Status of Plasma-based Experiments at the SPARC_LAB Test Facility

Enrica Chiadroni (INFN-LNF)

on behalf of the SPARC_LAB collaboration
Outline

❖ Motivation and goals
  ❖ Preservation of beam quality
  ❖ Drive a plasma-based facility
❖ Principle of plasma acceleration and focusing
❖ SPARC_LAB Test Facility
  ❖ High brightness photo-injector
❖ Preparation to plasma-based acceleration experiments
  ❖ External injection of high brightness electron bunches
  ❖ Active plasma lenses for final focusing
    ❖ Preliminary results
❖ Conclusions
Motivation

 ✓ Multi-GeV in cm scale plasma structures
   ✷ Mangles, Geddes, Faure et al., Nature 431, (2004): The dream beam
   ✷ P. Muggli et al, in Proc. of PAC 2011, TUOBN3: Driving wakefields with multiple bunches

 ➡ Acceleration, extraction and transport of stable and reliable high brightness electron beams
   ✷ S. Steinke et al., Nature 000 (2016) doi:10.1038/nature16525: Multi-stage coupling

 ➡ Plasma-based user facility
   ✷ H2020 EuPRAXIA Design Study  => P. A. Walker, TUPML044
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  - H2020 EuPRAAXIA Design Study => P. A. Walker, TUPML044
  - EuPRAAXIA@SPARC_LAB => M. Diomede, THPMK058

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Towards a Plasma-based Facility

- High quality: $\varepsilon_n \ll 1\text{mm mrad}, I_{\text{peak}} \sim k\text{A}, \frac{\Delta\gamma}{\gamma} \ll 1\%$
- External injection of high brightness electron beams

$\lambda_p(\mu m) \approx 3.3 \cdot 10^{10} n_p^{-1/2} (cm^{-3})$

$\lambda_p \approx 330\mu m \ @ \ n_p = 10^{16} cm^{-3}$
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- High efficiency
  \[ \frac{\Delta \gamma}{\gamma} \sim R \gamma_d \]

- Increase the transformer ratio
  \[ R = \frac{|E_{+,\max}|}{|E_{-,\max}|} \gg 2 \]

- Tailoring longitudinal current profile such that all longitudinal slices lose energy at the same rate
  - Asymmetric drive bunch current profile, i.e. triangular, double triangle, doorstep-like distributions, or multiple ramped bunch trains, overcome this limit

\[ \lambda_p(\mu m) \approx 3.3 \cdot 10^{10} n_p^{-1/2} (\text{cm}^{-3}) \]

\[ \lambda_p \approx 330 \mu m @ n_p = 10^{16} \text{cm}^{-3} \]

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The SPARC_LAB Test Facility

Sources for Plasma Accelerators and Radiation Compton with Lasers And Beams


https://www.google.it/maps/@41.8231995,12.6743967,3a,69.7y,130.68h,76.68t/data=!3m6!1e1!3m4!1sYyB35yaBMxJgQ92-wp3oYQ!2e0!7i13312!8i6656?hl=en

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H$_2$ generation and injection system

- Electrolytic generator (1 l of water → 1.4 m$^3$ Hydrogen)
- Pressure reduction system (300 mbar → 10 mbar in capillary)
- Electro-valve triggered by the HV discharge with tunable aperture (3 ms) and delay time (10 µs before discharge)
High Brightness Photo-Injector

High current operation (Velocity Bunching)
80 - 120 MeV beam energy
20 fs - 1 ps bunch duration

Beam energy (MeV) 30 - 170
Bunch charge (pC) 10 - 700
Rep. rate (Hz) 10
emittance (mm mrad) <2
energy spread (%) 0.04 - <1
Bunch length (ps) 0.02 - 10

Broad-band THz radiation
FEL (single spike + seeding)
Laser comb
Narrow-band THz radiation
Two-color FEL
resonant PWFA

High Brightness Photo-Injector

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- Broad-band THz radiation
- FEL (single spike + seeding)
- Laser comb
- LWFA (external injection)
- Narrow-band THz radiation
- Two-color FEL
- resonant PWFA

Generation of multi-bunch trains

Sub-relativistic electrons ($\beta_c < 1$) injected into a traveling wave cavity at zero crossing move more slowly than the RF wave ($\beta_{RF} \sim 1$). The electron bunch slips back to an accelerating phase and becomes simultaneously accelerated and compressed.
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### Laser profile on photo-cathode

<table>
<thead>
<tr>
<th>E (MeV)</th>
<th>ΔE/E (%)</th>
<th>σ_t (fs)</th>
<th>Q (pC)</th>
<th>ε_{nx} (mm mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>112.6</td>
<td>0.084</td>
<td>80</td>
<td>24</td>
</tr>
<tr>
<td>D4</td>
<td>112.3</td>
<td>0.159</td>
<td>42</td>
<td>75</td>
</tr>
<tr>
<td>D3</td>
<td>112.2</td>
<td>0.112</td>
<td>92</td>
<td>69</td>
</tr>
<tr>
<td>D2</td>
<td>112.3</td>
<td>0.087</td>
<td>113</td>
<td>36</td>
</tr>
<tr>
<td>D1</td>
<td>112.2</td>
<td>0.045</td>
<td>100</td>
<td>36</td>
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</table>

**Bunch Separation (µm)**

- W-D4 = 470 (0.02) \( \approx \frac{3}{2} \lambda_p \)
- D4-D3 = 420 (0.03)
- D3-D2 = 240 (0.03)
- D2-D1 = 270 (0.05)

**Laser profile on photo-cathode**

**Experimental Data**
Interaction with plasma

Hybrid kinetic-fluid simulation by Architect from measured drivers parameters

Beam parameters

Q_{witness} = 24 \text{ pC}
Q_{drivers(tot)} \sim 200 \text{ pC}
E = 112 \text{ MeV}
\Delta E/E = 0.1\%
\varepsilon_n \sim 1 \text{ mm mrad}
\sigma_t \text{ drivers} < 100 \text{ fs}
\sigma_t \text{ witness} \sim 80 \text{ fs}

Weakly non-linear regime*

\alpha = \frac{n_b}{n_p} > 1
\tilde{Q} = \frac{N_b k_p^3}{n_p} < 1

n_b \sim 5n_p \text{ and } \tilde{Q} \approx 0.8

The driver bunch spacing is non-uniform, following the experimental separation

Architect sim., courtesy of A. Marocchino

Q_{\tilde{\theta}} \approx 0.8

\tilde{Q} = \frac{n_b}{n_p} \text{ and } \tilde{Q} \approx 0.8

\sigma_{x,y}(\mu m)

\varepsilon_{nx,ny}(mm\ mrad)

\Delta E/E(\%)

**J. B. Rosenzweig et al., in 14th AAC Workshop, AIP Conference Proceedings, 1299, pp. 500-504 (2010)**

**P. Londrillo et al., NIM 740, 236 (2014)**

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Plasma-based Focusing

Discharge current in gas-filled capillary

- the bunch is focused by the azimuthal magnetic field generated by the discharge current density, according to Ampère’s law

\[ B_\phi(r) = \frac{\mu_0}{r} \int_0^r J(r') r' dr' \]

Advantages

- Cylindrical symmetry
- purely radial focusing effect
- Tunability
- Focusing strength \( k \propto \frac{1}{\gamma} \)
- High focusing gradient \( \sim kT/m \)
- short focal length
- weak chromaticity

J.-H. Röckemann et al., arXiv: 1803.06663v1

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The arrival time of the electron beam is scanned with respect to the discharge pulse in order to change the active plasma lens focusing.
Active Plasma Lens Experiments

Beam parameters at the plasma entrance

- \(Q\) (pC): 50 (5)
- \(E\) (MeV): 126.5 (0.04)
- \(\Delta E/E\) (%): 0.06
- \(\varepsilon_{nx}\) (mm mrad): 0.9 (0.1)
- \(\varepsilon_{ny}\) (mm mrad): 1.15 (0.05)
- \(\sigma_z\) (µm): 303 (6)
- \(\sigma_x\) (µm): 79 (2)
- \(\sigma_y\) (µm): 70 (2)

Plasma discharge parameters

- \(n_e \sim 10^{17}\) cm\(^{-3}\)
- \(V = 14\) kV
- \(I_{\text{peak}} = 170\) A
- \(R_0 = 500\) µm
- \(L = 1\) cm
- fully 3D printed plastic capillary
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Beam parameters at the plasma entrance:

- 0 ns:
  - \( x \)
  - \( y \)
- -160 ns:
  - \( x \)
  - \( y \)
- -350 ns:
  - \( x \)
  - \( y \)
- -600 ns:
  - \( x \)
  - \( y \)

rms transverse beam size (mm)

Delay (ns)

\( \sim 25 \mu\text{m} \)
Control of emittance growth
1D analytical model*: the distribution of plasma inside the capillary is at the equilibrium stage as soon as the discharge is initiated

- Equilibrium stage: balance between Ohmic heating and cooling due to the electron heat conduction
- Even with a 1 cm long capillary and 170 A peak current, a partial ionization of the gas occurs
- Non-linear magnetic field, since the current is forced closer to the axes

GPT simulations, courtesy of R. Pompili


E. Chiadroni et al., arXiv: 1802.00279

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Conclusions

✓ Plasma-based *acceleration provides* ultra-high gradients
  ❖ Plasma-based *facilities demand* high brightness beams, i.e.
    \[ \varepsilon_n \ll 1 \text{mm mrad}, I_{\text{peak}} \sim kA, \frac{\Delta \gamma}{\gamma} \ll 1\% \]
  ❖ Many potential applications possible for excellence in Science, e.g. FEL

✓ SPARC_LAB is becoming a test bench facility for plasma-based experiments
  ❖ *External injection schemes* are under investigation, being *promising for* preserving the *high brightness*
  ❖ *Plasma lenses* are promising for *final focus and extraction* from plasma accelerating module due to the \( kT/m \) up to \( MT/m \) plasma fields
  ❖ *Minimization of emittance growth* is mandatory for the proper integration into conventional *user* beam lines

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Drive a plasma-based user facility!

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Thank You for the attention!

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