EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

EuPRXIA@SPARC_LAB energy boosting to 5 GeV by LWFA and external injection

Andrea R. Rossi

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EuPRAXIA Conceptual Design Report

Plasma accelerators: Two types of plasma accelerators are foreseen at the PWFA $\frac{1}{\sqrt{2}}$ site of 1 $S₁$ $R_{\rm B}$ suit $Siders$ $\frac{1}{\sqrt{3}}$ a Cros m. Deliniko 3, P. Deliniko arabsas (j. Denis 15, D. Dienstein actrice), S. Dienstein actrice a $\frac{1}{2}$ be ont α are formally a. Given α . Given α . LIP-R O. Jakobsson²⁰, D.A. Jaroszynski¹⁵, S. Jaster-Merz¹, C. Joshi⁴⁹, M. Kaluza50,51, site of EuPRAXIA: one focussed on high beam quality for radiation generation and the other aiming to produce high-charge, high-average-power electron beams suitable for positron generation and as test beams. The *baseline* in both cases considers the external injection of the electron drive and witness beams from the RF accelerator into a weakly non-linear plasma stage to achieve beam-driven wakefield acceleration up to 1 GeV. The generated electron bunches based on current results comply with the requirements for both types of accelerator stages but could be optimised further towards high charge or high quality in the future. A detailed design is described in Section 17. Additionally, potential *future development paths* are foreseen through (1) increasing the energy reach to 5 GeV (see Sect. 17.2) as well as (2) improving the beam quality further, for example through using the RF-accelerated electron beam as a driver in a beam-driven plasma wakefield injector based on the Trojan horse injection mechanism (more details in Sect. 26).

Boundary conditions

But also an operating user facility!

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The interaction chamber, transfer line and diagnostic ELPRAXIA dipole

Only a placeholder!0

INTERACTION CHAMBER:

Contains plasma target and optics for matching and capture of the electron bunch(es)

TRANSFER LINE:

A chicane for separating driver(s) from witness.

Quadrupoles for transport and matching to the dipole.

Diagnostics.

A bending magnet that opens dispersion and allows energy measurement.

DUMP:

DIPOLE:

We assume 22 deg bending angle.

www.eupraxia-pp.org 4 and 4 μ

The spectrometer dipole @ 5 GeV

SESAME bending dipole @ 2.5 GeV

SC option?

Possible, but expensive.

Assuming a bending angle as the 1 GeV spectrometers (same resolution)

EuPRAXIA@SPARC_LAB bending di

https://www.sesame.org.jo/accelerators/technology/magnets-and-ids

Driver - Witness separation chicane: most probably not needed.

Transfer - matching line (3125 mm). Very rough approximation: \times 3 \approx 10 m Again, SC magnets could be a viable but expensive alternative.

²¹⁰⁰ $\frac{20}{4}$ mm m **E E** \sim **E** \sim $\frac{3}{2100}$ The European Physical Journal $\frac{1}{2}$

current ka 2 2.0 minutes and 2 2.0 minutes

Archer Train Structure and Transformer Ration
17.2.2 Driver Train Structure and Transformer Ratio 17.2.2 Driver Train Structure and Transformer Ratio the witness, including the beam-loading effect. Given the high current of the witness

We assume a train of driver bunches generated by an X-band RF linac up to the energy of 1.2 GeV. Increasing energy transfer in a PWFA stage requires a driving energy of 1.2 GeV. Increasing energy transfer in a PWFA stage requires a driving
structure with a higher transformer ratio R_T than the 1 GeV case. This condition can structure with a higher transformer ratio n_T than the 1 GeV case. This condition can
be obtained by utilising a train of drive electron bunches [192]. An energy increase be obtained by utilising a train of drive electron bunches [192]. An energy increase from 1.2 GeV to 5 GeV requires an effective transformer ratio of $R_T \approx 3.2$, whereby "effective" means the transformer ratio is evaluated using the average field acting the average field acting on We assume a train of driver bunches generated by an X-band RF linac up to the
generated $\frac{1}{2}$ and $\frac{1}{2$ From 1.2 GeV to 5 GeV requires an enective transformer ratio of $n_T \approx 5.2$, whereby M. Diomede³, E. Di Pasquale³, G. Di Pirro³, G. Di Raddo³, U. Dorda¹, $\frac{1}{2}$ for drivers and $\frac{1}{2}$ from $\frac{1}{2}$ $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ $\frac{1}{2}$. And energy increase $\frac{1}{2}$ from 1.2 GeV to 5 GeV requires an effective transformer ratio of $R_T \approx 3.2$, whereby (3 kA), the beam-loading effect generates a critical reduction of the acceleration have the condition for the maximum acceleration $\frac{1}{\sqrt{2}}$ is $\frac{1}{\sqrt{2}}$ in $\frac{1}{\sqrt{2}}$ and $\frac{1}{\sqrt{2}}$

…

1.00

we designed an ideal train of 3 drivers with ramped increasing charge densities A. Ferran Poussian Po the designed an ideal train of 3 drivers with ramped increasing charge dens we designed an ideal train of 3 drivers with ramped increasing charge densities. field and consequently reduces the effective transformer ratio. To avoid this problem, this problem, α between the bunches is constant, with ⇠ = 0*.*5*p*, corresponding to ⇠ ⇡106 m. we designed an ideal train of 3 drivers with ramped increasing charge densities. inside the ramps, reaching the matching the matching condition (Eq. (17.1)) at the beginning of \mathcal{L}

R. Fiorito4,5, R.A. Fonseca³⁸, G. Franzini³, M. Galimberti³⁹, A. Gallo³, ^a ⇠2.4 m plateau with a plasma density of *ⁿ^p* = 2*.*⁵ *·* ¹⁰¹⁶ cm³, preceded by a 1 cm Theoretically, this configuration allows reaching a transformer ratio of *R^T* = 2*N*,

emittance of the two bunches is chosen arbitrarily as $\varepsilon_{n,xy} = 1$ mm mrad. The charges Fracture of the two bundles is chosen at obtainty as $\varepsilon_{n,xy} = 1$ min matrix are $Q_1=40 \text{ pC}, Q_2=140 \text{ pC}, \text{and } Q_3=270 \text{ pC}$. They are properly calibrat $A\in\mathbb{R}$, B. Hidding $A\in\mathbb{R}$, B.J. Hookers $A\in\mathbb{R}$, T. Hookers $A\in\mathbb{R}$ are Q_1 =40 pC, Q_2 =140 pC, and Q_3 =270 pC. They are properly calibrated to obtain emittance of the two bunches is chosen arbitrarily as $\varepsilon_{n,xy} = 1$ mm mrad. The charges the plateau (Twiss functions ↵*x,y* ⇡ 1, *x,y* ⇡ 22 mm for all bunches). The transverse emittance of the two bunches is chosen arbitrarily as $\varepsilon_{n,xy} = 1$ mm mrad. The charges a maximum deceleration field with the bunches that is constant for all drivers. In all drivers α

... \ldots \ldots \mathbf{S} is the beam-loading effect generating effect generating \mathbf{S} and \mathbf{S} acceleration of the acceleration o tailored current profile transformer ratio. To avoid the effective transformation of the effective transformation

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EuPRA KIA^N Plasma chamber: the PWFA option 12 10 E^{*} E^{*} Electron bunch and bunch after 15 mm propagation with the 15 mm propagation w plasma. The bunch density is plotted with a *plasma* colour map, while the background is plotted with a grey colour map. The longitudinal acceleration \mathcal{L}

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> **1.1 GeV** (1 GV/m 600 MeV in **60cm** long capillary - density 1016 cm-3):

Eur. Phys. J. Special Topics 229, 3675–4284 (2020) $\overline{\text{THE EUROPEAN}}$ \overline{C} The Author(s) 2020, korrigierte Publikation (2021) **DHVSICAL JOUD** $\frac{\text{H}}{\text{https://doi.org/10.1140/epjst/e2020-000127-8}}$ PHYSICAL JOUR

over-imposed with a solid orange line.

THE EUROPEAN PHYSICAL JOURNAL S PECIAL TOPICS S in this method for the bin size \sim the step size with which to move the step size with which to move the bin field and consequently reduces the effective transformer ratio. To avoid this problem,

Review t the beam length (dz). Slice values are thus calculated in steps of size dz along the long t between the bunches is constant, with \mathbf{p}_i , constant, with \mathbf{p}_i , corresponding to \mathbf{p}_i , corresp T_{t} transverse injection is calibrated in order to have bunch for \mathbf{r}

EuPRAXIA Conceptual Design Report EuPRAXIA Conceptual Design Report therefore providing a better sampling of the bunch properties. \blacksquare ur n \blacksquare n \blacksquare $\$

gitudinal beam distribution, while the region of macroparticles taken into account for

Current ka 2 2.0 million and the current curre

 17.2 Numerical Design for the 5 GeV Case 17.2 Numerical Design for the 5 GeV Case

A. Beaton4,15, A. Beck¹⁶, M. Bellaveglia³, A. Beluze¹⁷, A. Bernhard¹⁸, A. Biagioni³, 17.2.3 Bunch Acceleration

 \overline{m} brinkmann \overline{m} and \overline{m} because \overline{m} , \overline{m} and \overline{m} , \overline{m} , The witness is designed with the energy of $E = 1.2 \text{ GeV}$ and an initial uncorrelated energy spread of $\sigma_E = 0.7$ %. As in the 1 GeV case, a triangular current shape is chosen to reduce the energy spread growth with an RMS bunch length of $\sigma_z = 3.6$ chosen to reduce the energy spread growth with an KMS bunch length of $v_z = 3.0$ pm. The transverse emittance is arbitrarly chosen as $\varepsilon_{n,xy} = 0.7$ mm mrad, and the Twiss functions are $\alpha_{x,y} \approx 1$ and $\beta_{x,y} \approx 22$ mm, to reach the matching condition Twiss functions are $\alpha_{x,y} \sim 1$ and $\beta_{x,y} \sim 22$ min, to feach the material conduction from equation (17.1) at the beginning of the plateau. The peak field is located at the bubble closure with a value of $E_z \approx 2.7$ GV/m (see Fig. 17.3). The bunch separation between the centroids of the last driver and the witness is set as 0.46 λ_p , corresponding to $\approx 97 \text{ µm}$ in order to minimise the energy spread growth. With this corresponding to \approx *n* μ m in order to minimise the energy spread growth. With this fixed, the mean accelerating gradient acting on the witness is $E_z \approx 1.6 \text{ GV/m}$. energy spread of $\sigma_E = 0.7$ %. As in the 1 GeV case, a triangular current shape is fixed, the mean accelerating gradient acting on the witness is $E_z \approx 1.6 \text{ GV/m}$.

T.C. Galvin 14, A. Ghaith 22, A. Ghaith 22, A. Ghaith 22, L.A. Ghigosa, L.A. Ghigo $E\r{u}' PRA$ and A

int chamber ≈ 3 m (contains PMQs) aSSUME: 1 GeV plasma target: $\approx 40 - 60$ cm,

• $E_{in} = 1.2$ GeV

•
$$
\langle E_z \rangle \approx 2.0
$$
 GeV

LWFA: external injection ar injection the peak current. This bunch core core contains 5 pC of charge. This bunch core contains 5 pC of charge. The s current are calculated as \sim \sim

LNF–18/03 May 7, 2018

EUPRAXIA@SPARC_LAB This choice is due to the fact that that the maximum length for the cable calculation \mathcal{S} m (mainly to the cable calculation) is defined by \mathcal{S}

Conceptual Design Report The 500 TW laser will have the parameters summarized in Table 11.2.

Table 11.2: Laser beam parameter for the upgraded FLAME laser.

 $\overline{\mathbf{u}\mathbf{e}}$ assume **discharge capillaries**. The high power laser pulse needs to be guided for the whole capillary length.

I am **NOT** considering the laser transport system! */* (ansidering the laser transport system)

250-500 MeV

Plasma chamber: the LWFA option

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ASSUME:

- *Ein* ∼ 0.5 − 1.0 GeV
- $\textbf{ } \left< E_z \right> \gtrsim 7.0$ GeV

5 GeV plasma target: ~ 50 cm, int chamber 3 m - 5 m

$2,5\frac{10^{17}}{1}$.
−■ — Plasma density Standard deviation $2,0$ www.eupraxia-pp.org $\frac{2.0}{2}$ The circuit of the circuit of the circuit of the state of t

EUPRAXIA@SPARC_LAB This choice is due to the fact that the maximum length for the cable can be only 8 m (mainly to

Conceptual Design Report The 500 TW laser will have the parameters summarized in Table 11.2.

	Units	value
Central wavelength	nm	800
Bandwidth	nm	$60 - 80$
Repetition rate	Hz	$1 - 5$
Max energy before compression	J	20
Max energy on target	J	13
Min pulse length	fs	25
Max power	TW	500
Contrast ratio		10^{10}
Laser spot size at focus (optics dependent)	μ m	$2 - 50$
Peak power density at focus (optics dependent)	W/cm ²	$10^{22} - 10^{19}$

Table 11.2: Laser beam parameter for the upgraded FLAME laser.

Straight PWFA

The most trivial solution is "invasive"!

It's implementation prevents facility operation for a long time and requires significant intervention and careful planning

Dogleg PWFA

PROS:

- Compatible with facility current layout
- All PWFA

CONS:

- Large bending angle (22 deg)
- Highly risky: dogleg + COMB structure

Dogleg PWFA: building constraints

Dogleg LWFA: injection @ 500 - 600 MeV

PROS:

- Compatible with facility current layout
- Dogleg with smaller angle (10 deg)
- Works with 12J laser on target
- Undulator room downstream

CONS:

- No PWFA at all
- Risky: long laser guiding
- Low rep rate
- Laser should be removed

EUPRA MA Dogleg LWFA @ 500 MeV: building constraints

PROS:

- Compatible with facility current layout
- Dogleg with smaller angle (10 deg)
- Lot of space downstream

CONS:

- No PWFA at all
- Lower injection energy, requires 1 PW laser
- Risky: long laser guiding
- Low rep rate

Hybrid PWFA + dogleg LWFA, option 1

From PWFA: $E_{\text{out}} = 1.0 - 1.7$ GeV

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PROS:

LWFA: $E_{in} = 1.0 - 1.7$ GeV $E_{out} = 5.0$ GeV $CONS$:

- Compatible with facility current layout
- PWFA + LWFA!
- Large angle dogleg
- Risky: long laser guiding
- Staging

Hybrid PWFA + dogleg LWFA, option 2

PROS:

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- Compatible with facility current layout
- Small dogleg angle (10 deg)
- Only 1D + 1W in dogleg
- PWFA + LWFA!

CONS:

- Comb structure in dogleg
- Risky: long laser guiding
- Staging

EUPRA Hybrid PWFA + LWFA 2: building constraints

Risk mitigation

• Hose instability/dispersion related problems: Dumper bunch, arXiv:2409.12041v1

Oscillation damper for misaligned witness in plasma wakefield accelerator

K.V. Lotov, I.Yu. Kargapolov, P.V. Tuev 1)*Novosibirsk State University, Novosibirsk 630090, Russia* 2)*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*

(Dated: 19 September 2024)

- Long guiding channel: filament, HOFI aling chidrinel. Midlitelit, Tion b $\mathbf r$
- misaligned, the damper perturbs the wakefield in such a wakefield in such a way that the witness shifts on-axis with no quality of witness shifts on α • Laser removal: plasma mirror

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Thanks for your attention

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Backup slides

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