Science Applications for the European Accelerator Research Infrastructure EuPRAXIA


Special thanks to the EuPRAXIA Collaboration

EAAC 2019, Sep 15 – 20 2019 Elba, Italy
EuPRAXIA Consortium

- 41 partner institutions
- >200 contributors
- 4 years of work
Possible Applications of Plasma Accelerators

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

Making existing applications more compact / better
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- Medical imaging
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- Active interrogation

Making new applications

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

Science Applications for the European Accelerator Research Infrastructure EuPRAXIA - M. Weikum
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
EuPRAXIA = European Plasma Accelerator with eXcellence In Applications

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A distributed infrastructure proposing facilities for
- Beam-driven plasma acceleration
- Laser-driven plasma acceleration
The Laser-Driven Site

Facility for **laser-driven** plasma accelerators

- **Plasma Injector**
- **High-Charge Plasma Accelerator**
- **Conversion & conditioning**
- **High-Quality Plasma Accelerator**
- **Undulators (conventional)**
- **Table-top test beam user area**
- **Ultra-compact positron source user area**
- **FEL user area 1**
- **FEL user area 2**

**Flowchart:**
- Laser
- RF Injector
- Plasma Injector
- High-Charge Plasma Accelerator
- Conversion & conditioning
- Undulators (conventional)
- Table-top test beam user area
- Ultra-compact positron source user area
- FEL user area 1
- FEL user area 2

**Legend:**
- Laser
- Electrons
- Positrons
- X-rays / γ-rays
The Laser-Driven Site

The Laser-Driven Site

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

THREE HIGH-POWER LASER SYSTEMS

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Energy on target</th>
<th>Pulse duration</th>
<th>Repetition rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>800 nm</td>
<td>5 – 100 J</td>
<td>≥ 20 – 60 fs</td>
<td>20 – 100 Hz</td>
</tr>
</tbody>
</table>
The Beam-Driven Site

Facility for **beam-driven** plasma accelerators

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**RF Injector** → **RF Accelerator** → **High-Quality Plasma Accelerator** → **Undulators (conventional)** → **ICS interaction** → **Conversion & conditioning** → **High-Charge Plasma Accelerator**

- **FEL user area 1**
- **FEL user area 2**
- **ICS γ-ray source user area**
- **HEP detector test user area**
- **GeV-class positron user area**

**laser** → **electrons** → **positrons** → **X-rays / γ-rays**
The Beam-Driven Site

A STATE-OF-THE-ART X-BAND LINAC

<table>
<thead>
<tr>
<th>Operating frequency</th>
<th>Field strength</th>
<th>Length</th>
<th>Final beam energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>~12 Hz</td>
<td>≤ 80 MV/m</td>
<td>10 m</td>
<td>~500 MeV</td>
</tr>
</tbody>
</table>

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

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>[GeV]</td>
<td>5.9</td>
</tr>
<tr>
<td><strong>Charge</strong></td>
<td>[pC]</td>
<td>22</td>
</tr>
<tr>
<td><strong>Bunch length</strong></td>
<td>[fs]</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>Energy spread</strong></td>
<td>[%]</td>
<td>0.32</td>
</tr>
<tr>
<td><strong>Transv. norm. emittance</strong></td>
<td>[mm mrad]</td>
<td>0.6 / 1.6</td>
</tr>
<tr>
<td><strong>Slice energy spread</strong></td>
<td>[%]</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Slice emittance</strong></td>
<td>[mm mrad]</td>
<td>0.4 / 0.7</td>
</tr>
</tbody>
</table>

(based on start-to-end simulations of the accelerator)
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 \(\rightarrow\) accelerator, laser, ... specialists (our community)
- Training \(\rightarrow\) aspiring experts (grow our community)
- Scientists interested in applications \(\rightarrow\) 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)
Finding Relevant Applications

Based on community interest

- Preliminary survey + workshops

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

PAEPA Workshop, Oct 2016, Palaiseau (France)
A Choice of Flagship Applications

Science Applications for the European Accelerator Research Infrastructure EuPRAXIA – M. Weikum
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.

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

* = [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

[Cole et al. PNAS. 115 (25): 6335-6340 (2018)]
Flagship Application 2: A GeV-Scale Positron Source

**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

**High-energy positron source**
- Energy: $\geq 1\text{GeV}$
- Beam duration: $\leq 10$ fs
- Positrons per shot: $\sim 10^7$


*Alejo et al. Sci. Reports. 9, 5279 (2019) [image courtesy G. Sarri, J. Clarke]*
Flagship Application 3: A Free-Electron Laser

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

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

Ultrashort FEL radiation pulses

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation wavelength</td>
<td>0.2 – 36.3 nm</td>
</tr>
<tr>
<td>Photons per pulse</td>
<td>2x10^9 – 3x10^{13}</td>
</tr>
<tr>
<td>Brightness</td>
<td>2x10^{30} – 6x10^{32} [*]</td>
</tr>
</tbody>
</table>

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

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

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, university labs, etc.

Science Applications for the European Accelerator Research Infrastructure EuPRAXIA – M. Weikum
Flagship Application 3: A Free-Electron Laser

**EAAC Poster:**
F. Villa, Monday

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

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Flagship Application 4: Accelerator R&D Test Beams

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

**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

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

[€PRAXIA] – M. Weikum


[B. Hidding et al., Appl. Sci. 2019, 9, 2626]
- Variety of laser, accelerator and photon science facilities already existing
- National programs with similar goals and science directions
Variety of laser, accelerator and photon science facilities already existing

National programs with similar goals and science directions

Complementary developments with EuPRAXIA etc.
EuPRAOXIA’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 EuPRAOXIA**

+ 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

etc.
Next Steps

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

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**Horizon 2020**

**EuPRAXIA**

- **Conceptual Design Phase**
  - 2015 - 2019
  - **TODAY**

- **Technical Design & Prototyping**
  - 2020 - 2025

- **Implementation & Construction**
  - 2026 - 2029

- **Operation**
  - From 2030

- **Plasma-based FELs**
- **Plasma accelerator industrialisation**
- **Plasma-based colliders**

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**Science Applications for the European Accelerator Research Infrastructure EuPRAXIA – M. Weikum**
EuPRAXIA = European Plasma Research Accelerator with EXcellence In Applications

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!

Especially:

16 Participants

25 Associated Partners
(as of December 2018)
For further information...
Plasma accelerators – a new technology

Accelerating fields on the order of

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

\( n_0 = \text{plasma electron density} \)

**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

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Plasma = ionised gas, can withstand extremely strong electric fields
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\( n_0 = \) plasma electron density
Facility Overview

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

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.

+ 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>[GeV]</td>
<td>1.0 – 5.9</td>
</tr>
<tr>
<td>Charge</td>
<td>[pC]</td>
<td>23 – 40</td>
</tr>
<tr>
<td>Beam duration</td>
<td>[fs]</td>
<td>7 – 13</td>
</tr>
<tr>
<td>Energy spread</td>
<td>[%]</td>
<td>0.1 – 1.1</td>
</tr>
<tr>
<td>Transv. Norm. emittance</td>
<td>[mm mrad]</td>
<td>0.4 – 1.2</td>
</tr>
</tbody>
</table>

### Ultrashort FEL radiation pulses

<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
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<td>Radiation wavelength</td>
<td>[nm]</td>
<td>0.2 – 36.3</td>
</tr>
<tr>
<td>Photons per pulse</td>
<td></td>
<td>2x10⁹ – 3x10¹³</td>
</tr>
<tr>
<td>Brightness</td>
<td>[*]</td>
<td>2x10³⁰ – 6x10³²</td>
</tr>
</tbody>
</table>

### Betatron source

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Values</th>
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<tbody>
<tr>
<td>Radiation wavelength</td>
<td>[nm]</td>
<td>0.6 – 110 keV</td>
</tr>
<tr>
<td>Photons per pulse</td>
<td></td>
<td>2x10⁸ – 4x10¹⁰</td>
</tr>
<tr>
<td>Brightness</td>
<td>[*]</td>
<td>2x10²¹ – 1x10²⁶</td>
</tr>
</tbody>
</table>

### Low-energy positron source (0.5 – 10 MeV)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam duration</td>
<td>[ps]</td>
<td>20 – 90</td>
</tr>
<tr>
<td>Positrons per shot</td>
<td></td>
<td>≥ 107</td>
</tr>
</tbody>
</table>

### High-energy positron source (≥ 1 GeV)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam duration</td>
<td>[fs]</td>
<td>≤ 10</td>
</tr>
<tr>
<td>Positrons per shot</td>
<td></td>
<td>~107</td>
</tr>
</tbody>
</table>

---

*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

EuPRAXIA – a Compact, Cost-Efficient Particle and Radiation Source | Maria Weikum

* Not including laser / RF infrastructure, beam delivery or undulators
### Technical Cases Studied

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LPI → HETL → 5 GeV (1 GeV)</td>
</tr>
<tr>
<td>2</td>
<td>LPI → LPAS → HETL → 5 GeV (1 GeV)</td>
</tr>
<tr>
<td>3</td>
<td>RFI → LPAS → HETL → 5 GeV (1 GeV)</td>
</tr>
<tr>
<td>4</td>
<td>RFI → LPAS → 2.5 GeV → LPAS → HETL → 5 GeV (1 GeV)</td>
</tr>
<tr>
<td>5</td>
<td>RFI → PPAS → HETL → 1 GeV</td>
</tr>
<tr>
<td>6</td>
<td>LPAS → PPAS → HETL → 5 GeV (1 GeV)</td>
</tr>
</tbody>
</table>

**EuPRAXIA**

– a Compact, Cost-Efficient Particle and Radiation Source

| Maria Weikum | Horizon 2020 |
EuPRAXIA’s Main Technical Challenges

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

<table>
<thead>
<tr>
<th>Technical Challenge</th>
<th>Proposed Solution</th>
</tr>
</thead>
</table>
| 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

Collaboration board

Scientific advisory board

Management support team

Project coordinator

Steering committee

WP1: Project management and technical coordination

WP2: Physics and simulation

WP3: High-gradient laser-plasma accelerating structures

WP4: Laser design and optimization

WP5: Electron beam design and optimization

WP6: FEL pilot application

WP7: High-energy physics and other pilot applications

WP8: Outreach and liaison

WP9: Alternative e-beam driven plasma structures

WP10: Use of other novel technologies

WP11: FEL application prototyping

WP12: Accel. prototyping and experiments at test facilities

WP13: Alternative radiation generation

WP14: Hybrid laser-electron-beam driven acceleration