Surfing Plasma Wakes: A New Paradigm for Particle Accelerators.

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Putting Beam Physics at the Forefront of Science
Sir John Adams Lecture
Dedicated to Sir John Adams
Director General CERN 1971 -1975
Accelerator Physics: A legacy of brilliant 20th Century Scientists

Cockcroft & Walton with Rutherford

Van de Graaff

Lawrence

Wilson

Adams

Richter

Van der Meer
International Linear Collider

Can Plasmas Play A Role in Future High-Energy Particle Accelerators?
- Smaller?
- Cheaper?
OUR VISION

To address critical physics issues for realizing a plasma-based accelerator at the energy frontier in the next decade. A byproduct will be compact accelerators for industry & science.
Particle Accelerators

Why Plasmas?

**Conventional Accelerators**
- Limited by peak power and breakdown
- 20-50 MeV/m

**Plasma**
- No breakdown limit
- 10-200 GeV/m
Tell us, in layman's terms, what your breakthrough means.

Certainly.

\[ K - \frac{4n^3 \sqrt{P}}{7} \]
**Conventional Accelerator**

- **Copper Structure with irises**
- **Powered by microwaves**
- **Energy Gain 20 MV/m**
- **Structure Diameter 10 cm**

**Plasma Accelerator**

- **Ionized Gas**
- **Lifetime, few picoseconds**
- **Powered by a Laser or electron beam pulse**
- **Energy Gain 20 GV/m**
- **Diameter 0.1-I mm**
From Microwave Cavities to Plasmas

"Accelerator Moore’s Law"

Working Machines Doing physics

Max. Energy in Plasma Experiments

E167
E164X
LBNL
E162
RAL
LOA
LBL
Osaka
ILC
KEK
UCLA
ILE
LLNL
UCLA

 YEAR
1930
1940
1950
1960
1970
1980
1990
2000
2010

BEAM ENERGY (MeV)
1
10
100
1000
10000
100000
1000000
10000000
Plasma Wakefield Accelerators
(Blowout Regime)

• Space charge force of the beam pulse displaces plasma electrons

• Plasma ion channel exerts restoring force => space charge oscillations.

• Linear focusing force on beams \((F/r=2\pi ne^2/m)\)

Rosenzweig et. 1990       Pukhov and Meyer-ter-vehn 2002 (Bubble)
Limits to Energy Gain: PWFA

- No dephasing
- No diffraction, but...
  - Head erosion
    \( L = \pi \sigma^2/\epsilon \gg L_R \)
  - Hosing
- Transformer Ratio:

\[
R \equiv \frac{\Delta \gamma_{\text{load}}}{\gamma_{\text{driver}}} \leq \frac{E_+ \cdot L}{E_- \cdot L} = \frac{E_+}{E_-}
\]
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 compression
- Dial FFTB $R_{56}$, measure incoming energy spectrum.
PWFA @FFT B done with single 30-40 GeV Bunch

Most Beam Electrons lose energy to wake
Electrons in beam tail gain energy from wake
Experimental Setup

- Electron beam from SLAC linear accelerator: 30-40 GeV
- Electron spatial distribution
- X-ray based spectrometer
- Electron spectrum
- Optical transition radiation (CTR)
- Plasma oven
- Trapped particles
- Imaging spectrometer
- Electromagnetic light in air gap
- Monochromator
- Beam stopper

10-100 GeV
**Lithium Plasma Source**

**How it works:**
1) Heated to 800°C to vaporize solid Li.
2) Li vapor diffuses out to the He transition region and condenses on wick.
3) The molten Li wicks back to center, vaporizes and begins the process again.

- Be (low-Z) windows separate the He from the FFTB beam line vacuum.
- The He pressure determines the Li vapor density, and the heater power determines the Li vapor length.
**BEAM-IONIZED PLASMA**

- Short bunch, \(E_r \approx 5.2 \times 10^{-19} N/\sigma_z \sigma_r\) (GV/m) > tunneling field (Kyldish, ADK)

Lithium vapor pressure curve

\[N=10^{10} e^-, \sigma_z=\sigma_r=20 \ \mu m\] in Li

\[
\begin{align*}
\Delta W & \sim 60 \text{ MeV} \left(\frac{l_p}{l_0}\right)^3 \text{ TW}
\end{align*}
\]
**BREAKING THE 1 GeV BARRIER**

- Initial Beam Energy $\approx 3.5 \times 10^{17} \text{ cm}^{-3}$
- Density $n_e = 3.5 \times 10^{17} \text{ cm}^{-3}$
- Length $L \approx 10 \text{ cm}$
- Number $N \approx 1.8 \times 10^{10}$
- Time $\tau \approx 50 \text{ fs}$

**Energy Change**
- Accelerated Electrons: $+2$ GeV
- Initial Beam Energy: $0$ GeV
- Decelerated Electrons: $-2$ GeV
Energy Gain Scales Linearly with Length

PLASMA LENGTH (cm)
Energy Loss of the drive beam electrons

Trapped Electron
Energy as High as 17 GeV

E.Oz et al PRL 2007
Energy Doubling of 42 Billion Volt Electrons Using an 85 cm Long Plasma Wakefield Accelerator

*Nature v 445, p741 (2007)*
Maximum Energy Peaks at 85 cm

Miaomiao Zhou
Successful Development of a Plasma Accelerator for High Energy Physics:

High Gradient Acceleration of positrons as well as electrons

Focusing of positrons and electrons to nanometer size

Head erosion, hosing instability and ion motion.

Small energy spread and beam divergence

High overall energy transfer efficiency

Excellent pointing stability and minimum jitter.
WAKEFIELD FIELDS for $e^-$ & $e^+$

- Transverse Field constant after plasma electrons blown-out
- Longitudinal field shows accelerating “spike”

$n_e = 1.5 \times 10^{14} \text{ cm}^{-3}$

Electron fields

Longitudinal $E$ [GV/m]

Transverse $E$ [GV/m]

$\tau$ (ps)

Beam Current (A)

Fields vary along r, stronger

Less Acceleration
Energy Gain & Loss of Positrons in a Plasma Wake

(OSIRIS Simulation Prediction:
Experimental Measurement:

Peak Energy Loss
64 MeV
65±10 MeV

Peak Energy Gain
78 MeV
79±15 MeV

5x10^8 e^+ in 1 ps bin at +4 ps

(Brent Blue et al Phys, Rev. Letts 2002)
**FOCUSING OF $e^-/e^+$**

- Beam images $\approx 1$ m from plasma exit ($\epsilon_x \neq \epsilon_y$)

\[
n_e = 0
\]

\[
n_e \approx 10^{14} \text{ cm}^{-3}
\]

- **Ideal Plasma Lens in Blow-Out Regime**

- **Plasma Lens with Aberrations**

M. Hogan et al, Phys. Rev. Letts. 2002
Radiation Loss: Ultimate Limit on Plasma Accelerators

Plasma Wiggler for collimated X-ray production 10 KV-100 MV

\[ \frac{dE}{dz} = \frac{1}{3} r_e m_e c^2 \gamma^2 k^2 K^2 = f(n_p^2, r_o^2, \gamma^2) = 4.3 \text{GeV} / \text{m} \]

Pair Production from Betatron X-Rays

FACET: Facility for Second Generation AA Research @SLAC

Figure 1-1. Schematic of the SLAC site with proposed FACET modifications to the beam delivery systems.
PLASMA AFTERBURNERS for FUTURE ACCELERATORS
PLASMA AFTERBURNER

Use Shaped Bunches
For Constant Energy Loss
And greater than 2 Transformer Ratio

Drive Beam Followed by a
Narrower Trailing Beam

Beam load 
flattens wake, reduces energy spread

Loaded wake
• \( N_{\text{load}} \approx 30\% N_{\text{max}} \)
• 1% energy spread
1 TeV Plasma Wakefield Accelerator

5, 100 GeV drive pulses, SC linac

“Yes, but what have you invented lately?”
“The challenge is to undertake and sustain the difficult and complex R&D needed to enable a feasible, cost and energy effective technology on the several decade horizon. Achieving these goals will require creativity and the development and maturation of new accelerator approaches and technologies.”

HEPAP Subpanel 2006

Lives of great men all remind us
We can make our lives sublime
And departing, leave behind us
Footprints on the sands of time

Henry Wadsworth Longfellow (1801-1882)
Experimental & Theory Collaborators

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