EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

Status and Future Perspectives of the EuPRAXIA Project

19 September 2019 – EAAC 2019

Ralph Assmann (DESY) for the EuPRAXIA Consortium

Coordinator EuPRAXIA Design Study

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

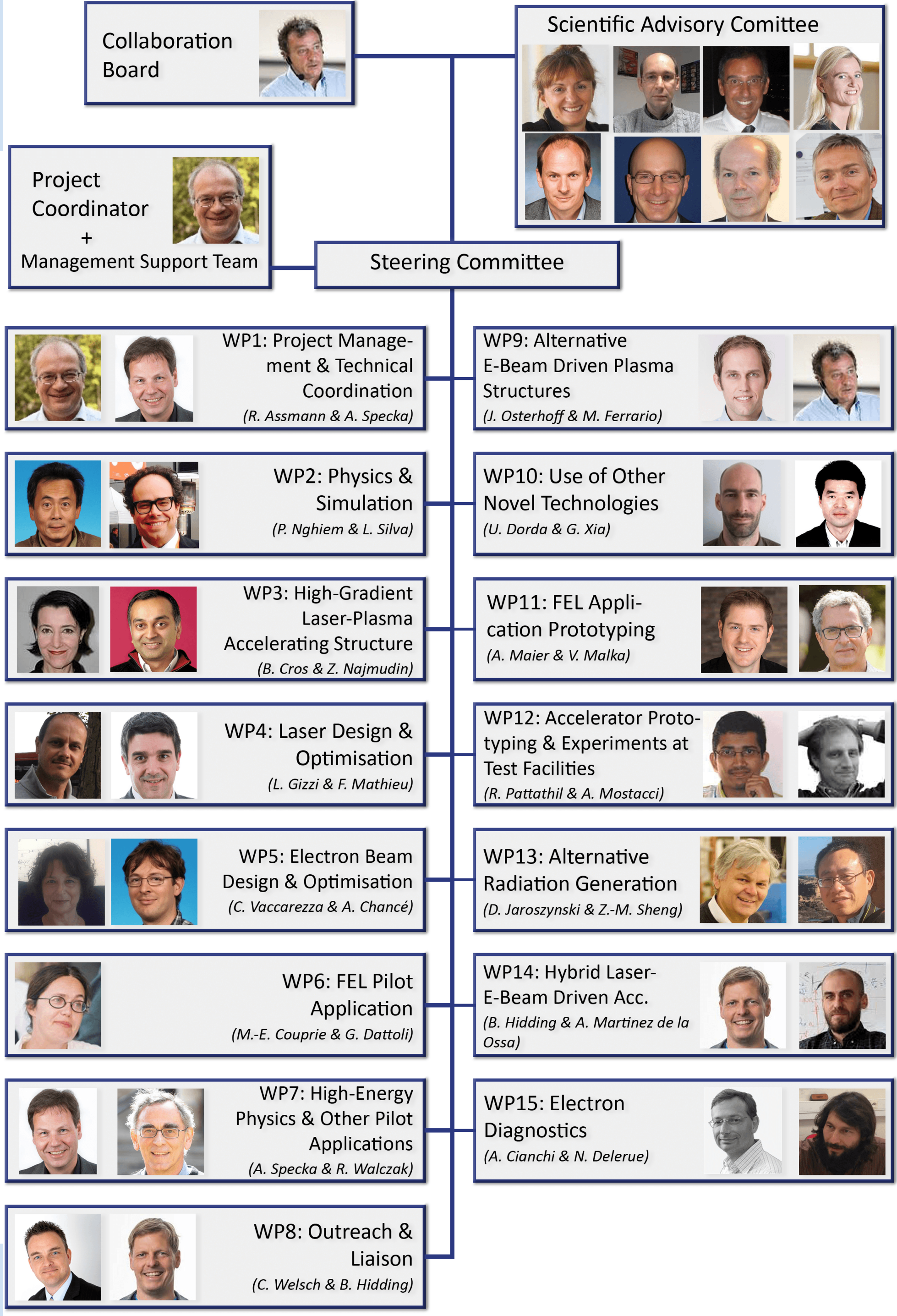
The EuPRAXIA Project

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 200 scientists contributed

- One of four DS's in physical science approved in H2020. Others: EuroCirCol (FCC), CompactLight (X band), Neutrino (ESS)

#EuPRAXIA
#plasma
#accelerator



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

EuPRAXIA Questions

- Could we build in the next 10 – 15 years an **accelerator facility based on plasma accelerators, lasers or beam drivers**?
- How would such a plasma-based large accelerator facility look like and would it have **advantages**?
- Could such a facility produce high **quality beams with some applications** and is there promise and interest for such a facility?
- **What would be needed** to build such a facility within the next 10 – 15 years, if it seems interesting?

Some Initial Design Goals (not complete)

Horizon 2020

up to 5 GeV electron beam energy

≤ 1 mm-mrad normalized 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

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≤ 1 % total energy spread

Major critical issue

Deliverable: CDR (end of October)

Horizon 2020

- Work on **technical solutions**, but also on **facility concept**
- Present status:
  - **555 pages** strong draft
  - Some contributions still coming, changes to be included
- Cannot be reported completely here.
- Selection of results and concepts → apologies
- For more details: read the CDR once it is published...

High Quality Beam

Simulations: Variety of Codes Used

ASTRA, Tstep, Elegant,

SMILEI, CALDER-C, Warp,

OSIRIS, ALaDYN, Qfluid,

FBPIC, CSRtrack, TraceWin,

Architect, VSim

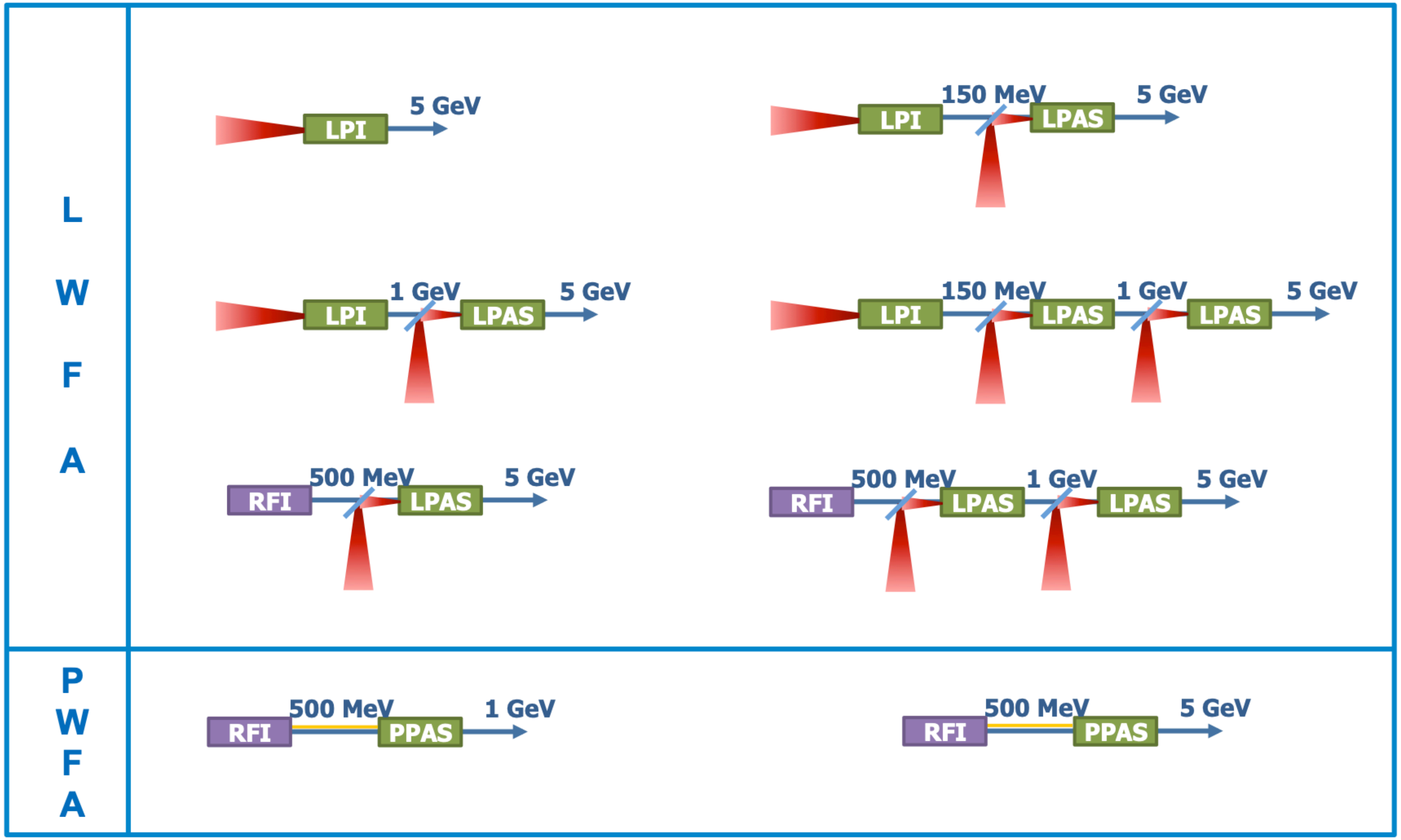
- Strong variety in codes used → less prone to a single source of errors

Horizon 2020

Technical EuPRAXIA Solutions

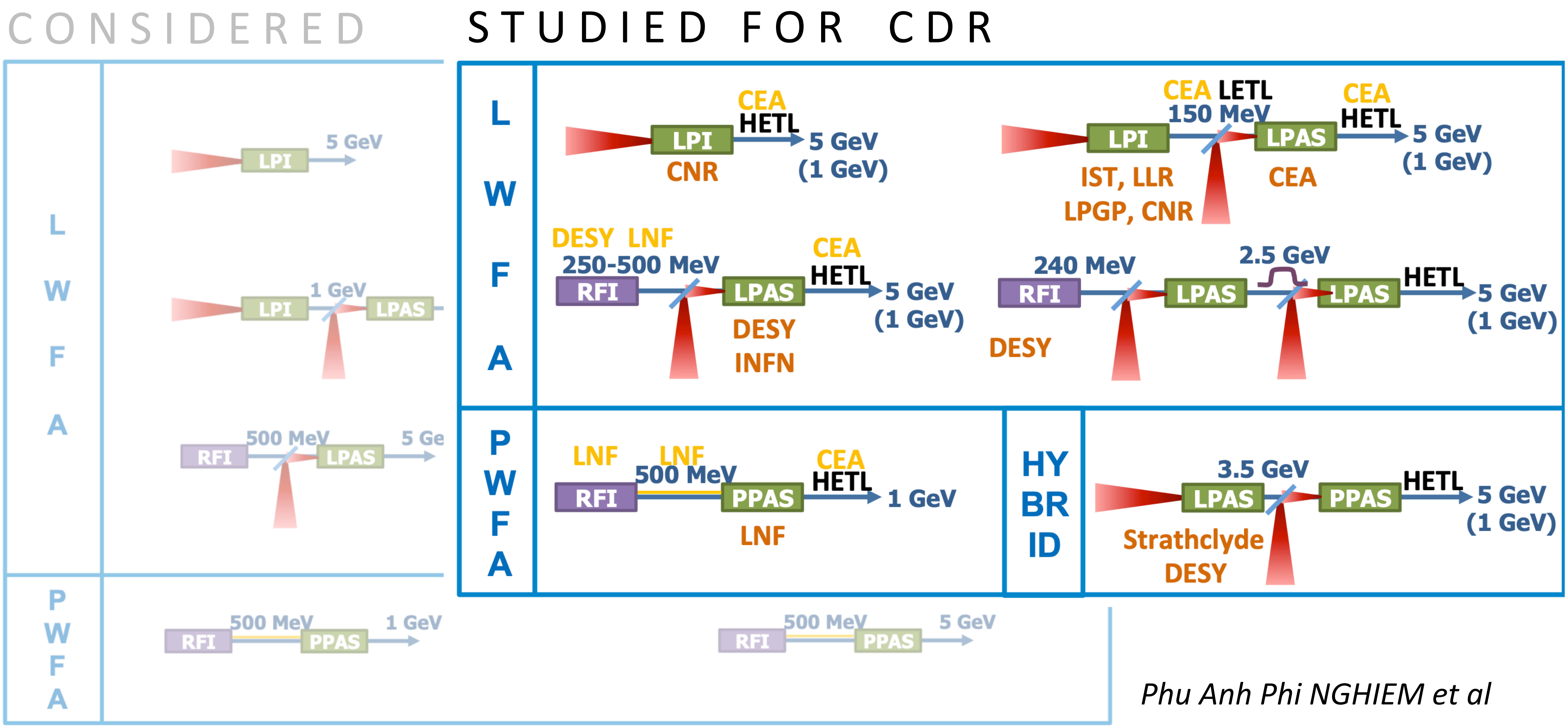
Horizon 2020

CONSIDERED



Phu Anh Phi NGHIEM et al

Technical EuPRAXIA Solutions



Phu Anh Phi NGHIEM et al

Down-Selection Process

- Mild down-selection process. WHY?
- Some realizations:
  - European research infrastructure landscape is quite diverse with different boundary conditions at various places → **one technology does not suit all needs**
  - The major cost drivers are infrastructure, RF, lasers, instrumentation, ... → very **little cost overhead to include several solutions** at one facility
  - Our solutions are innovative but paper solutions → **unavoidable risk can be mitigated by parallel approach**.
- Multiple site, multiple solution approach.

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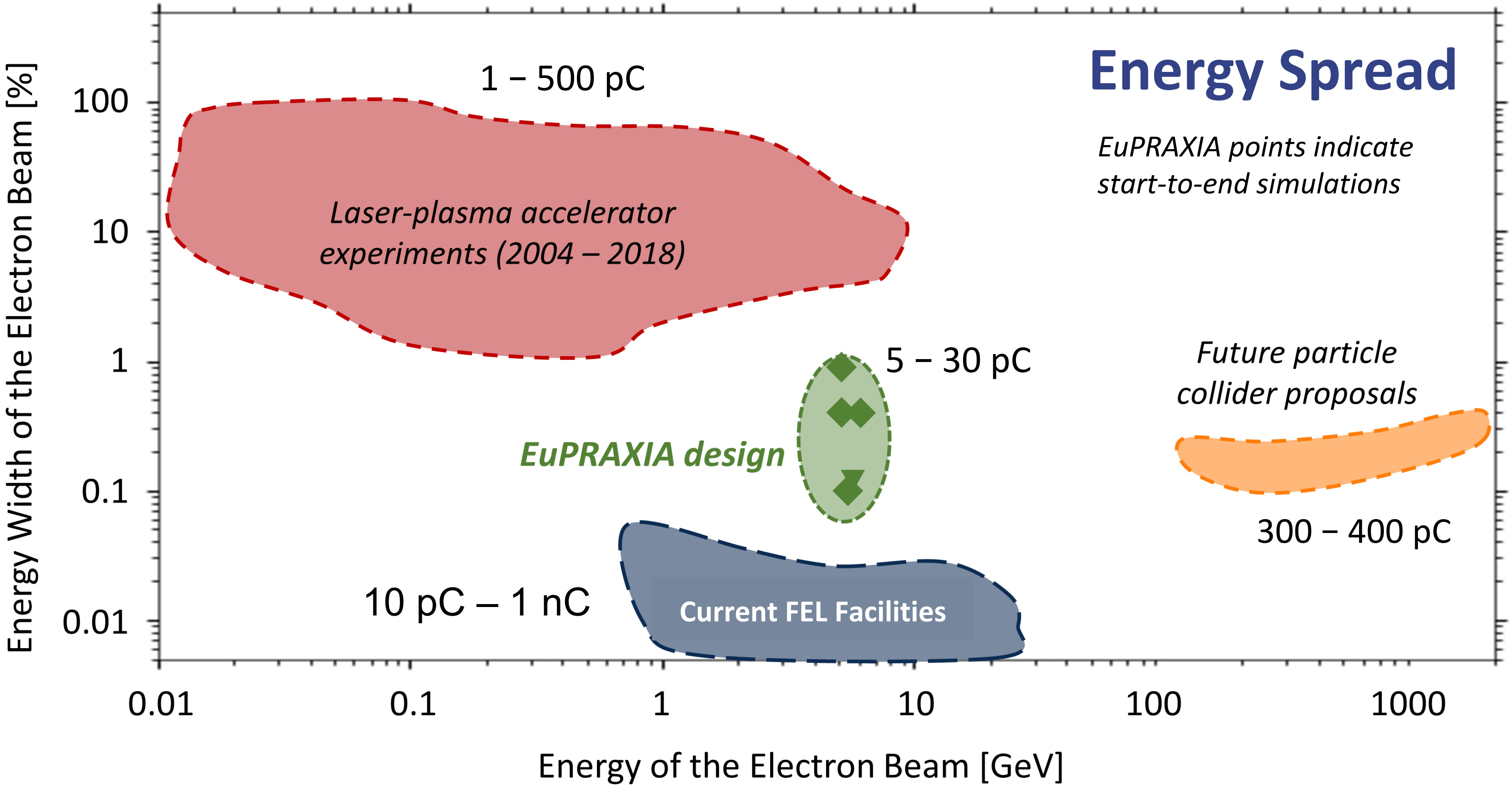
EuPRAXIA Design: High Quality Single Bunch

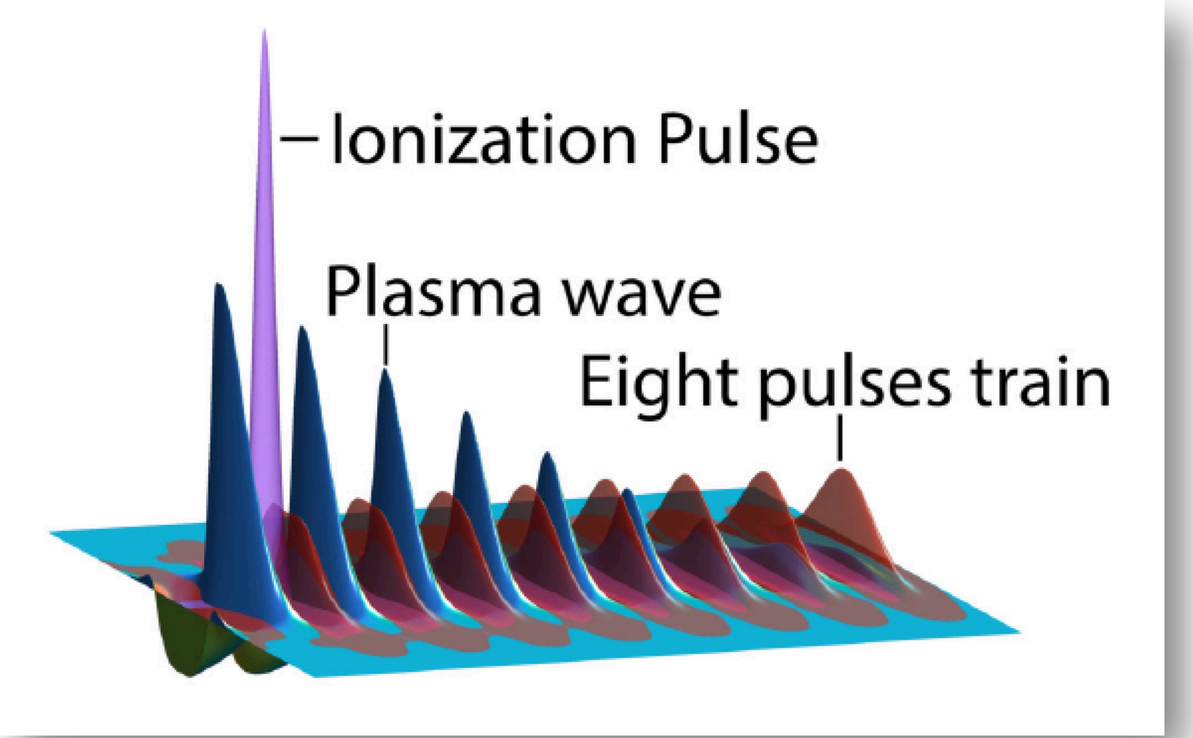


Resonant Multi-Pulse Ionization Injection

High-Quality 5GeV electron bunches with the Resonant Multi-Pulse Ionization injection

P. Tomassini, D. Terzani, F. Baffigi, F. Brandi, L. Fulgentini, P. Koester, L. Labate*, D. Palla and L. A. Gizzi*
Intense Laser Irradiation Laboratory, INO-CNR, Pisa (Italy)
* Also at INFN, Sect. of Pisa, (Italy)

Accepted by Physics of Plasmas



All optical scheme

Paolo Tomassini et al

Param.	$\sigma(E)/E$	ϵ_n	$\sigma(E)/E\|_{slice}$	$\epsilon_n\|_{slice}$	Q	I
R	$<1,\%$	$\ll 1\,\mu mrad$	$<0.1\%$	$\ll 1\,\mu mrad$	$\geq 30\,pC$	$>1\,kA$
O	$0.9\,\%$	$0.085\,\mu mrad$	$0.03\,\%(min)$	$0.085\,\mu mrad$	$30\,pC$	$2.5\,kA$

Compact Multi-Stage Plasma-Based Accelerator

Horizon 2020

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

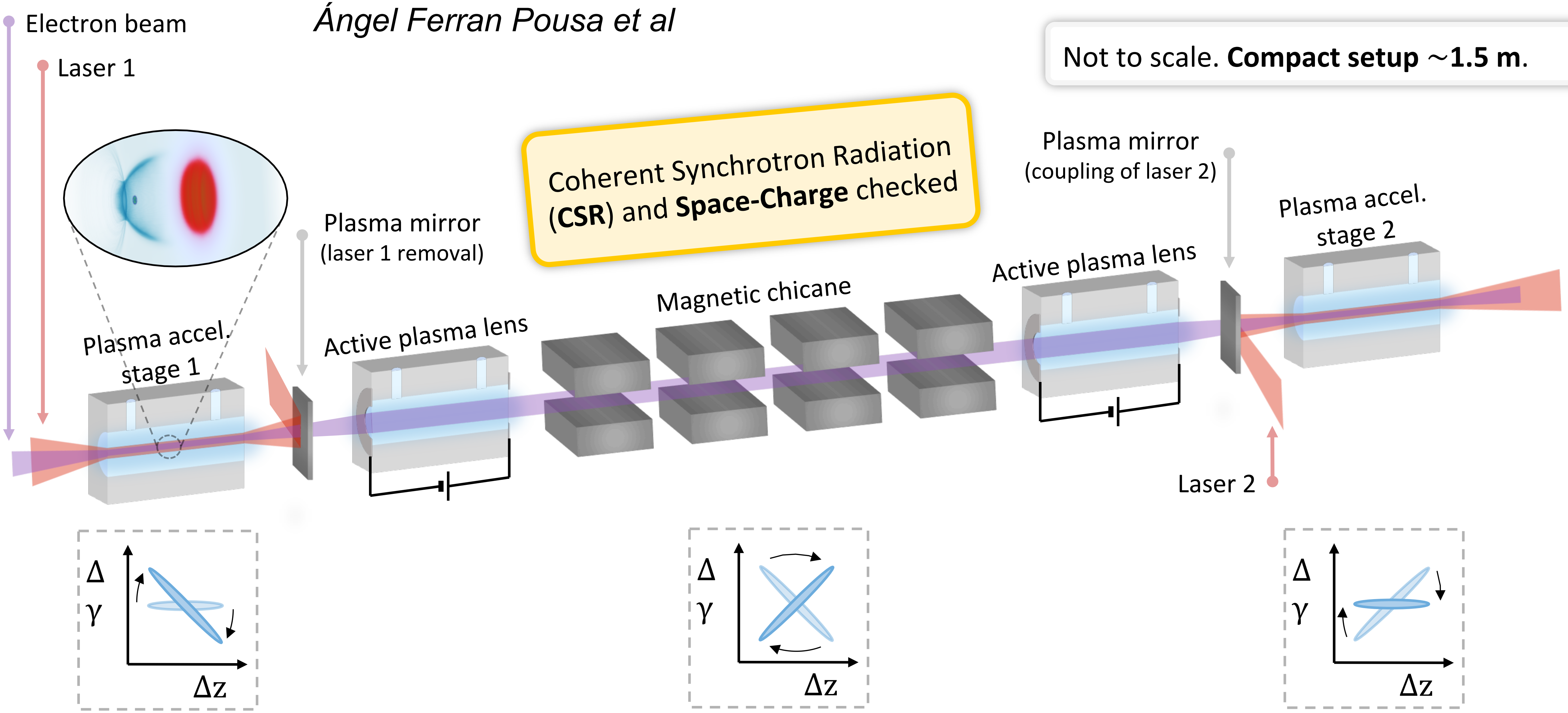
- 1.5 m long
- 5.5 GeV
- **0.03%** slice energy spread
- **0.12 %** total enery spread
- sub-micron emittance

Compact Multi-Stage Plasma-Based Accelerator

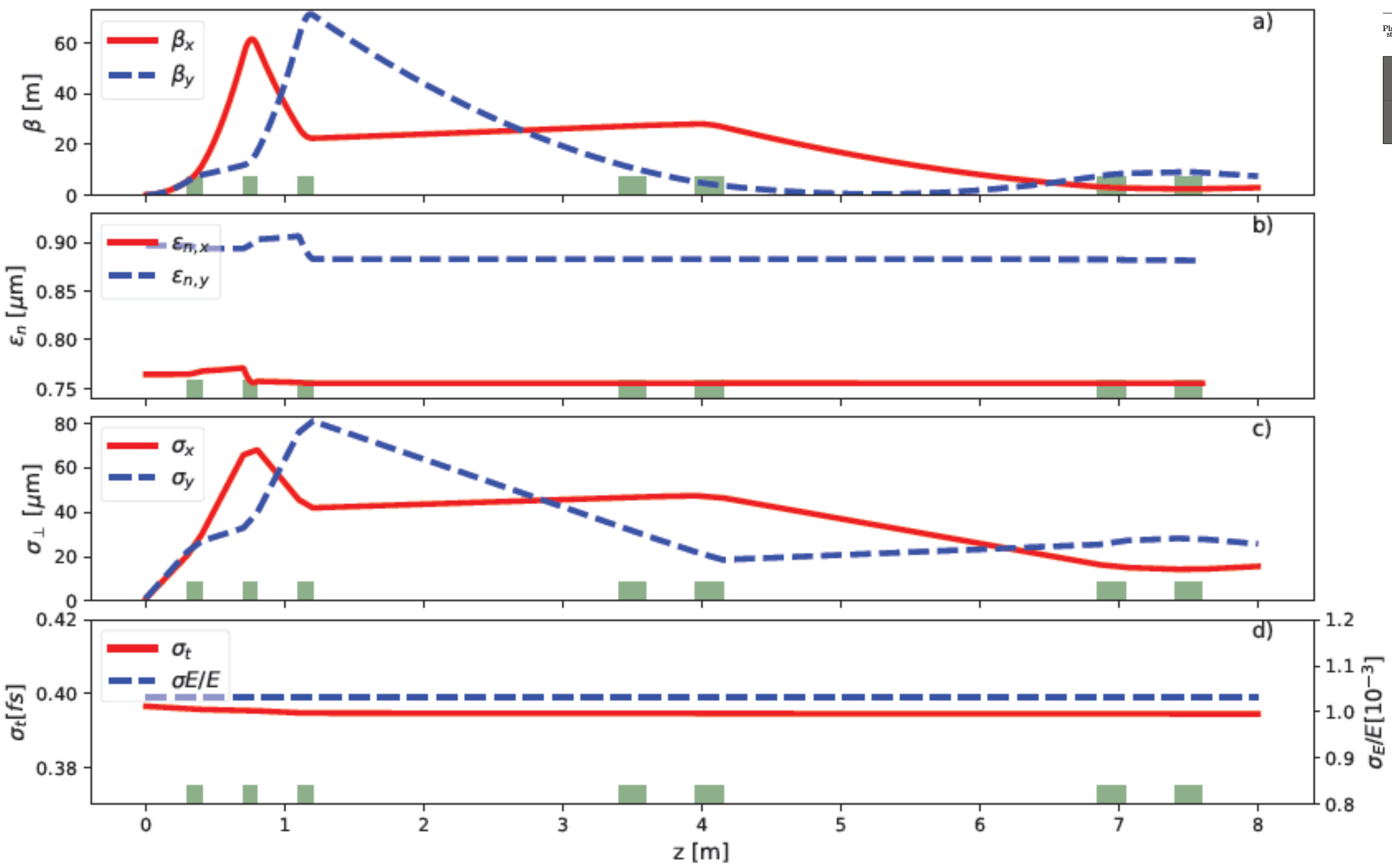
Horizon 2020

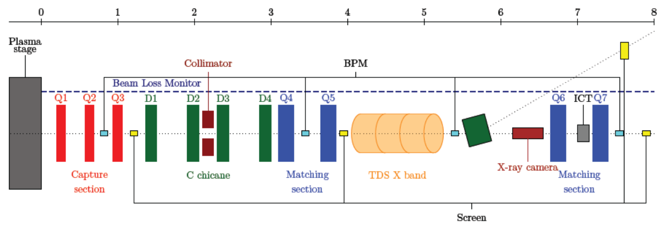
Ángel Ferran Pousa et al

Not to scale. **Compact setup ~1.5 m.**



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

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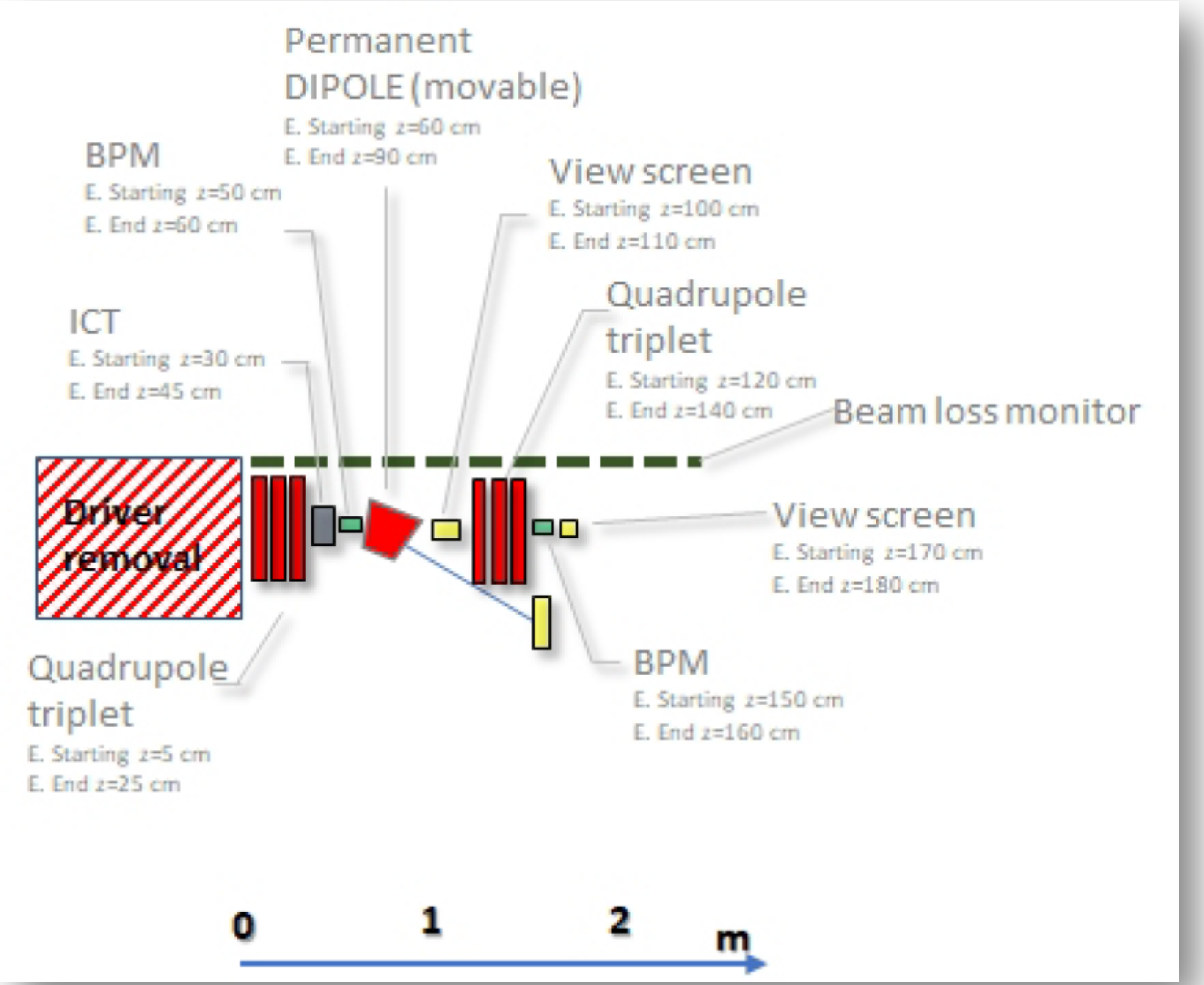


Example:

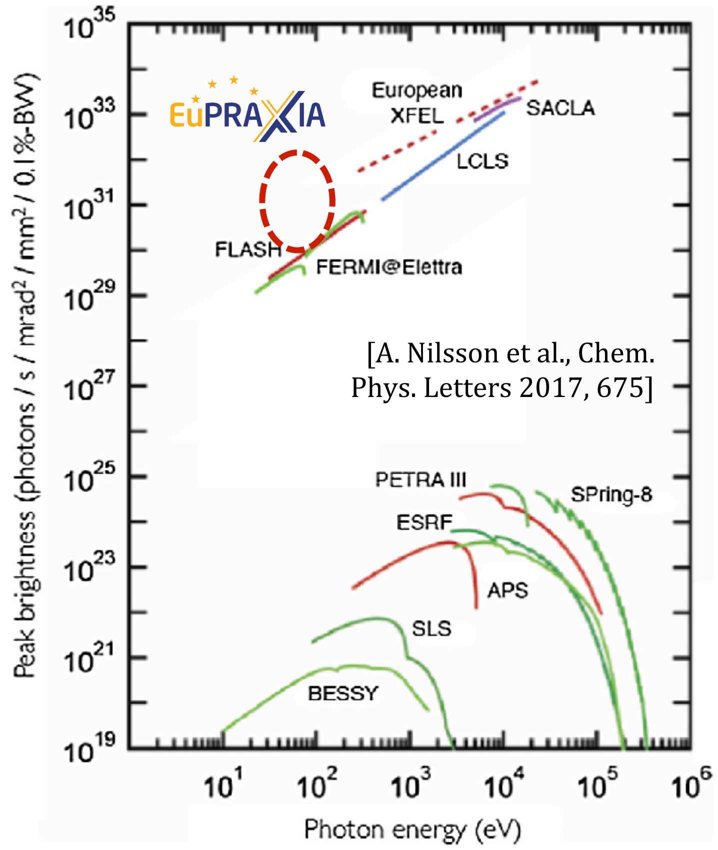
Permanent beam line from **laser-plasma injector to laser plasma accelerator**

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



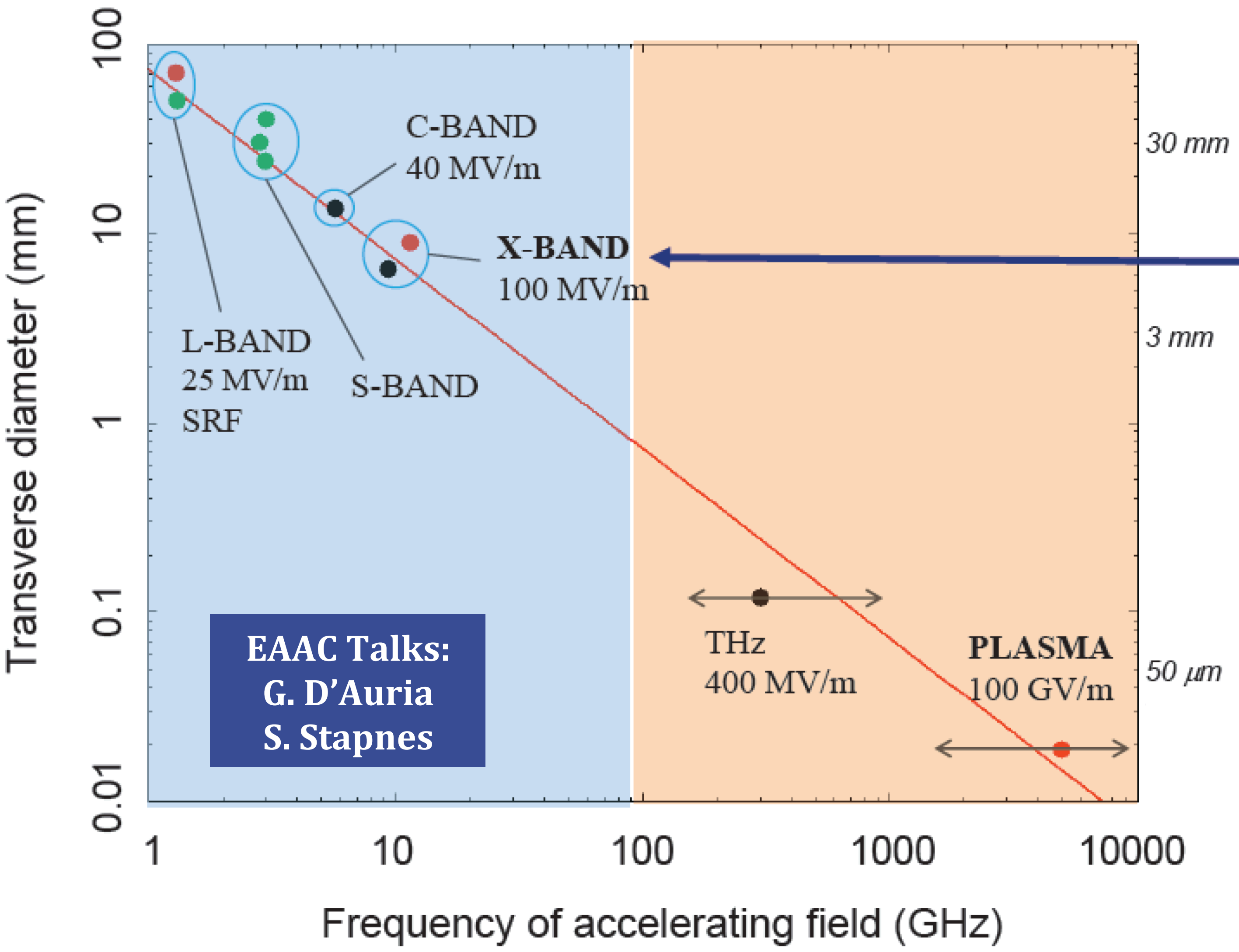
Ultrashort FEL radiation pulses	
Radiation wavelength	0.2 – 36.3 nm
Photons per pulse	2×10^{9} – 3×10^{13}
Brightness	2×10^{30} – 6×10^{32} [*]

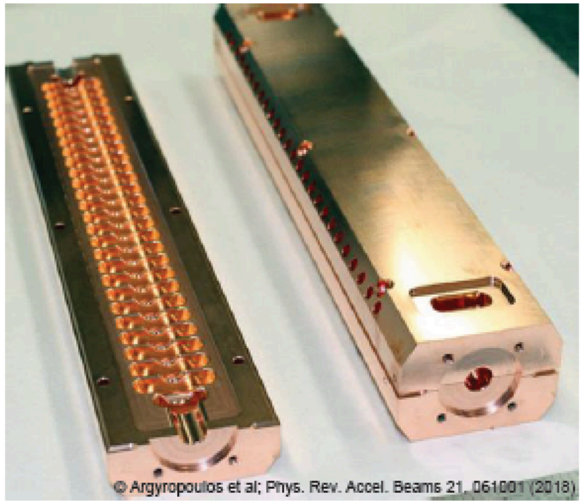
* = [mm mrad s (0.1% BW)]$^{-1}$

EuPRAXIA Features

EuPRAXIA Design: Most Compact 1 GeV RF Linac

Horizon 2020





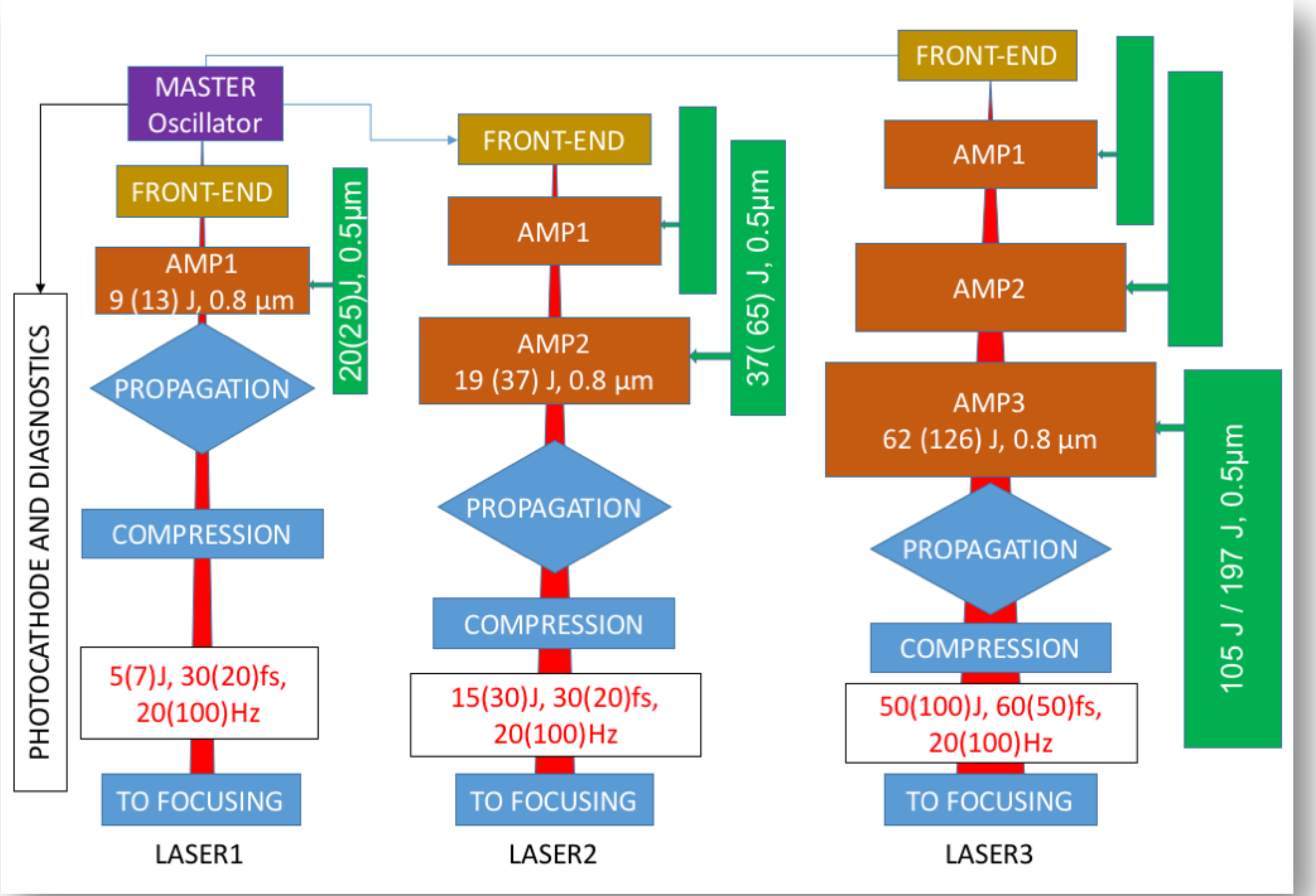
CERN

X Band RF Beam Driver

(Minimal Footprint at PWFA Site)

EuPRAXIA Design: 20 – 100 Hz Lasers

Horizon 2020

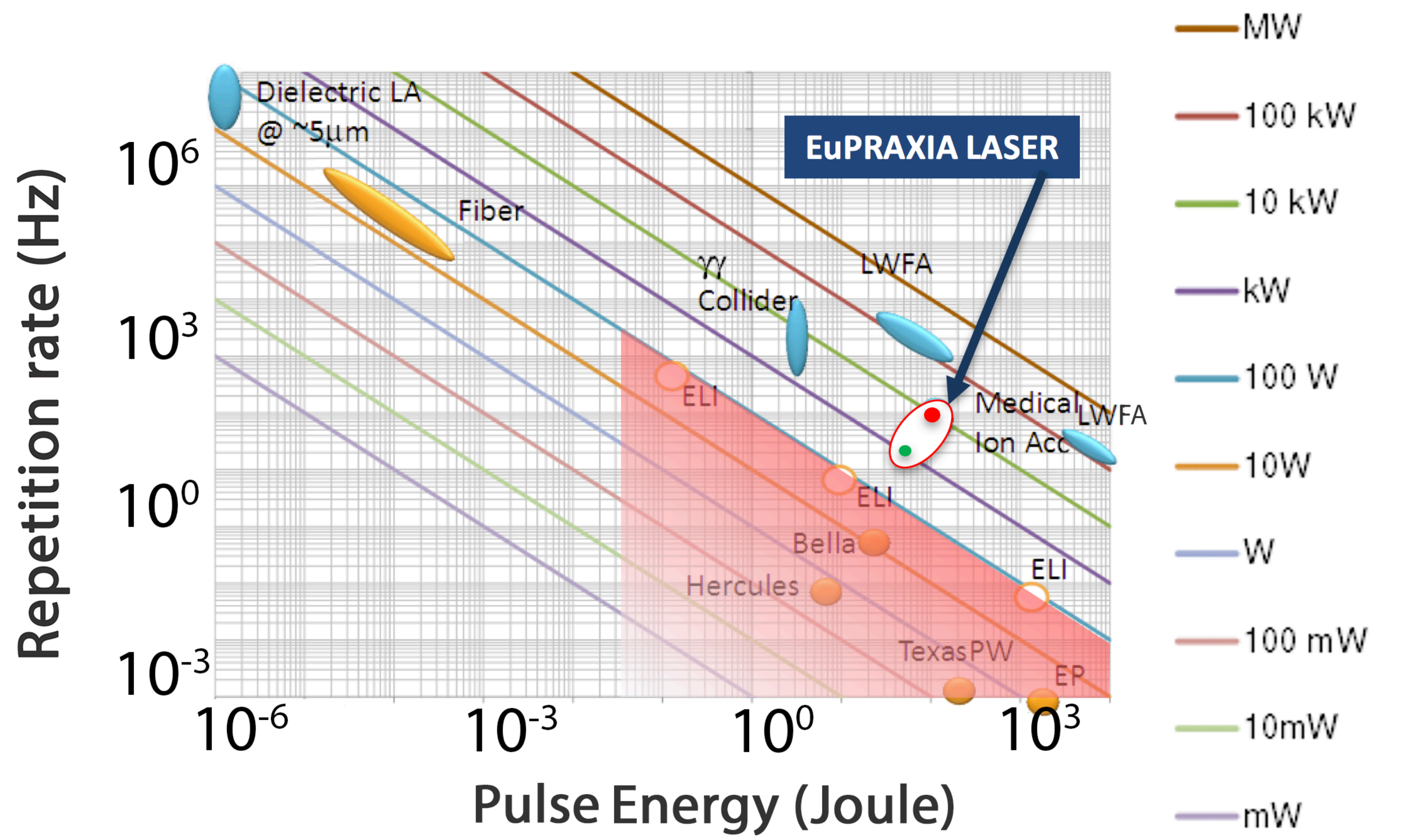


- **Three laser systems** for the laser-driven plasma accelerator facility
- Baseline: Start from lasers at present **state-of-the-art**, however, extended to 20 Hz and then to 100 Hz
- In parallel: **Development** of high efficiency, high average power lasers

Leo Gizzi, Francois Mathieu et al

EuPRAXIA Design: 20 – 100 Hz Lasers

Horizon 2020

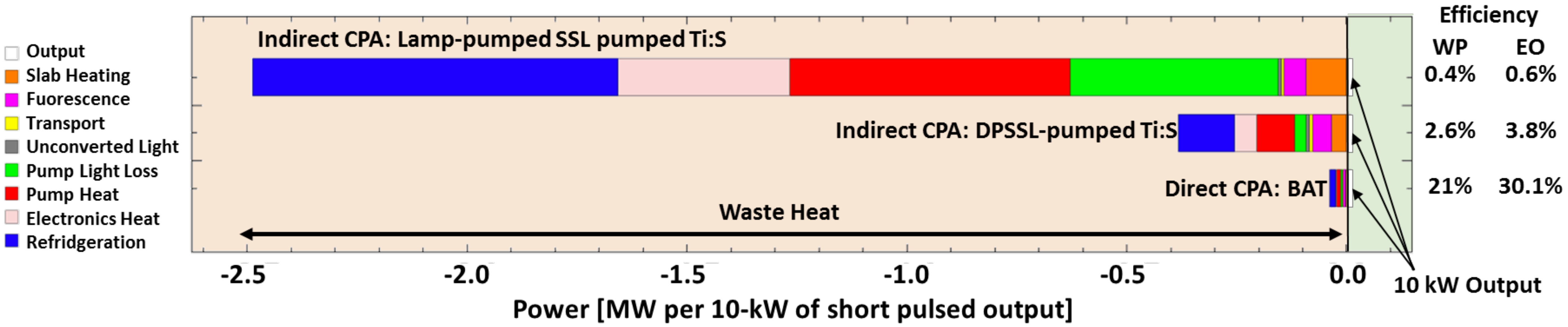


- EuPRAXIA lasers should enter into the **10 kW regime** at 100 Hz repetition rate
- First step: 20 Hz
- Beyond: High efficiency, kHz laser systems

Leo Gizzi, Francois Mathieu et al

Development Paths Required: Example Lasers

Laser efficiency at present is a problem → towards high efficiency solutions, enabling high average power



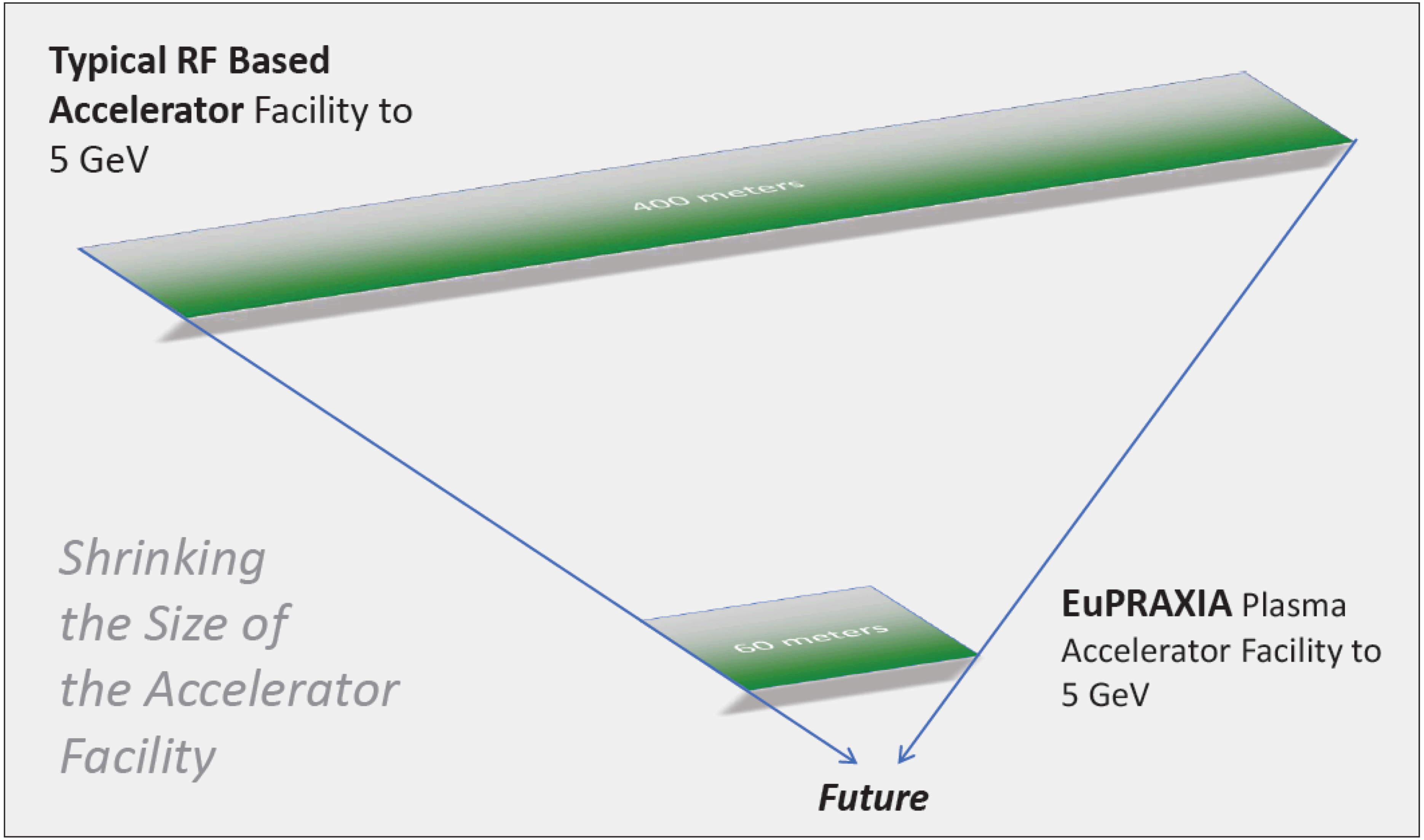
Courtesy C. Siders, EAAC 2017

KALDERA: The kHz laser development project at DESY → Talk by W. Leemans

Other **kHz developments**: S. Hooker, J. Faure (LAPLACE), ...

EuPRAXIA Design: Shrink the Facility

Horizon 2020

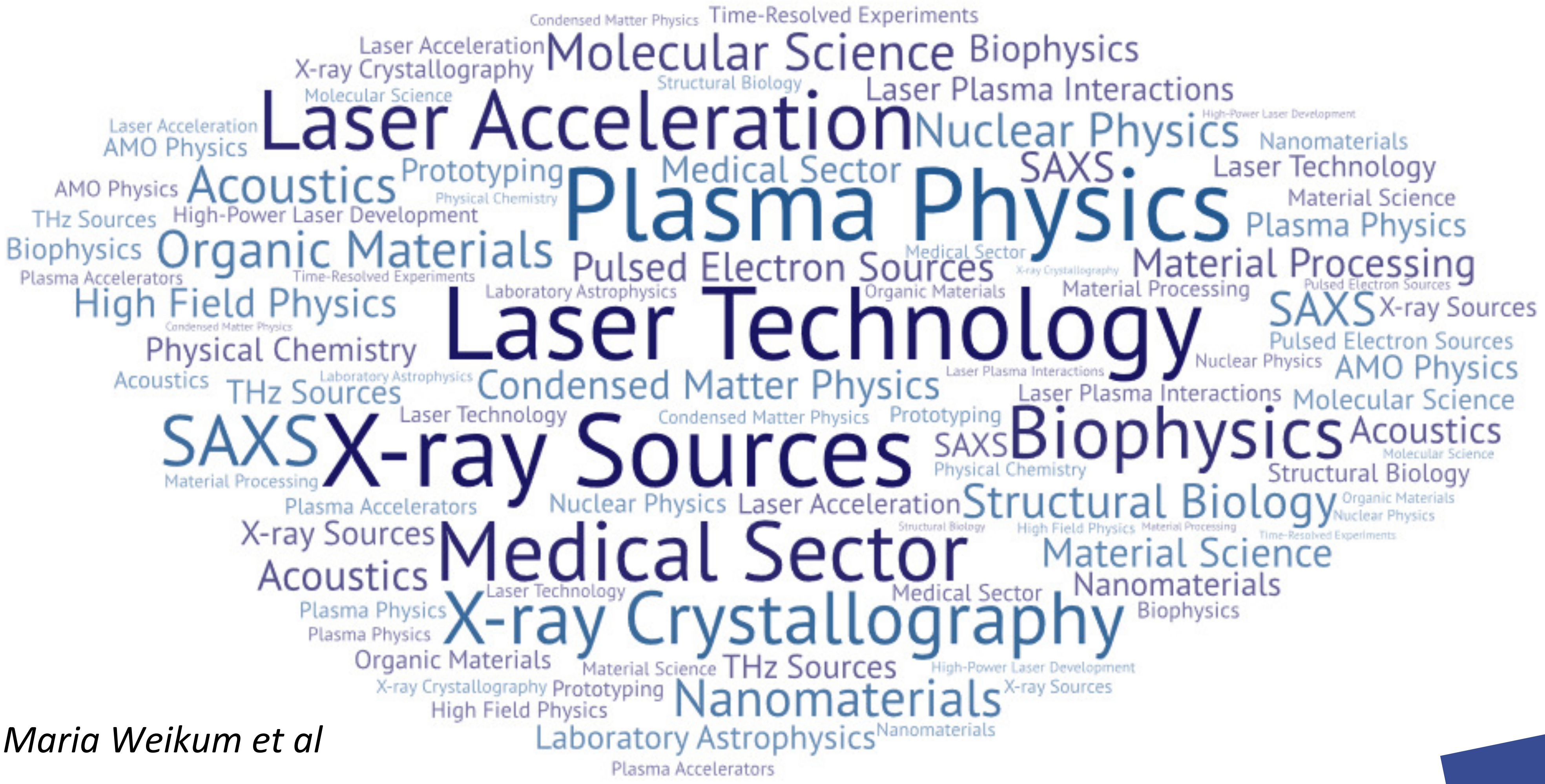


Facility:

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

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

EuPRAXIA Design: Interest in Science



Maria Weikum et al

Survey on scientific interests in EuPRAXIA

Feedback received from 30 groups with more than 1,000 researchers

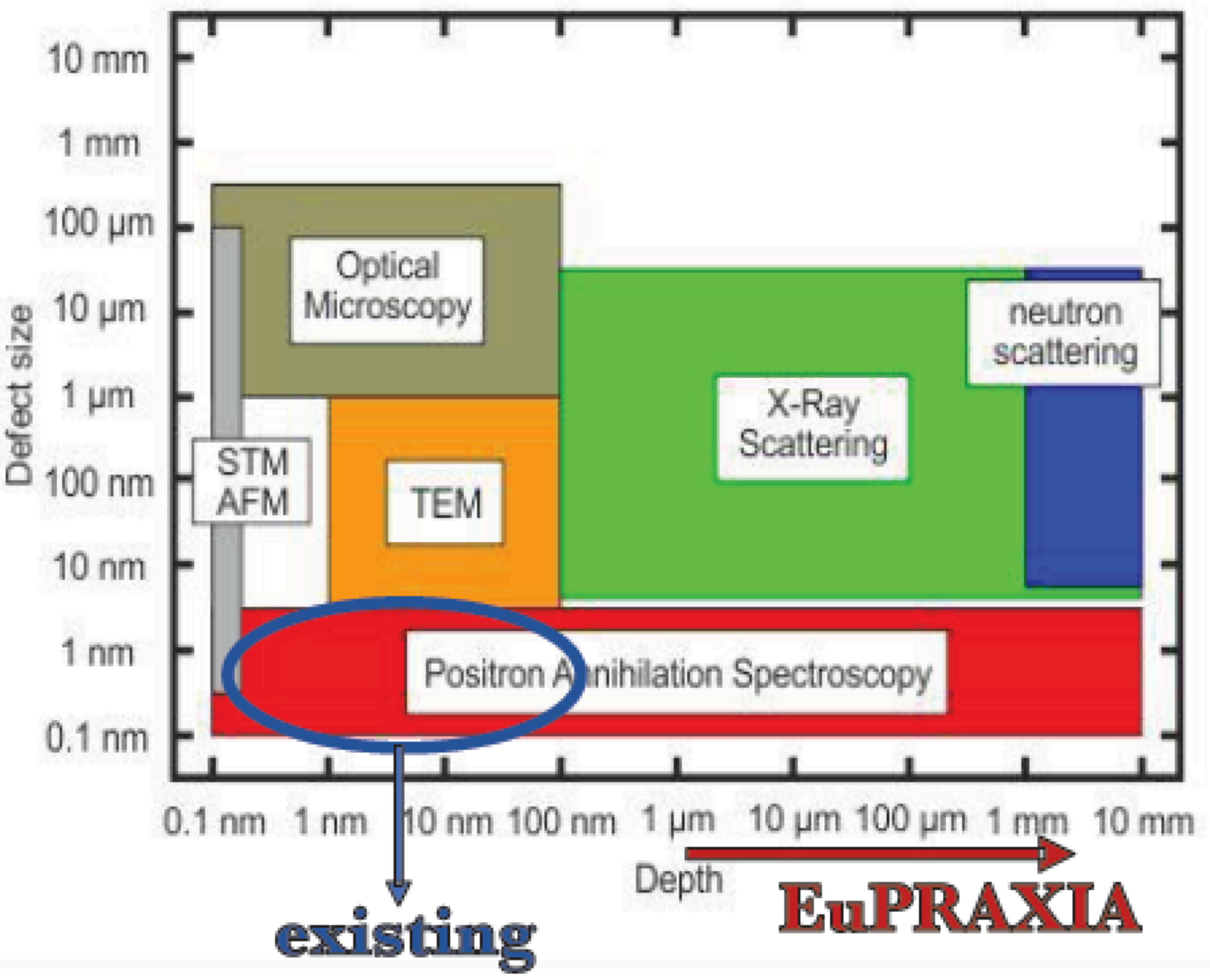
Word cloud shows expression of interest

EAAC Talks:
M. Weikum, Wed 18:00

Good news: Significant interest in a EuPRAXIA facility

Example: Positron Annihilation Spectroscopy

Horizon 2020



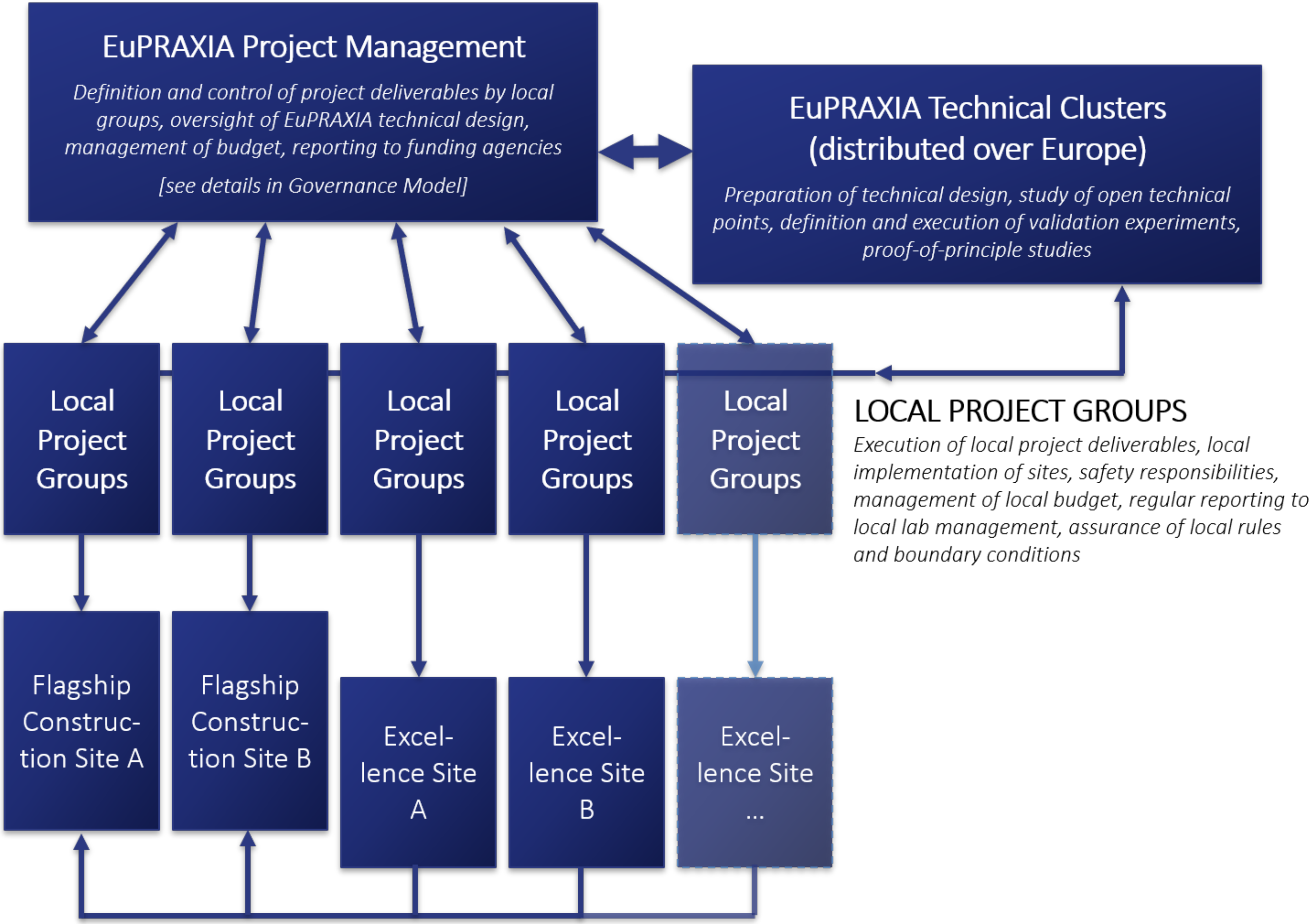
Courtesy M. Butterling, HZDR

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

EuPRAXIA Model and Sites


EuPRAXIA Project Management
Definition and control of project deliverables by local groups, oversight of EuPRAXIA technical design, management of budget, reporting to funding agencies
[see details in Governance Model]
EuPRAXIA Technical Clusters (distributed over Europe)
Preparation of technical design, study of open technical points, definition and execution of validation experiments, proof-of-principle studies
Local Project Groups
Local Project Groups
Local Project Groups
Local Project Groups
Local Project Groups
LOCAL PROJECT GROUPS
Execution of local project deliverables, local implementation of sites, safety responsibilities, management of local budget, regular reporting to local lab management, assurance of local rules and boundary conditions
Flagship Construction Site A
Flagship Construction Site B
Excellence Site A
Excellence Site B
Excellence Site …

Clusters

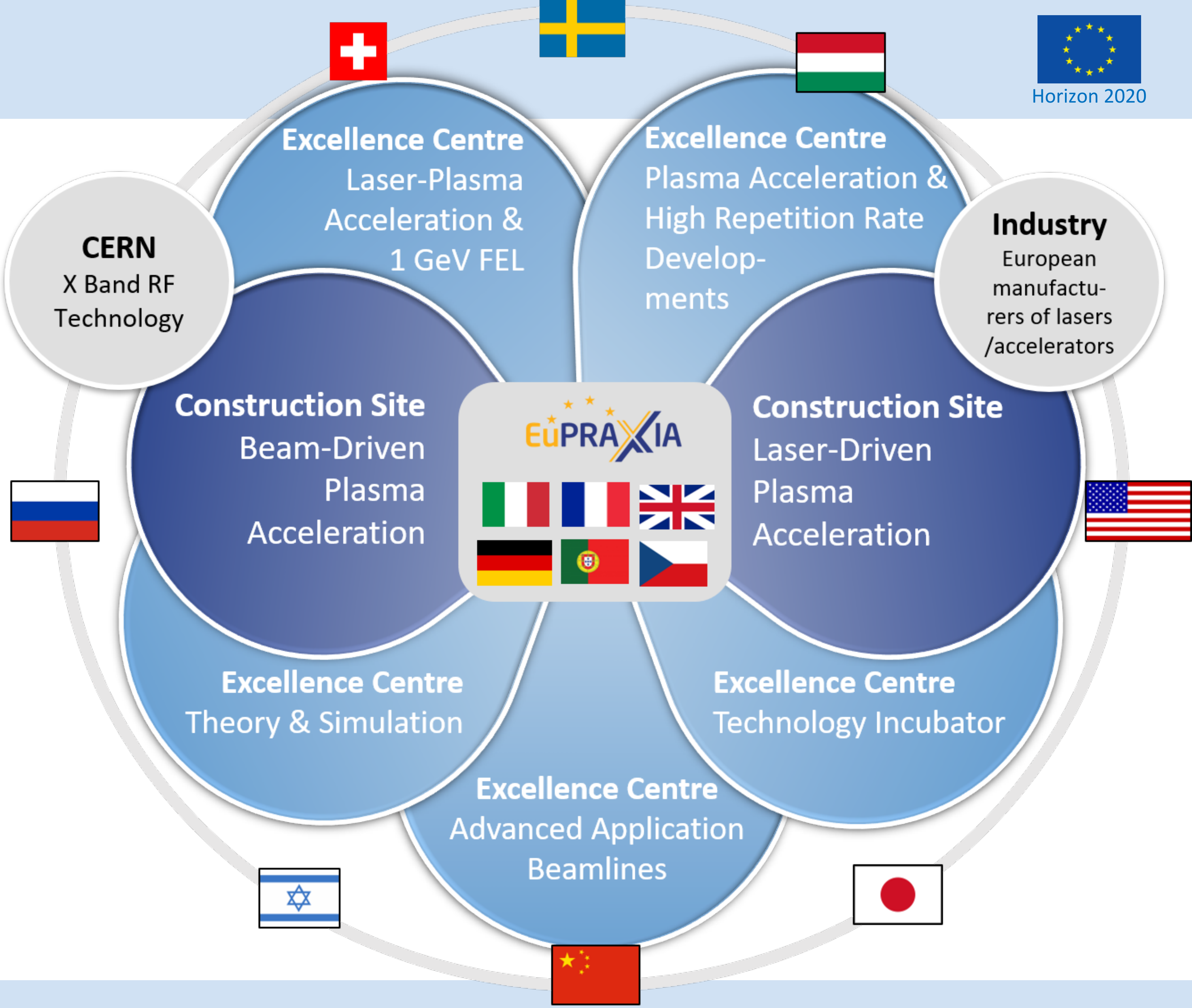
Connected to existing groups and facilities around Europe (see also excellence centers)

- **preparation of technical design**
- study of open technical points
- definition and execution of **validation experiments**
- proof-of-principle studies

Excellence Sites

Located at existing major facilities in Europe, profiting from ongoing investments

- demonstration of major **critical principles**
- construction of **prototypes**
- testing and qualification of prototypes
- construction/testing of **components for construction site(s)**



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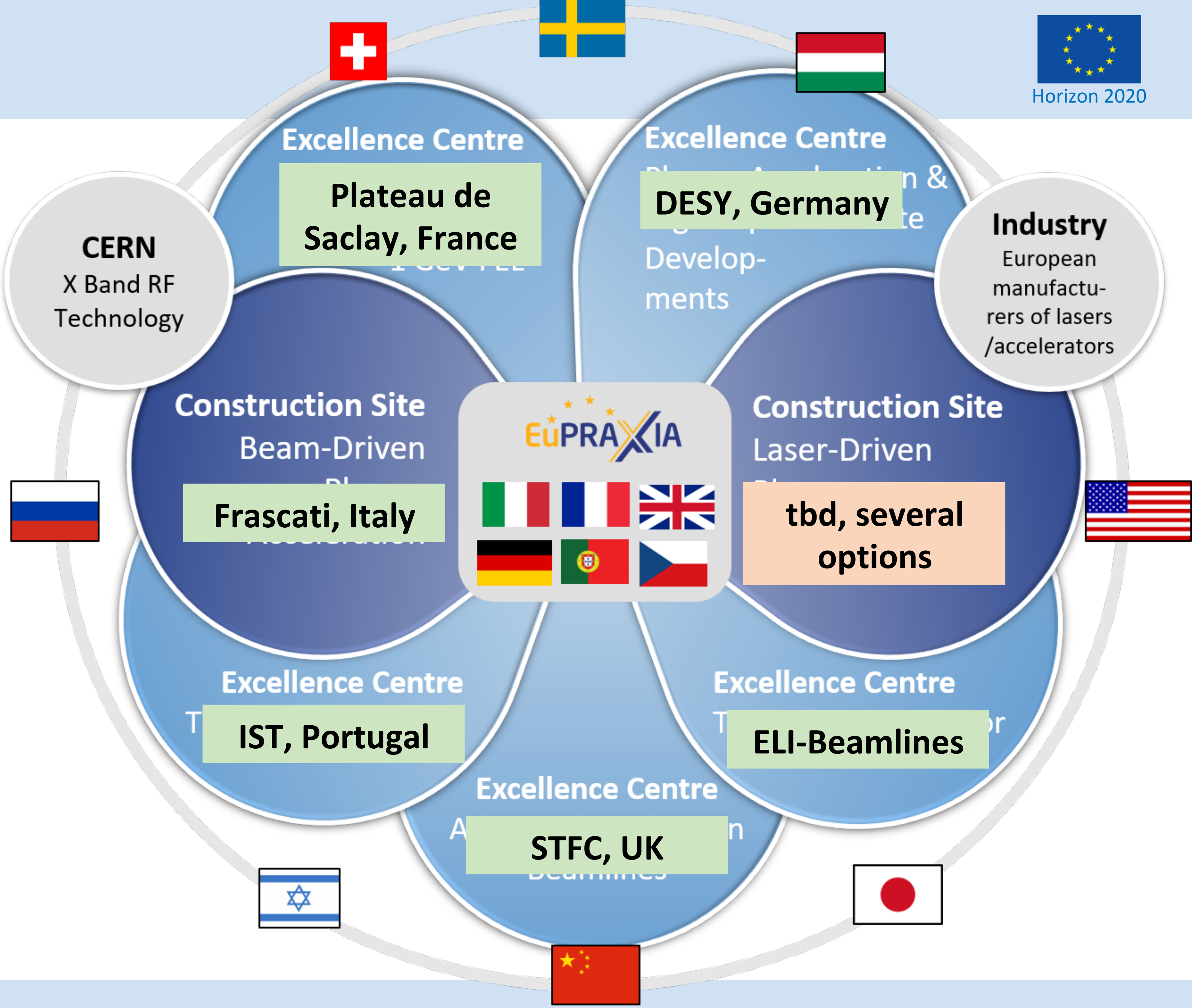
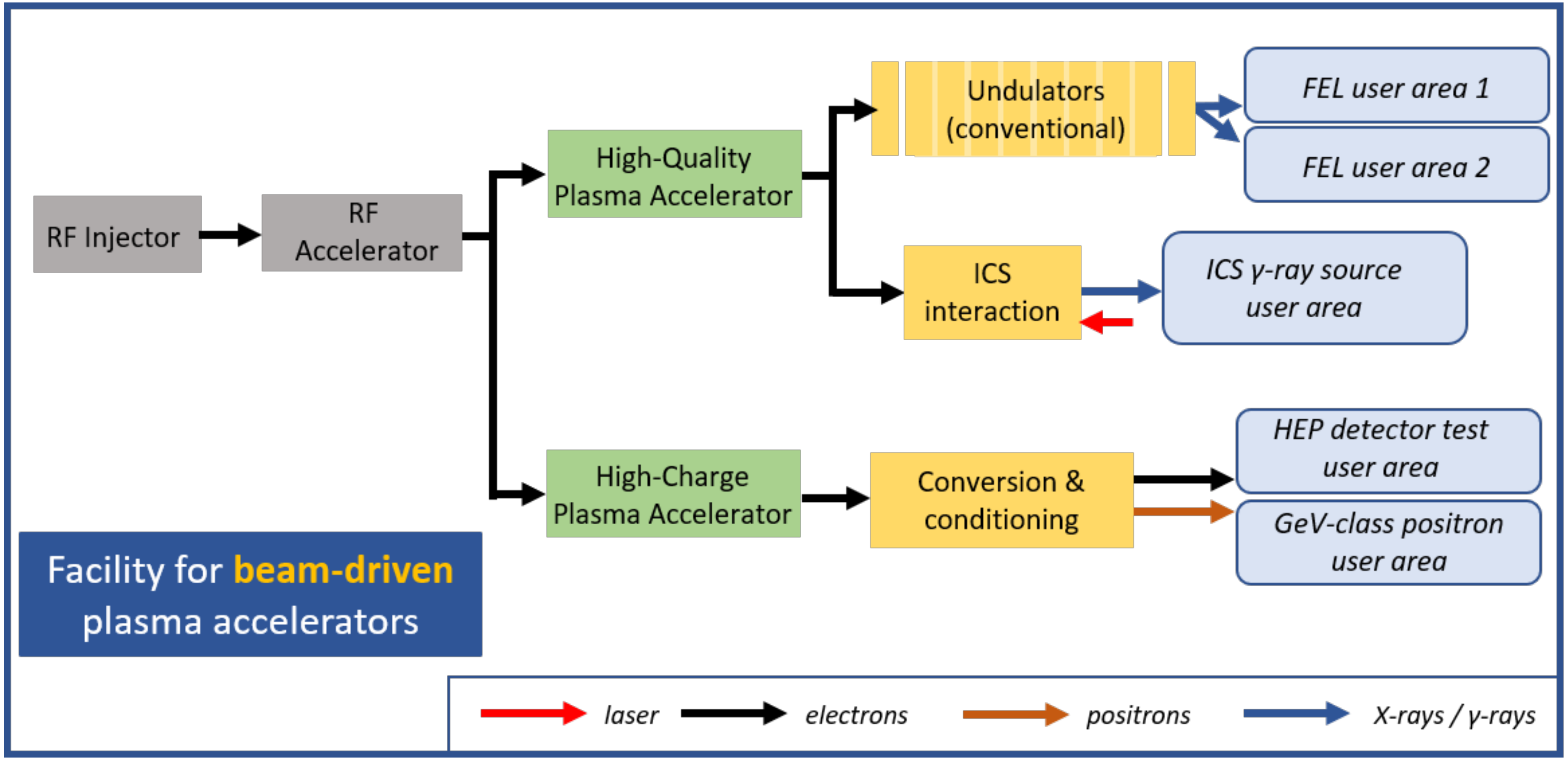


The Beam-Driven Construction Site



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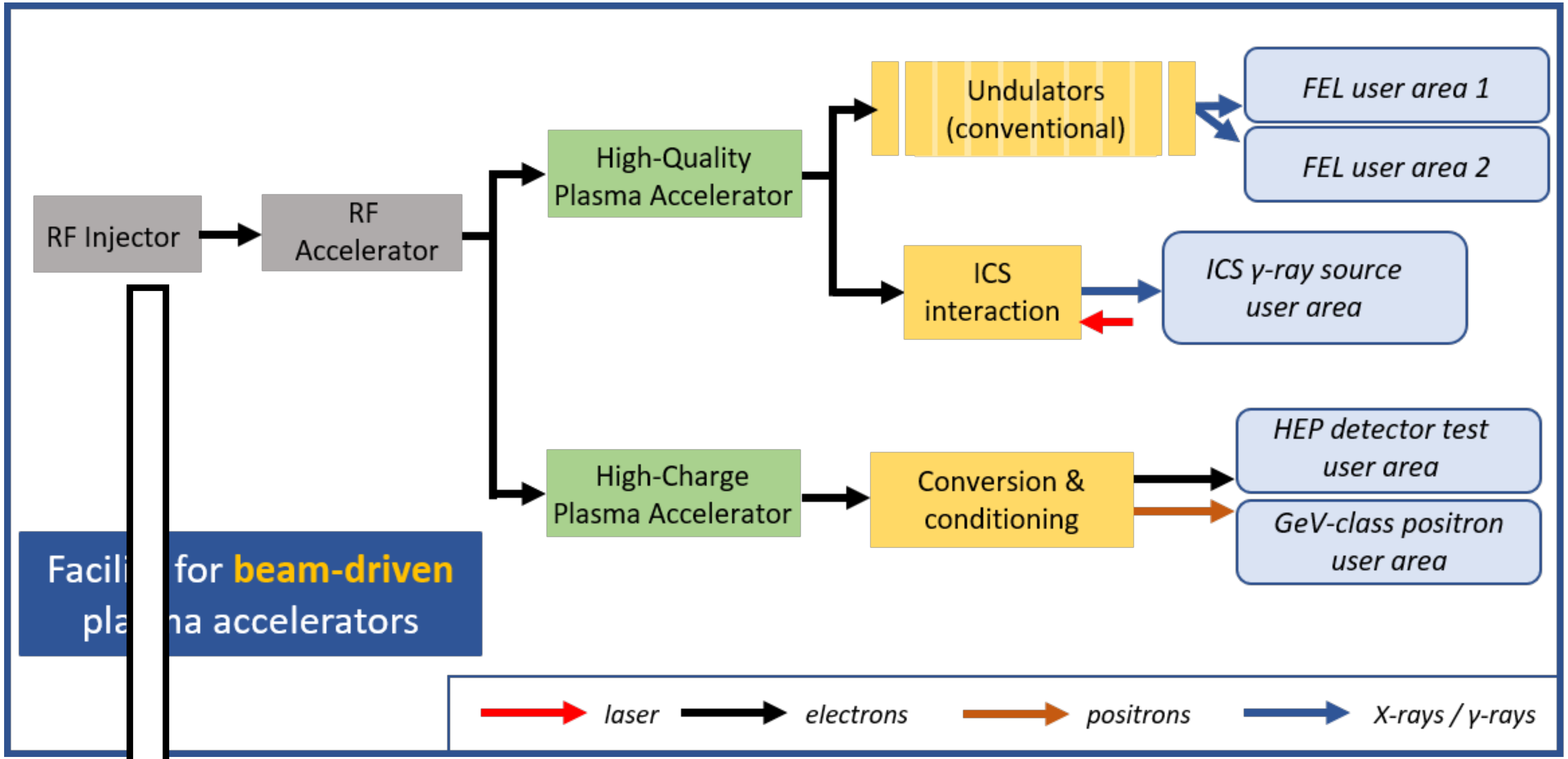
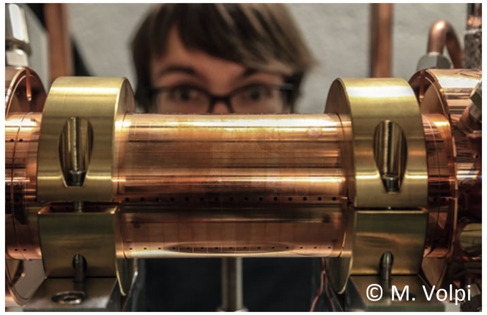
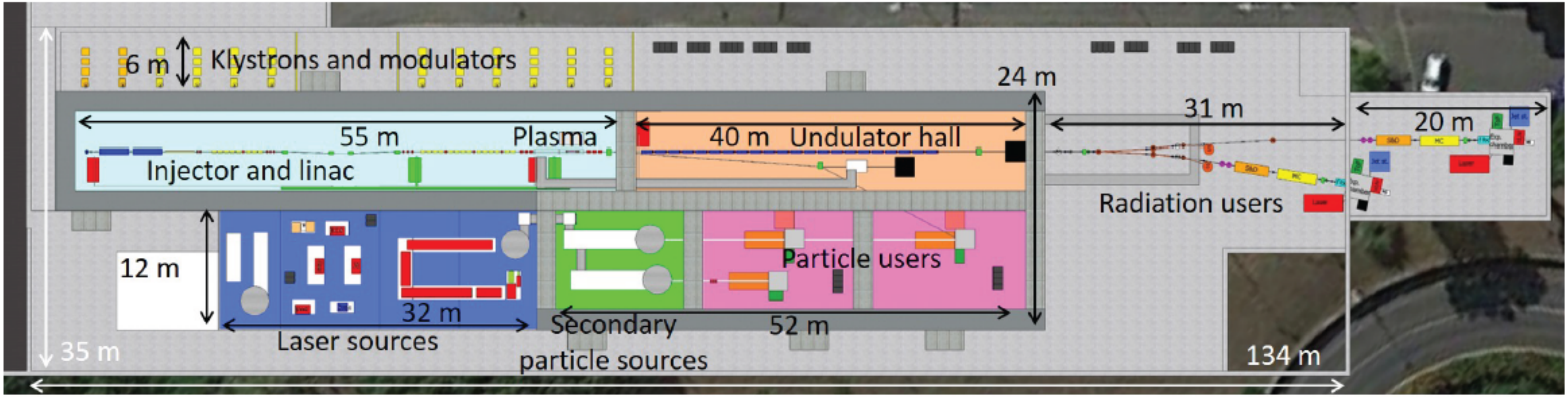


- Free-electron laser
- Gamma-ray source (inverse Compton scattering)
- GeV-class positron source
- High-energy physics detector testing stand

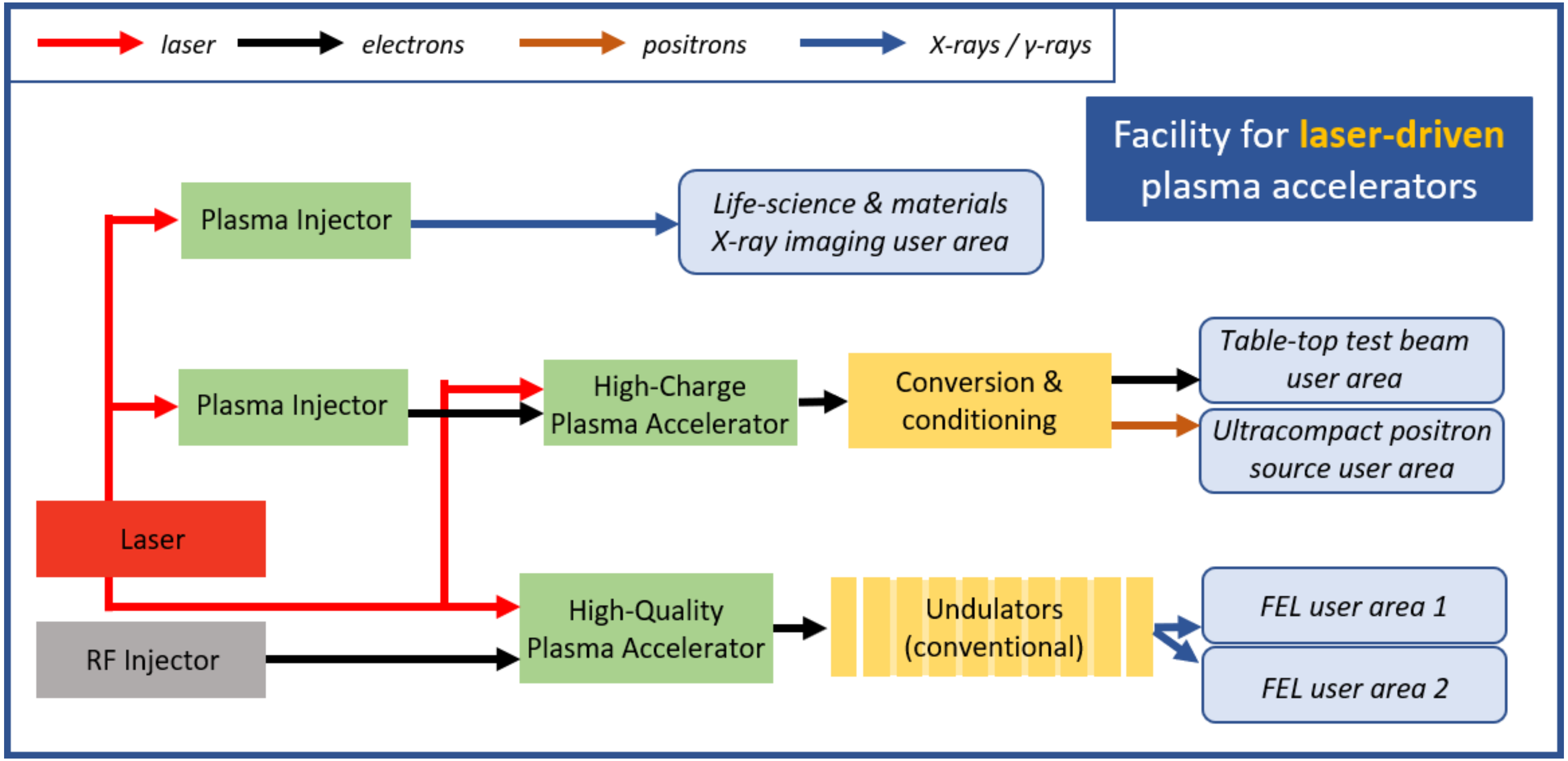
A STATE-OF-THE-ART X-BAND LINAC			
Operating frequency	Field strength	Length	Final beam energy
~12 Hz	≤ 80 MV/m	10 m	~500 MeV



Beam-Driven EuPRAXIA Site at Frascati

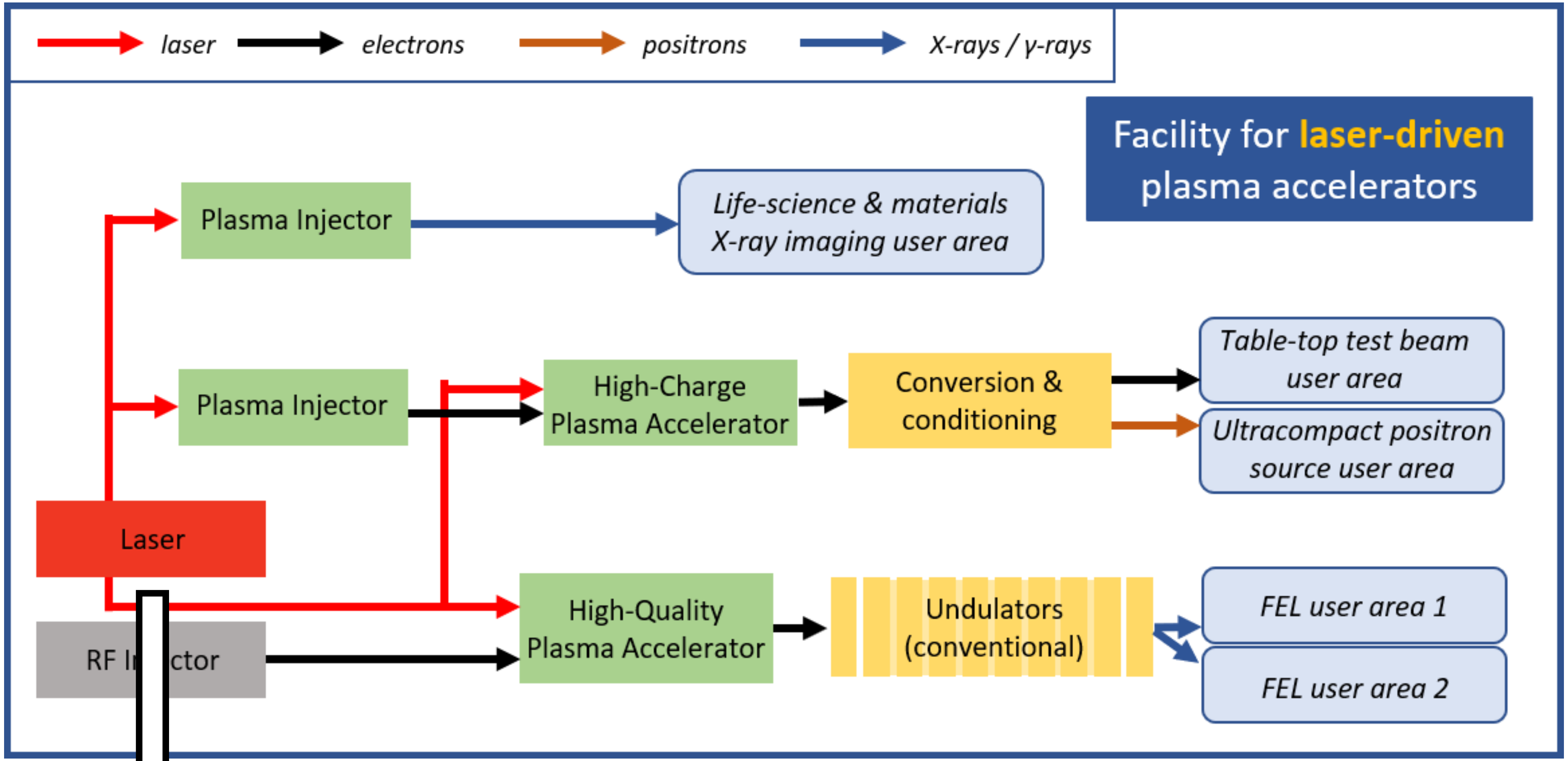


The Laser-Driven Construction Site



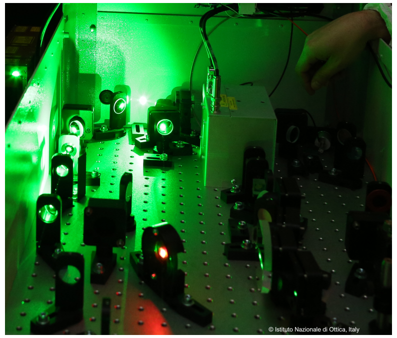
The Laser-Driven Construction Site

Horizon 2020

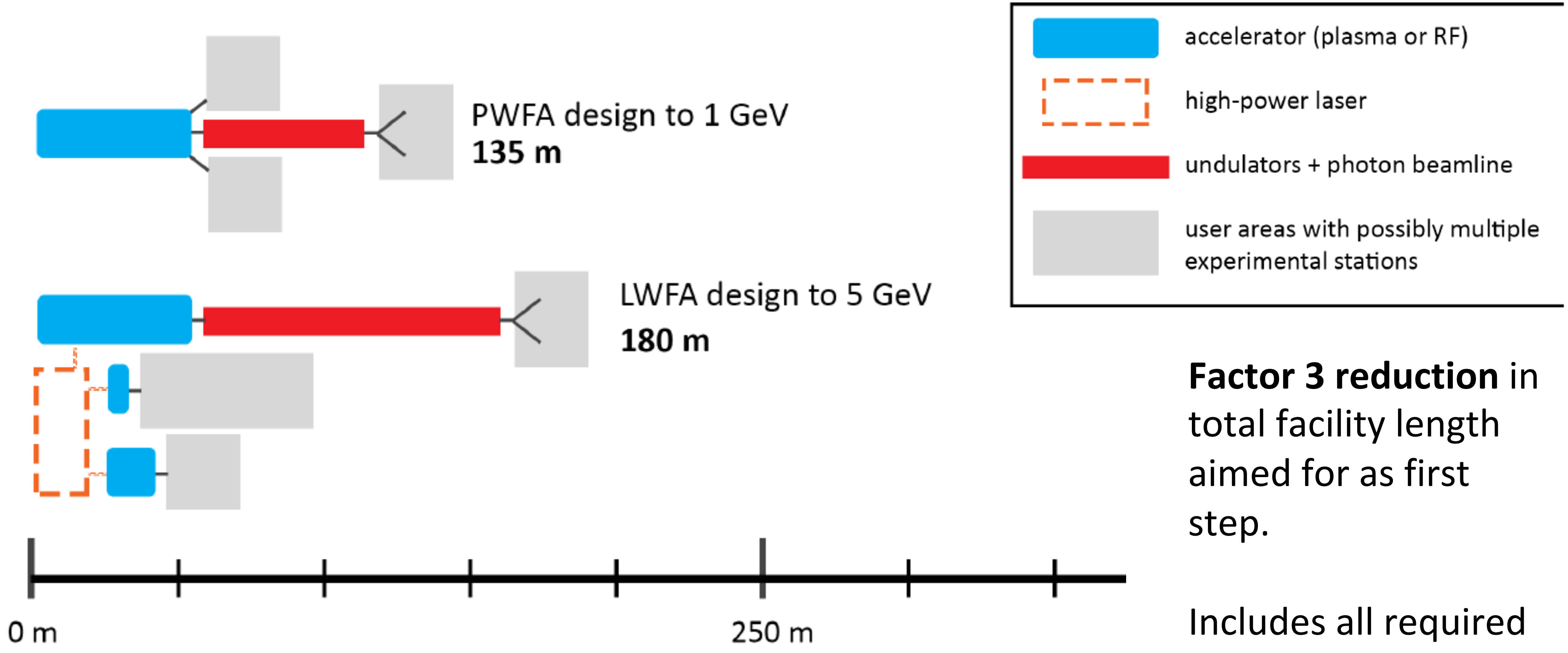


- Free-electron laser
- Life-science & materials X-ray imaging (betatron source)
- Ultracompact positron source
- Table-top test beams

THREE HIGH-POWER LASER SYSTEMS			
Wavelength	Energy on target	Pulse duration	Repetition rate
800 nm	5 – 100 J	≥ 20 – 60 fs	20 – 100 Hz



Footprint EuPRAXIA Facility



Factor 3 reduction in total facility length aimed for as first step.

Includes all required infrastructure.

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

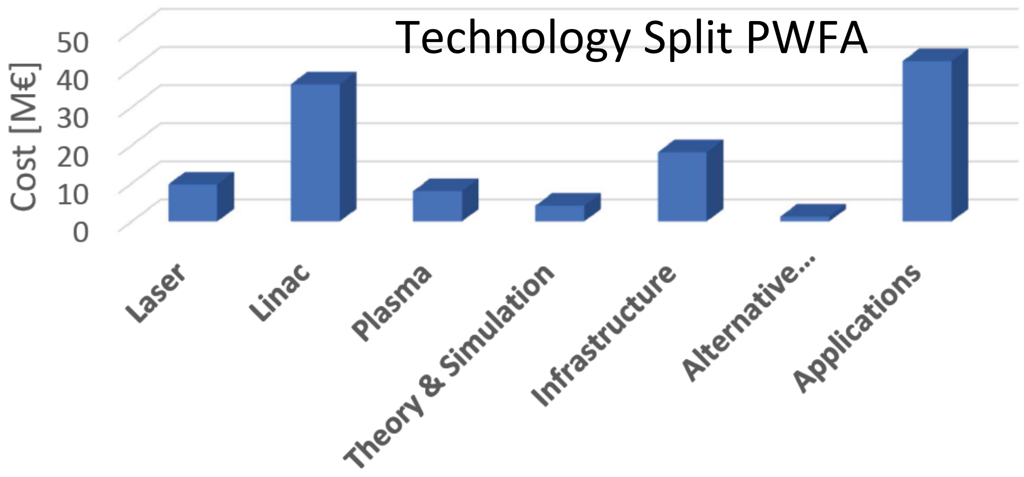
Horizon 2020

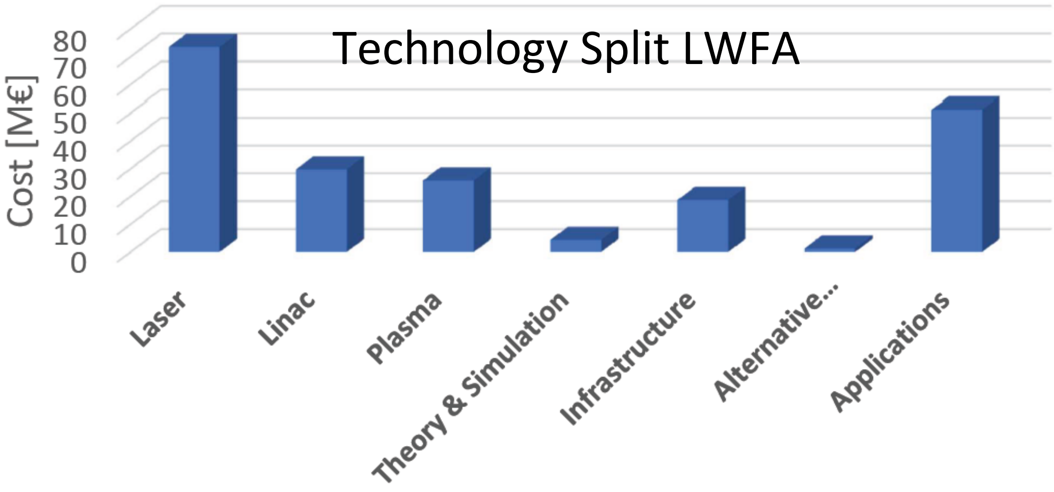
Scenario	Invest
Beam-driven plasma accelerator facility	
Full EuPRAXIA proposal	119 M€
Plasma accelerator facility with FEL	68 M€
Laser-driven plasma accelerator facility	
Full EuPRAXIA proposal	204 M€
Plasma accelerator facility with FEL	110 M€
Minimal laser plasma accelerator with FEL	75 M€

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!





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 (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:

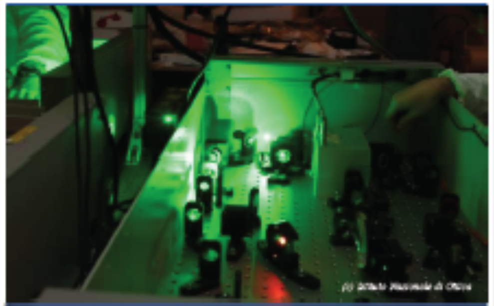
Publish CDR
Agree collaboration
Discuss with EU
Apply to ESFRI roadmap

Long-Term Scientific Program

Horizon 2020

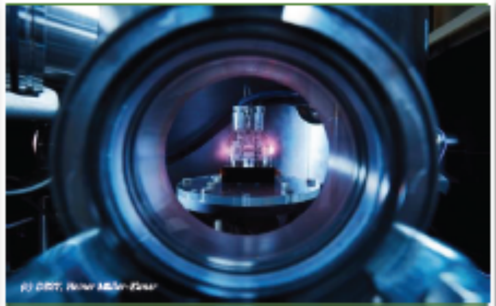
1. Reduced facility footprint

- *compact beamline components (undulators, magnets, etc.)*
- *compact diagnostics*
- *development of simplified, ultracompact prototype systems*



2. High power laser technology

- *high repetition rate*
- *high average power*
- *increased efficiency*
- *reduced footprint / cost*
- *robustness*

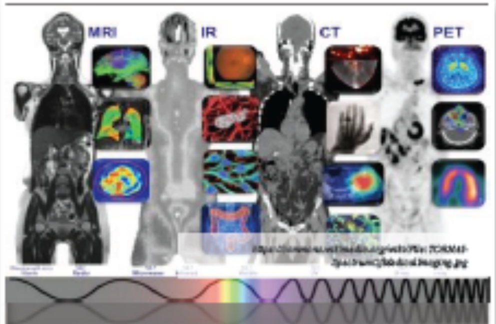


3. Accelerator technology

- *staging towards high energies*
- *advanced diagnostics*
- *hybrid plasma acceleration & other novel injection concepts*
- *beam control & quality*
- *ultrashort beams*

4. Plasma-based FEL

- *higher photon flux*
- *lower wavelength*
- *advanced undulator technologies*
- *ultrashort beams*
- *seeded FEL*



5. Method improvement for applications

- *medical imaging*
- *high-energy physics detectors*
- *material analysis (cargo scanning, structural analysis)*
- *positron generation and acceleration (plasma collider studies)*

Conclusion

- The CDR for EuPRAXIA, a **European accelerator facility based on plasma**, lasers and beam drivers, has been worked out with contributions from about 200 scientists.
  - **Technical clusters, five excellence centers and 1-2 construction sites** at existing laboratories could realize EuPRAXIA in the next 8-10 years.
  - **Hosts of excellence centers and one construction site have been identified**. Frascati would host the beam-driven plasma accelerator construction site.
  - Strong links to CERN and laser industry have been defined.
- EuPRAXIA can produce higher **quality beams for various applications.** Several parameters have advantages (short pulse length, short emission length, ...). In a survey we found strong interest for the facility.
- About **323 M€ invest would be needed over the next 8-10 years** to prepare the implementation, refine resource plans, perform the technical design, define implementation and to construct the facility.
- EuPRAXIA is a **new high-tech option for the European research infrastructure landscape**, connecting to cutting-edge science, innovation, European industry and international partners!

Consortium

16 Participants

25 Associated Partners

(as of December 2018)