Electron acceleration in plasma wakefield accelerators

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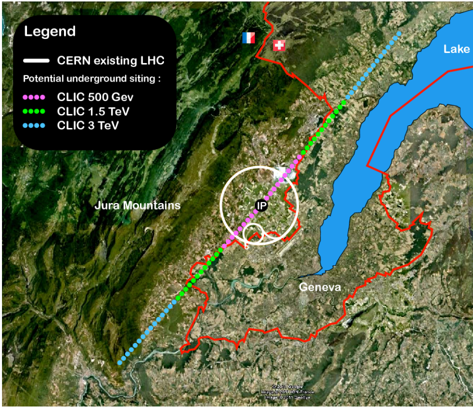
Conventional Particle Accelerators

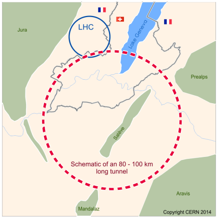
RF accelerators:

- LHC (CERN), 27 km, $\sqrt{s}$=14 TeV
- SLC (SLAC), 3.2 km, $\sqrt{s}$=100 GeV

In devolopment:

- LCC (ILC+CLIC), $\geq$30 km
- FCC, 80-100 km





Why Plasma Accelerators?

The energy gain for a particle: $\Delta E = GL$

G-acceleration gradient, L-distance

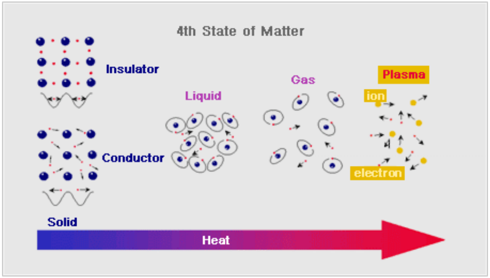
$$\boxed{G_{RF} = 20 - 100\ [MeV/m] \ll G_{plasma} = 1 - 100\ [GeV/m]}$$

Plasma wakefields accelerators:

$\Rightarrow$ Save space

$\Rightarrow$ Save costs

What Is Plasma?



"Plasma is loosely described as an electrically neutral medium of unbound positive and negative particles" (from Wikipedia)

Plasma Frequency: $\omega_{pe} = \sqrt{\frac{n_{oe} e^2}{\epsilon_o m_e}}, \quad n_{oe} - \textit{plasma density}$

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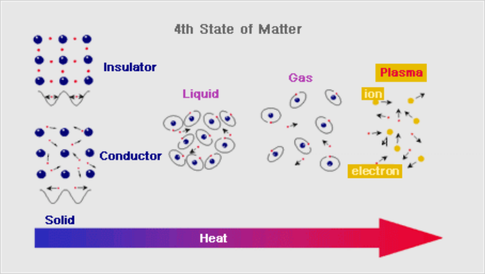

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Not any ionized gas can be called plasma!

Plasma Characters

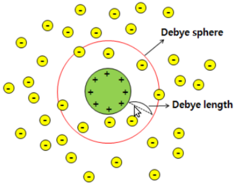
Particles must exhibit **collective behavior**

$\Rightarrow$ not only local forces but long range forces as well!

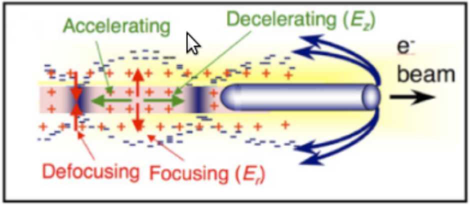
- The charged particles collide frequently with neutral atoms
  $\Rightarrow$ motion is controlled by hydrodynamic **not** electromagnetic forces.

Debye Length: The distance that a charge is screened by a factor of $\sim e$

- L dimension of a system $\gg \lambda_D = \sqrt{\frac{\epsilon_o KT}{n_{oe} e^2}}$ Debye length
- Plasma needs enough particles to exist $N_D \ggg 1$,
  $N_D = n_{oe} \cdot \frac{4}{3} \pi \lambda_D^3$



What Are Plasma Wakefields?



- An charged beam/laser pulse is injected into a neutral plasma.
- The space-charge field of the beam rapidly expels the plasma electrons.
- The plasma ions have $m_i \gg m_e \implies$ remain stationary during the time scale of the bunch length.
- $n_{bo} > n_{pe} \implies$ an ion column is formed.

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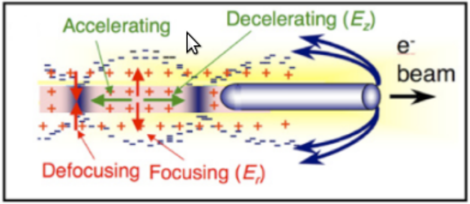
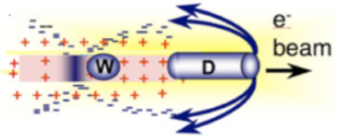
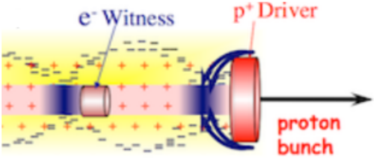


- The expelled plasma electrons now witness the space-charge field of the ion column and are pulled back in towards the beam axis.
- From momentum conservation $\Longrightarrow$ plasma electrons overshoot the axis.
- Plasma electron oscillate with ω_{pe}

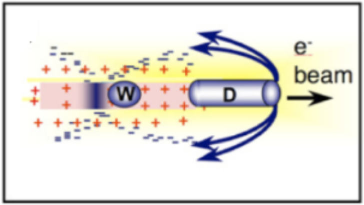
Plasma Wakefields: Drive Bunch

- Carry multi-kilojules of energy
- $L_z^{drive\ \ beam} \leq \lambda_{pe}$
- Same phase velocity as of the plasma wave $v_\phi^w = v_\phi^b$
- Negative charged beam : pencil shape
- Positive charged beam : pancake shape

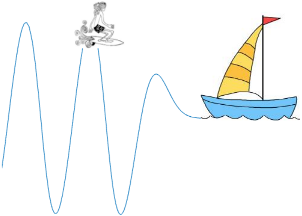


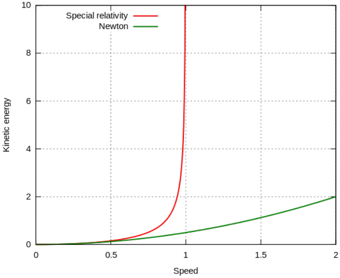


Plasma Wakefields: Witness Bunch

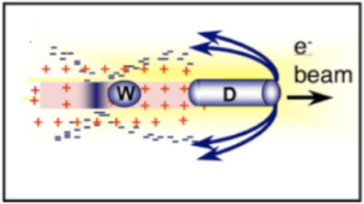


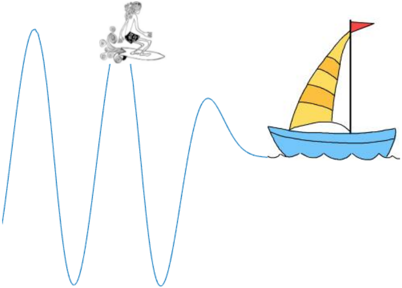
- **Initial energy:** relativistic ⇔ witness bunch stays on the same wakefield phase





- **Location:** useful phase - acceleration and focusing.





Energy conservation:

- The energy gain for a particle: $\Delta E = GL$
- $Q_{witness} < Q_{drive}$

Analytic Description

Assuming $\boxed{n_{bo} \ll n_{pe}}$

Linearization:

$n_e = n_0 + n_1$
$v_e = v_0 + v_1$
$E = E_0 + E_1$
$B = B_0 + B_1$

Equation of motion: $\frac{dv}{dt} m_e = -e(E + v \times B)$

Equation of continuity: $\frac{\partial n_e}{\partial t} + \nabla(n_e \cdot v_e) = 0$

Gauss law: $\nabla \cdot E = \frac{\rho}{\epsilon_o}$

Ampere law: $\nabla \times B = \mu_o(J + \epsilon_o \frac{\partial E}{\partial t})$

Solving for a frame moving in the speed of light - $\xi = ct - z$

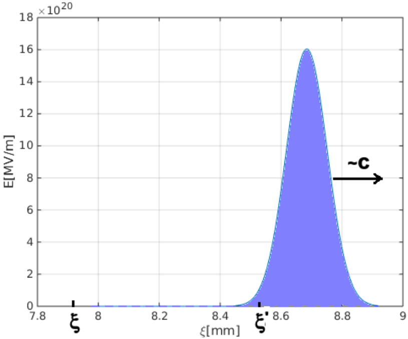
Linear Theory $n_{bo} \ll n_{pe}$

Longitudinal wakefield: $W_z(\xi, r) = \frac{e}{\epsilon_o} \int_{\xi}^{\infty} n_{b||}(\xi') \cdot cos(k_p(\xi' - \xi)) d\xi' \cdot R(r)$

Transverse wakefield: $W_r(\xi, r) = \frac{e}{\epsilon_o k_p} \int_{\xi}^{\infty} n_{b||}(\xi') \cdot sin(k_p(\xi' - \xi)) d\xi' \cdot \frac{dR(r)}{dr}$

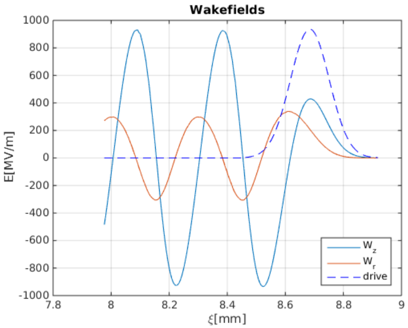
$$R(r) = k_p^2 \int_o^r r' dr' n_{b\perp}(r') I_o(k_p r') K_o(k_p r) + k_p^2 \int_r^{\infty} r' dr' n_{b\perp}(r') I_o(k_p r) K_o(k_p r')$$

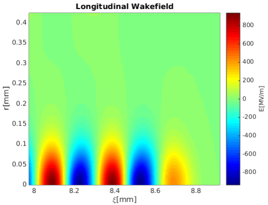
Moving Frame

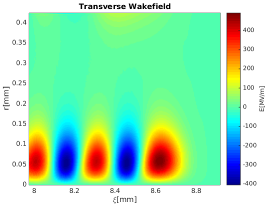


Longitudinal axis: $\xi = ct - z$, Transverse axis: r

Linear Theory $n_{bo} \ll n_{pe}$



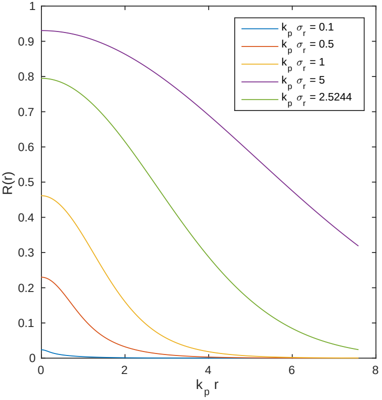


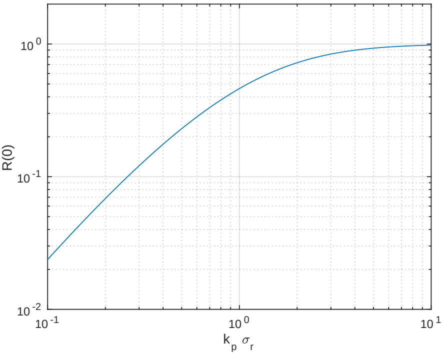


Linear Theory: R(r)

$$R(r) = k_p^2 \int_o^r r' dr' n_{b\perp}(r') I_o(k_p r') K_o(k_p r) + k_p^2 \int_r^\infty r' dr' n_{b\perp}(r') I_o(k_p r) K_o(k_p r')$$

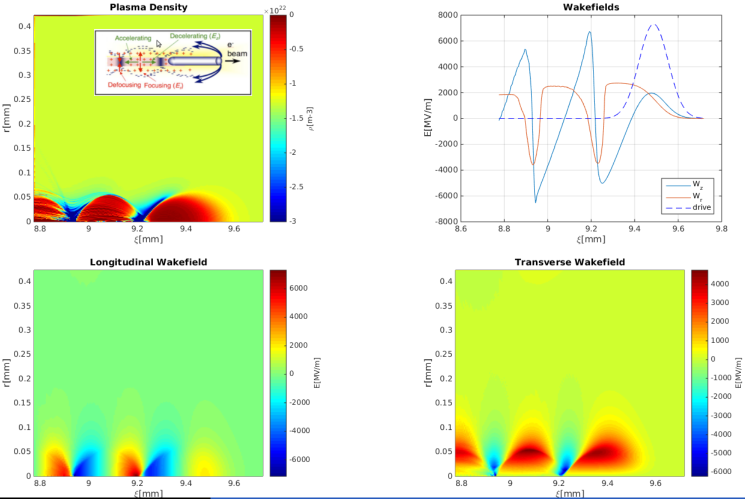
$$W_z(\xi, r) \propto R(r), \quad W_r(\xi, r) \propto \frac{dR(r)}{dr}$$



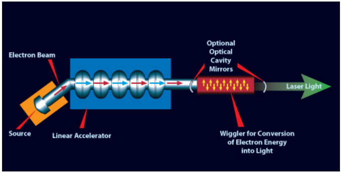


$$n_{bo} \geq n_{pe}$$

Inside the bubble: W_z independent of r, $W_r \propto r$

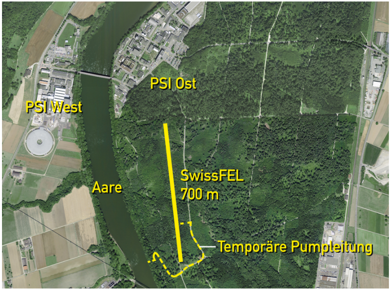


Swiss Free Electron Laser



- Free-electron lasers providing very intense and tightly focused beams of x-rays.
- X-rays can be used to map the atomic structure of materials, including biomolecules and nanometer scale structures.

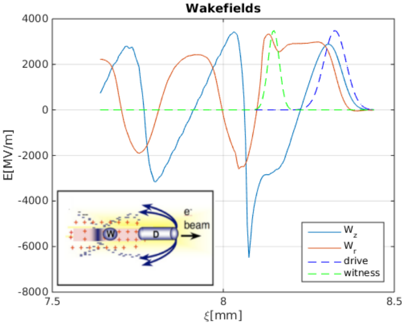
- The SwissFEL baseline design aims to produce FEL pulses covering the wavelength range 0.1-7 nm.



Accelerator beam parameters	
Beam energy	2.1-5.8 GeV
Peak current	2.7 kA
Charge	200 pC
Energy spread	350 keV
Emittance	0.43 mm mrad

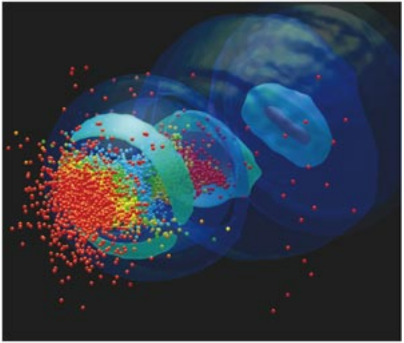
At the moment: maximum 5.8 GeV

we want: 13.6 GeV **to get:** x-ray with energy of 1 mJ.



Summary

- Plasma based accelerators can save costs and space compare to RF accelerators.
- The technique is base on a electromagnetic disturbance moving with relativistic velocity in plasma creating plasma wakefields.
- Particle beams can be accelerated "surfing" on the wakefield in the right phase.
- Adding plasma accelerator to the current design of the Swiss FEL can increase the photons intensity and energy.
- Using Simulations, this possibility is being studied.



Thank you for your attention!

Backup