JAI Lecture, Oxford, Sep 26th, 2013

Towards Hybrid Plasma-based Multi-color FELs

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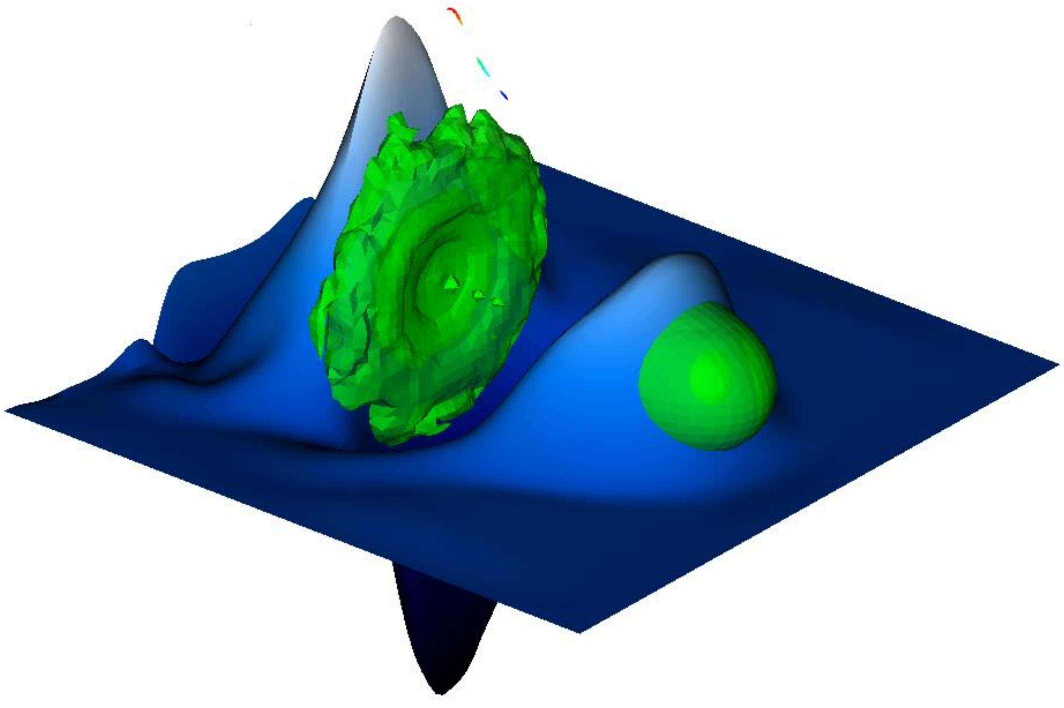
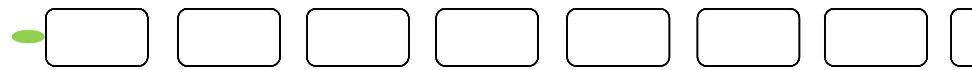
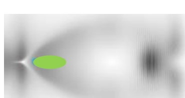


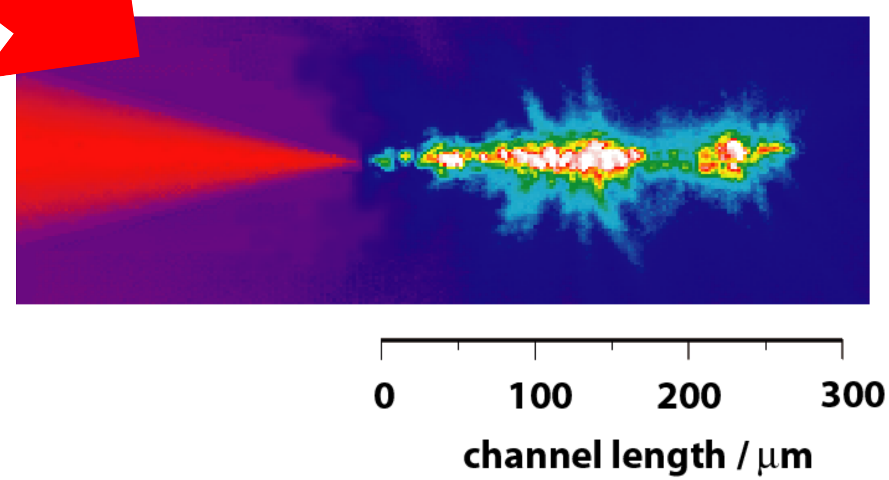
Shrinking accelerators from km to cm: Plasmas

Multiple static metallic cavities
w/ electric fields of ~50 MV/m



Single co-propagating plasma cavity
w/ electric fields of ~50 GV/m

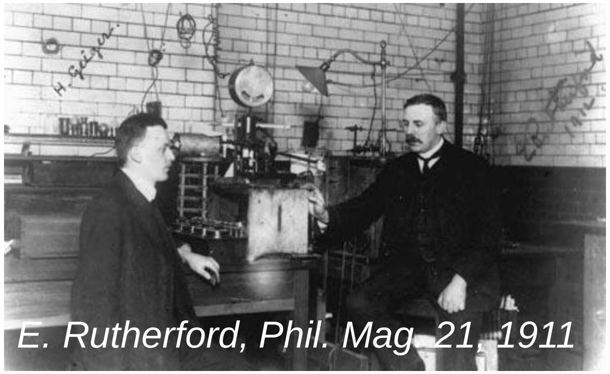




Prehistoric days: Plasma Wakefield Acceleration

Rutherford/Geiger 1911

World's first particle accelerator experiment:
Matter consists of electrons and ions


E. Rutherford, Phil. Mag. 21, 1911

Langmuir/Tonks 1928

"We shall use the name *plasma* to describe [a] region containing balanced charges of ions and electrons"

CERN 1956

Future particle accelerators:
Accelerate particles via collective fields by separating electrons and ions in plasmas
Veksler, Budker, Fainberg, Proc. CERN Symp. High Energy Accelerators, 1956

Project Matterhorn

Description and computation of nonlinear plasma oscillations
J. Dawson, Phys. Rev. 113, 383, 1959

UCLA 1979: LWFA

Produce transient charge separation in plasma via Laser Electron Accelerator
Tajima & Dawson, Phys. Rev. Letters 43, 1979

CPA 1986

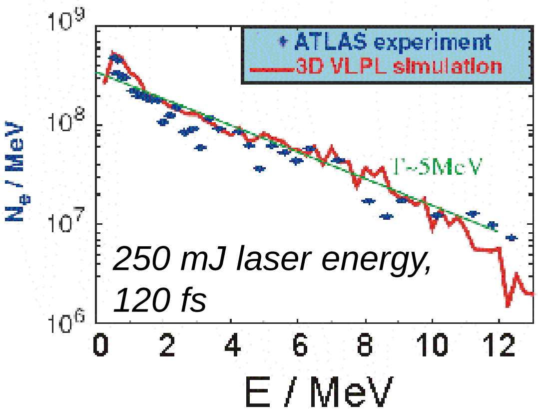
Chirped Pulse Amplification to produce intense enough lasers
Strickland & Mourou, Optics Comm. 56, 219, 1986

Stanford/UCLA 1985: PWFA

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma
Chen et al., Phys. Rev. Letters 54, 1985

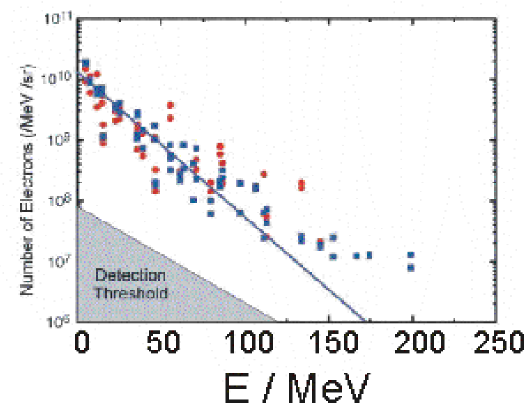
Modern LWFA History

Since 1990s: Exponential beams



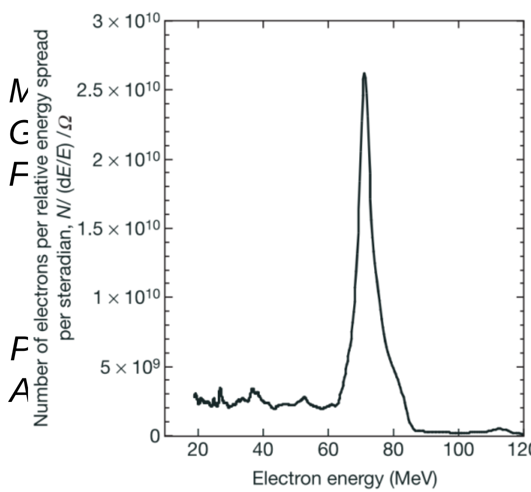
C. Gahn, Phys. Rev. Letters 83, 4772, 1999

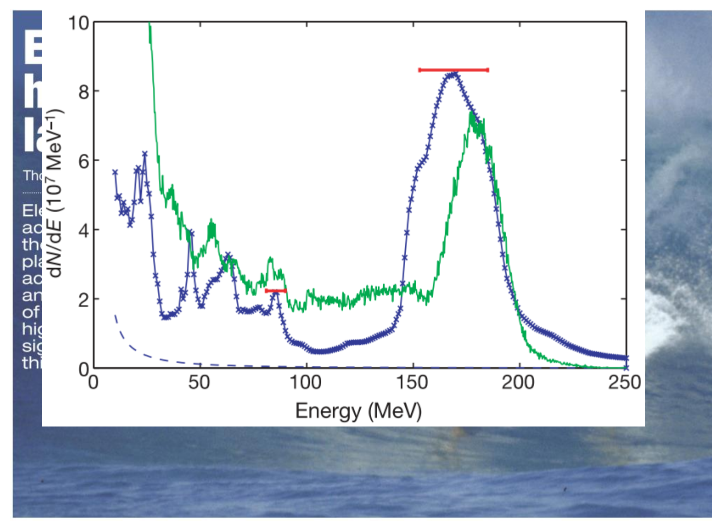
1 J laser energy, 30 fs



V. Malka, Science 22, 298, 5598, 2002

Since 2004: Quasi-monoenergetic beams



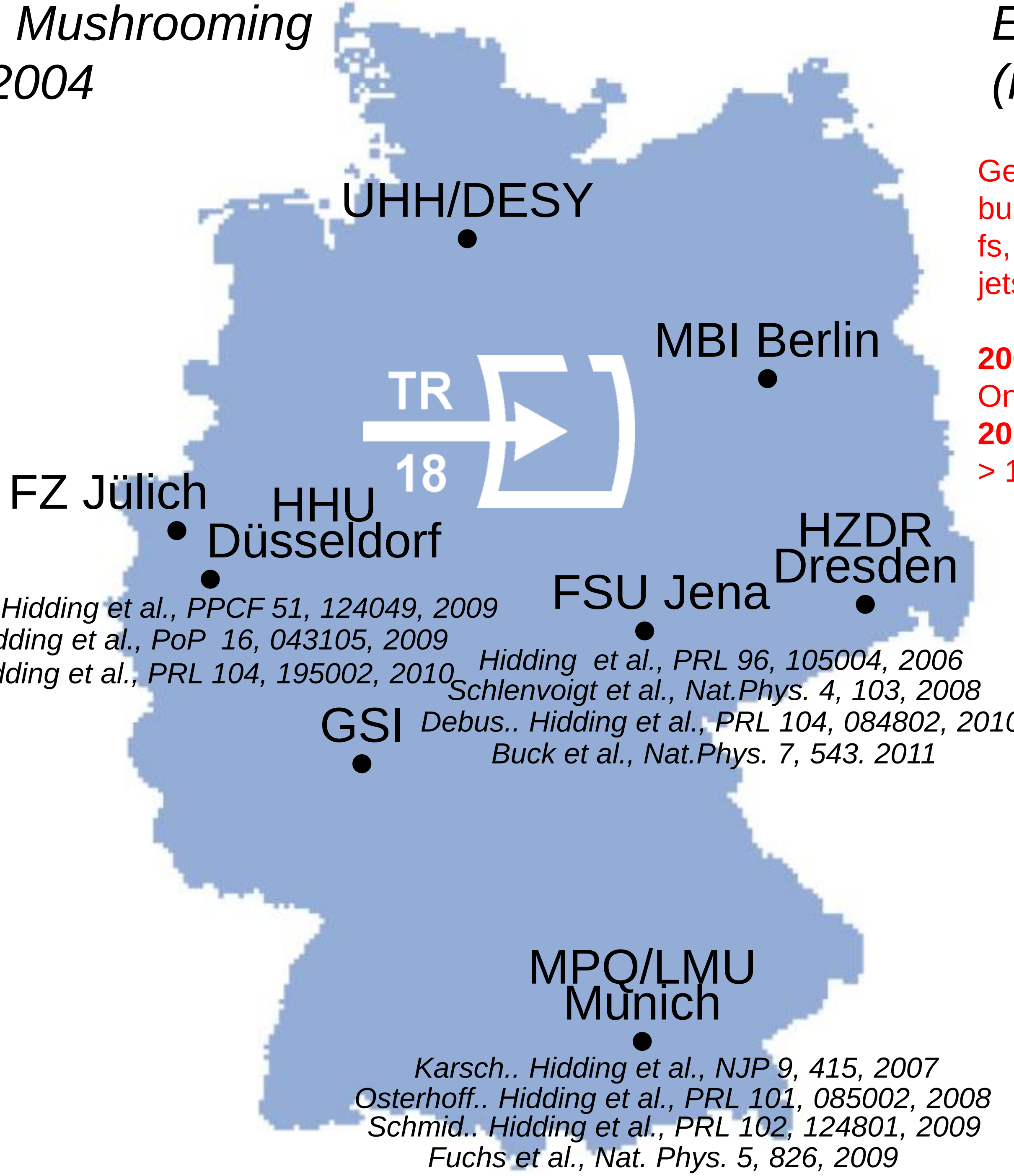


LWFA: Mushrooming since 2004

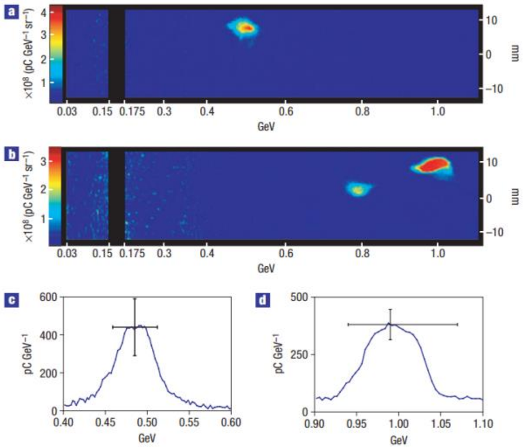
Example: Germany (non-exhaustive!)

Generation of µm-scale electron bunches up to 1 GeV with 8-80 fs, 30 mJ-3 J laser pulses in gas jets, capillaries and gas cells

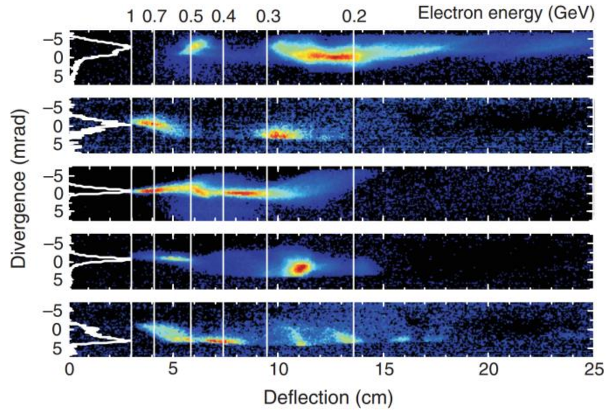
2004:
One laser system with 7 TW
2013:
> 10 laser systems w/ > 100 TW



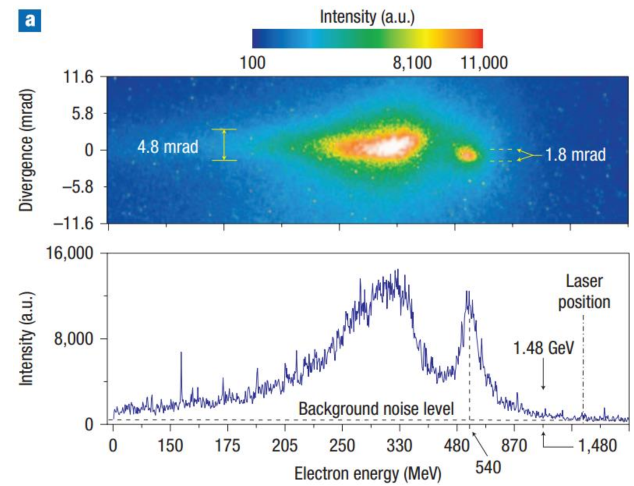
But: Limited beam quality & stability



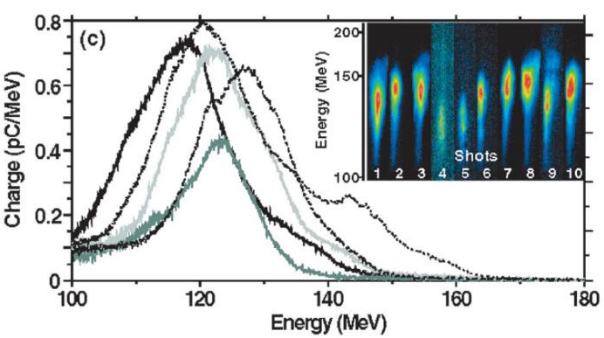
Leemans et al., Nat. Phys. 2006



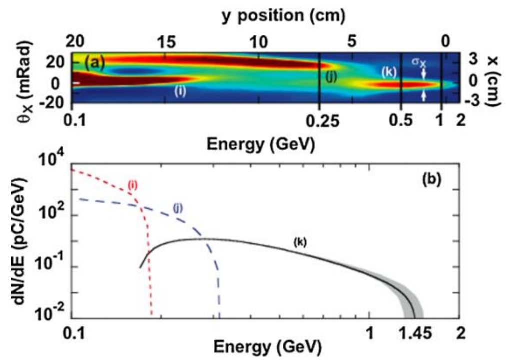
Karsch et al., NJP 9, 415, 2007



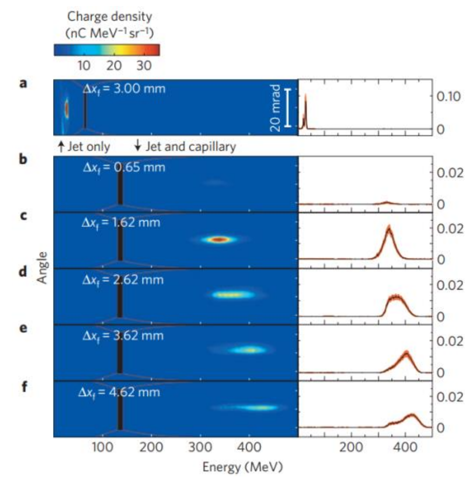
Hafz et al., Nat. Phot. 2008



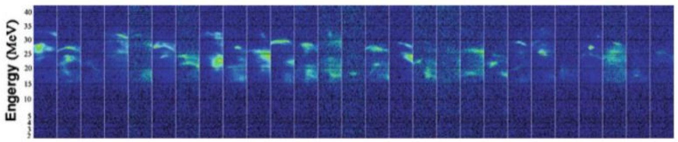
Osterhoff et al., PRL 2008



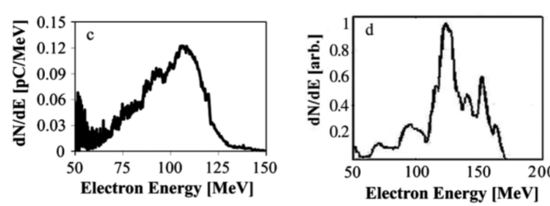
Clayton et al., PRL 2010



Gonsalves et al., Nat. Phys. 2011



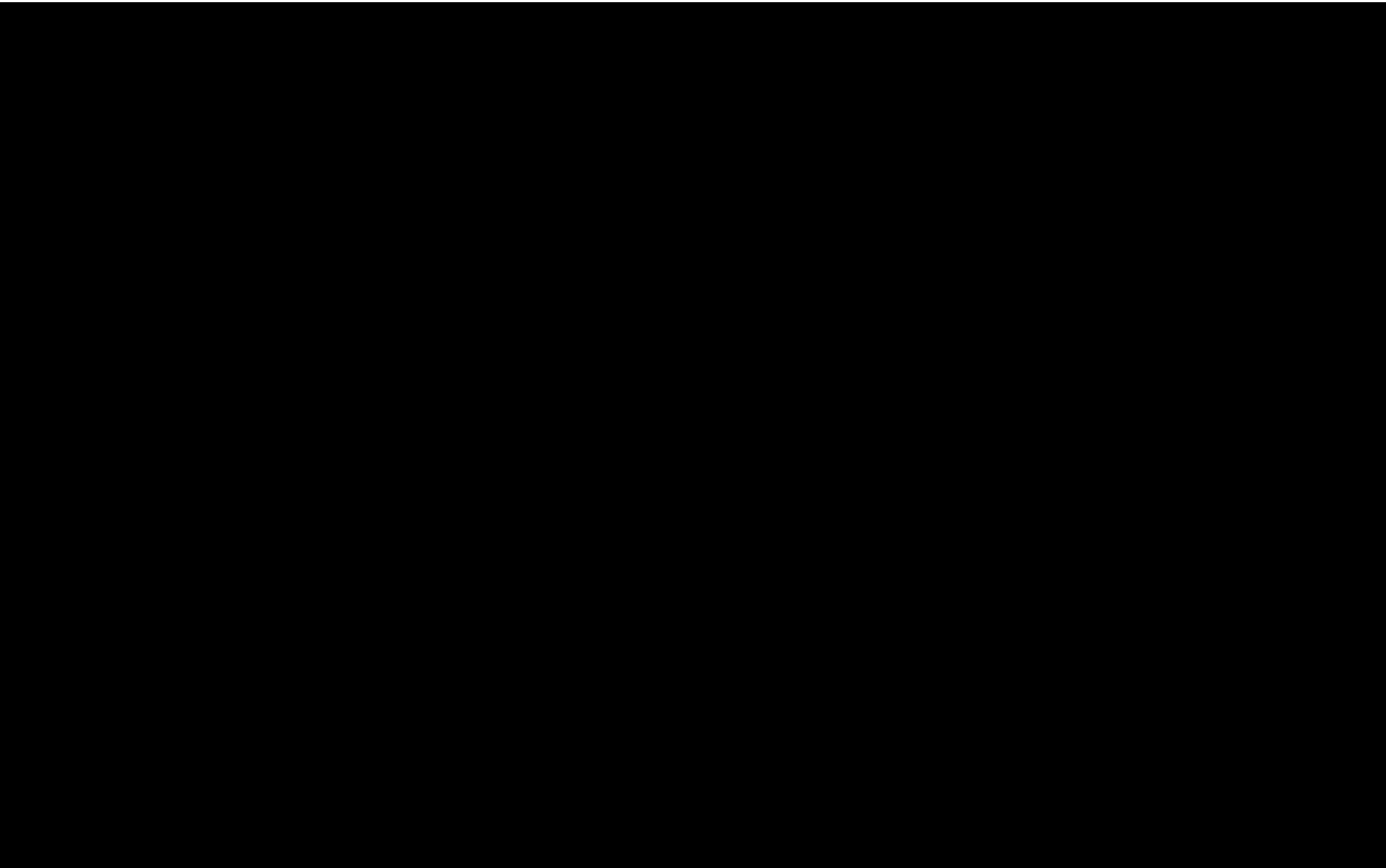
Schmid, PhD Thesis 2009



McGuffey et al., PRL 2010

Fundamental Issues of LWFA

Dephasing, Diffraction & Injection limit energy gain and beam quality:



Strategies: Dephasing, Diffraction & Injection

Dephasing:

Use longitudinally tapered plasma profile
Katsouleas, PRA 2056 (1986)

Diffraction:

Use transversally tapered plasma profile
e.g. Hooker et al., JOSA (2000), Leemans et al., Nat. Phys. (2006)

Injection:

External Injection
Clayton et al., PRL 70, 37 (1993) → *LAOLA@REGAE (DESY), HZDR, Frascati, France …*

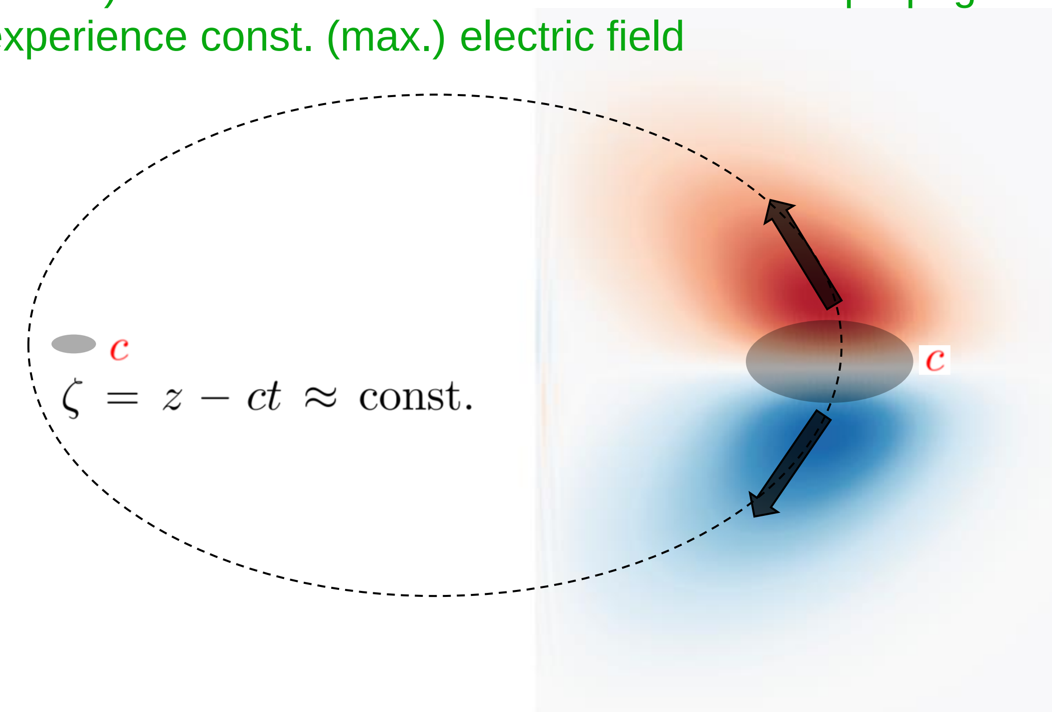
Plasma density transition
Bulanov et al., PRE 58, R5257 (1998), Suk et al., PRL 86, 1011 (2001), Gonsalves et al., Nat. Phys. 7, 862 (2011)

Colliding laser pulses:
Umstadter et al., PRL 76, 2073 (1996), Faure et al., Nature 444, 737 (2006)

Higher state ionization:
Chen et al., JAP 99, 056109 (2006), McGuffey et al., PRL 104, 025004 (2010) (w/ one laser pulse)
Umstadter et al., US Patent 5789876 A (1995), Bourgeois et al., acc. PRL (2013) (w/ two laser pulses)

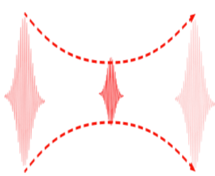
PWFA

„No“ dephasing: (relativistic) driver and accelerated electrons both propagate with ~ c
⇒ witness electrons experience const. (max.) electric field

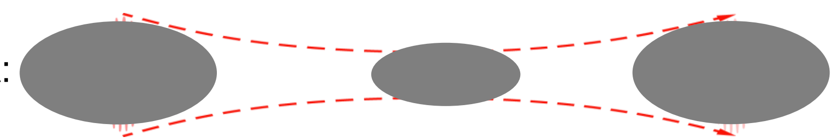


Much less problems with “diffraction” in PWFA

LWFA:



PWFA:



$$\omega(z) = \omega_0 \sqrt{1 + \left(\frac{z}{Z_R}\right)^2} \qquad Z_R = \pi\omega_0^2/\lambda$$

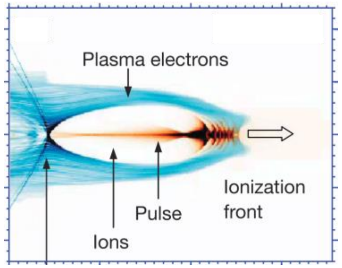
e.g., $Z_R \approx 400\,\mu\text{m}$ at $\omega_0 = 10\,\mu\text{m}$

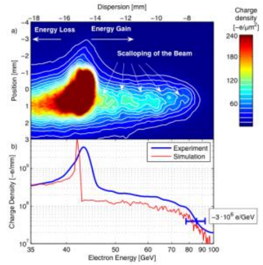
$$\sigma_r(z) = \sigma_{r0} \sqrt{1 + \left(\frac{z}{\beta^*}\right)^2} \qquad \beta^* = \sigma_{r0}^2 \gamma / \epsilon_n$$

e.g., $\beta^* \approx 20$ cm at $\sigma_{r0} = 10\,\mu\text{m}$,
$\gamma = 2000,\ \epsilon_n = 10^{-6}$ mrad

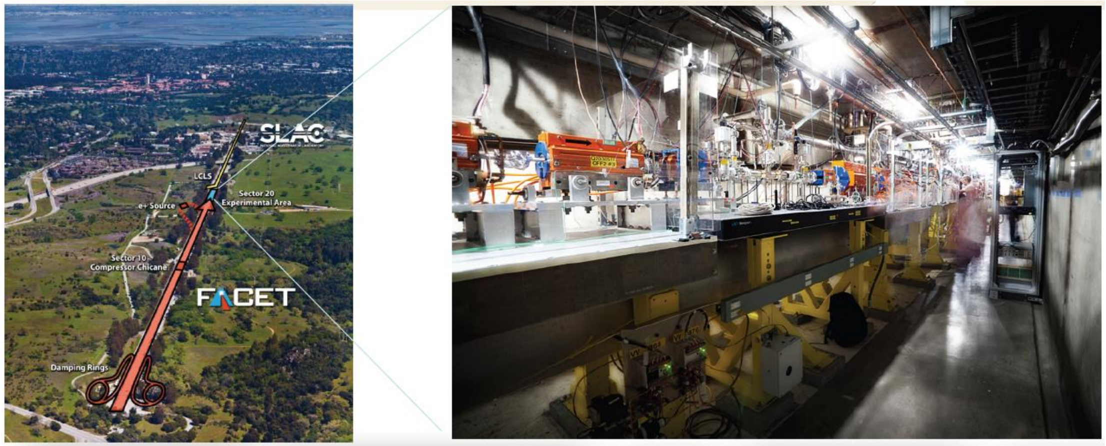
PWFA

SLAC: Energy doubling of 42 GeV electrons in a metre-scale PWFA!



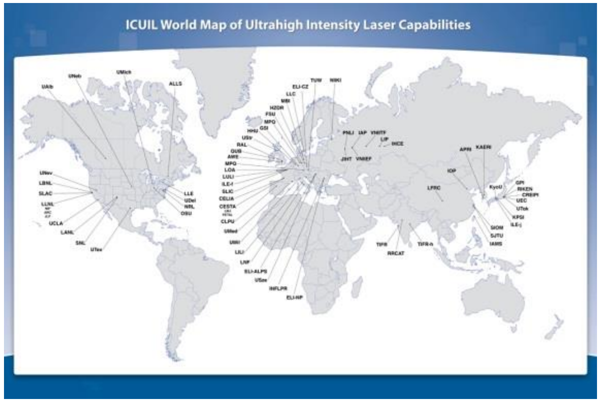


Blumenfeld et al., Nature 445, 741, 2007



But: only one high-energy (> 100 MeV) PWFA facility so far:

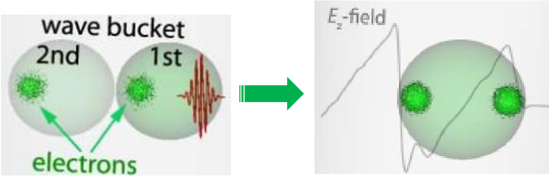
>100 LWFA-capable sites



Idea in 2010:
Use electron bunches from LWFA as particle drivers in subsequent PWFA (afterburner) stage – hybrid LWFA/PWFA

One main reason:
bunches need high current,
need to be compact.

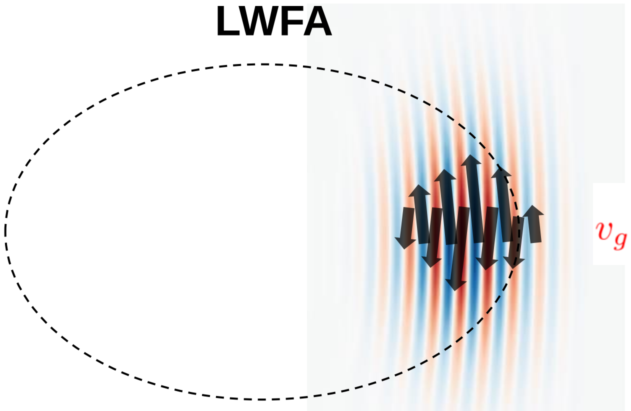
"Monoenergetic Energy Doubling in a Hybrid Laser-Plasma-Accelerator" by using a driver/witness double bunch, Hidding et al., PRL 104, 195002, 2010



LWFA vs. PWFA

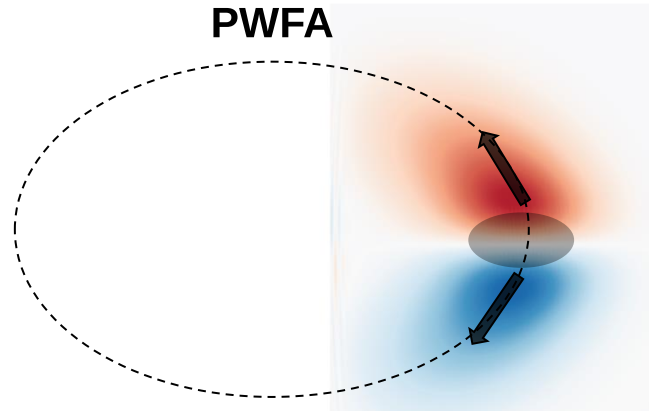
- Laser pulses: transversally oscillating wave, electron bunch: unipolar transverse fields
- Lasers can easily ionize matter, but intensities required to drive a plasma "bubble" orders of magnitude higher
- Electron bunches can drive a plasma "blowout", but intensities required to self-ionize orders of mag. higher
- PWFA: relativistic electrons move with ~c, no dephasing

LWFA



$$v_g = c\left(1 - \frac{\omega_p^2}{\omega_0^2}\right)^{1/2} < c$$

PWFA



c

ionization @~10^{14} W/cm^2 (easy)
bubble @~10^{18} W/cm^2 (hard)

ionization if E_r > 5 GV/m (hard)
blowout if $n_b > n_e$ (easy)

- Much longer acceleration distances with relativistic electron bunches (expansion vs. diffraction)

$$\omega(z) = \omega_0\sqrt{1 + \left(\frac{z}{Z_R}\right)^2} \qquad Z_R = \pi\omega_0^2/\lambda$$

free expansion:

$$\sigma_r(z) = \sigma_{r0}\sqrt{1 + \left(\frac{z}{\beta^*}\right)^2} \qquad \beta^* = \sigma_{r0}^2\gamma/\epsilon_n$$

e.g., $Z_R \approx 400\,\mu\text{m}$ at $\omega_0 = 10\,\mu\text{m}$

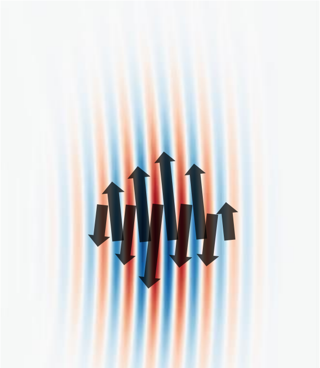
e.g., $\beta^* \approx 20$ cm at $\sigma_{r0} = 10\,\mu\text{m}$, $\gamma = 2000$, $\epsilon_n = 10^{-6}$ mrad

Hybrid LWFA & PWFA

Rethink LWFA and PWFA: laser pulses are great for ionization, while electron bunches are better drivers

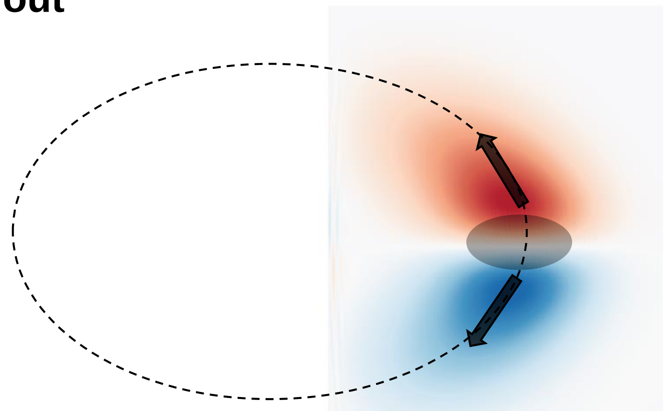
Use the best of both worlds!

Use oscillating fields from laser pulse to ionize and to generate low-transverse momentum electrons



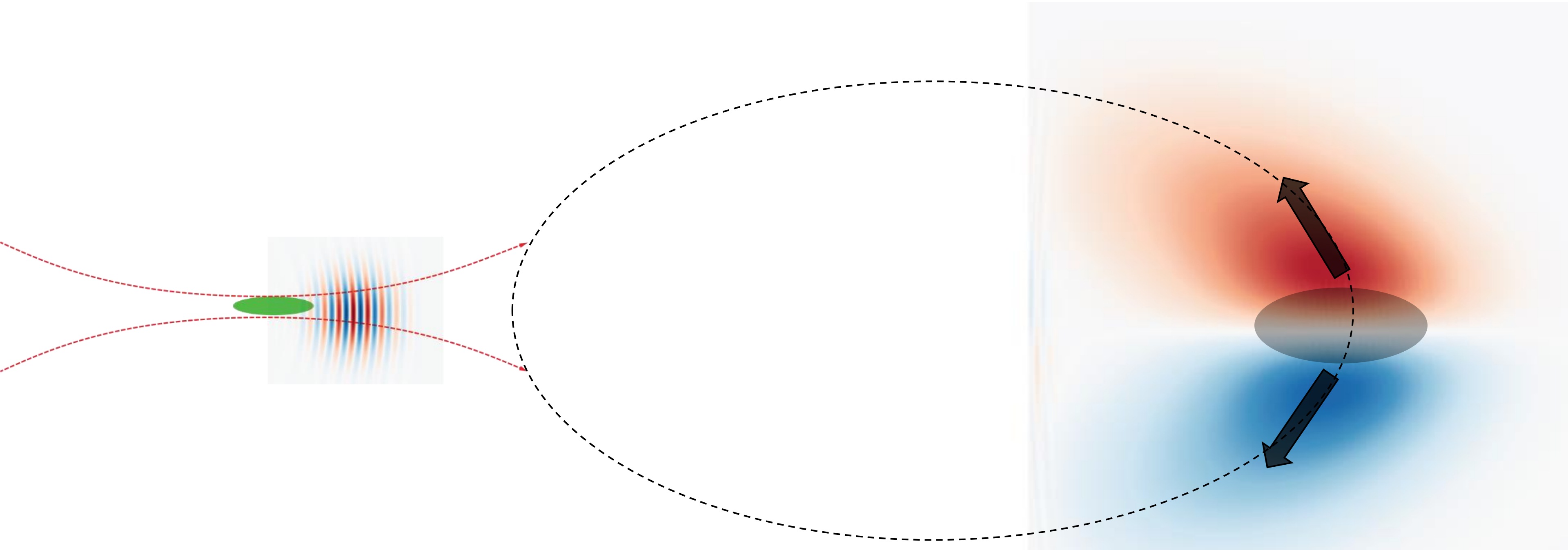
ionization @~10^{14} W/cm^2, produced electrons will receive very low transverse momentum (Lawson-Woodward)

Use unidirectional transverse fields from e-bunch to kick out electrons and to excite blowout



ionization if $E_r > 5$ GV/m
blowout if $n_b > n_e$

Combine both in media w/ at least two components:
Low-ionization-threshold (LIT), e.g. hydrogen
High-ionization-threshold (HIT), e.g. helium



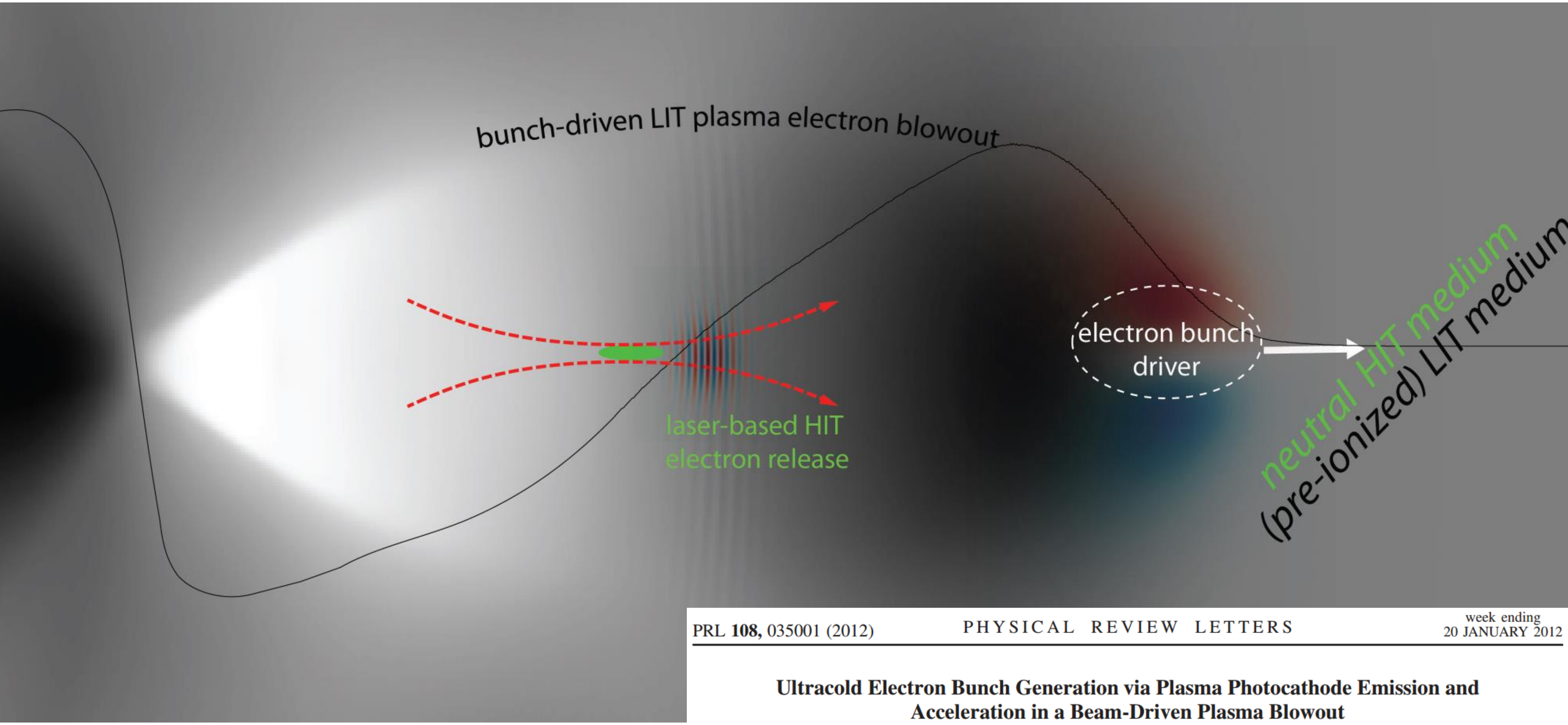
Synchronized laser pulse is strongly focused to HIT, releases HIT electrons in focus

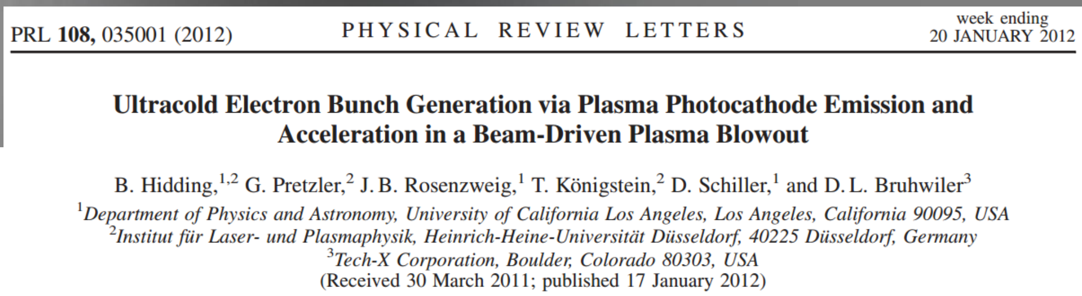
Driver bunch ionizes/expels LIT electrons, only, and excites plasma blowout

Beyond Injection: Trojan Horse Plasma Wakefield Acceleration, B. Hidding et al., AAC. APS proc. 2012

Injection: 1590–1600: Latin *injectus* past participle of *in (j) icere* to throw in, equivalent to *in*- + -*jec*- (combining form of *jac*- throw) + -*tus* past participle suffix

Underdense Photocathode PWFA




PRL 108, 035001 (2012) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2012

Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout

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[2]*Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany*
[3]*Tech-X Corporation, Boulder, Colorado 80303, USA*
(Received 30 March 2011; published 17 January 2012)

What's needed:

- LIT/HIT medium
- electron bunch driver to set up LIT blowout
- synchronized, low-intensity laser pulse to release HIT electrons within blowout

Various Potential LIT/HIT media candidates Applicable w/ conventional acc. and LWFA alike

For example

- gaseous H (13.6 eV)/He (24.6 eV)
- alkali metals Li, Na, Rb, Cs (~5 eV)/He (24.6 eV)
- Rb (4.2 eV)/Rb^+ (27.3 eV)
- Cs (3.9 eV)/Li (5.4 eV)

You want the lowest ionization thresholds (to decrease the transverse electron momentum), and a reasonable gap between LIT and HIT medium (ionization corridor)

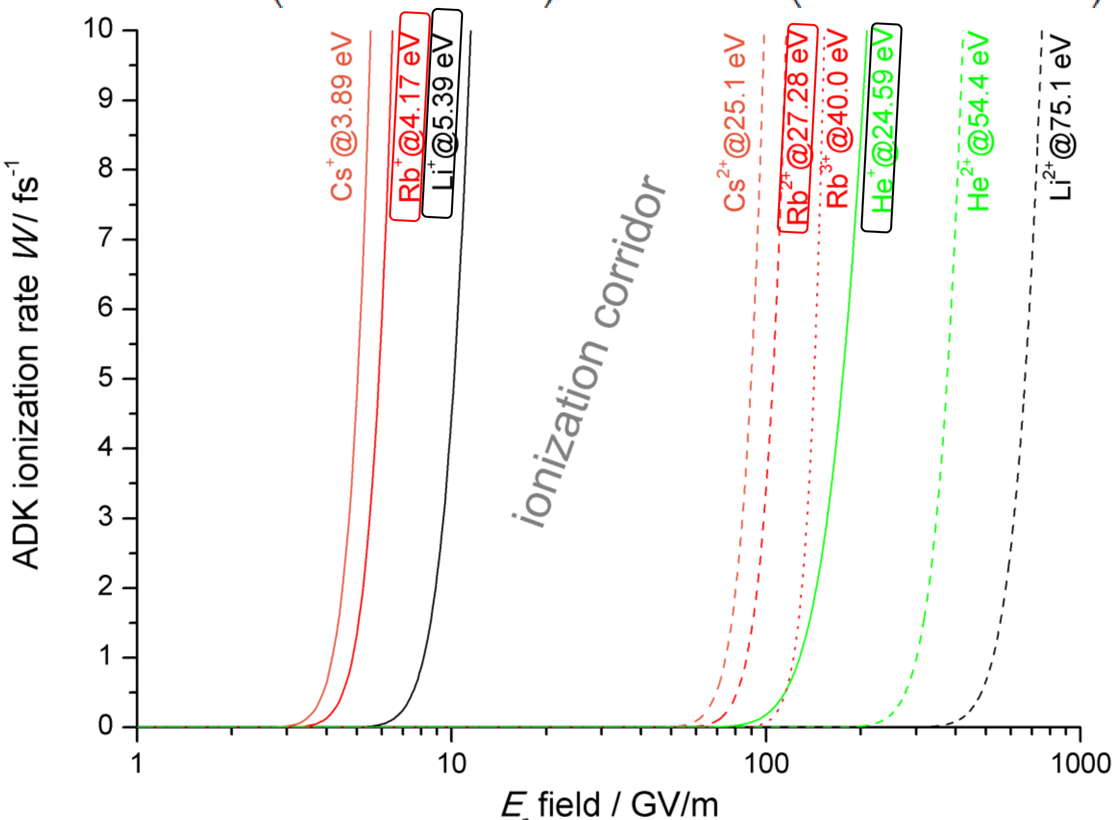
ADK ionization rates: $$W(\mathrm{s}^{-1}) \approx 1.52 \times 10^{15} \frac{4^{n^*} \xi_i [\mathrm{eV}]}{n^* \Gamma(2n^*)} \left(20.5 \frac{\xi_i^{3/2} [\mathrm{eV}]}{E [\mathrm{GV/m}]}\right)^{2n^*-1} \times \exp\left(-6.83 \frac{\xi_i^{3/2} [\mathrm{eV}]}{E [\mathrm{GV/m}]}\right)$$

Near future @ FACET:

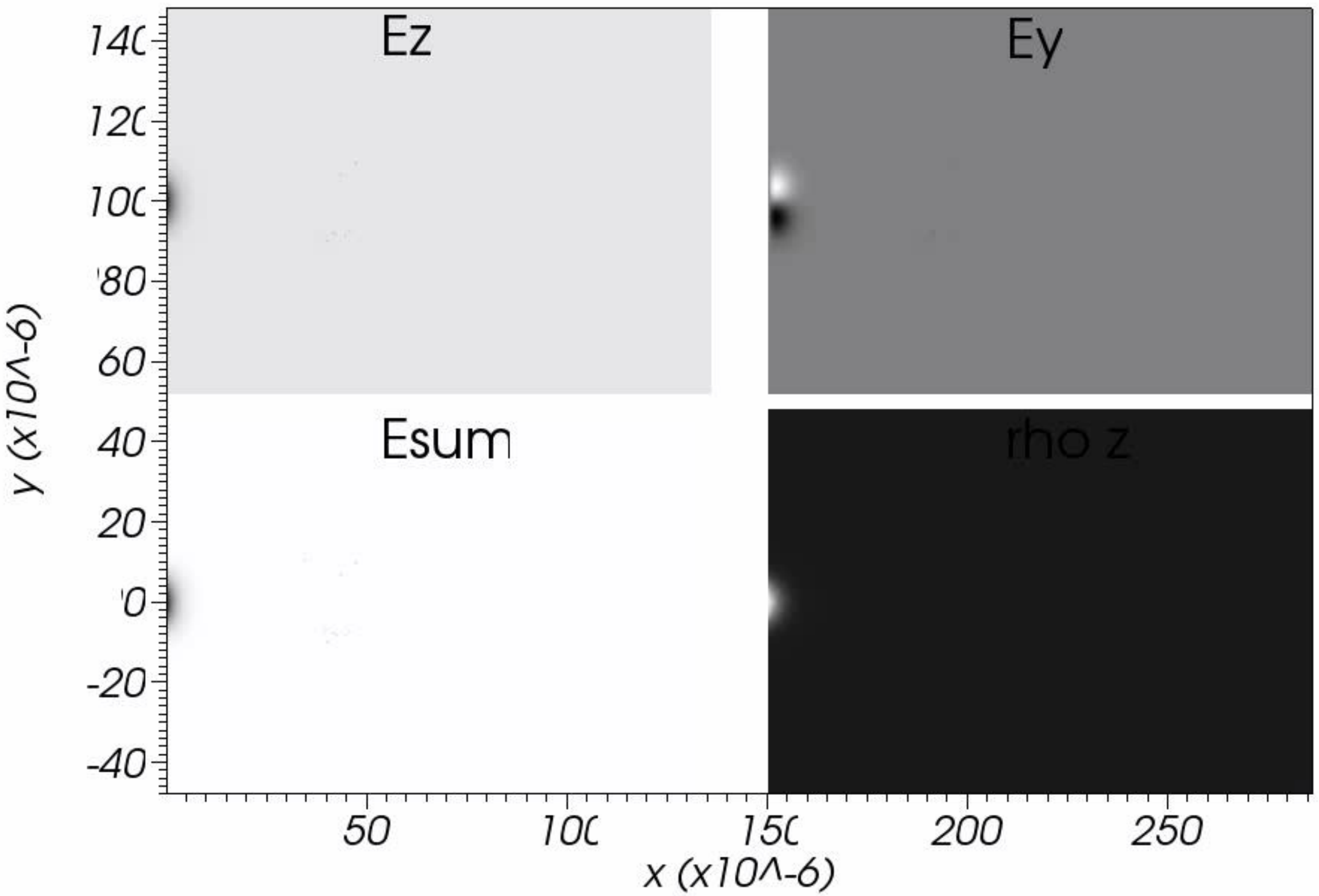
Li (ξ_i = 5.4 eV/He (ξ_i = 24.5 eV)

Rb (4.2 eV)/Rb^+ (27.3 eV)
Ar (15.8 eV)

SLAC and FLASH bunches have bunch parameters which are on the verge of self-ionizing alkali metals: R&D in Hamburg on (partial) preionization of alkali metal vapors → plasma lense → assisted self-ionization



Released electrons are compressed, trapped and then co-propagate dephasing-free at the end of the blowout



Both accelerating cavity and photocathode are co-moving in phase with the released electrons

Release laser:
Ti:Sapph, 800 nm,
25 fs, a_0=0.015, self-ionization of LIT medium by electron bunch

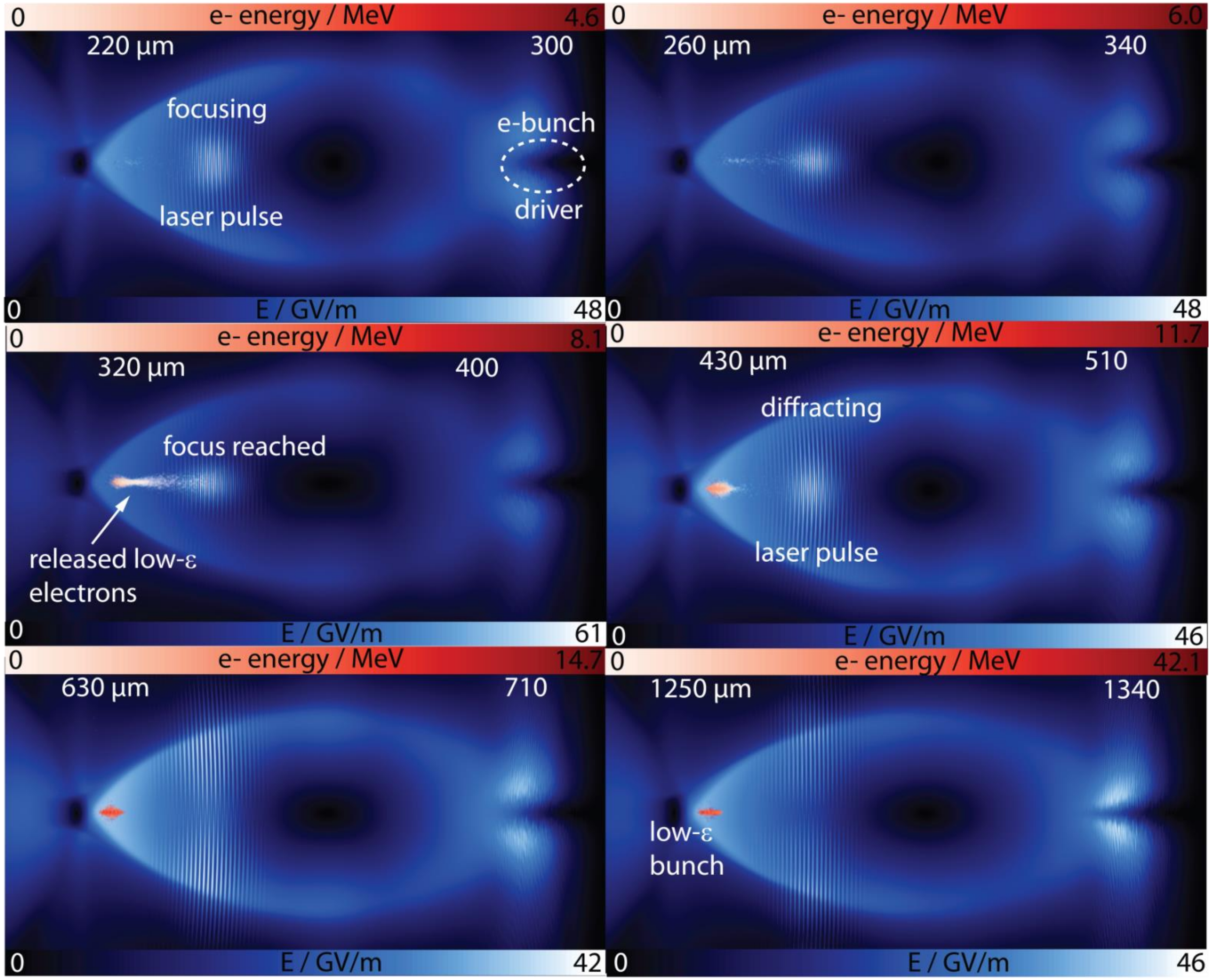
All simulations w/

VORPAL

TECH-X UK

Laser pulse intensity is crucial

Focus laser pulse intensity has to be just above the ionization threshold of the HIT medium (e.g., helium).



In contrast to LWFA schemes (~10^{18}-10^{19} W/cm^2), here the laser pulse intensity is of the order of ~10^{14}-10^{15} W/cm^2, only.

→ Transverse momentum of bunch electrons is very low → direct consequences for emittance & brightness!

What's the obtainable emittance (in collinear geometry)?

Rough estimation of laser contribution to normalized emittance:

$$\epsilon_{\mathrm{n}} \approx \sigma_{r\mathrm{HIT}}\sigma_{p_r,\mathrm{HIT}}/(mc) \approx w_0 a_0 / 2^{3/2}$$

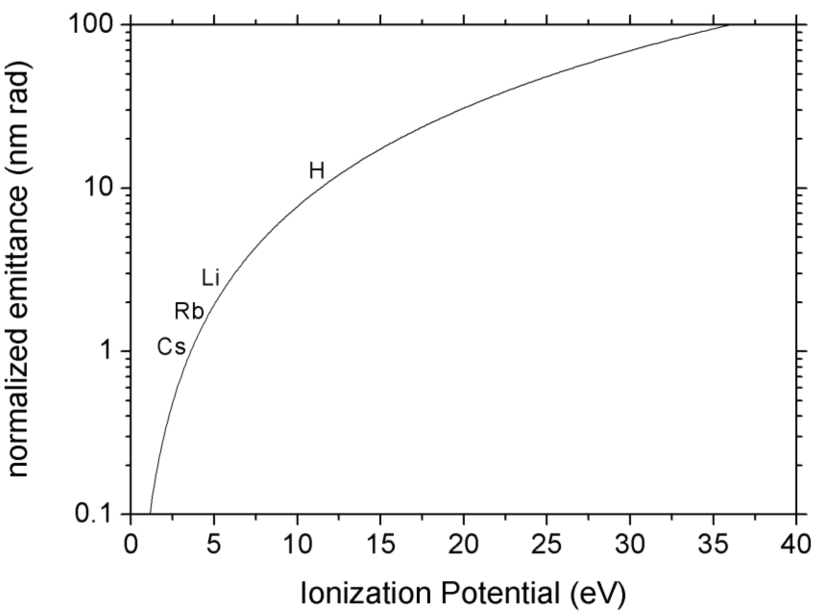
ω_0: laser focus size, a_0: laser potential

B. Hidding et al., PRL 108, 035001, 2012
Y. Xi et al., PRSTAB 2013
DE patent 2011, US patent 2012

Barrier Suppression Ionization

$$I_{\mathrm{BSI}}\,[\mathrm{W/cm^2}] \approx 4\times 10^9 \frac{\xi_i^4\,[\mathrm{eV}]}{Z^2} \qquad a_0 = \left(\frac{I}{2\epsilon_0 c}\right)^{1/2} \frac{e\lambda}{\pi m_e c^2}$$

HIT medium	ionization potential	I_{BSI} / W cm^{-2} @ 800 nm	a_0 at BSI threshold	$\varepsilon_{n,x} \approx \omega_0 a_0$ / 2.8 ω_0 = 5 μm
Cs	3.9 eV	9.2×10^{11}	0.00065	1.2×10^{-9} m rad
Rb	4.2 eV	1.2×10^{12}	0.00075	1.3×10^{-9} m rad
Li	5.4 eV	3.4×10^{13}	0.00126	7.1×10^{-9} m rad
H	13.6 eV	1.4×10^{14}	0.008	1.4×10^{-8} m rad
Cs+	25.1 eV	4.0×10^{14}	0.01362	2.4×10^{-8} m rad
Rb+	27.3 eV	5.6×10^{14}	0.016	2.8×10^{-8} m rad
He	24.5 eV	1.4×10^{15}	0.026	4.6×10^{-8} m rad
Li+	75.6 eV	3.2×10^{16}	0.125	2.2×10^{-7} m rad

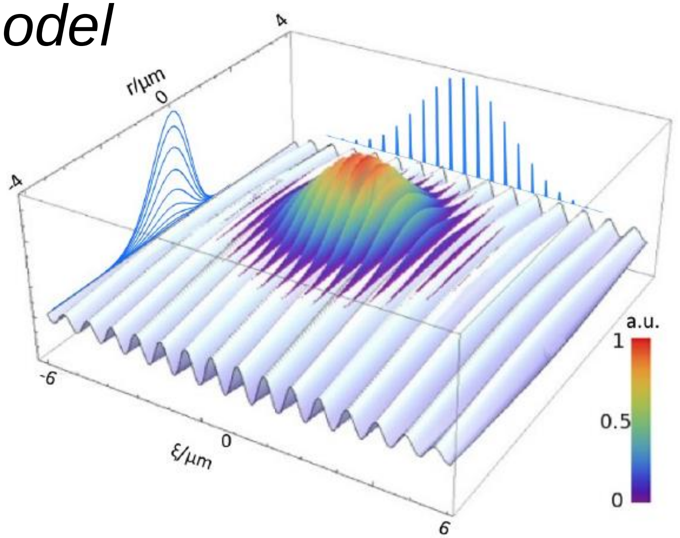


Note:

- *Barrier Suppression Ionization is an upper limit*
- *This is all in laser polarization plane → ε_n further decreased in perpendicular plane*
- *At 800 nm → ε_n further decreased w/ higher frequencies →* ***ε_n down to 10^{-10} m rad possible?***

PIC simulation results d'accord with hybrid model

Y. Xi et al., PRSTAB, 2013

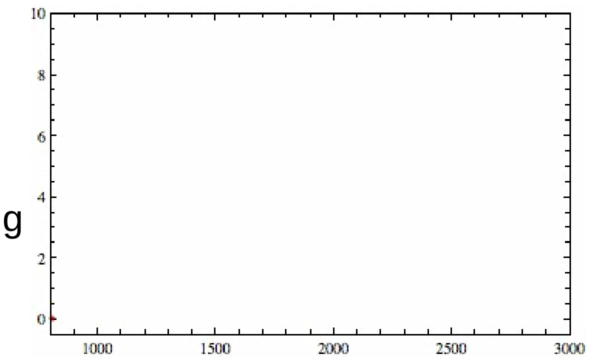


- Ionization based on ADK and YI (Yudin-Ivanov-model). *G. L. Yudin and M. Y. Ivanov, Phys. Rev. A, 64:013409, 2001.*

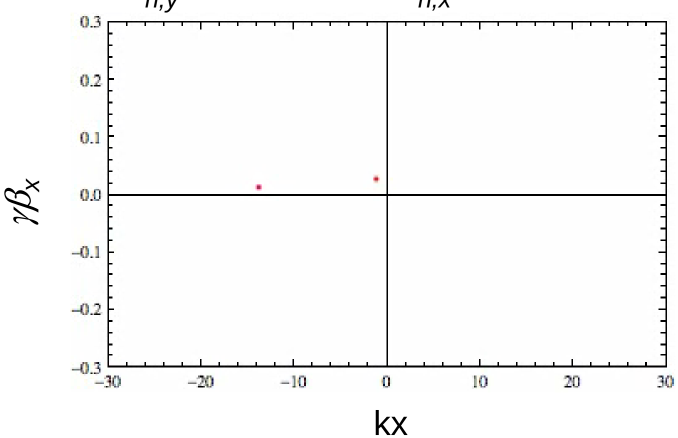
- Detailed numero-analytical analysis shows that $\varepsilon_{n,y}$ is about an order of magnitude lower, and increases slower than $\varepsilon_{n,x}$ as intensity increases. $\varepsilon_{n,y}$ down to the $\varepsilon_{n,y} \approx 10^{-9}$ m rad level or less.

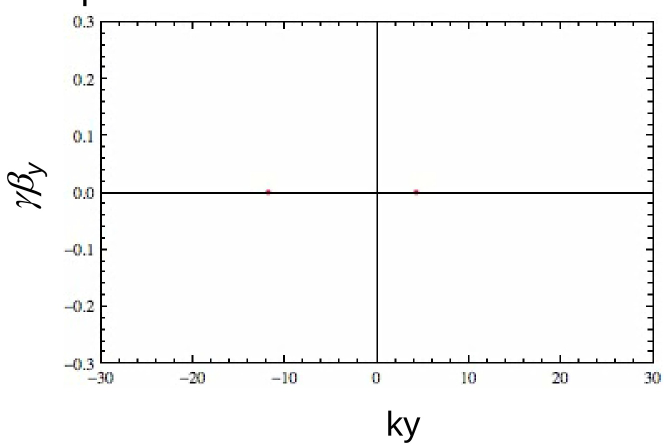
	RF photoinjector	underdense photocathode
beam emittance sources	RF field	ponderomotive motion
	thermal effects	phase mixing
	space charge	space charge

plasma velocity bunching



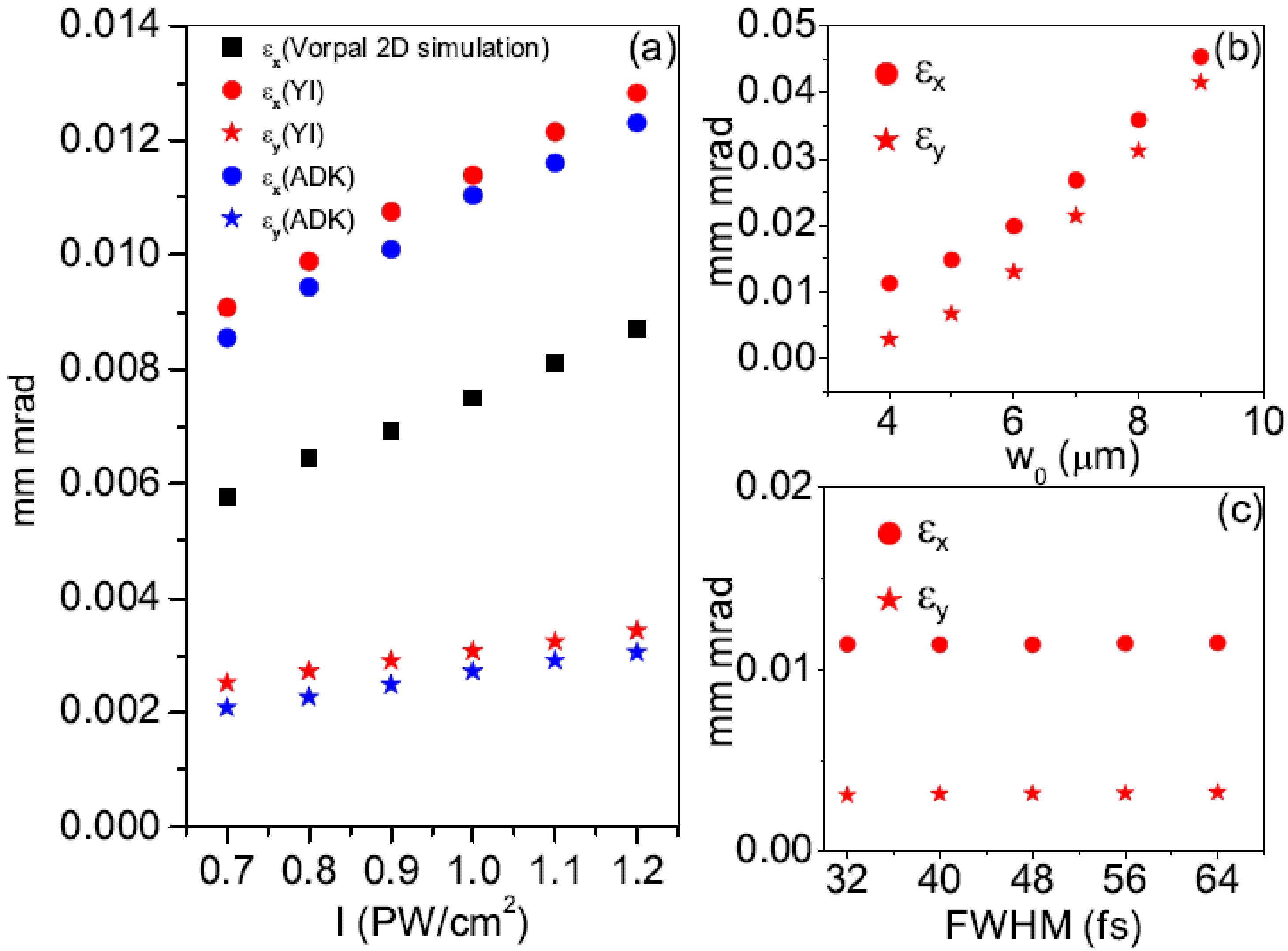
Laser linearly polarized in x-direction:
$\varepsilon_{n,y}$ smaller than $\varepsilon_{n,x}$ due to absence of ponderomotive motion





PIC simulation results d'accord with hybrid model

Y. Xi et al., PRSTAB, 2013



Very good agreement w/ crude laser contrib- only scaling

$$\epsilon_{\rm n} \approx \sigma_{r{\rm HIT}}\sigma_{p_r,{\rm HIT}}/(mc) \approx w_0 a_0 / 2^{3/2}$$

Emittance is the key!
for FEL, HEP…

- Ultralow emittance yields ultrahigh electron beam brightness even at low charge

$$\text{e.g., at } Q \approx 1pC,\ \sigma_z \approx 2.5\,\mu\text{m},\ I_p \approx 120\text{ A}$$
$$\Longrightarrow B \approx 2I_p/\epsilon_\text{n}^2 \approx 10^{19} - 10^{20}\ \text{Am}^{-2}\text{rad}^{-2}$$

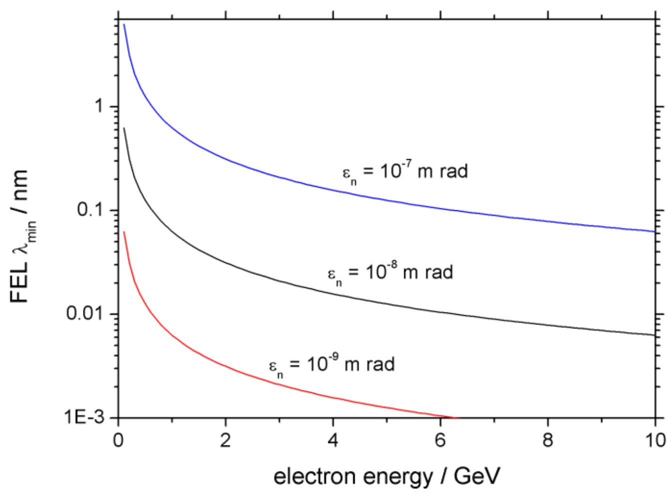
→ photon brightness
exceeds those of LCLS by wide margin

- gain length $L_{g,1D} = \dfrac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}} \propto B_e^{-1/3}$

exceeds those of LCLS by wide margin

- minimum theoretical FEL wavelength

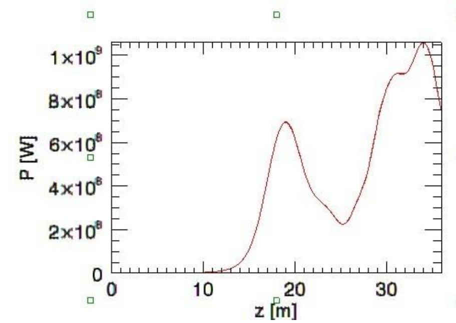
$$\text{e.g., with } \epsilon_n = 1 \times 10^{-9}\,\text{m rad at 1 GeV} \Longrightarrow \lambda_\text{min} \approx 4\pi\epsilon_\text{n}/\gamma < 0.1\text{Å}$$



exceeds those of LCLS by wide margin

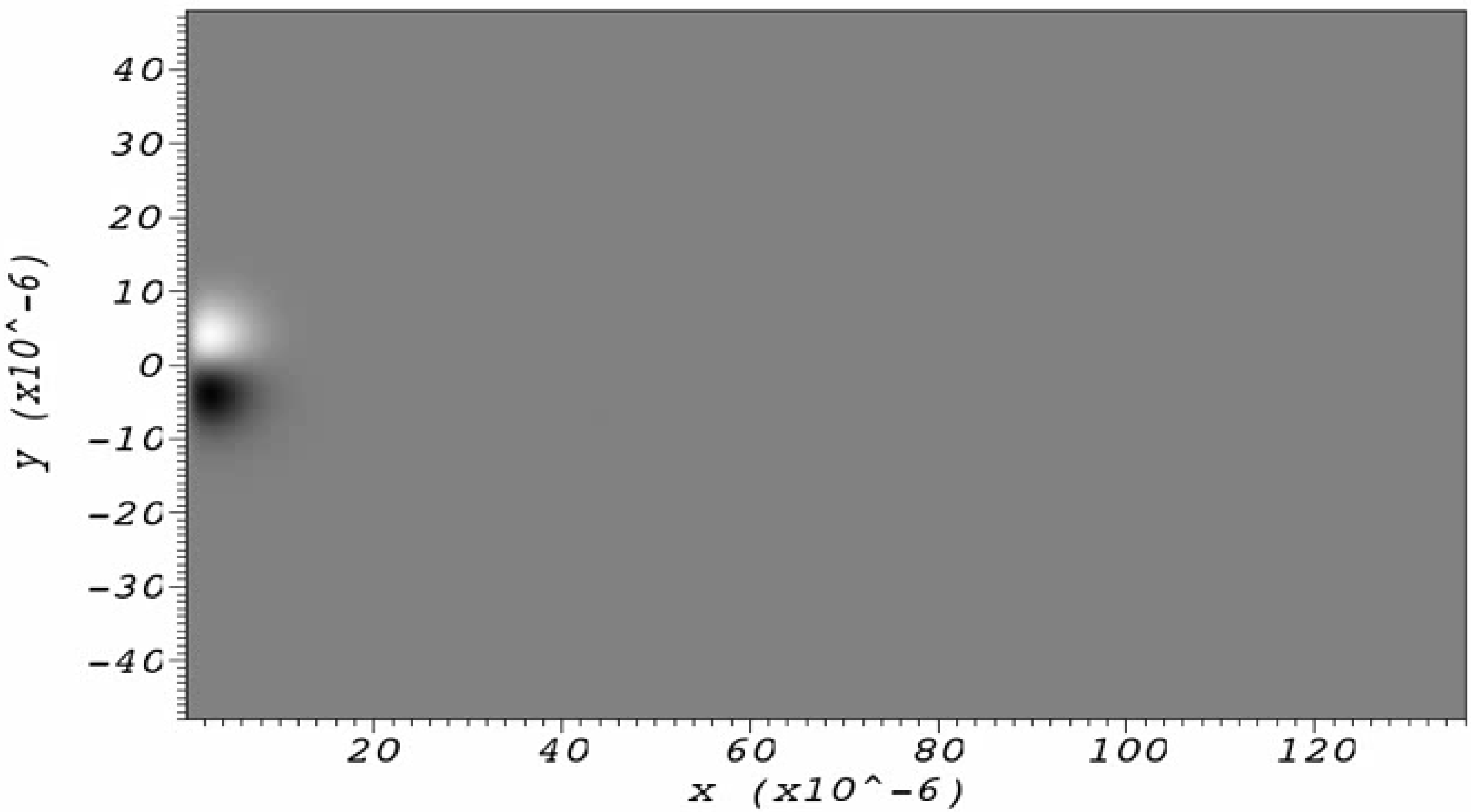
GENESIS calculation for 2 pC bunch, ε_n = 3 × 10^{-8} m rad (only)
w/ "Finndulator" as in O'Shea et al., PRSTAB 13, 070702 (2010),
4.3 GeV: LCLS performance after 20 m!

(First FEL calculations for the Trojan scenario, done in 2011)



- not "only" for X-ray FEL, also colliders need extremely high beam quality $L = \dfrac{fN^2}{4\pi\sigma_x\sigma_y}$

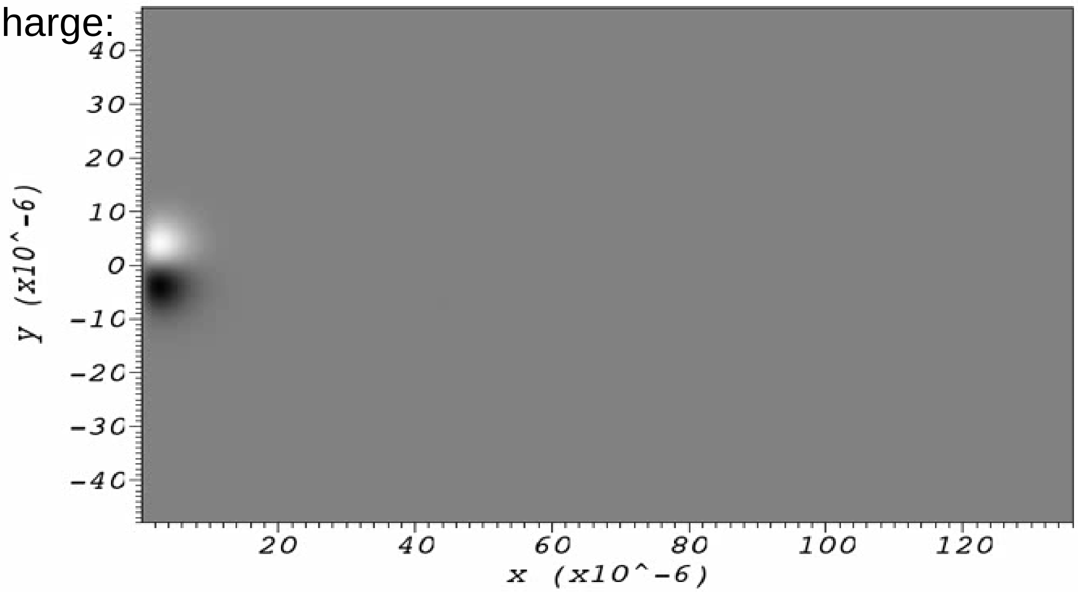
Work at higher laser frequencies, lower intensities and tight focusing: Attosecond electron bunches possible



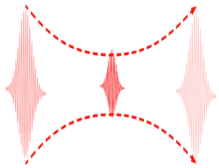
Tunability: charge

Tune charge via laser intensity, spot size and focusing (Rayleigh length)

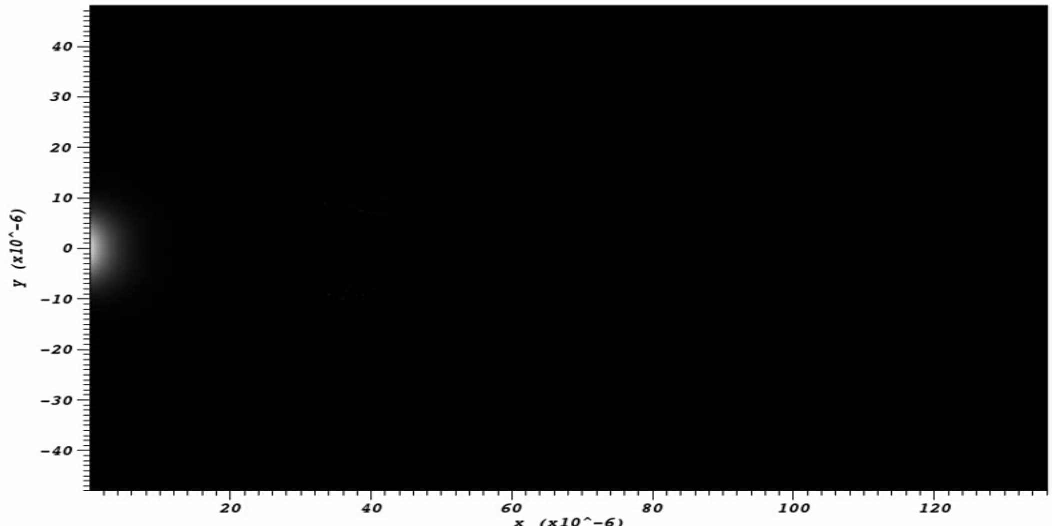
Low charge:



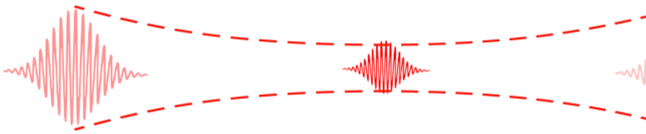
Low laser intensity, short Rayleigh length

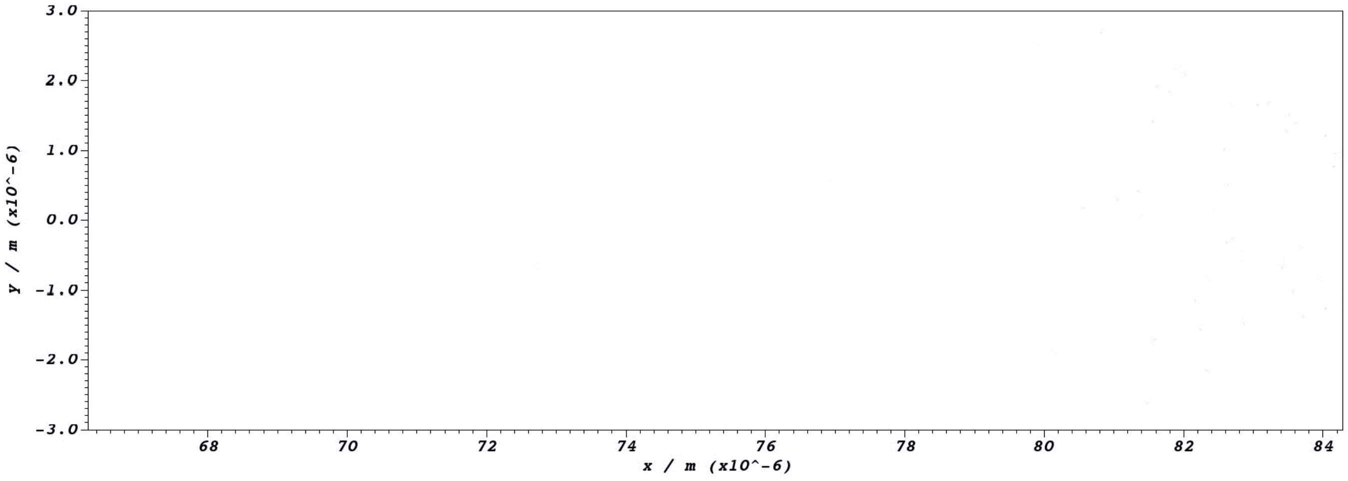


High charge:

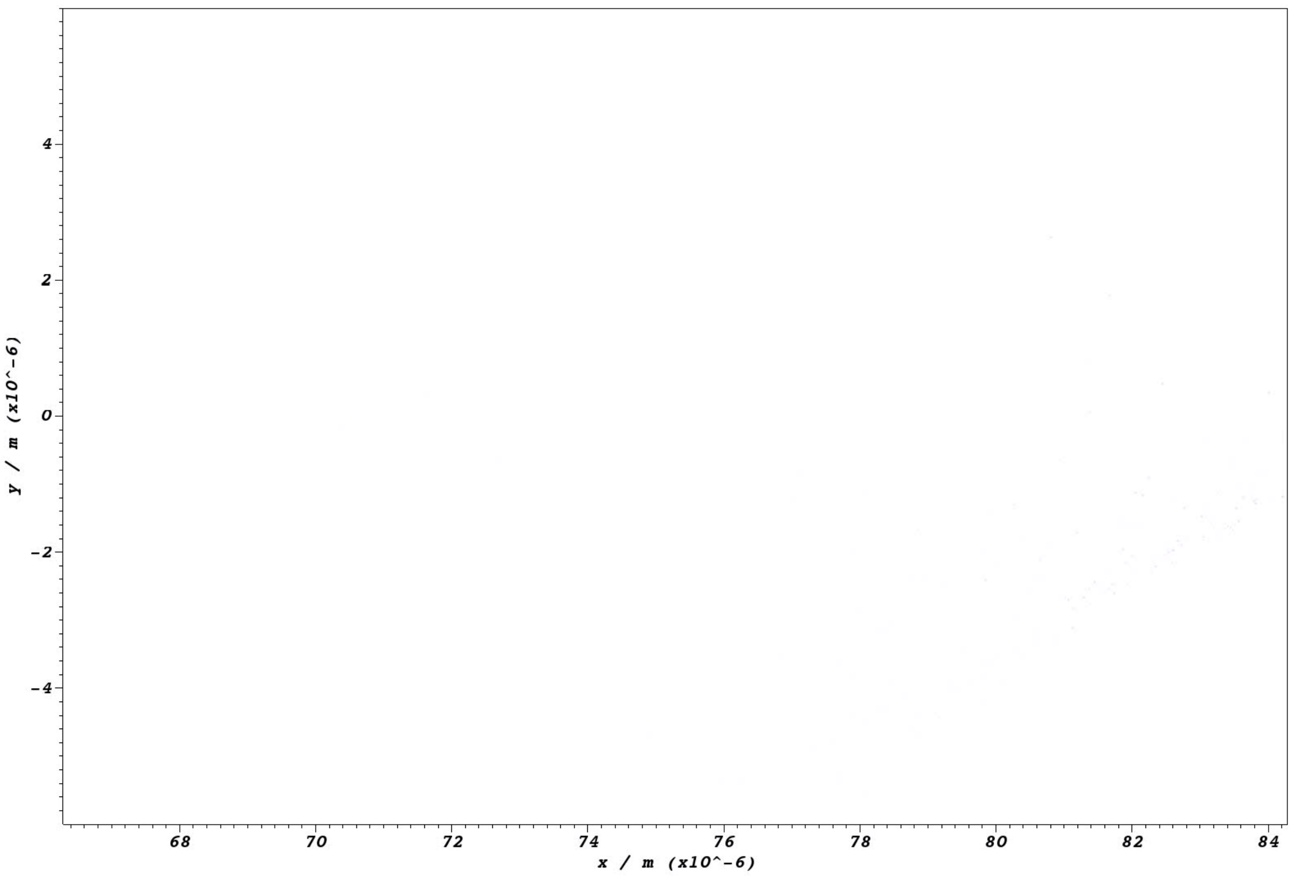


Higher laser intensity, longer Rayleigh length



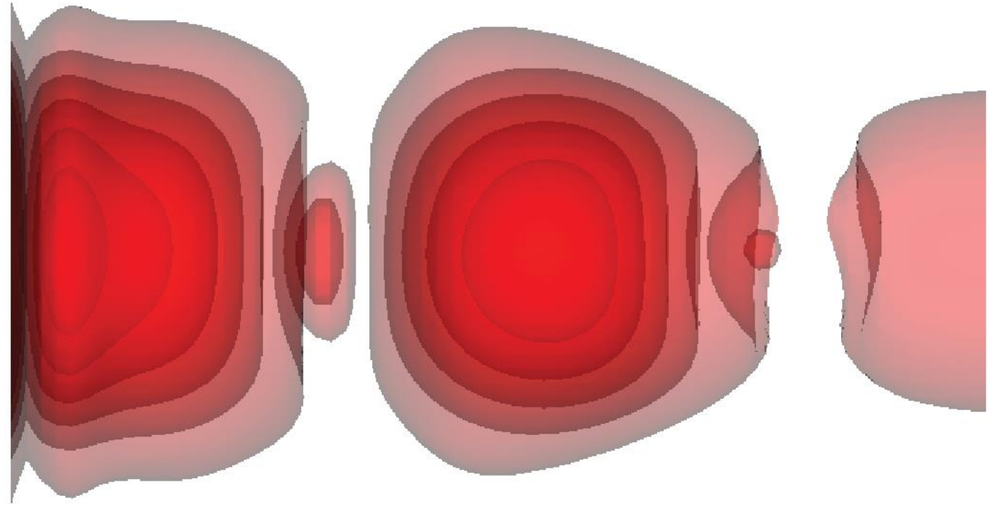


Unique electron fine “snake” structure reflects compressed laser pulse field maxima
→ Coherent radiation + HHG, e.g. in undulator (à la Stupakov et al., PRSTAB 16, 010702, 2013)



Off axis (e.g., 3 micron) electron release yields controlled betatron oscillations

Multi-bunch production

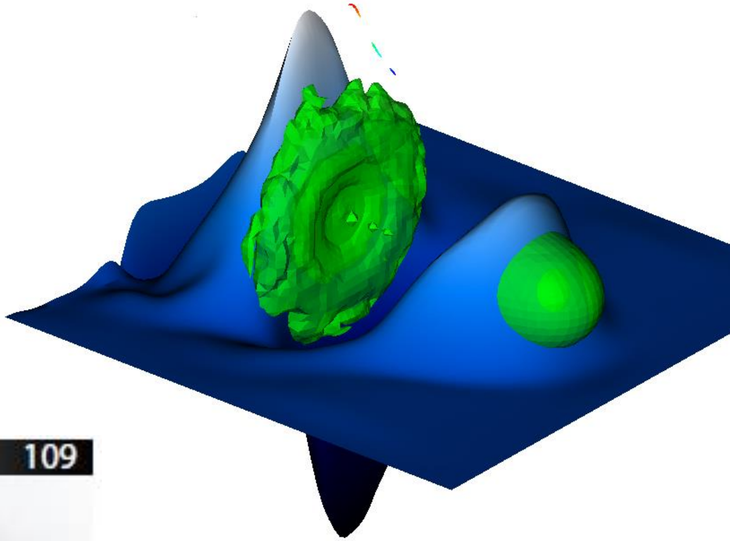


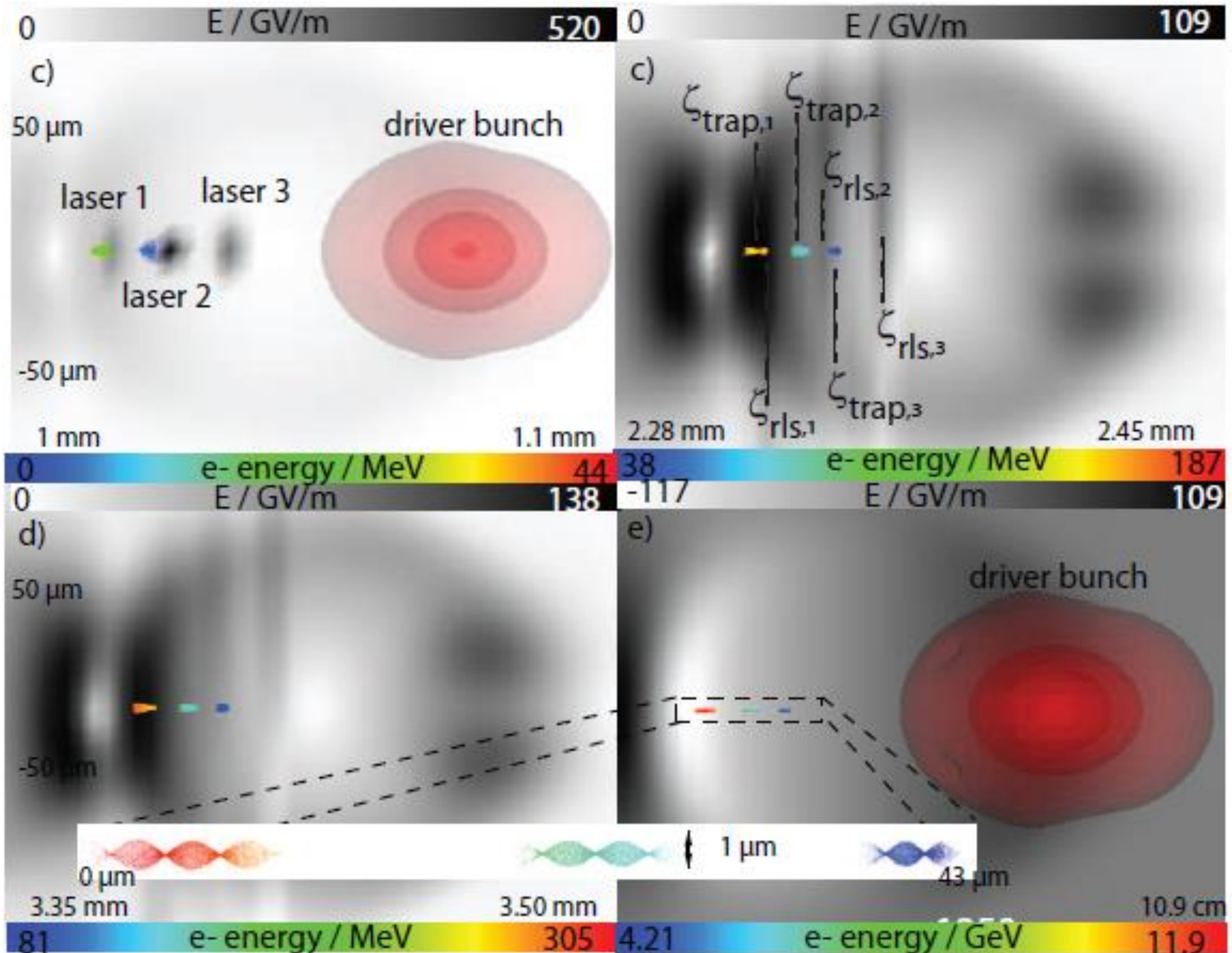
If the wake’s potential is large enough: trapping possible at various positions

Using multiple rls laser pulses leads to multi-bunches

FACET parameters, using Plasma/Li+ as LIT/HIT media

Multi-bunch production

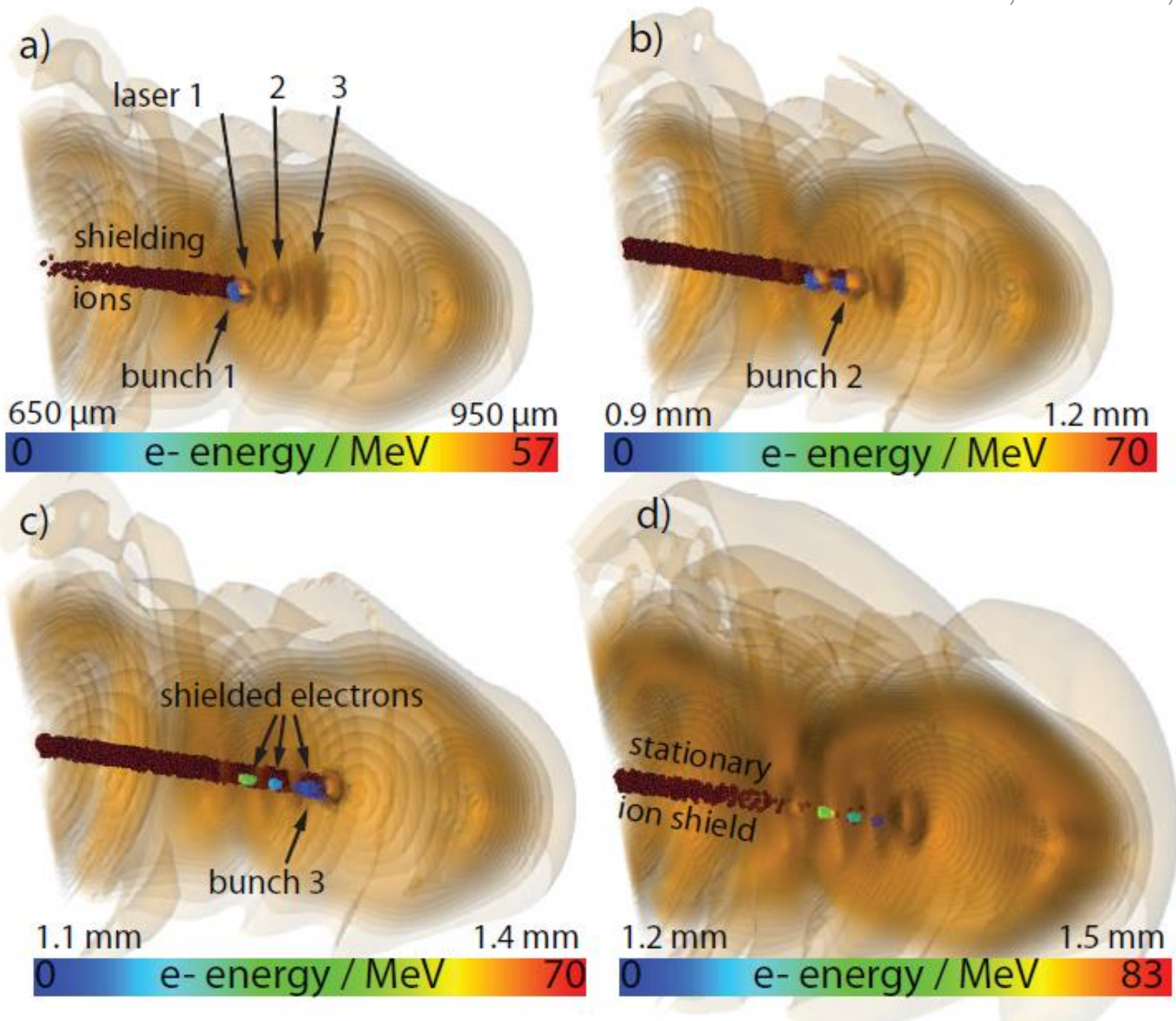




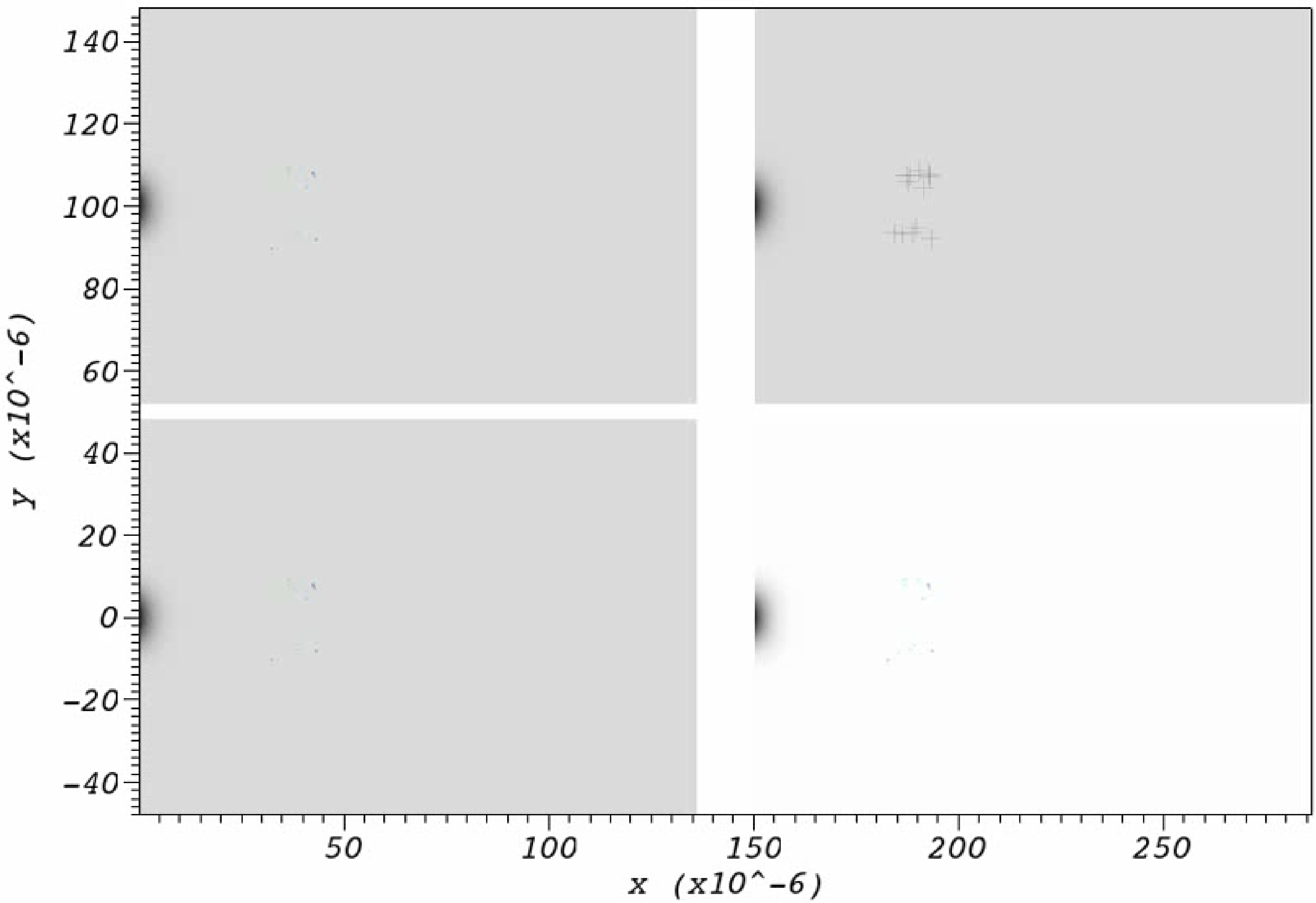
Multi-bunch production

Ion shield suggests focus position/release order & distance between rls positions $\zeta_{\mathrm{rls,n}} < \zeta_{\mathrm{rls,n+1}}$
in co-moving and lab frame

$z_{\mathrm{rls},1} < z_{\mathrm{rls},2} < z_{\mathrm{rls},3}$

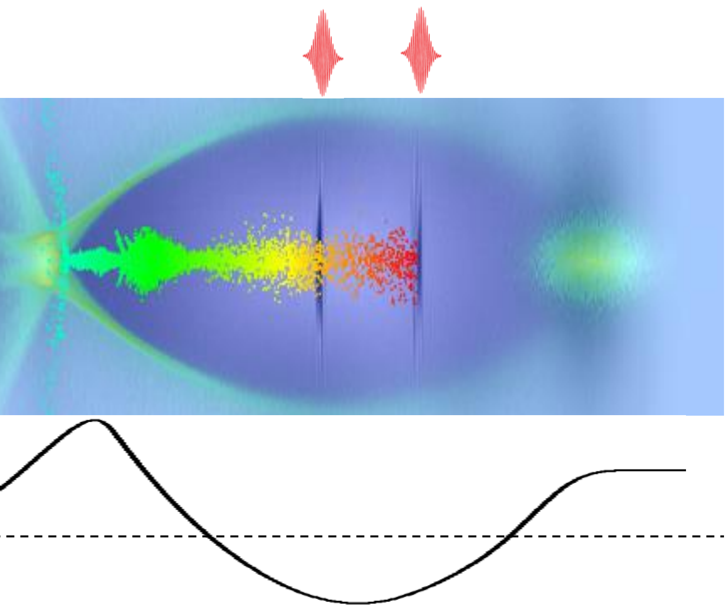


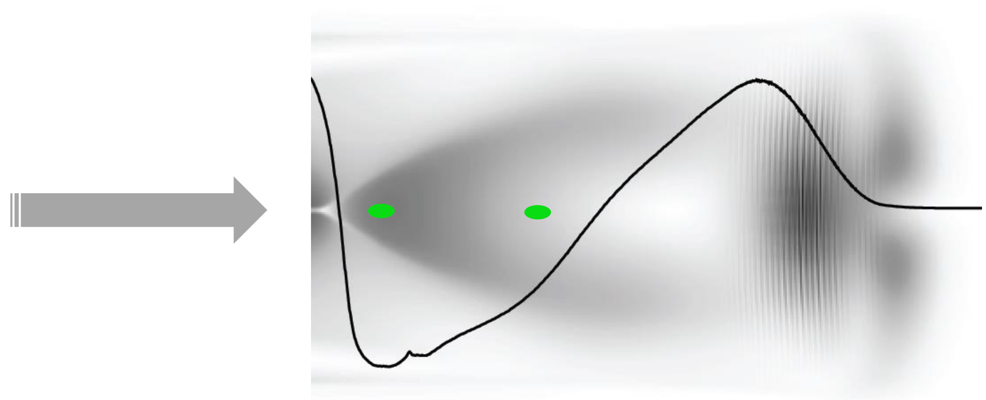
Photocathode + Space Charge Screening



Tunable, lowest emittance multi-color FEL

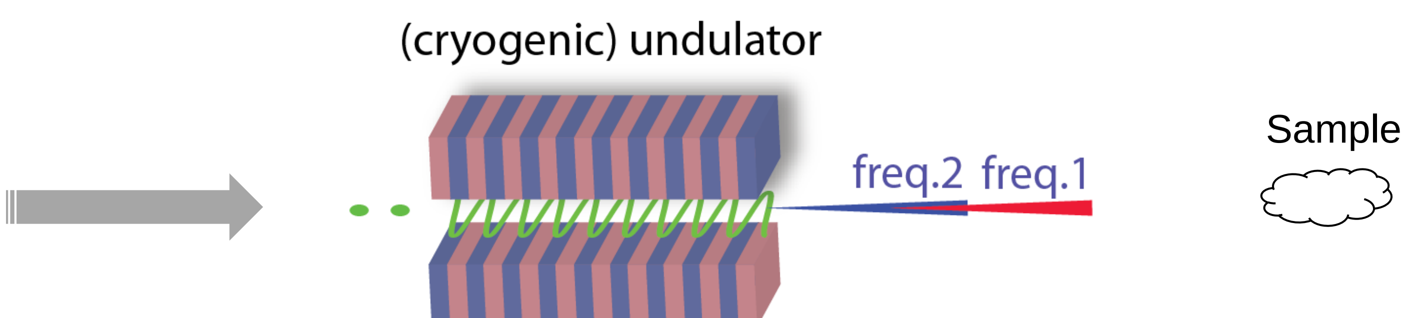
Multiple laser pulses (~50 µJ each) generate multiple bunches of highest quality, separated by few µm





trapping threshold potential Ψ_{trap}

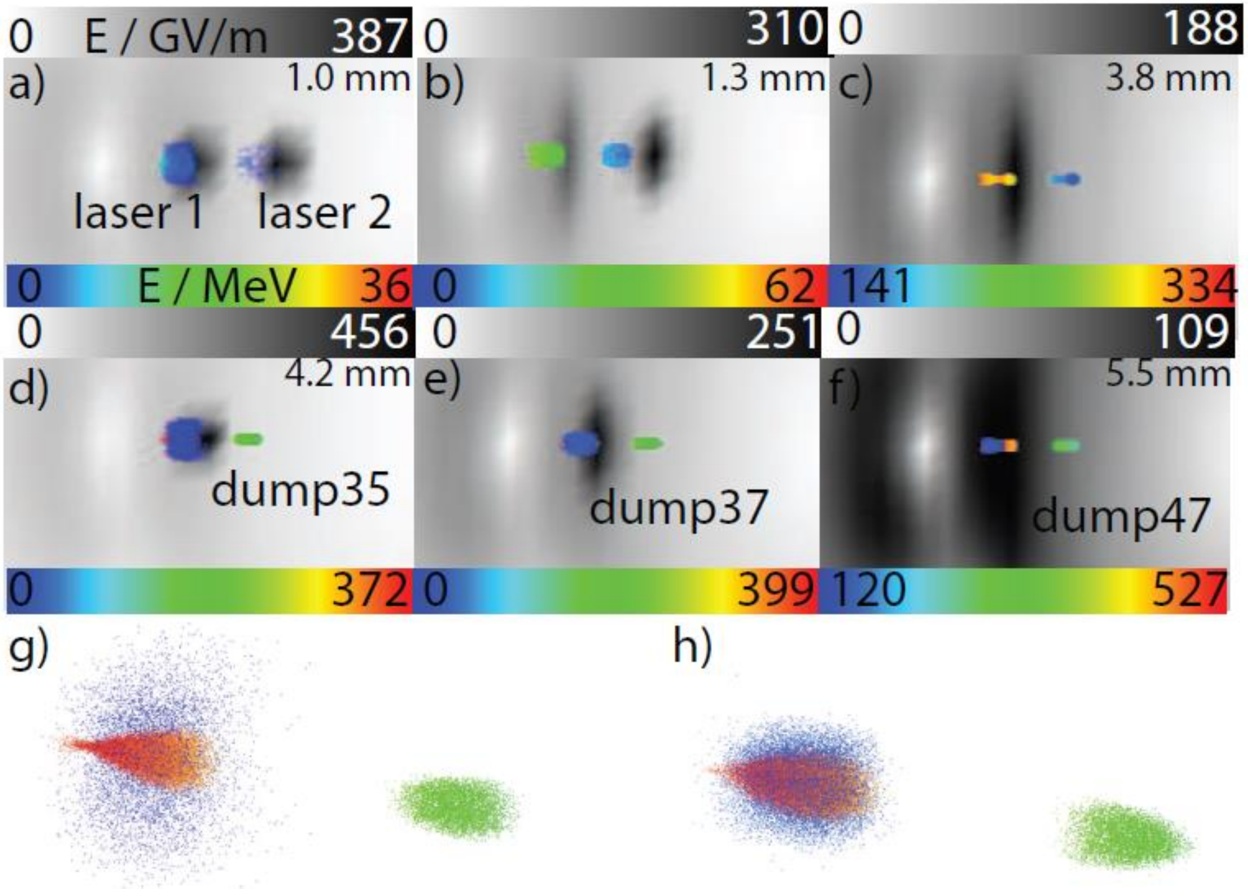
Electron bunch energies correlated to inter-bunch distance & release position, tunable in wide range



B. Hidding et al., to be submitted

Multi-bunch production

Energy tuning can be done by variation of release position in co-moving frame $\zeta = z - ct$ as well as in lab frame *z*



This way, fancy constellations can be produced: i.e. overlapping bunch hot and cold electron population, largely independent energy and delay tuning between bunches etc, bunch current shaping etc., tailored beam loading..

Preliminary PUFFIN 1D calculations

B. McNeill, L. Campbell

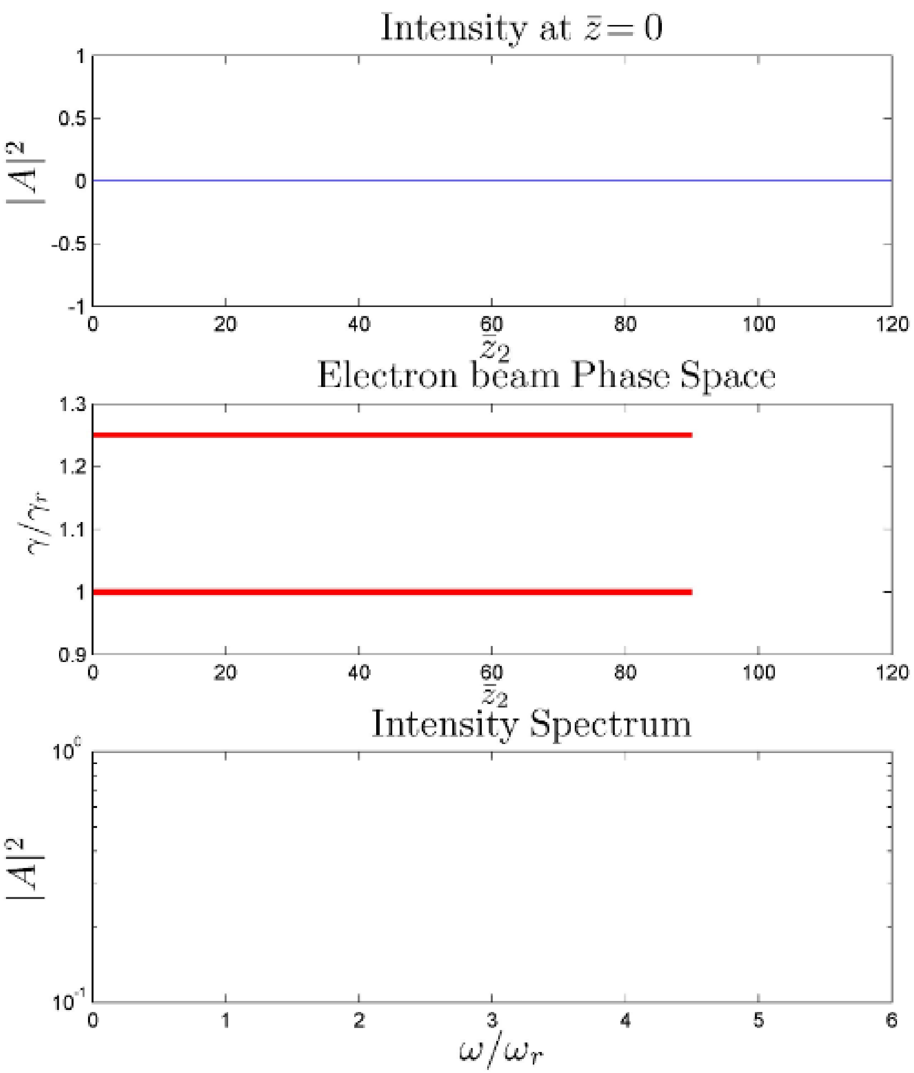
3d code: Phys. Plasmas 19, 093119 (2012)

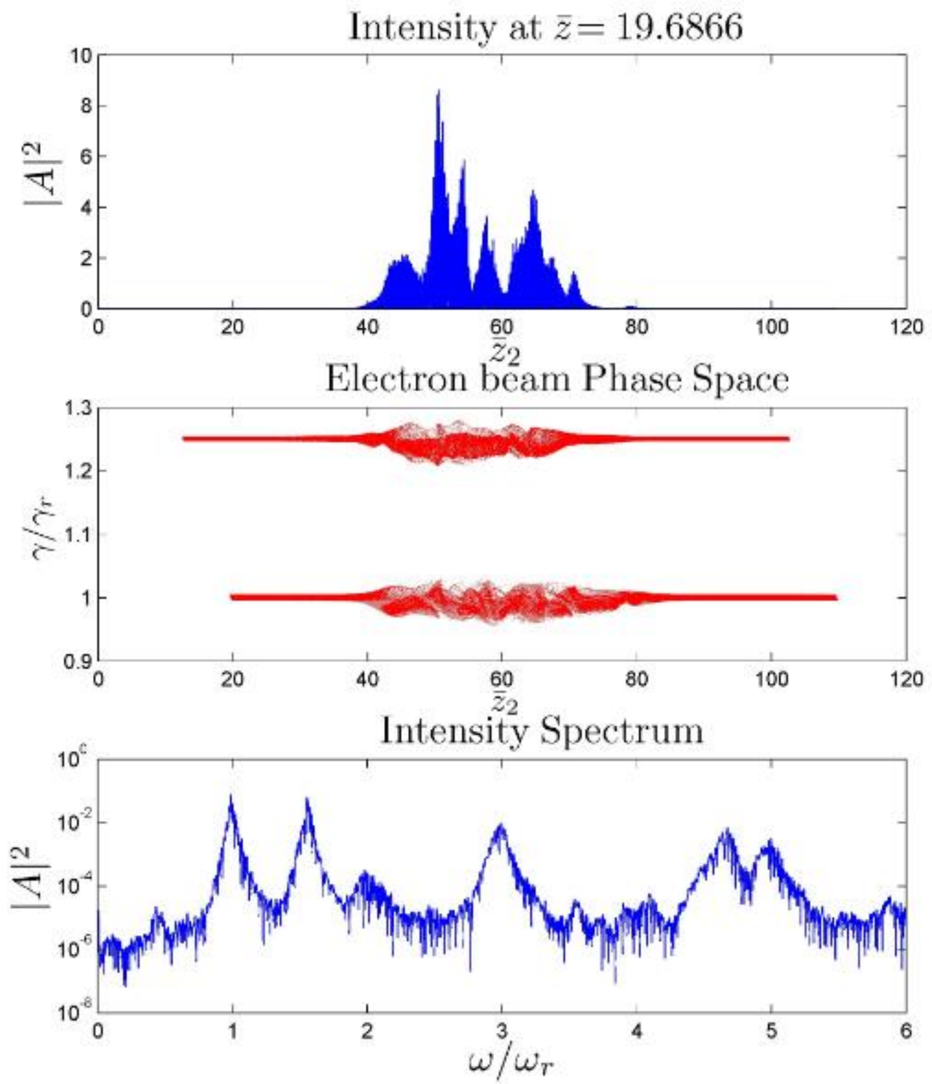
Preliminary PUFFIN 1D calculations
3d code: Phys. Plasmas 19, 093119 (2012)

B. McNeill, L. Campbell

University of Strathclyde Glasgow

Overlapping case:





Where/when to realize it?

FACET/SLAC

E-210 “Trojan Horse PWFA“ expt., beamtime for 2014/15

+ stable driver beam
+ high energy beam
+ most extensive PWFA experience
- synchronization difficult
- Ionization/preionization difficult

  Until recently!

Milestone: If this works, and if also the confidence level in extractable emittance is high enough → raise funding for Trojan FEL facilitie(s)

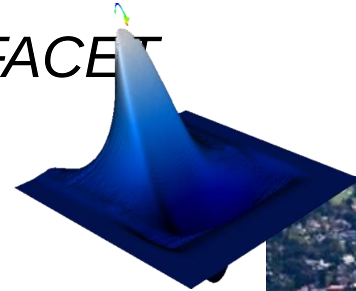
Photoinjector facilities (FLASHForward, FACET-II, SINBAD, CLARA?…)

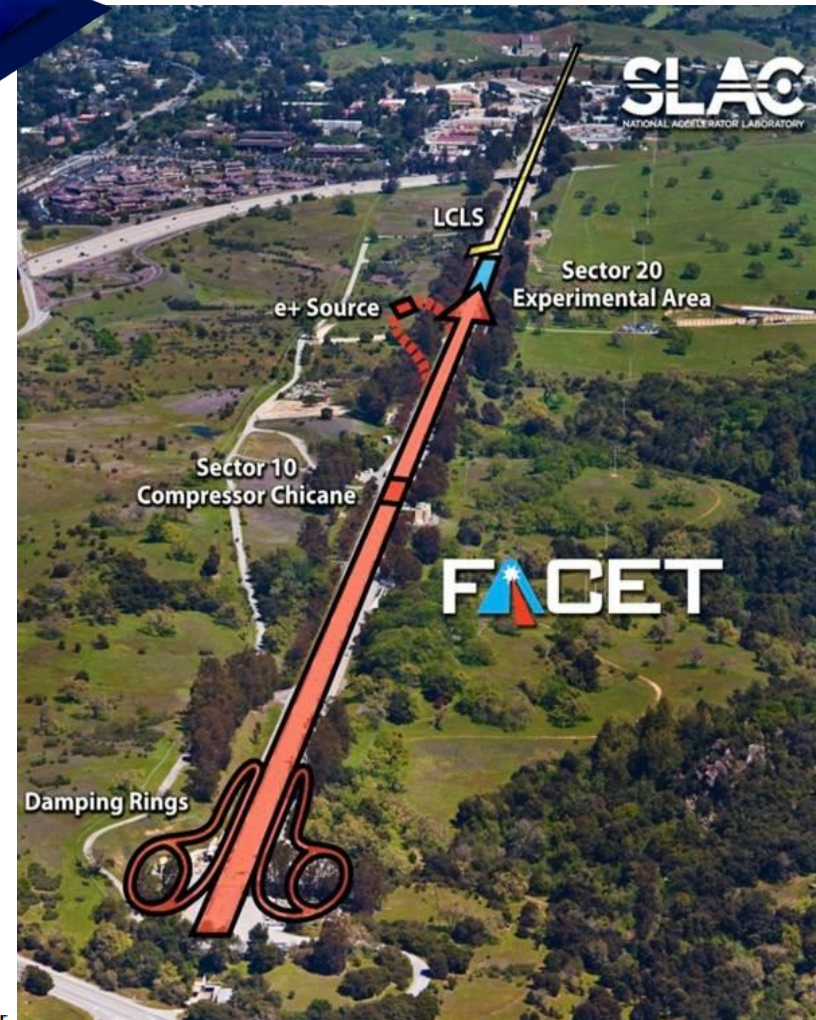
+ very stable beam, high rep rate
- no facility online yet / no plasma acc. expmts. done yet
- not before 2016 (FLASHforward..)

Laser-Plasma-Accelerators worldwide (Strathclyde, Frascati, Jena, RAL, UHH/DESY…?)!

+ availability & cost-effectiveness
+ inherent perfect synchronization between electron bunch and Trojan release pulse
- instable performance
- no purposeful PWFA experiment has been demonstrated yet
- so far low (10 Hz) rep rate for 100 MeV+ beams

E-210 Trojan Horse PWFA @ FACET



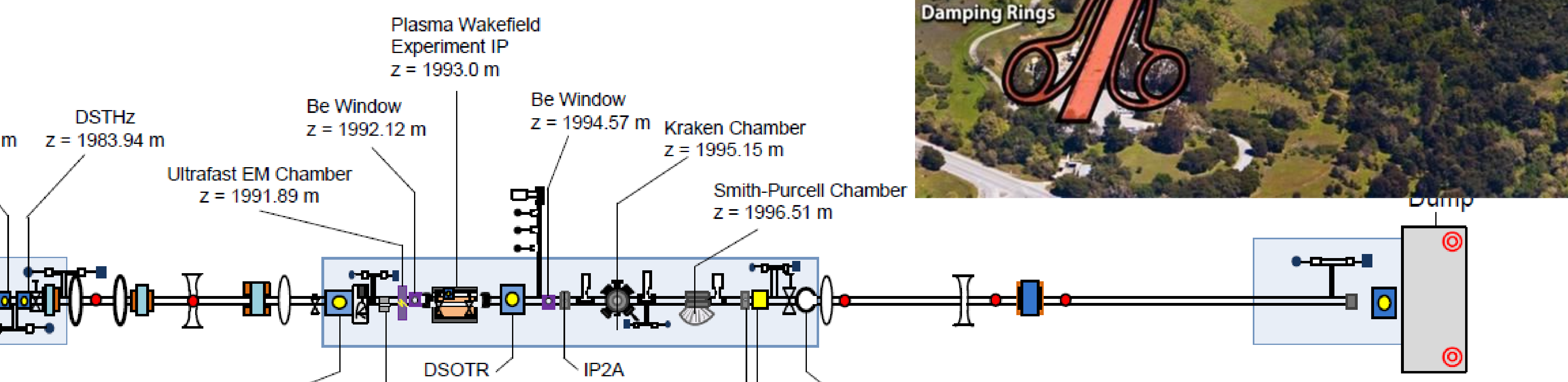


Pros:

- stable electron driver beam, can self-ionize Rb
- High energy bunch: 23 GeV
- 10-TW Laser system to be installed (until May 2013) for preionization (E-200 expt.) and E-210 expt.

Cons:

- Laser-jitter to master clock expected to be +-40 fs
- Electron beam jitter < 1 ps
- Needs 2 km accelerator



Hybrid Trojan Horse-based Future FEL facility?

w/ M. Hogan (SLAC) et al., 5th Generation Light Source Workshop, 2013

A Plasma Wakefield Accelerator Driven Compact X-FEL
Plasma is Energy AND Brightness Transformer

SLAC

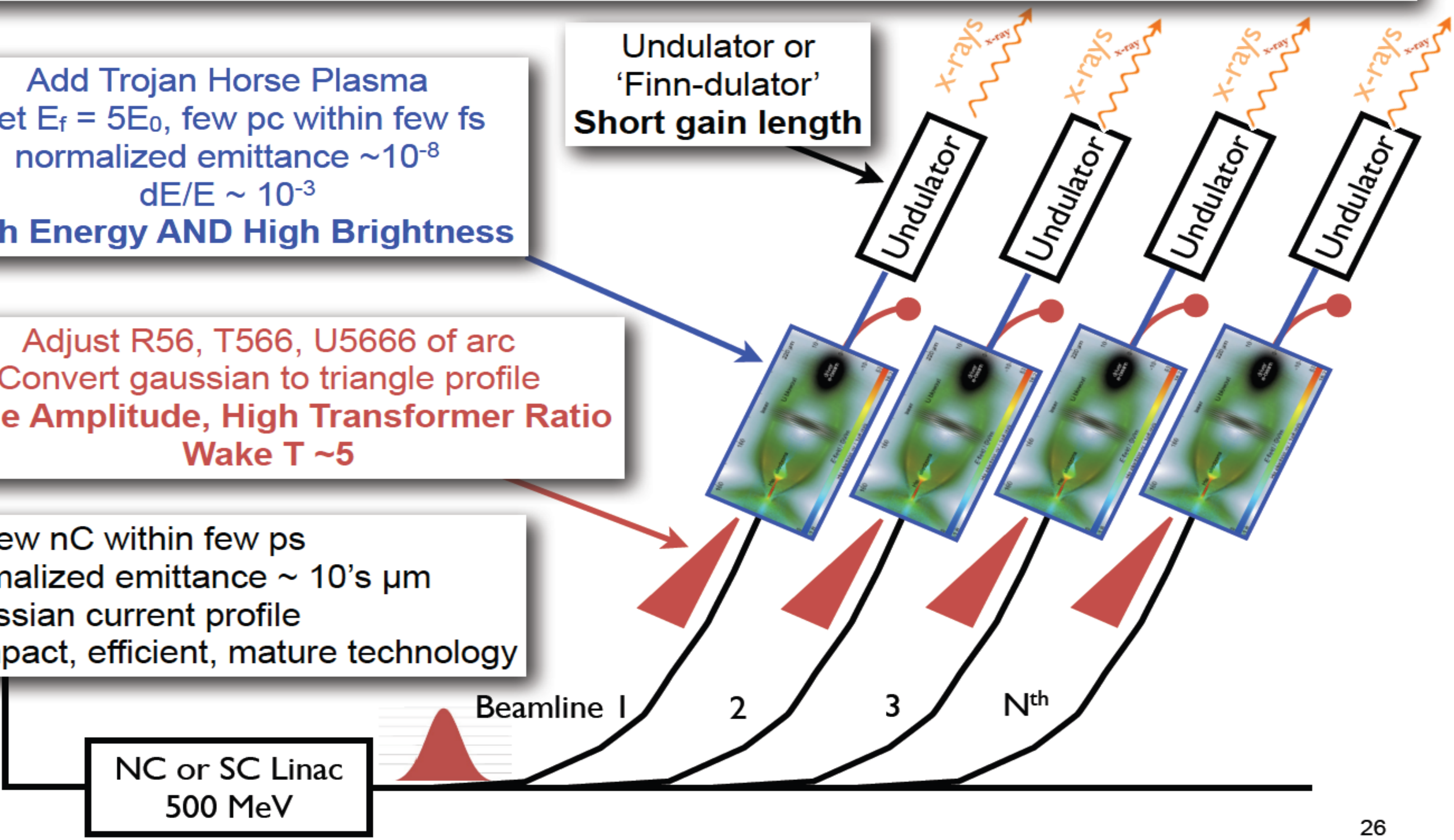
Compactness of plasmas accelerators, rep rate like rings with high brightness of linacs!

Add Trojan Horse Plasma
Get $E_f = 5E_0$, few pc within few fs
normalized emittance ~10^{-8}
dE/E ~ 10^{-3}
High Energy AND High Brightness

Undulator or
'Finn-dulator'
Short gain length

Adjust R56, T566, U5666 of arc
Convert gaussian to triangle profile
Large Amplitude, High Transformer Ratio
Wake T ~5

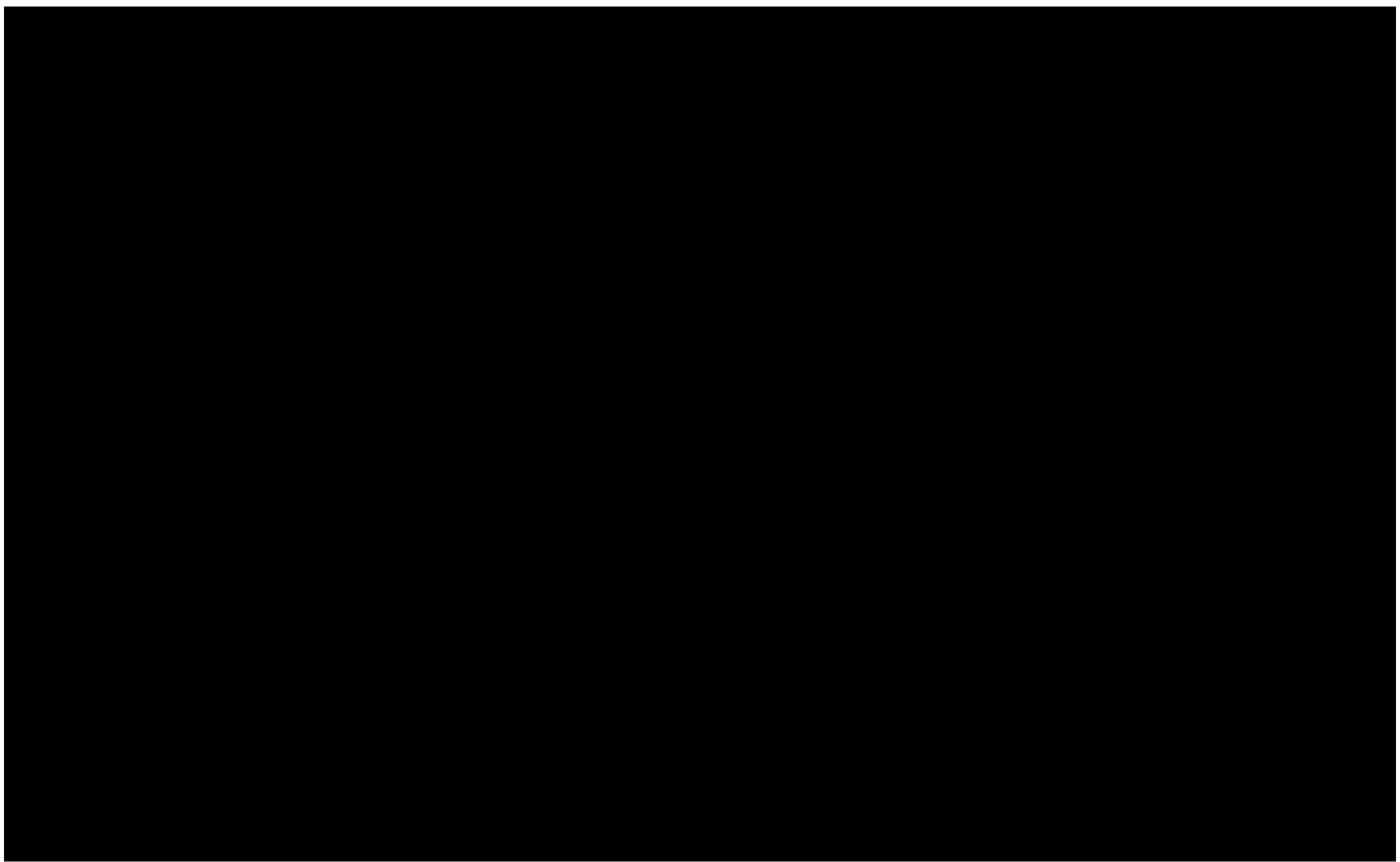
Q~ few nC within few ps
Normalized emittance ~ 10's μm
Gaussian current profile
Compact, efficient, mature technology



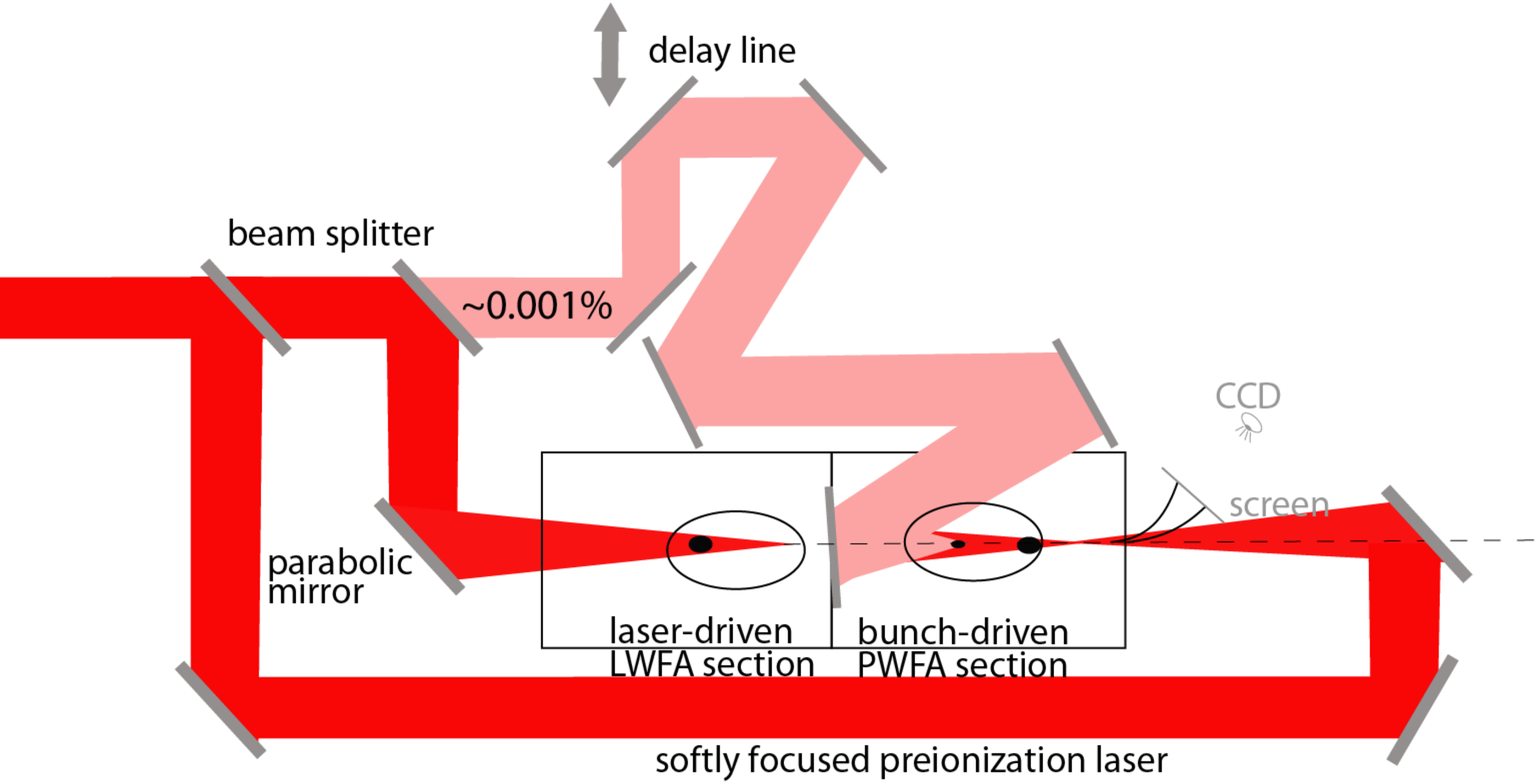
Scheme does also work w/ other high-brightness beam drivers, e.g. w/ FLASH driver:

Beam driver: Q ≈ 180 pC, $\sigma_z \approx$ 8.39 µm (rms), $\sigma_{x,y} \approx$ 7 µm (rms), E ≈ 1.2 GeV, ΔE ≈ 0.1%,
Medium: LIT: preionized plasma $n_{LIT} \approx 1.5 \times 10^{17}$ cm^{-3}, HIT: He (IP 24.6 eV), $n_{HIT} \approx 3 \times 10^{17}$ cm^{-3}
Laser: $\tau \approx$ 25 fs, λ = 0.8 µm, $w_0 \approx$ 5 µm $\Rightarrow Z_R \approx$ 10 µm, $a_0 \approx 0.03$, $I \approx 1.9 \times 10^{15}$ W/cm^2

Experiments to start 2016



Beam brightness transformer and stabilizer for Laser-plasma-accelerators



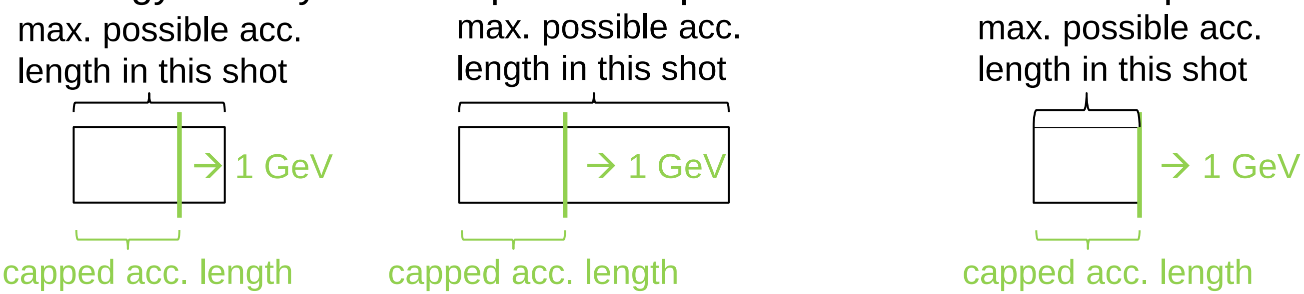
- Bunch quality transformer: energy, energy spread (see "Monoenergetic energy doubling", PRL 140195002, 2010), emittance

- e.g., LPA: ΔE_1 = 20 %, $\varepsilon_{n1} \sim 10^{-6}$ m rad → TROJAN: ΔE_2 = 0.1 %, $\varepsilon_{n2} \sim 10^{-8}$ m rad

Substantially different parameter goals for electron bunches from LWFA to be used for PWFA

- Energy spread does not matter, as long as the energy is sufficiently relativistic: all electrons move with ~c. In first approximation, a 1 GeV bunch with perfect energy spread won't drive a different plasma wake than a 1 GeV bunch with 30% spread

- Energy stability not so important: cap acceleration distance via preionization



- Even in case of current jitter, some stabilization is automatically achieved by the trapping process:

Even though the trapping position will be different, the acc. fields can be the same / very similar!

- Produce compact bunches with a lot of charge (via downramp injection?)

- Improve pointing

- Prevent dark current

- Can we somehow produce current upramp with LPA's for enhanced transformer ratio? …

SCAPA *Scottish Centre for the Application of Plasma Accelerators*

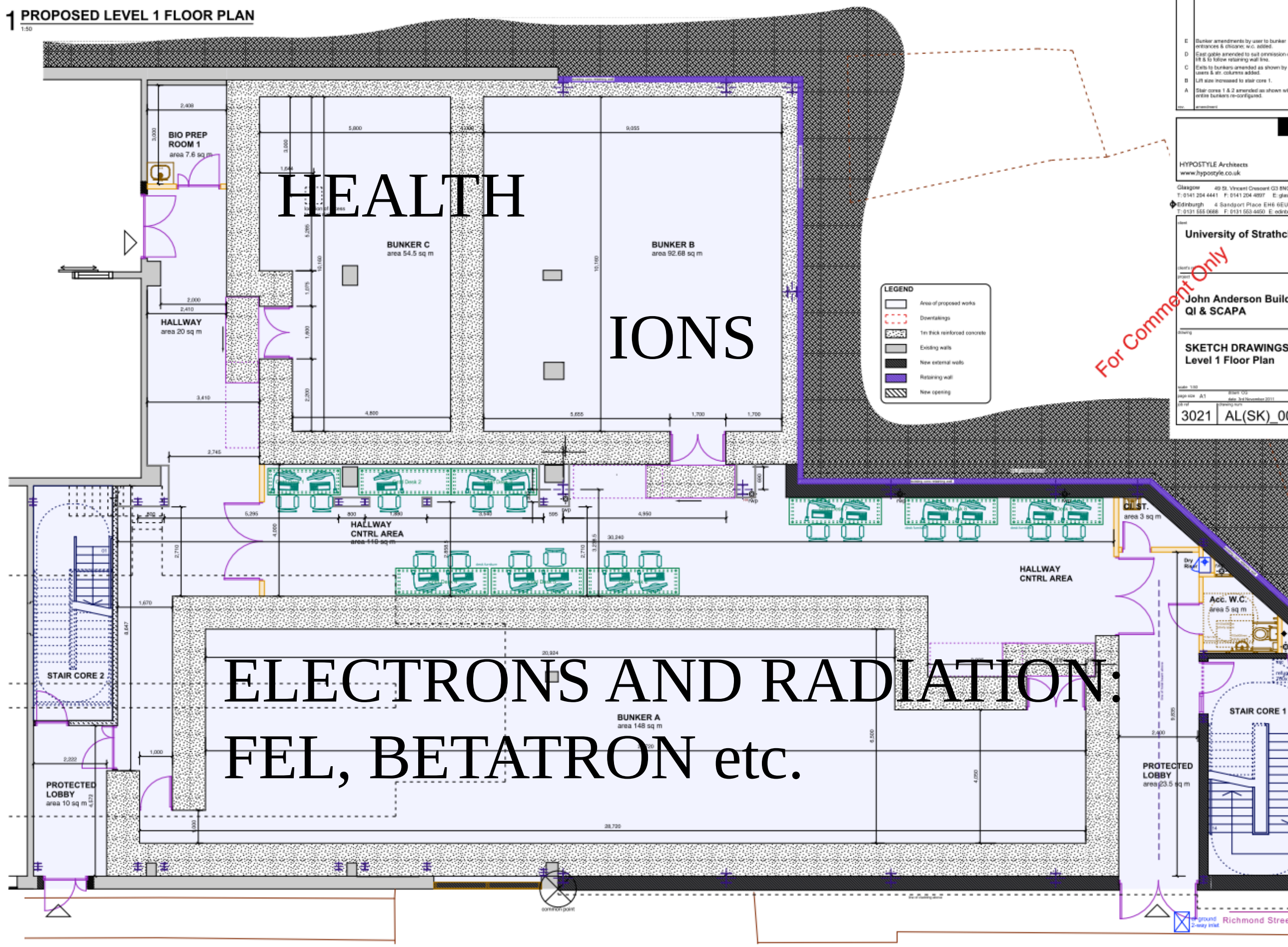
also part of Strathclyde Technology and Innovation Centre (TIC)

APPLICATIONS

- **Radiobiology**
- **Ultrafast Probing**
- **High-Resolution Imaging**
- **Radioisotope Production**
- **Detector Development**
- **Radiation Damage Testing**

Scottish Centre for the Application of Plasma Accelerators

also part of Strathclyde Technology and Innovation Centre (TIC)



APPLICATIONS

- **Radiobiology**
- **Ultrafast Probing**
- **High-Resolution Imaging**
- **Radioisotope Production**
- **Detector Development**
- **Radiation Damage Testing**

1200 m2 laboratory space, 3 shielded areas with 7 beam lines. 200-300 TW laser, 40 TW laser, sub-TW laser

Director: Dino Jaroszynski

Other key people: Paul McKenna, Zheng-Ming Sheng, Mark Wiggins, Gregory Welsh, Brian McNeill, Bernhard Hidding..

5th Generation Light Sources…

5^{th} 4D, high wavelength, compact?

4^{th} Free-Electron-Laser

3^{rd} Undulator radiation

2^{nd} Synchrotron radiation

1^{st} Bremsstrahlung

…need a 4th Generation Electron Source

4^{th} 10's of GV/m fields in plasmas & underdense photocathode PWFA

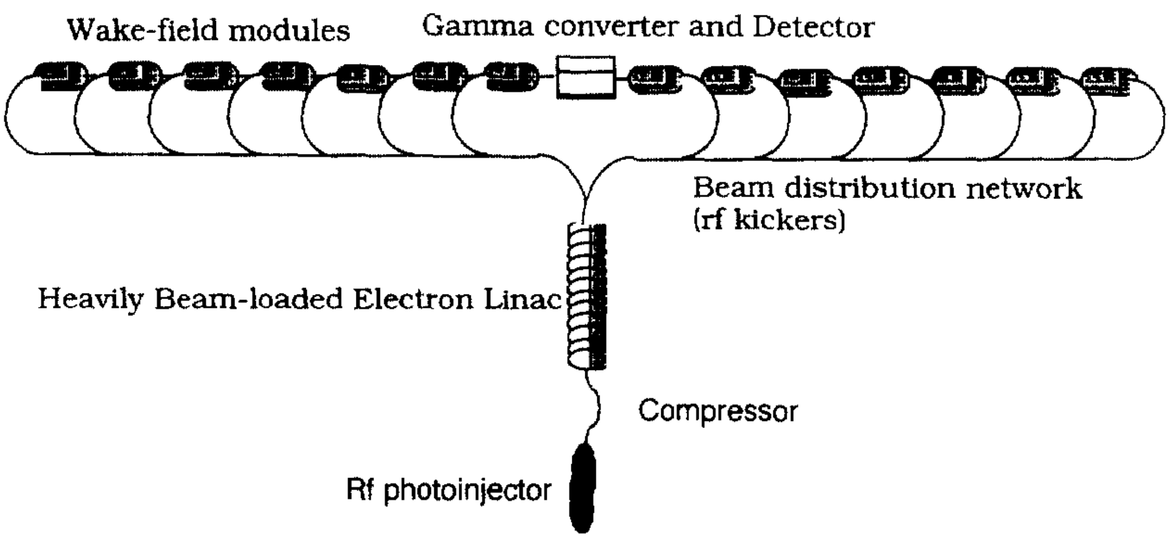
3^{rd} 10's of GV/m fields in plasmas (LWFA and PWFA)

2^{nd} 10's of MV/m fields, photocathode (e.g. FLASH, LCLS, XFEL)

1^{st} 10's of MV/m fields, thermionic cathode (e.g. SLAC)

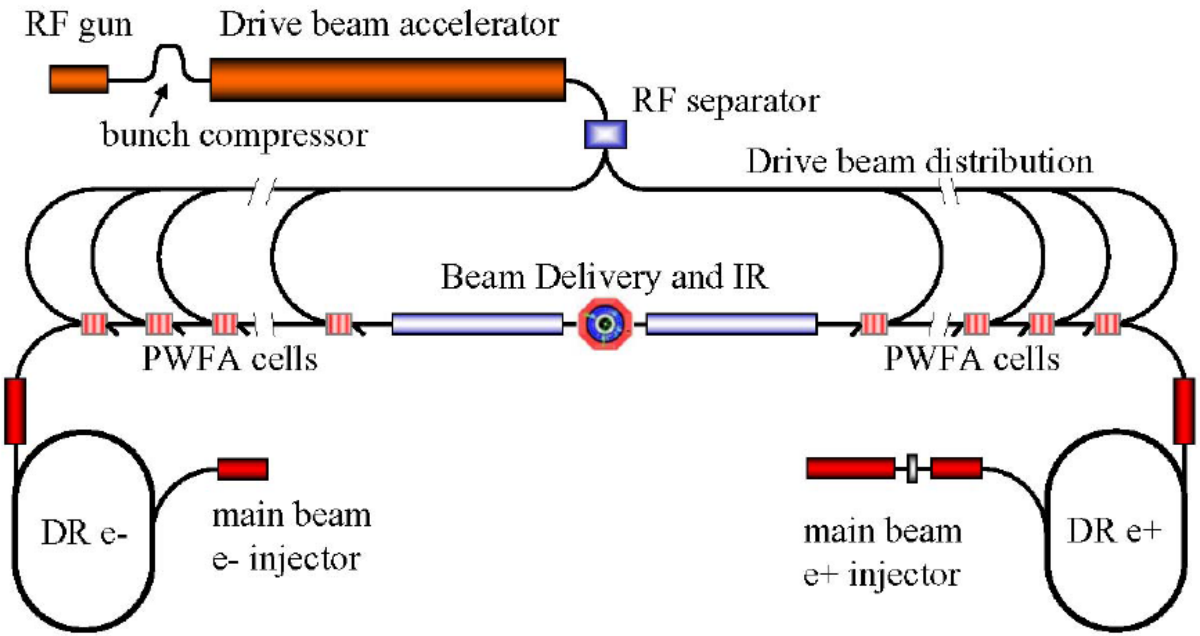
3rd way: All-optically powered TeV accelerator

PWFA-based:



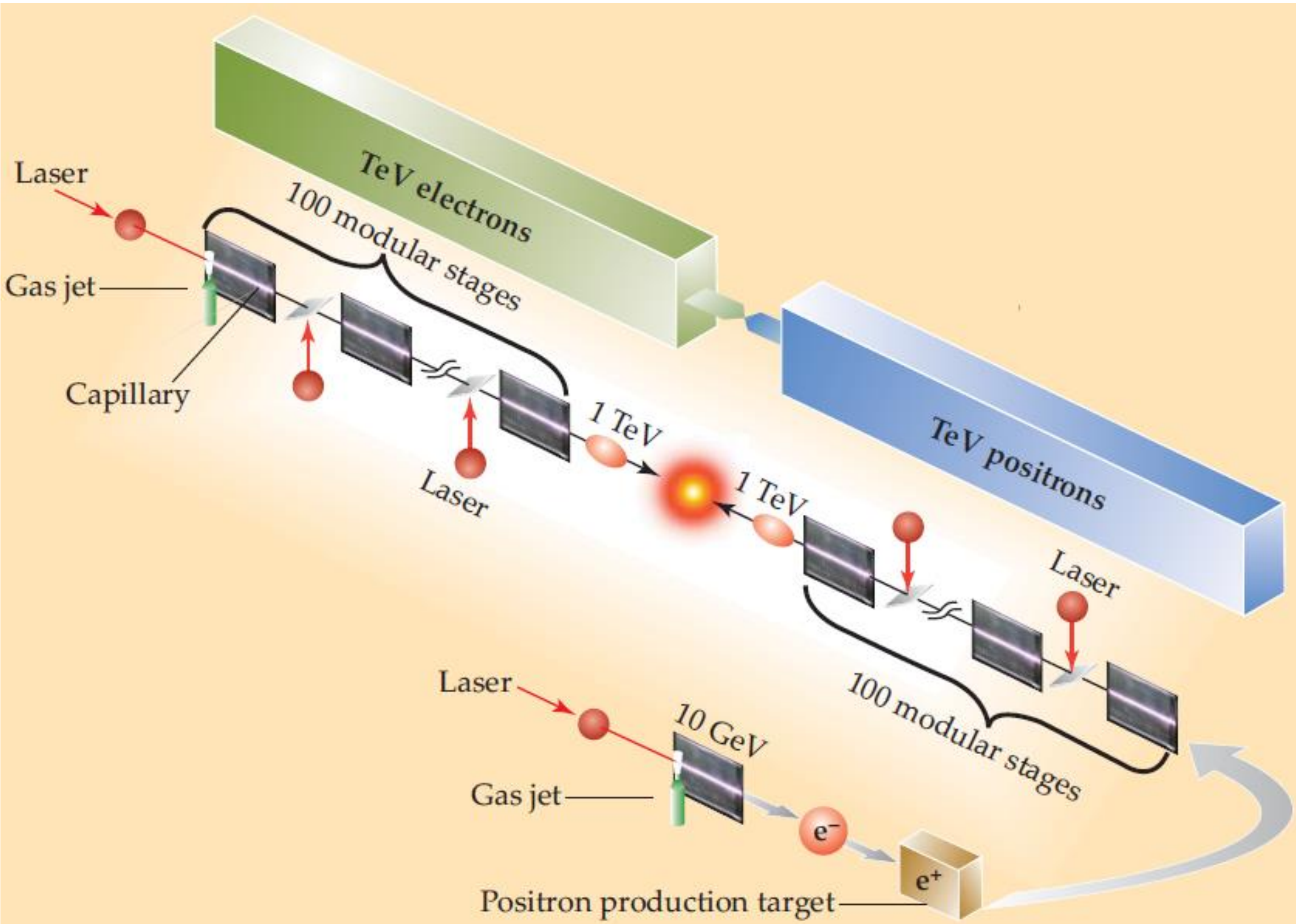
γ -γ-collider
Towards a Plasma Wake-field Acceleration-based Linear Collider, J.B. Rosenzweig et al., NIMA 410, 1998

e-e+ collider
A Concept of Plasma Wakefield Acceleration Linear Collider (PWFA-LC), A. Seryi et al., PAC 2009



3rd way: All-optically powered TeV accelerator

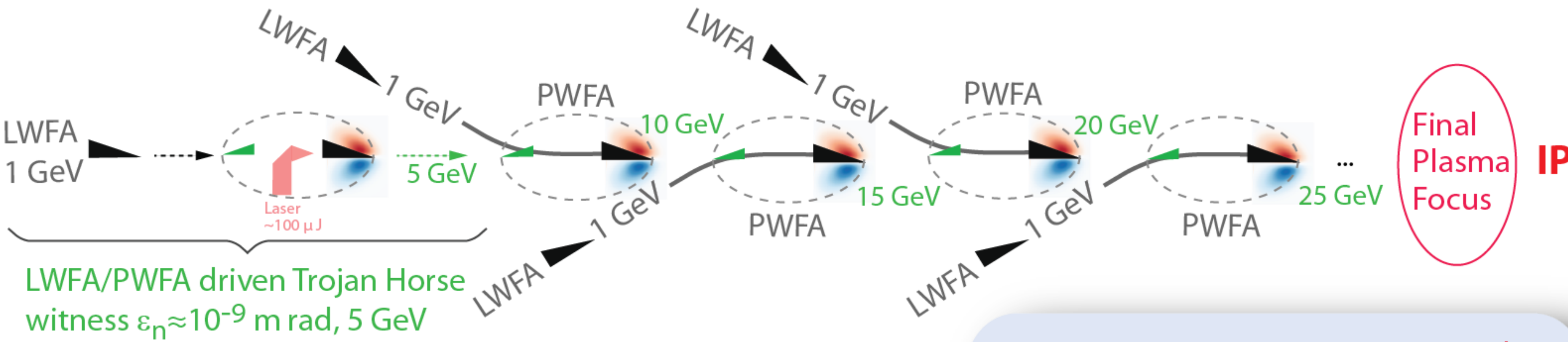
LWFA-based:



W. Leemans et al., Phys. Today, 2009

3^{rd} way: All-optically powered TeV accelerator

Hybrid-LWFA/PWFA-based:



200 stages, 100 TW LWFAs, 1 GeV each,
T~5, 5 GeV gain/stage, final energy = 1 TeV
100 kHz, $\varepsilon_n \approx 10^{-8}$ m rad
@ 5 pC, focused to100 nm: L~1e33

e- e+ collider? $\gamma\gamma$-collider?

..to be submitted

Literature 2011-2012

PCT International Patent Application

Title:	METHOD FOR GENERATING ELECTRON BEAMS IN A HYBRID LASER-PLASMA ACCELERATOR
Inventor(s):	Bernhard Hidding et al.
Priority Date:	June 18, 2011
Filing Date:	June 18, 2012
Ser. No.:	PCT/US12/043002

PRL **108,** 035001 (2012) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2012

Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout

B. Hidding,[1,2] G. Pretzler,[2] J. B. Rosenzweig,[1] T. Königstein,[2] D. Schiller,[1] and D. L. Bruhwiler[3]

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[2]*Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany*
[3]*Tech-X Corporation, Boulder, Colorado 80303, USA*

(Received 30 March 2011; published 17 January 2012)

Beam-driven plasma wakefield acceleration using low-ionization-threshold gas such as Li is combined with laser-controlled electron injection via ionization of high-ionization-threshold gas such as He. The He electrons are released with low transverse momentum in the focus of the copropagating, nonrelativistic-intensity laser pulse directly inside the accelerating or focusing phase of the Li blowout. This concept paves the way for the generation of sub-μm-size, ultralow-emittance, highly tunable electron bunches, thus enabling a flexible new class of an advanced free electron laser capable high-field accelerator.

Beyond Injection: Trojan Horse Underdense Photocathode Plasma Wakefield Acceleration

B. Hidding[*,†], J.B. Rosenzweig[†], Y. Xi[†], B. O'Shea[†], G. Andonian[†], D. Schiller[†], S. Barber[†], O. Williams[†], G. Pretzler[*], T. Königstein[*], F. Kleeschulte[*], M. J. Hogan[**], M. Litos[**], S. Corde[**], W. W. White[**], P. Muggli[‡], D.L. Bruhwiler[§,¶] and K. Lotov[‖,††]

[*]*Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany*
[†]*Particle Beam Physics Laboratory, Department for Physics and Astronomy, UCLA, USA*

Citation: AIP Conf. Proc. **1507**, 570 (2012); doi: 10.1063/1.4773760

View online: http://dx.doi.org/10.1063/1.4773760

[‖]*Budker Institute of Nuclear Physics SB RAS, 630090, Novosibirsk, Russia*
[††]*Novosibirsk State University, 630090, Novosibirsk, Russia*

Abstract. An overview on the underlying principles of the hybrid plasma wakefield acceleration scheme dubbed "Trojan Horse" acceleration is given. The concept is based on laser-controlled release of electrons directly into a particle-beam-driven plasma blowout, paving the way for controlled, shapeable electron bunches with ultralow emittance and ultrahigh brightness. Combining the virtues of a low-ionization-threshold underdense photocathode with the GV/m-scale electric fields of a practically dephasing-free beam-driven plasma blowout, this constitutes a 4th generation electron acceleration scheme. It is applicable as a beam brightness transformer for electron bunches from LWFA and PWFA systems alike. At FACET, the proof-of-concept experiment "E-210: Trojan Horse Plasma Wakefield Acceleration" has recently been approved and is in preparation. At the same time, various LWFA facilities are currently considered to host experiments aiming at stabilizing and boosting the electron bunch output quality via a trojan horse afterburner stage. Since normalized emittance and brightness can be improved by many orders of magnitude, the scheme is an ideal candidate for light sources such as free-electron-lasers and those based on Thomson scattering and betatron radiation alike.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **16**, 031303 (2013)

Hybrid modeling of relativistic underdense plasma photocathode injectors

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[1]*Department of Physics and Astronomy, University of California, Los Angeles, California, USA*
[2]*Institut für Experimentalphysik, Universität Hamburg & DESY, 22607 Hamburg, Germany*
[3]*University of Colorado at Boulder, 390UCB, Boulder, Colorado 80309, USA*
[4]*Institut für Laser- und Plasmaphyik, Heinrich-Heine-Universität Düsseldorf, Germany*

(Received 6 November 2012; published 25 March 2013)

The dynamics of laser ionization-based electron injection in the recently introduced plasma photocathode concept is analyzed analytically and with particle-in-cell simulations. The influence of the initial few-cycle laser pulse that liberates electrons through background gas ionization in a plasma wakefield accelerator on the final electron phase space is described through the use of Ammosov-Deloine-Krainov theory as well as nonadiabatic Yudin-Ivanov (YI) ionization theory and subsequent downstream dynamics in the combined laser and plasma wave fields. The photoelectrons are tracked by solving their relativistic equations of motion. They experience the analytically described transient laser field and the simulation-derived plasma wakefields. It is shown that the minimum normalized emittance of fs-scale electron bunches released in mulit-GV/m-scale plasma wakefields is of the order of 10^{-2} mm mrad. Such unprecedented values, combined with the dramatically increased controllability of electron bunch production, pave the way for highly compact yet ultrahigh quality plasma-based electron accelerators and light source applications.

Literature 2013-

Low transverse emittance electron bunches from two-color laser-ionization injection

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ABSTRACT

A method is proposed to generate low emittance electron bunches from two color laser pulses in a laser-plasma accelerator. A two-region gas structure is used, containing a short region of a high-Z gas (e.g., krypton) for ionization injection, followed by a longer region of a low-Z gas for post-acceleration. A long-laser-wavelength (e.g., 5 μm) pump pulse excites plasma wake without triggering the inner-shell electron ionization of the high-Z gas due to low electric fields. A short-laser-wavelength (e.g., 0.4 μm) injection pulse, located at a trapping phase of the wake, ionizes the inner-shell electrons of the high-Z gas, resulting in ionization-induced trapping. Compared with a single-pulse ionization injection, this scheme offers an order of magnitude smaller residual transverse momentum of the electron bunch, which is a result of the smaller vector potential amplitude of the injection pulse.

Literature 2013-

Phase Space Dynamics of Ionization Injection in Plasma Based Accelerators

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(Dated: June 19, 2013)

The evolution of beam phase space in ionization-induced injection into plasma wakefields is studied using theory and particle-in-cell (PIC) simulations. The injection process causes special longitudinal and transverse phase mixing leading initially to a rapid emittance growth followed by oscillation, decay, and eventual slow growth to saturation. An analytic theory for this evolution is presented that includes the effects of injection distance (time), acceleration distance, wakefield structure, and nonlinear space charge forces. Formulas for the emittance in the low and high space charge regimes are presented. The theory is verified through PIC simulations and a good agreement is obtained. This work shows how ultra-low emittance beams can be produced using ionization-induced injection.

Two-Pulse Ionization Injection into Quasi-Linear Laser Wakefields

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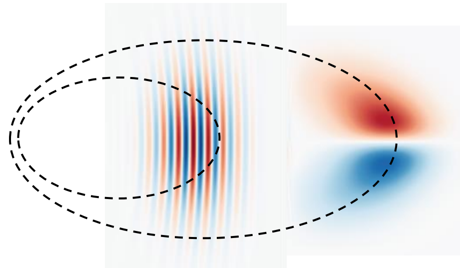
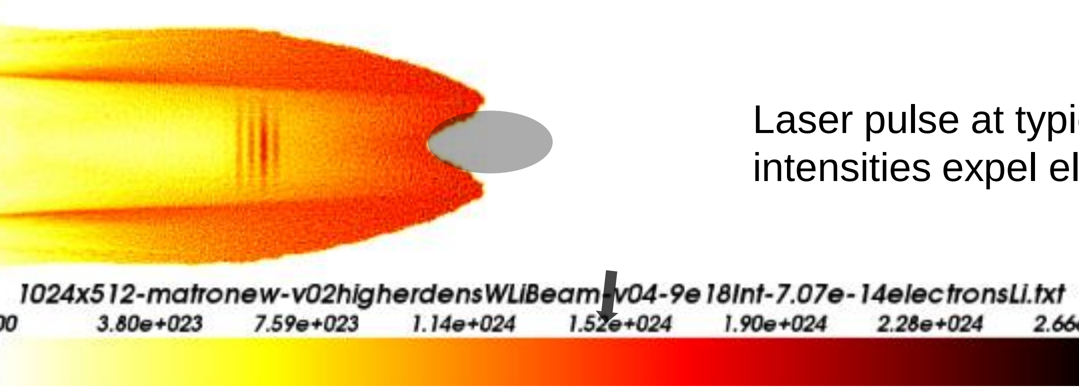
(Dated: July 1, 2013)

We describe a scheme for controlling electron injection into the quasi-linear wakefield driven by a guided drive pulse via ionization of a dopant species by a collinear injection laser pulse with a short Rayleigh range. The scheme is analyzed by particle in cell simulations which show controlled injection and acceleration of electrons to an energy of 370 MeV, a relative energy spread of 2%, and a normalized transverse emittance of 3.0 μm.

Trojan Horse (Pre)History

2008: Laser-driven bubble in a beam-driven blowout? ("Matryoshka acc..")





Laser pulse at typical (relativistic) LWFA intensities expel electrons

2008/2009: much better mode would be to have the laser pulse at minimal intensity ($a_0 << 1$), so that released electrons are "still" and remain still inside the blowout → "Trojan horse acc.", originally to be presented at AAC 2010 in Kardamili, Greece (sic!)

2010: spin –off idea: PWFA with electron beams from LWFA ("Hybrid energy doubling", PRL 104, 195002, 2010)

2011: DE patent, PRL submitted..

Summary

- electron bunches with unprecedented emittance ($\varepsilon_n \sim 10^{-9}$ - 10^{-10} m rad) and brightness may be possible (emittance preservation & extraction crucial)
- Unprecedented bunch shaping capabilities (more flexible than state-of-the-art photoinjectors)
- Trojan horse a bunch quality transformer (e.g., ΔE_1 = 20 %, $\varepsilon_{n1} \sim 10^{-6}$ m rad → ΔE_2 = 20 %, $\varepsilon_{n2} \sim 10^{-8}$ m rad)
- … and as a bunch energy transformer
- Output stabilizer for LWFA
- Scheme applicable for most diverse scenarios: hybrid conventional/PWFA accelerator (SLAC/Trojan Horse), hybrid photoinjector/PWFA accelerator (FLASH, FACET-II, CLARA etc.), hybrid LWFA/PWFA accelerators
- FEL game changer? Performance ***substantially*** better than XFEL may be possible: **Reduce costs from ~1 Mrd. € to ~5 Mio. €, size from km to m-scale, yet better performance** (e.g., multi-color FELs)
- HEP accelerator applications? TeV accelerators..

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Collaborators:

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FACET

E-210: Trojan Horse collaboration

UCLA

radiabeam TECHNOLOGIES

University of Strathclyde Glasgow

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