DESY, 2016-05-26
New Particle Physics Facilities
Seminar Series

Ultrahigh Brightness Facility Upgrades Based on Plasma Photocathodes

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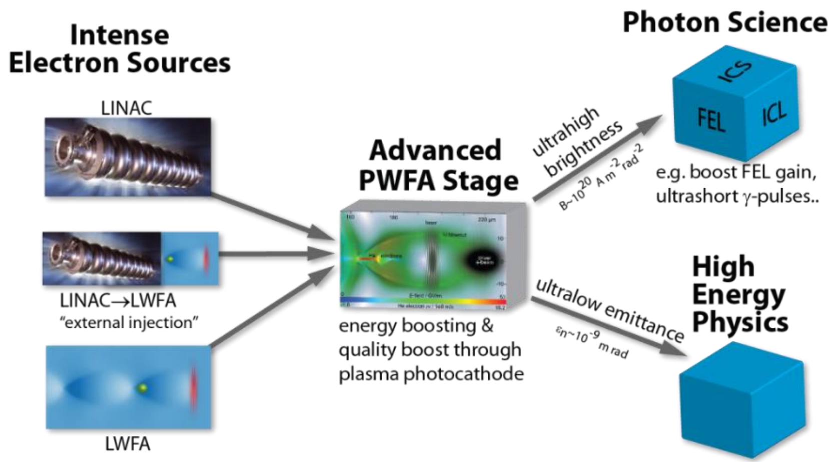
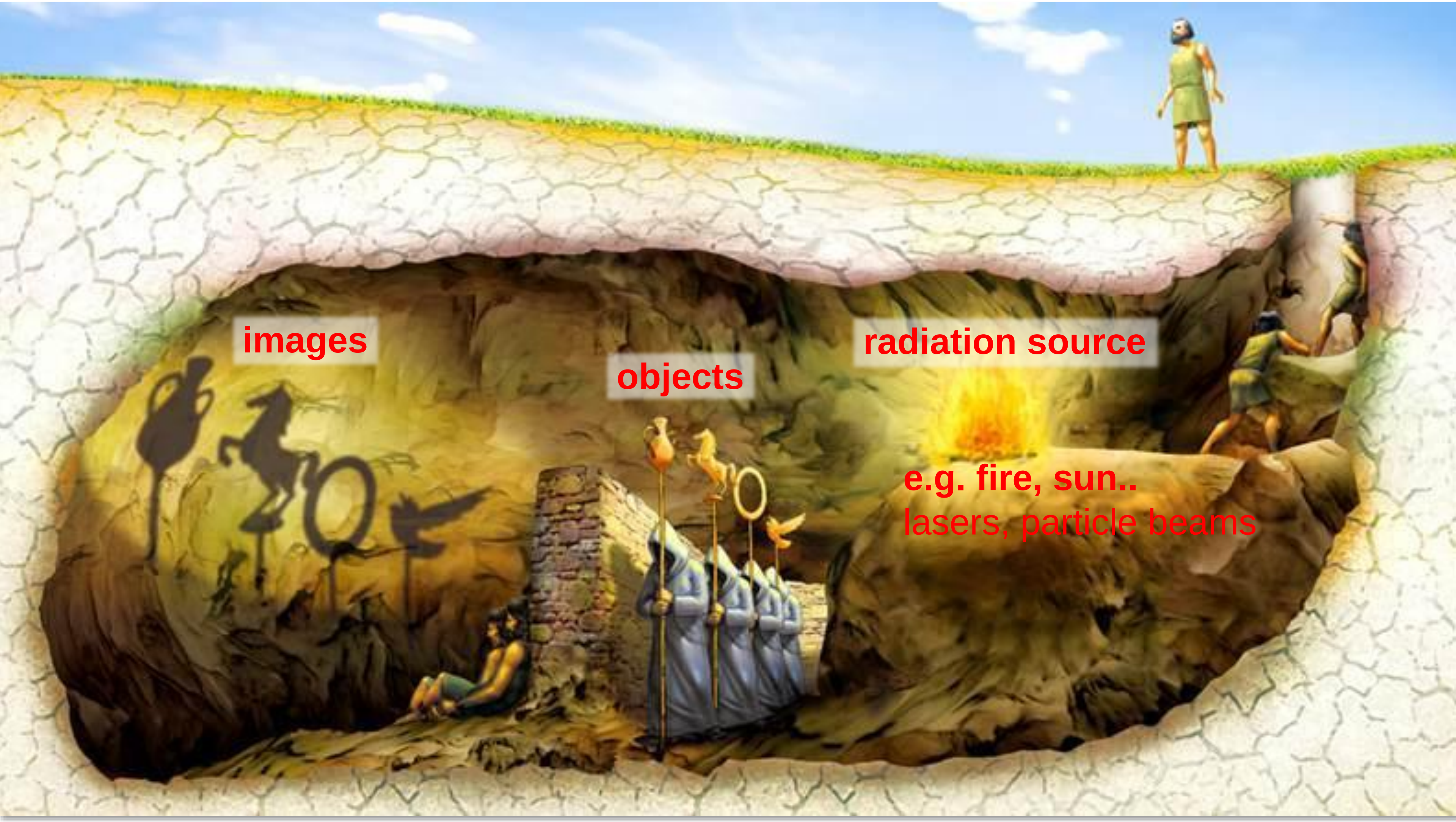
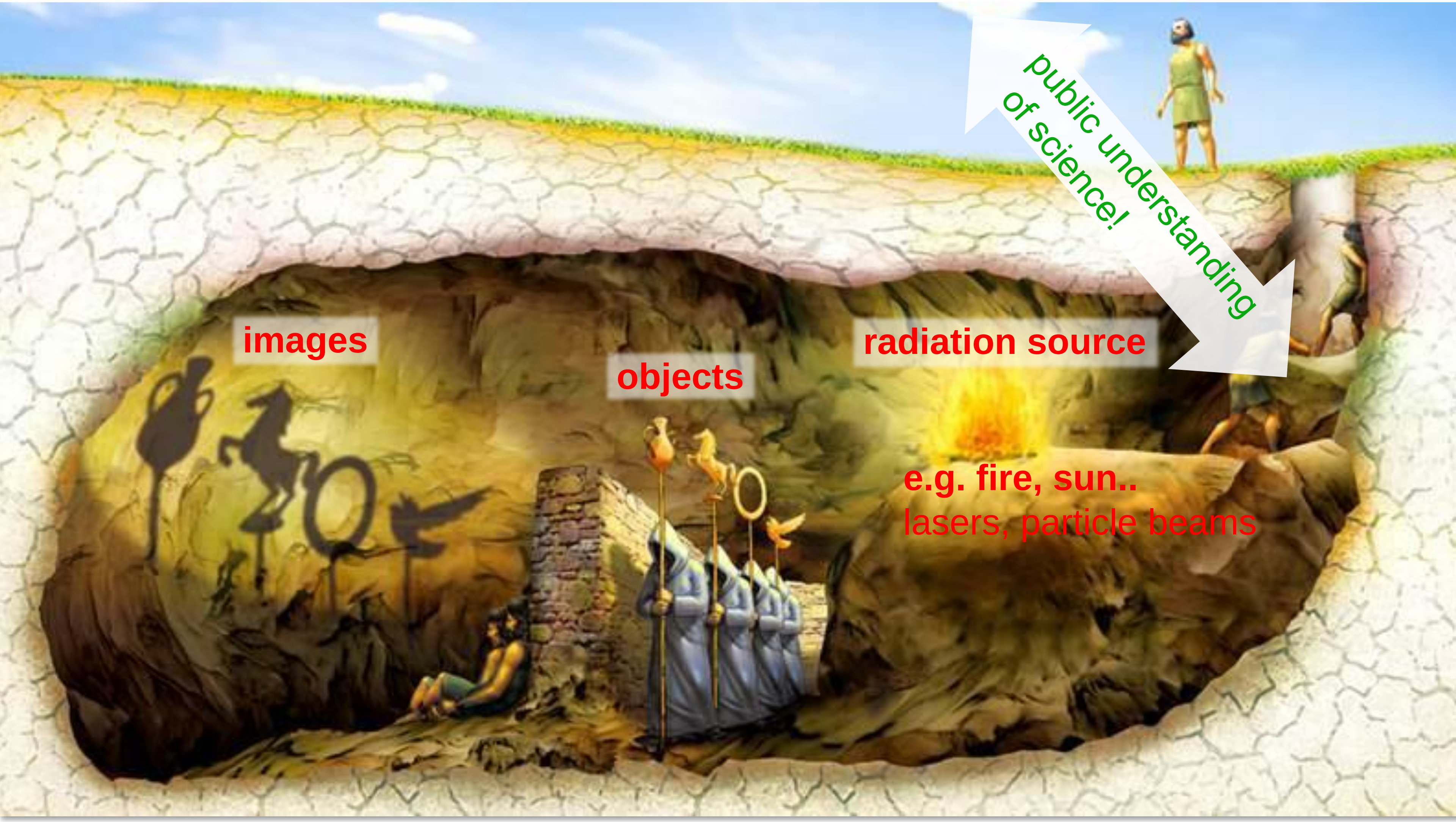


Radiation is a fundamental driver of knowledge.



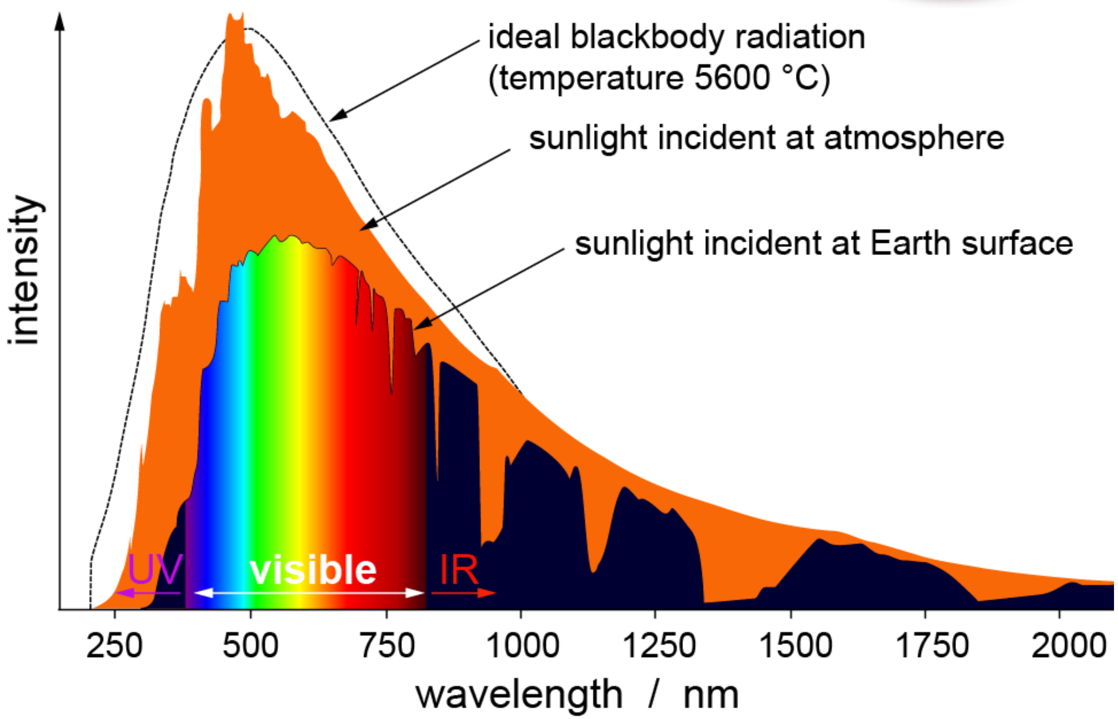
Greek Philosophy: Allegory of the cave; Analogy of the sun
Plato, Politeia, 380 BC

Radiation is a fundamental driver of knowledge.

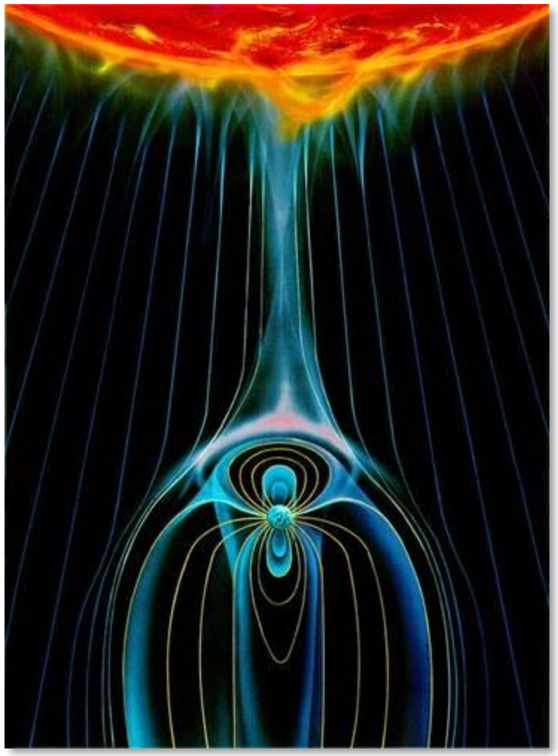


Greek Philosophy: Allegory of the cave; Analogy of the sun
Plato, Politeia, 380 BC

The Sun: fusion and plasma processes send broadband ***photon*** *and plasma* ***particle*** *radiation to Earth*



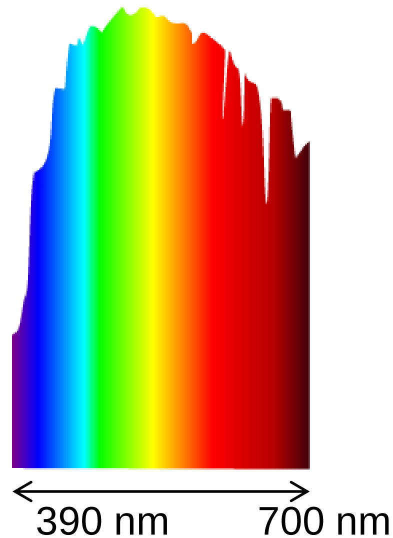
Atmosphere protects us
from too intense and too hard **photon** flux



Magnetosphere protects us from
too intense charged **particle** flux
(electrons, protons, ions..)

Sunlight has been the most powerful radiation source until < 100 years ago

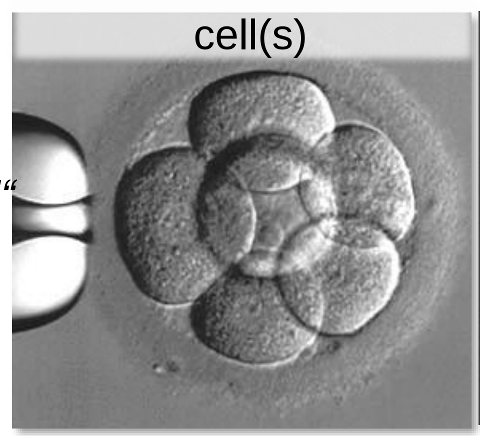
Hooke‘s microscope,
Micrographia, 1665



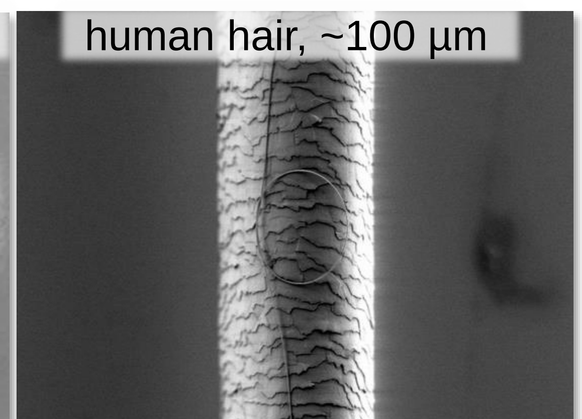
Abbe diffraction limit:
resolution of light microscopes (far field) < ~0.2 µm

Fine enough for cells, but..

NB:
Hooke coined the term "cell"

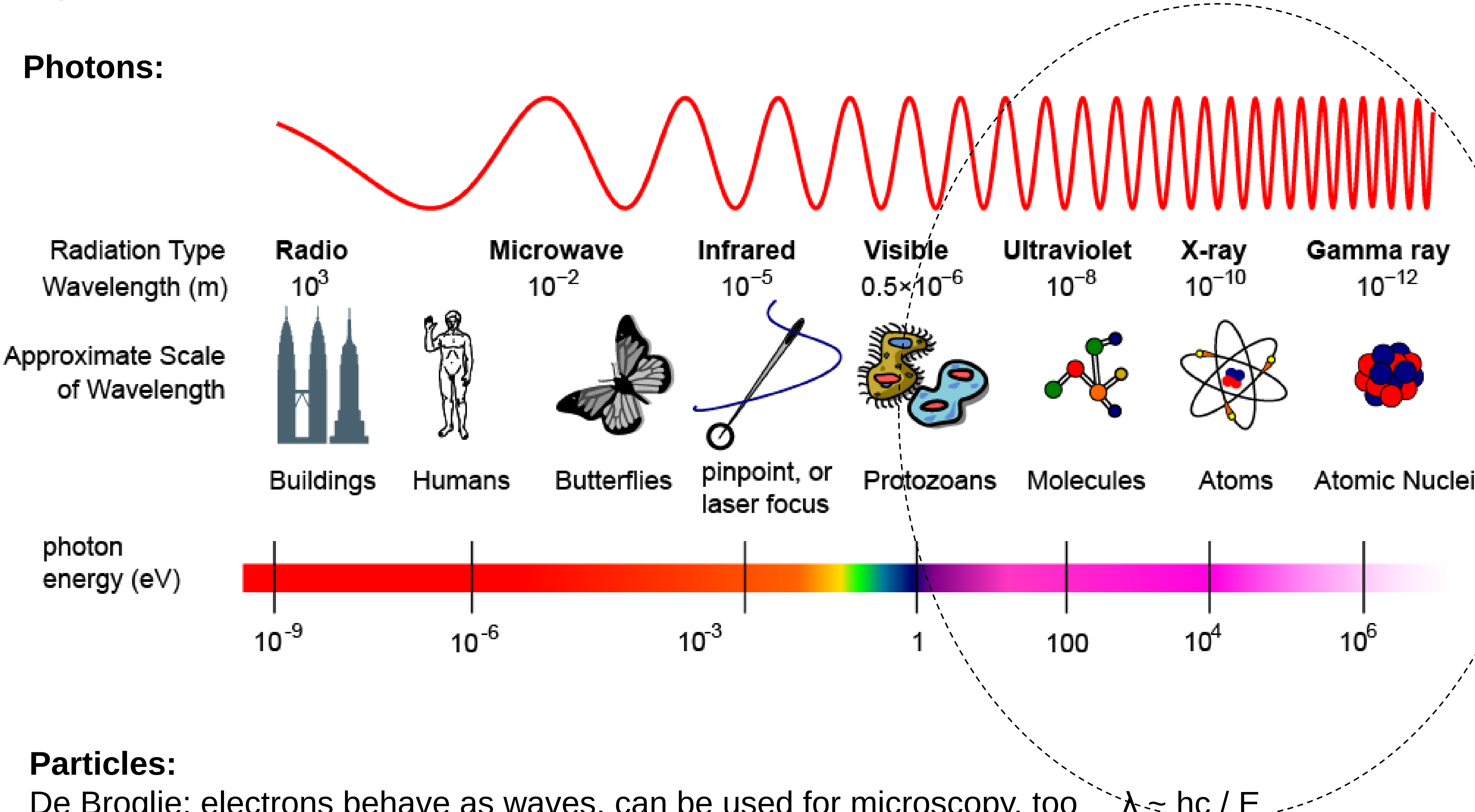


1-100 µm



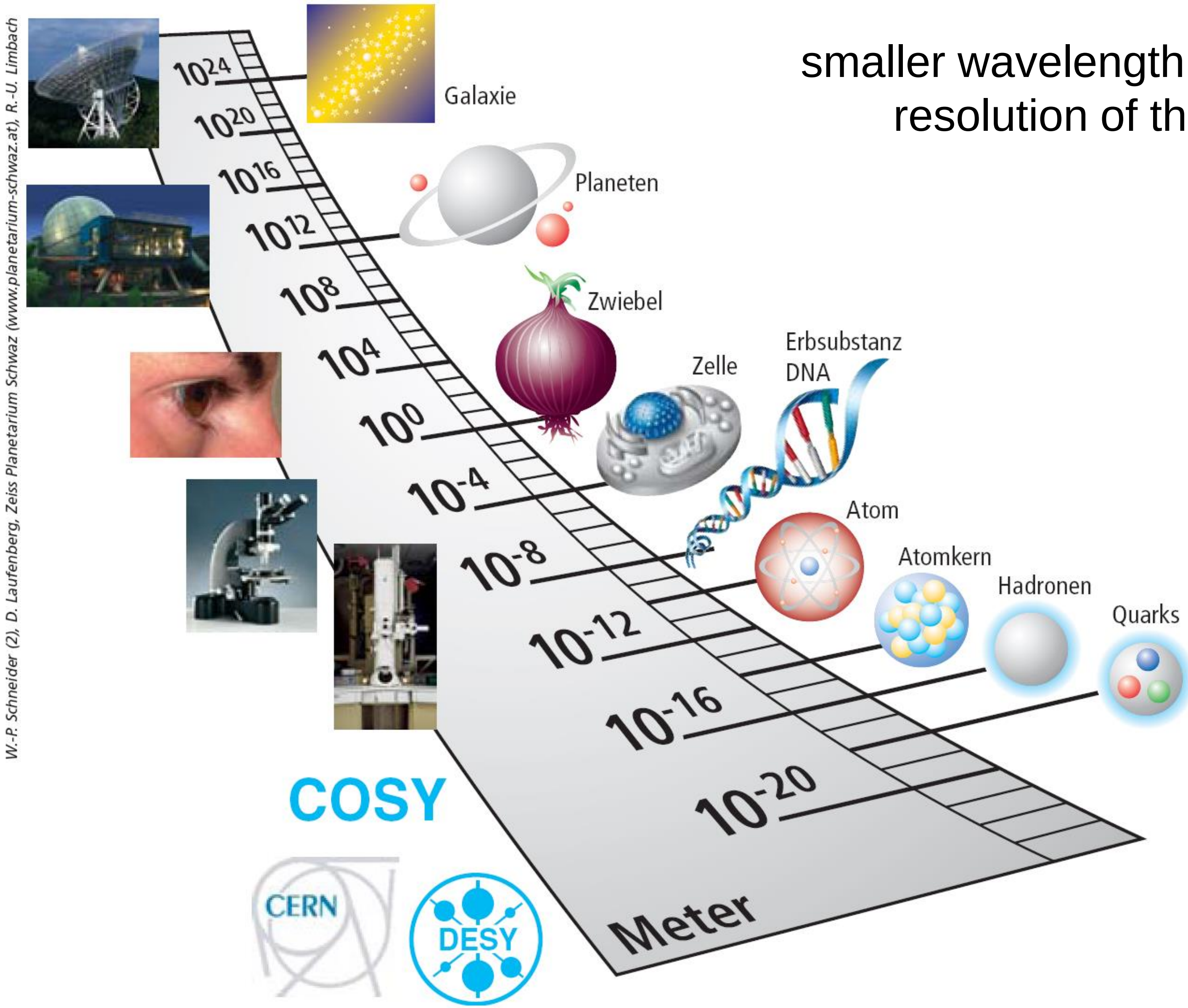
..we are interested in much smaller (and faster!) phenomena.
Shorter radiation wavelengths (i.e. higher photon energies), higher intensities and short pulses are required for ever smaller structures and shorter timescales of processes

Photons:



Particles:
De Broglie: electrons behave as waves, can be used for microscopy, too $\lambda \sim hc / E$

Particle acceleration: High energies needed to probe small structures



smaller wavelength λ allows for higher resolution of the microscope

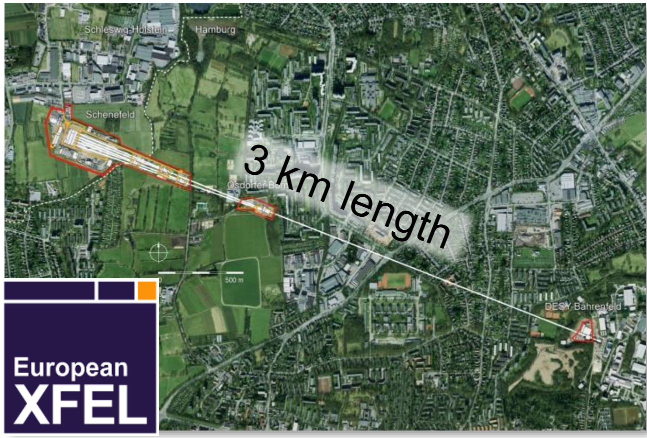
$$E \sim 1 / \lambda$$

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

Photons: e.g.

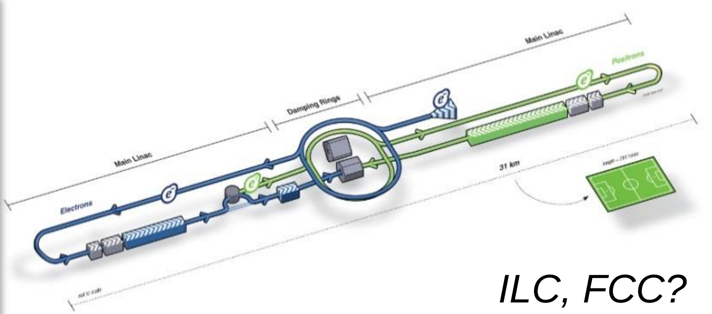
Diamond Light Source, Synchrotron, Oxfordshire, UK

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



European X-Ray Free Electron Laser, Hamburg, Germany

Particles: e.g.



ILC, FCC?

ilc 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

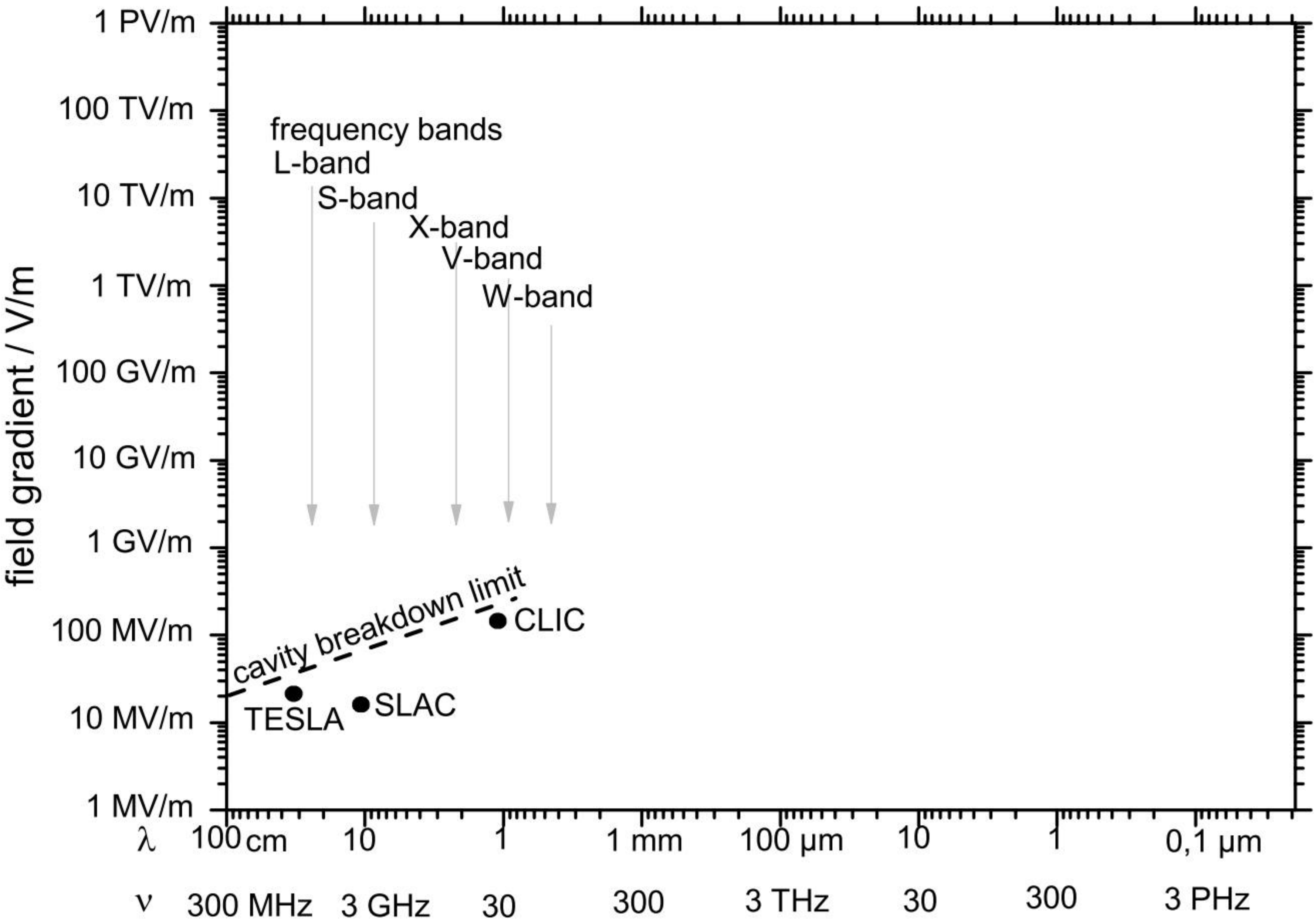
Criterion for Vacuum Sparking Designed to Include Both rf and dc*

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

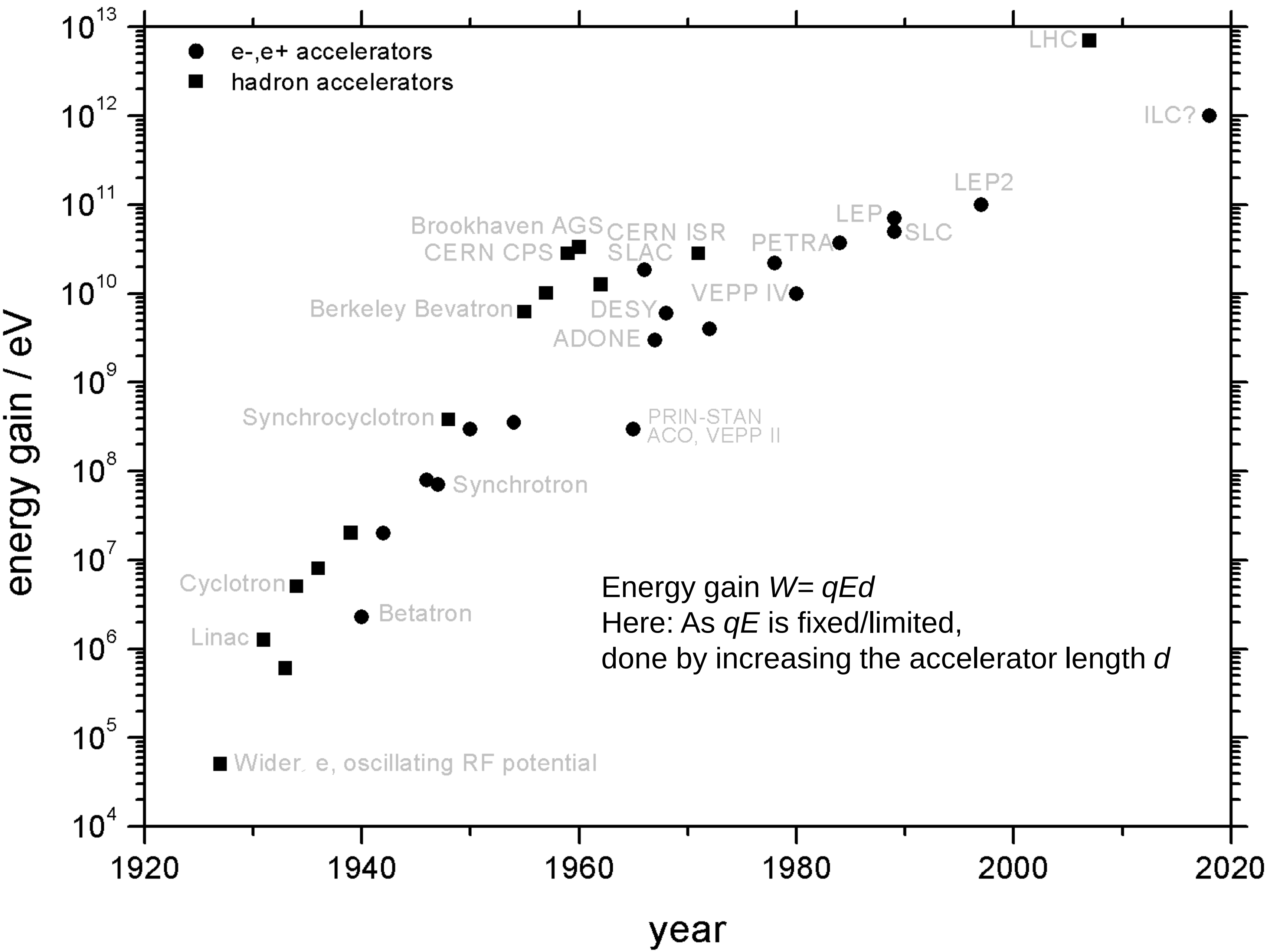
An empirical relation is presented that describes a boundary between no vacuum sparking and possible vacuum sparking. Metal electrodes and rf or dc voltages are used. The criterion applies to a range of surface gradient, voltage, gap, and frequency that extends over several orders of magnitude. Current 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.

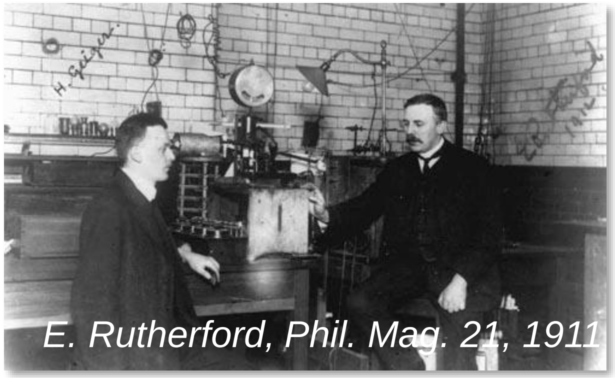
Our attention was focused on the laboratory experiments. The extensive broadening of concept which would include electrolytes, flames, the Heaviside layer, etc. may have lain in the back of Langmuir's brain. The semantic problem to be solved was sheath vs nonsheath.

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


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

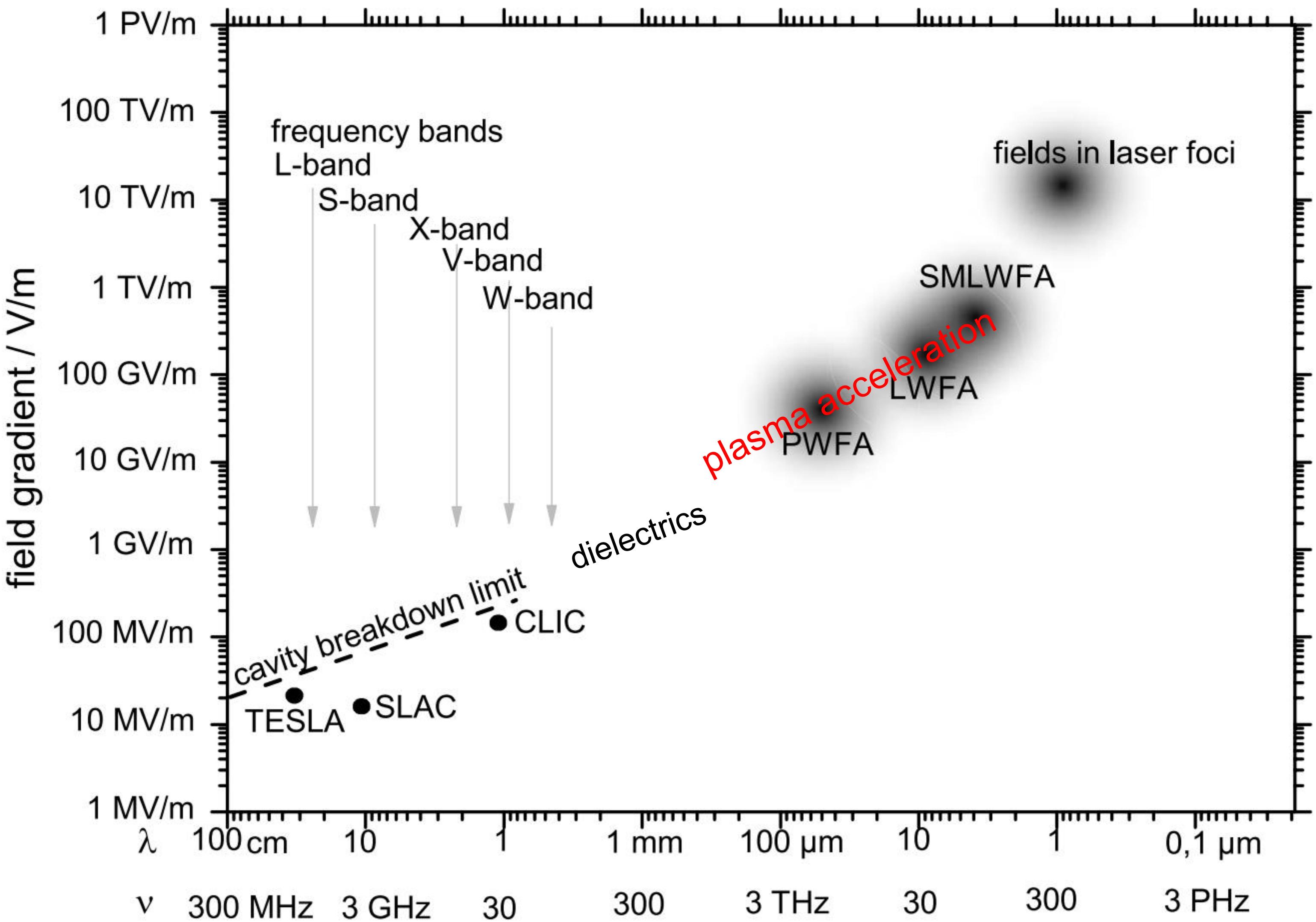
UCLA 1979: LWFA

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

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

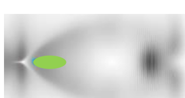
Plasma: tens of GV/m+ acceleration gradients allow shrinking of accelerator to sub-meter scale (energy gain W=qED)

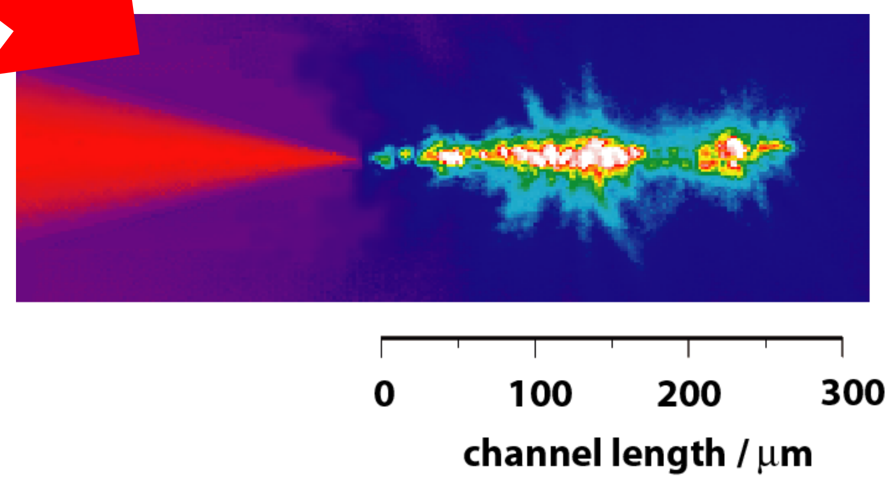


Shrinking accelerators from km to cm size

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

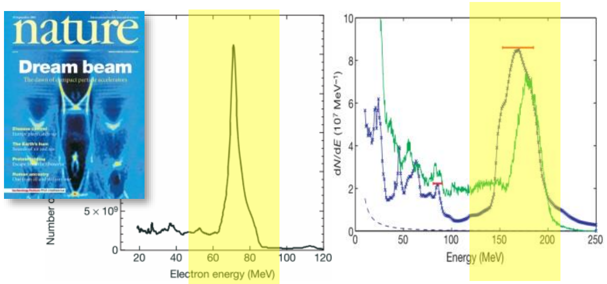
Single co-propagating plasma cavity
w/ electric fields of ~50 GV/m



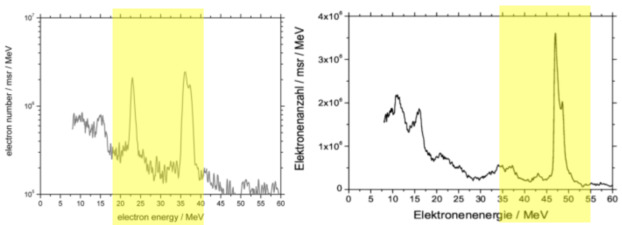


Indeed: Both LWFA (laser driven) and PWFA (electron beam driven) now routinely demonstrate multi-GeV energy gain

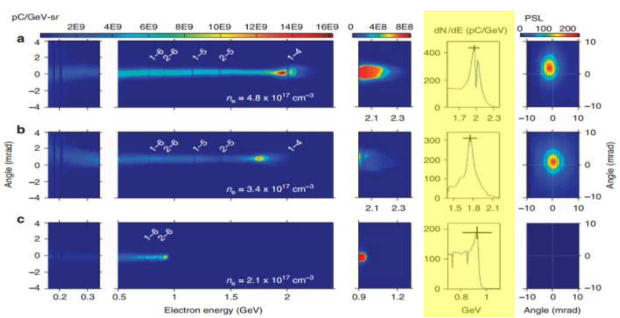
LWFA



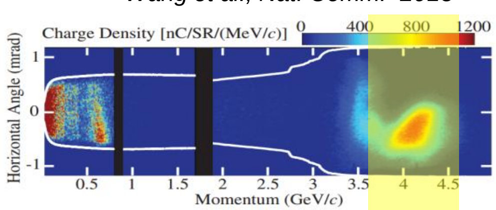
Mangles et al. (UK), Geddes et al. (USA), Faure et al. (France), Nature 2004



Hidding et al., PRL 2006

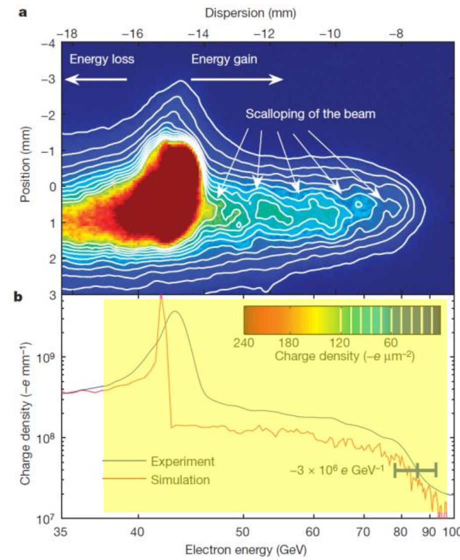


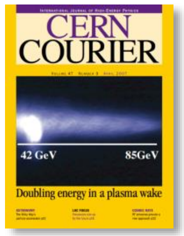
Wang et al., Nat. Comm. 2013



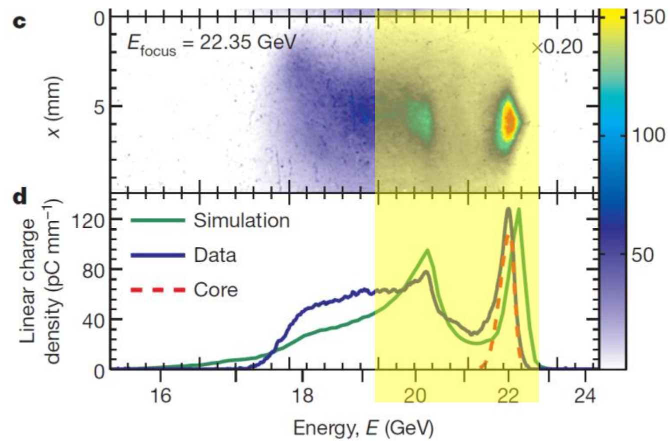
Leemans et al., PRL 2014

PWFA



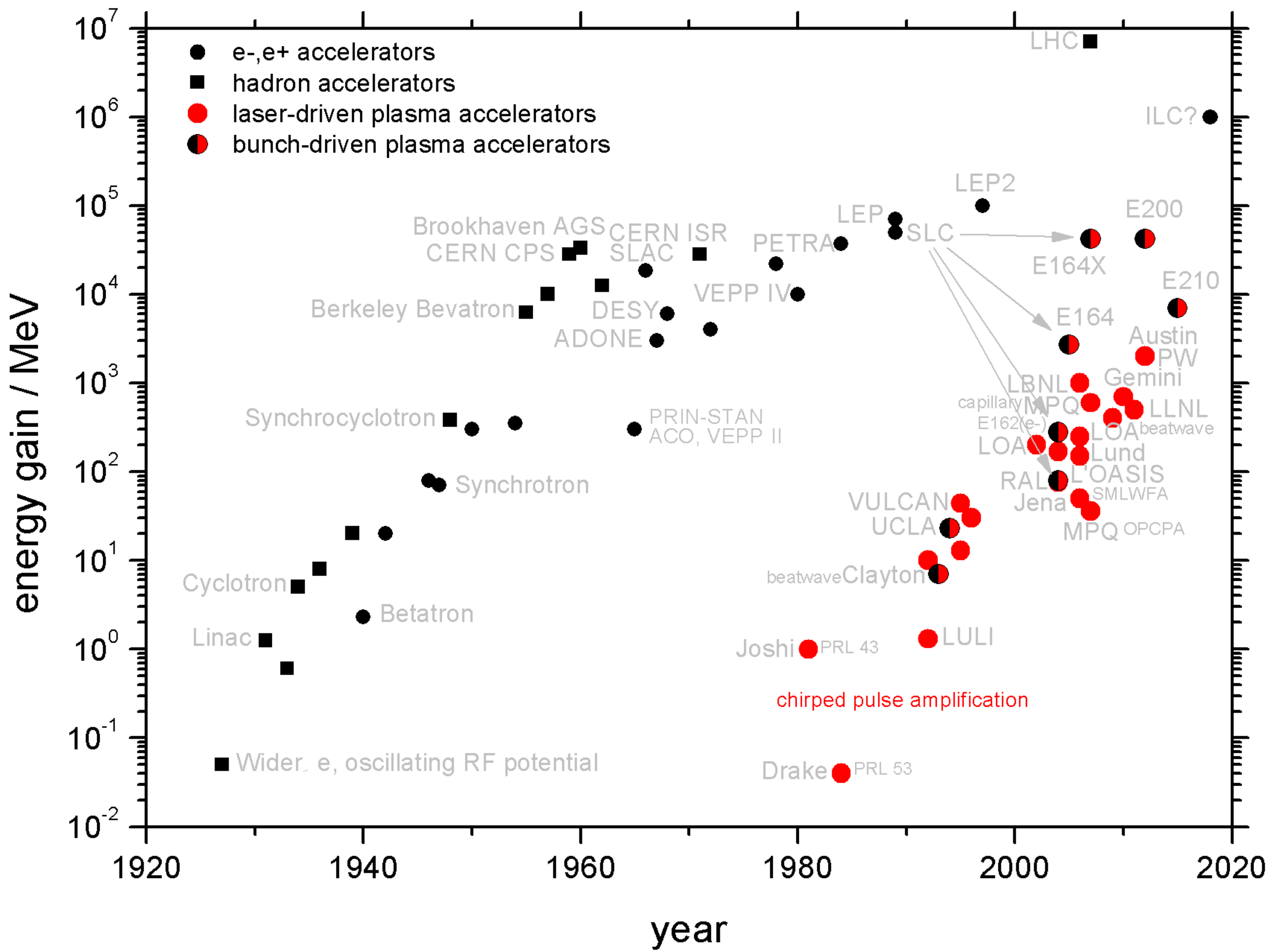


Blumenfeld et al., Nature 2007



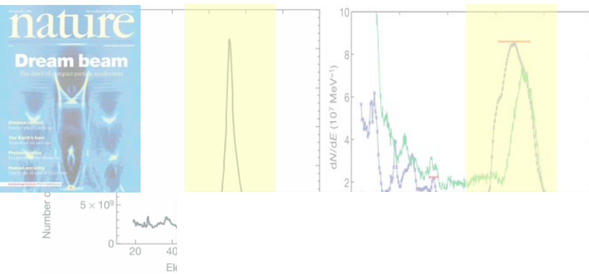
Litos et al., Nature 2014

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

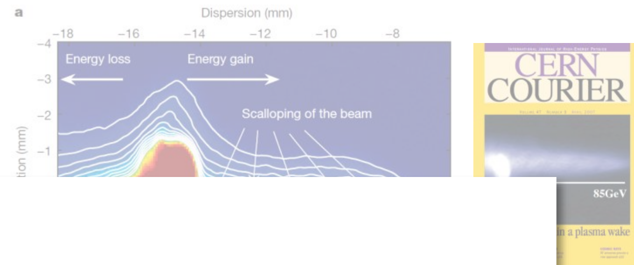


Indeed: Both LWFA and PWFA routinely demonstrate multi-GeV energy gain

LWFA



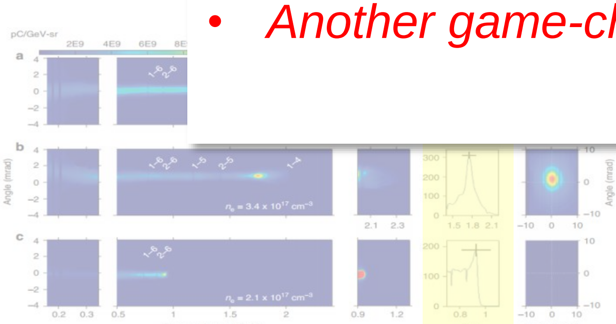
PWFA



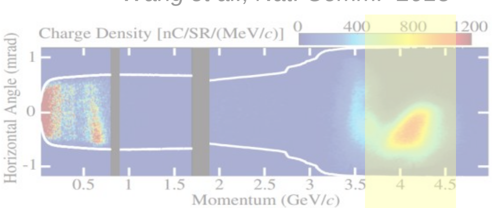
Mangles et al.
Faure et

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

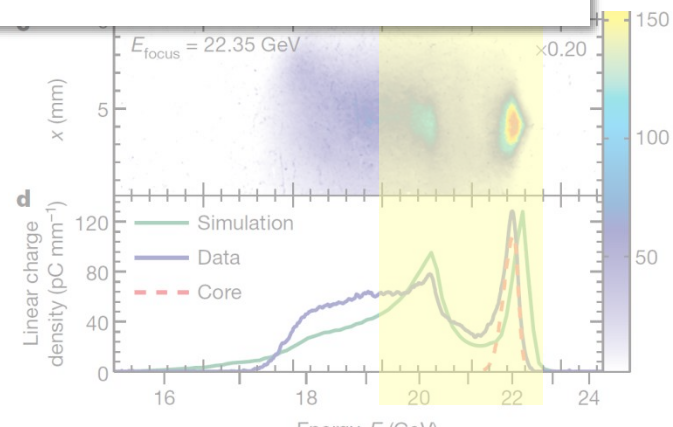
Hidd



Wang et al., Nat. Comm. 2013

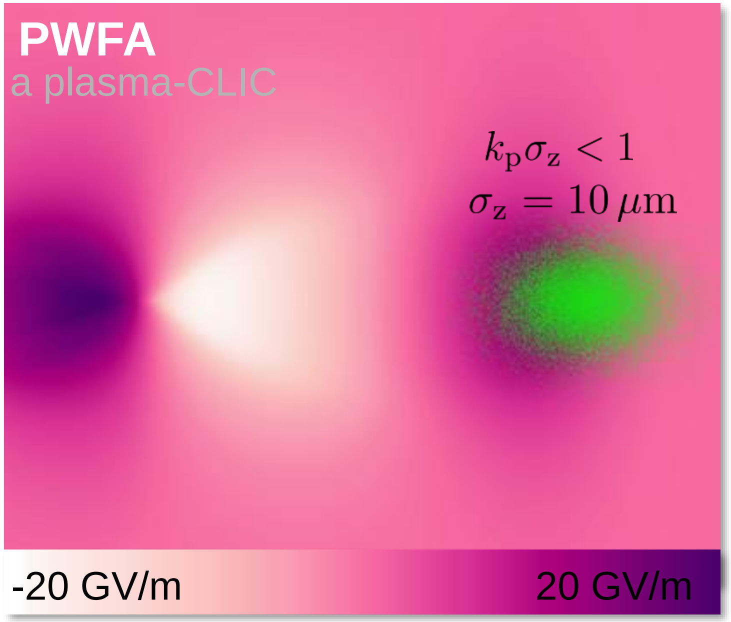


Leemans et al., PRL 2014



Litos et al., Nature 2014

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



plasma density

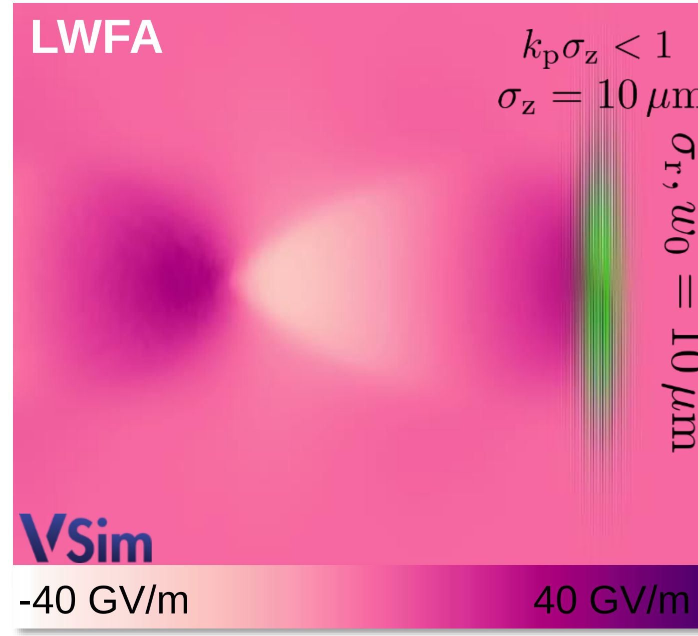
$$n_{\mathrm{p}} = 10^{17}\,\mathrm{cm}^{-3}$$

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

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

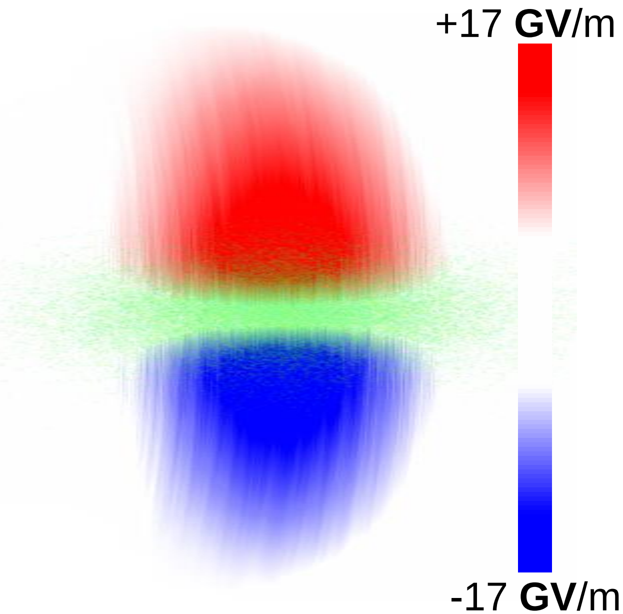
dimensionless light amplitude

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

- 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

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

PWFA

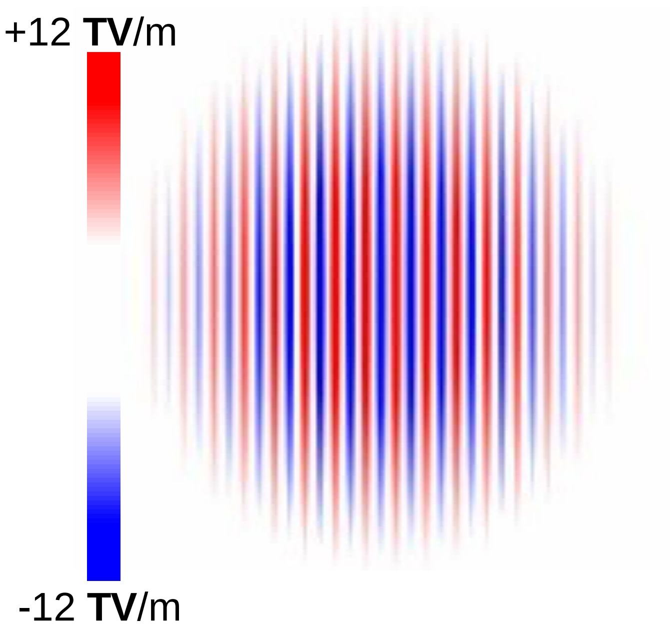


$$E_{\mathrm{r,PWFA}} \ll E_{\mathrm{r,LWFA}}$$

while accelerating plasma fields are similar

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

LWFA



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

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

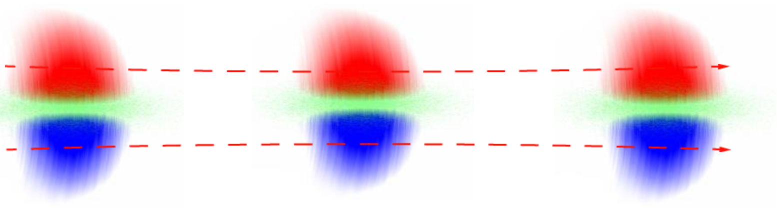
⇒ PWFA more efficient to excite plasma wave, LWFA much better to generate plasma

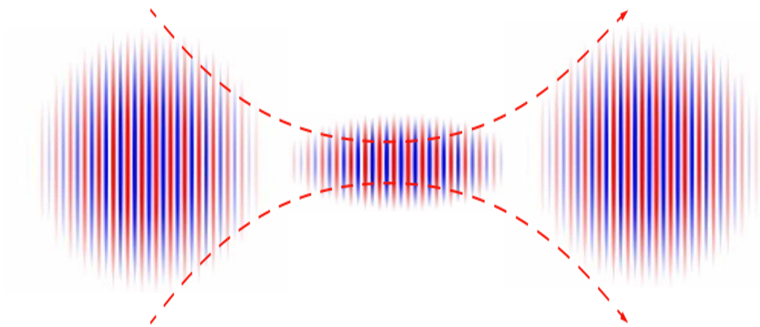
… *also profound differences: beam expansion (PWFA) vs. diffraction (LWFA)*

PWFA

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

LWFA





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

Both beams expand hyperbolically, but

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

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

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

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

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

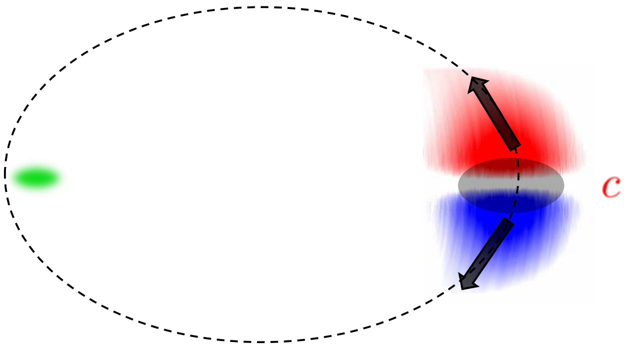
Ti:Sa laser (0.8 μm)

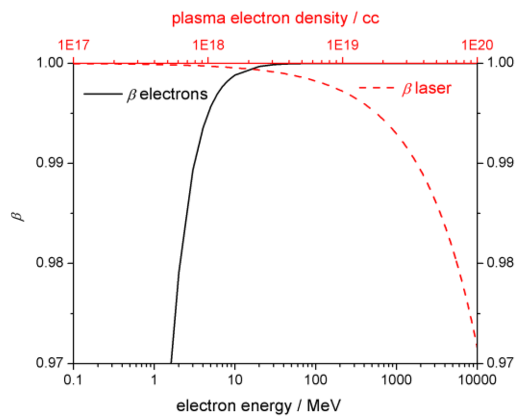
⇒ PWFA allows orders of magnitude longer acc. distances w/o any tricks (guiding etc.), LWFA allows to interact in very confined volume

… also profound differences: dephasing

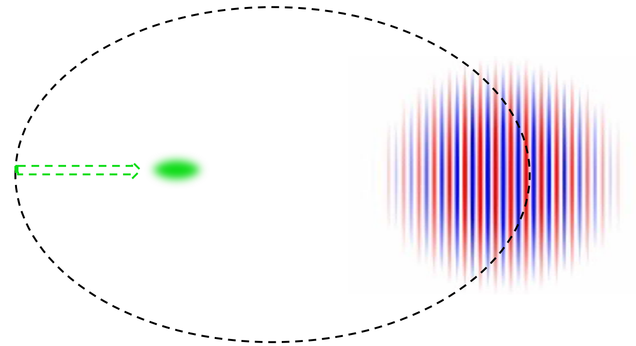
Electrons to be accelerated need to stay in proper phase of plasma wave

PWFA





LWFA



Electron beam(s) moves with c

⇒ witness bunch stays in proper phase and harvests 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

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

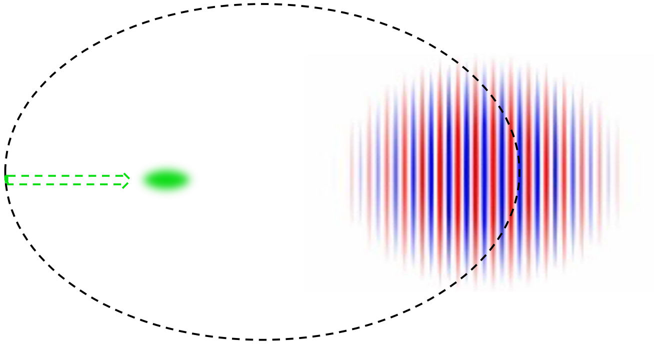
⇒ Self injection / dark current easy because $\gamma_{wake} = \gamma_{laser} \approx$ 10-100 for typical densities

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

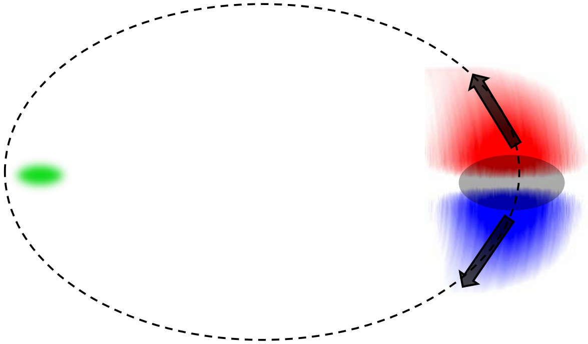
⇒ LWFA allows for easier self-injection, while PWFA in turn easily dark current free

LWFA vs PWFA summarized

- 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)

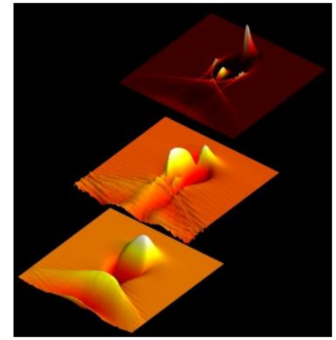


ionization if E_r > 5 GV/m (hard)
blowout if $n_b > n_e$ (easy)

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

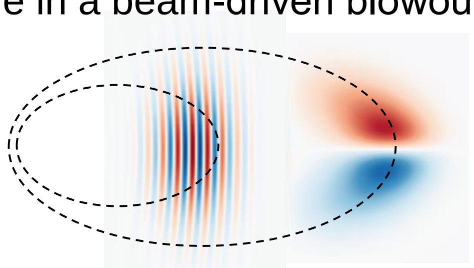
Take the best of both worlds: Hybrid Plasma Acceleration (Trojan Horse prehistory)

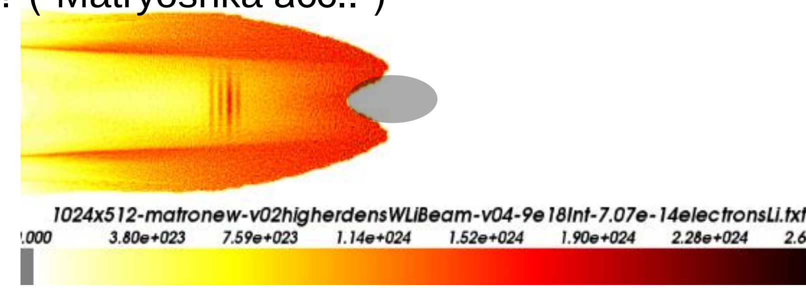
- Sequential combination:
  Use double bunches generated via LWFA (e.g. by injection into multiple buckets) as driver/witness pairs in subsequent, dephasing-free PWFA stage



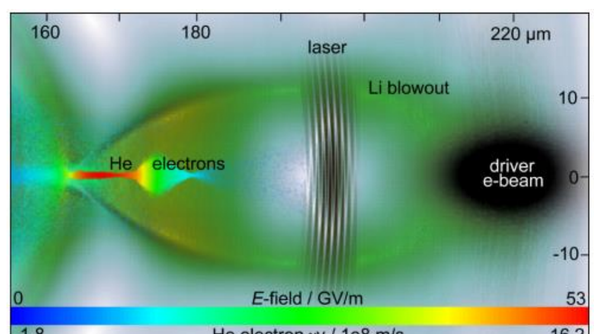
Hybrid energy doubling, PRL 104, 195002, 2010

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



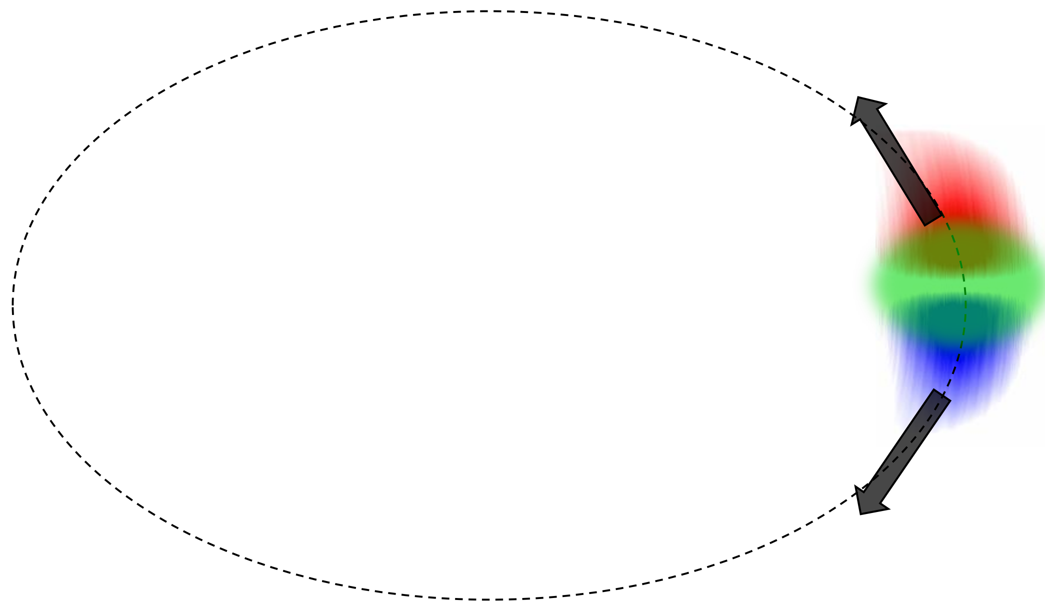


- 2008/2009: much better mode would be to have the laser pulse at minimal intensity (a_0<< 1), so that released electrons are “still” and remain still inside the blowout → “Trojan horse acc.”, originally considered for presentation at AAC 2010 in Kardamili, Greece (sic!)



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

Trojan Horse: Underdense Plasma Photocathode & Wakefield Acceleration



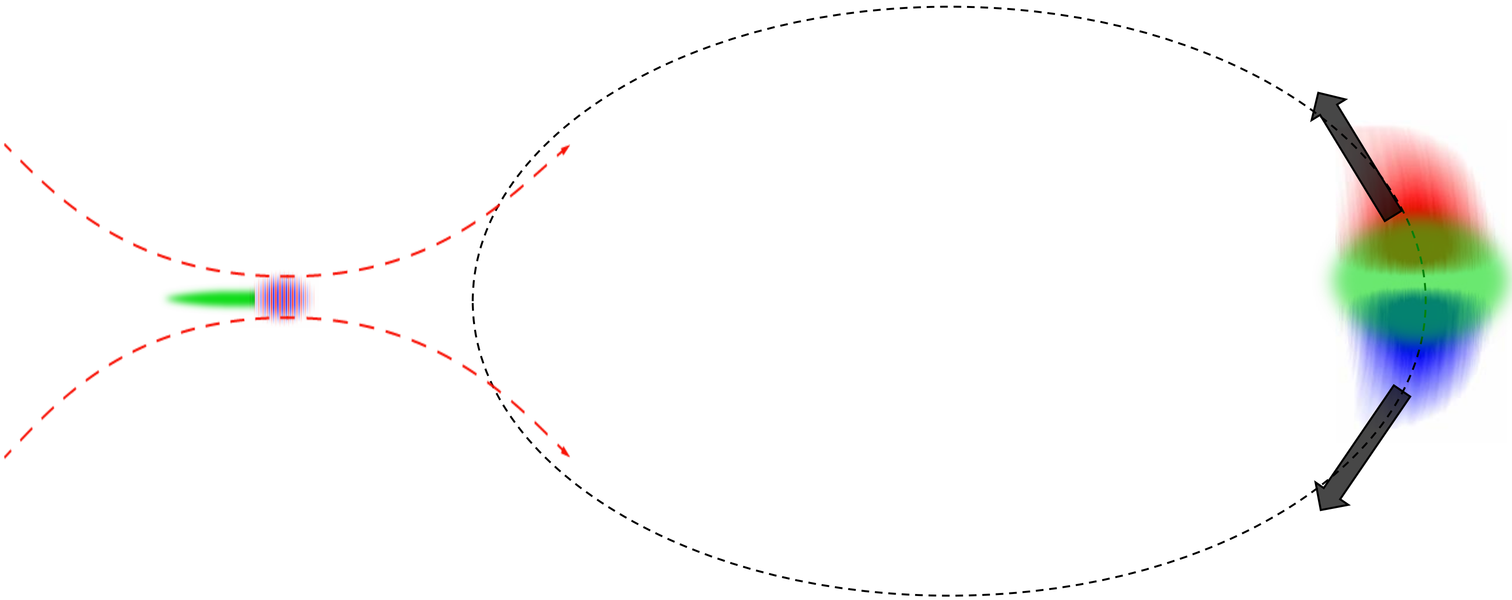
Step 1

- 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 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)

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

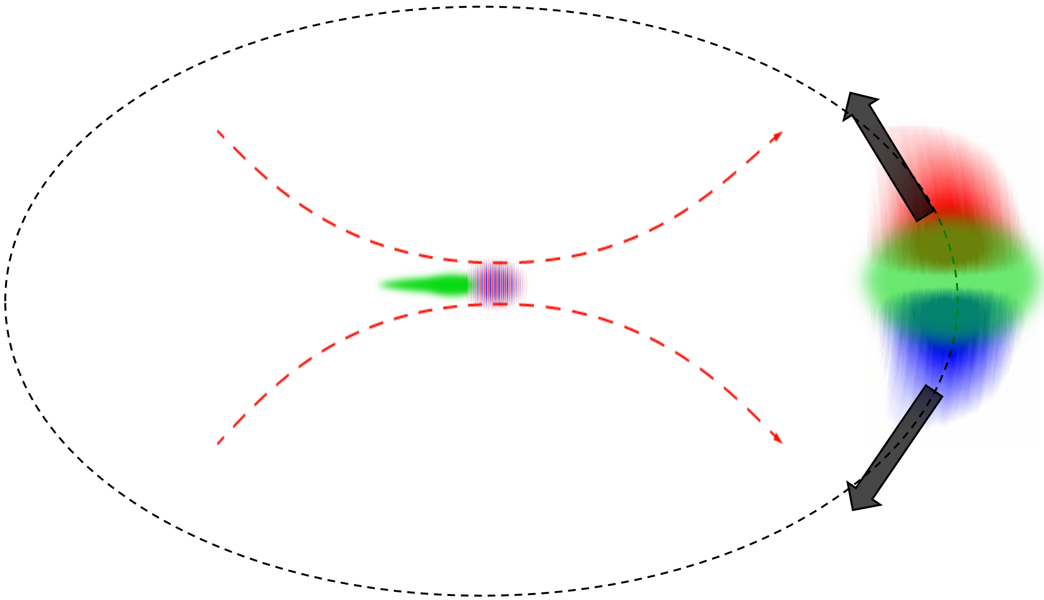
Take the best of both worlds: Hybrid Plasma Acceleration



Step 2

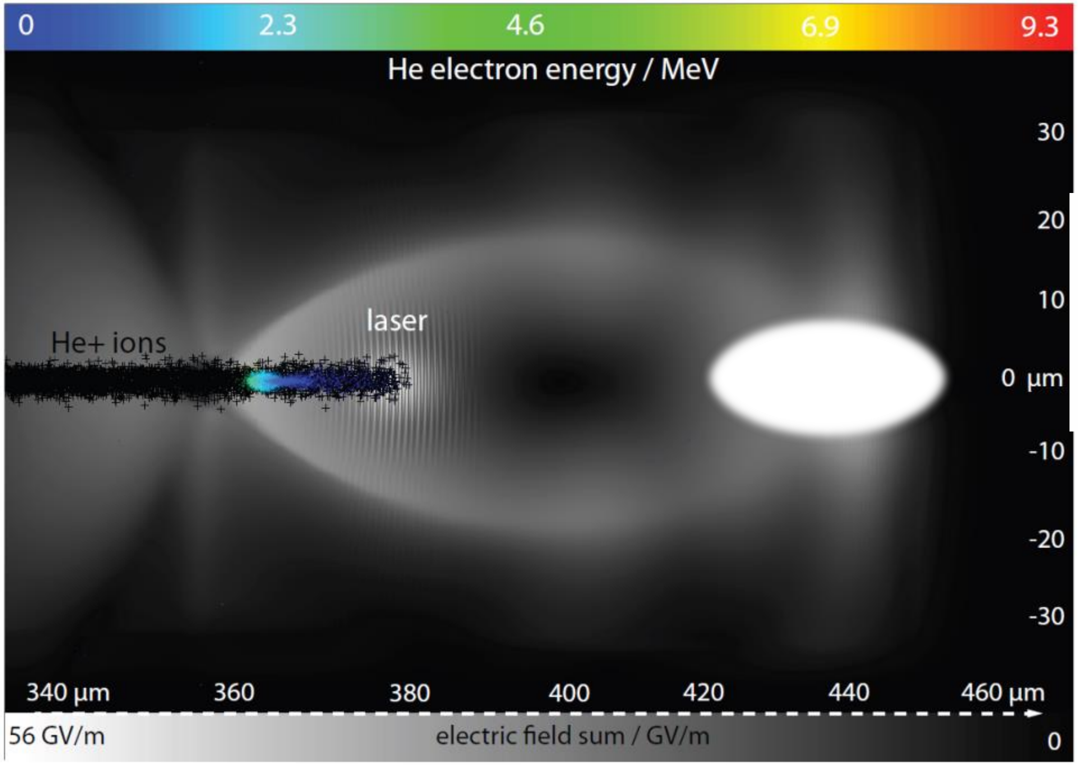
- A synchronized, low intensity laser pulse is focused strongly to the HIT level, releases He electron in confined volume at arbitrary position
- Tune released He electrons (i.e. charge) with He density, a_0, w_0, ω, τ, polarization, focus shape…

Take the best of both worlds: Hybrid Plasma Acceleration



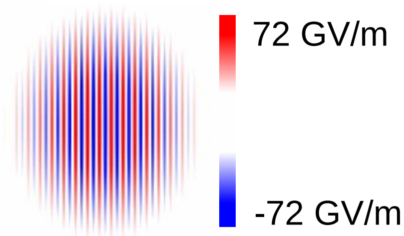
Step 3

- 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?

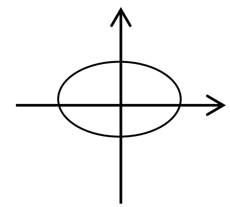
Laser kick contrib. to norm. emittance:



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

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

residual momentum



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

source size

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

crude scaling

- 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

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

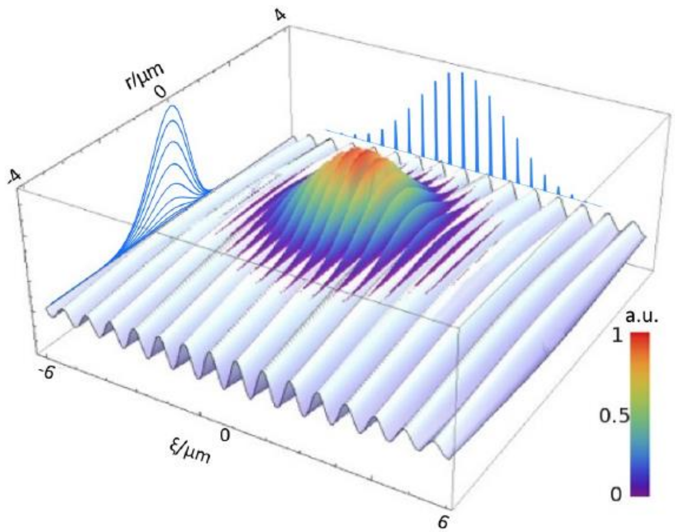
Refined scalings: C. Schroeder et al., PRSTAB 17, 101301, 2014, Y. Xi et al., PRSTAB 2013

→ 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

PIC simulation results d'accord with hybrid model

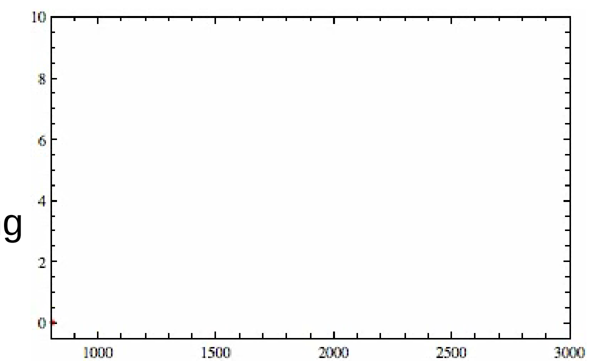
Y. Xi et al., PRSTAB, 2013



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

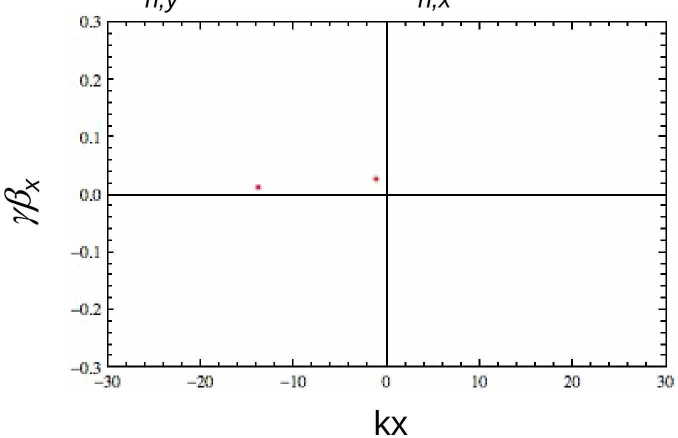
- Detailed numero-analytical analysis shows that $\varepsilon_{n,y}$ is about an order of magnitude lower, and increases slower than $\varepsilon_{n,x}$ as intensity increases. $\varepsilon_{n,y}$ down to the $\varepsilon_{n,y} \approx 10^{-9}$ m rad level or less.

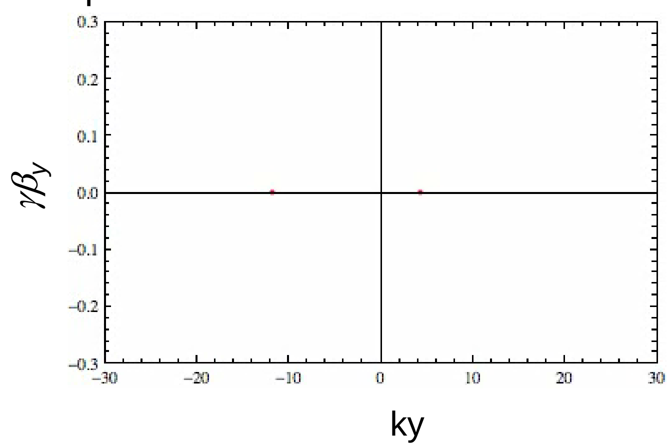
plasma velocity bunching

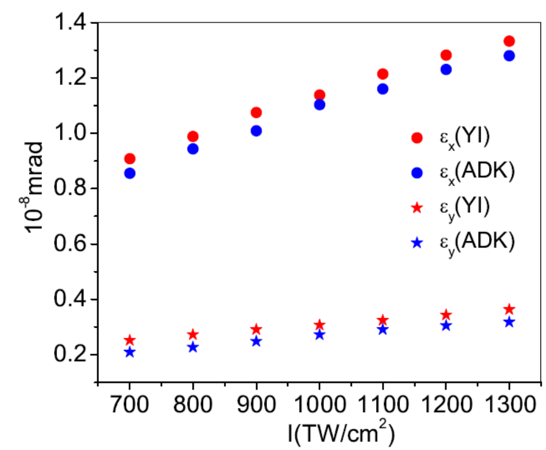


Laser linearly polarized in x-direction:

$\varepsilon_{n,y}$ 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

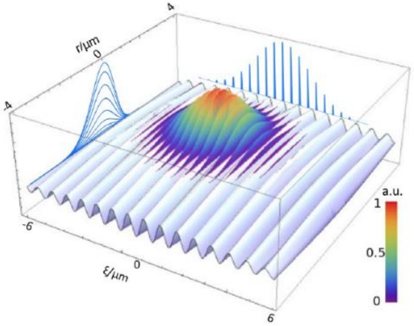
$$\epsilon_{\mathrm{th}} = \frac{w_0}{2}\sqrt{\frac{k_B T}{mc^2}}$$

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

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

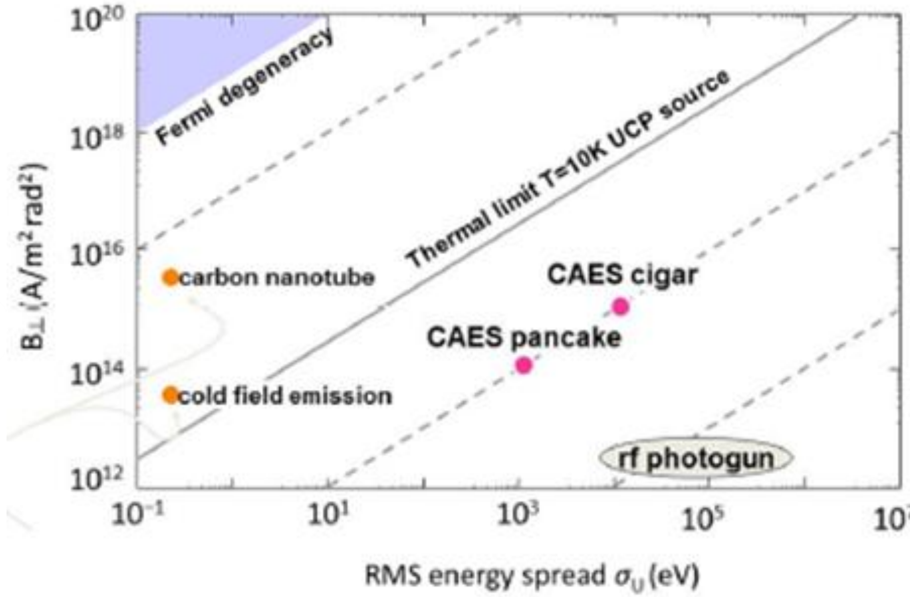


Note that plasma density n_p(HIT), e.g. He, can be independently tunable of n_p(LIT),
but in a homogeneous mixture (respect gas dynamics!)

BRIGHTNESS (5D) $B = \frac{2I}{\epsilon_n^2}$

Trojan

- Ultrashort, currents kA-scale (typical of plasma accelerators)
- Ultracold, norm. emittance 1e-9 scale (new!)



/from P. Musumeci

From J. Luiten

→ ***Ultrahigh electron brightness $B \sim 2I/\varepsilon_n^2$ up to 10^{20} Am^{-2} rad^{-2}*** *(maybe more)*

That's many orders of magnitude brighter than e.g. the LCLS.

Electron beam brightness is key for light sources..

Potentially game-changing: may allow plasma based accelerators to produce bunches with **much better** key characteristics (such as emittance, brightness, shortness (~as-regime),) than w/ conv. accelerators!

When looking back, disruptive emittance and brightness improvements have been prerequisites for next-gen. light sources…

Hidding et al., PRL 2012 & pat. 2011; Xi et al., PRSTAB 2013, Li et al., PRL 2013; Bourgeois et al., PRL 2013, Yu et al., ArXiV 2013..

5^{th} Generation Light Sources…

…need a 4^{th} Generation Electron Source

5^{th} 4D, ultrahard, compact?

4^{th} Free-Electron-Laser

3^{rd} Undulator radiation

2^{nd} Synchrotron radiation

1^{st} Bremsstrahlung

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)

Recap:

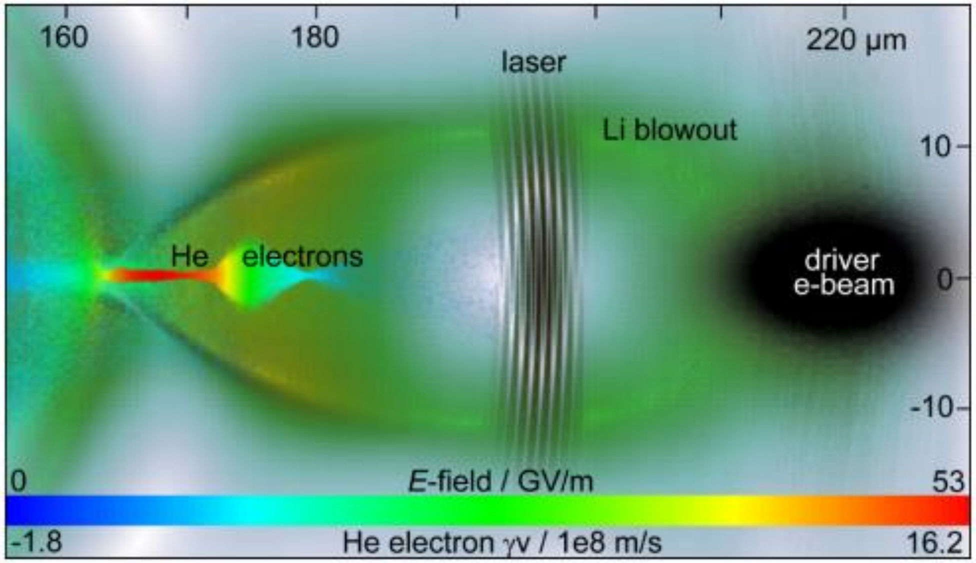
- ***Plasma accelerators*** **blocks can provide 10's of GV/m acceleration, sustained over metre-scale distances (proven)**

- ***Plasma photocathodes*** **can provide electron bunches with (5D) brightness orders of magnitude higher than with state-of-the-art photocathodes (so far theory only, albeit at high confidence level)**

... Experimental realisation?

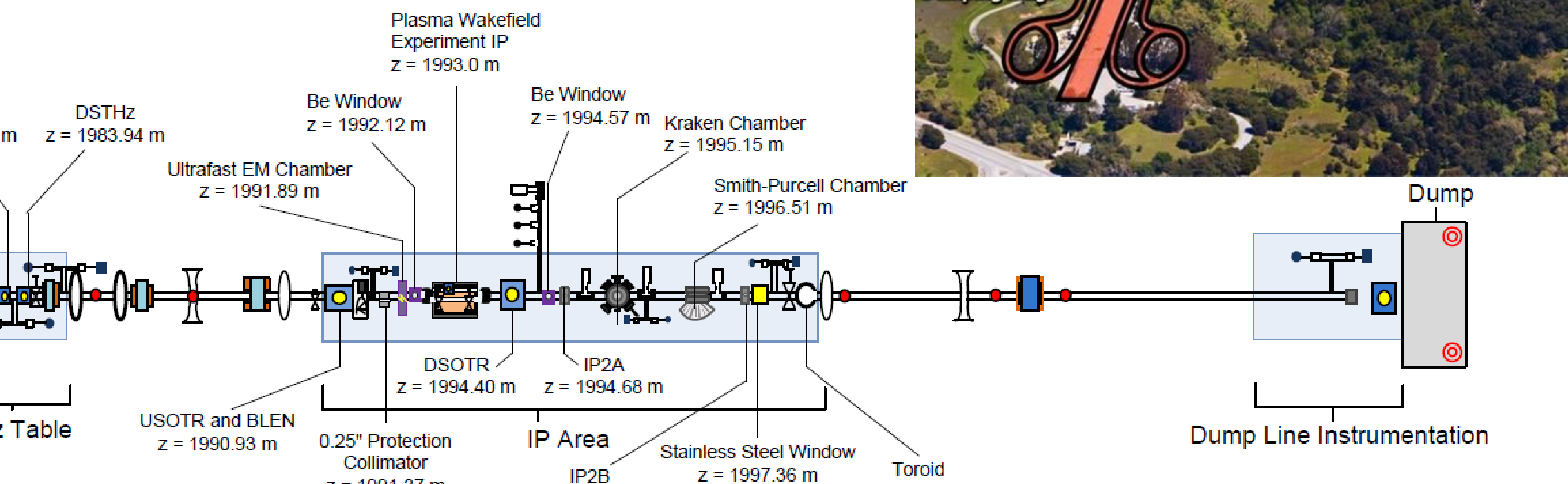
Major experimental challenges:

- **Electron-driven plasma wave has to be strong enough to trap, but must not be too strong, in order to avoid dark current**
- **Plasma has to be selectively preionized by preionization laser – plasma channel must be wide enough to host plasma wave over**
- **Spatio-temporal sychronization between preionization laser & electron beam driver (few ps, few micron/μrad level), electron beam plasma photocathode release laser (few tens of fs, better < 10 fs, few μm level)**



E210 Trojan Horse at FACET

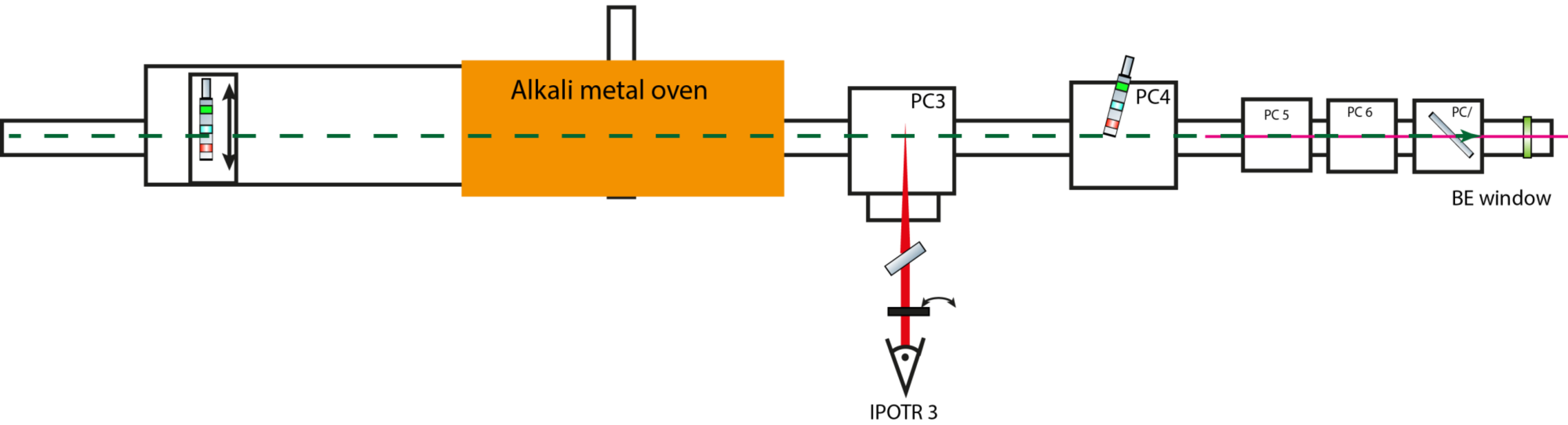
- Proposal submitted 2011
- Dramatic performance increase at FACET in last years:
- Started w/ self-ionized LIT alkali vapours, no laser
- Electron bunch quality boosted in 2012
- 10-20 TW synchronized Ti:Sa installed in 2013
- First laser-preionized argon/hydrogen in 2014/15
- Preionized H + He as HIT gas in 2015 (spring run)
- Synch. & time-of-arrival commissioning 2015 (spring run)
- Focused Trojan laser commissioning 2015
- **Full blown exp. with 4 laser arms in 2016 spring run**



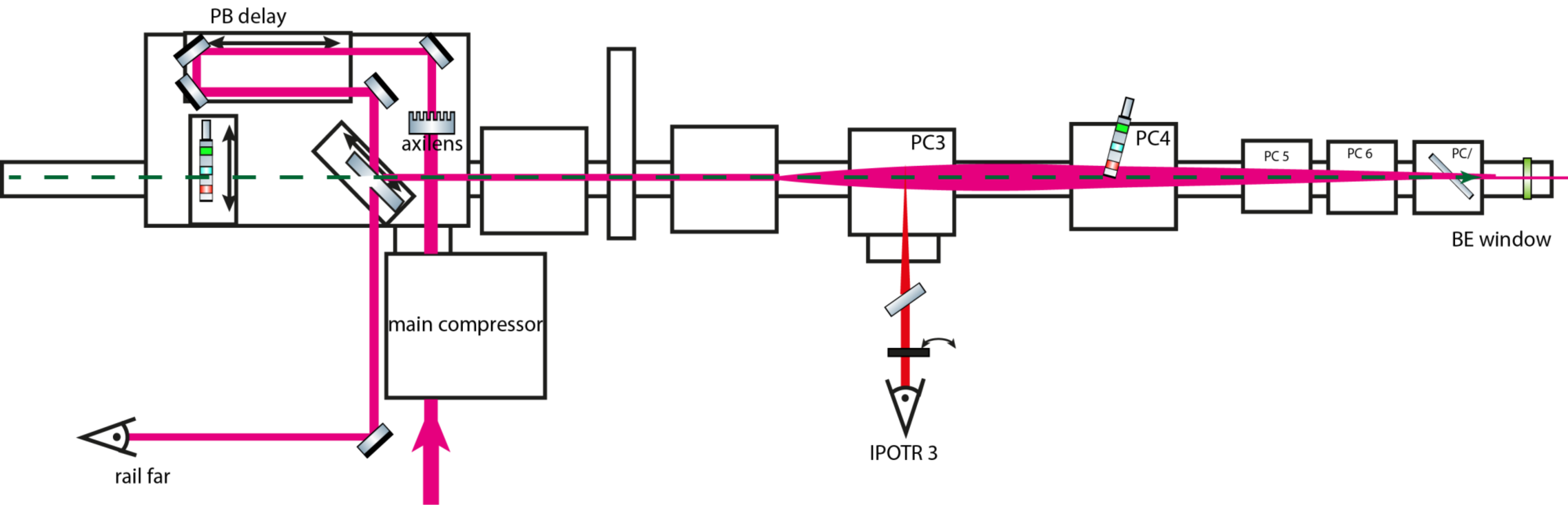
2016 setup:

Embargoed – publication pending

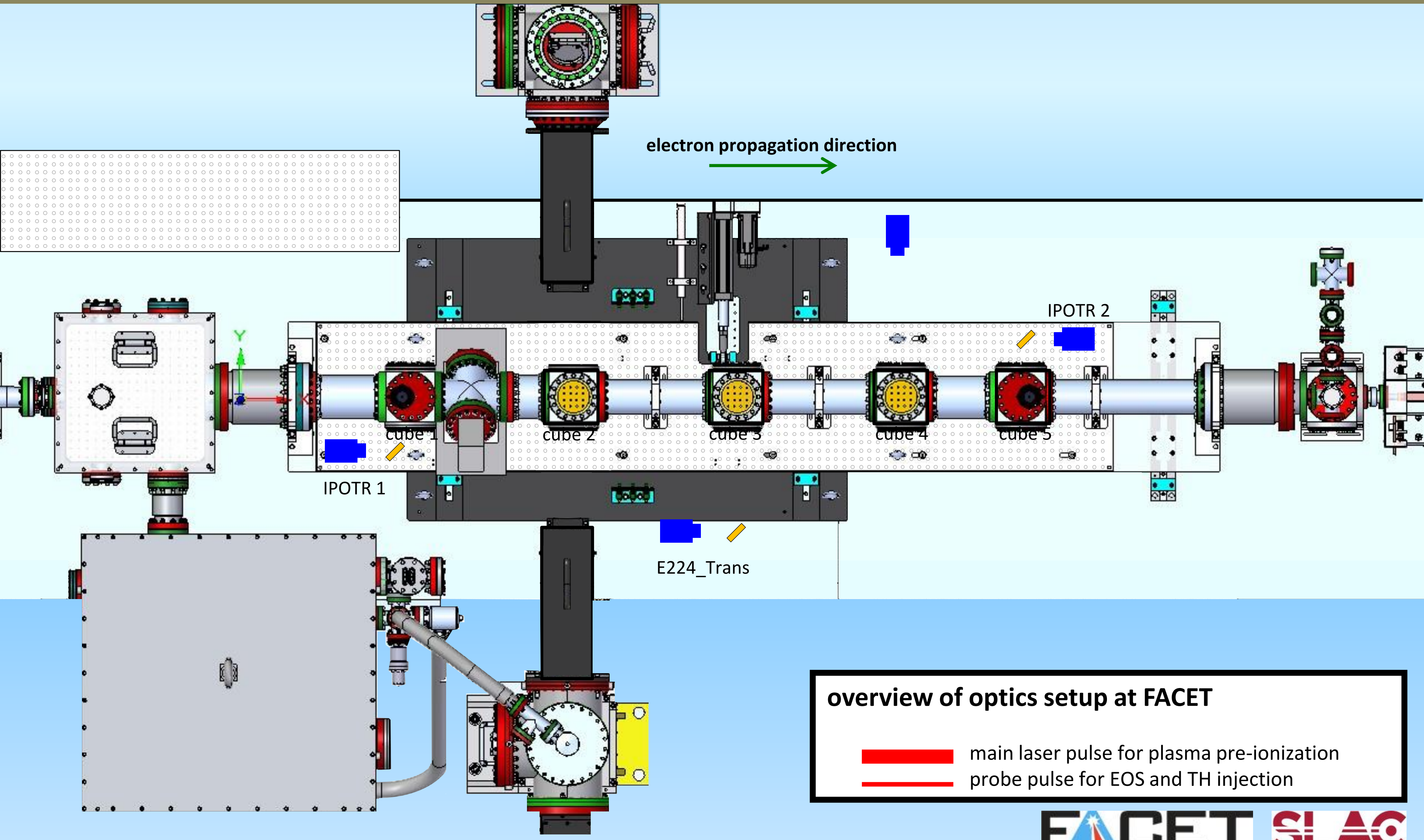
Pre-2012 setup: alkali metal oven, rely on FACET driver bunch self-ionization



E210 setup: RadiaBeam "Picnic basket" chamber and 20 TW preionization laser integration



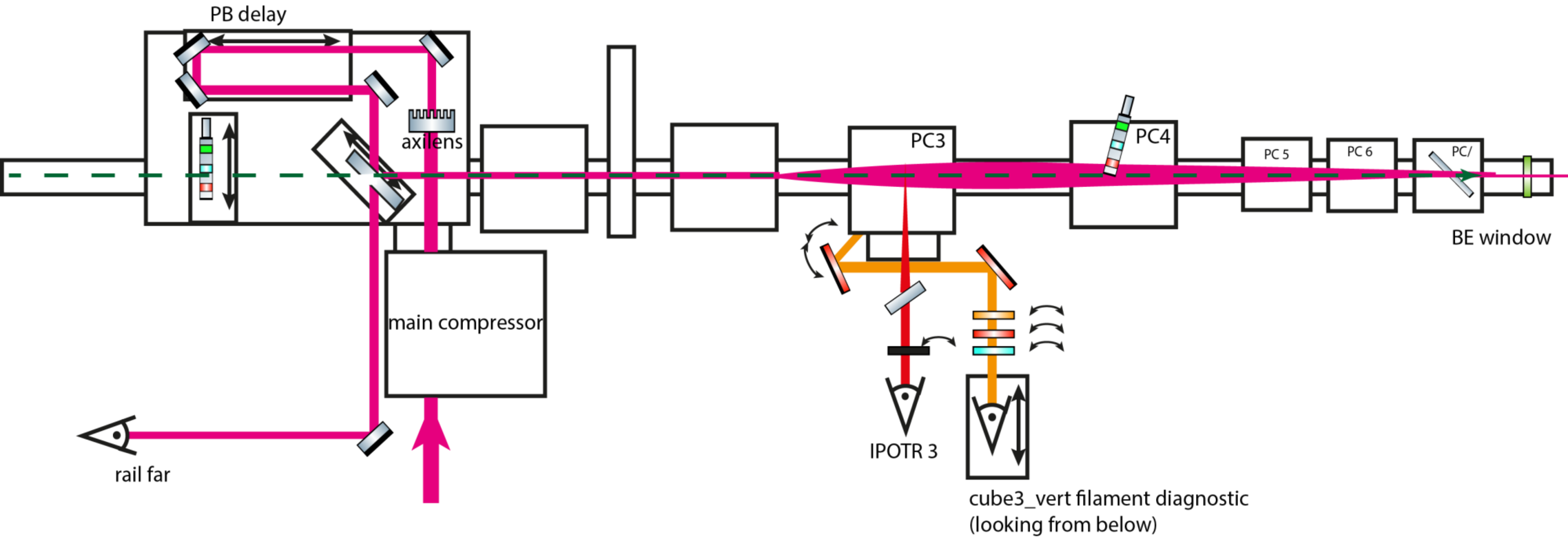
setup at FACET



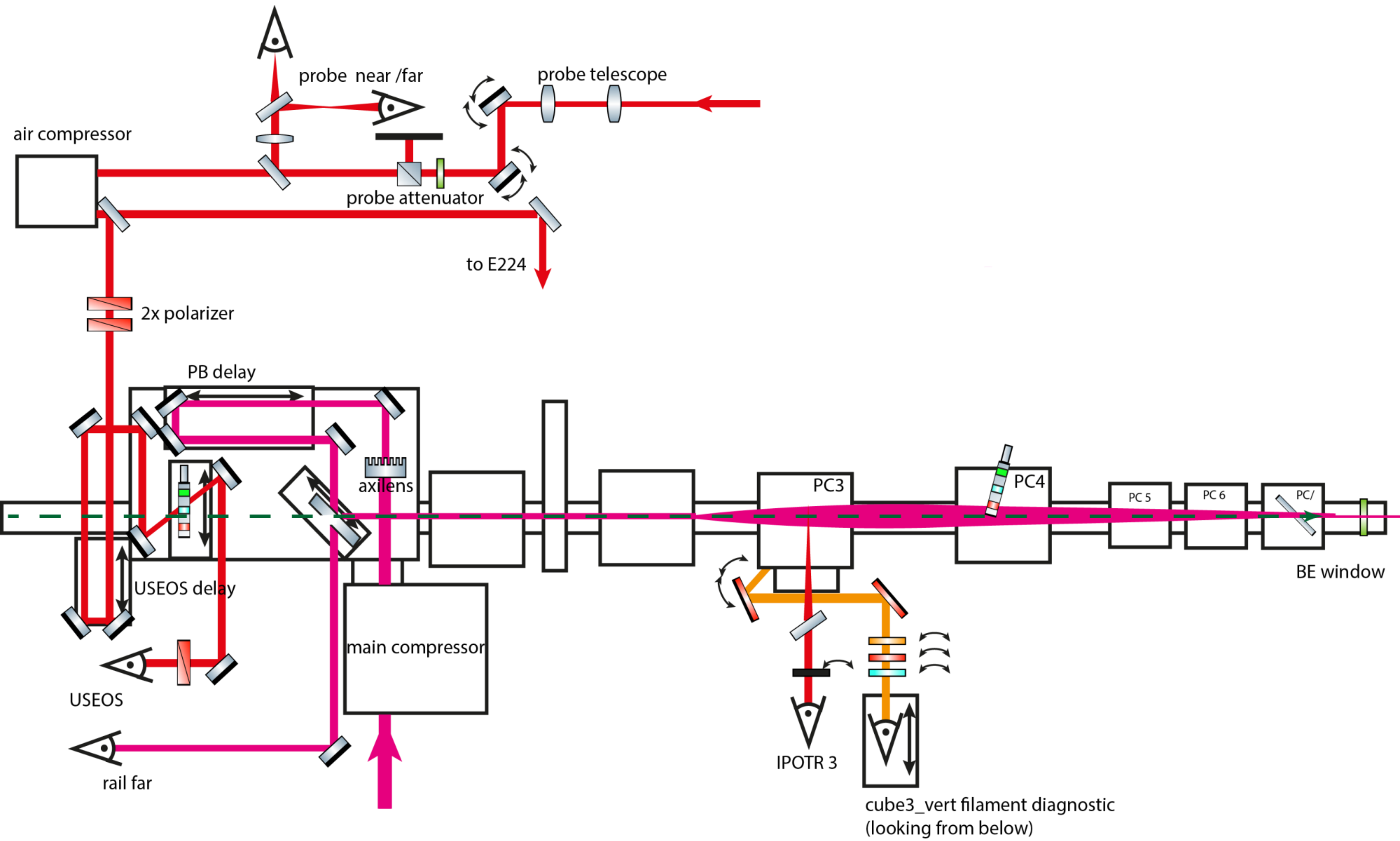
overview of optics setup at FACET

main laser pulse for plasma pre-ionization
probe pulse for EOS and TH injection

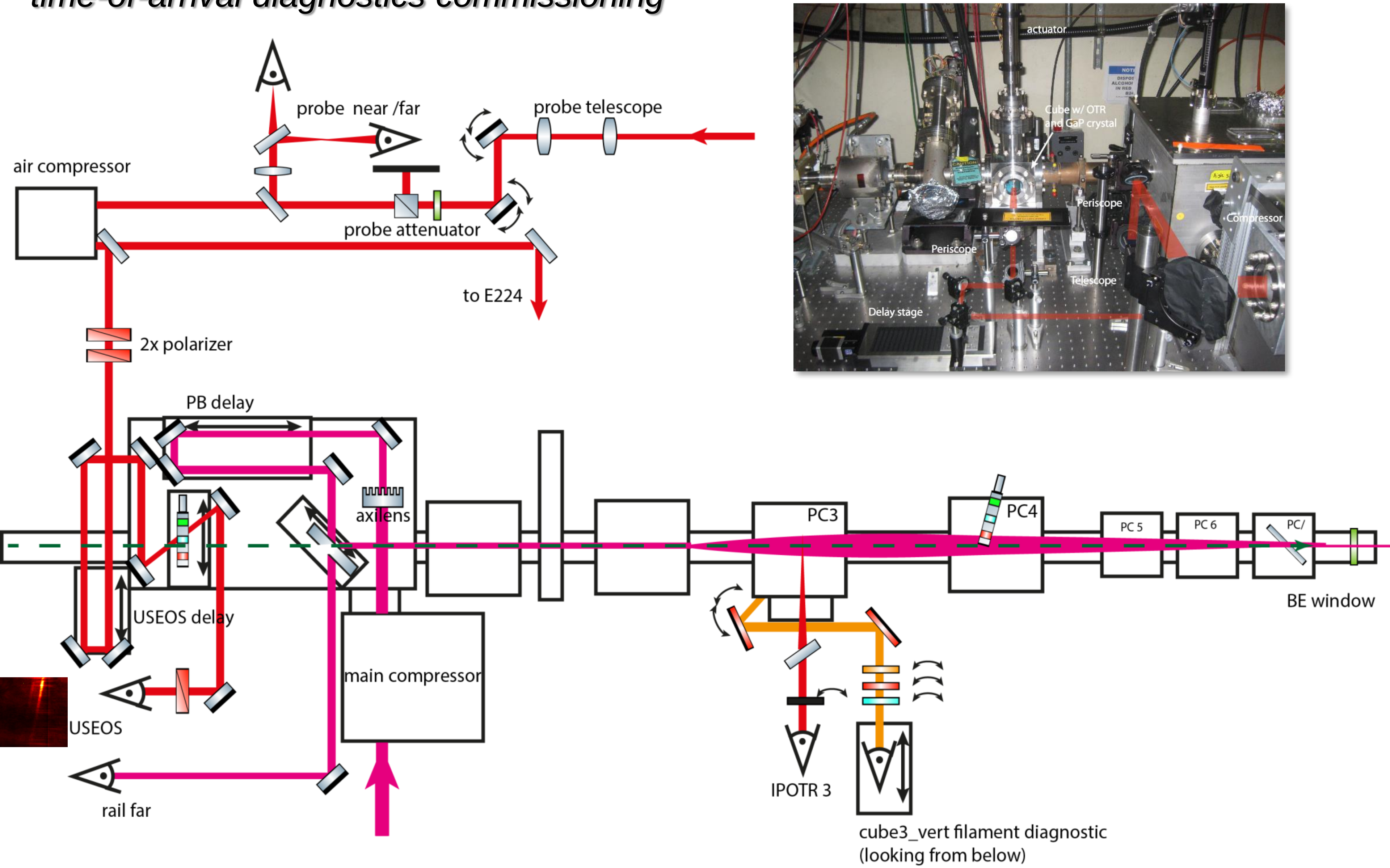
E210 setup: cube 3 vertical plasma filament diagnostics



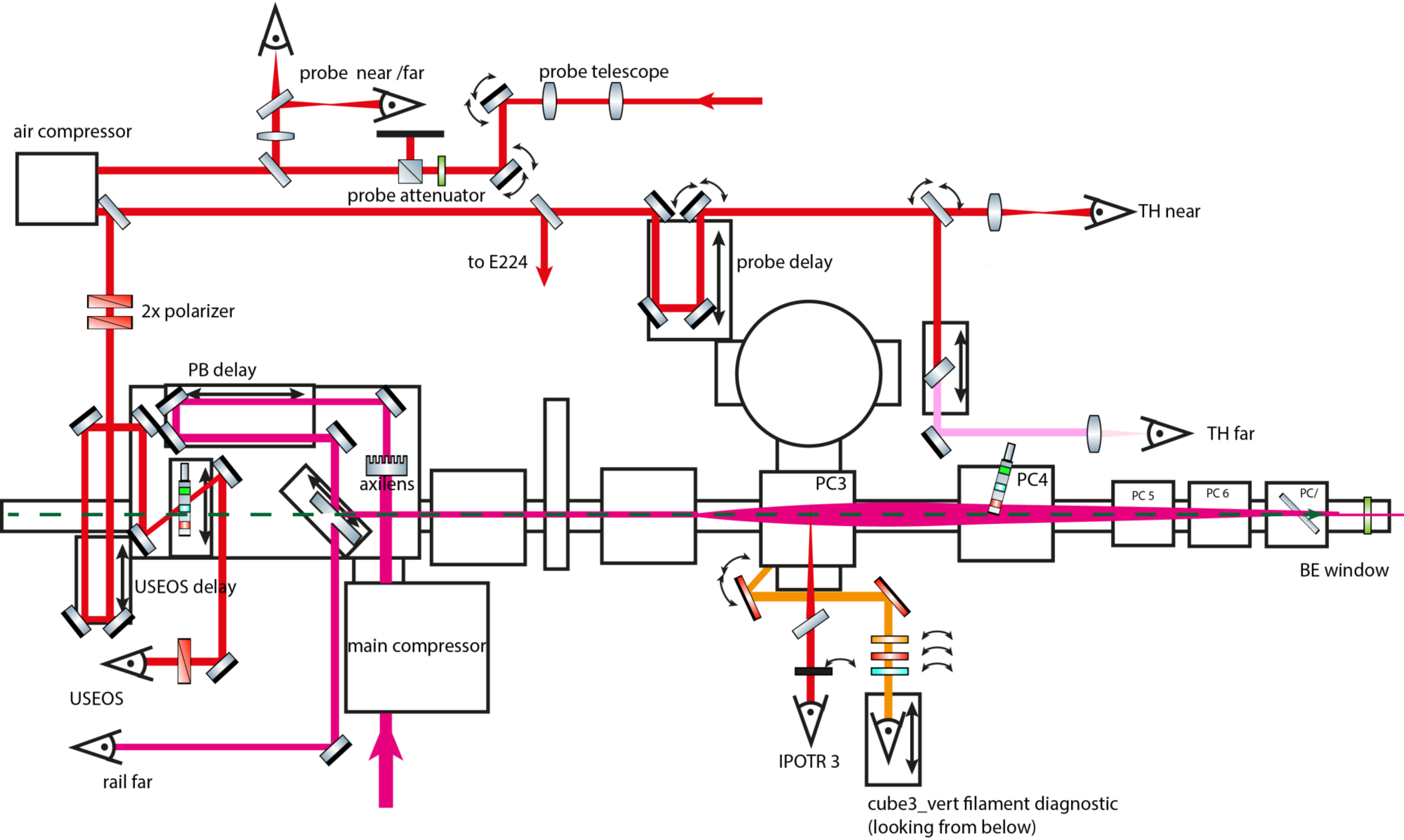
E210 setup: 2nd laser arm. Independently tunable air compressor and upstream EOS time-of-arrival diagnostics commissioning



E210 setup: 2nd laser arm. Independently tunable air compressor and upstream EOS time-of-arrival diagnostics commissioning

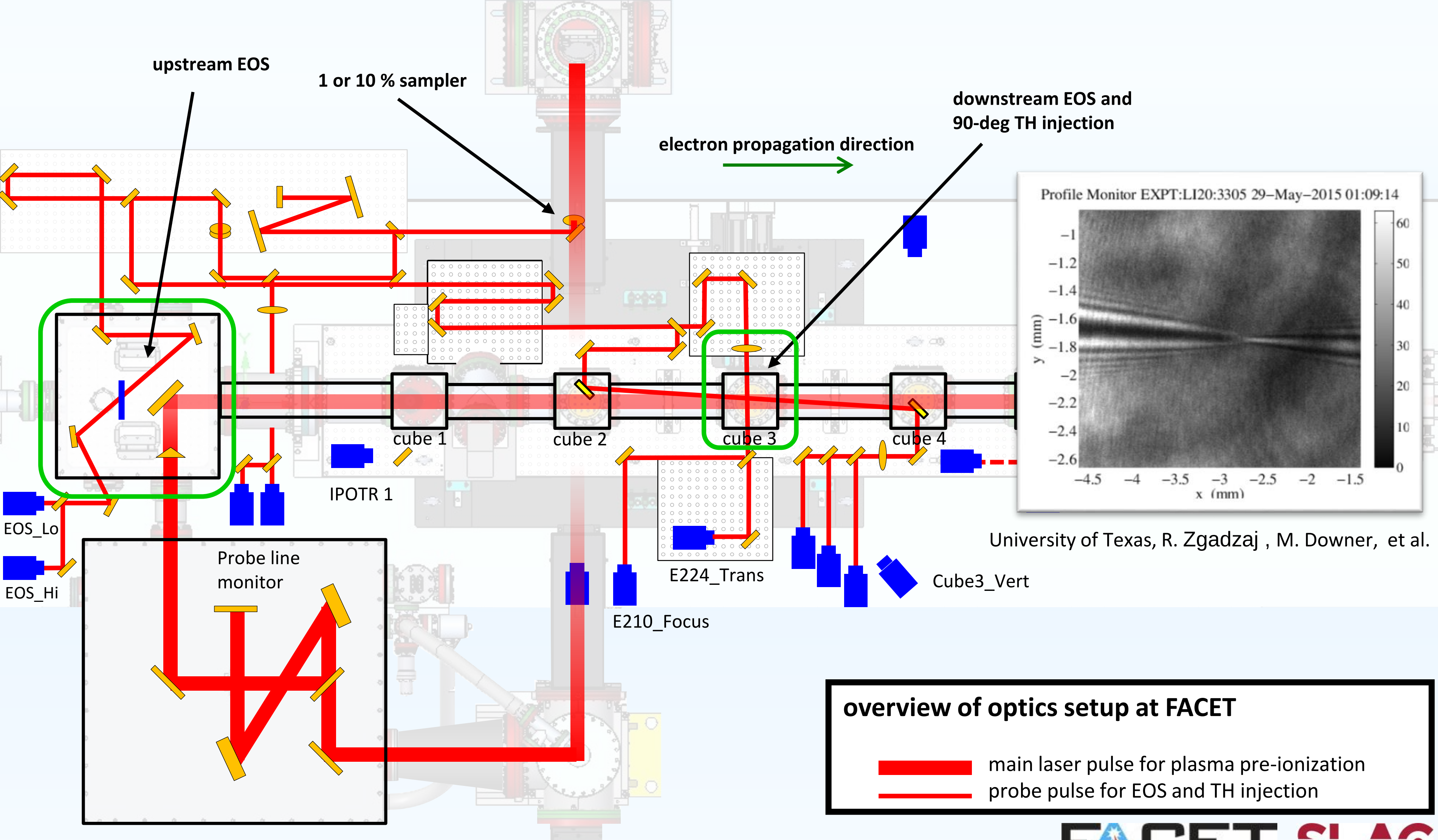


E210 setup: 3rd and 4th laser arm to E224 probing, downstream Trojan Horse (w/ independent delay line) and downstream EOS



setup at FACET

beam self-ionized experiments
laser pre-ionized experiments
Trojan Horse experiment
plasma imaging experiments

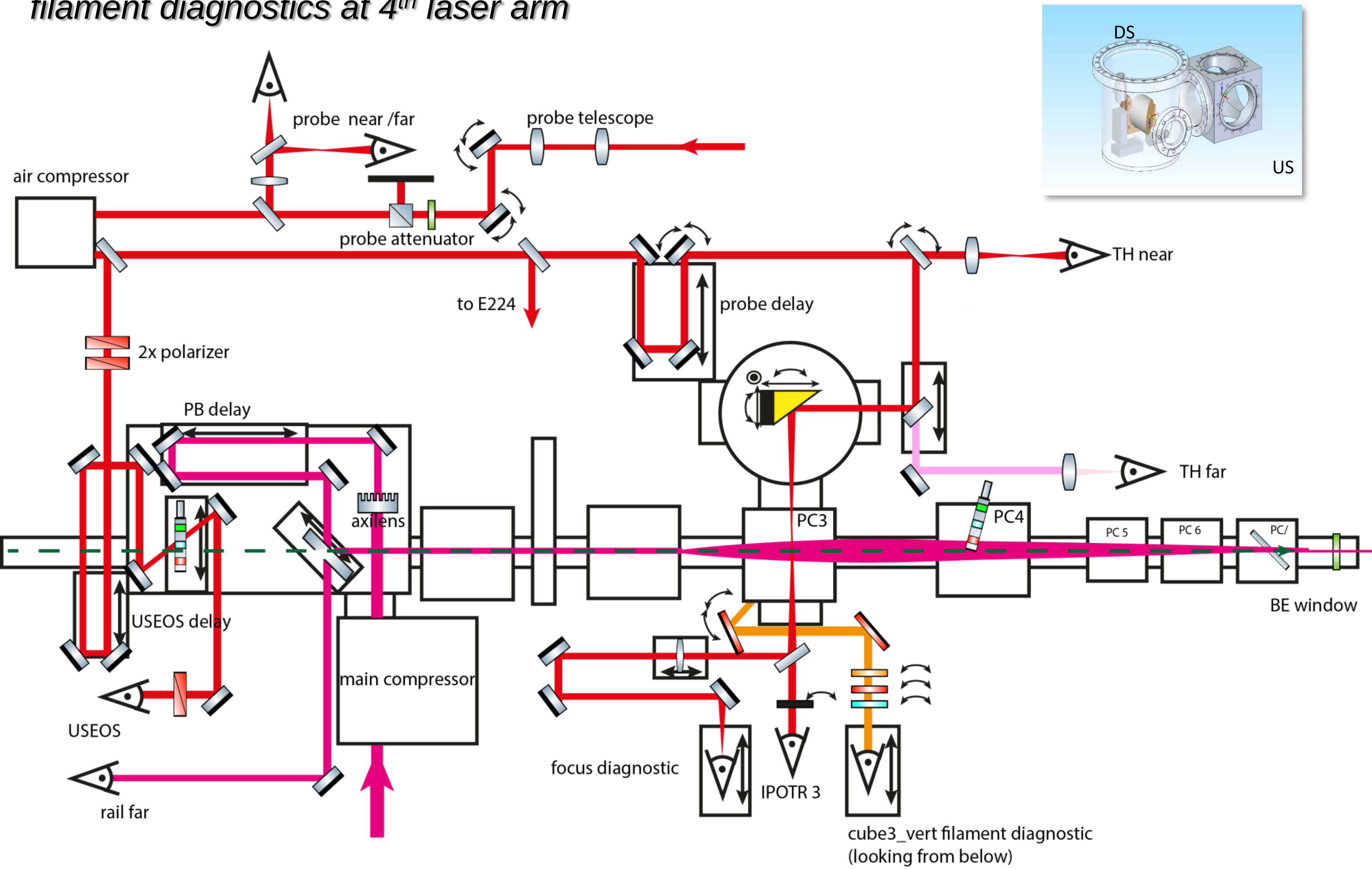


University of Texas, R. Zgadzaj , M. Downer, et al.

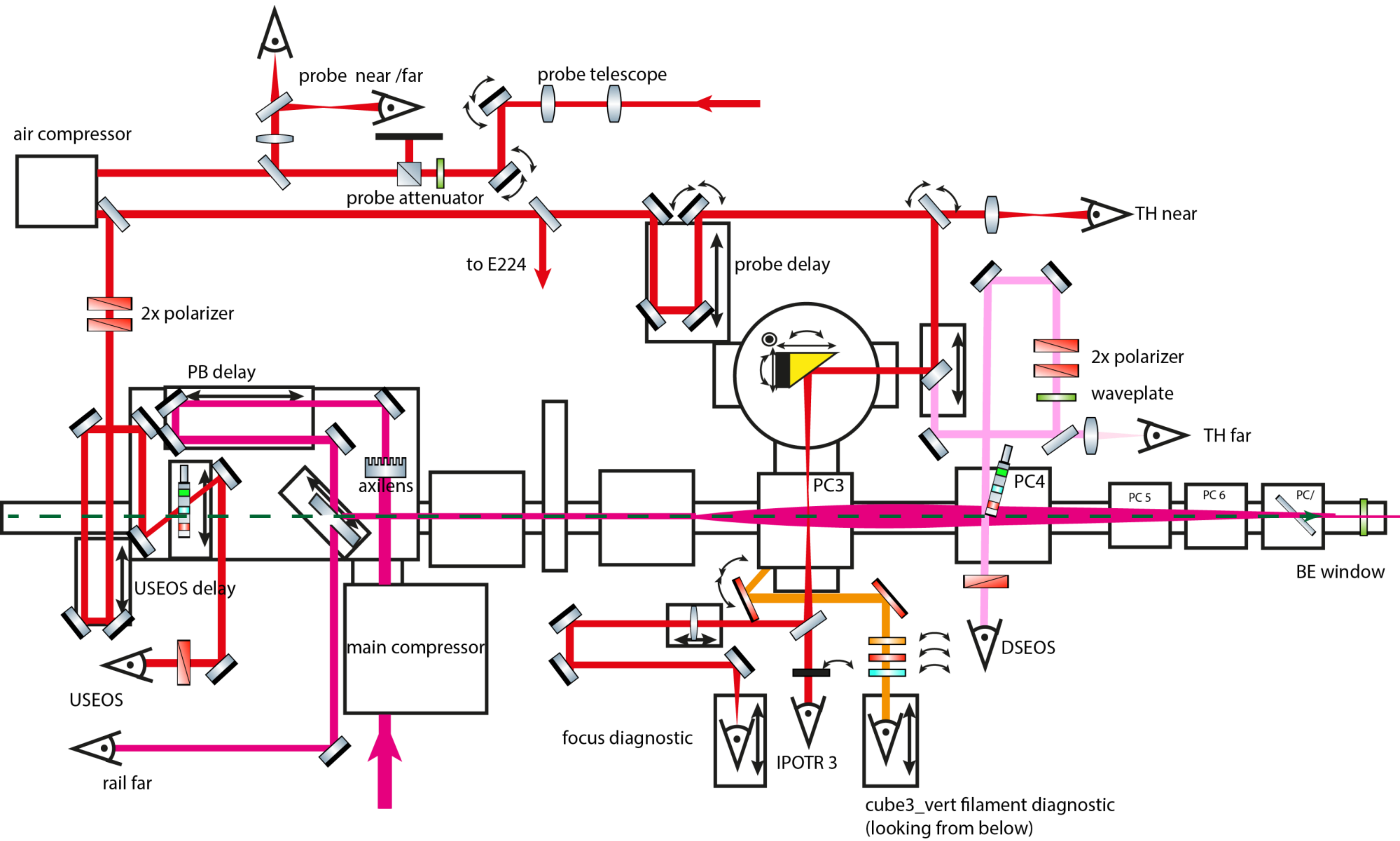
overview of optics setup at FACET

main laser pulse for plasma pre-ionization
probe pulse for EOS and TH injection

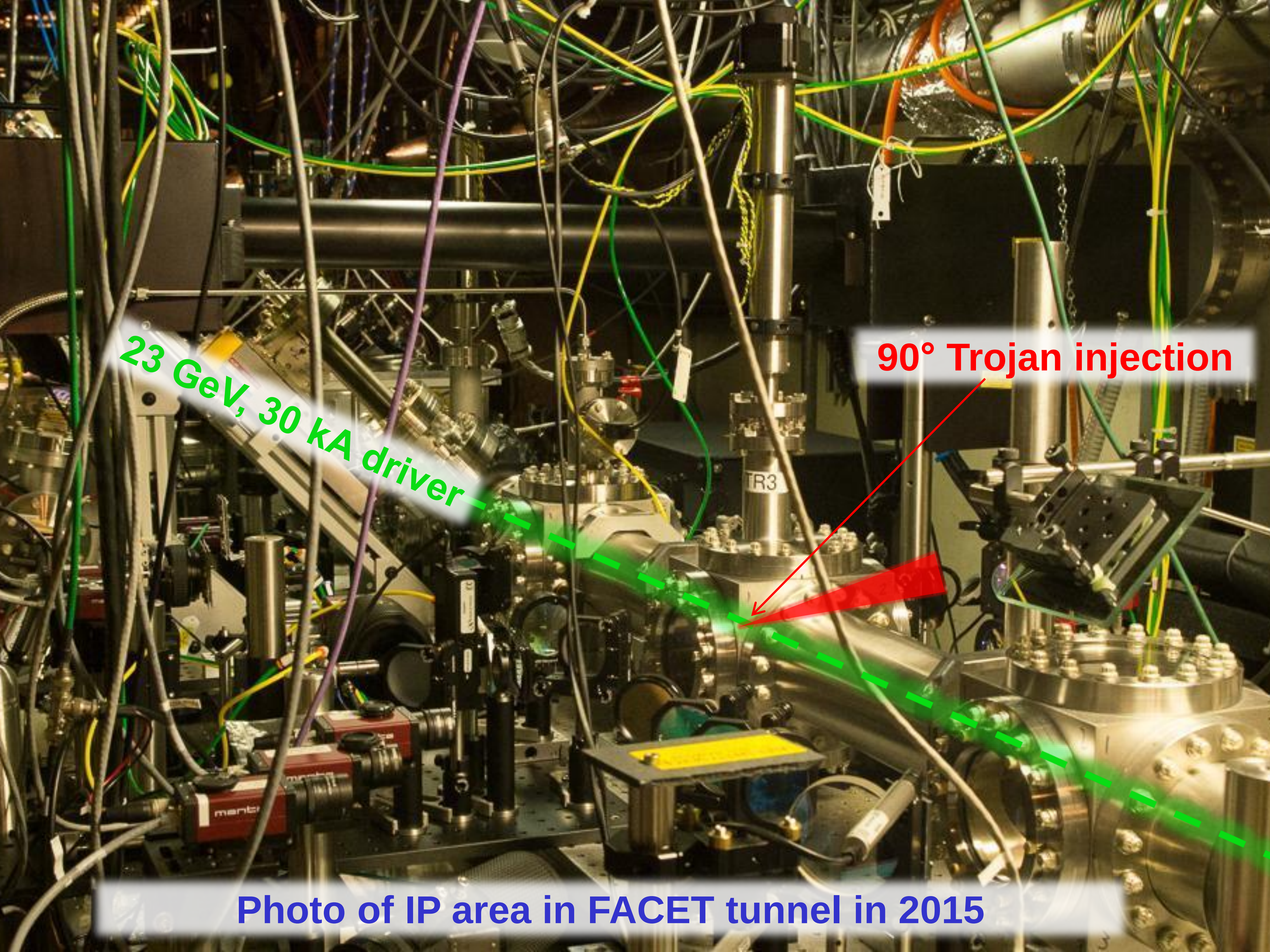
E210 setup: implement vacuum chamber off-axis parabola focusing and Trojan Horse filament diagnostics at 4th laser arm



E210 setup final: w/ downstream EOS (E224 probe not shown for simplicity)

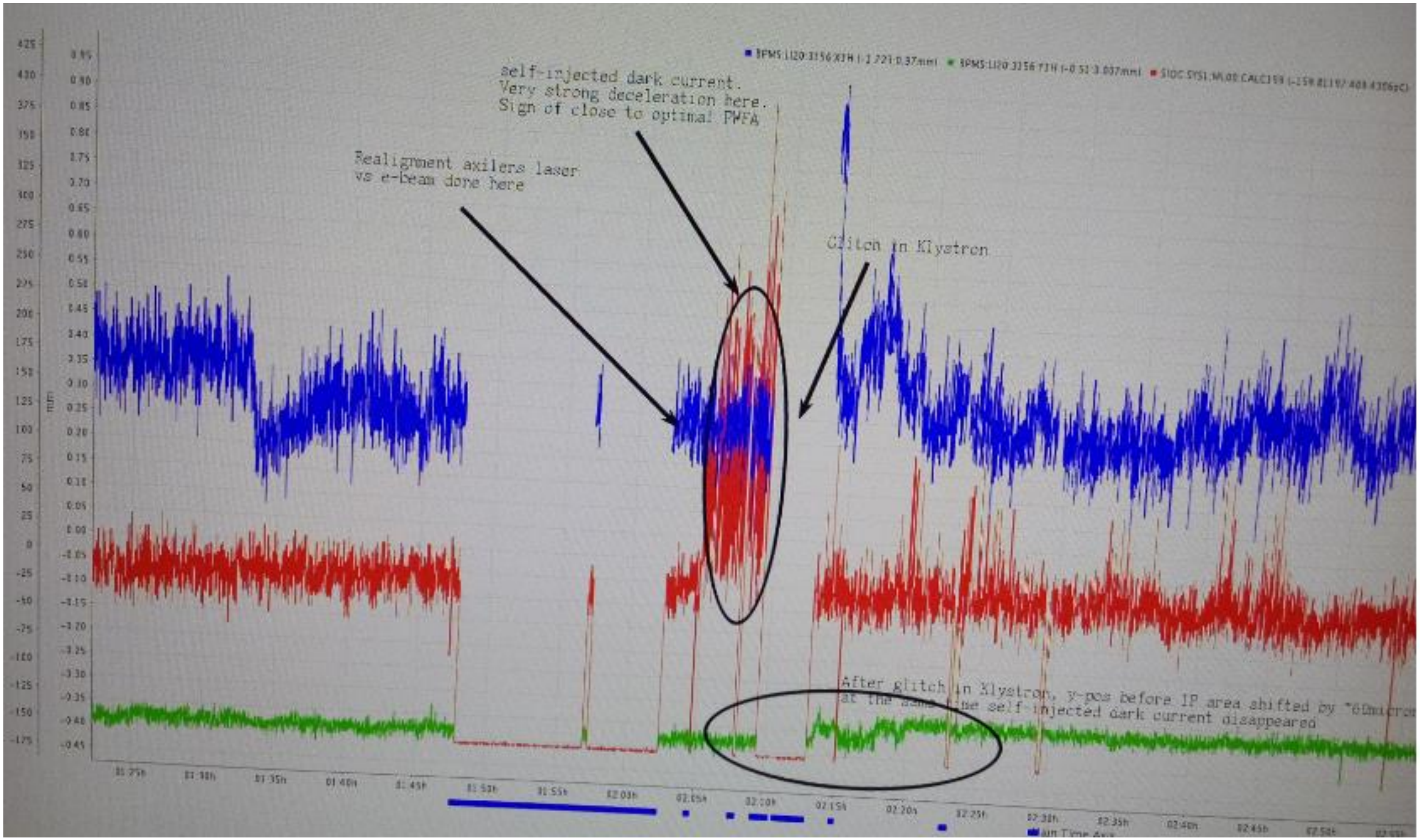


..most complex experiment at FACET to date..


23 GeV, 30 kA driver
90° Trojan injection
TR3
Photo of IP area in FACET tunnel in 2015

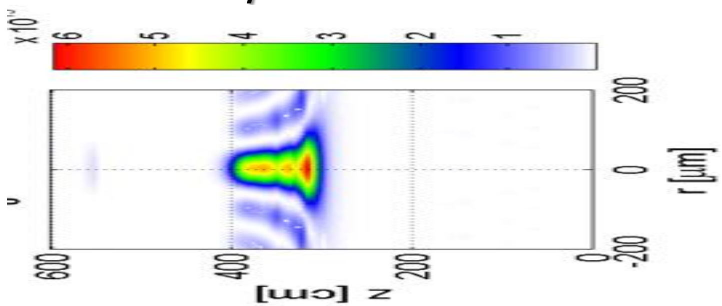
Spatiotemporal alignment between e-beam driver, upstream EOS, H2 preionization laser & plasma channel, He Trojan Horse laser crucial

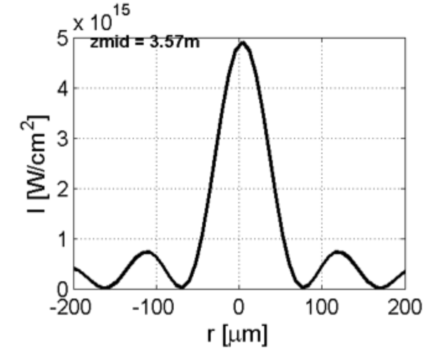
Example for jump in y-position of incoming e-beam vector (on BPM 3156) which killed the laser-triggered injection

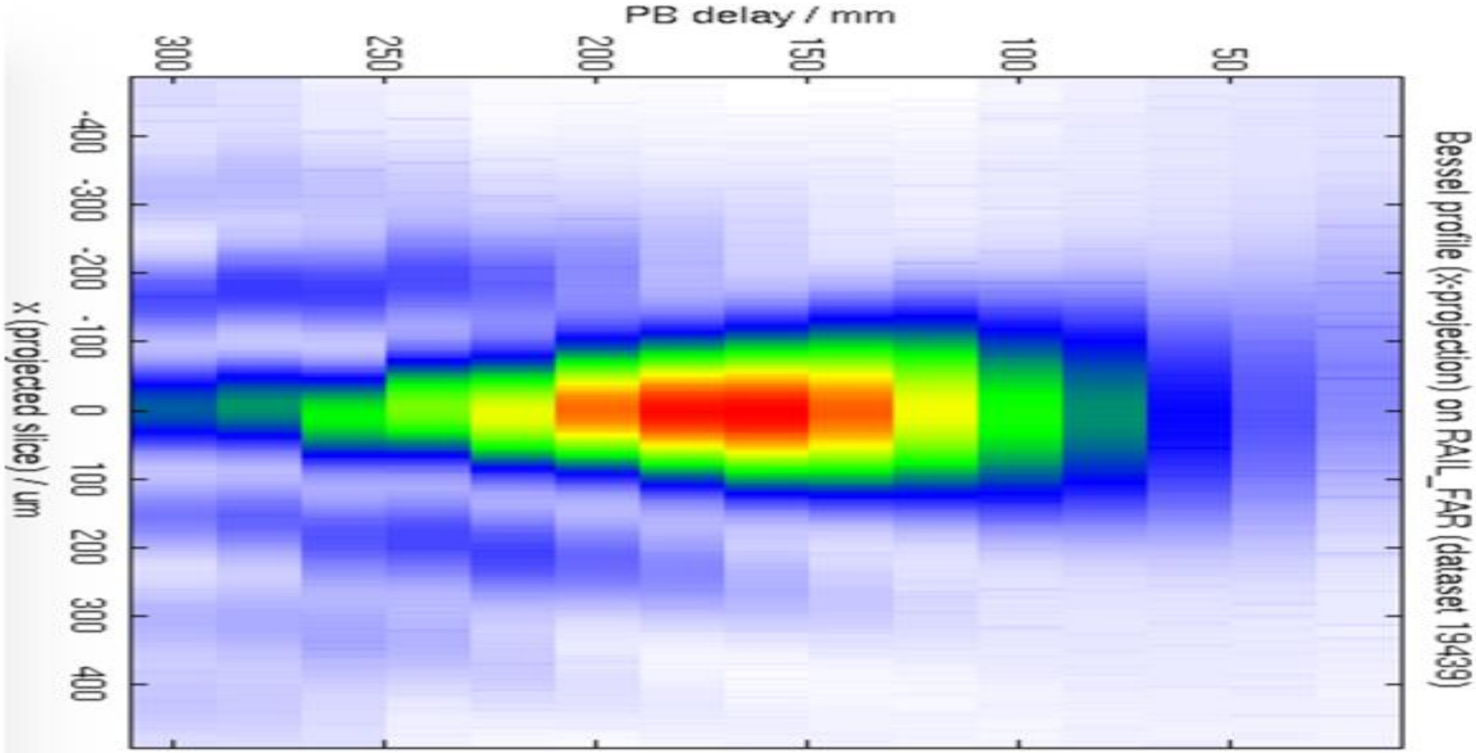


Alignment between e-beam driver and preionization laser

Calculated plasma profile obtained from Axilens laser intensity profile & tunnel ionization rates



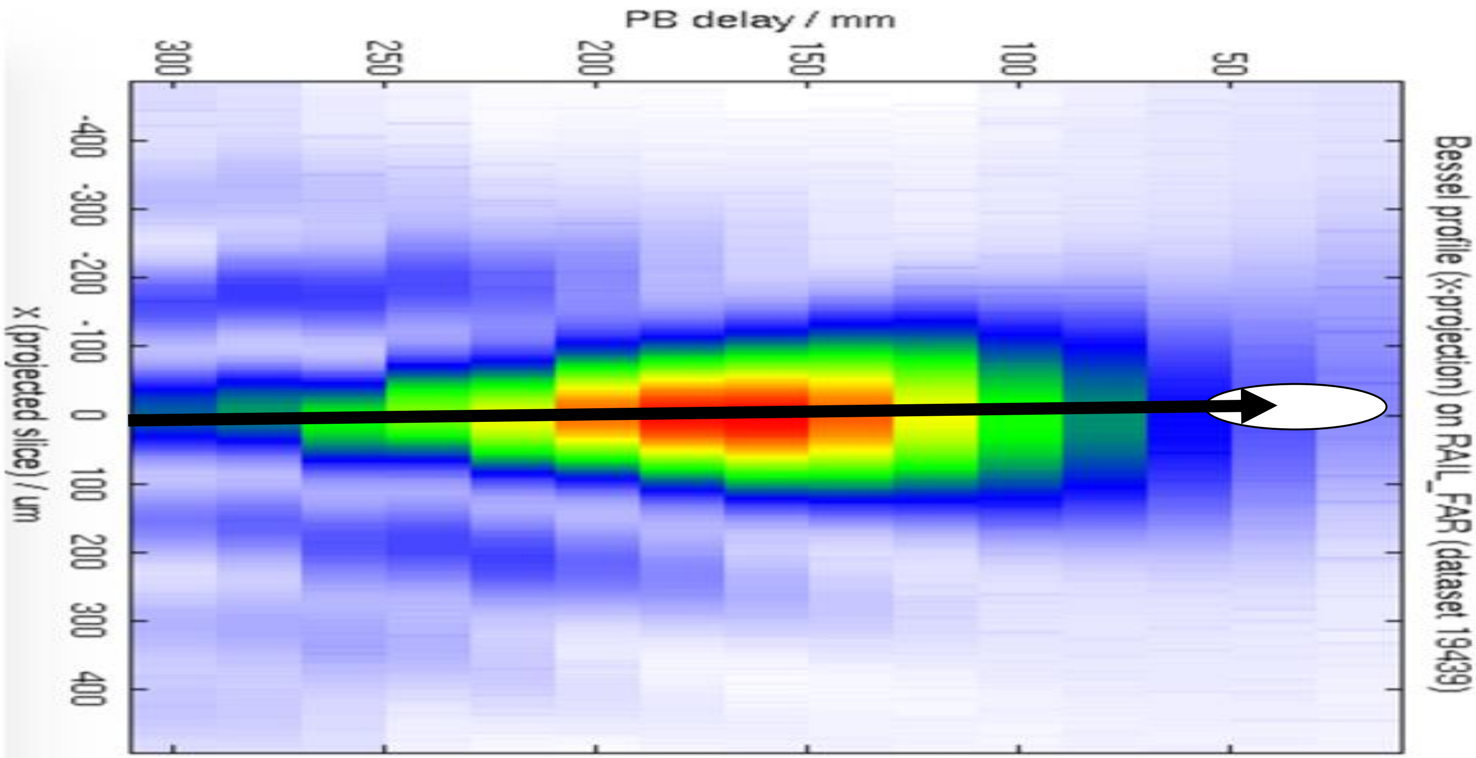




Measured Bessel profile of axilens laser (meters long, but ~150 ´µm wide)

Alignment between e-beam driver and preionization laser

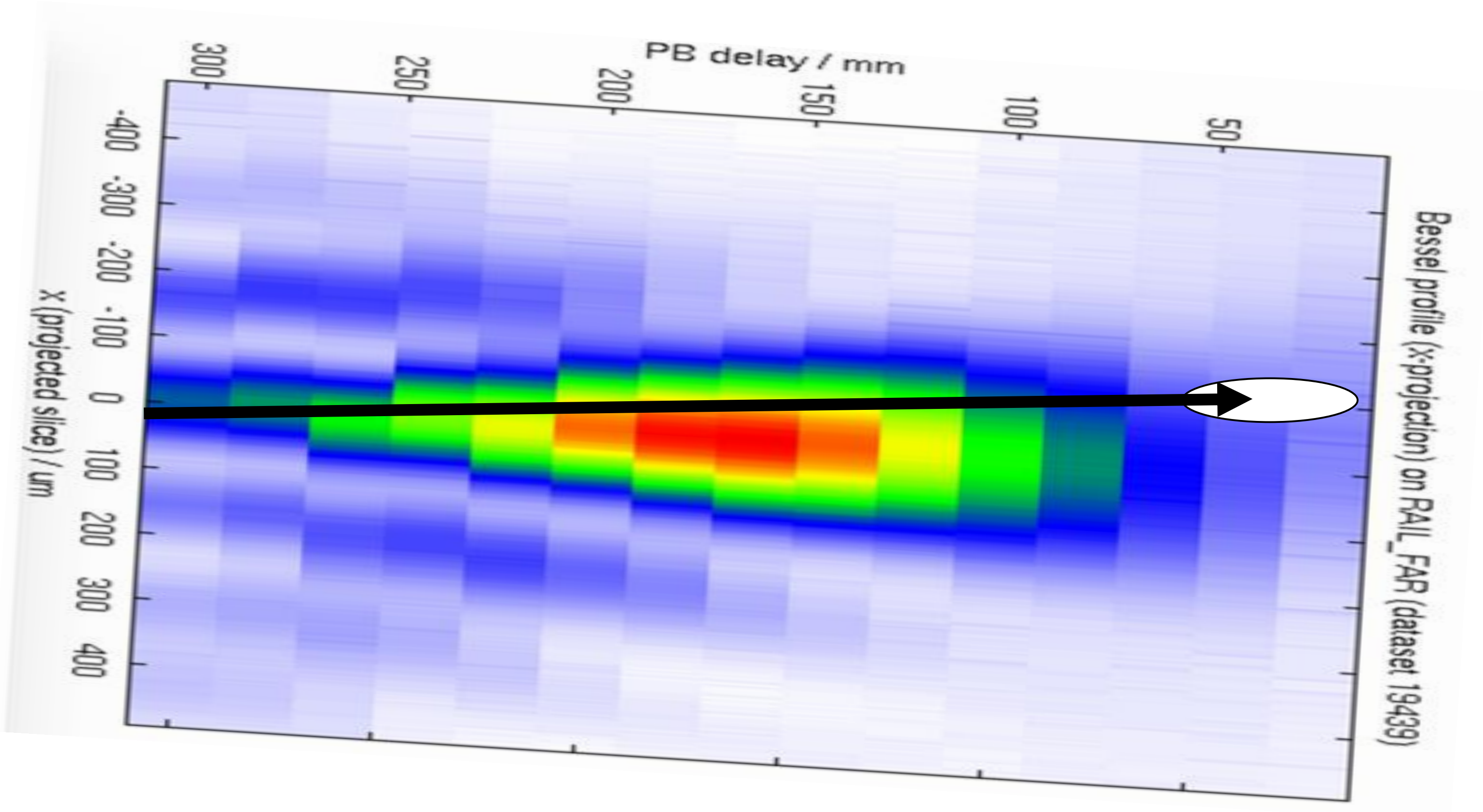
Preionization laser has to be exactly aligned with electron beam axis.
Laser and electron beam just right:



Measured Bessel profile of axilens laser (meters long, but ~150 ´µm wide)

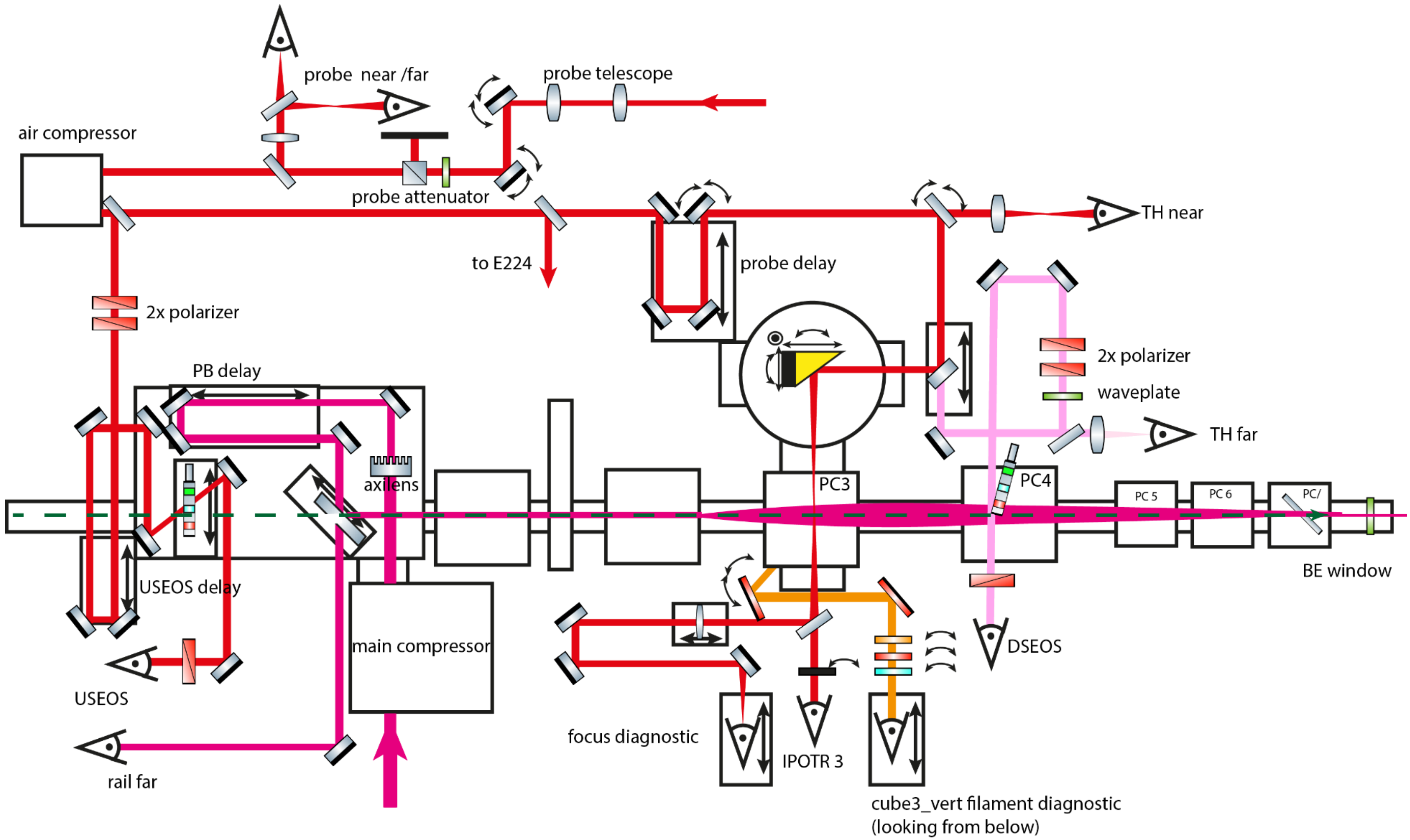
Alignment between e-beam driver and preionization laser

Preionization laser (or e-beam) slightly off:
Already if blowout touches walls at some point, the blowout collapses!
One wants to have a large plasma wavelength e.g. due to timing issues.
This is a real bottleneck!

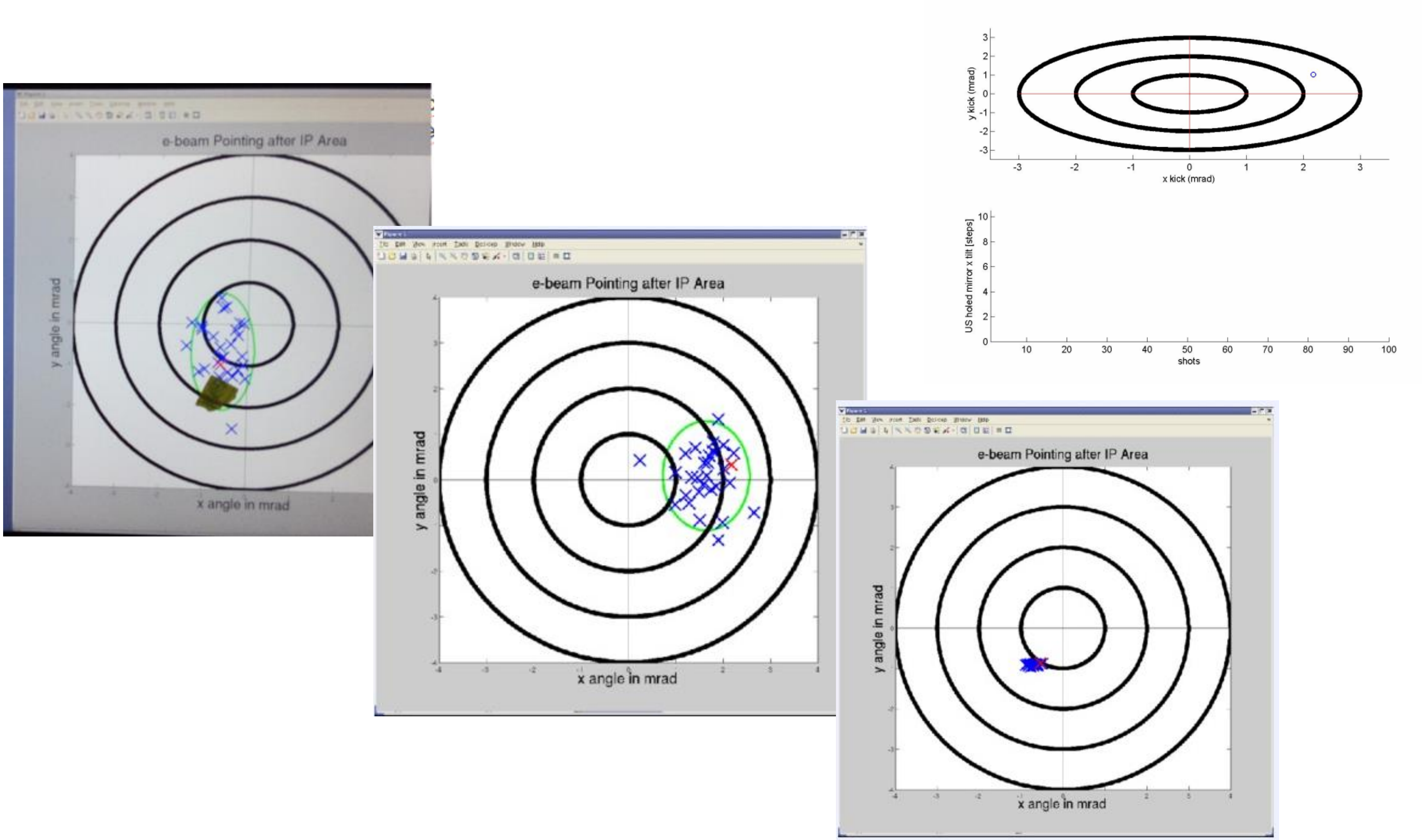


Measured Bessel profile of axilens laser (meters long, but ~150 ´µm wide)

Normal procedure: evacuate plasma chamber, realign laser beam (at low intensity) to electron beam axis (takes 1-2 hours w/safety procedures).. Then re-fill chamber with gas and hope alignment holds for a while



Advanced procedure in 2016: Make use of downstream BPMs and plasma response to find alignment (i.e. avoid “ultrafast plasma kicker”)



New diagnostic tool made life considerably easier, even allowed data taking after sunrise (thermal drift) because realignment could be done online.

Use plasma response: Enhanced plasma glow if spatio-temporal alignment is right is powerful, accurate and robust tool

Embargoed – publication pending

Alignment and timing of e-beam driver & preionization laser with 90° Trojan injection laser:

beam diameter = 10 mm

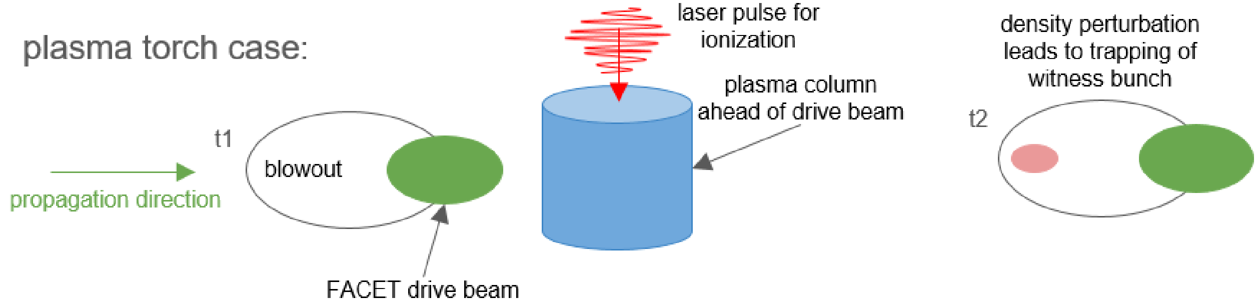
w0 = 11.64 µm

zR = 532 µm

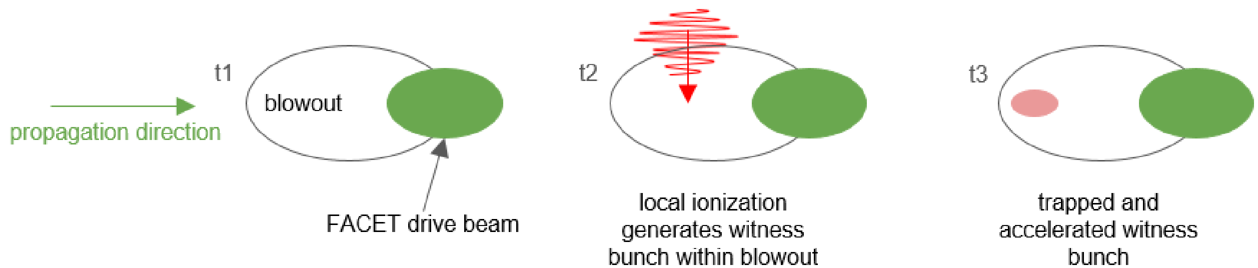
f = 9″ = 228.6 mm

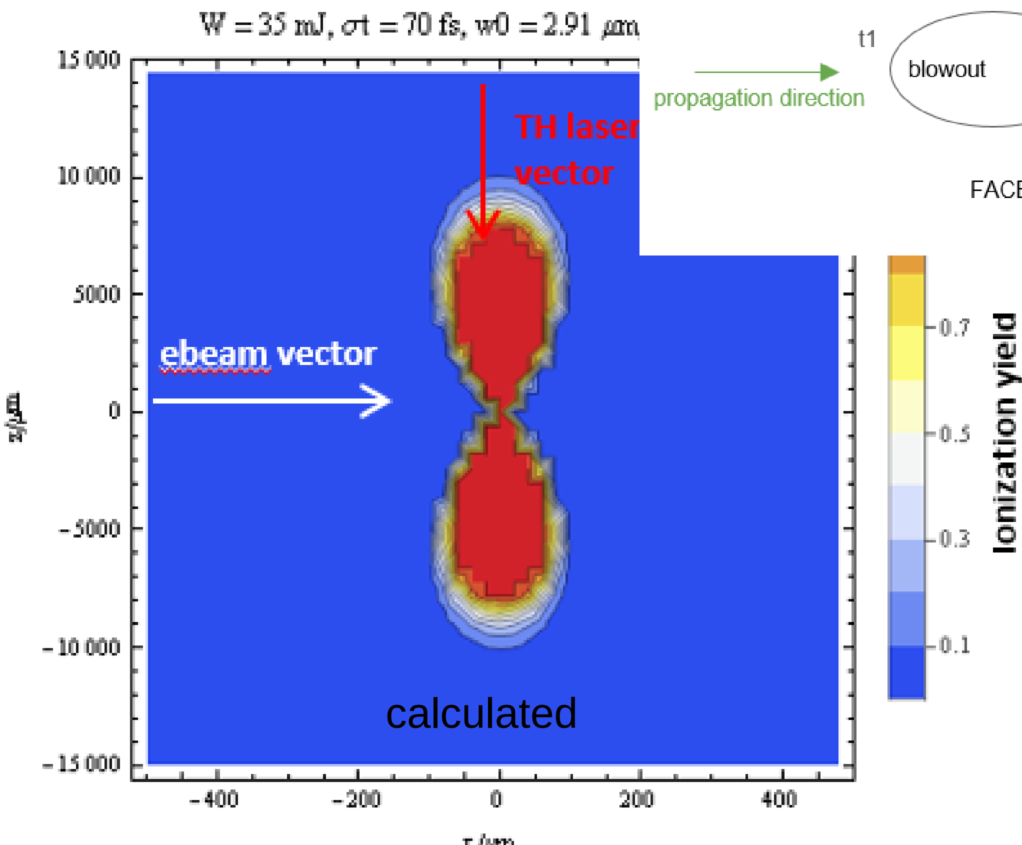
F/# = 22.86

plasma torch case:



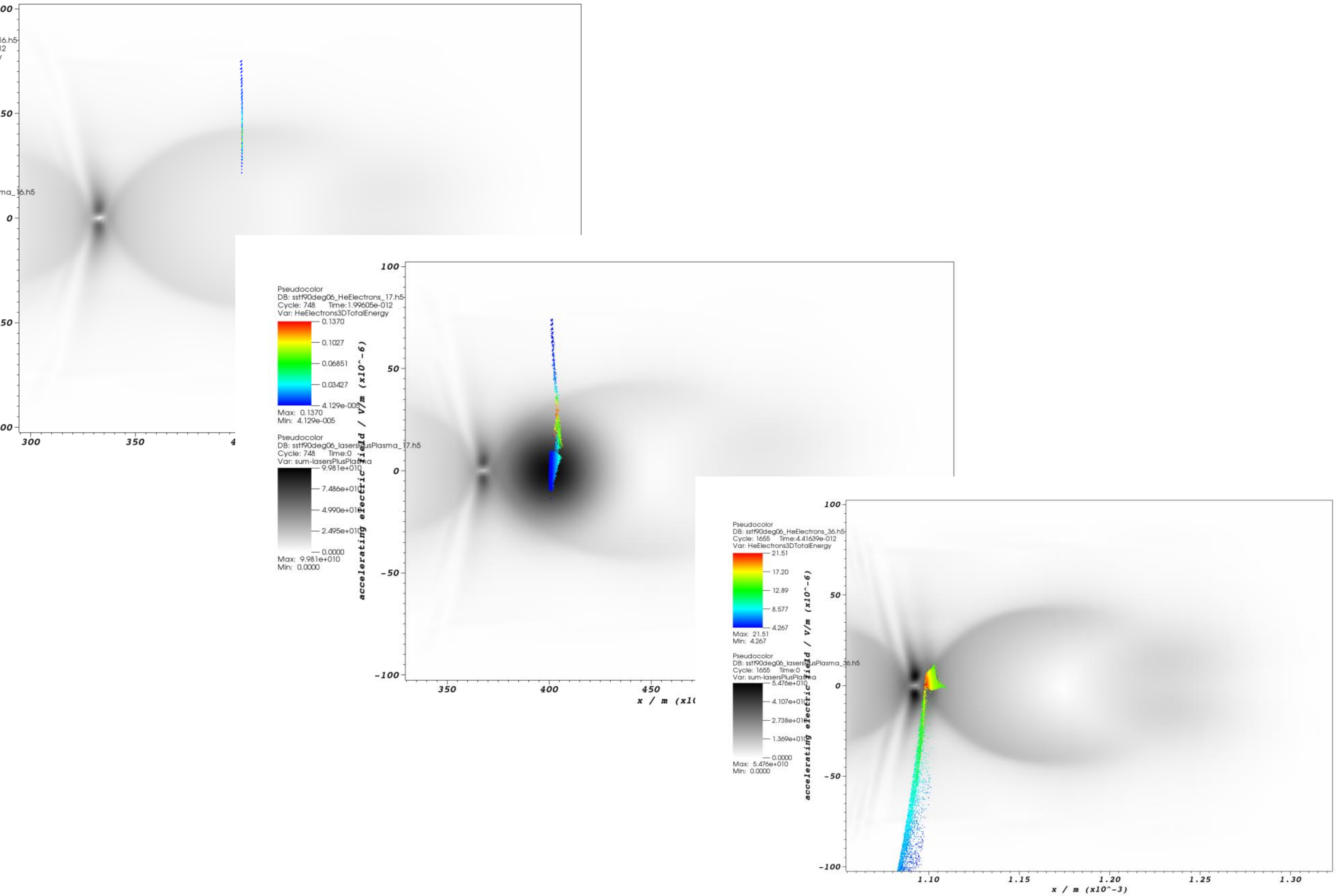
Trojan Horse case:



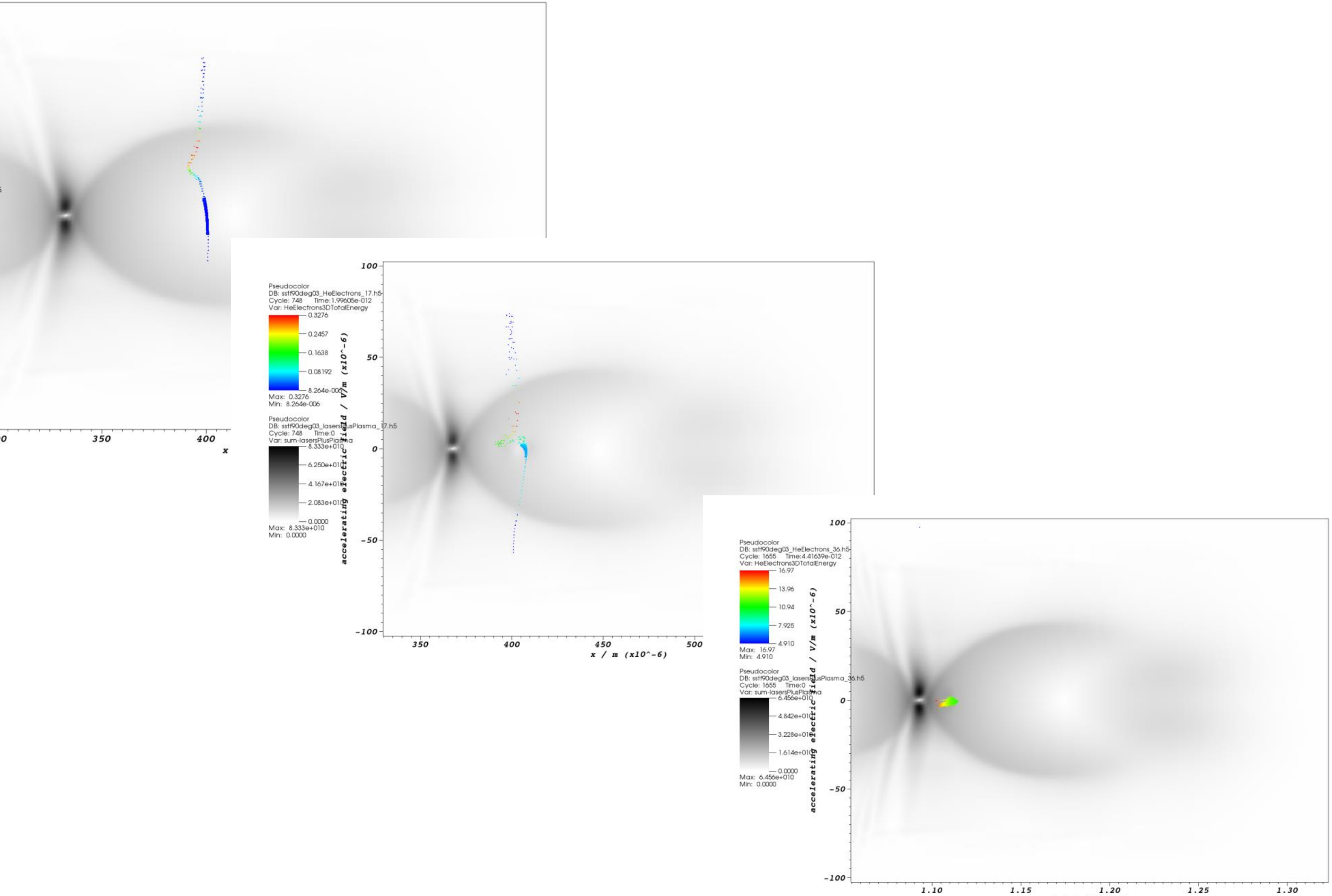


measured

3D PIC-simulation w / Vsim (high laser intensity case)



First laser-triggered injection, controlled PWFA



Experimental: Laser-triggered injection very robust: charge injected each shot

Embargoed – publication pending

Correlated Trapped charge on Spectrometer & DS BMP

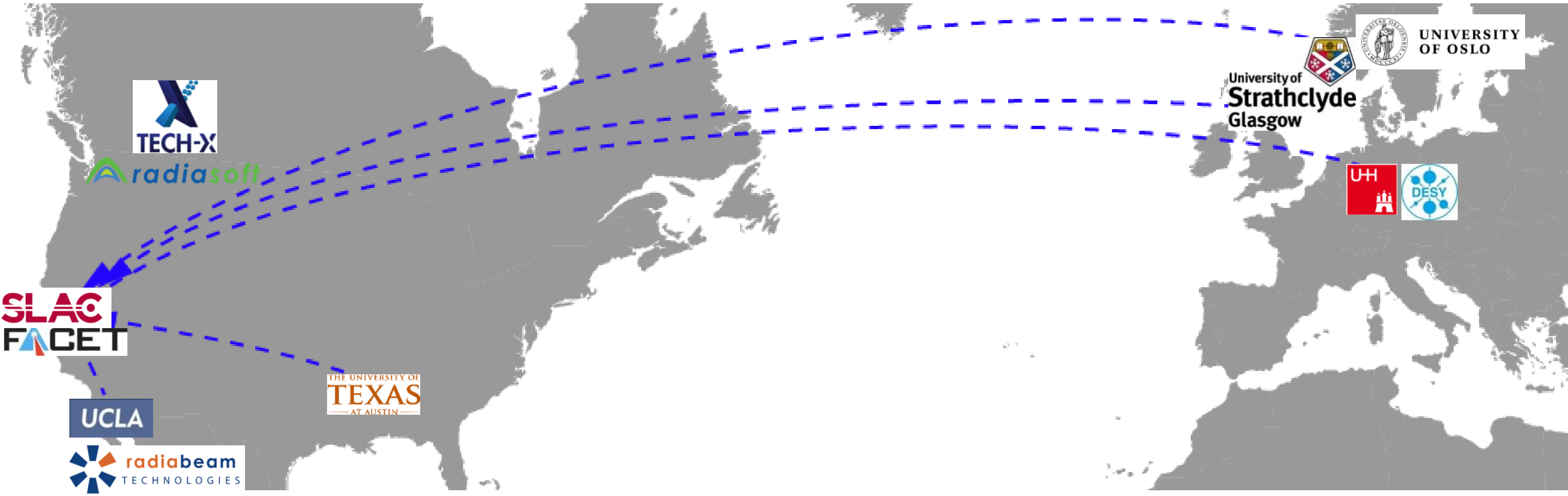
Embargoed – publication pending

few 100pC charge increase

More details see talk Dr. Grace Gloria Manahan / Strathclyde on May 31 and June 3rd

E210 2012-2016: Substantial international collaborative effort

hybrids.desy.de



Including various funding sources:

DFG

HELMHOLTZ GEMEINSCHAFT

vi-pwfa.desy.de

DAAD

SU2P

U.S. DEPARTMENT OF ENERGY

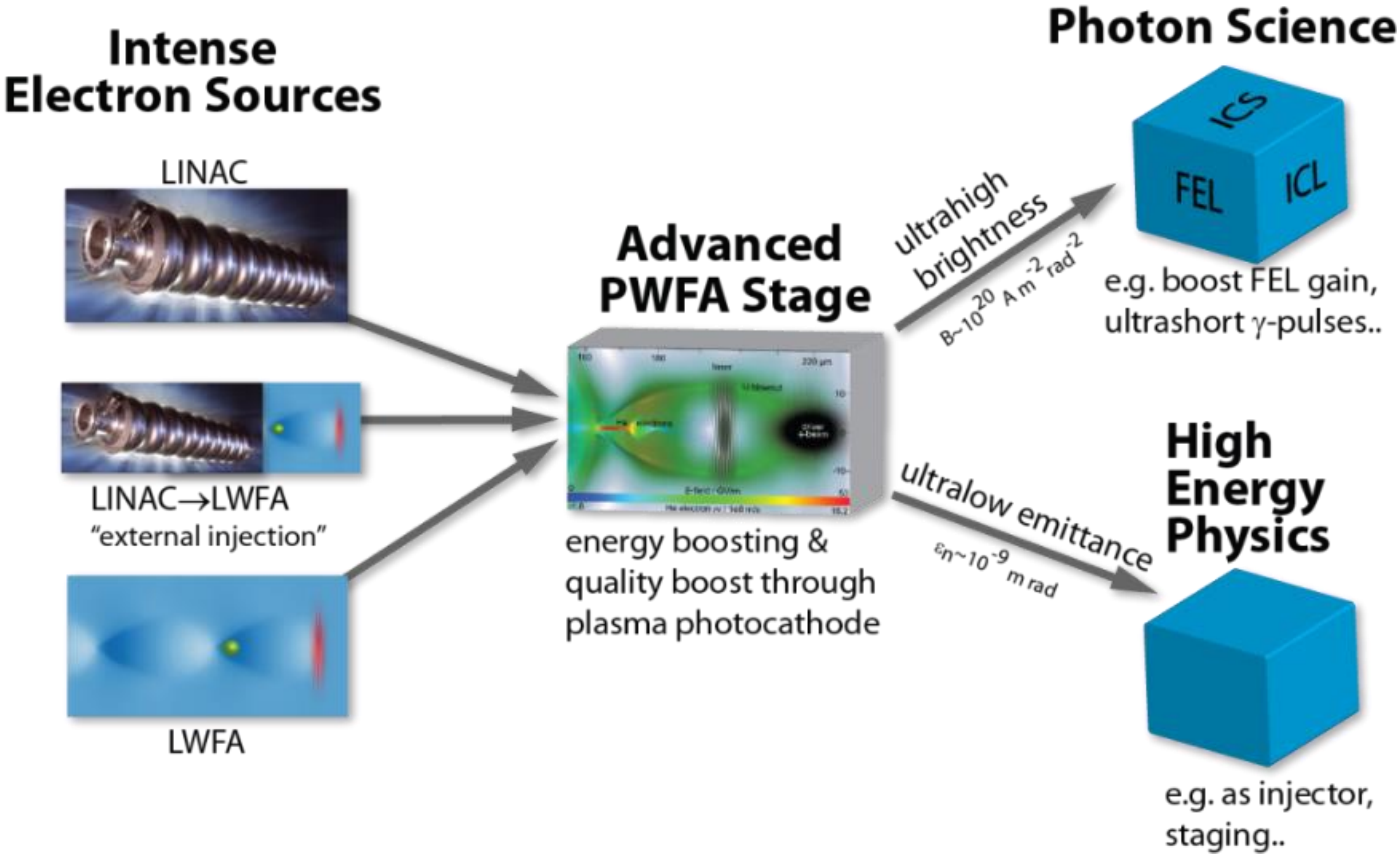
PIER

Spent ~4 years FTE at FACET,
u.a. O. Karger, A. Knetsch, T. Heinemann,
G. Manahan, P. Scherkl
Deng, Y. Xi
Andonian, B. Jacobson

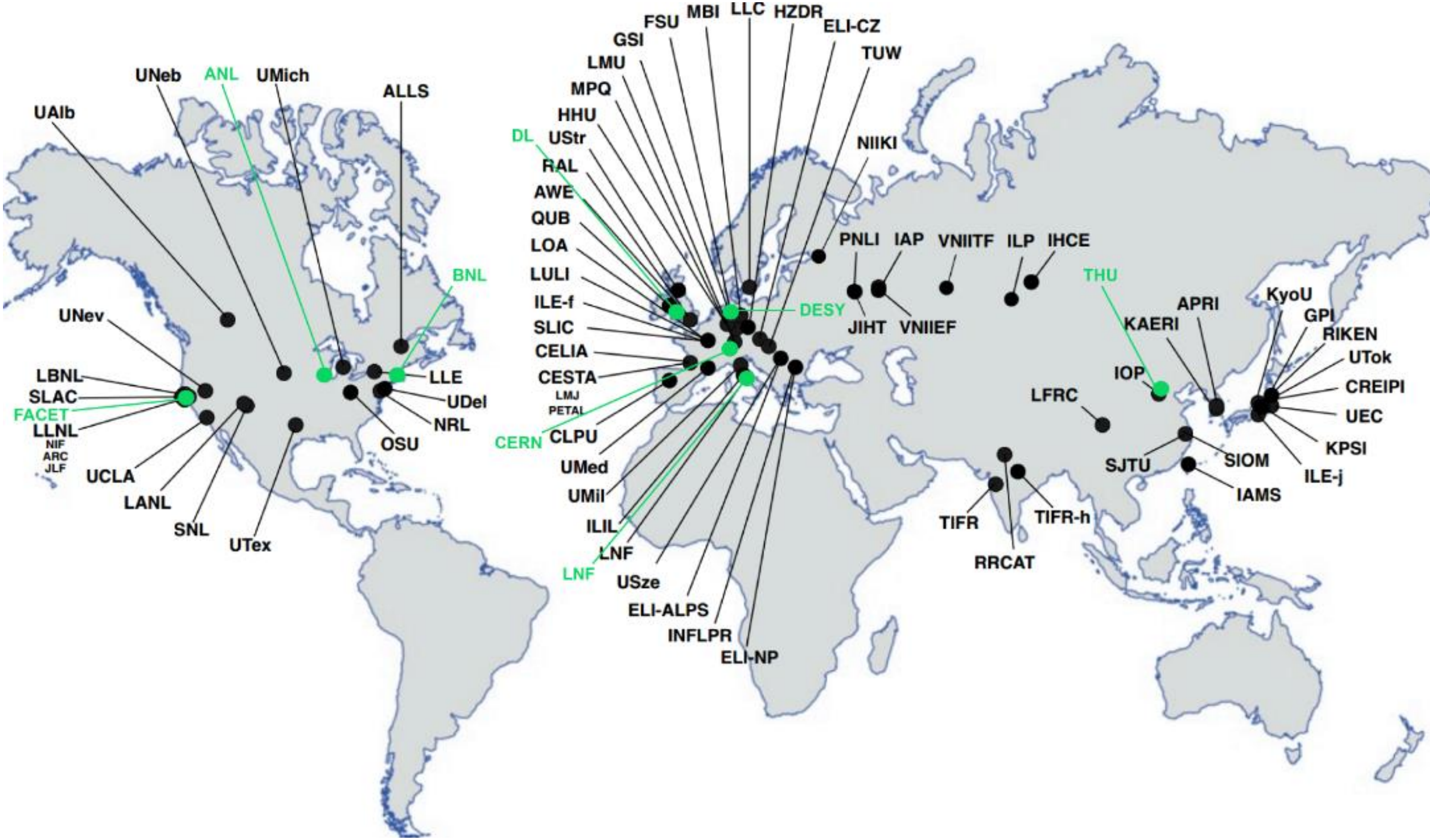
E210 Trojan Horse PWFA collab. at SLAC FACET 2012-2016:

- The most advanced and complex PWFA experiment to date
- By combining state-of-the-art accelerator techniques such as EOS and BPMs with plasma-based diagnostics, spatio-temporal alignment, monitoring and drift compensation is possible
- This allows meticulous control over preionization laser, electron beam, Trojan laser
- Laser-triggered, tunable plasma photocathode controlled injection of tens of pC-charges and acceleration to GeV levels robustly possible
- FACET: multi-GeV driver energies, ~10 kA+ drive beam currents (rather “too much” than “too little”), thermal cathode, large compression factor, +- 100 fs synchronization, 1960 Klystrons..

Future: Realise TH-PWFA as ultrahigh-brightness capability at various R&D labs, centers and facilities, for applications e.g. in photon science and HEP



Green: Planned or potential accelerator facilities for TH high brightness capability



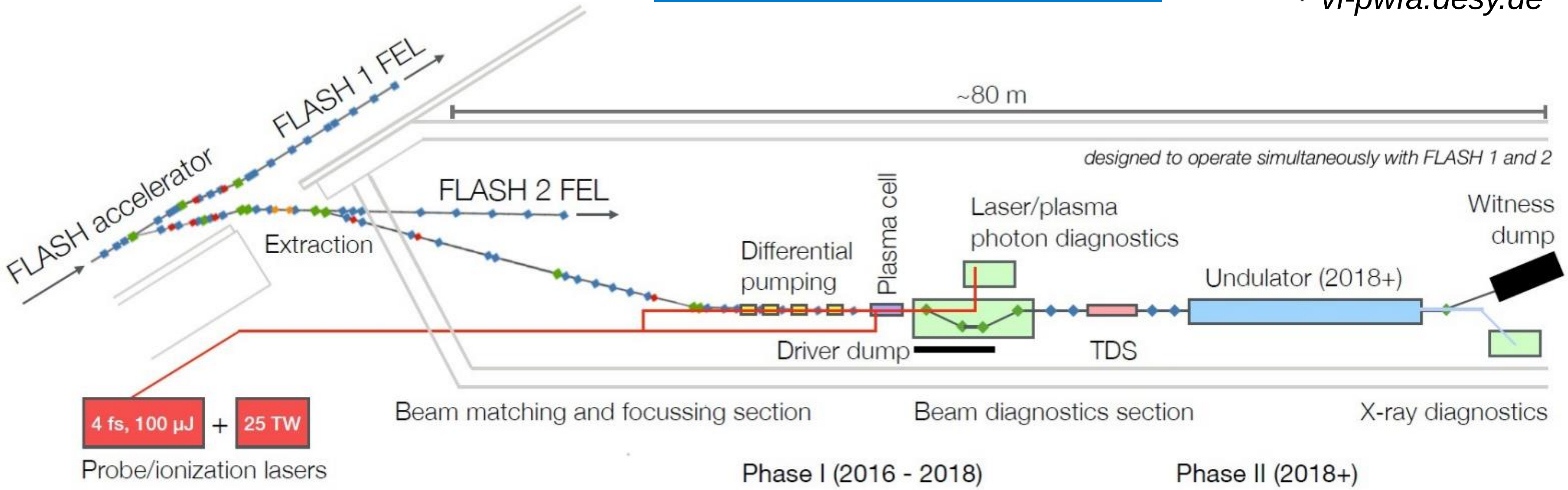
adapted from ICUIL

Future facility candidates for TH high brightness capability upgrades:

FLASHForward at DESY:

LAOLA *laola.desy.de*
Laboratory for Laser- and beam-driven plasma Acceleration

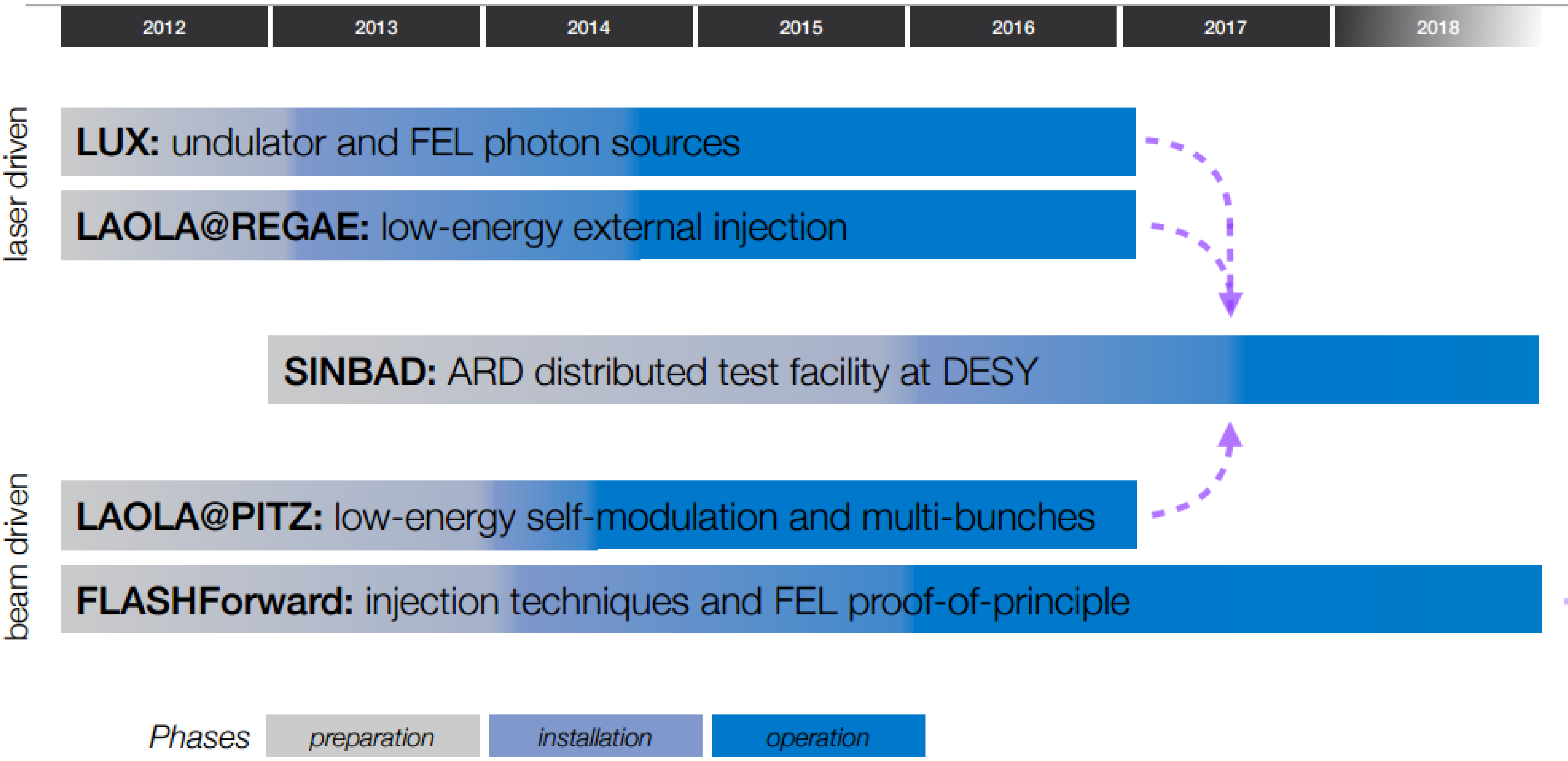
HELMHOLTZ GEMEINSCHAFT
vi-pwfa.desy.de



- Ramping up! (e.g., see talk by L. Schaper in this seminar series)
- Extensive (TH)-PWFA know-how obtained at FACET in previous years big asset
- Big asset: synchronization between e-beam and (ultrashort) laser < 30 fs, maybe < 10 fs possible (Group H. Schlarb et al.). Significant investment by B. Hidding & hybrids.desy.de in hardware potentially allowing this at FLASHForward for TH-PWFA
- Big challenge: Production of strong enough plasma wave when co-existing with FLASH Users, e.g. as regards drive beam current

Future facility candidates for TH high brightness capability upgrades:

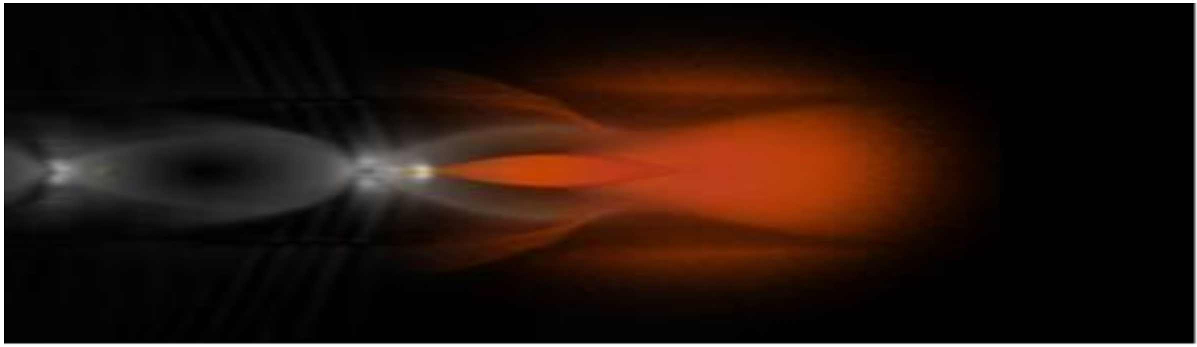
The LAOLA. collaboration and its plasma-wakefield strategy



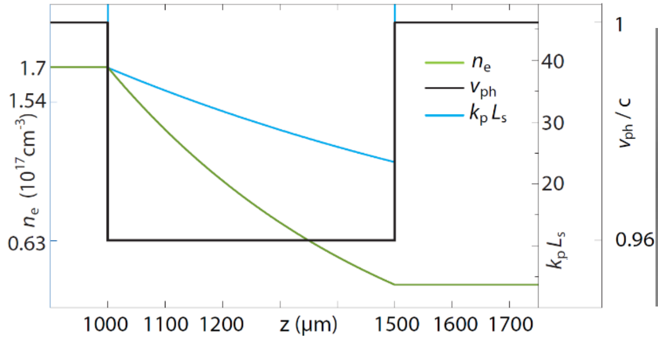
Main bottlenecks for TH-PWFA

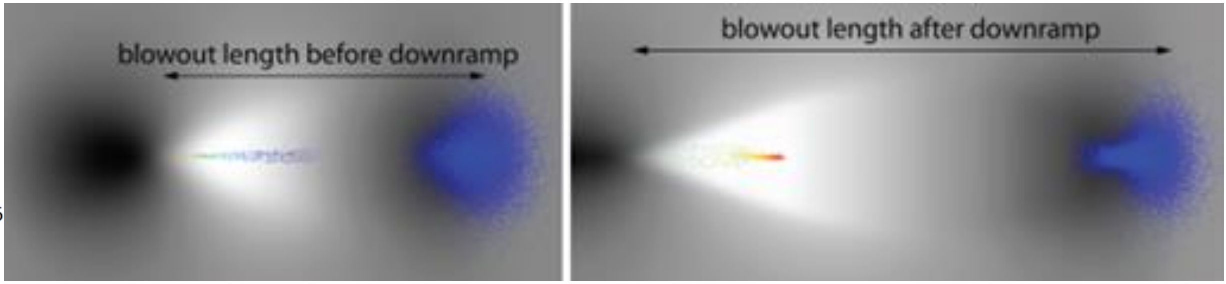
- Selective preionization and generation of wide enough plasma channel

  G.G. Manahan, PRAB 2016



- Drive beam current threshold for trapping: Use downramp-assisted TH to reduce current threshold from ~7kA to < 3kA *A. Knetsch et al., arXiv 2015*

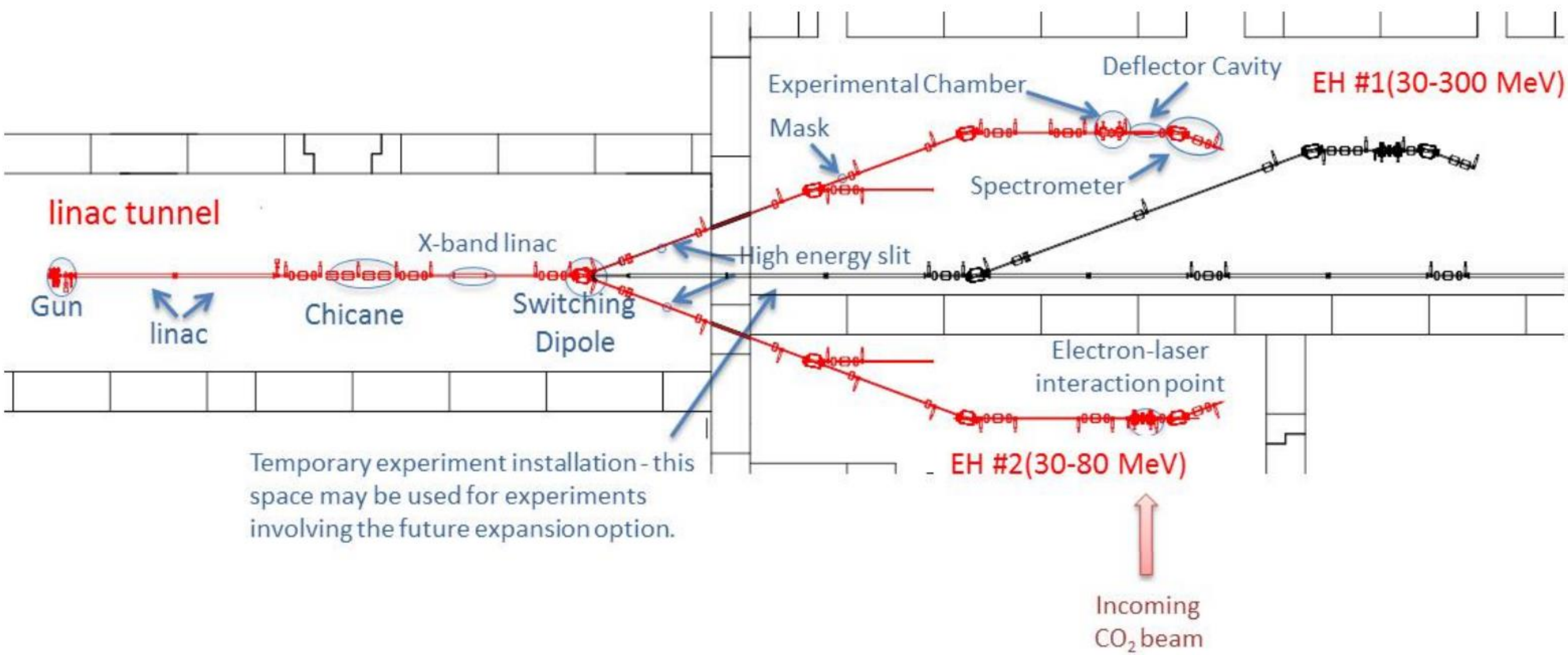




- Synchronization e-beam-laser: Fortunately, piggybacking on major R&D directions e.g. at DESY, motivated e.g. by the need for (X)FEL pump probe, seeding etc.

Future facility candidates for TH high brightness capability upgrades:

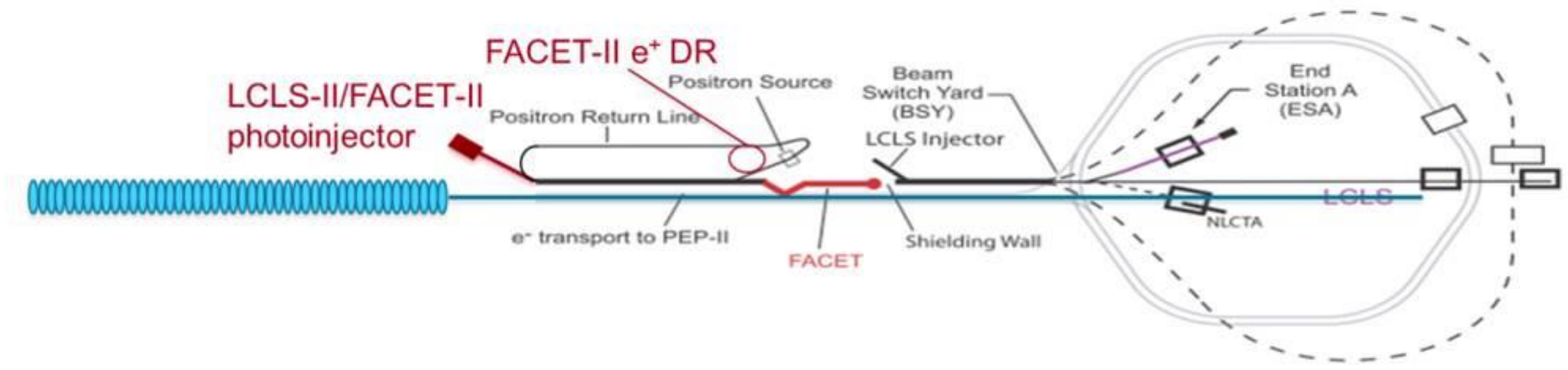
- BNL ATF-II (DOE Stewardship facility, TH foreseen)
- dedicated R&D facility, very good accessibility
- CO2 laser allows for unique options e.g. as regards preionization
- Synchronized Ti:Sapphire desirable



Future facility candidates for TH high brightness capability upgrades:

- CLARA: dedicated R&D accelerator, challenges and opportunities are that this accelerator is primarily a FEL test facility (e.g. for a potential UK-FEL)
- Synchronized multi-TW Ti:Saphhire already available since years
- Strathclyde’s membership in the Cockcroft Institute since April 2016 helpful..
- UK STFC Accelerator Strategy Board fostering coherent Plasma Accelerator Steering Strategy

Future facility candidates for TH high brightness capability upgrades: FACET-II



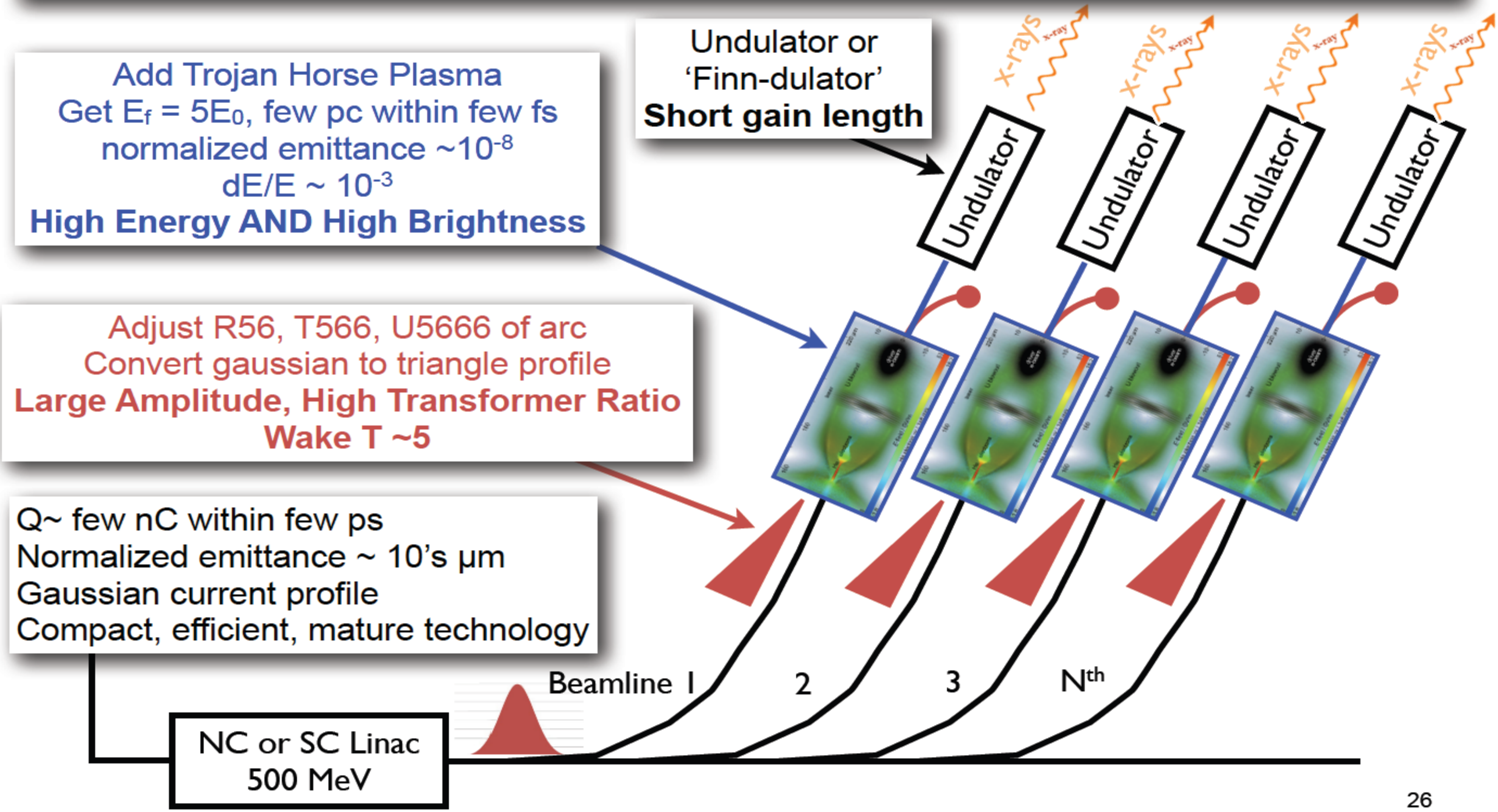
- Improving on FACET: Dedicated R&D system, for which TH is a flagship topic
- Photocathode instead of thermionic SLC cathode, still reaching ~10 kA, but much more stable etc.
- See talk by M. Hogan in this seminar series..

Hybrid Trojan Horse-based Future FEL facility?
w/ M. Hogan (SLAC) et al., 5th Generation Light Source Workshop, 2013

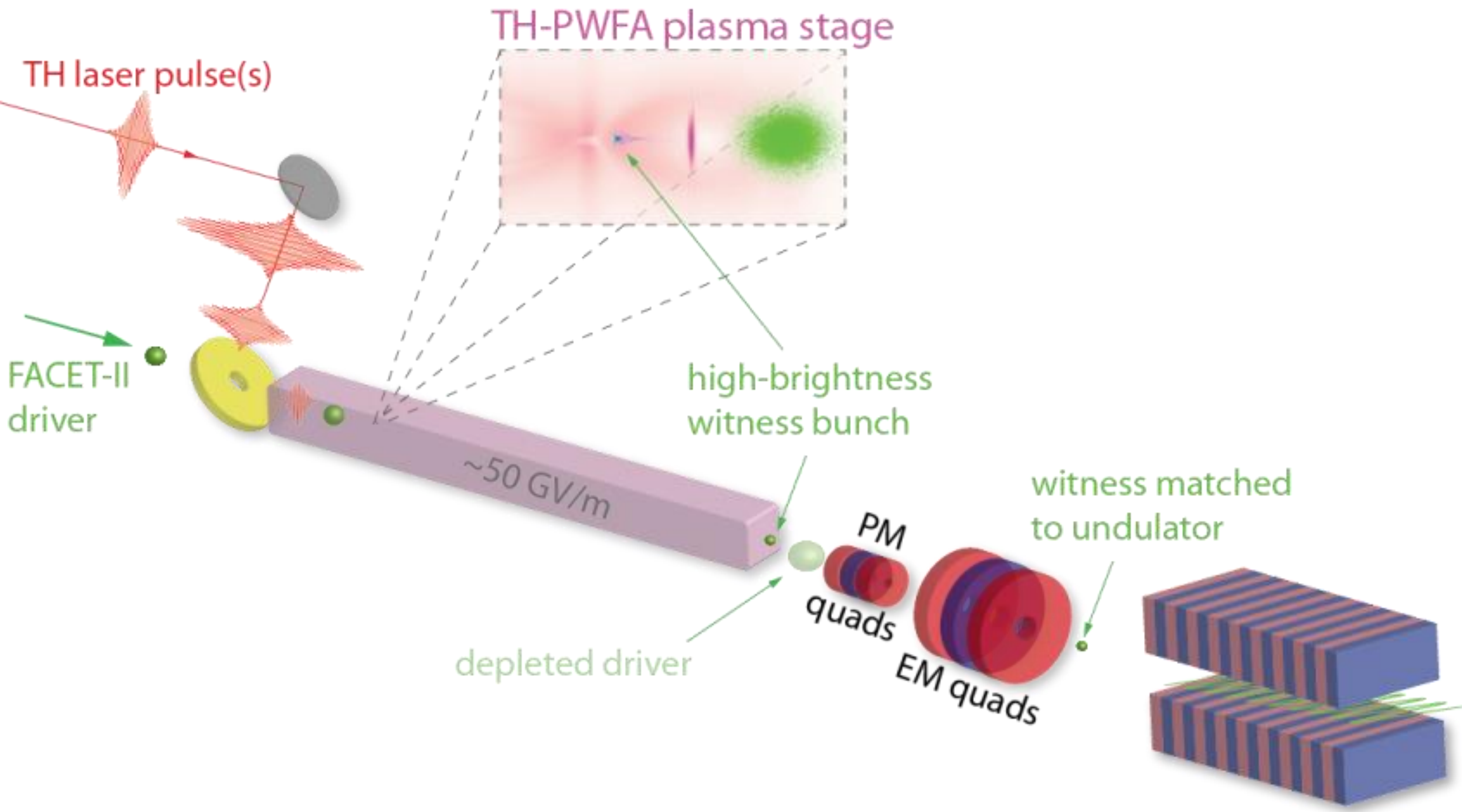
A Plasma Wakefield Accelerator Driven Compact X-FEL
Plasma is Energy AND Brightness Transformer

SLAC

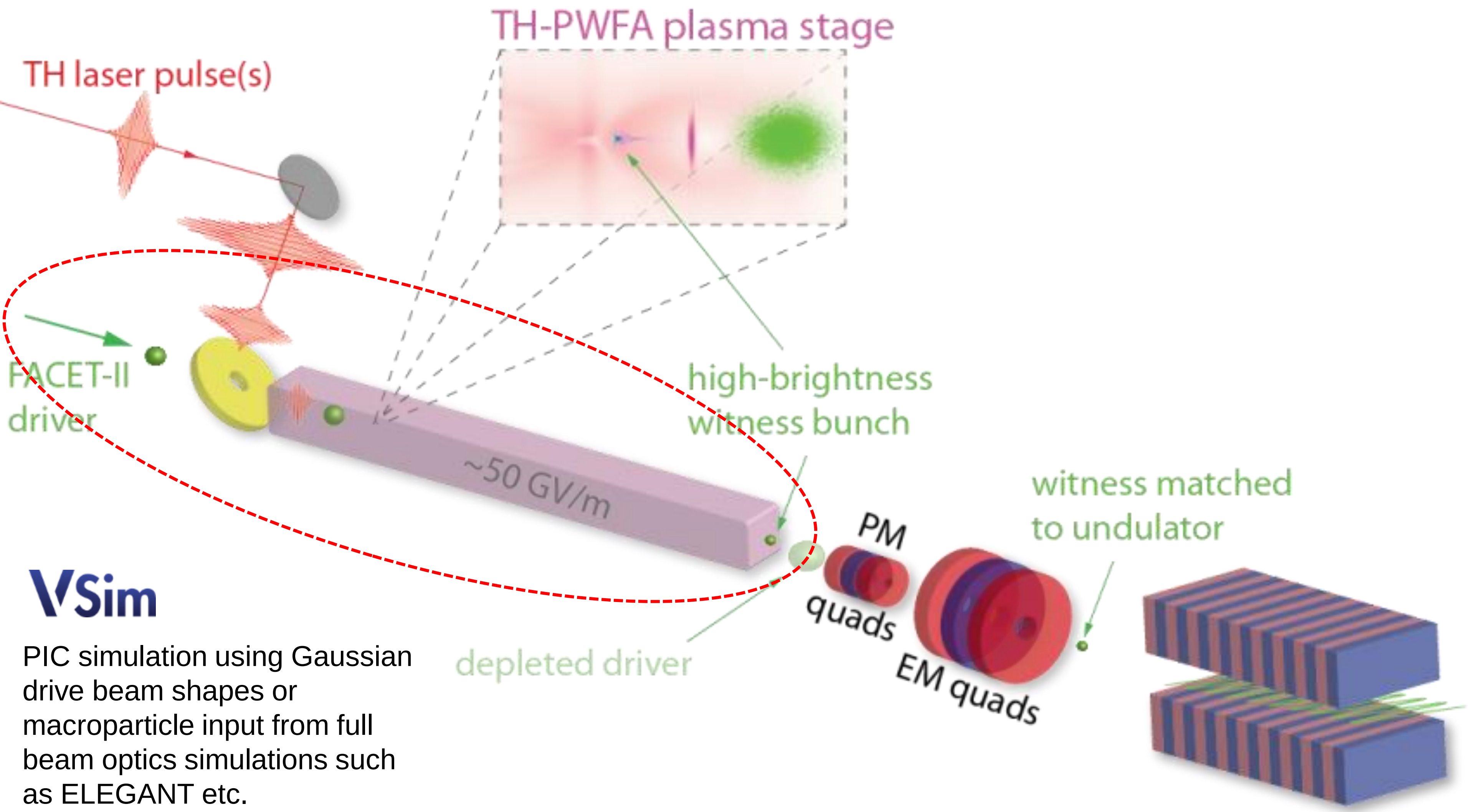
Compactness of plasmas accelerators, rep rate like rings with high brightness of linacs!



General schematic setup e.g. for FACET-II (collinear Trojan Horse)



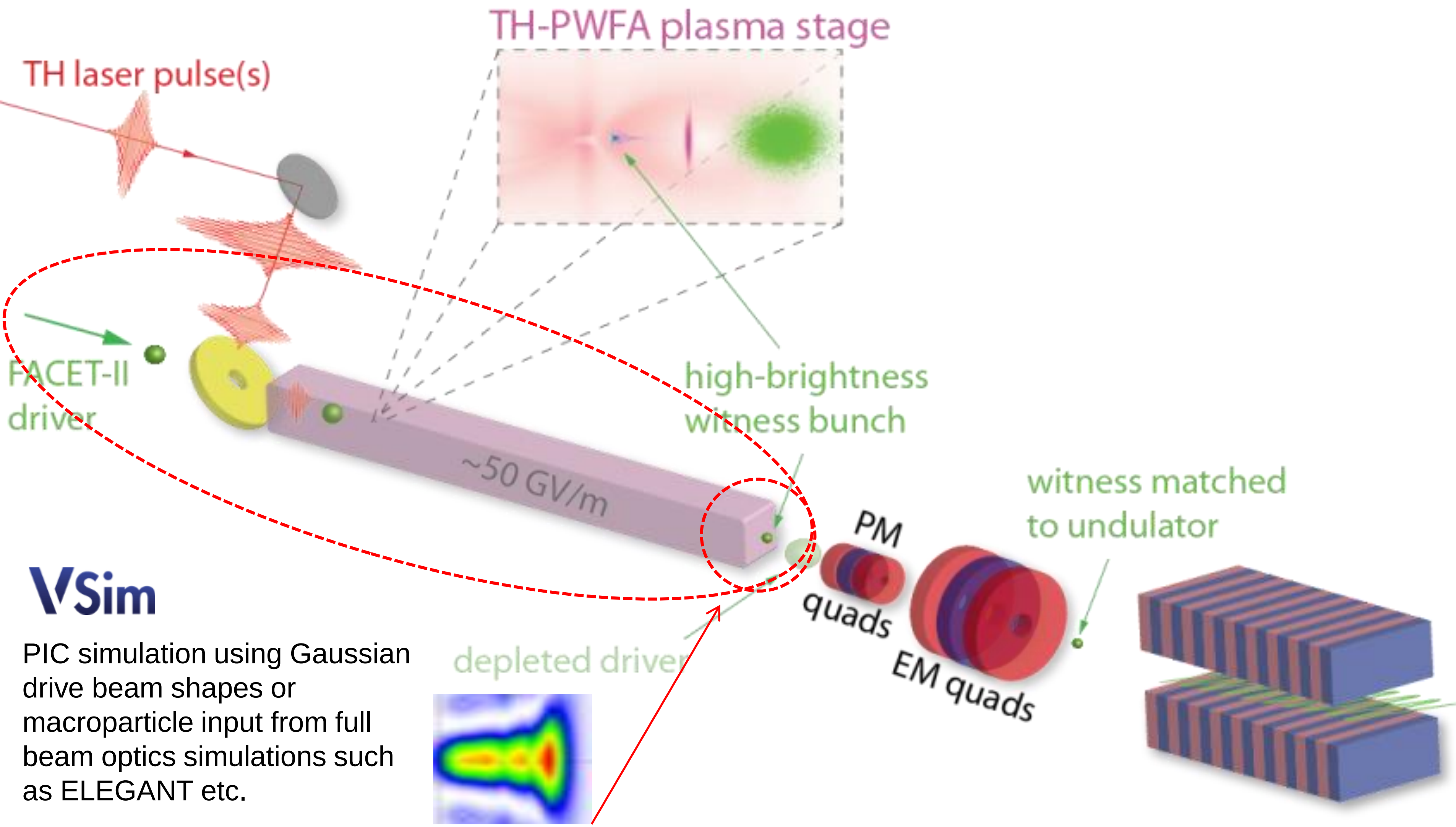
General schematic setup e.g. for FACET-II (collinear Trojan Horse)



VSim

PIC simulation using Gaussian drive beam shapes or macroparticle input from full beam optics simulations such as ELEGANT etc.

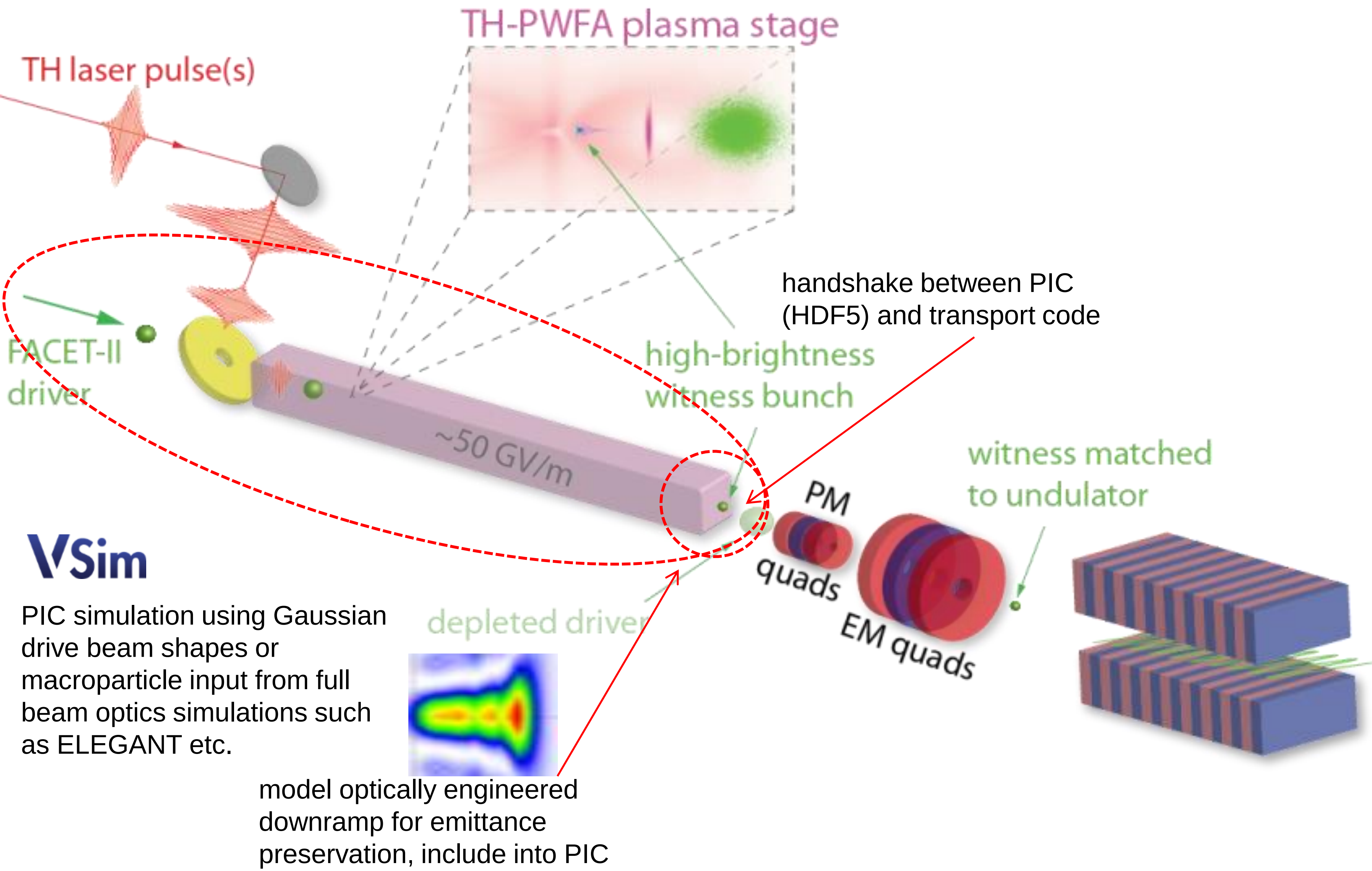
General schematic setup e.g. for FACET-II (collinear Trojan Horse)



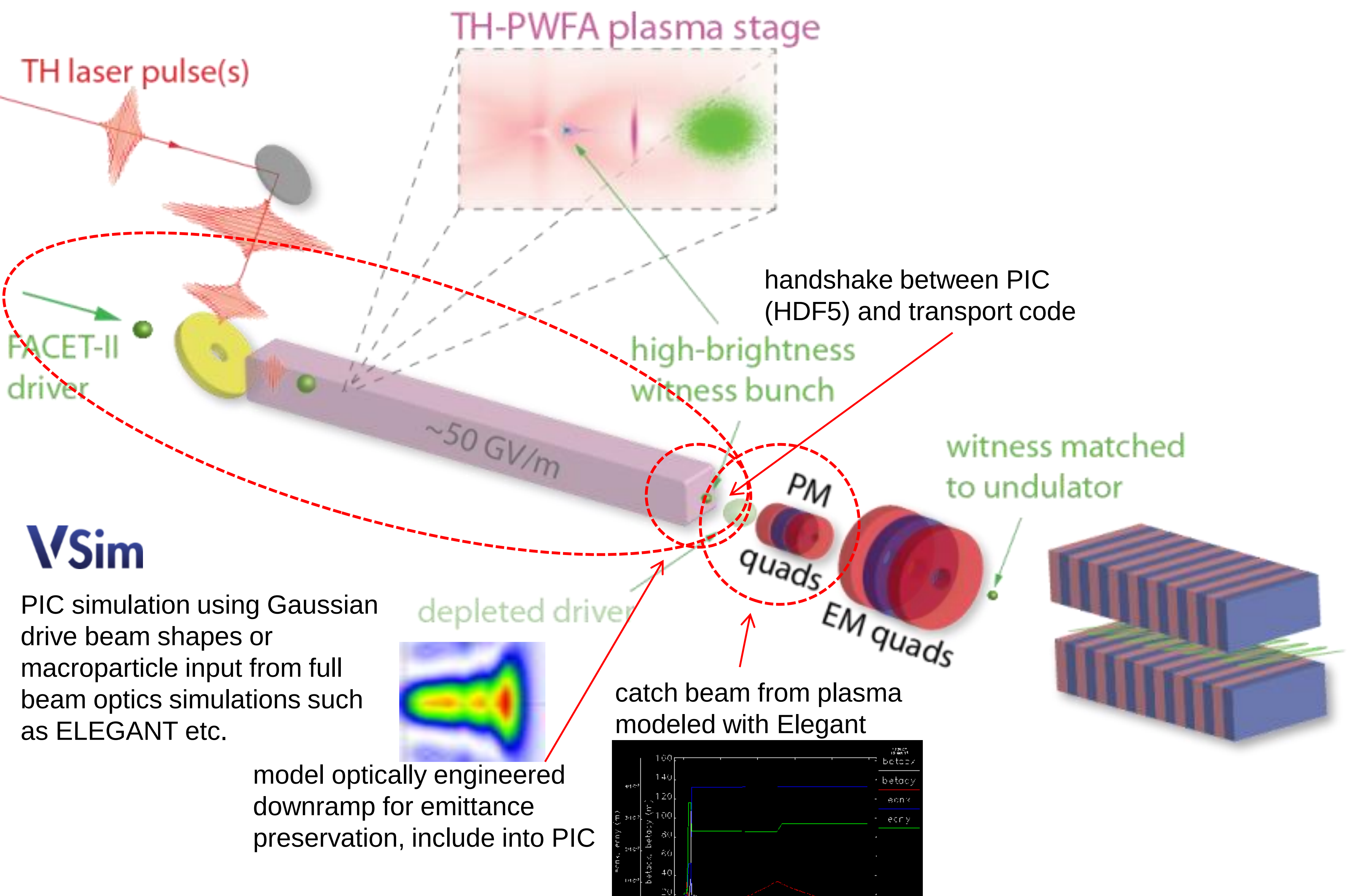
PIC simulation using Gaussian drive beam shapes or macroparticle input from full beam optics simulations such as ELEGANT etc.

model optically engineered downramp for emittance preservation, include into PIC

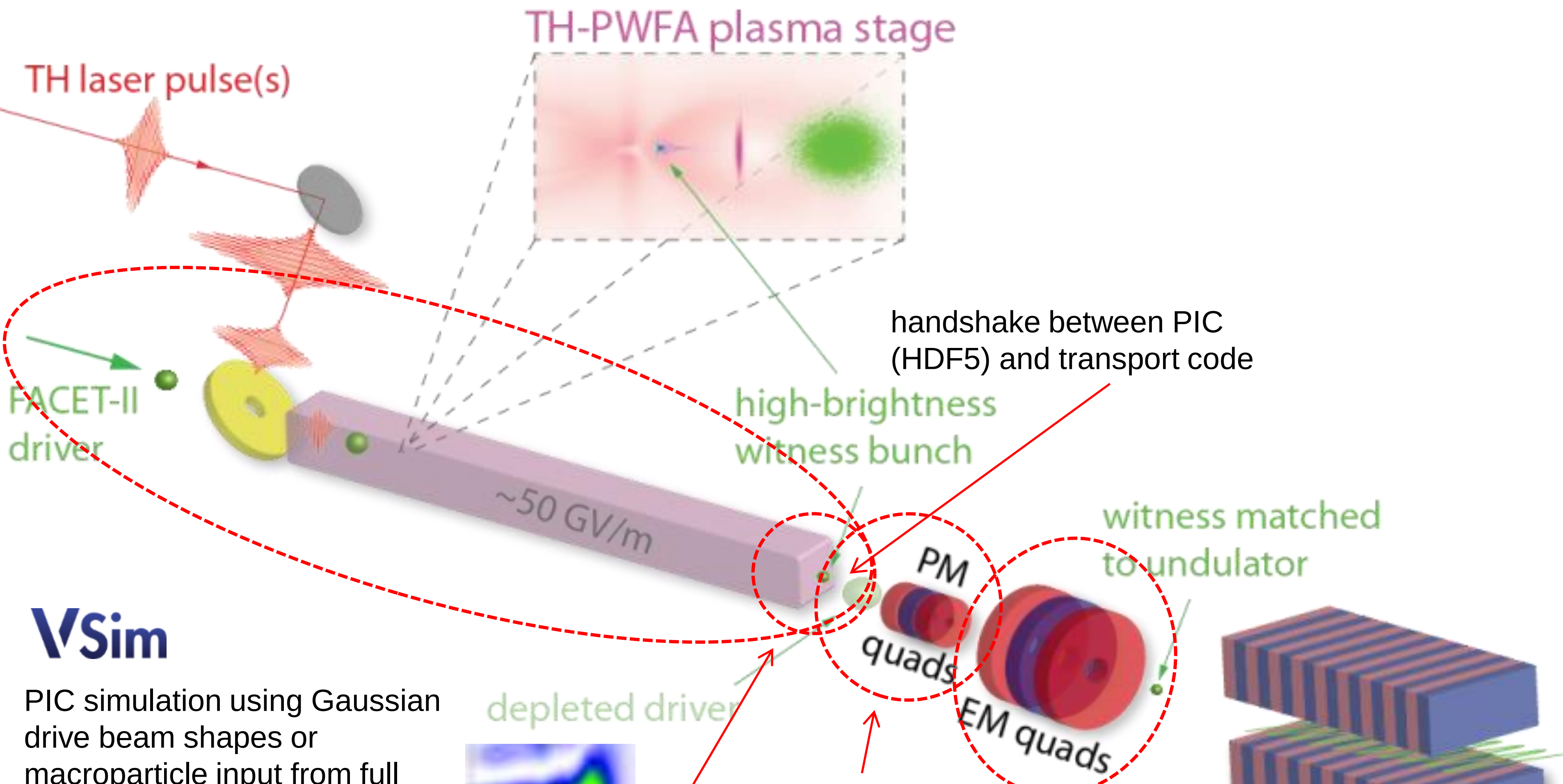
General schematic setup e.g. for FACET-II (collinear Trojan Horse)



General schematic setup e.g. for FACET-II (collinear Trojan Horse)



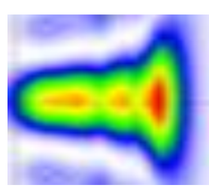
General schematic setup e.g. for FACET-II (collinear Trojan Horse)



handshake between PIC (HDF5) and transport code

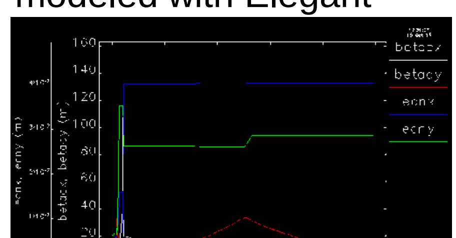
VSim

PIC simulation using Gaussian drive beam shapes or macroparticle input from full beam optics simulations such as ELEGANT etc.



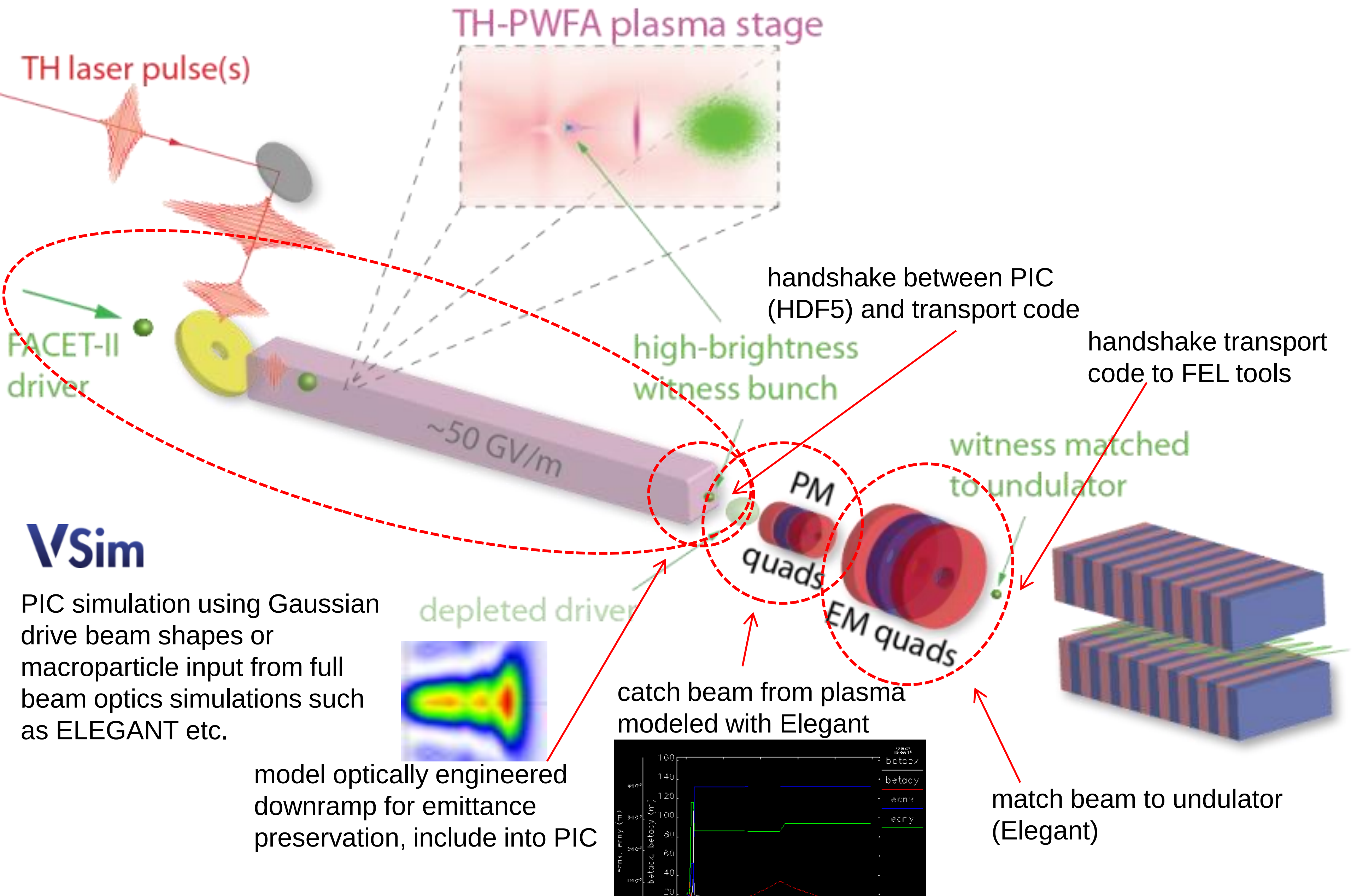
model optically engineered downramp for emittance preservation, include into PIC

catch beam from plasma modeled with Elegant

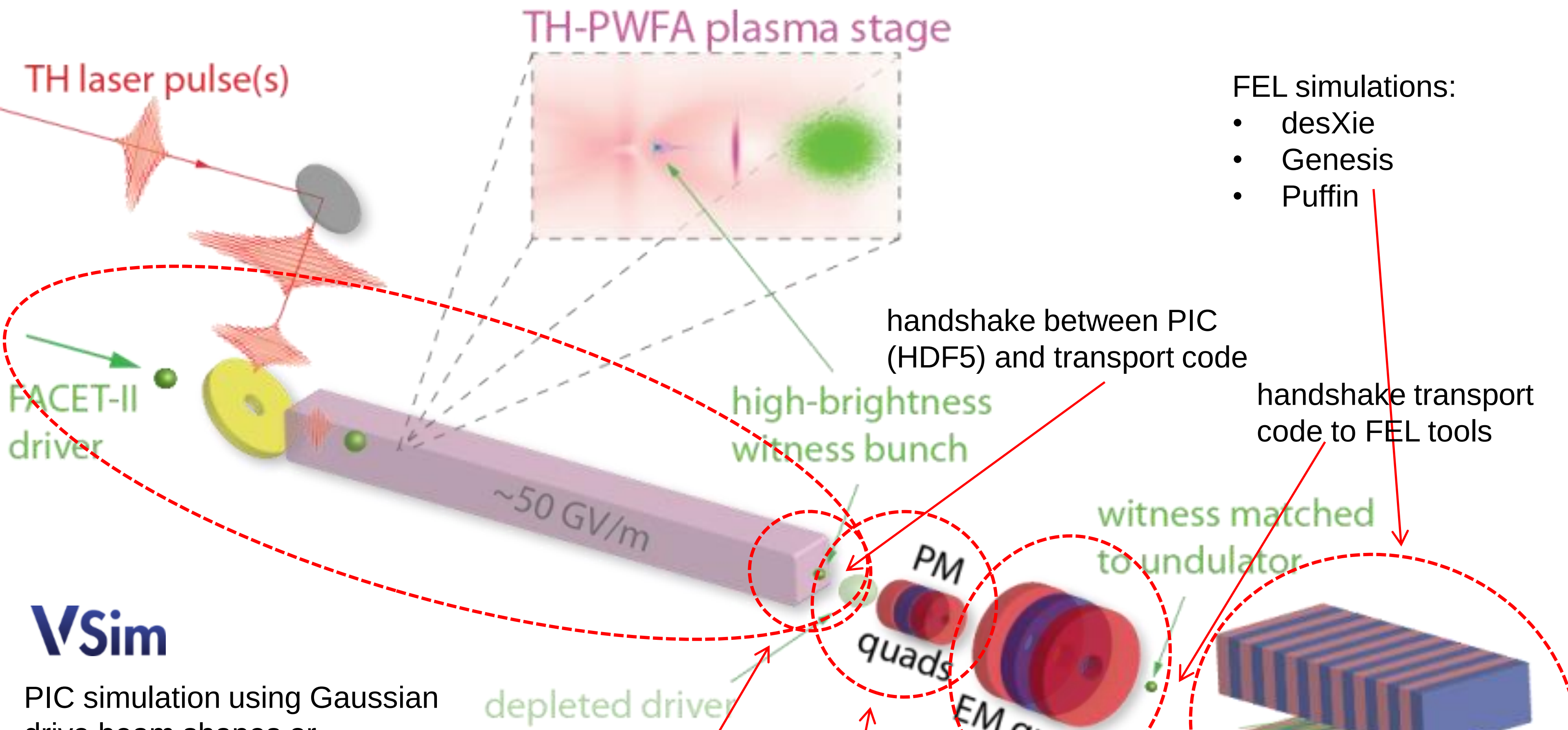


match beam to undulator (Elegant)

General schematic setup e.g. for FACET-II (collinear Trojan Horse)



Full 3D start-to-end simulations



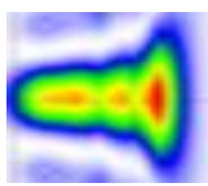
FEL simulations:

- desXie
- Genesis
- Puffin

handshake between PIC (HDF5) and transport code

handshake transport code to FEL tools

PIC simulation using Gaussian drive beam shapes or macroparticle input from full beam optics simulations such as ELEGANT etc.



model optically engineered downramp for emittance preservation, include into PIC

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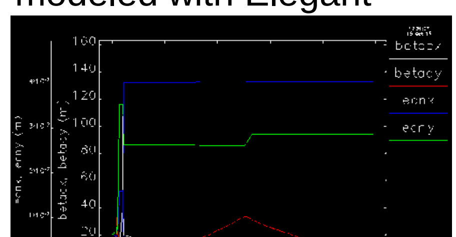
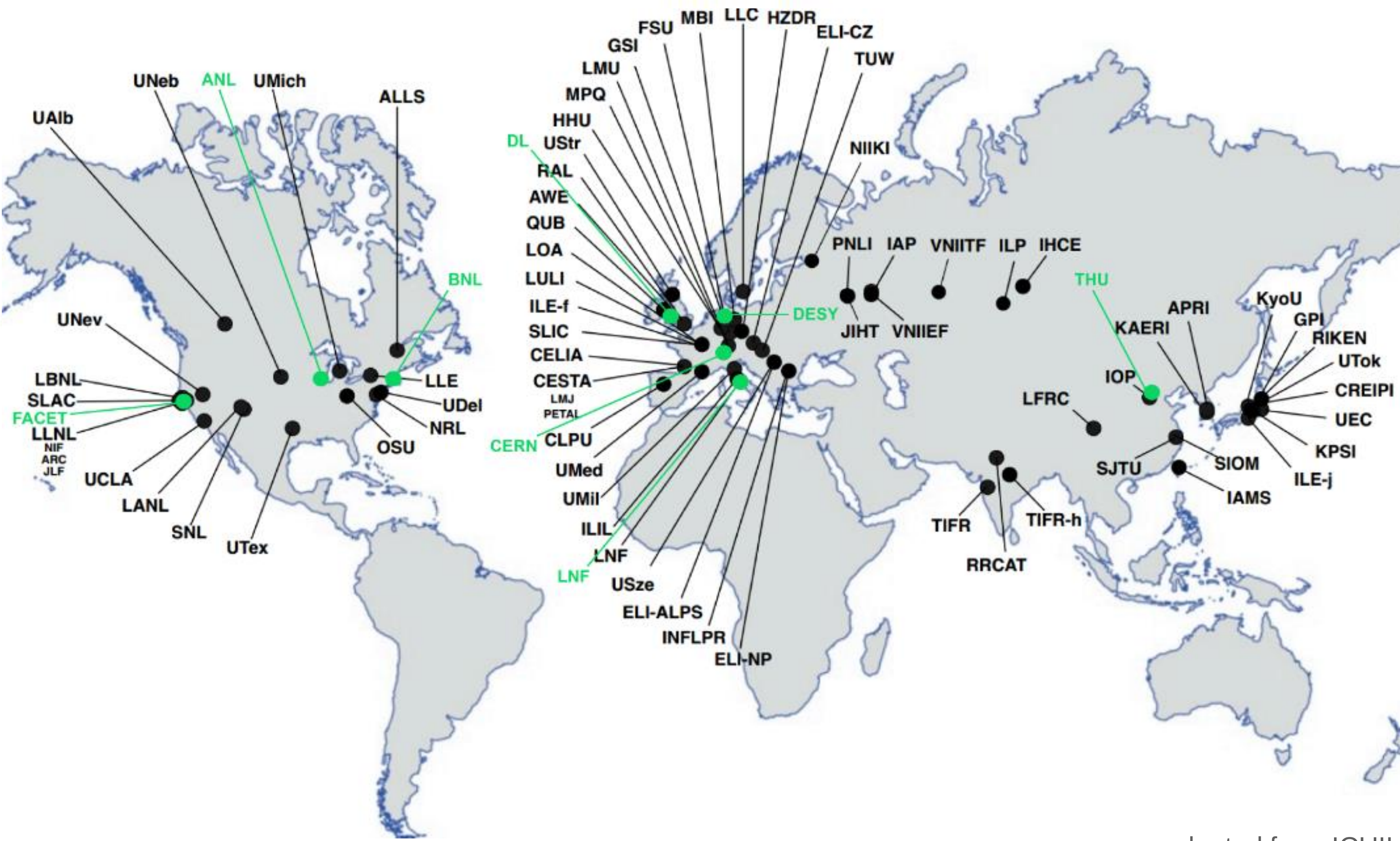


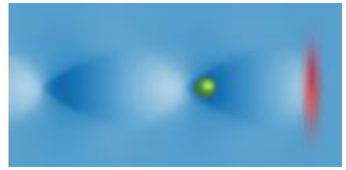
match beam to undulator (Elegant)

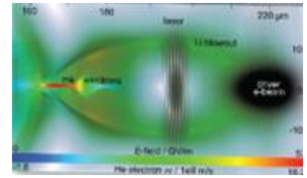
Export the Trojan Horse even further?
A beam brightness transformer for laser-plasma-labs worldwide



adapted from ICUIL

Intense Electron Sources: Hybrid LWFA → PWFA

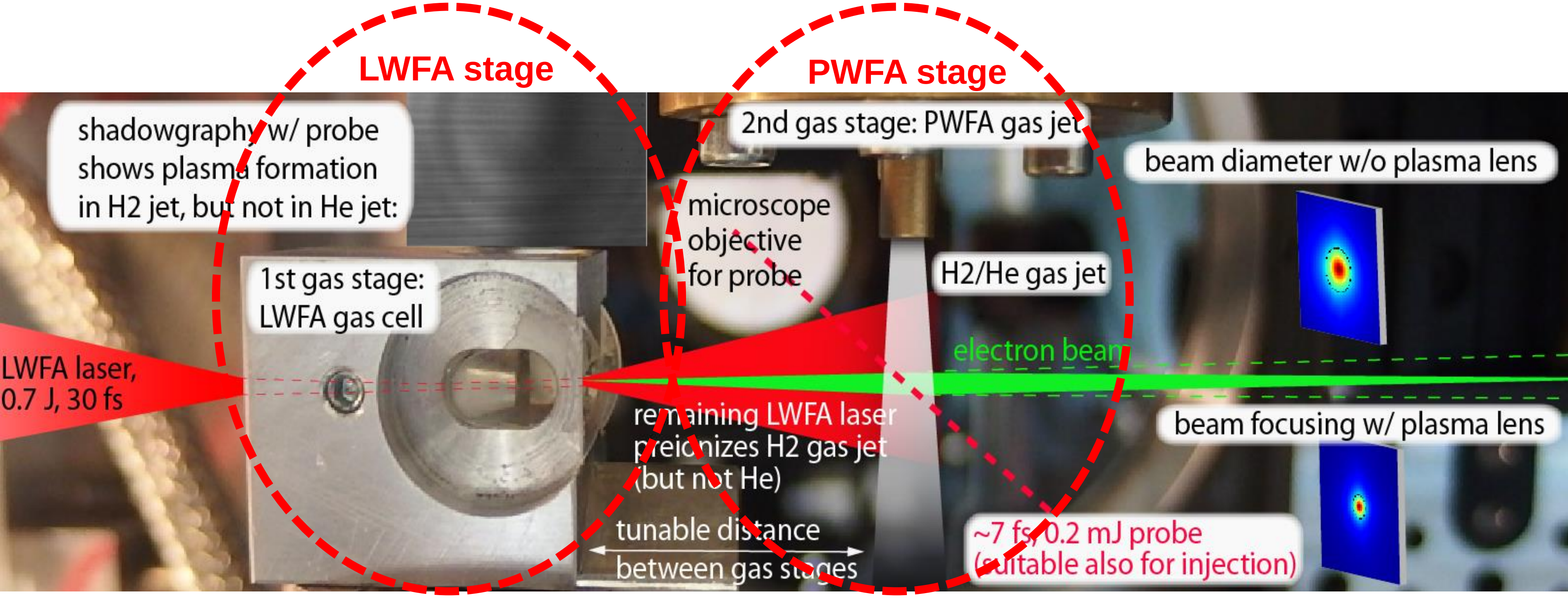




- LWFA can provide ~10 Hz, quasi-monoenergetic, ultrashort, multi-kA driver beams (e.g. M. Wiggins et al., PPCF 2010, O. Lundh et al., Nat. Physics 7, 2011)
- Often large energy spreads, limited emittance, probably especially at high current levels
- Use LWFA-generated electron beams for PWFA!
- Make use of compactness and unique feature of LWFA: generation of multi-kA, ultrashort electron bunches
- Don’t care much if energy spread is large and emittance is limited..
- See e.g. “Monoenergetic energy doubling” PRL 104, 195002, 2010 – here double bunch driver / witness type acceleration was considered
- Challenge is divergence control
- Inherently ~1 fs-scale synchronization between driver and laser

Intense Electron Sources:
Hybrid LWFA → PWFA

- First experiments towards LWFA→PWFA since 2014 at Jena with JETI laser:

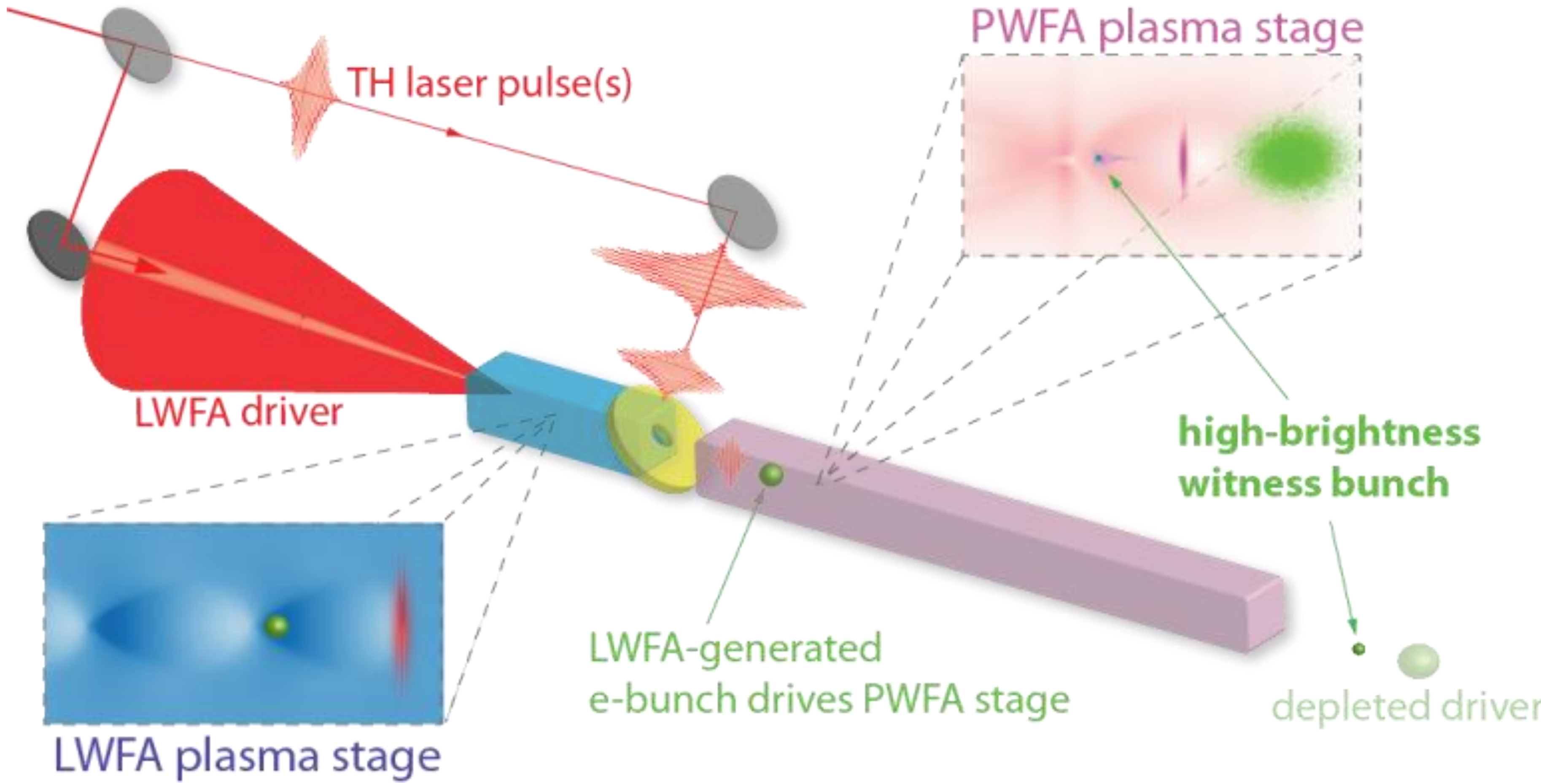


1. Selective ionization of H2/He mixture by LWFA laser remnant – H2 is ionized, He not -- this is what is needed for Trojan Horse!

2. Plasma lensing of LWFA-generated electron driver demonstrated

S. Kuschel et al., submitted
T. Heinemann et al., to be submitted

Intense Electron Sources: Hybrid LWFA → PWFA



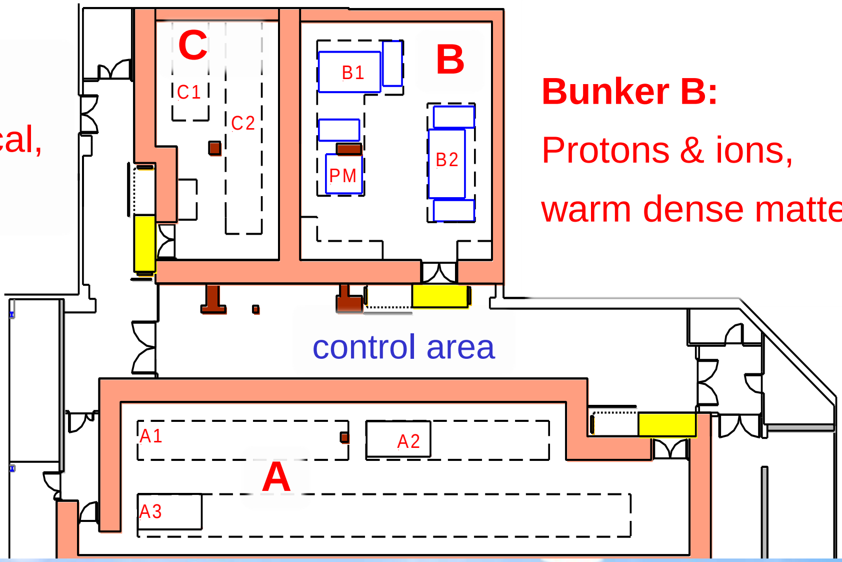
- LWFA-generated electron beam, optimized for high current – while substantial energy spread and energy jitter can be tolerated
- Refocusing/matching helpful, plasma lensing very helpful to reach high norm. $\tilde{Q} = \frac{N_b k_p^3}{n_p}$
- This electron beam drives PWFA in dephasing-free system
- ~100 µJ Ti:Sapphire TH laser pulse (inherently synchronized) used for underdense photocathode


SCAPA

SCAPA

Level 1: radiation caves, level 2: laser clean rooms

Bunker C:
Health, medical,
life sciences



Bunker B:
Protons & ions,
warm dense matter

Proposal for a Horizon 2020 Design Study on the "European Plasma Research Accelerator with eXcellence In Applications"
November 2015-2019

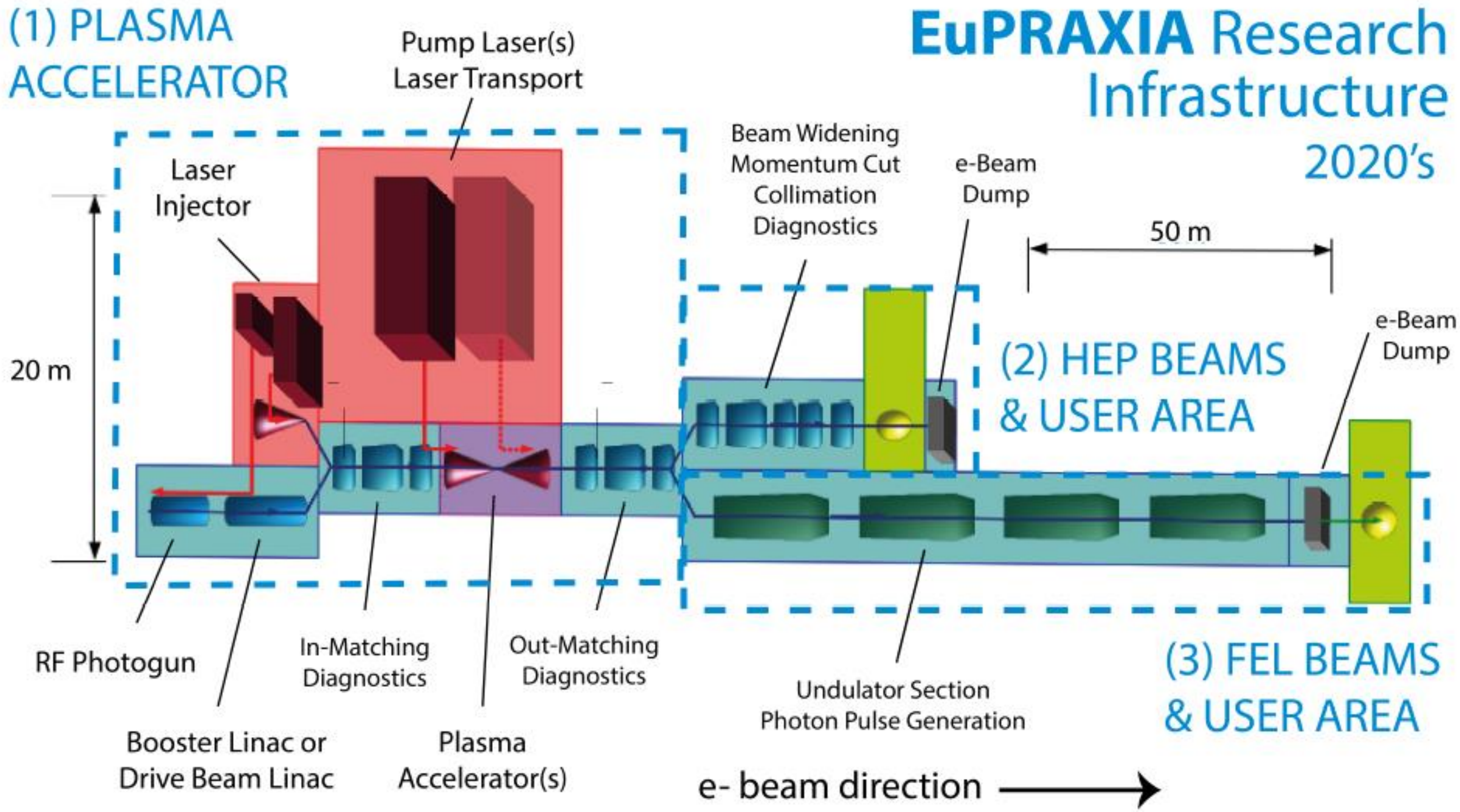
http://www.eupraxia-project.eu/

HORIZON 2020 – INFRADEV – 1– 2014 Design Study EuPRAXIA

Abstract

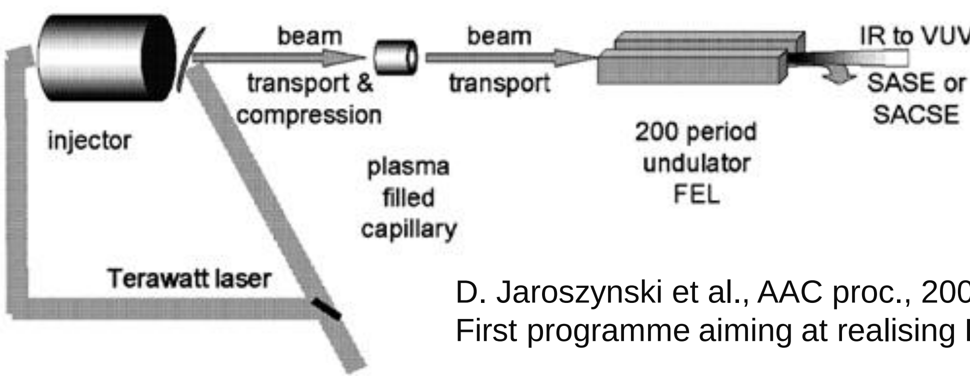
EuPRAXIA will produce a conceptual design report for the worldwide first 5 GeV plasma-based accelerator with industrial beam quality and user areas. EuPRAXIA is the required intermediate step between proof-of-principle experiments and ground-breaking, ultra-compact accelerators for science, industry, medicine or the energy frontier ("plasma linear collider"). The study will design accelerator technology, laser systems and feedbacks for improving the quality of plasma-accelerated beams. Two user areas will be developed for a novel Free Electron Laser and High Energy Physics detector science. An implementation model will be proposed, including a comparative study of possible sites in Europe, a cost estimate and a model for distributed construction and installation at one central site. EuPRAXIA will be a new large research infrastructure with an estimated footprint of about 250 m. If the design study is approved, then it will lay the foundation for a possible decision on construction in 2020.

WP14: Hybrid Laser-Electron-Beam Driven Acceleration. WP leads Strathclyde (Hidding) & DESY (de la Ossa)



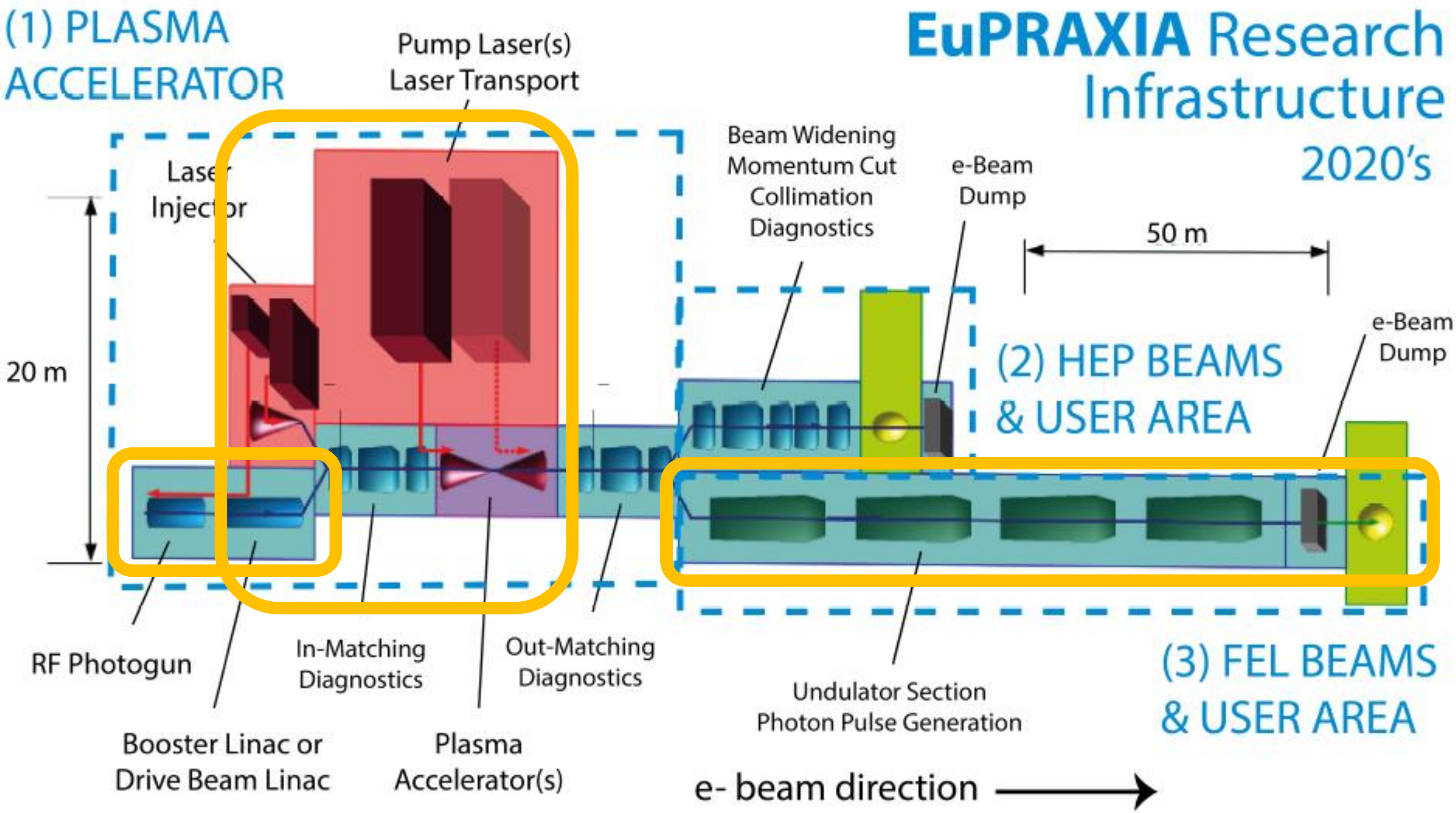
Forerunner in the UK: Advanced Laser-Plasma High-Energy Accelerators towards X-rays

ALPHA-X



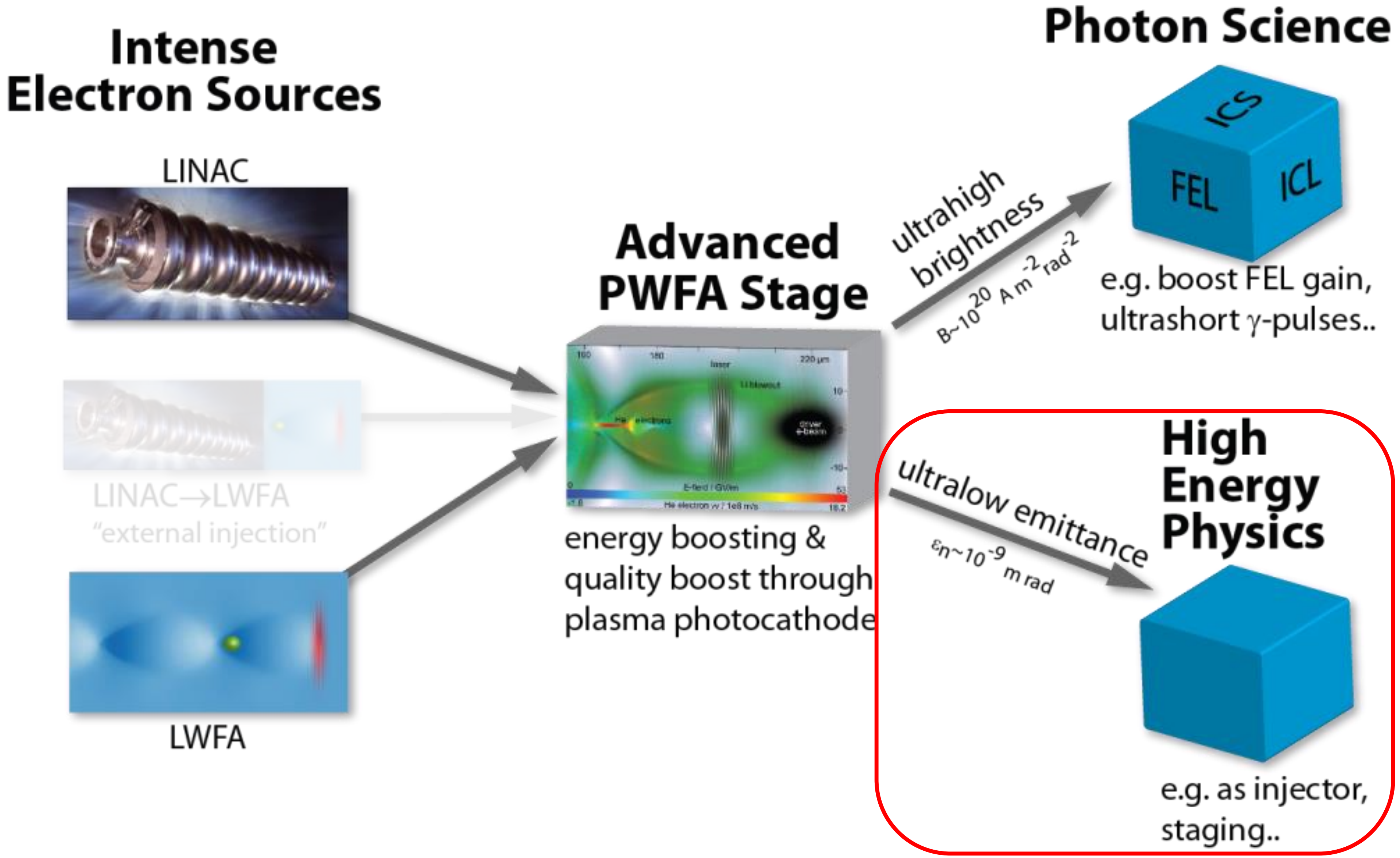
D. Jaroszynski et al., AAC proc., 2002
First programme aiming at realising LWFA-driven FEL

EuPRAXIA



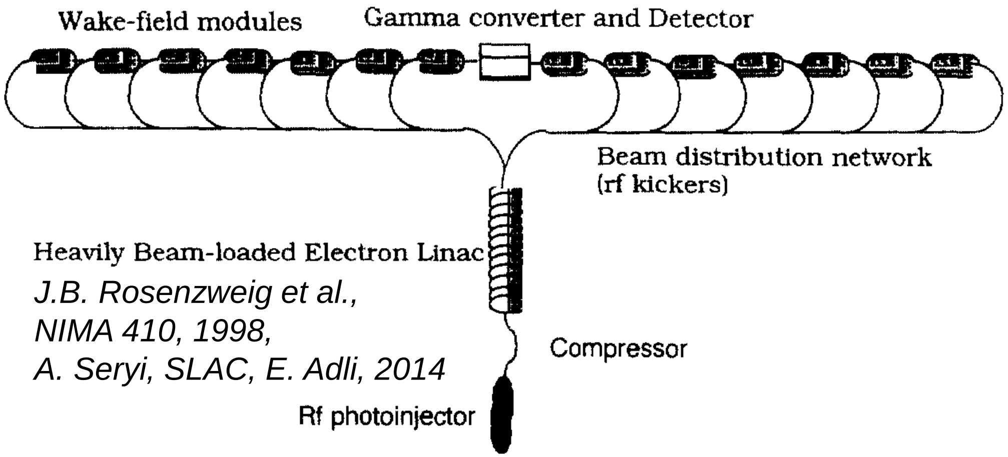
Constructive overlap with CLARA, CLF, SCAPA..
The UK can be a substantial contributor to this

High energy physics



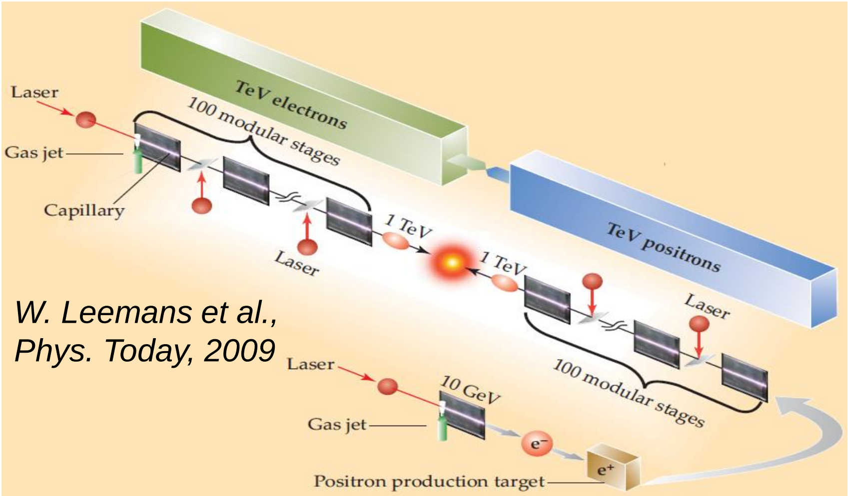
High Energy Physics

PWFA-based:



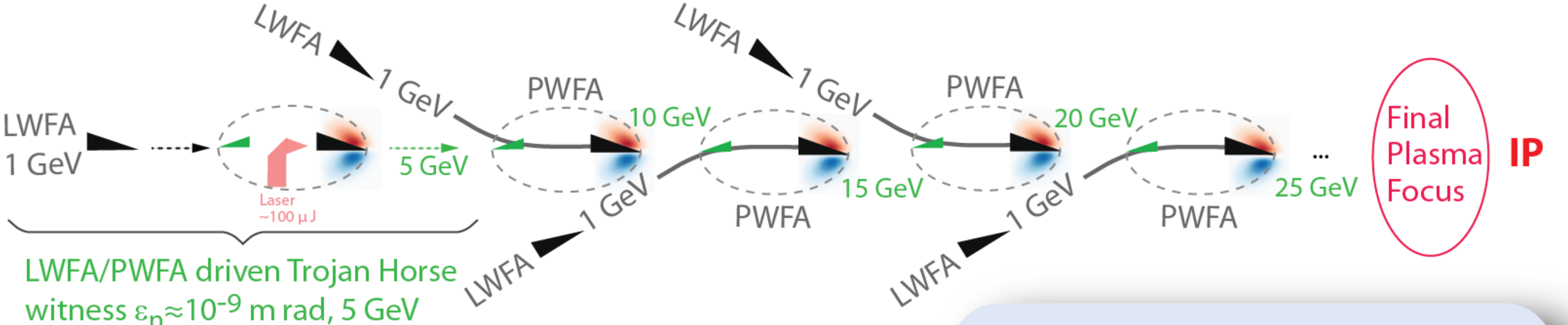
J.B. Rosenzweig et al.,
NIMA 410, 1998,
A. Seryi, SLAC, E. Adli, 2014

LWFA-based:



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

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

Can omit damping ring.
e- e+ collider? $\gamma\gamma$-collider?

.. work in progress..

Summary

- **LINAC electron beams can be used for PWFA, more and more facilities engaging**
- **LWFA electron beams can be used for PWFA, would multiply the number of facilities engaging in PWFA, allowing for perfectly synchronized TH-PWFA**
- **Laser systems essential (preionization, underdense photocathode, diagnostics, probing..)**
- **Experiments on LINAC→TH-PWFA at FACET E210 successfully concluded in 2016, LWFA →(TH-)PWFA in progress**
- **Trojan Horse underdense plasma photocathode may allow for unprecedented electron beam quality & brightness**
- **Enabler for substantial progress in applications in photon science: TH-FEL, TH-ICS, TH-ICL**
- **Also potentially useful for HEP.**
- **Multi-bunch capability and "designer" beams possible which further widen the opportunities**
- **Substantial R&D challenges to address in hybrid combined laser and beam driven plasma**
- **Opportunities for high brightness upgrades for various facilities e.g. at DESY**