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APPLICATIONS

EuPRAXIA
Preparatory Phase

WP9 Final Status Report

WP9 – RF, Magnets & Beamline Components

WP leaders: S. Antipov (DESY) & F. Nguyen (ENEA)

Final Meeting on September 23rd, 2026

Funded by
the European Union

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773. It is supported by in-kind contributions by its partners and by additional funding from UK and Switzerland.

WP9: what is all about?

- Compact magnets (both electromagnets and permanent magnets) for beam capture and transport
- Radiofrequency high power sources and structures for conventional acceleration
- Magnetic undulators for free-electron laser generation

High quality, high stability electron and photon beams in compact physical layout

- Primary objective: steer the technical progress on the development and design of accelerator components
  - Specify in detail Excellence Centers
  - Review potential prototype R&D
  - Coordinate funding requests
- Update concepts, parameters towards TDR

Undulators

- ENEA (Italy)
- ALBA (Spain)
- ELI (Czech Republic)
- INFN (Italy)
- UKRI (Great Britain)

Beamline magnets

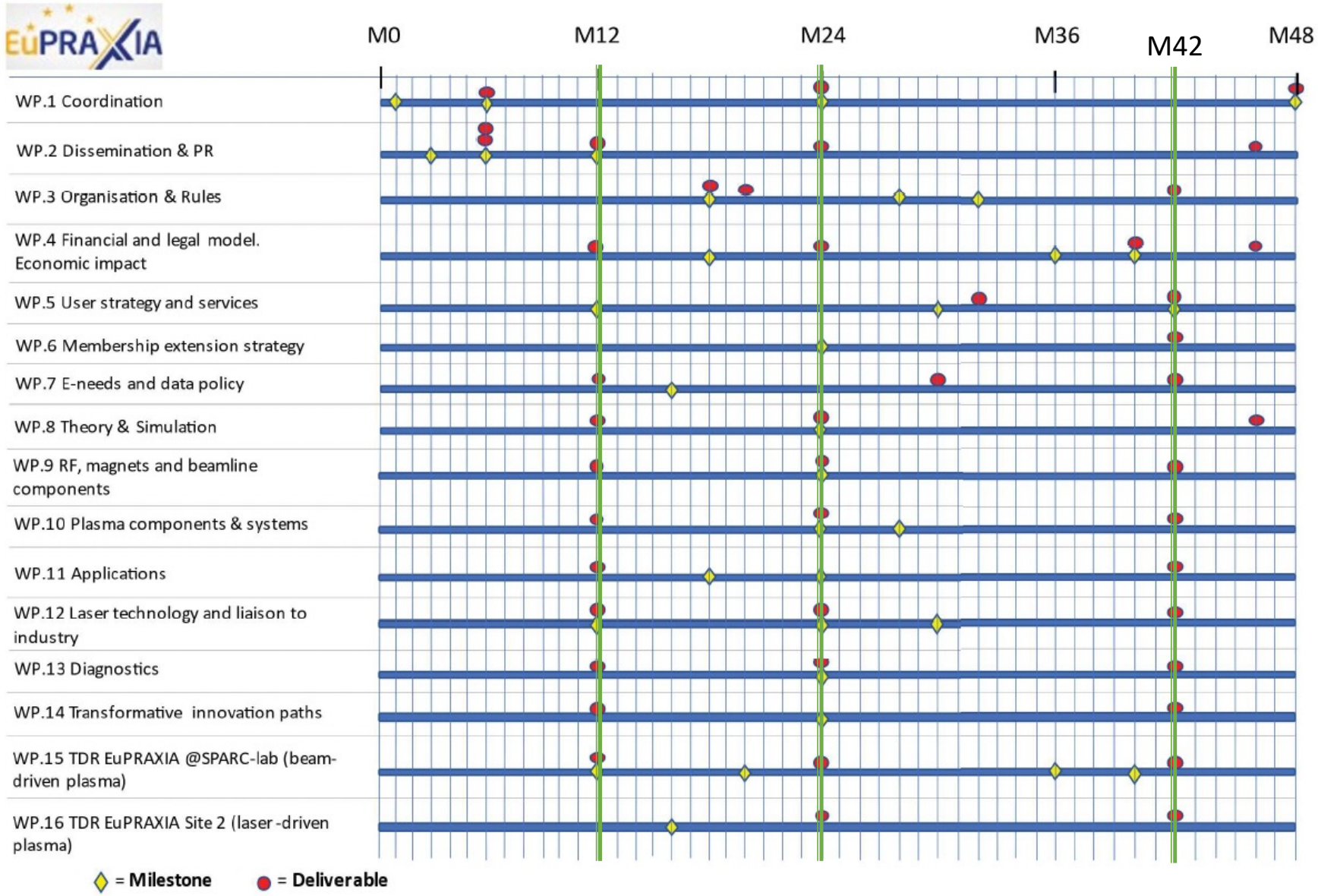
- ALBA (Spain)
- CERN (Switzerland)
- ELI (Czech Republic)
- IASA (Greece)
- INFN (Italy)
- UKRI (Great Britain)

RF components

- CERN (Switzerland)
- CLPU (Spain)
- DESY (Germany)
- IASA (Greece)
- INFN (Italy)
- La Sapienza (Italy)

Timeline

- **8 Work Package meetings + Multiple discussions with WP16 (2nd site)**
- **3 Deliverable Documents + 1 Milestone Report --> all released on time**



Deliverables/Milestones: to take home

Funded by the European Union

- **D9.1 Report on structures to be funded from national/bilateral/european level for RF, Magnets and beamlines components (M12)**
- **D9.2 Report on technical results achieved in the field of RF, Magnets and beamlines components (M24)**
- **M.20 Update of concepts for EuPRAXIA, systems status report (M24)**
- **D9.3 TRL Report and maturity assessment on the development of RF, Magnets and beamlines components (M42)**

Progress on permanent magnet quadrupoles suggests that 30% stronger magnets can be used for the capture triplet → tuning the quadrupole triplets without changing the magnet positions → variable aperture PMQ

To allow laser propagation and maintain good quality normalized emittance, beneficial to use an active plasma lens → more flexible a setup also in terms of energy tuning → see WP10

Facility design driven by the undulator technology → approx. 20 m undulator beamline fits within the 2nd site floor constraints

D9.3 focus: Technology Readiness Level

Funded by the European Union

DocID	Ver.	Status
EuPRAXIA PP_WP9_DLV3_07.04.26	0.2	draft
Project	**Deliverable**	**Grant N.**
EuPRAXIA PP	WP9-DLV3	101079773
Lead beneficiary:		**Due date:**
DESY		Apr 2026

EuPRAXIA-PP

24/03/2026

TRL report and maturity assessment on the development of RF, magnets and beamline components

Abstract

This deliverable presents the maturity assessment of RF components, compact beamline magnets, and undulators as part of the EuPRAXIA-PP initiative. The report provides an overview of the state-of-the-art technologies in conventional accelerator components relevant to the EuPRAXIA FEL facilities and electron beamlines. Key findings include the evaluation of RF components, the analysis of compact beamline magnets, and the assessment of undulator systems, with the focus on the readiness of respective technologies for integration within the EuPRAXIA FEL facilities. The deliverable aims to guide the integration of these technologies into the overall EuPRAXIA project, ensuring optimal performance and reliability of the accelerator components.

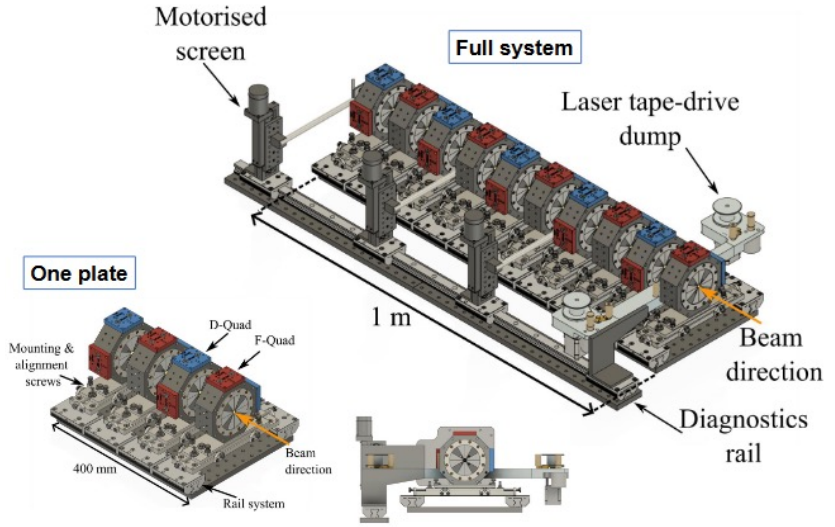
	Name	Institute	Date
Authored by	S. Antipov, F. Nguyen, et al.	DESY/ENEA	24/03/2026
Approved by WP Coordinator	S. Antipov/F. Nguyen	DESY/ENEA	xx/yy/20zz
Reviewed by Project Office	A. Falone/M. Ferrario/A. Ghigo/P. Campana	INFN	xx/yy/20zz

TRL LEVEL	TRL Description
TRL 1	Basic principles observed – Scientific research begins to be translated into applied research and development (R&D).
TRL 2	Technology concept formulated – The basic principles are explored, and practical applications are identified.
TRL 3	Experimental proof of concept – Active R&D is initiated, including analytical and laboratory studies to validate predictions.
TRL 4	Technology validated in lab – Basic technological components are integrated to establish that they work together.
TRL 5	Technology validated in relevant environment – The technology is tested in a simulated or relevant environment
TRL 6	Technology demonstrated in relevant environment – A prototype system is tested in an environment similar to the operational one.
TRL 7	System prototype demonstration in operational environment – A working prototype is demonstrated in a real operational setting.
TRL 8	System complete and qualified – The technology is proven to work in its final form and under expected conditions.
TRL 9	Actual system proven in operational environment – The technology is fully commercialized and operational in its intended setting.

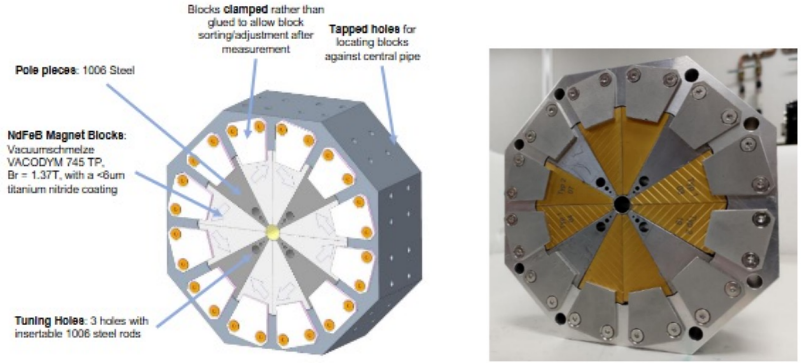
Compact magnets

- Standard beamline electromagnets are a mature technology
- Combined function, integrated diagnostic designs might need to be adapted for the specific configuration:
  - A space-saving measure
  - Mechanical tolerances, cross-talk to be verified
- Compact capture magnets still require prototyping

Sub-system	TRL	Comment
EM dipoles, quadrupoles	9	Technology is fully commercialized. Magnets operate within standard mechanical and magnetic tolerances.
Steerer magnets	9	Technology is fully commercialized. Comparable specs are deployed across numerous accelerators.
Combined-function EMs	8	Technology is established but must be adapted to specific constraints (mech tolerances, cross-talk).
EMs with beam diag	8	Technology is established but must be adapted to specific constraints (mech tolerances, cross-talk).
Magnet power supplies	8	Based on design, installation, and operational experience of multiple facilities worldwide.
Compact PMQs for capture	6	Technology demonstrated in a relevant environment. A dedicated prototyping phase shall follow.
Tunable PMQs for transfer	7	Demonstrated in an operational environment, replaced an EMQ for a period of 18 months.



*FODO focusing channel array based on permanent magnet quadrupoles developed at **UKRI***

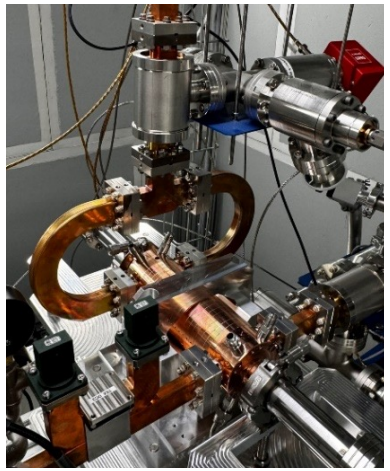


Hybrid PMQ design, incorporating NdFeB blocks

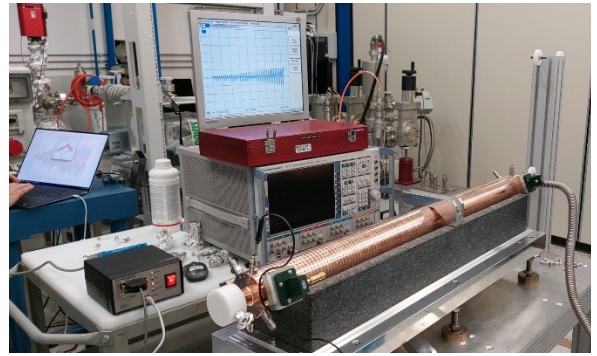
Radiofrequency components

- X-band development advanced from prototype testing to full-scale structure validation
- Full-scale structure ready for high-power conditioning at TEX
- Many RF components have been prototyped and tested, reaching TRL 7-8

Sub-system	TRL	Comment
X-band power source	6	Commercially available. Ready to be tested at TEX to reach the nominal parameters.
X-band structure	6	In-house design. Final full-scale prototype ready to be tested, tuning-free tech to be finalized.
BOC pulse compressor	6	PSI design. Ready to be tested with the nominal power at TEX. Already tested at parter laboratory at a reduced repetition rate and power.
RF load	8	Fabricated and tested at nominal peak and average power (50 Hz, 0.6 μs)



X-band prototype installed for high RF power testing at TEX

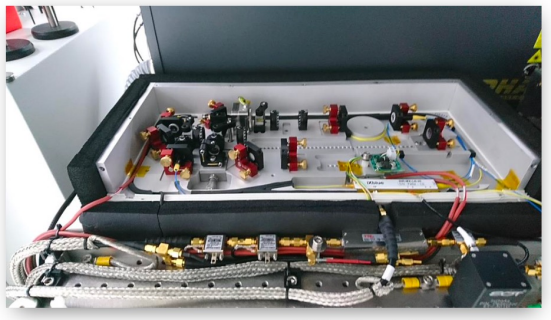


RF characterization measurements

Additional X-band station at TEX

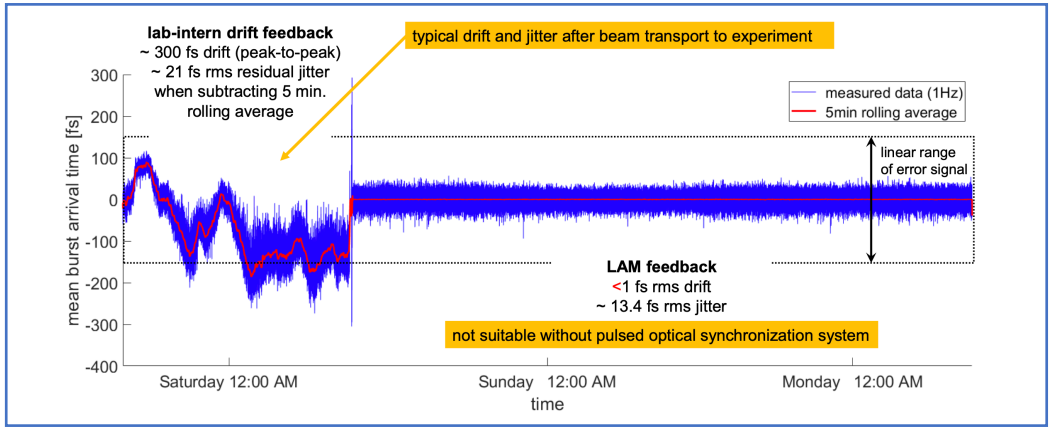
Laser-RF synchronization

- Few-femtosecond synch. is feasible
- No off-the-shelf solution
- System design depends on
  - Reference distribution
  - Environmental control
  - Facility integration



MZM-based laser-RF sync setup

System	TRL	Comment
Direct conversion (RF clock synch)	8	Most of the components commercially available, although the complete system has not been commercialized.
MZM-based locking	6-7	Systems or system prototypes tested in relevant conditions. TRL depends on specific wavelength and repetition rate.
Optical cross-correlator laser-to-laser locking	8	Most of the components commercially available, although the complete system has not been commercialized.

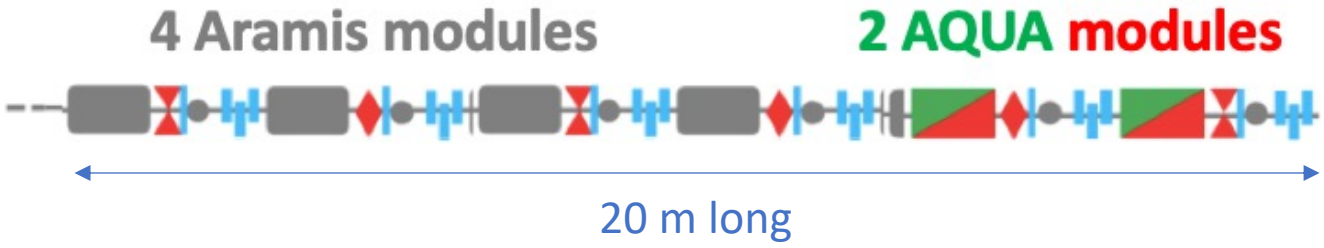


LAM feedback providing fs long-term sync in user experiment

Undulator beamline under design for the 2nd site

Initial operation:

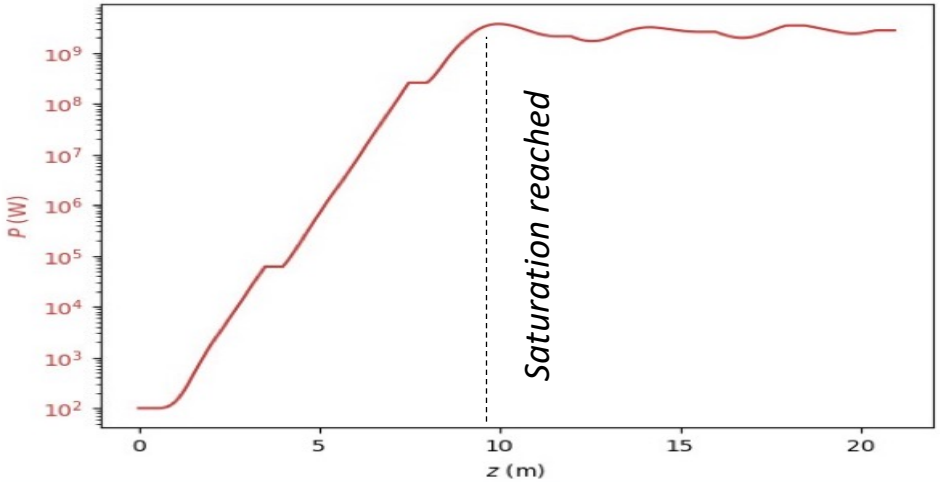
- Beam energy 1 GeV
- Resonant wavelength 4 nm
- Peak current 2.8 kA



Similar scheme proposed in "The CompactLight Design Study"
Eur. Phys. J. Spec. Top. 233 (2024) 1-208

Parameter	ARAMIS undulator	APPLE-X undulator
Period	15 mm	18 mm
Module length	3.5 m	2 m
No. of modules	4	2
K-parameter	1.44	0.838

System	TRL	Comment
ARAMIS undulators	9	Undulator technology routinely in use at SwissFEL since 2017
APPLE-X undulators	7	Short-period undulators have been successfully developed and implemented in various labs. Additional systems-integration might be required.
Undulator vacuum chamber	4	Combines small thickness with strict mechanical tolerances. Validated only through numerical simulation.



Numerical simulation in Genesis: Emitted power reaches saturation after about 10 m.

Conclusions

- **WP9 successfully achieved all planned objectives and deliverables**
- **Key accelerator technologies have progressed to advanced maturity levels, towards reducing technical risks for EuPRAXIA implementation**
- **Compact magnets, X-band RF systems and undulator concepts have demonstrated the requested feasibility and performance**
- **The performed work provides a robust technological basis for the implementation of future plasma-based FEL facilities**

WP9 Today's contributions:

M. Miceski
Towards a Compact LWFA-Driven Soft X-Ray FEL at ELI ERIC

M. Opromolla
The ARIA seeded Free-Electron Laser beamline at EuPRAXIA@SPARC_LAB

Thank you for your attention!

Funded by the European Union

EuPRAXIA_PP WP9 seventh meeting

Zoom link: https://desy.zoom.us/j/95449458932?pwd=VDI2WGlwSHZXVEkvQndLWjRDeFVrdz09Meeting ID: 954 4945 8932Passcode: 6211

14 June 2024 10:30

... » Strutture INFN » Laboratori Nazionali di Frascati » Divisione Acceleratori » EUPRAXIA » EUPRAXIA PP

EuPRAXIA_PP WP9 sixth meeting

Zoom link: https://desy.zoom.us/j/95449458932?pwd=VDI2WGlwSHZXVEkvQndLWjRDeFVrdz09Meeting ID: 954 4945 8932Passcode: 6211

17 May 2024 10:30

... » Strutture INFN » Laboratori Nazionali di Frascati » Divisione Acceleratori » EUPRAXIA » EUPRAXIA PP

EuPRAXIA_PP WP9 fifth meeting

Zoom link: https://desy.zoom.us/j/95449458932?pwd=VDI2WGlwSHZXVEkvQndLWjRDeFVrdz09Meeting ID: 954 4945 8932Passcode: 6211

18 April 2024 14:30

... » Strutture INFN » Laboratori Nazionali di Frascati » Divisione Acceleratori » EUPRAXIA » EUPRAXIA PP

Introductory meeting WP9

Link:https://infn-it.zoom.us/j/98567023672?pwd=Q3hnQ2R6T01ZdG91dnB0QnVyYzlmQT09ID riunione: 985 6702 3672Codice d'accesso: 440133

09 April 2024 10:45

... » Strutture INFN » Laboratori Nazionali di Frascati » Divisione Acceleratori » EUPRAXIA » EUPRAXIA

EuPRAXIA_PP WP9 fourth meeting

Zoom link to the meetingZoom ID: 954 4945 8932; Passcode: 6211

25 March 2024 09:30

... » Strutture INFN » Laboratori Nazionali di Frascati » Divisione Acceleratori » EUPRAXIA » EUPRAXIA PP

EuPRAXIA_PP WP9 third meeting

Zoom Link to the meeting

11 July 2023 15:00

... » Strutture INFN » Laboratori Nazionali di Frascati » Divisione Acceleratori » EUPRAXIA » EUPRAXIA PP

Thursday 18 Apr 2024, 14:30 → 15:30 Europe/Rome

Description Zoom link: https://desy.zoom.us/j/95449458932?pwd=VDI2WGlwSHZXVEkvQndLWjRDeFVrdz09

14:35 → 14:55 **RF system choices for the EuPRAXIA 1st site**

Speakers: Enrica Chiadroni (Università La Sapienza), Luigi Faillace (Istituto Nazionale di Fisica Nucleare)

EuPRAXIA WP9 Me...

14:55 → 15:05 **Laser-to-RF synchronization**

Speaker: Throsten Lamb (DESY)

EuPRAXIA_WP9_Sy...

Thank you to the whole WP9 crew for contributions, attendance & motivations

Friday 17 May 2024, 10:30 → 12:00 Europe/Rome

Description Zoom link: https://desy.zoom.us/j/95449458932?pwd=VDI2WGlwSHZXVEkvQndLWjRDeFVrdz09

10:30 → 10:50 **Undulator options for EuPRAXIA: 1st site choices**

Speaker: Federico Nguyen (ENEA)

EuPRAXIA-PP_WP9...

10:50 → 11:05 **Magnet design for EuPRAXIA@SPARC_LAB**

Speaker: Lucia Sabbatini (Istituto Nazionale di Fisica Nucleare)

EuPRAXIA-PP-2024...

EuPRAXIA-PP Consortium

Funded by the European Union

Coordinator

INFN Istituto Nazionale di Fisica Nucleare

Consiglio Nazionale delle Ricerche

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Università di Roma Tor Vergata

Imperial College London

Queen's University Belfast

UKRI UK Research and Innovation

University of Liverpool

University of Oxford

University of Strathclyde Glasgow

CERN

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Empa Materials Science and Technology

EPFL

Paul Scherrer Institut PSI

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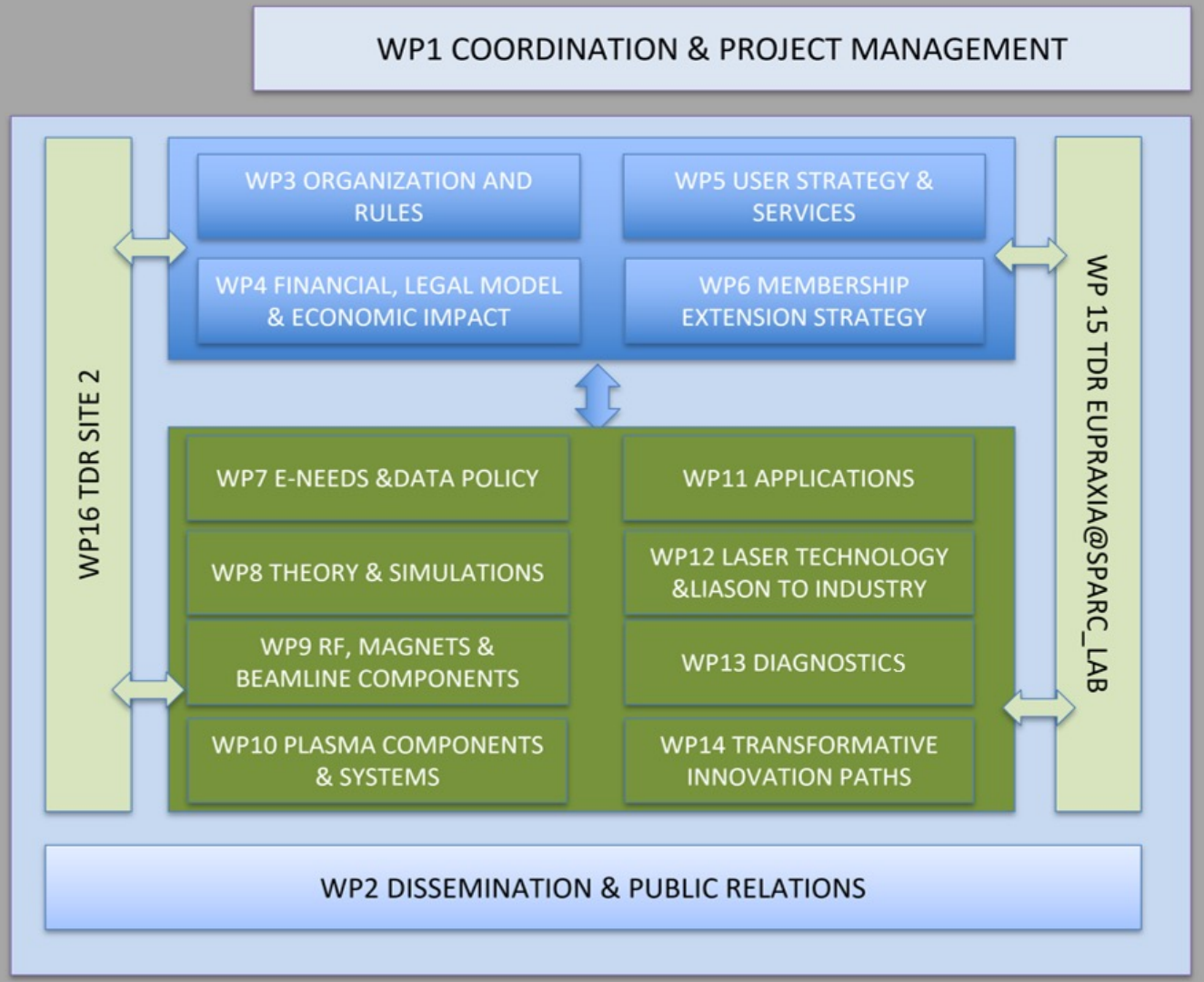
Pécsi Tudományegyetem University of Pécs

SZTE University of Szeged

Wigner

UCLA

EuPRAXIA-PP Structure



Selected Committees and Boards

GOVERNING BOARD
(decision-making body, 1 representative per institute)

Steering Committee
(coordinator plus WP leaders plus experts)

Scientific/Technical Advisory Board
(external experts in user services, RI implement-tation, ESFRI aspects and technical themes)

Board of Financial Sponsors
(connection to decision makers and funding authorities)

Acknowledgements

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EuPRAXIA Doctoral Network

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EuAPS

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