External Injection in Plasma Accelerators

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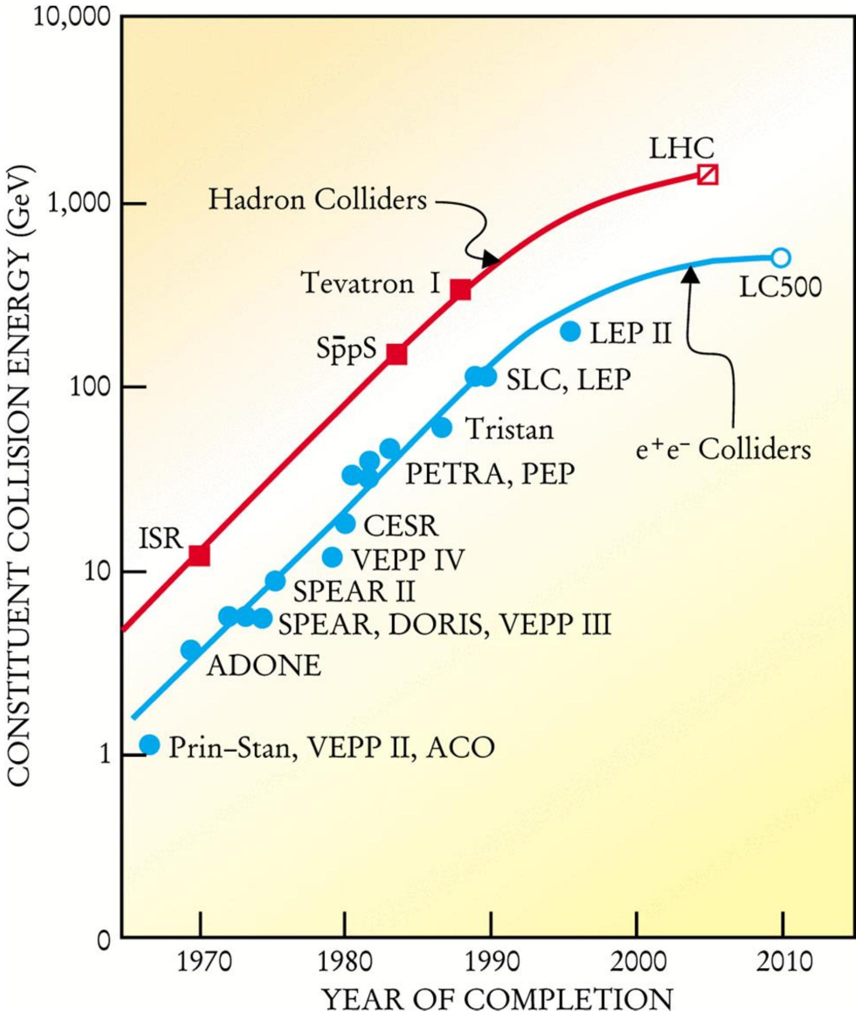
Today's accelerators?

- **Applications:** Science and Light production, Industry, Medicine…
- **First accelerator:** Electrostatic Field
- **Radiofrequency (RF):** Accelerating resonant field in a cavity.
- **Limit:** Breakdown Material

$$E_{acc,max} = 220[f(GHz)]^{\frac{1}{3}}$$

- **Current Limits:** $E_{acc} \approx 150\ MV/m$



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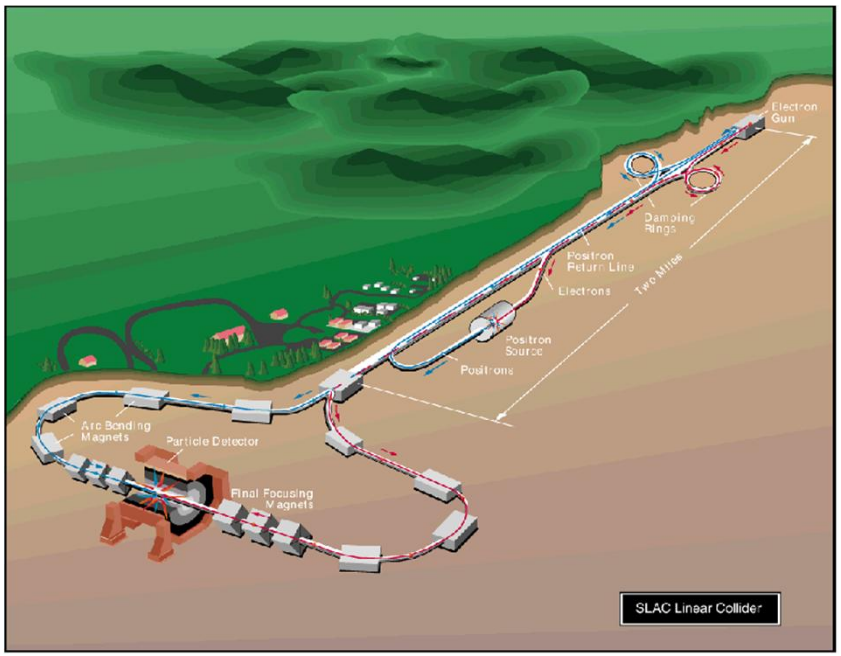
Money, A lot of money!

Stanford Linear Collider (SLC) 1962

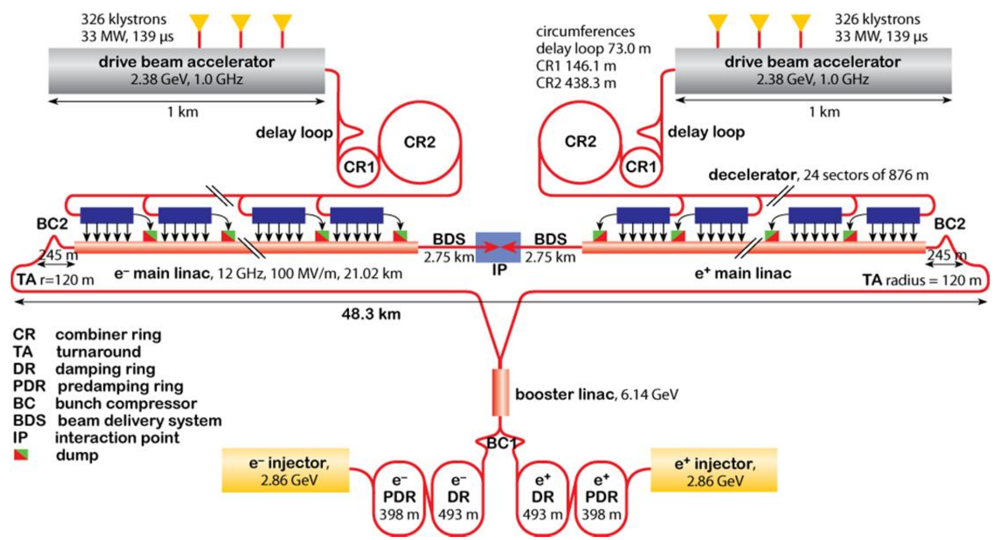
$E_{acc} \approx 20\ MV/m$ Frequency: 3 GHz



$L \sim 3km$ $E_{c.m.} \sim 90\ GeV$

Compact Linear Collider (CLIC) project

$E_{acc} \approx 100\ MV/m$ Frequency: 12 GHz



$L \sim 48km$ $E_{c.m.} \sim 3\ TeV$

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Why plasma?

$$E_0\left[\frac{V}{m}\right] \cong 96\sqrt{n_0\ (cm^{-3})}$$

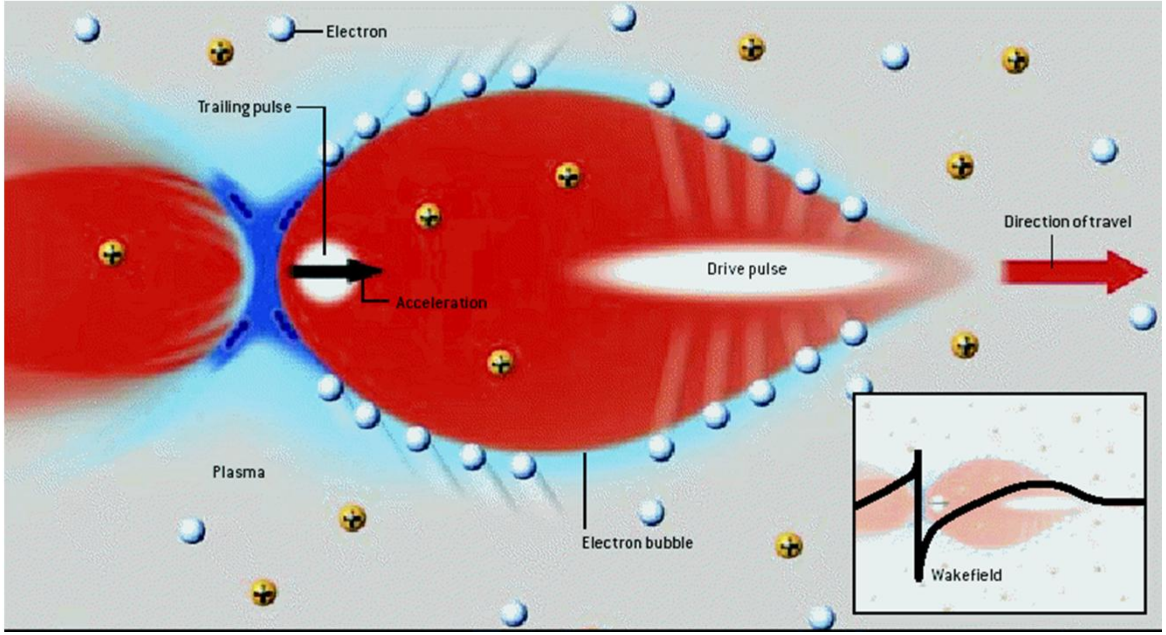
How much is this? $n_0 = 10^{18}\ cm^{-3}$ we obtain $E_0 \cong\ 100\ GV/m$

Problem?

$$\lambda_p = 2\pi c\sqrt{\frac{\varepsilon_0 m}{n_0 e^2}} \cong 30\ \mu\text{m}$$

PWFA

LWFA



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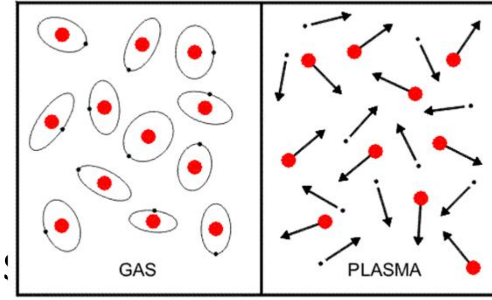
Plasma Acceleration



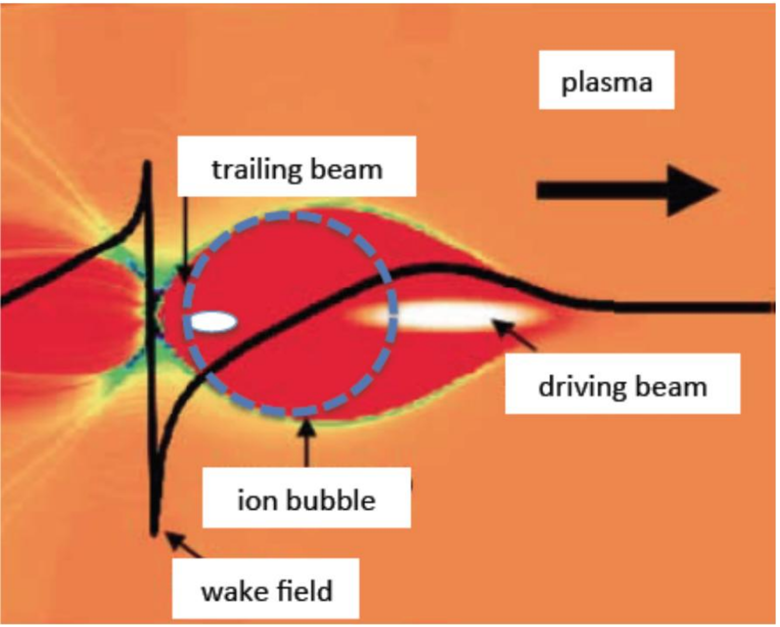
- Driver pulse creates a perturbation that travel in the pla

$$\lambda_p = 2\pi c\sqrt{\frac{\varepsilon_0 m}{n_0 e^2}}$$ where n_0 is the plasma density

Possible driver configurations

Particle beam (PWFA)	Laser pulse (LWFA)
Coulomb Repulsion blows out electrons	Ponderomotive Force of the laser blows out electrons $F_p \propto \nabla E^2$

A Simple Model

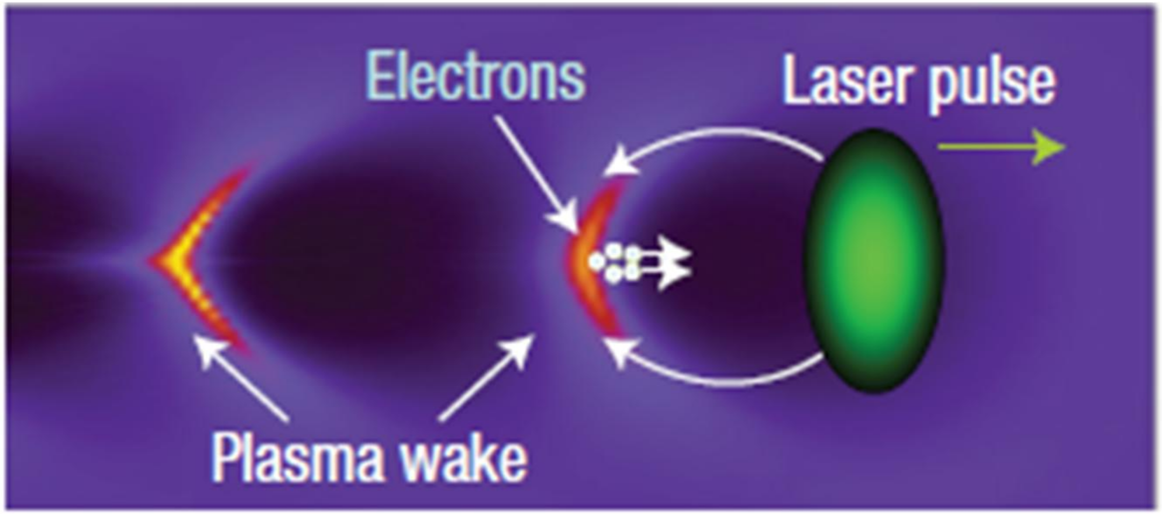


The accelerating field in the wake in the region of interest is linear so we can approximate the bubble with a uniform charged sphere:

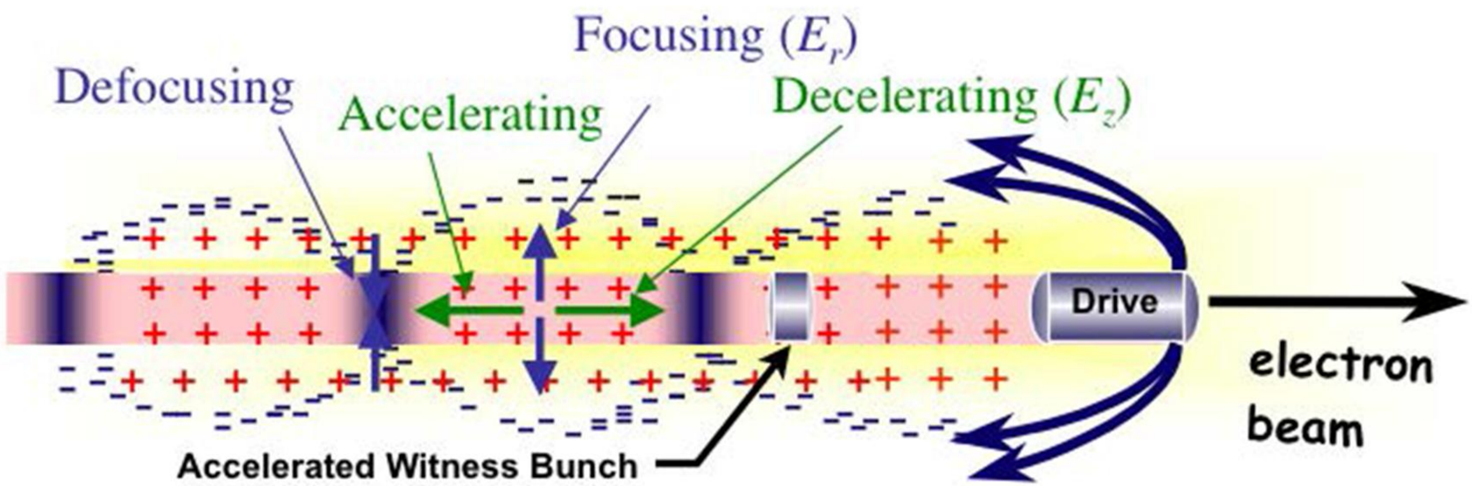
$$E_r = \frac{en_0}{3\varepsilon_0} r$$ Radial symmetric field

- Bunch witness in the accelerating bubble area, is accelerated by the wake of the driving beam

Self Injection Vs External Injection



- **<u>Problems?</u>** :
- High Energy spread.
- Difficult to control!



LWFA and PWPA

1. Intense laser pulse drives a large E field (wake field), which accelerates particles in shorter distances (tens of Microns) when compared to conventional accelerators.
2. When Electron density at the walls reaches a threshold value, self injection occurs at the back of the bubble

Advantages:

1-High accelerating gradient (100GV/m)

Disadvantages:

1- Large energy Spread due to self injection

LWFA

PWPA

1. Intense laser pulse drives a large E field (wake field), which accelerates particles in shorter distances (tens of Microns) when compared to conventional accelerators.

What makes a good injection scheme?

1- Small energy spread.

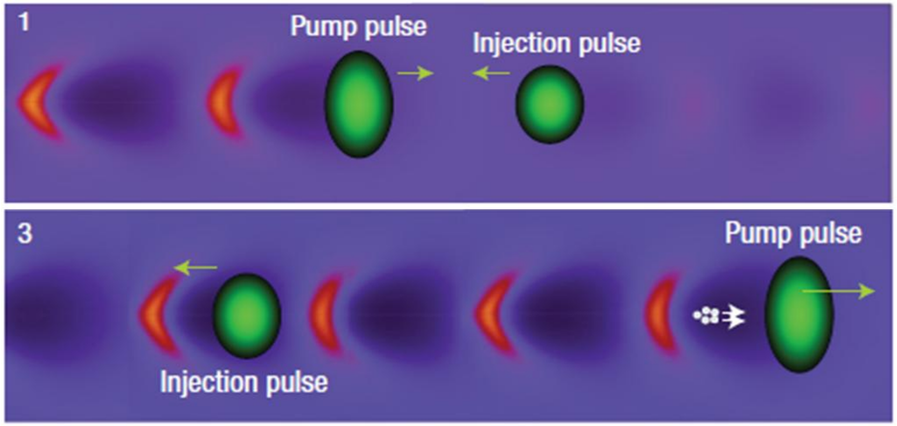
2-Short electron bunch.

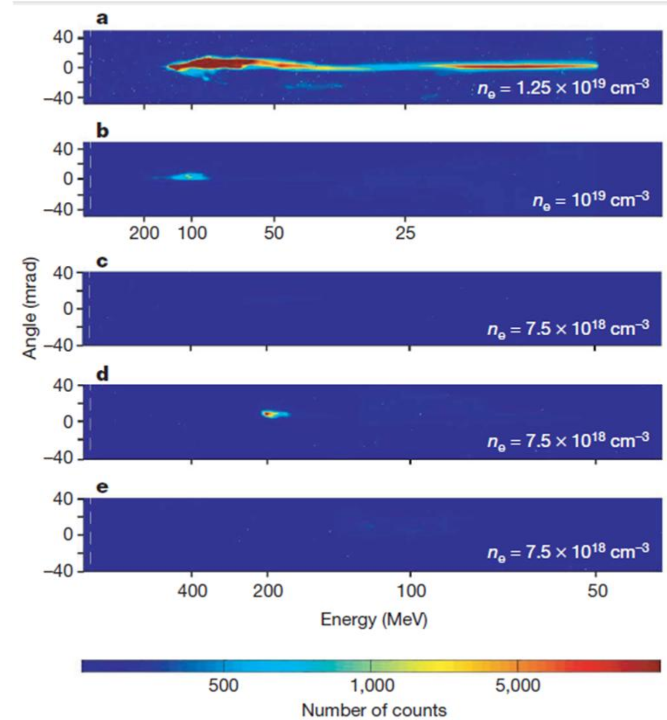
3- Control of accelerated charge.

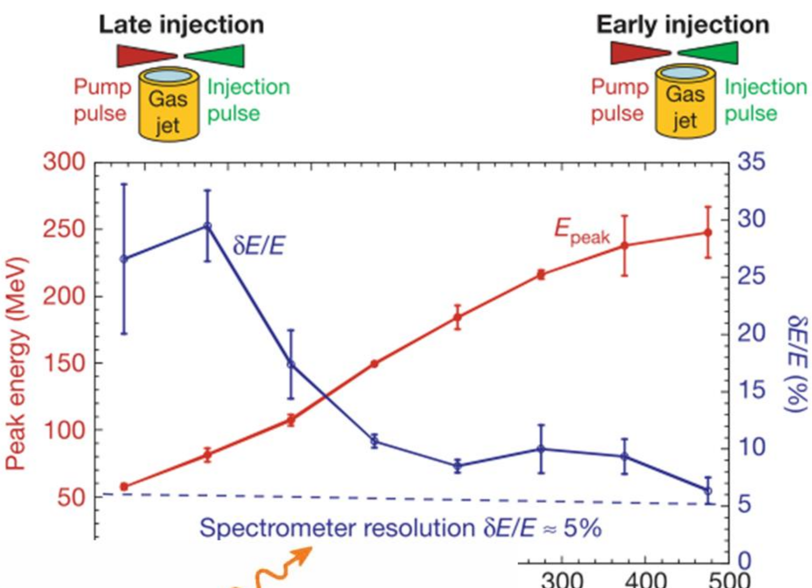
4- Tuning beam energy.

Colliding Pulse Injection Mechanism [J. Faure et al 2006]

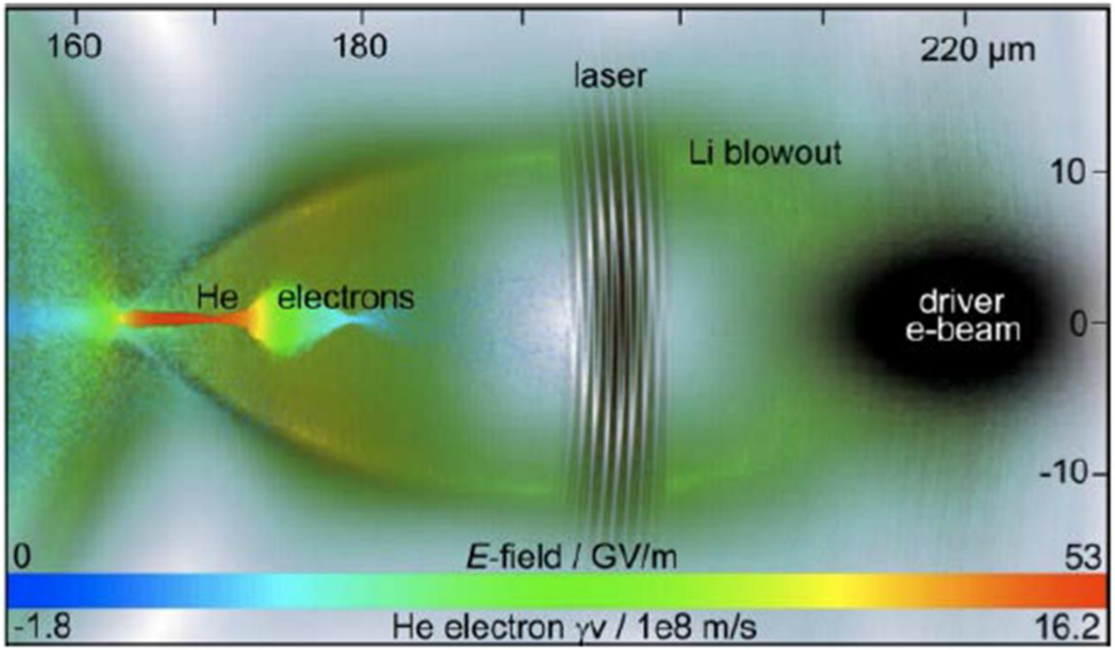
- 1st laser: 3.4x10^18 W/cm^2 (a=1.3)
- 2nd laser: 4x10^17 W/cm^2 (a=0.4)







Ultra Cold Electron Bunch Generation, B. Hidding et al [2012]



1- Mixture of two gases He and Li, which has a lower ionization E compared to He.

2- Electron bunch is sent in the gas:

Where, σ_r= 5 µm σ_z= 7 µm Q= 300pC E= 200 MeV

3- This beam has a transverse Field $E_{r,\,max}$ =27 GV/m, that is sufficient to ionizes Li but not He.

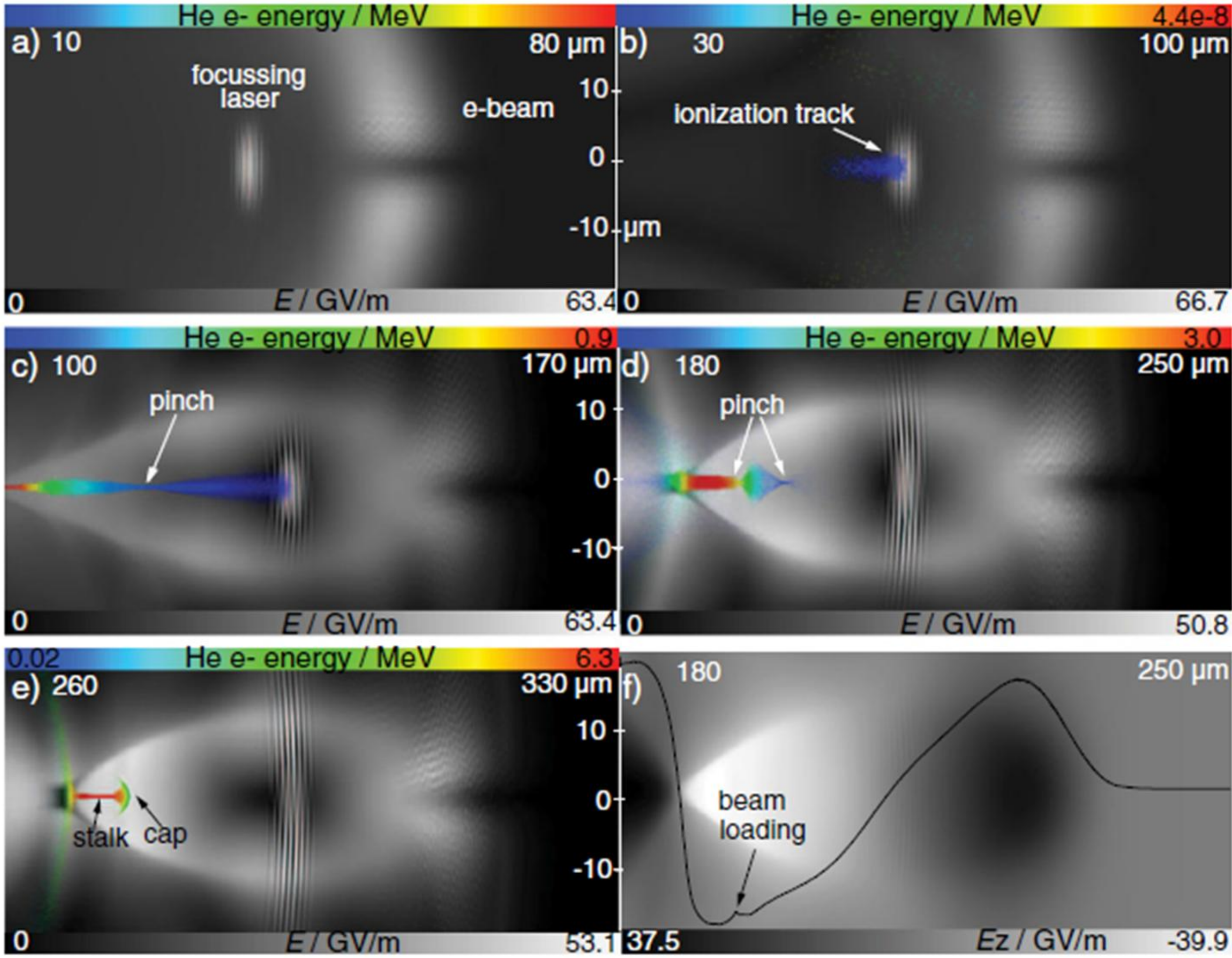
Where, $n_{e,Li}$= 3.3×10^{17} cm^{-3} , λ_p (Li) ~60 mm ,n_b~ 6.6 ×10^{17} cm^{-3}

4-Ti : Sapphire laser (I= 7 ×10^{14} Wcm^{-2} E_o= 72GV/m) is focused inside the bubble.

5- Electrons from He are captured and accelerated by the longitudinal field inside the bubble.

Result of acceleration

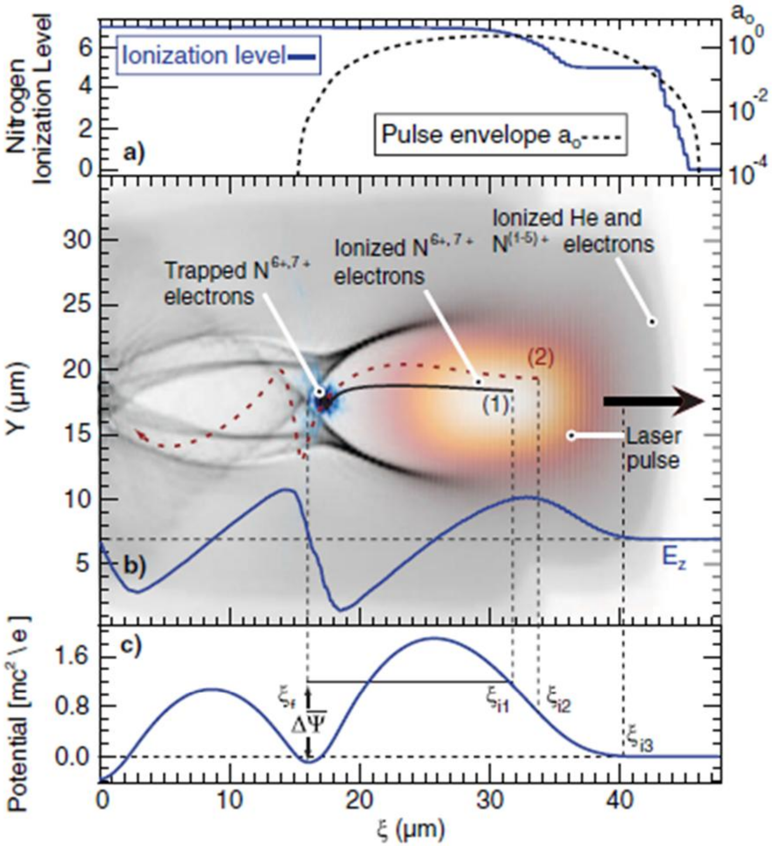
1- Final Energy of the witness after 9 mm of plasma is:
E= 300 MeV, $\Delta E = 3\%$
$\epsilon \sim 10^{-8}$ m rad, Q= 2pC

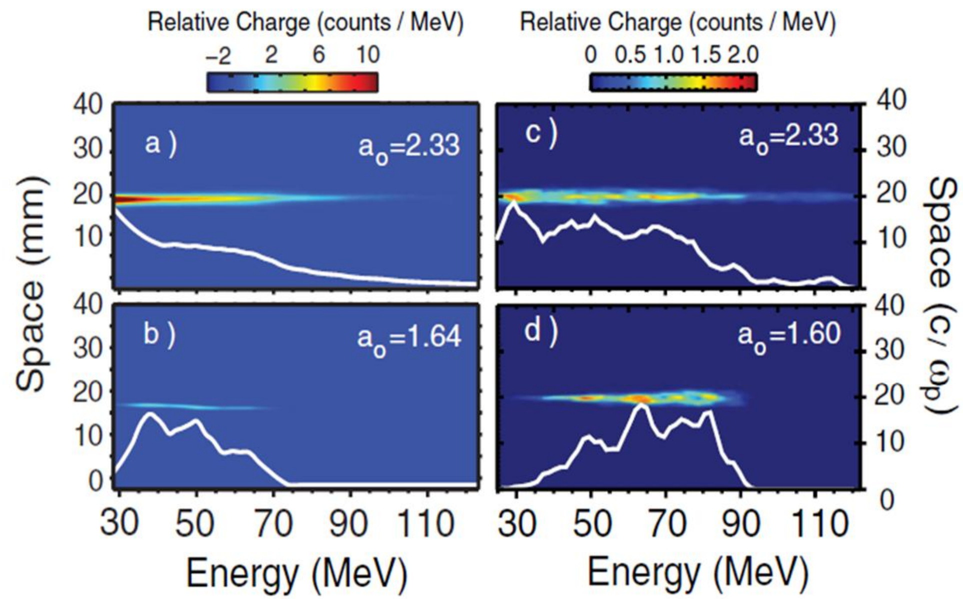


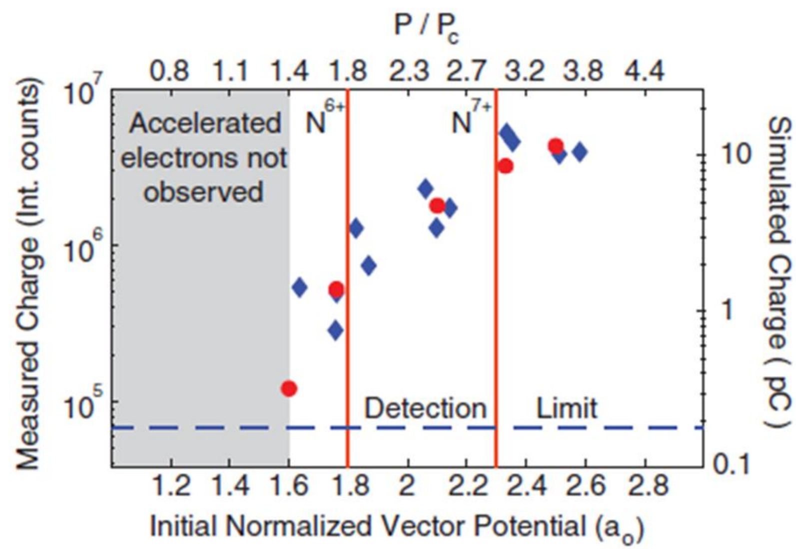
Advantages:
1- Controlled injection
2- Very low Emittance.

Disadvantages:
1- Synchronization between electron bunch and laser.

Injection Using Tunnel Ionized Electron ,A. Pak et al [2010]







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Summary

- We presented the advantages of plasma-based acceleration over the RF counterpart.

- The key point to having low energy spread is to control the injection mechanism.

- PWFA with external injection seems to be the most simple and promising technique to have low Energy spread and good control over accelerated charge.
- A promising field that is still growing, hopefully It can achieve compact accelerator or help reducing size and cost of current accelerator

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References

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- A. Pak et al., Phys. Rev. Lett. 104, 025003 (2010).
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