2026-07-30
AAC LA
WG #1

Heinrich Heine University Düsseldorf

Proposal for FACET-III

Bernhard Hidding *et al.*

or

Continue FACET as High-Brightness Pivot Facility

Bold step by DoE and SLAC in 1992 proposal: "Low emittance beams from photocathode linacs will enable LCLS"

SLAC-PUB-15058

A 4 to 0.1 nm FEL Based on the SLAC Linac*.

C. Pellegrini

UCLA Physics Department, 405 Hilgard Avenue, Los Angeles CA 90024

March 2, 1992

Abstract

We show that using existing electron gun technology and a high energy linac like the one at SLAC, it is possible to build a Free Electron Laser operating around the 4 nm water window. A modest improvement in the gun performance would further allow to extend the FEL to the 0.1 nm region. Such a system would produce radiation with a brightness many order of magnitude above that of any synchrotron radiation source, existing or under construction, with laser power in the multigigawatt region and subpicosecond pulse length.

In this paper we will first use a simple one dimensional FEL model to obtain and discuss the FEL scaling laws for the short wavelength region. Following the discussion of reference 1, we will show that for operation of an FEL at short wavelengths it is important to:

a. use an electron beam with small emittance and large longitudinal brilliance;
b. use a large beam energy, in the multi GeV region, to maximize the output radiation power;
c. use more focusing than that provided naturally by the undulator.

We will then apply these scaling laws to design a 4nm FEL working in the Self Amplified Spontaneous Emission mode of operation. We will then

* Work supported by the USDepartment of Energy under contract No. DE-FG03-92ER40693

Using The SLAC Two-Mile Accelerator For Powering An FEL*

William A. Barletta[1], Andrew M. Sessler[2]

and

Li-Hua Yu[3]

March 15, 1992

A parameter survey is made, employing the recently developed 2D formalism for an FEL, of the characteristics of an FEL using the SLAC accelerator. Attention is focused upon a wavelength of 40 Å (the water window) and a 1 Å case is also presented. We consider employing the SLAC linac with its present operating parameters and with improved parameters such as would be supplied by a new photo-cathode injector. We find that improved parameters are necessary, but that the parameters presently achieved with present-day photo-cathode guns are adequate to reach the water window.

3. Very Much Improved Normalized Emittance

A further decrease of normalized emittance will improve the FEL performance even more. Taking

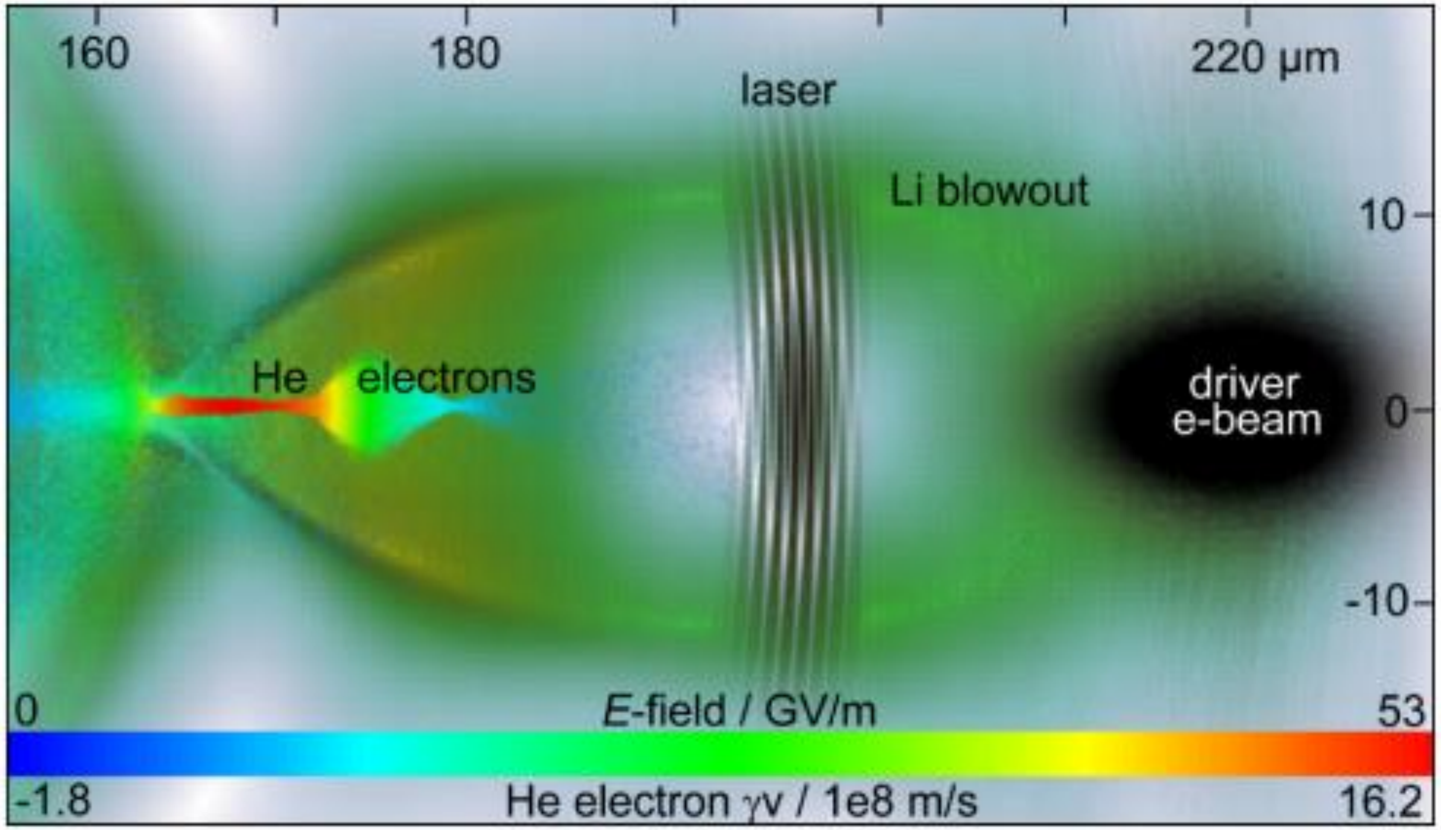
$$\varepsilon_n = 2.5\pi \times 10^{-6}\ \mathrm{m}$$

and keeping $\Delta E/E < 5 \times 10^{-4}$, we obtain the two cases shown in Table 2 at 40 Å. One can see that the either case (without and with extra focusing) yields parameters of considerable interest.

In order to reach a wavelength of 1 Å requires an even smaller normalized emittance and a larger peak current. Taking

$$\varepsilon_n = 1 \times 10^{-6}\ \text{meters},$$
$$I = 5\ \mathrm{kA},$$
$$(\Delta E/E) = 10^{-4},$$

Plasma photocathode aka Trojan Horse: 10 nanometre-rad scale normalized emittance?



can be estimated to be $\epsilon_n \approx \sigma_{r,\mathrm{He}} \sigma_{p_r}/(mc) \approx w_0 a_0 / 2^{3/2} \approx 2.6 \times 10^{-8}$ m rad. This is one of the critical advantages of the acceleration scheme, which opens up the possibility of its use in future advanced free electron laser (FEL)-based x-ray light sources, where emittance has a limiting effect on performance and reachable wavelength. For example, an approximation for the minimum wavelength based on the above emittance and an energy similar as in the Linac Coherent Light Source (LCLS) results in $\lambda_{\min} \approx 4\pi\epsilon_n/\gamma_{\mathrm{LCLS}} \approx 0.1$ Å, about 1 order of magnitude better than the current LCLS performance [27]. We have also performed GENESIS simulations of the case in which the beam presented here is accelerated up to 4.3 GeV, and used with a next generation undulator [28]; this scenario promises a 1.5 Å SASE FEL that saturates in ~20 m, a dramatically shorter distance than the LCLS.

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

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

B. Hidding,[1,2] G. Pretzler,[2] J. B. Rosenzweig,[1] T. Königstein,[2] D. Schiller,[1] and D. L. Bruhwiler[3]
[1]*Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California 90095, USA*
[2]*Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany*

Bold step by DoE and SLAC in 2011:
"Trojan Horse Plasma photocathode will enable next-generation XFELs"

hhu

Heinrich Heine
Universität Düsseldorf

Trojan Horse Plasma Wakefield Acceleration

A proposal to the Facility for Advanced Accelerator Experimental Tests (FACET) at SLAC

Application for beamtime in 2012/13

These electrons are then trapped, collected at the end of the blowout and accelerated and focused in the GV/m plasma fields. Because of the marginal transverse momentum transferred to the He electrons during at-threshold-photoionization, the normalized emittance can be as low as $\varepsilon_n \approx \sigma_{r,\,He}\ \sigma_{pr} / (mc) \approx w_0\, a_0 / 2.8 \approx 2.6 \times 10^{-8}$ m rad when the laser pulse is focused to a spot size of $w_0 \approx 4$ µm, where $\sigma_{r,\,He}$ is the laser focus diameter and σ_{pr} is the transverse momentum. This is confirmed by PIC simulations, which also show that the generated electron bunch can have transversal size as small as 150 nm in the transversally focusing plasma blowout field. GENESIS simulations show that such a bunch, although having a charge of a few pC, only, can be used for excellent FEL performance. For example, assuming the electron beam is accelerated to some 4.3 GeV, the LCLS performance would be exceeded after an undulator length of about 20 meters. At an energy of 14 GeV, the minimum FEL wavelength would be reduced to $\lambda_{min} \approx 4\pi\varepsilon_n / \gamma_{LCLCS} \approx 0.01$ nm and the brightness would amount to $B \approx 2\, I_p / \varepsilon_n^2 \approx 7 \times 10^{17}$ A/m^{-2} rad^{-2}. Both parameters are one or two orders of magnitude better than the current LCLS performance. This would demonstrate a dramatically increased beam quality from a plasma accelerator. In addition, shifting the laser pulse off-axis, allows for off-axis injection of electrons, which leads to pronounced betatron-like oscillations which could be used directly for x-ray generation, and might pave the way to reach the undulator regime in an electrostatic plasma undulator [6]. The concept (dubbed "Trojan Horse" acceleration) would work not only with Li/He, but also with Cs or Rb, the second ionization

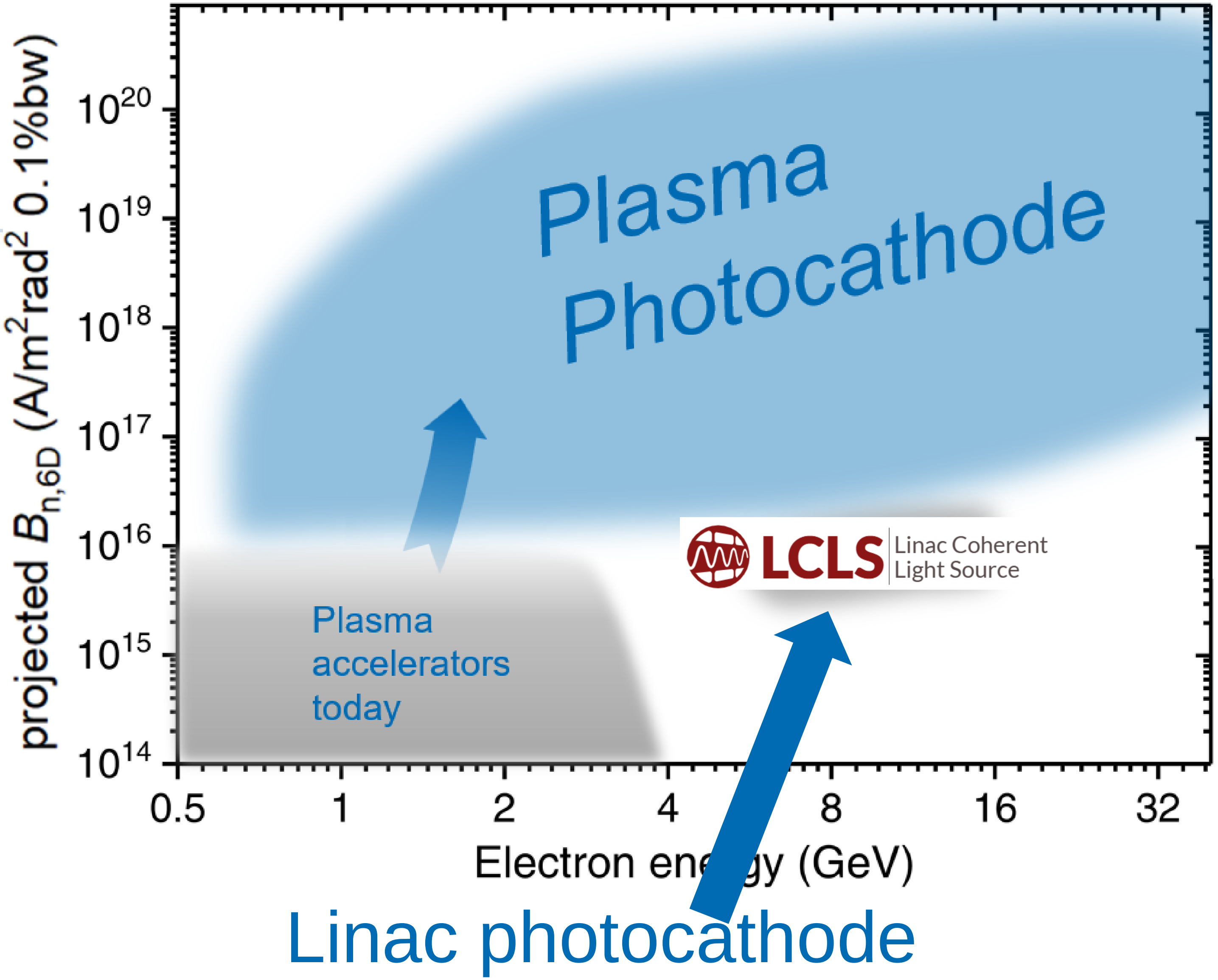
UCLA
Trojan Horse Plasma Wakefield Acceleration
October 2011
Proposal to
FACET

duesseldorf.de/~hidding/eu1.avi. Note that in the simulation, a somewhat higher lithium plasma density is used in order to reduce the window size and save simulation time (full PIC, the laser wavelength has to be resolved, and electron bunch, and two gases (He and Li) must be simulated). The FACET beam is able to drive the acceleration process over meter-scale lengths, and the electrons are collected exactly at the end of the blowout, where the fields are highest. GENESIS simulations show, that at 4.3 GeV, the FEL performance in a cryogenic undulator such as the one described in [5] would match the LCLS. At 14 GeV, a beam with such an emittance would allow for a minimum FEL wavelength which is an order of magnitude harder than the minimum LCLS wavelength: $\lambda_{min} \approx 4\pi\varepsilon_n / \gamma_{LCLS} \approx 0.01$ nm.

Finally, the concept also allows for another advanced light source application: By releasing

$$B_{6\mathrm{D}} = \frac{I}{\epsilon_{\mathrm{n}}^2 \cdot 0.1\%\sigma\mathrm{w}}$$

- Linac photocathode and 10x brighter beams: enabled LCLS
- Plasma acceleration: 1000x smaller accelerators
- Plasma photocathode: 100,000x brighter beams?



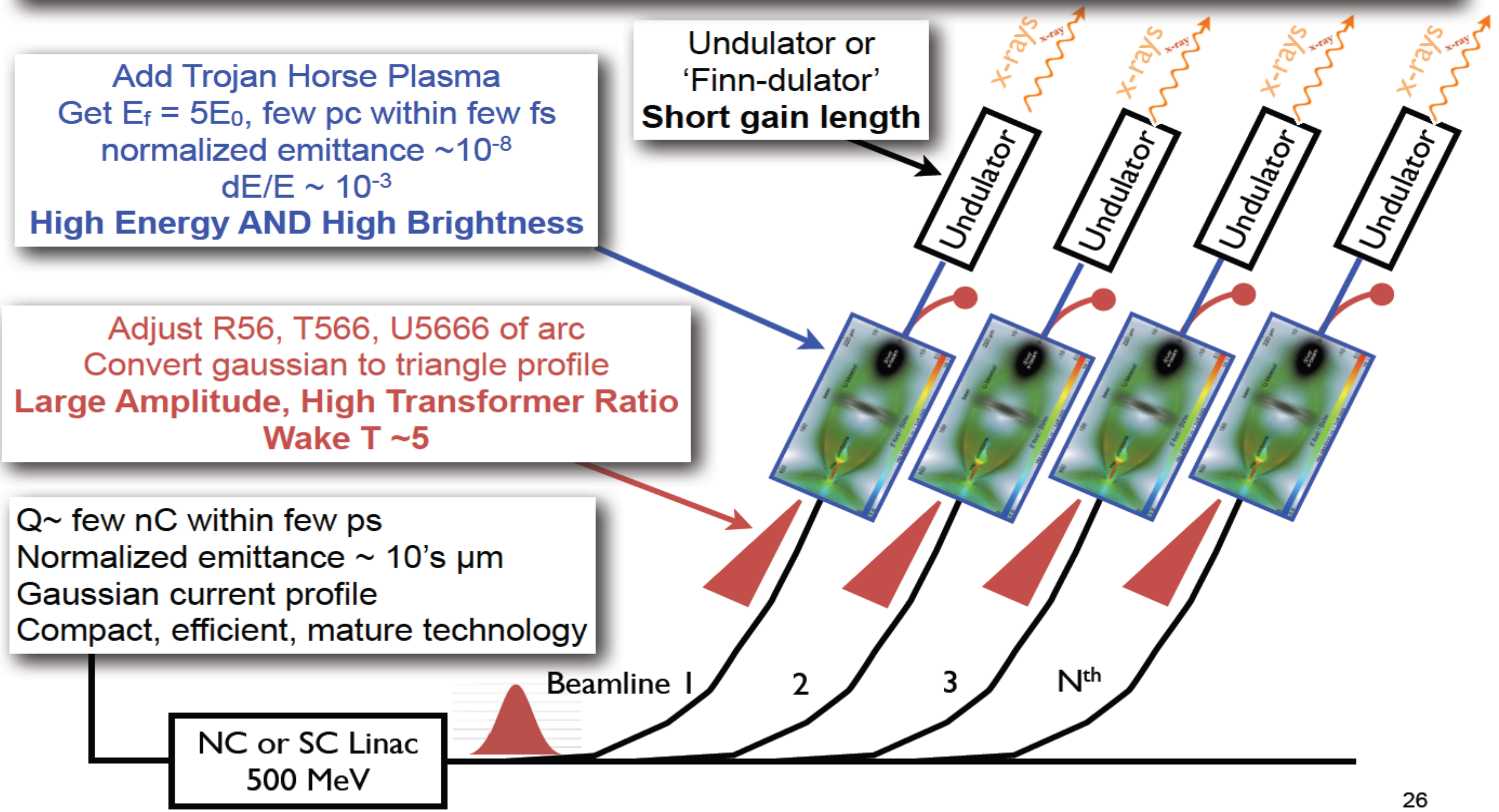
Hybrid Trojan Horse-based Future FEL facility?

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!



Heinrich Heine Universität Düsseldorf

DoE co-funded
E-210: Trojan Horse Underdense Photocathode at FACET

Heinrich Heine
Universität Düsseldorf

Plasma Photocathode Beam Brightness Transformer for Laser-Plasma Accelerators

Awardee

RADIABEAM TECHNOLOGIES, LLC
1717 STEWART ST
SANTA MONICA, CA, 90404-4021
USA

Awarding Agency

DOE

Award Year: 2014
UEI: Q6NDLV47NBT5
HUBZone Owned: No
Woman Owned: No
Socially and Economically Disadvantaged: No
Congressional District: 33

SBIR
Phase II

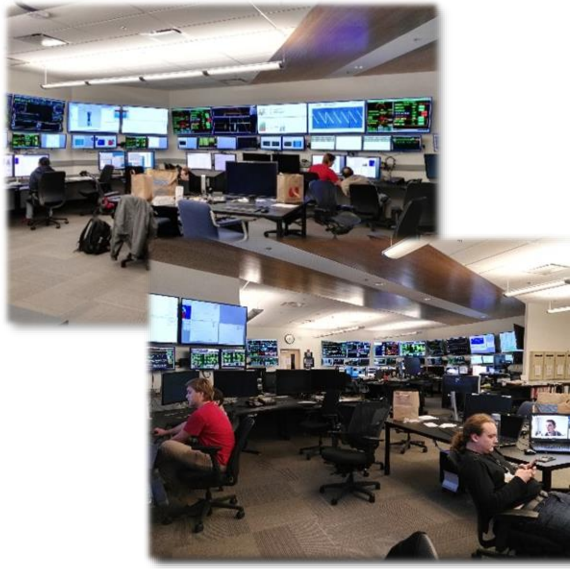
Total Award Amount: $999,959

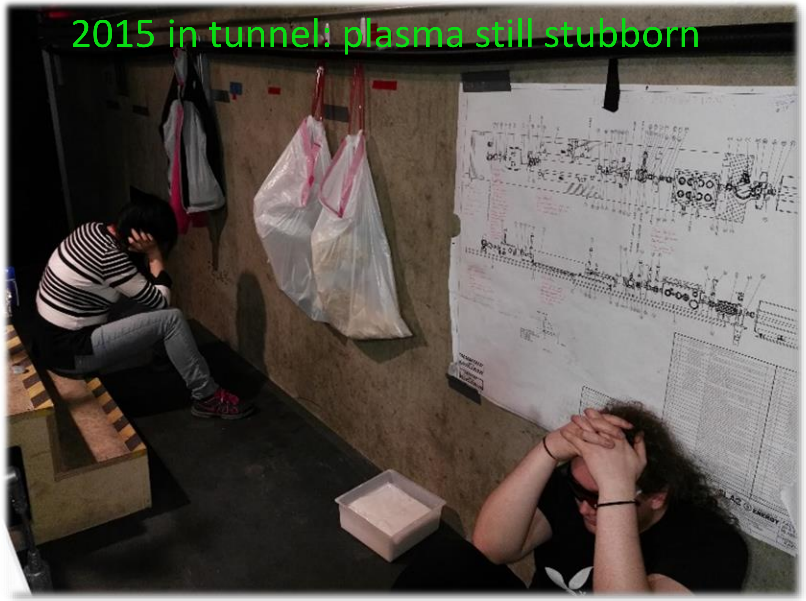
Contract Number: DE-SC0009533
Agency Tracking Number: 211488
Solicitation Topic Code: 33a
Solicitation Number: DE-FOA-0001019

E210 international team: >20 Professors, Post-docs, PhD-Students from 6 universities in 4 countries (UCLA, Strathclyde, Hamburg, Austin, Oslo, Boulder) + industry (RadiaBeam + Tech-X + Radiasoft) + SLAC FACET team

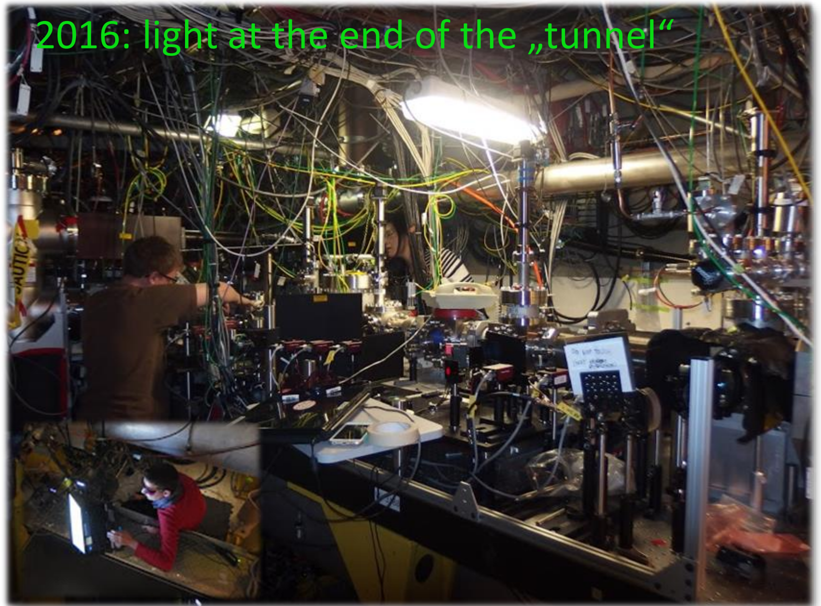
- From “University Users at FACET” slides for 2016-06-08 DoE Review, B. Hidding et al.

2013 at SAREC – cautiously optimistic





2015 in tunnel: plasma still stubborn



2016: light at the end of the „tunnel“

Success..

..at last!

SLAC

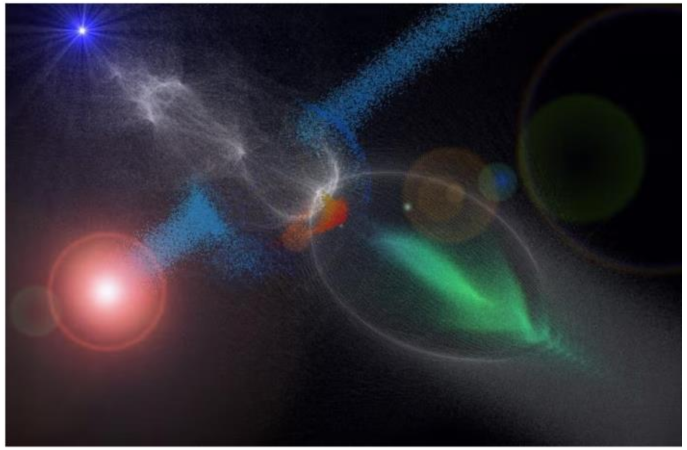
ABOUT RESEARCH FACILITIES & CENTERS WORK WITH US

Heinrich Heine Universität Düsseldorf

AUGUST 12, 2019

Atomic 'Trojan horse' could inspire new generation of X-ray lasers and particle colliders

At SLAC's FACET facility, researchers have produced an intense electron beam by 'sneaking' electrons into plasma, demonstrating a method that could be used in future compact discovery machines that explore the subatomic world.



LETTERS

https://doi.org/10.1038/s41567-019-0610-9

nature physics

Generation and acceleration of electron bunches from a plasma photocathode

A. Deng[1,2,14], O. S. Karger[3,14], T. Heinemann[4,5,6], A. Knetsch[6], P. Scherkl[4,5], G. G. Manahan[4,5], A. Beaton[4,5], D. Ullmann[4,5], G. Wittig[3], A. F. Habib[4,5], Y. Xi[1], M. D. Litos[7], B. D. O'Shea[8], S. Gessner[8], C. I. Clarke[8], S. Z. Green[8], C. A. Lindstrøm[9], E. Adli[9], R. Zgadzaj[10], M. C. Downer[10], G. Andonian[1,11], A. Murokh[11], D. L. Bruhwiler[12], J. R. Cary[13], M. J. Hogan[8], V. Yakimenko[8], J. B. Rosenzweig[1] and B. Hidding[4,5*]

HOME EUPRAXIA FOR BEGINNERS EVENTS CONTACT US INTRANET

EuPRAXIA

Heinrich Heine
Universität Düsseldorf

THE BRIGHTEST ELECTRON BEAMS OF THE WORLD

2017 - 07 - 021

High-quality, bright electron beams have paved the way to realise knowledge-generating machines such as free-electron-lasers (FEL's) – however, those require kilometre-scale accelerators such as the Stanford LCLS or the Hamburg XFEL. EuPRAXIA therefore aims at a **compact** European plasma accelerator with **superior** beam quality.

A new study co-funded by EuPRAXIA in context of "WP14: Hybrid Laser-Electron-Beam Driven Acceleration" proposes to realise electron beams not only in ultracompact setups, but also with orders of magnitude better brightness than state-of-the-art. This may enable future *compact* free-electron lasers with a shot-by-shot performance substantially better than today obtainable even from the best of today's large machines such as LCLS or XFEL, and may have transformative effect on this and other important areas of research in natural, life and material sciences. It may be a unique path forward for EuPRAXIA to realize the goal of compact hard x-ray free-electron-lasers, and to fertilize plasma-based linear collider and high energy physics efforts.

The study, recently published in *Nature Communications*
plasma photocathode technique, which is known in the c

eupraxia-project.eu/the-brightest-electron-beams-of-the-world.html

A video demonstrating the process is found here: https://www.nature.com/articles/ncomms15705#supplementary-information . One of the lead authors is Fahim Ahmed Habib, a first-year PhD student within the Strathclyde Centre for Doctoral Training P-PALS [http://ppals.phys.strath.ac.uk/]. He says: "It is extraordinarily exciting to have found a path to generate electron beams with not only ultrahigh 5D-brightness, but also ultrahigh 6D-brightness by making use of our novel dechirper technique".

Claudio Pellegrini (not involved in the study), one of the father's of the LCLS, the world's first hard x-ray laser at Stanford in the US, says "The path towards realizing the LCLS required a fundamental improvement of the electron beam quality obtainable from conventional accelerators. The approach Manahan et al. suggest now is very promising as regards obtaining a further step change in electron beam quality, this time to be enabled with plasma accelerators. This holds great prospects for the construction of future compact hard x-ray FEL's".

PWFA-X-FEL proposals in 2018 and 2022: Ahead of its time?

Heinrich Heine Universität Düsseldorf

1st FACET-II PAC Report 9 – 12 October 2018

ID46: Plasma-based hard X-ray FEL with ultrahigh gain and sub-fs capability

PIs: Bernhard Hidding, Fahim Ahmad Habib

Findings

The PIs propose to use the high-quality electron beams generated by other proposals, i.e. the plasma photocathode and de-chirping technique, to drive a free-electron laser experiment.
This FEL experiment requires several other proposals to be successfully demonstrated first. The proposal seems to be rather conceptual and there seem significant technical challenges to be overcome. More details are required to evaluate the technical feasibility.

Ranking: None at this time

Reason for Ranking

Scientific merit: Very High
Technical risk: Very High
Suitability: Suitable for FACET-II. However, the proposal requires a number of associated experiments to be completed successfully in order to go forward.

Recommendations and Additional Comments

The proposal is ahead of its time. The PIs should re-submit the proposal in a future call and should continue to work on a more detailed proposal. In particular, they should study the separation of the main beam from the other by products of the acceleration process (drive bunch, escort bunches) while maintaining the high brightness of the main beam.

FACET-II PAC 2022-10-26

University of Strathclyde

PWFA-X-FEL

Re-submission ID: 46 (PAC 2018)

PIs: Bernhard Hidding, Fahim Habib
Scottish Centre for the Application of Plasma-Based Accelerators SCAPA,
Department of Physics, University of Strathclyde,
Scottish Universities Physics Alliance SUPA, UK
& The Cockcroft Institute

STFC PWFA-FEL: http://pwfa-fel.phys.strath.ac.uk/
ERC NeXource: http://nexource.phys.strath.ac.uk/

Facility upgrades

- For the proof-of-concept foals of the current proposal, no facility upgrades are required, but beamline components and diagnostics towards the fully fledged version
- Beamline components: suitable chicane see

  White Paper: FACET-II Experimental Area Chicane

  C. Emma[1], E. Gerstmayr[1], R. Hessami[1], K. Larsen[1], R. Robles[1], D. Storey[1], S. Meuren[1], P. Manwani[3], N. Majernik[3], G. Andonian[3], J. Rosenzweig[3], A. Marinelli[1]

  [1] *SLAC National Accelerator Laboratory, Menlo Park, California, 94025 USA*
  [2] *Stanford University, 450 Serra Mall, Stanford, CA 94305*
  [3] *University of California, Los Angeles, 90095, USA*

  May 6, 2021
- PMQs: based on RBT design
- Undulator: strong R&D towards advanced ones e.g. at UCLA; today's undulators good for PoC
- For future R&D and exploitation e.g. at a "FACET-III" as sketched on slide 9: Exploitation of Plasma-X-FELs, ultra-high brightness electron beams and laser beams combined for probing matter and vacuum under extreme conditions: Laser system upgrade is desired
- To fully leverage the novel capabilities of the PWFA-X-FEL expanding the space downstream of the electron spectrometer would be desirable

DoE Basic Energy Sciences
Highlight in 2024

U.S. DEPARTMENT of ENERGY

Policy & Priorities | Leadership & Organization | Topics | News & Events | About | Funding Opportuniti

Basic Energy Sciences › Ice-Cold Plasma Electron Beams Prepare to Power Future Hard X-ray Laser Beams

Ice-Cold Plasma Electron Beams Prepare to Power Future Hard X-ray Laser Beams

Scientists chart a path to sub-femtosecond hard X-ray Free-Electron-Laser pulses powered by compact plasma-based accelerators.

Basic Energy Sciences

September 11, 2024

nature communications

Article

https://doi.org/10.1038/s41467-023-36592-z

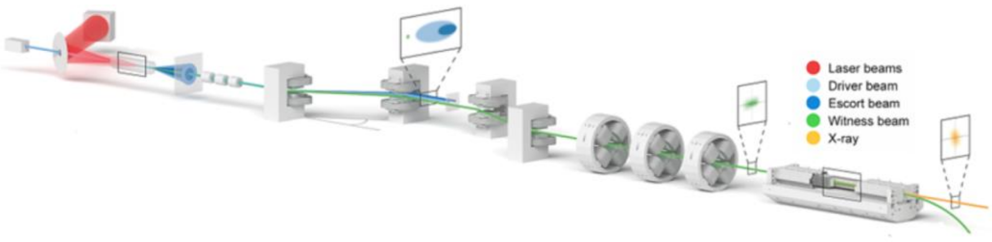
Attosecond-Angstrom free-electron-laser towards the cold beam limit

Received: 30 March 2022

Accepted: 8 February 2023

Published online: 24 February 2023

A. F. Habib[1,2], G. G. Manahan[1,2], P. Scherkl[1,2,3], T. Heinemann[1,2], A. Sutherland[1,2], R. Altuiri[1,4], B. M. Alotaibi[1,4], M. Litos[5], J. Cary[5,6], T. Raubenheimer[7], E. Hemsing[7], M. J. Hogan[7], J. B. Rosenzweig[8], P. H. Williams[2,9], B. W. J. McNeil[1,2] & B. Hidding[1,2,10]



Schematic of a plasma wakefield accelerator using optical laser beams and electron driver, escort, and witness beams for generating bright, coherent X-ray laser beams with attosecond duration and sub-Angstrom wavelength.

Image courtesy of the University of Strathclyde

The research shows how to produce, extract, and isolate these ultrabright beams in a beam transport line without charge and quality loss. In undulators, such electron beams can then produce bright sub-femtosecond hard X-ray pulses like what is produced at the Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory, but in a much shorter distance. Several aspects of this new PWFA scheme may be tested at the SLAC's Facility for Advanced Accelerator Experimental Tests (FACET-II), a DOE user facility. In the long term, researchers envision that compact high-brightness beams from PWFAs could lead to complementary compact XFELs and to more exotic research such as coherent photon-photon colliders.

DoE BES is in an outstanding position to continue the global leadership on high-brightness and XFEL at SLAC

Heinrich Heine
Universität Düsseldorf

- 10-fold electron brightness increase has enabled LCLS and changed the world
- Plasma photocathode could increase brightness by 100,000x. This would transform the XFEL landscape
- Plasma photocathode proof-of-concept was realized at FACET during the last weeks of its operation
- FACET-II has now regained improved capabilities to demonstrate Trojan Horse-II, and the full potential of collinear plasma photocathodes with 10’s nm rad scale emittance for XFEL
- FACET-II, co-located with LCLS, is the ideal location to produce the next generation of XFELs that will truly democratize X-ray lasers and provide capabilities thus far impossible
- By funding FACET-II(I), DoE BES can continue its global leadership on high-brightness science and applications
- **By ending FACET-II prematurely, DoE would risk losing its global leadership on high-brightness science and next-generation XFELs and their application**

Backup

Heinrich Heine
Universität Düsseldorf

LCLS

9 Sept 2019 | Conference Proceedings

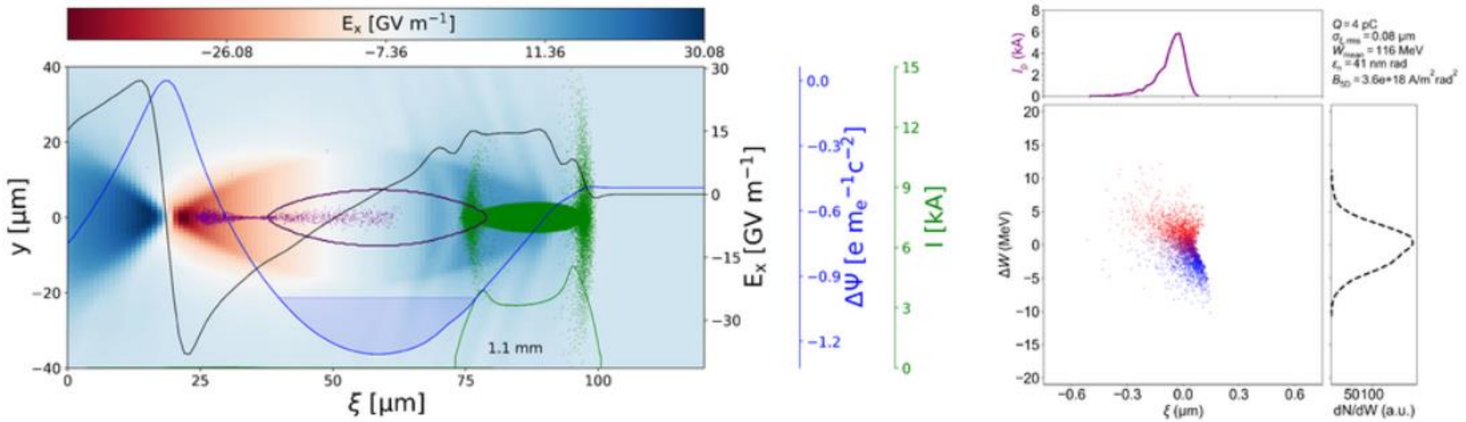
Plasma accelerator-based ultrabright x-ray beams from ultrabright electron beams

Ahmad Fahim Habib, Paul Scherkl, Grace Gloria Manahan, Thomas Heinemann, Daniel Ullmann, Andrew Sutherland, Alexander Knetsch, Michael Litos, Mark Hogan, James Rosenzweig, Bernhard Hidding | Author Affiliations

Proceedings Volume 11110, https://doi.org/10.1117/12.2530976 | Event Info

Heinrich Heine Universität Düsseldorf

Fig. 4



3D PIC-simulation of a LCLS-II electron beam-driven Trojan Horse PWFA brightness booster stage. In the left panel, an LCLS-II-like (green dots) electron driver excites a nonlinear PWFA stage with a plasma photocathode laser injecting ultracold electrons (purple dots) within the trapping potential (purple solid ellipse). The blue line indicates the wake potential and the black line represents the corresponding longitudinal GV/m-scale accelerating gradient. In the right panel, the plasma photocathode injected witness beam longitudinal phase space with its current profile (purple solid line) and the spectral density (dashed black line) are shown. The witness beam has a peak current of $I_{pk} \approx 6$ kA with normalized emittance of $\epsilon_n \approx 41$nm resulting in ultrahigh 5D brightness $B_{5D} \approx 3.6 \times 10^{18}$ A/mrad^2. This would constitute a 5D brightness boost by a factor of three to four orders of magnitude.