Omega}}_{\substack{\text{single } e^-\\ \text{TR spectrum}}}$$

form factor: $\left|\int f(\mathbf{x}) \exp(-i\,\mathbf{k}\cdot\mathbf{x})\, d^3\mathbf{x}\right|^2$

PROS

- nearly non-invasive
- unprecedented time resolution down to ~1 fs; beats deflection cavities, e-o methods, streak cameras

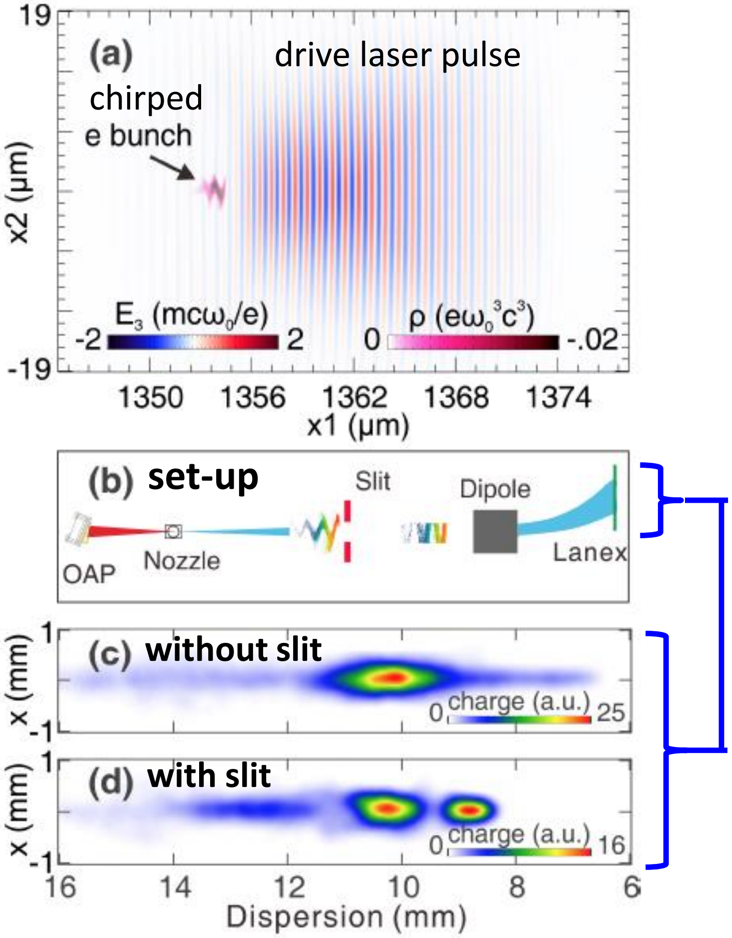
CONS

- multi-shot
- insensitive to bunch shape *f*(**x**) details
- identifies only the shortest feature

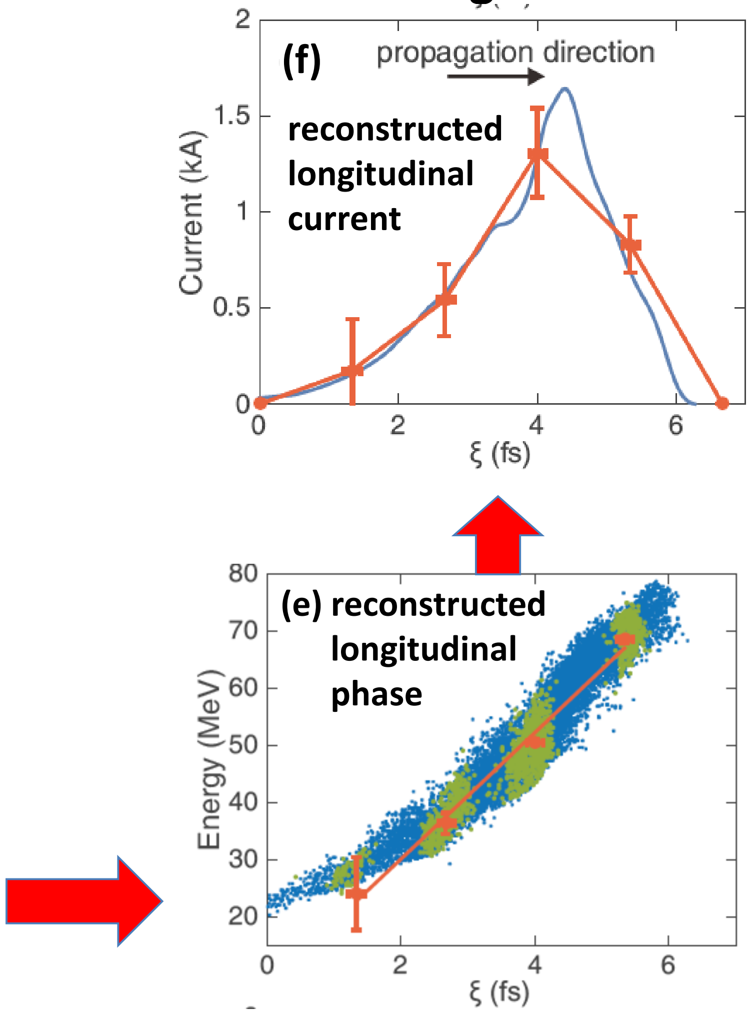
Laser cycle provides fs-"clock" for measuring duration of chirped ultrashort LPA e$^-$ bunches

Zhang et al., *Phys. Rev. ST Accel. Beams* **19**, 062802 (2016)

Measurement



Reconstructed longitudinal current profile



"Beam-loaded" LWFAs can support Q ~ nC with I_{peak} ~ 100 kA, the key component for future compact light sources

- **Demonstrated GeV LWFAs limited to ≤ 50 pC → $I_{peak} \sim 5 \times 10^{-11}$ C/10^{-14} s = 5 kA**

Wang, *Nat. Comms* **4**, 1988 (2013)
Kim, *PRL* **111**, 165002 (2013)
Leemans, *PRL* **113**, 245002 (2014)

- **Theoretically, such LWFAs can support Q ~ 1 nC → $I_{peak} \sim 10^{-9}$ C/10^{-14} s = 100 kA**

Pukhov & Meyer-ter-Vehn, *Appl. Phys. B* **74**, 355 (2002)

- **Self-fields of such high trapped charge re-shape the accelerating field ("beam-loading") in ways that can be beneficial.**

Gordienko & Pukhov, *Phys. Plasmas* **12**, 043109 (2005)
Lu *et al.*, *Phys. Rev. ST Accel. Beams* **10**, 061301 (2007)
Tzoufras *et al.*, *PRL* **101**, 1 (2008); *Phys. Plasmas* **16**, 056705 (2009)

- **Beam-loaded PWFAs recently imparted ΔE ~ 10 GeV to Q ~ 1 nC bunches, exploiting flattening of accelerating fields to maintain narrow ΔE/E ...**

Litos *et al.*, *Nature* **515**, 92 (2015)

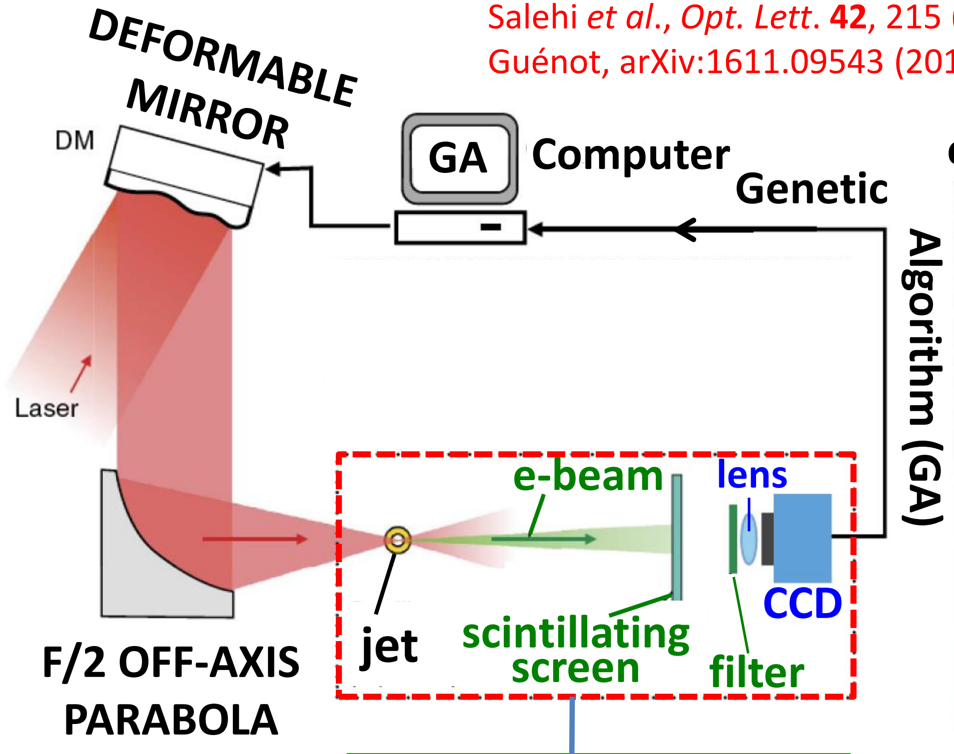
... an inspiration for LWFA development!

LWFA at 1 kHz rep rates enables coherent control of beam profile

He *et al.*, *Nat. Comms*. **6**, 7156 (2015) – U. Michigan: 0.1 MeV, .05 pC

Salehi *et al.*, *Opt. Lett*. **42**, 215 (2017) – U. Maryland: 1 MeV, 1 pC

Guénot, arXiv:1611.09543 (2016) – LOA: 5 MeV, 1 pC



$$\mathrm{FOM} = \sum_{(ij)} \frac{I_{ij}}{\left| r_{ij} - r_0 \right|^{n}}$$

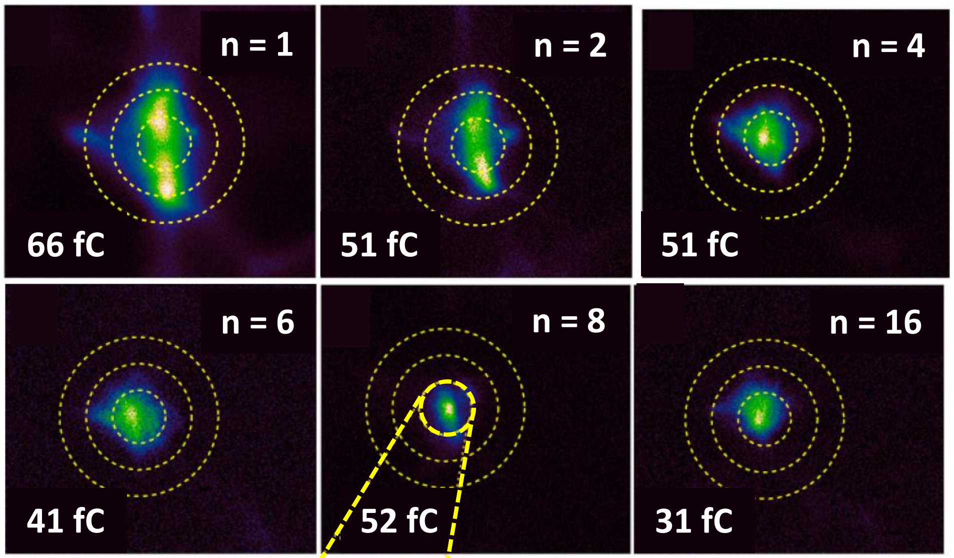
exponent

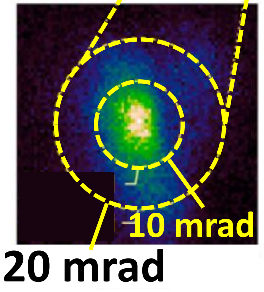
I_{ij} = pixel intensity

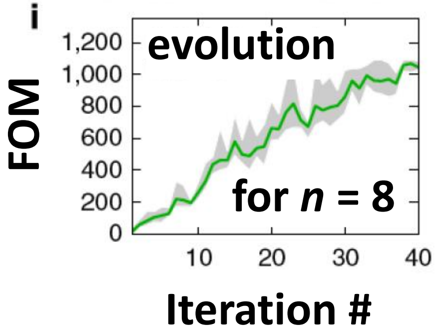
r_0 = beam radius (optimization target)

e-beam energy distribution similarly optimized

e-beam spatial profile optimization for various *n*



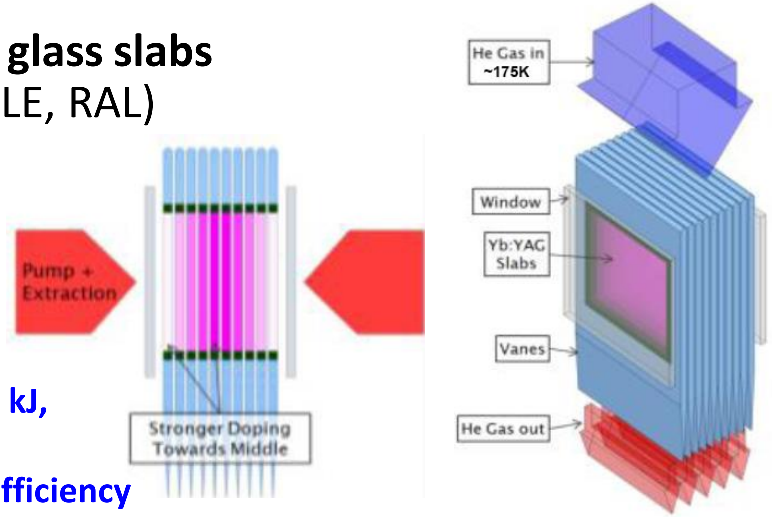




New High-Average Power TW/PW Lasers for GeV LWFAs are emerging

Cooled glass slabs

(DiPOLE, RAL)

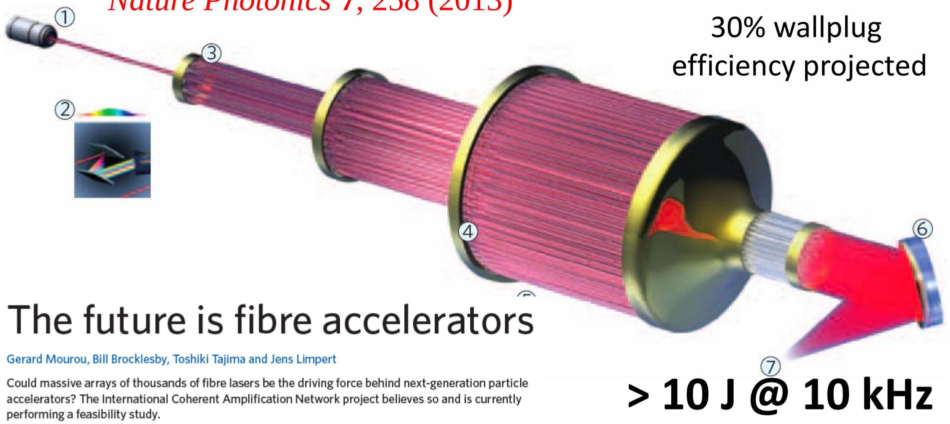


multi-J to kJ,
multi-Hz,
multi-% efficiency

Coherent Fiber Networks

Nature Photonics **7**, 258 (2013)

30% wallplug efficiency projected



The future is fibre accelerators

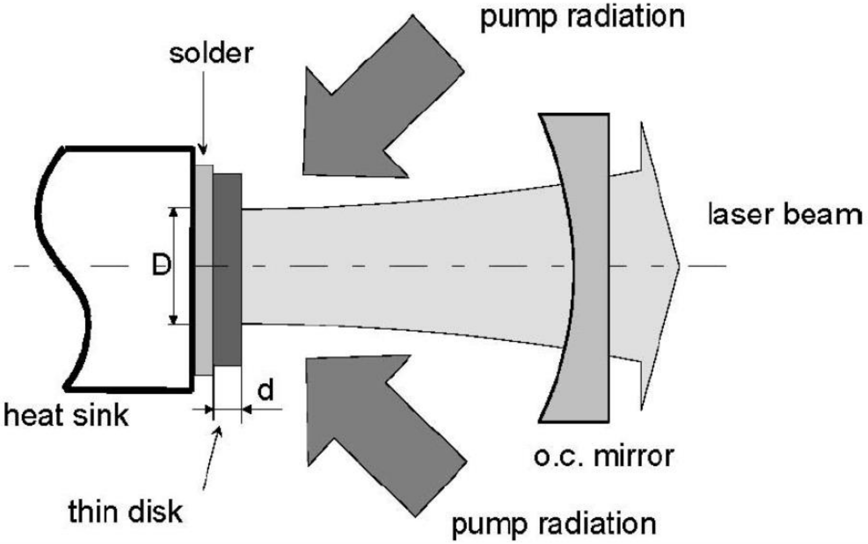
Gerard Mourou, Bill Brocklesby, Toshiki Tajima and Jens Limpert

Could massive arrays of thousands of fibre lasers be the driving force behind next-generation particle accelerators? The International Coherent Amplification Network project believes so and is currently performing a feasibility study.

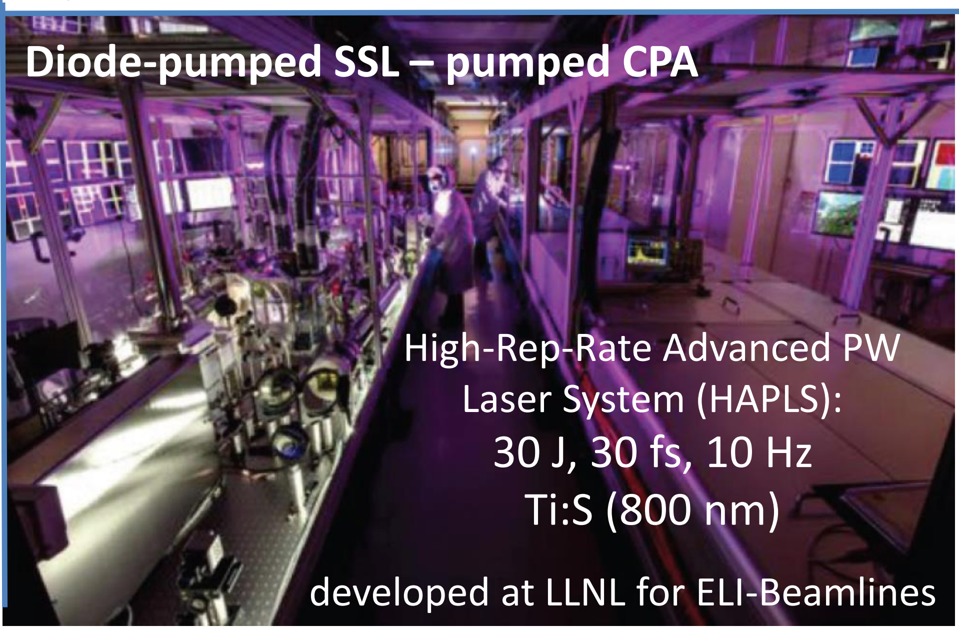
> 10 J @ 10 kHz

Thin-disc lasers

Giesen, *IEEE-JSTQE* **13**, 598 (2007)



Diode-pumped SSL – pumped CPA



High-Rep-Rate Advanced PW Laser System (HAPLS):
30 J, 30 fs, 10 Hz
Ti:S (800 nm)

developed at LLNL for ELI-Beamlines

1. Energy E | 2. Spread ΔE/E | 3. Emittance ε_n | 4. Bunch length σ_z | 5. Charge Q | 6. Rep Rate

The U. S. DOE has placed new, high priority on HAP laser development for LWFAs

U.S. DEPARTMENT OF
ENERGY

Efficient, high-rep-rate
high-peak-power laser
technologies are emerging

Workshop on Laser Technology for Accelerators

Summary Report

January 23-25, 2013

- **LWFA e-beam properties**
  - Energy (2-4 GeV)
  - Energy Spread (> 1 %)
  - Normalized transverse emittance (~ 0.1π mm-mrad)
  - bunch duration (few fs)
  - charge (~ 0.5 nC)
  - rep rate (1 Hz @ GeV, 1 kHz @ low MeV)
- **LWFA implementation** *
  - **Staging**
  - **Diagnostics**
  - **Computations**
  - **Short-Term applications**

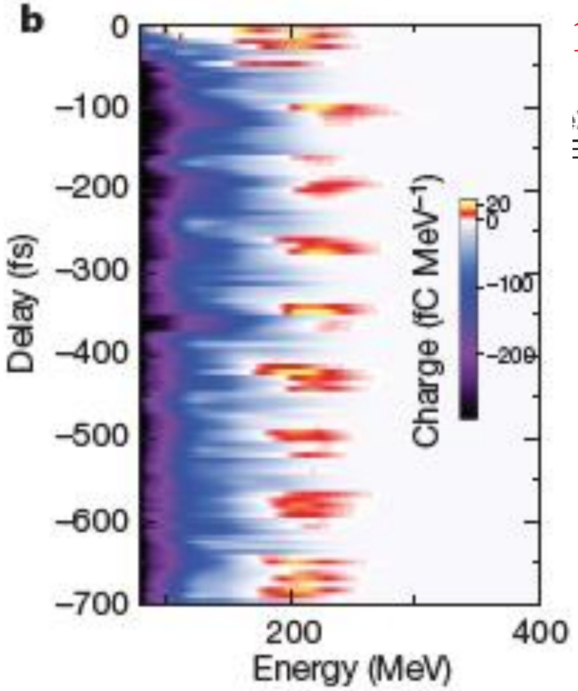
* Much recent progress, many future challenges

2016

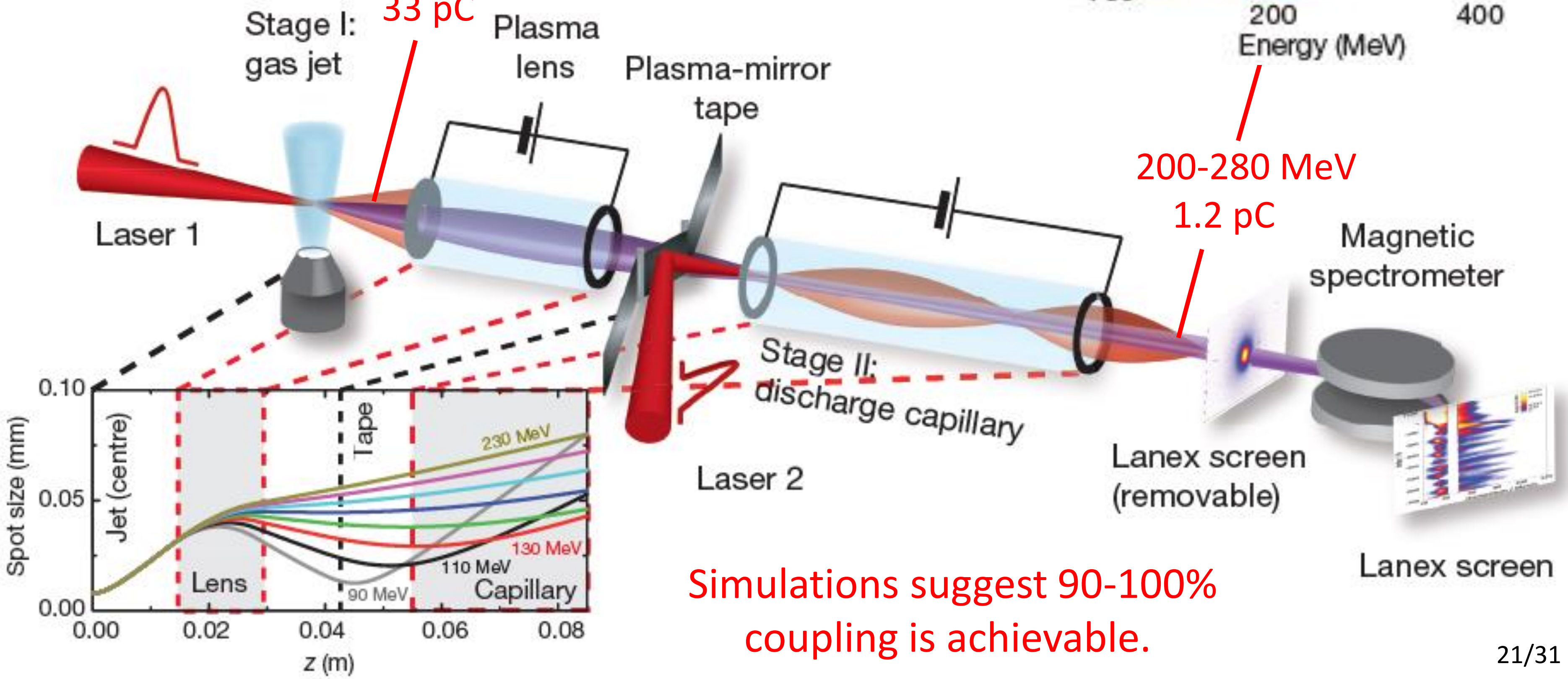
Multistage coupling of independen accelerators

S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Danie
K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]

16)
16525



75-125 MeV
33 pC



200-280 MeV
1.2 pC

Simulations suggest 90-100% coupling is achievable.

Matlis, *Nature Phys.* **2**, 749 (2006)

nature physics | VOL 2 | NOVEMBER 2006 | www.nature.com/naturephysics

Snapshots of laser wakefields

N. H. MATLIS[1]*, S. REED[2], S. S. BULANOV[2], V. CHVYKOV[2], G. KALINTCHENKO[2], T. MATSUOKA[2], P. ROUSSEAU[2], V. YANOVSKY[2], A. MAKSIMCHUK[2], S. KALMYKOV[1], G. SHVETS[1] AND M. C. DOWNER[1]*

[1]FOCUS Center, Department of Physics, University of Texas at Austin, 1 University Station C1600, Austin, Texas 78712-1081, USA

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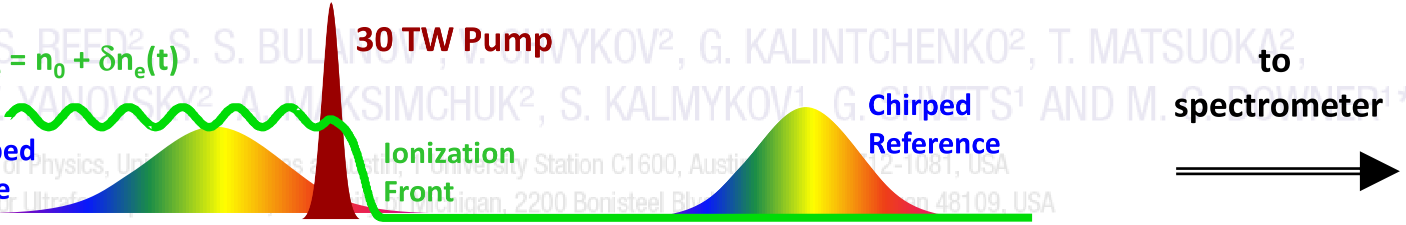
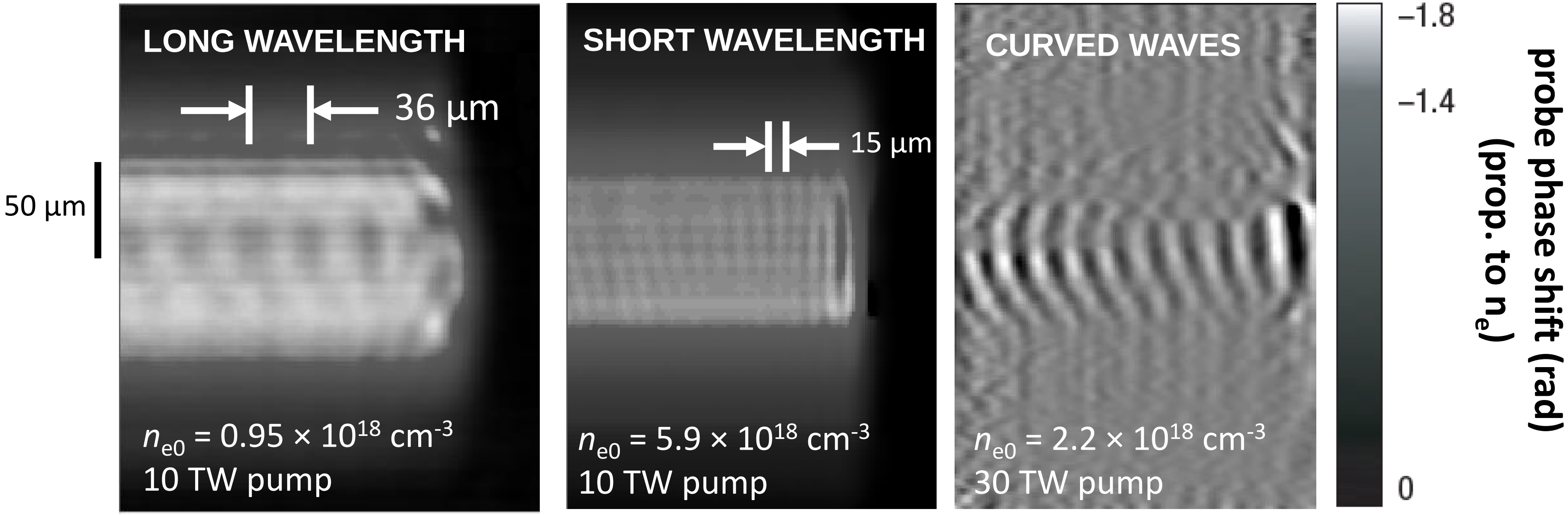


Laser-plasma accelerators come in many shapes & sizes

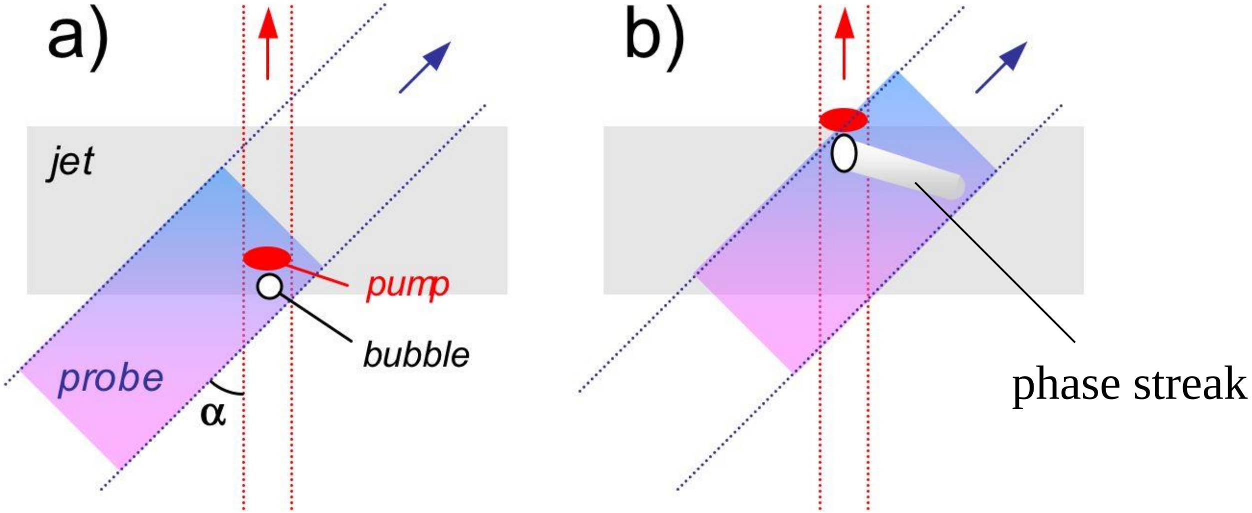


The ability to capture pictures of plasma waves helps us understand and improve laser-plasma accelerators

Frequency-Domain “Streak Camera” records EVOLUTION of Plasma Bubble in ONE shot

P. Dong *et al.* , *Phys. Rev. Lett.* **104**, 134801 (2010)
Z. Li *et al.*, *Opt. Lett.* 35, 4087 (2010);
------------ *Phys. Rev. Lett.* **113**, 085001 (2014)
------------- *Nat. Comms.* **5**, 3085 (2014)

Zhengyan Li
PhD 2014



- Phase streak is a temporal sequence of the object’s projections
- We can record several of them simultaneously to recover the object’s evolving structure tomographically

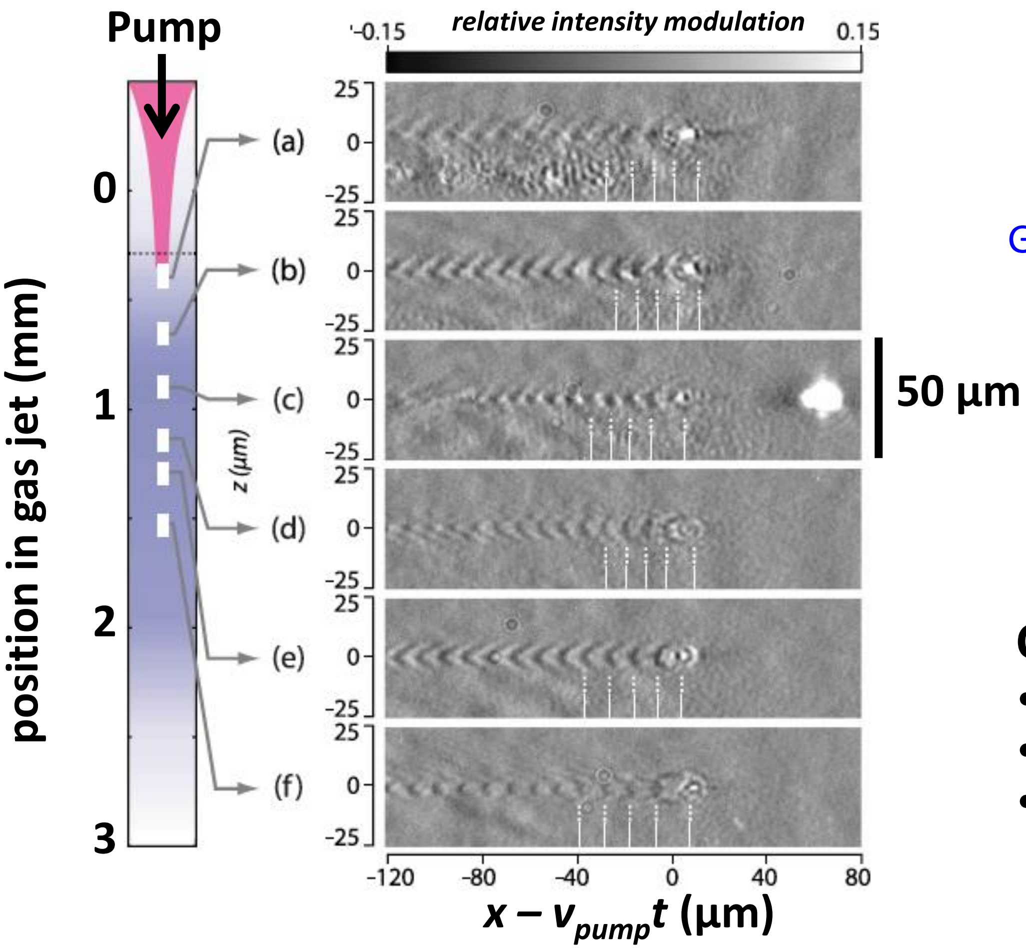
Transverse few-cycle probe shadowgraphically images wake at selected Δt

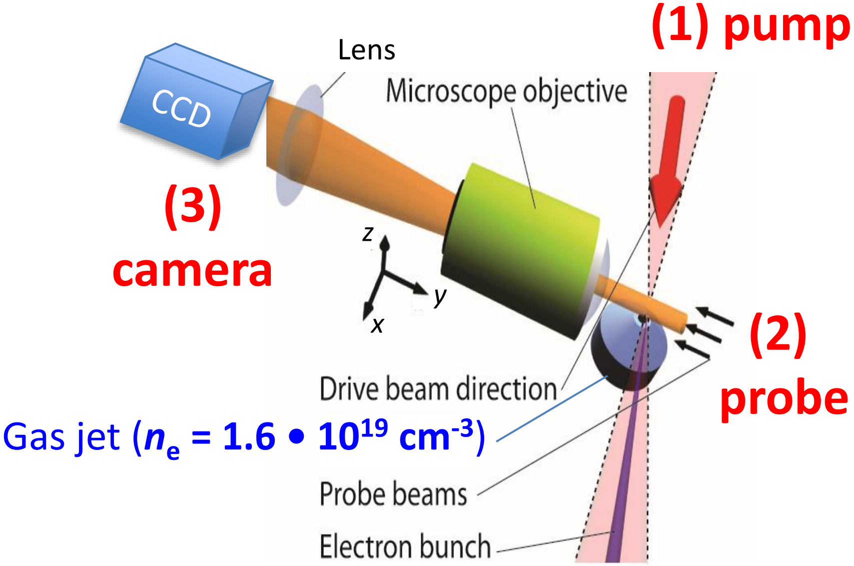
Buck, *Nat. Phys.* **7**, 453 (2011); Sävert, *PRL* **115**, 055002 (2015)

(1) **40-TW, 30 fs laser pulse drives plasma wake.**

(2) **6 fs synchronized probe pulse impinges transversely.**

(3) **Probe shadowgraphs imaged at selected Δt.**





PROS

- single-shot, non-invasive
- µm resolution,

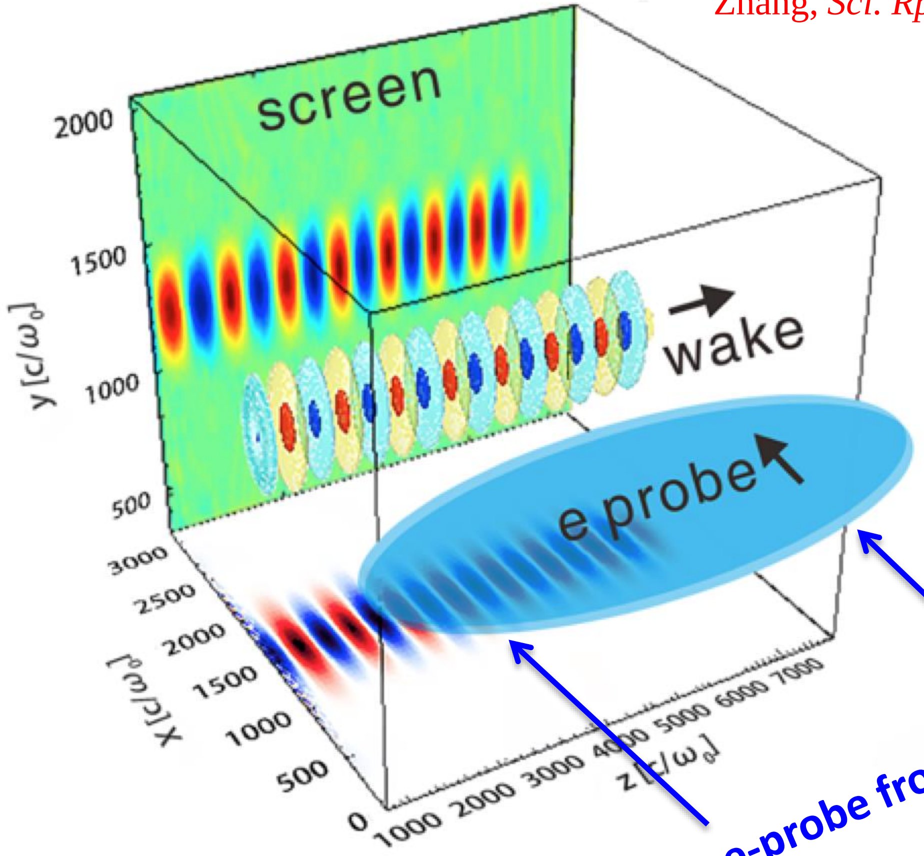
CONS

- dynamic info requires multiple shots
- **challenging to scale to n_e < 1e19 cm^{-3}**
- requires extremely short probe pulse

Tsinghua University

4 fs e-probe from one LPA probes E-fields of another

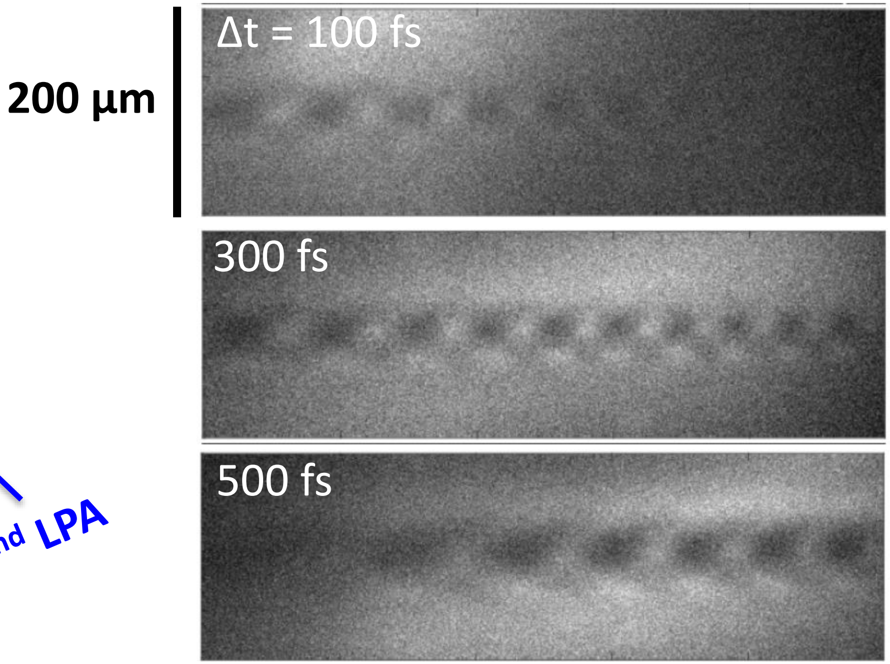
Zhang, *Sci. Rpts.* **6**, 29485 (2016)



~4 fs e-probe from 2nd LPA

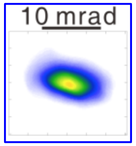
e-snapshots at

$n_{e0} = 2•10^{17}$ cm^{-3}

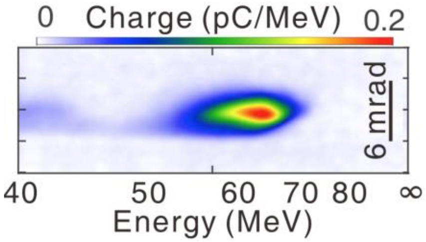


wake propagation

Profile, energy spectrum of e-probe:

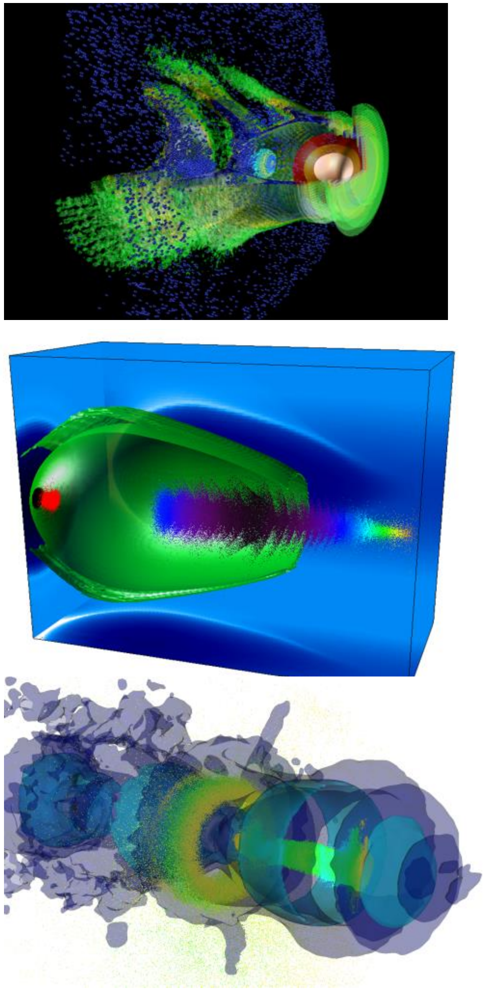


spatial profile



LWFA research has spurred development of computational methods & codes *

Courtesy Warren Mori

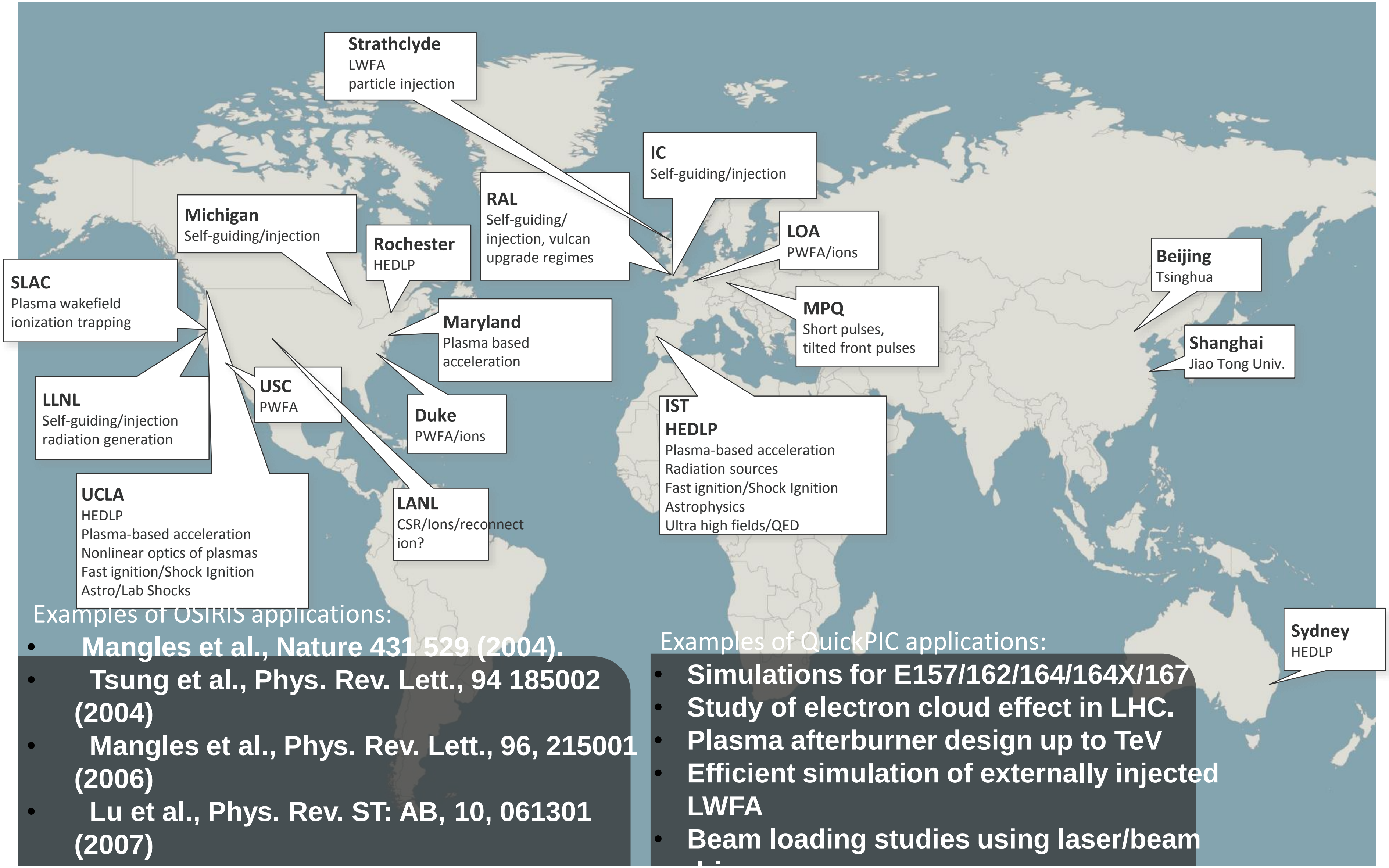


- **Novel algorithms and methods:**
  - **Moving Window**
  - **Parallel PIC codes**
  - **Quasi-static PIC codes**
  - **Ponderomotive Guiding Center**
  - **Close coupling between simulations and experiments**
  - **Lorentz boosted frames (early concept began at universities)**
  - **GPU and Many Core PIC algorithms**

- **Widely used production codes:**
  - **OSIRIS** (UCLA + IST)
  - **WAKE** (U. Maryland)
  - **QuickPIC** (UCLA + UMaryland + IST)
  - **turboWAVE** (NRL + UCLA + UMaryland**)**
  - **UPIC-EMMA** (UCLA + IST + TsinghuaU)

*** and vice versa**

A worldwide network of OSIRIS/QuickPIC-based research has developed



Strathclyde
LWFA
particle injection

IC
Self-guiding/injection

RAL
Self-guiding/injection, vulcan upgrade regimes

LOA
PWFA/ions

Michigan
Self-guiding/injection

Rochester
HEDLP

Beijing
Tsinghua

SLAC
Plasma wakefield
ionization trapping

MPQ
Short pulses,
tilted front pulses

Maryland
Plasma based acceleration

Shanghai
Jiao Tong Univ.

USC
PWFA

LLNL
Self-guiding/injection
radiation generation

Duke
PWFA/ions

IST
HEDLP
Plasma-based acceleration
Radiation sources
Fast ignition/Shock Ignition
Astrophysics
Ultra high fields/QED

UCLA
HEDLP
Plasma-based acceleration
Nonlinear optics of plasmas
Fast ignition/Shock Ignition
Astro/Lab Shocks

LANL
CSR/Ions/reconnection?

Sydney
HEDLP

Examples of OSIRIS applications:

- **Mangles et al., Nature 431 529 (2004).**
- **Tsung et al., Phys. Rev. Lett., 94 185002 (2004)**
- **Mangles et al., Phys. Rev. Lett., 96, 215001 (2006)**
- **Lu et al., Phys. Rev. ST: AB, 10, 061301 (2007)**

Examples of QuickPIC applications:

- **Simulations for E157/162/164/164X/167**
- **Study of electron cloud effect in LHC.**
- **Plasma afterburner design up to TeV**
- **Efficient simulation of externally injected LWFA**
- **Beam loading studies using laser/beam**

Courtesy Warren Mori

Where is LWFA Computing Going?

Support experiments (at Universities and National Labs)

Enable ability to understand complicated physics

Extend studies to parameters not accessible in the laboratory

Discovery

Real-time steering of experiments

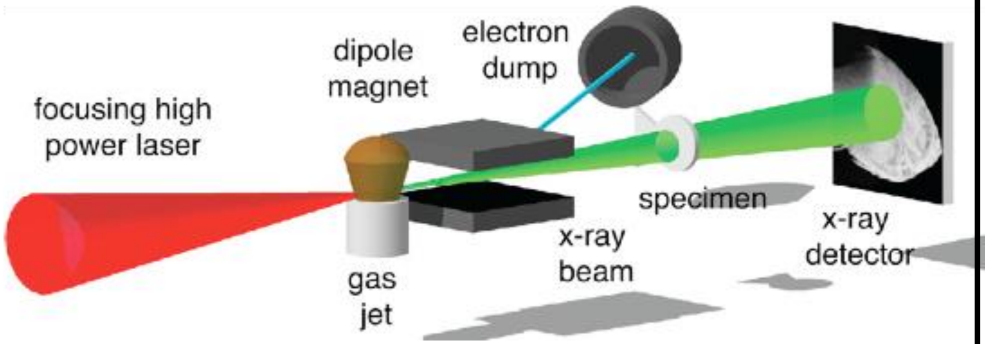
Rapid parameter scans to determine how changes in inputs effects outputs (experimental observables and physical processes)

Hardware and algorithmic improvement could lead to speed ups of 10^4+

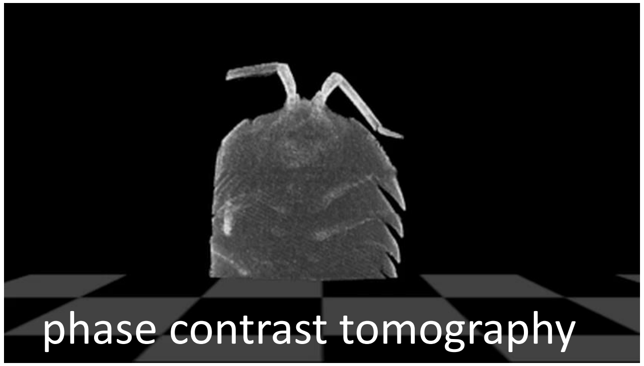
Courtesy Tom Antonsen

Near-term LWFA light source applications will spur LWFA improvements needed for XFELs, colliders

Kneip, *Appl. Phys. Lett.* **99**, 093701 (2011);
Nature Phys. **6**, 980 (2010)



- miniature synchrotron-like source based on betatron x-rays from LWFA
- peak brightness comparable to 3rd generation synchrotrons demonstrated


phase contrast tomography

Reviews: Corde, *Rev. Mod. Phys.* **85**, 1 (2013)
Albert *et al.*, *Plasma Phys. Control. Fusion* **56**, 084015 (2014)

LWFA light sources

source	hν range (keV)	hΔν	photons pulse^{-1}	τ (fs)	rep rate (Hz)	
Beta-tron	**1-80**	**100%**	**10^8**	**tens**	**≤ 1**	← current
	1-150	✓	✓	✓	**>30**	← desired
Comp-ton	**10^2 to 10^5**	**50%**	**10^8**	**tens**	**≤ 1**	← current
	✓	**< 1%**	**10^{10}**	✓	**>100**	← desired

LWFA improvements needed:

- **higher rep rate**
- **<1% ΔE/E**
- **ε_n < 1 mm-mrad**
- **1% rms jitter**

Applications:

- x-ray phase contrast imaging
- x-ray absorption spectroscopy (EXAFS, XANES)
- Nuclear physics (resonance fluorescence, medical radio-isotopes, photofission)
- ultrashort positron sources for LWFA

Current LWFA Challenges

1) Complete the scientific foundation of a future e^-e^+ collider

- demonstrate high-quality, reliable, high-rep-rate ~10 GeV modules
  - dephasing-/depletion-limited, beam-loaded, controlled injection, < 1% $\Delta E/E$
  - develop repeatable, high-rep-rate plasma targets
- demonstrate efficient inter-stage coupling
  - near-unity charge & emittance preservation
- demonstrate e^+ acceleration
  - develop injection sources, hollow-channel accelerators for focusing
- continue developing innovative diagnostics for...
  - sub-µm, sub-fs bunch characterization; single-shot wake visualization
- develop fully predictive PIC simulations

2) Develop tabletop radiation sources & applications

- XFEL: requires 0.1% $\Delta E/E$, perhaps in slice energy spread
- Compton: tunable multi-MeV γ-ray sources for nuclear science
- Betatron: wide-band multi-keV x-ray sources for materials, HED, biomedicine

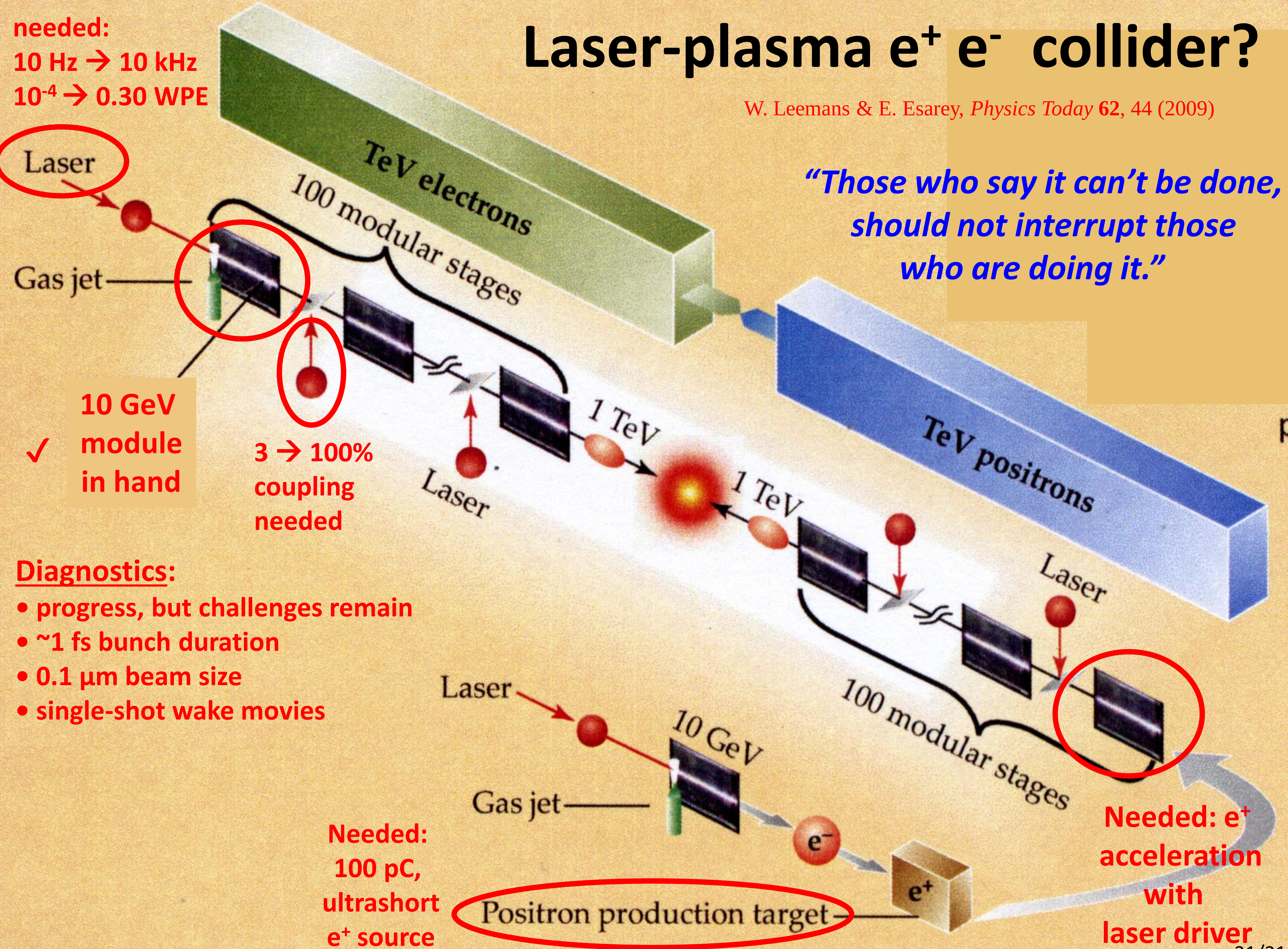
3) Develop efficient, high-average-power PW lasers

- improved wall-plug efficiency
- model technologies: cooled glass slabs, coherent fiber networks, “Thin Disc” (active mirrors), diode-pumped OPCPA (*e.g.* HAPLS)
- mid-IR multi-TW lasers

Laser-plasma $e^+ e^-$ collider?

W. Leemans & E. Esarey, *Physics Today* **62**, 44 (2009)

"Those who say it can't be done, should not interrupt those who are doing it."



needed:
10 Hz → 10 kHz
10^{-4} → 0.30 WPE

✓ **10 GeV module in hand**

3 → 100% coupling needed

<u>Diagnostics</u>:

- **progress, but challenges remain**
- **~1 fs bunch duration**
- **0.1 µm beam size**
- **single-shot wake movies**

Needed: 100 pC, ultrashort e^+ source

Needed: e^+ acceleration with laser driver