Plasma wakefield accelerators.

EuPRAXIA and ALEGRO projects.

Roman Walczak
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Outline

- Brief introduction to plasma wakefield acceleration
  - history and basic ideas
  - roadmaps
  - basic techniques
- EuPRAXIA
  - structure
  - CDR
  - pilot applications
  - next stages
- ALEGRO
  - considered technologies
  - milestones
  - challenges
- Summary

History

- T. Tajima and J.M. Dawson, Laser Electron Accelerator, PRL Vol. 43, 267 (July 1979)

- One very high intensity (short) laser pulse

OR

- two not so short high energy pulses with the beat frequency matching plasma frequency.

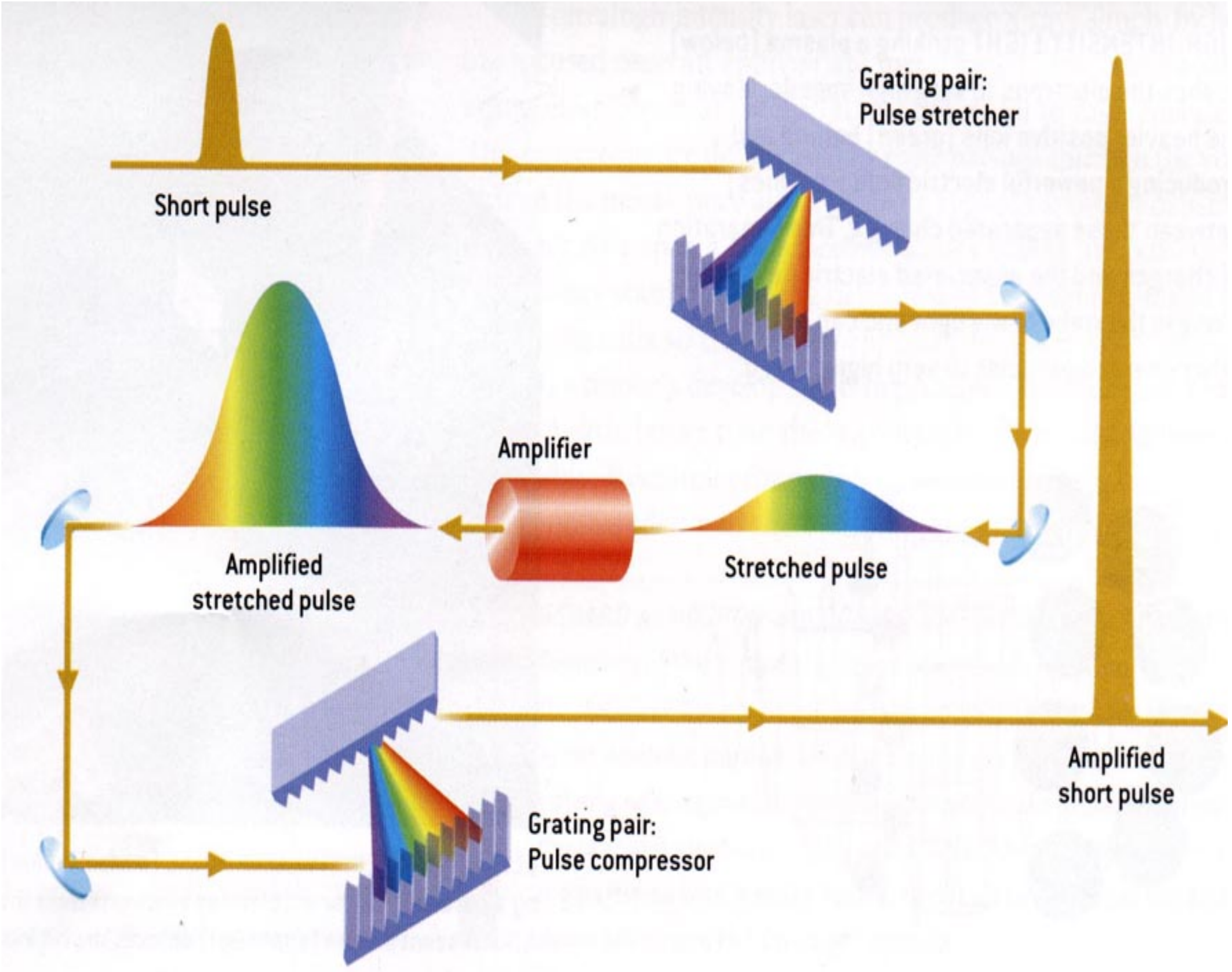
Plasam wakefield acceleration was born

Heroic efforts of beat-wave accelerators era followed

until CPA invention

History

Strickland et Mourou, Opt.Comm.56, 219 (1985)



Laboratories

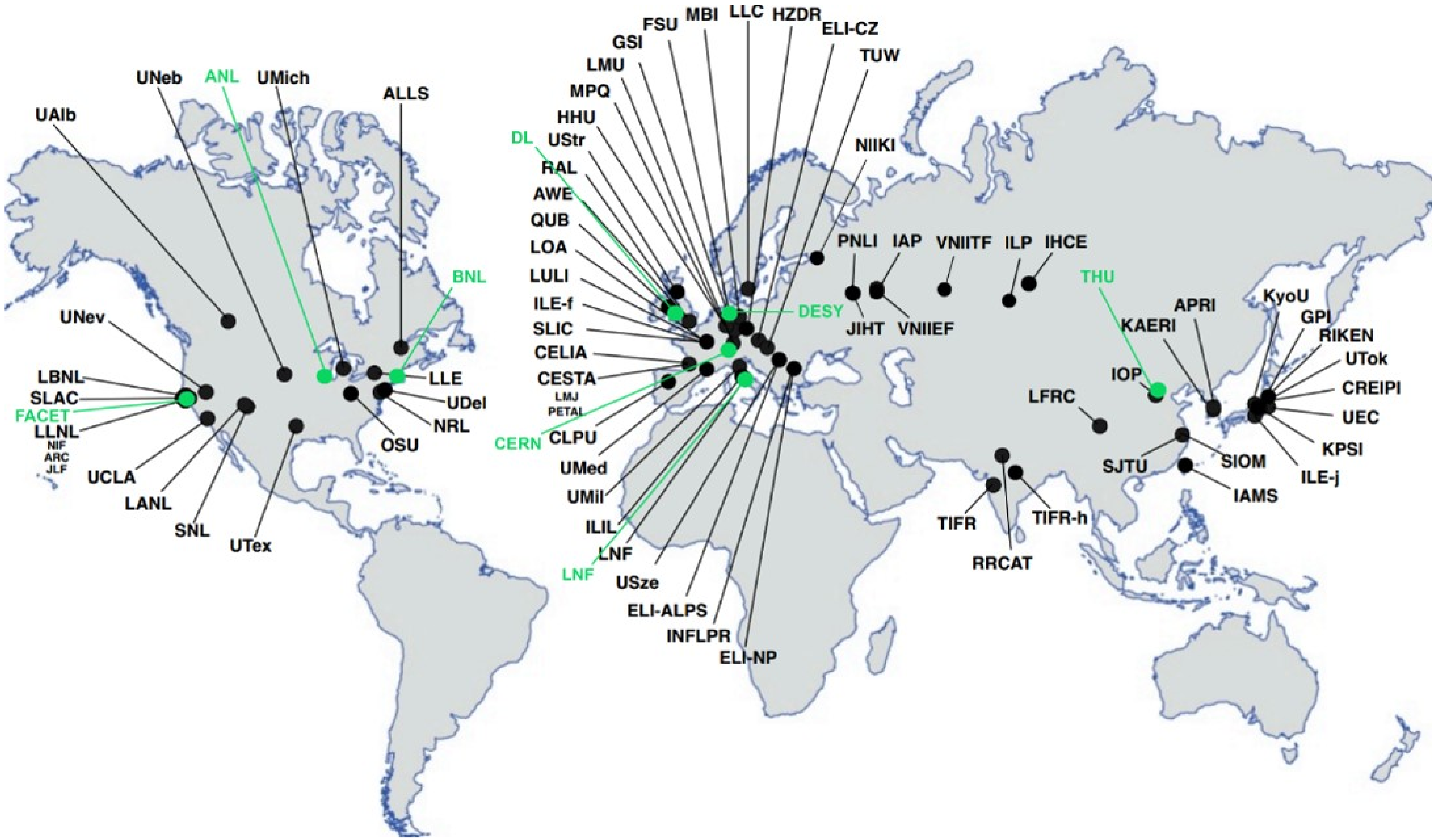
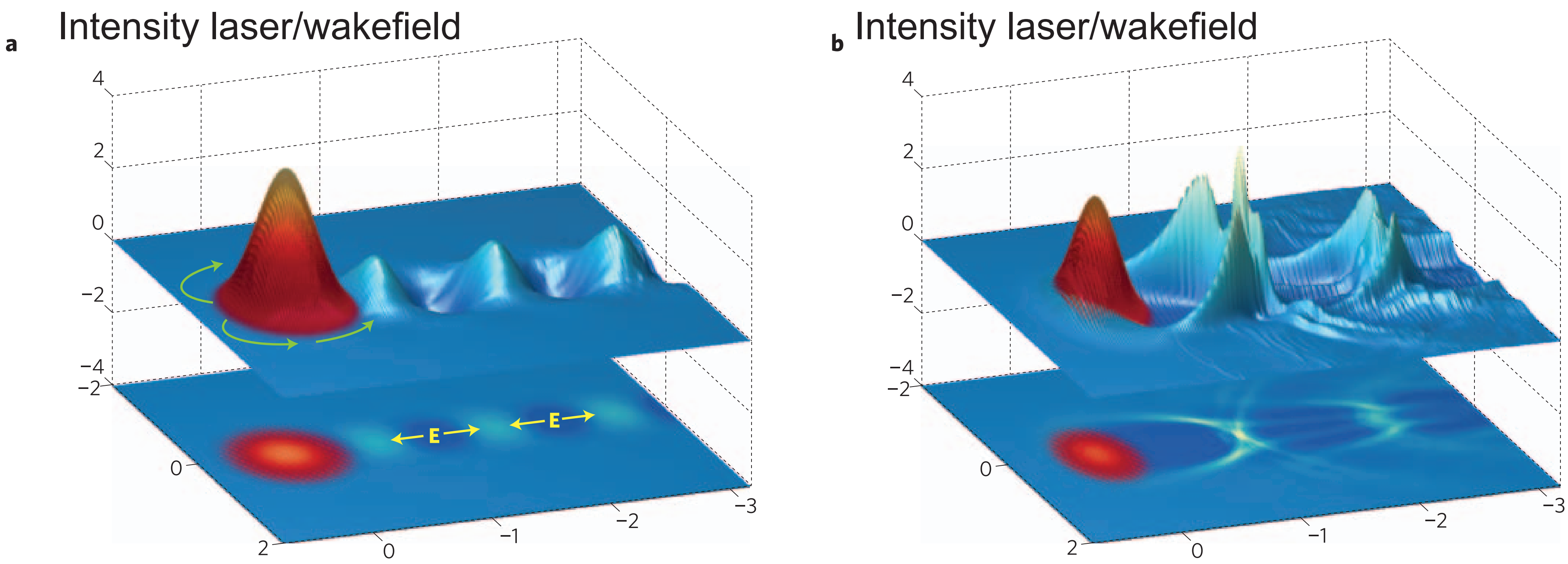


Figure 2: Non-exhaustive overview of laboratories working on (or with the capacity to work on) laser-driven (black) and particle beam-driven (green) plasma wakefield R&D. Based in part on the map of high-power laser laboratories produced by the International Committee on Ultra-high Intensity Lasers (ICUIL).[21]

credit: PWASC; UK roadmap

Basic ideas

REVIEW ARTICLE NATURE PHOTONICS DOI: 10.1038/NPHOTON.2013.234



linear regime

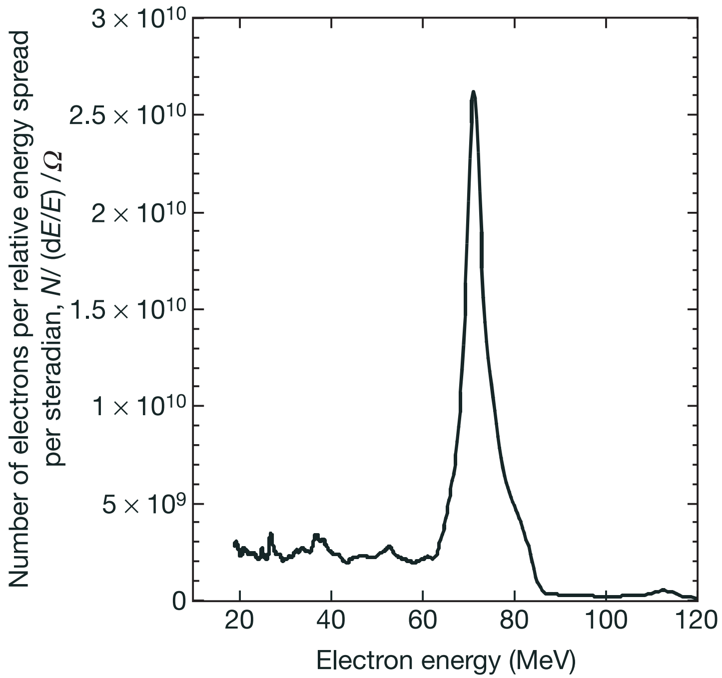
bubble regime

the spatial coordinats are in units of plasma wavelength

cold plasma frequency $\omega_p = (4 \pi e^2 n_0 / m_e)^{1/2}$

plasma wavelength $\lambda_p = 2 \pi c / \omega_p$

▶ The breakthrough



2004

Monochromatic beam

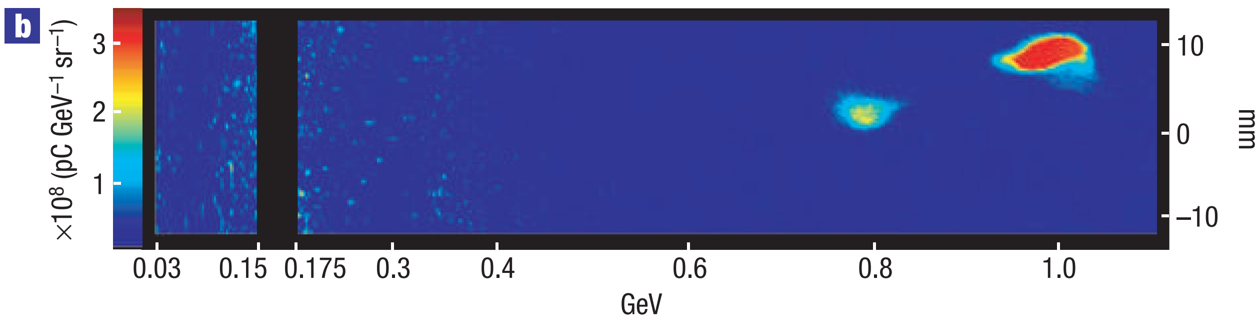
CLF, IC, Strathclyde, UCLA.

S.P.D. Mangles et al., Nature 431, 535-538 (2004)

and

J. Faure et al. , Nature 431, 541-544, (2004)

C.G.R. Geddes et al., Nature 431, 538-541 (2004)



2006

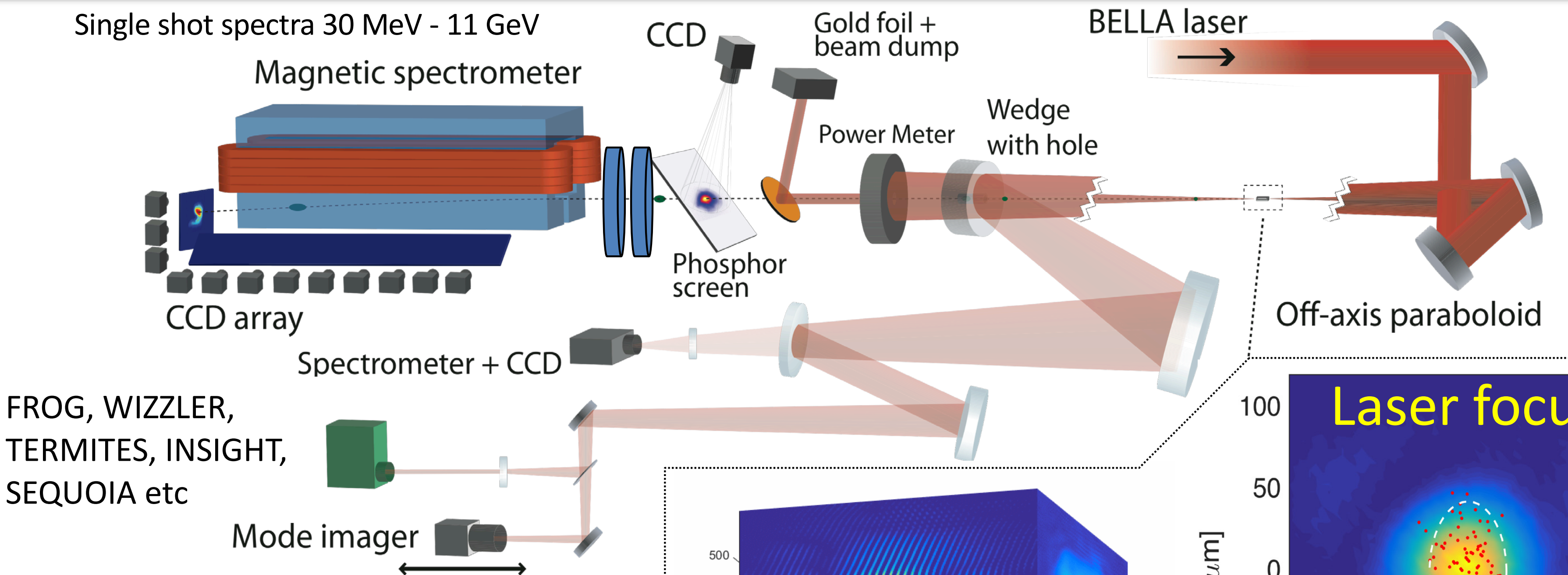
GeV beam

LBNL, Oxford, Tokyo.

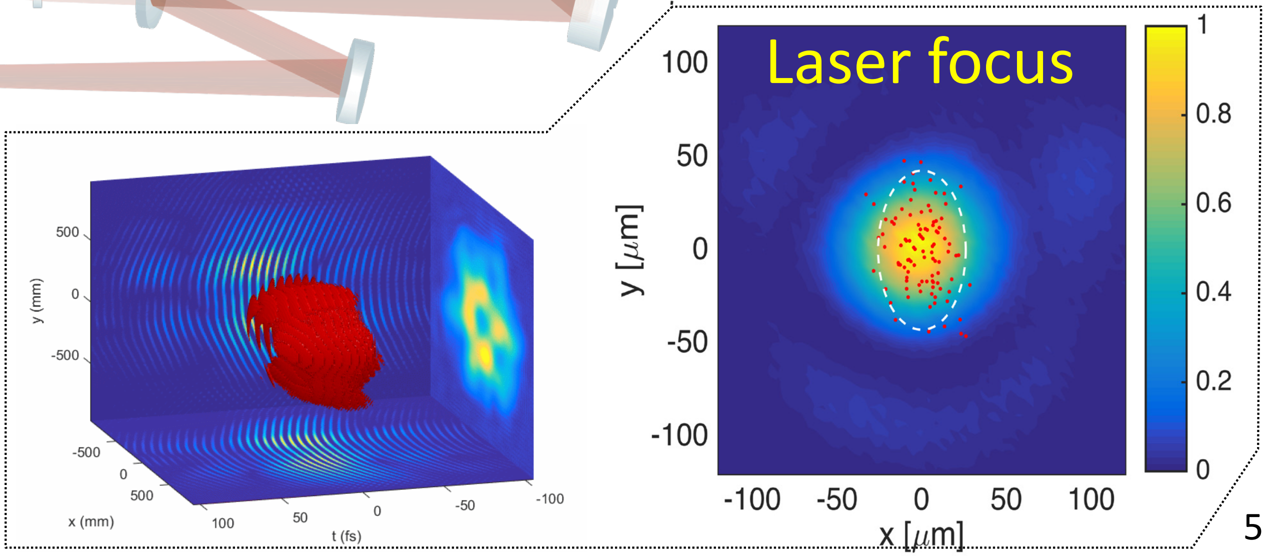
W.P. Leemans et al.,

Nat.Phys. 2, 696 (2006)

Simultaneous diagnostics for both laser and electron beam



On target (focus)	Maximum value
Peak Power	1.2 [PW] (for 31fs)
Peak Intensity	1.7 [10^{19} W/cm²] (for w_0 53μm)



K. Nakamura et al., IEEE JQE (2017)
A. Jeandet et al., Jphys Photonics (2019)

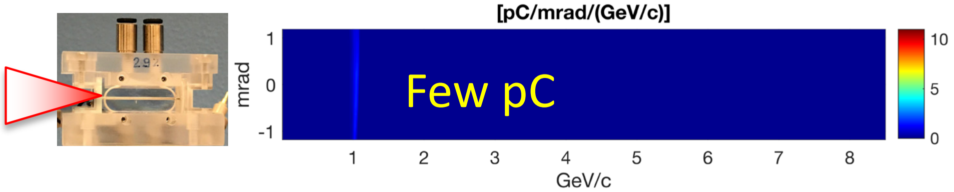
5

slide presented by T. Gonsalves at EAAC 2019

Increasing laser power and reducing plasma density has increased charge and maximum energy to 8GeV

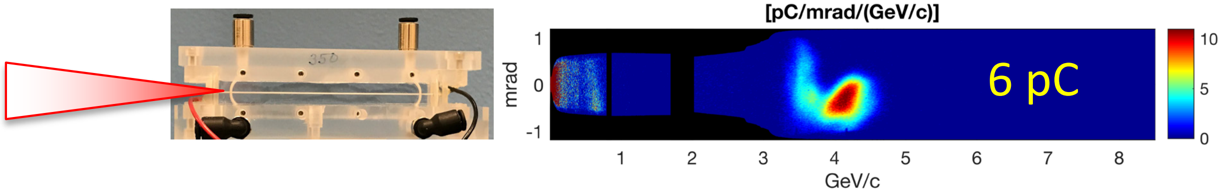
TREX: W. P. Leemans et al., *Nat. Phys.* (2006)

3 cm; 40 TW; ~**5×10^{18} cm^{-3}**



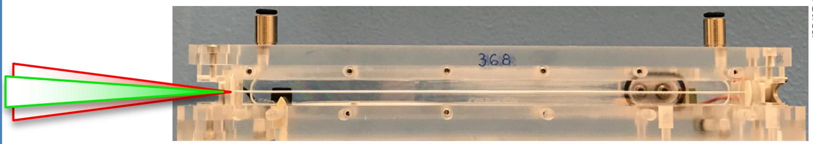
BELLA: W. P. Leemans et al., *PRL* (2014)

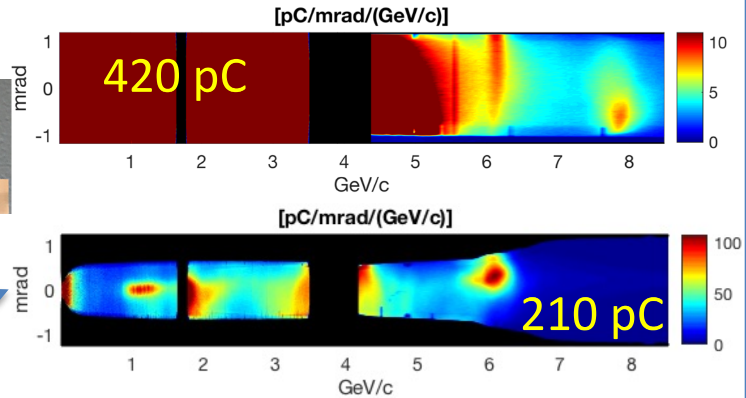
9 cm
300 TW
~0.7×10^{18} cm^{-3}



BELLA with heater: Gonsalves et al., *PRL* (2019)

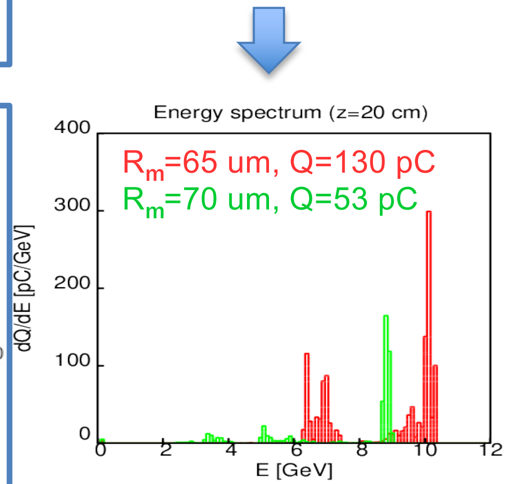
20 cm; 850 TW; **0.27×10^{18} cm^{-3}**





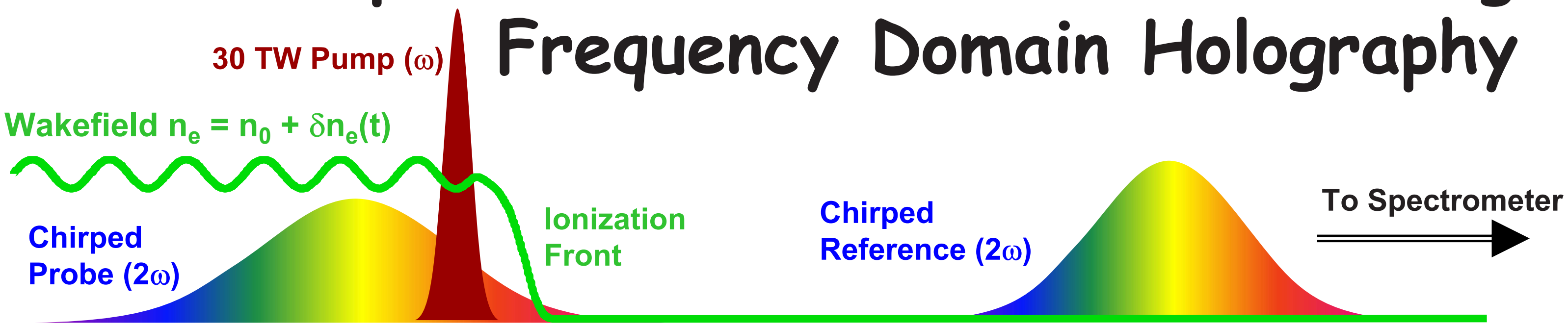
Charge density axis x10

10GeV simulation @ n_0=0.22x10^{18} cm^{-3}

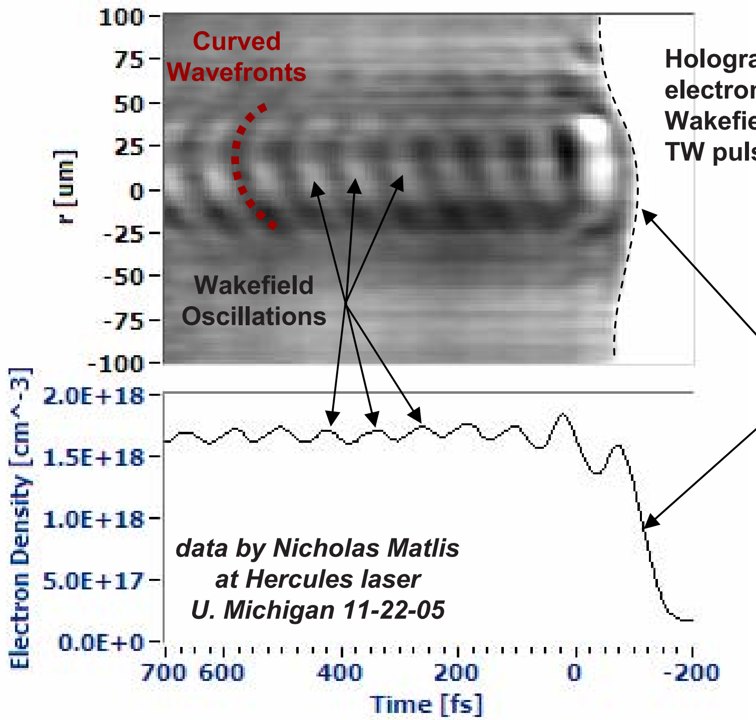


slide presented by T. Gonsalves at EAAC 2019

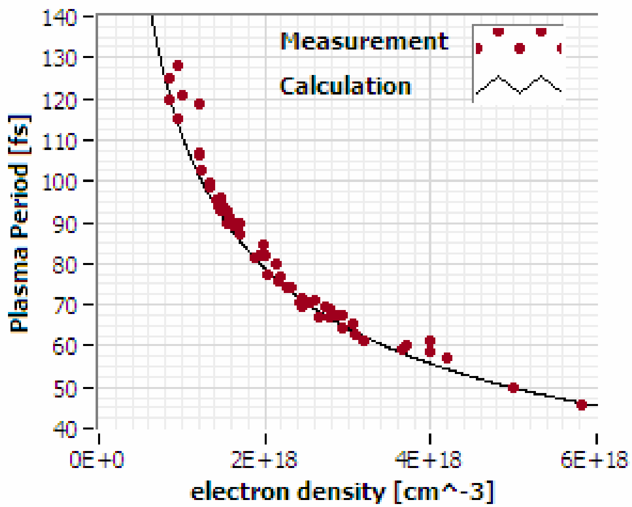
Snapshots of Laser Wakefields using Frequency Domain Holography



Chirped Frequency Domain Holography Optical Pulse Configuration



Holographically Reconstructed electron density profile of a Wakefield produced by a 30 TW pulse



Verification of dependence of Wakefield periodicity on plasma density (no fitting parameters)

FOCUS

Center for the Advancement of Frontiers in Optical Coherent and Ultrafast Science
The University of Michigan and the University of Texas at Austin
NSF Award 0114336

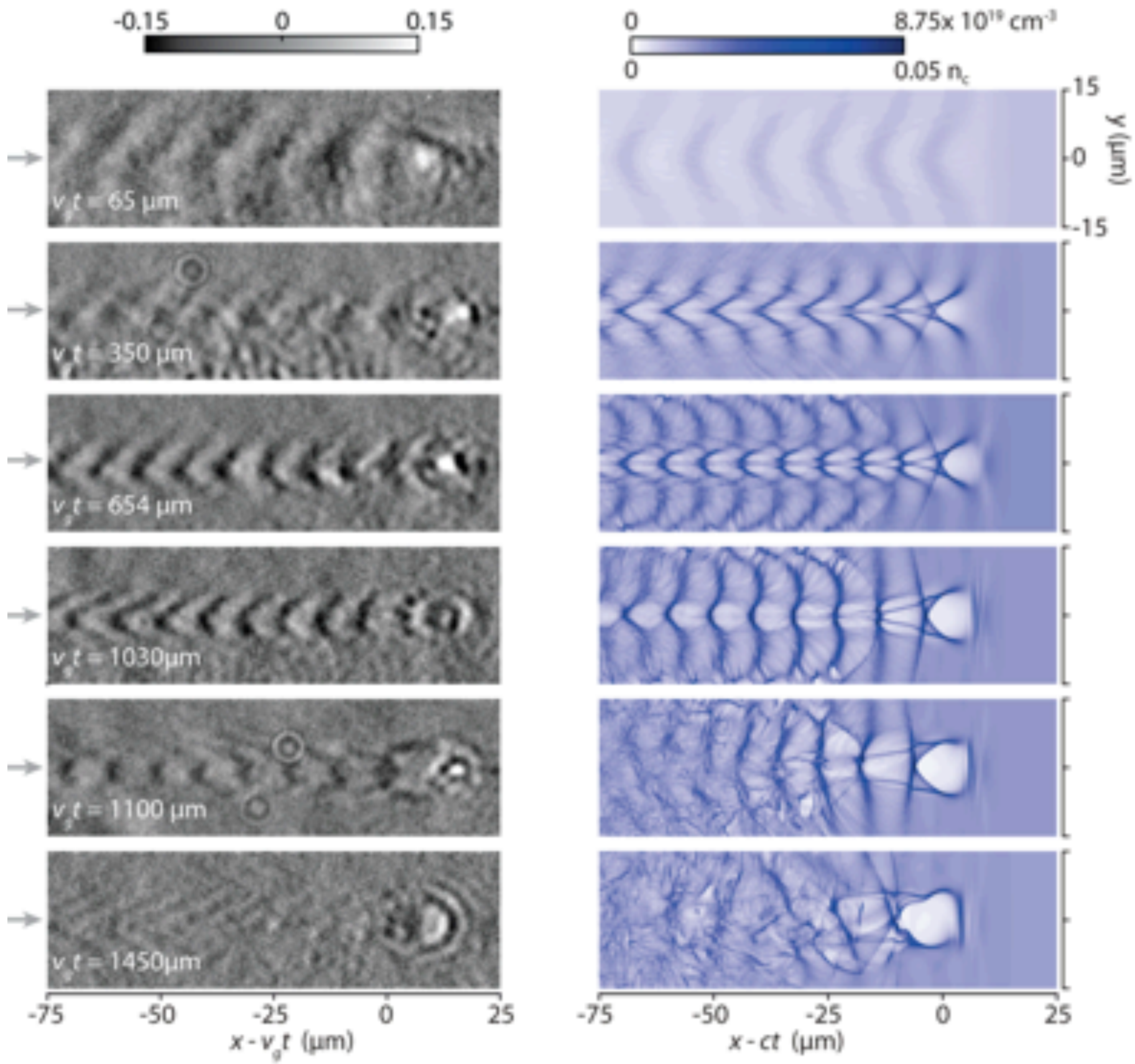
credit: M. C. Downer

Diagnostics

A. Sävert, *et al. Phys. Rev. Lett.* **115**, 055002 (2015)

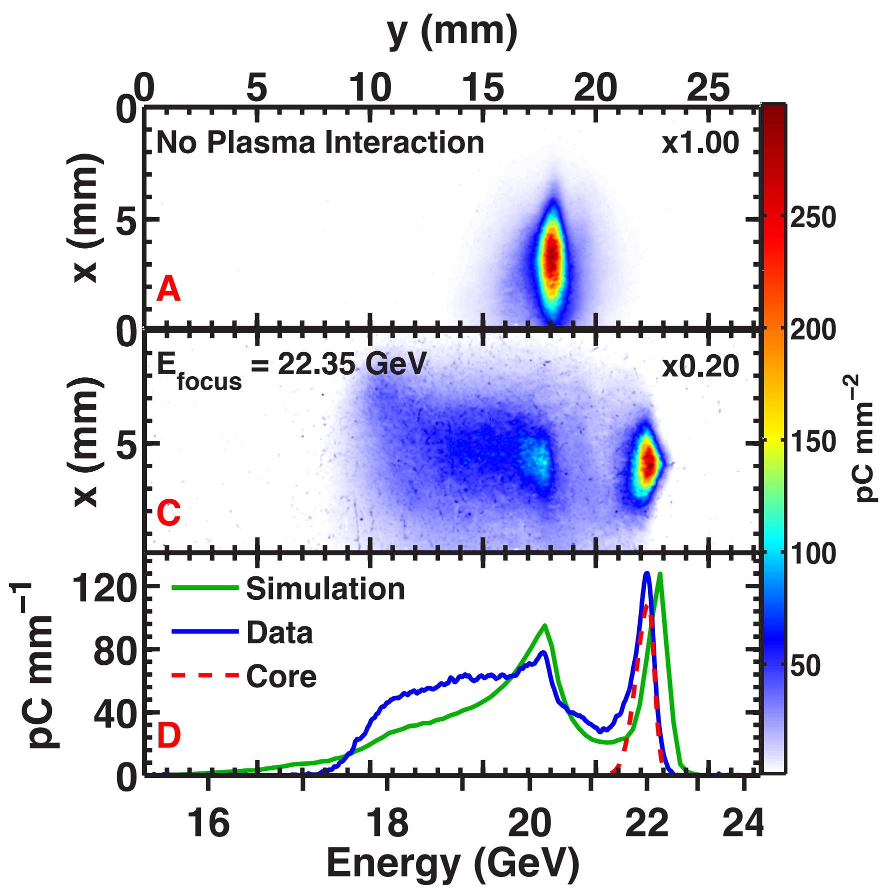
- Transverse shadowgraphy with ultrfast probe pulse
- Direct observation of wakefield
- Excellent agreement with simulations

IC and IOQ Jena



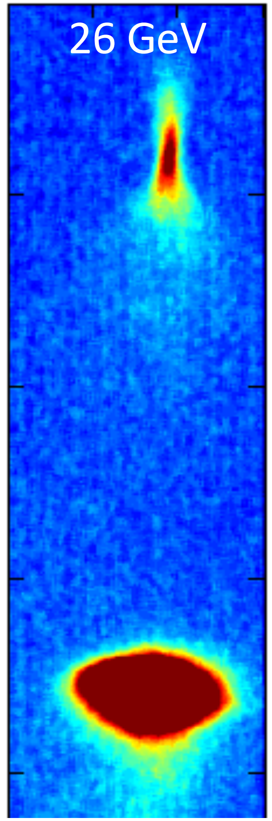
credit: Z. Najmudin

FACET two-bunch results



- *1.7 GeV* energy gain in *30 cm* of Li vapour plasma.
- 2% energy spread.
- Accelerated bunch has charge ~ *70 pC*
- Up to *30%* wake-to-bunch energy transfer efficiency (mean *18%*).
- *6 GeV* energy gain in *1.3 m* of plasma.

1.3 m plasma



2014

M. Litos et al., Nature **515** (2014) 92

credit: M. Wing, Physics at the Terascale 2015

Proton Drivers for PWFA

Proton bunches as drivers of plasma wakefields are interesting because of the very large energy content of the proton bunches.

Drivers:

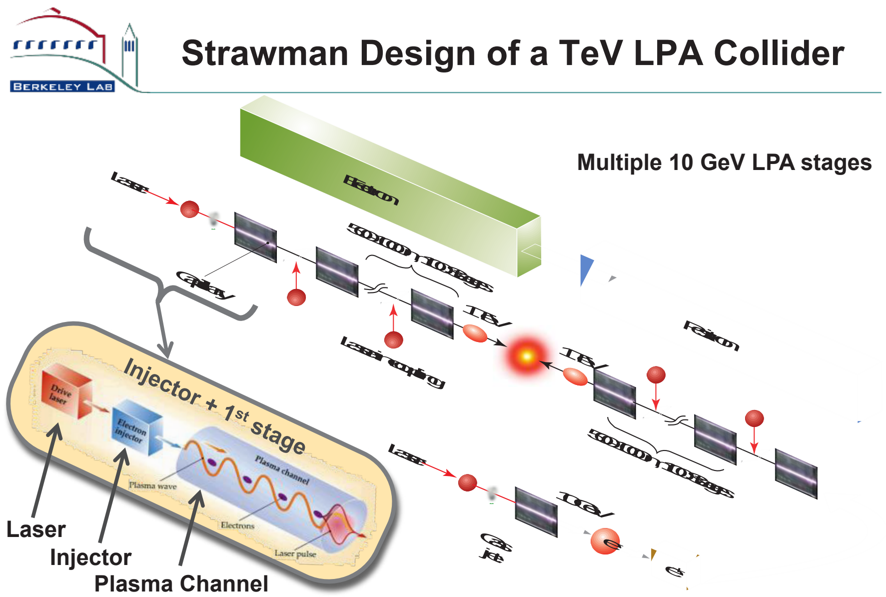
PW lasers today, ~40 J/Pulse

FACET, 30J/bunch

SPS 20kJ/bunch
LHC 300 kJ/bunch

Witness:

10^{10} particles @ 1 TeV ≈ few kJ



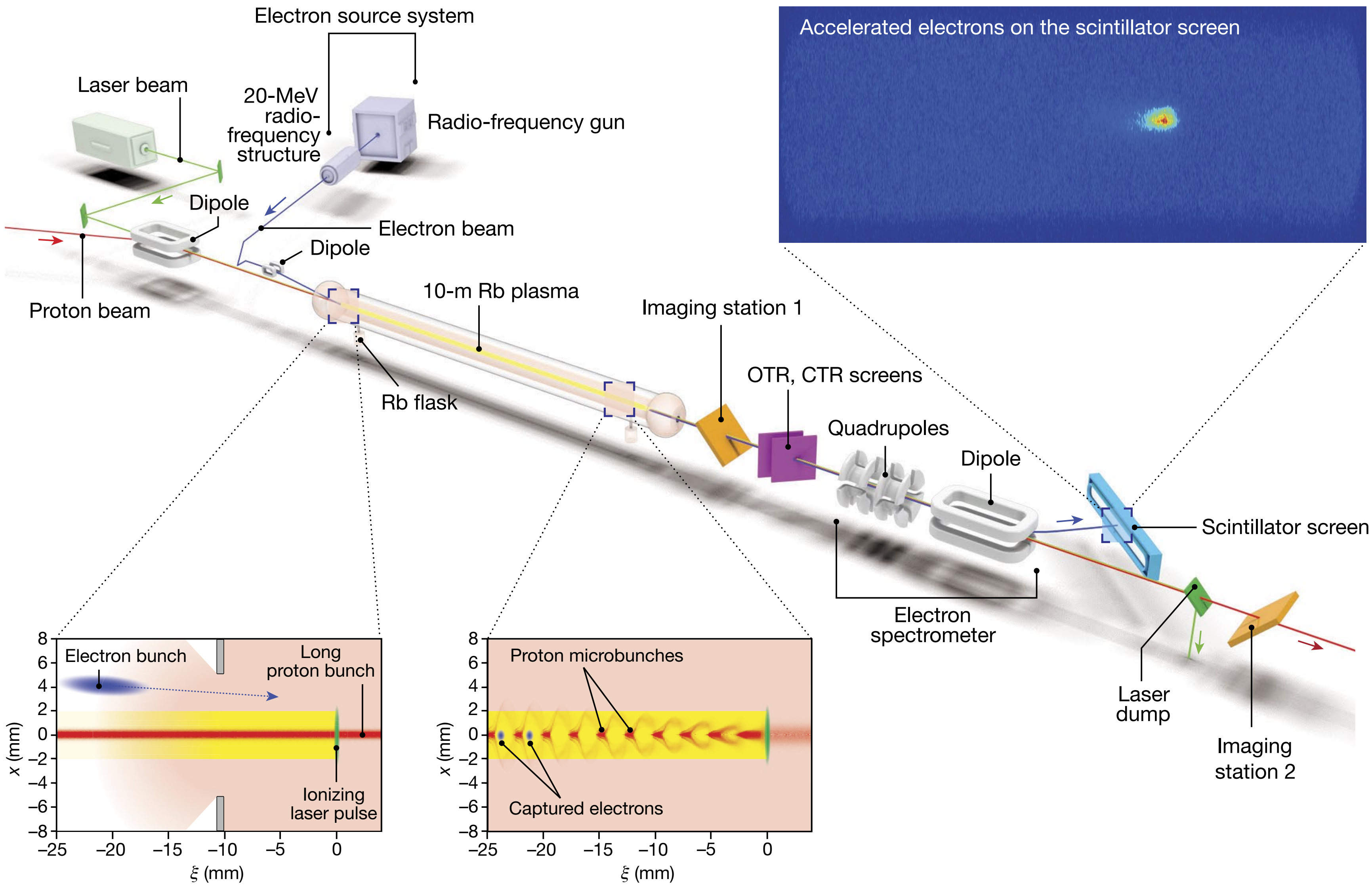
Leemans & Esarey, Physics Today, March 2009

Energy content of driver allows to consider single stage acceleration

credit: A. Caldwell, SPSC Meeting 2015

Recent results

RESEARCH LETTER



AWAKE https://doi.org/10.1038/s41586-018-0485-4

Emerging directions

Emerging main directions:

In the US

- a roadmap to high energy colliders; TeV energies

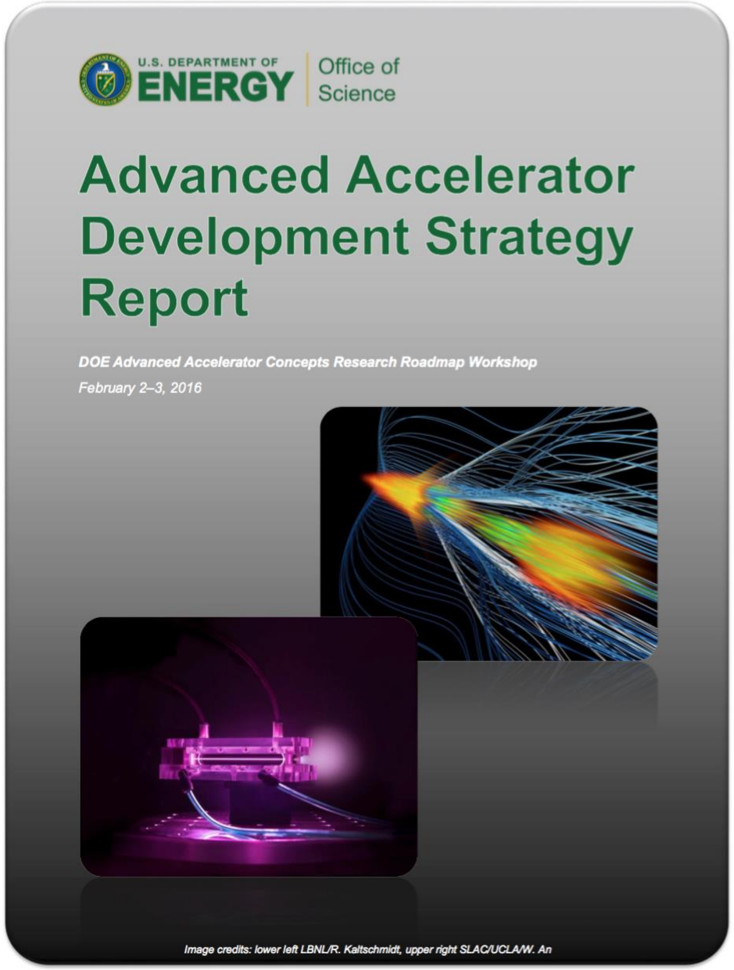
In Europe

- a roadmap to light sources; GeV energies

All agree

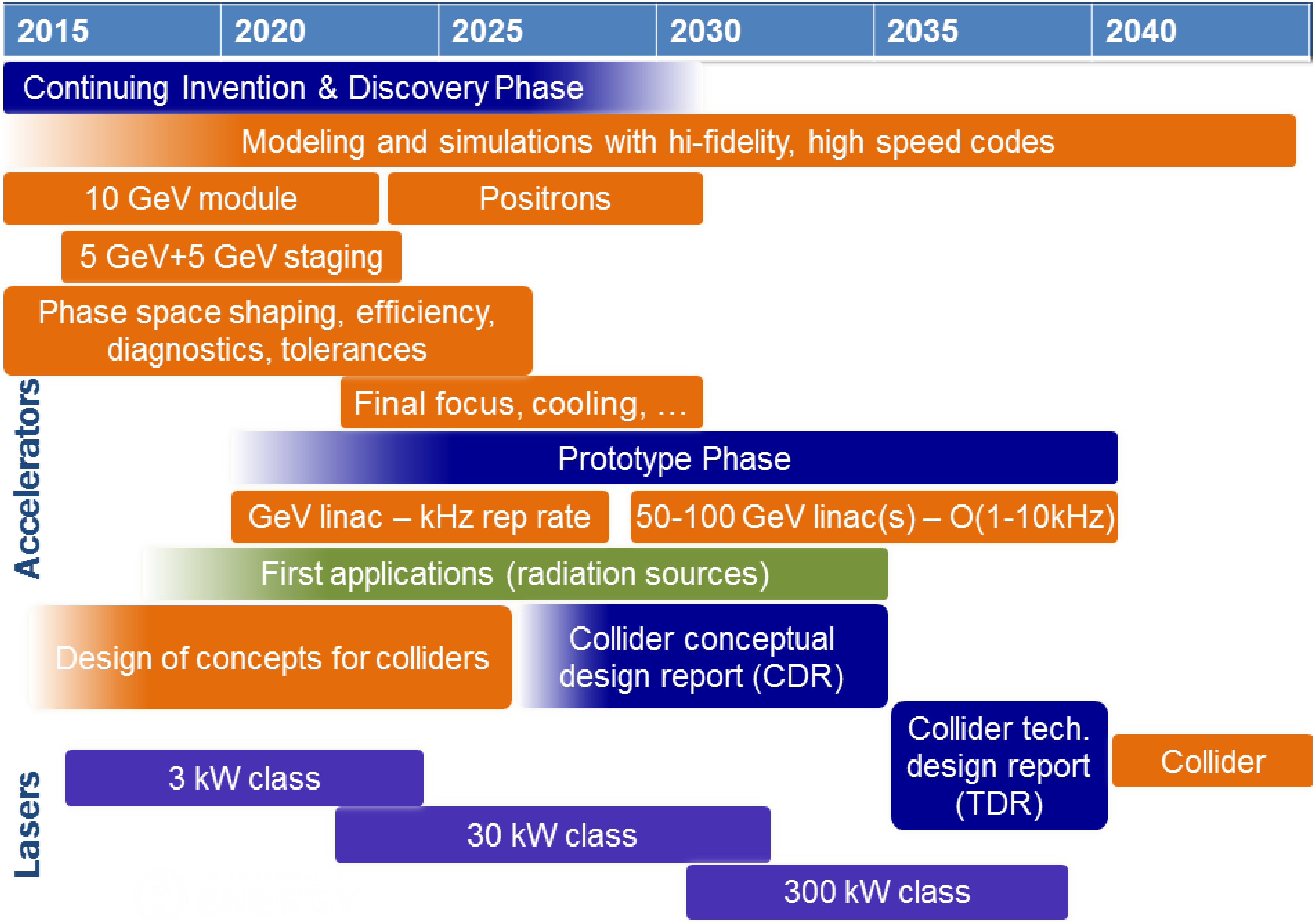
- more efficient, higher repetition rate lasers are needed

Two new developments in the U.S.
Strategy roadmap from DOE-HEP and from Big Idea Summit



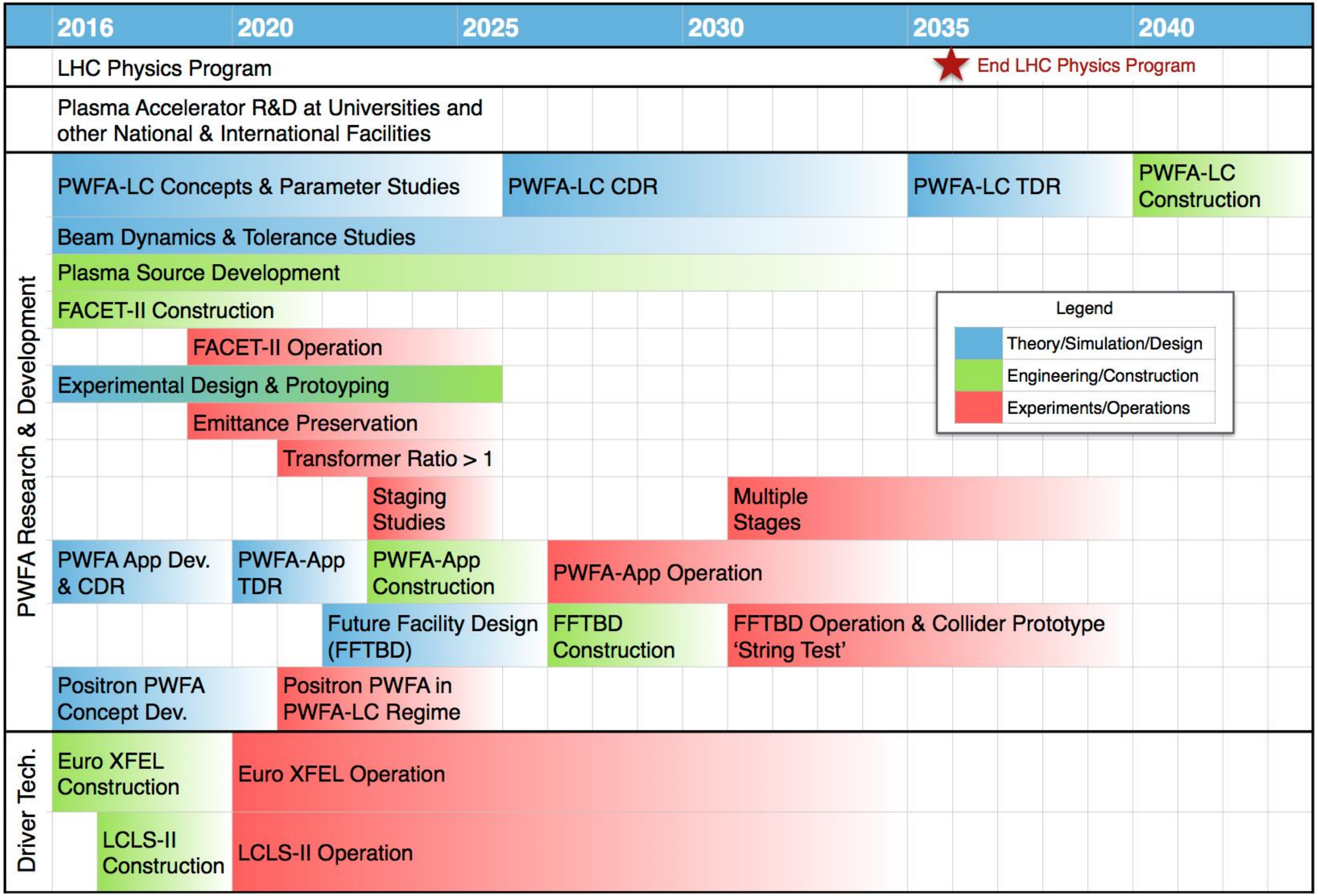
W. Leemans, Pisa 29.6.2016

US roadmap


2015
2020
2025
2030
2035
2040
Continuing Invention & Discovery Phase
Modeling and simulations with hi-fidelity, high speed codes
10 GeV module
Positrons
5 GeV+5 GeV staging
Phase space shaping, efficiency, diagnostics, tolerances
Final focus, cooling, …
Prototype Phase
GeV linac – kHz rep rate
50-100 GeV linac(s) – O(1-10kHz)
First applications (radiation sources)
Design of concepts for colliders
Collider conceptual design report (CDR)
Collider tech. design report (TDR)
Collider
3 kW class
30 kW class
300 kW class
Accelerators
Lasers

US roadmap

Beam Driven Plasma Accelerator Roadmap for HEP



PROBLEMS

There are Big Problems out of reach of today's technology

National Security	Industry	Medicine	Discovery Science
National Nuclear Security Administration		National Institutes of Health; National Cancer Institute	U.S. Department of Energy; Office of Science
▪ Compact and portable radiation sources. ▪ Replacement of radioactive sources.	▪ Energy efficient manufacturing, irradiation, sterilization ▪ Lithography near the atomic limit ▪ Environmental remediation, flue gas cleanup, and petroleum cracking ▪ Surface treatment of materials	▪ Highly-targeted modalities of cancer treatment in compact, cheap systems. ▪ Cases will increase by 45% in US by 2030; global medical linac sales: $7.5B by 2020.	▪ How do we deliver a boost in performance within a reasonable footprint beyond the next-generation scientific facilities already on the horizon?
▪ Need: Compact machines for high-energy electron beams	▪ Need: Compact machines for very high-power, low-energy electron beams	▪ Need: Ultra-compact machines for low-energy electron beams	▪ Need: Compact machines for high-energy electron beams

W. Leemans, Pisa 29.6.2016

HIGH ENERGY COMPACT ACCELERATORS OPEN NEW APPLICATIONS BUT REQUIRE HIGHER AVERAGE POWER

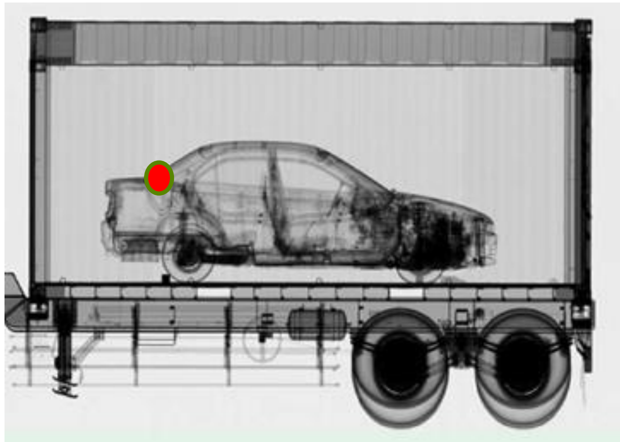
Industry and Science

Bright, compact photon sources

Need to go from hours to seconds

Security

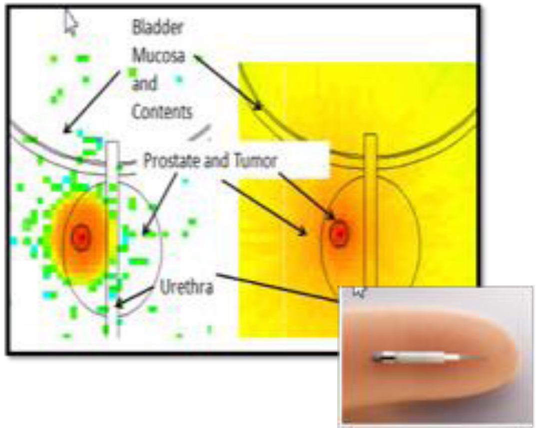
Compact high energy photon sources
for detecting special materials



Cargo scanning needs 1000x more power

Medical

Arthroscopic accelerators for medical treatment and inspection



Performance demo is underway.

Key Challenges to be overcome: Engineering for stability, tunability, and reliability and 100x higher average power using new laser technology

W. Leemans, Pisa 29.6.2016

UK roadmap

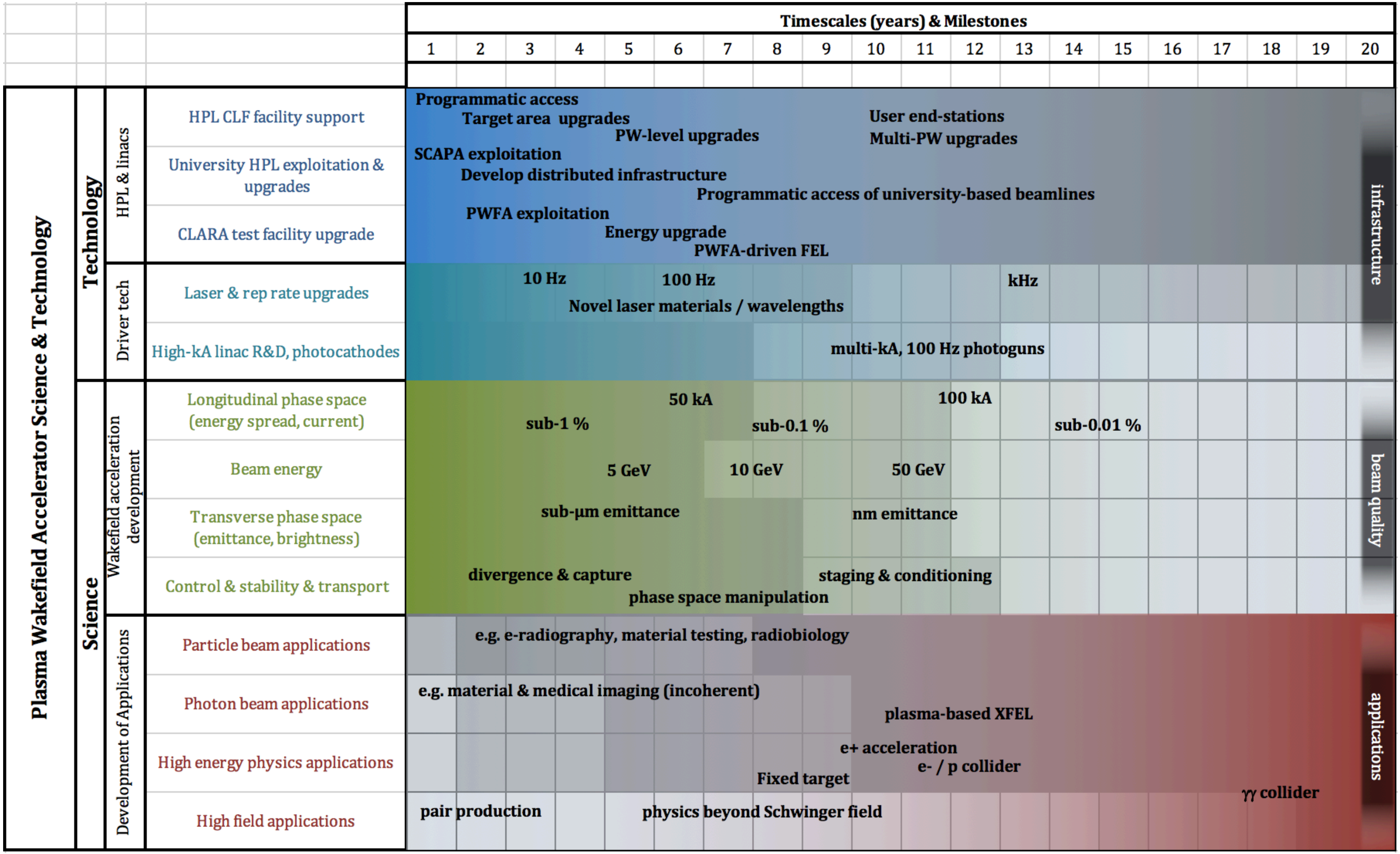


Figure 8: Timeline for scientific and technological research and development on plasma wakefield accelerators.

credit: PWASC

European Network EuroNNAc for Novel Accelerators

EuPRAXIA – Addressing the Quality Issue

Horizon2020

- Our question for the next 4 years:

Assuming no resource limits – What would be the best 1 – 5 GeV e- plasma accelerator we can build? And what could we use it for (pilot users)?

EuPRAXIA

NOVEL FUNDAMENTAL RESEARCH

COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

"RF unit test" for plasma accelerators

EuPRAXIA structure

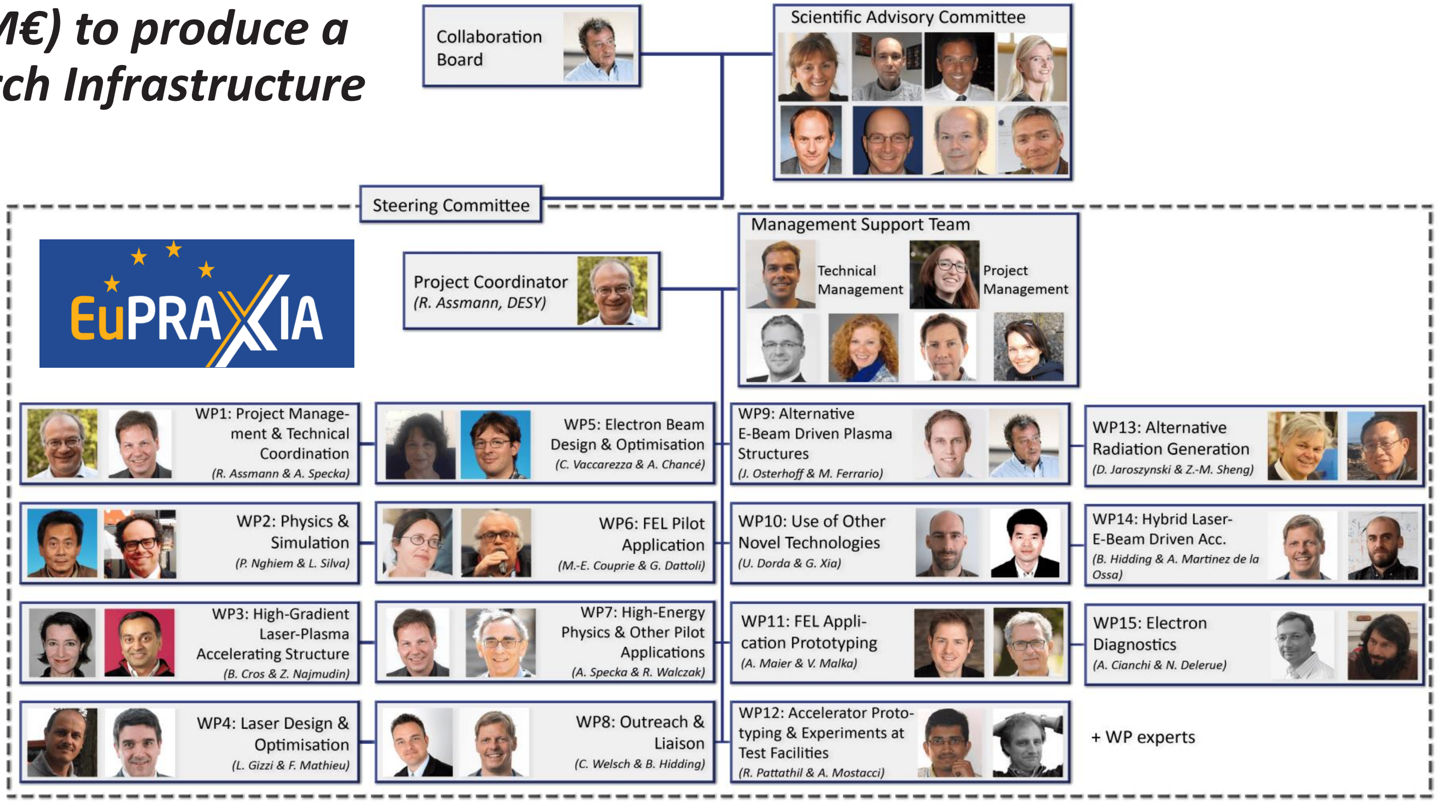
EuPRAXIA

The Project

Horizon 2020

EU funded Consortium (3 M€) to produce a CDR for a European Research Infrastructure

- EU design study in 4th and final year: **16 beneficiaries, 25 associated partners, 15 Work Packages, 30 WP Leaders, more than 250 scientists contributed**
- One of four DS's in physical science approved in H2020. Others: EuroCirCol (FCC), CompactLight (X band), Neutrino (ESS)



#EuPRAXIA #plasma #accelerator

EuPRAXIA - R. Assmann, Final Yearly Meeting - 10/2019

EuPRAXIA structure

The Consortium – Growing in the Course

Horizon 2020

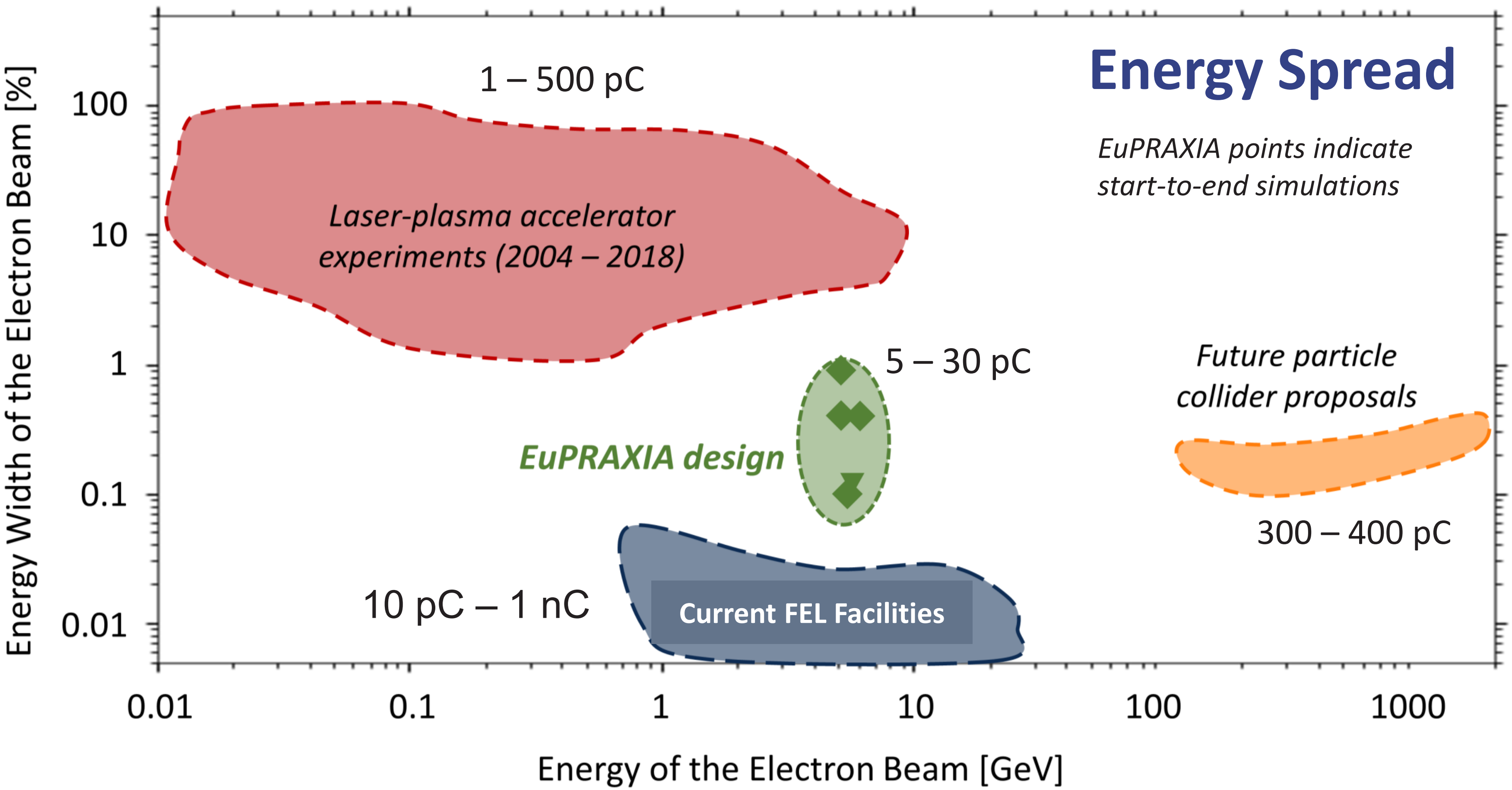
ASSOCIATED PARTNERS
(November 2018)

1. Shanghai Jiao Tong University, China
2. Tsinghua University Beijing, China
3. ELI – Extreme Light Infrastructure – Beamlines, International
4. PhLAM – Laboratoire de Physique des Lasers Atomes et Molécules, Université de Lille 1, France
5. Helmholtz-Institut Jena, Germany
6. Helmholtz-Zentrum Dresden-Rossendorf, Germany
7. Ludwig-Maximilians-Universität München, Germany
8. Wigner Fizikai Kutatóközpont, Hungary
9. CERN – European Organization for Nuclear Research, International
10. Kansai Photon Science Institute/Japan Atomic Energy Agency, Japan
11. Osaka University, Japan
12. RIKEN SPring-8 Center, Japan
13. Lunds Universitet, Sweden
14. CASE – Center for Accelerator Science and Education at Stony Brook University and Brookhaven National Laboratory, USA
15. LBNL – Lawrence Berkeley National Laboratory, USA
16. UCLA – University of California Los Angeles, USA
17. KIT – Karlsruher Institut für Technologie, Germany
18. Forschungszentrum Jülich, Germany
19. Hebrew University of Jerusalem, Israel
20. Institute of Applied Physics of the Russian Academy of Sciences, Russia
21. Joint Institute for High Temperatures of the Russian Academy of Sciences, Russia
22. Università degli Studi di Roma "Tor Vergata", Italy
23. Queen's University Belfast, UK
24. Ferdinand-Braun-Institut, Germany
25. University of York, UK

EuPRAXIA - R. Assmann, Final Yearly Meeting - 10/2019

OUTCOME: High Quality Single Bunch Design

Horizon 2020



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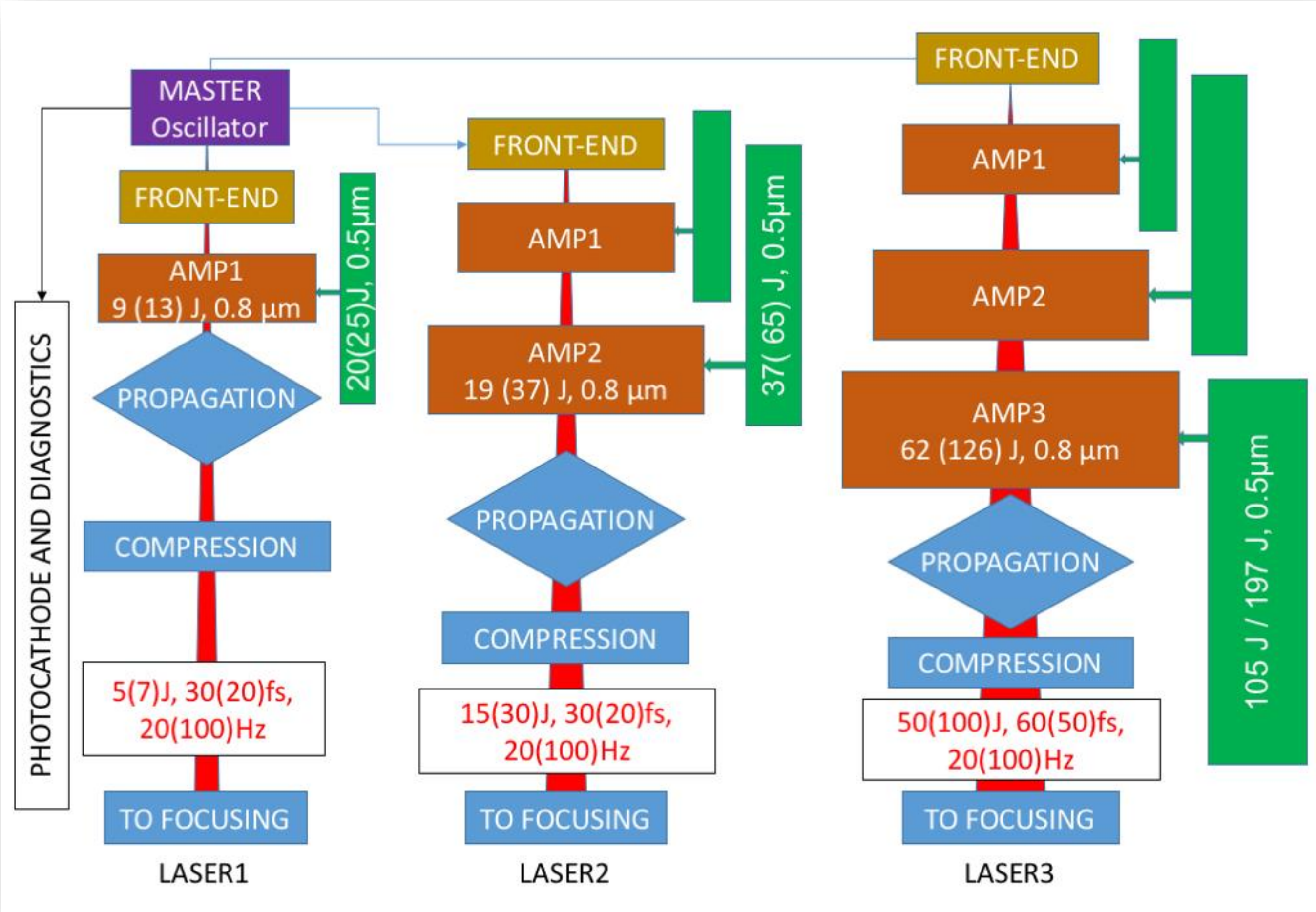
OUTCOME: 20 – 100 Hz Lasers Designs

Horizon 2020



- **Three laser systems** for the laser-driven plasma accelerator facility
- Baseline: Start from lasers at present **state-of-the-art**, however, extended to 20 Hz and then to 100 Hz
- In parallel: **Development** of high efficiency, high average power lasers

Leo Gizzi, Francois Mathieu et al

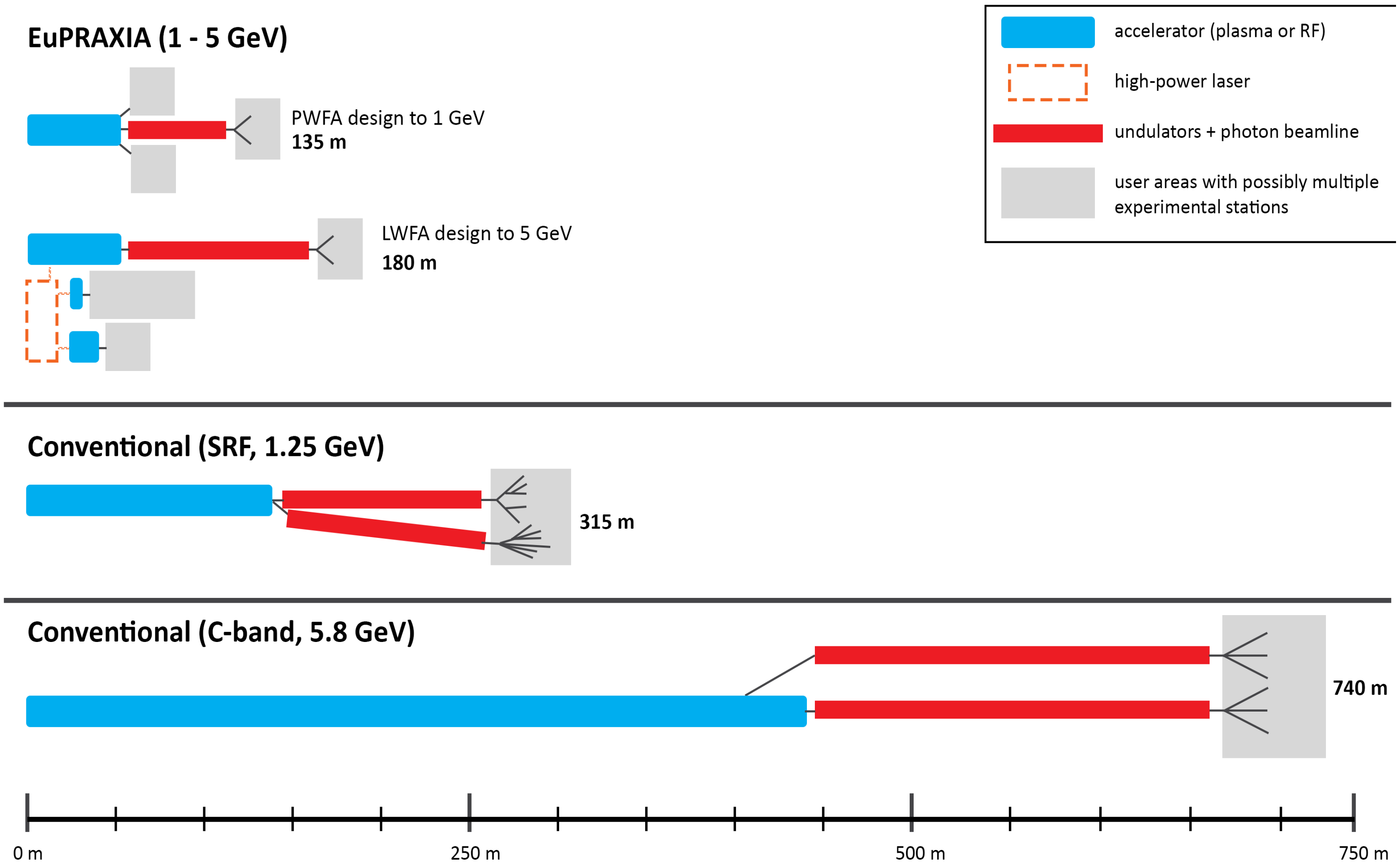
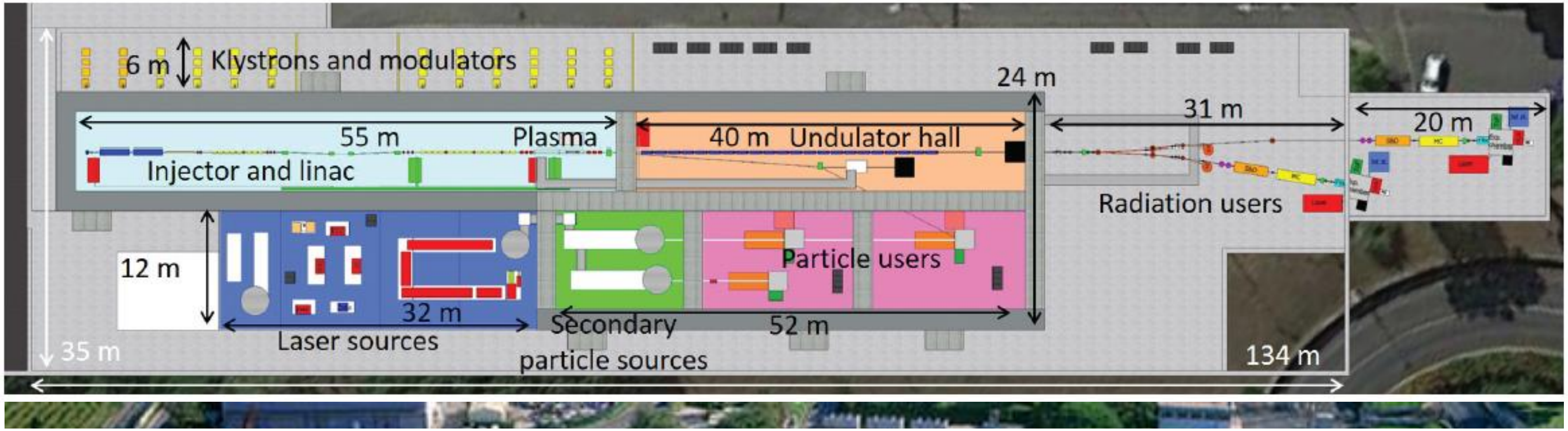


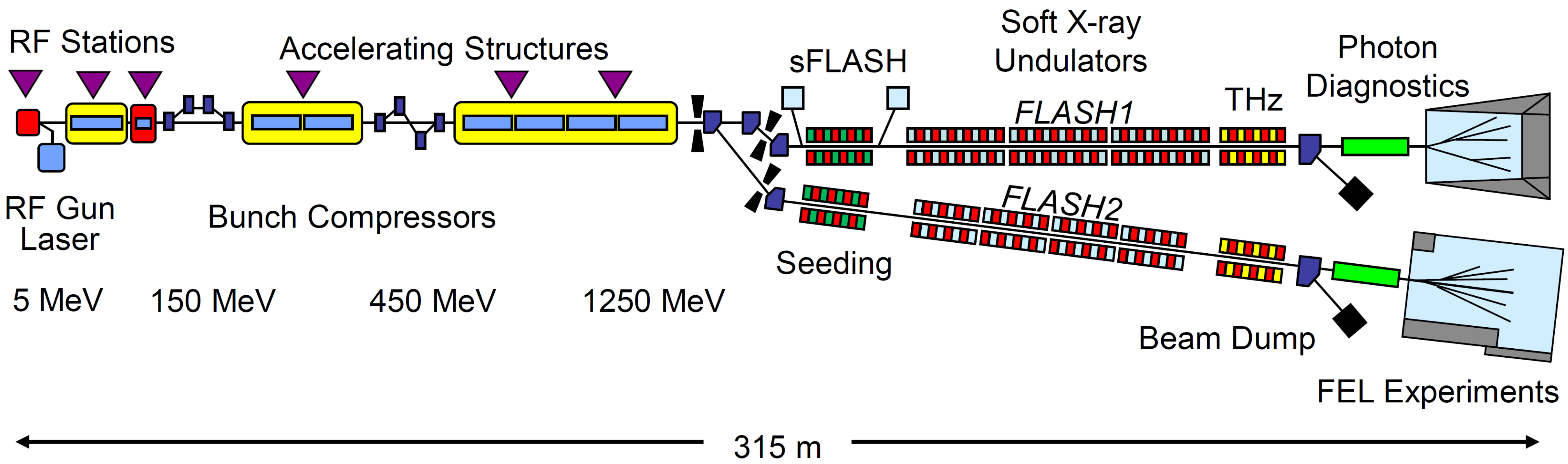
Figure 3.6: Comparison of the expected EuPRAXIA machine length with parameters for facilities of equivalent beam energies based on conventional RF-technologies [151, 152]. The transverse size is not to scale. It is noted that such facilities tend to offer FEL performance parameters which are not achievable with the EuPRAXIA design. Gains in size must therefore be put into the context of performance limitations with the EuPRAXIA approach.

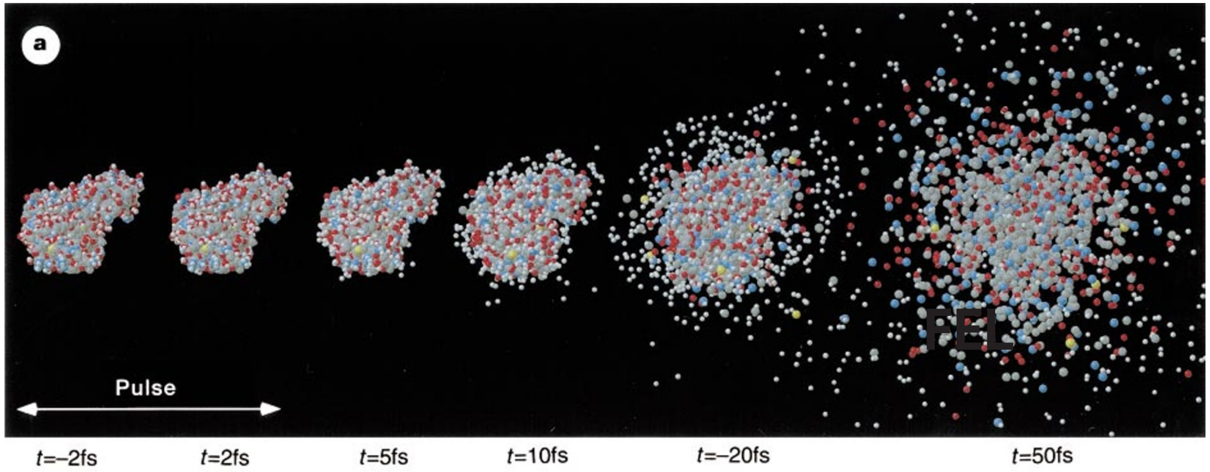
Quantity	Baseline Value
Laser systems	
Wavelength	800 nm
Energy on target	5–100 J
Pulse duration	$\geq$20–60 fs
Repetition rate	20–100 Hz
High-energy electron beam from beam-driven plasma accelerator (PWFA)	
Energy	1.0–5.0 GeV
Charge	30–40 pC
Bunch duration	$\sim$13 fs
Energy spread	0.4–1.1 %
Normalised emittance	0.7–1.2 mm mrad
High-energy electron beam from laser-driven plasma accelerator (LWFA)	
Energy	5.0–6.0 GeV
Charge	23–30 pC
Bunch duration	3–11 fs
Energy spread	0.1–0.9 %
Normalised emittance	0.1–1.4 mm mrad

Free-electron laser	
Radiation wavelength	0.19–35.9 nm
Pulse duration	0.4–15 fs
Saturation length	16–126 m
Photons per pulse	1.9×10^9–7.2×10^{11}
Brightness	2×10^{28}–4.8×10^{32} photons/[mm^{2}mrad^{2}s(0 1%BW)]
Betatron source	
Photon energy	0.6–110 keV
Source size	1.4–2.4 µm
Photons per pulse	2×10^8–4×10^{10}
Peak X-ray brightness	2×10^{21}–1×10^{26} photons/(mm^{2}mrad^{2}s[0 1%BW])
Inverse Compton source	
Photon energy	≥100 MeV
Pulse duration	∼30 fs
Divergence	<1 mrad
Low-energy positron source	
Positron energy	0.5–10 MeV (tunable)
Beam duration	20–90 ps
Positrons per shot	$\geq 1 \times 10^6$
High-energy positron source	
Positron energy	≥1.0 GeV (tunable)
Beam duration	≤10 fs
Positrons per shot	$\sim 1 \times 10^7$

OUTCOME: Beam-Driven Site at Frascati



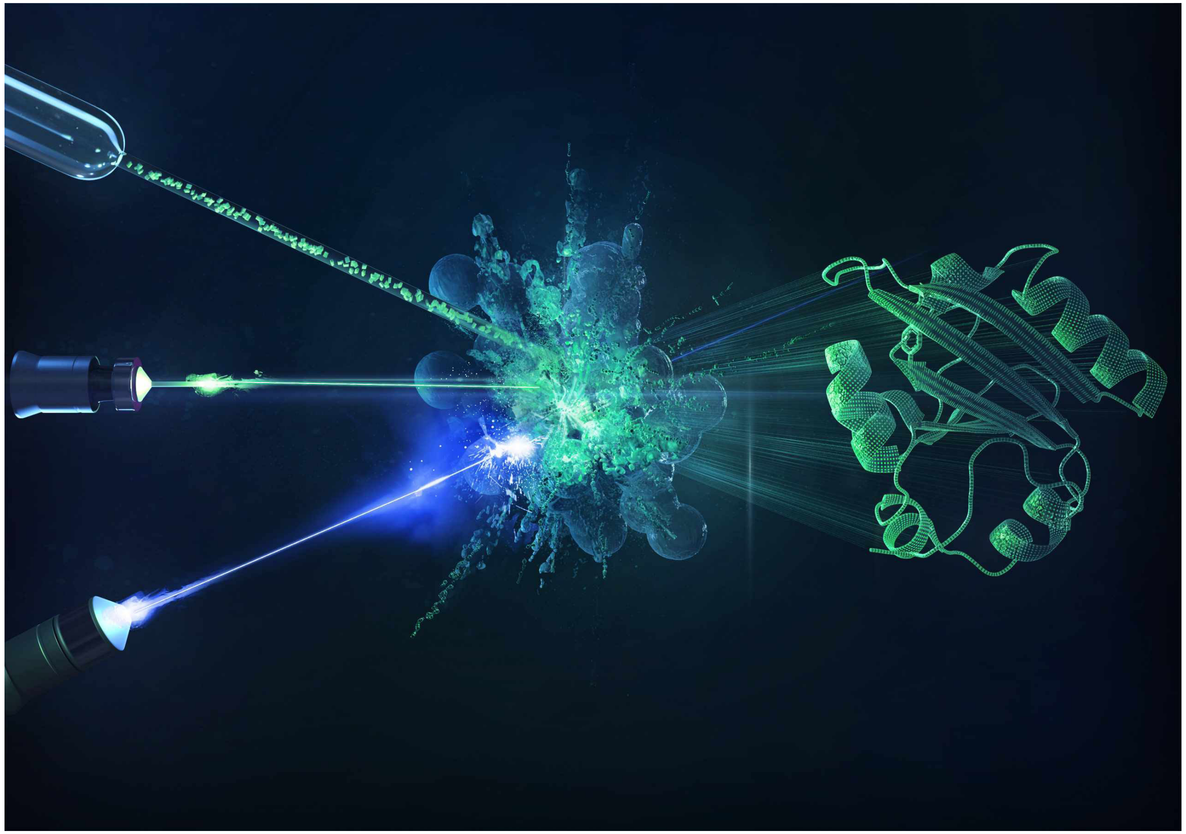




Diffraction before destruction

Effect of X-ray pulse (2fs FWHM, 12 keV) on T4 Lysozyme was simulated.
A proteine showed at different times with resepct to the arrival of the X-ray pulse.

Nature **406** (2000), 752-757



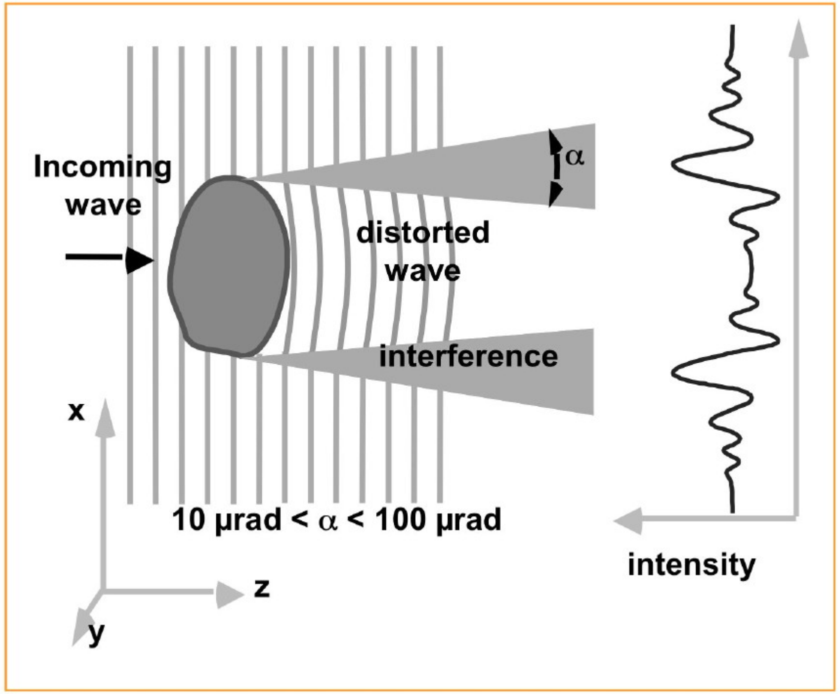
Time-resolved serial femtosecond crystallography (TR-SFX) at the European XFEL.

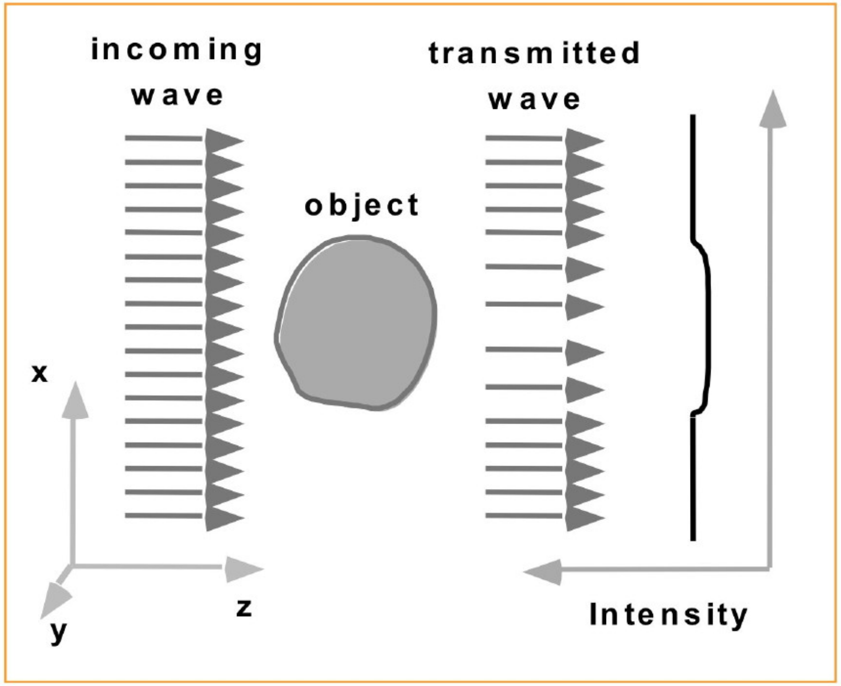
Microcrystals are injected into the reaction initiated by blue laser pulses.

The reaction is probed by the XFEL pulses.

Science 3**46** (2014), (6214) 1242-6

Phase Contrast Imaging vs. Conventional Radiology





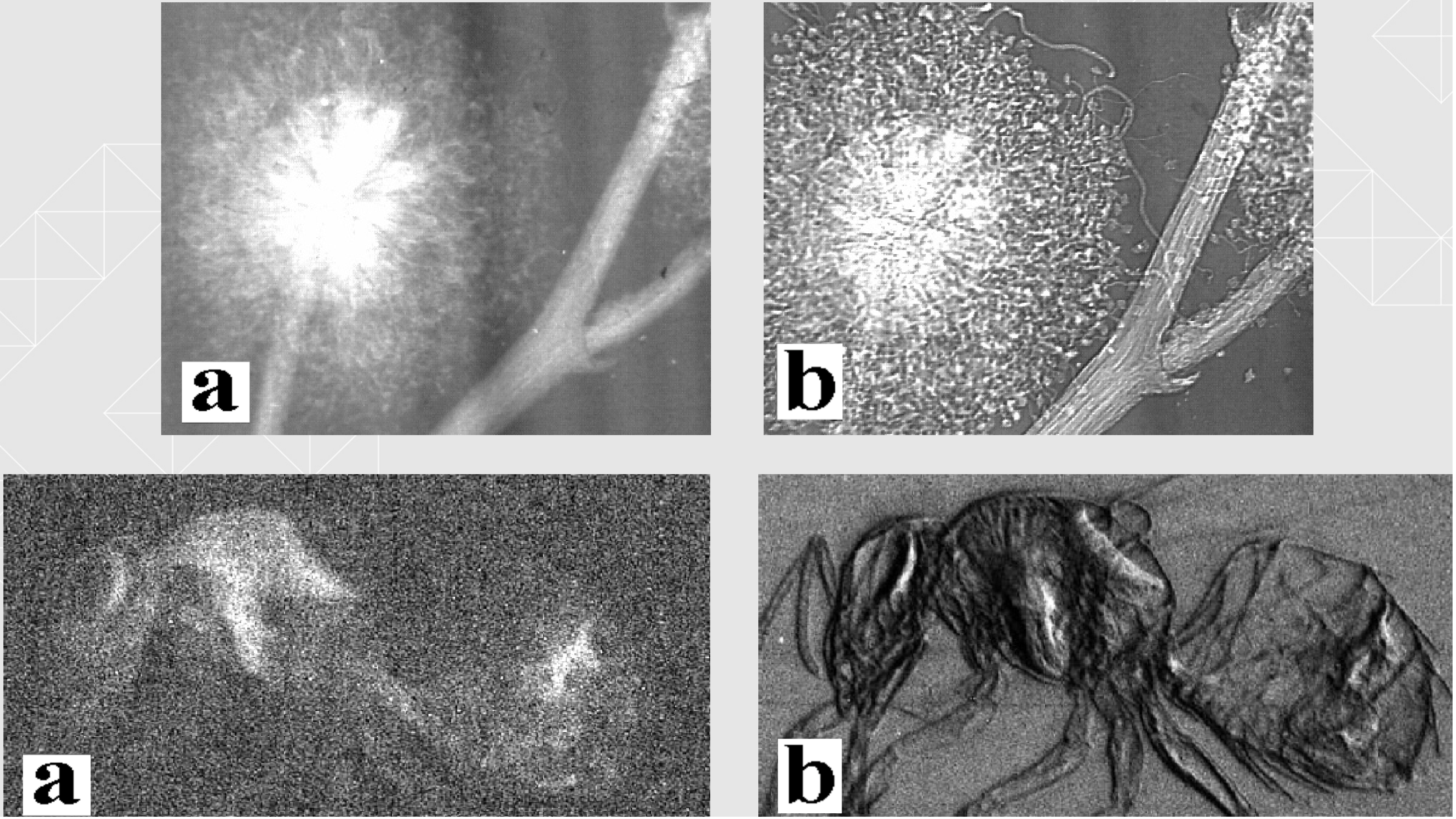
Refractive index: $n = 1 - \delta + i\,\beta$; $\delta >> \beta$ ->
phase contrast ($\Delta I/I_0 \sim 4\pi\delta\Delta z/\lambda$) >> absorption contrast ($\Delta I/I_0 \sim 4\pi\beta\Delta z/\lambda$)

Two possible approaches:
- **detect interference patterns**
- **detect angular deviations**

credit: A. Olivo UCL Engineering Department

X rays imaging

a) absorption **b) phase contrast**

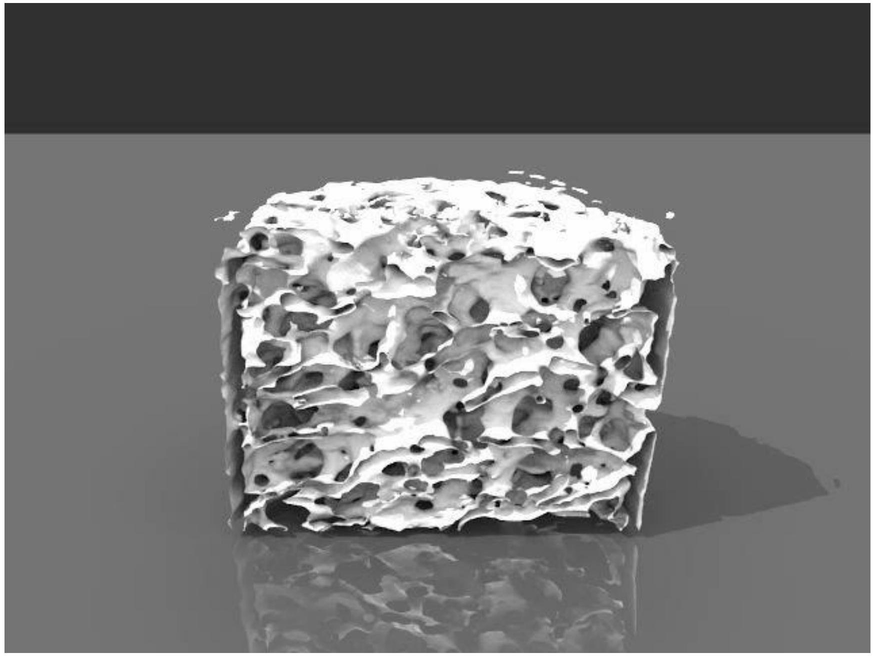


credit: A. Olivo UCL Engineering Department

X-ray tomographic imaging using Gemini

Betatron x-rays generated by CLF's GEMINI laser was used for tomographic imaging of trabecular bone tissues

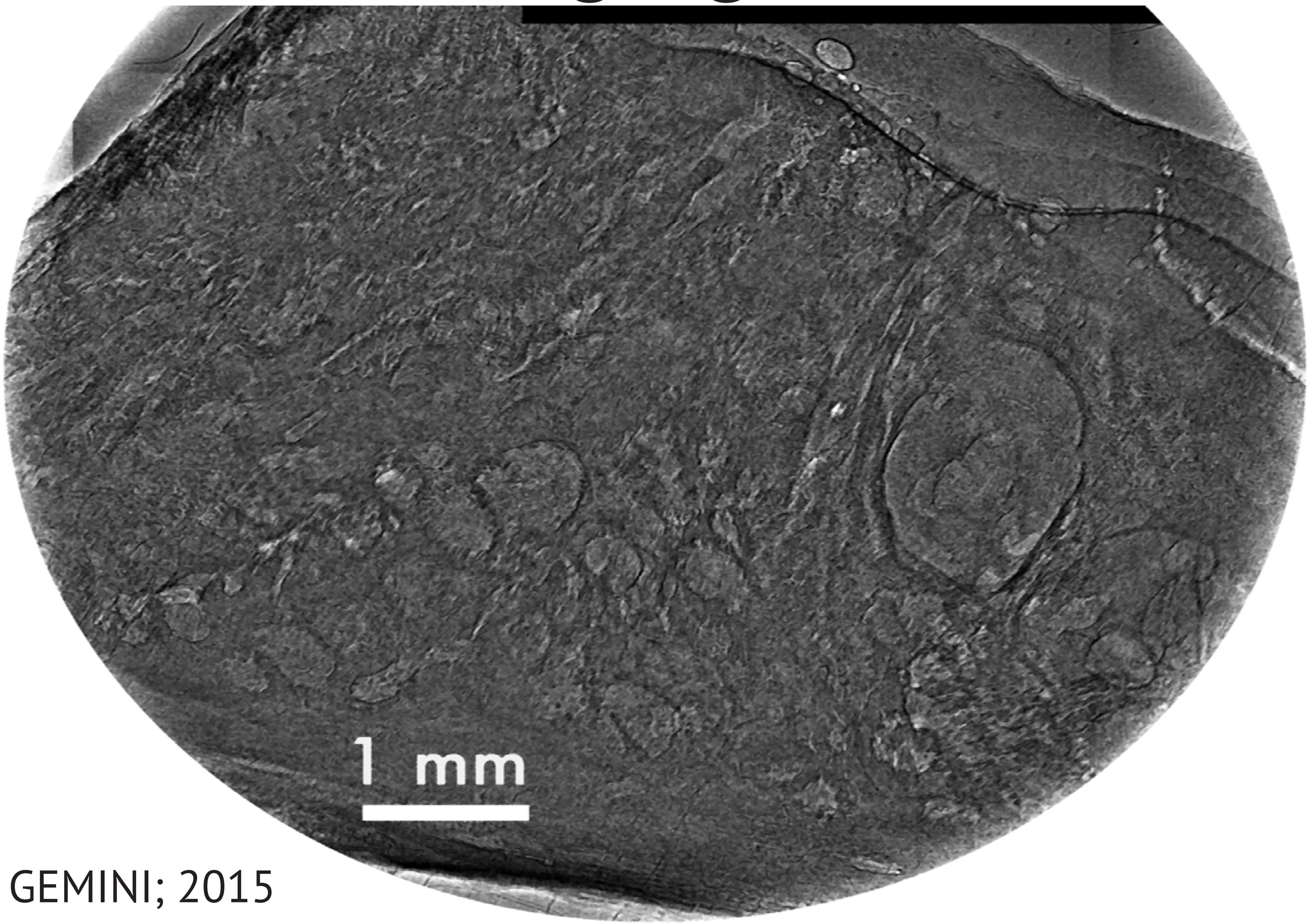
The semi-coherent x-rays produced by the laser accelerated electrons enable phase-contrast imaging, bringing the dream of compact, affordable high resolution x-ray imaging for medical and biological applications a step



Cole, Sci. Reports (2015)
https://www.llnl.gov/str/Sep06/Kinney.html
http://www.skyscan.be

credit: R. Pattathil and Z. Najmudin

Prostate Imaging with Gemini



IC at CLF's GEMINI; 2015

Lopes N. et al. X-ray phase contrast imaging of biological specimens with femtosecond pulses of betatron radiation from a compact laser plasma wakefield accelerator. In Preparation (2016).

credit: Z. Najmudin

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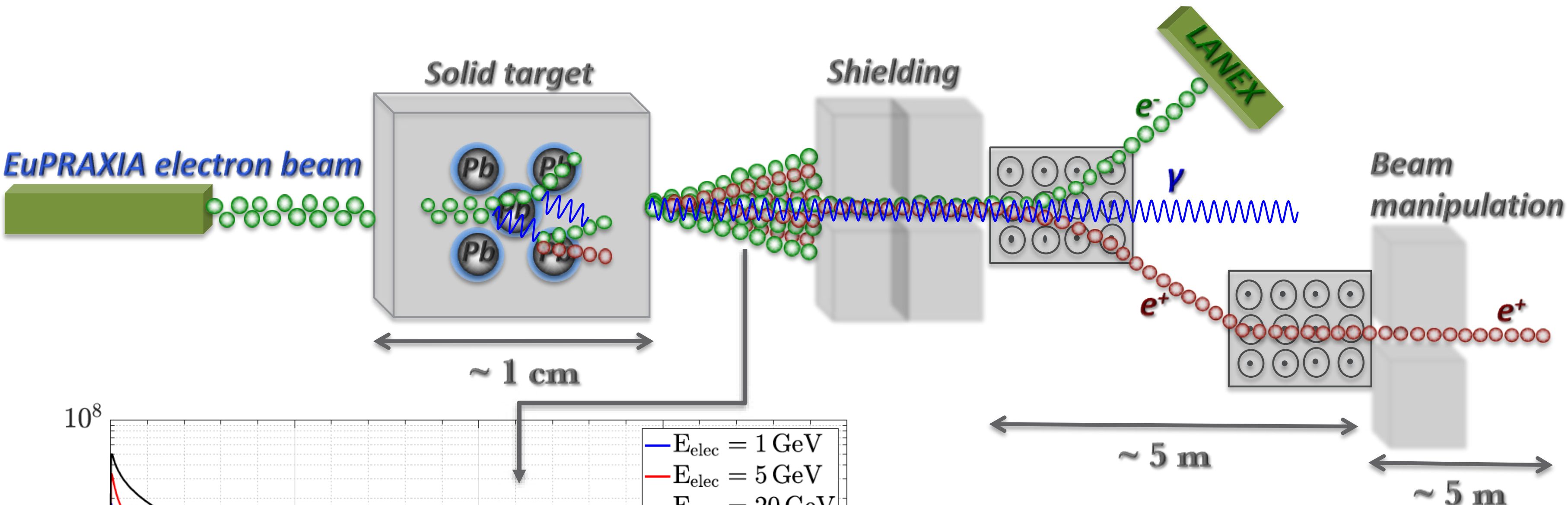
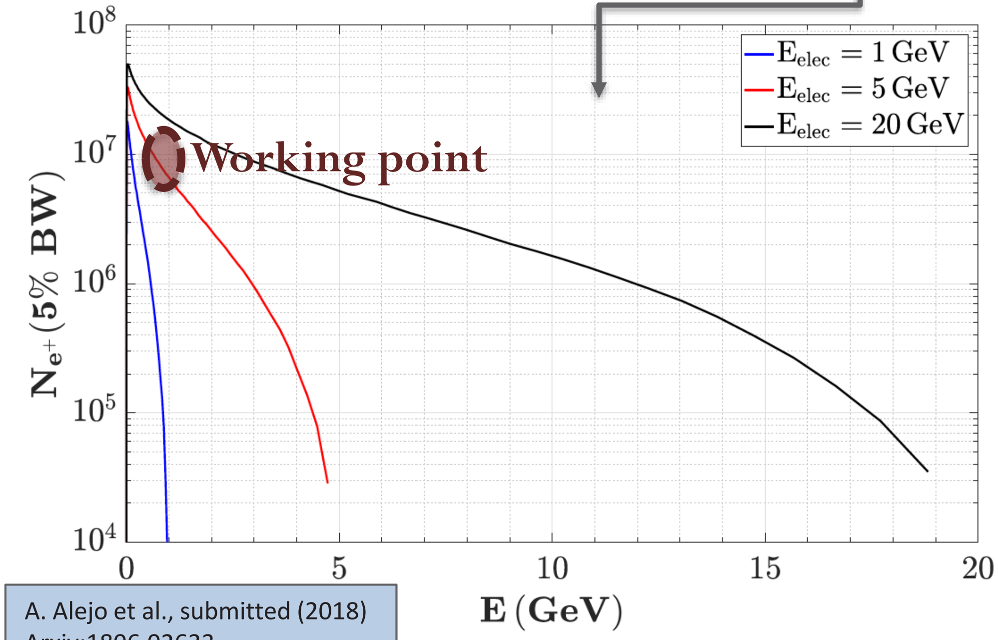
High-energy positrons

EuPRAXIA





A. Alejo et al., submitted (2018)
Arxiv:1806.02633

Assuming 100 pC at 5 GeV (5%)

- 10^7 positrons at 1 GeV (5%)
- Source size: 15 micron
- Divergence: 10 mrad
- Duration: 5 fs
- Emittance: 0.3 micron
- Rep. rate: 0.1 – 1 kHz
- Positrons/s: $10^9 – 10^{10}$

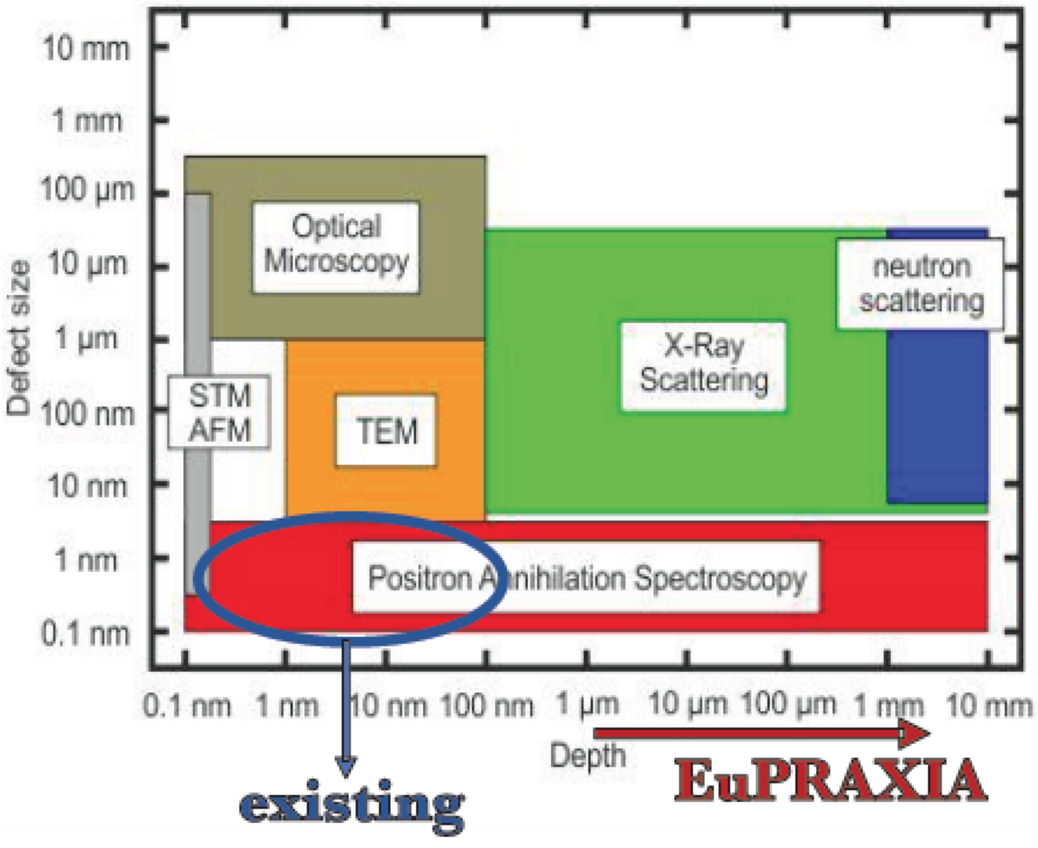
10^8 for 1 nC broadband electron beam

Liverpool 04/07/2018

credit: G. Sarri

OUTCOME: Positron Annihilation Spectroscopy

Horizon 2020



Courtesy M. Butterling, HZDR

Quantity	Baseline Value
Low-Energy Positron Source	
Positron energy	0.5–10 MeV (tunable)
Energy bandwidth	±50 keV
Beam duration	20–90 ps
Beam size at user area	2–5 mm
Positrons per shot	$\geq 10^6$

- EuPRAXIA would provide access to unique regime of detecting small defects at large penetration depths
- Does not require highest quality of electron beam

Gianluca Sarri et al

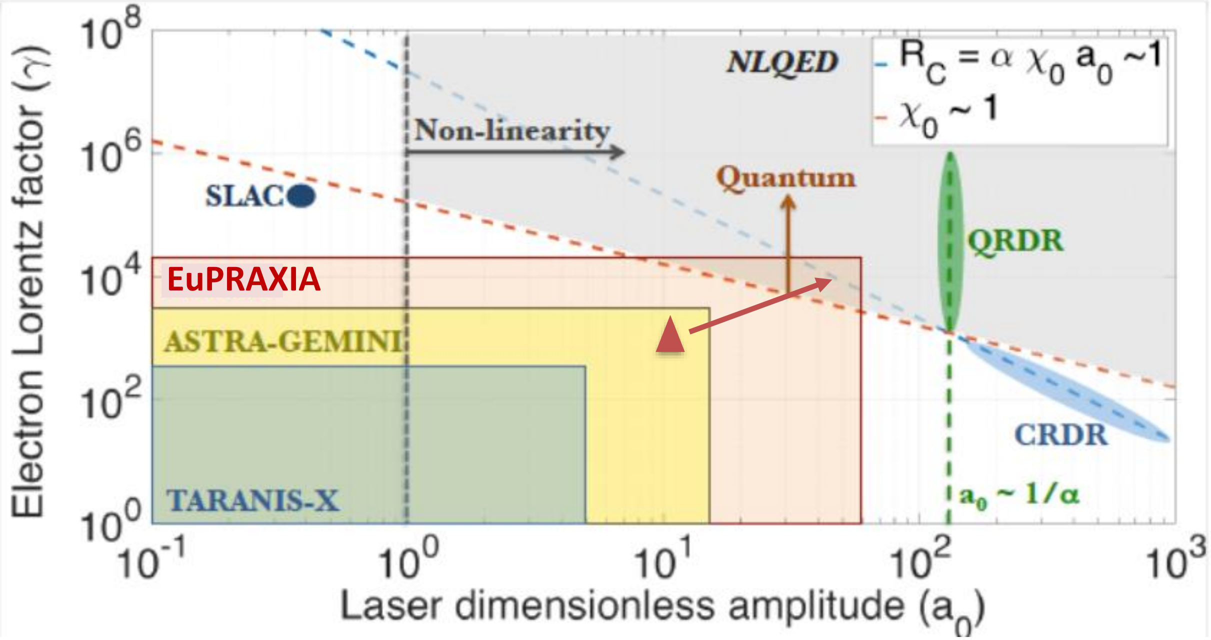
QUEEN'S UNIVERSITY BELFAST

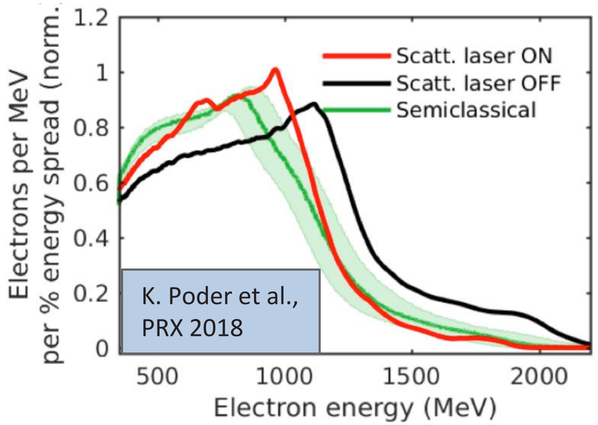
High-field QED

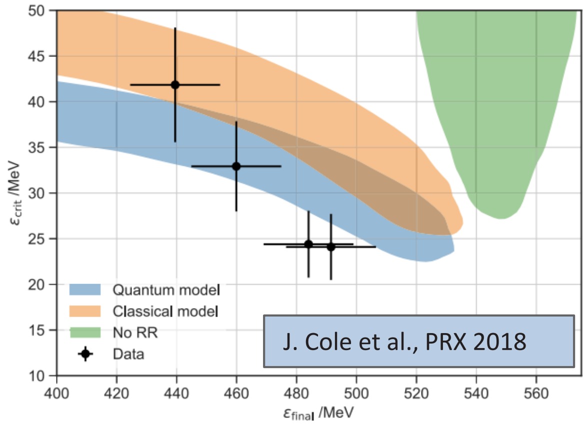
EuPRAXIA

Unique opportunity to have a **narrowband ultra-relativistic electron beam** synchronized with a **PW-scale laser at a high repetition rate**

Studies of high-field quantum electrodynamics **(> Schwinger field)** and access exotic phenomena such as: **quantum radiation reaction, photon-photon scattering, pair production**







Unique facility for high-field QED:
- **high-energy**
- **narrow bandwidth**
- **stability**

Liverpool 04/07/2018

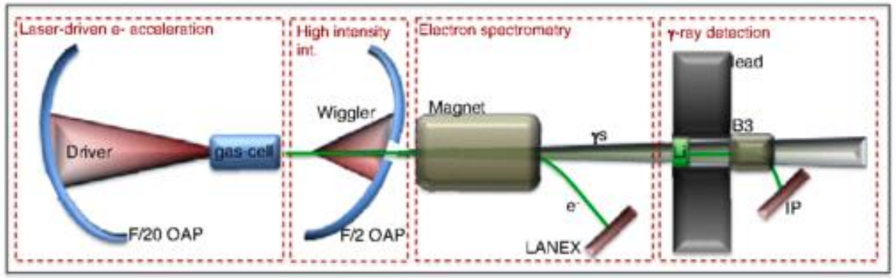
credit: G. Sarri

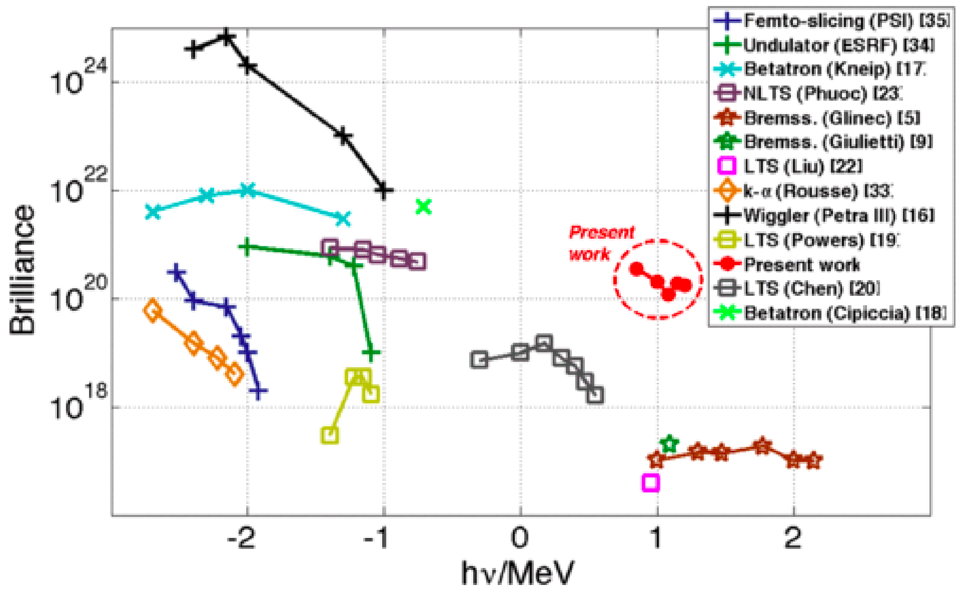
Brightest ever gamma ray source!

QUB-led team produced a gamma-ray beam in the multi-MeV range with highest peak brilliance ever produced!

They used nonlinear–Thompson scattering: scattering the north beam off an electron beam produced by the south beam

Gemini is uniquely placed to do such experiments with its dual–beam capability





Phys. Rev. Lett. **113**, 224801 (2014)

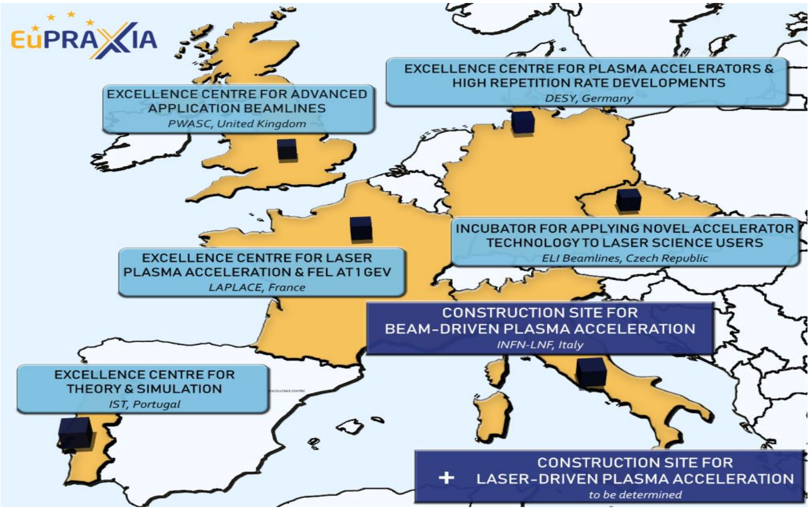
credit: R. Pattathil and G. Sarri

EuPRAXIA next stages

EuPRAXIA

Horizon 2020

OUTCOME Implementation Model



EuPRAXIA - R. Assmann, Final Yearly Meeting - 10/2019

EuPRAXIA next stages

	TDR phase	Construction phase	Sum
Invest			
Total	119 M€	204 M€	323 M€
Beam-driven	34 M€	85 M€	119 M€
Laser-driven	85 M€	119 M€	204 M€
Personpower			
Total	981 FTE	854 FTE	1835 FTE
Beam-driven	294 FTE	283 FTE	577 FTE
Laser-driven	687 FTE	571 FTE	1258 FTE
Duration			
Total	6 years	4 years	10 years
Beam-driven	4 years	4 years	8 years
Laser-driven	6 years	4 years	10 years

EuPRAXIA next stages

OUTCOME: Plan Ahead

EuPRAXIA — Horizon 2020

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	...	2065	2066
Project Phases	Conceptual Design Phase		Technical Design Phase (Jan 2020 – Dec 2025)						Implementation & Construction (Jan 2026 – Dec 2029)				Operation (Jan 2030 – Dec 2065)				Decommissioning

- **Submission of CDR**

Step 2

- Development of future user and stakeholder support
- Calculation of detailed, realistic budget & cost-benefit analysis
- **Submission of ESFRI Roadmap Application**

Step 3

- **Technical design of excellence centre sites**
- Prototyping of essential machine components
- ESFRI Review 1

...

- **Technical design of construction site(s)**
- Decision on legal structure & governance model for implementation and operation
- Procurement of funding for implementation & operation

- Development of long-term science programme

- ESFRI Review 2
- **Procurement and delivery of each essential component**
- **Installment of each essential component**
- **Commissioning of each essential component**

- **Start of operation**

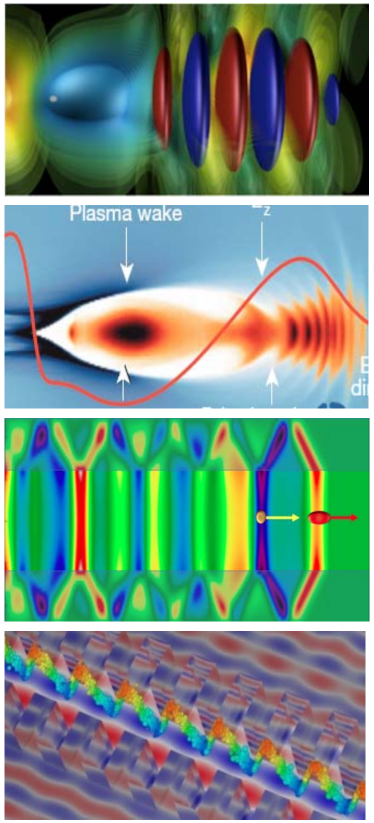
Next steps:

Publish CDR
Agree collaboration
Discuss with EU
Apply to ESFRI roadmap

EuPRAXIA - R. Assmann, Final Yearly Meeting - 10/2019

Advanced and Novel Accelerator concepts (ANAs): definition

Acceleration gradients larger then 1GV/m



- Wakefields driven in **plasma** by **intense** laser beams : **LWFA**
- Wakefields driven in **plasma** by **particle** beams: **PWFA**
- Wakefields driven in **structures** (e.g.dielectric tubes) by **particle** beams: **SWFA**
- Wakefields driven in **dielectric structures** by **short-pulse** lasers: **DLA**

slide presented by B. Cros at AAC 2018

Advanced LinEar collider study GROup: organisation

ALEGRO
Advanced LinEar collider st

ICFA
ICFA ANA

B Cros
C Schroeder
P Muggli

ALEGRO Steering Group

Euronnac

ALEGRO Working Groups

PC | CMD | TMS | LWFA | PWFA | SWFA | DLA | PAC

Opened to contributions fror interested scientists worldwid

ALEGRO WG titles and leaders:

PC: Physics Case (M Peskin, J Tian)
CMD: Collider Machine Design (A Seryi, D Schulte, H Yamamoto)
TMS:Theory, Modelling, Simulations (JL Vay, J. Vieira)
LWFA: Laser wakefield Accelerators (C. Schroeder, S. Hooker, B. Cros)
PWFA: Plasma wakefield Accelerators (J Osterhoff, E Gschwendter, P Muggli)
PAC: Positron acceleration (S. Gessner, S. Corde)
SWFA: Structure wakefield accelerator (P Piot, J Powe
DLA: Dielectric laser accelerator (J England, B Cowan)

http://www.lpgp.u-psud.fr/icfaana/ana-publications-2017

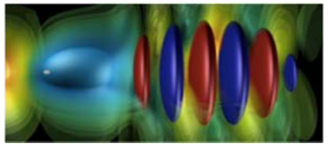
slide presented by B. Cros at AAC 2018

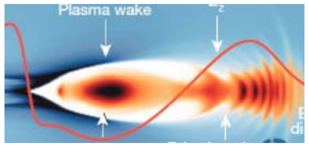
Scientific roadmap for a collider up to design report delivery

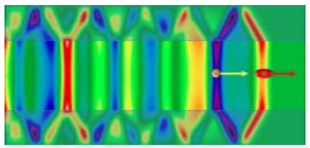
ALEGRO
Advanced LinEar collider study GROup

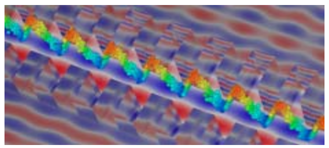
ANAR2017 workshop and report http://www.lpgp.u-psud.fr/icfaana/

2017 - 2022	2022 - 2027	2027 - 2032	2032-2037
e- sources: optimization	**e- acceleration :** Optimization of all parameters		
e+ sources: Concept devt	**e+ acceleration:** demonstration		
Driver development			
Accelerating structures			
Beam transport and coupling			









5 Ys – Injector, Accelerator stages with controlled parameters

10 Ys – x10 Improved beam quality at higher energy

15 Ys – Reliable staged accelaration, 10 GeV module

20 Ys – Advanced Linear Collider CDR and TDR

Address specific challenges :
Staging →
Reliability →
Polarization →
Efficiency →
Beam Delivery System →

slide presented by B. Cros at AAC 2018

ALEGRO2020 Workshop

previous meetings:
ANAR 2017 CERN
ALEGRO 2018 Oxford
AAC 2018 Breckenrige
ALEGRO 2019 CERN

In memory of Prof Jerzy Pniewski

Prof Jerzy Pniewski giving a lecture at Heidelberg University on the occasion of receiving Honory Doctorate from Heidelberg University.

This photograph was taken by U, Uhrmacher.

Roman Walczak
University of Oxford
Warsaw University, 28 Feb 2020

Summary

- Plasma wakefield accelerators are in transition from subjects of research only to subjects of research and applications.

- EuPRAXIA (funded by H2020) concluded four years of design studies with a CDR. Five excellence centres and two construction sides are proposed to develop plasma accelerators offering pilot users electron beams as well as secondary beams of photons and positrons.

- EuPRAXIA new Consortium Agreement is being discussed and submission of ESFRI roadmap application is in preparation. There is an opportunity for new institutions to join.

- ALEGRO, a world wide collaboration supported by ICFA, is studying options for applications of high gradient acceleration technologies in particle physics. The next of its yearly meetings will be in Hamburg in March.

History

RL 83 057

BEAT-WAVE LASER ACCELERATORS

FIRST REPORT OF THE R.A.L. STUDY GROUP

J. D. Lawson

Participants	Field of Interest
J E Allen*	Plasma Physics
R Bingham	Plasma Physics
J Butterworth	Particle Beam Transport
F E Close	High Energy Physics
R G Evans	Plasma Physics and Lasers
J D Lawson	Accelerators
G H Rees	Accelerators
R D Ruth+	Accelerators

* University of Oxford.

\+ Lawrence Berkeley Laboratory and CERN.

From the Abstract:
An attempt is being made to see what is involved in constructing a high energy accelerator using laser beat-wave principle...

High energy means here TeV level

Please note participants' fields of interest