Multi–GeV Plasma Wakefield Acceleration Experiments

Rasmus Ischebeck, for the E–167 collaboration

Plasma wakefield acceleration

Existing experimental apparatus

Proposed next experiments: E–167
- Physical goals
- Improvements to the apparatus
Evolution of Electron Accelerators
(Livingston Plot)

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Basic Requirements for Electron Accelerators beyond ILC

- Energy \( W \gtrsim 5 \text{ TeV} \) \( W = E \cdot e \cdot L \) \( \text{(Linac)} \)

- Luminosity \( \mathcal{L} \gtrsim 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \)

\[ \mathcal{L} = \frac{I^2}{4 \pi f \sigma_x \sigma_y} \]

⇒ Beam power \( P \approx 100 \text{ MW} \)

- Cost \( C \lesssim 5 \cdot 10^9 \)

- High accelerating fields
- Low emittance (small diameter)
- High bunch charge
- Good efficiency

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Plasma Waves

- Plasma wavelength:
  \[ \lambda_p \approx \sqrt{\frac{10^{15} \text{cm}^{-3}}{n_p}} \text{ mm} \]

- Wave breaking field: maximum field achievable in a plasma, occurring when the electron density becomes singular

- As calculated from non-relativistic one-dimensional theory:
  \[ E_0 = \frac{4\pi \varepsilon_0 c m_e}{e} \omega_p \]
  or, as a function of the plasma density
  \[ E_0 \approx \sqrt{\frac{n_p}{\text{cm}^{-3}}} \frac{\text{V}}{\text{cm}} \]

- In our case, \( n_p \approx 10^{17} \text{ cm}^{-3} \) \( \implies \) \( E_0 \approx 30 \text{ GV/m} \)
Plasma acceleration

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Scaling Laws (Linear Theory)

- Electric field at a distance $\zeta$ behind the bunch

$$\vec{E} = \frac{eN_b}{2\pi\varepsilon_0} k_p^2 e^{-\frac{k_p^2 \sigma_z^2}{2}} \sin(k_p \zeta) \quad \text{where} \quad k_p = \sqrt{n_p e^2 / (4\pi\varepsilon_0^2 m_e c^2)}$$

- Match bunch length to the plasma wavelength
(maximize the longitudinal electric field for a given bunch length)

$$k_p = \frac{\sqrt{2}}{\sigma_z} \quad \Leftrightarrow \quad n_p = \frac{m_e c^2}{2\pi e^2 \sigma_z^2}$$

$$\Rightarrow \quad \vec{E} = \frac{eN_b}{\pi\varepsilon_0 \sigma_z^2} e^{-1} \sin(k_p \zeta)$$

$$\text{or} \quad \vec{E}_{\text{max}} \approx 100 \left( \frac{N_b}{2 \cdot 10^{10}} \right) \left( \frac{20 \mu m}{\sigma_z} \right)^2 \frac{\text{GV}}{\text{m}}$$

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Plasma Acceleration (E–164X)

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Courtesy Mark Hogan
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Particle tracking in 2D...

- Energy profile
  - 0.08% at 1.19 GeV
  - 1.2% at 1.19 GeV
  - 1.1% at 1.2 mm
  - 1.6% at 1.2 mm
  - 1.6% at 1.2 mm
  - 1.5% at 1.5%
Lithium Oven

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Field Ionization of the Lithium Vapor

For lower beam density the ionization threshold occurs later in the bunch.

For higher beam density the ionization threshold occurs earlier in the bunch.

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Courtesy Caolionn O'Connell
Existing Diagnostics

- e\textsuperscript{-} beam from SLAC linear accelerator
- e\textsuperscript{-} spectrum X-ray based spectrometer
- e\textsuperscript{-} spatial distribution optical transition radiation (OTR)
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- positron production from betatron X-rays
- e\textsuperscript{-} spectrum imaging spectrometer
- e\textsuperscript{-} bunch length autocorrelation of coherent transition radiation (CTR)
- plasma light spectrum grid spectrometer
- plasma oven

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Plasma wakefield acceleration

Existing experimental apparatus

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- Physical goals
- Improvements to the apparatus
Proposed Next Experiments: E–167

- Address issues important for a useful accelerator
  
  Variation of oven length & plasma density
  Hose instabilities
  
  Trapped particles
  
  Bunch shaping
  Twin bunch

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Improvements to the Apparatus

- Plasma oven with variable length
- Detection of accelerated ions with a fast beam current transformer
- Improvements to diagnostics
  - Positron source from betatron x-rays
  - Plasma light spectrometer
  - Electron bunch shape (OTR)
  - Electron bunch length (CTR autocorrelator)
- Time-resolved measurements of the plasma light spectrum and of OTR
- Twin bunch scheme
Increased Energy Reach

- Variable length oven: 10 – 30 cm
- Oven is removable
- Increased energy aperture
- Larger phosphor for spectrometer
Beam tilt and hose instability effects

- A transverse tilt in the electron beam can be amplified by the plasma wake
- Limits the applicability of plasma wakefield accelerators?

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Detection of Trapped Particles

- Downstream charge as a function of bunch length
- Fast beam current transformer will be installed downstream of the plasma
Positron Source from Betatron X–Rays

Improvements to the apparatus:
• detect electrons and positrons simultaneously
• install a new pole piece for the magnet
• improve the shielding

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Improvements to the Experimental Apparatus

- Optical transition radiation (OTR)
  - increased resolution
  - shielding from Čerenkov light
  - time–resolved measurements
  - measurements in the middle of the chicane
- Plasma light spectrometer
  - increased resolution
  - time–resolved measurement
Bunch Length Measurement

• Using coherent transition radiation (CTR)

• For a bunch length \( \approx \lambda \) the emission is coherent
  \( \Rightarrow \) the pulse energy is increased by a factor \( N_b \)
Coherent Transition Radiation of a Gaussian Beam

\[ \frac{dW}{d\Omega d\nu} = \frac{N_b^2 e^2}{4 \pi^3 \varepsilon_0 c (1 - \beta^2 \cos^2 \vartheta)^2} \exp \left( -\frac{\nu^2}{4 \pi^2 c^2 \beta^2} (\sigma_z^2 + \beta^2 \sigma_r^2 \sin(\vartheta^2)) \right) \]

Considering:

- the finite size of the foil
- near field diffraction of the radiation and the imaging by the mirror
- absorption in the vacuum window and air
- spectral sensitivity of the detector

and integrating over solid angle and frequency yields:

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Bunch Length Measurement

- Existing autocorrelator

\[ \sigma_z = 9 \, \mu m \]
Single-Bunch Autocorrelator

- Mach–Zehnder geometry
- Use a segmented FIR detector
Twin Bunch Scheme

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Twin Bunch Scheme
Simulations

- Energy loss by bremsstrahlung
- Beam dynamics

Development in the chicane

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Twin Bunch Scheme

Simulations

- Energy loss by bremsstrahlung
- Beam dynamics

- Development in the following linac sections

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Twin Bunch Scheme

Resulting Current Distribution

phase space

current distribution

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Twin Bunch Scheme

Experimental Considerations

- Material and thickness of absorber
- Compression process
- Particle loss simulations
- Installation in the linac
Summary

- Existing experimental setup includes state-of-the-art beam diagnostics:
  - Non-invasive energy spectrum
  - Sub-picosecond bunch length

- Experimental results:
  - Acceleration of 3 GeV in a 10 cm plasma

- E-167 will allow to:
  - Reach higher energies and address hose instability issues
  - Analyze trapped particles
  - Accelerate separate bunches

- Pave the road towards a useful plasma wakefield accelerator

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This talk is available at http://www.slac.stanford.edu/~rasmus