Plasma Wakefield Acceleration in the FFB (E-164X & E-167)

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Outline

• Introduction to PWFA
• Building on previous work
• Short bunches
  – How we make & measure them
  – Need a plasma to match them
• Phase space retrieval via LiTrack
• Multi-GeV energy gain
• Future directions
• Conclusion
PWFA:
Plasma Wakefield Acceleration

- Looking at issues associated with applying the large focusing (MT/m) and accelerating (GeV/m) gradients in plasmas to high energy physics and colliders.
- Built on E-157 & E-162 which observed a wide range of phenomena with both electron and positron drive beams: focusing, acceleration/de-acceleration, X-ray emission, refraction, tests for hose instability…

Linear PWFA Theory:

- $E_{z,\text{linear}} \propto \frac{N}{\sigma_z^2}$ => Short bunch!
- For $k_p \sigma_r \ll 1$ and $k_p \sigma_z \approx \sqrt{2}$ or $n_p \propto \frac{1}{\sigma_z^2}$

- $E_z$: accelerating field
- $N$: # e-/bunch
- $\sigma_z$: gaussian bunch length
- $k_p$: plasma wave number
- $n_p$: plasma density
- $n_b$: beam density

- A single bunch from the linac drives a large amplitude plasma wave which focus and accelerates particles
- For a single bunch the plasma works as an energy transformer and transfers energy from the head to the tail
Located in the FFTB
Beam-Plasma Experimental Results (6 Highlights)

**Focusing e⁻**

\[ \sigma_0 \text{ Plasma Entrance } = 50 \mu \text{m} \]
\[ \varepsilon_N = 12 \times 10^{-5} \text{ (m rad)} \]
\[ \beta_0 = 1.16 \text{ m} \]

Phase Advance \( \Psi \propto n_e^{1/2}L \)


**X-ray Generation**

*Physical Review Letters* 1 April 2002


**Wakefield Acceleration e⁺**

![Graph](Image)

**Matching e⁻**

L = 1.4 m
\[ \alpha_0 = 14 \mu \text{m} \]
\[ \varepsilon_N = 18 \times 10^{-5} \text{ m-rad} \]
\[ \beta_0 = 6.1 \text{ cm} \]
\[ \alpha_0 = 0.6 \]

Phase Advance \( \Psi \propto n_e^{1/2}L \)


**Electron Beam Refraction at the Gas-Plasma Boundary**

\[ \theta \propto 1/\sin \phi \]

\[ \theta \approx \phi \]

○ BPM Data

– Model

*Nature 411*, 43 (3 May 2001)

**Wakefield Acceleration e⁺**

![Graph](Image)

E-164X:

\[ \sigma_z = 10 - 20 \mu m \]

> 10 GeV/m gradient!

(\(\sigma_r\) dependent! \(k_p \sigma_r \approx 1\))

Electric Field (GV/m)

\[ f_p = 2.8 \text{ THz}, \ W = 3 \text{MT/m} \ @ \ n_e = 10^{17} \ cm^{-3} \]
Short Bunch Generation In The SLAC Linac

Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)

- Bunch length/current profile is the convolution of an incoming energy spectrum and the magnetic compressio
- Dial FFTB $R_{56}$, measure incoming energy spectrum.

30 kA
80 fsec FWHM
28 GeV

Existing bends compress to <100 fsec

1.5%
First Measurement of SLAC Ultra-short Bunch Length!

NDR compressor voltage: 41.8 MV/m, 2-6BNS phase -19°

\[ \sigma_z \approx 9 \ \mu m \]

\[ \sigma_z \approx 18 \ \mu m \]

or

\[ \tau \approx 60 \ \text{fs} \]
CTR Energy Correlates with Bunch Length

**Linac Wake Loss**

- Wake energy loss
- Linac phase
- THz power

**Graphical Data**
- Relative Energy @ end of linac
- FFBT Pyrometer Signal
- Pyrometer signal [arb. units]
- Linac phase offset from crest [deg. S-Band]
Non-Invasive Energy Spectrometer Upstream of Plasma
Phase Space Retrieval via LiTrack

*K. Bane & P. Emma

- Extension of previous work on SLC
- More compression stages
- More free parameters
- Shorter bunches
- Requires good measurements, good intuition or really good guessing!
- Not automated (yet!)
- Single shot and non-destructive!
Below 100μm Bunch Length At Threshold For Self-Ionization

Peak Field For A Gaussian Bunch

\[ E = 6GV/m \frac{N}{2 \times 10^{10}} \frac{20\mu}{\sigma_r} \frac{100\mu}{\sigma_z} \]

Ionization Rate for Li

\[ W_{Li} [s^{-1}] \approx \frac{3.60 \times 10^{21}}{E^{2.18}[GV/m]} \exp\left(\frac{-85.5.}{E[GV/m]}\right) \]

See D. Bruhwiler et al, Physics of Plasmas 2003

**Space charge fields are high enough to field (tunnel) ionize - no laser!**

- No timing or alignment issues
- Plasma recombination not an issue

- However, can’t just turn it off!
- Ablation of the head
Accelerating Gradient > 27 GeV/m!
(Sustained Over 10cm)

- Large energy spread after the plasma is an artifact of doing single bunch experiments
- Electrons have gained > 2.7 GeV over maximum incoming energy in 10cm
- Confirmation of predicted dramatic increase in gradient with move to short bunches
- First time a PWFA has gained more than 1 GeV
- Two orders of magnitude larger than previous beam-driven results
- Future experiments will accelerate a second “witness” bunch

Accepted for publication Phys. Rev. Lett. 2005
How We Quantify The Data

- No longer have time resolution
- Must quantify particles with energies above maximum incoming energy

**Note:** The head of the bunch (25% of the highest energy electrons in the plasma off case) is below ionization threshold and not affected by the lithium vapor.
**A Simple Picture (Cartoon!)**

**Changing Bunch Length**
**Fixed Plasma Density**

- Wake amplitude increases
- **Less** of the bunch population samples the Maximum accelerating gradient

**Fixed Bunch Length**
**Changing Plasma Density**

- Wake amplitude increases
- **More** of the bunch population samples the Maximum accelerating gradient
A Simple Picture (Cartoon!)

Changing Bunch Length
Fixed Plasma Density

- Wake amplitude increases
- **Less** of the bunch population samples the Maximum accelerating gradient

Fixed Bunch Length
Changing Plasma Density

- Wake amplitude increases
- **More** of the bunch population samples the Maximum accelerating gradient
Maximum Energy Gain (at fixed $n_p$) is Bunch Length Dependent
Maximum Energy Gain (at fixed $\sigma_z$) is Plasma Density Dependent

Changing Plasma Density: $1.0e17$, $2.5e17$ and $3.5e17$

Energy Spread is filling the pipe!
Future Experiments

• Increased energy aperture in the FFTB (Summer 2005)
  - Try for 10GeV energy gain!
  - Test for instabilities (electron hose etc…)

• Two bunches via notch collimator in linac chicane or FFTB (Early 2006)
Over the past 5 years
20 Peer reviewed publications covering all aspects of beam plasma interactions: Focusing (e⁻ & e⁺), Transport, Refraction, Radiation Production, Acceleration (e⁻ & e⁺)

This years accomplishments

First measurement of the SLAC Ultra-short Bunch Length

Demonstration of Field Ionized Plasma Source

Measured Accelerating Gradients > 27 GeV/m (over 10cm) in a PWFA