European
Plasma Research
Accelerator with
eXcellence In
Applications

Science Applications for the European Accelerator Research Infrastructure EuPRAXIA

Maria Weikum, P.A. Walker, R.W. Assmann, J. Clarke, M.-E. Couprie, M. Ferrario, F. Nguyen, C.D. Murphy, Z. Najmudin, G. Sarri, A. Specka, M.J.V. Streeter, R. Walczak

Special thanks to the EuPRAXIA Collaboration

EAAC 2019, Sep 15 – 20 2019 Elba, Italy

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

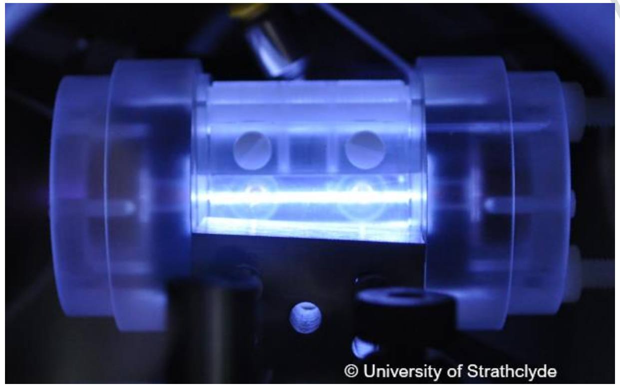
EuPRAXIA Consortium

- 41 partner institutions
- >200 contributors
- 4 years of work

Possible Applications of Plasma Accelerators

Making existing applications more compact / better

- Material imaging & analysis
- Active interrogation
- Material processing
- Nuclear physics
- Photon science (crystallography, ultrafast imaging, spectroscopy, etc.)
- Radioisotope production
- Medical imaging
- etc.
- High-energy physics (high-field physics, colliders)



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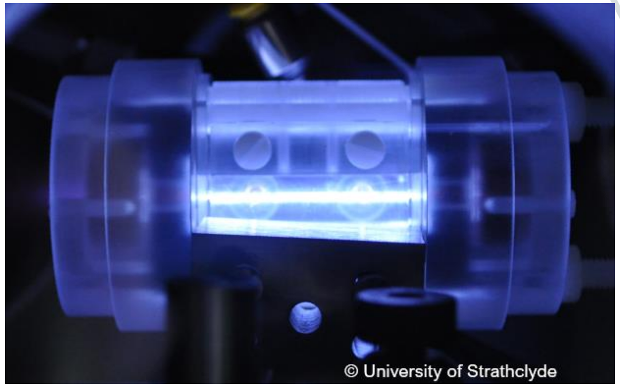


Making new applications

- Free-Electron Lasers in universities?
- Compact particle colliders?
- Mobile accelerator-based analysis units?
- Miniature particle / radiation sources for medicine?
- ?

The EuPRAXIA Project

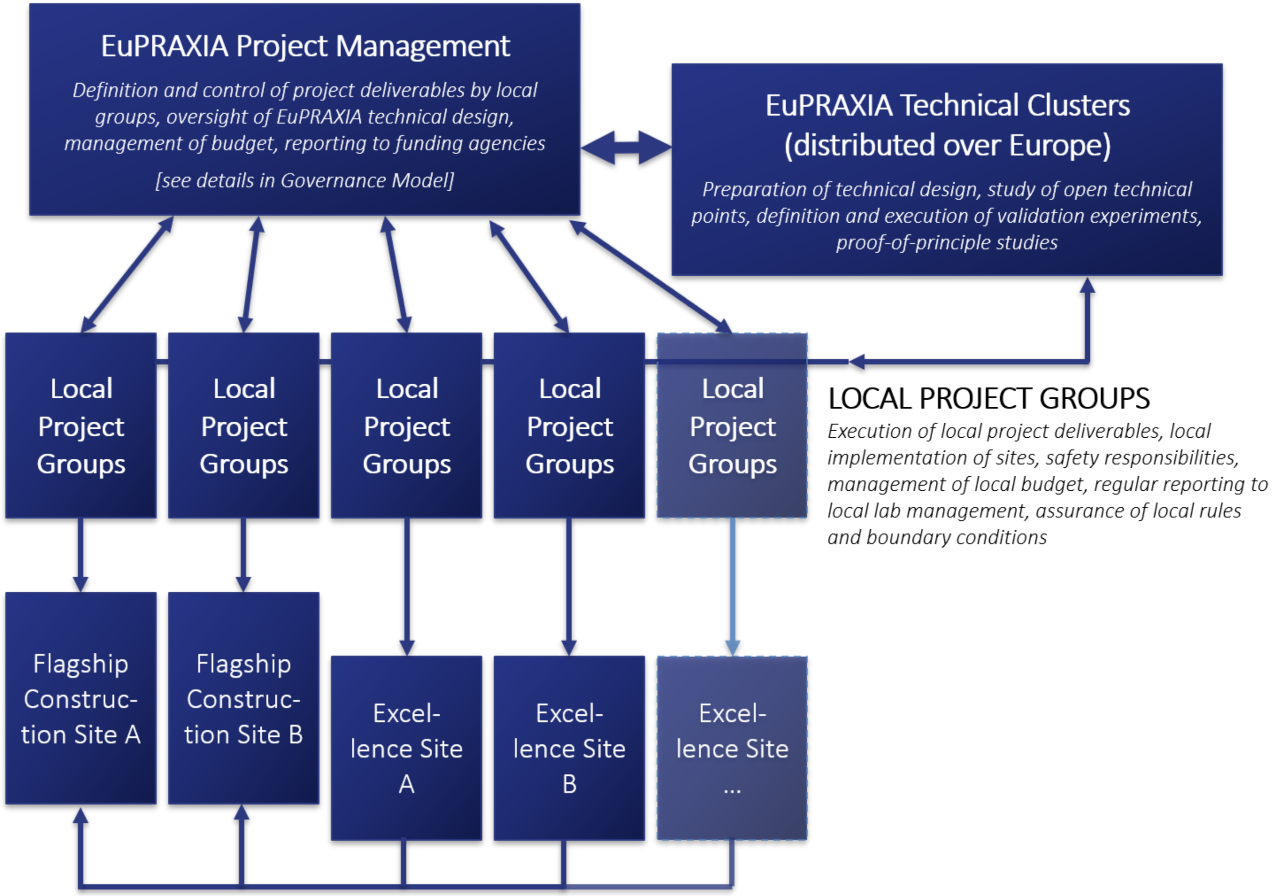
EuPRAXIA = European Plasma Accelerator with eXcellence In Applications

EuPRAXIA is a Horizon2020-funded conceptual design study for a 5 GeV electron plasma accelerator with high beam quality

- **Objectives**:

1. Show plasma accelerator technology can achieve high quality beams (usable).
2. Show benefit in size and cost versus conventional accelerator technology.

A distributed infrastructure proposing facilities for
- **Beam-driven plasma acceleration**
- **Laser-driven plasma acceleration**



Horizon 2020

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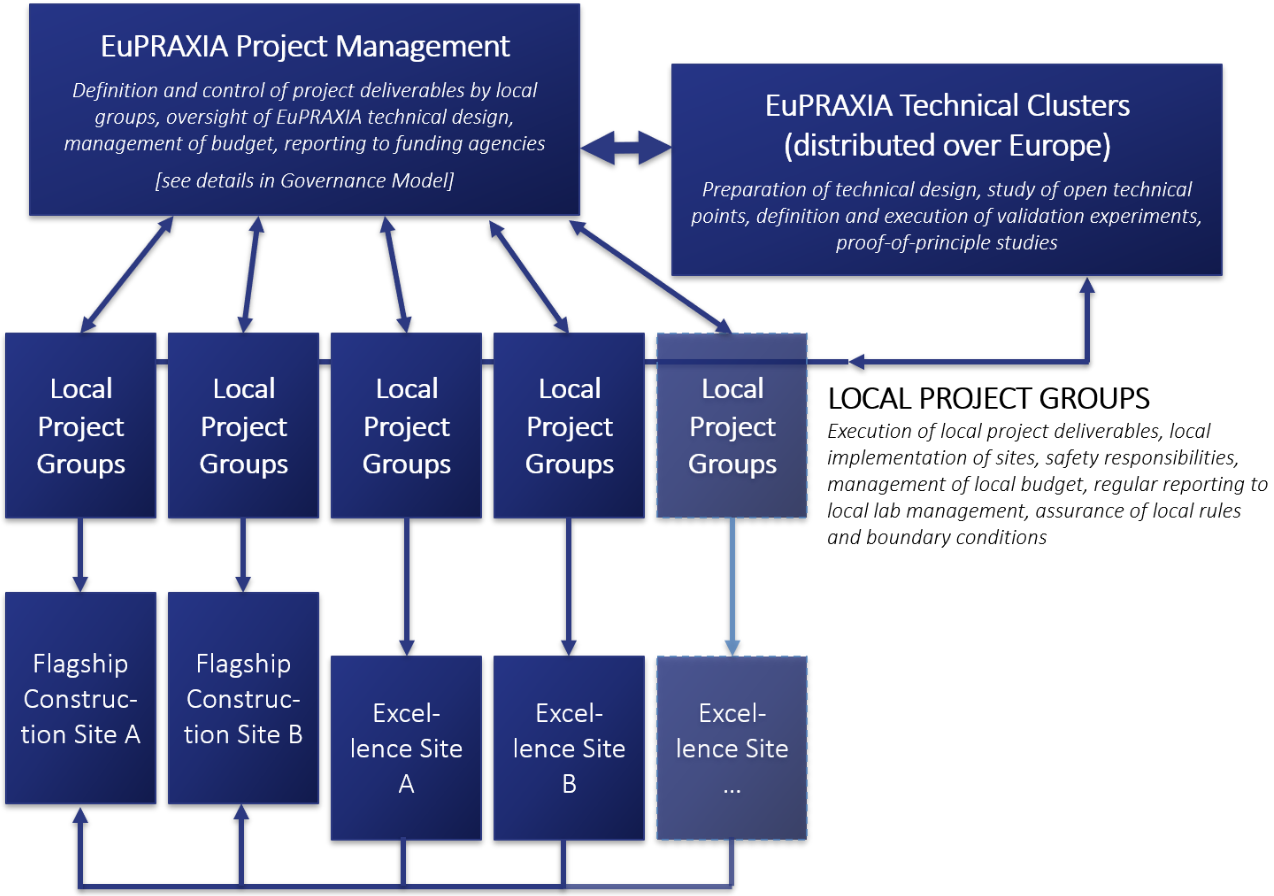

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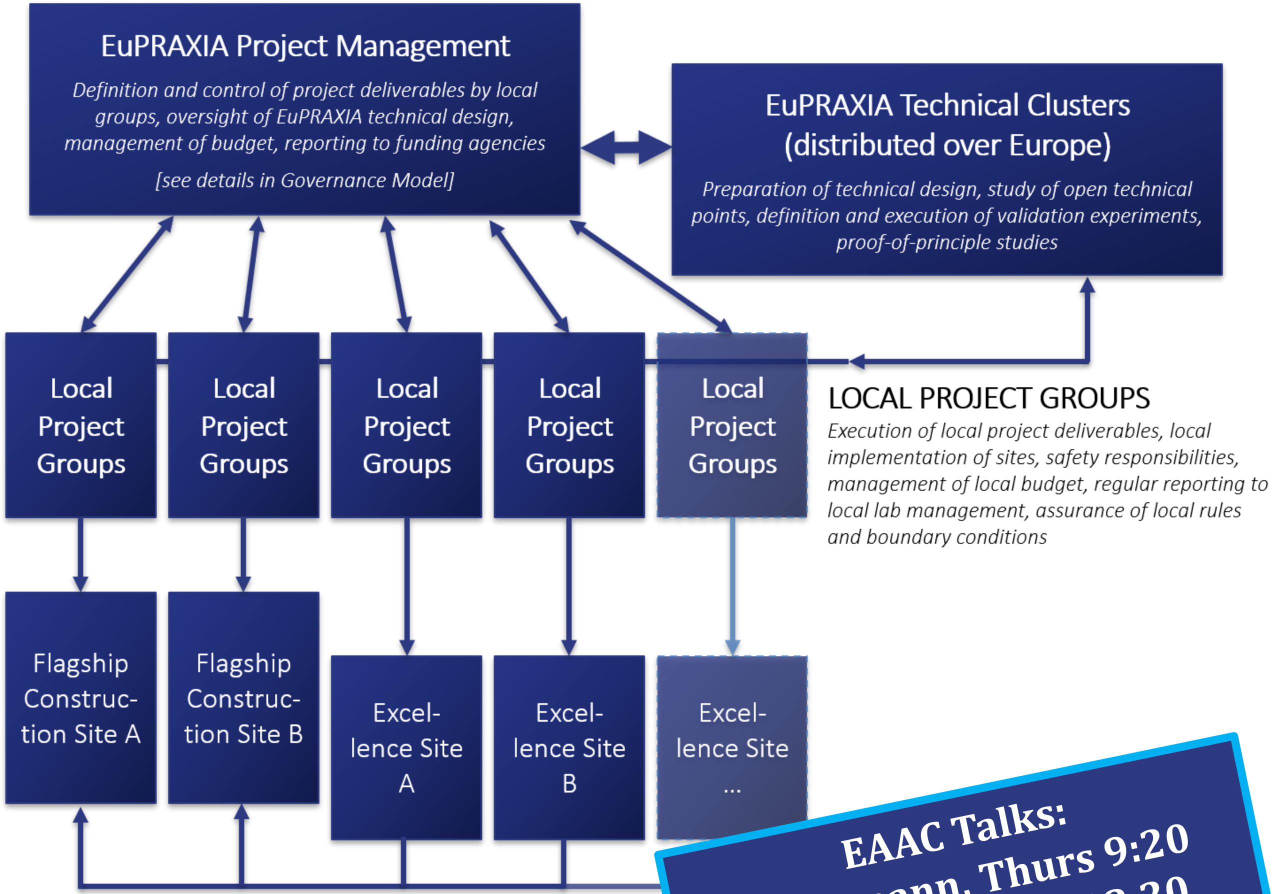
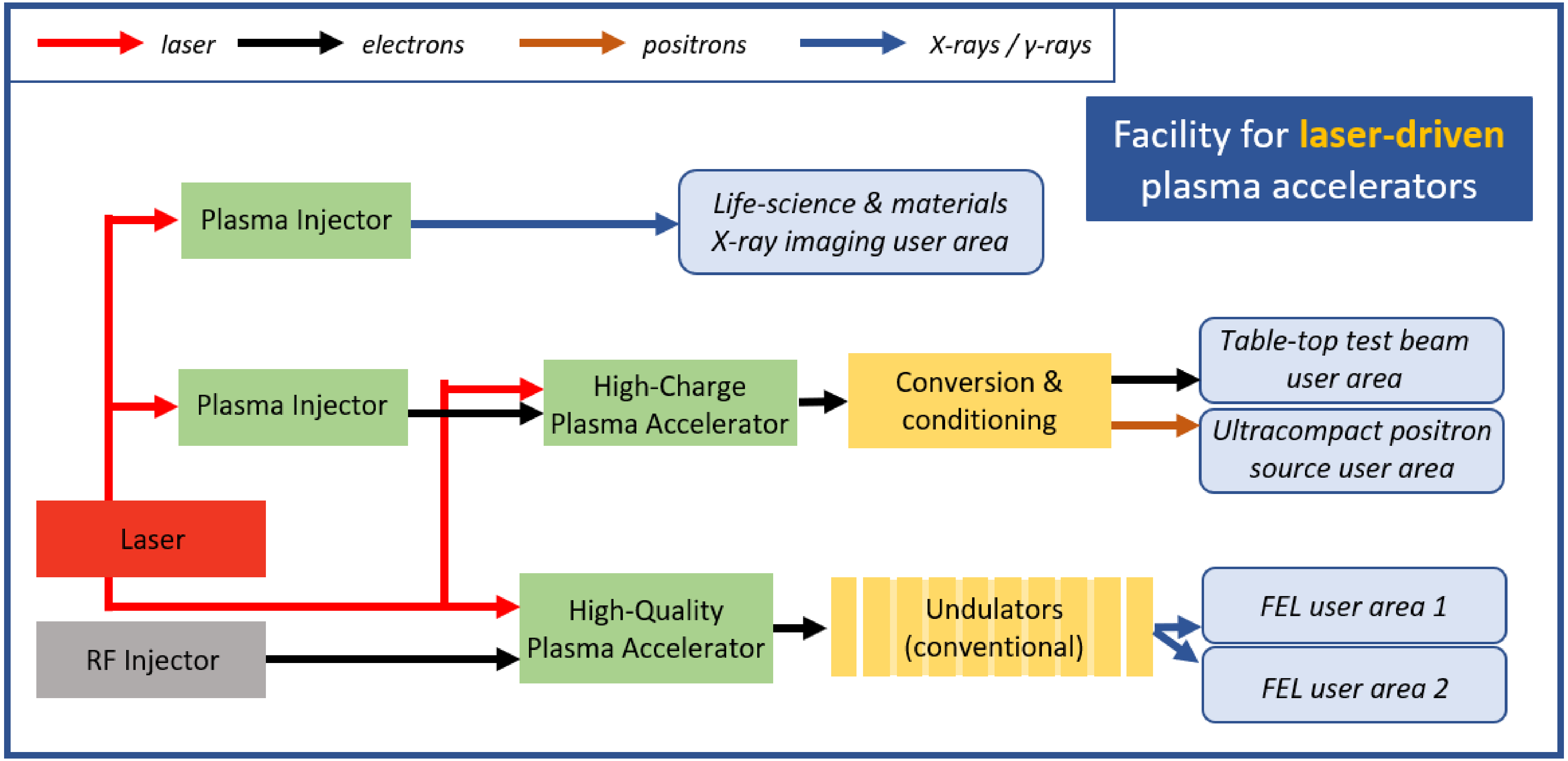


EAAC Talks:
R. Assmann, Thurs 9:20
R. Walzcak, Wed 18:20

The Laser-Driven Site



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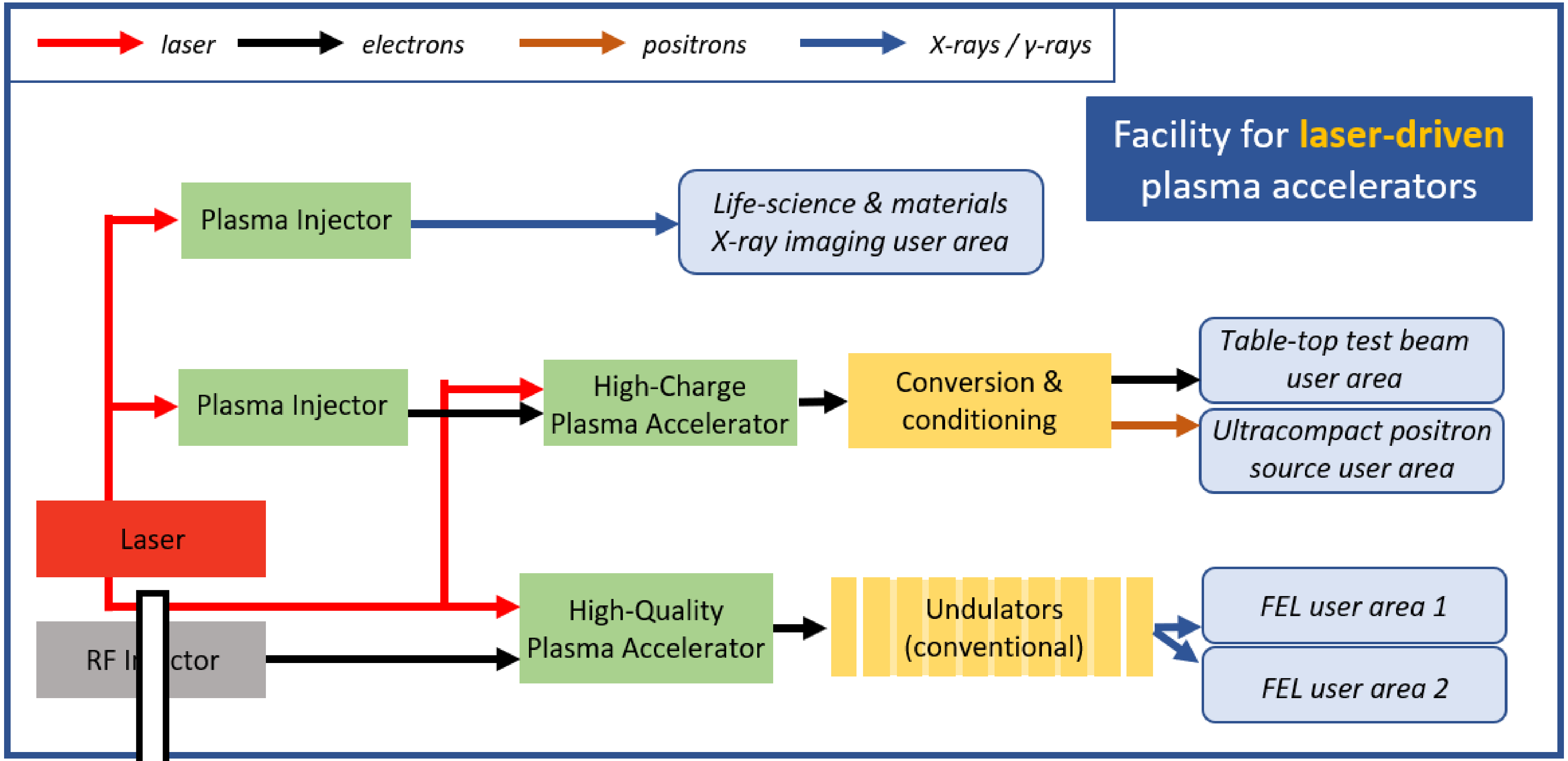
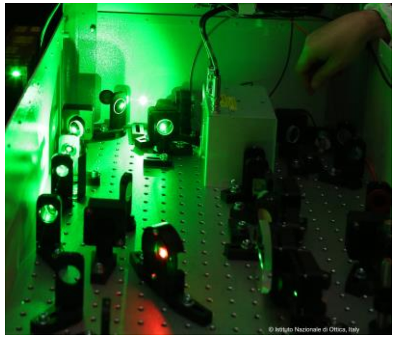


- Free-electron laser
- Life-science & materials X-ray imaging (betatron source)
- Ultracompact positron source
- Table-top test beams

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



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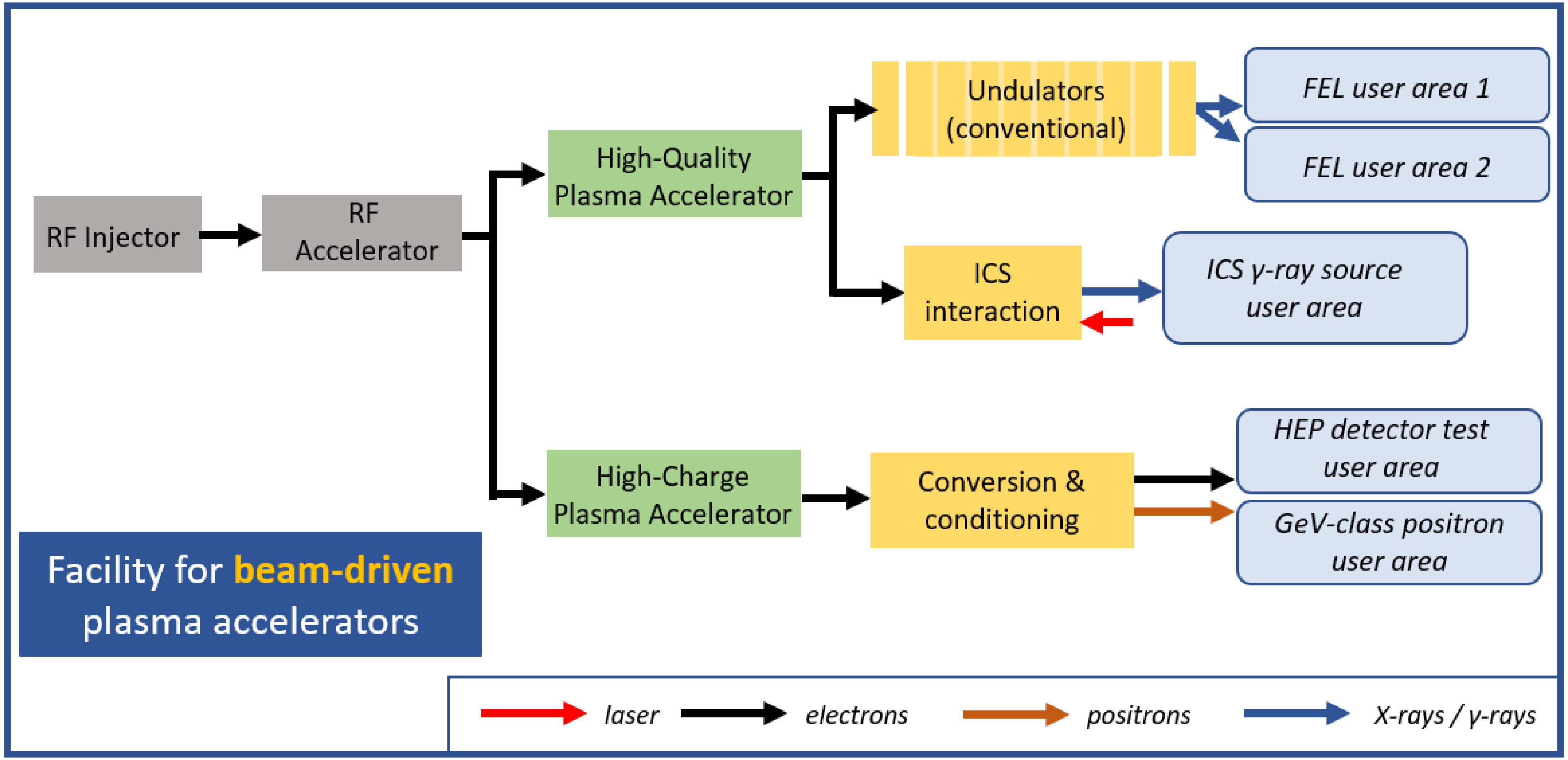

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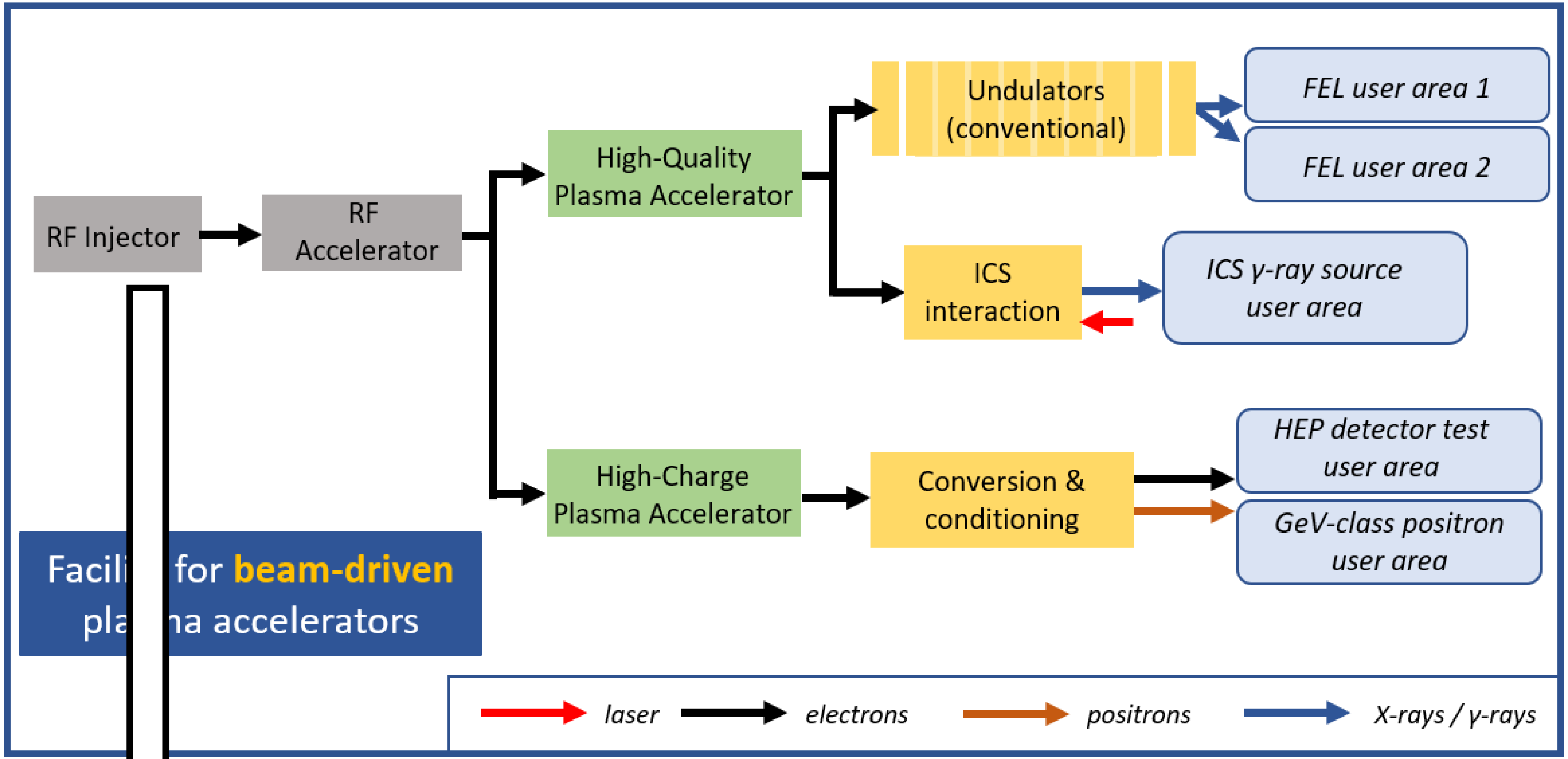


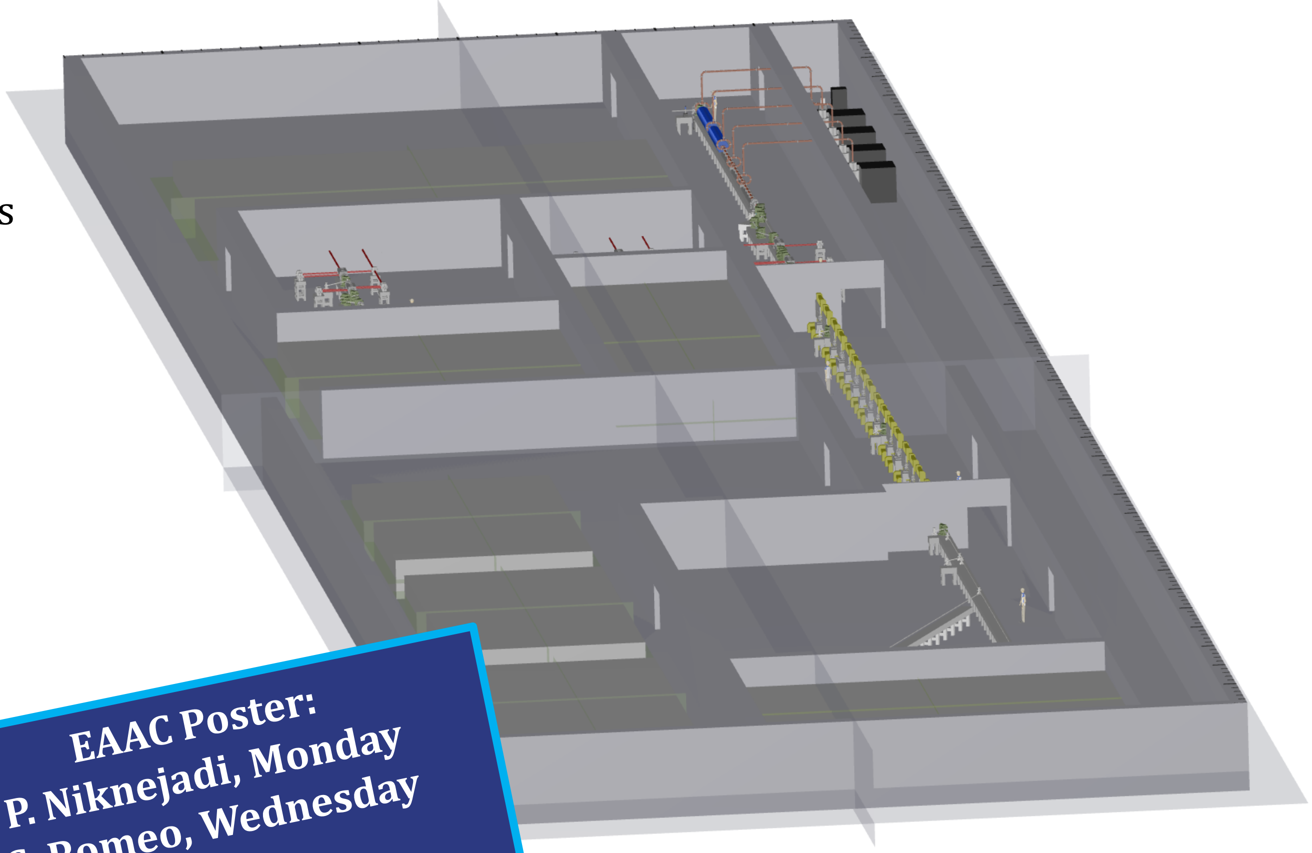
- Free-electron laser
- Gamma-ray source (inverse Compton scattering)
- GeV-class positron source
- High-energy physics detector testing stand

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

Expected Performance

EuPRAXIA has developed several complementary solutions.

Example: A multi-stage LWFA scheme with external injection from an RF injector (240 MeV) and two plasma accelerator stages *[A. Ferran Pousa et al. Phys. Rev. Lett. 123, 054801 (2019)]*



Energy	[GeV]	5.9
Charge	[pC]	22
Bunch length	[fs]	3.5
Energy spread	[%]	0.32
Transv. norm. emittance	[mm mrad]	0.6 / 1.6
Slice energy spread	[%]	0.06
Slice emittance	[mm mrad]	0.4 / 0.7

(based on start-to-end simulations of the accelerator)

EAAC Poster:
P. Niknejadi, Monday
S. Romeo, Wednesday

EAAC Talks:
A. Ferran Pousa, Wed 16:20
A. Rossi, Wed 18:20

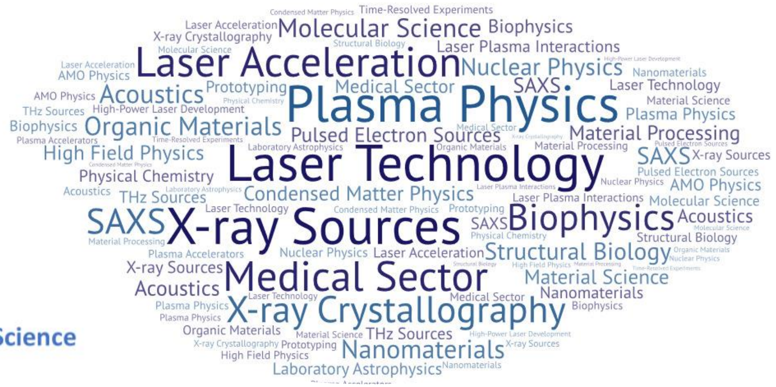
A Demonstration Facility

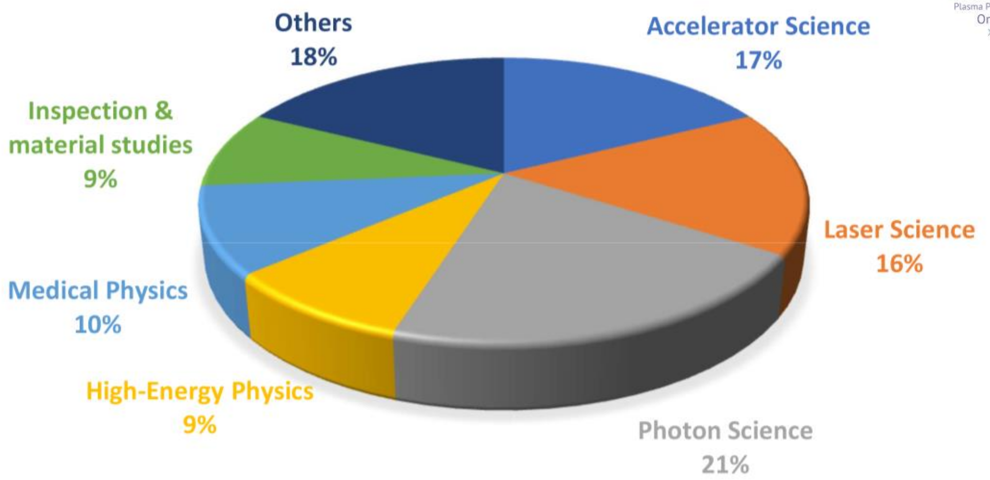
- EuPRAXIA is a demonstration facility: demonstrate the high quality beams required for possible applications
- Scientific applications open the door to first pilot users after demonstration goals have been achieved
- Three user groups:
  - Co-development → accelerator, laser, … specialists (our community)
  - Training → aspiring experts (grow our community)
  - Scientists interested in applications → pilot users
- EuPRAXIA is not a traditional user facility, but a step towards it

Finding Relevant Applications

Based on community interest

- Preliminary survey + workshops





PAEPA Workshop, Oct 2016, Palaiseau (France)

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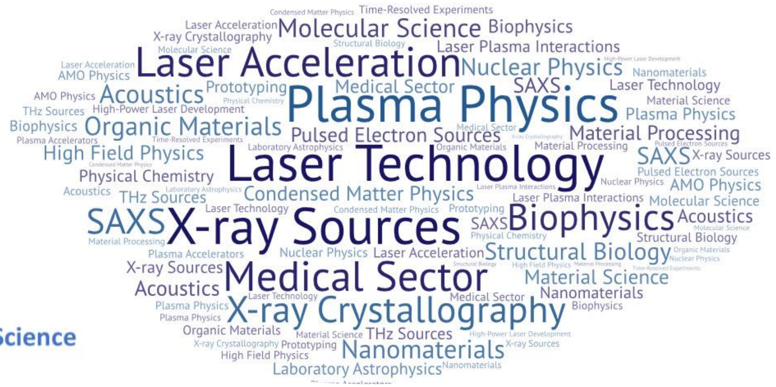
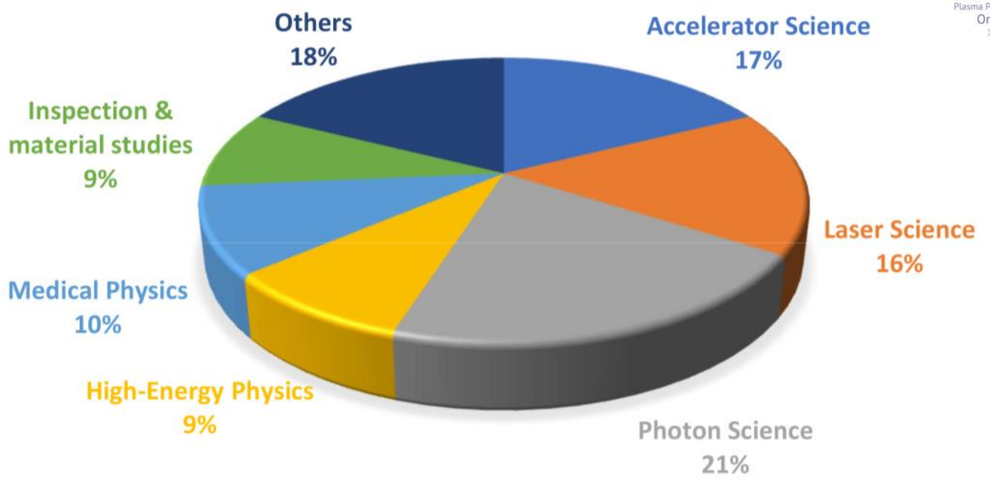


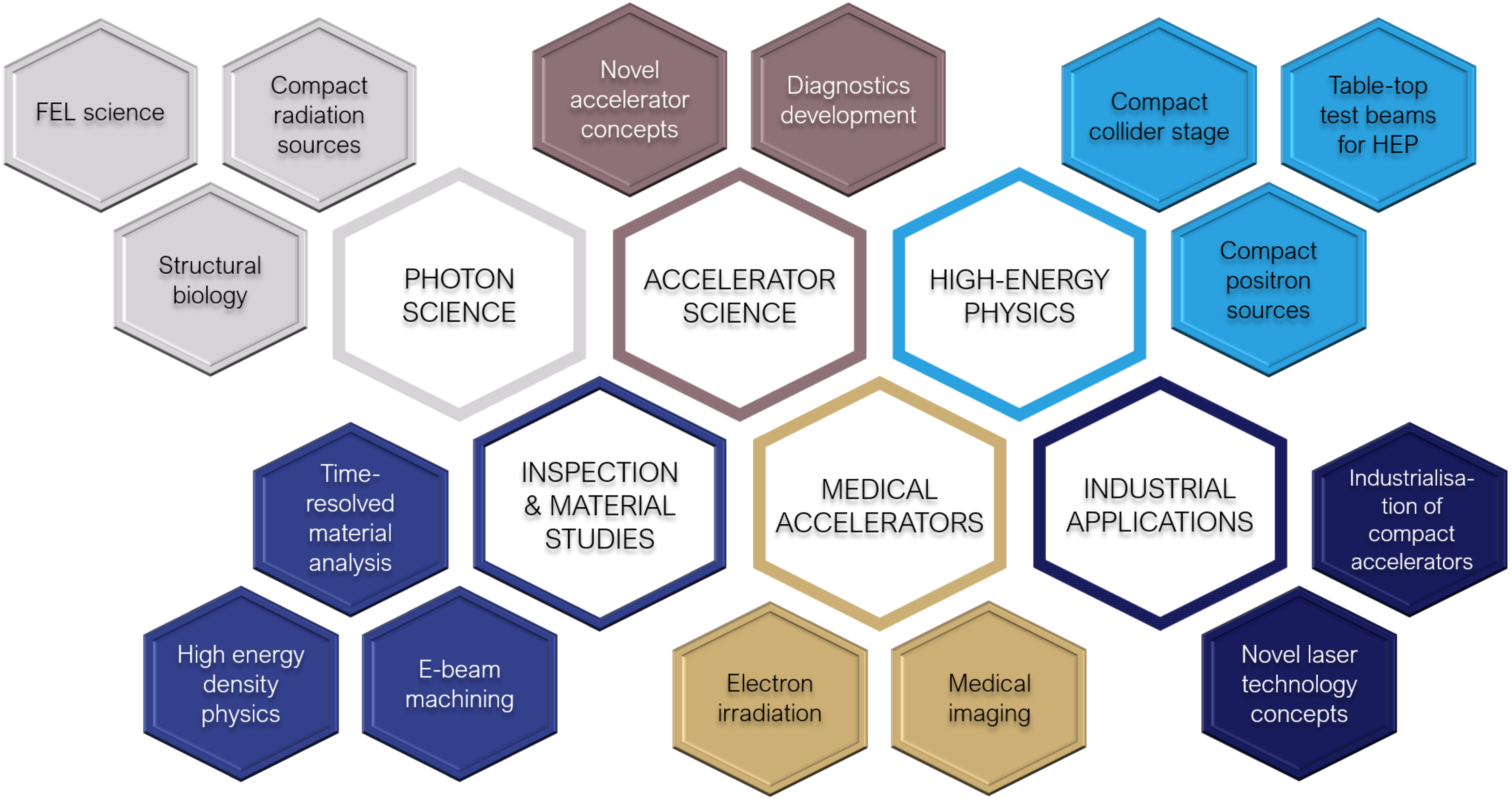


PAEPA Workshop, Oct 2016, Palaiseau (France)

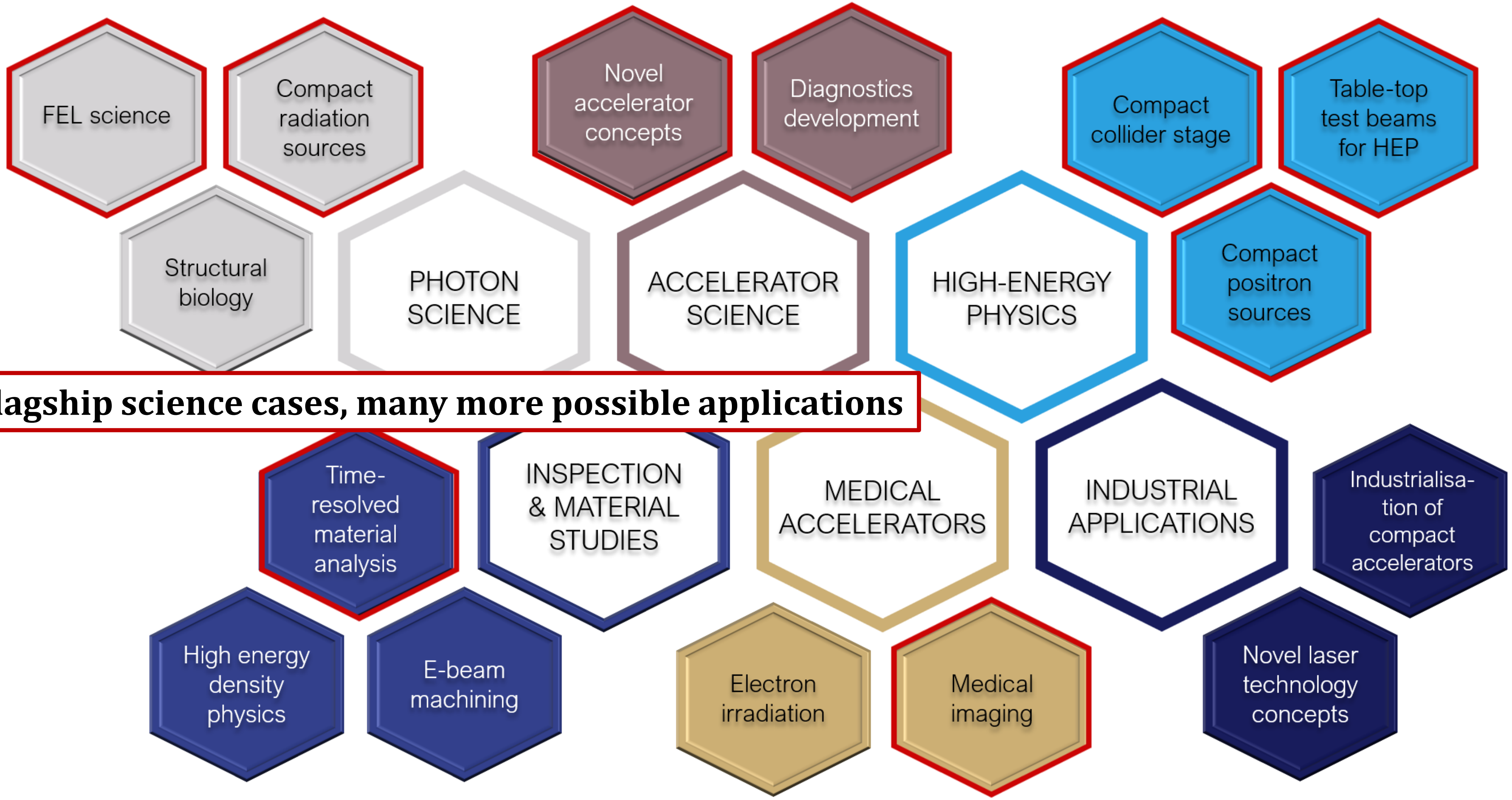
Based on project strategy

- Variation in complexity and beam quality requirements
  → Risk mitigation
- Emphasis on strengths of laser-driven / beam-driven plasma acceleration techniques
- Emphasis on clear benefits of plasma acceleration

A Choice of Flagship Applications

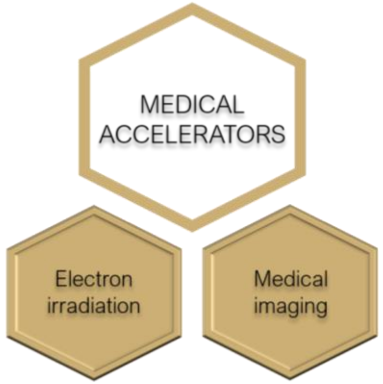


A Choice of Flagship Applications

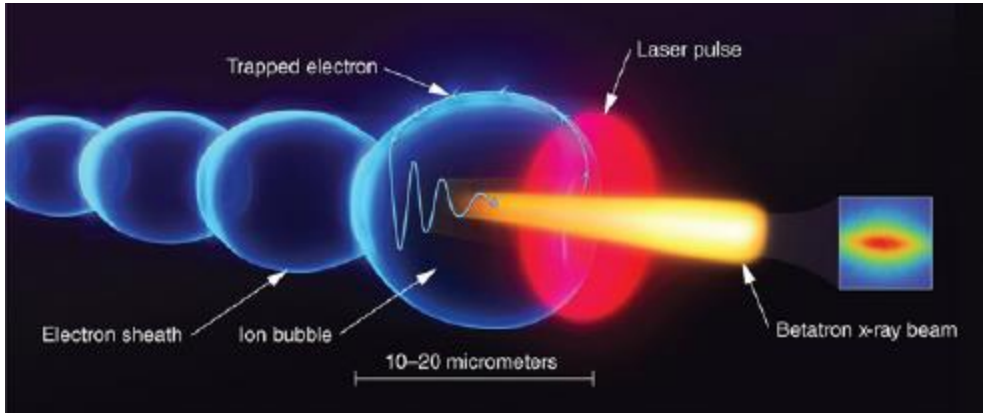


Flagship science cases, many more possible applications

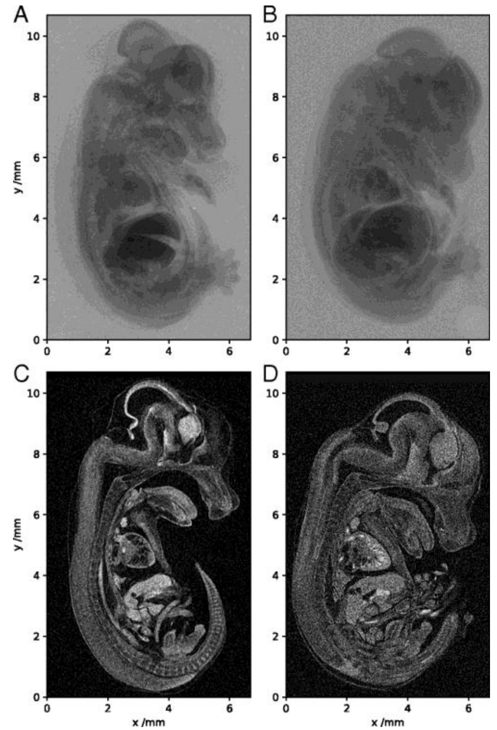
Flagship Application 1: A Compact X-Ray Source



EuPRAXIA WP 7
Z. Najmudin et al.



[Albert et al. Plasma Phys. Control. Fusion. 56 (8): 084015 (2014)]



[Cole et al. PNAS. 115 (25): 6335-6340 (2018)]

Betatron source	
Radiation wavelength	0.6 – 110 keV
Photons per pulse	$2x10^{8} – 4x10^{10}$
Brightness	$2x10^{21} – 1x10^{26}$ [*]

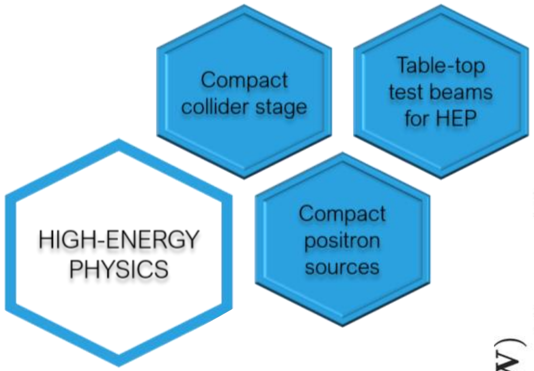
* = $[\text{mm mrad s (0.1\% BW)}]^{-1}$

TODAY
- ✓ Commercial X-ray tubes with low photon count / resolution
- ✓ Low-rep rate betatron experiments

EuPRAXIA
- ➢ High-rep rate betatron source operation
- ➢ Testing of in-vivo / biological samples
- ➢ Development of highly optimised setups

FUTURE
- ❑ Application in hospitals / medical centres

Flagship Application 2: A GeV-Scale Positron Source

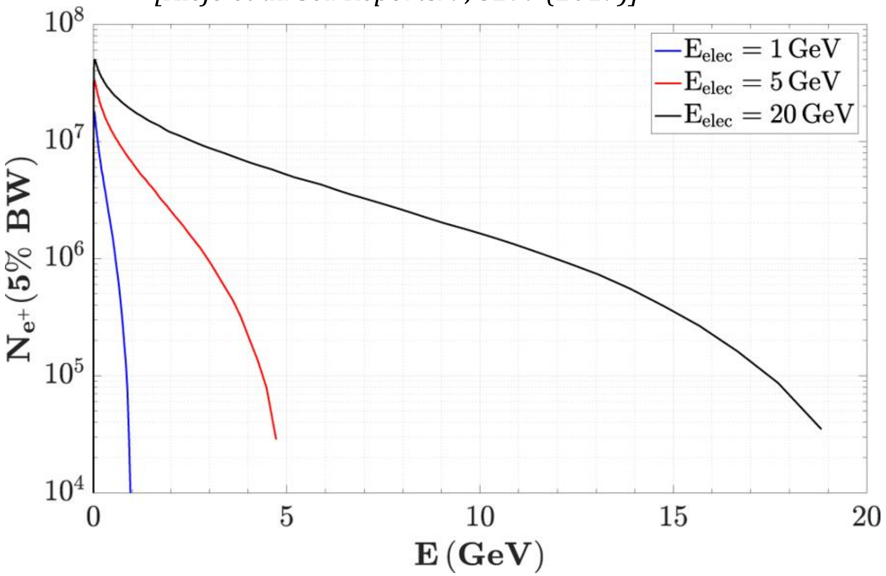


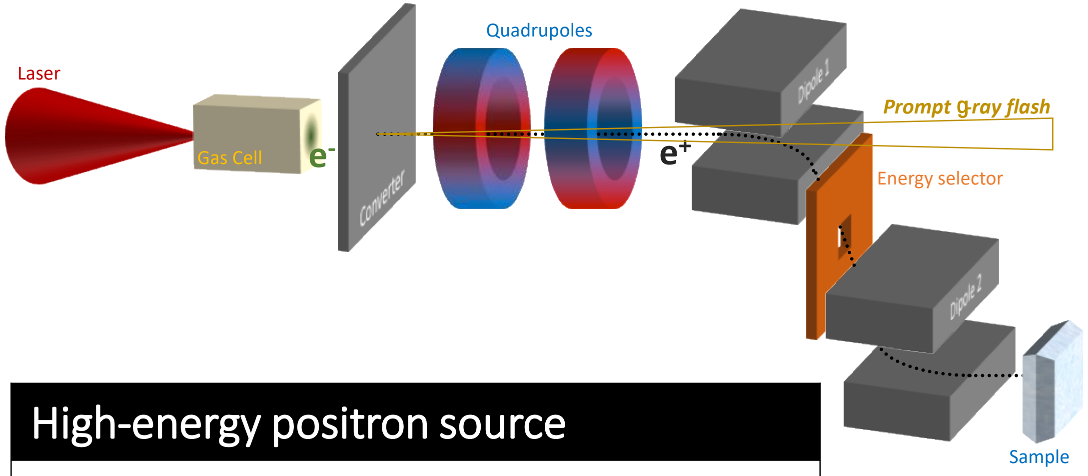
EuPRAXIA WP 7
G. Sarri et al.

[image courtesy G. Sarri, J. Clarke]

G. Sarri et al. Nat Commun. (2015) ***6****:6747.*
G. Sarri et al. Plasma Phys Control Fusion. (2016) ***59****:014015.*

[Alejo et al. Sci. Reports. 9, 5279 (2019)]





High-energy positron source	
Energy	≥ 1GeV
Beam duration	≤ 10 fs
Positrons per shot	~10^7

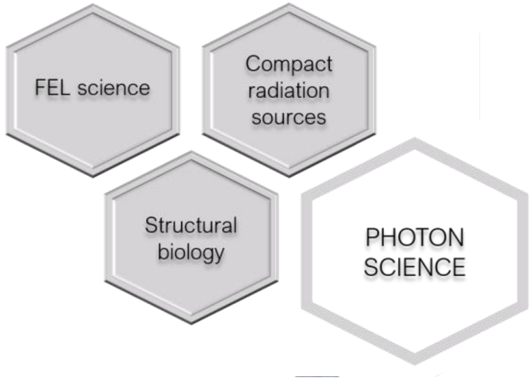
TODAY
- ✓ Very few high-energy positron sources for collider R&D

EuPRAXIA
- ➢ 100Hz, GeV plasma-based positron beams for acceleration / transport experiments
- ➢ Ultrashort positron pulse durations

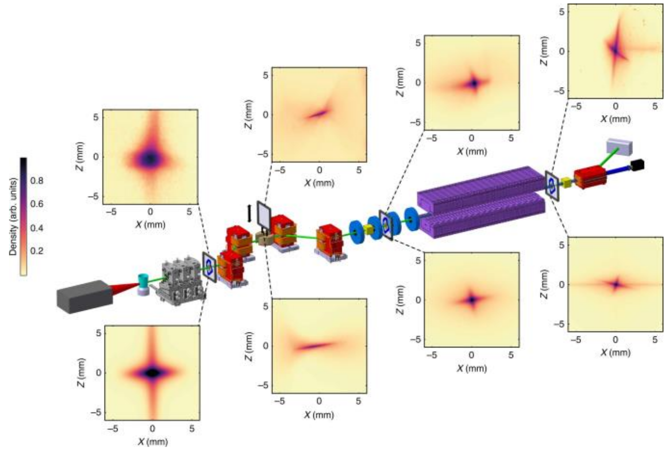
FUTURE
- ❑ Compact future e- - e+ collider

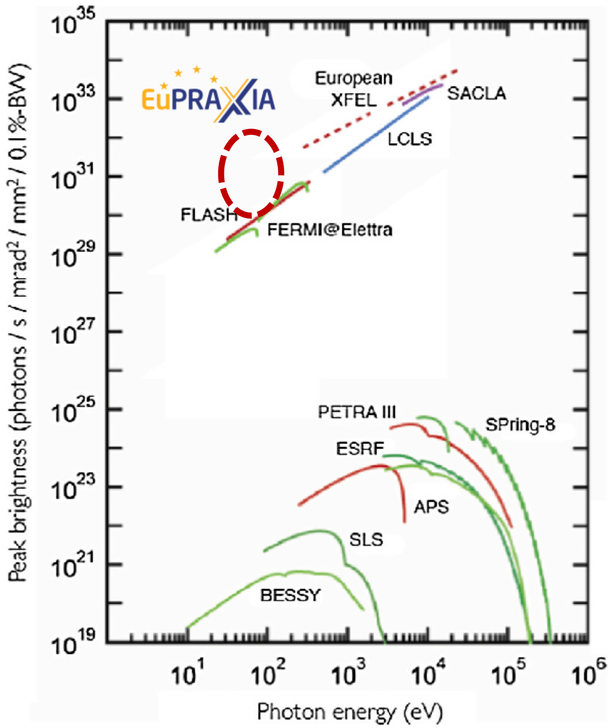
Flagship Application 3: A Free-Electron Laser

Horizon 2020



[T. Andre et al., Nat. Commun. 2018, 9, 1334]





EuPRAXIA WP 6
M.-E. Couprie, F. Nguyen et al.

Ultrashort FEL radiation pulses	
Radiation wavelength	0.2 – 36.3 nm
Photons per pulse	$2\times10^{9} – 3\times10^{13}$
Brightness	$2\times10^{30} – 6\times10^{32}$ [*]

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

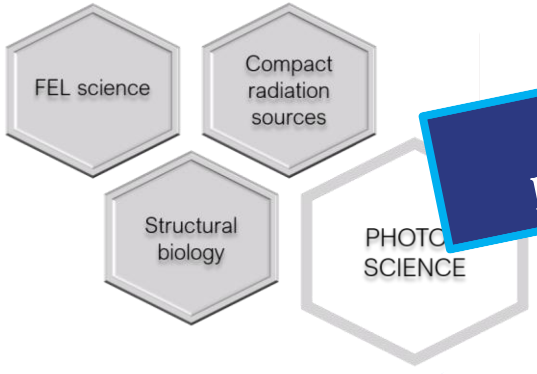
[A. Nilsson et al., Chem. Phys. Letters 2017, 675]

TODAY
- ✓ Large-scale operation of RF-based FELs
- ✓ Plasma-based test experiments in progress

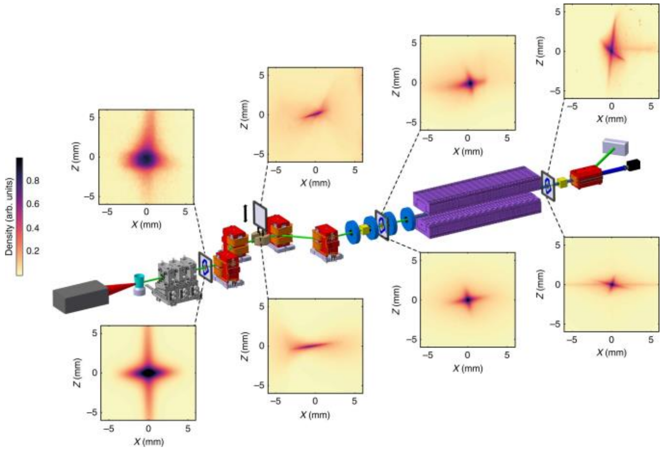
EuPRAXIA
- ➢ First demonstration of a multi-GeV plasma-based FEL
- ➢ Pilot user experiments
- ➢ Footprint reduction by factor 3 and more

FUTURE
- ❑ Application of compact, “cheap” FELs in hospitals, uni-versity labs, etc.

Flagship Application 3: A Free-Electron Laser



EAAC Poster: F. Villa, Monday



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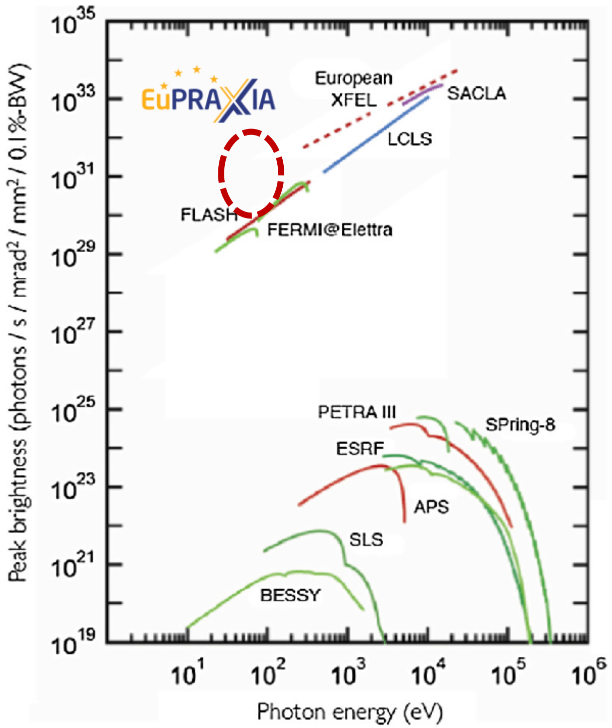

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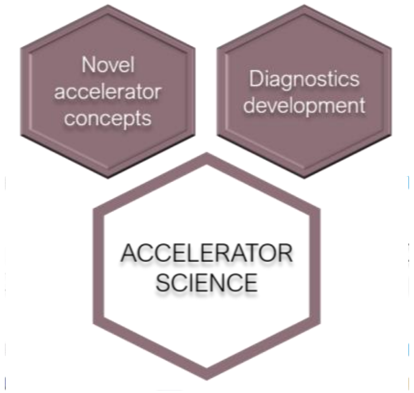
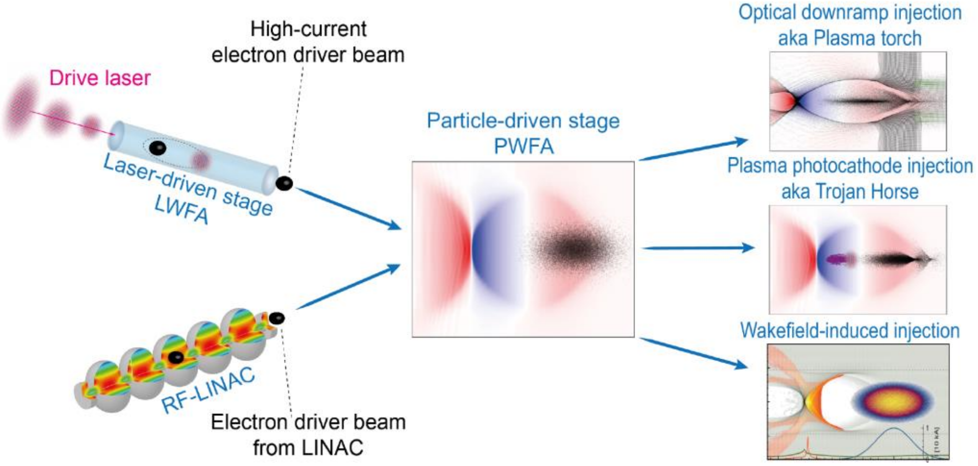
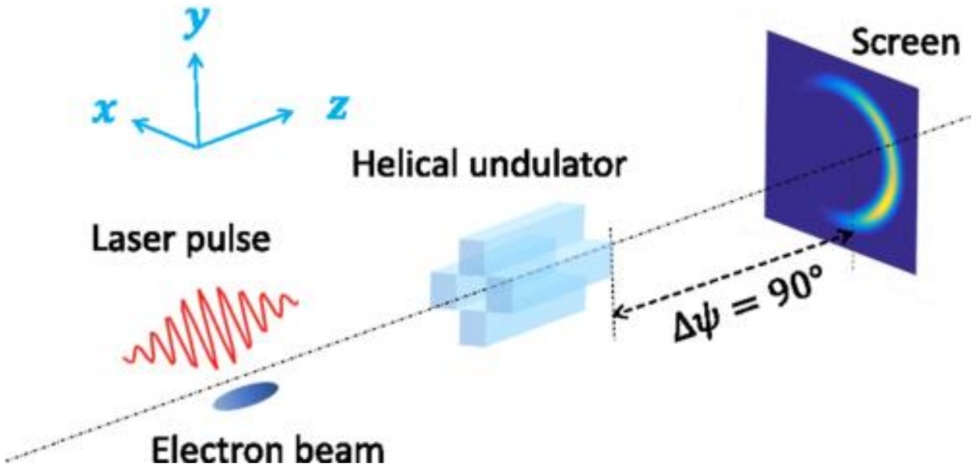
Flagship Application 4: Accelerator R&D Test Beams





[B. Hidding et al., Appl. Sci. **2019**, 9, 2626]

[Z. Zhang et al. Phys. Rev. Accel. Beam **2017**, 20, 050702]



- Multi-GeV, fs-scale, high quality electron beams
- Multiple plasma accelerator setups (external injection, internal injection, staging, etc.)
- 20 – 100 Hz repetition rate

→ **Diagnostics testing, R&D on plasma acc. concepts / techniques, etc.**

TODAY

✓ Short-term plasma acc. experiments at laser facilities

✓ Few accelerator test facilities for ultrashort beams / high energies / ...

EuPRAXIA

➢ Several dedicated plasma acceleration beamlines

➢ Femtosecond-scale test beams at GeV energy

FUTURE

❑ Facilities based on next generation accelerator technology

EuPRAXIA's Role in Europe

- Variety of laser, accelerator and photon science facilities already existing
- National programs with similar goals and science directions

etc.

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→ **Complementary developments with EuPRAXIA**

SCAPA

CALA

CLF central laser facility

FF▸▸

Cilex Apollon

etc.

EuPRAXIA's Role of Europe

- Variety of laser, accelerator and photon science facilities already existing
- National programs with similar goals and science directions

→ **Complementary developments with EuPRAXIA**

SCAPA, CALA, CLF central laser facility, FF▸▸, Cilex Apollon etc.

+ increase overall "user" capacity

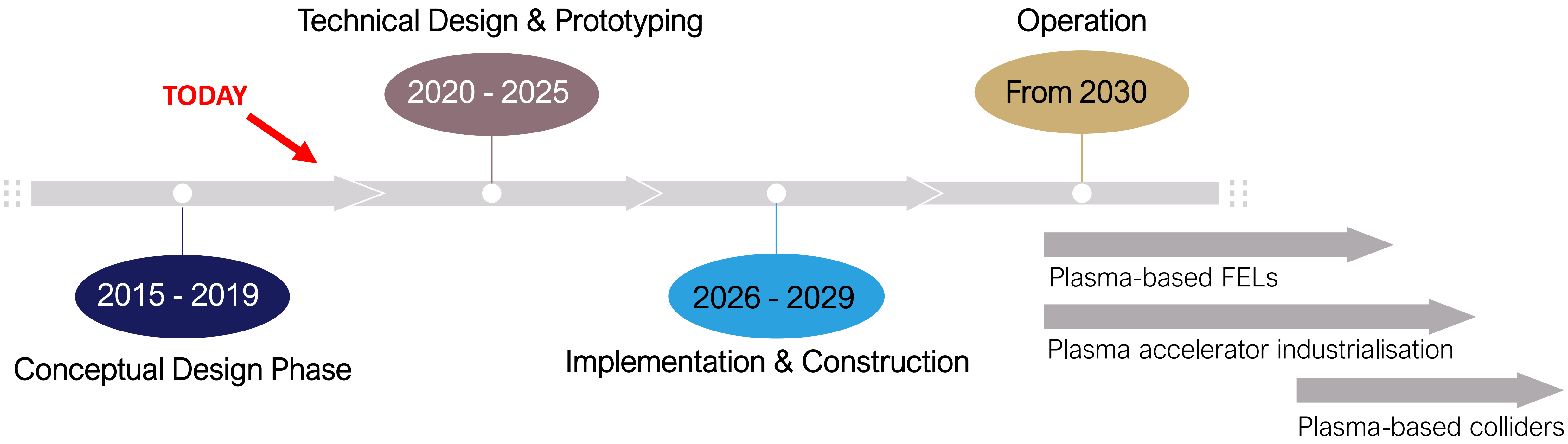
+ increase impact and synergy from international collaboration

+ unique facility dedicated to plasma accelerator technology, demonstrating scalability and pushing miniaturisation of accelerator-based machines

+ necessary intermediate step between proof-of-principle experiments and future routine facilities

Next Steps

- Submission of **<u>Conceptual Design Report in Oct 2019</u>**
- Application to ESFRI Roadmap 2021?
- Completion of facility in 10 year timeframe, *subject to funding*



Conclusions

- EuPRAXIA = **E**uropean **P**lasma **R**esearch **A**ccelerator with E**X**cellence **I**n **A**pplications
- One-of-a-kind test facility based on plasma accelerator technology with varied applications
- An intermediary step to new, advanced applications for plasma accelerators

Thank you for your attention!
Any questions / comments / ideas?

Many thanks to the EuPRAXIA Consortium!

Horizon 2020

Especially: *- Work Package 6 on the Free-Electron Laser Pilot Application: M.-E. Couprie, F. Nguyen, et al.*
- Work Package 7 on High-Energy Physics & Other Pilot Applications: J. Clarke, C.D. Murphy, Z. Najmudin, G. Sarri, A. Specka, M.J.V. Streeter, R. Walczak, et al.

16 Participants

25 Associated Partners

(as of December 2018)

Backup Slides

For further information...

Plasma accelerators – a new technology

Accelerating fields on the order of

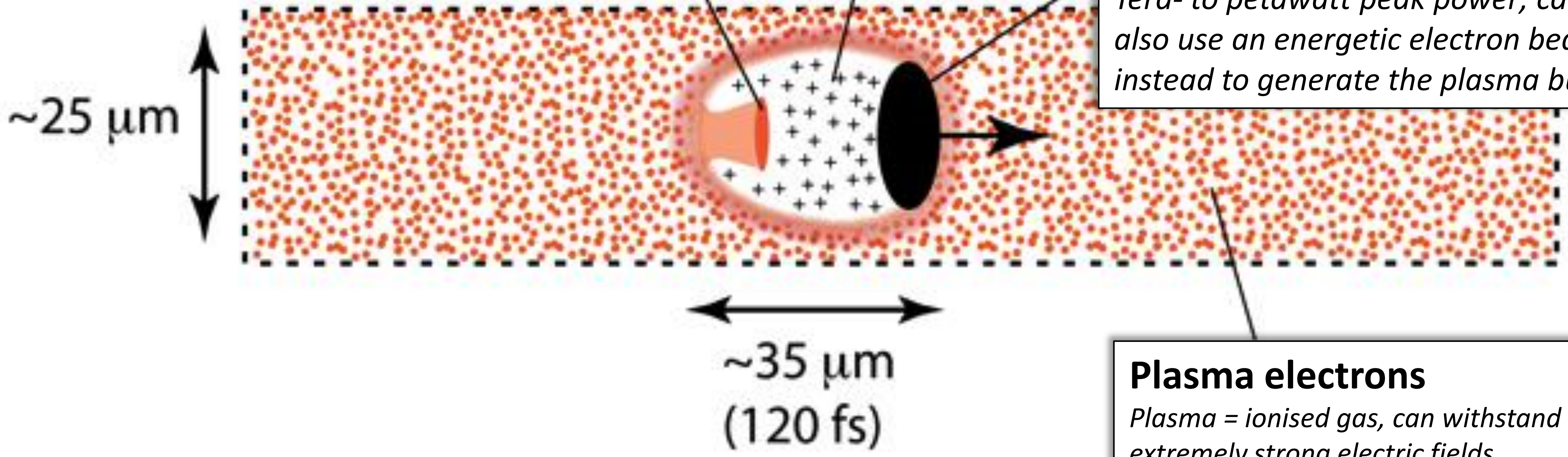
$$E_0\left[\frac{V}{m}\right] \sim 96\sqrt{n_0\ [cm^{-3}]}$$

(n_0 = plasma electron density)

Plasma bubble
Accelerating gradients of order GV/m to TV/m; plasma electrons are pushed out of the way by drive laser / e-beam & create this cavity

Trapped electron beam
Can be accelerated to GeV-level in cm distances, if placed at right position within plasma bubble

Drive laser pulse
Tera- to petawatt peak power; can also use an energetic electron beam instead to generate the plasma bubble



Plasma electrons
Plasma = ionised gas, can withstand extremely strong electric fields

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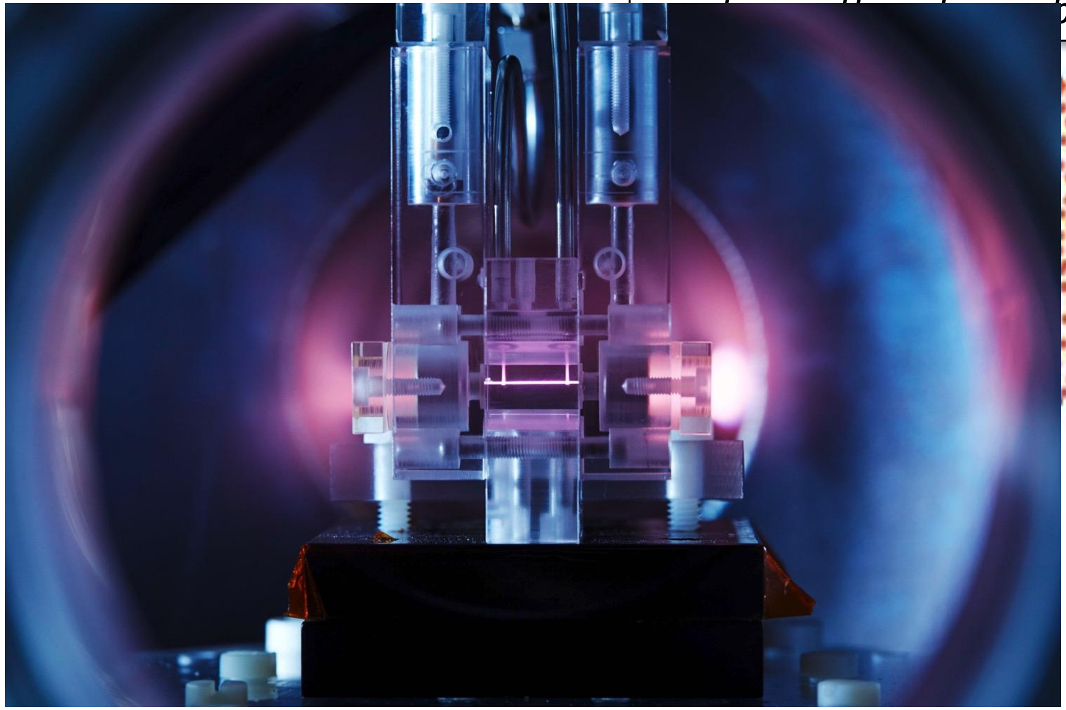

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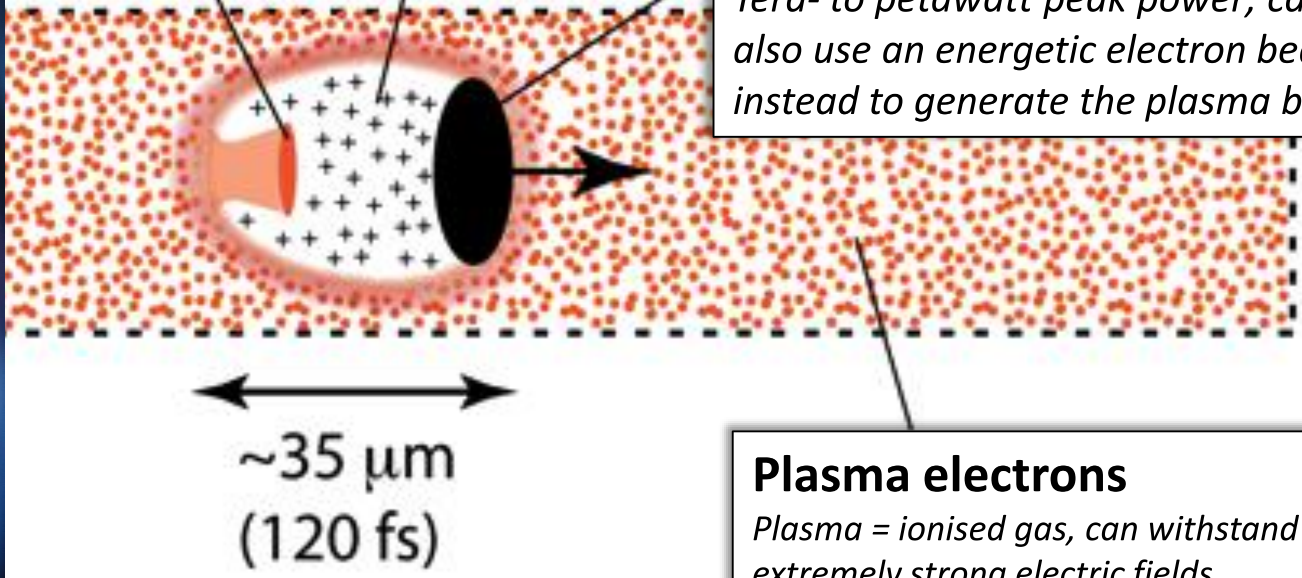

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Plasma = ionised gas, can withstand extremely strong electric fields

Facility Overview

Caveat: These are preliminary estimations of the EuPRAXIA technical goals; more finalised parameters will be available in the EuPRAXIA Conceptual Design Report in Oct 2019.

A Demonstrator Facility for Compact Accelerator Development & Applications

High-quality electron beams

- Energy up to **5 GeV**
- Down to **sub-percent energy spread**
- Single to tens of **femtoseconds** duration
- **Micrometre**-scale spot size

Free-Electron Laser (FEL)

- **Nano- to sub-nanometre** wavelength
- Single to tens of **femtoseconds** duration
- Up to **10^{10} – 10^{12} photons per pulse**

Sub-Petawatt Laser Pulses

- Primarily as acceleration drivers, yet some availability for **pump-probe experiments**
- Energy up to **100 J** on target
- **20 – 100 Hz** repetition rate

Compact radiation sources

- **X-rays / γ-rays** from betatron radiation & Compton scattering
- Single **femtosecond** duration
- **Micrometre**-scale spot size

Positrons & neutrons

- Low-energy and high-energy **positron sources for material studies** & other applications
- Possibility for **neutron source under investigation**

+ Future development paths towards....

- ... Higher repetition rate
- ... Sub-femtosecond beam durations
- ... Higher photon flux
- ... Shorter FEL wavelengths

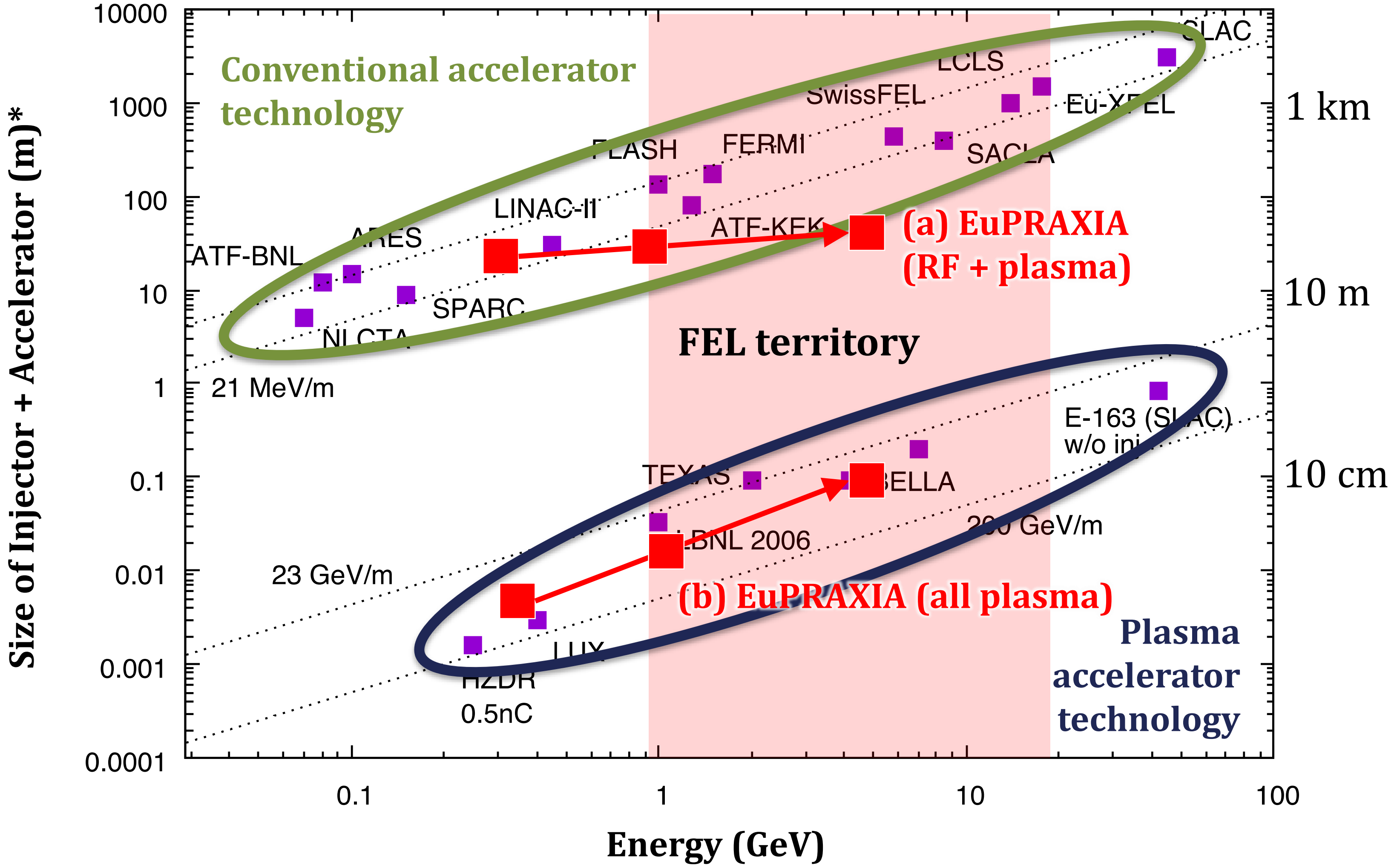
Preliminary Parameter Table

High-energy, ultrashort electron beams		
Energy	[GeV]	1.0 – 5.9
Charge	[pC]	23 – 40
Beam duration	[fs]	7 – 13
Energy spread	[%]	0.1 – 1.1
Transv. Norm. emittance	[mm mrad]	0.4 – 1.2
Ultrashort FEL radiation pulses		
Radiation wavelength	[nm]	0.2 – 36.3
Photons per pulse		$2x10^{9}$ – $3x10^{13}$
Brightness	[*]	2x1030 – 6x1032
Betatron source		
Radiation wavelength	[nm]	0.6 – 110 keV
Photons per pulse		2x108 – 4x1010
Brightness	[*]	2x1021 – 1x1026
Low-energy positron source (0.5 – 10 MeV)		
Beam duration	[ps]	20 – 90
Positrons per shot		≥ 107
High-energy positron source (≥ 1GeV)		
Beam duration	[fs]	≤ 10
Positrons per shot		~107

Note that the table above is not self-consistent and to-date only preliminary. More detailed lists are available upon request.

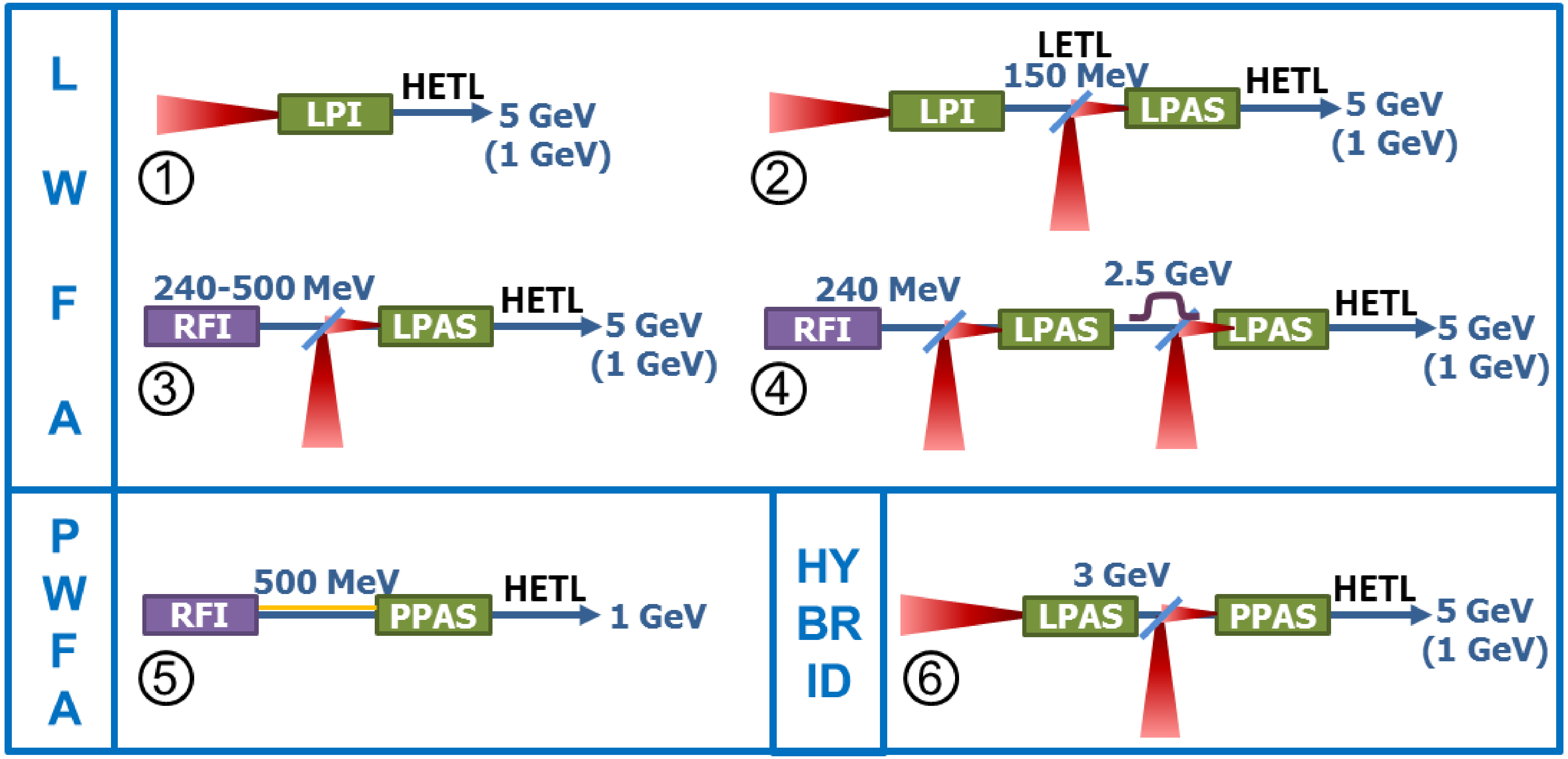
EuPRAXIA's Position in the Accelerator Landscape

Horizon 2020



** Not including laser / RF infrastructure, beam delivery or undulators*

Technical Cases Studied



EuPRAXIA's Main Technical Challenges

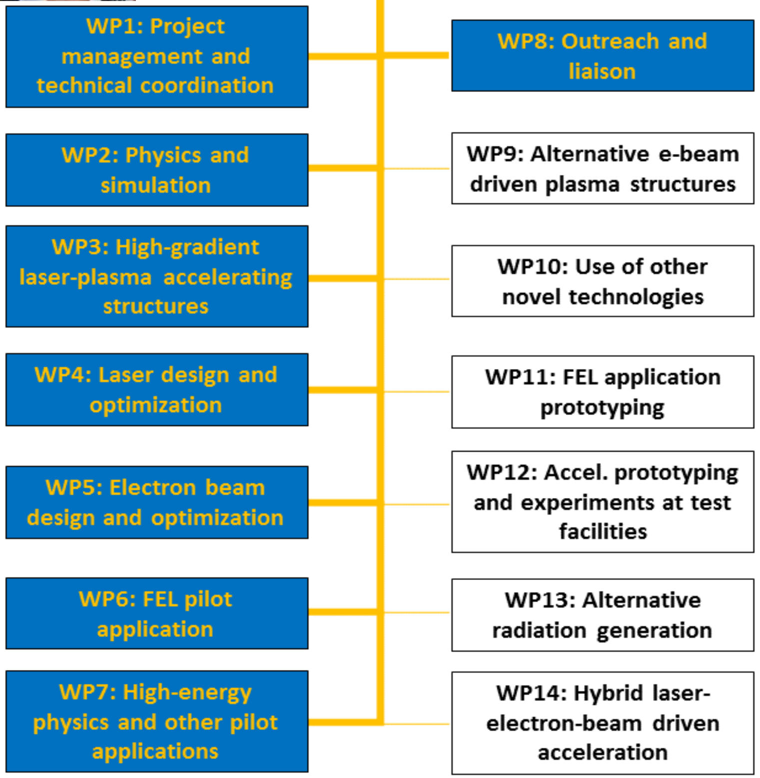
Horizon 2020

Note: This list is merely designed to give an overview, it is not comprehensive and does not cover any details of the proposed solutions.

Technical Challenge	Proposed Solution
Beam energy spread reduction	Optimisation of injection mechanisms Development of novel injection mechanisms External injection from RF accelerator
Beam emittance reduction	Advanced beam control via transfer lines
Laser – e-beam synchronisation	Development of novel synchronisation schemes
Shot-to-shot stability	Advanced diagnostics Feedback & control system Tight control over laser tolerances
Operability & maintainability	Advanced diagnostics Feedback & control system
Increase in repetition rate	Development of heat control mechanisms in laser systems Differential pumping for vacuum systems
Accelerator staging	Advanced beam control via transfer lines Use of active plasma lenses for compact, strong focusing
Plasma-based FEL operation	Ongoing, large-scale „prototyping“ activities (e.g. LUX, COXINEL) Tight control of electron beam parameters and dynamics

Management Structure

Heads of Project and of Supervisory Boards



Steering Committee