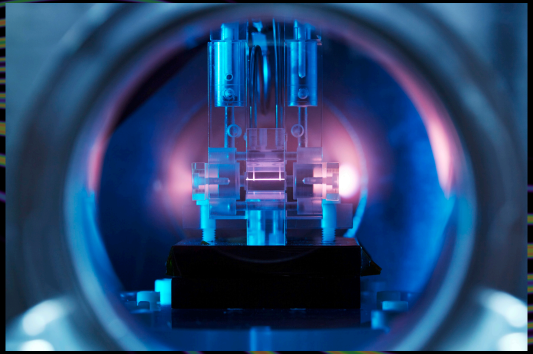
New Technologies for Linear Acceleration

On future new technologies for linear acceleration, including plasma - recent results and challenges for building high energy and high luminosity Higgs factory

Supporting the High Energy Frontier



Linear Collider Workshop 2019

29 October 2019, Sendai, Japan

European Network for Novel Accelerators

EuroNNAc 3

supported by EU via ARIES

Ralph W. Aßmann
Leading Scientist Accelerator R&D
DESY

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Thanks for input and material to:
Massimo Ferrario, Barbara Marchetti, Brigitte Cros, Ulrich Dorda, Ulrich Schramm, Wim Leemans, Jens Osterhoff, Athony Hartin, Patric Muggli, Allen Caldwell, Edda Gschwendtner, Frank Mayet, Willi Kuropka, Angel Ferran Pousa, Maria Weikum, Andreas Walker, Franz Kärtner, EuPRAXIA collaboration

MT
MATTER AND TECHNOLOGIES

DESY

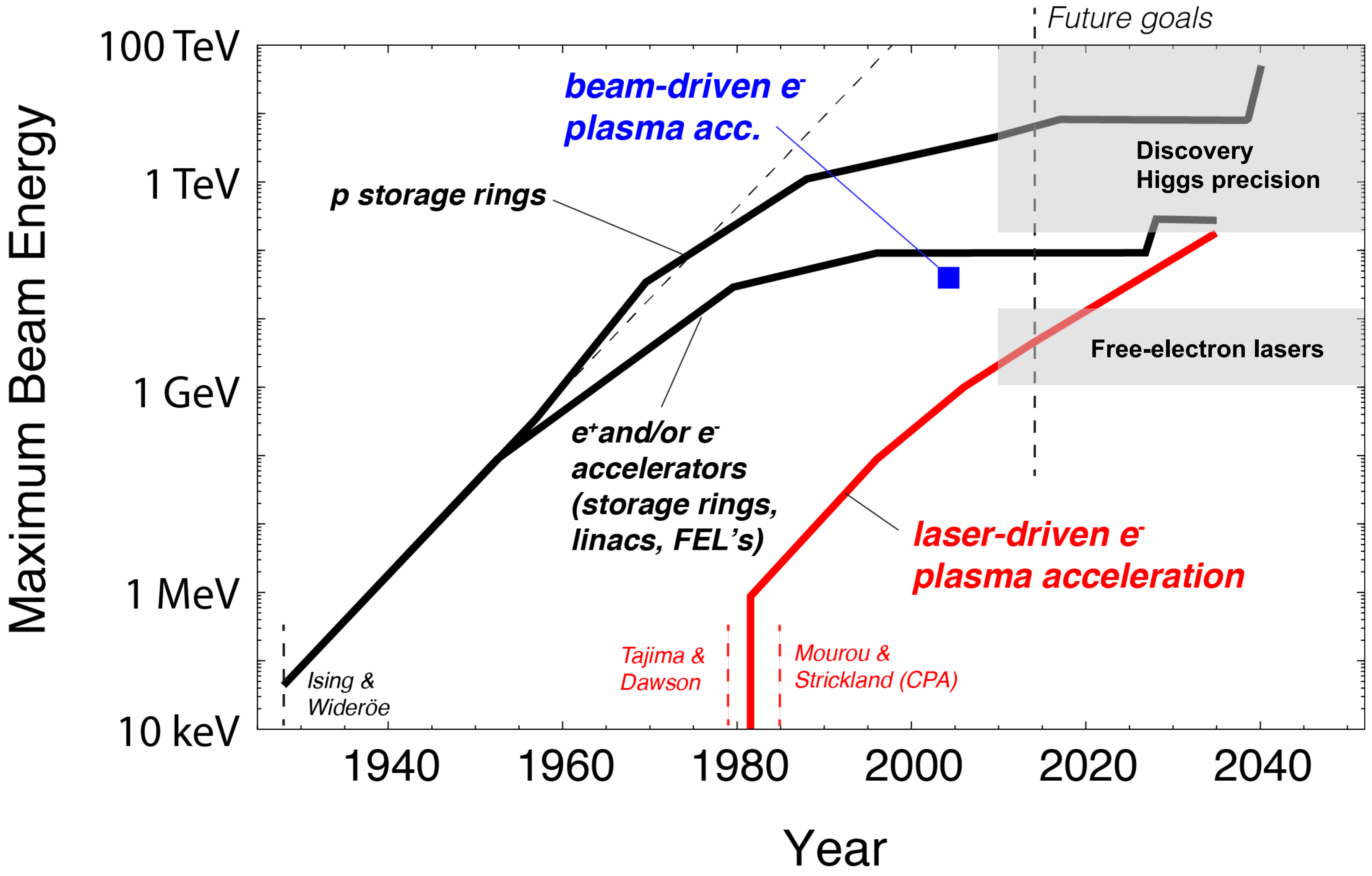
Livingston Plot: Progress at the Energy Frontier

Great success story: RF-based particle accelerators for discoveries and precision

Master-pieces of technology:

- LHC, LHC HiLumi
- SuperKEKb
- LEP, LEP-2
- Tevatron
- SLC
- HERA
- RHIC
- …

Progress slowing down → **R&D** → new ideas and technologies?



Comparison Novel Accelerators

Possibilities and Limits

- Three main concepts with possible gradients in the **GV/m regime**:
  - **P**lasma **W**ake **F**ield **A**cceleration, **D**ielectric **L**aser **A**cceleration, **THz**-based acceleration

	PWFA	DLA (Optical)	DLW (Thz)	S-Band (ARES)
Acceleration gradient	$\sim 100\,\mathrm{GeV/m}$	$\sim 1\,\mathrm{GeV/m}$	$< 10\,\mathrm{GeV/m}$	< 110 MeV/m (25 MeV/m)
Period	$< 300\,\mathrm{\mu m}$	$0.8\,\mathrm{\mu m} - 10\,\mathrm{\mu m}$	$\sim 1\,\mathrm{mm}$	10 cm
Typical bunch charge	$< 30\,\mathrm{pC}$	$< 1\,\mathrm{fC}$	$< 5\,\mathrm{pC}$	< 20 pC
Typical bunch length	$< 30\,\mathrm{fs}$	$< 1\,\mathrm{fs}$	$< 10\,\mathrm{fs}$	< 2 fs *…compressed*
Repetition rate	$< 10\,\mathrm{Hz}$	$\sim 1\,\mathrm{MHz}$	$> 0.1\,\mathrm{kHz}$	< 50 Hz
Aperture	$< 10\,\mathrm{\mu m}$	$\sim$ Period length	$\sim 1\,\mathrm{mm}$	~ 30 mm
Average Current	$< 0.3\,\mathrm{nA}$	$< 1\,\mathrm{nA}$	$> 0.5\,\mathrm{nA}$	< 1 nA
Peak Current	$> 0.3\,\mathrm{kA}$	$< 0.3\,\mathrm{A}$	$> 0.15\,\mathrm{kA}$	> 0.15 kA

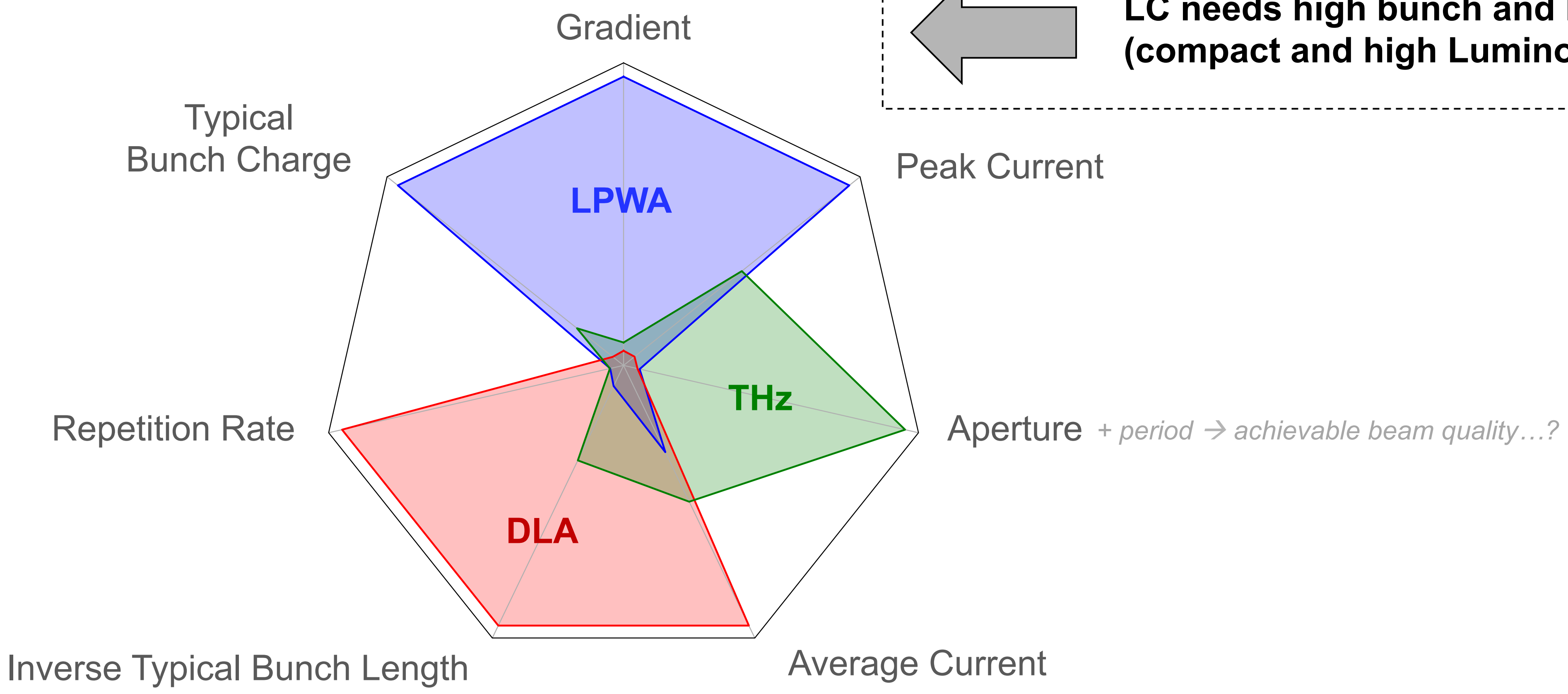
From PhD Frank Mayet, UHH & DESY

Comparison Novel Accelerators

Possibilities and Limits

$$E_{\mathrm{th}} \propto \frac{f^{1/2}}{\tau^{1/4}}$$

Achievable surface field



LC needs high bunch and high gradient (compact and high Luminosity)

From PhD Frank Mayet, UHH & DESY

- **Message**: The different concepts cater to different applications!

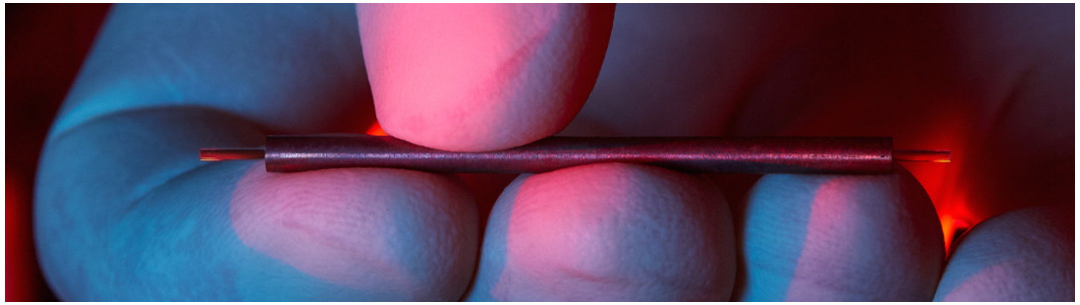
Dielectric Accelerators

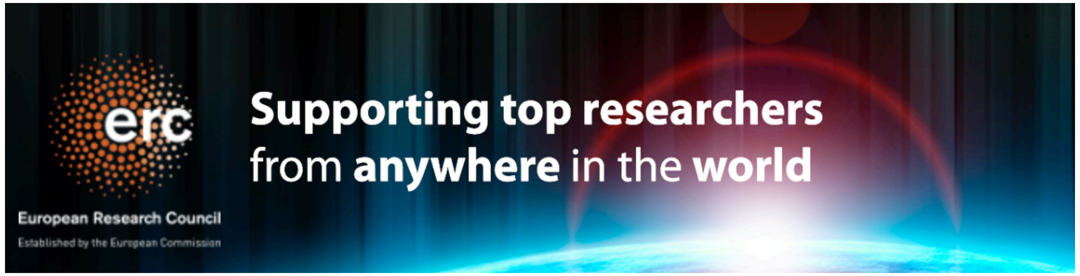
AXSIS – THz Accelerator for Science

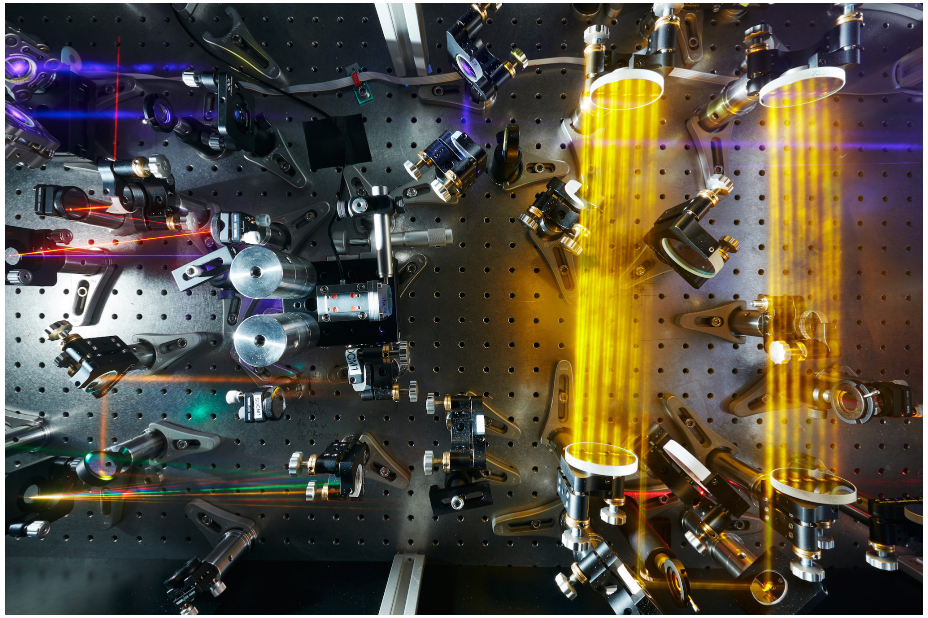
Vacuum dielectric accelerator

European Research Council
Established by the European Commission

- 1 GeV/m possible but low absolute energies achieved so far
- **AXSIS project (ERC synergy grant)** at DESY/Uni Hamburg: THz laser-driven accelerator with atto-second science → *Kärtner/Fromme/Chapman/Assmann*



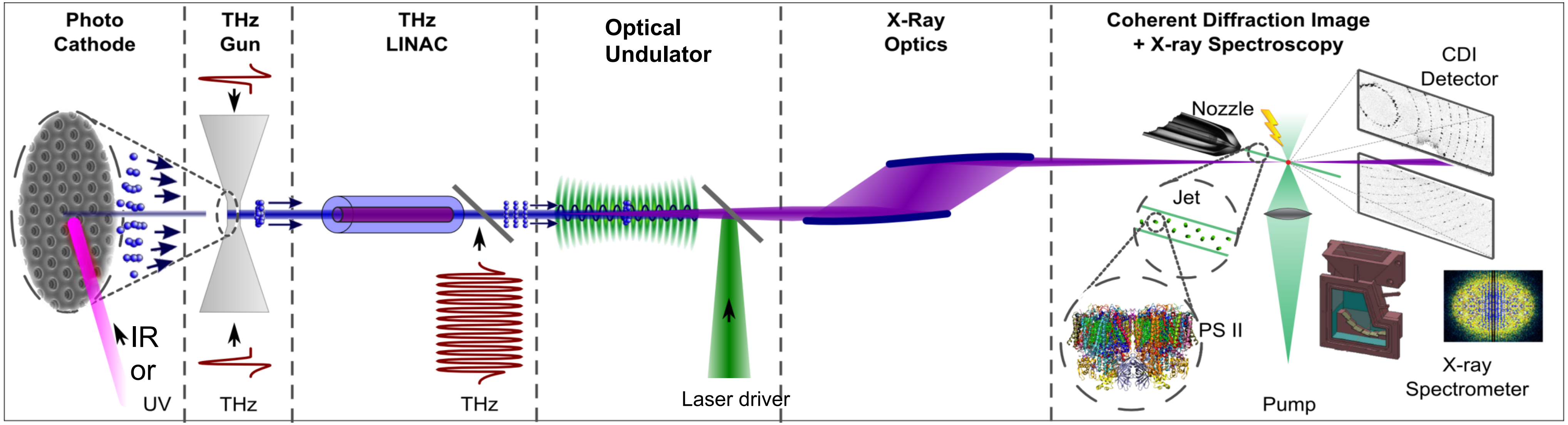




AXSIS

Attosecond X-ray Science – Imaging and Spectroscopy

Compact Coherent X-ray Source with sub-fs pulses + Science Application



ps, 1-J-Lasers,
auto-synchronization
kHz operation

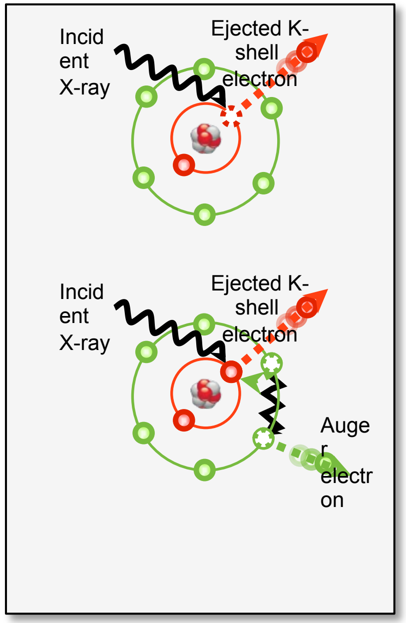
→ has its own science case
→ seeding of large scale FELs
→ solve access to large facilities

FXK. et al., doi:10.1016/j.nima.2016.02.080

Auger decay

sub-fs exposures required

Auger decay rates
O: 3 fs
S: 1 fs
Mn: 0.2 fs



Next year(s) AXSIS goal:

1 – 15 MeV

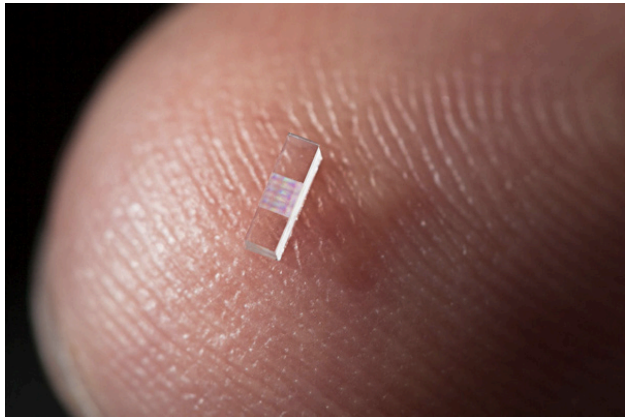
X rays

< 100's W

ACHIP Collaboration

Vacuum dielectric accelerator

- **"Accelerator on a Chip"** grant from Moore foundation
- Lasers drive **structures that are engraved on microchips** (e.g. Silicium)



Accelerator on a Chip International Program

DESY
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
TECH-X
Stanford University
PURDUE UNIVERSITY
PAUL SCHERRER INSTITUT PSI
國立清華大學 NATIONAL TSING HUA UNIVERSITY
UCLA
TECHNISCHE UNIVERSITÄT DARMSTADT
Los Alamos NATIONAL LABORATORY EST. 1943
FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
HAMAMATSU PHOTON IS OUR BUSINESS
GORDON AND BETTY MOORE FOUNDATION
SLAC NATIONAL ACCELERATOR LABORATORY

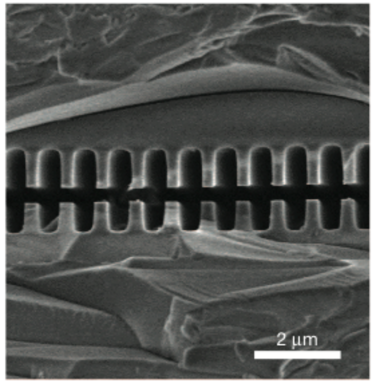
ACHIP Dielectric Structures

Slide from Frank Mayet, DESY

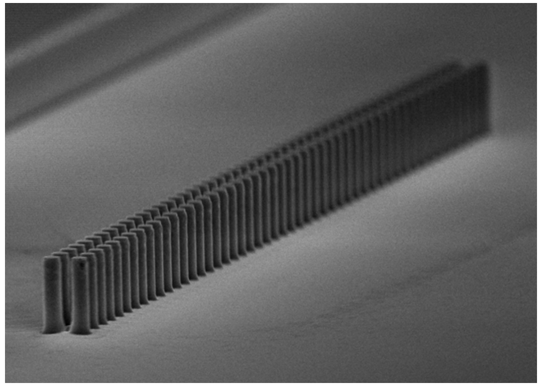
Fields in Grating Type Dielectric Laser Acceleration Structures

- **Real structures:** Examples

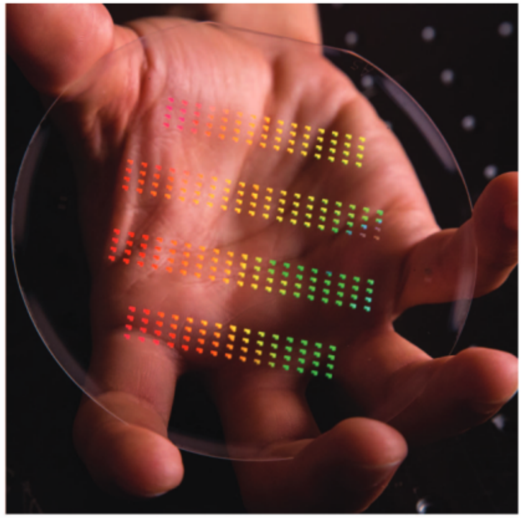
"Our" DESY/PSI type structure developed and produced by Stanford University



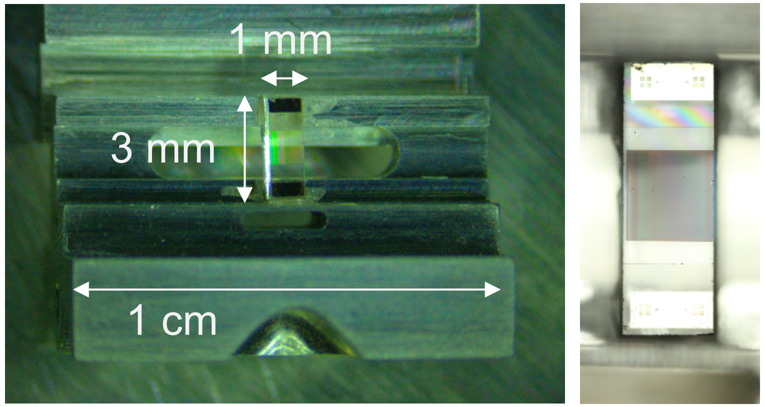
Dual Grating



Dual Pillar Structure



Multiple Structures on a Wafer



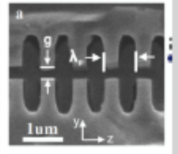
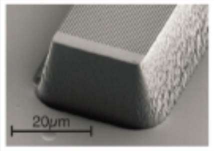
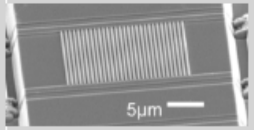
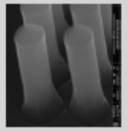
2 µm SiO_2 Dual Grating mounted on a Sample Holder (*B. Herrmann, PSI*)

- **Message**: Breakdown threshold of dielectrics (Si, SiO_2, …) in the optical regime (< 9 GV/m) + coupling efficiency into the sync. harmonic of ~0.25 → **~GV/m gradients**, moderate laser pulse energy requ. (~mJ)

1. Peralta, E. A. et al. **Demonstration of electron acceleration in a laser-driven dielectric microstructure.** *Nature* **503**, 91–94 (2013).
2. Breuer, J., Hommelhoff, P. et al. **Dielectric laser acceleration of nonrelativistic electrons at a single fused silica grating structure: Experimental part.** *PRST- Accelerators and Beams* **17**, 021301 (2014).

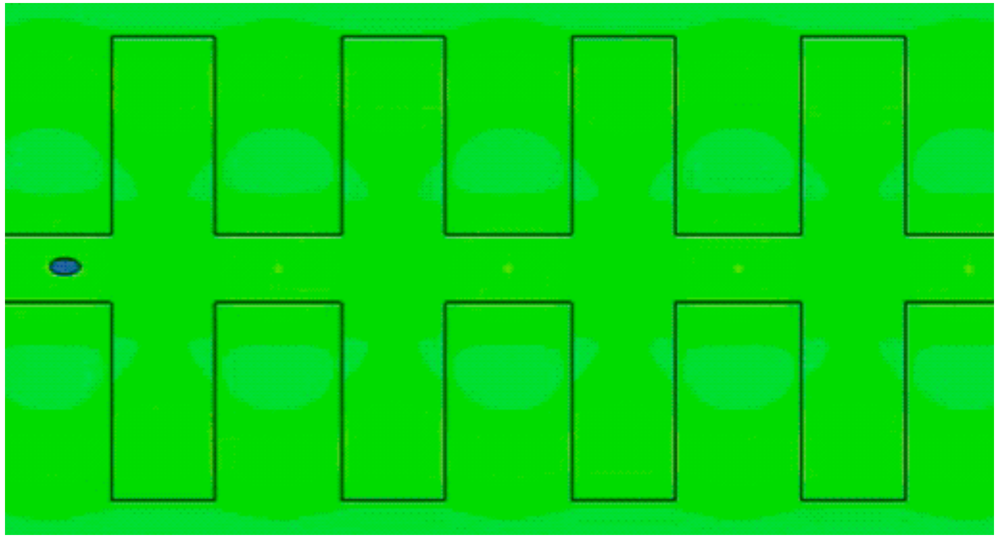
ACHIP Dielectric Structures

Fields in Grating Type Dielectric Laser Acceleration Structures

	SLAC & UCLA	Hommelhoff Erlangen	Si Single Grating	Si Dual Pillars
				
Electron Energy	8 MeV	30 keV	96.3 keV	86.5keV
Relativistic β	0.998	0.33	0.54	0.52
Laser Energy	150 uJ	160 nJ	5.2 nJ	3.0 nJ
Pulse Length	40 fs	110 fs	130 fs	130 fs
Interaction Length	~20 um	11 um	5.6 um	5.6 um
Peak Laser Field	8 GV/m	2.85 GV/m	1.65 GV/m	~1.1 GV/m
Max Energy Gain	**30 keV**	**0.275 keV**	**1.22 keV**	**2.05 keV**
Max Acc Gradient	**~1.5 GV/m***	**25 MeV/m**	**220 MeV/m**	**370 MeV/m**
G_{max}/E_p	~0.18	~0.01	~0.13	~0.4

J. England et al., Rev. Mod. Physics, V. 86, (2014)

Longitudinal Electric Field Component



CST simulation/animation courtesy of W. Kuropka

Next year(s) ACHIP goal: **1 MeV shoe-box accelerator** *(< 10's W)*

Work ongoing on compact injector, laser coupling, accelerator

Plasma Accelerators

Options for Driving Plasma Wakefields

Drivers characterized also by stored energy (LC needs about 15 MJ stored per collider bunch)

Courtesy M. Kaluza

- **Laser pulse**:
  - Industrially available, steep progress, path to low cost
  - Limited energy per drive pulse (up to **50 J** @ 5 Hz)
- **Electron bunch**:
  - Short bunches (need μm) available
  - Need long RF accelerator
  - More energy per drive pulse (up to **500 J**)
- **Proton bunch**:
  - Only long (inefficient) bunches
  - Need very long RF accelerator
  - Maximum energy per drive pulse (up to **100,000 J**)

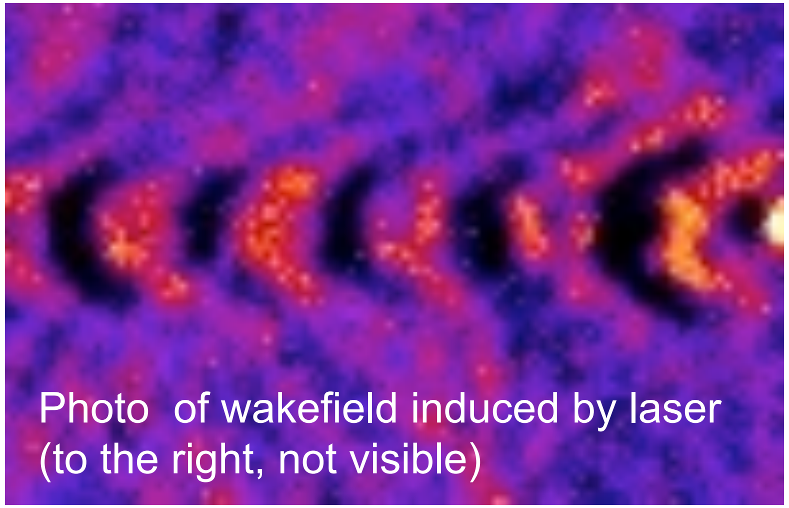
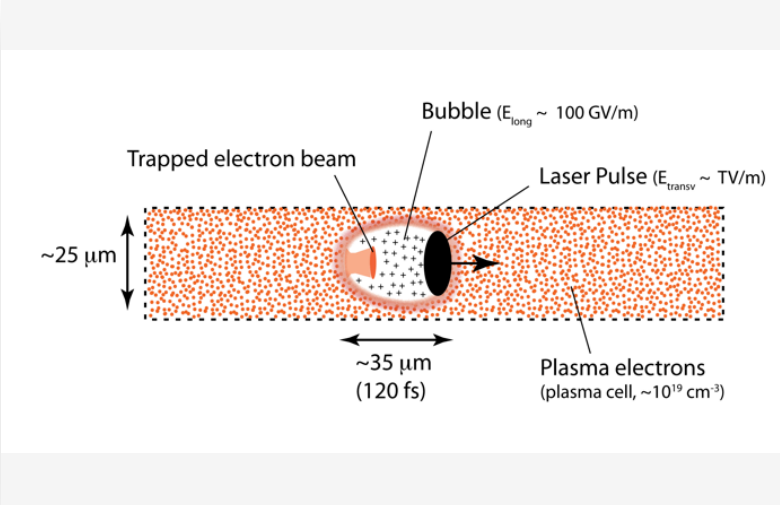


Photo of wakefield induced by laser (to the right, not visible)



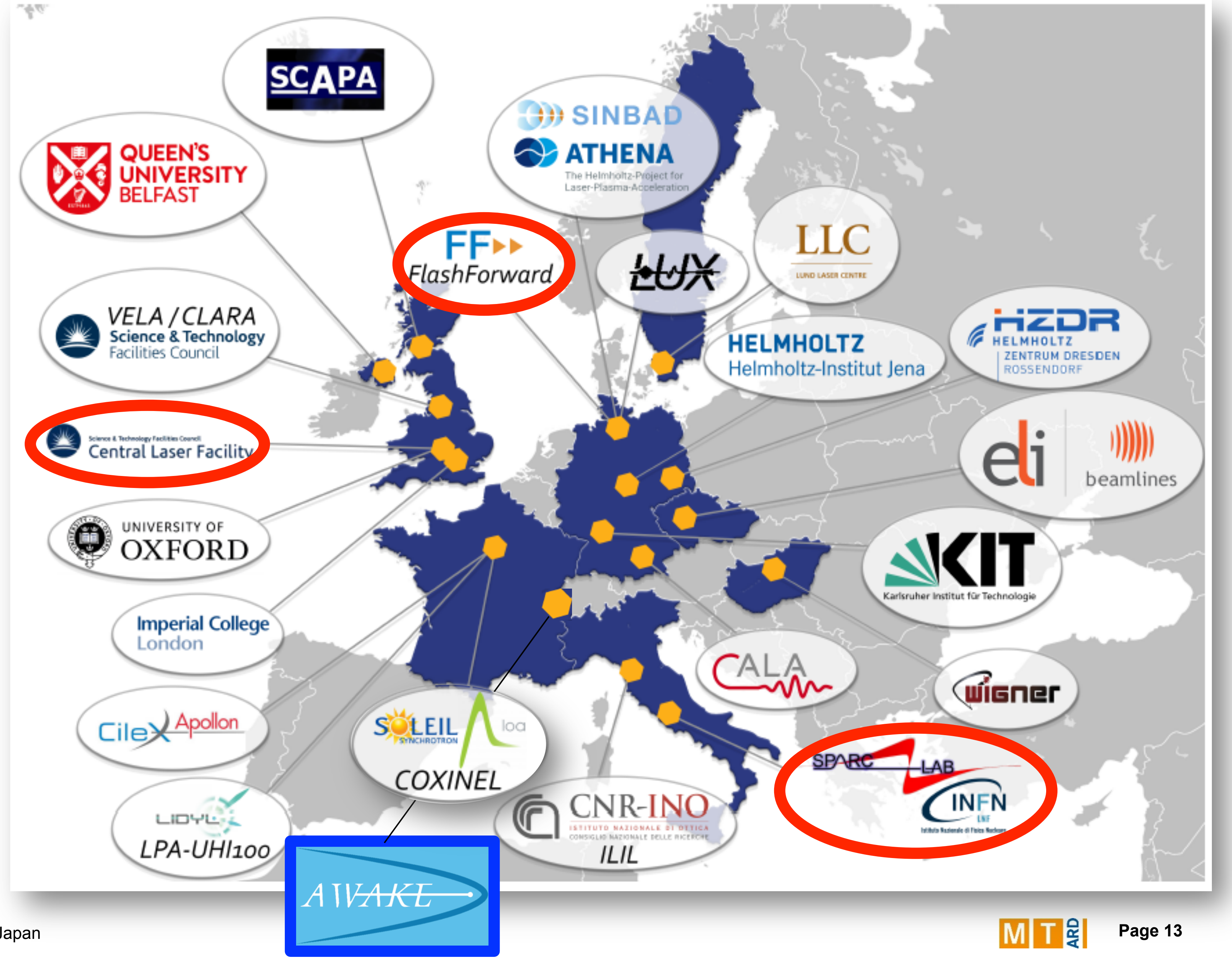
Facilities

Europe here

Most with laser-driven plasma accelerator facilities or ambition but...

electron beam driven

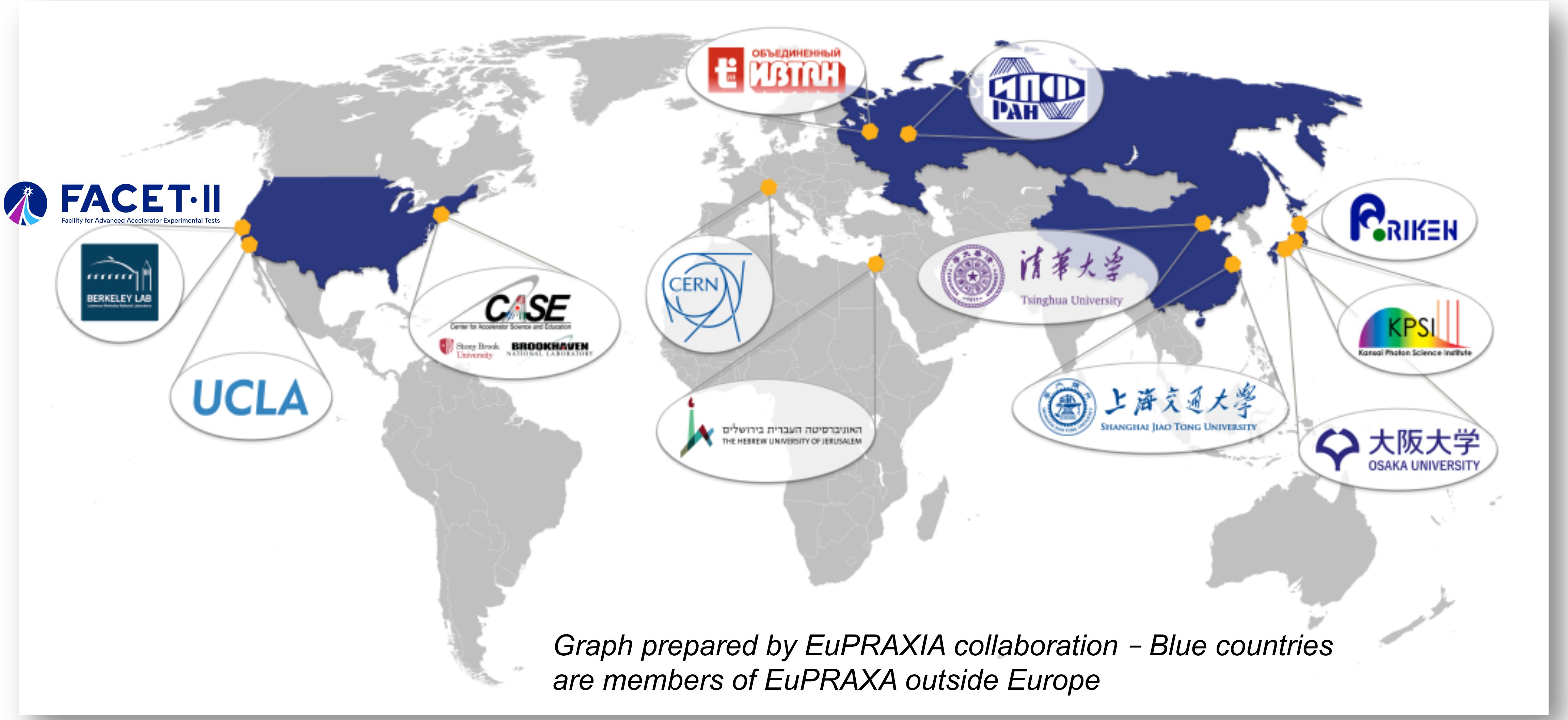
proton beam driven



Graph prepared by EuPRAXIA collaboration – Blue countries are members of EuPRAXA

Facilities

World-wide



Graph prepared by EuPRAXIA collaboration – Blue countries are members of EuPRAXA outside Europe

Major Progress Achieved World-Wide

Quick overview, not complete and no details (see ESSP talks in Granada for more details)

- **LBNL**: 8 GeV electron beams created with laser pulse in 20 cm of plasma, two stage plasma acceleration, work on plasma lenses, ...
- **SLAC**: 30 GeV electron acceleration through an electron beam driver, first positron acceleration, efficiency of plasma accelerator assessed (30%), ...
- **Tsinghua**: HQ external injection of electrons into a plasma accelerator, ...
- **CERN**: 2 GeV electron acceleration from proton-driven plasma wakefield (AWAKE)
- **DESY**: X ray emission from 1 GeV laser-wakefield electron bunch, >24 h operation of a laser plasma accelerator, stability improvements, plasma dechirper for reduction of electron spread, work on plasma lenses, high transformer ratio (>> 2), ...
- **HZDR**: 500 pC charge with > 10 kA, ...
- **Frascati INFN/LNF**: plasma dechirper for reduction of electron spread, work on plasma lenses, ...
- **LOA/Soleil**: transport of laser wakefield accelerated electrons, X ray emission from laser-wakefield electron bunch, ...
- **STFC/Oxford**: High resolution medical imaging with X rays from laser wakefield acc, ...
- **Osaka**: magnetic steering of laser wakefield accelerated electrons, two stages, ...
- ...

2 – 8 – 30 GeV
Two stages
Plasma lenses
Transport e-
X rays prod.
1st positron acc.
Plasma dechirper
Steering e- beam
24 h operation
500 pC (> 10 kA)
$\gamma\varepsilon$ < 1 mm-rad
Up to 1 Hz
...

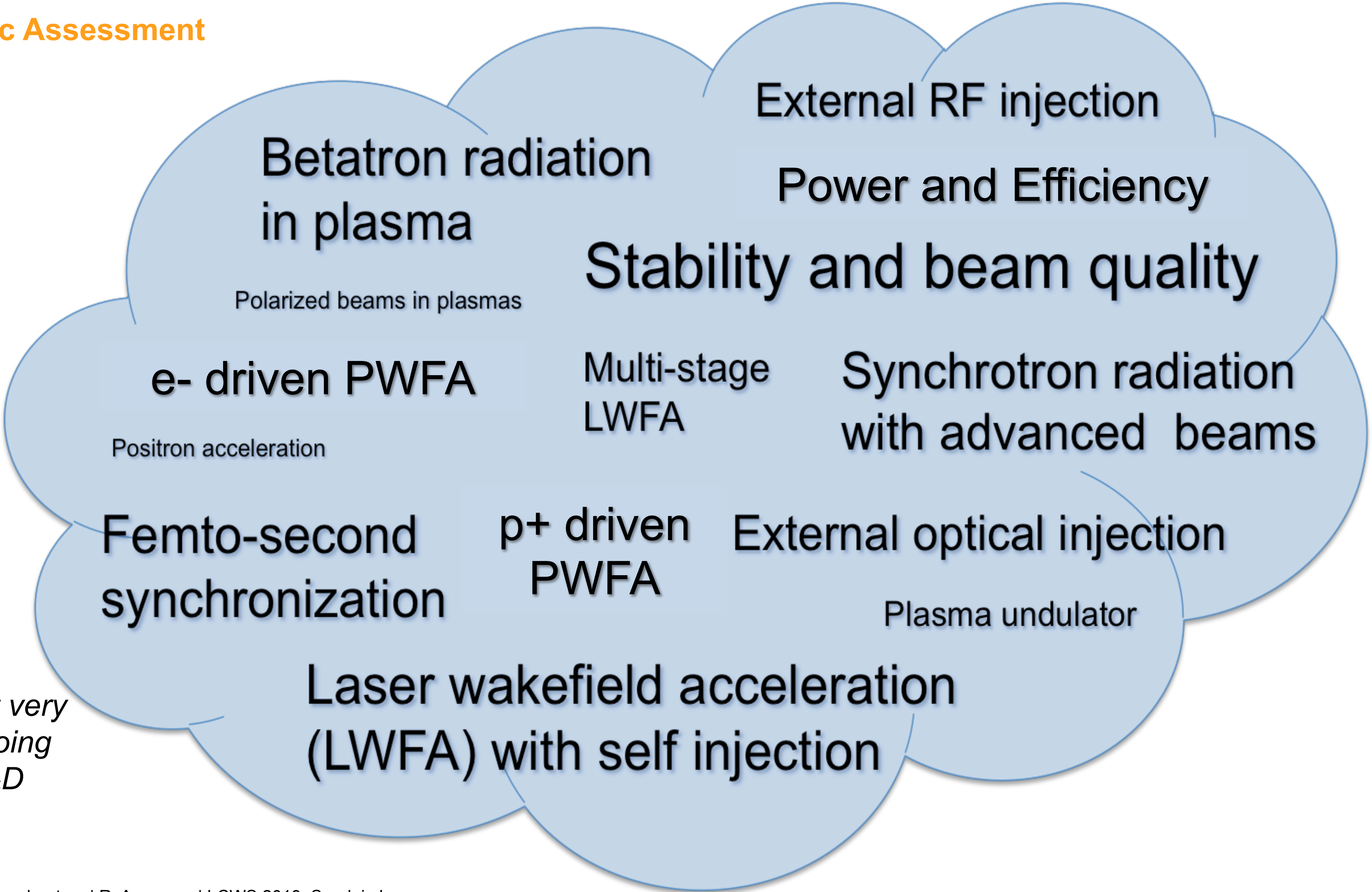
*

** Not all achieved the at same time*

Plasma Linear Collider I
Ready to go for a full collider?

R&D Paths Plasma Accelerators

EuroNNAc Assessment



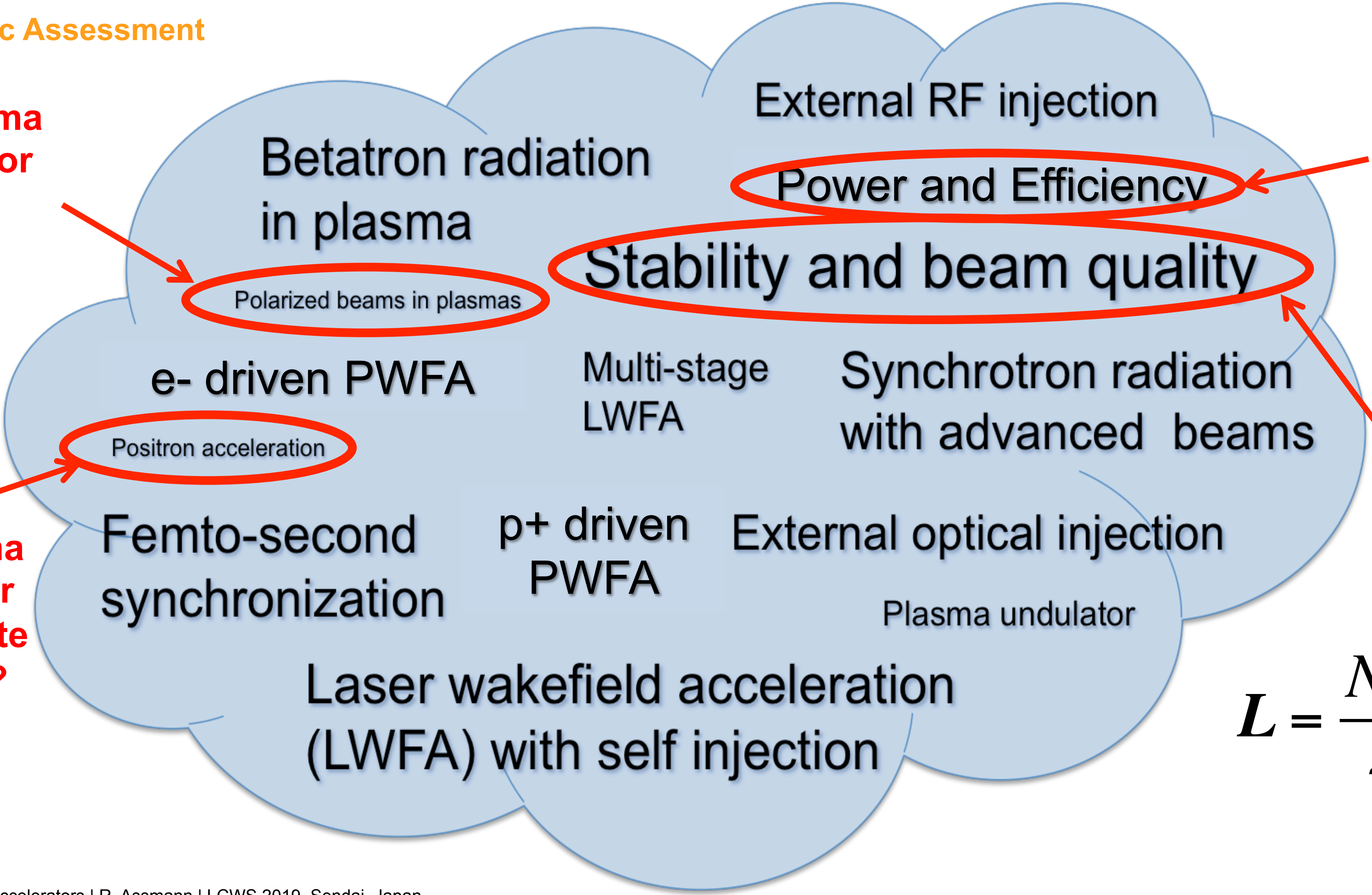
Sizes reflect very roughly ongoing efforts in R&D topics

R&D Paths Plasma Accelerators

EuroNNAc Assessment

Can plasma accelerators deliver polarized beams?

Can plasma accelerators accelerate positrons?



Can plasma accelerators deliver integrated luminosity?

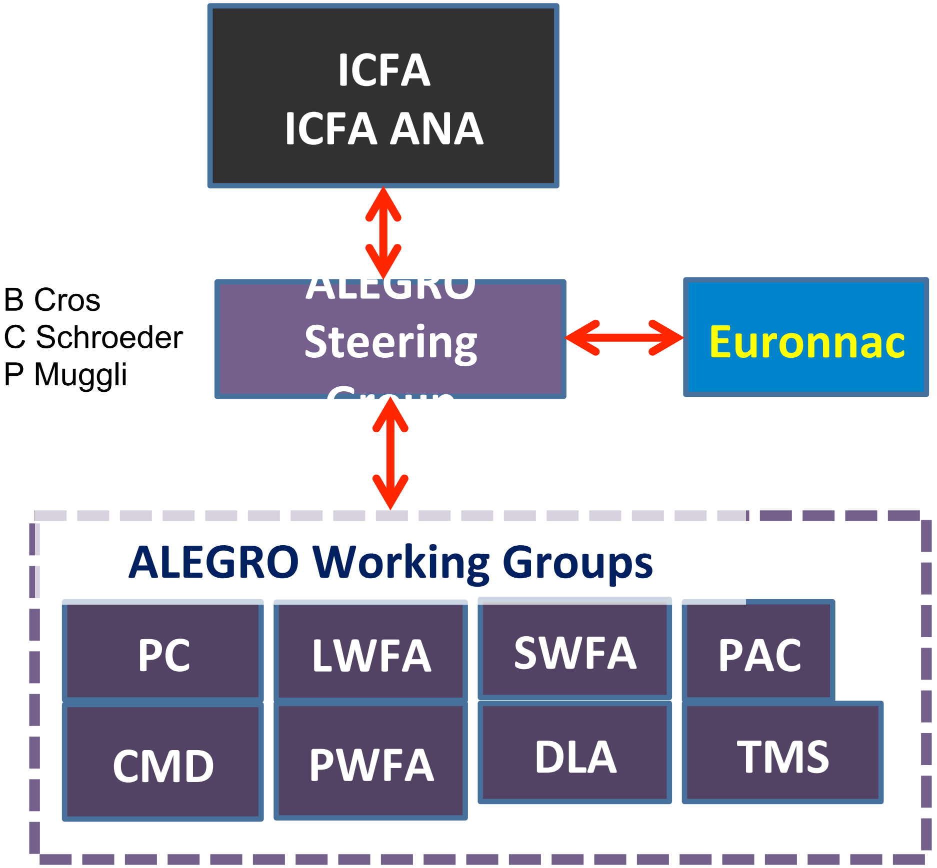
Can plasma accelerators deliver peak luminosity?

$$L = \frac{N_{e+} N_{e-} f_r}{4\pi\sigma_x\sigma_y}$$

Advanced LinEar collider study GROup

Advanced Linear Collider related activities based on Advanced and Novel Acceleration (ANA) concepts

- To foster and trigger Advanced Linear Collider related activities based on Advanced and Novel Acceleration (ANA) concepts
- Provide a framework to amplify international coordination, broaden the community, involving accelerator labs/institutes
- Identify topics of ANAs requiring intensive R&D and facilities needed



ALEGRO input for the 2020 update of the European Strategy for Particle Physics: comprehensive overview

Contacts: B. Cros[1], P. Muggli[2]
on behalf of ALEGRO collaboration,
member list at http://www.lpgp.u-psud.fr/icfaana/alegro/alegro-members

[1] LPGP, CNRS, Université Paris Sud, Orsay France, email: brigitte.cros@u-psud.fr
[2]Max Planck Institute for Physics, Munich, Germany, email: muggli@mpp.mpg.de

Advanced and Novel Accelerators (ANAs) can provide acceleration gradients orders of magnitude greater than conventional accelerator technologies, and hence they have the potential to provide a new generation of more compact, high-energy machines. Four technologies are of particular interest, all of which rely on the generation of a wakefield which contains intense electric fields suitable for particle acceleration. In the laser wakefield accelerator (LWFA) and plasma wakefield accelerator (PWFA) the wakefields are driven in a plasma by intense laser or particle beams, respectively; in the structure wakefield accelerator (SWFA), the wake is excited by a particle bunch propagating through a structured tube; and in the dielectric laser accelerator (DLA), a laser pulse directly drives an accelerating mode in a dielectric structure.

ALEGRO
Advanced LinEar collider study GROup

Material from Brigitte Cros & Patric Muggli

http://www.lpgp.u-psud.fr/icfaana/alegro

Advanced LinEar collider study GROup

Advanced Linear Collider related activities based on Advanced and Novel Acceleration (ANA) concepts

ALEGRO proposal

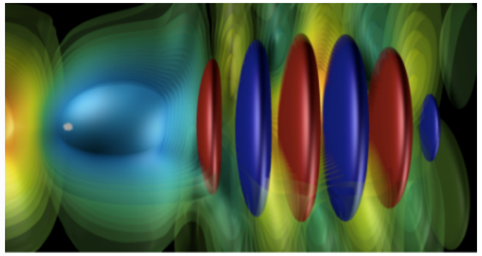
- ALEGRO proposes as **a long-term goal** the design of a e^+/e^-/gamma collider with up to 30 TeV in the center of mass –

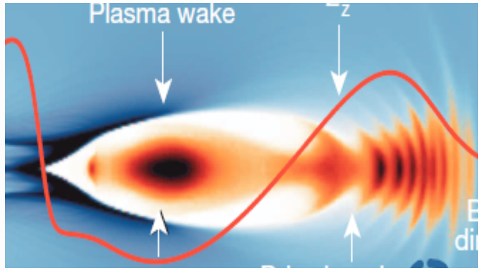
the Advanced Linear International Collider (ALIC).

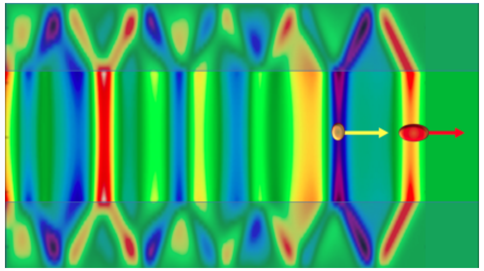
- The major goal for the community **over the next five to ten years is the construction of dedicated ANA facilities** that can reliably deliver high-quality, multi-GeV electron beams from a small number of stages.

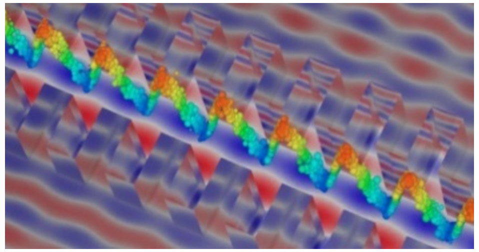
A number of key topics related to what could be the **front end of ALIC, consisting of an injector plus accelerator module**, and producing beams in the 5-25 GeV range, are planned to be addressed:

- External injection
- Bunch quality, efficiency, stability and reproducibility
- Plasma sources
- Operation at high repetition rate
- High-quality electron (e^-) and positron (e^+) bunches
- Independently shaped drive- and main-beam
- Multi-stage challenges with high-energy beams





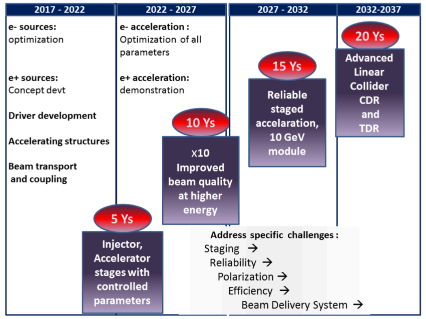




Timeline estimated:

End of 2030's → technical design worked out

Construction afterwards → operation **end of 2040's** or in the 2050's



Material from Brigitte Cros & Patric Muggli

LC Challenges Example

See 2017 ANAR Talk

- 1998 study Yokoya/Assmann: 1 TeV plasma linac, driven by (1) beam or (2) laser
- Tolerance for 200% emit. growth
- Found **≈20 nm** rms offset tolerance beam to driver (e.g. laser) for normalized emitt. of **4e-8 m-rad**
- Early estimate...

European Network EuroNNAc for Novel Accelerators | EuPRAXIA

Tolerances from Emittance Growth

Horizon2020

Nuclear Instruments and Methods in Physics Research A 410 (1998) 544–548

Transverse beam dynamics in plasma-based linacs

Ralph Assmann[1a,*], Kaoru Yokoya[b]

[a] Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA
[b] High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan

Single stage approaches avoid this problem (→ AWAKE) but can develop other problems.

Table 1
Parameters of the two 1 TeV linac designs and the accelerated beam. We only list parameters that are important for the discussion of the transverse beam dynamics. The focusing field for the LWFA case is a simplified estimate

Parameter	PWFA	LWFA
Plasma density	2×10^{14} cm^{-3}	10^{17} cm^{-3}
Accelerating gradient	1 GeV/m	30 GeV/m
Acc. wavelength	2 mm	100 μm
Focusing field	6000 T/m	600000 T/m
Module length	6 m	1 m
Injection energy	1 GeV	1 GeV
Final energy	1 TeV	1 TeV
Number of modules	167	33

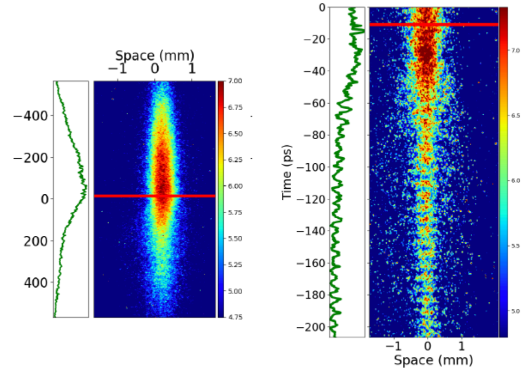
In this case we can calculate the tolerances on the offsets Δx for a total emittance growth of 200%. We find tolerances on σ_x/σ_0 of 0.08 (PWFA) and 0.18 (LWFA).

AWAKE: Proton-Driven Plasma Acceleration at CERN

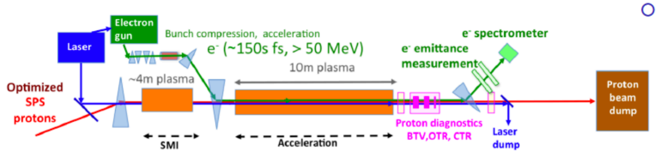
Using energy stored in protons for driving plasma acceleration

AWAKE Outlook

[W. Bartmann et al, AWAKE++, CERN-PBC-REPORT-2018-005]



- **Goals for AWAKE Run 1 (2016-2018) achieved**: Self modulation of proton bunch in plasma, Electron capture and GeV level acceleration
- **AIMs for run 2 (2021-2024)**:
  - Scalable acceleration to 1 GV/m, 100 pC
  - Control emittance to 10 mm mrad
  - High energy electron beams (to order 10 GeV)
- **Goals after the end of run 2:** Increase beam energy ($\geq$ 50 GeV). Use beams for novel and worthwhile physics experiments
- **We are studying three possible experiments**
  - Dark photon beam dump experiment
  - Non perturbative QFT tests
  - High energy ep collisions



A. Hartin | AWAKE physics applications | 4/16

Material from Anthony Hartin (AWAKE collaboration)

→ **1 GV / m** by 2024

→ **50 GeV** e- beam

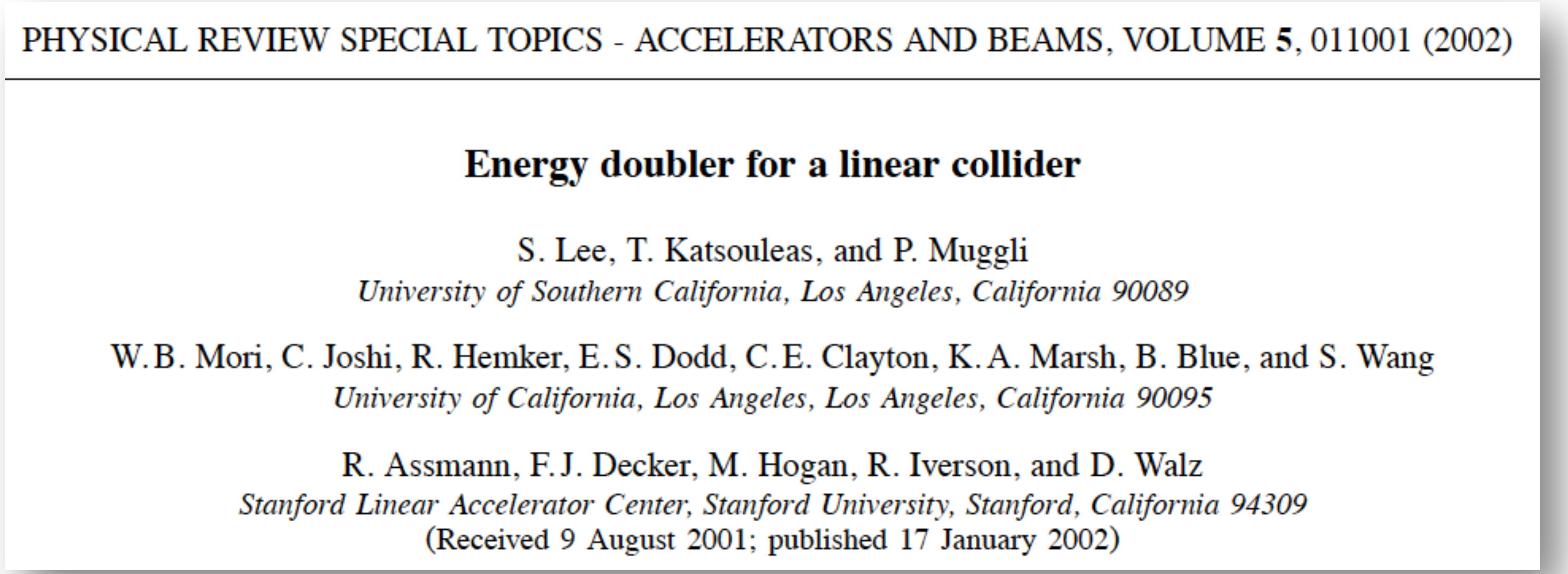
Ideas for **first particle physics experiments**

Plasma Linear Collider II

Ready to go for a plasma booster?

Plasma Booster

Published in 2002 for the SLC


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 5, 011001 (2002)

Energy doubler for a linear collider

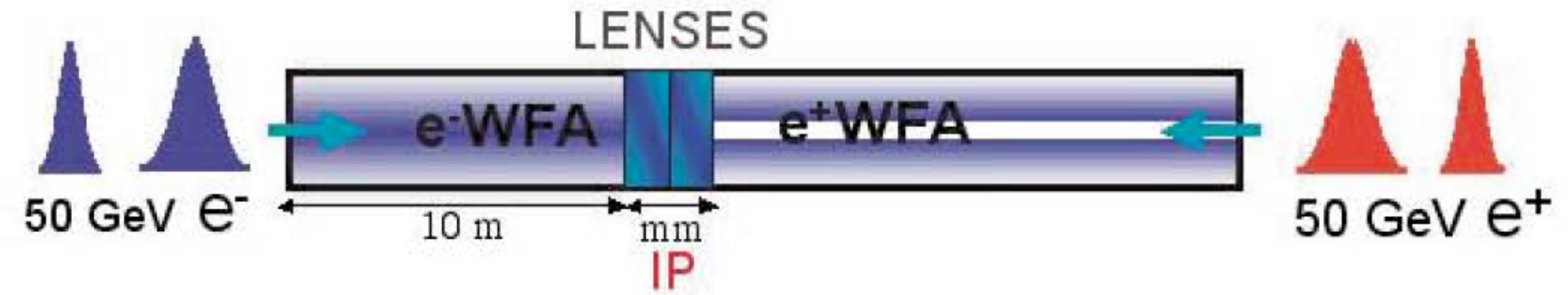
S. Lee, T. Katsouleas, and P. Muggli
University of Southern California, Los Angeles, California 90089

W.B. Mori, C. Joshi, R. Hemker, E.S. Dodd, C.E. Clayton, K.A. Marsh, B. Blue, and S. Wang
University of California, Los Angeles, Los Angeles, California 90095

R. Assmann, F.J. Decker, M. Hogan, R. Iverson, and D. Walz
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
(Received 9 August 2001; published 17 January 2002)

Collider bunch
e- bunch to be injected into plasma

Driver pulse
Laser, e- or p+ bunch



Plasma wakefield accelerator

Plasma lenses

Plasma Booster

Published in 2002 for the SLC

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **5**, 011001 (2002)

Energy doubler for a linear collider

S. Lee, T. Katsouleas, and P. Muggli
University of Southern California, Los Angeles, California 90089

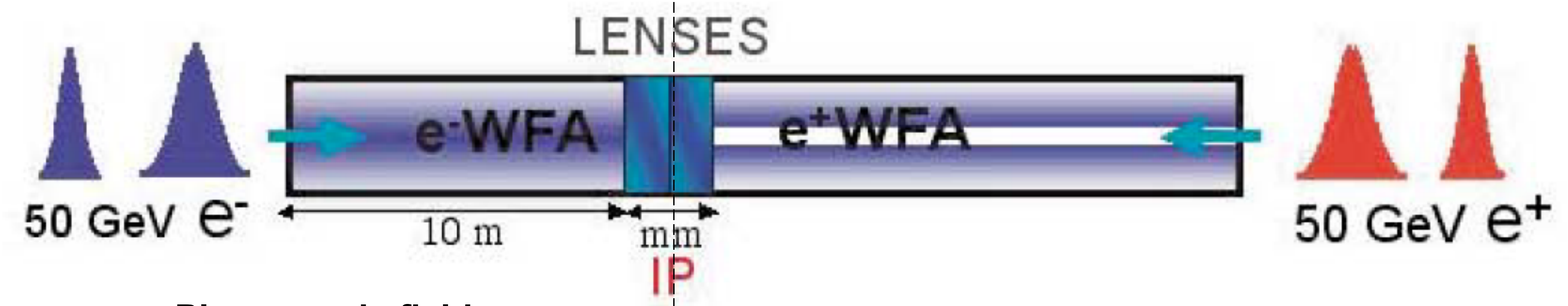
W. B. Mori, C. Joshi, R. Hemker, E. S. Dodd, C. E. Clayton, K. A. Marsh, B. Blue, and S. Wang
University of California, Los Angeles, Los Angeles, California 90095

R. Assmann, F. J. Decker, M. Hogan, R. Iverson, and D. Walz
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

(Received 9 August 2001; published 17 January 2002)

Collider bunch
e- bunch to be injected into plasma

Driver pulse
Laser, e- or p+ bunch



Plasma wakefield accelerator

Plasma lenses

We have much of this in hand → system test?

EuPRAXIA: The Demonstration Facility (System Test for a Plasma Booster)

Required intermediate step between proof of principle and production facility – make one acc. unit!

PRESENT EXPERIMENTS

Demonstrating
100 GV/m routinely

Demonstrating **GeV** electron beams

Demonstrating basic **quality**

EuPRAXIA INFRASTRUCTURE

Engineering a high quality, compact plasma accelerator

5 GeV electron beam for the second half of the 2020's

Demonstrating user readiness

Pilot users from FEL, HEP, medicine, ...

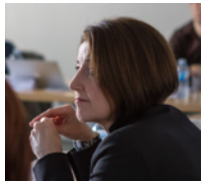
PRODUCTION FACILITIES

Plasma-based **linear collider** in 2040's

Plasma-based **FEL** in 2030's

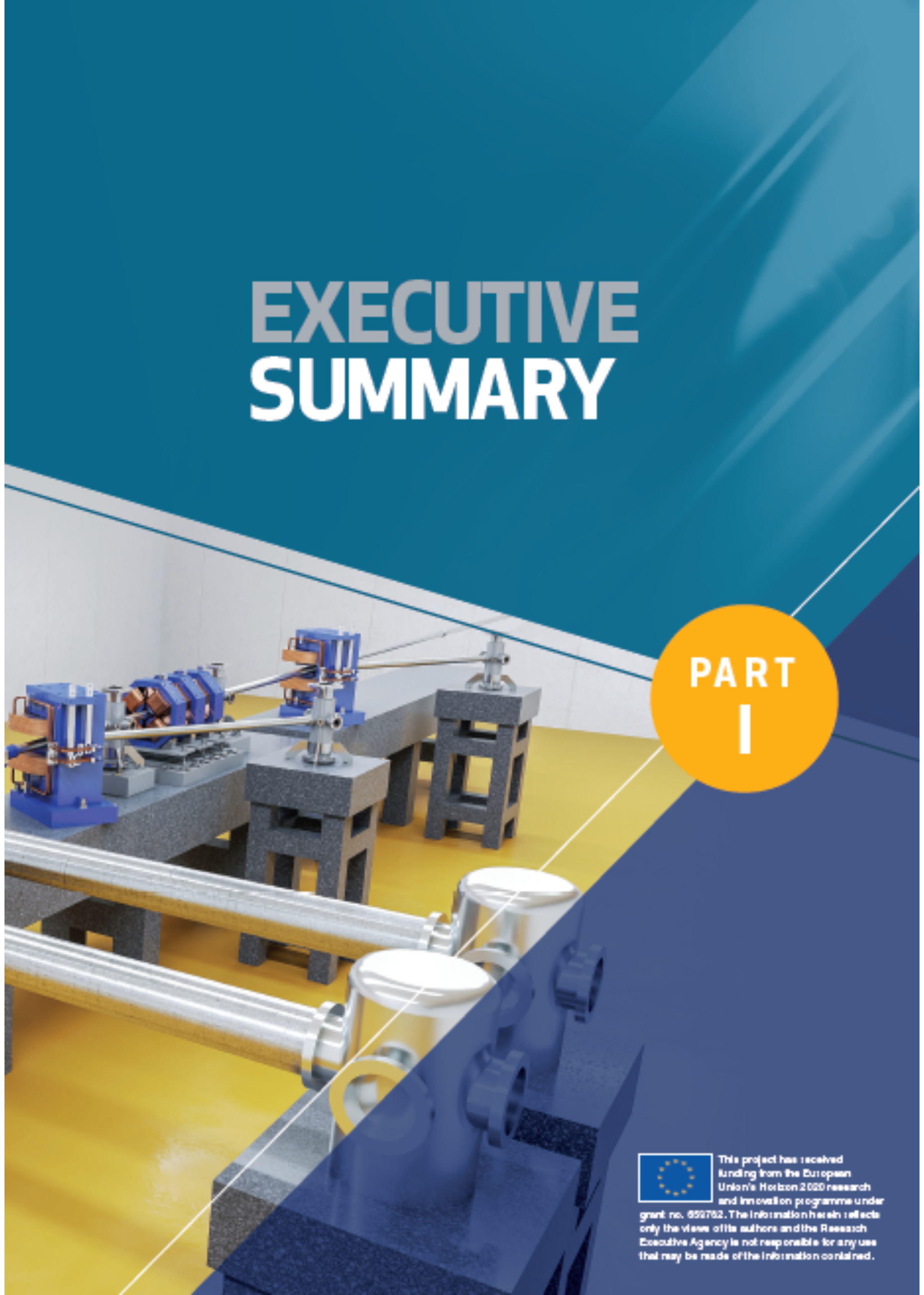
Medical, industrial applications soon





CONCEPTUAL
DESIGN
REPORT
EuPRAXIA
European Plasma Research
Accelerator with eXcellence
In Applications


EXECUTIVE
SUMMARY
PART
I
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant no. 653782. The information herein reflects only the views of its authors and the Research Executive Agency is not responsible for any use that may be made of the information contained.


EuPRAXIA
THE RE
INFRAS
CONCE

The Consortium

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

The EuPRAXIA Project

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

- CDR ready: 653 pages
- EU design study (2015 – 2019):
  16 beneficiaries, 25 associated partners,
  15 Work Packages, 30 WP Leaders,
  more than 240 scientists from 71 institutes contributed
- One of four DS's in physical science approved in H2020.
  Others: EuroCirCol (FCC), CompactLight (X band), Neutrino (ESS)

#EuPRAXIA
#plasma
#accelerator

Some Initial Design Goals (not complete)

Up to 5 GeV electron beam energy

≤ 1 mm-mrad transverse emittance

30 pC charge in electron beam

10 femto-s electron bunch duration

Basically proven in the field

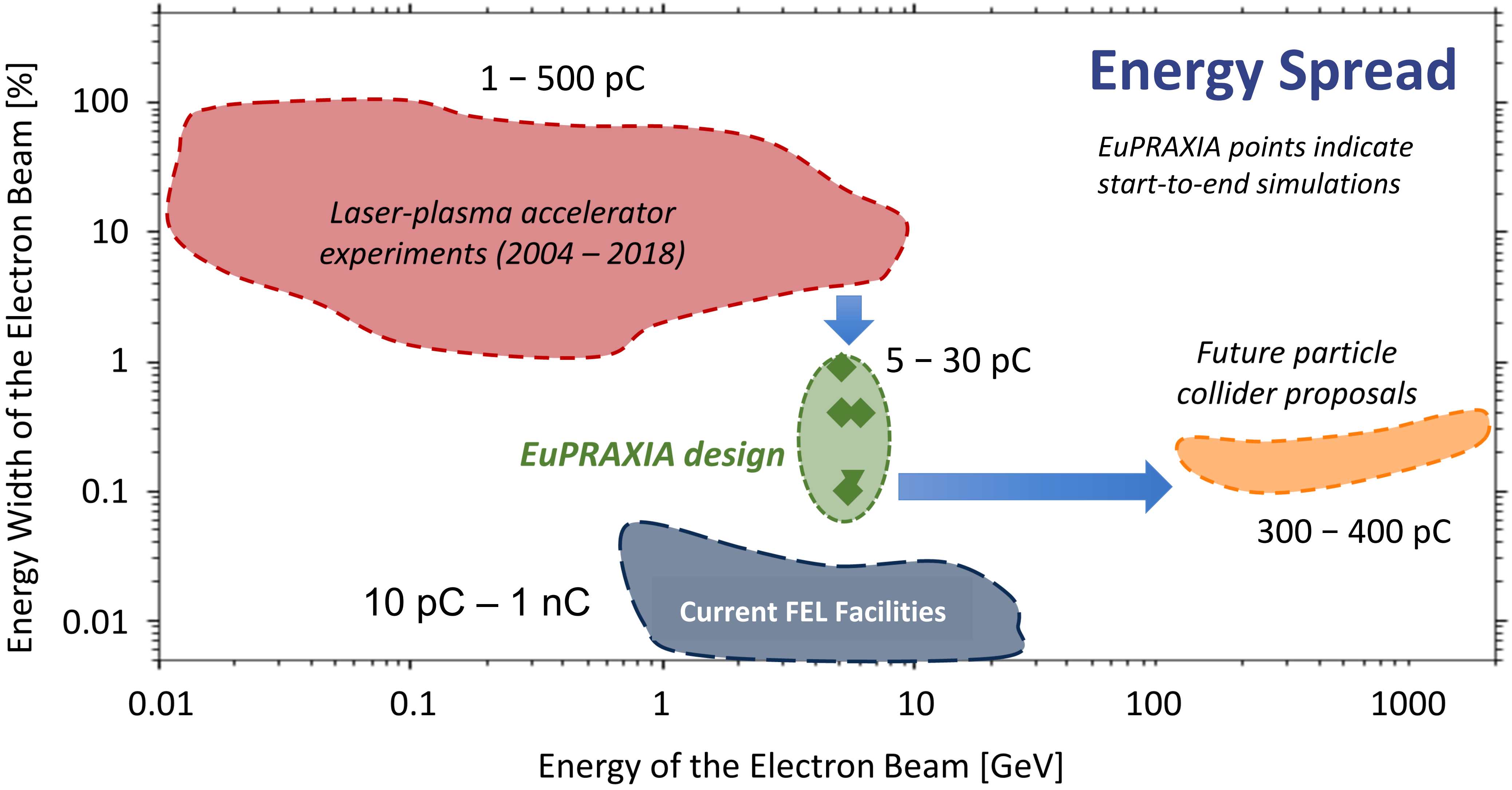
≤ 250 m facility length

To be evaluated

≤ 1 % total energy spread

Major critical issue

EuPRAXIA Design: High Quality Single Bunch



Compact Multi-Stage Plasma-Based Accelerator

PHYSICAL REVIEW LETTERS **123,** 054801 (2019)

Compact Multistage Plasma-Based Accelerator Design for Correlated Energy Spread Compensation

A. Ferran Pousa,[1,2,*] A. Martinez de la Ossa,[1] R. Brinkmann,[1] and R. W. Assmann[1]
[1]*Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany*
[2]*Institut für Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germany*

(Received 20 November 2018; revised manuscript received 10 June 2019; published 31 July 2019)

The extreme electromagnetic fields sustained by plasma-based accelerators could drastically reduce the size and cost of future accelerator facilities. However, they are also an inherent source of correlated energy spread in the produced beams, which severely limits the usability of these devices. We propose here to split the acceleration process into two plasma stages joined by a magnetic chicane in which the energy correlation induced in the first stage is inverted such that it can be naturally compensated in the second. Simulations of a particular 1.5-m-long setup show that 5.5 GeV beams with relative energy spreads of 1.2×10^{-3} (total) and 2.8×10^{-4} (slice) could be achieved while preserving a submicron emittance. This is at least one order of magnitude below the current state of the art and would enable applications such as compact free-electron lasers.

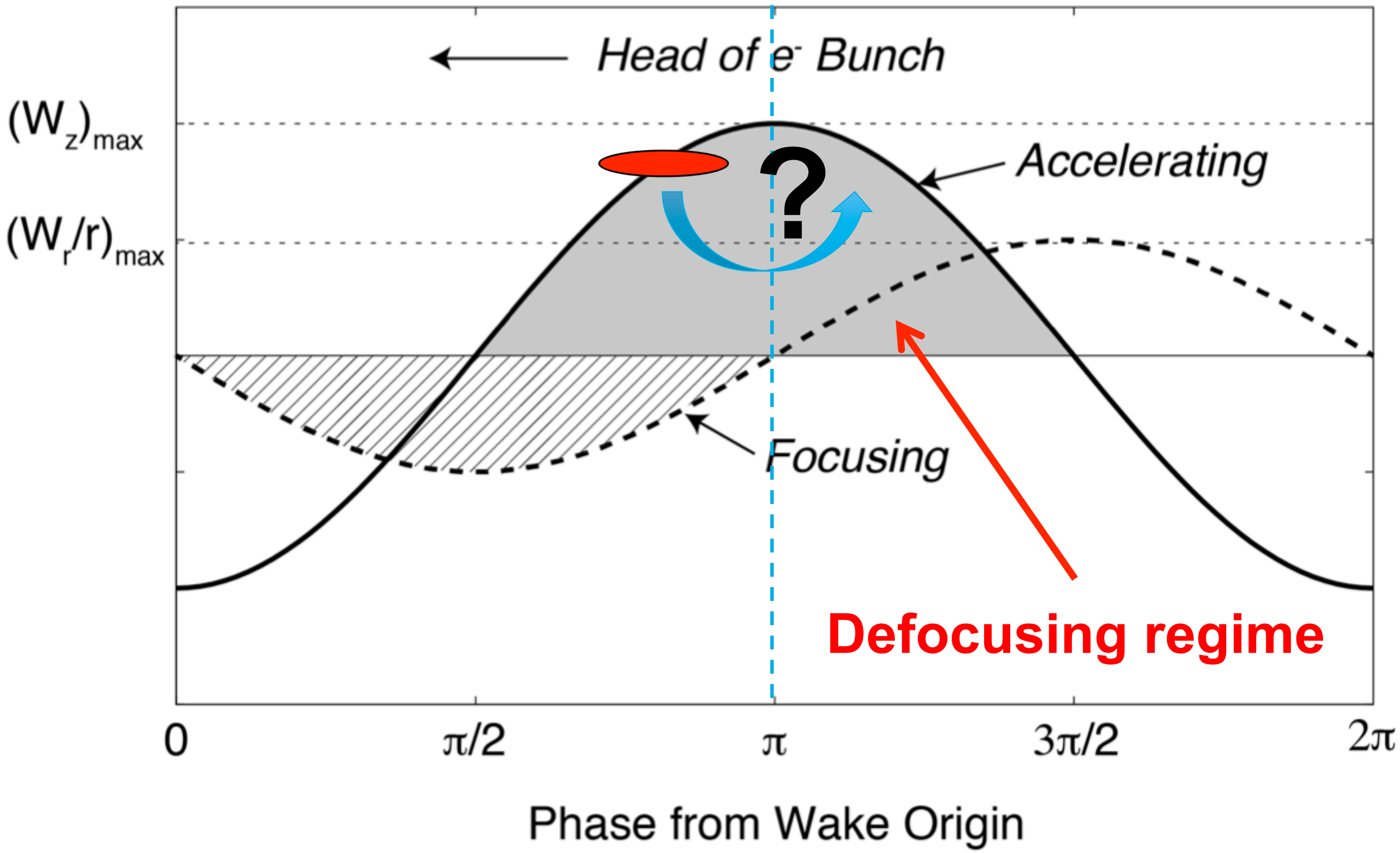
DOI: 10.1103/PhysRevLett.123.054801

Combined RF plus optical scheme

- 1.5 m long
- 5.5 GeV
- **0.03%** slice energy spread
- **0.12 %** total energy spread
- sub-micron emittance

Ideal 5 GeV LC stage?

Use Alternating Accelerating Slopes for Plasmas?

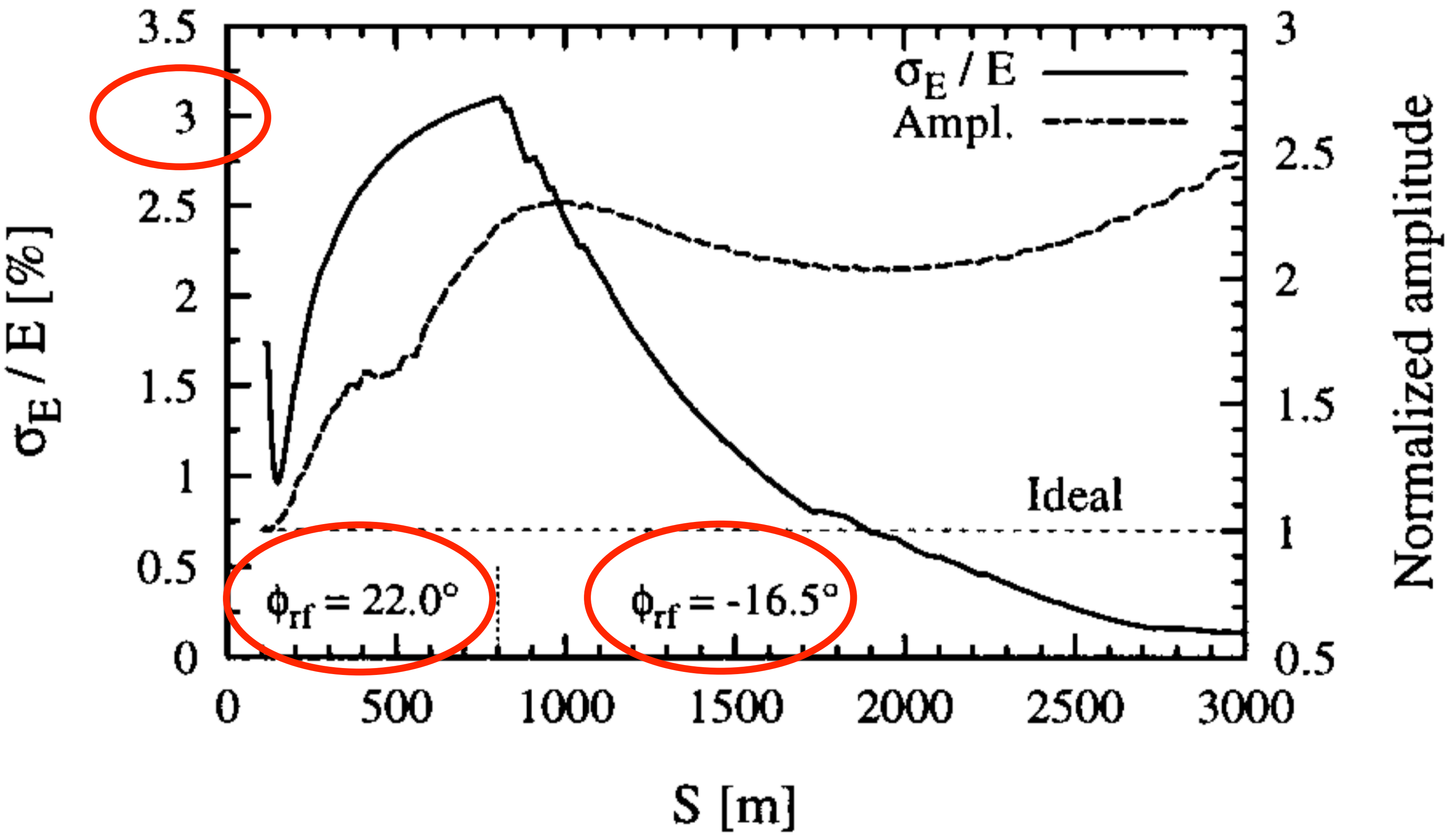


Electron bunch (w/o beam loading) in plasma accelerators always on **positive slope of accelerating voltage →** correlated energy spread

Jumping the RF phase **for plasma accelerators is not possible due to the focusing requirement**

Correlated energy spread is building up along plasma accelerator

SLC: RF Linac with High Energy Spread

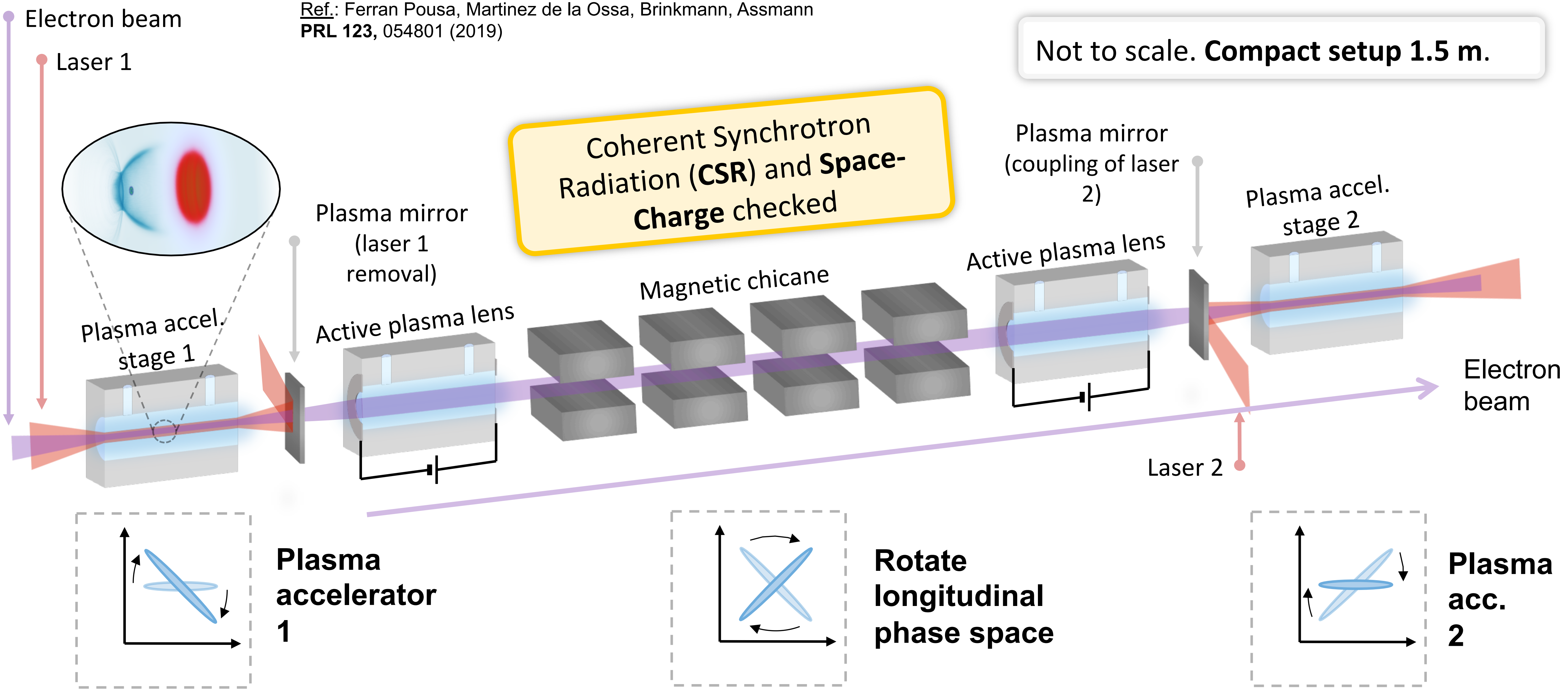


- High current linacs are affected by the beam-breakup instability
- This is cured by **BNS damping, requiring large energy spread**
- The **SLAC linac** operated for the SLC collider successfully in this mode

See R. Assmann, SLAC-PUB-7576 (1997)

Compact Multi-Stage Plasma-Based Accelerator

<u>Ref.</u>: Ferran Pousa, Martinez de la Ossa, Brinkmann, Assmann
PRL 123, 054801 (2019)



Simulation Results

Correlated Energy Spread Compensation in Multi-Stage Plasma-Based Accelerators

A. Ferran Pousa,[1,2,*] A. Martinez de la Ossa,[1] R. Brinkmann,[1] and R. W. Assmann[1]
[1]Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany
[2]Institut für Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germany
(Dated: November 20, 2018)

The extreme electromagnetic fields sustained by plasma-based accelerators allow for energy gain rates above 100 GeV/m but are also an inherent source of correlated energy spread. This severely limits the usability of these devices. Here we propose a novel compact concept which compensates the induced energy correlation by combining plasma accelerating stages with a magnetic chicane. Particle-in-cell and tracking simulations of a particular 1.5 m-long setup with two plasma stages show that 5.5 GeV bunches with a final relative energy spread of 1.2×10^{-3} (total) and 5.5×10^{-4} (slice) could be achieved while preserving sub-micron emittance. This at least one order of magnitude below current state-of-the-art and paves the way towards applications such as Free-Electron Lasers.

Plasma-based accelerators (PBAs), driven either by charged particle beams (plasma wakefield accelerator, PWFA [1]) or intense laser pulses (laser wakefield accelerator, LWFA [2]), are able to sustain accelerating gradients in excess of 100 GeV/m [3]. These extreme gradients are orders of magnitude higher than those achievable with radiofrequency technology and offer a path towards miniaturized particle accelerators with ground-breaking applications in science, industry and medicine [4].

Steady progress over the past decades has led to the successful demonstration of electron bunches with multi-GeV energy [5–8], micron-level emittance [9, 10] and kilo-ampere current [11, 12]. However, the high amplitude and short wavelength ($\sim 100\ \mu$m) of the wakefields naturally imprint a longitudinal energy correlation (or chirp) along the accelerated (witness) bunch, leading to a large relative energy spread typically on the 1-10 % range [13]. This is a long-standing issue for PBAs which critically impacts the beam quality [14], particularly for applications such as Free-Electron Lasers (FELs) [15] where a relative energy spread $\lesssim 0.1\%$ is required [16].

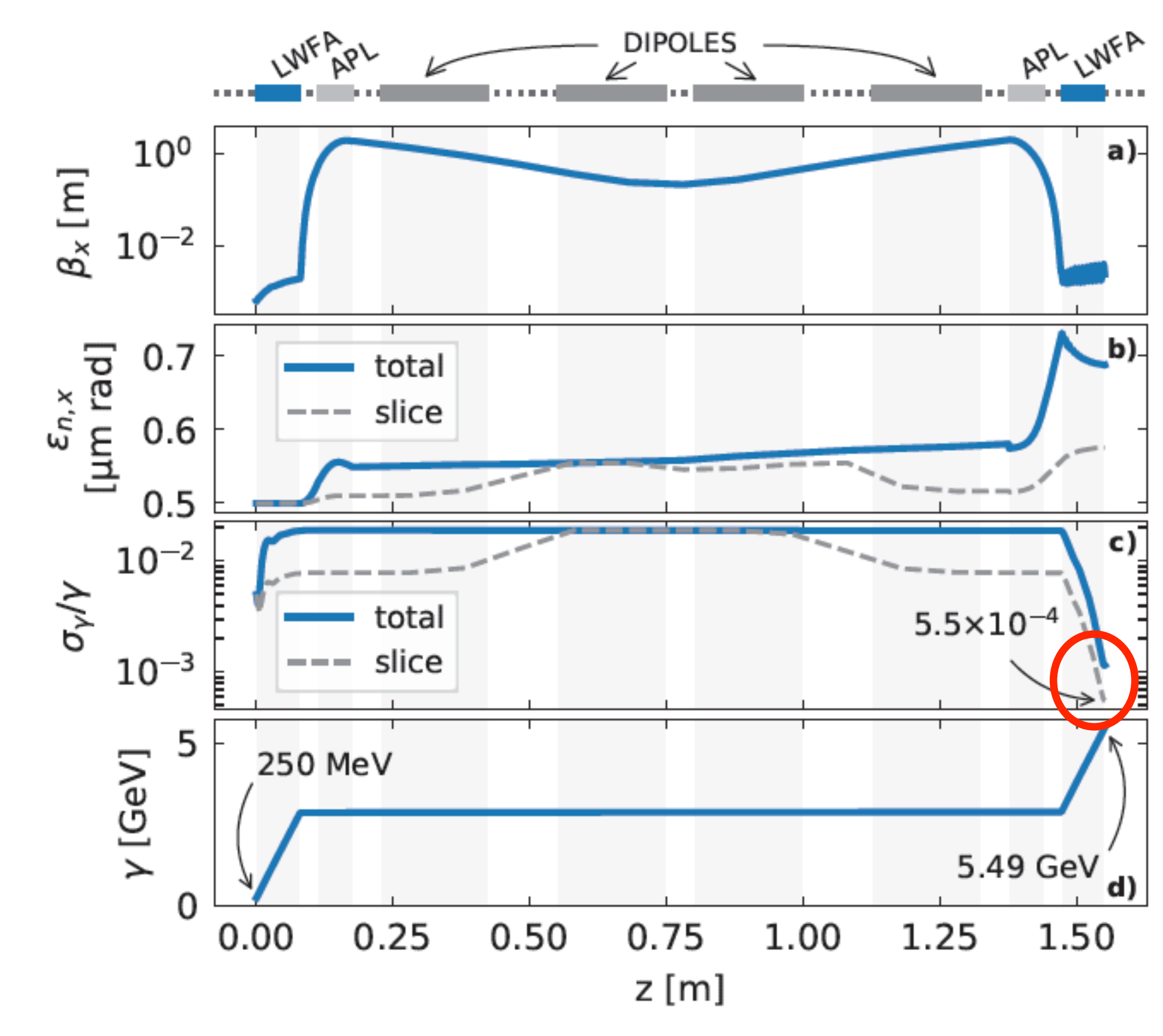
Solving this issue is therefore key for demonstrating the usability of these devices. A well known concept for mitigating the correlated energy spread is that of beam loading [17–19], in which the witness bunch itself is used to flatten the slope of the accelerating fields. This, however, relies on a very precise shaping of the current profile and has yet to be demonstrated with the desired performance. Furthermore, since the optimal profile depends on the wakefield structure, a certain energy spread will always develop in LWFAs, where the wakefield experienced by the bunch will change due to the laser evolution [20] as well as dephasing [21]. Alternative ideas have also been proposed in order to achieve, in average, a flat accelerating gradient. These include modulating [22] or tailoring [23] the plasma density profile as well as injecting a secondary bunch [24], but they show limited success or remain to be experimentally realized. A different approach contemplates stretching the bunch in order to minimize the slice energy spread [25].

In this Letter we propose a novel concept for compensating the correlated energy spread by taking advantage of the naturally occurring energy chirp. The scheme, illustrated in Fig. 1, consists mainly on two identical plasma accelerating stages joined by an intermediate magnetic chicane in which the longitudinal energy correlation of the bunch is inverted. Thus, the energy chirp generated in the first stage is compensated in the second. Numerical simulations with the Particle-in-Cell (PIC) code FBPIC [26] as well as the tracking codes ASTRA [27] and CSRtrack [28] show that multi-GeV beams with unprecedented energy spread could be obtained with this method. Although LWFA stages are used here, the core idea behind the scheme would be equally valid in the case of a particle driver.

In order to introduce this concept, the blowout regime [29, 30] of plasma acceleration will be considered. In this case the laser or beam driver is able to expel all background plasma electrons, leaving behind an ion cavity with uniform focusing gradient, $K = (m/2ec)\omega_p^2$, and an approximately constant longitudinal electric field slope, $E'_z \equiv \partial_z E_z \simeq (m/2e)\omega_p^2$, along most of the accelerating phase. Here $\omega_p = \sqrt{n_p e^2/m\epsilon_0}$ is the plasma frequency, e and m the electron charge and mass, ϵ_0 the vacuum permittivity and n_p the unperturbed plasma density. In order to describe the position and energy of the particles along the accelerator it is also useful to introduce the speed-of-light coordinate, $\xi = z - ct$, as well as the relativistic Lorentz factor, $\gamma = 1/\sqrt{1-(\boldsymbol{v}/c)^2}$, where t is the time and $\boldsymbol{v}$ and z are, respectively, the particle velocity and longitudinal position in the laboratory frame. Within the generated cavity, electrons perform transverse oscillations (known as betatron motion) with a frequency $\omega_\beta(t) = \sqrt{eK/m\gamma(t)}$, while their energy evolves as $\gamma(t) = \gamma_0 - (e/mc)E_z t$.

For a particle bunch with average energy $\bar{\gamma}(t) = \langle\gamma(t)\rangle$ centered at $\bar{\xi}$, the longitudinal chirp can be expressed as $\chi(t) = \langle\Delta\xi\Delta\gamma(t)\rangle / \langle\Delta\xi^2\rangle\,\bar{\gamma}(t)$, where $\Delta\gamma(t) = \gamma(t) - \bar{\gamma}(t)$ and $\Delta\xi = \xi - \bar{\xi}$. A simple expression for the chirp evolution within a plasma stage can be obtained if a constant

<u>Ref.</u>: Ferran Pousa, Martinez de la Ossa, Brinkmann, Assmann
PRL 123, 054801 (2019)



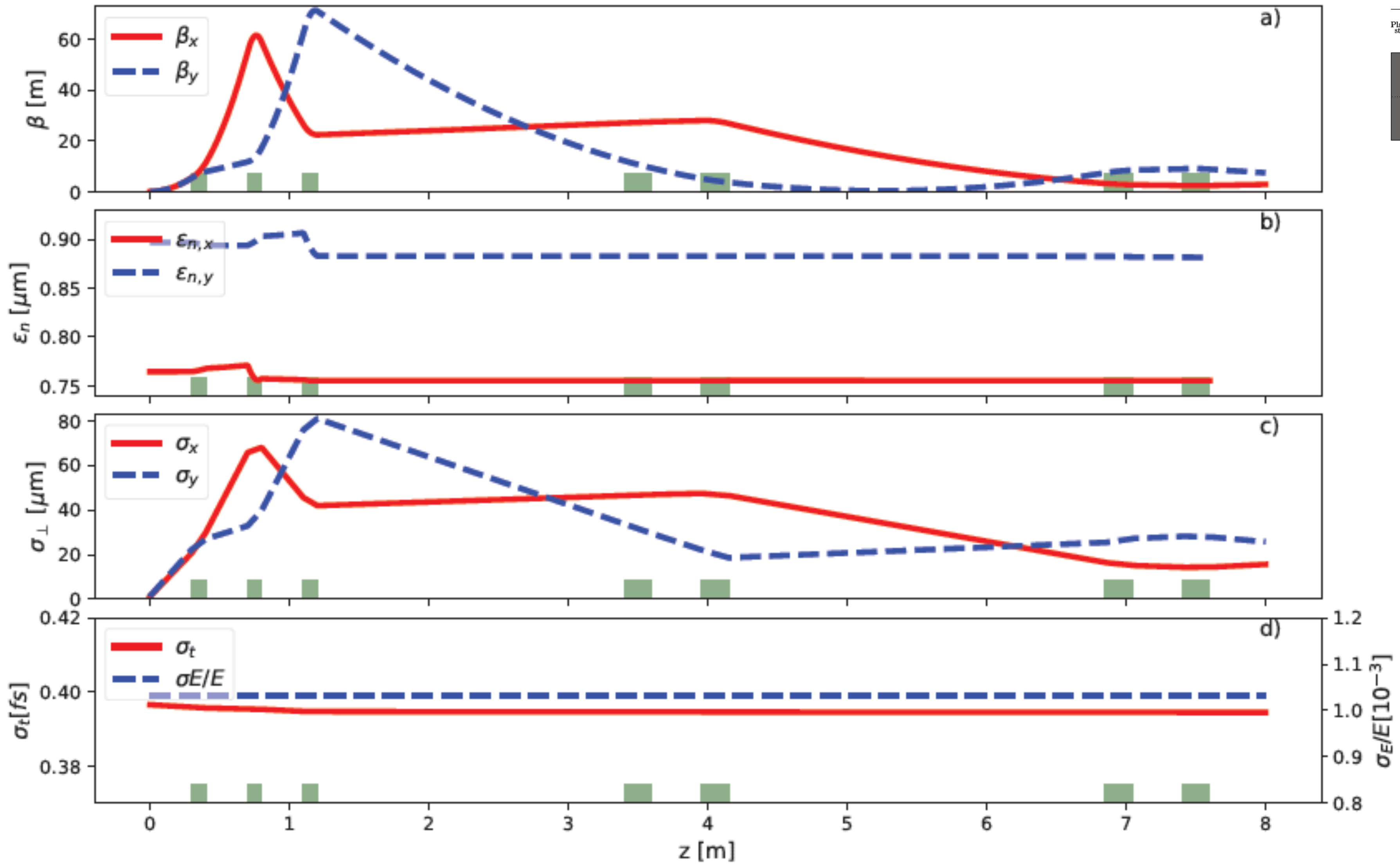
Beta function

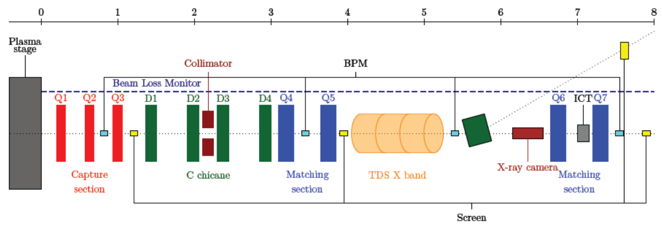
Norm. emittance

Energy spread
total and slice

Beam Energy
5.5 GeV

Beam Transport Design

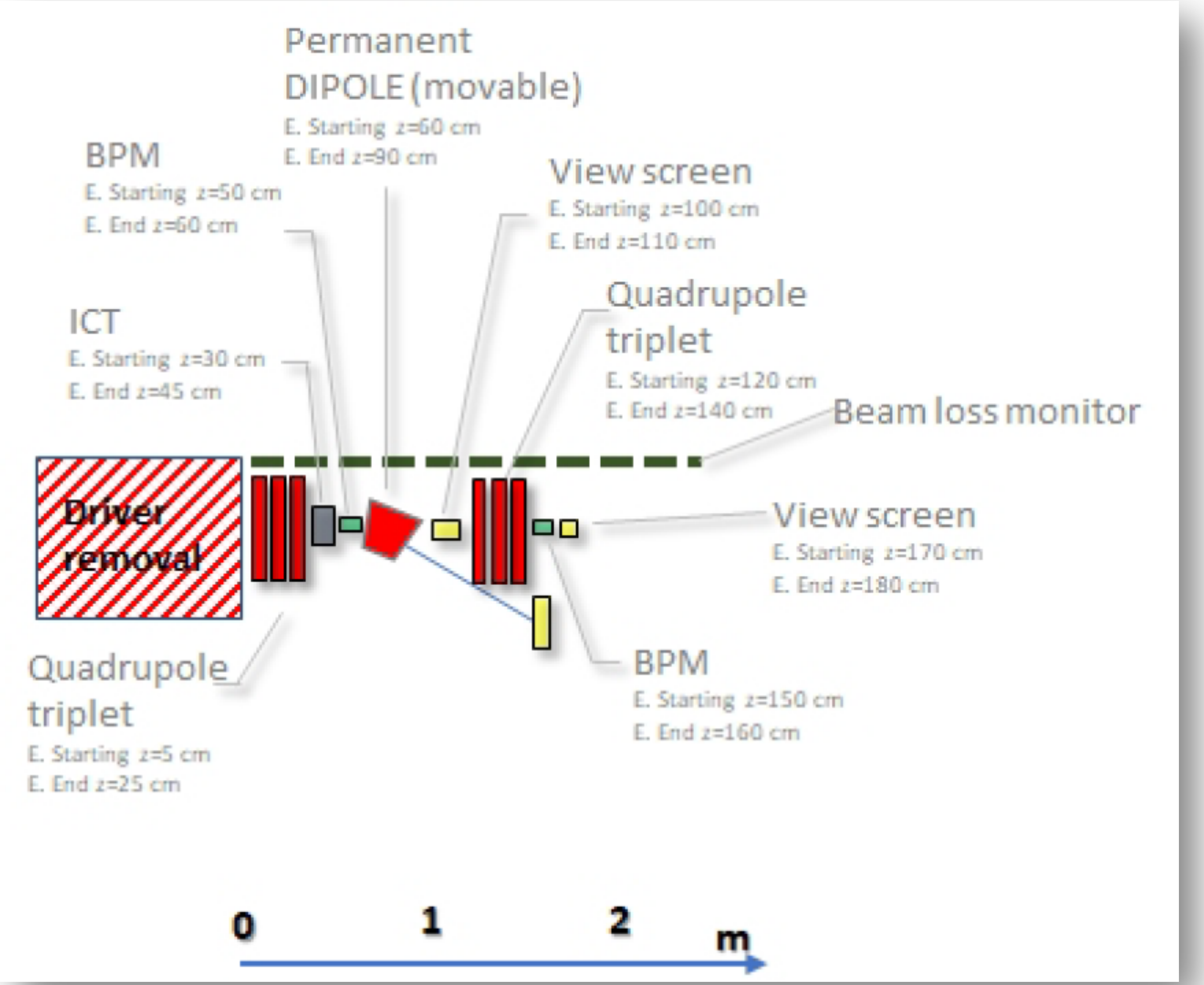




- Here: high energy **beam transport over 8 meters**
- Preserved beam quality is achieved in the design
- Space has important benefits

A. Chance et al

Diagnostics: Electron Beam



Example:

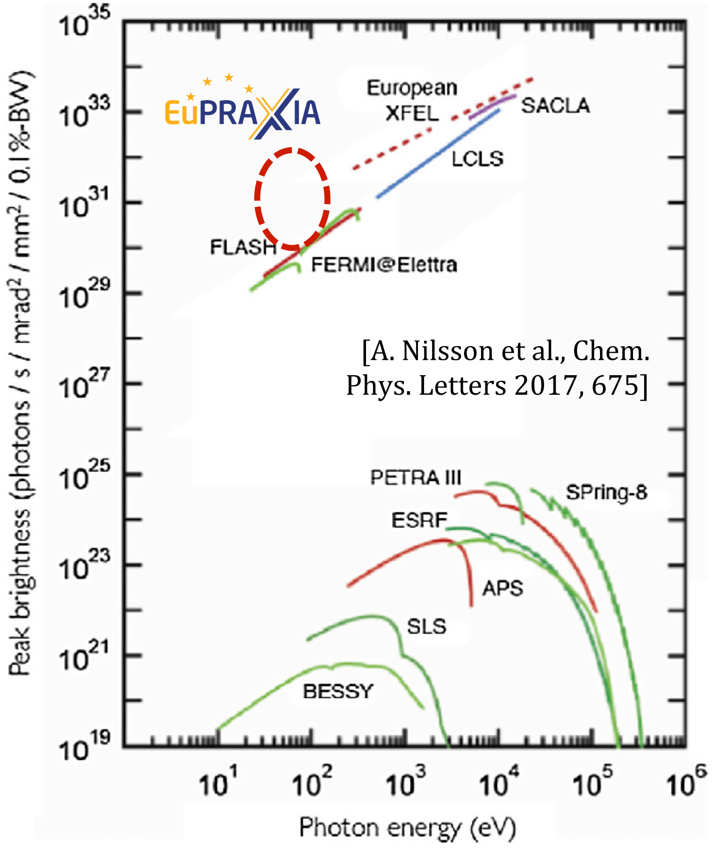
Permanent beam line from **laser-plasma injector to laser plasma accelerator**

Use space in beam transport for beam diagnosis

A. Cianchi, N. Delerue et al

Start-to-End Simulations for FEL

	Units	1 GeV PWFA
Rms Energy Spread	%	1.1
Peak current	kA	2.0
Bunch charge	pC	30
RMS Bunch Length	µm(fs)	3.82(12.7)
RMS Normalized Emittance	mm mrad	1.1
Slice Energy Spread	%	0.034
Slice norm.emittance (x/y)	mm mrad	0.57/0.615
Undulator period	mm	15
Undulator Strength K(a_w)		1.13(0.8)
Undulator length	m	30
ρ (1D/3D)	$\times 10^{-3}$	2.5/1.8
Radiation wavelength	nm(keV)	2.98(0.42)
Photon Energy	µJ	6.5
Photon per pulse	$\times 10^{10}$	10
Photon BandWidth	%	0.9
Rep. rate	Hz	10-100



Ultrashort FEL radiation pulses	
Radiation wavelength	0.2 – 36.3 nm
Photons per pulse	2×10^{9} – 3×10^{13}
Brightness	2×10^{30} – 6×10^{32} [*]

* = $[\text{mm mrad s } (0.1\% \text{ BW})]^{-1}$

RF gun and wave structures along the FEL-beamline used to ***generate an electron beam of few hundred MeV energy for external injection*** *into a plasma accelerator stage.*

Plasma accelerator section of the FEL-beamline at the laser-driven construction site*. The RF-injector producing the electron beam is seen in the background.*

The beginning of the ***undulator section generating FEL radiation*** *from the accelerated electron beam. In the background the accelerator can be seen in the adjacent part of the tunnel.*

Design: Medical Imaging X Rays

Has Unique Advantages – Already Working Today – Too Slow at the Moment

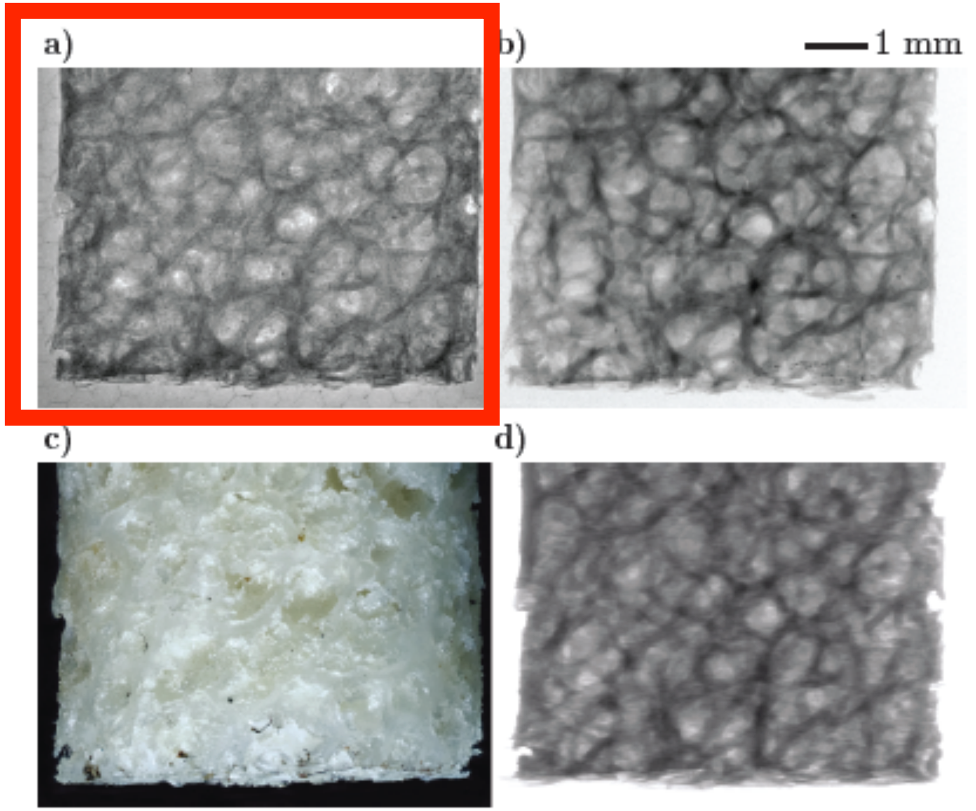
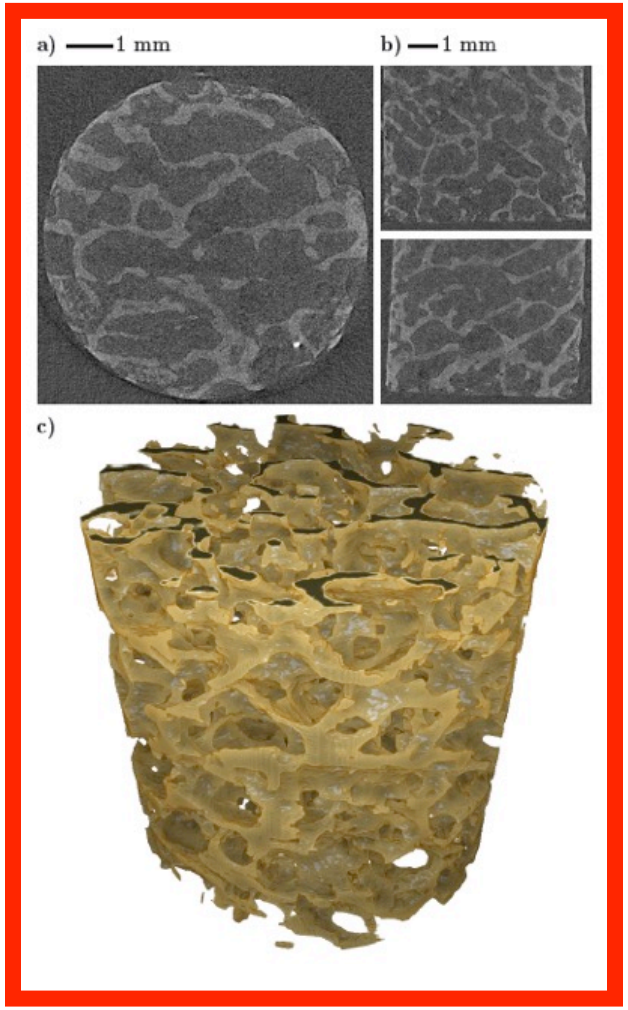
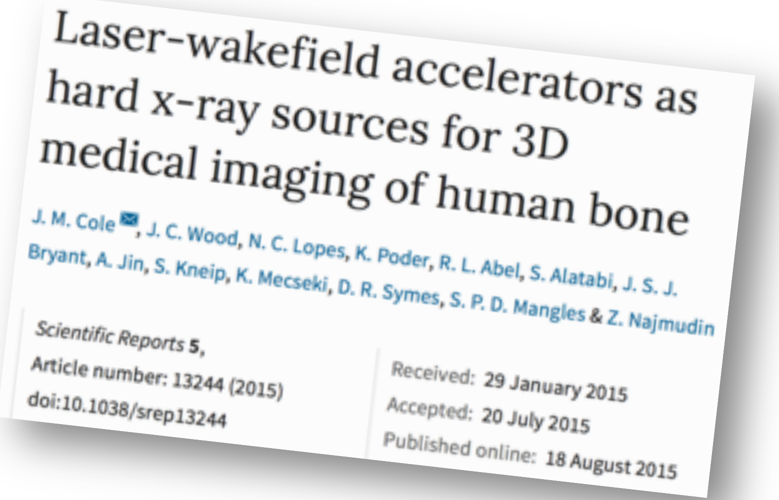


Figure 3. Images of the bone sample recorded with a) the betatron x-ray source b) conventional μCT scanning c) composite macro photography d) virtual illumination of the 3D reconstruction by a source of $E_{crit} = 33\,\mathrm{keV}$.



2015 publication from J.M. Cole et al., John-Adams-Institute, UK: "Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone". Nature Scientific Reports 5, 13244 (2015)


Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone

J. M. Cole, J. C. Wood, N. C. Lopes, K. Poder, R. L. Abel, S. Alatabi, J. S. J. Bryant, A. Jin, S. Kneip, K. Mecseki, D. R. Symes, S. P. D. Mangles & Z. Najmudin

Scientific Reports 5, Article number: 13244 (2015)
doi:10.1038/srep13244

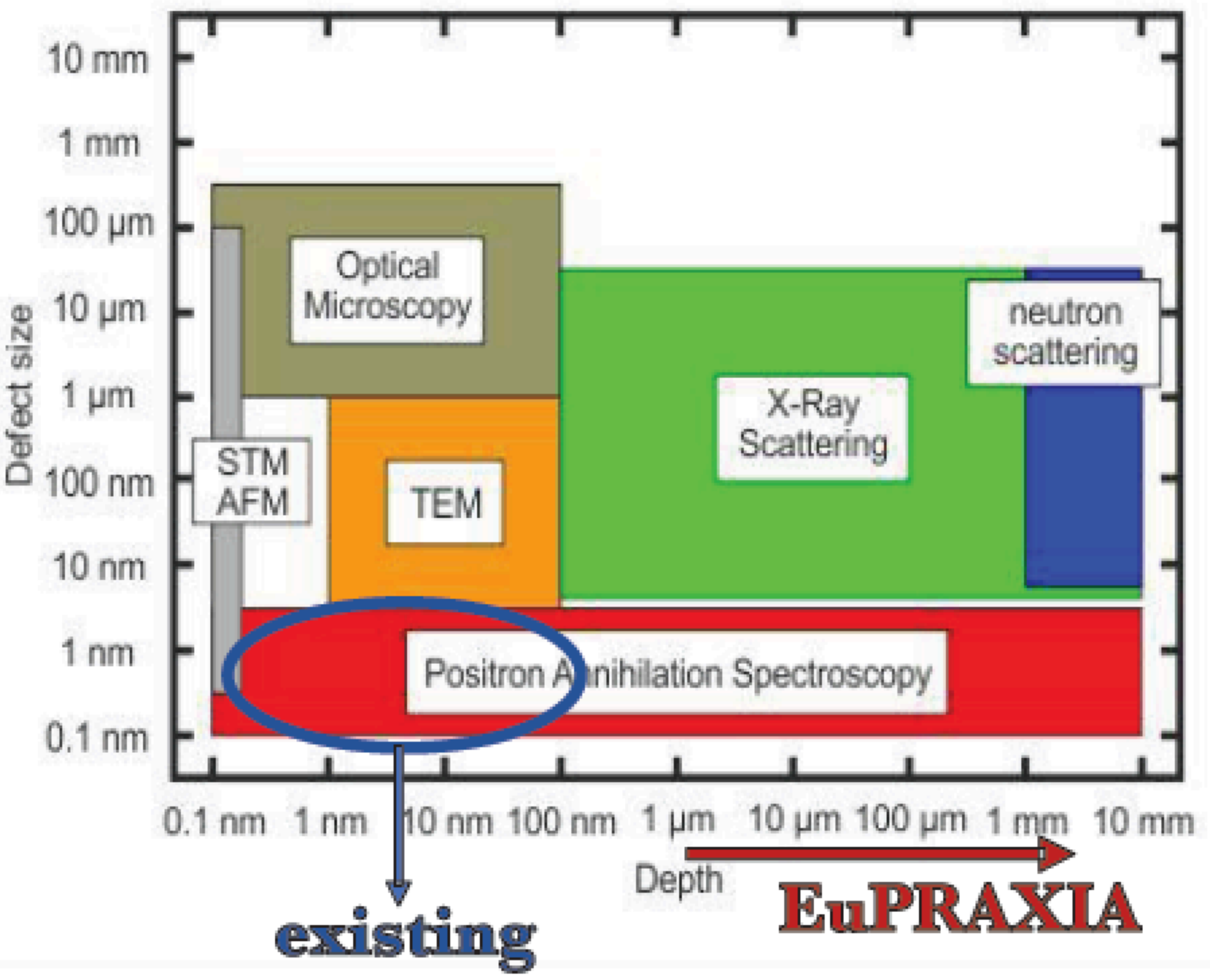
Received: 29 January 2015
Accepted: 20 July 2015
Published online: 18 August 2015

Laser plasma based betatron X ray source

EuPRAXIA

Fully plasma-based beamline for generating betatron radiation as a ***compact X-ray source for medical imaging and material analysis****. The user area is behind the wall on the right.*

Design: Positron Annihilation Spectroscopy



Courtesy M. Butterling, HZDR

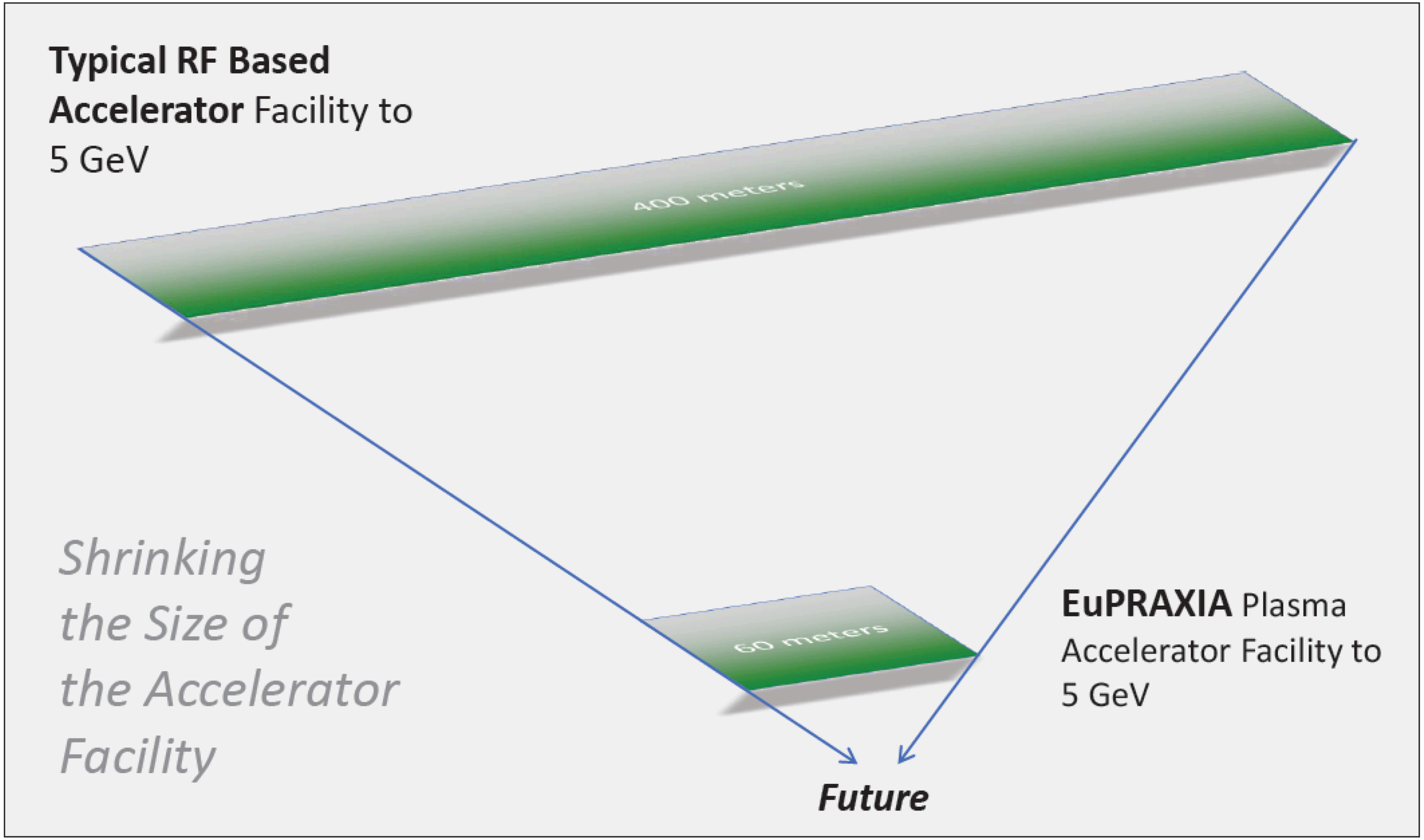
Quantity	Baseline Value
Low-Energy Positron Source	
Positron energy	0.5–10 MeV (tunable)
Energy bandwidth	±50 keV
Beam duration	20–90 ps
Beam size at user area	2–5 mm
Positrons per shot	$\geq 10^6$

- 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

*Fully plasma-based beamline for generating **electron and positron beams**. The accelerator stages can be seen in the front. In the back the beamline splits and leads to two user areas behind the back wall.*

EuPRAXIA Design: Shrink the Facility



Facility:

- Shielding
- RF galleries
- Klystron
- Beam transport
- Focusing
- Plasma accelerator
- ...

Factor 6-7 reduction in accelerator facility length (**factor 3** in total facility length)

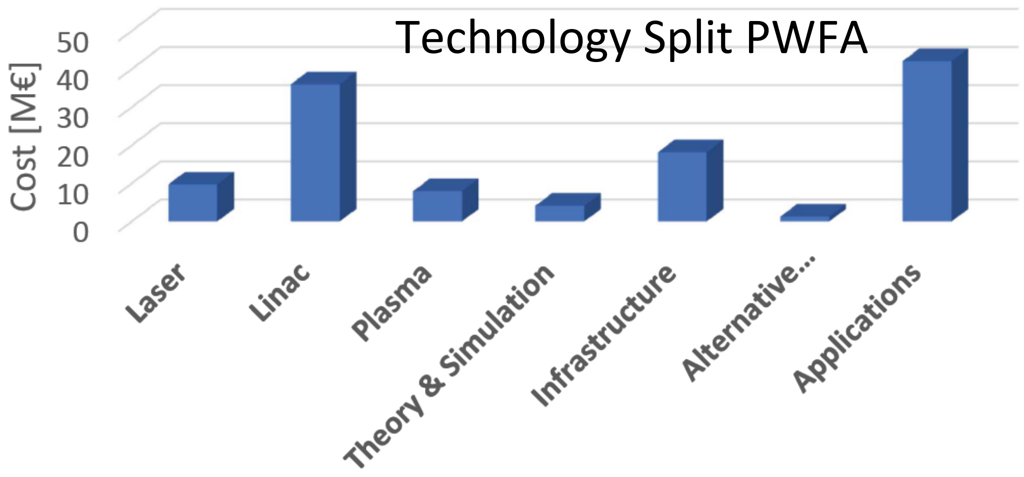
Cost Estimate in CDR (to be detailed and reviewed in technical design phase)

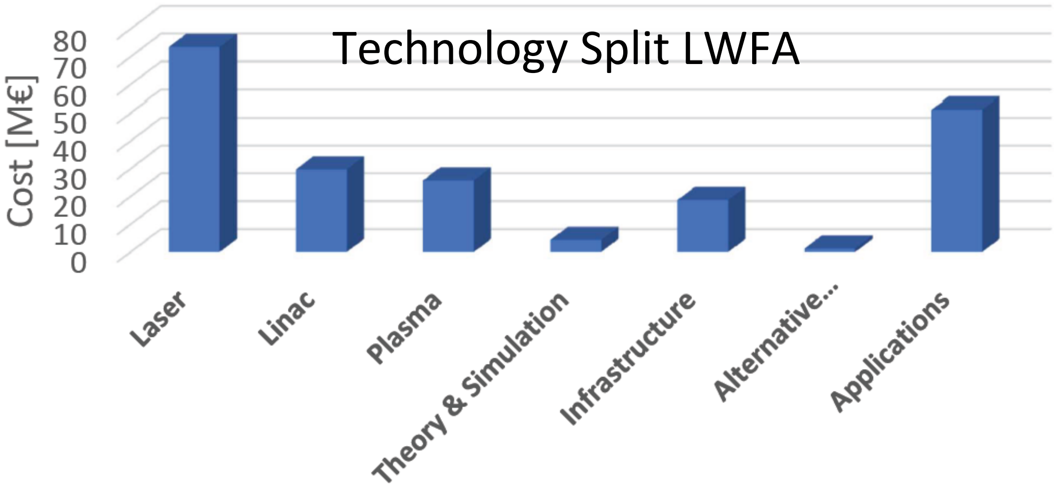
Scenario	Invest
Beam-driven plasma accelerator facility	
Full EuPRAXIA proposal	119 M€
Plasma accelerator facility with FEL	68 M€
Laser-driven plasma accelerator facility	
Full EuPRAXIA proposal	204 M€
Plasma accelerator facility with FEL	110 M€
Minimal laser plasma accelerator with FEL	75 M€

Full cost: 323 M€

Duration: 8 – 10 years

Reduced cost systems possible, e.g. 1 construction site only, pre-existing invest, ... Full project will be fully European and will bundle capabilities

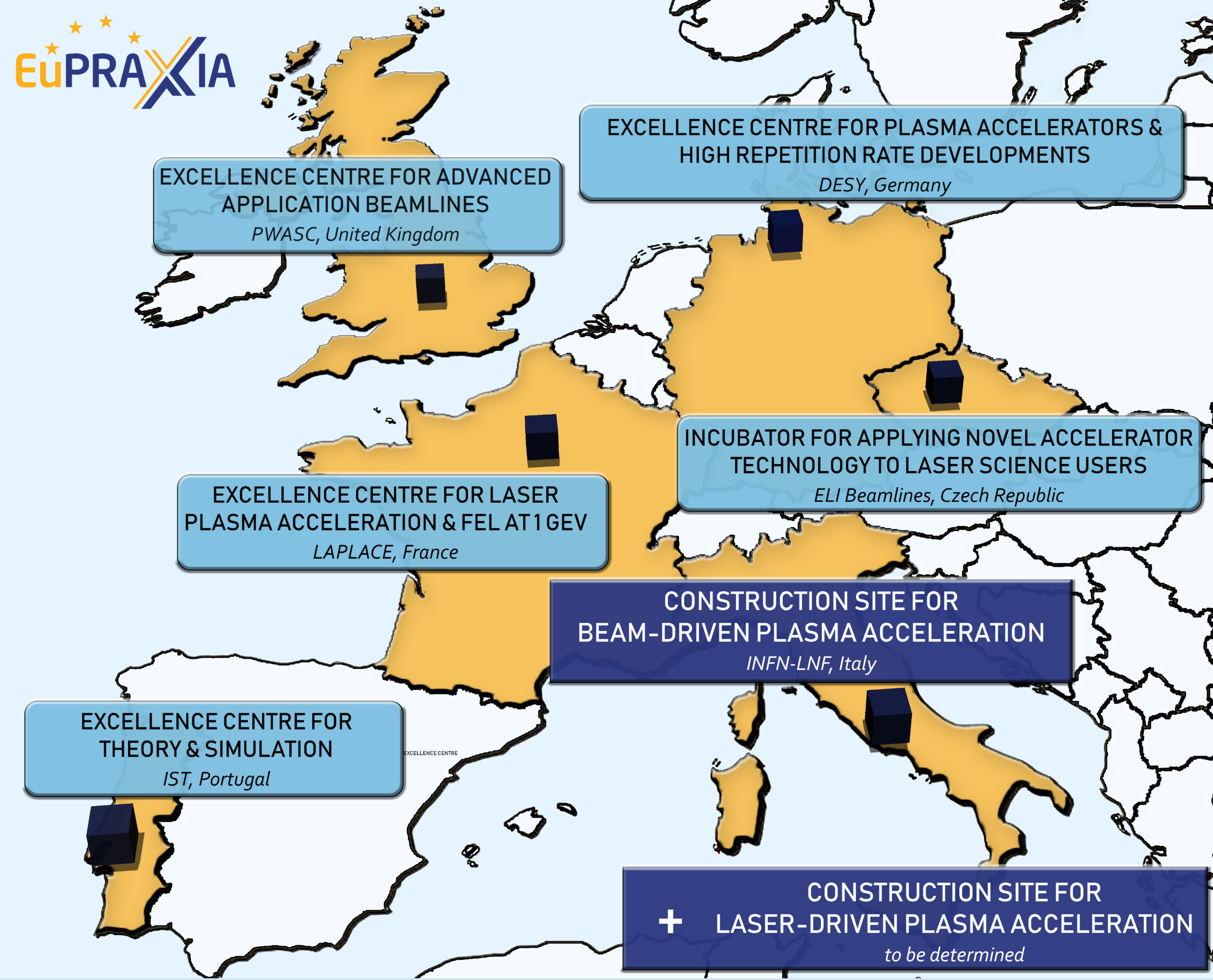




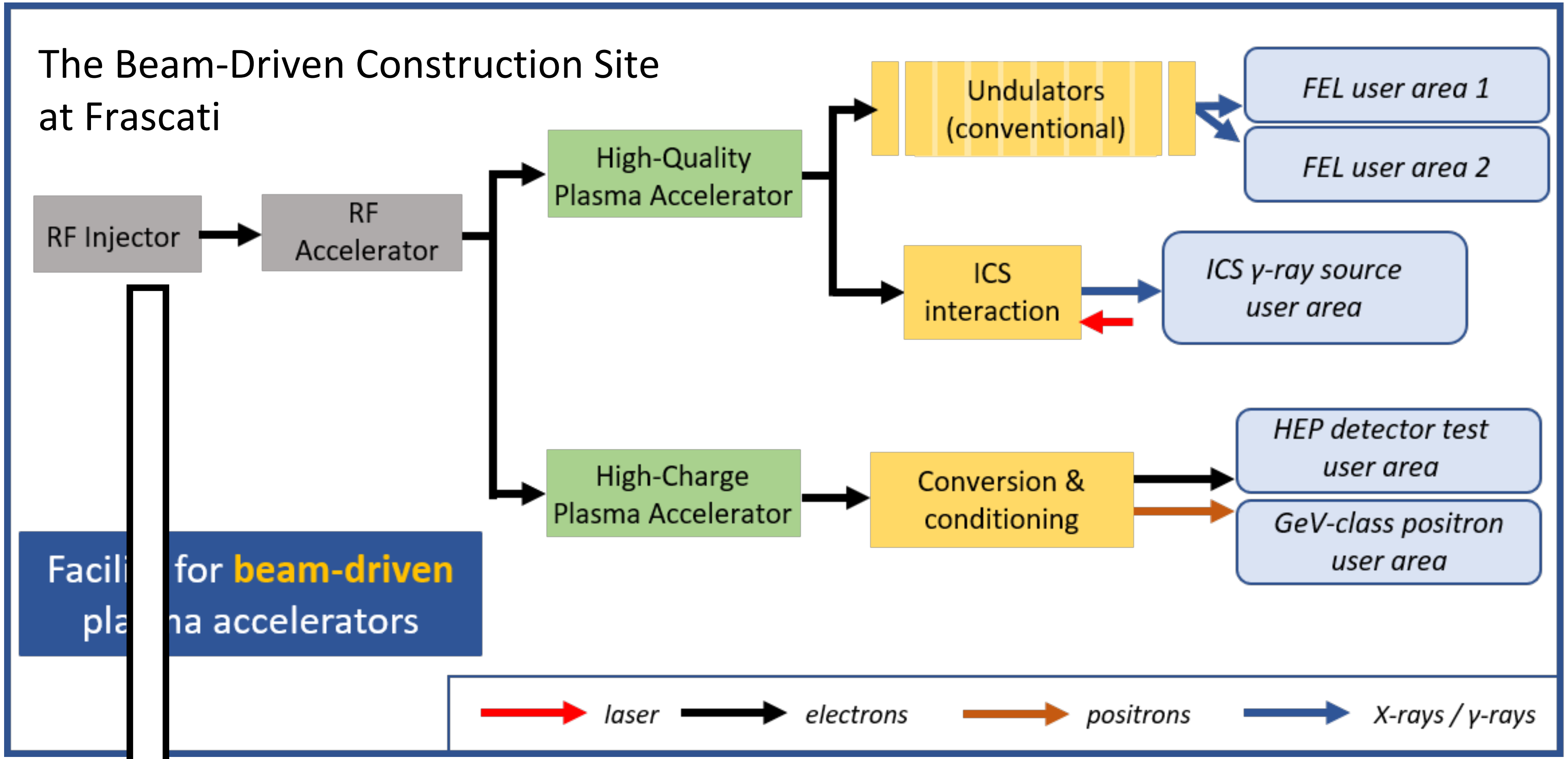
EuPRAXIA Implementation
Where and who?

Designing a **European project** → building a facility together as optimum solution

Example how this can work: **ATLAS and CMS** in particle physics. Many institutes, local facilities with two central installations

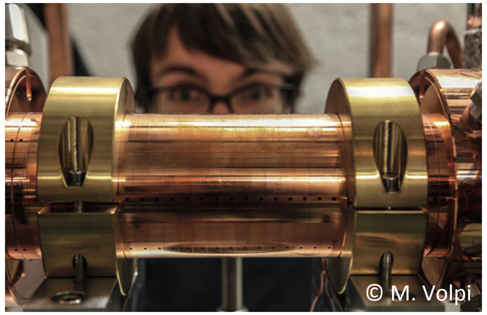


EuPRAXIA: 1 GeV X Band Linac → Synergy with LC

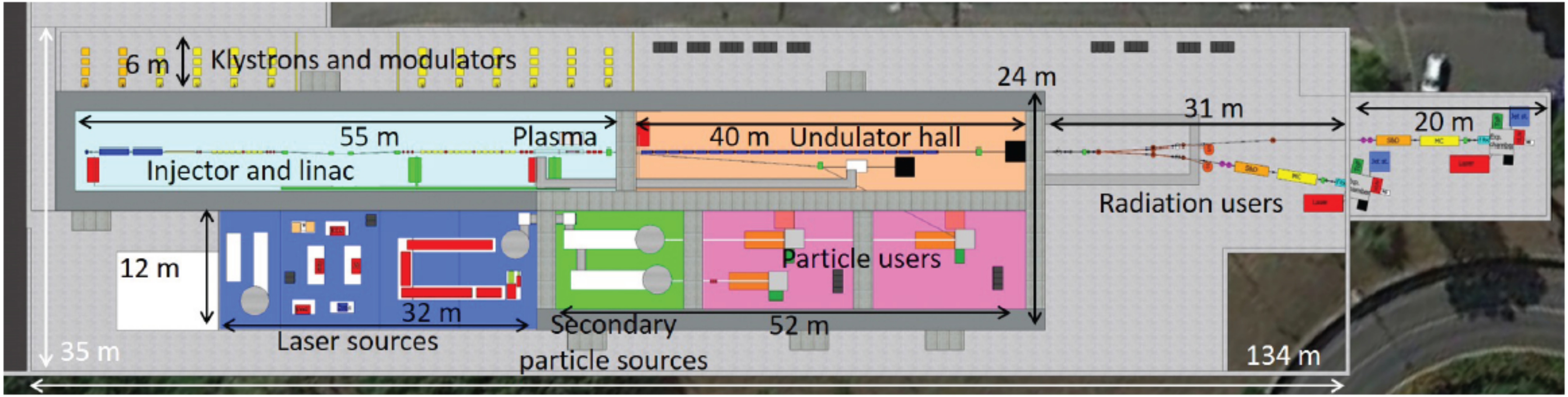


- Free-electron laser
- Gamma-ray source (inverse Compton scattering)
- GeV-class positron source
- High-energy physics detector testing stand

A STATE-OF-THE-ART X-BAND LINAC			
Operating frequency	Field strength	Length	Final beam energy
~12 Hz	≤ 80 MV/m	10 m	~500 MeV



Beam-Driven EuPRAXIA Site at Frascati



EuPRAXIA 1 GeV X Band linac in Frascati can be considered as CLIC demonstrator (including plasma booster)

Main Project Milestones & Deliverables

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, Prototyping** *(Jan 2020 – Dec 2024)*						**Implementation & Construction & First OP** *(Jan 2026 – Dec 2029)*				**Full Operation** *(Jan 2030 – Dec 2065)*				**Decom-missioning**

- **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**
- **Installation of each essential component**
- **Commissioning of each essential component**

- **Start of full operation**

- **The beam-driven site will start OP in second half of the 2020's**
- **Conservative planning – can be accelerated**

Next steps:

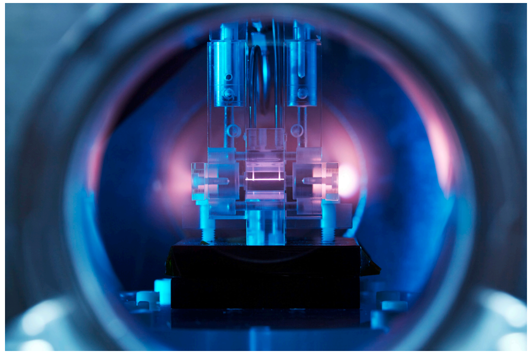
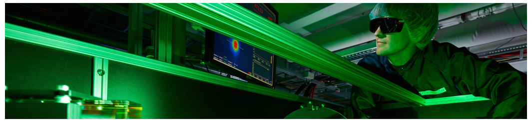
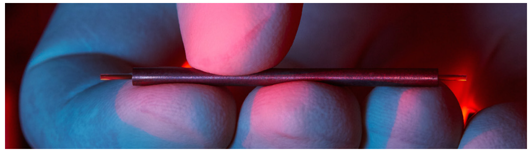
Publish CDR → on its way: **submission Oct 31**

May 2020: Apply to ESFRI roadmap

Conclusion

Advanced Accelerator Technology

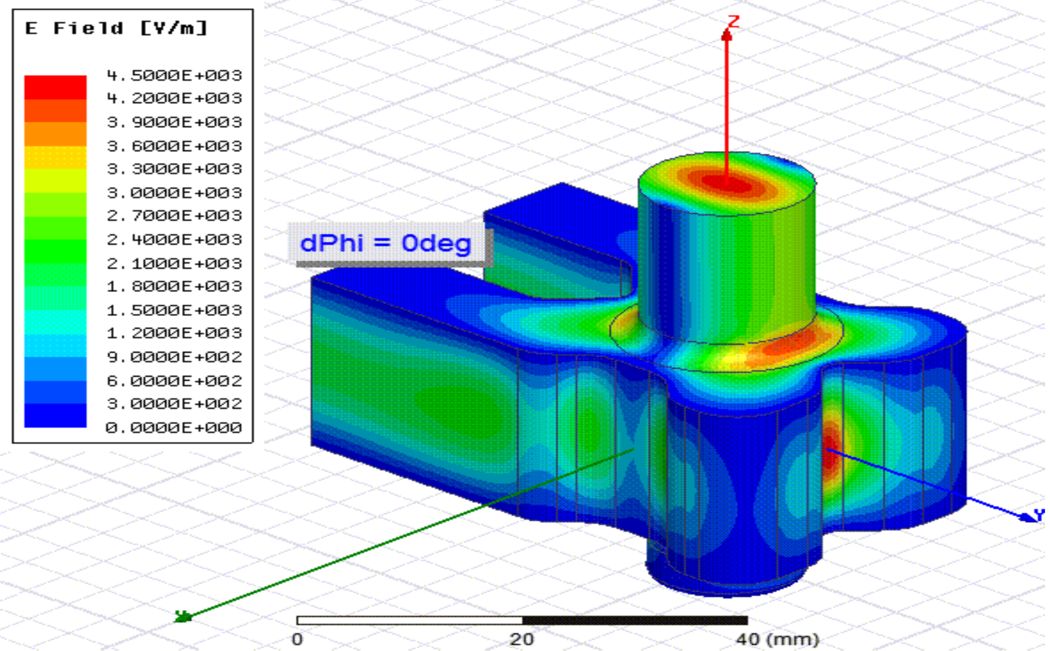
- Field is **developing metallic RF technology**: new possibilities for colliders.
- Progress in peak energy slowing. Practical limitations: **size and cost**.
- **Dielectric accelerators** promising but low charge and low beam energy so far: at this stage aiming at other applications primarily.
- **Plasma accelerators** open the horizon to transformative steps with several orders of magnitude to be gained.
  - **Great progress** in the field but still very long way to a full plasma LC.
  - **Ready to build the "plasma booster demonstration" facility EuPRAXIA**. CDR completed. Provides design, cost, schedule.
  - Many applications of EuPRAXIA create **societal benefits**.
  - Great **synergy with LC** → 1 GeV X Band linac of EuPRAXIA as CLIC demonstrator! Should push a common strategy together.
- The **future is ~~bleak~~ bright** (but does not come for free)...


Thank you for your attention

Spin-Off from CLIC Technology: Femto-Second Diagnostics

X Band Transverse Deflecting Structure with Variable Polarization (DESY – CERN – PSI collaboration)



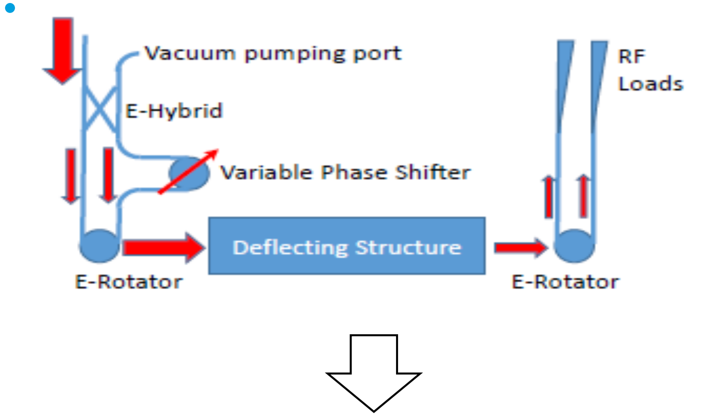
Variable Polarization Circular TE11 Mode Launcher

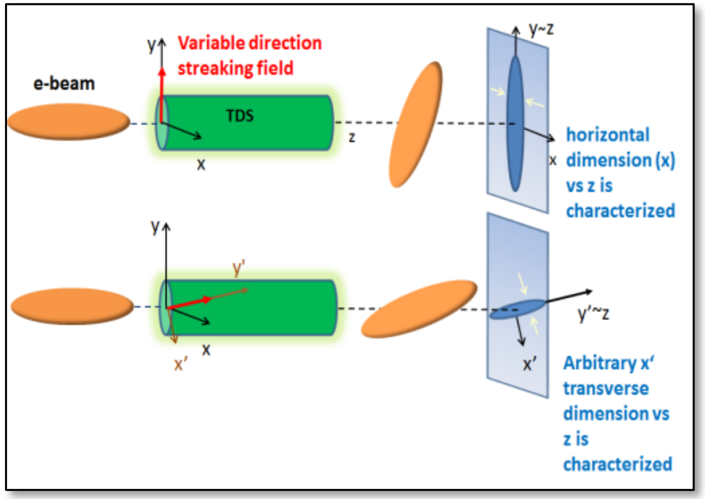
A. Grudiev, CLIC-note-1067 (2016)

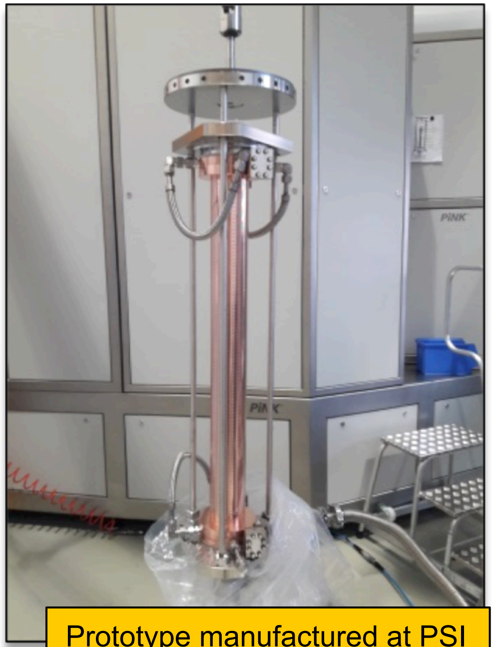
Novel X-band TDS Concept with Variable Polarization

Phase difference between port 1 and port 2:

- 0 degree -> vertically streaking field







Prototype manufactured at PSI