Bernhard Hidding

Fundamentals and Applications of Hybrid LWFA-PWFA

Scottish Centre for the Application of Plasma-Based Accelerators SCAPA,
Department of Physics, University of Strathclyde,
Scottish Universities Physics Alliance SUPA, UK

Strathclyde Centre for Doctoral Training P-PALS
Plasma-based Particle and Light Sources http://ppals.phys.strath.ac.uk/

Strathclyde Space Institute

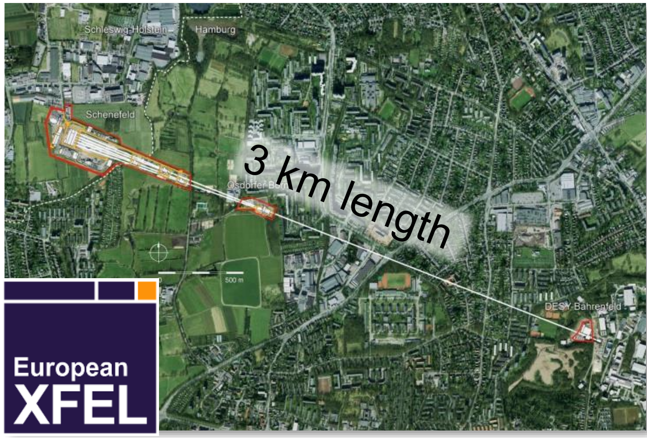
& The Cockcroft Institute

The need for high energy particles has led to greatest machines in the world

Photons: e.g.

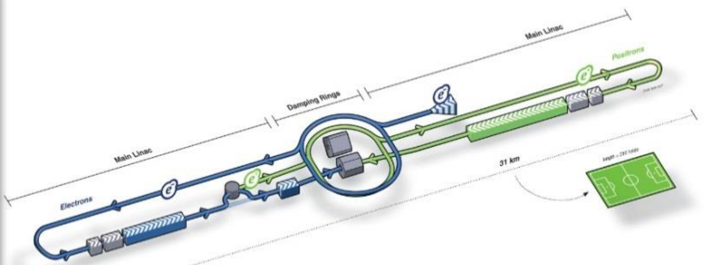
Diamond Light Source,
Synchrotron, Oxfordshire, UK

Linac Coherent Light Source,
X-ray FEL, SLAC, USA



European X-Ray Free Electron
Laser, Hamburg, Germany

Particles: e.g.



ILC, FCC?

international linear collider

Facilities size is the result of limited accelerating electric fields

- Huge particle energies are needed to resolve molecular and atomic structures
- Accelerating electric fields in conventional accelerators are limited to the ~50 MV/m level, because of breakdown of accelerating cavity walls (Kilpatrick criterion*), involving production of "microplasmas"

- Energy gain *W* is given by the product of charge *q*, electric field *E* and acceleration length *d*: $W = qEd$
- As particle charge is constant and fields are limited, the only way to reach high particle energies is to increase the acceleration distance, i.e. the length of the (linear) accelerator *d*

* *"Criterion for Vacuum Sparking Designed to Include Both RF and DC", W.D. Kilpatrick, Review of Scientific Instruments (1957)*

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 28, NUMBER 10 OCTOBER, 1957

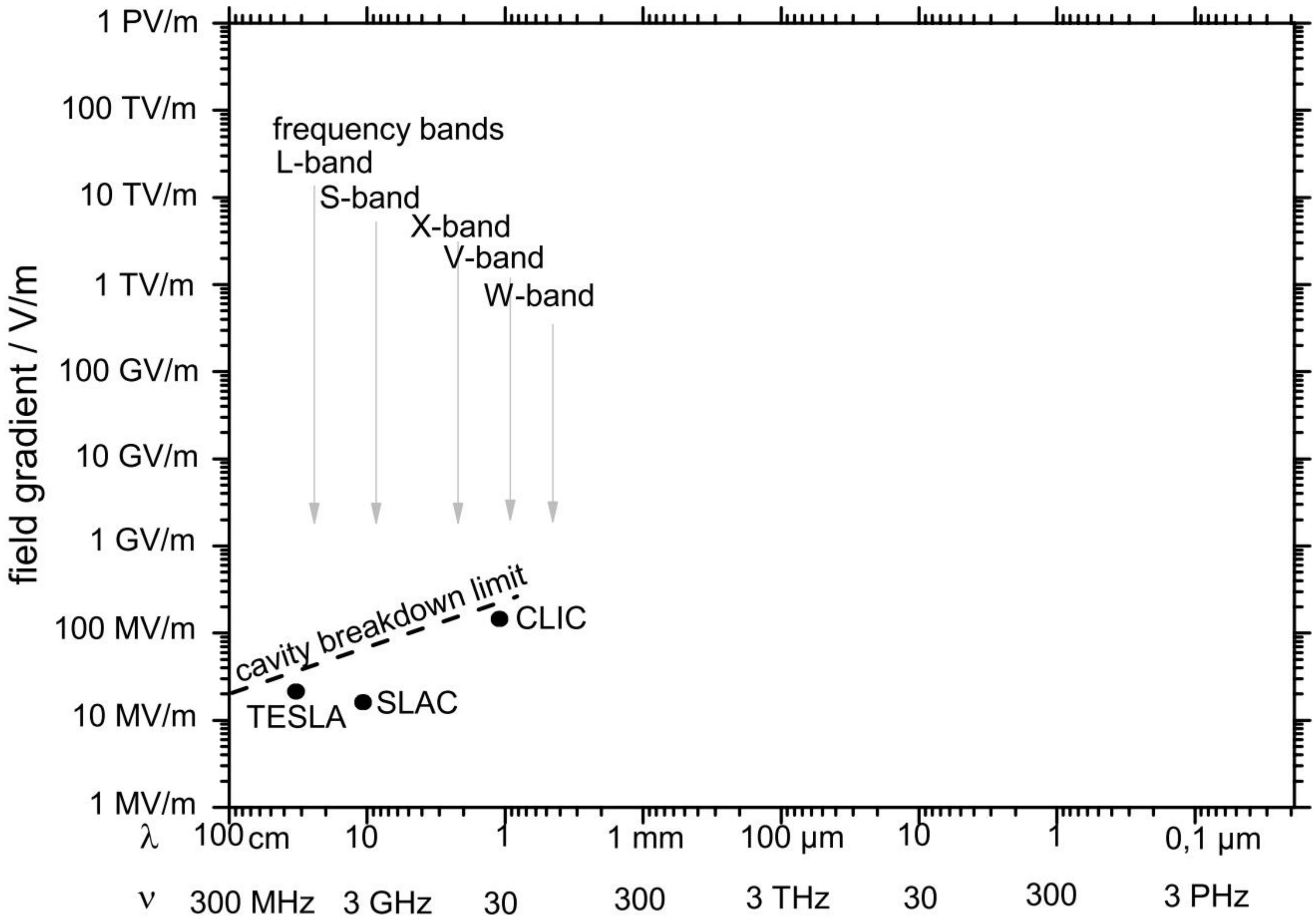
Criterion for Vacuum Sparking Designed to Include Both rf and dc*

W. D. Kilpatrick
Radiation Laboratory, University of California, Berkeley, California
(Received May 31, 1957)

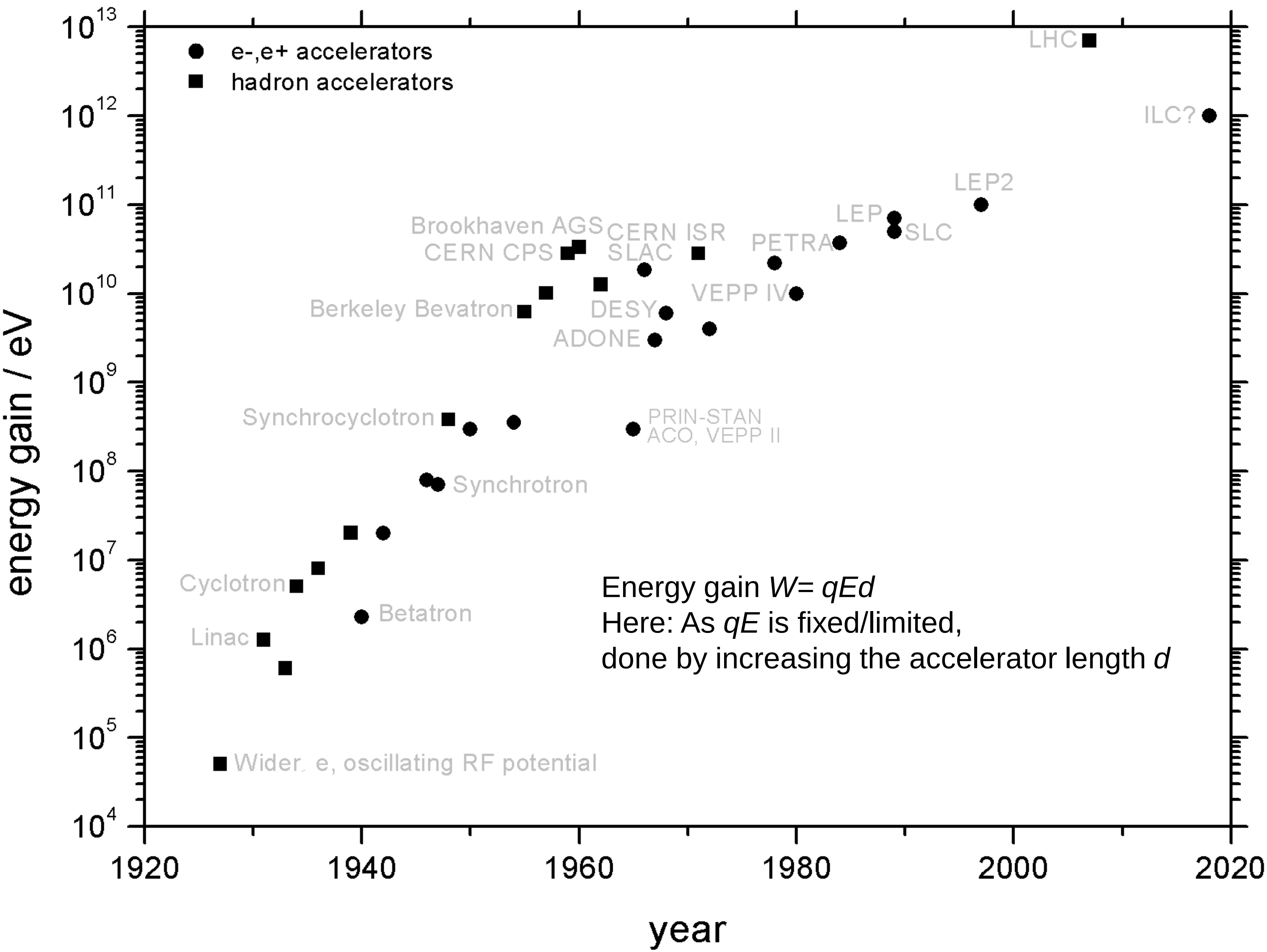
An empirical relation is presented that describes a boundary between no vacuum sparking and possible vacuum sparking. Metal electrodes and rf or dc voltages are used. The criterion applies to a range of surface gradient, voltage, gap, and frequency that extends over several orders of magnitude. Current due to field emission is considered necessary for sparking, but—in addition—energetic ions are required to initiate a cascade process that increases the emitted currents to the point of sparking.

*Increasing the rf frequency increases the obtainable accelerating gradient**

**true in first approximation up to ~X-band, one can go beyond Kilpatrick.. very complex physics..*



Livingston plot: "Moore's Law" for accelerators



First “particle acceleration” experiments:

e.g. Rutherford/Geiger 1911

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

E. Rutherford, Phil. Mag. 21, 1911

The Birth of "Plasma"

LEWI TONKS
407 Oakridge Drive, Schenectady, New York
(Received 24 April 1967)

The origin of the "plasma" of gaseous electronics need not be mythological. The author was there.

THE word *plasma* has achieved universal and unquestioned usage in the description of phenomena in ionized gases and has, at times, even been applied to such other nonphysiological entities as flames, electrolytes, conductors at low temperatures, and the Heaviside layer. Yet how a term, which four decades ago was only used to describe a part of the blood, came to be used in this new sense has never been authoritatively told. There have been a number of guesses, some of them stated as fact, which elaborated on the knowledge that Irving Langmuir initiated the usage. At least one is far more vivid and colorful than the actual event.[1] Had the authors' putative date been correct, I would have been tempted to leave the imaginative extravaganza unquestioned.

As I was working with Langmuir at the time that he appropriated "plasma" for gaseous electronics and I was the only scientist present at the event, I am surely the one most able to give an authoritative account of it. Incidentally, Langmuir's notebooks and mine have both been searched in vain for the first adaptation of "plasma" to the low-pressure arc, the object of our investigations at the time. The first written use (excluding unknown correspondence) must, therefore, have been in the manuscript of "Oscillations in Ionized Gases" [Proceedings of

"Say, Tonks, I'm looking for a word. In these gas discharges we call the region in the immediate neighborhood of the wall or an electrode a 'sheath,' and that seems to be quite appropriate; but what should we call the main part of the discharge? The conductivity is high so that you can't apply a potential difference to it like you can to a sheath—it all is taken up by the sheaths. And there is complete space-charge neutralization. I don't want to invent a word, but it must be descriptive of this kind of region as distinct from a sheath. What do you suggest?"

My reply was classic: "I'll think about it, Dr. Langmuir."

The next day Langmuir breezed in and announced, "I know what we'll [*sic*] call it! We'll call it the 'plasma.'" The image of blood plasma immediately came to mind; I think Langmuir even mentioned blood. In the light of the contemporary state of our knowledge, the choice seemed very apt.

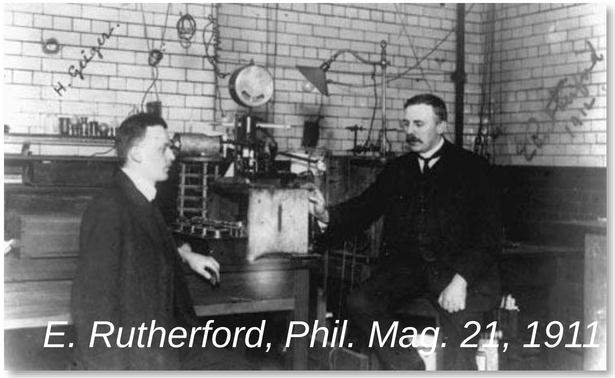
Our attention was focused on the laboratory experiments. The extensive broadening of concept which would include electrolytes, flames, the Heaviside layer, etc. may have lain in the back of Langmuir's brain. The semantic problem to be solved was sheath vs nonsheath.

Quite definitely, neither the oscillatory characteristics of plasmas nor "the seething move-

Prehistoric days: Plasma Wakefield Acceleration

Rutherford/Geiger 1911

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



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

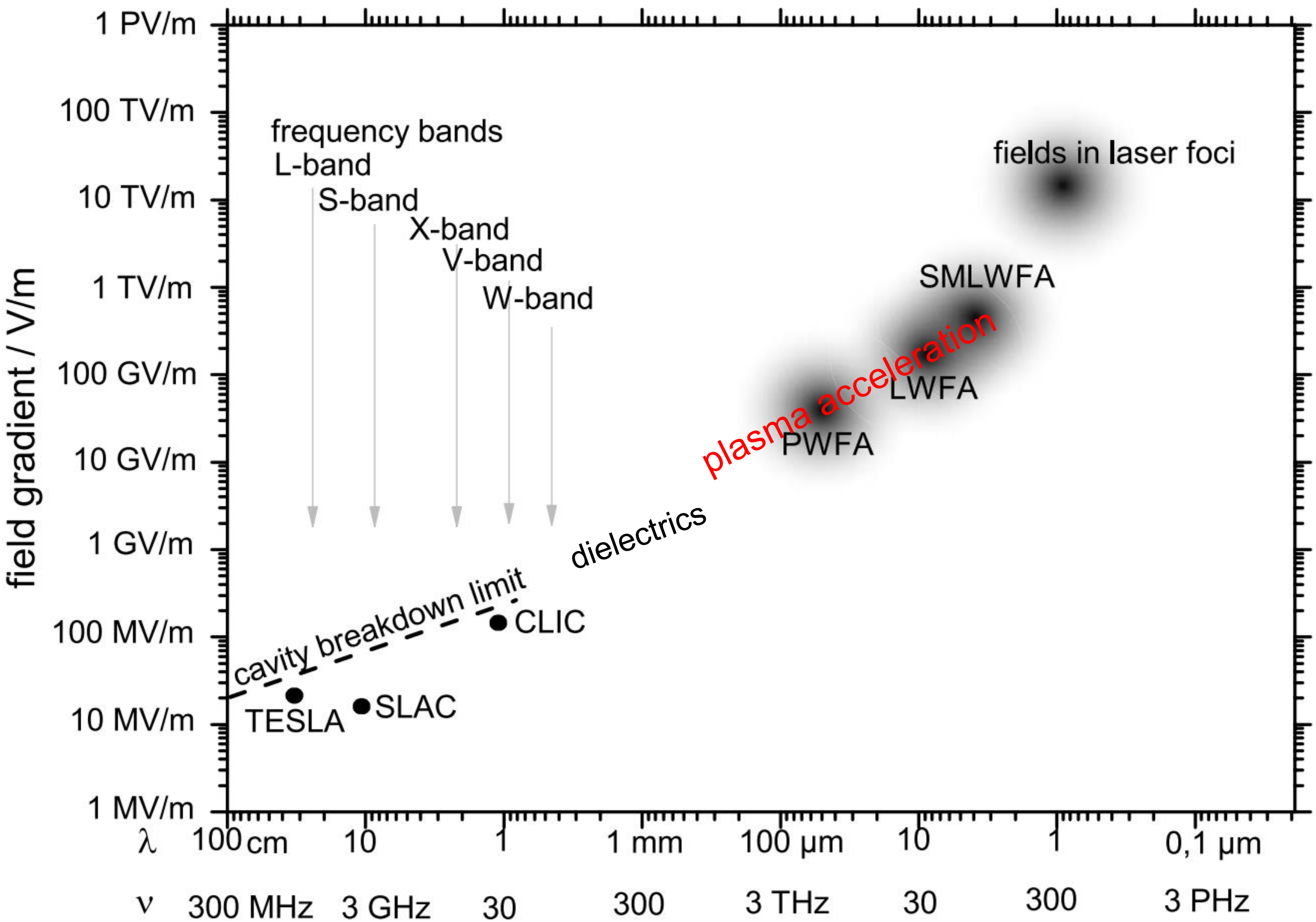
UCLA 1979: LWFA

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

Stanford/UCLA 1985: PWFA

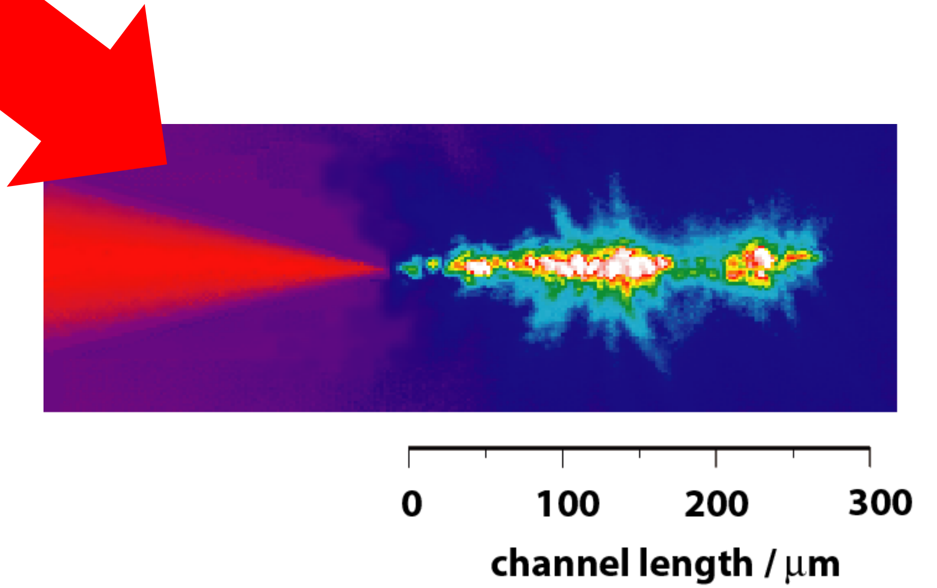
Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma
Chen et al., Phys. Rev. Letters 54, 1985

Plasma: tens of GV/m+ acceleration gradients allow shrinking of accelerator to sub-meter scale (energy gain W=qED)

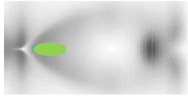


Shrinking accelerators from km to cm size

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

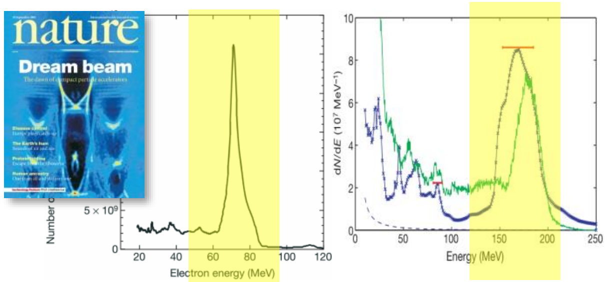


Single co-propagating plasma cavity
w/ electric fields of ~50 GV/m

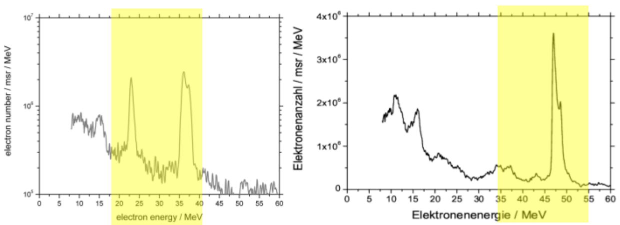


Indeed: Both LWFA (laser driven) and PWFA (electron beam driven) now routinely demonstrate multi-GeV energy gain

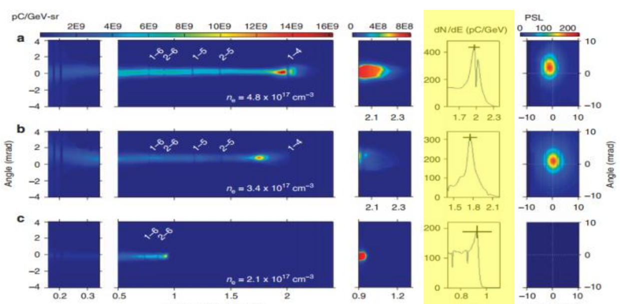
LWFA



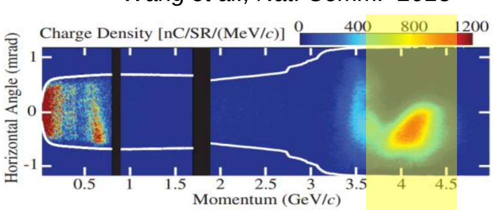
Mangles et al. (UK), Geddes et al. (USA), Faure et al. (France), Nature 2004



Hidding et al., PRL 2006

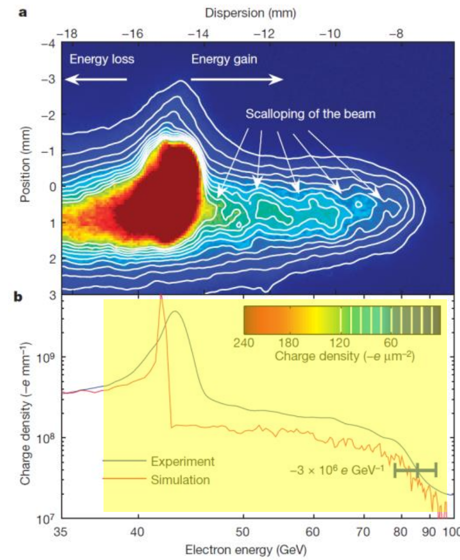


Wang et al., Nat. Comm. 2013

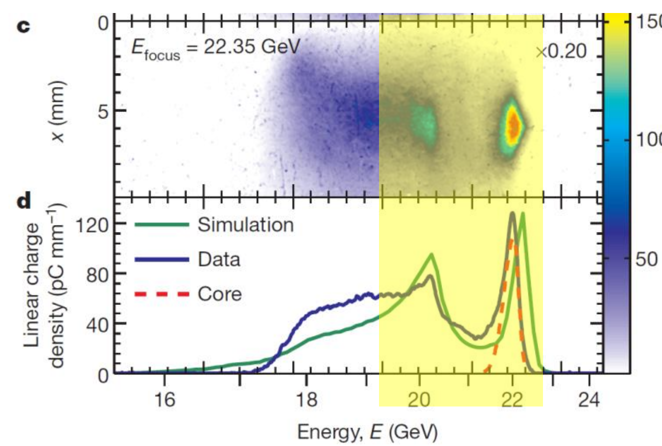


Leemans et al., PRL 2014

PWFA

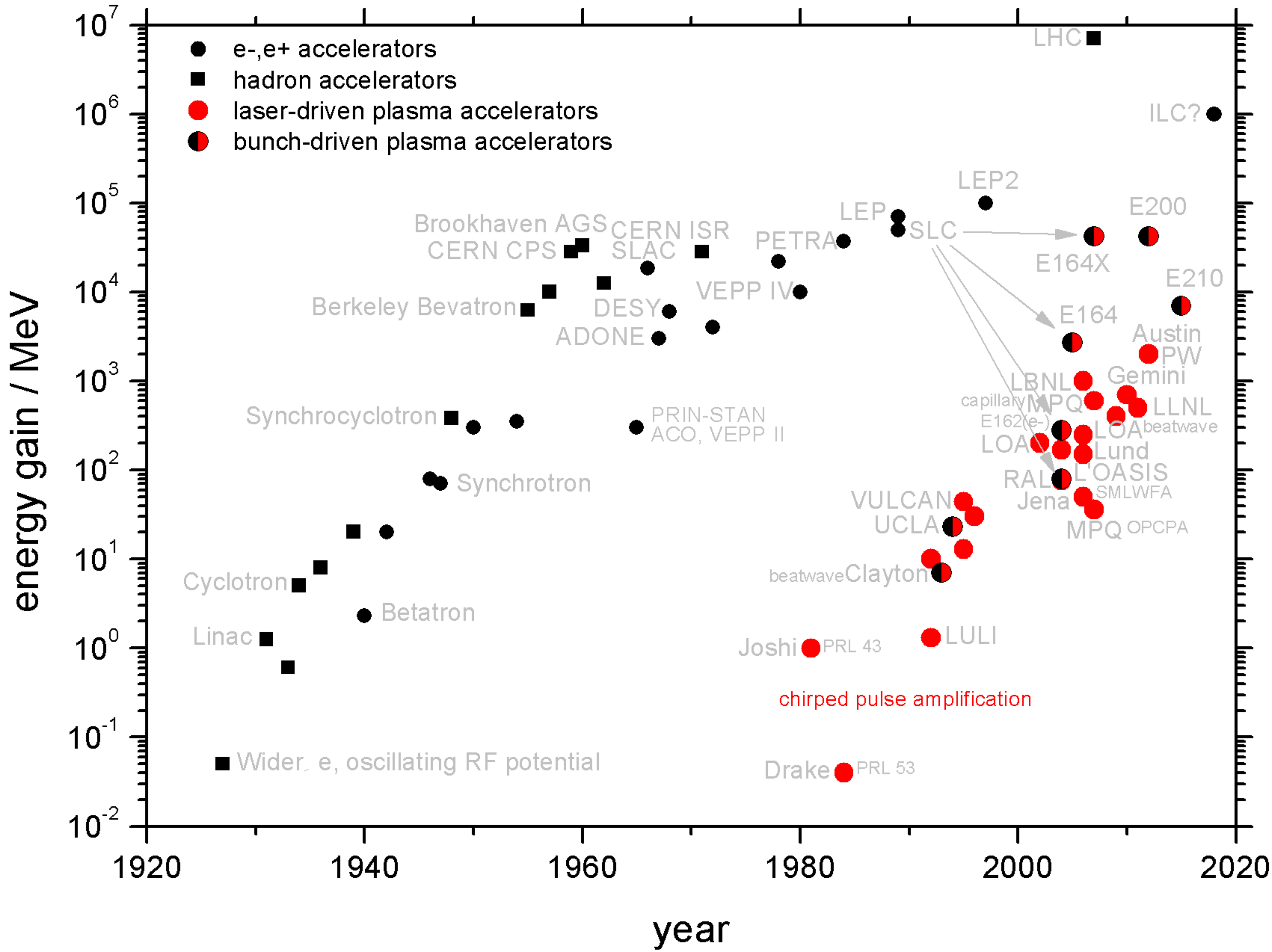


Blumenfeld et al., Nature 2007



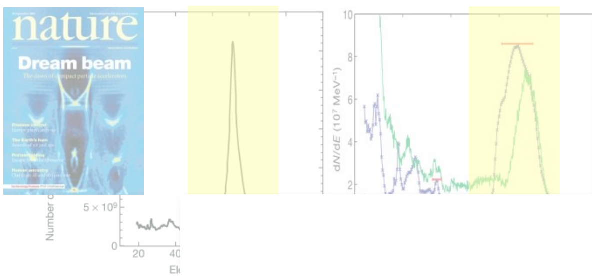
Litos et al., Nature 2014

Livingston plot: with plasma accelerators (ignoring beam quality etc.)

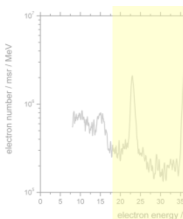


Indeed: Both LWFA and PWFA routinely demonstrate multi-GeV energy gain

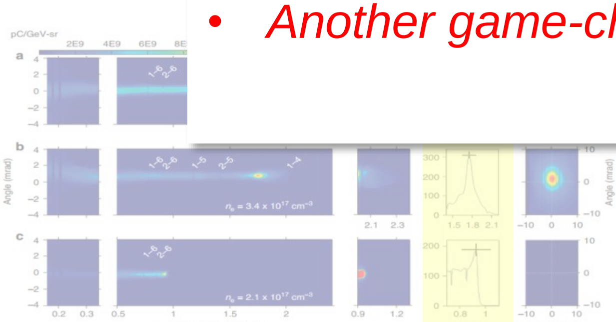
LWFA



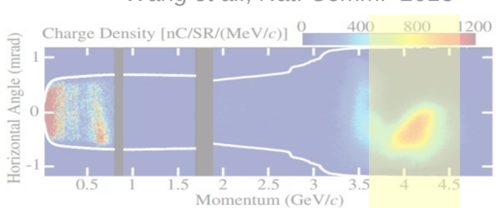
Mangles et al.
Faure et



Hidd

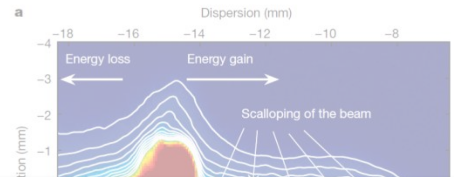


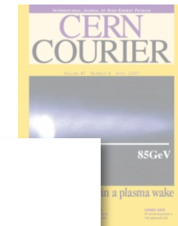
Wang et al., Nat. Comm. 2013



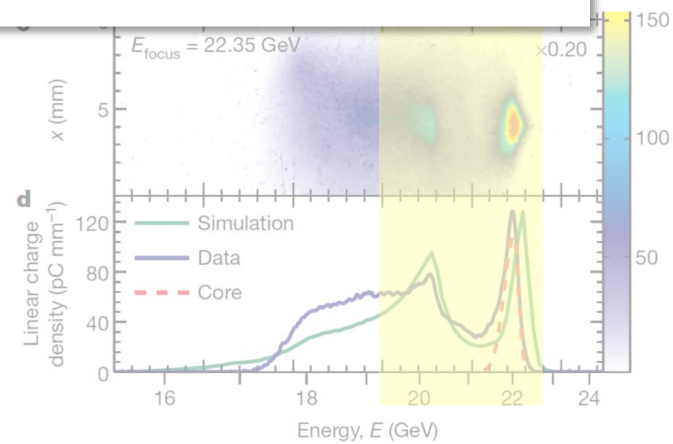
Leemans et al., PRL 2014

PWFA





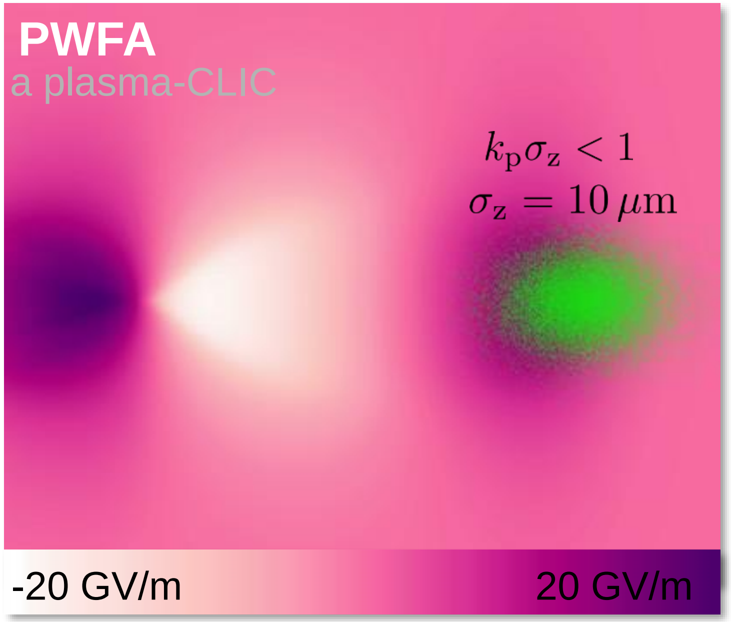
- *Fantastic energy gains, increase of energy & beam quality by order of magnitude in a decade, ultrashort & high current (many kA), ongoing steady progress..*
- *But: stability, tunability, beam quality so far still limited*
- *Another game-changer is required..*



Litos et al., Nature 2014

Hybrid LWFA & PWFA

Many similarities between PWFA "blowout" and LWFA "bubble" generation…



plasma density

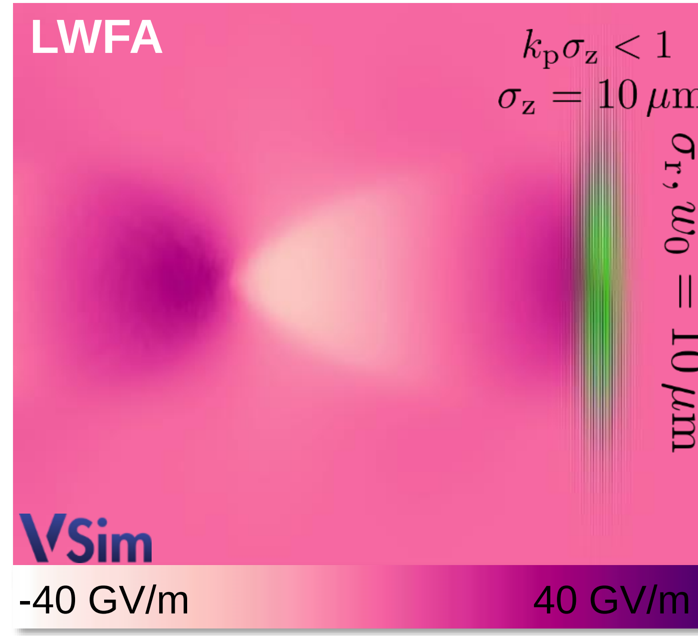
$$n_\mathrm{p} = 10^{17}\,\mathrm{cm}^{-3}$$

plasma wavelength
(i.e. blowout/bubble size)

$$\lambda_\mathrm{p} \approx 106\,\mu\mathrm{m}$$

plasma skin depth

$$k_\mathrm{p}^{-1} \approx 16\,\mu\mathrm{m}$$



dimensionless
beam charge

$$\tilde{Q} = \frac{N_b k_p^3}{n_p} \approx 3$$

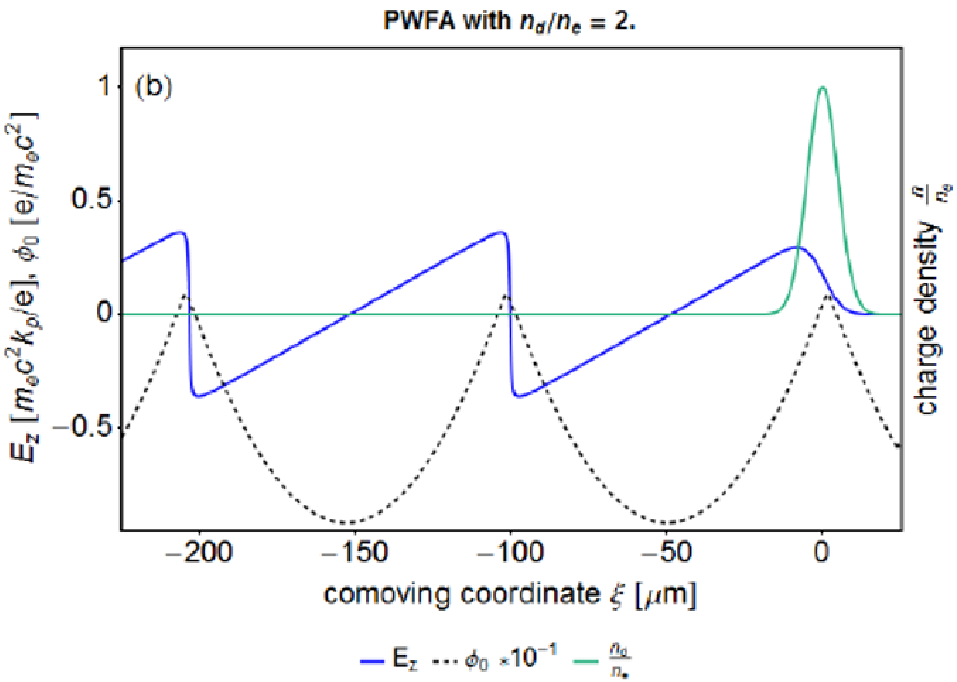
dimensionless
light amplitude

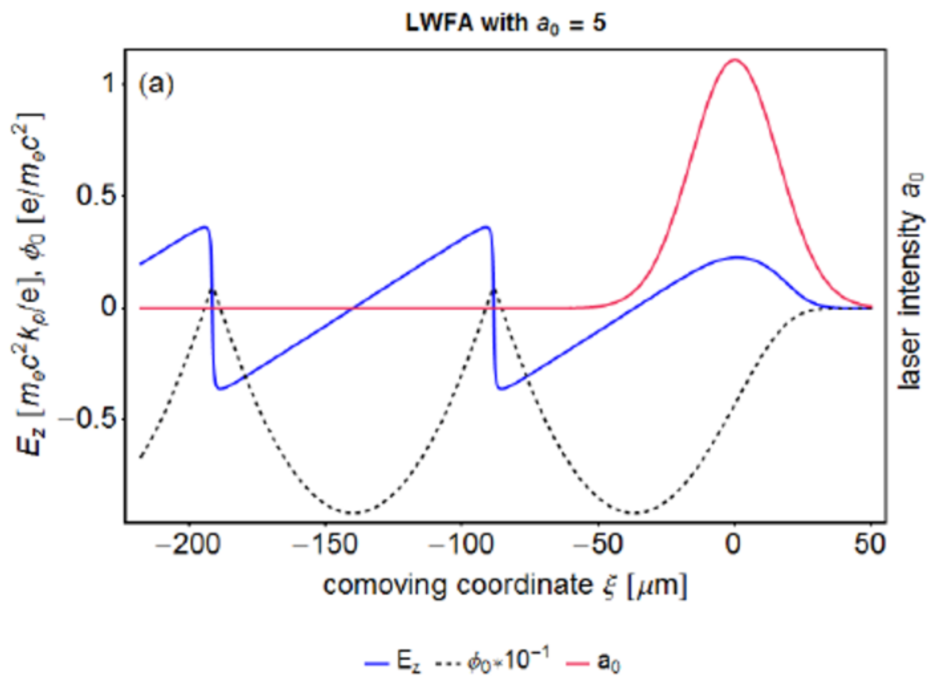
$$a_0 = \frac{eE}{m_0 \omega c} \approx 3$$

$$\tilde{Q} = \frac{N_b k_p^3}{n_p} \begin{cases} < 0 & \text{linear regime} \\ \approx 0 & \text{quasilinear} \\ > 0 & \text{nonlinear (blowout regime)} \end{cases}$$

- PWFA: Chen et al. PRL 1985, Rosenzweig et al. PRL 1988, Rosenzweig et al. PRA 1990, Assmann et al. SLAC 1998, Blumenfeld et al. 2007, Litos et al. Nature 2014
- LWFA: Tajima & Dawson PRL 1979, Clayton et al. PRL 1990, Pukhov & MtV ABP 2002, Faure/Mangles/Geddes et al. Nature 2004, Leemans et al. PRL 2014

Plasma wake excitation





- 1D nonlinear model in co-moving frame (quasi-static approximation):

$$\frac{\partial^2\phi}{\partial z^2} = -\frac{4\pi e}{m_e c_0^2}\rho$$

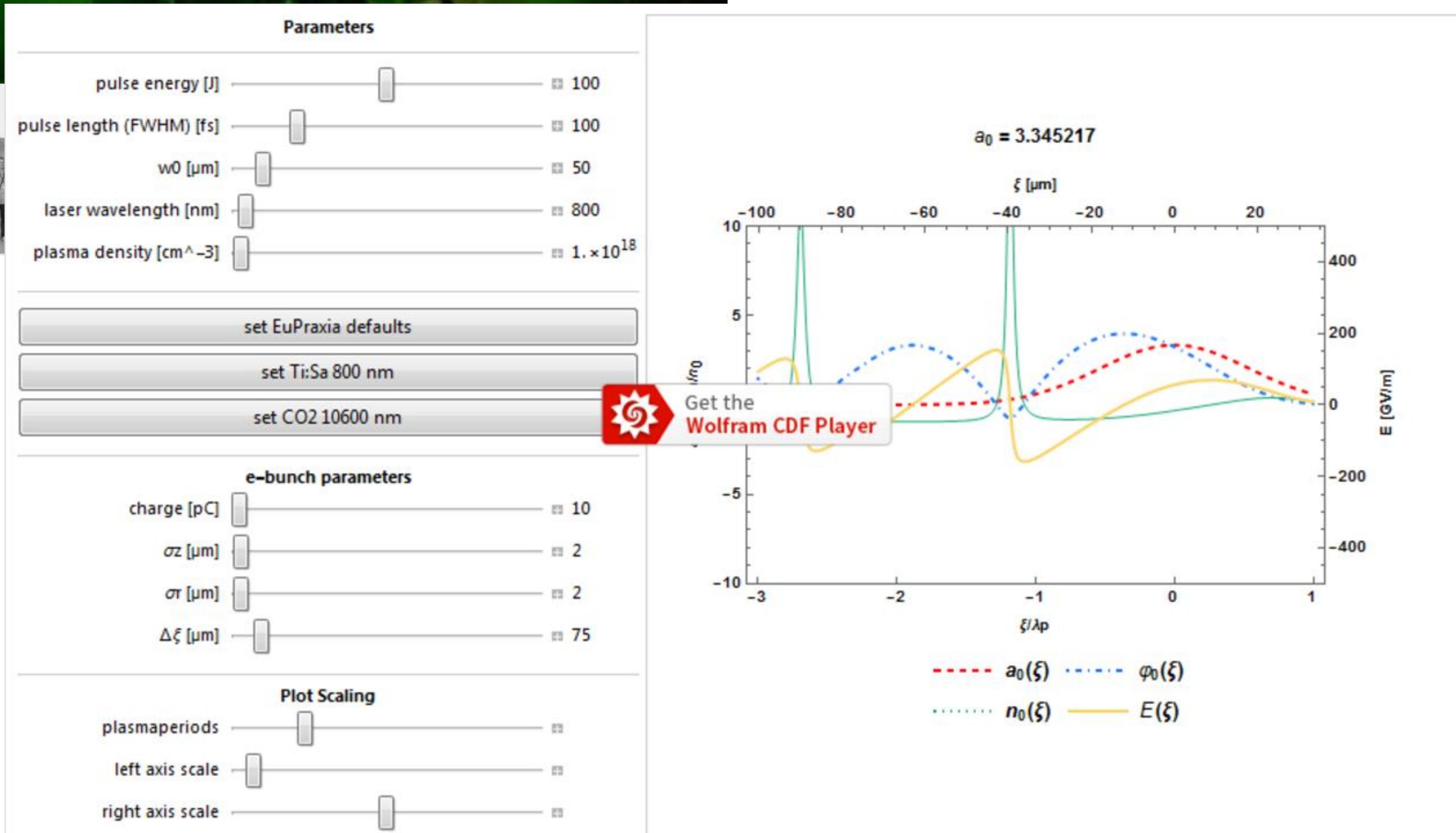
Poisson

$$\begin{aligned}\frac{\partial^2\phi}{\partial z^2} &= \frac{4\pi e^2}{m_e c_0^2}(n_e - n_0 + n_d)\\ &= \frac{4\pi e^2 n_0}{m_e c_0^2}\left(\frac{n_e}{n_0} + \frac{n_d}{n_0} - 1\right)\\ &= k_p^2\left(\frac{n_e}{n_0} + \frac{n_d}{n_0} - 1\right).\end{aligned}$$

$$k_p^{-2}\frac{\partial^2\phi}{\partial\xi^2} = \underbrace{\frac{n_d}{n_0}}_{\text{e-beam}} + \underbrace{\frac{1+a_0^2}{2(1+\phi)^2}}_{\text{laser}} - \frac{1}{2}$$

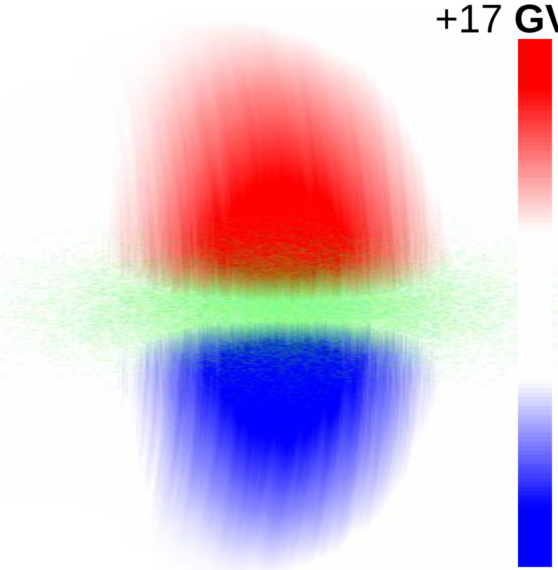
- longitudinal electric field E_z and electrostatic potential ϕ are similar for PWFA and LWFA
- Detailed lecture on this e.g. in Nadjmudin‘s talk. Script see on SCDT webpage:

http://ppals.phys.strath.ac.uk/ tools&links

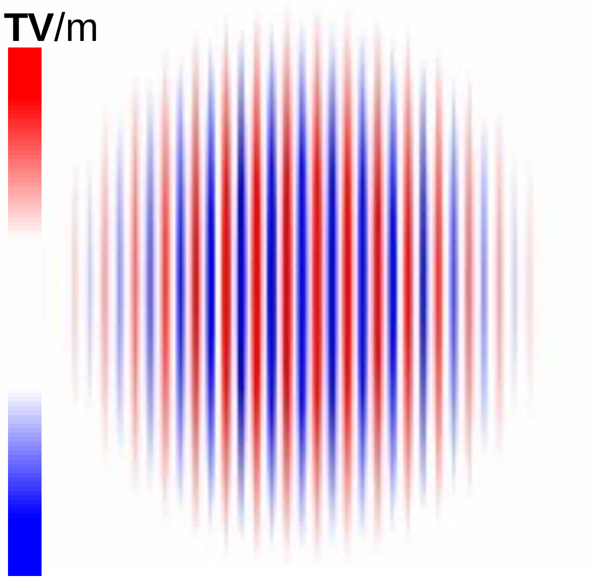


… but also profound differences: unipolar (PWFA) vs. oscillating (LWFA) fields

PWFA



LWFA



$$E_{\mathrm{r,PWFA}} \ll E_{\mathrm{r,LWFA}}$$

while accelerating plasma fields are similar

Intuitively clear: you want unidirectional fields to expel electrons off axis

Coulomb force

$$F_{\mathrm{Coulomb}} = e\mathbf{E}$$

$$E_r(r,z) = \frac{Ne}{2\pi^{3/2}\epsilon_0\sigma_z r}\left[1 - \exp\left(-\frac{r^2}{2\sigma_r^2}\right)\right]$$

ponderomotive force

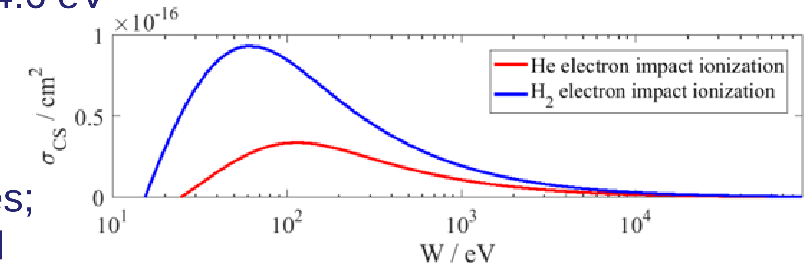
$$F_{\mathrm{pond}} = -\frac{e^2}{4m\omega^2}\nabla\mathbf{E^2} \propto \nabla\mathbf{I}$$

⇒ PWFA more efficient to excite plasma wave, LWFA much better to generate plasma

Ionization processes: SPI/MPI, impact ionization, Tunneling, BSI

- No single photon ionization (SPI) at typical laser frequencies: $h\nu << \xi_i$ (ionization potential)

  For example H2: $\xi_i \approx 15.4$ eV, H: $\xi_i \approx 13.6$ eV, He: $\xi_i \approx 24.6$ eV

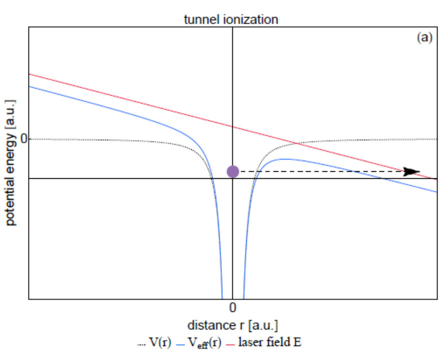


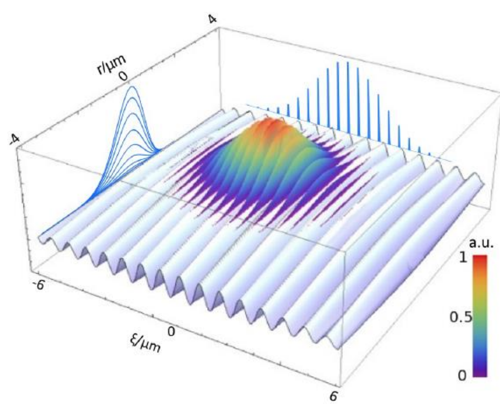
- Impact ionization by electron drive beam negligible:

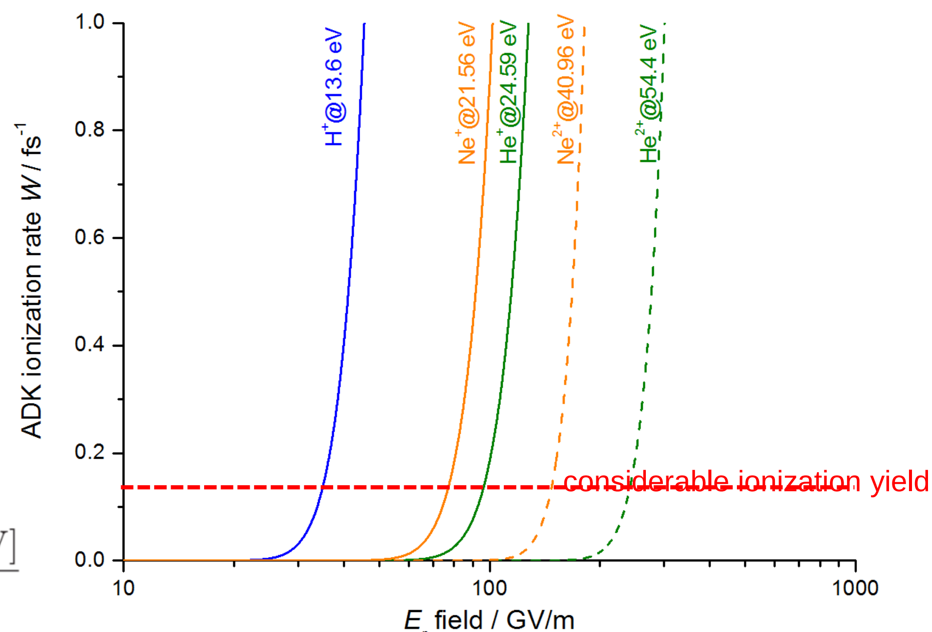
- Keldysh parameter: $\gamma_k << 1$ tunneling ionization dominates; $\gamma_k >> 1$ MPI dominates. For 800 nm laser wavelength and intensities sufficient to ionize He, MPI negligible.

At higher harmonics (400 nm, 233 nm etc.), MPI is important and Yudin-Ivanov model should be used

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







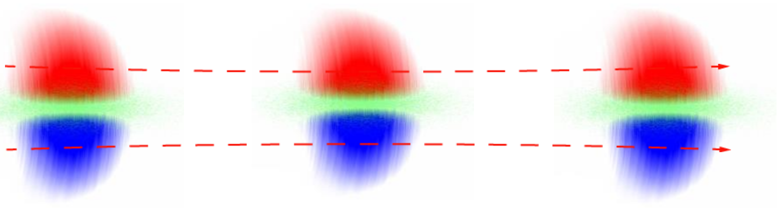
- At even higher intensities, Barrier Suppression Ionization

$$I_{\mathrm{BSI}} [\mathrm{W/cm^2}] \approx 4 \times 10^9 \frac{\xi_i^4 [\mathrm{eV}]}{Z^2}$$

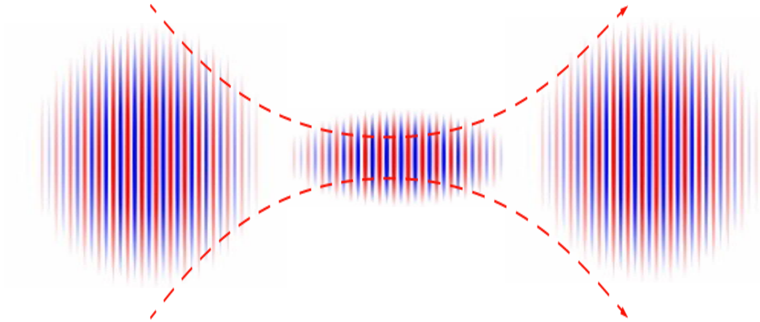
… also profound differences: *beam expansion (PWFA) vs. diffraction (LWFA)*

Electron/photon density needs to stay intense over long acceleration distance

PWFA



LWFA



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

Both laser and electron beam expands hyperbolically, but

$$\omega(z) = \omega_0\sqrt{1+\left(\frac{z}{\boxed{Z_R}}\right)^2}$$

Betatron length $\boxed{\beta^*} = \sigma_{r0}^2\gamma/\epsilon_n$

Rayleigh length $\boxed{Z_R} = \pi\omega_0^2/\lambda$

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

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

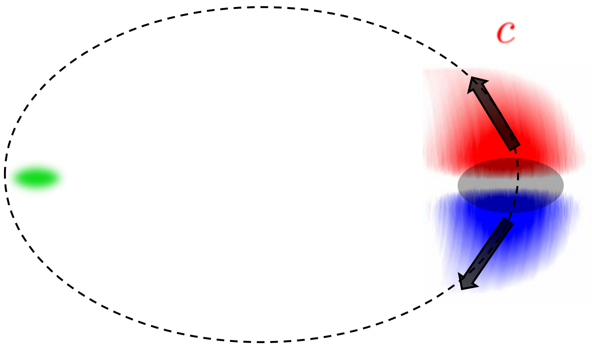
Ti:Sa laser (0.8 µm)

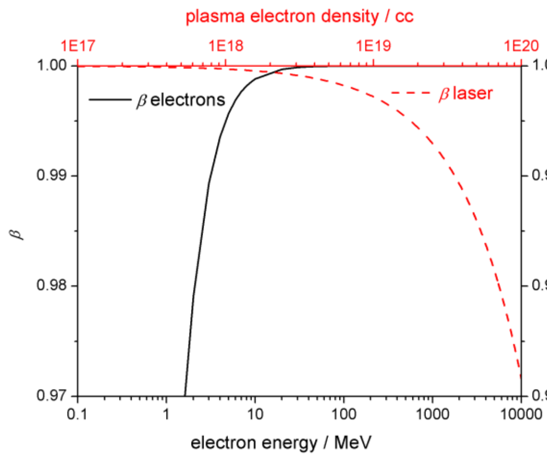
⇒ PWFA allows orders of magnitude longer acc. distances w/o any tricks (guiding etc.), LWFA allows to interact in very confined volume

… also profound differences: dephasing

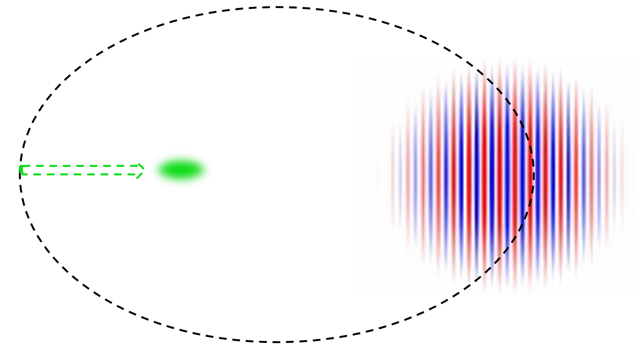
Electrons to be accelerated need to stay in proper phase of plasma wave

PWFA





LWFA



Electron beam(s) moves with *c*

⇒ witness bunch stays in proper phase and harnesses max. acc. fields

⇒ No dark current: self injection difficult because wake moves fast: $\gamma_{wake} = \gamma_{driver} = 10^4$ e.g. for 10 GeV drive beam

Laser beam moves with group velocity in plasma $v_g = c\left(1 - \frac{\omega_p^2}{\omega_0^2}\right)^{1/2} < c$

⇒ witness bunch moves forward, samples different field regions and reaches dephasing limit after distance

$$L_d \approx \lambda_p^3/\lambda^2 = n_c/n_e^{3/2}$$

⇒ Self injection / dark current easy because $\gamma_{wake} = \gamma_{laser} \approx$ 10-100 for typical densities

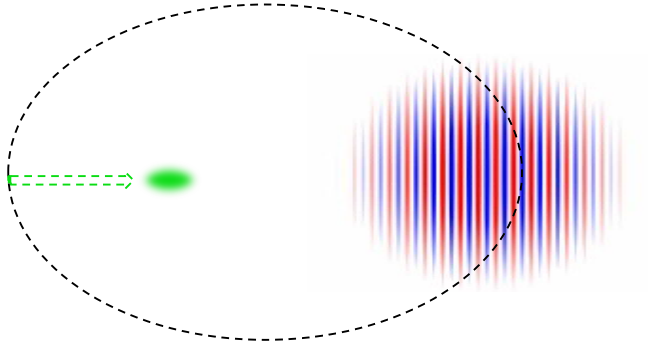
⇒ PWFA allows orders of magnitude longer acc. distances w/o dephasing, while dephasing can help make bunches "monoenergetic" w/ LWFA

⇒ LWFA allows for easier self-injection, while PWFA in turn easily dark current free

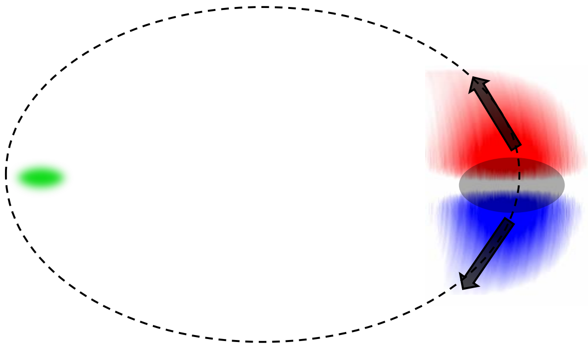
LWFA vs PWFA summarized

Hidding et al., J. Phys. B 47, special x-ray issue 2014

- Electron bunches: drive plasma wave efficiently due to unidirectional fields
- Lasers w/ oscillating field structure only able to drive plasmas due to ponderomotive force
- Lasers can easily ionize matter, because of diffraction can do so in very confined area
- Electron bunches can be produced with very high rep rate from state-of-the-art sources
- Electron bunches are not good for ionizing matter
- Electron bunches move with c, allow for dephasing-free accelerator systems
- No dark current in PWFA systems because of high gamma
- Electron bunches are stiff: don't expand much transversally (limited diffraction) – long acc. distances



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)

⇒ Electron bunches are better plasma drivers, laser pulses great for injection!

Injection and trapping

- Trapping: accelerating electrons must catch up with wave so that $\gamma_{electron} \geq \gamma_{wave} = \gamma_p$
- If electrons initially at rest, trapping condition: wake electrostatic potential energy ≥ kinetic energy the electrons need to gain

$$-e\Delta\phi' \geq E'_{\mathrm{kin}} = E_0(\gamma_p - 1) = m_0 c^2(\gamma_p - 1)$$

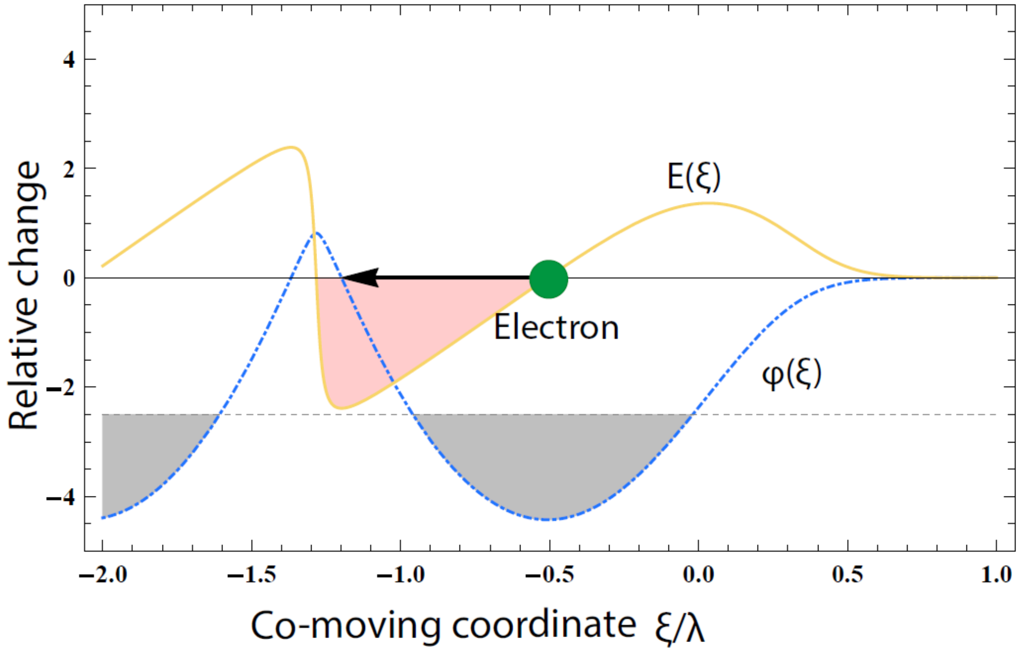
Hamiltonian of electron in electromagnetic field:

$$\mathcal{H} = \underbrace{\gamma m c^2}_{\text{electron energy}} - \underbrace{e\phi}_{\text{scalarpotential}}$$

Where is trapping the easiest?

Right in center of the blowout: an electron released there always sees accelerating fields, and can catch up with the plasma wave most easily.

Great spot to release electrons for injection – but how to put them there?



Relativistic identities

$$\vec{\beta} = \frac{\vec{v}}{c} = \sqrt{1 - \frac{{E_0}^2}{(E+E_0)^2}} \cdot \frac{\vec{v}}{|\vec{v}|} = \sqrt{1 - \frac{1}{\gamma^2}} \cdot \frac{\vec{v}}{|\vec{v}|} = \frac{\vec{p}}{\sqrt{(m_0 c)^2 + p^2}}$$

Lorentz factor:

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \sqrt{1 + \frac{p^2}{(m_0 c)^2}} = \frac{\sqrt{(m_0 c)^2 + p^2}}{m_0 c} = \frac{E}{E_0} + 1$$

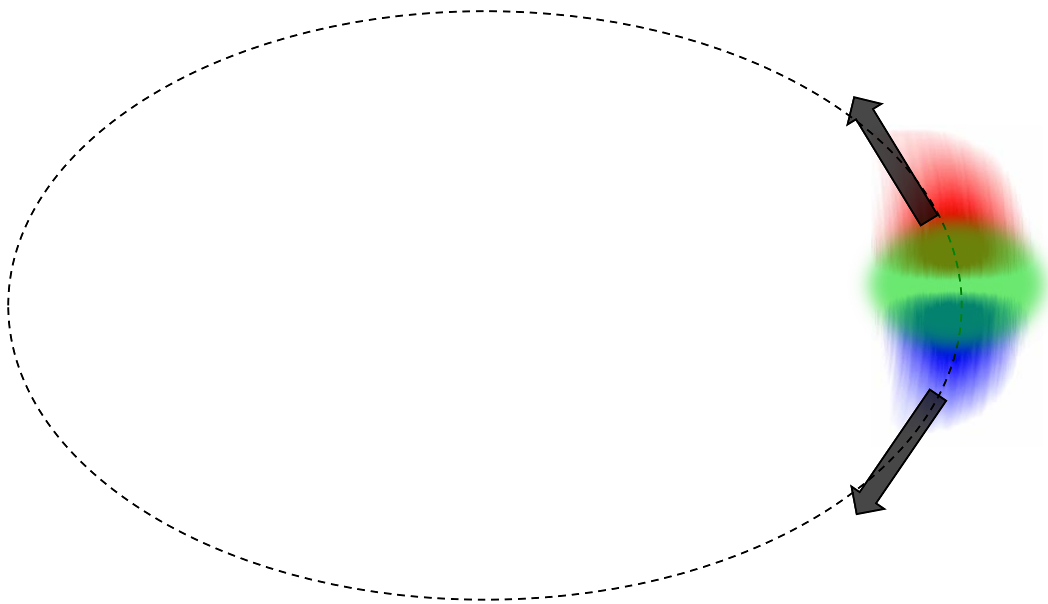
In contrast: phase velocity of plasma wave γ_p driven by laser pulse is the group velocity of laser pulse, which is plasma electron density-dependent

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

$$\vec{p} = m_0\, c\, \gamma\, \vec{\beta} = m_0\, c\sqrt{\gamma^2 - 1} \cdot \frac{\vec{v}}{|\vec{v}|} = m_0\, c\sqrt{\frac{\beta^2}{1-\beta^2}} \cdot \frac{\vec{v}}{|\vec{v}|} = \sqrt{\frac{E^2}{c^2} + 2E\, m_0} \cdot \frac{\vec{v}}{|\vec{v}|}$$

$$E_{kin} = E_0\,(\gamma - 1) = E_0\left(\sqrt{1 + \frac{p^2}{(m_0 c)^2}} - 1\right) = E_0\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right)$$

Trojan Horse: Underdense Plasma Photocathode & Wakefield Acceleration

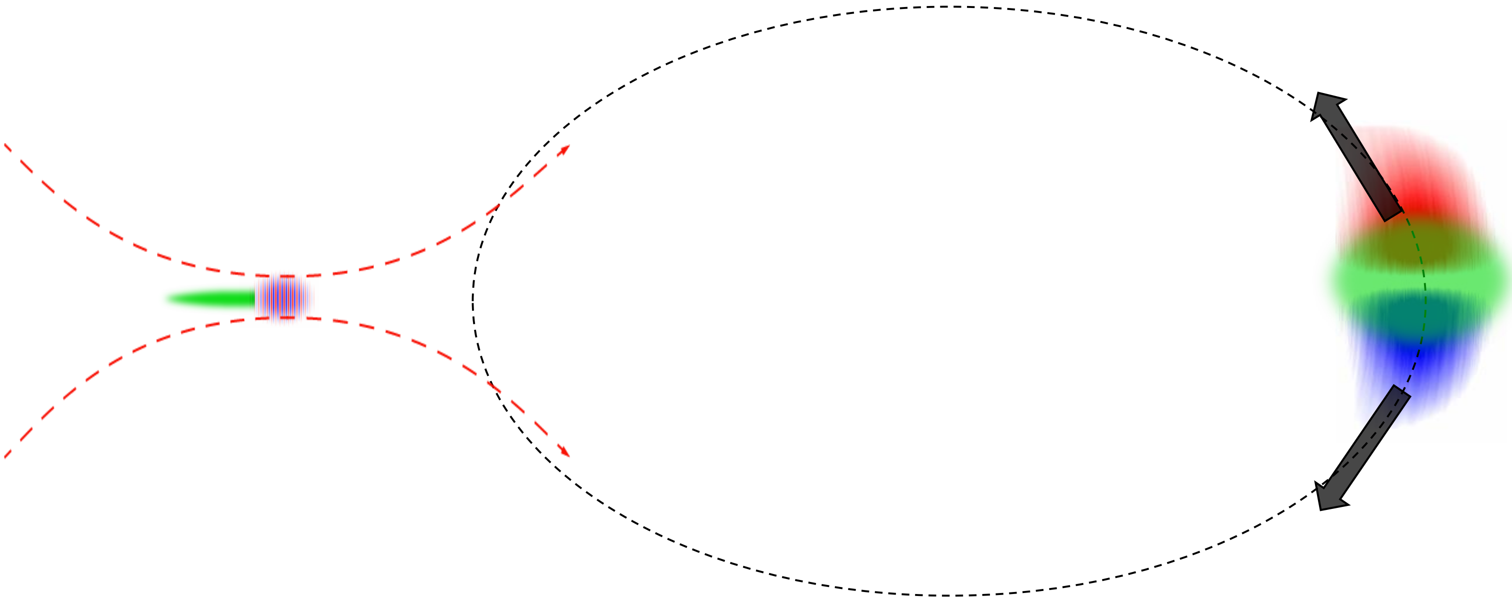


Step 1

- Electron beam driver sets up dephasing free, dark current free plasma cavity in low-ionization threshold (LIT) plasma such as hydrogen ($\xi_i \approx 13.6$ eV)
- A high-ionization threshold (HIT) gas is present such as Helium ($\xi_i \approx 24.6$ eV), not ionized by driver nor wake (density can be tuned independently of LIT density)

$$I_{\mathrm{BSI}}\,[\mathrm{W/cm^2}] \approx 4 \times 10^9 \, \frac{\xi_i^4\,[\mathrm{eV}]}{Z^2}$$

Take the best of both worlds: Hybrid Plasma Acceleration

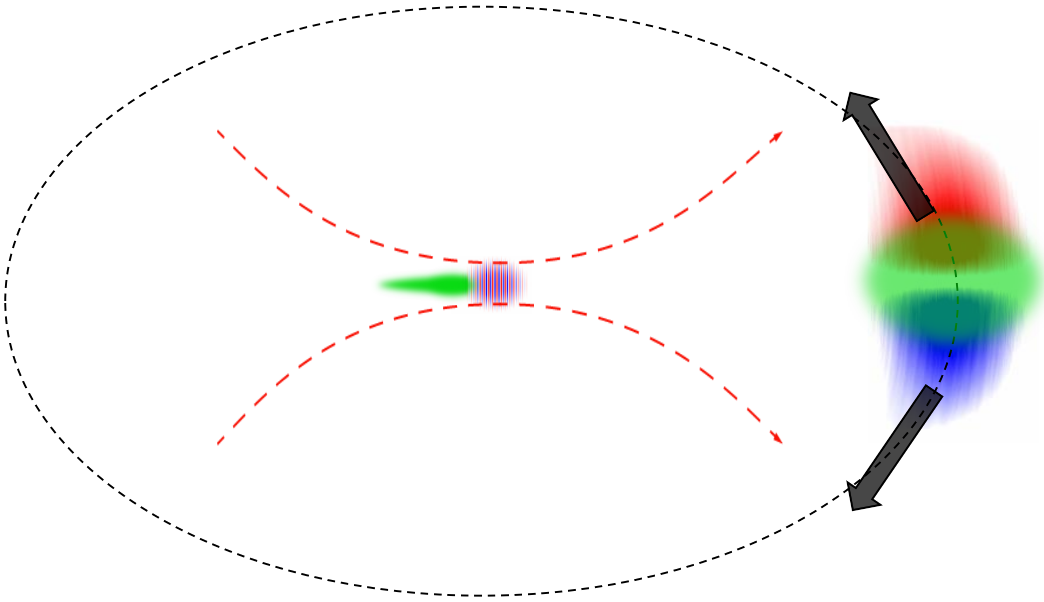


Step 2

- A synchronized, low intensity laser pulse is focused strongly to the HIT level, releases He electrons in confined volume at arbitrary position

- Tune released He electrons (i.e. charge) with He density, a_0, w_0, ω, τ, polarization, focus shape…

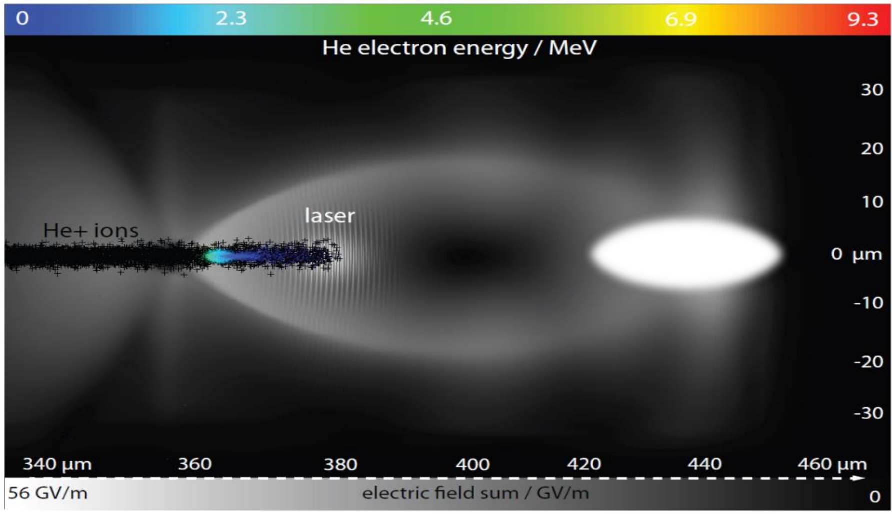
Take the best of both worlds: Hybrid Plasma Acceleration



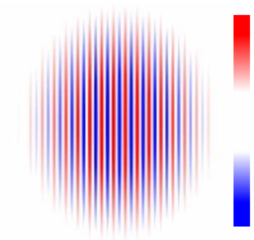
Step 3

- Released He electrons fall behind but are compressed and trapped in ideal phase
- Ultracold electrons are rapidly accelerated (mitigating space charge effects) and are accelerated as long as driver can excite plasma wave

Why witness bunches ultracold?



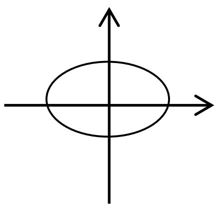
Laser kick contrib. to norm. emittance:



$$E_0 = a_0 \frac{2\pi m_e c^2}{e\lambda}$$

$$\sigma_{p_r}/(mc) \;\approx\; a_0/2$$

residual momentum



$$\sigma_{\mathrm{r,He}} \approx w_0/\sqrt{2}$$

source size

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

$$\epsilon_y \simeq \epsilon_x = k_p w_i^2 a_i \left(\frac{3\pi r_e}{4\sqrt{2}\alpha^4\lambda_i}\right)\left(\frac{U_H}{U_I}\right)^{3/2}$$

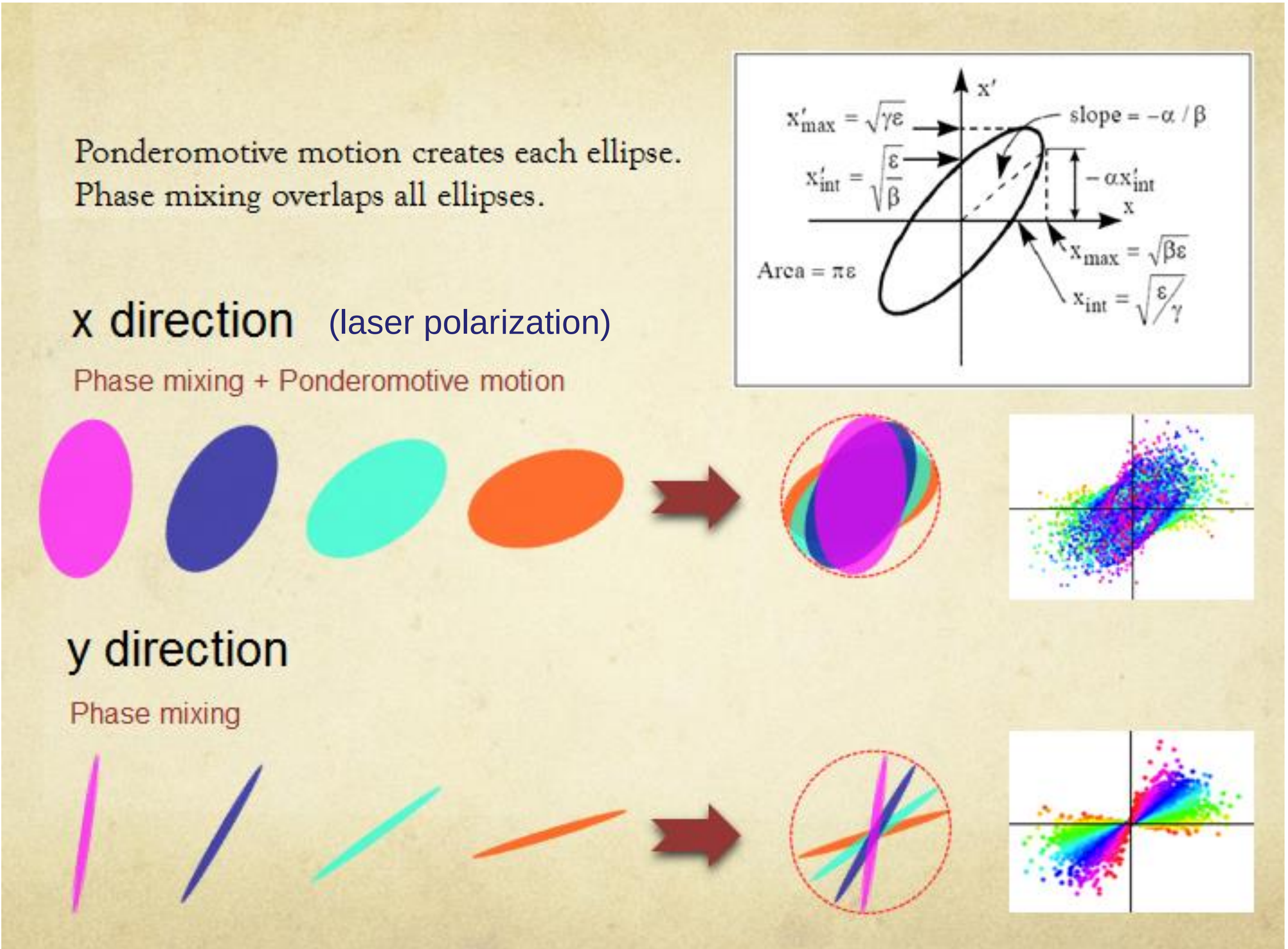
Refined scalings: C. Schroeder et al., PRSTAB 17, 101301, 2014, Y. Xi et al., PRSTAB 2013

- Because the laser pulse intensity is **4 orders of magnitude** lower than in LWFA! a_0=0.018 instead of a_0>1
- Because the initial phase space volume is low
- Because the electrons are rapidly accelerated (space charge impact decreases as γ^{-2})
- Because initial ion shielding by released He ions

→ normalized emittance ε_n down to 10^{-9} m rad

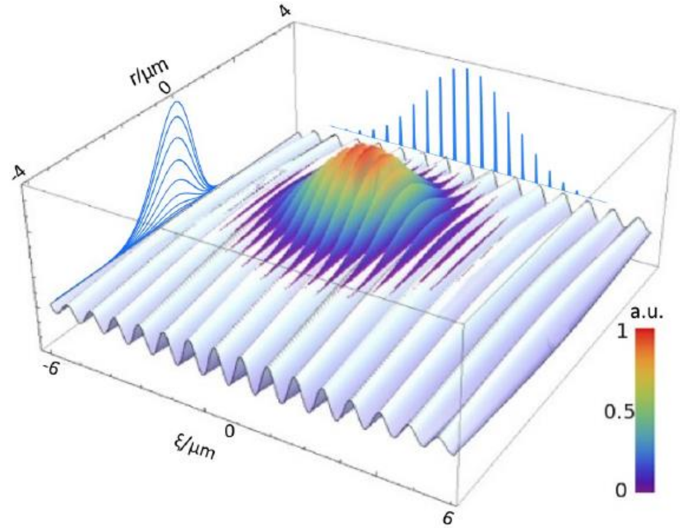
B. Hidding et al., PRL 108, 035001, 2012, Y. Xi et al., PRSTAB 2013, DE patent 2011, US patent 2012

Ponderomotive force and phase mixing



PIC simulation results d'accord with hybrid model

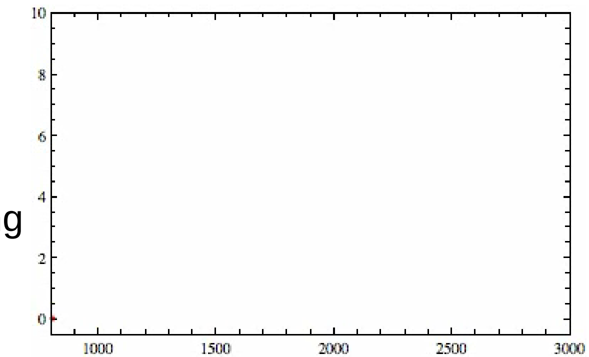
Y. Xi et al., PRSTAB, 2013



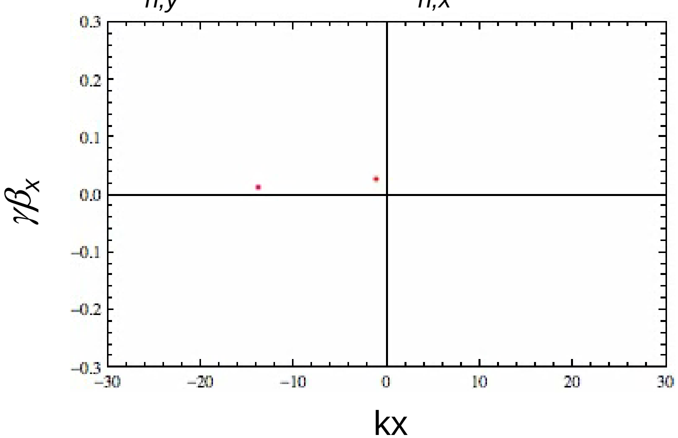
- Ionization based on ADK and YI (Yudin-Ivanov-model). *G. L. Yudin and M. Y. Ivanov, Phys. Rev. A, 64:013409, 2001.*

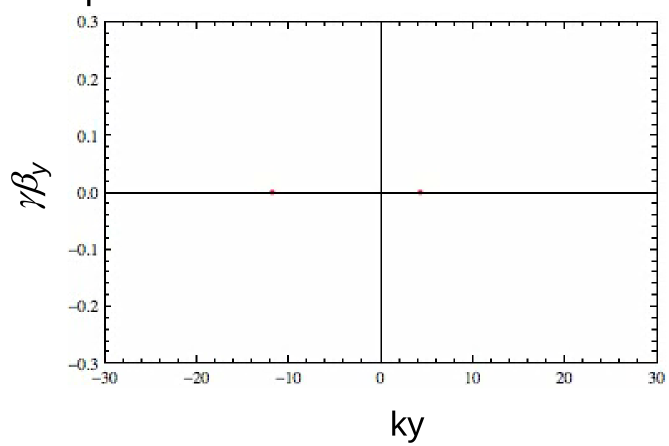
- Detailed numero-analytical analysis shows that $\varepsilon_{n,y}$ is about an order of magnitude lower, and increases slower than $\varepsilon_{n,x}$ as intensity increases. $\varepsilon_{n,y}$ down to the $\varepsilon_{n,y} \approx 10^{-9}$ m rad level or less.

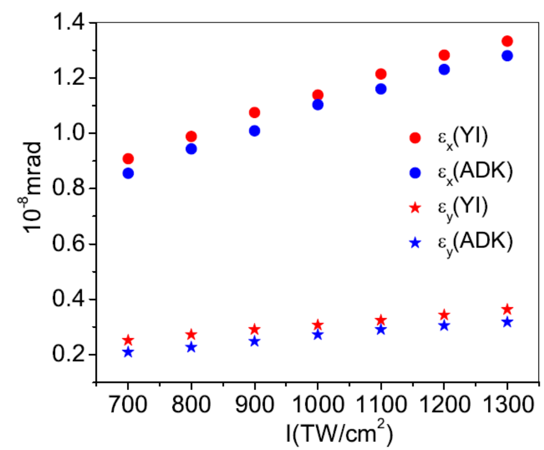
plasma velocity bunching



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







Similarities and differences of plasma photocathodes to rf photocathodes

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

residual momentum due to laser kick
electrons released at different betatron phases

$$\epsilon_{\mathrm{th}} = \frac{w_0}{2}\sqrt{\frac{k_B T}{mc^2}}$$

approx. 0.5 mm mrad in standard photocathodes

In state-of-the-art rf photoguns, typically charges of 0.1-1 nC are released by lasers with spot sizes of the order of 1 mm. This leads to space charges 1-10 MV/m – a substantial fraction of the acc. field of ~100 MV/m. (J. Luiten, Int. J. Modern Physics A 22, 3882-3897, 2007)
Acc. and focusing fields in plasma are two orders of magnitude larger!

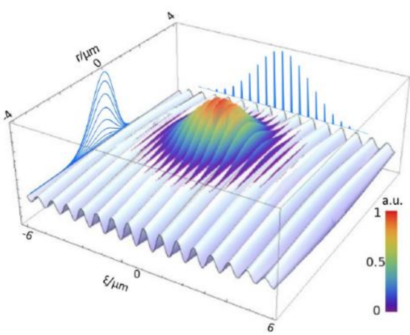
- Tunability: Neglecting high laser frequencies, the released charge can be approximated by

$$Q \propto \pi w_0^2 Z_R n_p \propto w_0^4$$

Rough estimate when operating at ionization threshold: cylinder with Rayleigh length

$$N_e \approx n_{\mathrm{HIT}} \sum_{(z_w - z_r)/c}^{(z_w + z_r)/c} T/2 \int \Gamma(x, y, \xi, t) \mathrm{d}V$$

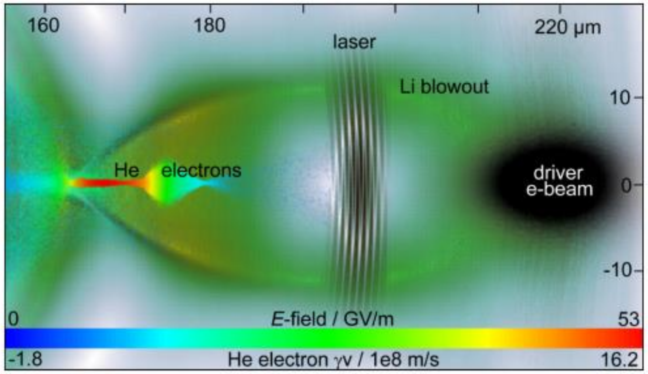
Exactly: integrated over ionization rates



Note that plasma density n_p(HIT) such as He, can be independently tunable of n_p(LIT) such as H!

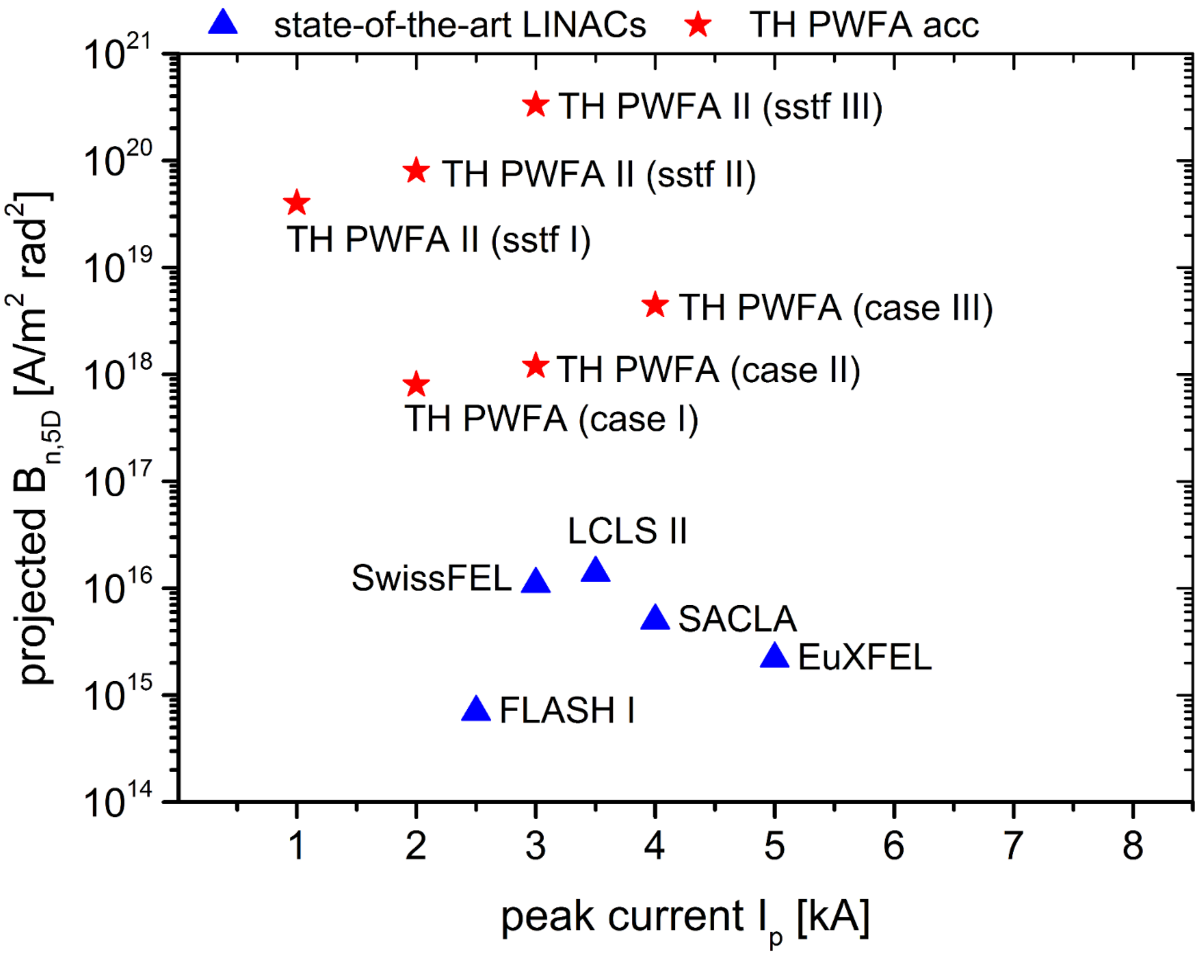
Ultrahigh 5D brightness of TH mechanism

Ultracold electrons from plasma photocathode produce normalized emittance orders of magnitude lower than state-of-the-art



$$B = \frac{2I}{\epsilon_{\mathrm{n}}^2}$$

⇒ Allows 5D brightness many orders of magnitude brighter than state-of-the-art



Emittance and brightness are key parameters which enable/determine performance in applications such as HEP (luminosity) or light sources (e.g. gain in FEL)

Hybrid Trojan Horse-based Future XFEL 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

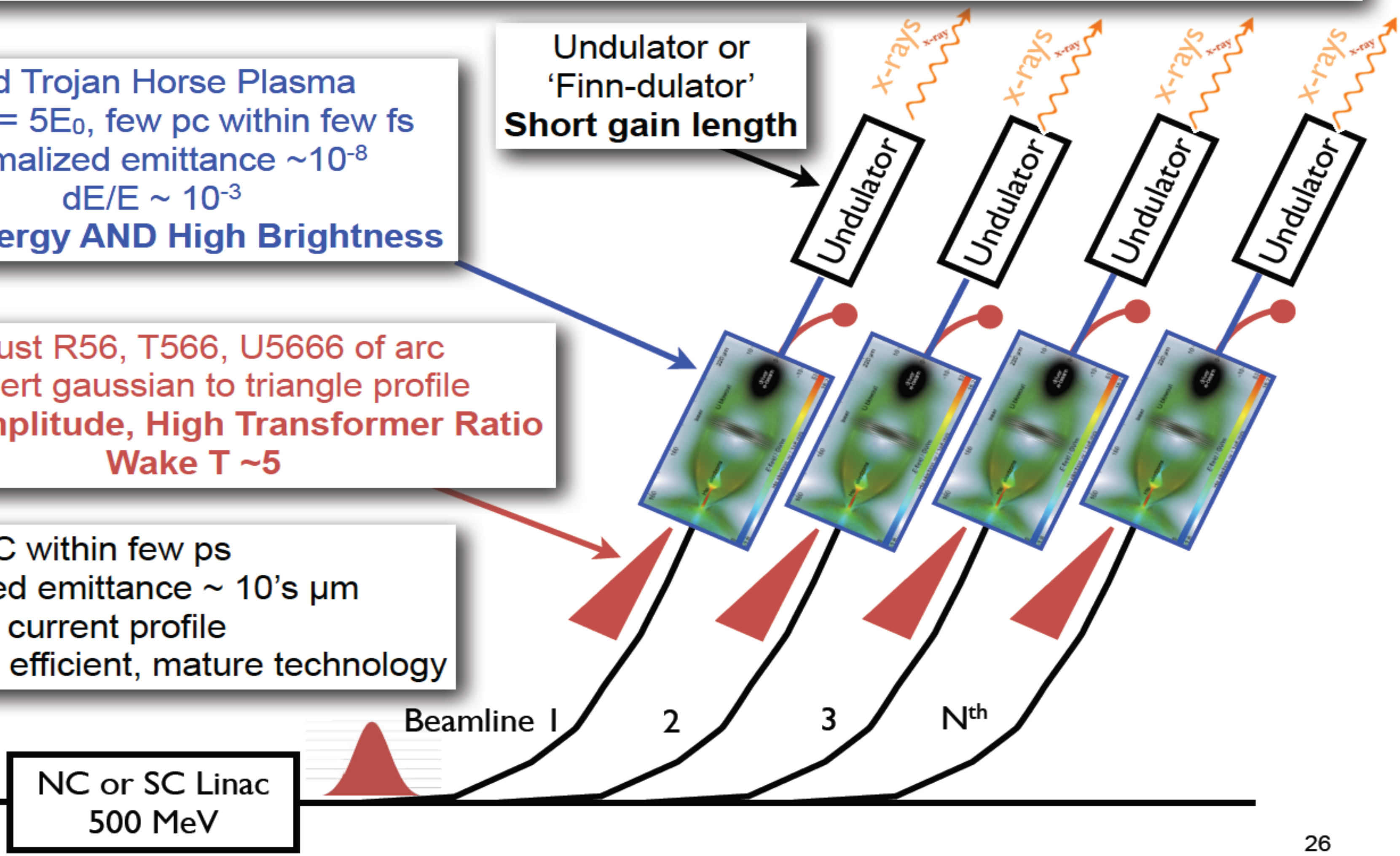
Compactness of plasmas accelerators, rep rate like rings with high brightness of linacs!

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

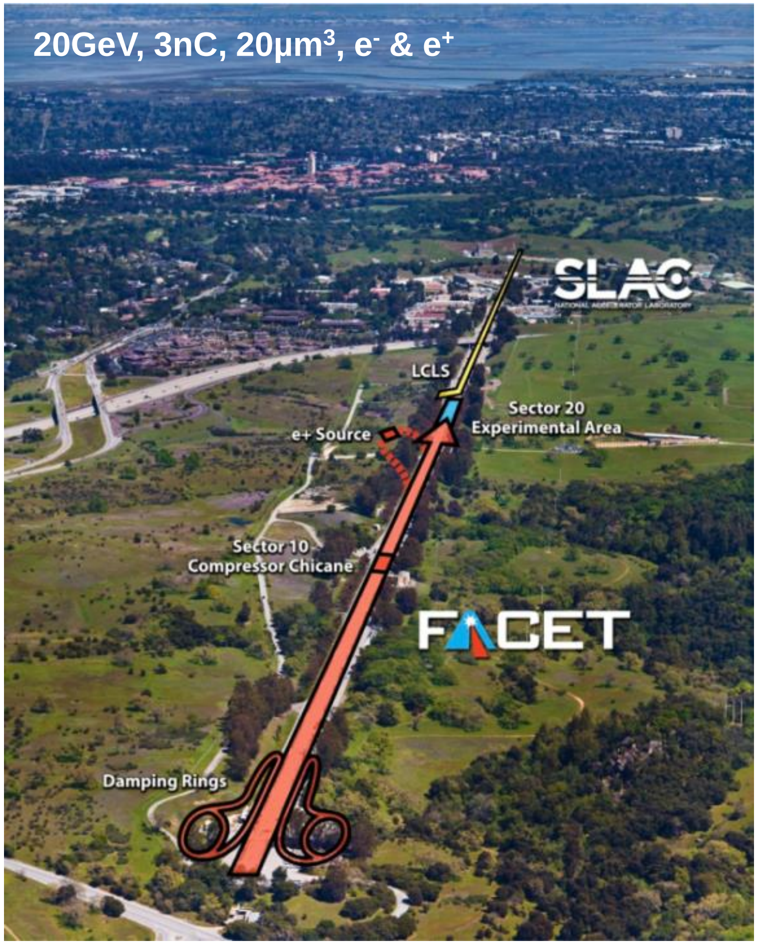
Adjust R56, T566, U5666 of arc
Convert gaussian to triangle profile
Large Amplitude, High Transformer Ratio
Wake T ~5

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



E210 Trojan Horse Experiment at

FACET – the premier facility for PWFA



Timeline:
- CD-0 2008
- CD-4 2012, Commissioning (2011)
- Experimental program (2012-2016)

"E210: Trojan Horse PWFA" experiment approved in 2011

A National User Facility:
- Externally reviewed experimental program
- >200 Users, 25 experiments, 8 months/year operation

Key PWFA Milestones:

√Mono-energetic e- acceleration

√High efficiency e^- acceleration (*Nature* **515**, Nov. 2014)

√First high-gradient e^+ PWFA (*Nature* **524**, Aug. 2015)

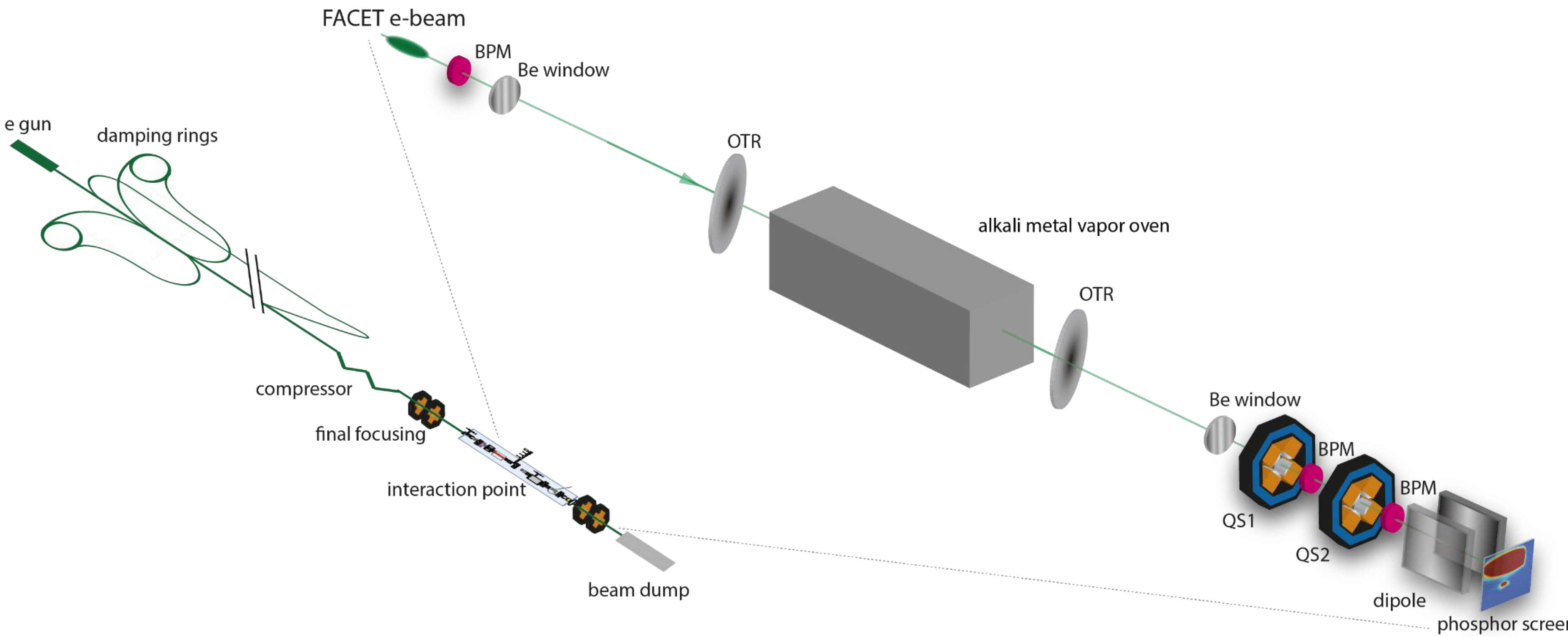
E210: Multi-institutional, cross-continental collaboration of academia (Strathclyde—UCLA—Hamburg—Oslo—Texas—Boulder), research centers (SLAC—DESY) and industry (RadiaBeam—Tech-X—Radiasoft)

PI's B. Hidding (Strathclyde) & J.B. Rosenzweig (UCLA)

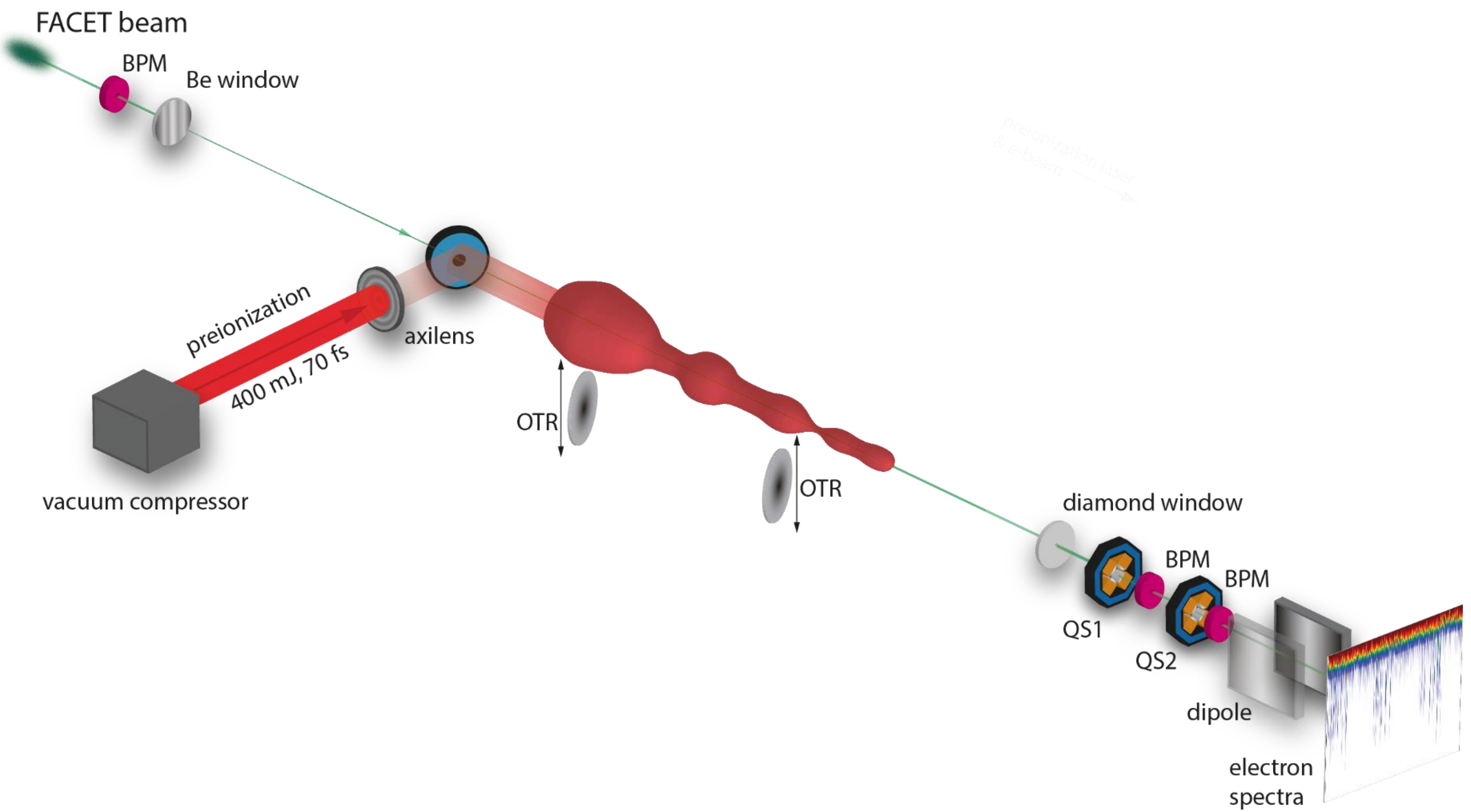
2012-2017, experiments at FACET ramping up from 2013-2016

Supported e.g. by Beam Brightness Transformer for Laser-Wakefield Accelerators DOE R&D program, RadiaBeam Technologies 2012-2016, EuPRAXIA WP14 etc.

2012 at FACET: use hot alkali metal vapor, self-ionized by driver beam



2013/14:
Ti:Sapphire commissioning, optical pre-ionization of (noble) gas



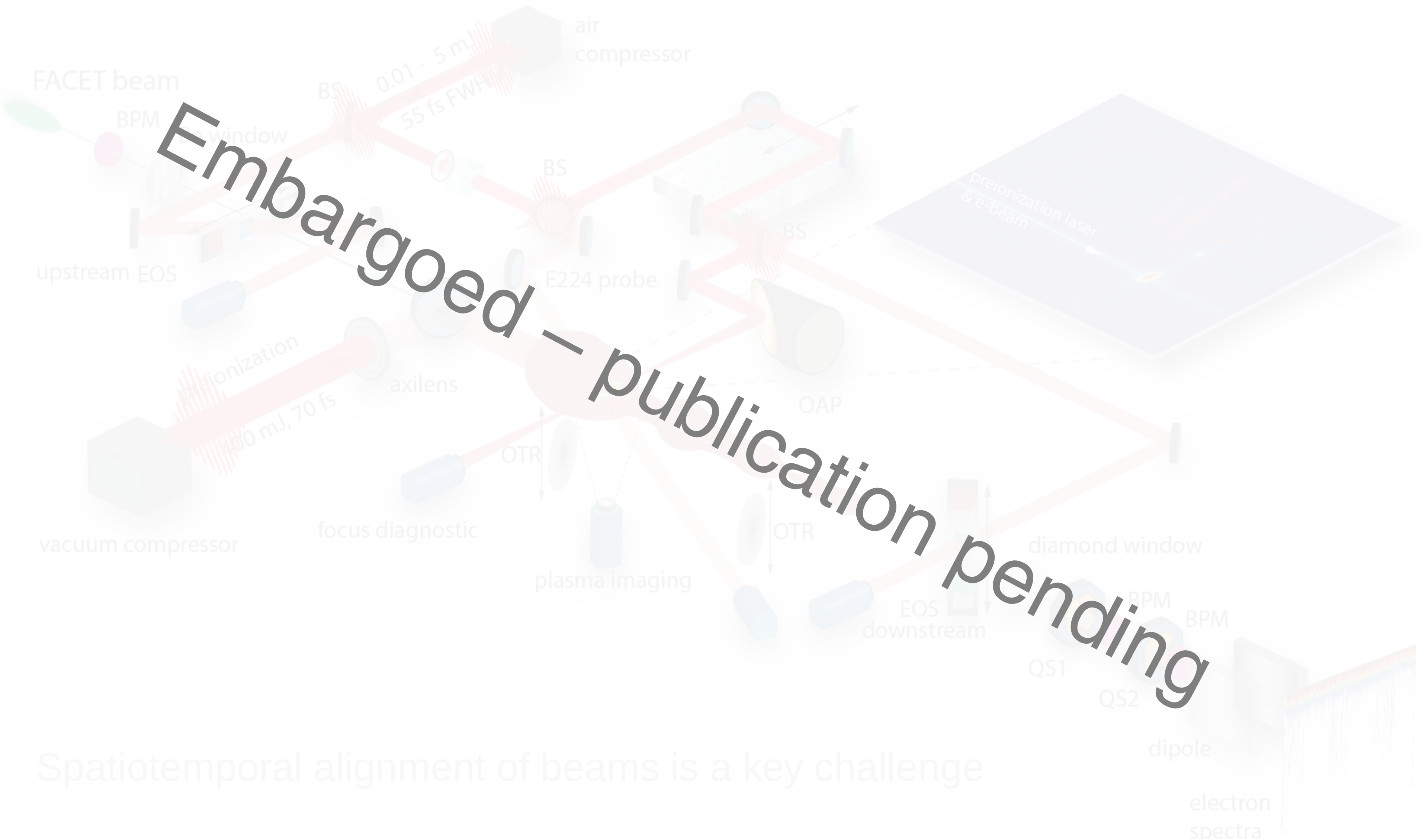
2013/14:
Commissioning of electro-optical sampling based time-of-arrival diagnostics, separate air compressor to allow for independently tunable beams

Embargoed – publication pending

2015: Add Trojan Horse plasma photocathode laser (in 90° geometry)

Embargoed – publication pending

2016: Full E210 setup with two independently tunable main laser arms, up to 5 laser beams (1 preionization, 2 EOS, 1 Trojan photocathode, 1 E224 probing) from vacuum and air compressor, and SLAC linac electron beam



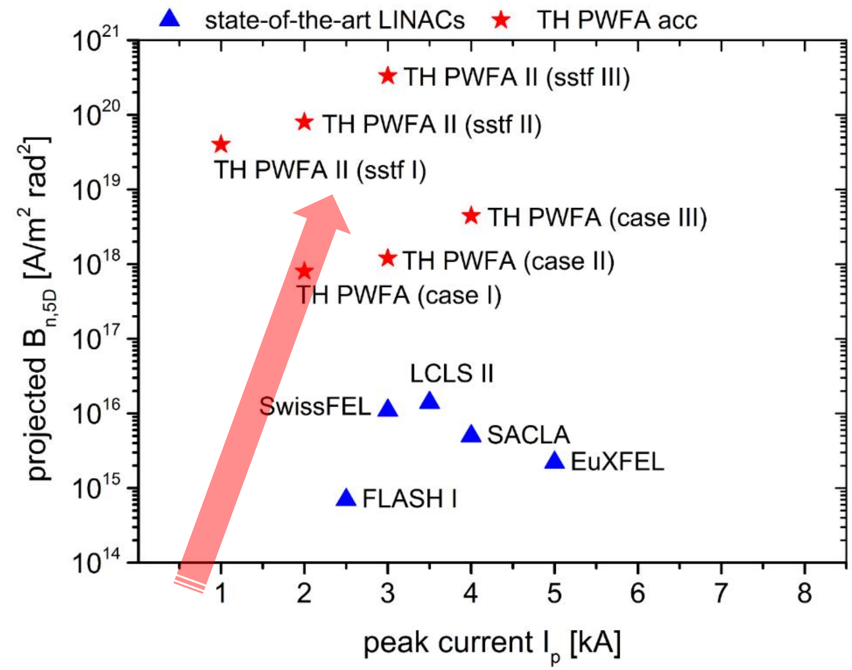
Embargoed – publication pending

Spatiotemporal alignment of beams is a key challenge

Spatiotemporal alignment of beams is a key challenge: Preionization laser pulse and electron beam

Embargoed – publication pending

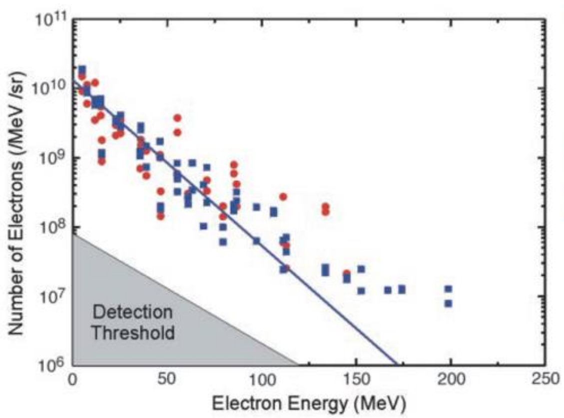
The energy spread challenge



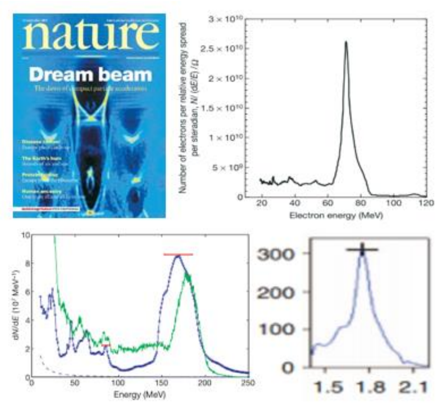
Prospect for tunable bunches with ultralow emittance and ultrahigh 5D-brightness is great, but

EuPRAXIA
NOVEL FUNDAMENTAL RESEARCH
COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

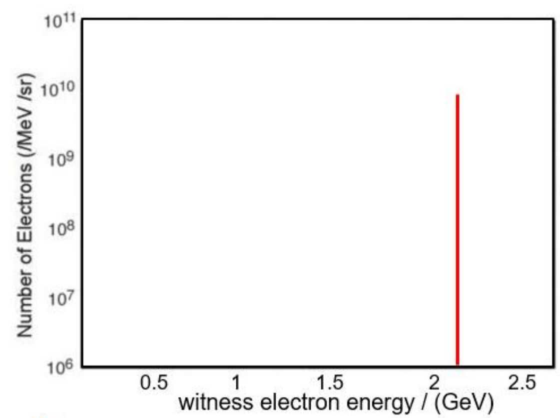
Energy spread is a big problem, can be showstopper for FEL, for example.
New approach to reduce energy spread by two orders of magnitude is needed!



exponential spectra, pre 2004

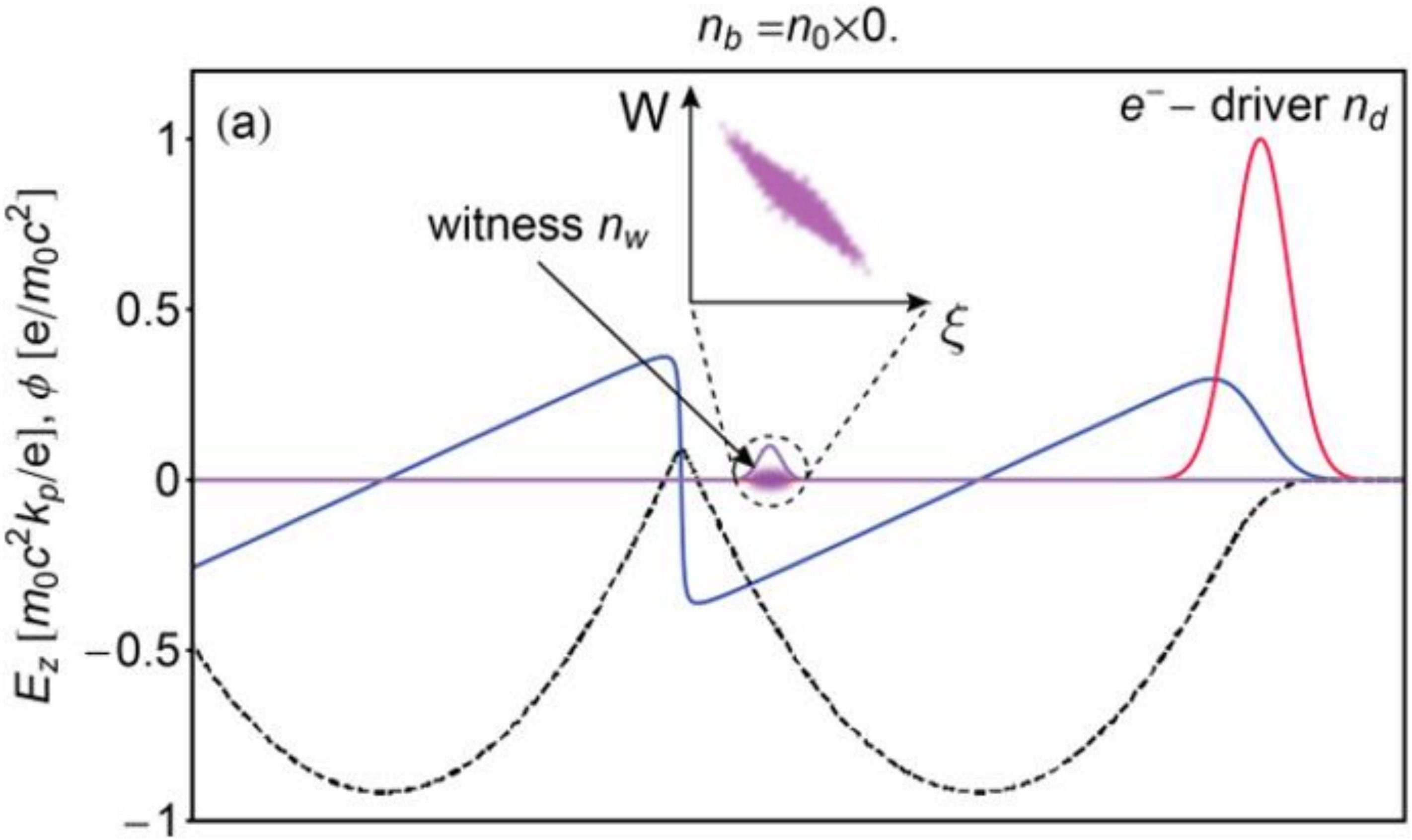


quasimonoenergetic beams, 2004 - today



NeXource: relative energy spreads < 0.01%

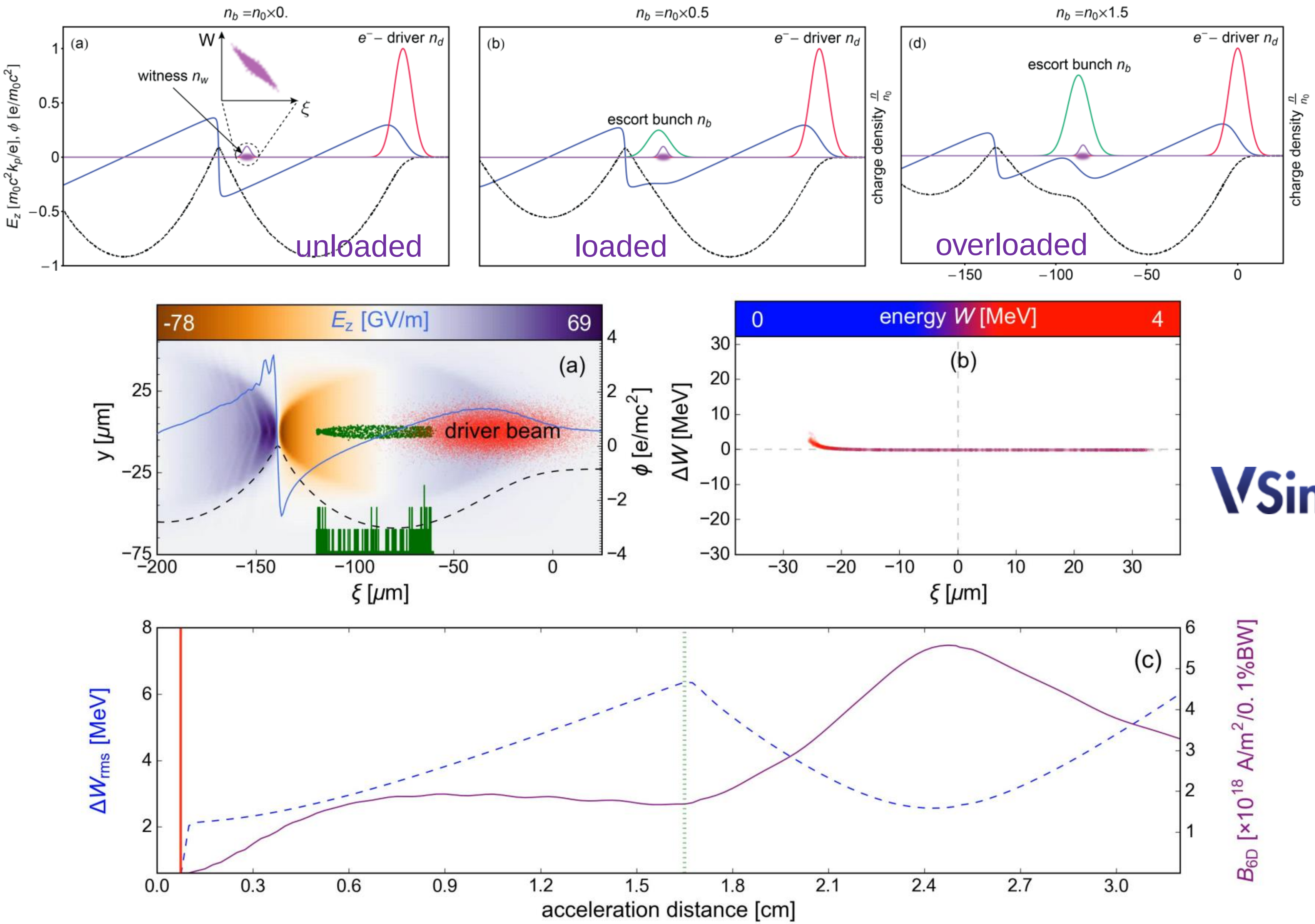
Path is open to ultralow TH emittance and ultrahigh 5D-brightness, but energy spread may destroy beam quality during extraction & transport
$\Rightarrow$ showstopper e.g. for FEL



“the energy spread&chirp problem“:
‘steep‘ price to be paid for ultrahigh energy gradients.
How to get rid of energy chirp/spread, how to generate ultrahigh 6D brightness bunches?

Concept of TH-released "escort beam" for chirp control

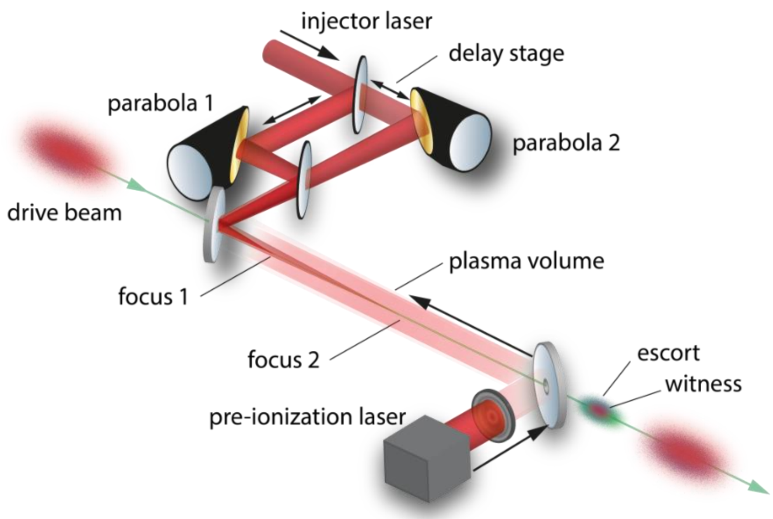
Tailored beam loading via escort bunch allows chirp control:

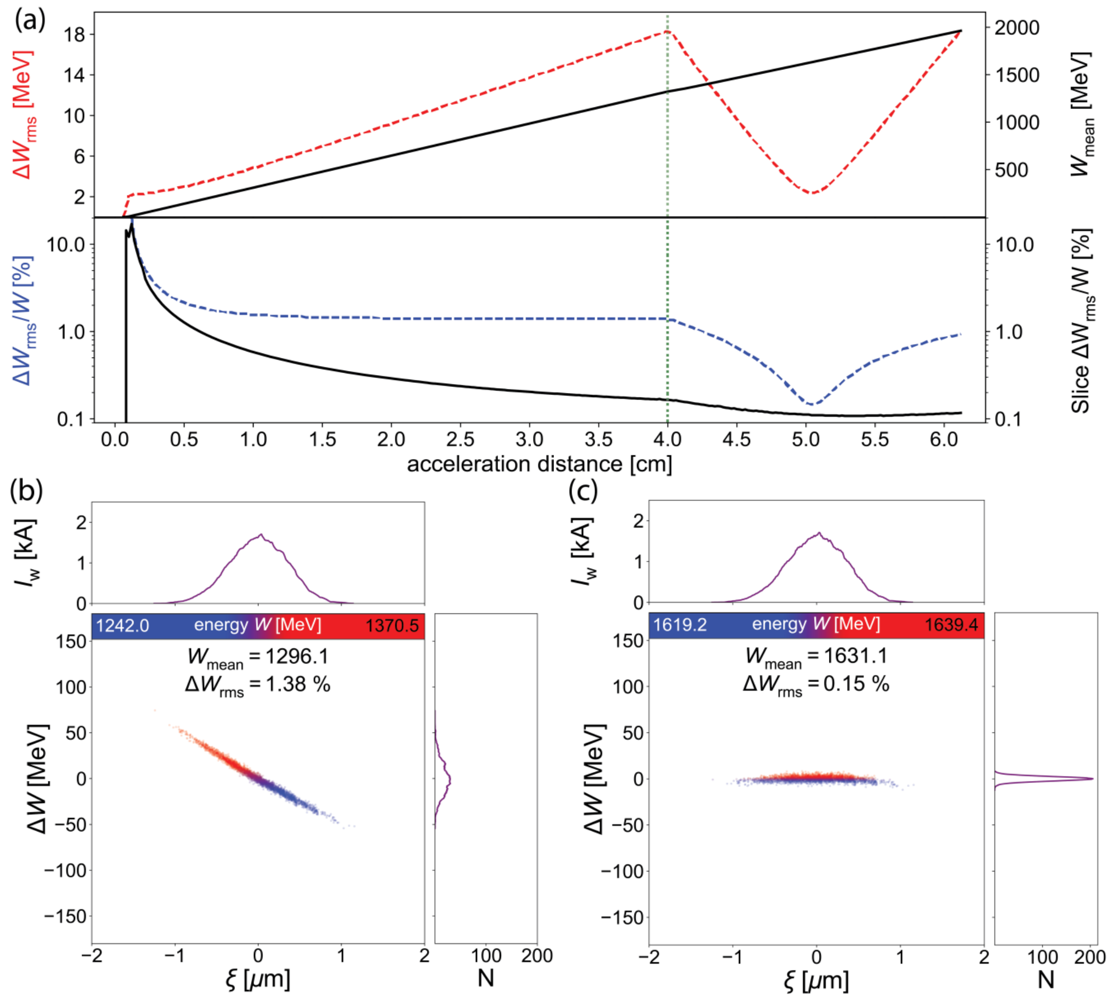


G.G. Manahan, F. Habib et al., *Nat. Comm.* 8, 15705 (2017)

Energy and energy spread control

Works at any energy:





	Before dechirping	After dechirping
z_{acc}	14.8 cm	22.9 cm
Q	8 pC	8 pC
σ_z	2.6 μm	2.6 μm
I_{peak}	2.0 kA	2.0 kA
$\bar{E}$	922 MeV	1404.3 MeV
σ_E	1.12 %	0.033 %
ϵ_n	40 nm · rad	43 nm · rad

Residual energy spread scaling

Residual energy scaling:

$$\Delta W_{\mathrm{res,max}} = \ 2\ E_{\mathrm{z,trap}}\ Z_{\mathrm{R}}$$

Generalized:

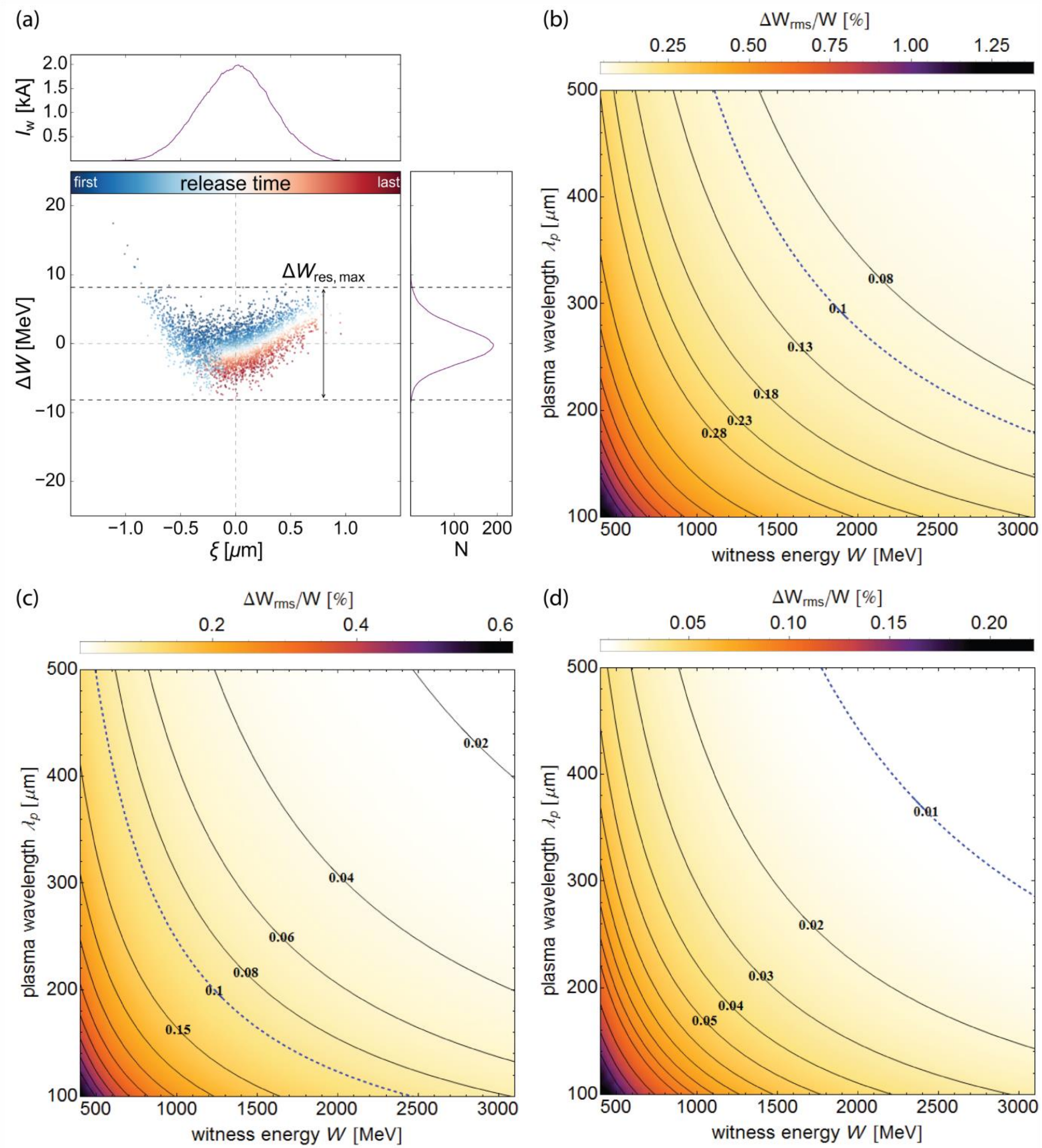
$$\Delta W_{\mathrm{res,max}} \approx 2\pi/5\ E_{\mathrm{z,trap}}\ \ w_{0,\mathrm{w}}^{2}\ /\ \lambda_{\mathrm{L}}$$

$$\approx 96\ n_0^{1/2}\ \ [\mathrm{cm}^{-3}]\ 2\pi/5\ w_{0,\mathrm{w}}^{2}\ /\ \lambda_{\mathrm{L}}$$

The residual energy spread scaling suggests the use of low plasma (LIT) densities.

Similar trend as in LWFA (energy gain vs. dephasing), but for completely different reasons

$$\Delta W_{\mathrm{res,rms}} \approx \Delta W_{\mathrm{res,max}}\ /\ 5 \approx 2/5\ E_{\mathrm{z,trap}}\ Z_{\mathrm{R}} \approx 2\pi/5\ E_{\mathrm{z,trap}}\ w_0^{2}\ /\ \lambda_{\mathrm{L}}.$$

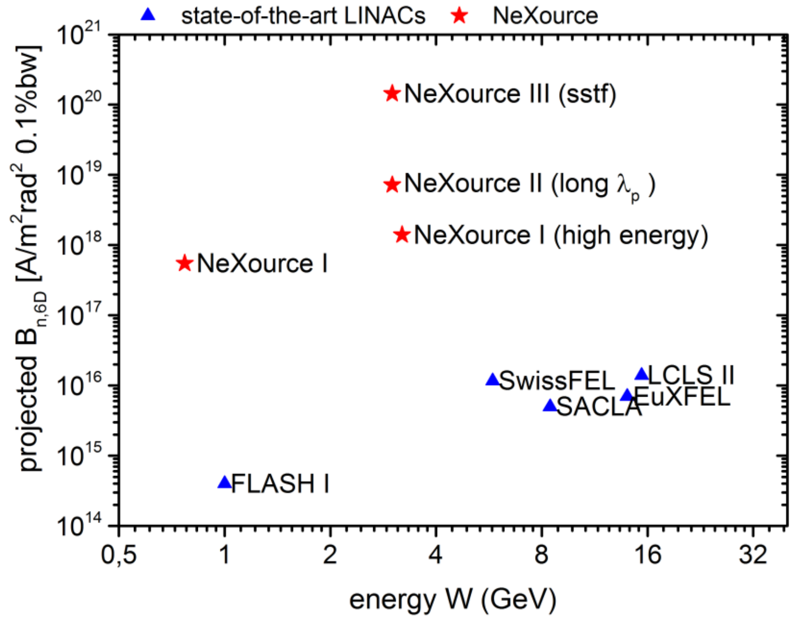


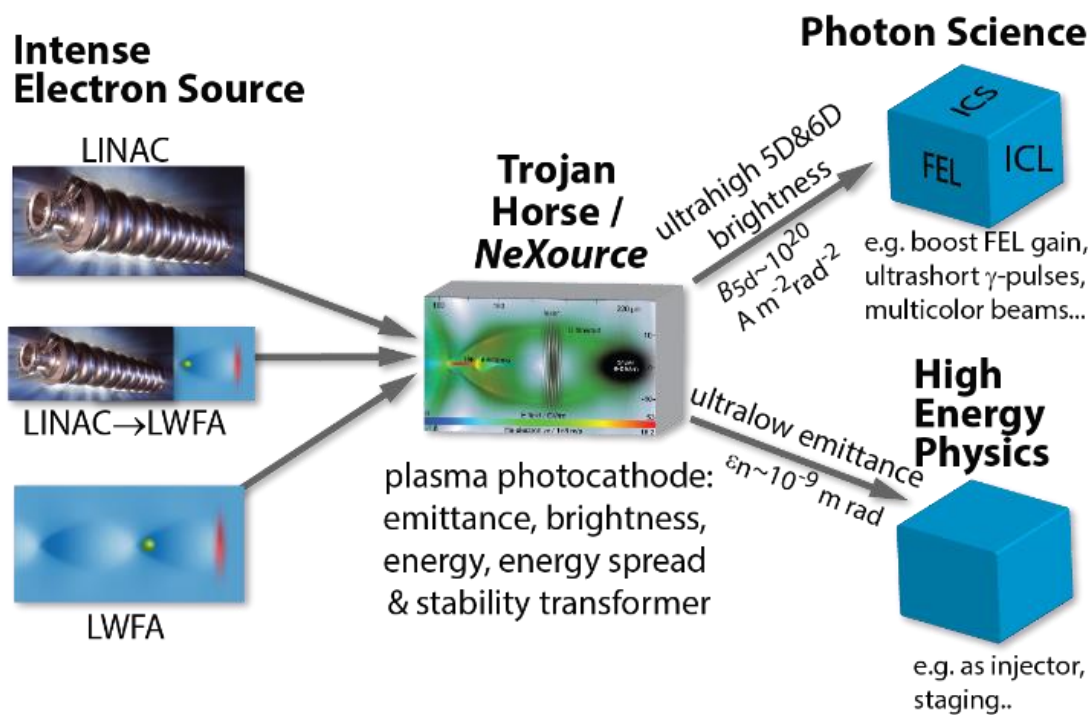
Ultrahigh 6D brightness

Emittance & brightness and energy spread is combined into 6D brightness:

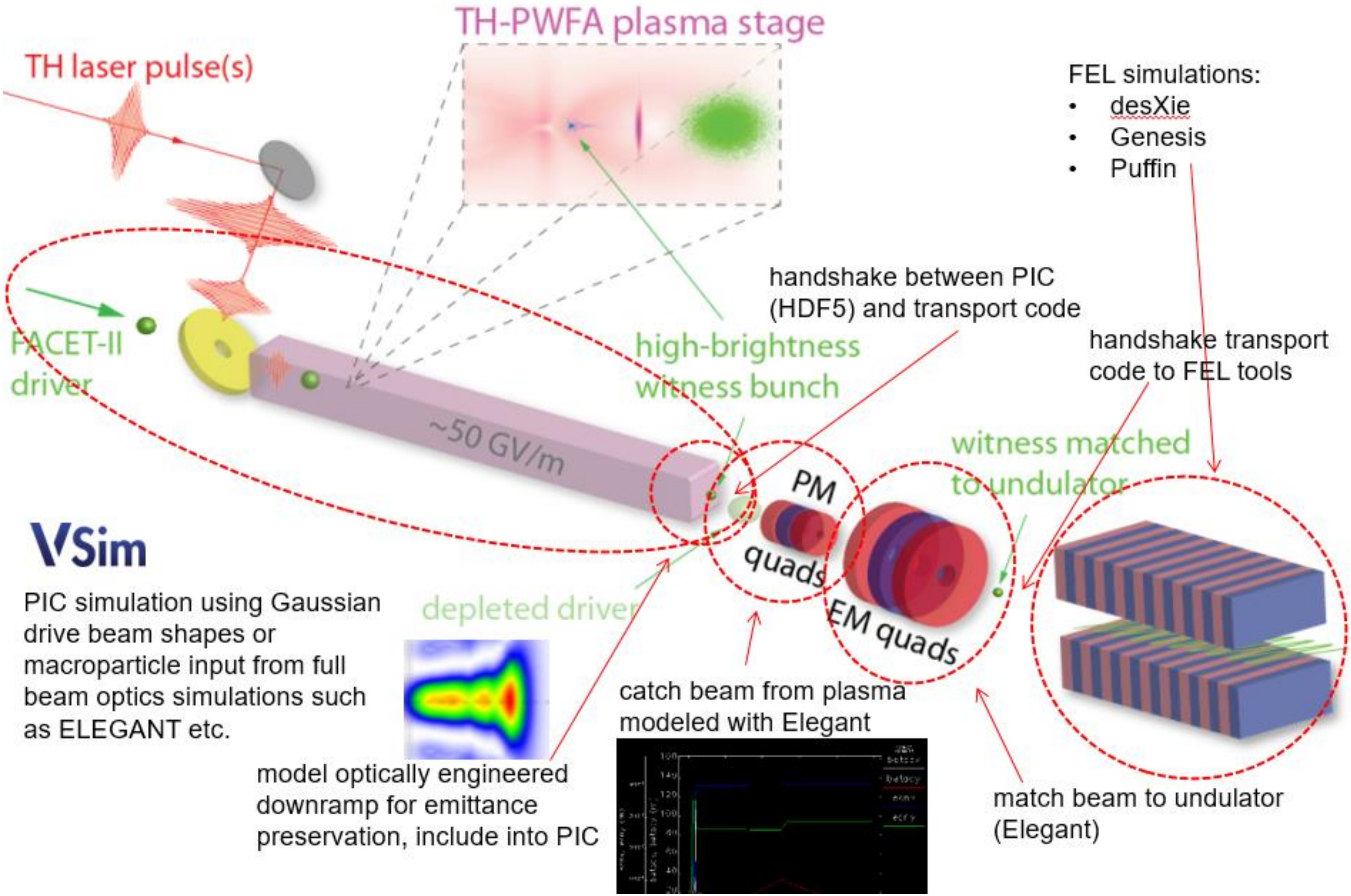
$$B_{n,6D} = \frac{I_p}{\epsilon_{n,x}\epsilon_{n,y}0.1\%\sigma_W}$$

Comparison with state-of-the-art accelerator systems reveals increase by orders of magnitude of 6D brightness!



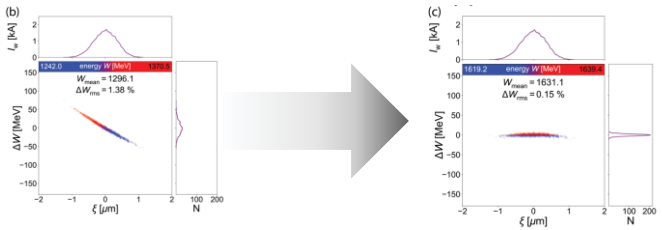


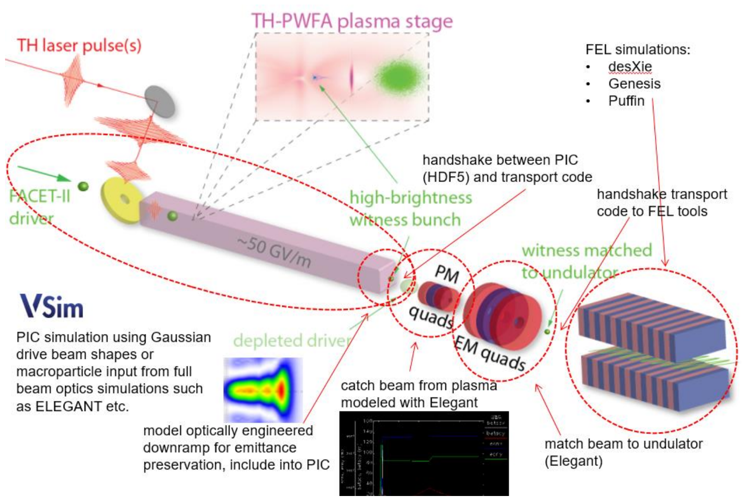
Photon science: FEL



Energy spread compensation and ultrahigh 6D brightness: NeXource project

- TH mechanism for ultralow emittance and unprecedented 5D-brightness
- However, substantial correlated energy spread (chirp) is side-effect of GV/m fields
- New chirp compensation technique *NeXource* allows to remove correlated energy spread and generate ultrahigh 6D-brightness beams (reduction of energy spread by 2 orders of magnitude)





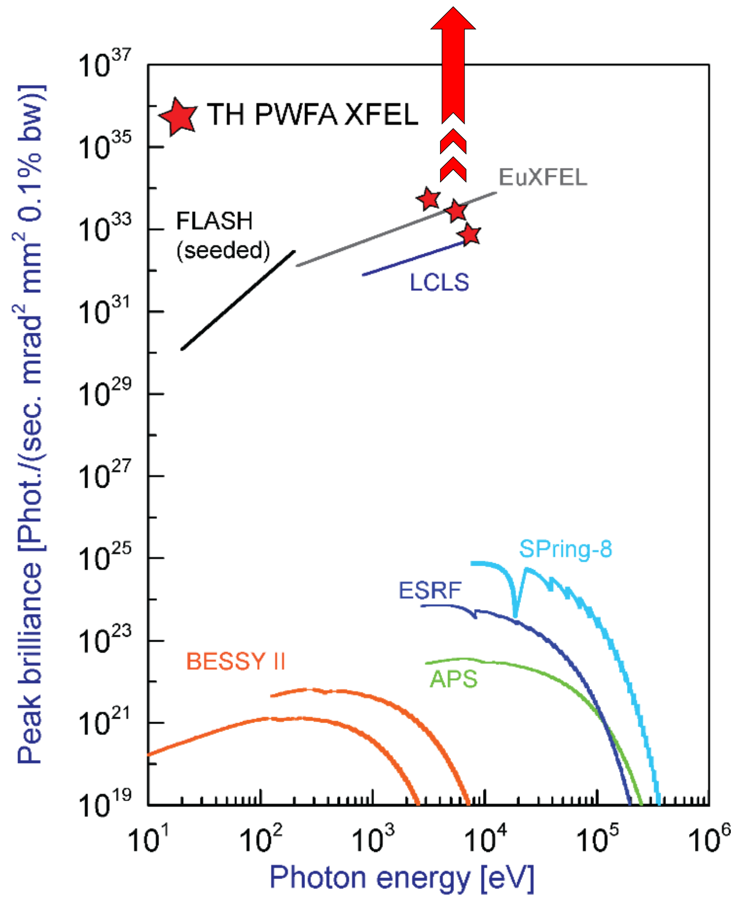
- This is a key step towards key applications such as 5th generation light sources
- E.g. for the race towards plasma-based FEL which is a main driver in the worldwide community: Beat Pierce parameter, fulfil Pellegrini criterion, and harness ultrahigh gain to realise compact hard x-ray FELs

$$\epsilon_n < \lambda_r \langle \gamma \rangle / 4\pi \quad ✔ \quad \langle \sigma_\gamma / \gamma \rangle \ll \rho \quad ✔ \quad L_{g,1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}} \propto B_e^{-1/3}$$

- Preliminary start-to-end simulations look extremely exciting

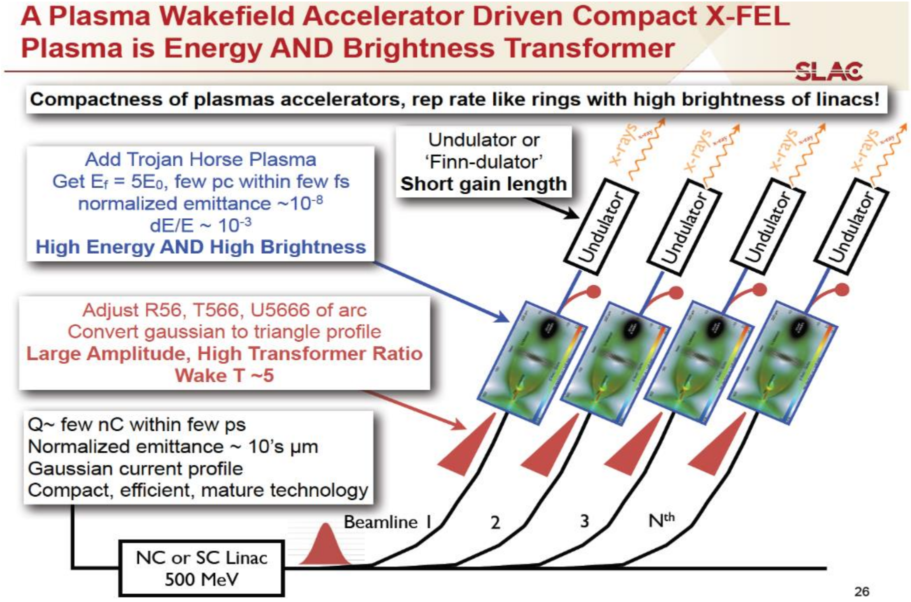
Ultrahigh 6D-brightness: enabling 5th generation light sources

preliminary start-to-end simulations:



4.45 angstrom, bandwidth ~ 0.1% , saturation power 35 GW
FWHM pulse duration sub-fs

Make concept compact: Use LWFA output for PWFA



500 MeV linac: Still big machine

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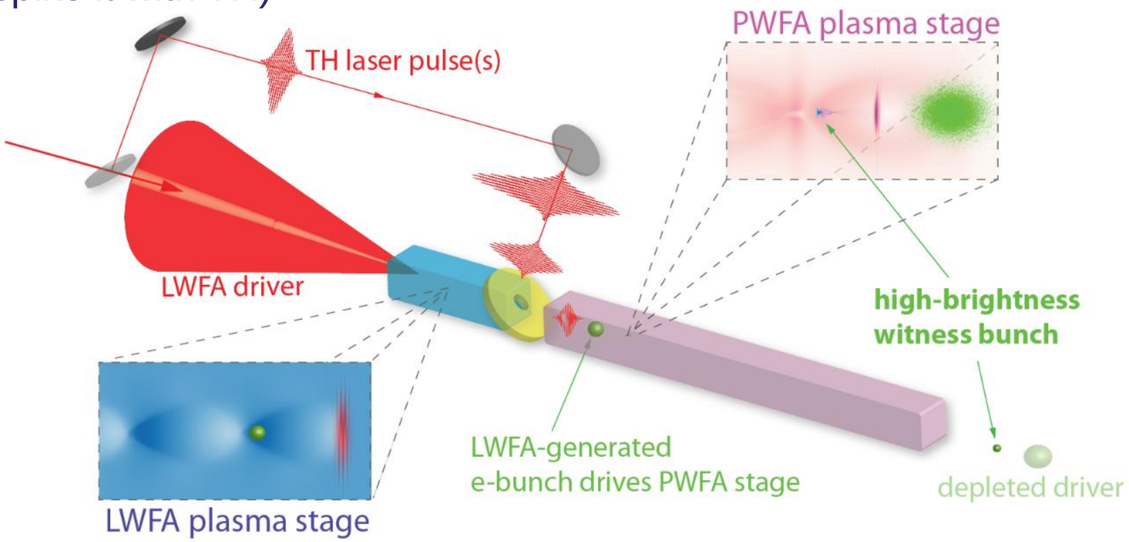
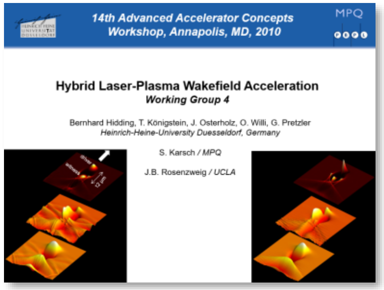
COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

Compact option for EuPRAXIA: generate PWFA driver beams via LWFA (and then spike it with TH)

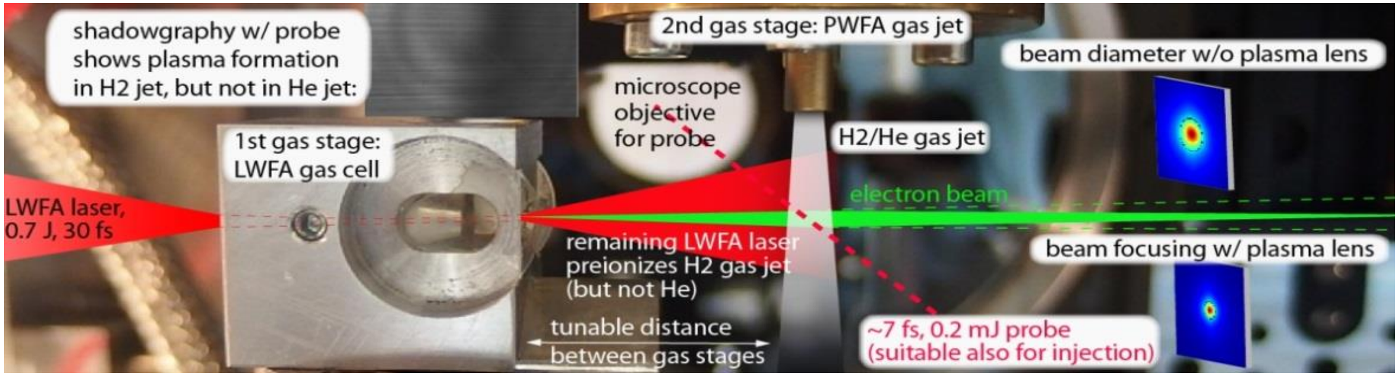


Make concept compact: Use LWFA output for PWFA



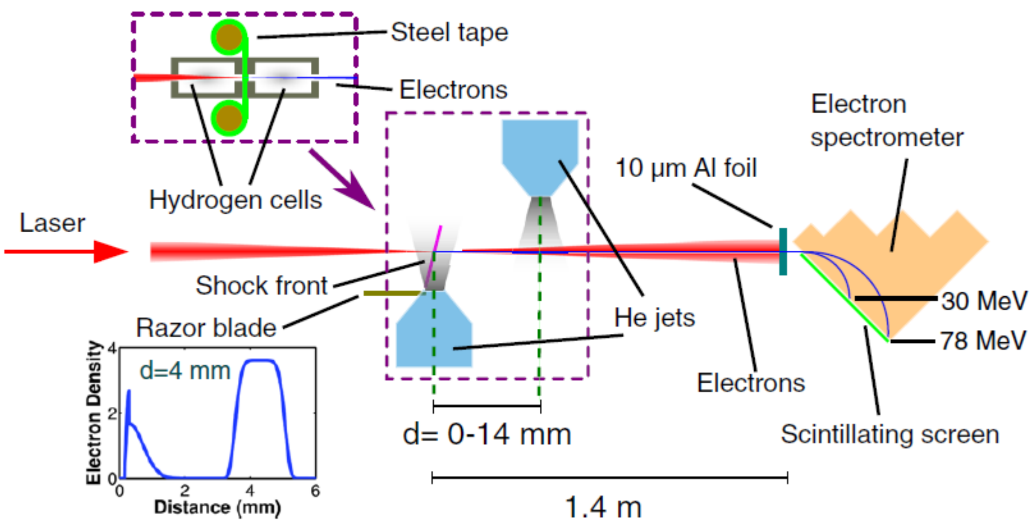
"Hybrid energy doubling"

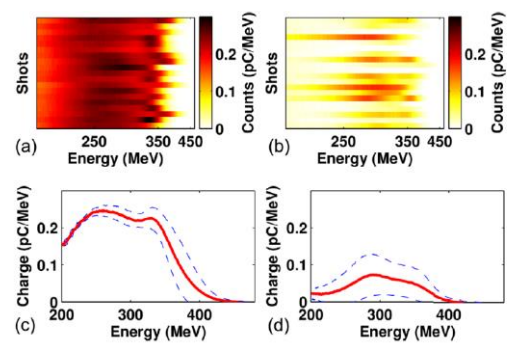
PRL 104, 195002, 2010



Experiments FSU Jena: use laser remnant from LWFA stage to preionize H_2, but not He in PWFA stage (i.e. 2nd gas jet), Kuschel et al: PRAB 2016

Joint WP14 campaign(s) at HZDR Dresden, promising results as regards plasma lensing and bunch deceleration



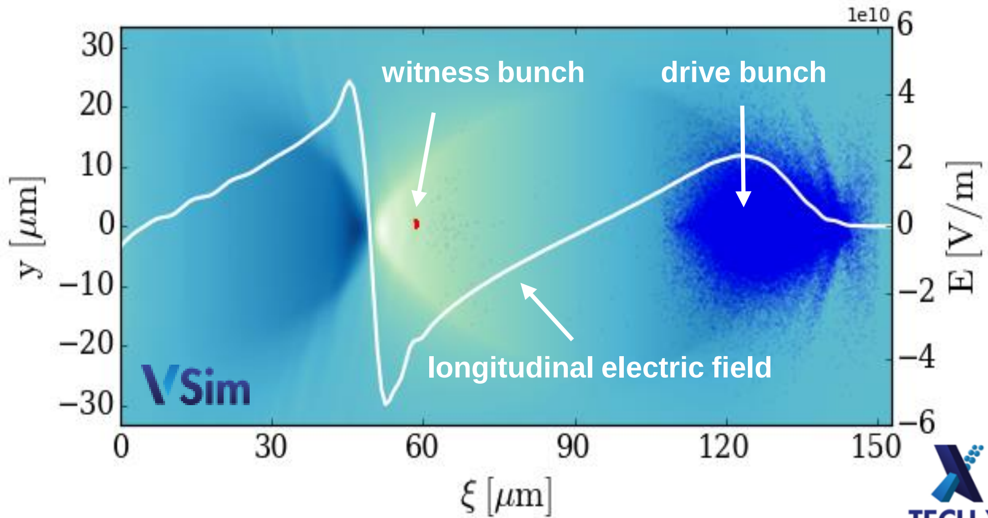


Chou.. Karsch et al., "Collective deceleration", PRL 2016

Beam quality transformation and stabilization

Witness:

$\sigma_x \approx \sigma_y \approx \sigma_z \approx 0.6$ µm
$Q \approx 7.3$ pC
$\gamma \approx 610$ after ≈ 9 mm
$\Delta\gamma/\gamma \approx 2.5\%$
$\varepsilon_n \approx 2.4 \times 10^{-8}$ mrad
$B_{5D} \approx 3.7 \times 10^{19}$ A/m^{2}rad^2



TECH-X

Driver:

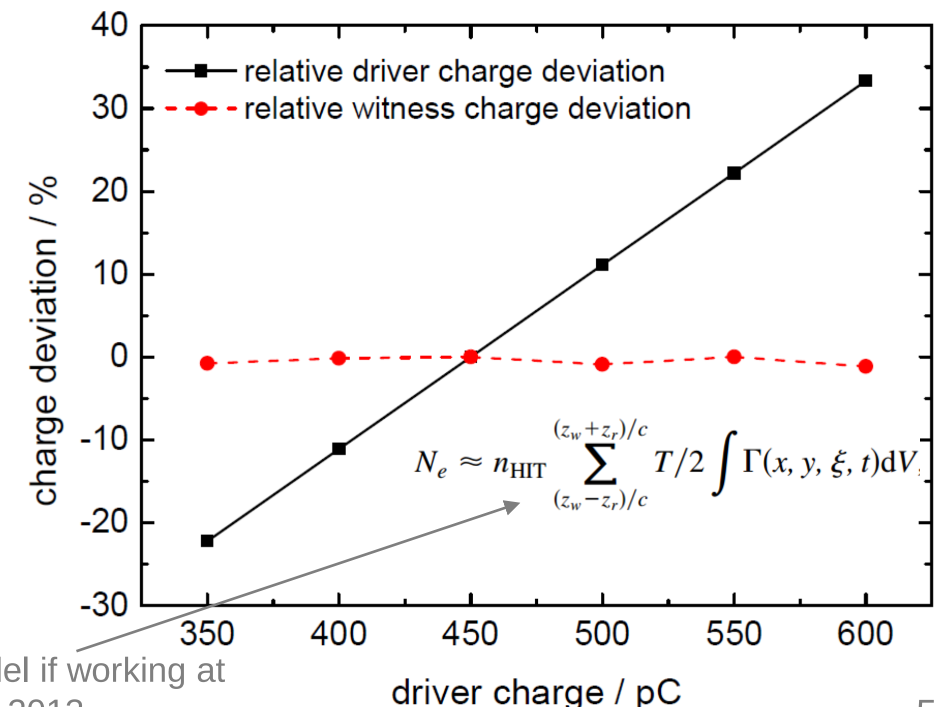
$\sigma_x = \sigma_y = \sigma_z = 7$ µm
$Q = 400$ to 600 pC
$\gamma = 500$ to 2000
$\Delta\gamma/\gamma = 10\%$ to 40%
$\varepsilon_n = 2.25 \times 10^{-6}$ mrad

preionized Hydrogen-Neon mixture:

LIT: H and Ne @ $n_e = 1.5 \times 10^{17}$ cm^{-3}
HIT: Ne^+ @ $n_e = 9 \times 10^{16}$ cm^{-3}

TH laser: $a_0 = 0.041$, $w_0 = 5$ µm, $\tau = 25$ fs,
$\lambda = 800$ nm

- Excellent trapped witness charge stability < 1%, independent of drive beam over 350-600 pC range



need to take into account MPI via Yudin-Ivanov model if working at elevated laser frequencies, see, Y. Xi et al, PRSTAB 2013

Witness energy and Δγ/γ resilience vs. jitter of driver energy and spread

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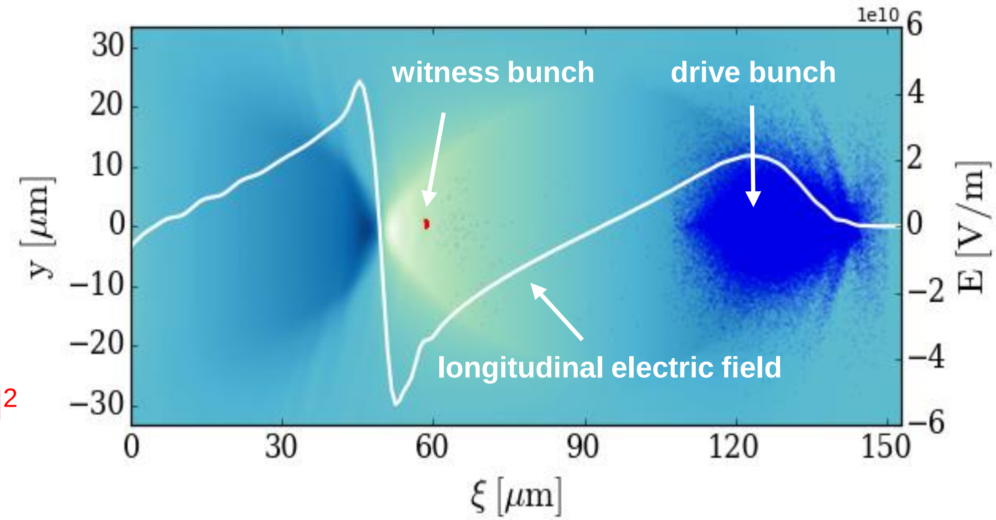

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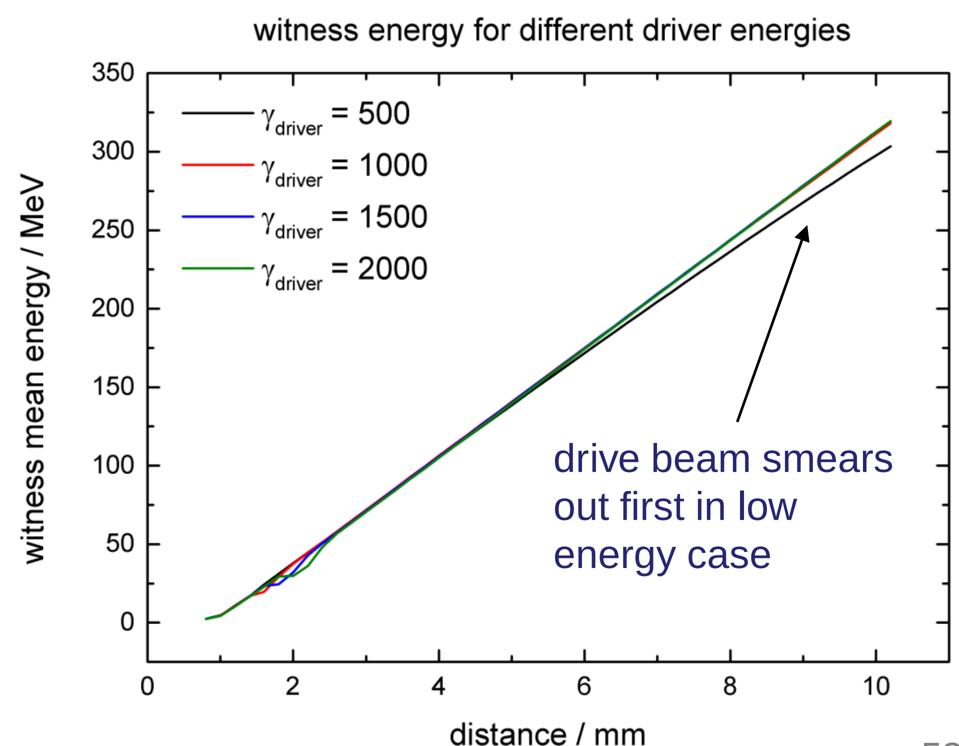
- Drive beam electron energy varied from E = 250-1000 MeV (conservative choice given that 4 GeV+ has already been reached in experiments)
- Witness energy stable on (sub) %-level, only 250 MeV driver case leads to reduced final energy. Need to cap plasma at desired working point (trade-off energy stability vs. max. energy)
- Reason combination of depletion and driver beam longitudinal lengthening



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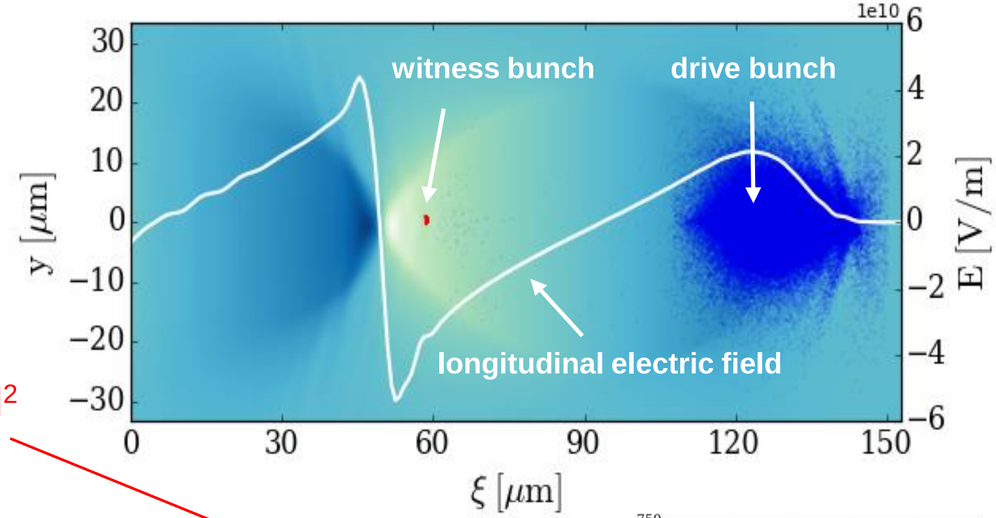

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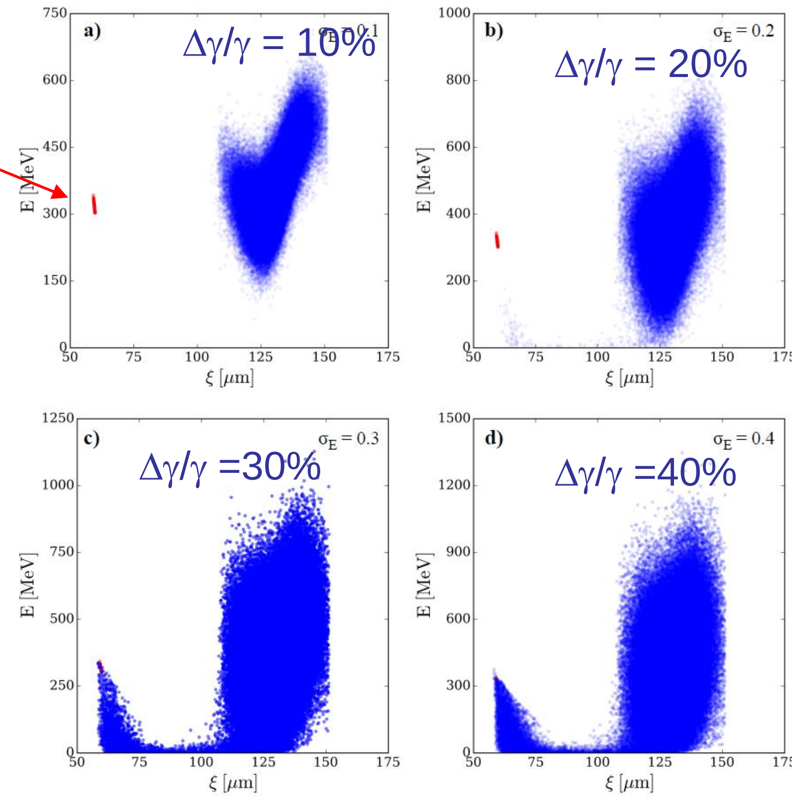

- Energy spread ~2.5% in all cases, even if driver has Δγ/γ of tens of % (here: uncorrelated)
- Note: this is the low energy limiting γ=500 case, at higher energies driver degradation is reduced and stability and energy gain is increased

..to be published

Summary

- Hybrid plasma acceleration: make the best out of two worlds and combine LWFA and PWFA features

- Use Trojan Horse plasma photocathode method to produce controllable bunches with emittance and 5D-brightness orders of magnitude better then state-of-the-art (first successful experiments at SLAC FACET)

- Combine Trojan Horse technique with dechirper and produce 6D brightness beams orders of magnitude better, beat Pellegrini, Pierce at same time (theory but doability easier than Trojan Horse). No experiments yet

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- Use LWFA output (high current etc.) for driving PWFA's and make system really compact (first encouraging experiments)

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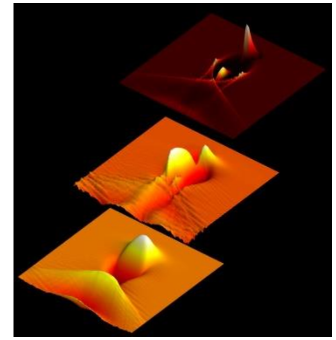
Backup

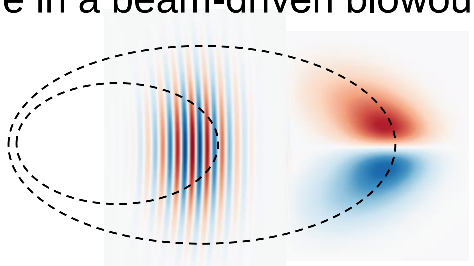
Take the best of both worlds: Hybrid Plasma Acceleration (Trojan Horse prehistory)

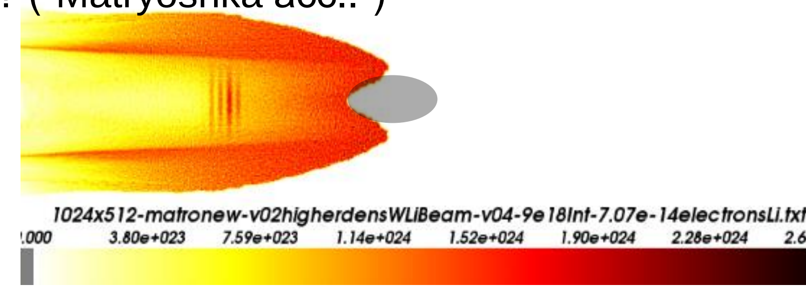
- Sequential combination:
  Use double bunches generated via LWFA (e.g. by injection into multiple buckets) as driver/witness pairs in subsequent, dephasing-free PWFA stage



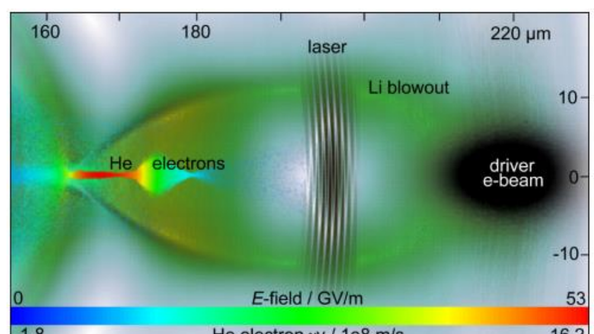
Hybrid energy doubling, PRL 104, 195002, 2010

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





- 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 considered for presentation at AAC 2010 in Kardamili, Greece (sic!)



Ultracold electron bunch generation aka Trojan Horse, PRL 108, 035001, 2012

5th Generation Light Sources…

…need a 4th Generation Electron Source

- 5th: 4D, ultrahard, compact?
- 4th: Free-Electron-Laser
- 3rd: Undulator radiation
- 2nd: Synchrotron radiation
- 1st: Bremsstrahlung

- 4th: 10's of GV/m fields in plasmas & underdense photocathode PWFA
- 3rd: 10's of GV/m fields in plasmas (LWFA and PWFA)
- 2nd: 10's of MV/m fields, photocathode (e.g. FLASH, LCLS, XFEL)
- 1st: 10's of MV/m fields, thermionic cathode (e.g. SLAC)

Export Trojan