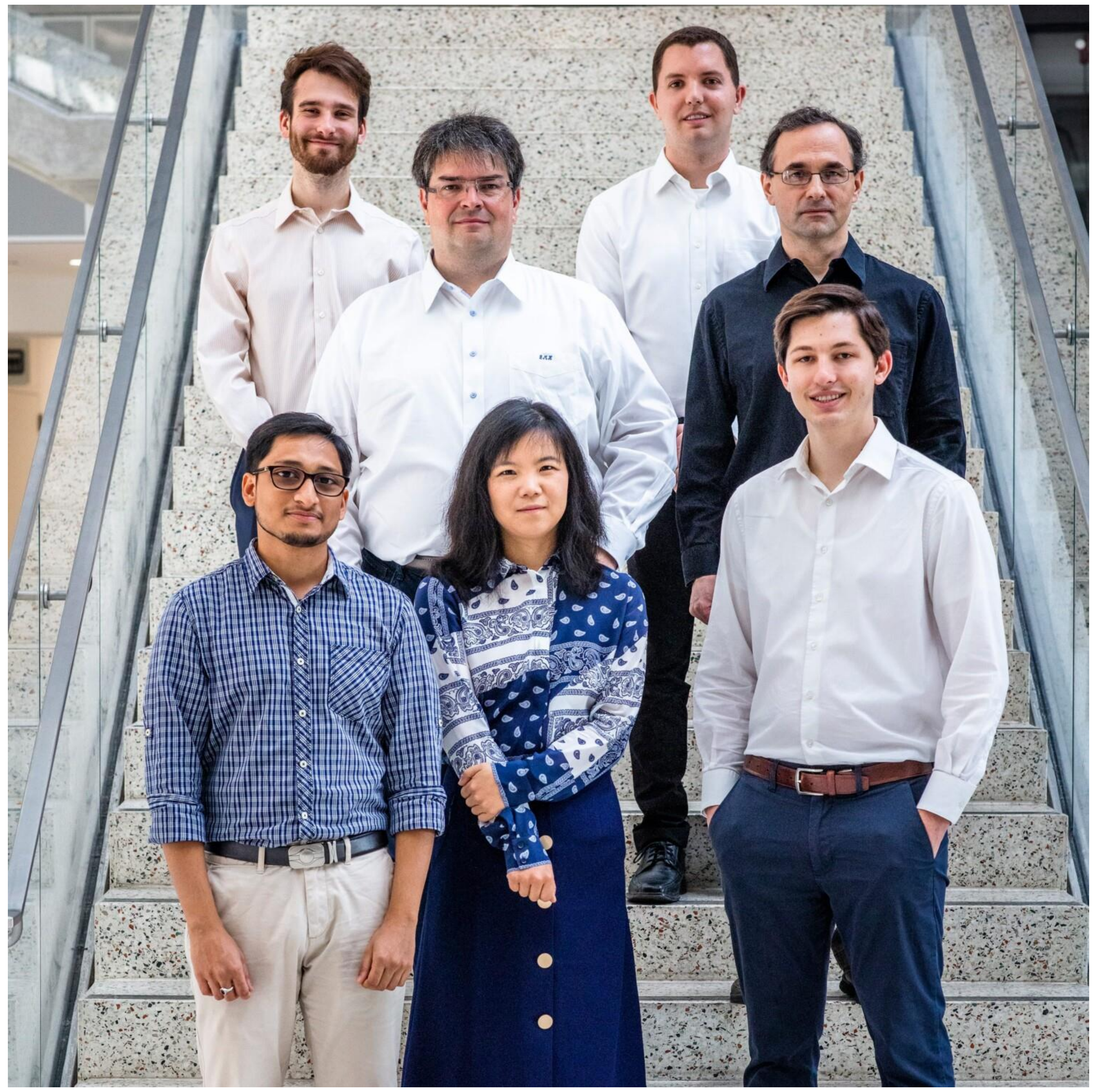
High charge, >10 GeV laser plasma electron acceleration
-
Design considerations for laser-accelerators and -XFELs

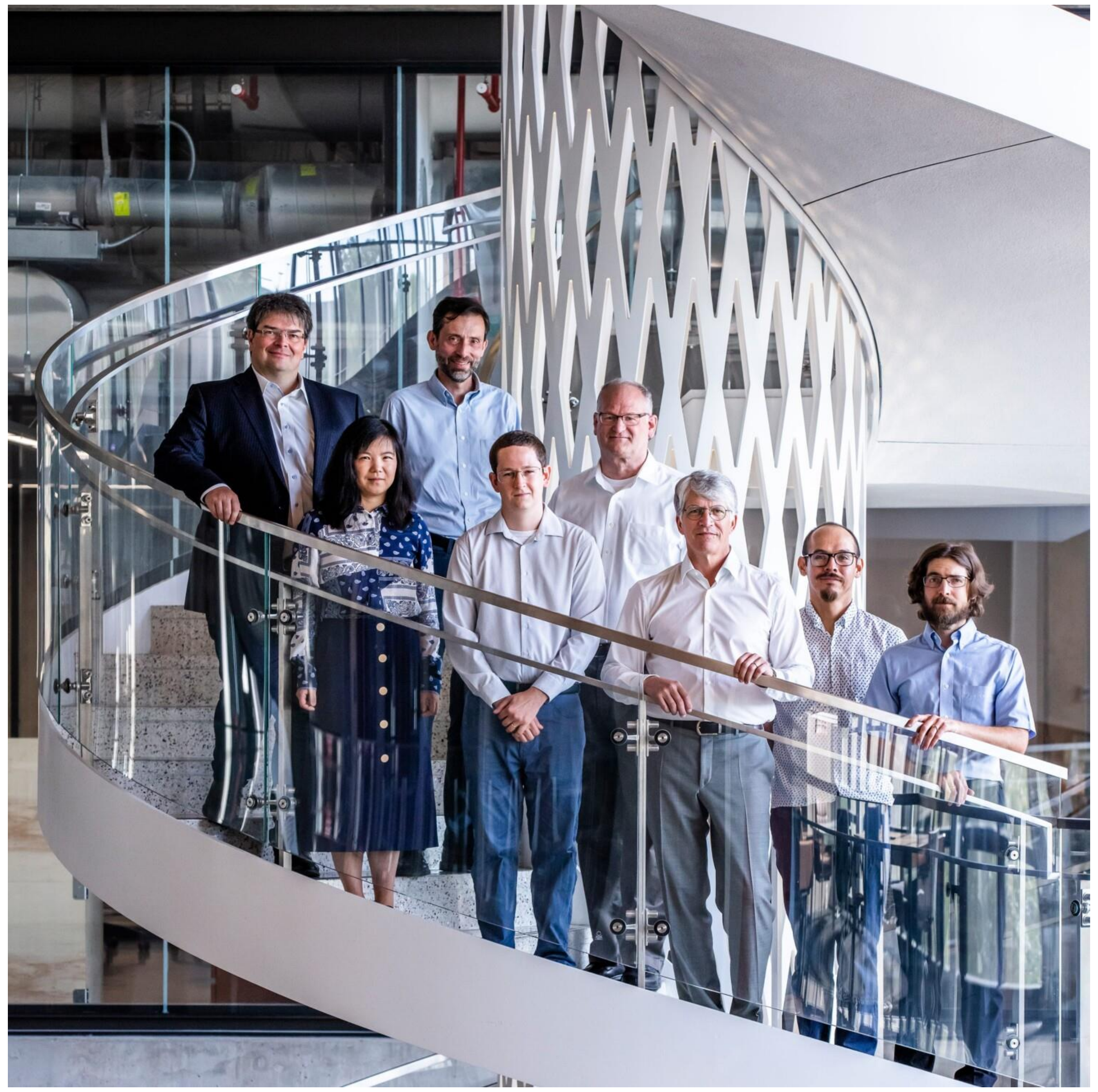
B. M. Hegelich
University of Texas at Austin

-

Linac 2022, Liverpool, September 2, 2022

Acknowledgements



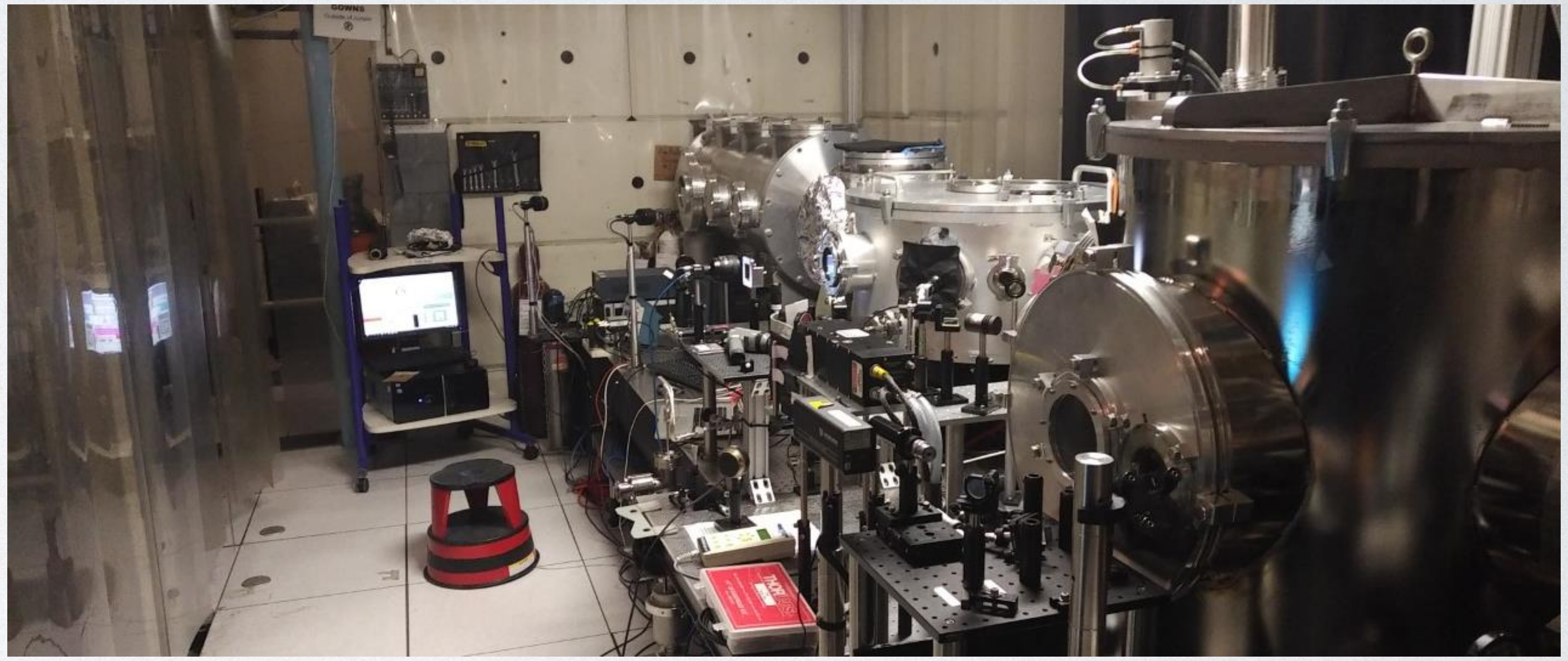


B. M. Hegelich, M. Downer

- Senior Scientists & Postdocs:
  - Constantin Aniculaesei, Ou Zhang Labun, Lance Labun, Rafal Zsagad
- Graduate Students
  - Ritwik, Sain, Eddie McCary, Drue Hood-McFadden, Austin Gottfredson, Xuejing Jiao, Ganesh Tiwari, Scott Luedtke, Paul King, Andrea Hannash

- Sponsors
- Air Force Office of Scientific Research
- US Department of Energy
- Institute for Basic Science, Republic of Korea

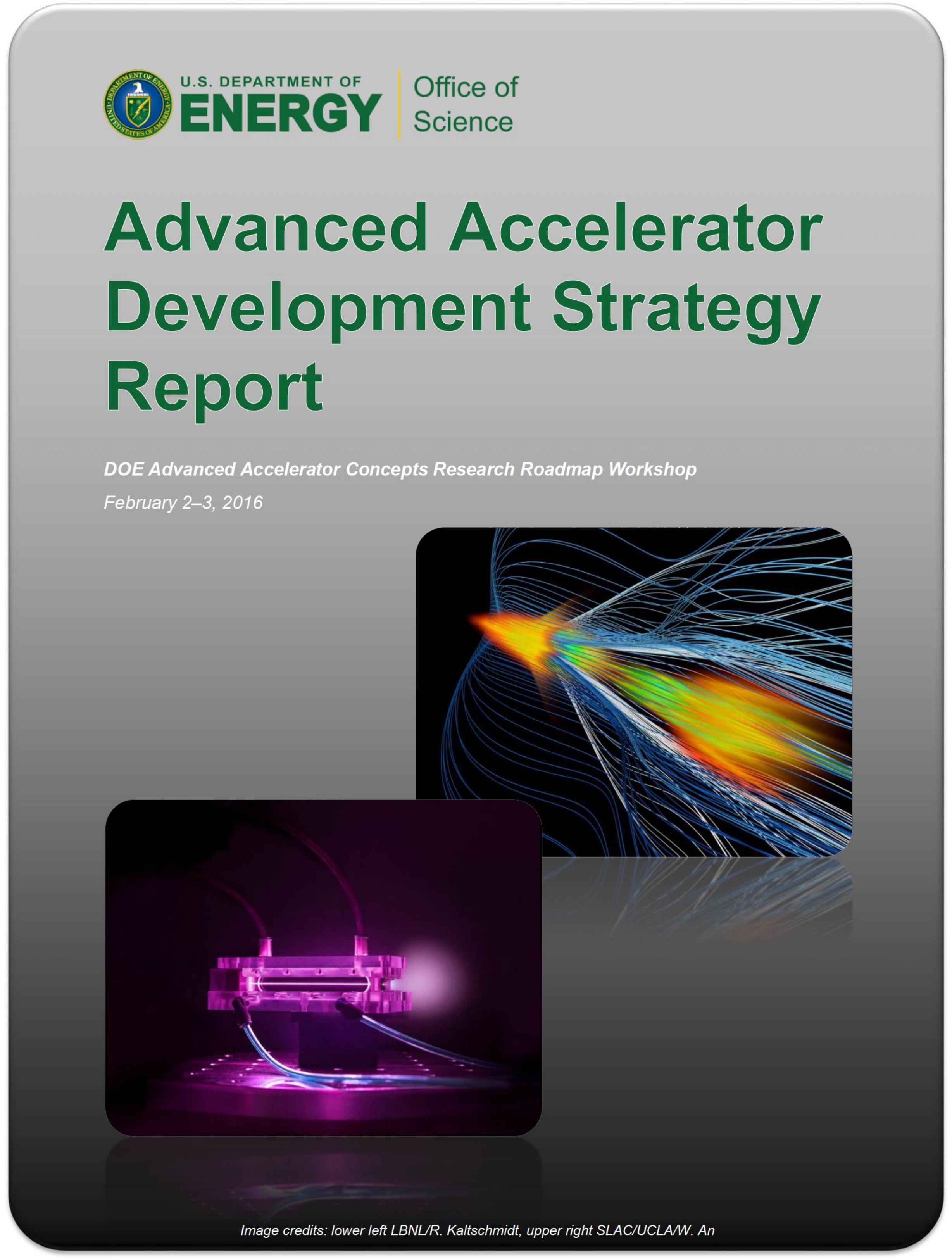
LASER WAKEFIELD ACCELERATION (LWFA)

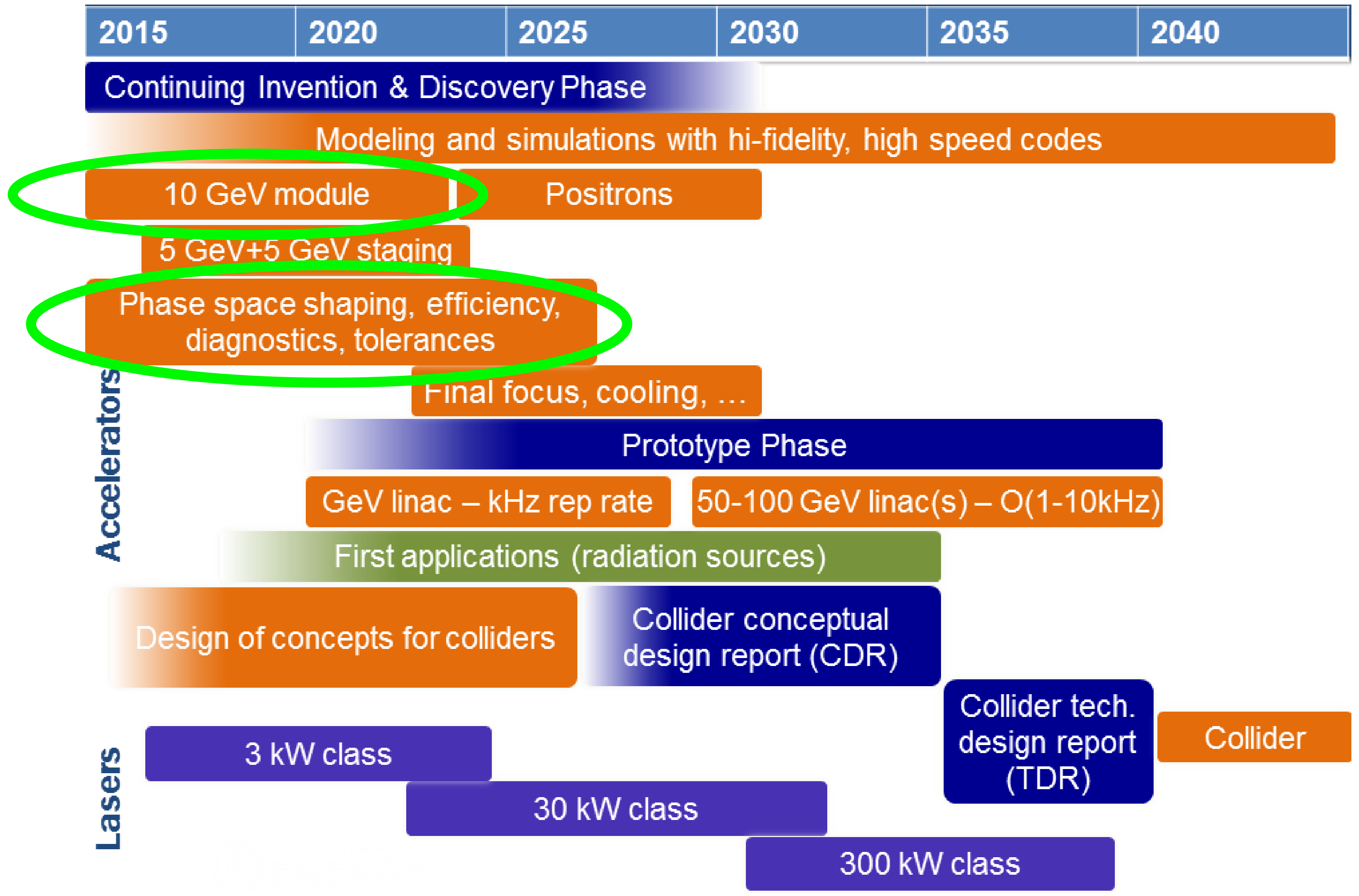


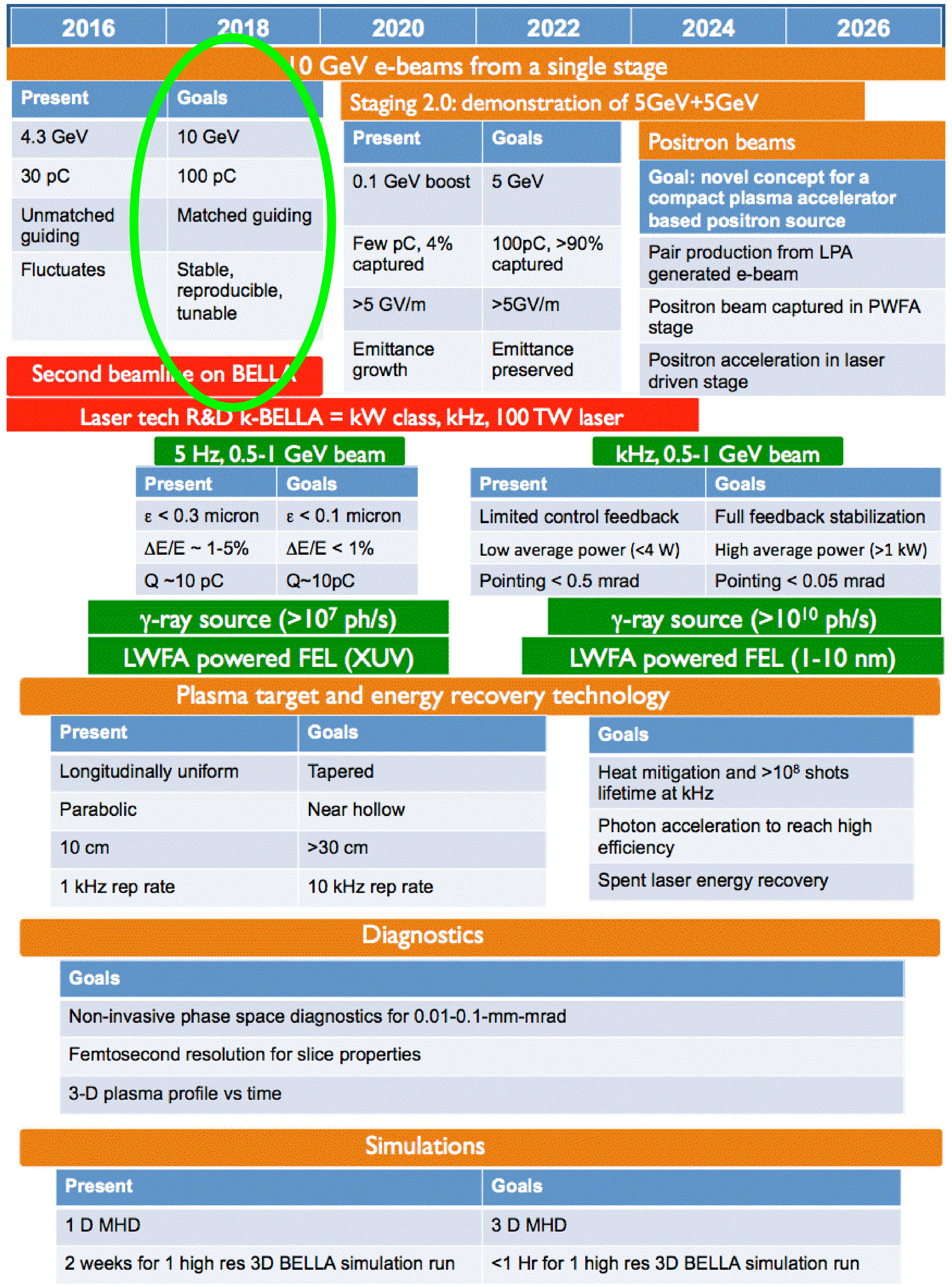
SHRINKS ACCELERATORS FROM ~KM TO ~CM (~M)

Compact accelerators and laser-driven XFELs

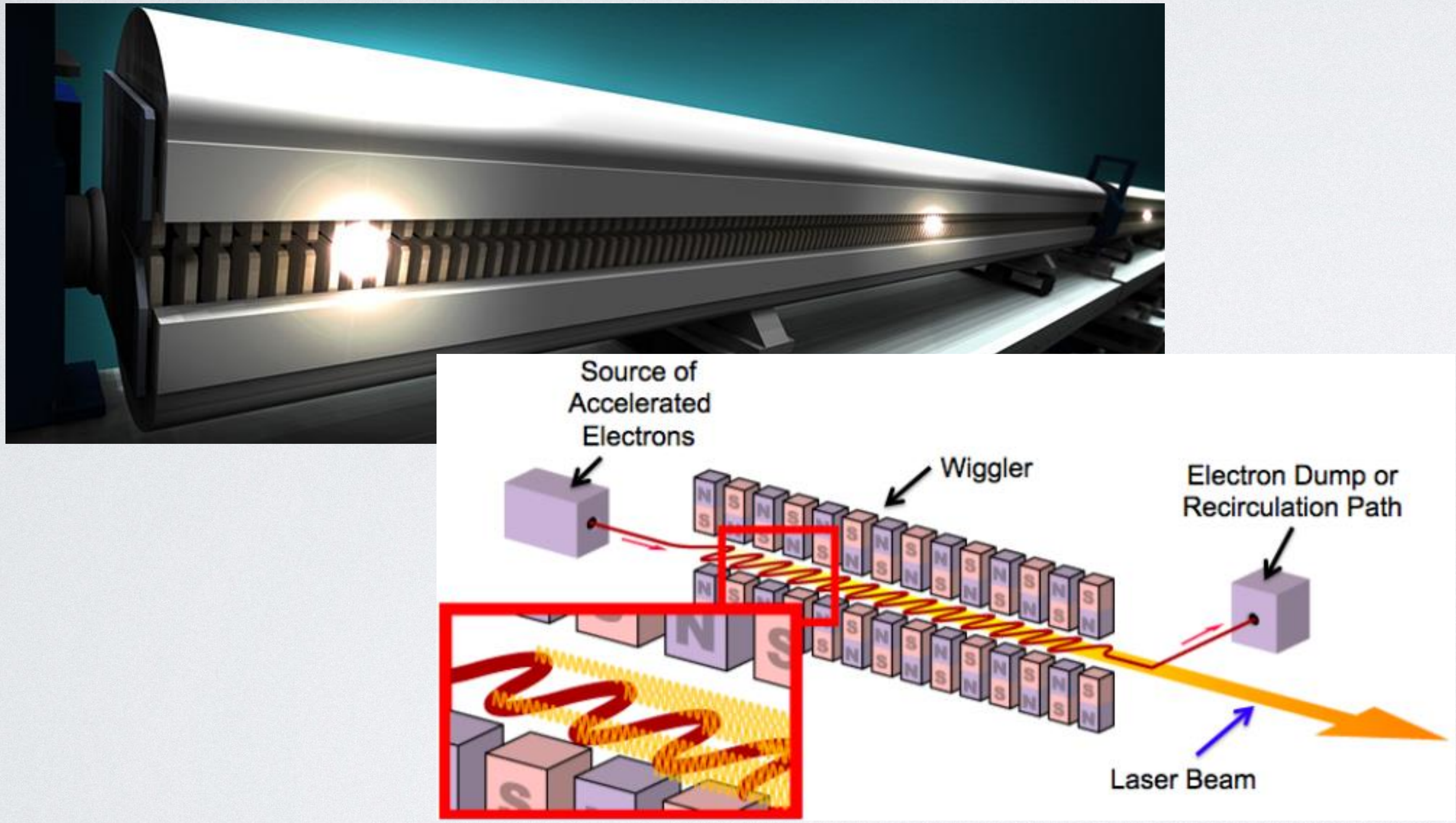
Community Milestone: 10 GeV from a single stage

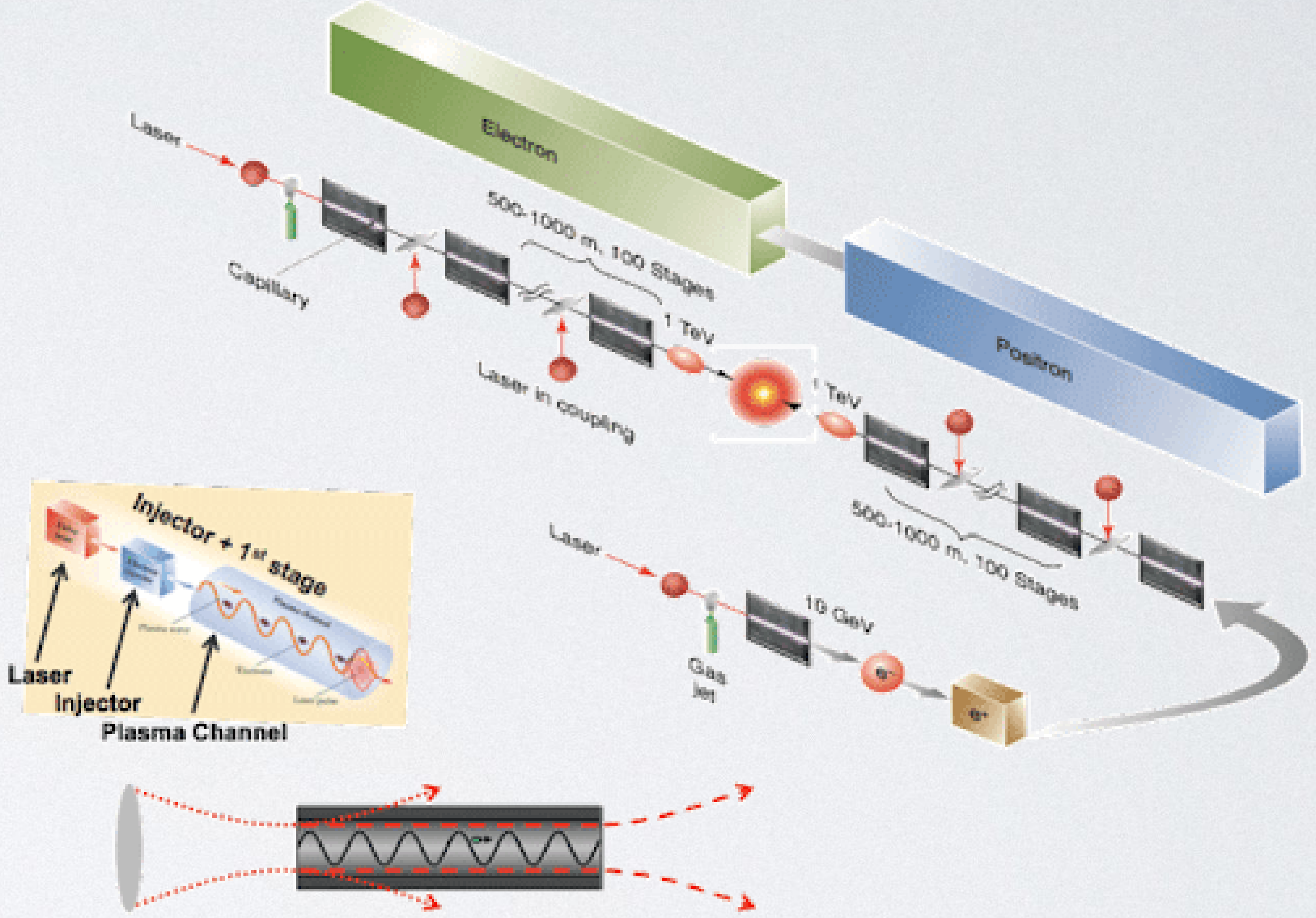






GRAND CHALLENGE:
10GeV from single laser-stage





enables room-sized XFEL and affordable TeV collider

(necessary but not sufficient!)

Current record LWFA energy: LBNL - Bella-laser: 7.8 GeV (2019)

PHYSICAL REVIEW LETTERS 122, 084801 (2019)

Editors' Suggestion | Featured in Physics

Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide

A. J. Gonsalves,[1,*] K. Nakamura,[1] J. Daniels,[1] C. Benedetti,[1] C. Pieronek,[1,2] T. C. H. de Raadt,[1] S. Steinke,[1] J. H. Bin,[1] S. S. Bulanov,[1] J. van Tilborg,[1] C. G. R. Geddes,[1] C. B. Schroeder,[1,2] Cs. Tóth,[1] E. Esarey,[1] K. Swanson,[1,2] L. Fan-Chiang,[1,2] G. Bagdasarov,[3,4] N. Bobrova,[3,5] V. Gasilov,[3,4] G. Korn,[6] P. Sasorov,[3,6] and W. P. Leemans[1,2,†]

[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*University of California, Berkeley, California 94720, USA*
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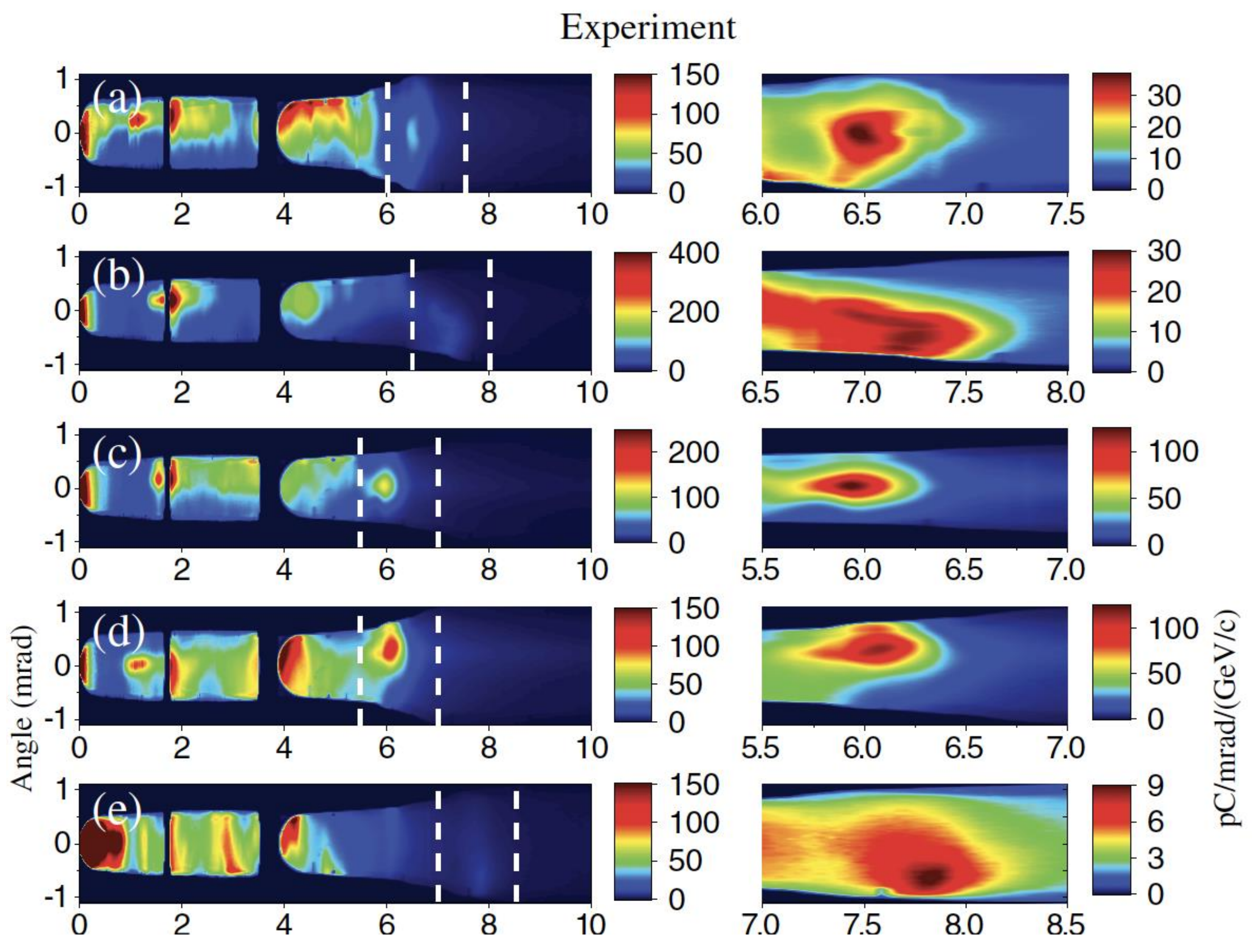
[5]*Faculty of Nuclear Science and Physical Engineering, CTU in Prague, Brehova 7, Prague 1, Czech Republic*
[6]*Institute of Physics ASCR, v.v.i. (FZU), ELI-Beamlines Project, 182 21 Prague, Czech Republic*

(Received 7 December 2018; revised manuscript received 30 January 2019; published 25 February 2019)

Guiding of relativistically intense laser pulses with peak power of 0.85 PW over 15 diffraction lengths was demonstrated by increasing the focusing strength of a capillary discharge waveguide using laser inverse bremsstrahlung heating. This allowed for the production of electron beams with quasimonoenergetic peaks up to 7.8 GeV, double the energy that was previously demonstrated. Charge was 5 pC at 7.8 GeV and up to 62 pC in 6 GeV peaks, and typical beam divergence was 0.2 mrad.

DOI: 10.1103/PhysRevLett.122.084801



RF accelerator bunch injection into LWFA accelerator - Tsinghua Univ., Y. Wu et al. (2020)

nature physics
LETTERS
https://doi.org/10.1038/s41567-021-01202-6
Check for updates

High-throughput injection–acceleration of electron bunches from a linear accelerator to a laser wakefield accelerator

Yipeng Wu[1,2], Jianfei Hua[1✉], Zheng Zhou[1], Jie Zhang[1], Shuang Liu[1], Bo Peng[1], Yu Fang[1], Xiaonan Ning[1], Zan Nie[2], Fei Li[2], Chaojie Zhang[2], Chih-Hao Pai[1], Yingchao Du[1✉], Wei Lu[1✉], Warren B. Mori[2] and Chan Joshi[2]

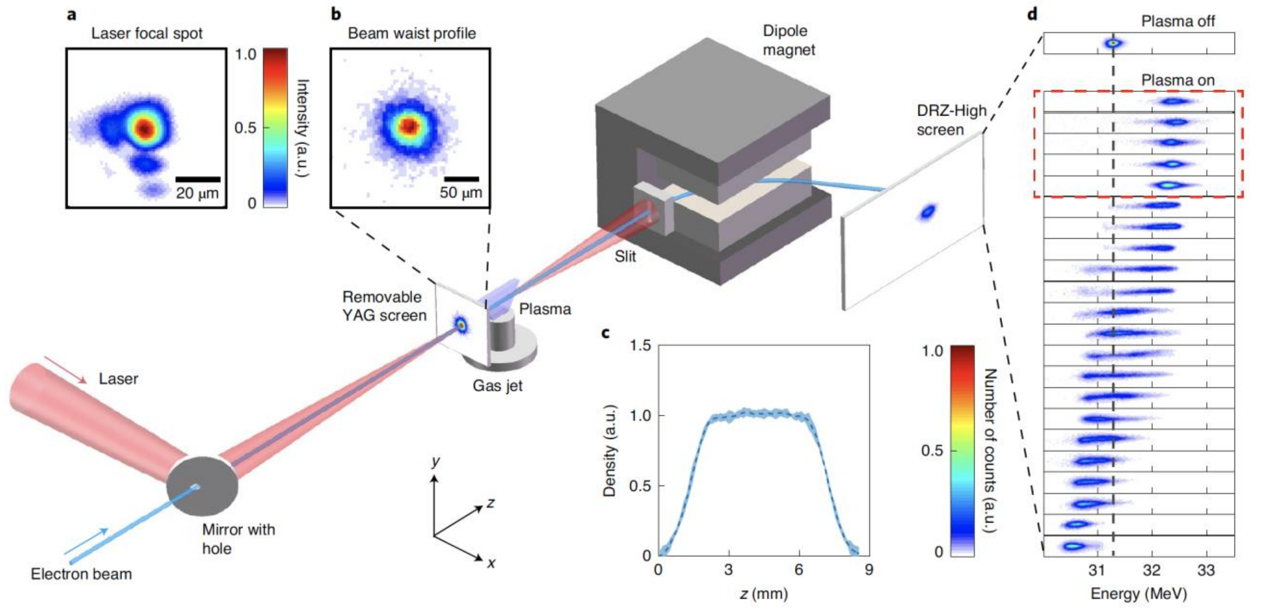


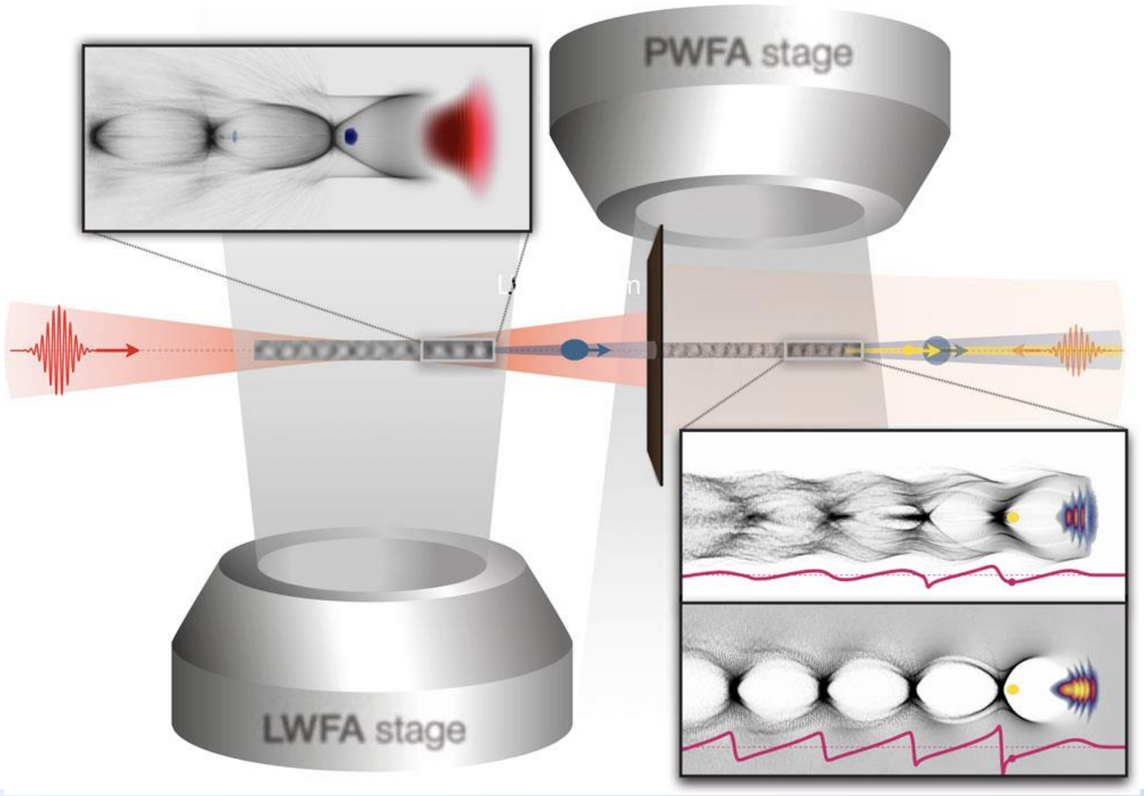
Fig. 1 | Experimental layout. a,**b**, A laser pulse is focused and sent collinearly with the electron beam using a mirror with a 3-mm-diameter central hole. The laser focal spot is shown in **a** and the electron beam waist profile (measured using a removable cerium-doped yttrium-aluminium-garnet (YAG) screen) is shown in **b**. **c**, Measured neutral density profile of the gas jet along the longitudinal axis z (the blurred region shows the r.m.s. spread of five shots). The beam energy spectra are recorded by a spectrometer composed of a 1-mm-wide lead slit, a permanent dipole magnet of ~1 T, a 25-µm-thick aluminium foil (not shown) and a phosphor screen (DRZ-High). The lead slit introduces an uncertainty in the incoming beam position relative to the spectrometer, and thus, its width induces an energy measurement uncertainty of ~0.05 MeV. The thin aluminium foil is placed between the dipole magnet and the DRZ-High screen (very close to the DRZ-High screen) to block the scattered residual drive laser and ambient light. **d**, A group (sorted by decreasing mean energy) showing the energy-dispersed beam distributions induced by the ~100 fs timing jitter under the same experimental condition ($z_f = -4.5$ mm and $n_p = 6 \times 10^{17}$ cm^{-3}).

LWFA powered PWFA - Kurz et al., HZDR (2020)

ARTICLE
https://doi.org/10.1038/s41467-021-23000-7 OPEN
Check for updates

Demonstration of a compact plasma accelerator powered by laser-accelerated electron beams

T. Kurz[1,2,10✉], T. Heinemann[3,4,5,10], M. F. Gilljohann[6,7], Y. Y. Chang[1], J. P. Couperus Cabadağ[1], A. Debus[1], O. Kononenko[8], R. Pausch[1], S. Schöbel[1,2], R. W. Assmann[3], M. Bussmann[1,9], H. Ding[6,7], J. Götzfried[6,7], A. Köhler[1], G. Raj[8], S. Schindler[6,7], K. Steiniger[1], O. Zarini[1], S. Corde[8], A. Döpp[6,7], B. Hidding[4,5], S. Karsch[6,7✉], U. Schramm[1,2], A. Martinez de la Ossa[3] & A. Irman[1✉]



Longterm stable operation of an LWFA using Bayesian Optimization and Machine Learning - Desy (2021)

PHYSICAL REVIEW LETTERS 126, 104801 (2021)

Bayesian Optimization of a Laser-Plasma Accelerator

Sören Jalas,[1,*] Manuel Kirchen,[1] Philipp Messner,[2,1,3] Paul Winkler,[3,1] Lars Hübner,[3,1] Julian Dirkwinkel,[3] Matthias Schnepp,[1] Remi Lehe,[4] and Andreas R. Maier[3,1]

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Optimal Beam Loading in a Laser-Plasma Accelerator

Manuel Kirchen,[1,*] Sören Jalas,[1] Philipp Messner,[2,1] Paul Winkler,[3,1] Timo Eichner,[1] Lars Hübner,[3,1] Thomas Hülsenbusch,[3,1] Laurids Jeppe,[1] Trupen Parikh,[3] Matthias Schnepp,[1] and Andreas R. Maier[3,1]

[1]*Center for Free-Electron Laser Science and Department of Physics Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*
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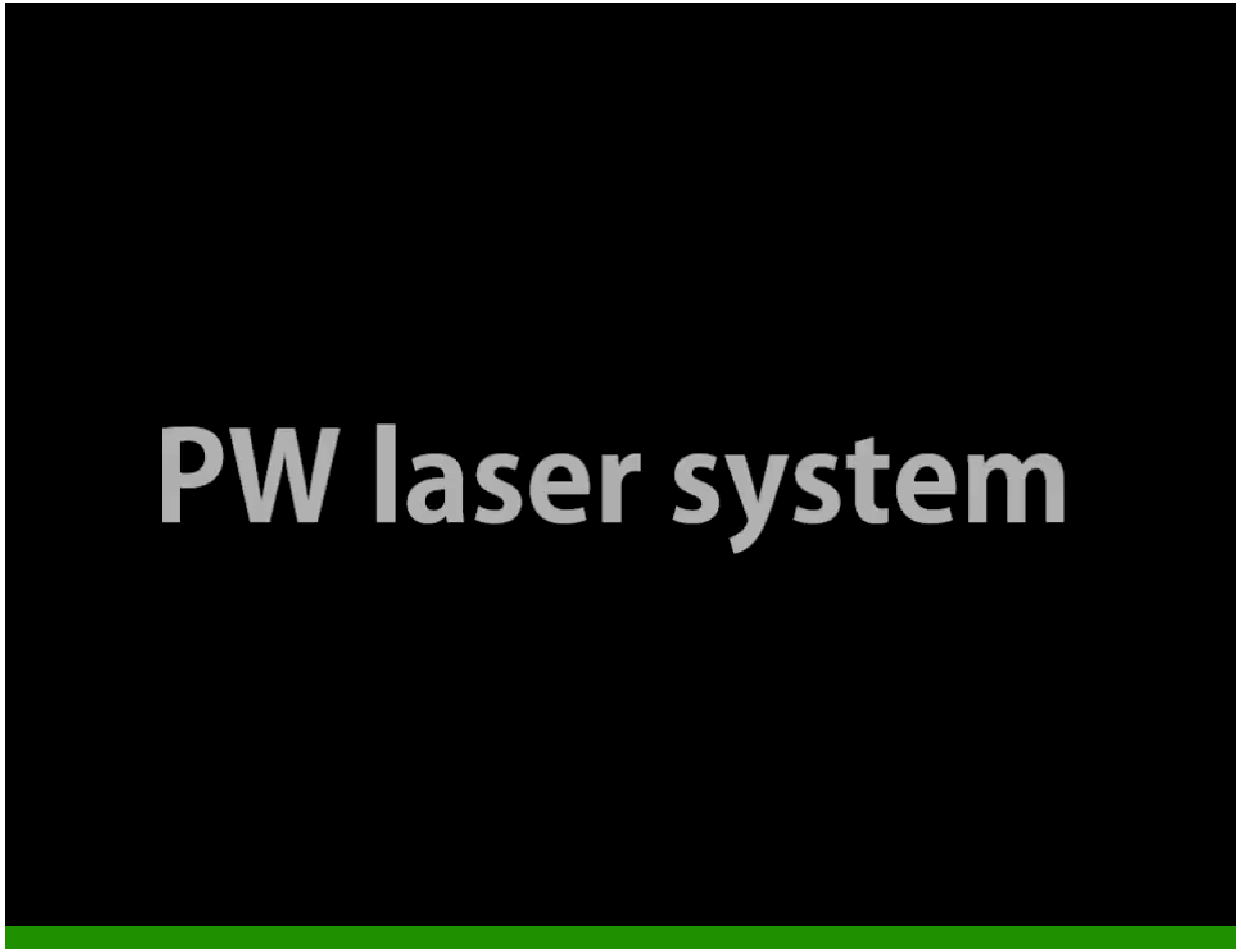
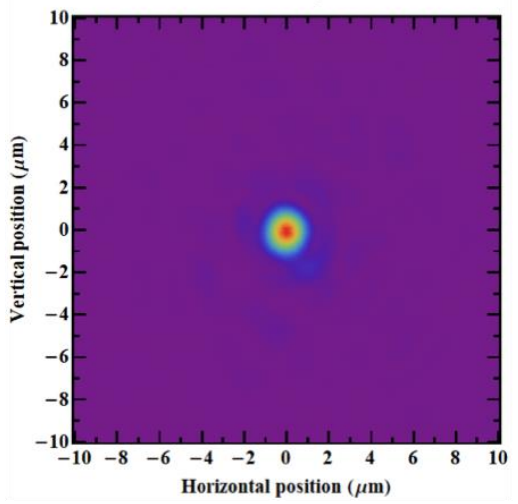
(Received 11 August 2020; revised 16 December 2020; accepted 2 March 2021; published 26 April 2021)

- <1.2% rms energy spread @ 284 MeV, 44pC, by optimal beam loading through ionization injection

The 4 +1 PW laser system at the Center for Relativistic Laser Science in South Korea

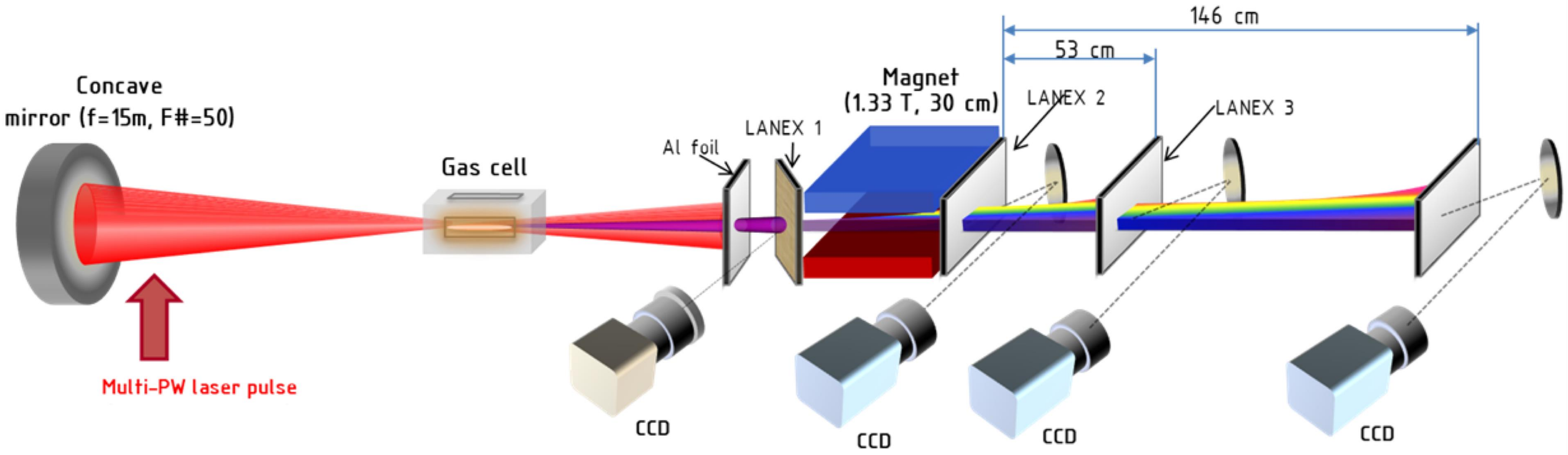


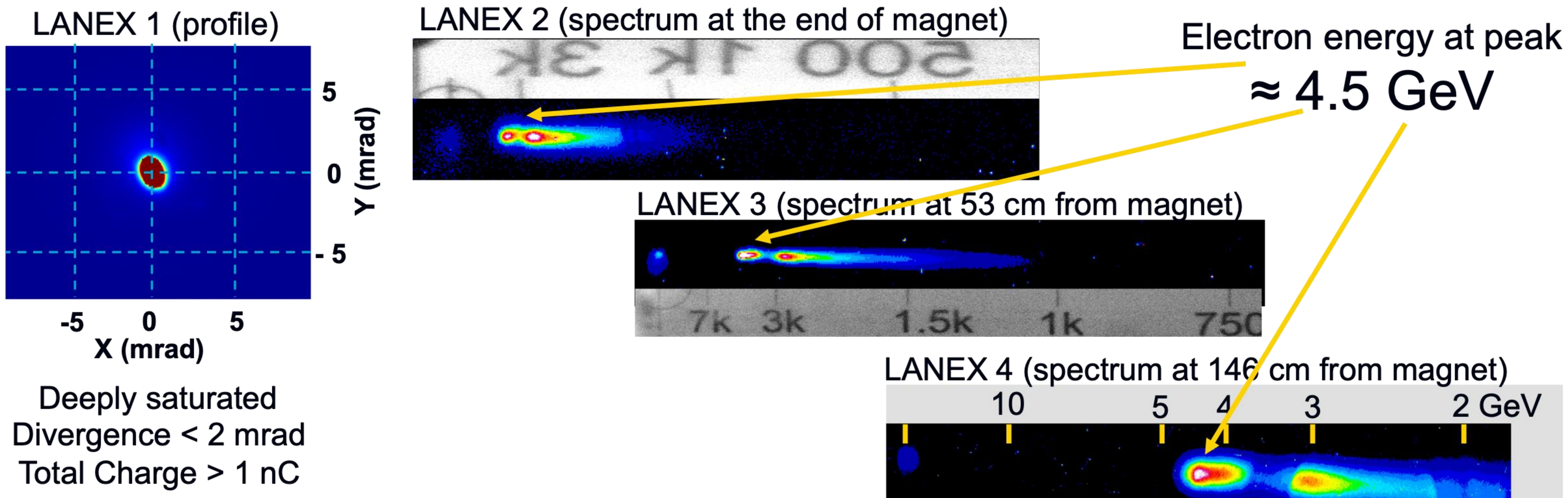
Focal Spot



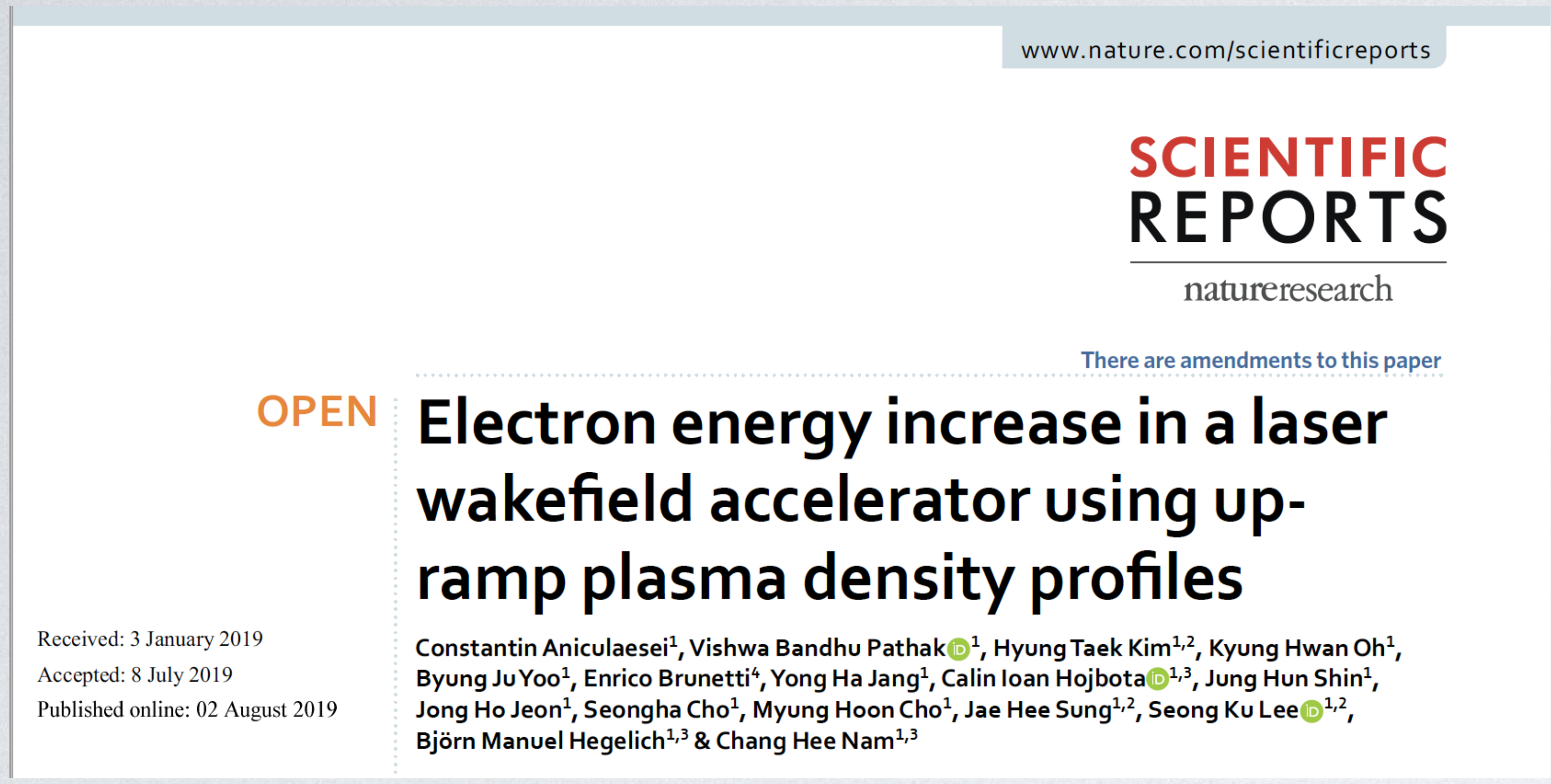
CoReLS laser can in principle produce electron bunches for collision experiment with $\chi>1$

- Laser parameters :
  - 52 J on target, 25fs => 2PW
  - focal spot ≈ 50 µm (FWHM), + 30 fs (GDD +350 fs-2),
  - $I \approx 4.2 \times 10^{19}$ W/cm^2, $a_0 \approx 4.5$
- Gas medium :
  - He mixed with 1-% Ne,
  - 7-cm gas cell
  - plasma density ≈ 1.5×10^{18} elec./cc





Nanoparticle-assisted electron injection into a wakefield at a 50 TW laser


www.nature.com/scientificreports

SCIENTIFIC REPORTS
natureresearch

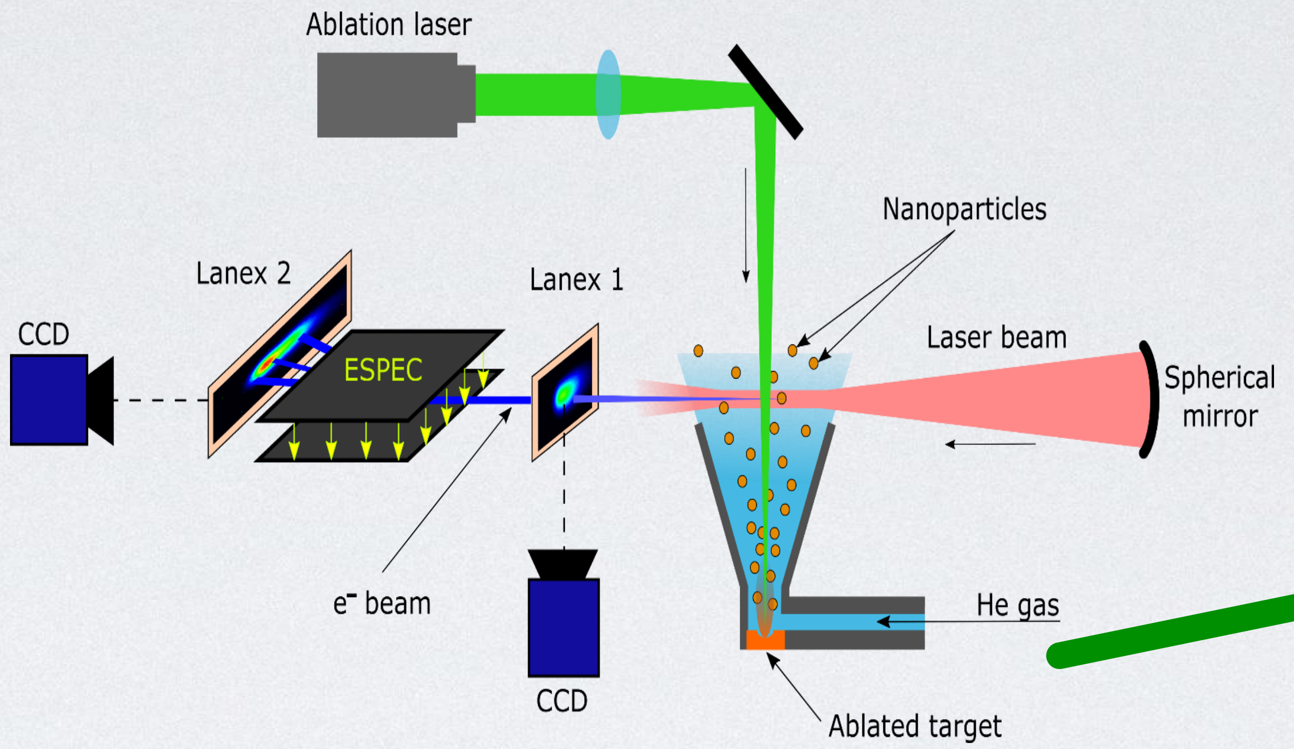
There are amendments to this paper

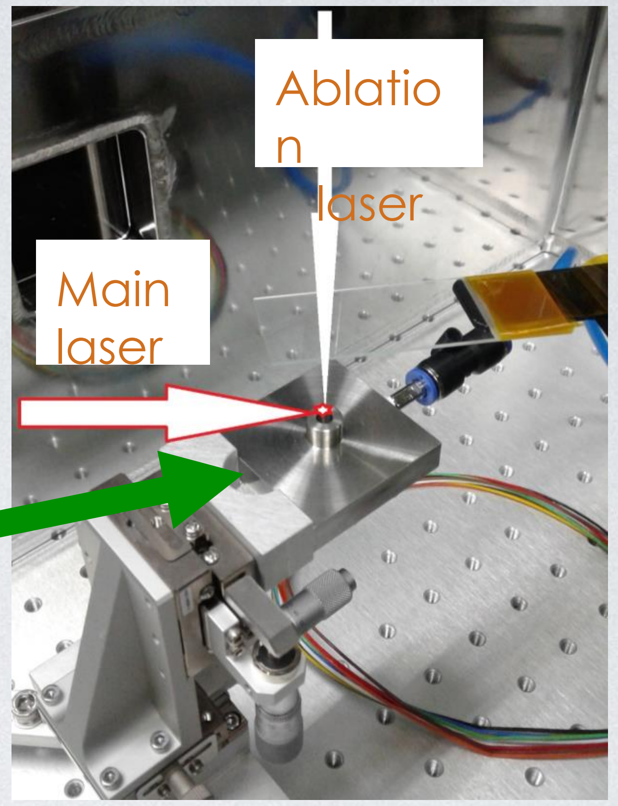
OPEN

Electron energy increase in a laser wakefield accelerator using up-ramp plasma density profiles

Received: 3 January 2019
Accepted: 8 July 2019
Published online: 02 August 2019

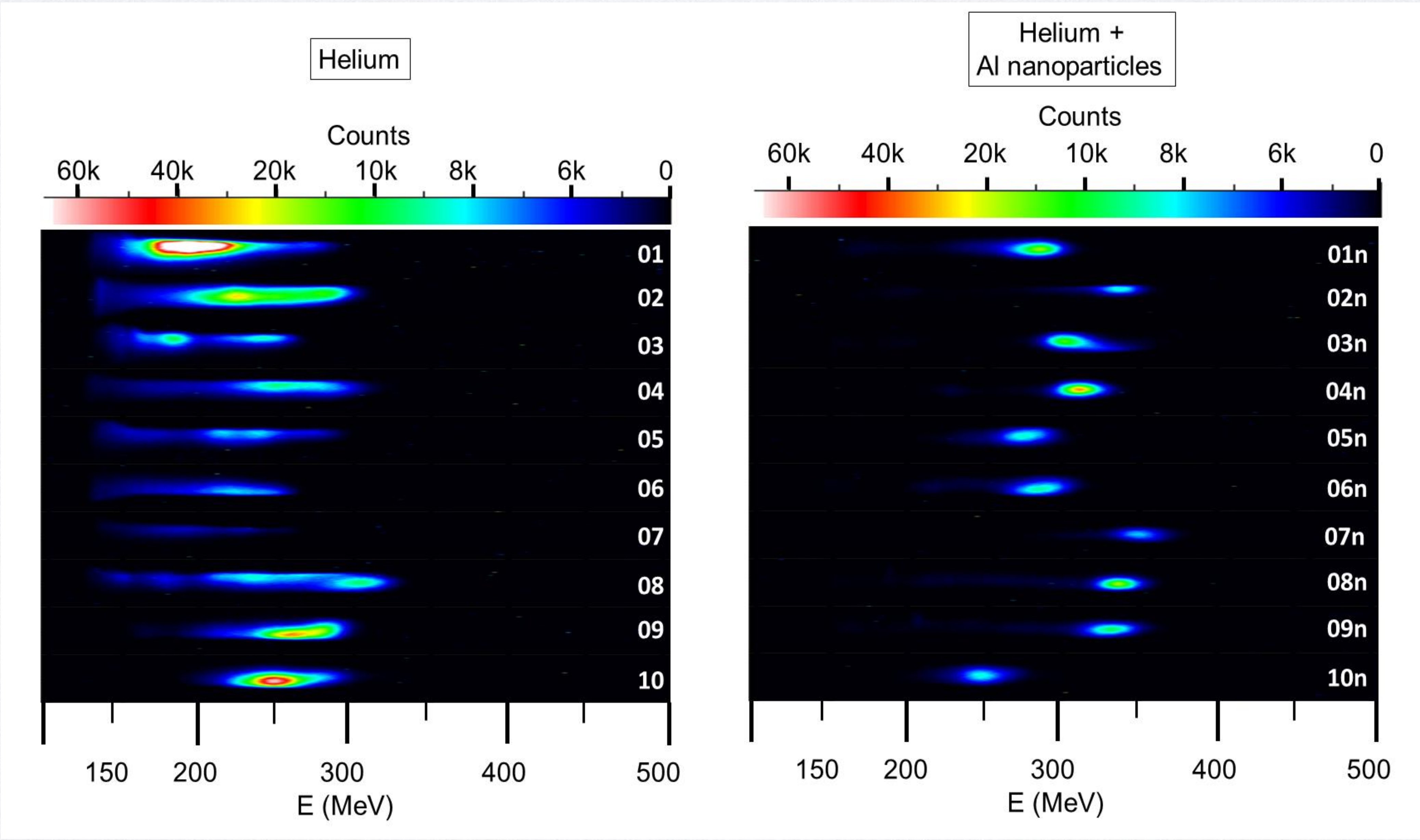
Constantin Aniculaesei[1], Vishwa Bandhu Pathak[1], Hyung Taek Kim[1,2], Kyung Hwan Oh[1], Byung Ju Yoo[1], Enrico Brunetti[4], Yong Ha Jang[1], Calin Ioan Hojbota[1,3], Jung Hun Shin[1], Jong Ho Jeon[1], Seongha Cho[1], Myung Hoon Cho[1], Jae Hee Sung[1,2], Seong Ku Lee[1,2], Björn Manuel Hegelich[1,3] & Chang Hee Nam[1,3]



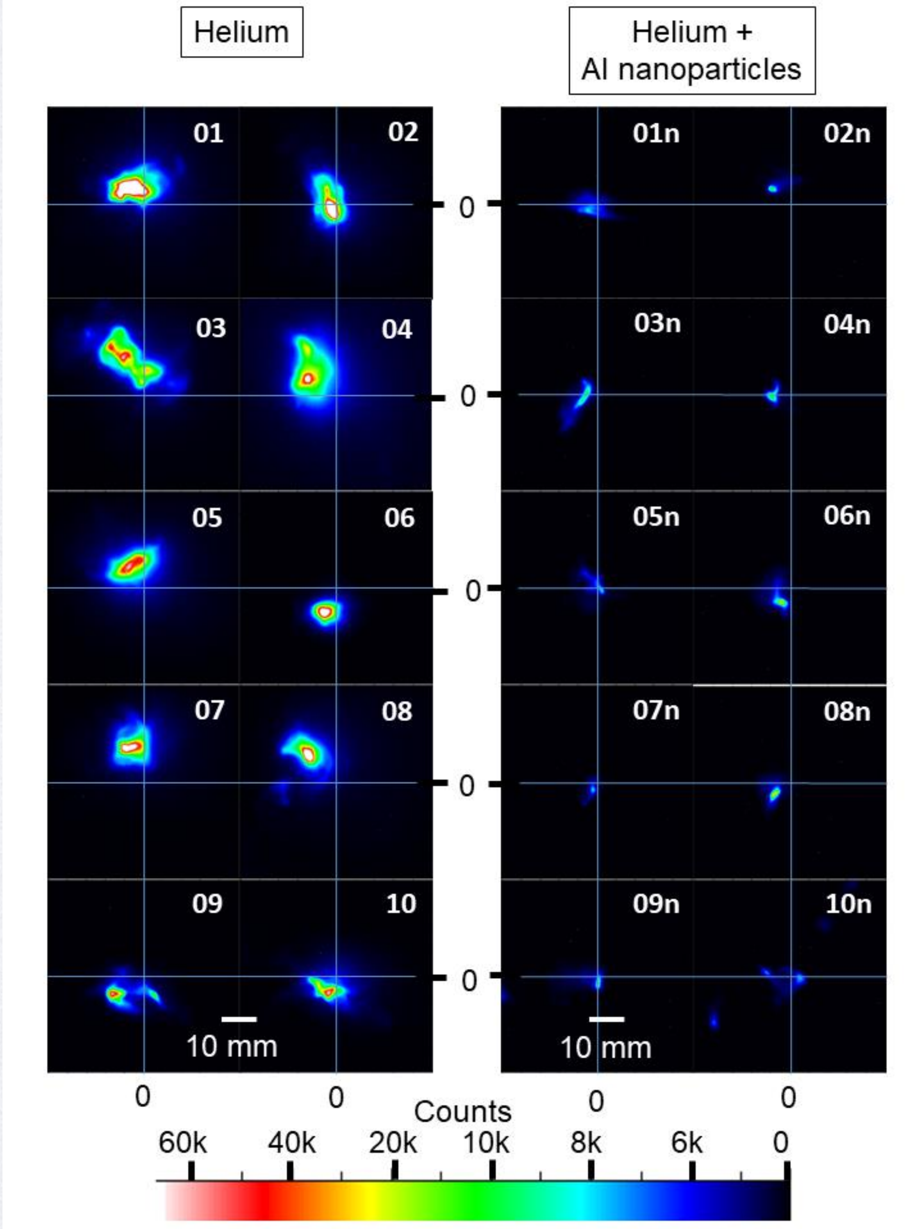


- The hybrid gas target can generate supersonic gas jets doped with any kind of nanoparticles
- The density and size of nanoparticle controlled by the laser energy, pulse width and fluence
- ***Electron peak energy and energy spread greatly improved***
- ***Electron beam divergence decreased***

no nanoparticles | with nanoparticles



no nanoparticles | with nanoparticles



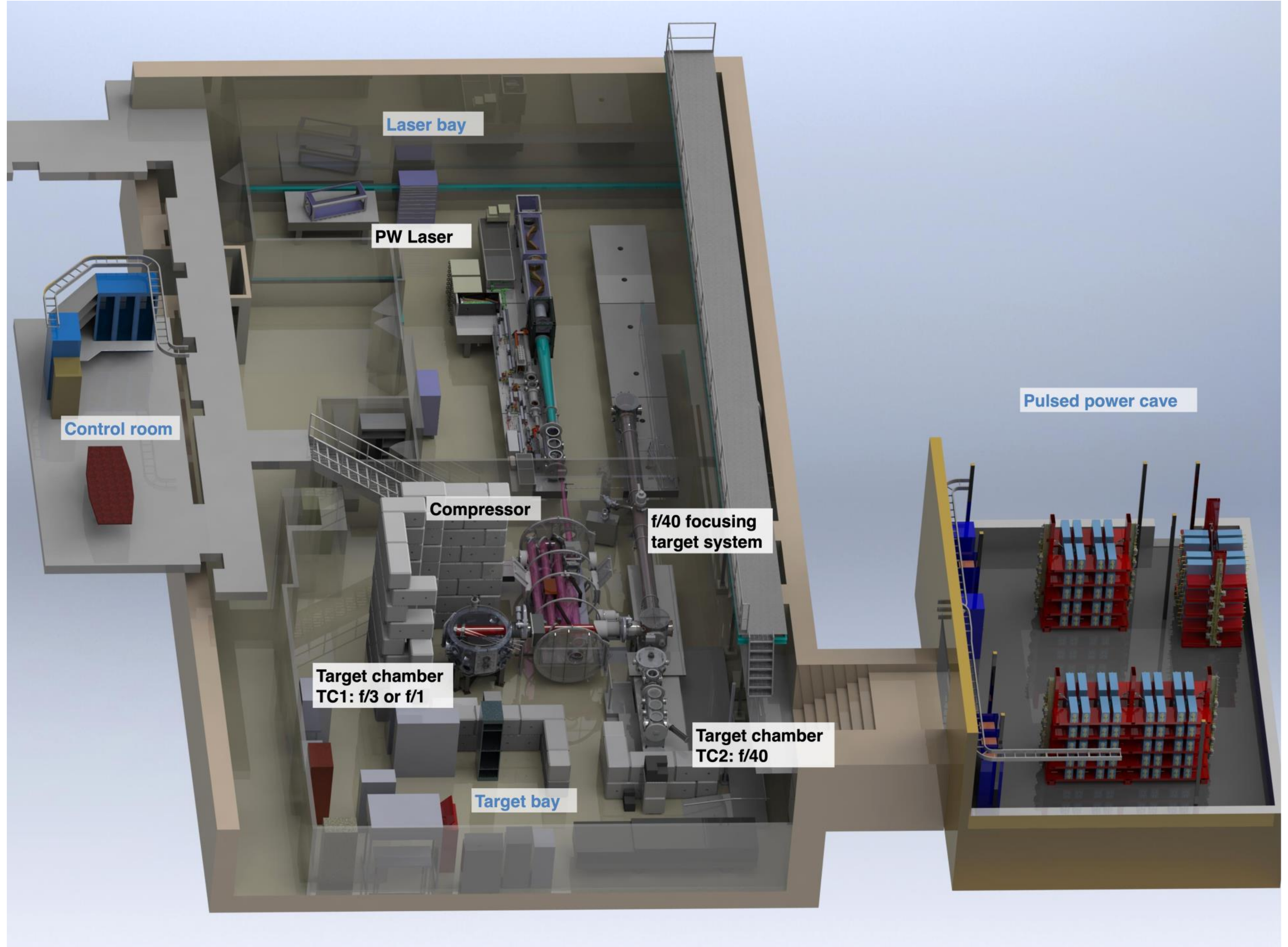
The Texas Petawatt Laser at UT Austin

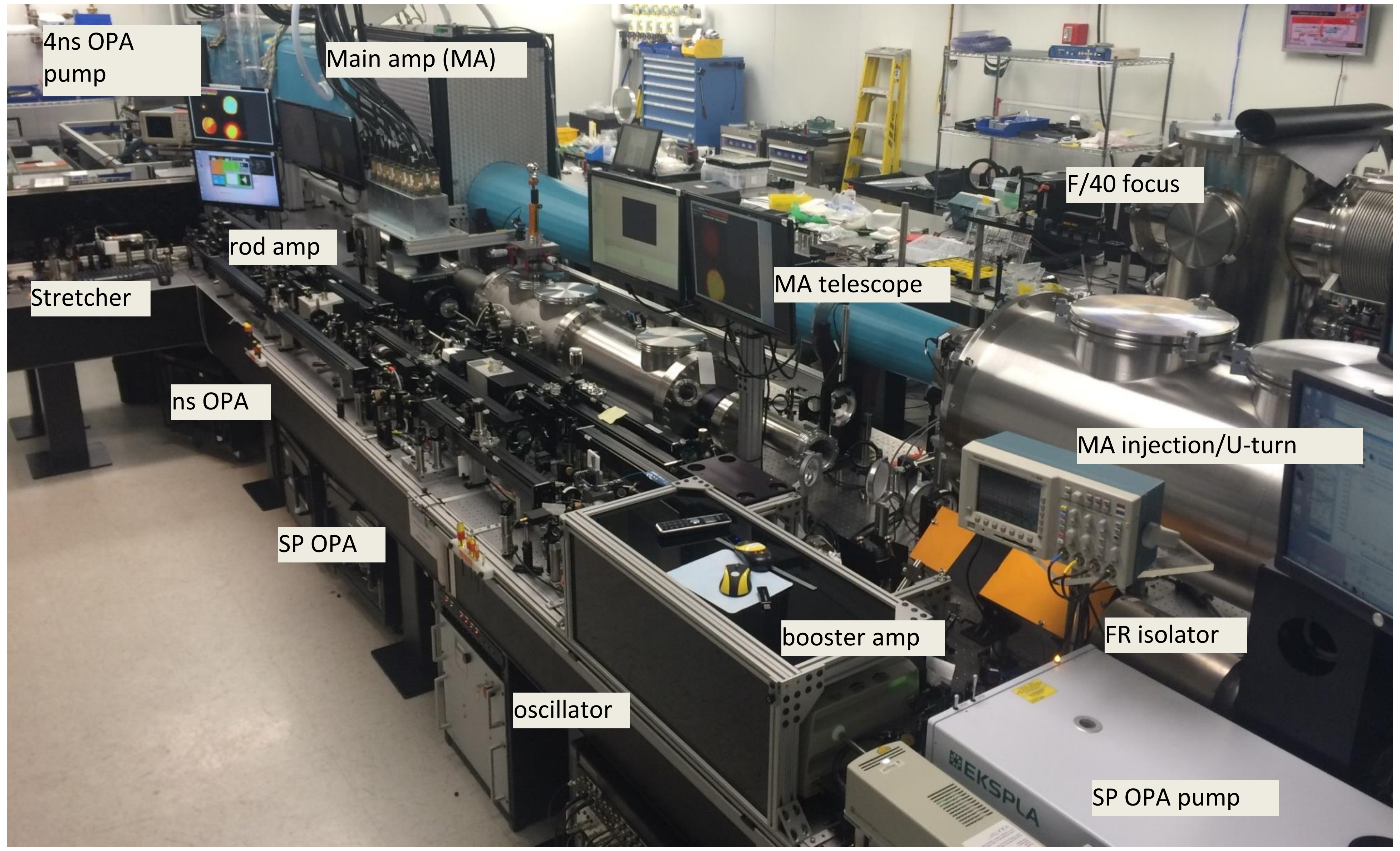
Laser Parameters:

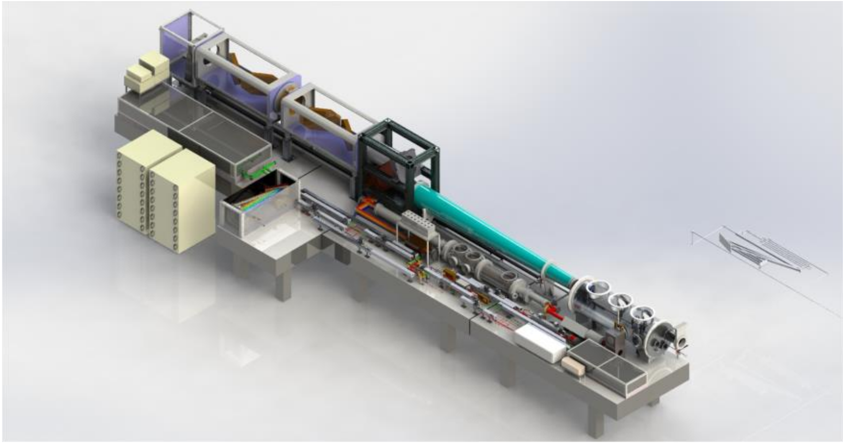
- 150 J
- 150 fs
- 1 shot/hr
- 2 Target Areas:
  - F/40: 2×10^{18} W/cm^2
  - F/3: 10^{21} W/cm^2
  - F/1: $>3\times10^{22}$ W/cm^2

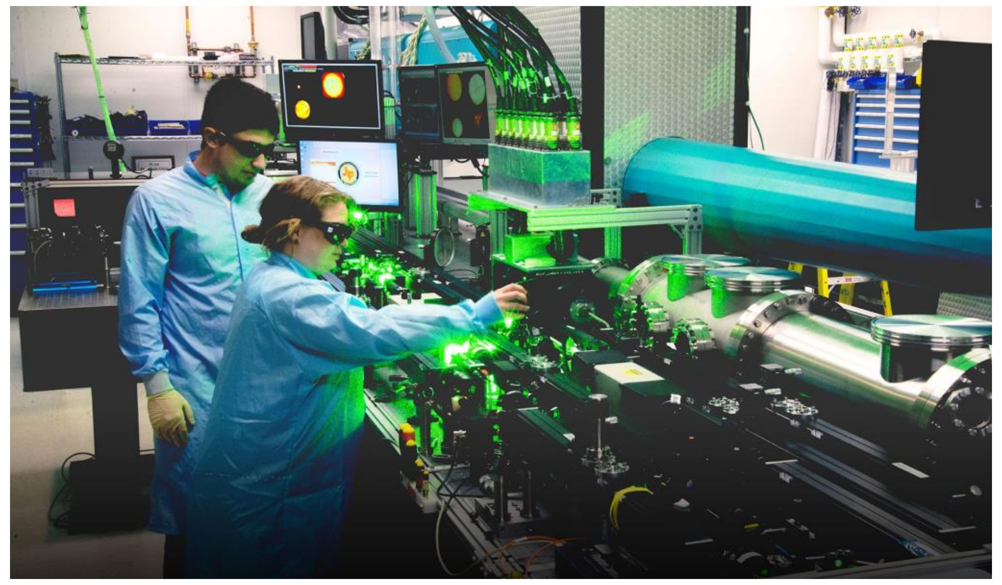
Demonstrated Performance

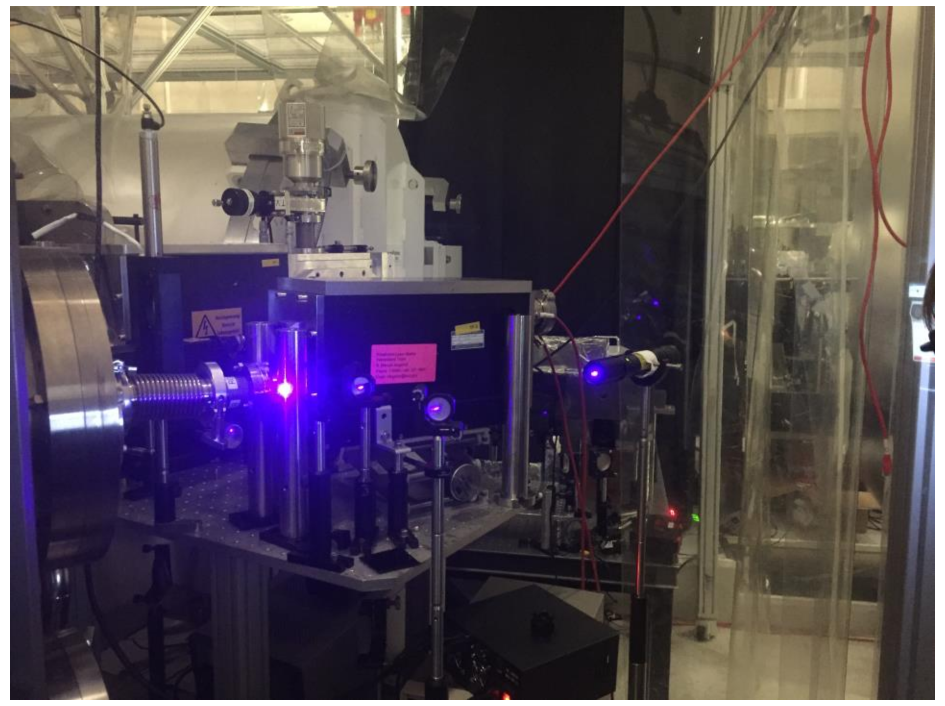
- 3 GeV electrons
- 100 MeV protons
- 600 MeV carbon
- 4.4 GeV Au
- $>10^{10}$ neutron/shot
- >50 MeV γ-ray beam

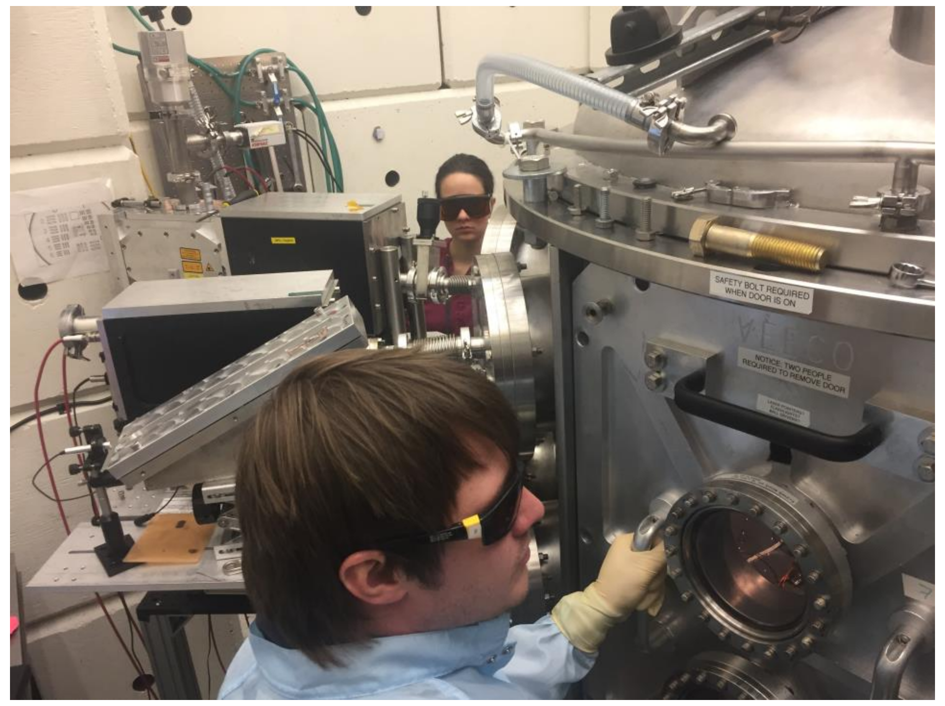












Canonical TPW LWFA result: 2012 record
Xiaoming Wang, M. Downer, et al.

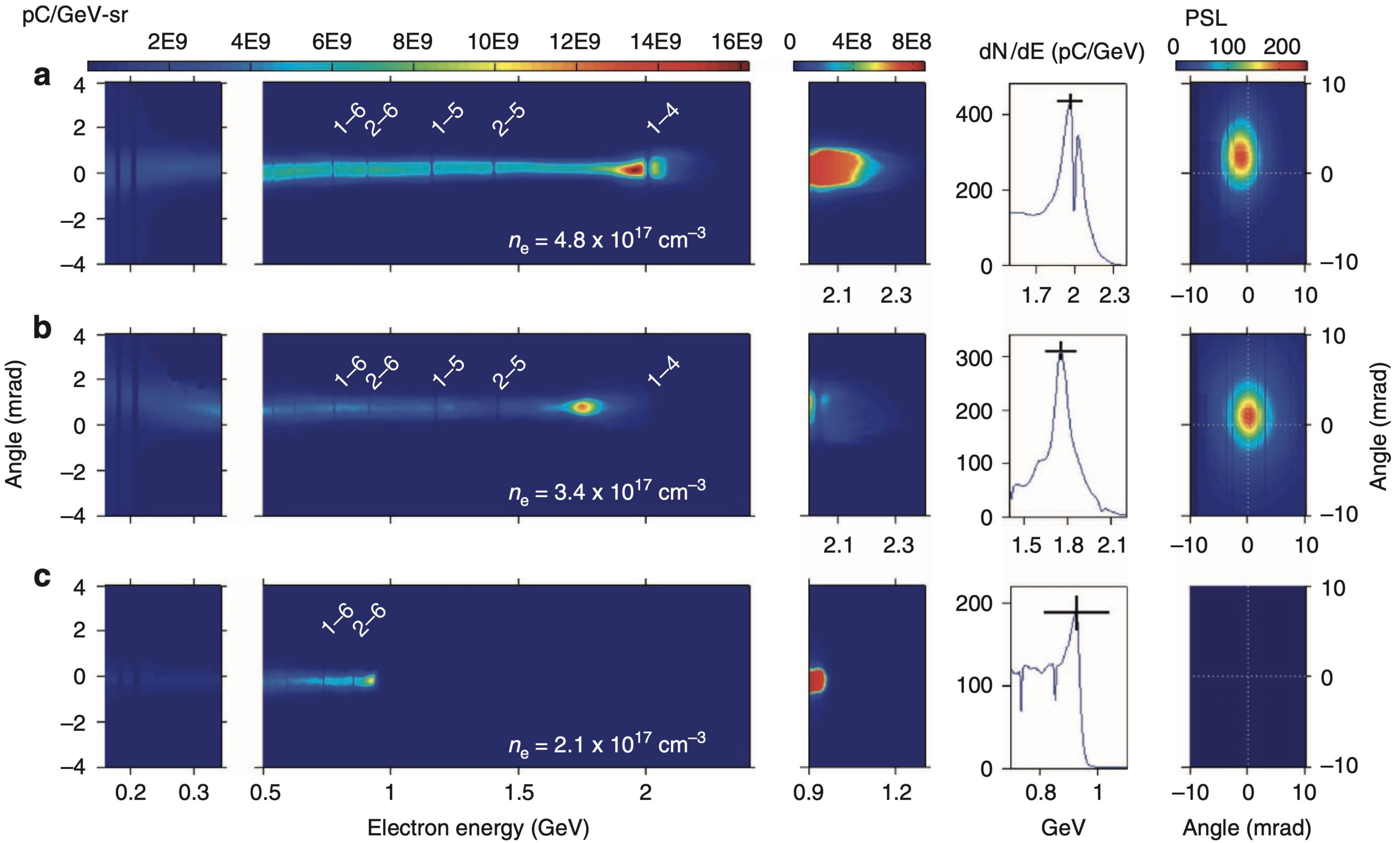
nature COMMUNICATIONS

ARTICLE

Received 2 Dec 2012 | Accepted 8 May 2013 | Published 11 Jun 2013 DOI: 10.1038/ncomms2988 OPEN

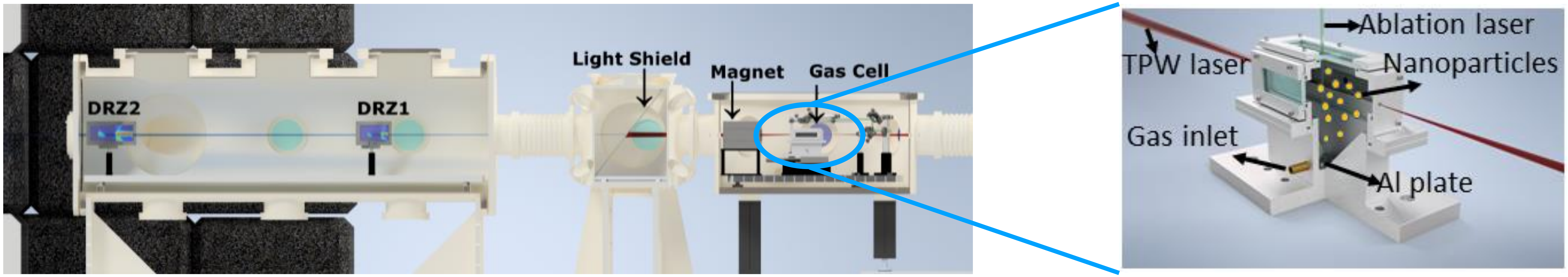
Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV

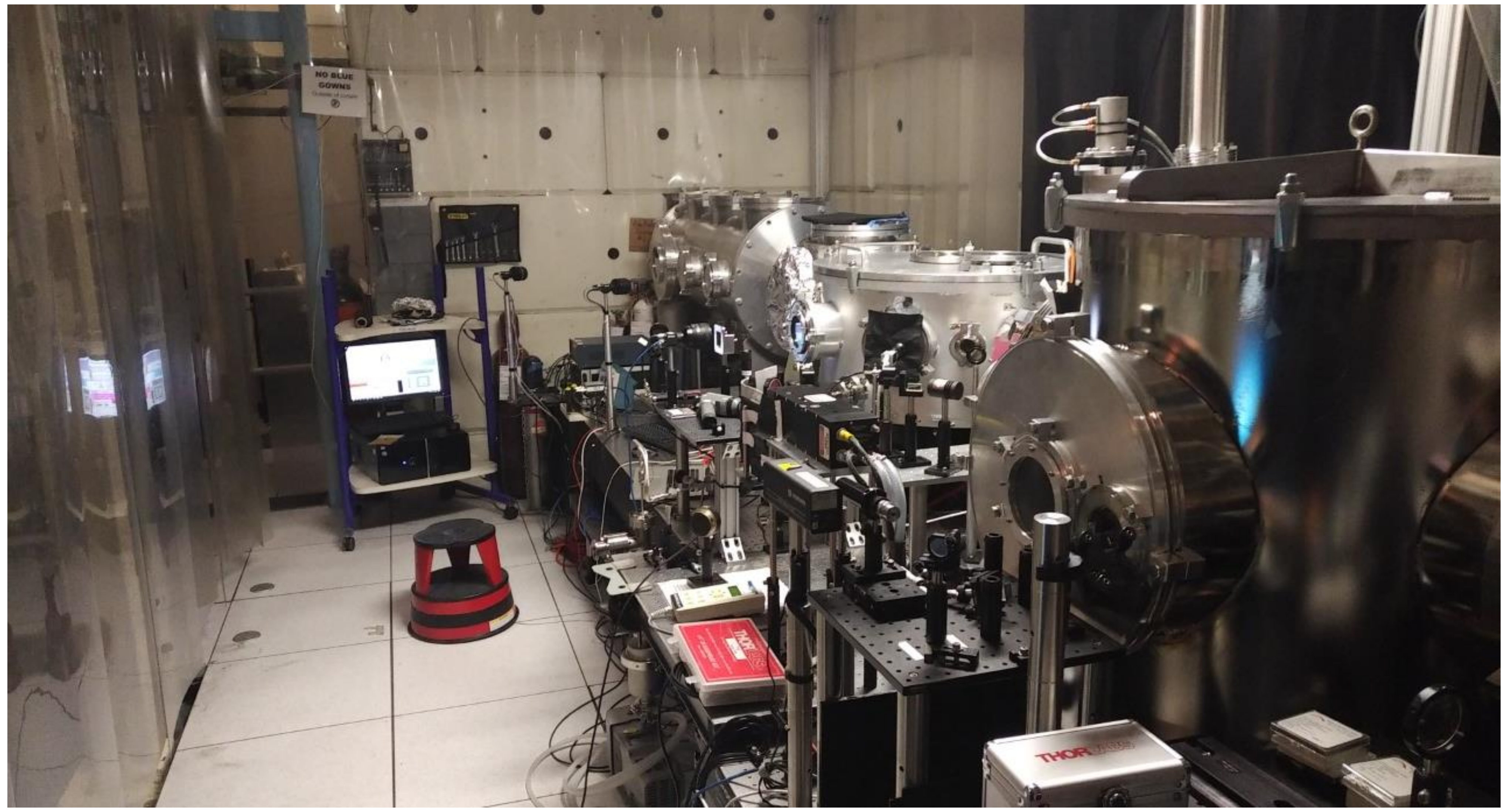
Xiaoming Wang[1], Rafal Zgadzaj[1], Neil Fazel[1], Zhengyan Li[1], S. A. Yi[1], Xi Zhang[1], Watson Henderson[1], Y.-Y. Chang[1], R. Korzekwa[1], H.-E. Tsai[1], C.-H. Pai[1], H. Quevedo[1], G. Dyer[1], E. Gaul[1], M. Martinez[1], A. C. Bernstein[1], T. Borger[1], M. Spinks[1], M. Donovan[1], V. Khudik[1],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

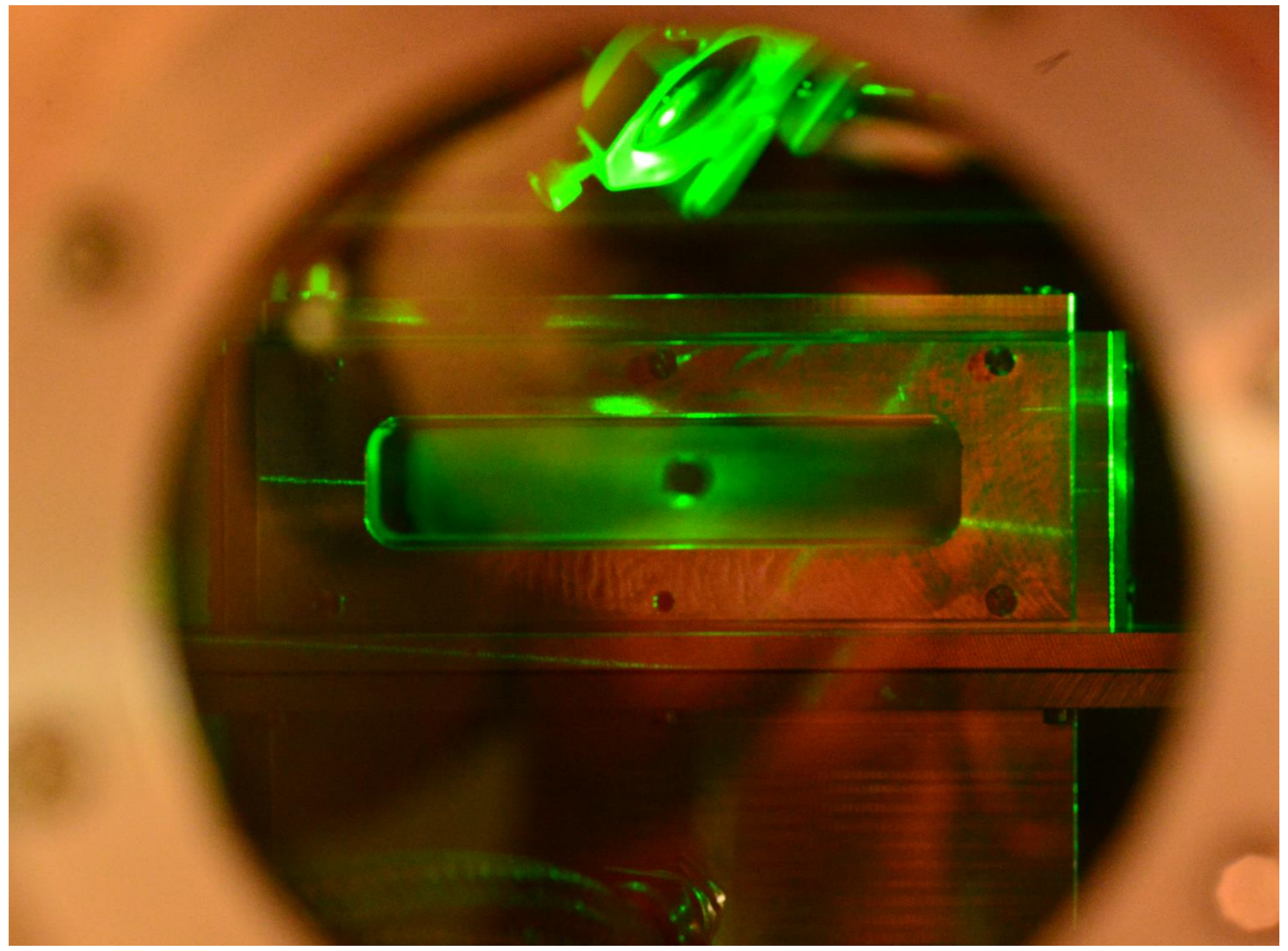


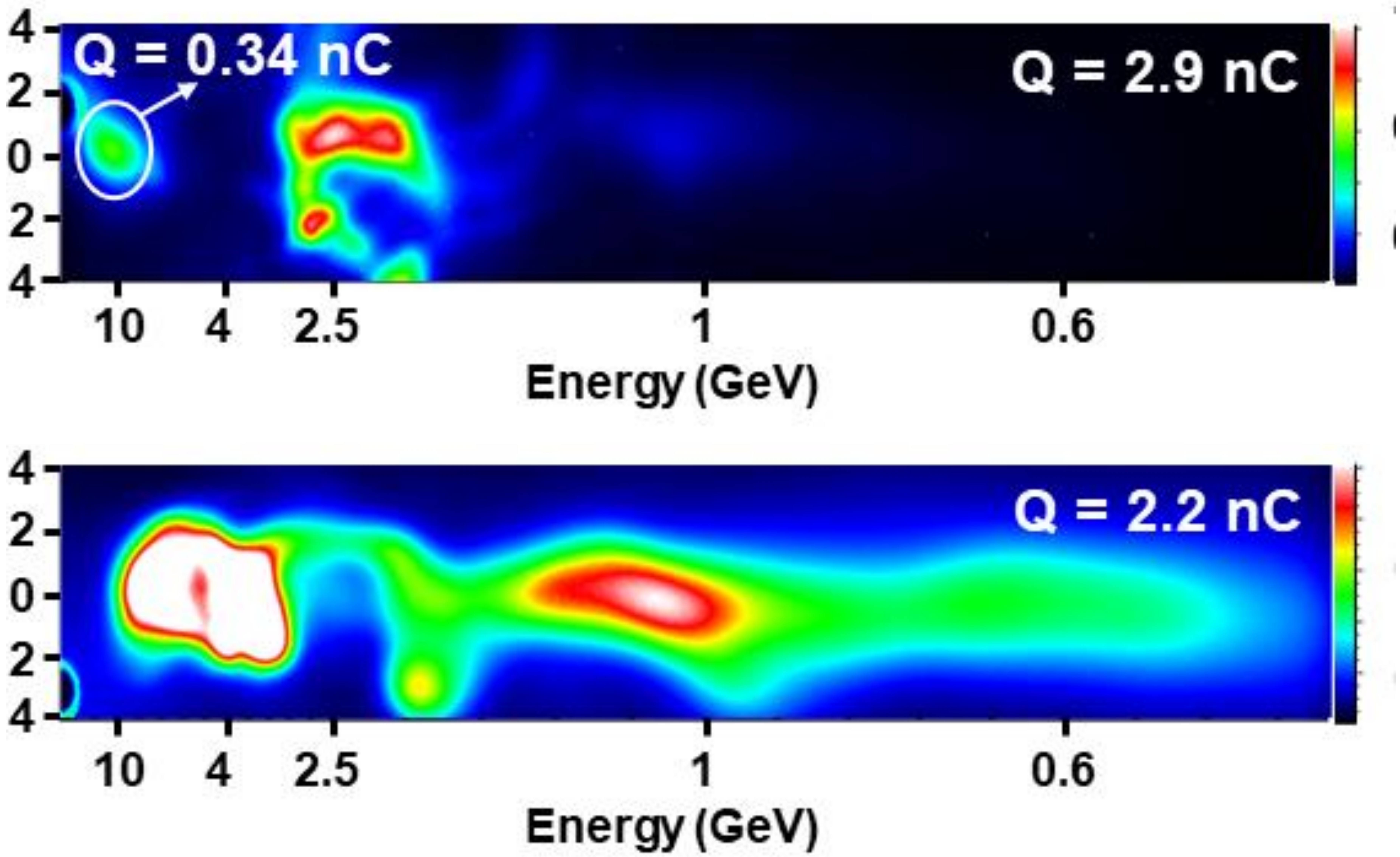
Relativistic Quantum Photonics

Experimental Setup

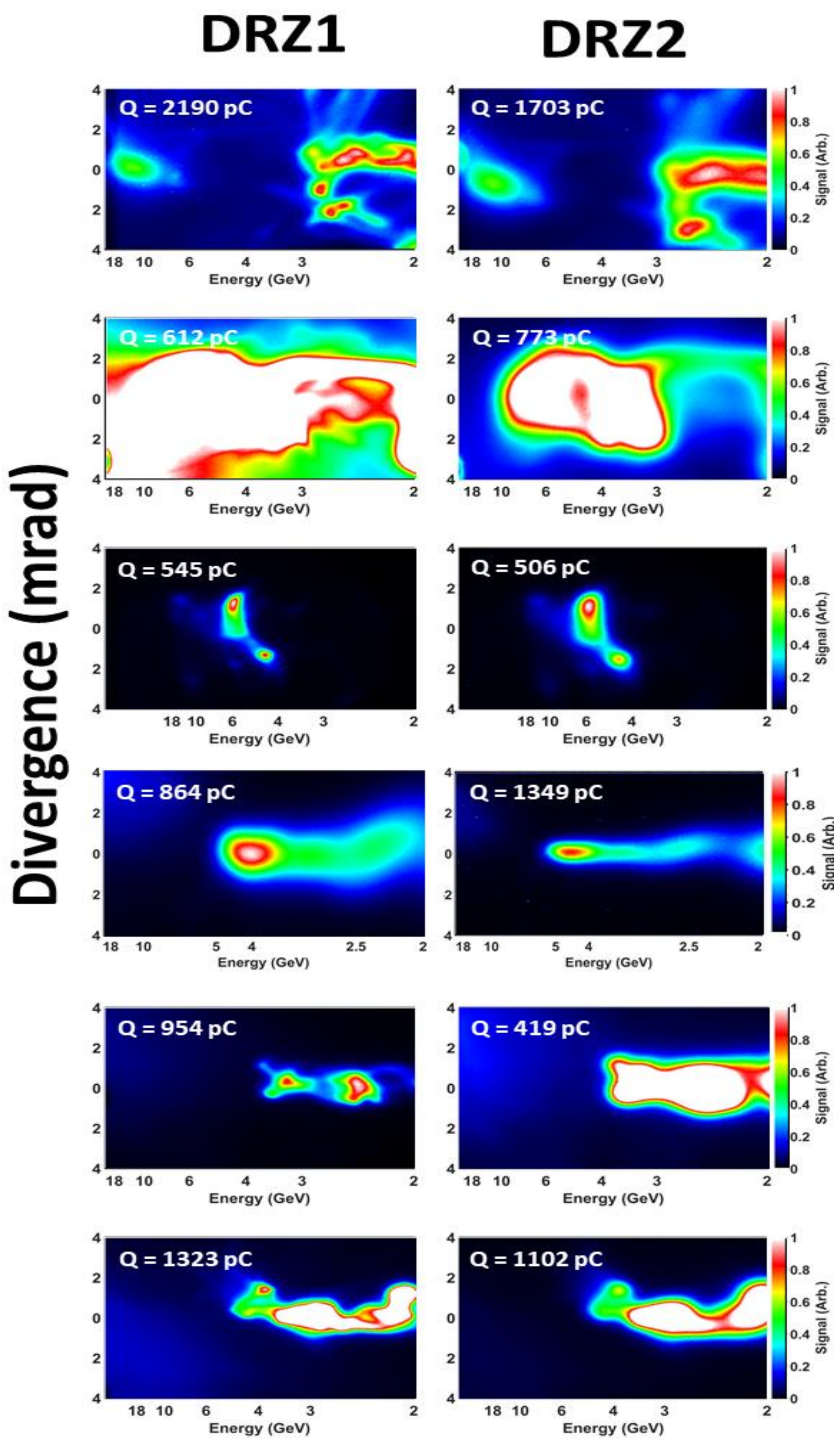


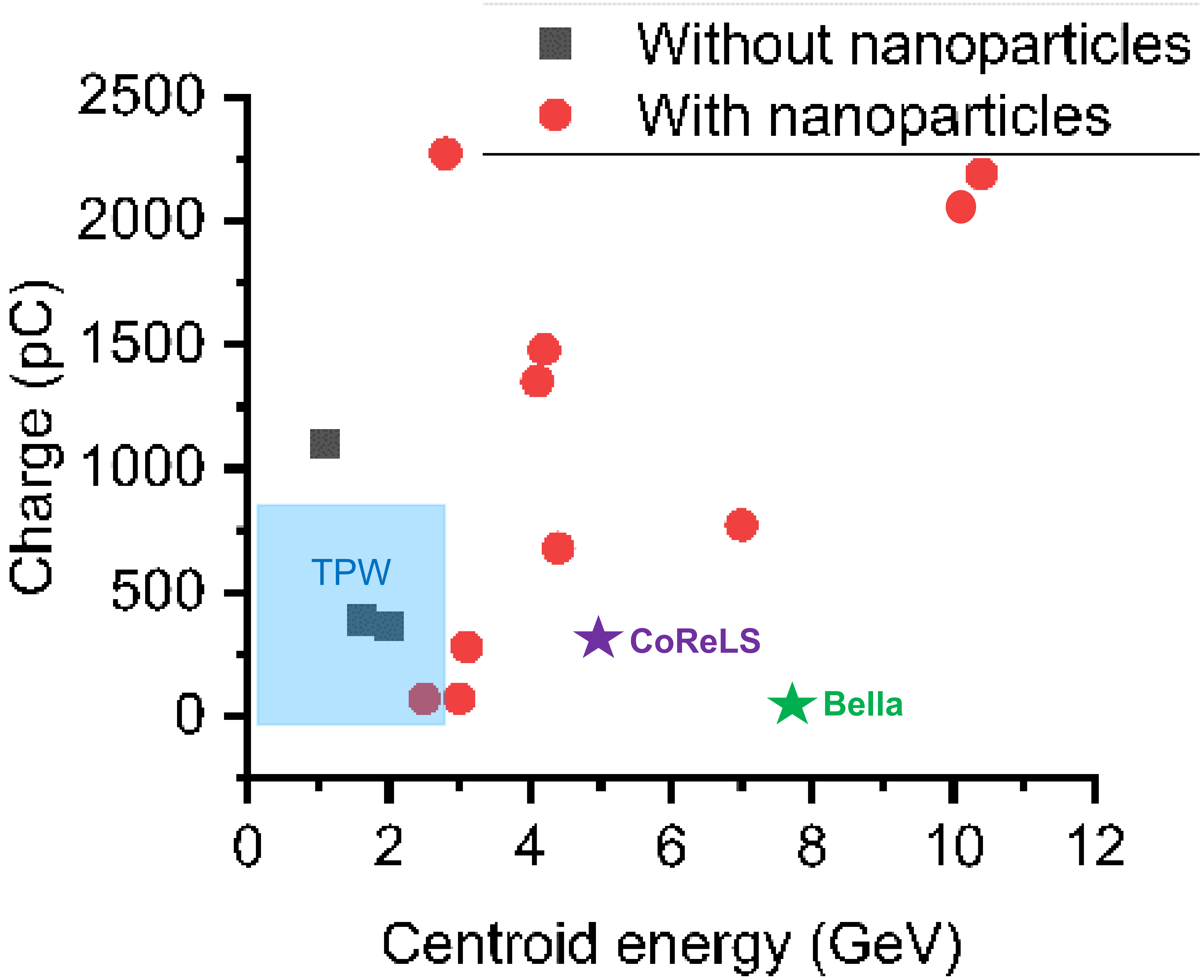






Q = 0.34 nC
Q = 2.9 nC
4
2
0
2
4
10
4
2.5
1
0.6
Energy (GeV)
Q = 2.2 nC
4
2
0
2
4
10
4
2.5
1
0.6
Energy (GeV)


DRZ1
DRZ2
Divergence (mrad)
Q = 2190 pC
Q = 1703 pC
Q = 612 pC
Q = 773 pC
Q = 545 pC
Q = 506 pC
Q = 864 pC
Q = 1349 pC
Q = 954 pC
Q = 419 pC
Q = 1323 pC
Q = 1102 pC
Energy (GeV)
Signal (Arb.)


Without nanoparticles
With nanoparticles
Charge (pC)
Centroid energy (GeV)
TPW
CoReLS
Bella

Article

Free-electron lasing at 27 nanometres based on a laser wakefield accelerator

https://doi.org/10.1038/s41586-021-03678-x

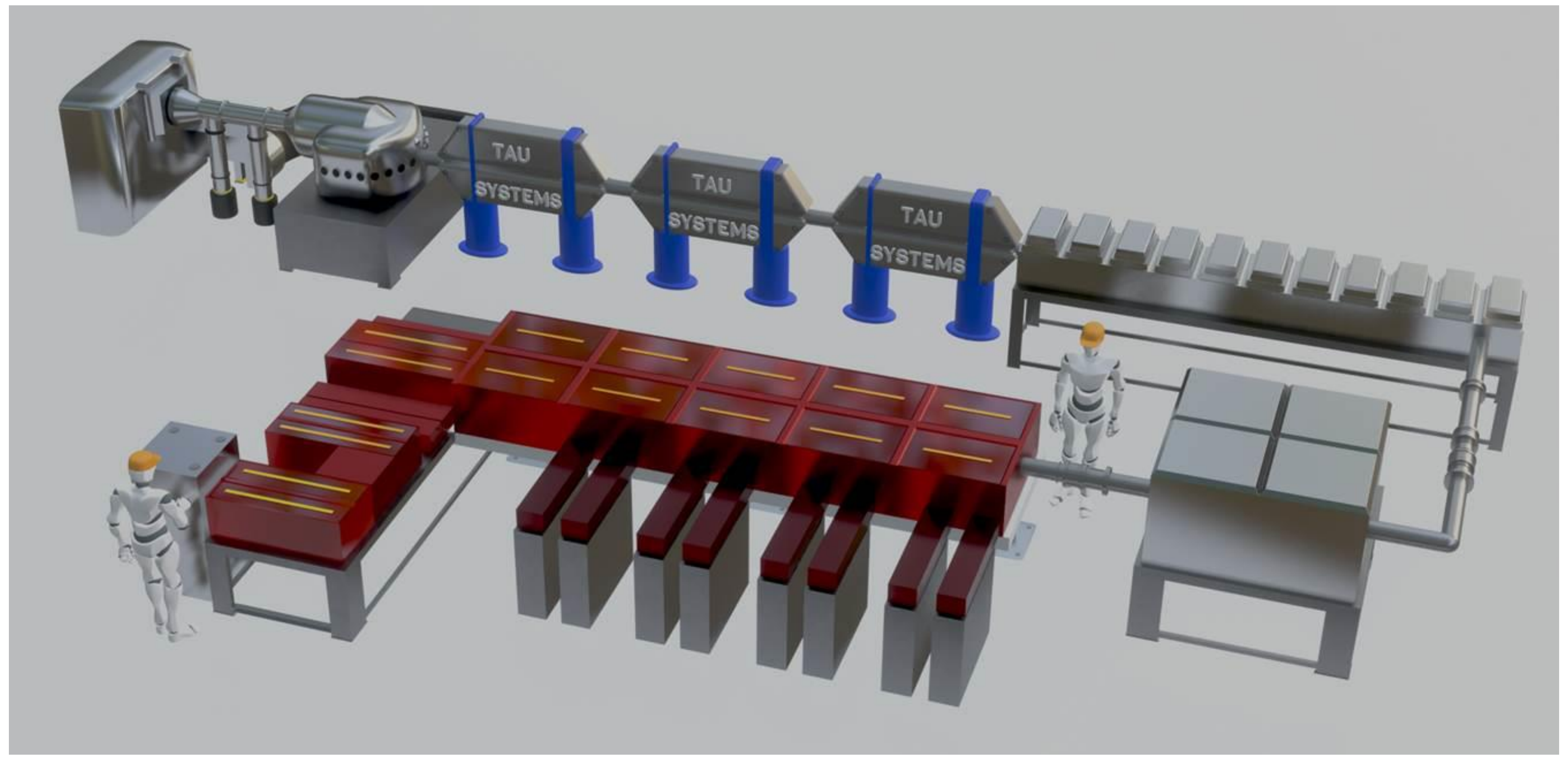
Received: 5 August 2020

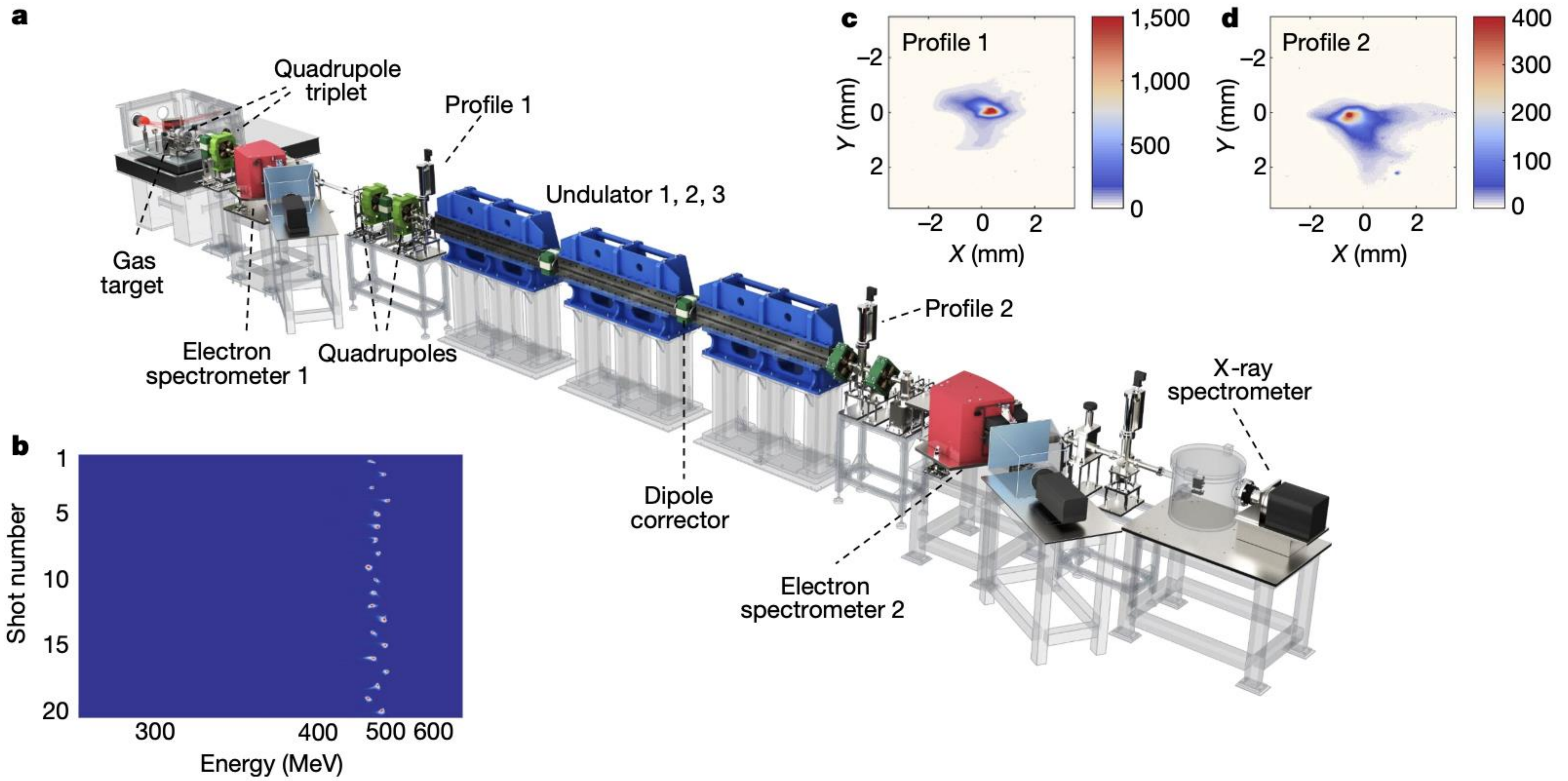
Accepted: 28 May 2021

Published online: 21 July 2021

Wentao Wang[1,4]✉, Ke Feng[1,4], Lintong Ke[1,2], Changhai Yu[1], Yi Xu[1], Rong Qi[1], Yu Chen[1], Zhiyong Qin[1], Zhijun Zhang[1], Ming Fang[1], Jiaqi Liu[1], Kangnan Jiang[1,3], Hao Wang[1], Cheng Wang[1], Xiaojun Yang[1], Fenxiang Wu[1], Yuxin Leng[1], Jiansheng Liu[1]✉, Ruxin Li[1,3]✉ & Zhizhan Xu[1]

516 | Nature | Vol 595 | 22 July 2021





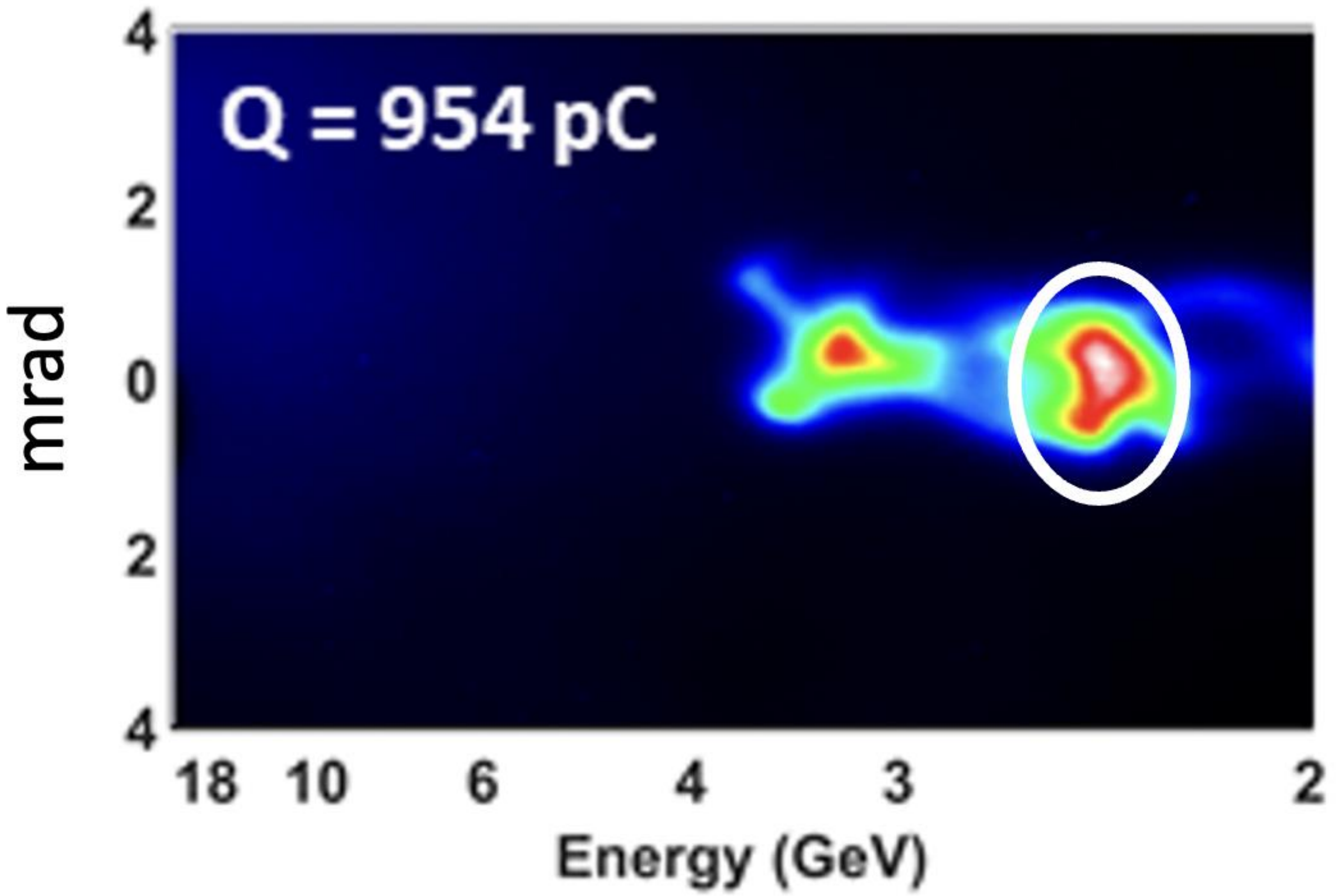
A recent article in Nature establishes the ability to achieve single pass FEL gain using beam from a reasonably stabilized LWFA beam.

Texas Petawatt Beams: FEL Potential?

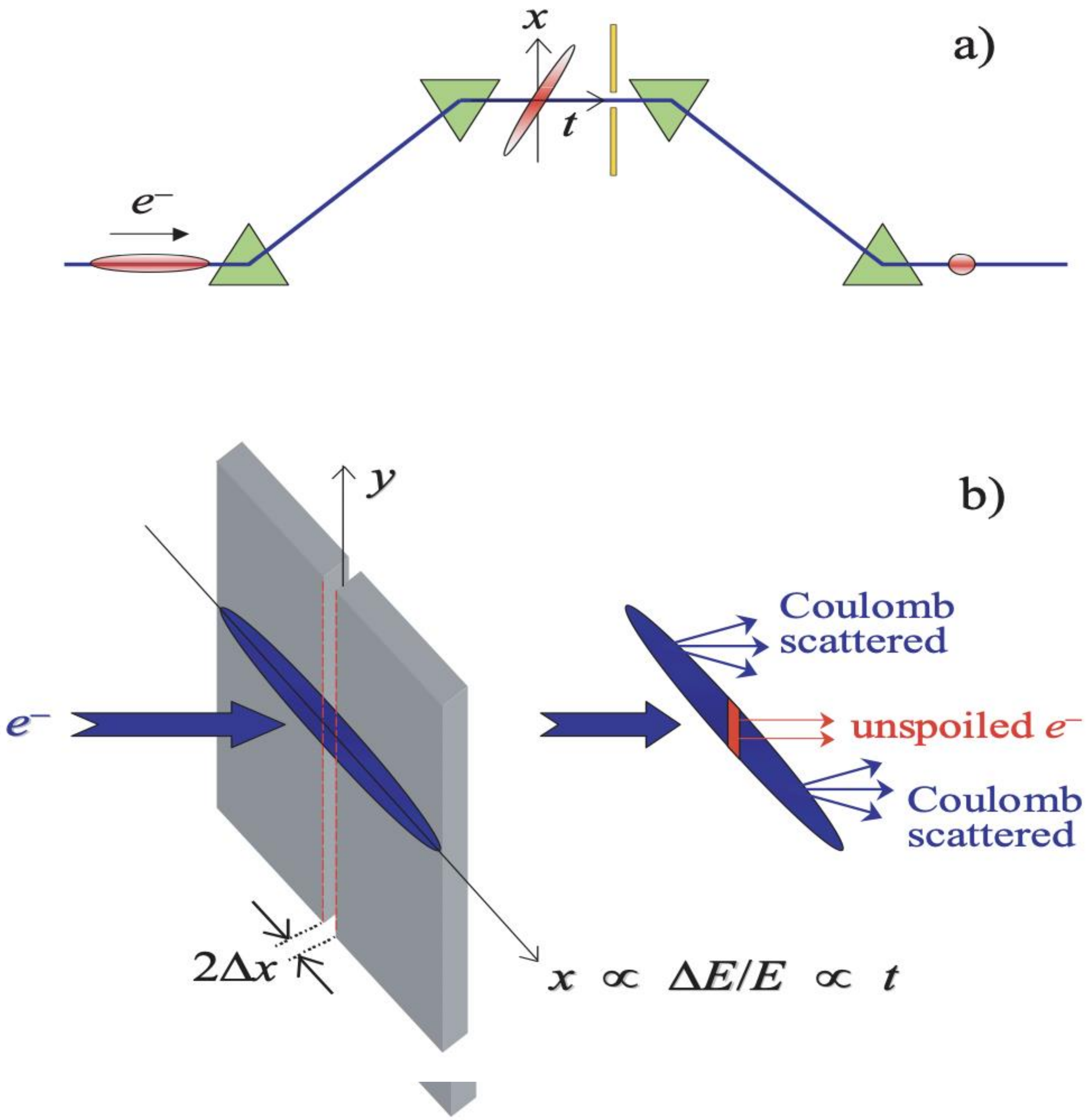
The Texas Petawatt Laser system can be used to generate beams with interesting possibilities, as the energies and charge delivered are significant.

The rough beam parameters for the shot shown in the white circle are given below. While certainly impressive, they are not quite suitable to drive a free-electron laser as the energy spread is too large. Additional beam manipulation must be done.

Quantity	Value
Energy [GeV]	2.3
rms Energy Spread [%]	2
Charge [pC]	800
rms Bunch Length [fs]	40
Geometric Emittance [nm-rad]	0.3



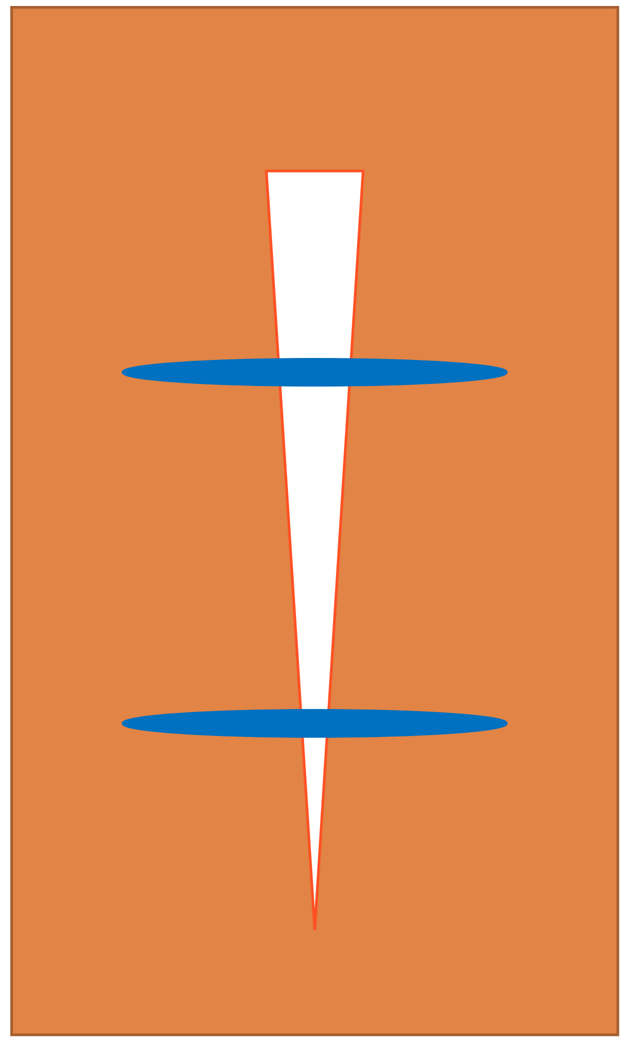
Beam Slicing to Improve the Beam Properties



Femtosecond and sub-femtosecond x-ray pulses from a SASE-based free-electron laser

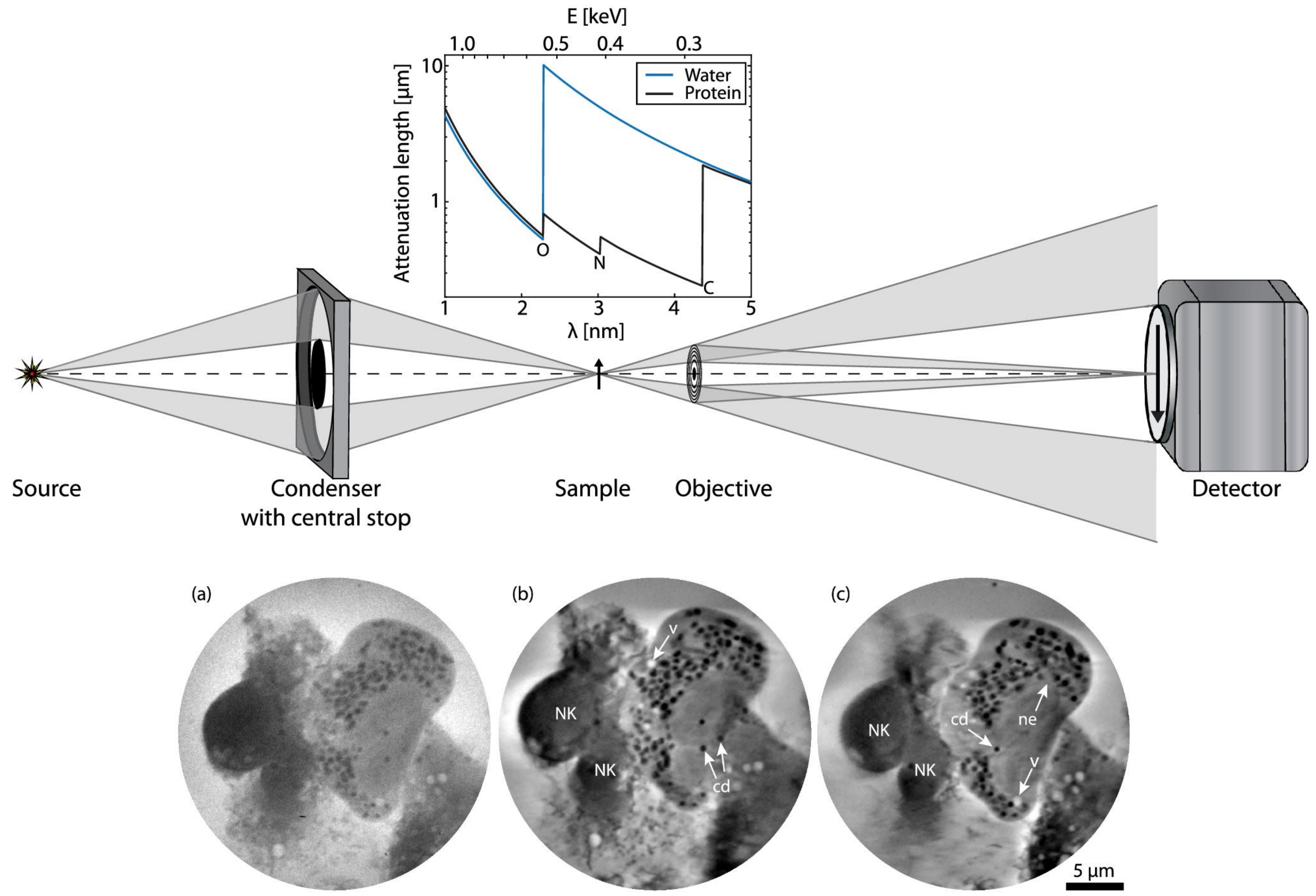
P. Emma, et al.

SLAC-PUB-10002



If we add a dispersive section that has controllable R_{56} and can be made isochronous and dispersion free as necessary, and if the LWFA generated electron beam has small slice emittance, then one could slice out a small potion of the beam with reasonable energy spread. This potion of the bunch would have parameters suitable for single pass FEL operation.

FEL Operation at the the Water Window



Laboratory water-window x-ray microscopy

Mikael Kördel, Aurélie Dehlinger, Christian Seim, Ulrich Vogt, Emelie Fogelqvist, Jonas A. Sellberg, Holger Stiel, and Hans M. Hertz

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Conclude: We may already have beam properties within regions of the TPW laser laser wakefield accelerated beams that could potentially drive a single pass FEL in the water window to saturation

Slicing the beam in afore mentioned manner and using a parameterization for FEL performance* gives the following beam and FEL properties. Saturation in the water window is achieve with a 16.4-m long undulator

Quantity	Value
Energy [GeV]	2.3
rms Energy Spread [%]	0.5
Charge [pC]	200
rms Bunch Length [fs]	10
Geometric Emittance [nm-rad]	0.3
Undulator Period [cm]	2.78
Undulator K value	2.6
Resonant Wavelength [nm]	3.0
Resonant Photon Energy [eV]	413
Average Beta in Undulator [m]	1.5
FEL Rho Parameter	0.005
1d FEL Gain Length [m]	0.245
Eta: 3d beam quality reduction term	2.44
3d FEL Gain Length [m]	0.84
3d FEL Saturation Length [m]	16.4
3d Saturated Peak Power [GW]	32.4

DESIGN OPTIMIZATION FOR AN X-RAY FREE ELECTRON LASER DRIVEN BY SLAC LINAC *

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Summary

- Wakefield Accelerators hold a huge potential to make accelerators and light sources ubiquitous and accessible
- Impressive recent progress
  - demonstration of PWFA with both electron and proton bunches (Facet, AWAKE)
  - staging of LWFA - PWFA (HZDR and others)
  - injection of RF accel. bunch into LWFA (Tsinghua)
  - >24h stable LWFA operation with ML (Des)
  - LWFA-driven FEL @ 27nm (SIOM)
  - >10 GeV, ~500s pC by nanoparticle assisted LPWFA (UT Austin)
- How to optimize emittance, energy spread, reproducibility simultaneously?
- What is the most promising laser-driver?

Open Positions

- Scientist: LWFA, Laser-based x-ray generation, XFELs, beam lines, and diagnostics
  Experimental: Postdoc/Staff Scientist (jun./sen)

- Laser Scientists/Engineers/Technicians: ultrahigh intensity lasers, high average power lasers, spatio-temporal pulse control, ML, control systems
  Staff Scientist (jun./sen.)

- Control systems engineer: lasers and/or accelerators

- XFEL applications in structural biology, macromolecular chemistry: single particle imaging, serial femtosecond chrystallography, …

- *Industry competitive salary (US), unlimited contract*