Institute for Research in Fundamental Sciences

Review of Plasma-Based Wakefield Accelerators as an Energetic Particle Source

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Outline

- Motivation
- Basic principles of Plasma-based wakefield acceleration
- Injection mechanisms
- Energy gain limitations
- Recent results

Motivation

Particle accelerators use electric and magnetic fields to speed up to light velocity.

Discoveries went hand in hand with theoretical understanding of underlying laws of nature

- Increasing energies makes particles of larger and larger mass accessible
- Increasing particle energies probe smaller and smaller scales of matter

Medicine | Industry | Fundamental physics | Producing energy

30’000 accelerators worldwide!

Motivation

Conventional Accelerating Technology

Today's RF cavities or microwave technology:
Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.

- Typical gradients:
- LHC: 5 MV/m , 27 km , 7 TeV
- ILC: 35 MV/m , 20 km , 1 TeV
- CLIC: 100 MV/m , 48 km , 3 TeV

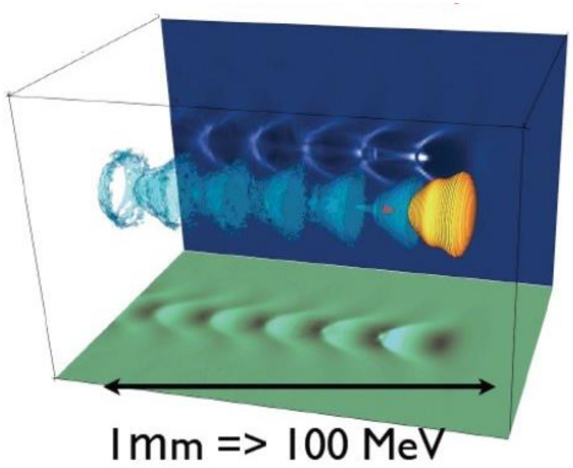
However:

- Accelerating fields are limited to <100 MV/m
- In metallic structures, a too high field level leads to break down of surfaces, creating electric discharge.
- Fields cannot be sustained, structures might be damaged.
- several tens of kilometers for future linear colliders and longer means more expensive.

Motivation

1 m => 100 MeV (gain)

Accelerating electric field < 100 MeV/m



With this new technology:
No magnets, no RF, no vacuum needed

Accelerating electric field < 100 GeV/m

Plasma-Based Wakefield Acceleration

1979, T. Tajima, J. Dawson

Use a plasma to convert the transverse space charge force of a beam driver into a longitudinal electrical field in the plasma

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective accelerators, present-day electron beams[3] yield electric fields of ~10^7 V/cm and power densities of 10^{13} W/cm^2.

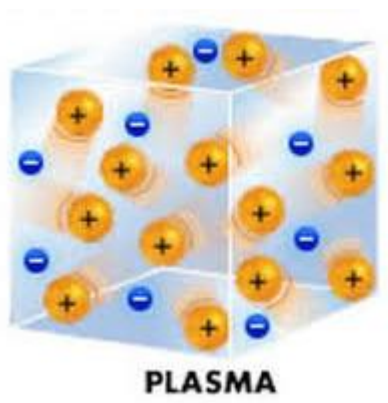
the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p . \qquad (2)$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes $2\pi c/\omega_p$. The mechanism for generating the wakes can be simply seen by the following approximate

What is a plasma?

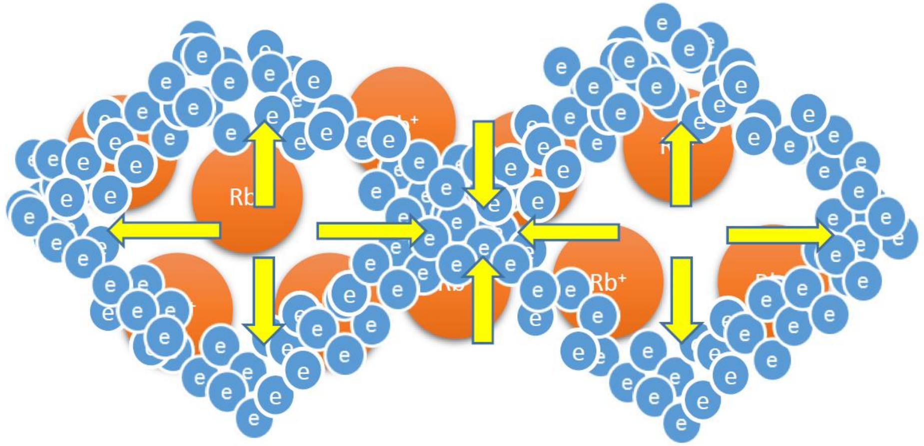
Plasma is already ionized or “broken-down” and can sustain electric fields up to 100 GV/m.



- **Quasi-neutrality:** the overall charge of a plasma is about zero.

- **Collective effects:** Charged particles must be close enough together that each particle influences many nearby charged particles.

- **Electrostatic interactions dominate** over collisions or ordinary gas kinetics.



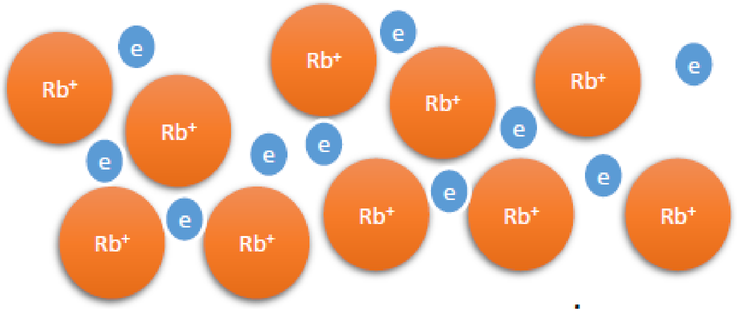
Wakefields created by collective motion of plasma particles are called plasma wakefields.

How to create a plasma wakefield ?

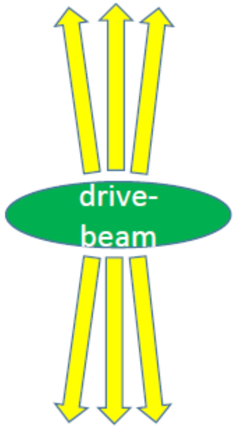
when a boat travels through water it produces a wave behind it - a “wake”.
The phase velocity of the wave is just the speed of the boat.

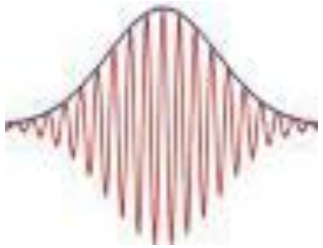
What we want:
Longitudinal electric field to accelerate charged particles.

Our Tool:
A plasma



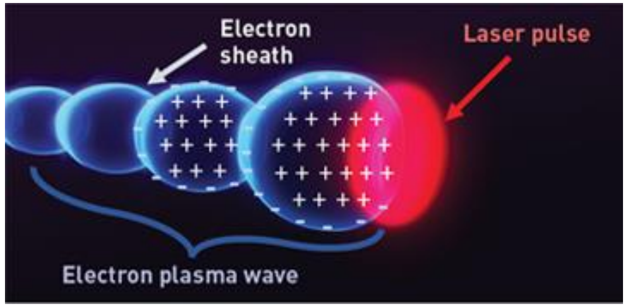
Our driver:
Charged particle bunches or Laser pulses



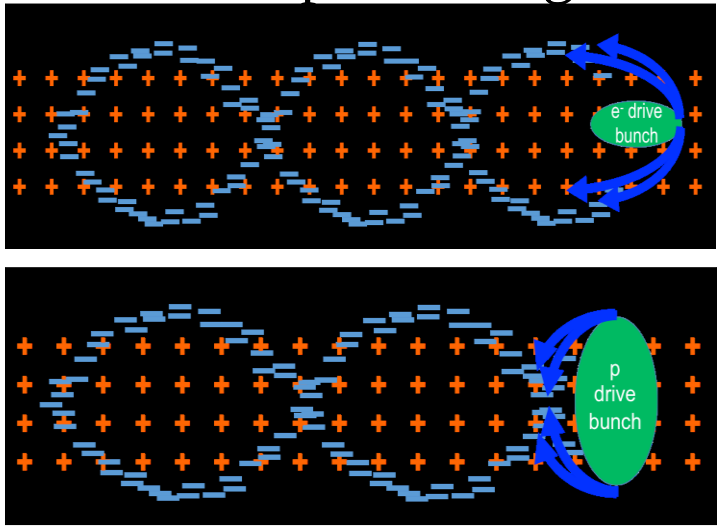


Principle of Plasma Wakefield Acceleration

Laser drive beam (Laser wakefield accelerators , LWFAs) ➔
Ponderomotive force



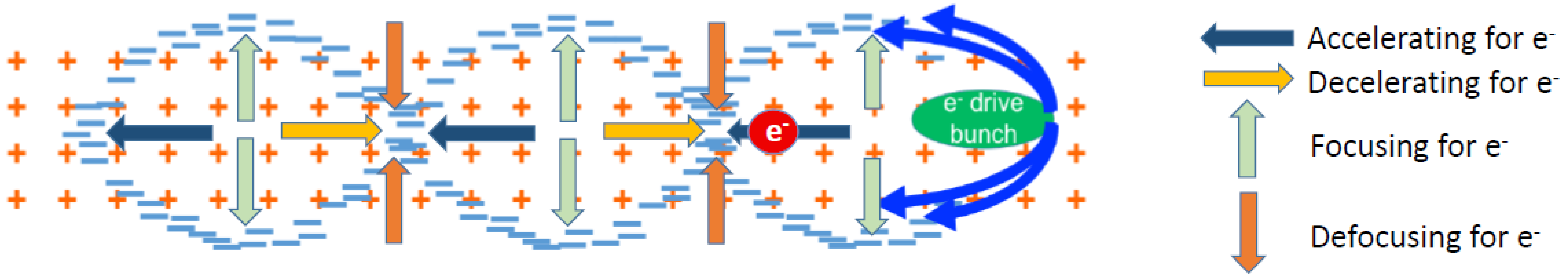
Charged particle drive beam ➔ (Plasma wakefield accelerators , PWFAs)
Transverse space charge field

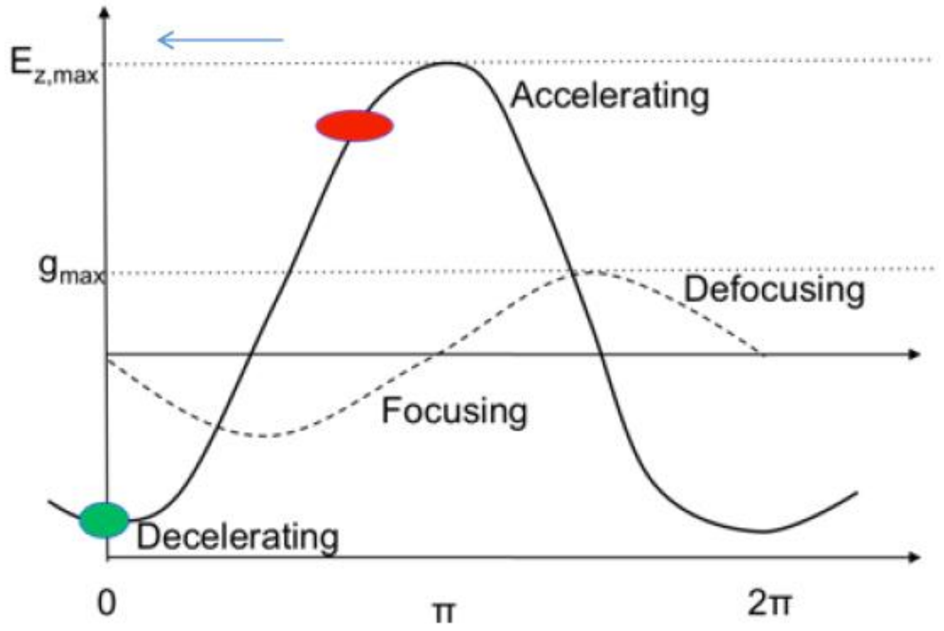


Plasma wave/wake excited by a laser pulse or a relativistic particle bunch

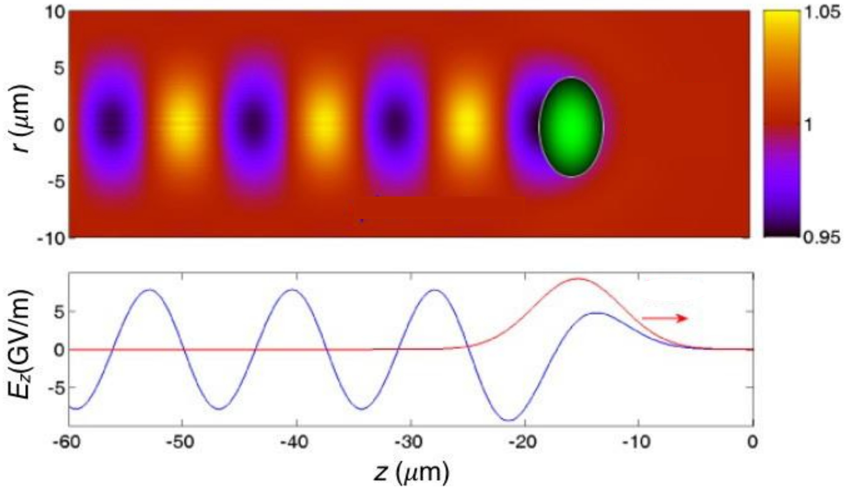
- Plasma e- are expelled by space charge force
- Plasma e- rush back on axis

Where to Place the Witness Beam ?





From linear to nonlinear regime



Linear regime:

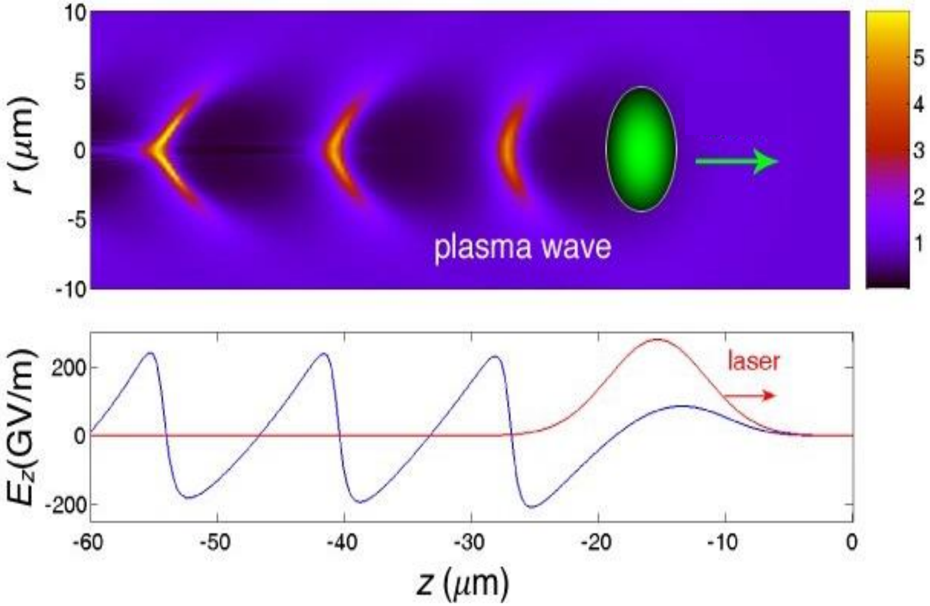
$n_b \ll n_p$

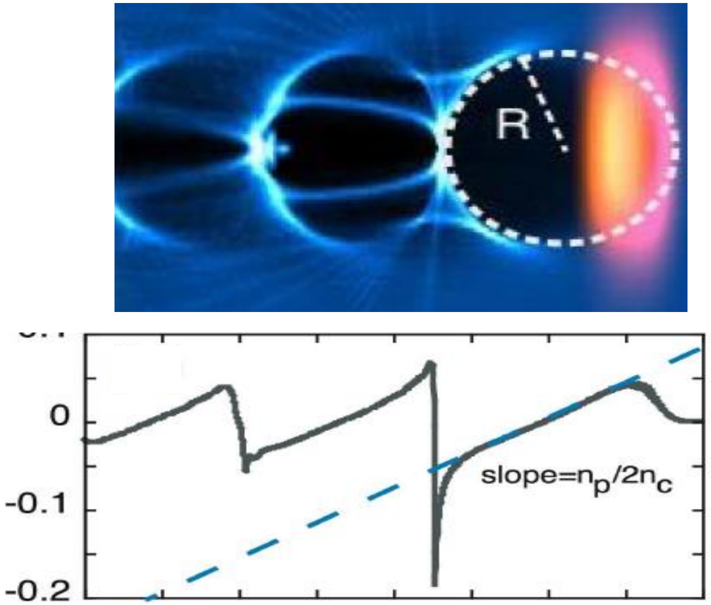
$a < 1$

Non-linear wakes:

$n_b \sim n_p$

$a = 1$



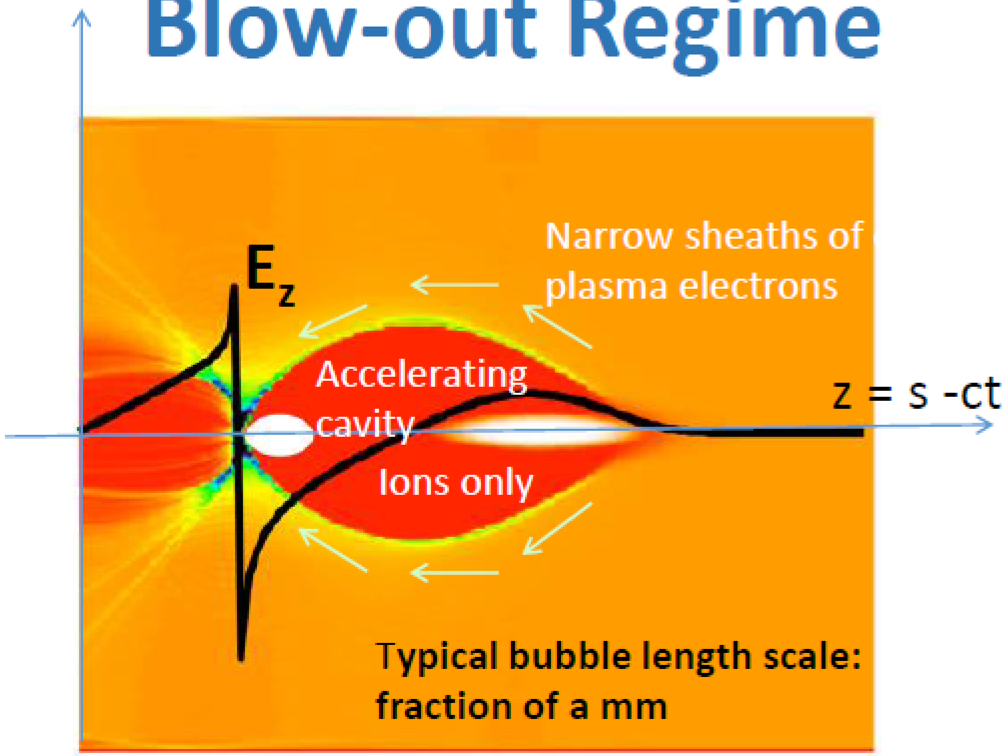


Blow-out regime:

$n_b \gg n_p$

$a > 1$

Blow-out Regime



- **Space-charge force** of the driver blows away **all the plasma electrons** in its path, leaving a uniform layer of ions behind (ions move on a slower time scale).
- Plasma electrons form a **narrow sheath** around the evacuated area, and are **pulled back by the ion-channel** after the drive beam has passed
- An **accelerating cavity** is formed in the plasma
- The back of the blown-out region: **ideal for electron acceleration**

→ **High efficiencies** for energy transfer from drive beam to loaded witness bunch (80-90% according to sim.)
→ **High charge witness** acceleration possible → charge ratio to witness of same order
→ **Linear focusing in r**, for electrons; very strong quadrupole (MT/m)
→ **High transformer ratios (>2)** can be achieved by shaping the drive bunch
→ **E_r independent of x**, can **preserve incoming emittance** of witness beam

Injection mechanisms

Injector is of prime importance

Determines the performances of the overall accelerator : charge, energy spread, emittance

Better to decouple the injection mechanism from the acceleration mechanism

Indivudual adjustment of parameters, stability, control

External injection

Fine definition of beams delivered by conventional photo-injectors

Issues:

to achieve an ultra-short bunch < $\lambda_p/4$ ~10μm (30 fs)
Synchronization between laser and injected beam

Internal injection

Various mechanisms more or less complex to implement

Issues:

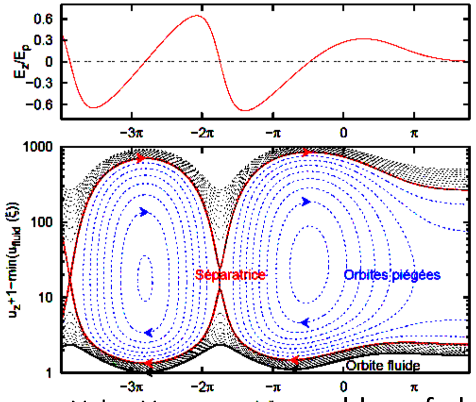
to achieve high charge > 100 pC, and low energy spread

$\Rightarrow$ the trapping of e- by the plasma wave should be highly localized

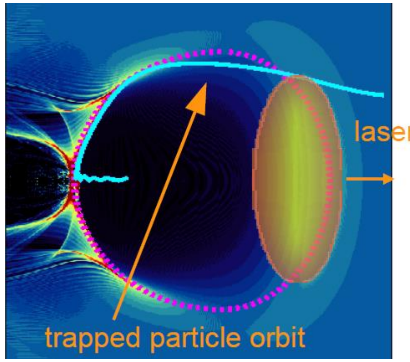
Internal injection

Self-injection

Needs strong wakefield to trap the cold plasma e-



Vph ≈ Vg cold e- of plasma



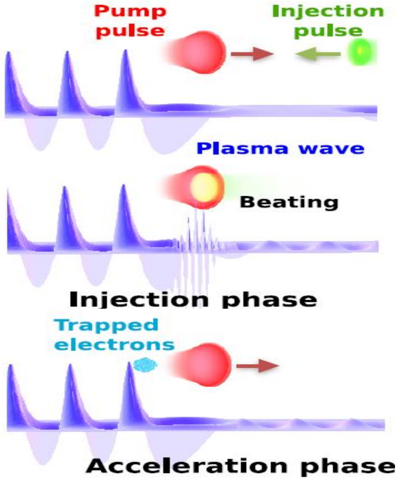
- On-axis or off-axis injection
- Non-linear regime
- Self-guiding

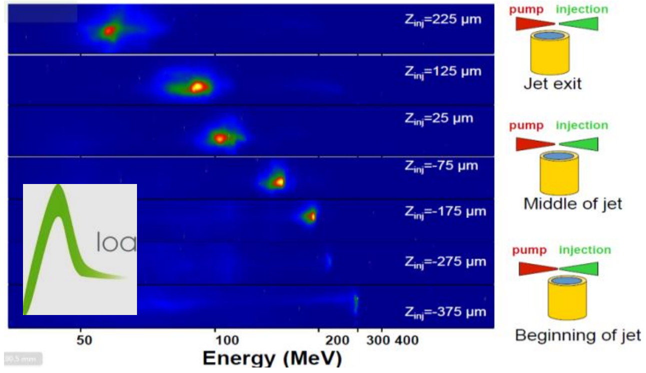
⇒ Uneasy to control

Optical injection

Laser pulses colliding

Main pulse : to excite plasma wave below the self-injection threshold
Counter-propagating injection pulse: to generate a beating with main pulse → triggers the injection

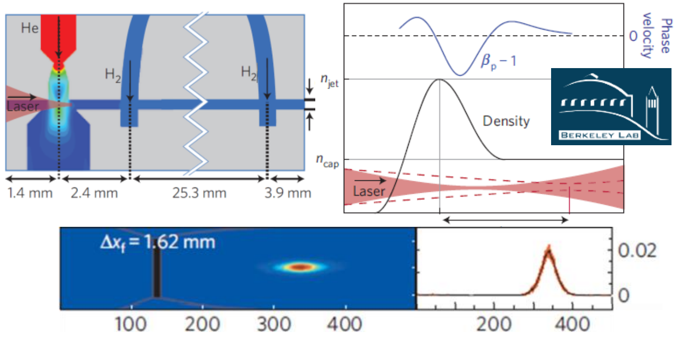




Faure et al, Nature 444 (2006)

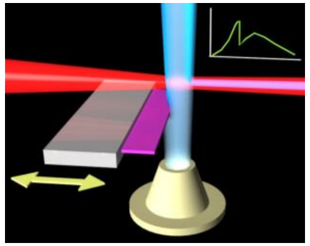
Density downramp

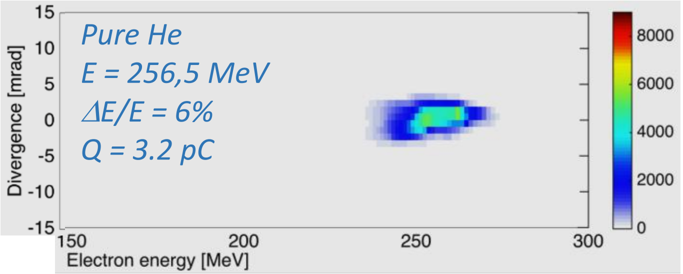
- **soft gradient** $L_{grad} >> \lambda_p$
→ slows down the plasma wave



- **sharp density ramp** $L_{grad} \leq \lambda_p$
→ Increase of the bubble size
places e- at the right phase
→ Localize injection → reduce E spread

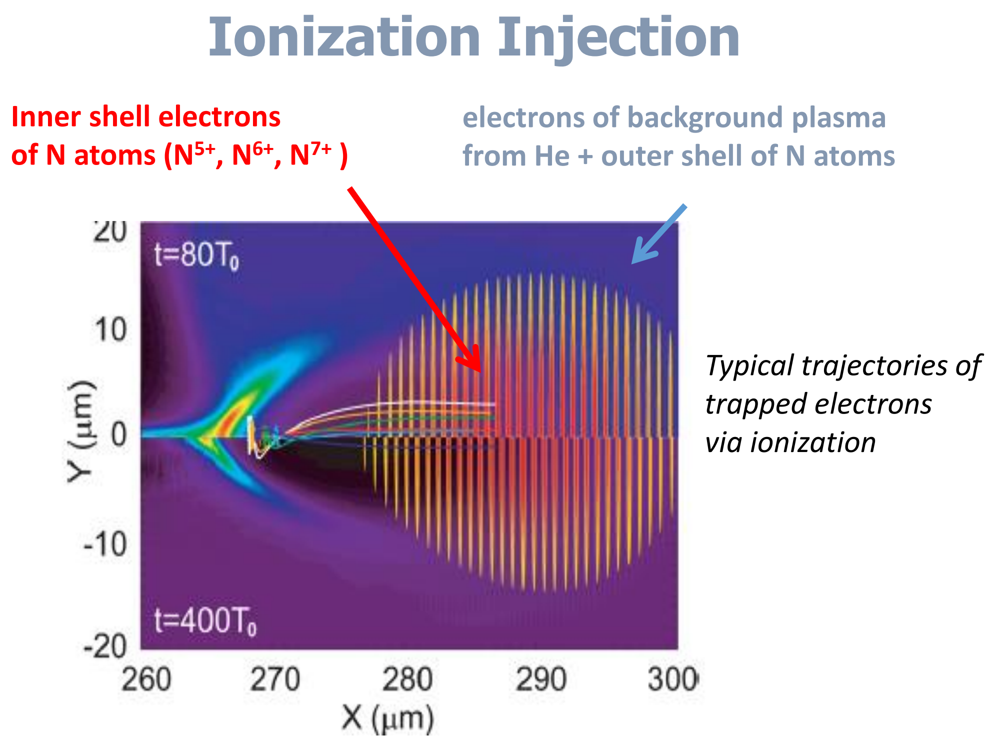
movable blade





A.J. Gonsalves et al, Nature Physics (2011)

Internal injection



Gas mixture He + N (or Kr)

Ionization of inner shells of high Z atom (N,Kr,Ar) at the peak intensity of the laser pulse

→ e- injected at the proper phase for trapping and acceleration to high energies

Potential for high charge ~ 100 pC but high E_spread

A. Pak et al, Phys. Rev. Lett. 104 (2010)

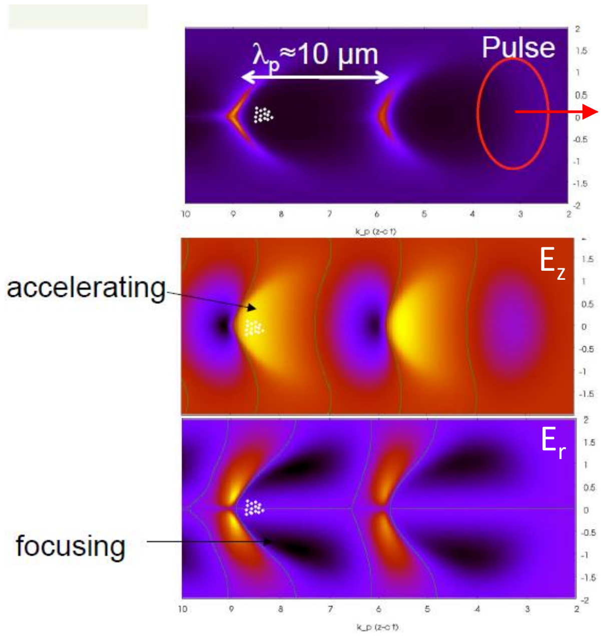
External Injection

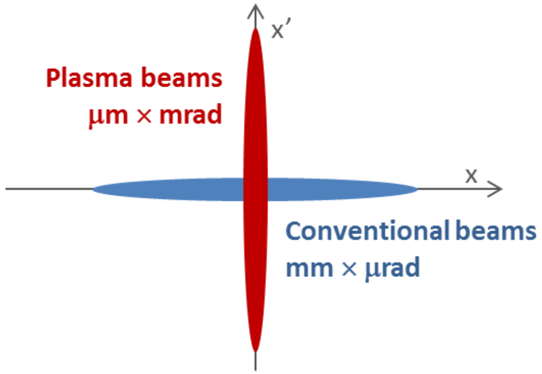
- **Challenges for external injection schemes**
  - To synchronize injected beam and laser (a few fs)
  - To inject ultrashort bunches ~10 fs << λ_p

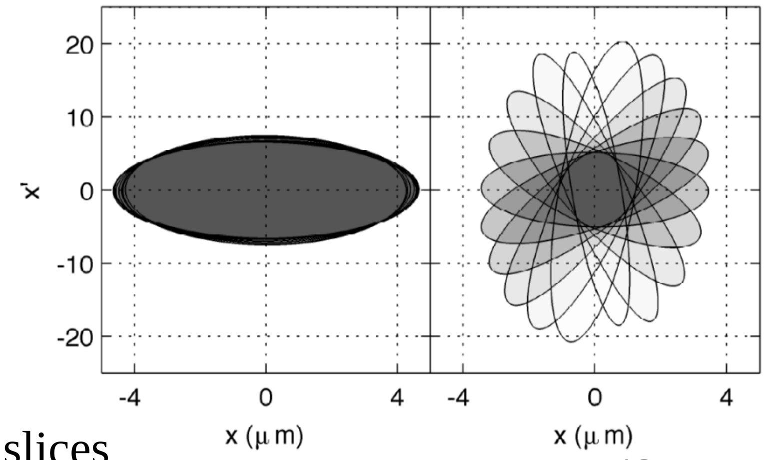
    $\Rightarrow$ high-performance conventional accelerator using compression techniques
  - To match the injected beam

    to the strong focusing fields of the plasma

    in order to avoid a strong emittance growth







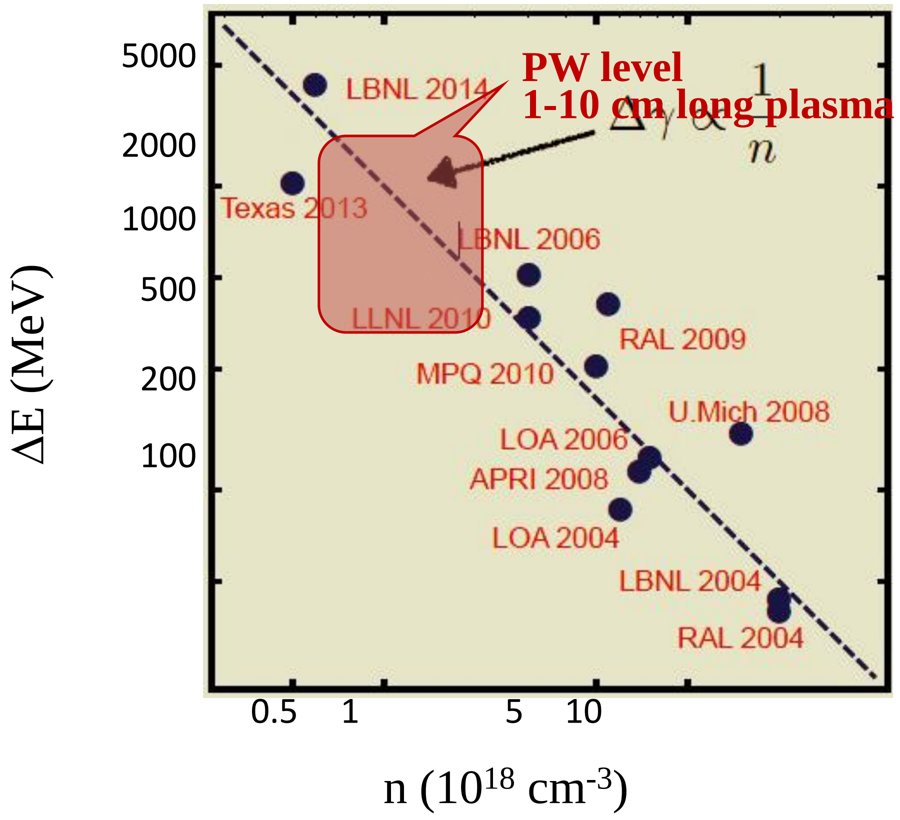
If external beam not matched to the plasma structure

$\Rightarrow$ beam decoherence

Due to the scattering of betatron frequencies and energies between the different beam slices

Energy gain limitations

- ❑ Finite Plasma length
- ❑ Dephasing length $L_{max} \propto n_0^{-3/2}$, $n_0 \nearrow \Rightarrow \lambda_p \searrow$
- ❑ Energy depletion $L_{deplete} \propto \lambda_p{}^3/\lambda_L{}^2 \propto n_0^{-3/2}$



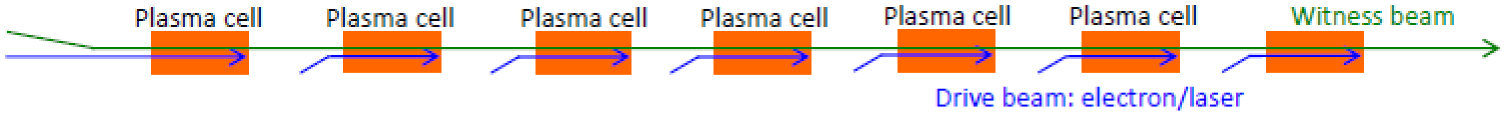
- ❖ Accelerating Gradient $G \sim E_0 = mc\omega_p/e \propto \sqrt{n_0}$
- ❖ Energy Gain $W = G \times L_{acc} \propto 1/n_0$
- ❖ Laser peak power

To increase the energy gain in a plasma module:
Decrease the density and increase the laser power

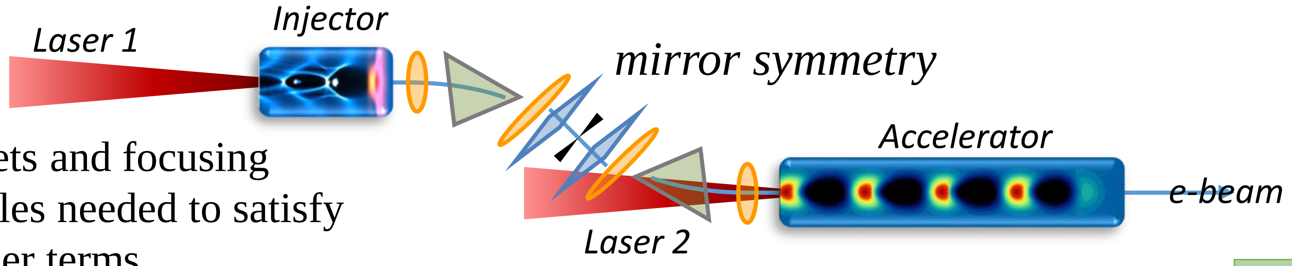
To higher beam energy

Multi-stage schemes

- For higher beam energy, laser depletion needs staging
- Challenges for staging scheme
  - Large divergence + energy spread of beam produced by LPA
    ⇒ strong demand on beam optics
    ⇒ strong emittance growth in the drift after the plasma
  - Coupling of laser beams to the plasma structures in a narrow and busy room



Under study: EuPRAXIA, Cilex-Apollon, …



In addition to the two bending magnets and focusing quadrupoles, extra dipoles + sextupoles needed to satisfy synchronismand to cancel higher order terms

A. Chancé et al, NIM A 740 (2014)

To higher beam energy

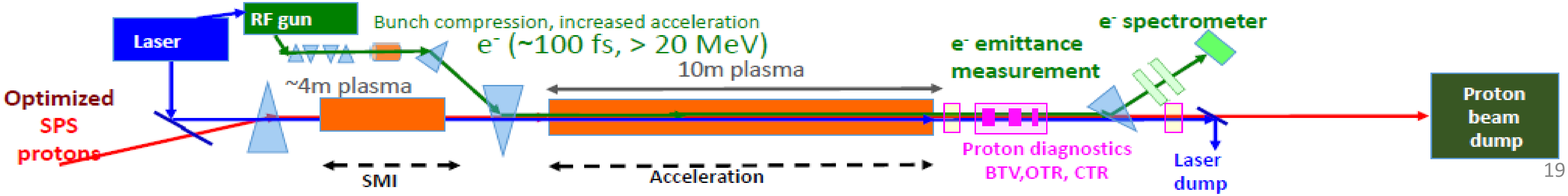
Proton drivers:
large energy content in proton bunches allows to consider single stage acceleration:

•A single SPS/LHC bunch could produce an electron bunch in a single PDWA stage.

AWAKE

Preliminary Run 2 electron beam parameters

Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim$ 50 MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim$ 10 μm

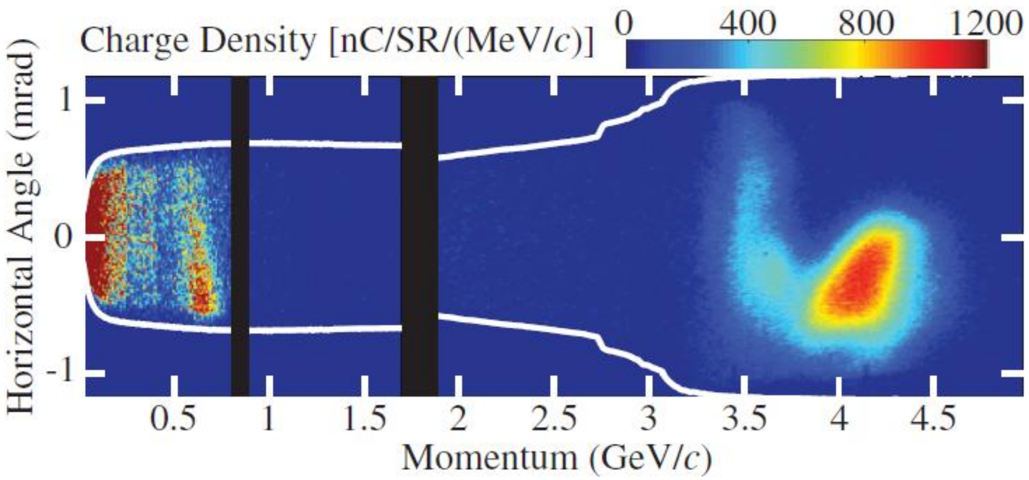


Wakefield accelerators e-beams differ tremendously from those produced by conventional accelerators

- Larger energy & angular spreads (1-2 orders of magnitude)
- Smaller source size (1-2 orders of magnitude)
- Smaller transverse emittance (in principle)
- Shorter bunch length

Large divergence and energy spread lead to severe demand on beam optics at the exit of the plasma

LWFA – Energy gain world record



BELLA (Berkeley Lab Laser Accelerator)

Peta-Watt Laser

U> 42 J τ~30 fs

	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

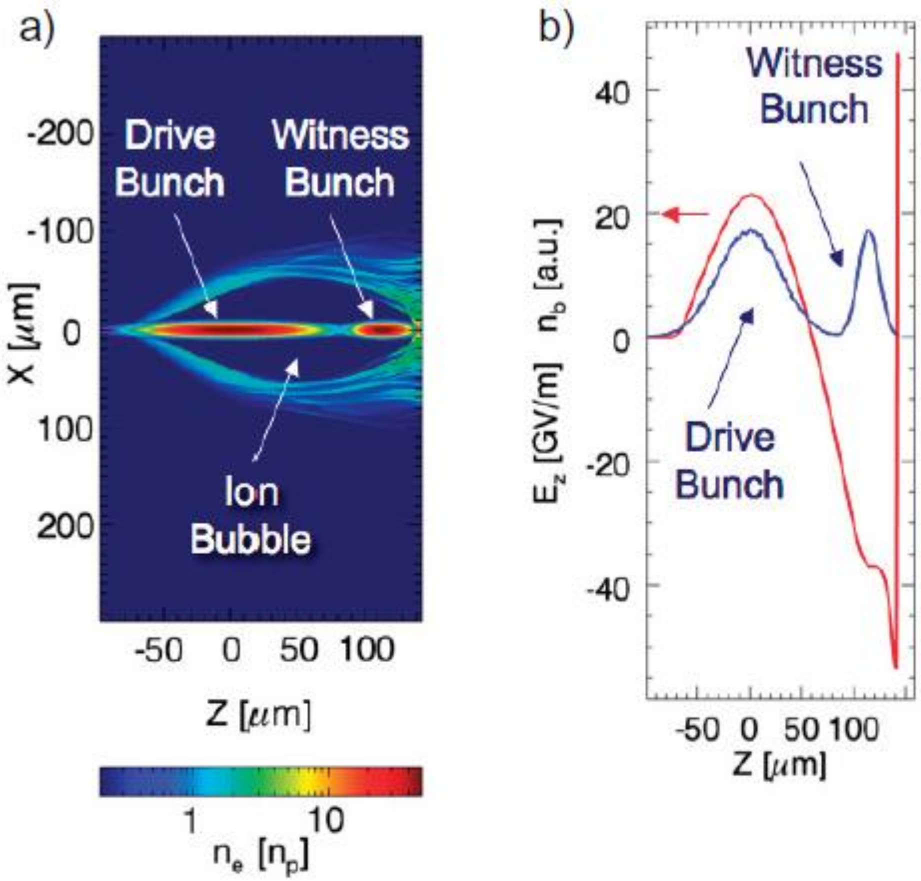
Structure = 9 cm capillary discharge

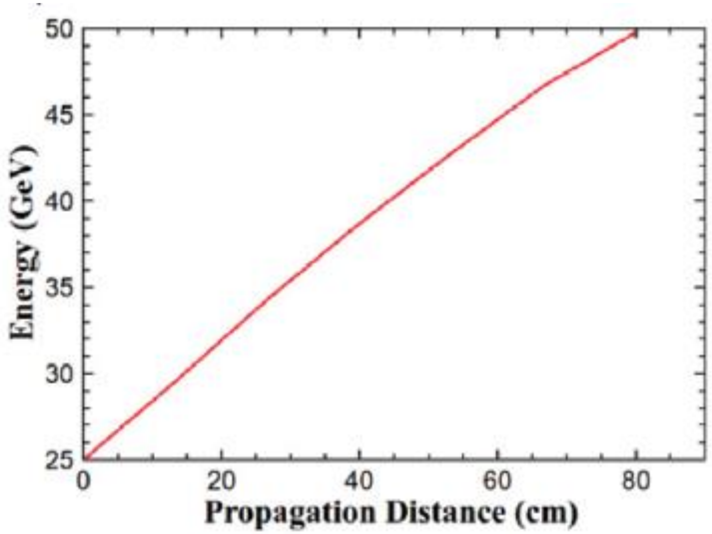
Plasma density n_0~ 6-7 × 10^{17} cm^{-3}

Achieved with laser peak power ~ 300TW

W.P. Leemans et al, PRL 113, 245002 (2014)

PWFA – Energy gain world record : FACET (SLAC)





Plasma cell: lithium vapor

- Length 80 cm, density 4×10^{17} cm^{-3}

bunch

- Energy 23 GeV, Charge 1.02 nC, Emittance 100 mm mrad,

Result

- Energy gain = 27 GeV
- Total efficiency 30%
- Final energy spread 0.7 %
- Emittance 130 mm mrad

Summery

- Plasma-based wakefield accelerators are an exciting and growing field with a huge potential.

- High potential for various applications because of its compact size.

- Many encouraging results in plasma wakefield acceleration technology:

  Energy 1-5 GeV (LWFA) & 80 GeV (PWFA), Charge 10-500 pC, Bunch length 5-10 fs, Energy spread 1-5%, Emittance (norm.) << 1 mm.mrad at source.

Some other references

- W.P. Leemans et al, "Multi-GeV Electron Beams from Capillary-Discharge-Guided Sub-petawatt Laser Pulses in the Self-Trapping Regime", PRL 113, 245002 (2014)
- X. Wang et al., "Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV", Nature Communications | 4:1988 | DOI: 10.1038/ncomms2988
- O. Lundh et al. "Few femtosecond, few kiloampere electron bunch produced by a laser-plasma accelerator", Nature Physics 7, 219–222 (2011)
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- G. Golovin et al. "Intrinsic beam emittance of laser accelerated electrons measured by x-ray spectroscopic imaging", Scientific Reports | 6:24622 | DOI: 10.1038/srep24622 (2016)
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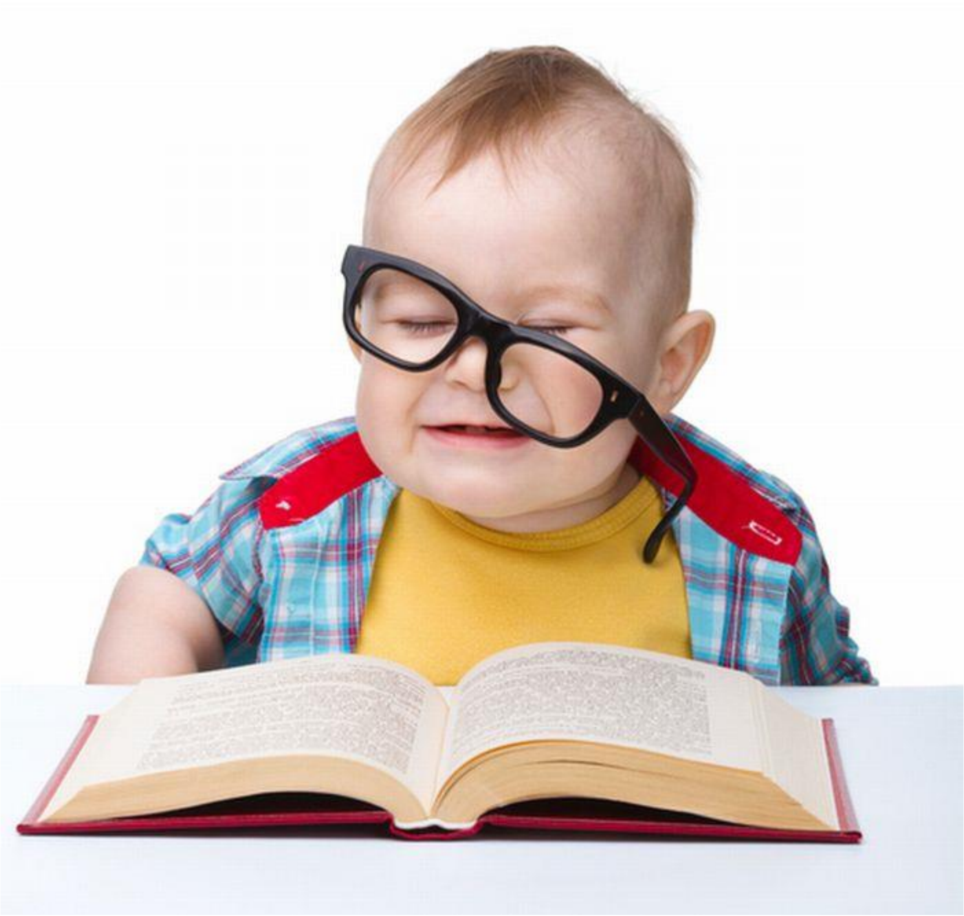

WISH YOU HEALTH and WEALTH!