EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA R&D for Plasma Colliders (EuCOLL)

Massimo Ferrario (INFN)

on behalf of the EuPRAXIA Collaboration

17 September 2024

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

EuPRAXIA

European Strategy for Particle Physics
Accelerator R&D Roadmap

Funded by the European Union

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Accelerator R&D Roadmap

European Strategy Update

Laboratory Directors Group

European Strategy for Particle Physics - Accelerator R&D Roadmap

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Introduction & conclusion

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High-field magnets

Panel members: P. Védrine[b,†] (Chair), L. García-Tabarés[k] (Co-Chair), B. Auchmann[g], A. Ballarino[a], B. Baudouy[b], L. Bottura[a], P. Fazilleau[b], M. Noe[o], S. Prestemon[p], E. Rochepault[b], L. Rossi[q], C. Senatore[r], B. Shepherd[s]

High-gradient RF structures and systems

Panel members: S. Bousson[c,‡] (Chair), H. Weise[e] (Co-Chair), G. Burt[d], G. Devanz[b], A. Gallo[f], F. Gerigk[a], A. Grudiev[a], D. Longuevergne[c], T. Proslier[b], R. Ruber[t]

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High-gradient plasma and laser accelerators

Panel members: R. Assmann[e,f,**] (Chair), E. Gschwendtner[a] (Co-Chair), K. Cassou[c], S. Corde[z], L. Corner[i], B. Cros[aa], M. Ferrario[f], S. Hooker[bb], R. Ischebeck[g], A. Latina[a], O. Lundh[cc], P. Muggli[dd], P. Nghiem[b], J. Osterhoff[e], T. Raubenheimer[w,ee], A. Specka[ff], J. Vieira[gg], M. Wing[hh]

Associated members: C. Geddes[p], M. Hogan[w], W. Lu[v], P. Musumeci[ii]

Bright muon beams and muon colliders

Panel members: D. Schulte[a,††] (Chair), M. Palmer[jj] (Co-Chair), T. Arndt[o], A. Chancé[b], J. P. Delahaye[a], A. Faus-Golfe[c], S. Gilardoni[a], P. Lebrun[a], K. Long[h,kk], E. Métral[a], N. Pastrone[ll], L. Quettier[b], T. Raubenheimer[w,ee], C. Rogers[h], M. Seidel[g,mm], D. Stratakis[nn], A. Yamamoto[y]

Associated members: A. Grudiev[a], R. Losito[a], D. Lucchesi[oo,pp]

Energy-recovery linacs

Panel members: M. Klein[i,‡‡] (Chair), A. Hutton[x] (Co-Chair), D. Angal-Kalinin[qq], K. Aulenbacher[rr], A. Bogacz[x], G. Hoffstaetter[ss,jj], E. Jensen[a], W. Kaabi[c], D. Kayran[jj], J. Knobloch[tt,uu], B. Kuske[uu], F. Marhauser[x], N. Pietralla[vv], O. Tanaka[y], C. Vaccarezza[f], N. Vinokurov[ww], P. Williams[qq], F. Zimmermann[a]

Associated members: M. Arnold[vv], M. Bruker[x], G. Burt[d], P. Evtushenko[xx], J. Kühn[uu], B. Militsyn[qq], A. Neumann[uu], B. Rimmer[x]

Sub-Panel on CERC and ERLC: A. Hutton[x] (Chair), C. Adolphsen[w], O. Brüning[a], R. Brinkmann[e], M. Klein[i], S. Nagaitsev[nn], P. Williams[qq], A. Yamamoto[y], K. Yokoya[y], F. Zimmermann[a]

The FCC-ee R&D programme

Authors: M. Benedikt[a,γ], A. Blondel[yy,r,δ], O. Brunner[a], P. Janot[a], E. Jensen[a], M. Koratzinos[zz],

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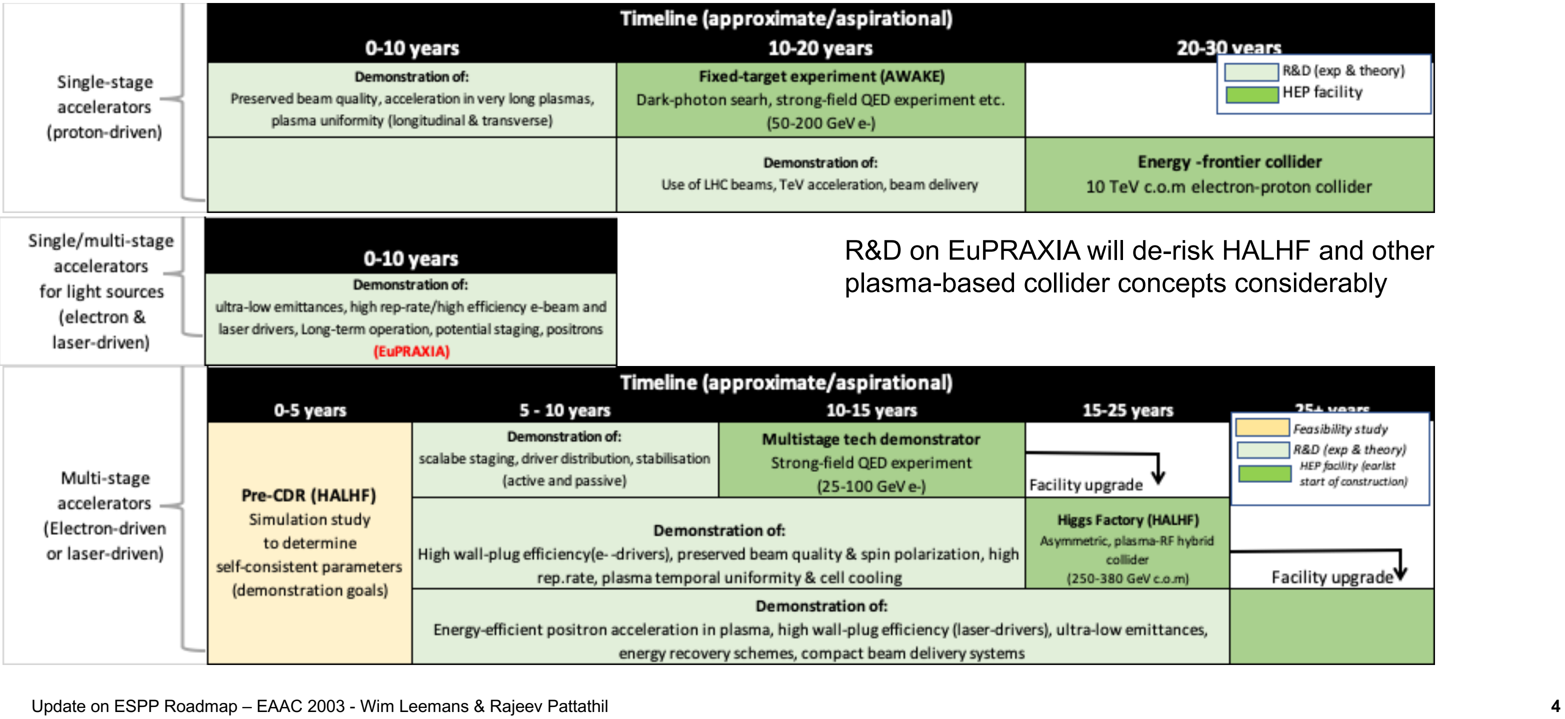
Open issues relevant for a LC design:

- high quality electron beams production and acceleration,
- high quality positron beams production and acceleration,
- high repetition rate,
- high efficiency,
- multiple modules staging
- polarized beams

ESPP Roadmap Update – Plasma Accelerators

Funded by the European Union

There are a number of large, international projects at different levels of development that explore some accelerator schemes and address issues relevant for application to particle physics like EuPRAXIA at LNF, AWAKE at CERN, HALHF in Europe, FACET II in the US.



Single-stage accelerators (proton-driven)

Timeline (approximate/aspirational)		
0-10 years	**10-20 years**	**20-30 years**
Demonstration of: Preserved beam quality, acceleration in very long plasmas, plasma uniformity (longitudinal & transverse)	**Fixed-target experiment (AWAKE)** Dark-photon searh, strong-field QED experiment etc. (50-200 GeV e-)	
	Demonstration of: Use of LHC beams, TeV acceleration, beam delivery	**Energy -frontier collider** 10 TeV c.o.m electron-proton collider

R&D (exp & theory)
HEP facility

Single/multi-stage accelerators for light sources (electron & laser-driven)

0-10 years
Demonstration of: ultra-low emittances, high rep-rate/high efficiency e-beam and laser drivers, Long-term operation, potential staging, positrons **(EuPRAXIA)**

R&D on EuPRAXIA will de-risk HALHF and other plasma-based collider concepts considerably

Multi-stage accelerators (Electron-driven or laser-driven)

Timeline (approximate/aspirational)				
0-5 years	**5 - 10 years**	**10-15 years**	**15-25 years**	**25+ years**
Pre-CDR (HALHF) Simulation study to determine self-consistent parameters (demonstration goals)	**Demonstration of:** scalabe staging, driver distribution, stabilisation (active and passive)	**Multistage tech demonstrator** Strong-field QED experiment (25-100 GeV e-)	Facility upgrade	
	Demonstration of: High wall-plug efficiency(e- -drivers), preserved beam quality & spin polarization, high rep.rate, plasma temporal uniformity & cell cooling		**Higgs Factory (HALHF)** Asymmetric, plasma-RF hybrid collider (250-380 GeV c.o.m)	Facility upgrade
	Demonstration of: Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser-drivers), ultra-low emittances, energy recovery schemes, compact beam delivery systems			

Feasibility study
R&D (exp & theory)
HEP facility (earlist start of construction)

Update on ESPP Roadmap – EAAC 2003 - Wim Leemans & Rajeev Pattathil

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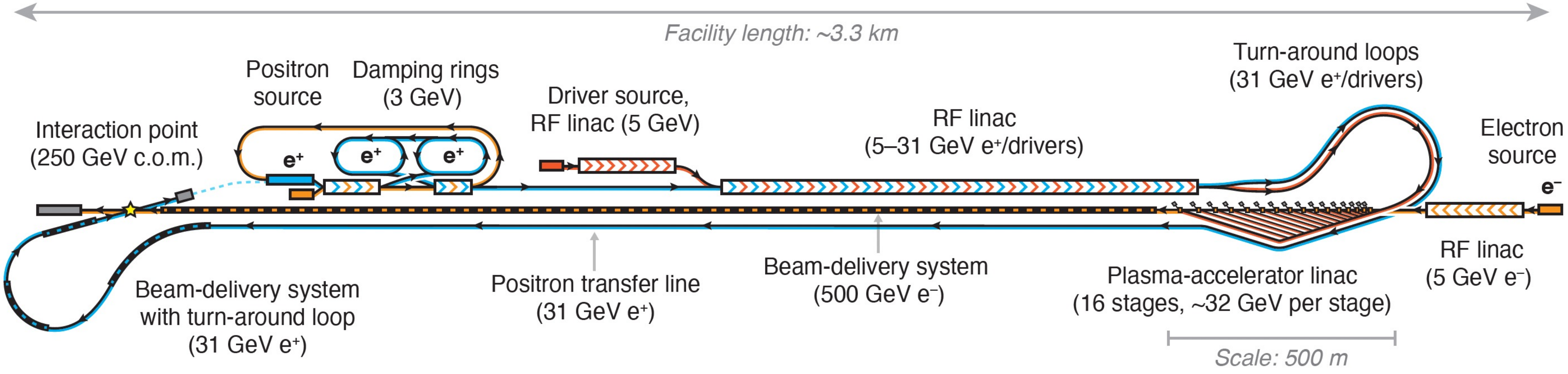
An indirect contribution to collider studies is a plasma injector for the large CEPS collider developed in China. Similar plans exist for PETRA4 and possibly for FCCee.

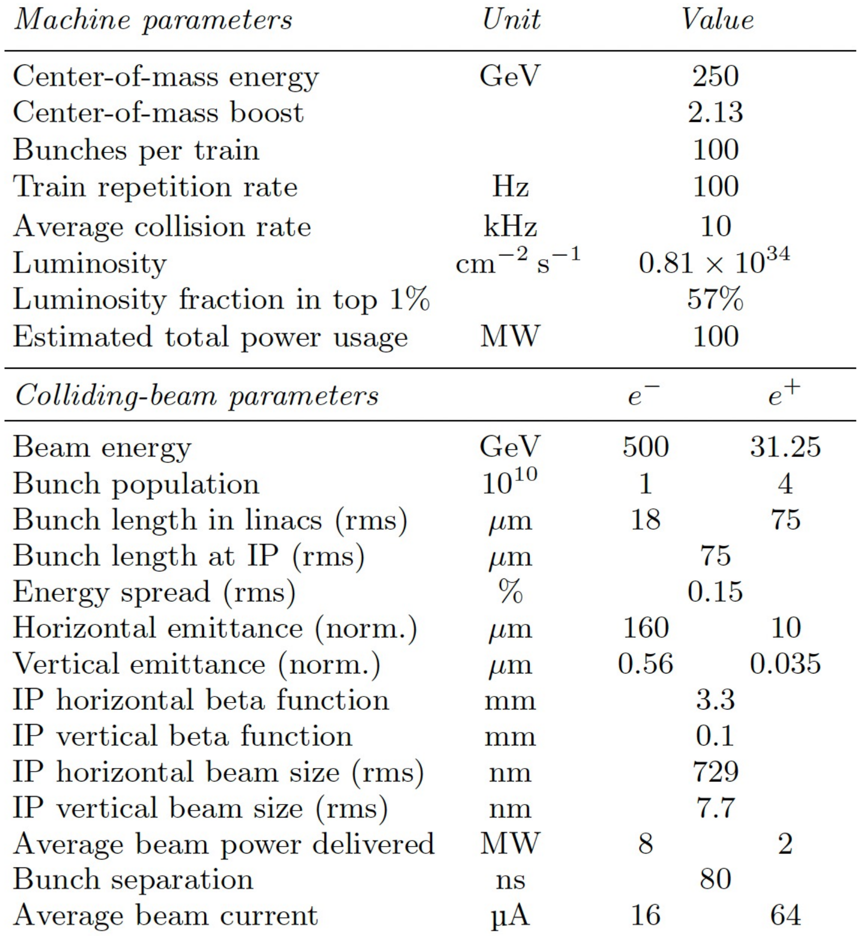
Hybrid Asymmetric Linear Higgs Factory (HALHF)

B. Foster, R. D’Arcy & C.A. Lindstrøm



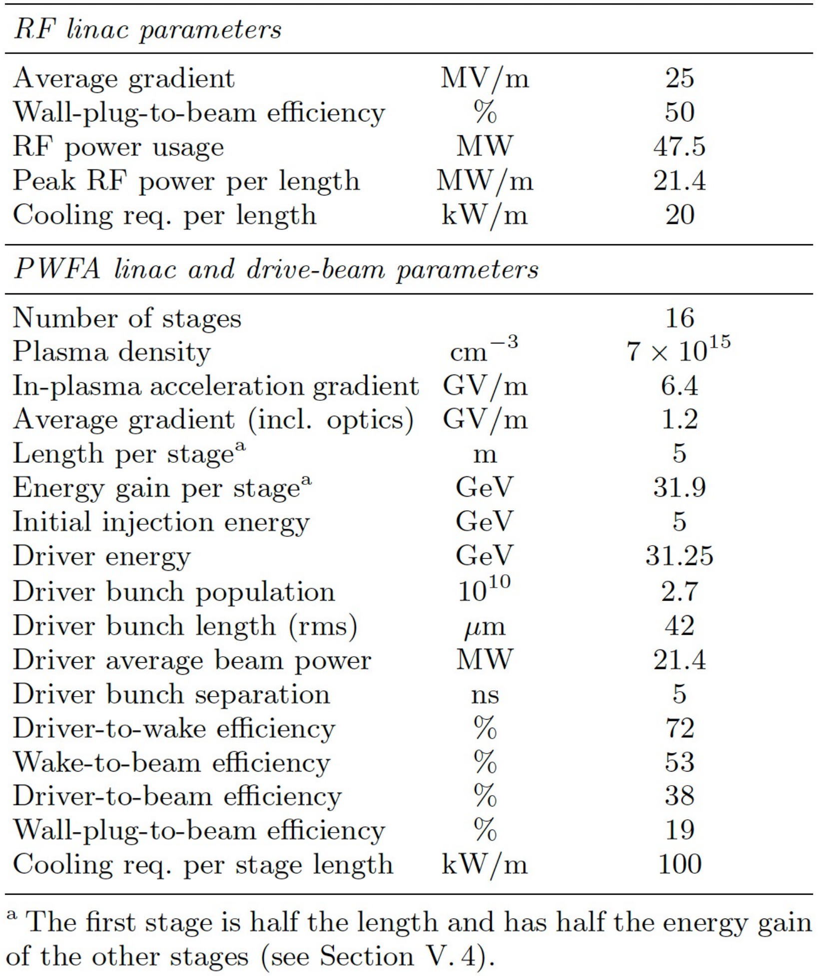
Foster, D’Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)
Lindstrøm, D’Arcy and Foster, arXiv:2312.04975

HALHF Parameter Table



Machine parameters	*Unit*	*Value*
Center-of-mass energy	GeV	250
Center-of-mass boost		2.13
Bunches per train		100
Train repetition rate	Hz	100
Average collision rate	kHz	10
Luminosity	$\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	0.81×10^{34}
Luminosity fraction in top 1%		57%
Estimated total power usage	MW	100

Colliding-beam parameters		e^-	e^+
Beam energy	GeV	500	31.25
Bunch population	10^{10}	1	4
Bunch length in linacs (rms)	μm	18	75
Bunch length at IP (rms)	μm	75	
Energy spread (rms)	%	0.15	
Horizontal emittance (norm.)	μm	160	10
Vertical emittance (norm.)	μm	0.56	0.035
IP horizontal beta function	mm	3.3	
IP vertical beta function	mm	0.1	
IP horizontal beam size (rms)	nm	729	
IP vertical beam size (rms)	nm	7.7	
Average beam power delivered	MW	8	2
Bunch separation	ns	80	
Average beam current	µA	16	64



RF linac parameters		
Average gradient	MV/m	25
Wall-plug-to-beam efficiency	%	50
RF power usage	MW	47.5
Peak RF power per length	MW/m	21.4
Cooling req. per length	kW/m	20

PWFA linac and drive-beam parameters		
Number of stages		16
Plasma density	cm^{-3}	7×10^{15}
In-plasma acceleration gradient	GV/m	6.4
Average gradient (incl. optics)	GV/m	1.2
Length per stage[a]	m	5
Energy gain per stage[a]	GeV	31.9
Initial injection energy	GeV	5
Driver energy	GeV	31.25
Driver bunch population	10^{10}	2.7
Driver bunch length (rms)	μm	42
Driver average beam power	MW	21.4
Driver bunch separation	ns	5
Driver-to-wake efficiency	%	72
Wake-to-beam efficiency	%	53
Driver-to-beam efficiency	%	38
Wall-plug-to-beam efficiency	%	19
Cooling req. per stage length	kW/m	100

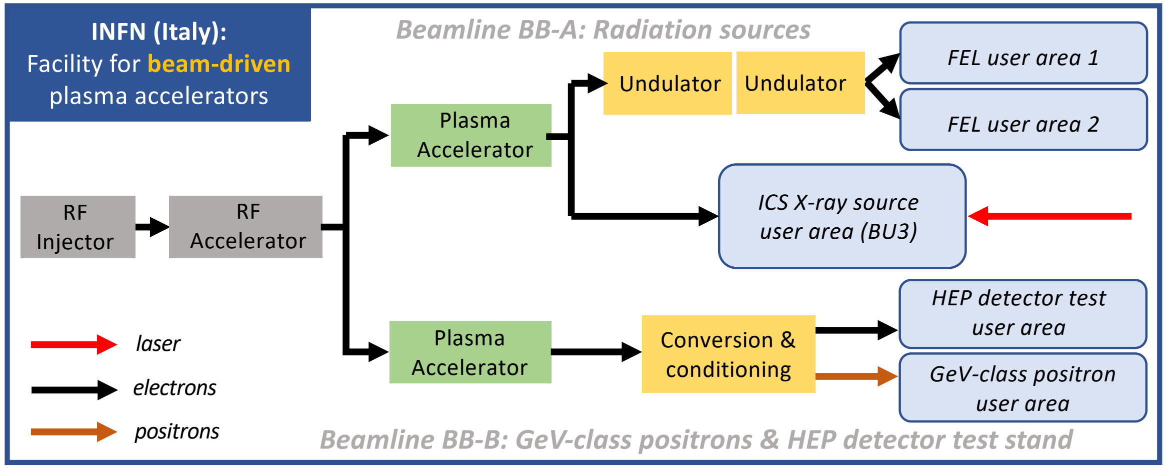
[a] The first stage is half the length and has half the energy gain of the other stages (see Section V. 4).

B. Foster, CLIC Plenary, 12/23

EuPRAXIA Phased Implementation

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



INFN (Italy):
Facility for **beam-driven**
plasma accelerators

Beamline BB-A: Radiation sources

RF Injector

RF Accelerator

Plasma Accelerator

Undulator

Undulator

FEL user area 1

FEL user area 2

ICS X-ray source user area (BU3)

Plasma Accelerator

Conversion & conditioning

HEP detector test user area

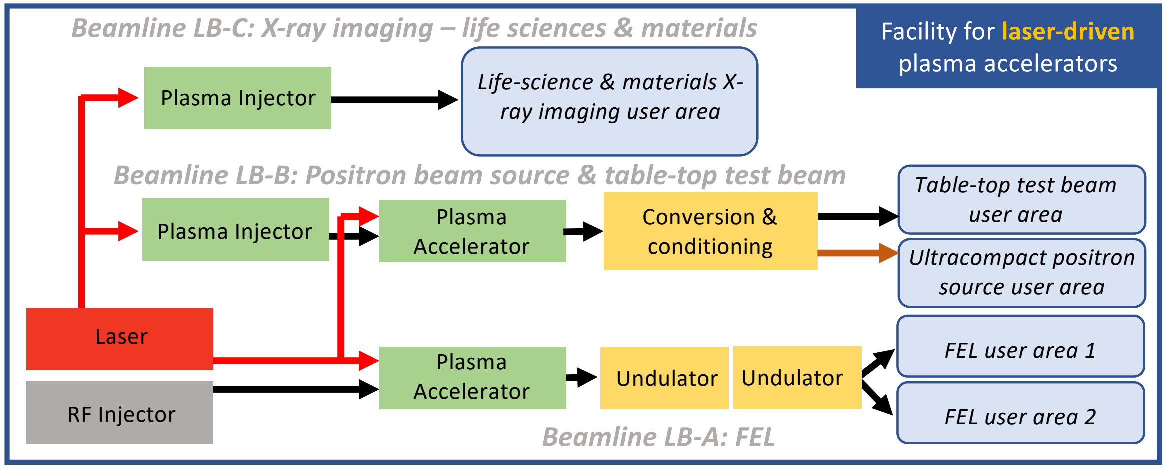
GeV-class positron user area

Beamline BB-B: GeV-class positrons & HEP detector test stand

laser

electrons

positrons



Facility for **laser-driven**
plasma accelerators

Beamline LB-C: X-ray imaging – life sciences & materials

Plasma Injector

Life-science & materials X-ray imaging user area

Beamline LB-B: Positron beam source & table-top test beam

Plasma Injector

Plasma Accelerator

Conversion & conditioning

Table-top test beam user area

Ultracompact positron source user area

Laser

RF Injector

Plasma Accelerator

Undulator

Undulator

FEL user area 1

FEL user area 2

Beamline LB-A: FEL

EuCOLL: EuPRAXIA R&D for Plasma Collider

Funded by the European Union

EuPRAXIA, if properly supported, will be able to shading light among some still open issues relevant for a LC design:

WP1 Plasma accelerator theory and simulations (LNF, Mi, RM1,RM2, Pisa, ITS, QUB)

WP2 - High repetition rate plasma module (LNF, LNS)

WP3 High efficiency plasma acceleration, high tranformer ratio mode (LNF, RM1, Mi)

WP4 Positron source and acceleration (QUB, LNF, RM2)

WP5 – Scalable laser driver technology (Pisa, LNF)

In addition it may provide fundamental information about long term machine operation and its reliability and, also very important, training of the next generation Accelerator Scientist.

WP1 financial request: ***210 k€*** *(Instrumentation 50 k€, Personnel 150 k€, Travel 10 k€)*

WP2 financial request: ***360 k€*** *(Instrumentation 200 k€, Personnel 150 k€, Travel 10 k€)*

WP3 financial request: ***210 k€*** *(Instrumentation 150 k€, Personnel 50 k€, Travel 10 k€)*

WP4 financial request: ***370 k€*** *(Instrumentation 190 k€, Personnel 150 k€, Travel 30 k€)*

WP5 financial request: ***190 k€*** *(Personnel 180 k€, Travel 10 k€)*

EuCOLL Total financial request: ***1.340 M€***

WP1 Plasma accelerator theory and simulations (LNF, Mi, RM1,RM2, Pisa, ITS, QUB)

Funded by the European Union

Task 1.1: Development of Simplified Models and Codes

Objective: Develop simplified models and fast running codes that can accurately represent the dynamics of plasma acceleration while reducing computational costs. Include thermal effects in evaluating the acceleration process and its performances.

Task 1.2 *Development of Lattice Boltzmann Models and Codes*

Objective: Lattice Boltzmann it is a mesoscopic method, midway between the macroscopic approach of fluid codes that use macroscopic quantities, and the microscopic one of particle-in-cell methods (PIC). Upgrade of an existing code is proposed.

Task 1.3: Development of Discharge Process Codes

Objective: Develop specialized codes to model the discharge processes in staged plasma discharge modules.

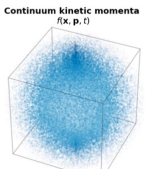
Task 1.4: Machine Learning for Optimization

Objective: Utilize machine learning techniques to optimize plasma acceleration processes and improve overall efficiency.

Task 1.5: Muon Collider applications

Objective: The high acceleration gradients provided by plasma-based acceleration present a promising approach to minimizing particle losses for the acceleration of both muons and pions. In collaboration with IST (Lisbon) we propose to performe beam dynamics studies with the OSIRIS code of muon acceleration by plasma and design a proper plasma target for muon generation.

Microscopic simulations
Continuum kinetic momenta

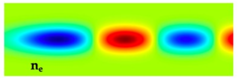


PIC

- ✓ Able to catch most of the physics
  High computational cost

Macroscopic simulation
No kinetic momenta

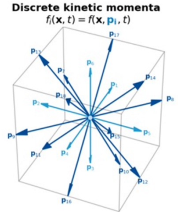
Macroscopic quantities



Fluid

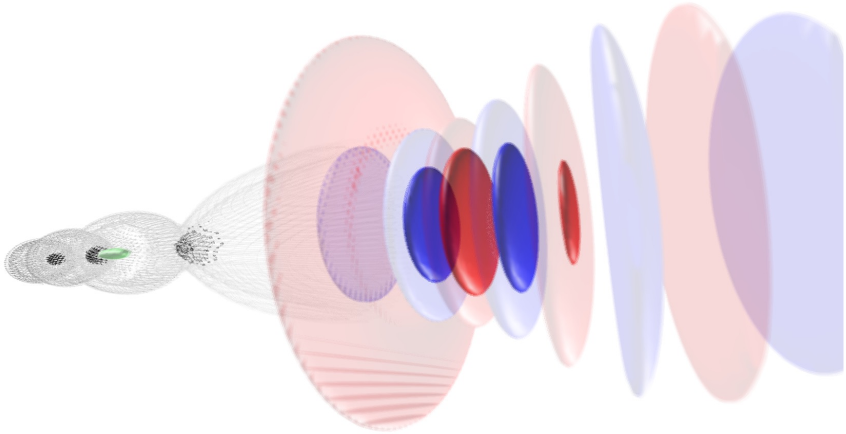
- ✓ Low computational cost
  Limited reproducible physical effects

Mesoscopic simulation
Discrete kinetic momenta



Lattice Boltzmann

- ✓ Low computational cost
- ✓ Able to catch most of physical effects



WP2 - High repetition rate plasma module (LNF, LNS)

Funded by the European Union

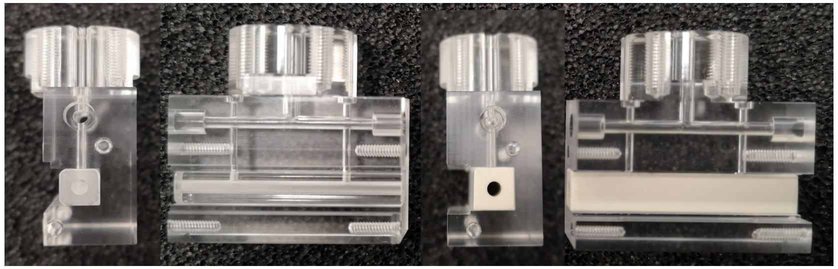
Task 2.1 - Study of a new generation of materials capable of withstanding the high temperatures produced during the plasma formation, which at the same time are machinable to produce long but very thin structures. This includes the use of 3D-printing techniques.

Task 2.2 - Study of plasma source segmentation techniques for making devices having lengths of several meters, where plasmas with controllable densities can be produced. A crucial part of this study is the development of high-voltage source systems for plasma formation.

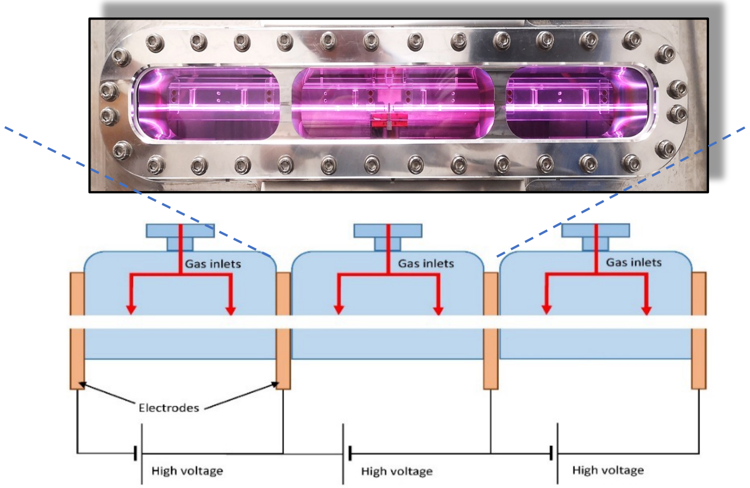
Task 2.3 - Optimization of the capillary discharge technique for high-power lasers, focusing on enhancing the density profile and mechanical resistance of the capillary. The objective is to increase the total electron charge and energy.

Task 2.4 - Investigate new approaches to capillary electron acceleration by incorporating oriented nanotube structures. This involves coupling capillary discharge with aligned capillary designs to improve beam emittance.

Sapphire **Ceramics**



60 cm long Plasma module (1 GV/m), tested



WP3 High efficiency plasma acceleration (LNF, RM1, Mi)

Funded by the European Union

The goal of this WP will be to design and implement within EuPRAXIA@SPARC_LAB a working point for efficient plasma wakefield acceleration. This can be achieved by maximizing the ratio between the maximum decelerating gradient within the drive bunch and the maximum accelerating gradient within the witness bunch (the so-called *transformer ratio*), and by fully depleting the energy of the drive bunch [Chen et al., PRL 56 12 (1986)].

The transformer ratio can be maximized by tailoring the current density profile of the drive bunch (e.g. triangular shape [Loisch et al., PRL 121, 064801 (2018)]) or by generating a train of drive bunches with ramped charge.

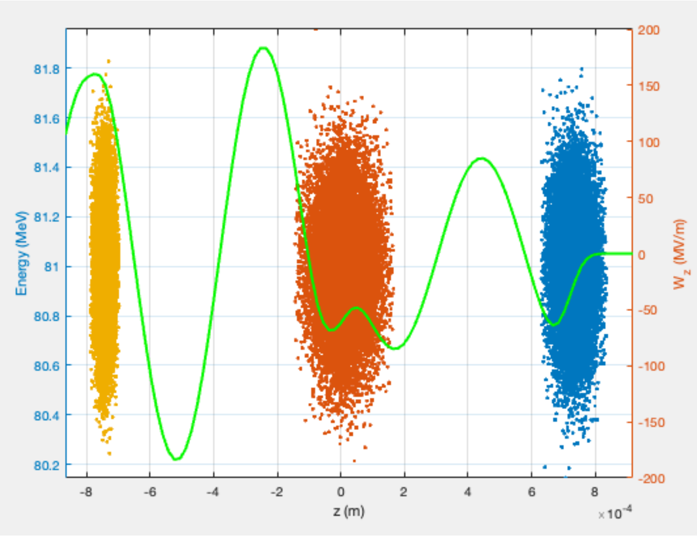
The work of this WP will be divided in the following tasks:

Task 3.1 - Beamline and plasma simulations to identify suitable working point for high-efficiency and high-quality acceleration.

Beam manipulation and masking techniques will be studied to generate the required beam current distributions.

Task 3.2 - Preliminary proof-of-principle experiments will be conducted at the SPARC_LAB facility to support the following studies and experiments.

Task 3.3 – Integration within EuPRAXIA@SPARC_LAB of beam manipulation and masking techniques to generate drive bunches with the current distribution identified with the previous tasks.



WP4 Positron source and acceleration (QUB, LNF, RM2)

Funded by the
European Union

Task 4.1 Positron beam production at EuAPS facility

Once the electron beam and x-ray characteristics have been optimised in terms of peak brightness and energy, the electron beam will also be used to generate high-energy positron beams during their interaction with mm-scale high-Z solid targets.

Task 4.2 Positron beam characterisation

The generated positron beams will be characterised by measuring, simultaneously, energy spectrum, total charge and energy-dependent divergence and source size, using a diagnostic method pioneered by the group of Prof. Sarri (see, e.g., Refs. [4]).

Task 4.3: selection and guiding of narrowband, low emittance positron beams.

Following the first proof-of-principle experimental demonstration [9] and numerical modelling [11], we aim to produce pC-scale positron beams with a 5% bandwidth at 1 GeV, micron-scale normalised emittance and femtosecond-scale duration. These are characteristics required for efficient injection in following plasma accelerator modules

Task 4.4: feasibility study of positron Wakefield acceleration .

A first design of a plasma module for the post-acceleration of the positron beam will be prepared towards the first demonstration of an all-optical staged acceleration beamline

WP4: Laser-driven positron sources

- Plasma-based positron acceleration is **a challenging task!**
- Most research has been carried out numerically
- In preparation for the design of a plasma-based (or plasma-assisted…) positron arm for a collider, **it is necessary to experimentally test** these accelerators, in order to identify the best and most practical ways to accelerate positrons in a plasma.
- **A first step** would thus be to provide positron beam facilities to the community

For meaningful experimental studies, it is necessary to provide witness beams with remarkably demanding characteristics:

- short duration:	$\sigma_z \sim 10\ \mu m$
- low normalized emittance:	$\varepsilon_n \sim \mu m$
- "reasonable charge":	$Q \sim 0.1 - 20$ pC
- "reasonable energy":	$E \sim$ 100s of MeV
- low energy spread:	$\Delta E/E \sim$ few %

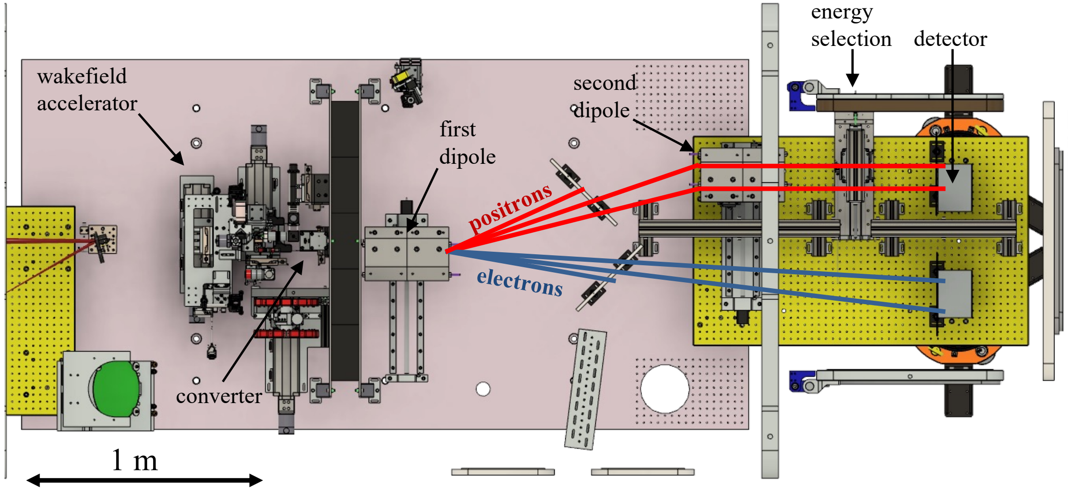
- fs-scale synchronization and µm-scale overlap with driver beams

A possible roadmap for the experimental development of high-quality positron beams could be:

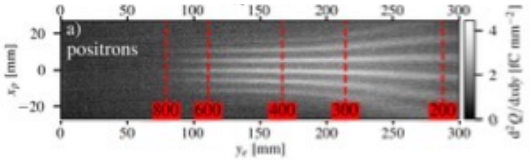
1. **SHORT TERM** (5-10 years)	*Development of positron test beam facilities in Europe (e.g. EuPRAXIA, EPAC…)*
2. **MEDIUM TERM** (10 – 20 years)	- *Converging onto specific acceleration schemes* - *Experimental demonstration of 10s of GeV high-quality beams*
3. **LONG TERM** (>20 years):	- *Demonstration of ~100 GeV high quality beams in a hybrid scheme (conventional injector + plasma accelerating modules)*

Positron sources with 150TW laser

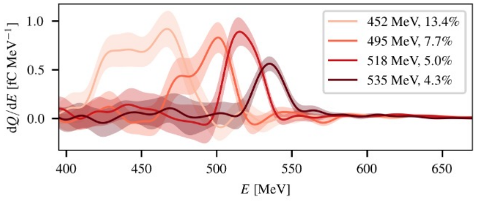
High-quality positron beams at 500 MeV demonstrated with a 150 TW laser (CLF):



Measured energy-dependent emittance



Tuneable energy selection (~5%)



Obtained positron beam properties

- Energy: 500 MeV
- Bandwidth: ΔE/E ~ 5%
- Charge: 0.2 pC
- Norm. Emit.: 15 µm
- Duration: < 30 fs

- Results obtained with ~1.2 nC electron beams with maximum energy of ~ 900 MeV
- Numerical modelling indicates efficient capture and post-acceleration in a plasma afterburner with ~ 10 GV/m fields

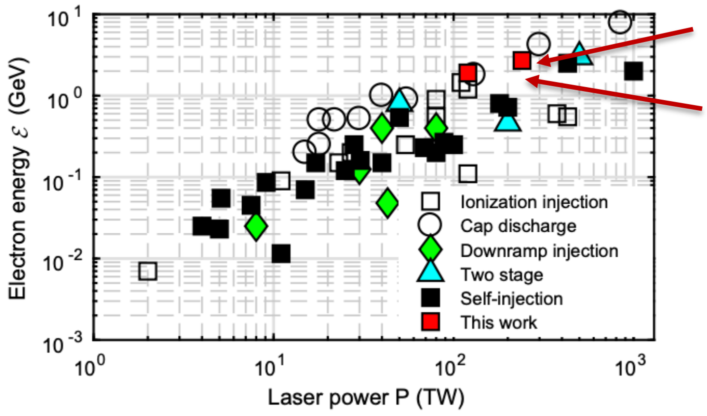
Streeter at al., Sci. Rep. 14, 6001 (2024)

Sarri et al., PPCF 64, 044001 (2022)

Poder et al., PRL. 132, 195001 (2024)

Positron sources at EuPRAXIA

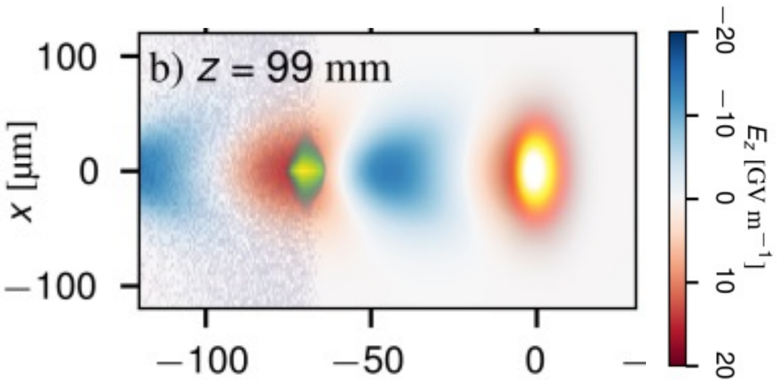
For efficient positron production, desirable to have broadband electron beams with ~ GeV maximum energy and nC-scale total charge.



Up to 3 GeV demonstrated

FLAME (6J, 30 fs)

The EuAPS line can generate the required electron beams for the generation of positron beams with pC charge in a 5% bandwidth around, micron-scale normalized emittance and ~20 fs duration



Numerical modelling indicates that these positron beams can be captured and accelerated in a wakefield with ~ 10 GV/m accelerating fields

Streeter at al., Sci. Rep. 14, 6001 (2024)

Sarri et al., PPCF 64, 044001 (2022)

Poder et al., PRL. 132, 195001 (2024)

WP5 – Scalable laser driver technology (Pisa, LNF)

Funded by the European Union

The use of lasers as power drivers for future plasma accelerators relies on entirely new technologies capable of high efficiency scalable systems. As a baseline, the laser-driven pillar of the EuPRAXIA infrastructure relies on multi-kW average power, petawatt peak power, ultra-short pulse laser systems with ultra-short pulse duration, down to 30 fs or less, combined with an energy per pulse up to 100 J at a repetition rate for user applications up to 100 Hz and beyond. Indeed, scaling of existing systems to kW average power still requires innovative solutions, including the transition from a flashlamp pumping to the efficient, fully diode pumping, and sustainable thermal management in both the amplifier and the whole transport chain, from the compressor to the target plasma. As shown in the figure, these specifications are beyond the current state of the art and require dedicated effort to overcome existing technological bottlenecks.

Based on the activity carried out for the laser development of EuPRAXIA, this work package will aim at the definition of the next generation of laser driver systems and will provide a conceptual design report for the development of energy efficient higher repetition rate (kHz-level and beyond) laser drivers addressing some of the key issues associated with it (thermal management in gain media, compressors, optics lifetime, quality and stability etc.)

Task 5.1 – Assessment of 100 Hz operation @EUAPS

The 100 Hz 40 TW laser system that will be available at the CNR pillar of EUAPS will be a unique system that meets the specifications of the laser front-end system expected for the EuPRAXIA laser. This task will carry out a detailed characterization of the performance of this system to define a benchmarking working point to be used as a reference for the design of future systems.

Task 5.2 – Scalable platforms of laser power driver

Starting from a review of existing ultrashort pulse laser platforms, this task will shortlist the most scalable ones and will identify the most promising for laser massive scaling towards a collider design.

Task 5.3 – Conceptual design of a collider laser power driver

This task will provide a conceptual design of a selected laser technology compatible with a multi-staged approach to a collider design.

Thank for your attention