EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

Introduction of the EuPRAXIA Project

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This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

Zimányi winter school 2024, 06-12, Wigner RCP

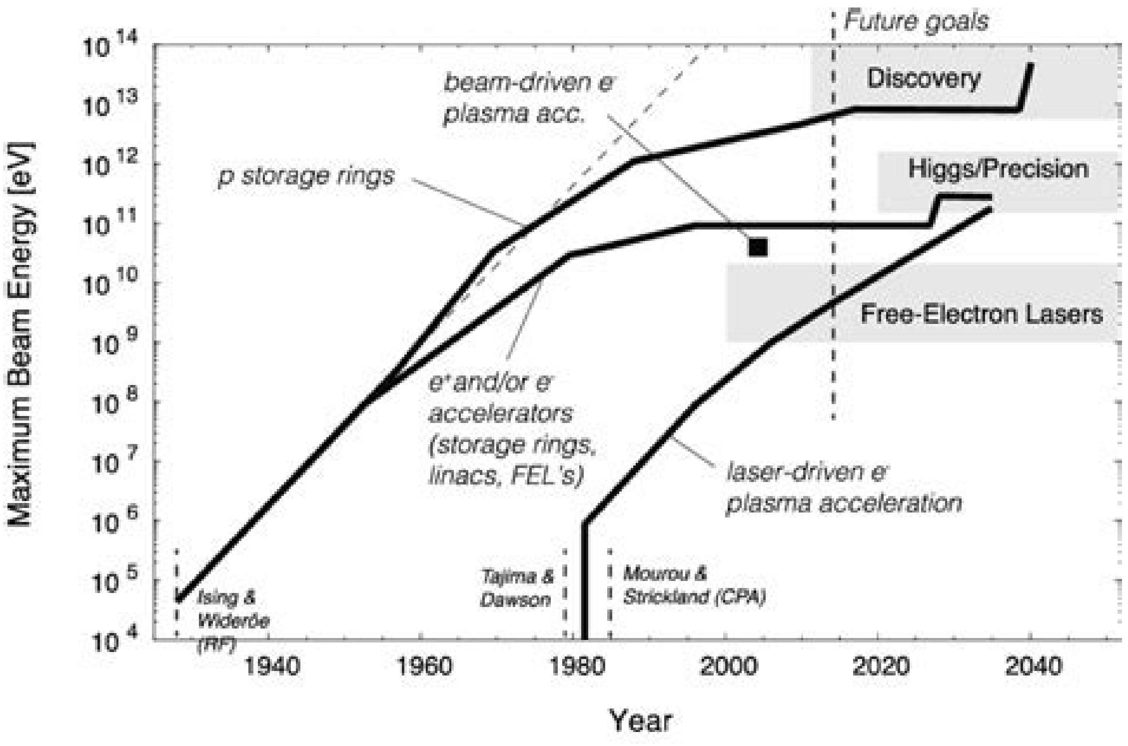
Structure of the talk

Funded by the European Union

- Main motivation for plasma accelerators
- The basic physics of plasma accelerators
- The EuPRAXIA project itself
- Future plans
- Summary and Outlook

The main motivation of plasma accelerators

Funded by the European Union



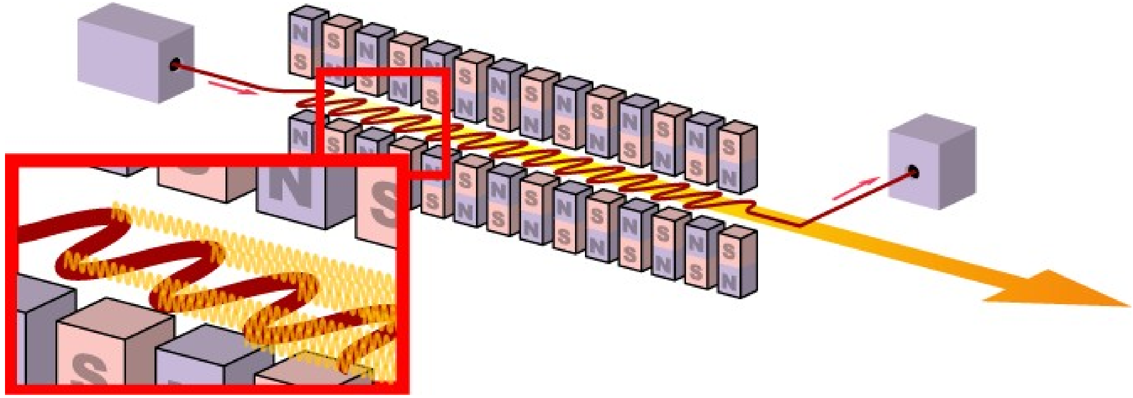
- The Livingstone plot shows
- that in 2024 the conventional linacs and colliders achieved their physical limits in the magnitude of 100 MeV/meter

- 1) Big question how to go further?
- 2) Why to go further?
- Answer 1A): use the same technology
- and plan/build even larger Very Large Hadron Collider (VLHC) near Chicago 235 km long
- OR Future Circular Collider near CERN
- 90 -100 km 100 TeV for pp
- Answer 1B): use some other technology
- a) accelerating particles in plasma
- (main part of the present talk)
- b) dielectric wall accelerators
- Answer 2): one aim is High Energy Physics but that is not the main goal, today we have 30'000 accelerators world-wide and to make them cheaper smaller for applications

The main motivation of plasma accelerators

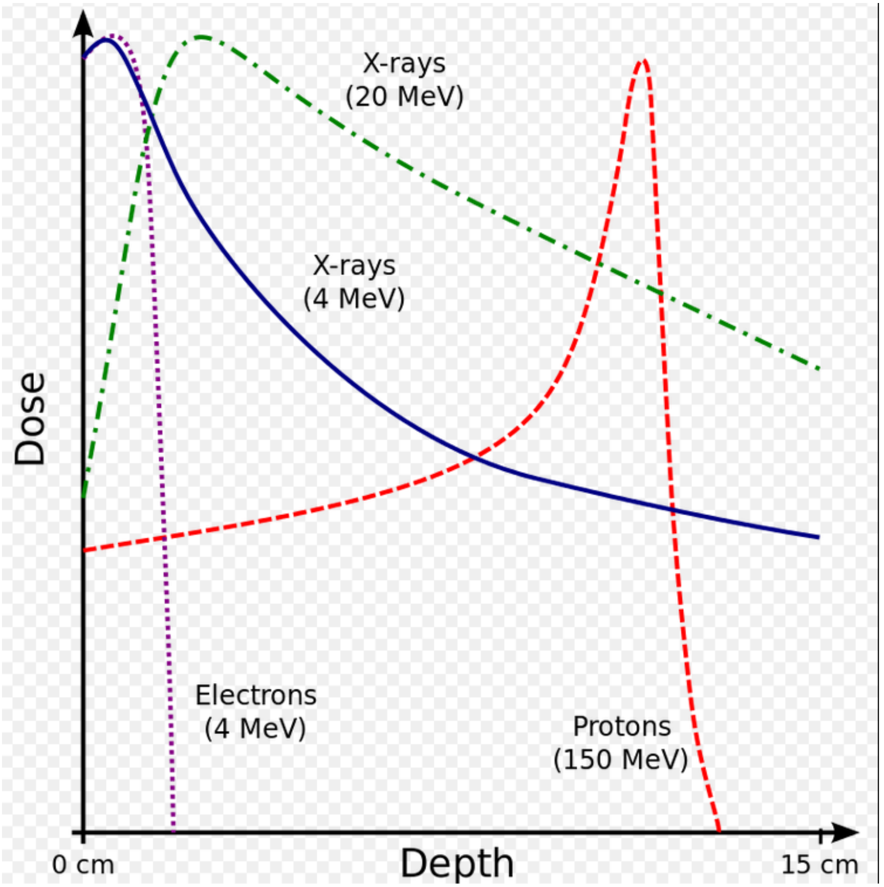
- Answer 2A): for Why to go further
- if we have cheap, compact
- accelerator for electrons then with free
- electron lasers we can produce tunable
- short duration UV, XUV even soft X-ray
- radiation which are heavily used in material science

- How a free electron laser looks like?
- What is the main idea behind?



The main motivation of plasma accelerators

- Answer 2B): why to go further?
- To have compact heavy ion accelerators
- for the hadron therapy as application
- against cancer
- Physics: the Bragg curve, energy deposition of
- charged particles



Such centres already exist:

GSI Darmstadt, (Germany),

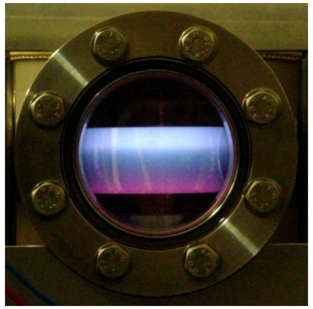
Heidelberg, (Germany), Pavia (Italy)
Statistics say: till 2013 almost 100’000 patients were treated with proton therapy

The main motivation of plasma accelerators

- Answer 1A): How to go further?
- My explanation: now we accelerate with vacuum with RF it has limits so change the conditions
- plasma with laser
- (no upper limit for E field gradient) (has higher frequency)
- (Per definition: plasma is an ionised gas, (when T is large enough everything will be a plasma)

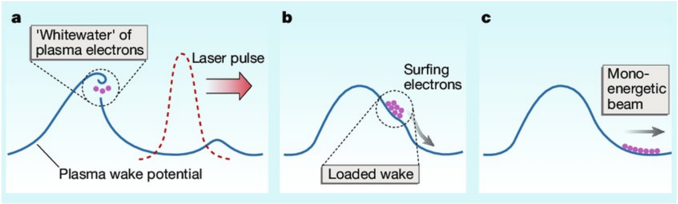
That is what exactly happens:

examples for plasmas:



- need to fill a volume with some gas (eg. H_2, Rb)
- it should be ionized (with charged particles, of with strong electromagnetic
  field eg. laser,
  producing a strong charge separation,
  producing a propagating charge wave,
  (there are many ways to do it)
- inject the electrons which we want to accelerate at the right phase
  (there are many way to do that, the two steps can happen in one step)
  I explain only two ways

wake field

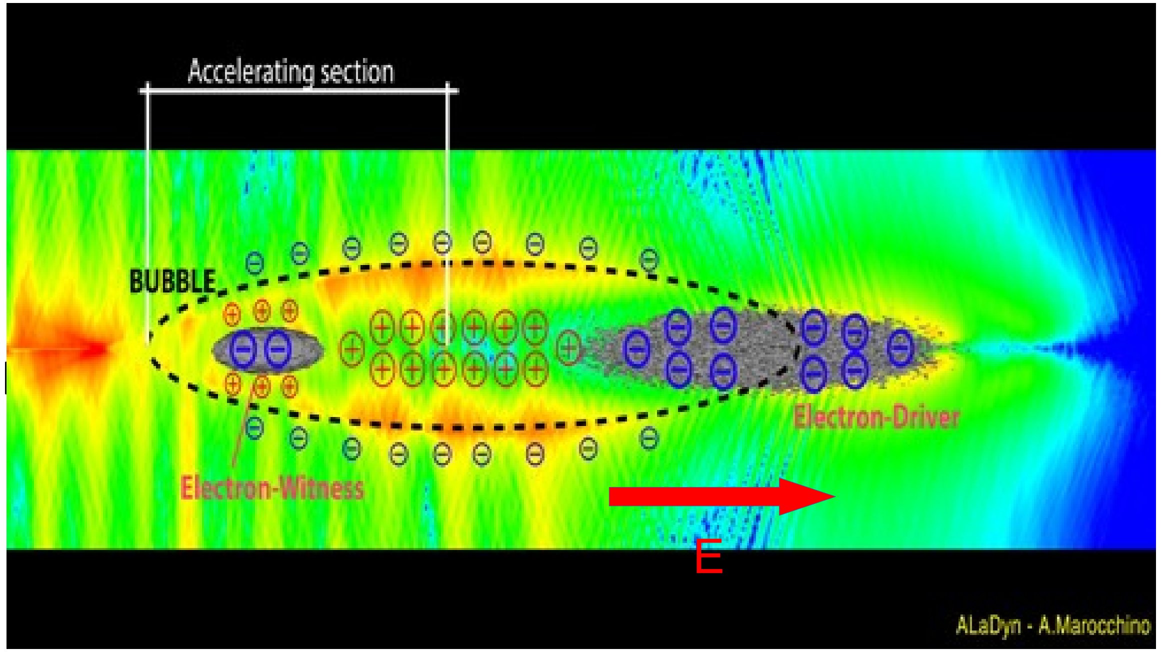


Particle driven plasma wake field acceleration

Funded by the European Union

- First a plasma is produced, does not matter how (the big volume is neutral from seeing from outside)
- than like a “ fist strike into water” we shoot an energetic charged particle bunch (can be electron, positron or even proton)

that makes a strong charge separation, eg. when an electron bunches is used (driver), it pushes out the



electrons creating a void with a positive charge

then electrons are injected into the void which

will be accelerated (whitness bunch)

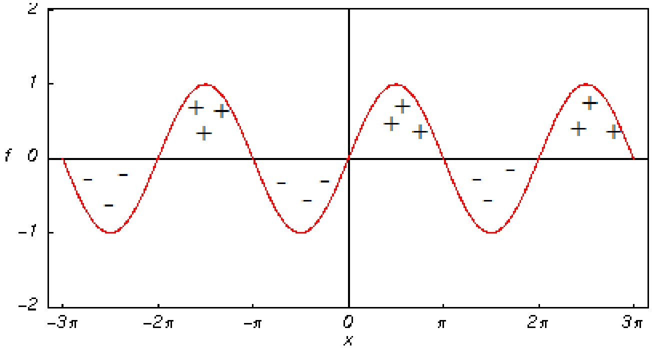
If it is at the proper space at the proper time

Such a proof of principle experiment is AWAKE CERN

Assmann, R.; et al. (2014). "Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics" Plasma Physics and Controlled Fusion. 56 (8): 084013

Laser driven plasma wake field acceleration

Remarks: 1) with a plain wave there is no way to accelerate an electron,



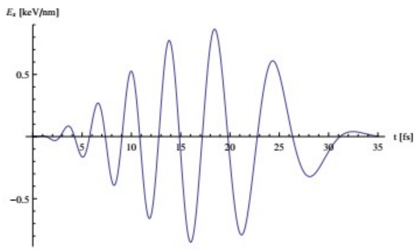
E(x,t)

Propagation direction
which is diagonal to el.field E(x,t)
we want to accelerate electron paralel to x also a problem

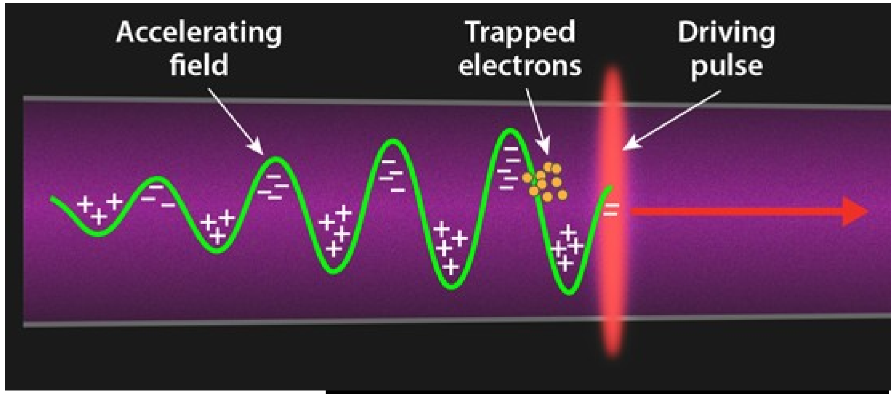
The solution: is to break the symmetry:
-so apply finite duration pulses
- apply chirp which is time dependent frequency

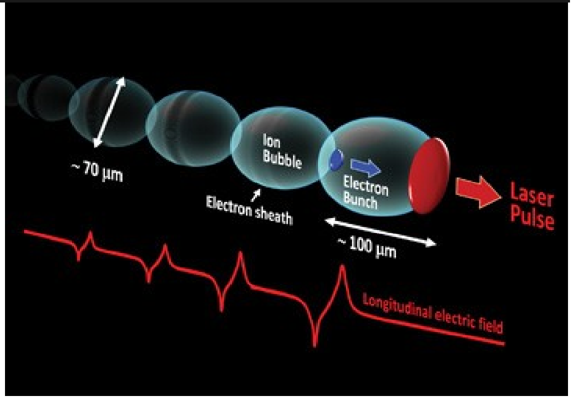
It is possible to accelerate electrons in vacuum with lasers as well but not so effective

Tajima, T.; Dawson, J. M. (1979). "Laser Electron Accelerator PRL 43(4) 267-270



In plasma we can make spatial charge separation, can have horizontal electric field gradient whic is used for electron acceleration





In such a way 3.4 GeV/cm electron acceleration was achieved in Berkley

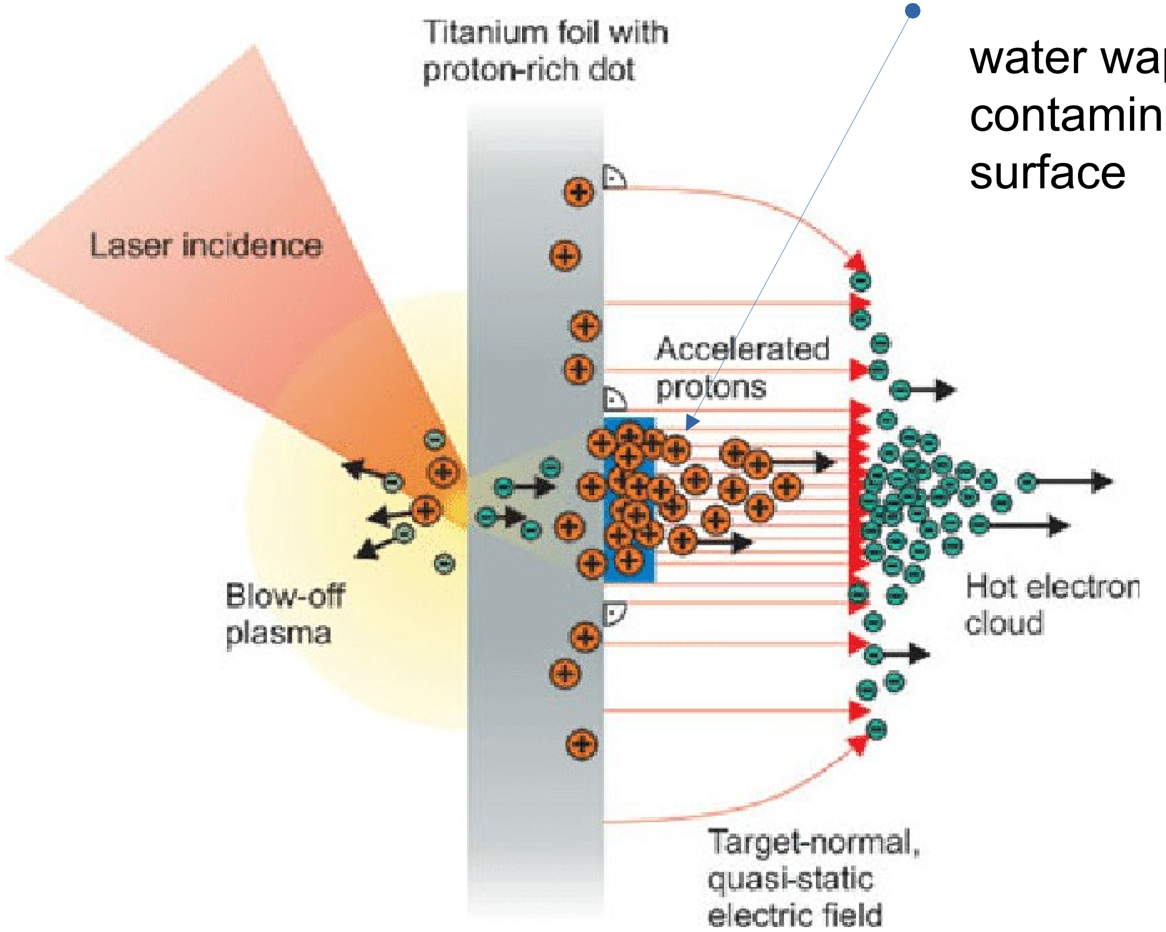
Some general remarks on heavy particles

Till now only electrons are considered, and accelerated:

What to do with protons or heavy ions?

It is not effective to use this method, other schemes are used

Target -Normal Sheath Acceleration (TNSA)
Ions are much more heavier than electrons so
E < 10 MeV for protons



water wapor, contaminated surface

Snavely, et all.
"Intense High-Energy Proton Beams from Petawatt-Laser Irradiation of Solids".
Physical Review Letters. (2020) 85 (14): 2945–2948.

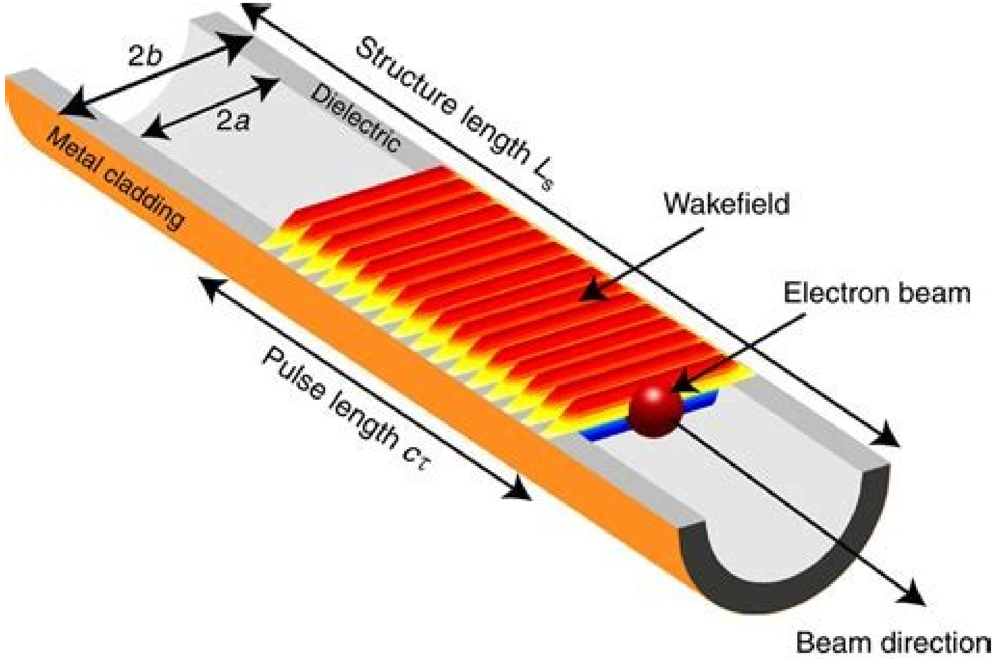
Dielectric wall accelerator

Funded by the European Union

The other very promising and innovative approach
- works for electrons and ions as well
- E >200 MeV/m is possible
- a wave guide from a dielectric is positioned into a traveling wave of a high gradient electric field

This would be ideal, for protons and for hadron therapy

Ultra-High-Current Electron Induction Accelerators
Physics today [0031-9228] Kapetanakos, year:1985 vol:38 iss:2 pg:58



An now finally what is EuPRAXIA Project??

Funded by the European Union

An international consortium to plan, build up and operate all the set-ups I mentioned before on two sites

Now 18 countries are included,

EuPRAXIA =

The number of joined institutes are always increasing now > 50

Story board – it started in 2015

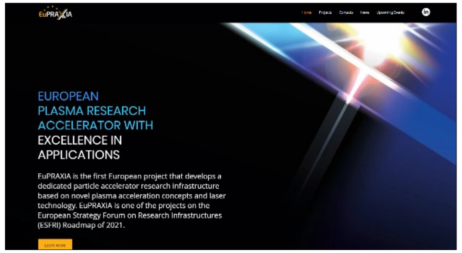
- EuPRAXIA Design Study 2015-19
- ESFRI Roadmap approved VI.2021
- EuPRAXIA PP & DN grants XI.2022 → XI.2026
- EuPRAXIA Consortium & ESFRI submission 2019 → IX.2020
- ESFRI Preparatory Phase 2021→2026

The CDR Conceptual Design Study was published in
Eur. Phys. J. Special Topics **229**, 3675–4284 (2020) ©
https://doi.org/10.1140/epjst/e2020-000127-8

600+ page CDR, 240 scientists contributed

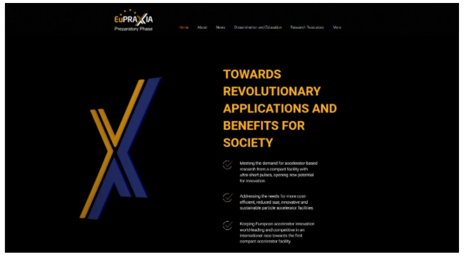
EuPRAXIA Web Structure

Funded by the European Union



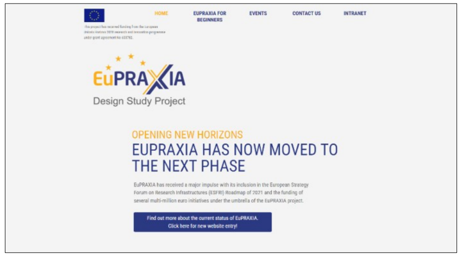
www.eupraxia-facility.org

Preparatory Phase



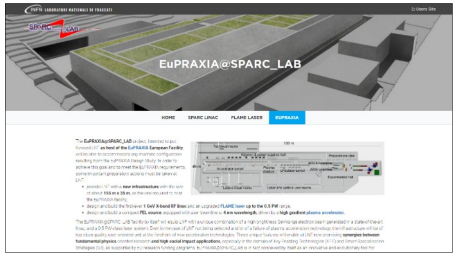
www.eupraxia-pp.org

Design Study (2015 – 2019)



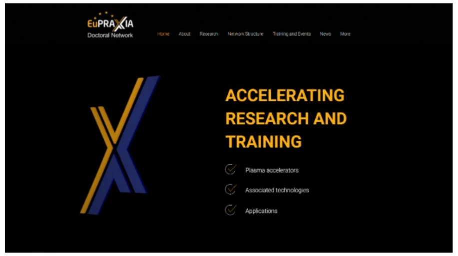
www.eupraxia-project.eu

SPARC_LAB



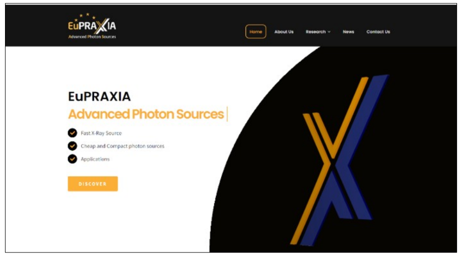
sparclab.lnf.infn.it

Doctoral Network



www.eupraxia-dn.org

Advanced Photon Sources



euaps.infn.it

The EuPRAXIA CDR

Funded by the European Union

- First ever design of a **plasma accelerator facility**.
- **Conceptual Design Report for a distributed research infrastructure** funded by EU Horizon2020 program. Completed by 16+25 institutes.
- Challenges addressed by EuPRAXIA since 2015:
  - **Can plasma accelerators produce usable electron beams**?
  - **For what can we use those beams** while we increase the beam energy towards HEP and collider usages?
- Next phase consortium: **> 50 institutes**
- Preparatory Phase project: **2022 – 2026** (approved)
- Start of 1st operation: **2029**

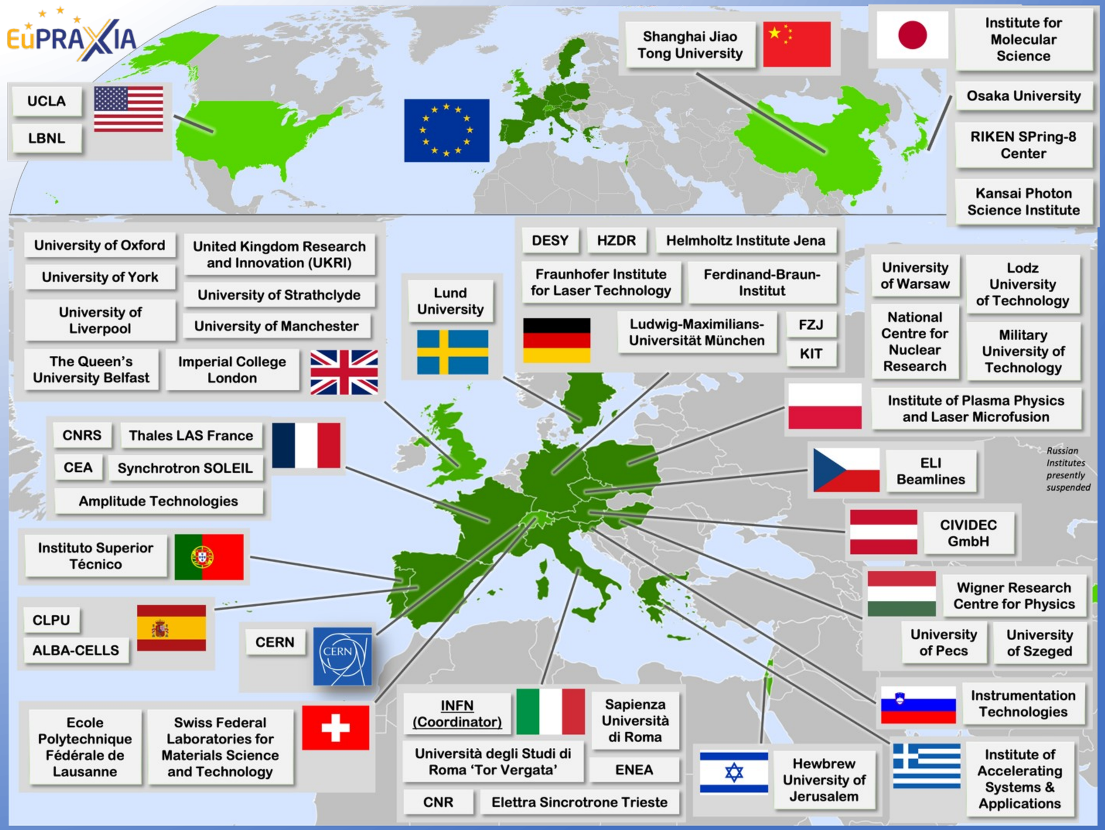
http://www.eupraxia-project.eu

600+ page CDR, 240 scientists contributed

Wide International Collaboration

Funded by the European Union

- **The EuPRAXIA Consortium today: 54 institutes** from **18 countries** plus CERN
- Included in the **ESFRI** Road Map
- **Efficient fund raising:**
  - **Preparatory Phase** consortium (funding EU, UK, Switzerland, in-kind)
  - **Doctoral Network** (funding EU, UK, in-kind)
  - **EuPRAXIA@SPARC_LAB** (Italy, in-kind)
  - **EuAPS Project** (Next Generation EU)



EuPRAXIA Doctoral Network

- In the framework of Marie Skłodowska-Curie Actions a doctoral network started in sept 2023
- all together 12 PhD students were recruted and applied all around the world
- Dr. Carsten Welsh (University of Liverpool is the main organiser in this project)
- beyond studing physics they develop their other soft skills, having numerous extra courses eg. how to give a good talk etv.

- eg. Andres Leiva Genre from Argentina works at University of Pécs, THz accelerator in dielectric media

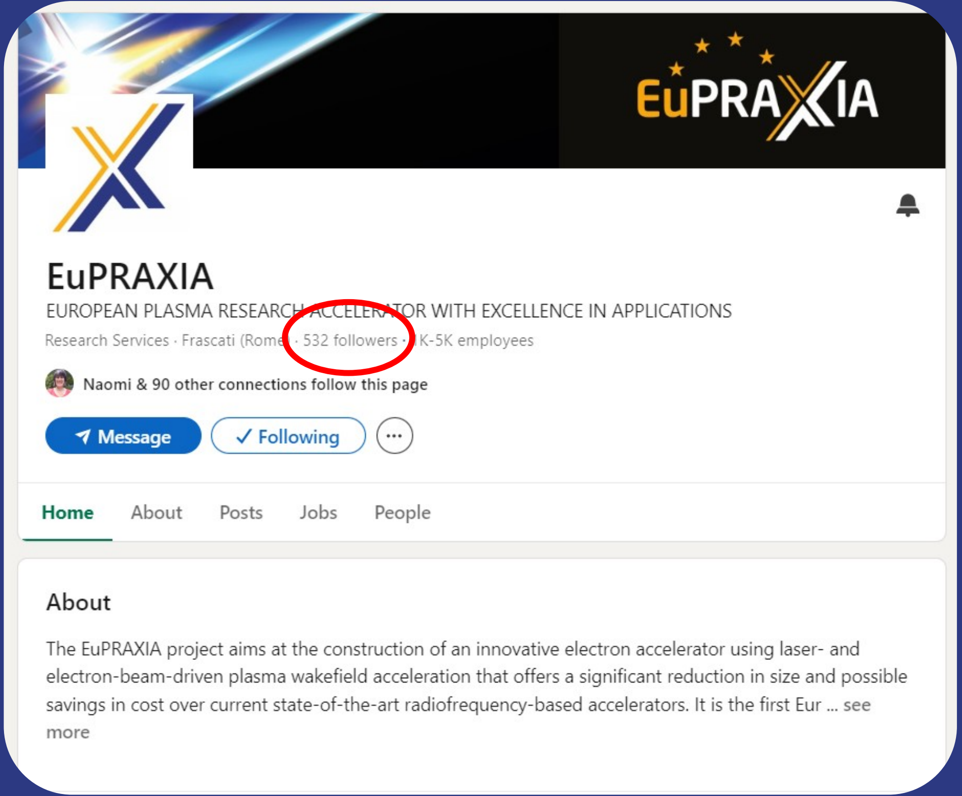
EuPRAXIA-DN: Global Minds,

Accelerating Tomorrowhttps://www.youtube.com/watch?v=6NPgxCdffrE

Social Media (it is done very professional)

Funded by the European Union

- All activities are supported by ULIV's and INFN's established social media channels:
  - X/Twitter: @livuniphysics, @QUASAR_6group, @INFN_, @INFN_LNS
  - Facebook: @theQuasarGroup, @IstitutoFisicaNucleare, @infn.lns
  - Instagram: @livuniphysics, quasar_6roup, @infn_insights, @lnf_infn
  - LinkedIn: EuPRAXIA, QUASAR Group Project T.E.A.M.



- Social media campaigns to boost visibility

EuPRAXIA_PP Project Coordinator: Pierluigi Campana (INFN)
(in september 2024)

Funded by the European Union

Coll. Board
M. Ferrario

Steering Committee

Scientific and Technical Advisory Board

Board of Financial Sponsors

WP1 - Coordination & Project Management
P. Campana, INFN
M. Ferrario, INFN

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C. Welsch, U Liverpool
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A. Specka, CNRS
A. Ghigo, INFN

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A. Falone, INFN

WP5 - User Strategy and Services
F. Stellato, U Tor Vergata
E. Principi, ELETTRA

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B. Cros, CNRS
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R. Fonseca, IST
S. Pioli, INFN

WP8 - Theory & Simulation
J. Vieria, IST
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WP9 - RF, Magnets & Beamline Components
S. Antipov, DESY
F. Nguyen, ENEA

WP10 - Plasma Components & Systems
K. Cassou, CNRS
R. Shalloo, DESY

WP11 - Applications
G. Sarri, U Belfast
E. Chiadroni,U Sapienza

WP12 - Laser Technology, Liaison to Industry
L. Gizzi, CNR
P. Crump, FBH

WP13 - Diagnostics
A. Cianchi, U Tor Vergata
R. Ischebeck, EPFL

WP14 - Transformative Innovation Paths
B. Hidding, U Dusseldorf
S. Karsch, LMU

WP15 - TDR EuPRAXIA @SPARC-lab
C. Vaccarezza, INFN
R. Pompili, INFN

WP16 - TDR EuPRAXIA Site 2
A. Molodozhentsev, ELI-Beamlines
R. Pattahil, STFC

There are 16 Workpackages

Up to date informations

(in september 2024)

The deliverables, deadlines status reports are always mentioned by the work package leaders

the present status of the Workpackages can be found: EuPRAXIA PP Annual Meeting 2024 2024 Sept 22 -28 Isola d'Elba Italy

https://agenda.infn.it/event/41613/

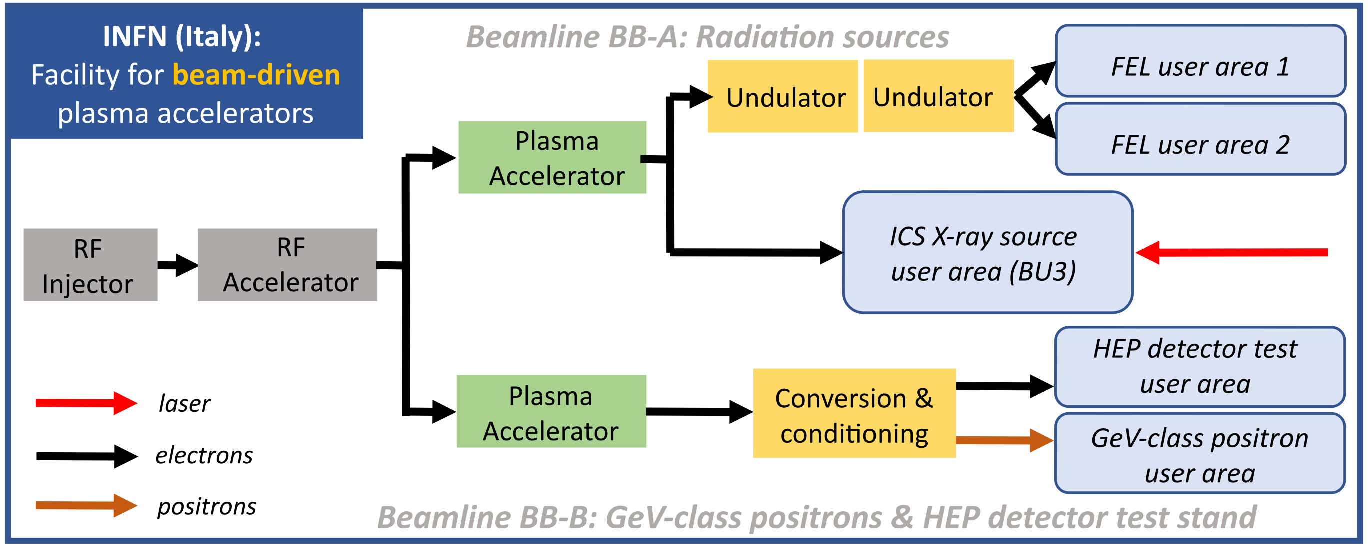
Phased Implementation of Construction Sites

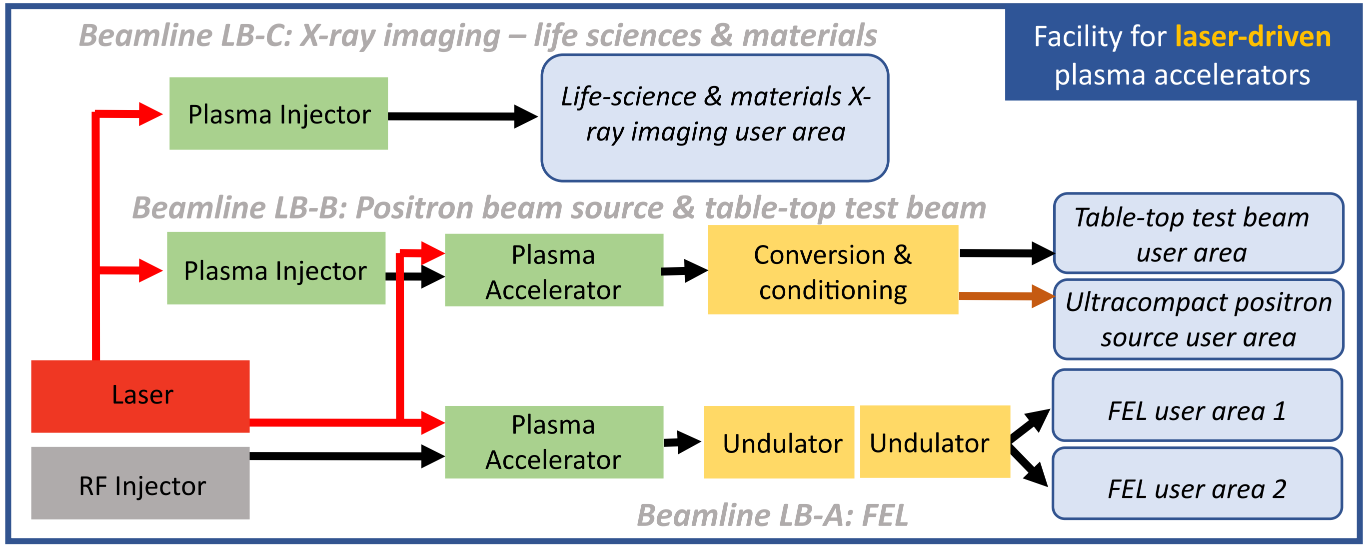
Funded by the European Union

	Laser-driven	Beam-driven
Phase 1	✓ FEL beamline to 1 GeV + user area 1 ✓ Ultracompact positron source beamline + positron user area	✓ FEL beamline to 1 GeV + user area 1 ✓ GeV-class positrons beamline + positron user area
Phase 2	✓ X-ray imaging beamline + user area ✓ Table-top test beams user area ✓ FEL user area 2 ✓ FEL to 5 GeV	✓ ICS source beamline + user area ✓ HEP detector tests user area ✓ FEL user area 2 ✓ FEL to 5 GeV
Phase 3	✓ High-field physics beamline / user area ✓ Other future developments	✓ Medical imaging beamline / user area ✓ Other future developments

ELI Beamlines/ELI-ERIC (Prag)
EPAC (Oxford)
Centro de Léseres Pulsados (Salamanca)
CNR (Pisa)

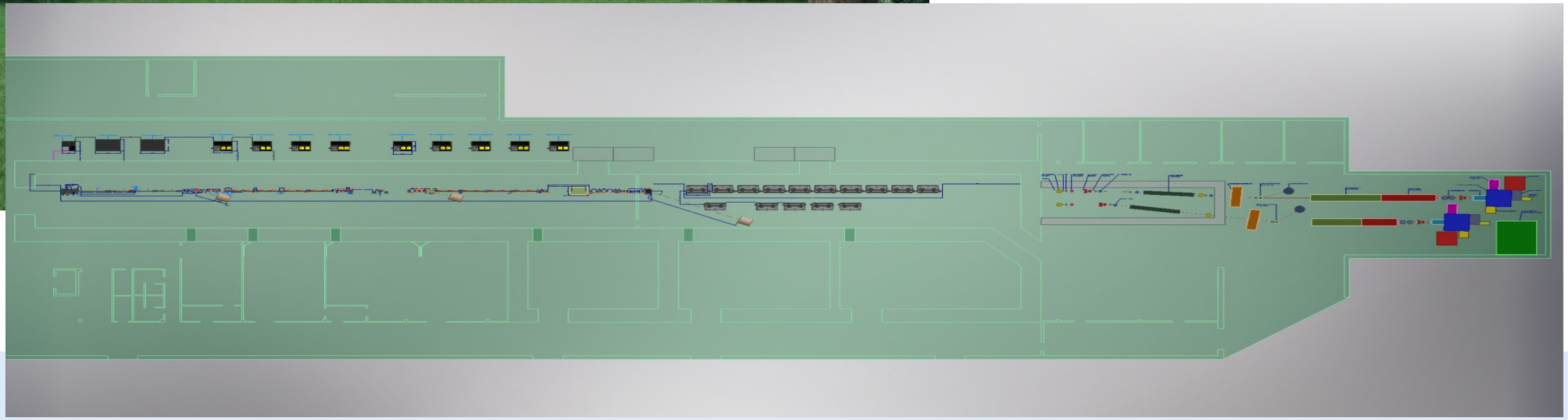
Frascati Itali FIXED





EuPRAXIA Headquarter and Site 1: EuPRAXIA@SPARC_LAB

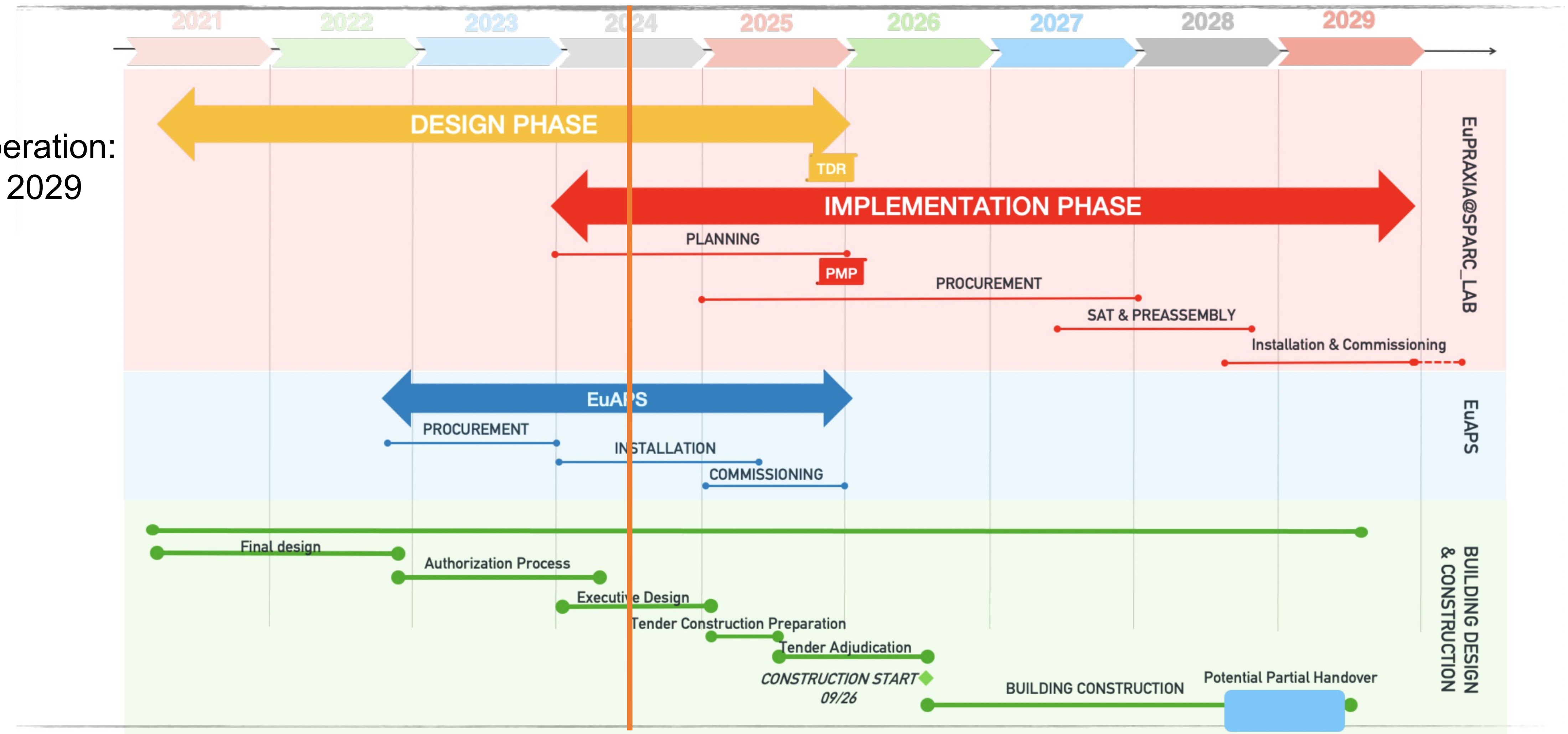
Funded by the European Union



- Frascati`s future facility
- > 130 M€ invest funding
- Beam-driven plasma accelerator
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator (X band with CERN)

EuPRAXIA@SPARC_LAB baseline updating

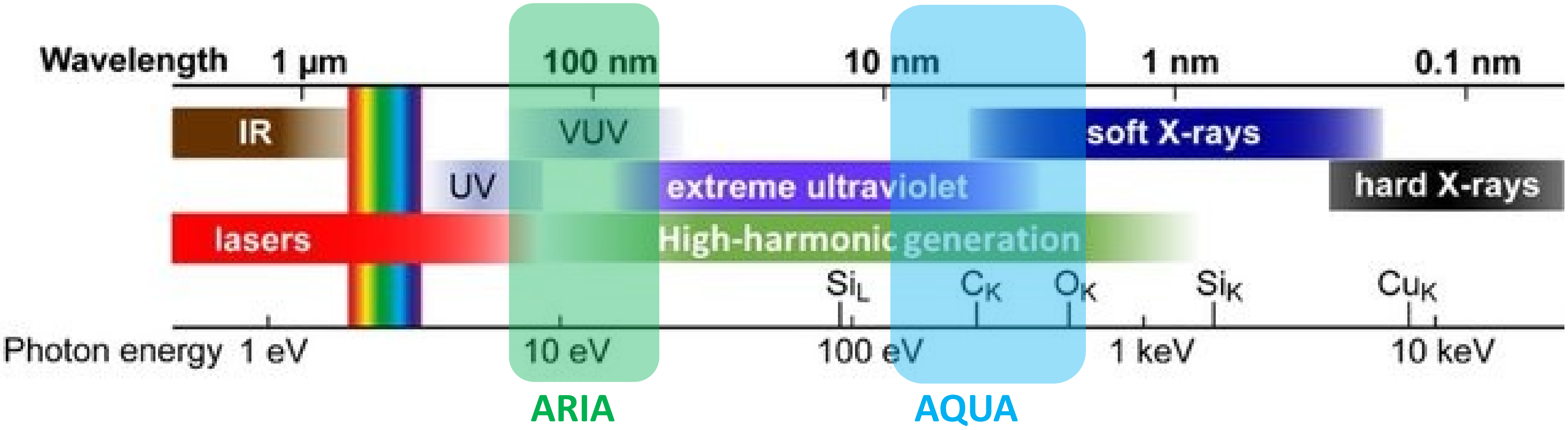
in operation:
after 2029



Funded by the European Union

Usage of EuPRAXIA@SPARC_LAB

ARIA will be complementary to the other EuPRAXIA@SPARC_LAB FEL beamline, **AQUA**
AQUA is a soft-X-ray SASE FEL beamline that will deliver photons in the region between 4 and 10 nm

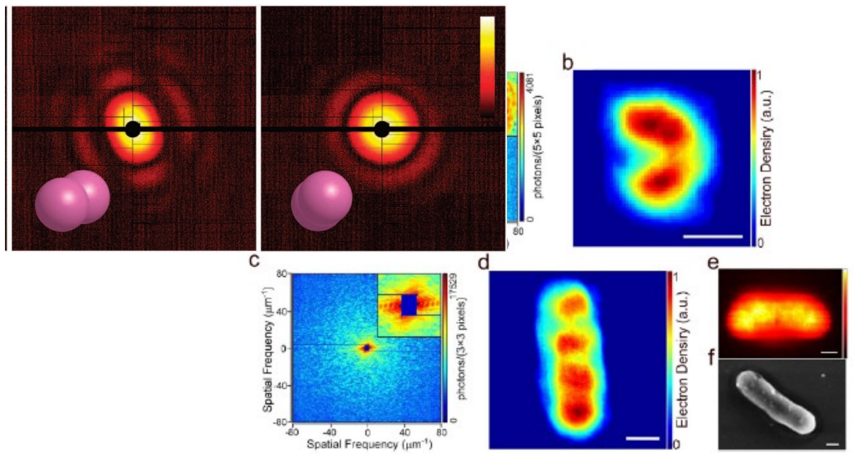


Parameter	Value
Wavelength	4-10 nm
Photons/pulse	10^{10} - 10^{11}
Pulse duration	< 50 fs
Repetition rate	100 Hz

Science @ **AQUA** in a nutshell

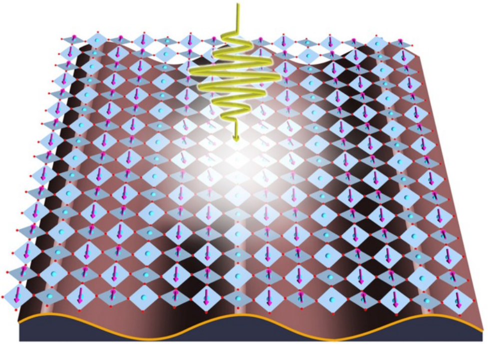
What is is good for?

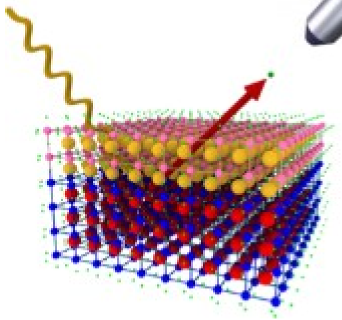
Coherent imaging in the **water window**, including stereoimaging schemes



Hydrated environment measurements on bacteria, viruses, nanoparticles, ashes…

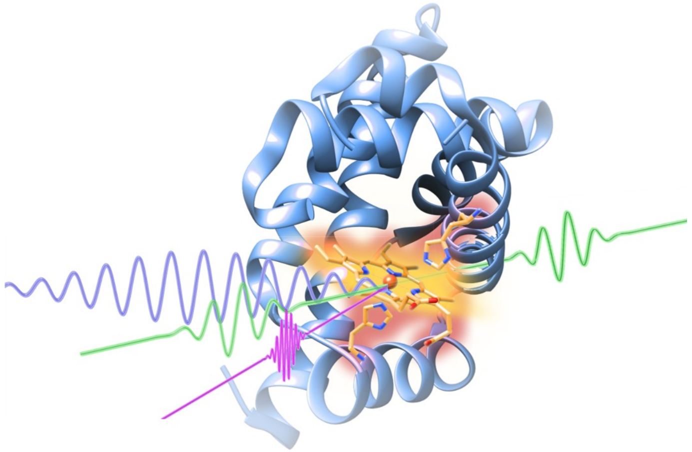
X-ray & **Photoemission** pump-probe spectroscopy





Ultrafast studies on hydrocarbons, aminoacids, alloys, warm-dense matter, cuprates, catalysts, batteries

Ultrafast
Raman spectroscopy
on metalloproteins
and organometallic molecules



EuPRAXIA second site

Funded by the European Union

The first two sites have larger chances…
For us in Middle Europe Prague is favourable...

EPAC has also a neutron center which is an advantage

Site candidate's visits
Serious of workshops

07/ 2023- 01/ 2024

2nd site selection criteria → 07/2024
"Bit-Book" preparation → **12/2024**

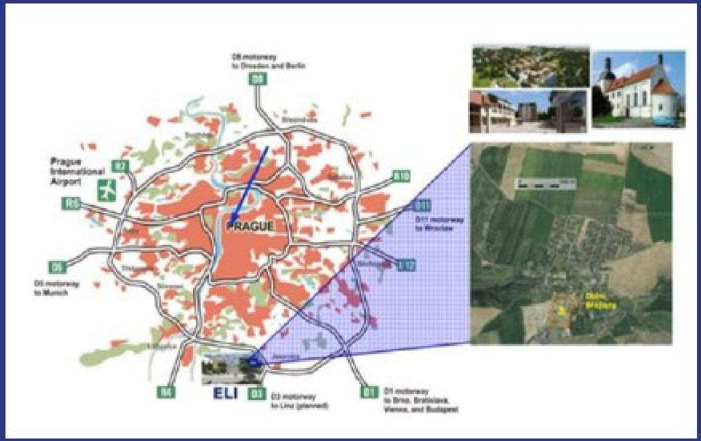
Goal: CB-decision of the 2nd site proposal → 03/2025
Status report on TDR for 2nd site → 04/2026

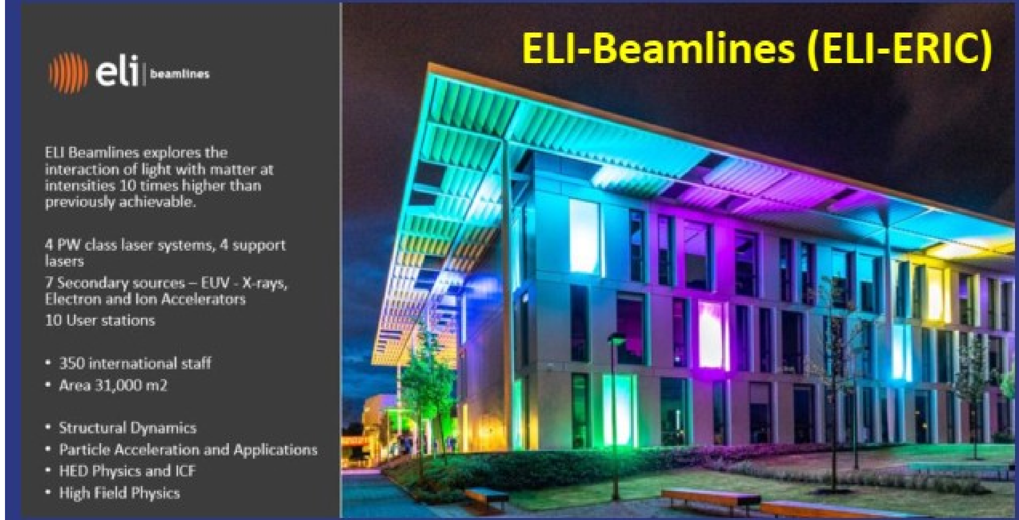
ELI-Beamlines: LPA-FEL vision

Funded by the European Union

Overview of existing facility

Location: near Prague (CZ)



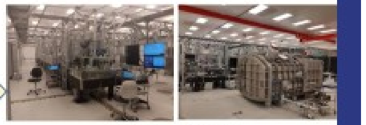


PRE-INVESTED BUDGET

... wo personal cost

ELI-beamlines building (offices, labs, halls)	Total: ~ 100 MEur
L2-LUIS technology	
L2-laser hall (including relevant technology)	~ 5 MEur
L2-DUHA laser	~ 5.5 MEur
L2-to-E5 laser beam transport	~ 1.5 MEur
E5 experimental hall @ Local Control Room (including vacuum, cooling, cabling, gases, compressed air, CS, MSI, PSS, Radiation-MS)	~ 10 MEur
E5 LUIS technology	~ 2.5 MEur
(L2-Hall) + (E5-Hall) + (L2-Laser) + (L2-BT) + LUIS	~ 25 MEur

L2-hall and DUHA-Laser



E5-hall and LUIS

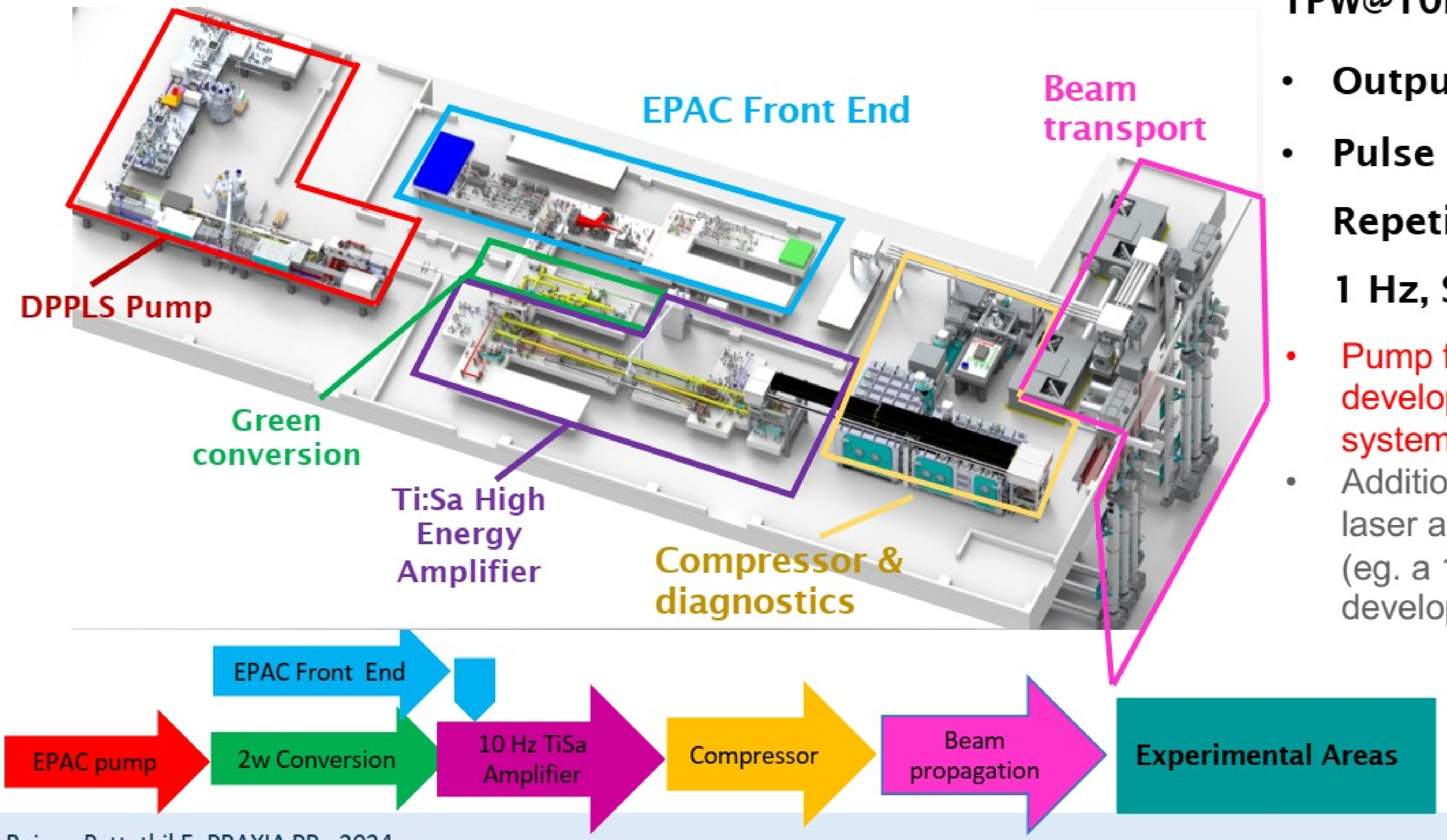
Presented: EuPRAXIA CoE workshop / June 5-7, 2023

www.eupraxia-pp.org

EuPRAXIA second site, Oxford

Funded by the European Union

EPAC Laser system



1PW@10Hz

- **Output Energy 30 J**
- **Pulse duration ≤ 30 fs**

  Repetition rate 10 Hz, 1 Hz, Shot on Demand
- Pump for Ti:S is CLF developed 100J DiPOLE system.
- Additional space for future laser and experimental areas (eg. a 100Hz system under development)

Rajeev Pattathil EuPRAXIA PP - 2024

Last but not least the planned prices

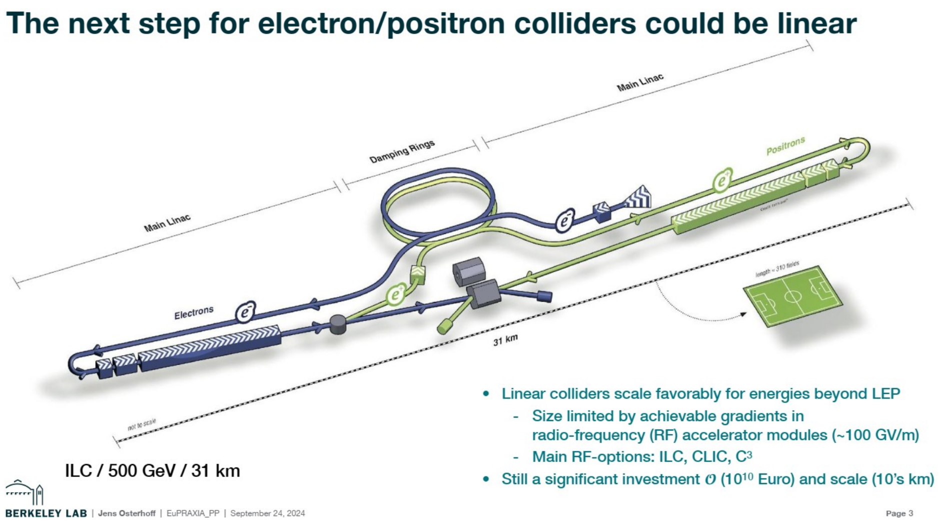
Funded by the European Union

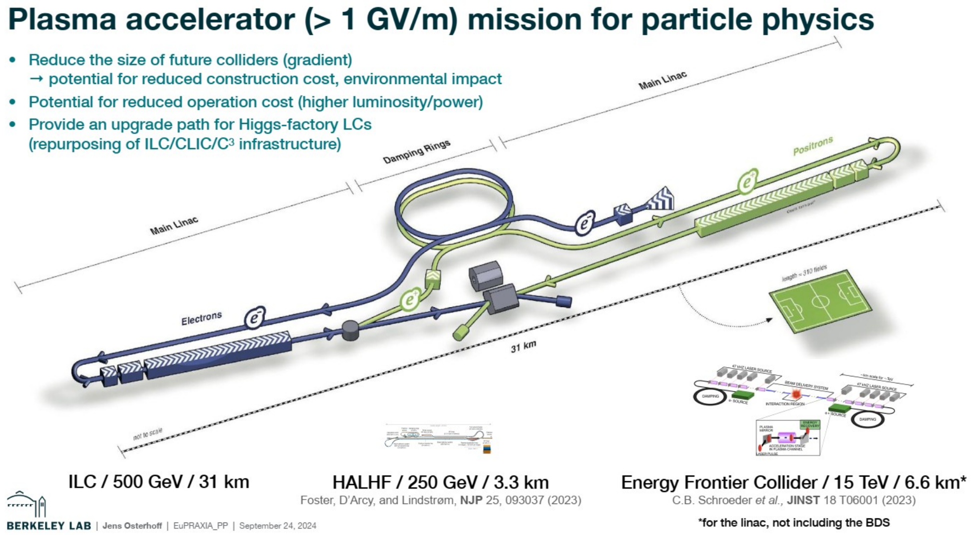
- The LHC in CERN was > $7*10^9$ (billion) euro 2010
- The European Spallation Sources was < $2*10^9$ (billion) euro - green field investment with a 1km long LINAC 1GeV proton 2022
- ELI-ALPS Hungary was about 300 million Euro – green field investment 2020
- EuPRAXIA Beam Driven site in Italy – "development on a site" > 130 million Euro
- EuPRAXIA laser driven ELI Beamlines/ELI-ERIC (Prag) - 20 million Euro
  EPAC (Oxford) - 60 – 80 millio Euro

Future plans after EuPRAXIAs in operation

- Overview of plasma based linear collider efforts
  Jens Osterhoff – Lawrence Berkley National Lab

speculation if it could be done with plasma accelerator, it is known that for electron it is fine but for pozitron the gradiane is much smaller it could be asymmetric





Possible usages of EuPRAXIAs in operation

Towards radiotherapy with ultha high dose rate the FALSH effect

1

Dose rate >40Gy/s
Total dose > 2-10Gy
Maximum irradiation time <200ms
Instantaneous dose rate >10^5-10^6 Gy/s
Role of pulse time structure unclear (average vs instantaneous dose rate)

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journal homepage: www.clinicaloncologyonline.net
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Overview

Biological Benefits of Ultra-high Dose Rate FLASH Radiotherapy: Sleeping Beauty Awoken

M.-C. Vozenin [*†], J.H. Hendry [‡], C.L. Limoli [§]

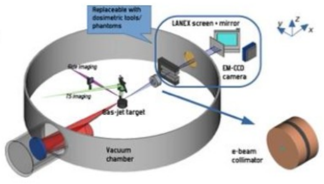
Radiotherapy and Oncology 139 (2019) 18–22

Treatment of a first patient with FLASH-radiotherapy

Jean Bourhis [a,b,*], Wendy Jeanneret Sozzi [a], Patrik Gonçalves Jorge [a,b,c], Olivier Gaide [d], Claude Bailat [c], Fréderic Duclos [a], David Patin [a], Mahmut Ozsahin [a], Francois Bochud [c]

OPEN

Toward an effective use of laser-driven very high energy electrons for radiotherapy: Feasibility assessment of multi-field and intensity modulation irradiation schemes



Luca Labate[1], Daniele Palla[1], Daniele Panetta[2], Federico Avella[1], Federica Baffigi[1], Fernando Brandi[1], Fabio Di Martino[3], Lorenzo Fulgentini[1], Antonio Giulietti[1], Petra Köster[1], Davide Terzani[1,4], Paolo Tomassini[1], Claudio Traino[3] & Leonida A. Gizzi[1]

Scientific Reports | (2020) 10:17307

2

Towards Societal Applications: Laser-driven radioisotope production — eli nuclear physics

- ***The full chain of radioisotope production with lasers has never been demonstrated***. *Small laser (hundreds of TW) systems have the greatest potential.*
- *Several studies (review: Z.Sun AIP Adv. 2021) shown isotope production based on single/few shots events, and then extrapolated to hours beamtime.*
- *2 examples: ^{11}C with **proton** beams via $^{11}B(p,n)^{11}C$ and ^{62}Cu with **gamma** beams via $^{63}Cu(\gamma,n)^{62}Cu$:*

Ref. ^{11}C prod.	E [J]	Pulse T [fs]	Rep. [Hz]	Activ [MBq]	Obs.
Tayyab et al. 2019	2.4	25	1	9	7-10 shots (2-3 min) meas. Cu,Al, Ni foils
Singth et al. 2018	3	30	1	7.6	Spectrum meas. Al foils, analysys in *Penas et al.*
Penas et al. 2024	25	250	1	21.7	174 shots at 0.1 Hz meas., Al foils
ELI-NP estim.	**8**	**23**	**1**	**30**	PIC + TENDL21 CS, water-leaf tg.

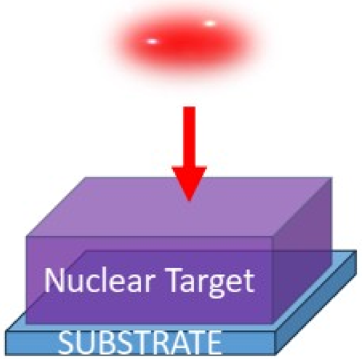
Ref. ^{62}Cu prod.	E [J]	Pulse T [fs]	Rep. [Hz]	Activ [MBq]	Obs.
Ma et al. 2019	11.5	33	1	180	PIC + Geant4, Varlamov CS
Lobok et al. 2022	4	30	1	87	PIC + Geant4
ELI-NP estim.	**2.3**	**23**	**1**	**35**	**PIC + Geant4, TENDL21 CS.**

Possible usage of EuPRAXIAs in operation

Funded by the European Union

Laser-Driven Nuclear Reactions

eli nuclear physics



Laser Boron Fusion Reactor

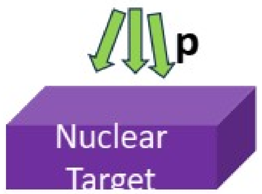
H. Hora *et al.*, "Laser Boron Fusion Reactor With Picosecond Petawatt Block Ignition," in *IEEE Transactions on Plasma Science*, vol. 46, no. 5, pp. 1191-1197, May 2018, doi: 10.1109/TPS.2017.2787670.

Aneutronic fusion of hydrogen with the boron isotope 11, **$H^{11}B$**.

At local thermal equilibrium, is 10^{5} times more difficult than fusion of deuterium and tritium (DT)
But at extreme nonequilibrium plasma conditions the fusion of $H^{11}B$ is comparable to DT fusion

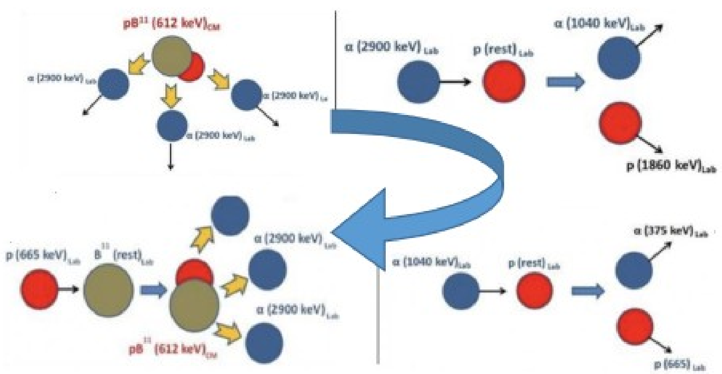
Method

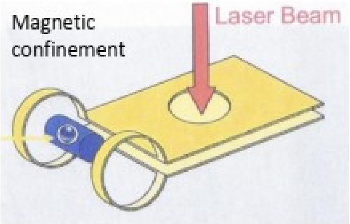
- **H11B rod a cm size**
- **Main laser for driven-ignition:** 30PW laser energy and ps pulse duration
- **A second laser for magnetic field generation of ~10 kT:** 1kJ energy and ns pulse duration

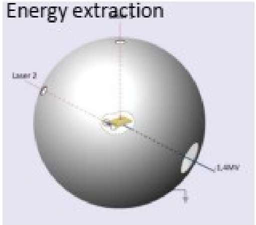


Pitcher-Catcher Nuclear Reactions

Nuclear reaction schema







Using a container electrostatically charged to -1.4 MV, it will be possible to generate about **277 kWh** of energy per laser **shot**.

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- EuAPS

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Thank you for your attention!