EuPRAXIA, A STEP TOWARD A PLASMA-BASED ACCELERATOR WITH HIGH BEAM QUALITY

Phu Anh Phi NGHIEM (CEA-IRFU) et al.
EuPRAXIA Consortium

16 Participants

25 Associated Partners

Private companies
EuPRAXIA scope

From Acceleration to Accelerator
From Proof of principle to User’s Facility

Mission: Produce a Conceptual Design Report for the world's first

- high energy ~GeV plasma-based electron accelerator
  driven by laser or electron beam

- with “industrial quality”
  24/7 user operation
  high reliability, reproducibility
  high repetition rate ≥ 10 Hz toward 100 Hz

- with high beam quality and high beam charge

- with user areas: FEL & HOPA
**EuPRAXIA requirements**

Critical parameters of the electron beam required at Injection or Acceleration stages

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LP Injector exit</th>
<th>RF Injector exit</th>
<th>Accelerator exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>150 MeV</td>
<td>250-500 MeV</td>
<td>5 GeV (1 GeV)</td>
</tr>
<tr>
<td>Q</td>
<td>30 pC</td>
<td>30 pC</td>
<td>30 pC</td>
</tr>
<tr>
<td>τ (FWHM)</td>
<td>10 fs</td>
<td>10 fs</td>
<td>10 fs</td>
</tr>
<tr>
<td>ΣE/E</td>
<td>5%</td>
<td>0.2 %</td>
<td>1%</td>
</tr>
<tr>
<td>ΣE,E/S/E</td>
<td>t.b.d.</td>
<td>t.b.d.</td>
<td>0.1 %</td>
</tr>
<tr>
<td>εn</td>
<td>1 mm.mrad</td>
<td>1 mm.mrad</td>
<td>1 mm.mrad</td>
</tr>
<tr>
<td>εn,s</td>
<td>t.b.d.</td>
<td>t.b.d.</td>
<td>1 mm.mrad</td>
</tr>
</tbody>
</table>

**OBJECTIVE:**

- Provide beam at 5 GeV meeting 'perfectly' FEL and HOPA requirements
- Provide also beam at 1 GeV 'usable' for FEL and HOPA as a 'commissioning' step

at the applications!

P. A. Phi Nghiém et al., Seminar- California, October-November 2019
Beam parameters at 5 GeV at the user's doorstep

Energy (GeV) | Charge (pC) | \( \varepsilon \) (\( \mu \)m) | \( \sigma_{E/E} \) (%) | \( \tau_{\text{FWHM}} \) (fs) | slice\( \varepsilon \) (\( \mu \)m) | slice\( \sigma_{E/E} \) (%)
---|---|---|---|---|---|---
5 | 40 | 1.5 | 1.5 | 15 | 1.5 | 0.15
6 | 30 | 1.0 | 1.0 | 10 | 1.0 | 0.10
7 | 20 | 0.5 | 0.5 | 5 | 0.5 | 0.05
8 | 10 | 0.0 | 0.0 | 0 | 0.0 | 0.00
"Physics experiment" approach: often built around a laser facility

"Accelerator" approach: like for a conventional accelerator

- a) Definition of the desired beam parameters (TLR)
- b) Large exploration / optimization of beam inject./accelerat. in plasmas
- c) Selection of the appropriate configurations
- d) Optimization of beam extraction, transport
- e) Estimation of sensitivity to errors
- f) Determination of needed laser and plasma systems

Issues: for plasma-based accelerator
- Simulations are very time consuming
- Many simulation codes → reliability, robustness?
1. Inj./Acc. configurations studied. Results and Selections

2. Lessons learned: how to obtain high beam energy AND charge AND quality

3. Optimization of beam extraction and transport

4. Estimation of sensitivity to errors

5. Specifications for plasma and laser systems
1. Inj. / Acc. configurations studied. Results and Selections

2. Lessons learned: how to obtain high beam energy AND charge AND quality

3. Optimization of beam extraction and transport

4. Estimation of sensitivity to errors

5. Specification for plasma and laser systems
Inj. / Accel. schemes studied

- **LPAS** 5 GeV (1 GeV)
- **HETL**
- **RFI** 240-500 MeV
- **LPAS** 5 GeV (1 GeV)
- **240 MeV**
- **RFI**
- **LPAS** 5 GeV (1 GeV)
- **2.5 GeV**
- **LPAS**
- **HETL**
- **5 GeV** (1 GeV)
- **RFI**
- **LPAS** 5 GeV (1 GeV)
- **5 Gev**
- **LPAS**
- **HETL**
- **5 GeV** (1 GeV)
- **RFI**
- **LPAS** 5 GeV (1 GeV)
- **3 GeV**
- **LPAS**
- **HETL**
- **5 GeV** (1 GeV)
- **RFI**
- **PPAS** 500 MeV
- **HETL**
- **1 GeV**
- **HYBRID**
- **LPAS**
- **PPAS** 5 GeV (1 GeV)
**Inj. / Accel. schemes studied**

11 European institutes
21 contributors

- A. Beck
- A. Chancé
- E. Chiadroni
- A. Ferran Pousa
- A. Giribono
- B. Hidding
- P. Lee
- X. Li
- A. Marocchino
- A. Martinez de la Ossa
- F. Massimo
- G. Maynard
- A. Mosnier
- P.A.P. Nghiem
- A.R. Rossi
- T. Silva
- E. Svystun
- P. Tomassini
- C. Vaccareza
- J. Vieira
- J. Zhu
<table>
<thead>
<tr>
<th>Energy</th>
<th>Technique and Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFI 240 MeV</td>
<td>S-band, RF &amp; Magn. compression</td>
</tr>
<tr>
<td>RFI 500 MeV</td>
<td>S-band &amp; X-band, Comb technique</td>
</tr>
<tr>
<td>LPI 150 MeV</td>
<td>Wave-breaking injection and nonlinear regime</td>
</tr>
<tr>
<td></td>
<td>Shock-front injection and blow-out regime</td>
</tr>
<tr>
<td></td>
<td>Ionization injection and nonlinear regime</td>
</tr>
<tr>
<td></td>
<td>Downramp injection and blow-out regime</td>
</tr>
<tr>
<td></td>
<td>Resonant Multiple Ionization Injection (ReMPI)</td>
</tr>
<tr>
<td>LPAS 5 GeV</td>
<td>ReMPI, 1 LPAS</td>
</tr>
<tr>
<td></td>
<td>Quasi-linear regime, injector+LPAS</td>
</tr>
<tr>
<td></td>
<td>Blow-out regime, injector +2 LPAS+chicane</td>
</tr>
<tr>
<td>PPAS 1 GeV</td>
<td>Weakly-nonlinear regime</td>
</tr>
<tr>
<td>LPAS-PPAS</td>
<td>Trojan Horse Injection and blow-out regime</td>
</tr>
<tr>
<td></td>
<td>Wakefield Induced Ionization Injection and blow-out regime</td>
</tr>
</tbody>
</table>
### Inj. / Accel. techniques studied

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Technique Description</th>
<th>Code(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFI 240</td>
<td>S-band, RF &amp; Magn.compression</td>
<td>ASTRA</td>
</tr>
<tr>
<td>RFI 500</td>
<td>S-band &amp; X-band, Comb technique</td>
<td>Tstep, Elegant</td>
</tr>
<tr>
<td>LPI 150</td>
<td>Wave-breaking injection and nonlinear regime</td>
<td>SMILEI</td>
</tr>
<tr>
<td></td>
<td>Shock-front injection and blow-out regime</td>
<td>CALDER-C</td>
</tr>
<tr>
<td></td>
<td>Ionization injection and nonlinear regime</td>
<td>Warp</td>
</tr>
<tr>
<td></td>
<td>Downramp injection and blow-out regime</td>
<td>OSIRIS</td>
</tr>
<tr>
<td></td>
<td>Resonant Multiple Ionization Injection (ReMPI)</td>
<td>ALaDYN, QFluid</td>
</tr>
<tr>
<td>LPAS 5 GeV</td>
<td>ReMPI, 1 LPAS</td>
<td>ALaDYN, QFluid</td>
</tr>
<tr>
<td></td>
<td>Quasi-linear regime, injector+LPAS</td>
<td>FBPIC, QFluid, Warp</td>
</tr>
<tr>
<td></td>
<td>Blow-out regime, injector +2 LPAS+chicane</td>
<td>FBPIC, Astra, CSRtrack</td>
</tr>
<tr>
<td>PPAS 1 GeV</td>
<td>Weakly-nonlinear regime</td>
<td>Architect</td>
</tr>
<tr>
<td>LPAS-PPAS</td>
<td>Trojan Horse Injection and blow-out regime</td>
<td>VSim</td>
</tr>
<tr>
<td></td>
<td>Wakefield Induced Ionization Injection and blow-out regime</td>
<td>OSIRIS</td>
</tr>
</tbody>
</table>


And others ............
Beam parameters obtained at 150 MeV

All the configurations

![Graph showing beam parameters at 150 MeV]
Beam parameters obtained at 150 MeV

Configurations closest to the requirements Selected for start-to-end simulations

![Graph showing beam parameters obtained at 150 MeV]

- Energy (MeV)
- Charge (pC)
- \( \varepsilon_x \) (\( \mu \)m)
- \( \varepsilon_y \) (\( \mu \)m)
- \( \sigma E/E \) (%)
- \( \tau_{FWHM} \) (fs)
Beam parameters obtained at 1 GeV

All the configurations

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Charge (pC)</th>
<th>( \varepsilon ) (µm)</th>
<th>( \sigma_{E/E} ) (%)</th>
<th>( \tau_{FWHM} ) (fs)</th>
<th>slice( \varepsilon ) (µm)</th>
<th>slice( \sigma_{E/E} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>40</td>
<td>1.5</td>
<td>1.5</td>
<td>15</td>
<td>1.5</td>
<td>0.15</td>
</tr>
<tr>
<td>1.0</td>
<td>30</td>
<td>1.0</td>
<td>1.0</td>
<td>10</td>
<td>1.0</td>
<td>0.10</td>
</tr>
<tr>
<td>0.5</td>
<td>20</td>
<td>0.5</td>
<td>0.5</td>
<td>5</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>0.0</td>
<td>10</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Beam parameters obtained at 1 GeV

Configurations closest to requirements

Selected for start-to-end simulations

Energy (GeV) 1.5 1.0 0.5 0.0
Charge (pC) 40 30 20 0
\( \varepsilon \) (\( \mu \)m) 1.5 1.0 0.5 0.0
\( \sigma_{E/E} \) (%) 1.5 1.0 0.5 0.0
\( \tau_{FWMH} \) (fs) 15 10 5 0
slice\( \varepsilon \) (\( \mu \)m) 1.5 1.0 0.5 0.0
slice\( \sigma_{E/E} \) (%) 0.15 0.10 0.05 0.00

RFI 500MeV+PPAS wnIr
RFI 500MeV+LPAS qIr
LPI rempl 150MeV+LPAS qIr

Required value
Beam parameters obtained at 5 GeV

All the configurations

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Charge (pC)</th>
<th>ε (µm)</th>
<th>σE/E (%)</th>
<th>τ_{FWHM} (fs)</th>
<th>sliceε (µm)</th>
<th>sliceσE/E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>40</td>
<td>1.5</td>
<td>1.5</td>
<td>15</td>
<td>1.5</td>
<td>0.15</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>1.0</td>
<td>1.0</td>
<td>10</td>
<td>1.0</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>0.5</td>
<td>0.5</td>
<td>5</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Required value
Configurations closest to the requirements

Beam parameters obtained at 5 GeV

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Charge (pC)</th>
<th>$\varepsilon$ (µm)</th>
<th>$\sigma E/E$ (%)</th>
<th>$\tau_{FWHM}$ (fs)</th>
<th>slice $\varepsilon$ (µm)</th>
<th>slice $\sigma E/E$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>40</td>
<td>1.5</td>
<td>1.5</td>
<td>15</td>
<td>1.5</td>
<td>0.15</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Required value
Beam parameters obtained at 5 GeV

1-LPAS configurations closest to the requirements
quasilinear acceleration with external injection

Four experts
Four institutes

Three codes used:
- Warp 3D
- QFluid ~3D
- FBPIC 3D

Four beam inputs:
- BiGaussian
- LPI 150 MeV
- RFI 240 MeV
- RFI 540 MeV

Close parameters of laser & plasma
⇒
Close results

Very robust configuration !!!
Beam parameters obtained at 5 GeV

- LPAS ReMPI: very low emittance
- RFI 240 MeV+2LPAS bor+CHICANE: very low energy spread

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Charge (pC)</th>
<th>ε (µm)</th>
<th>σE/E (%)</th>
<th>τFWHM (fs)</th>
<th>sliceε (µm)</th>
<th>sliceσE/E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>40</td>
<td>1.5</td>
<td>1.5</td>
<td>15</td>
<td>1.5</td>
<td>0.15</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>1.0</td>
<td>1.0</td>
<td>10</td>
<td>1.0</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>0.5</td>
<td>0.5</td>
<td>5</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

LPAS ReMPI: very low emittance
RFI 240 MeV+2LPAS bor+CHICANE: very low energy spread
1. Inj. / Acc. configurations studied. Results and Selections

2. Lessons learned: how to obtain high beam energy AND charge AND quality

3. Optimization of beam extraction and transport

4. Estimation of sensitivity to errors

5. Specifications for plasma and laser systems
Decoupling injection and acceleration

Accelerator: stability, reliability, reproducibility ← simplicity!
High energy, high charge and high quality ← sophistication!

**TWO STAGES:**
**INJECTION** + **ACCELERATION**

- high charge
- high quality
- high energy

**also FOR THE INJECTOR ITSELF:** uncouple injection and acceleration

150 MeV

- Downramp injection
- ReMPI
Decoupling injection and acceleration

One stage, ReMPI

Injection stage
He+Ar$^8^+$ (50%)
Gas cell

Acceleration stage
He, parabolic profile
Capillary tube

Plasma

$n_e = 2.1 \times 10^{17} \text{ cm}^{-3}$

Laser

Ionization pulse

Plasma wave

Eight-pulse driver
High beam quality and high charge

For injection: higher charge $\Rightarrow$ higher emittance

Downramp injection

Judicious choice of
- ramp sharpness
- density jump

ReMPI

Judicious choice of
- ionization pulse strength & size
- ionization potential of the gas

charge

emittance
High beam quality and high charge

For acceleration: minimize energy spread in the presence of high charge

In the presence of significant beam loading

Minimizing energy spread by optimizing the bunch length

Minimizing slice energy spread by optimizing jointly the plasma density & the laser strength

\[
\frac{\sigma_{E,S}}{E_0} \quad \text{Av. energy gain by wakefield} \quad n_p
\]
High beam quality and high charge

For acceleration: minimize energy spread in the presence of high charge

Two plasma stages with magnetic chicane

Energy dechirping
1. Inj. / Acc. configurations studied. Results and Selections

2. Lessons learned: how to obtain high beam energy AND charge AND quality

3. Optimization of beam extraction and transport

4. Estimation of sensitivity to errors

5. Specification for plasma and laser systems
The key issue: minimize emittance growth

It is well known: beam extraction and transport $\rightarrow$ important emittance growth

Floettmann, PRAB 2003; Dornmair, Floettmann & Maier, PRSTAB 2015, …

Xu et al. PRL 2016 …

But: only solutions of downramp without space charge nor beam loading

And: three pending questions without explicit answer

1- Which emittance? (Phase or Trace emittance?)

2- In which circumstances? (Drift or Focusing element?)

3- Which parameters govern the emittance growth?

Answer $\equiv$ Know how to mitigate emittance growth
The two emittances

**Trace Emittance**

\[
\varepsilon_{tr} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}
\]

\[
\varepsilon_{tr,n} = \beta_r \gamma_r \varepsilon_{tr}
\]

**Phase Emittance**

\[
\varepsilon_{ph} = \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle xp_x \rangle^2}
\]

\[
\varepsilon_{ph,n} = \frac{\varepsilon_{ph}}{m_0 c}
\]

After some algebra:

\[
\varepsilon_{ph}^2 = \varepsilon_{tr}^2 \left( \frac{p_z^2}{\varepsilon_{tr}^2} + \alpha^2 \sigma_p^2 \right)
\]

\[
\varepsilon_{ph,n} = \varepsilon_{tr,n} \text{ when } \alpha = 0.
\]

RMS beam size, divergence, Emittance, Twiss parameters

\(x, p_x\) are conjugate variables

Should minimize growth of both emittances
Through a drift of length $l$, the coordinates change as:

\[
\begin{align*}
    x &= x_0 + x'_0 l \\
    x' &= x'_0
\end{align*}
\]

\[
\begin{align*}
    \varepsilon^2_{tr} - \varepsilon^2_{tr0} &= 0. \\
    \varepsilon^2_{ph} - \varepsilon^2_{ph0} &= \varepsilon^2_{tr0} \sigma_p^2 \gamma_0 l (\gamma_0 l - 2\alpha_0)
\end{align*}
\]

Migliorati et al. PRSTAB 2013; Sciscio et al., JAP 2016; etc.: As $\varepsilon^2_{tr0}$ and $\sigma_p^2$ are big in plasma acceleration, big emittance growth is unavoidable.

**NO! Minimizing $l$ or/and minimizing $\gamma_0$ can help preserving emittance!**
Emittance evolution through a thin lens

Through a thin lens of focusing gradient $K$, the coordinates change as:

$$\begin{align*}
    x &= x_0 \\
    x' &= Kx_0 + x'_0
\end{align*}$$

$$\begin{align*}
    \frac{\varepsilon_{tr}^2 - \varepsilon_{tr0}^2}{\varepsilon_{tr0}^2} &= \beta_0^2 K^2 \left( \frac{\sigma_p}{p_0} \right)^2 \\
    \varepsilon_{ph}^2 - \varepsilon_{ph0}^2 &= 0
\end{align*}$$

Emittance growth is minimized when:

- **Minimizing $\beta_0$ ≡ Minimizing $\gamma_0$ in the upstream drift**
- **Minimizing $K_0$**

Role of the transfer line

Role of the plasma downramp

Role of the acceleration plasma
Particle tracking

TraceWin code (CEA)
The three key roles

In the **plasma**: minimize Emittance and Energy Spread 
(as done previously)

In the **downramp**: minimize $\gamma$
  
  by tuning the ramp length (whatever its shape)

In the **transfer line**: minimize the first drift and use the smoothest focalization 
  $\rightarrow$ use as few quadrupoles as possible (~6)
Plasma exit 5 GeV

Tuning the ramp length (whatever its shape)  
⇒ Minimizing $\gamma_0$  ⇒ Minimizing emittance growth
Plasma exit 150 MeV

\[ P = 150 \text{ MeV} \]

\[ n_e / \text{le} 18 \text{ cm}^3 \]

\[ \gamma = 7000 \text{ m}^{-1} \]
\[ \gamma = 3500 \text{ m}^{-1} \]
\[ \gamma = 200 \text{ m}^{-1} \]
Plasma downramp

- Plasma exit 3 GeV
- Plasma exit 6 GeV

First plasma stage

Second plasma stage

\[ \frac{n_p}{10^{27}} \text{ [cm}^{-3}\text{]} \]

\[ \beta_x \quad \beta_y \]

\[ \gamma_x \quad \gamma_y \]

\[ \varepsilon_n \quad \varepsilon_{n,x} \quad \varepsilon_{n,y} \]

\[ \varepsilon_{\text{slice}} \quad \varepsilon_{\text{slice},x} \quad \varepsilon_{\text{slice},y} \]

\[ z \text{ [cm]} \]

\[ \gamma \text{ [1/m]} \]
Transfer line

Rule: smoothest focusing $\rightarrow$ number of quadrupoles = number of constraints (~6)

**LETL 150 MeV**

- Beam sizes [μm]
- Normalized emittances [μm]

**HETL 5 GeV**

- Beam sizes [μm]
- Normalized emittances [μm]

**Total emittance growth from LPAS injection to end user: 22%**
1. Inj. / Acc. configurations studied. Results and Selections

2. Lessons learned: how to obtain high beam energy AND charge AND quality

3. Optimization of beam extraction and transport

4. Estimation of sensitivity to errors

5. Specifications for plasma and laser systems
Heavy simulations!!! To be completed

Errors ≡ Jitters
The most critical points are:

In the plasma stages: For laser and electron beams,
- Position vibrations should be a small fraction of their size
  → consistency of error simulations
  → stability of the selected schemes, no surprising error amplification
- Departure to cylindrical symmetry should be very tightly controlled
  Strong effects on final emittance and slice energy spread

In the transport lines:
  Magnet position vibrations in the capture section should be < \( \mu m \)
  Strong effects on final electron beam position
    → vibration dampers to mitigate low-frequency vibrations
    → fast feedback to compensate high-frequency vibrations
1. Inj. / Acc. configurations studied. Results and Selections

2. Lessons learned: how to obtain high beam energy, charge AND quality

3. Optimization of beam extraction and transport

4. Estimation of sensitivity to errors

5. Specifications for plasma and laser systems
Specifications for laser & plasma

150 MeV "ReMPI"

**Driving laser:** decomposed in 4 subpulses, delay 160 fs
120 TW, 4 J, \( w_0 = 30 \mu m \) (\( a_0 = 1, \tau_{\text{FWHM}} = 30 \text{ fs} \))

**Ionizing laser:** 3rd harmonic
1.0 TW, 0.07 J, \( w_0 = 3.8 \mu m \) (\( a_0 = 0.53, \tau_{\text{FWHM}} = 45 \text{ fs} \))

**Symmetrization laser:** 3rd harmonic, delay 40 fs
0.7 TW, 0.02 J, \( w_0 = 11 \mu m \) (\( a_0 = 0.14, \tau_{\text{FWHM}} = 25 \text{ fs} \))

**Plasma:** radially uniform, length 3.5 mm + 1 mm ramp
N preionized up to \( 5^+ \), density \( n_0 = 5 \times 10^{17} \text{ cm}^{-3} \)
+ 3 mm passive plasma lens, \( n_0 = 1.4 \times 10^{16} \text{ cm}^{-3} \)

150 MeV "Downramp Injection"

**Laser:** 35 TW, 1.05 J, \( w_0 = 18 \mu m \) (\( a_0 = 1.8, \tau_{\text{FWHM}} = 30 \text{ fs} \))

(a0 will be x 2 by self focusing)

**Plasma:** radially uniform, ~3.5 mm long
~1 mm upramp, ~0.1 mm plateau at \( n_0 = 6 \times 10^{18} \text{ cm}^{-3} \)
~0.15 mm downramp, 1.8 mm accelerating plateau at \( n_0 = 4 \times 10^{18} \text{ cm}^{-3} \)

Exit ramp exponential \( L_{\text{exp}} = 0.1 \text{ mm} \)
+ passive plasma lens ~4 mm at \( n_0 = 1 \times 10^{16} \text{ cm}^{-3} \)

5 GeV Quasilinear acceleration with external injection

**Laser:** \( P = 400 \text{ TW}, E = 60 \text{ J}, w_0 = 45 \mu m \) (\( a_0 = 2.42, \tau_{\text{FWHM}} = 141 \text{ fs} \))
Bi gaussian

**Plasma:** parabolic in \( r \), \( \Delta n/n_c = 1 \) to 0.3
unniform in \( z \), 30 to 50 cm long, \( n_0 = 1 \) to 2 \( 10^{17} \text{ cm}^{-3} \)
entrance and exit ramps ~2 cm

Specifications for plasma:
\( n_0 = \sim 10^{17} \text{ cm}^{-3} \), parabolic in \( r \)
With tunable density, length tunable radial profile tunable ramp lengths
Specifications for laser & plasma

Laser parameters for 5 GeV

Required laser parameters: for qlr, $P = 400$ TW, $E = 60$ J, $w_0 = 45$ µm ($a_0 = 2.42$, $\tau_{\text{FWHM}} = 141$ fs)

others, $P = 1000$ TW

Bi-Gaussian pulse

$\lambda = 800$ nm

LPAS rempi:
driver pulse decomposed into 8 sub-pulses
ionization pulse at 4th harmonic

RFI 240 MeV+2LPAS bot+CHICANE:
two identical driver pulses for the two stages
Laser parameters for 1 GeV

Bi-Gaussian pulse
\[ \lambda = 800 \text{ nm} \]

LPAS rempi:
driver pulse decomposed into 8 sub-pulses
ionization pulse at 4th harmonic

RFI 500 MeV+LPAS:
cosine squared in longitudinal

Specifications for laser & plasma

Required laser parameters: \( P = 200 \text{ TW}, E = 30 \text{ J}, w_0 = 30 \mu\text{m} \) (\( a_0 = 2.57, \tau_{\text{FWHM}} = 141 \text{ fs} \))
Laser parameters for 150 MeV

Required laser parameters:

- **P = 50 TW, E = 1.5 J, w₀ = 20 µm** (a₀ = 1.93, τ_{FWHM} = 29 fs)
- **P = 250 TW, E = 10 J, w₀ = 30 µm** (a₀ = 2.87, τ_{FWHM} = 38 fs)

**Bi-Gaussian pulse**

λ = 800 nm

LPI rempi:
driver pulse decomposed into 4 sub-pulses
ionization pulse at 3rd harmonic
Tremendous simulations and optimizations have been performed by many contributors

→ Many results obtained on different injection/acceleration schemes and techniques

→ First down selection performed for S2E simulations

→ Issues of emittance growth addressed and solved

→ Thorough S2E simulations done

→ Beam parameters at user's doorstep very close to all the requirements

A certain level of sophistication is necessary

Solutions do exist, at least one configuration is robust

Other schemes or techniques remain promising
Further progress is still possible
The EuPRAXIA project has been studied as for a regular ACCELERATOR project.