Laser, Synchrotron Radiation and Particle Beam Test Facilities at LNF

Scuola per Dottorato "LNF Test Labs"

16-19 June 2014

INFN-LNF

Novel Acceleration Techniques

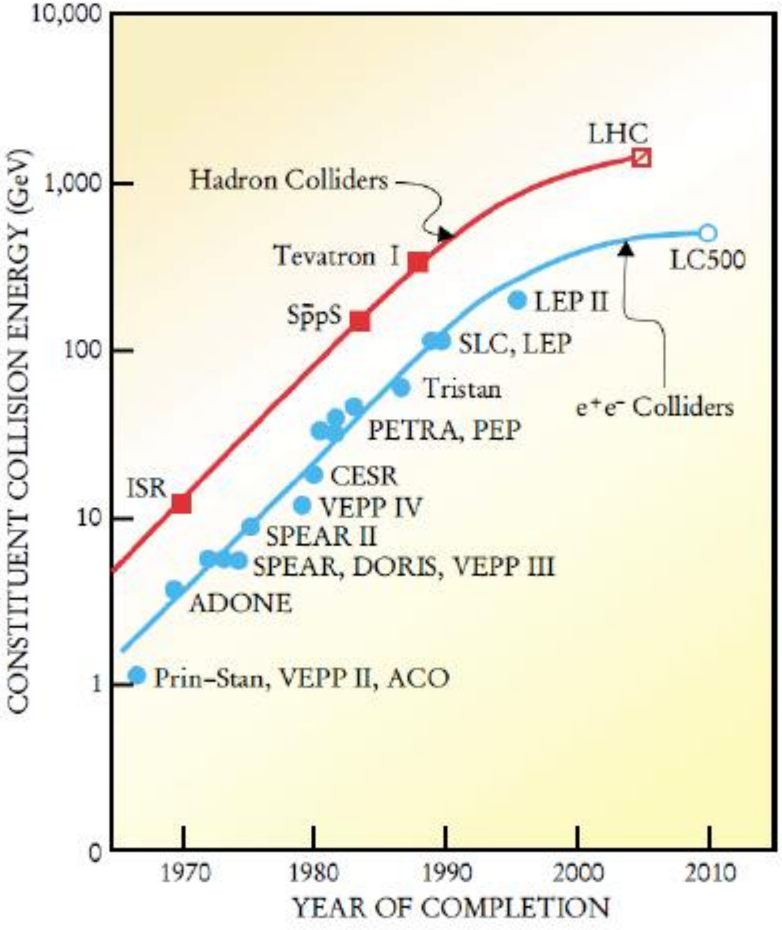
A first insight

LTL-2014 (LNF Test Labs – 2014)

Enrica Chiadroni (INFN-LNF)

Energy frontier accelerators

Livingston Plot



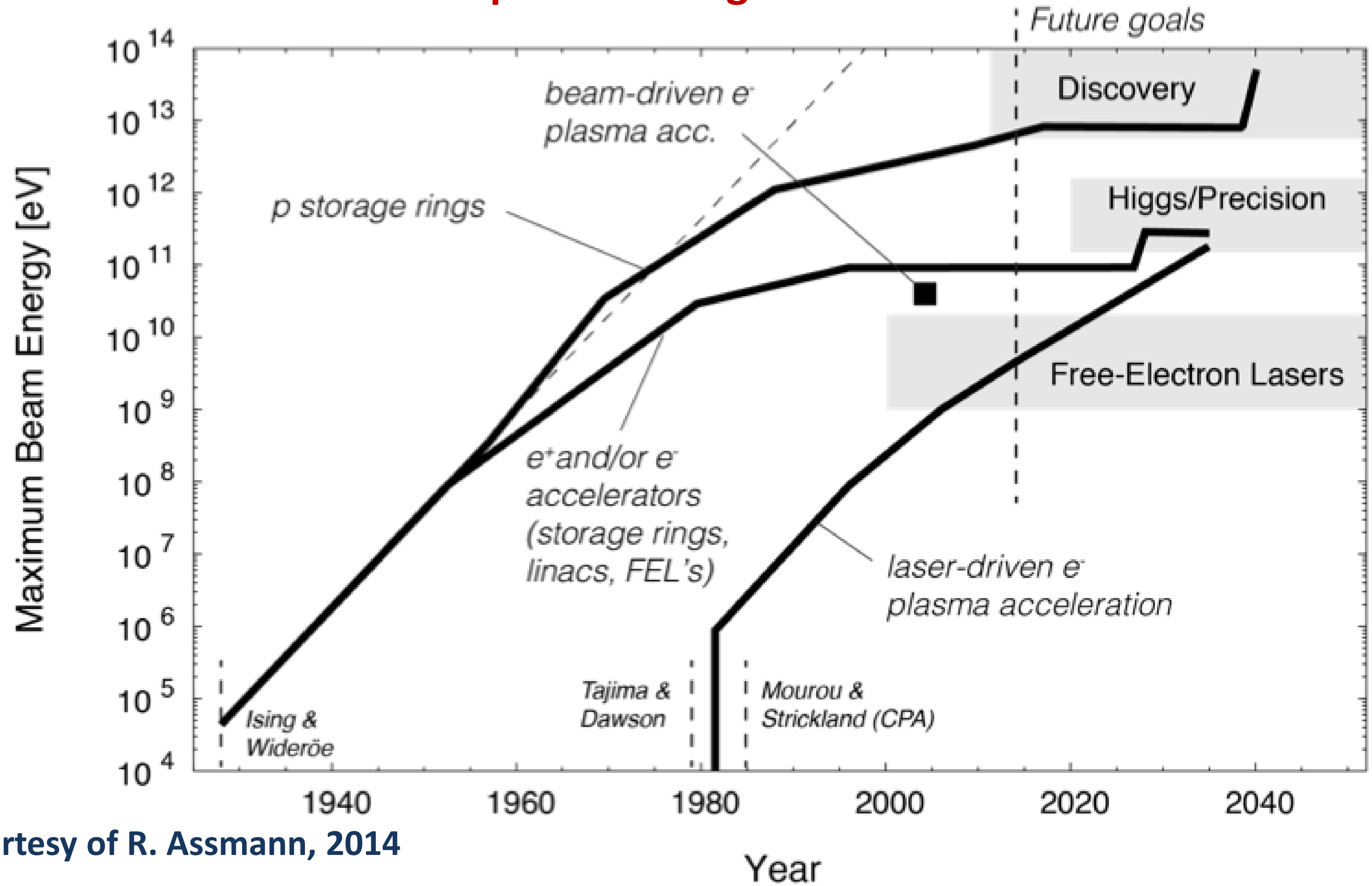
M. Tigner, DOES ACCELERATOR-BASED PARTICLE PHYSICS HAVE A FUTURE? *Phys. Today* (2001)

Saturation of accelerator technology

- **Practical limit** reached conventional accelerator technology (RF metallic structures)
- **Gradient limited by material breakdown**
    - e.g. X-band demonstration around 100 MV/m)
- **Ultra-high gradients require structures to sustain high fields**
    - Dielectric structures (higher breakdown limits): ~1 GV/m
    - Plasmas: ~10 GV/m

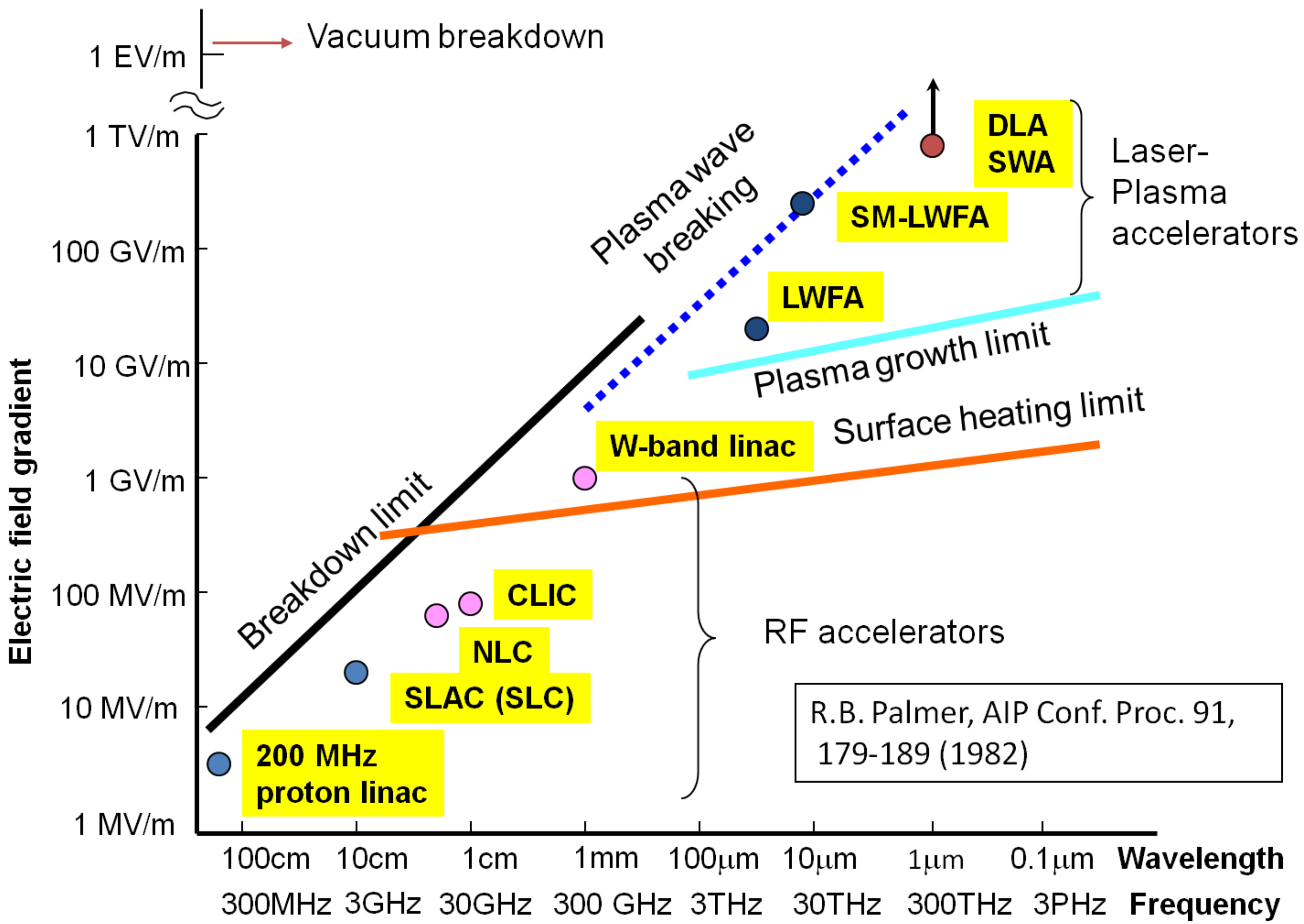
Energy frontier accelerators

Updated Livingston Plot



Courtesy of R. Assmann, 2014

Accelerating field limits



Scientific interest

- **Plasma-based accelerators** are of great interest because of their ability to
  - **sustain ultra-high acceleration gradients** (~10 GV/m), enabling the development of compact accelerators
  - **produce extremely short electron bunches** (< plasma wavelength), enabling the production of advanced, extremely intense, radiation sources

- **Applications** of plasma-based accelerators
  - Radiation generation
  - High-energy physics

For additional details & references, see
- Tajima & Dawson, Phys. Rev. Lett. (1979)
- Esarey, Schroeder, Leemans, Rev. Mod. Phys. 81, 1229 (2009)

Method

- **High gradients require high peak power**
  - Laser driven
  - Particle beam driven

- **Critical developments**
  - Acceleration in vacuum and gases
    - Intrinsically limited by diffraction, electron slippage, ionization, and smallness of laser wavelength
  - Plasma-based acceleration
    - Acceleration is the result of the axial field of the plasma wave and not the laser field directly
  - Development of laser technology for high peak power delivery
    - Development of Chirped-Pulse Amplification making ready available compact sources of intense, high power, ultra-short laser pulses

Acceleration in vacuum

- In vacuum, the motion of an electron in a laser field $\vec{E}(\vec{r},t) = \vec{E}_s(\vec{r},t)\cos(\omega t)$

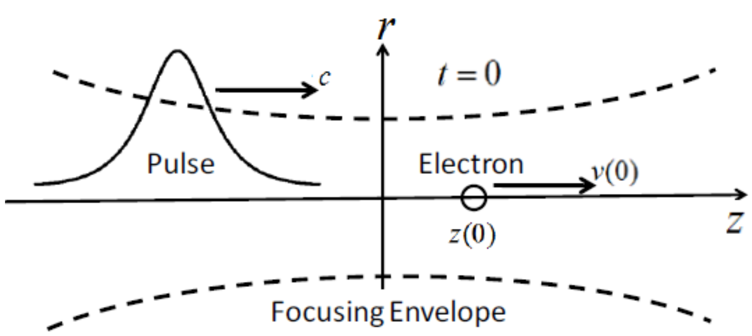
is determined by the Lorentz force equation,

$$\frac{d\vec{p}}{dt} = -e\left[\vec{E} + \frac{1}{c}\left(\vec{v} \times \vec{B}\right)\right]$$

Linear response of the electron to the electric field ***E*** of the laser:
it is responsible for **"direct" laser accele**ration

Non-linear response to the ***vxB*** force:
it is responsible for "**ponderomotive" laser acceleration**

Let consider an electron initially (t=0) on the beam axis of the laser at z = z(0), moving in the longitudinal direction with velocity v(0) = v(0)z



We are interested in the net energy the electron extracts from the laser field as the pulse propagates indefinitely.

No limit to the interaction distance

Acceleration in vacuum

- When a laser field propagating along the *z* axis is focused in vacuum, the laser spot size and intensity, assuming a fundamental Gaussian mode, evolve as

$$r_s = r_0 \sqrt{1 + \frac{z^2}{Z_R^2}} \qquad I = I_0 \frac{r_0^{\,2}}{r_s^{\,2}} e^{-\frac{2r^2}{r_s^{\,2}}}$$

$$Z_R = \frac{k r_0^{\,2}}{2}$$ the Rayleigh length

The finite laser spot size implies the existence of an axial component of the laser electric field via

$$\nabla \cdot \vec{E} = 0, \text{i.e. } E_z \approx \frac{1}{k r_0} E_\perp$$

- The amplitude of the axial field can be very large

    - the axial field might be directly used for laser acceleration

However, $v_{ph} > c$ and near the focus is $\frac{v_{ph}}{c} \cong 1 + \frac{1}{k Z_R}$

Since $v_{ph} > c$, **electrons** with $v_z < c$ **will phase slip with respect to the accelerating field and decelerate**.

Lawson-Woodward Theorem

This phase slippage argument forms the basis for the so-called Lawson-Woodward theorem which states that, under certain conditions:

the net energy gain of a relativistic electron interacting with an electromagnetic field <u>in vacuum</u> is zero

<u>The theorem assumes that</u>
(i) the laser field is in vacuum **with no walls or boundaries present**
(ii) the electron is highly relativistic ($v \approx c$) along the acceleration path
(iii) no static electric or magnetic fields are present
(iv) the region of interaction is infinite
(v) ponderomotive effects (nonlinear forces, e.g. $\mathbf{v} \times \mathbf{B}$ force) are neglected

J.D. Lawson, IEEE Trans. Nucl. Sci. NS-26, 4217, 1979
P.M. Woodward, J. Inst. Electr. Eng. 93, 1554, 1947

Acceleration mechanism must violate the Lawson-Woodward theorem, in order to achieve a non-zero net energy gain

Direct Acceleration

- **Introduce optics** to limit the laser-electron interaction to approximately a region of length $2Z_R$ about the focus, **such that minimal phase slippage occurs**
  - this method requires that **optics** be **placed near the focus** and are **susceptible to laser damage at high intensity**
  - the **electron bunch must pass through a small aperture** in the optics, which can **limit the amount of charge that can be accelerated**

Acceleration in gases

- **Finite energy gains** can be achieved
  - **introduce a background of gas** into the interaction region (e.g. inverse Cherenkov accelerator (Kimura *et al., 1995*))
  - **the gas can reduce** the **phase velocity** of the laser field to less than *c,* reducing the slippage

- In principle, **diffraction can be overcom**e
  - **optical guiding** self-focusing in the gas
    - Nevertheless, **ionization of the gas**, which occurs at a relatively low laser intensity 10^{14} W/cm^2 (for λ about 1μm) and **increases the phase velocity**, remains a fundamental limitation to the accelerating field in gas-filled devices

- **Fundamental limitation** to all concepts that rely on electron acceleration through the direct interaction linear or nonlinear with the laser field
  - **smallness of the laser wavelength**, typically on the order of a micron

Plasma-based Acceleration

Plasma-based accelerators can overcome many of the fundamental limitations that restrict laser acceleration in vacuum and gases.

Plasma

- Gas parzialmente o completamente ionizzato globalmente neutro con dimensioni molto maggiori della **lunghezza di Debye*** e risposta temporale molto maggiore di ω_p^{-1}

- An ionized gas is a plasma ⇔ it exhibits a **collective behavior** (coupled by the self-consistent electro-magnetic fields)
    - Coulomb shielding
    - plasma oscillations

- Potential energy (nearest neighbor) << kinetic energy
    - particles do not bind $e^2 n^{1/3} \ll k_B T_e$

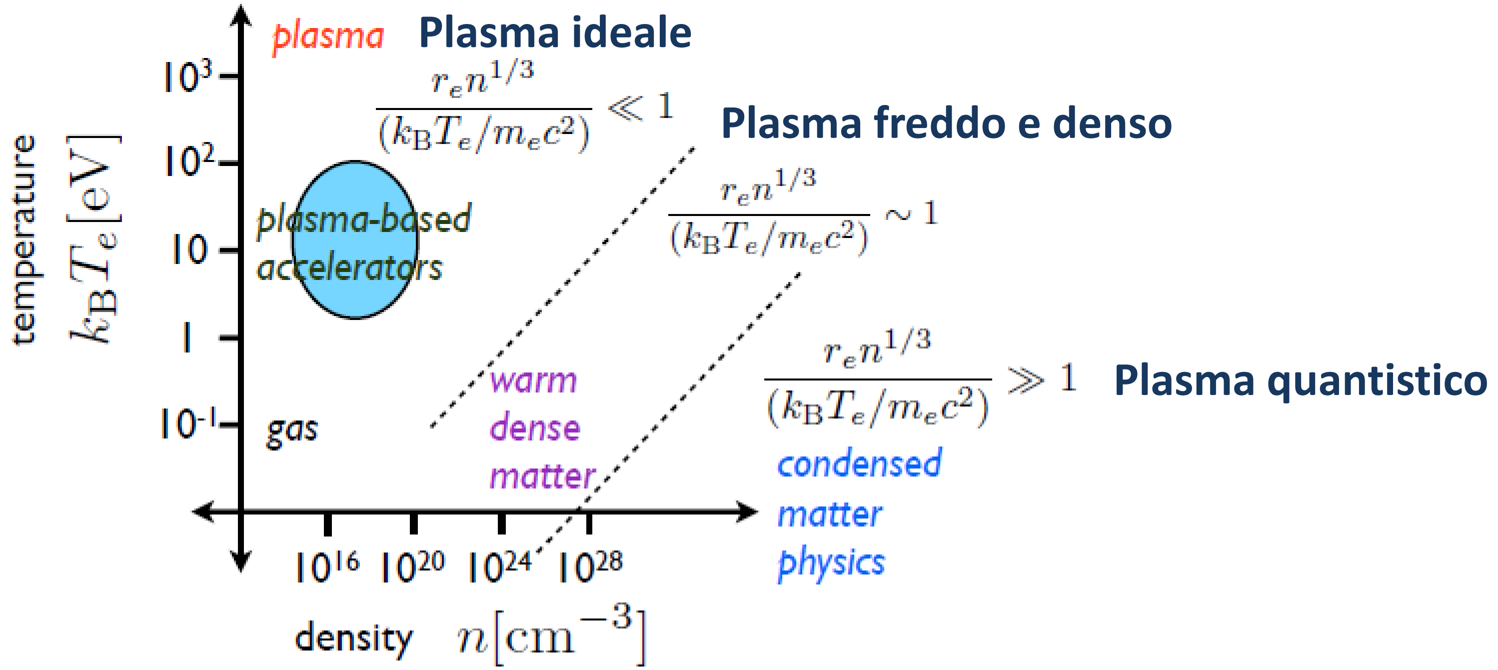
$$* \lambda_D = \sqrt{\frac{kT\varepsilon_0}{ne^2}}$$

It describes a **screening distance**, beyond which charges does not feel other charges inside of the Debye length.
A charge in a plasma will attract opposite charges and repel like charges to the point that its electric field is screened by the charges it has attracted, so particles outside the screening charges are unaware of the presence of the interior charge.

Plasma-based Acceleration

- ionization potential ~ tens of eV
- $<10^{14}$ cm^{-3} gradient too low (<GV/m)
- 10^{21} cm^{-3} critical density for micron wavelength laser

$n_{cr}[cm^{-3}]=1.1*10^{21}/(\lambda[\mu m])^2$



Plasma-based Acceleration

Plasma-based accelerators can overcome many of the fundamental limitations that restrict laser acceleration in vacuum and gases.

- **Fully ionized plasma**
  - Ionization and breakdown are not limitations
- **Preformed plasma channels and self-focusing**
  - Diffraction can be overcome
- **Acceleration is the result of the axial field of the plasma wave** and not the laser field directly
  - The phase velocity of plasma wave is typically equal to the group velocity of the laser pulse (and is less than *c*)
  - The **plasma acts as a transformer**, converting the transverse laser field into the axial electric field of the plasma wave
- The **accelerating wavelength is the plasma wavelength**, typically 10-1000 times larger than the laser wavelength

However, plasma-based acceleration methods have their own limitations

- Electron dephasing
  - Tapering density or capillary
- Pump depletion
  - staging
- Laser-plasma instabilities

Ponderomotive force

We want to study the **response of a homogeneous plasma to a high frequency field** whose amplitude is spatially dependent

Charge q in an **oscillating** electric field with a **non-uniform envelope**

$$\vec{E}(\vec{r},t) = \vec{E}_s(\vec{r},t)\cos(\omega t)$$

↑ Laser Field (**LWFA**)

Hypotheses

Hyp. I $\vec{E}_s(\vec{r},t)$ is slowly varying envelope approximation (**SVEA**), i.e. is constant over $T = 2\pi/\omega$

$$\vec{E}_s(\vec{r},t) \approx \vec{E}_s(\vec{r})$$

Hyp. II **Non relativistic** equation of motion

$$m\frac{d\vec{v}}{dt} = q\left[\vec{E}(\vec{r},t) + \vec{v}\times\vec{B}(\vec{r},t)\right]$$

$\vec{v}\times\vec{B}(\vec{r},t) \ll \vec{E}(\vec{r},t)$ but not negligible (**II order theory**).

Ponderomotive force

Hyp. III

Position of q = "**slow**" drift + "**fast**" oscillation

$$\vec{r}(t) = \vec{r}_0(t) + \delta\vec{r}_1(t)$$

$$\delta\vec{r}_1(t) \ll \vec{r}_0(t) \qquad |\vec{v}_0| \ll |\vec{v}_1| \qquad \left|\frac{d\vec{v}_0}{dt}\right| \ll \left|\frac{d\vec{v}_1}{dt}\right|$$

Let's first neglect the **B** field and Taylor expand the **E** field around : $\vec{r}_0(t)$

$$m\frac{d\vec{v}}{dt} = m\frac{d\vec{v}_0}{dt} + m\frac{d\vec{v}_1}{dt} = q\left[\underbrace{\vec{E}_s(\vec{r}_0) + (\delta\vec{r}_1 \cdot \nabla)\,\vec{E}_s(\vec{r}_0)}_{\approx \vec{E}_s(\vec{r}_0)}\right]\cos(\omega t)$$

Hyp. III →

$$m\frac{d\vec{v}_1}{dt} \approx q\vec{E}_s(\vec{r}_0)\cos(\omega t)$$

Ponderomotive force

$$m\frac{d\vec{v}_1}{dt} = q\vec{E}_s(\vec{r}_0)\cos(\omega t)$$

$$\vec{v}_1 = \frac{q}{m\omega}\vec{E}_s(\vec{r}_0)\sin(\omega t)$$

$$\delta\vec{r}_1 = -\frac{q}{m\omega^2}\vec{E}_s(\vec{r}_0)\cos(\omega t)$$

Moreover from Maxwell equation:

$$\nabla \times \vec{E} = \left[\nabla \times \vec{E}_s(\vec{r}_0)\right]\cos(\omega t) = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{B}(\vec{r}_0, t) = -\frac{1}{\omega}\left[\nabla \times \vec{E}_s(\vec{r}_0)\right]\sin(\omega t)$$

Ponderomotive force

Then, the particle motion equation $$m\frac{d\vec{v}}{dt} = q\left[\vec{E}(\vec{r},t) + \vec{v}\times\vec{B}(\vec{r},t)\right]$$

$$m\frac{d\vec{v}}{dt} = m\frac{d\vec{v}_0}{dt} + m\frac{d\vec{v}_1}{dt} =$$

$$= q\vec{E}_s(\vec{r}_0)\cos(\omega t) + \left[\overbrace{\frac{-q^2}{m\omega^2}\left(\vec{E}_s(\vec{r}_0)\cdot\nabla\right)\vec{E}_s(\vec{r}_0)\cos(\omega t)^2}^{q(\delta\vec{r}_1\cdot\nabla)\vec{E}_s(\vec{r}_0)\cos(\omega t)}\right.$$

$$\left.\underbrace{-\frac{-q^2}{m\omega^2}\vec{E}_s(\vec{r}_0)\times\left(\nabla\times\vec{E}_s(\vec{r}_0)\right)\sin(\omega t)^2}_{q\vec{v}_1\times\vec{B}(\vec{r},t)}\right]$$

Ponderomotive force

Then, the particle motion equation $$m\frac{d\vec{v}}{dt} = q\left[\vec{E}(\vec{r},t) + \vec{v}\times\vec{B}(\vec{r},t)\right]$$

$$m\frac{d\vec{v}_0}{dt} = \frac{-q^2}{m\omega^2}\left[\left(\vec{E}_s(\vec{r}_0)\cdot\nabla\right)\vec{E}_s(\vec{r}_0)\cos(\omega t)^2 + \vec{E}_s(\vec{r}_0)\times\left(\nabla\times\vec{E}_s(\vec{r}_0)\right)\sin(\omega t)^2\right]$$

$$\langle\cos(\omega t)^2\rangle_T = 1/2 \qquad \langle\sin(\omega t)^2\rangle_T = 1/2$$

$$\left\langle m\frac{d\vec{v}_0}{dt}\right\rangle_T = \frac{-q^2}{2m\omega^2}\left[\underbrace{\left(\vec{E}_s(\vec{r}_0)\cdot\nabla\right)\vec{E}_s(\vec{r}_0) + \vec{E}_s(\vec{r}_0)\times\left(\nabla\times\vec{E}_s(\vec{r}_0)\right)}_{\frac{1}{2}\nabla\left[E_s(\vec{r}_0)^2\right]}\right]$$

$$\left\langle m\frac{d\vec{v}}{dt}\right\rangle_T = \left\langle m\frac{d\vec{v}_0}{dt}\right\rangle_T = \frac{-q^2}{4m\omega^2}\nabla\left[\vec{E}_s(\vec{r}_0)^2\right]$$

non linear force acting on the charge q

Ponderomotive force

$$\left\langle m\frac{d\vec{v}}{dt}\right\rangle_T = \left\langle m\frac{d\vec{v}_0}{dt}\right\rangle_T = \frac{-q^2}{4m\omega^2}\nabla\left[\vec{E}_s(\vec{r}_0)^2\right]$$

Ponderomotive force

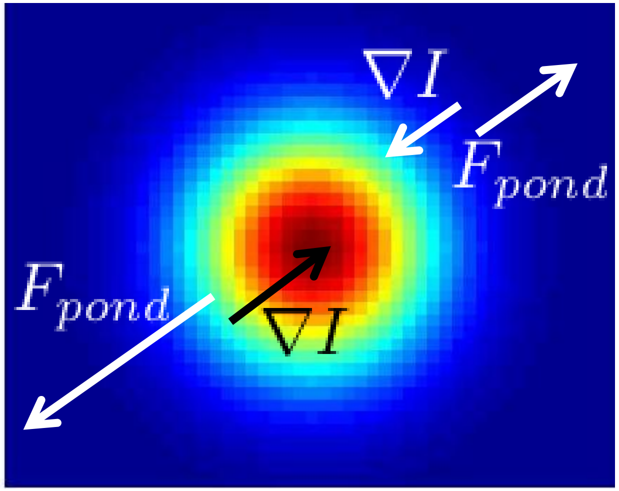
Ponderomotive force per unit volume

$$n\frac{-q^2}{4m\omega^2\epsilon_0}\nabla\left[\epsilon_0 E_s(\vec{r}_0)^2\right] = -\frac{\omega_p^2}{\omega^2}\nabla\left[\frac{\langle\epsilon_0 E^2\rangle}{2}\right]$$

$$F_{pond} \propto -q^2\frac{\nabla(\text{wave intensity})}{m} = -q^2\frac{\nabla I}{m}$$

Any charge escapes from the region of greater radiation intensity, like under a pressure ...

Electrons undergoes to a greater force than ions (force depends on the mass, ... **pondus**)

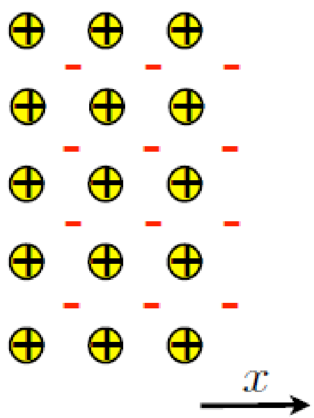


Plasma Acceleration: Basic Principles

Electron plasma wave (Langmuir wave):
In the linear (a<<1) 3D regime, wakefield generation can be examined using the cold fluid equations:

- Perturbation to collisionless neutral plasma (equal number of electrons and ions)
- Dynamics governed by coupled Maxwell and Vlasov equations

$$\delta n \sim \exp[-i\omega(t - x/\beta_p)]$$



Poisson equation:

$$\partial_x E = -4\pi e \delta n$$

Continuity equation:

$$\partial_t \delta n + n_0 \partial_x \delta v = 0$$

Momentum equation:

$$\partial_t \delta v = -(e/m_e)E$$

1. **Natural frequency of oscillation** is the plasma frequency:

$$\omega = \omega_p = \sqrt{\frac{4\pi n_0 e^2}{m_e}}$$

2. **Amplitude of plasma wave electric field**:

$$|E| = \left(\frac{m_e c \omega_p}{e}\right) \beta_p \frac{\delta n}{n_0}$$

Plasma Acceleration: Basic Principles

Which is the maximum accelerating field a plasma can sustain?

Poisson equation:

$$\nabla \cdot E = -4\pi e\,(n_e - n_i)$$

Continuity equation:

$$\partial_{ct} n_e + \nabla \cdot (n_e \beta) = 0$$

Momentum equation:

$$dp/dt = -e(E + \beta \times B)$$

$$|E| = \left(\frac{m_e c \omega_p}{e}\right) \beta_p \frac{\delta n}{n_0}$$

With $\beta_p = \dfrac{v_p}{c}$ and large density perturbation $\delta n \approx n_0$

$$E \sim E_0 = m_e c \omega_p / e \simeq 96\sqrt{n_0[\mathrm{cm}^{-3}]}$$

cold wavebreaking field ➔ field at which a cold plasma wave breaks

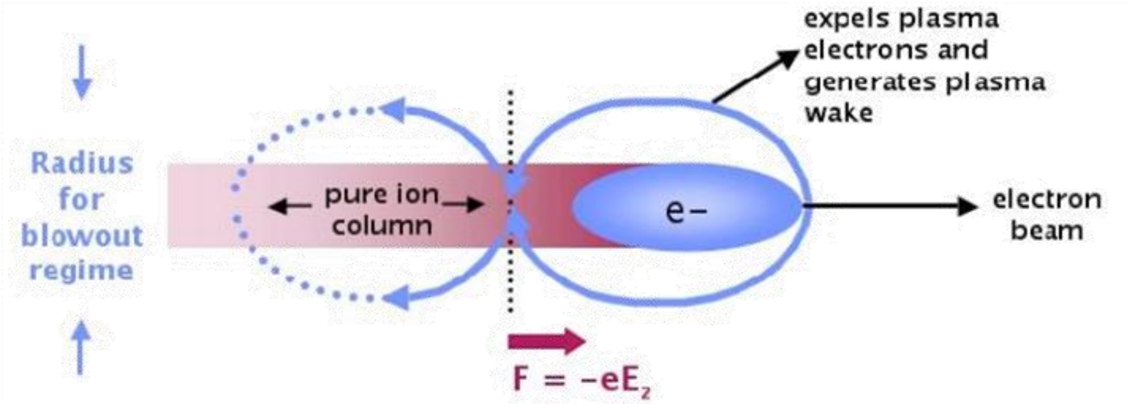
E.g., for ~10^{18} cm^{-3}, gradient ~100 GV/m

Limits to electron energy gain

- **Laser pulse diffraction**
  - Limits laser-plasma interaction length to ~ Rayleigh range (typically most severe)
  - Controlled by transverse plasma density tailoring (plasma channel) and/or relativistic self-guiding and ponderomotive self-channeling
    - guiding: capillary
- **Electron dephasing**
  - Slippage between e-beam and plasma wave
  - $L_{\text{dephase}} = \lambda_p/2(1-\beta_p) \approx \lambda_p^3/\lambda^2$ is the distance it takes a trapped electron to outrun a plasma wave that propagates at a subluminous phase velocity
  - Determined by plasma wave phase velocity (approximately laser group velocity)
    - Controlled by longitudinal plasma density tailoring (plasma tapering):
      - tapering density or capillary
- **Laser pulse energy depletion**
  - Rate of laser energy deposition into plasma wave excitation
  - $L_{\text{deplete}} \propto n^{-3/2}\lambda^{-2}$
    - staging

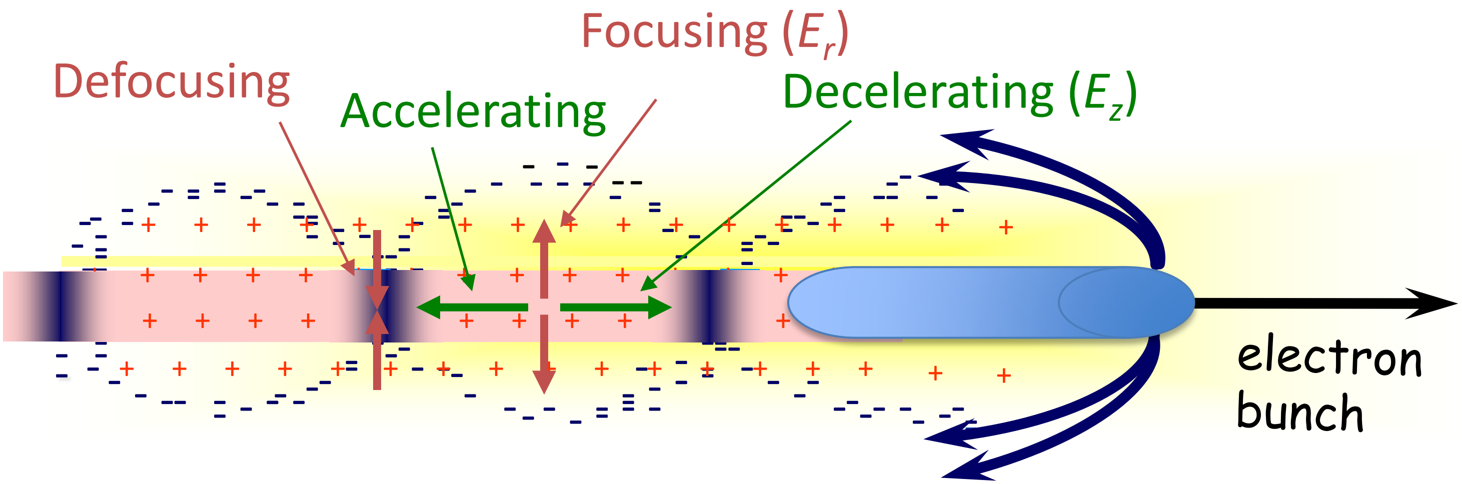
Particle beam-driven Plasma Wakefield Accelerator (PWFA)

The high-gradient wakefield is driven by an intense, high-energy charged particle beam as it passes through the plasma.
The space-charge of the electron bunch blows out the plasma electrons which rush back in and overshoot setting up a plasma oscillation.



First demonstration of the excitation of a wakefield by a relativistic beam **in the linear regime** (*beam density typically less than the plasma density)*(**J. Rosenzweig et al.,** ***Phys. Rev. Lett. 61, 98 (1988)***).
The change in energy of a witness beam with a variable delay was used to map the wakefield induced by the drive beam.
The peak acceleration gradient was just 1.6 MeV/m, however **the experiment clearly showed the wakefield persisting for several plasma wavelengths**.

Single Bunch PWFA

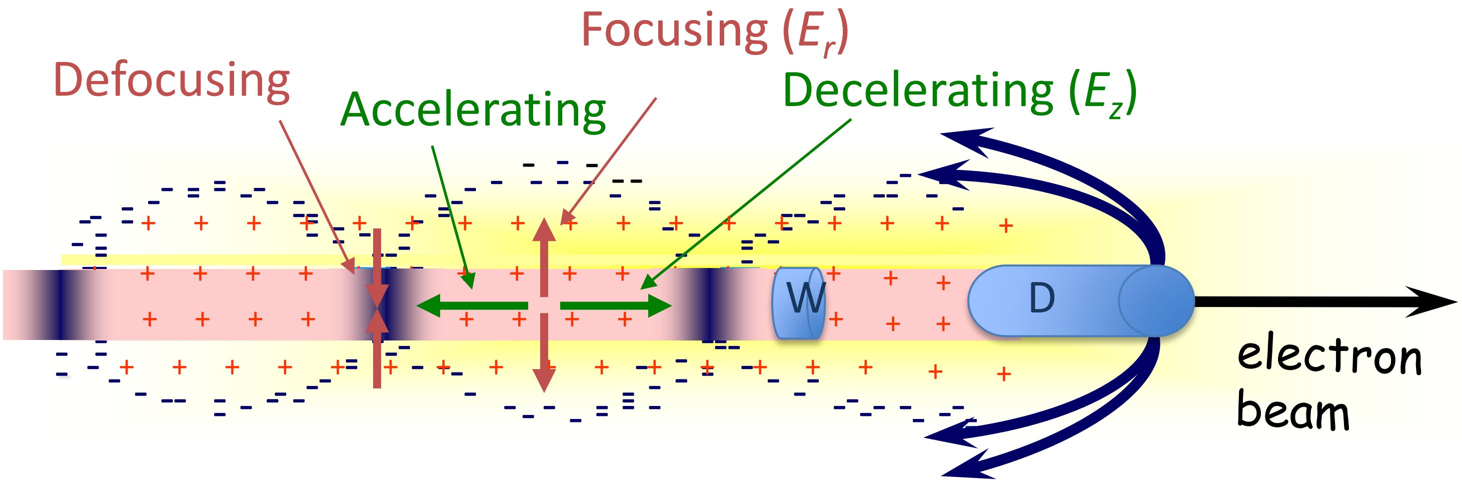


-Plasma wave/wake is excited by a relativistic particle bunch
- The plasma wave oscillates with plasma frequency ω_p

- Plasma e^- are expelled by space charge forces
=> energy loss + focusing
- Plasma e^- rush back on axis => energy gain

Single bunch for particle acceleration (**$\Delta E/E \sim 1$**)

2-bunch Train PWFA



A second, appropriately phased accelerating beam (**witness beam**), containing fewer particles than the **drive beam**, is then accelerated by the wake.

Bunch train (D+W) for bunch acceleration (**ΔE/E<<1**)

PWFA Characteristics

Relativistic, short, dense bunch(es):

Accelerating gradient: $E_{z,accel}(V/m) \cong 2\times10^{-9}\dfrac{N}{\sigma_z^2}$ with $\dfrac{\sigma_z}{\lambda_{pe}} \cong \dfrac{1}{\sqrt{2}\pi}$ and $\dfrac{\sigma_r}{\lambda_{pe}} << 2\pi$
(max., single bunch, lin.)

Typically for 1GV/m: $N = 2\times10^{10}$ $\sigma_z \cong 200\mu m$ $\sigma_r << 137\mu m$ in $n_e = 1.4\times10^{15}cm^{-3}$

Blowout, nonlinear regime: $\dfrac{n_b}{n_e} > 1$ $(\sigma_r < 67\mu m)$

Pure ion column focusing: $\dfrac{B_\theta}{r} = \dfrac{1}{2}\dfrac{n_e e}{\varepsilon_0 c} \cong 42kT/m$ free of geometric aberrations

Wavebreaking field: $E_{WB} = 3.6GV/m$

Combination of large transverse focusing gradient and large accelerating field leads to large energy gain

All the beam particles and the wake are ultra-relativistic → no dephasing!

High energy (per particle) drive bunch

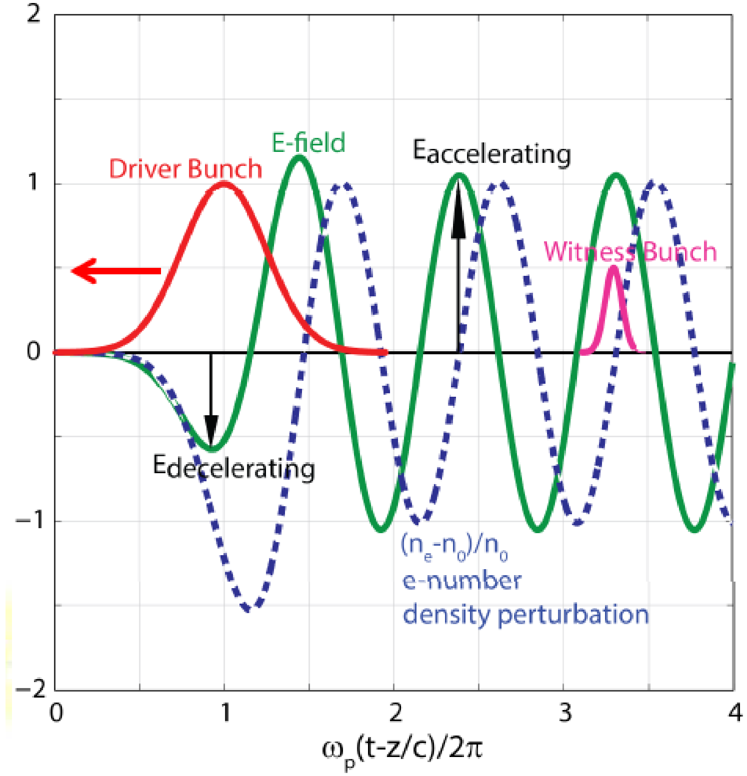
Transformer Ratio: limits energy gain in PWFA

The **key parameter** that determines the energy gain is the **Transformer Ratio**, defined as the ratio of the maximum accelerating field behind the driving bunch and the maximum decelerating field inside the driving bunch

$$R = \frac{E_{accelerating}}{E_{decelerating}}$$

A test charge injected in correspondence of $E_{accelerating}$ gains an energy approximately equal to

$$\Delta W = R\gamma_{driver}$$

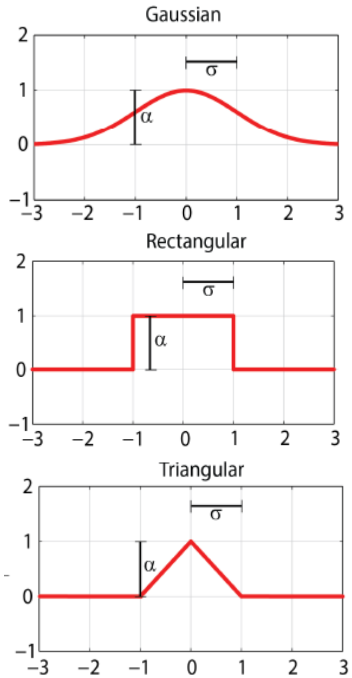


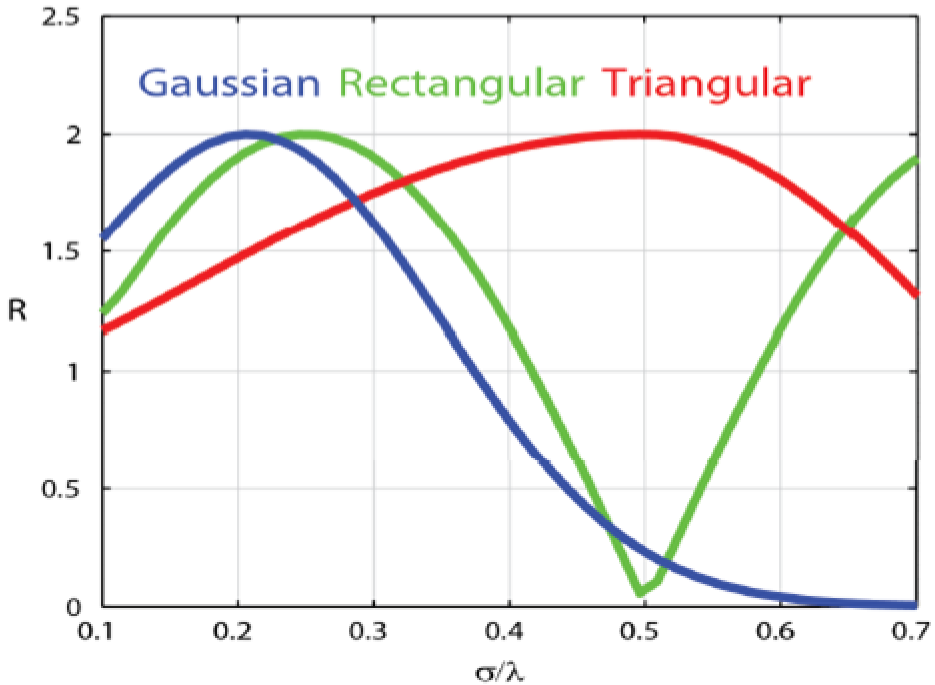
F. Massimo et al., NIM A **740**, 242–245 (2014)

Transformer Ratio: limits energy gain in PWFA

The transformer ratio critically depends on the bunch shape and on the density ratio

Linear regime: $\alpha = \dfrac{n_{driver,peak}}{n_0}$ **= 10^{-4}**





- Under general considerations (symmetric bunches):

$$R = E_+/E_- \leq 2$$

F. Massimo et al., NIM A **740**, 242–245 (2014)

Transformer Ratio: limits energy gain in PWFA

- Higher transformer ratios can be achieved using shaped (asymmetric) bunches:

R. Ruth et al., PA (1985)

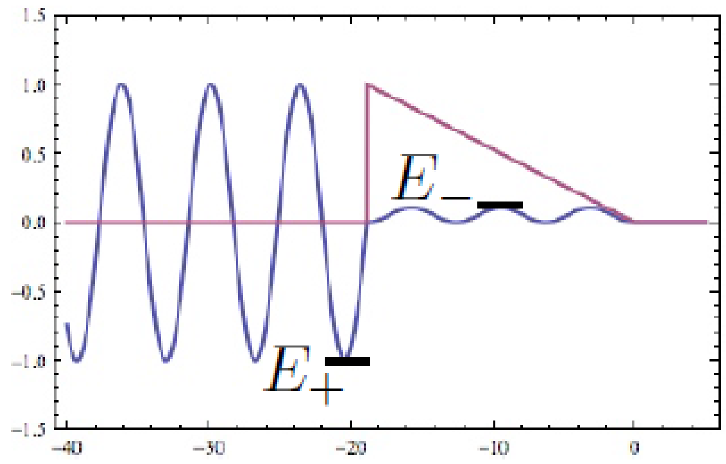
- Triangular beam: $R = \pi(L_b/\lambda_p)$

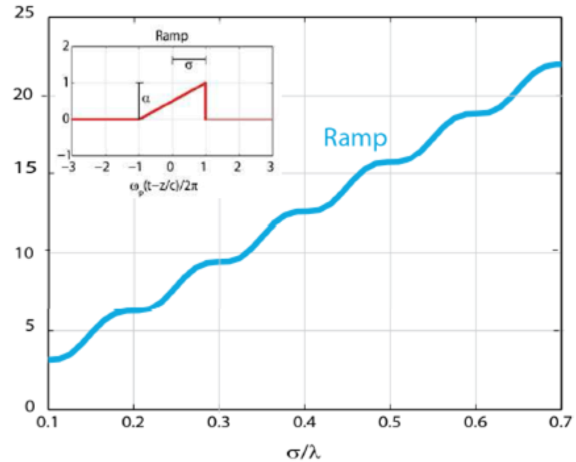
- Bunch train: $R \leq 2\sqrt{M_b}$

- Improved transformer ratio in nonlinear blowout regime using ramped bunch

W. Lu et al., PAC (2009)

$$R \sim \frac{L_b}{R_b}\left(\frac{n_0}{n_b}\right)^{1/2}$$

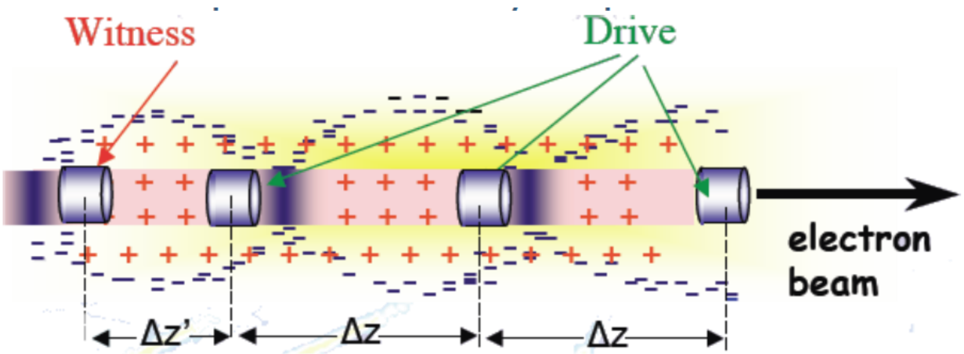




F. Massimo et al., NIM A **740**, 242–245 (2014)

Multi-bunch Train: Resonant PWFA

- Weak blowout regime with resonant amplification of plasma wave by a train of HBEBs injected into the preformed plasma (by electric discharge)
  - 5GV/m with a train of 3 bunches, 100 pC/bunch, 20 μm spot size, n_e 10^{22} e/m^{-3} at λ_p = 300 μm



$\Delta z=\lambda_p$ (resonance) $\sigma_z \leq \lambda_p/2$

$$E_{acc}[MV/m] = 244\,\frac{N_b}{2\times 10^{10}}\left(\frac{600}{\sigma_z[\mu m]}\right)^2 \times N_T^2$$

- Ramped bunch train configuration to enhance transformer ratio
- Synchronization with an external laser is not needed
- Challenge: creation and manipulation of driver bunches and matching all the bunches with the plasma
  - High quality bunch preservation during acceleration and transport

Generation and Manipulation of Bunch Trains at SPARC_LAB

P. O. Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
M. Ferrario. M. Boscolo et al., Int. J. of Mod. Phys. B, 2006

(Parmela code)

Charge vs. Time

Energy vs. Time

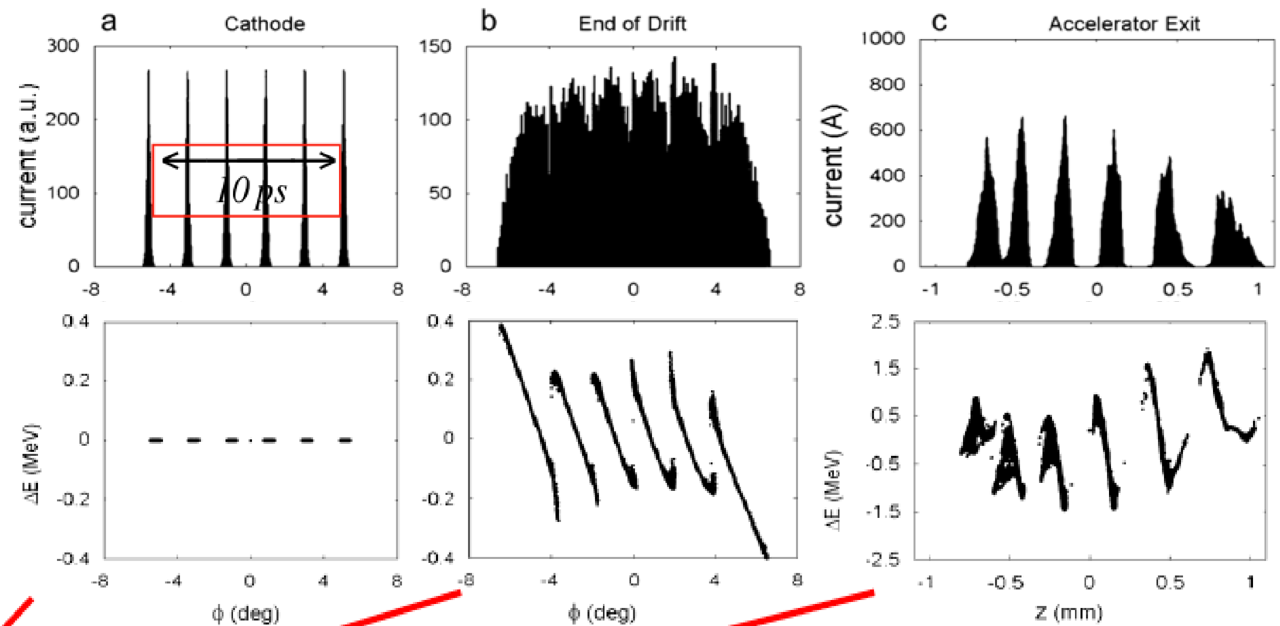
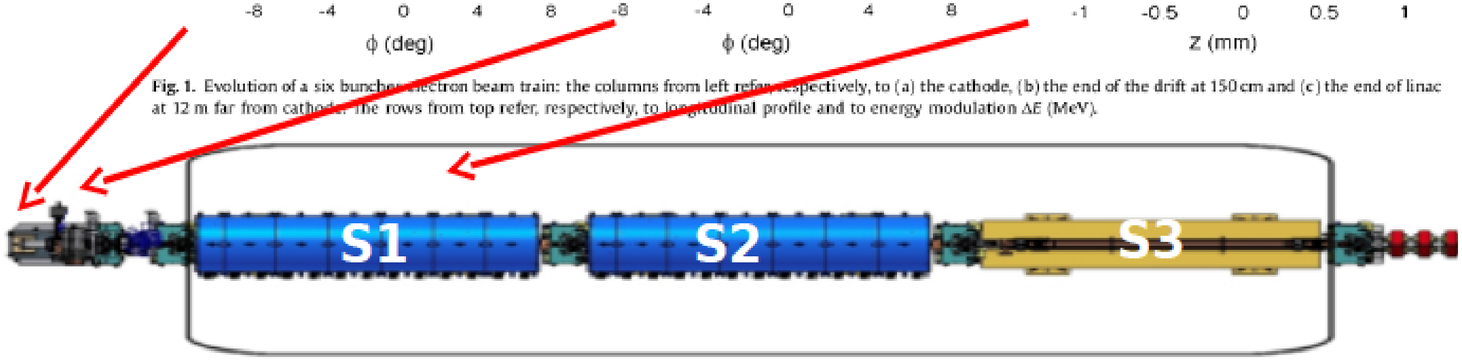


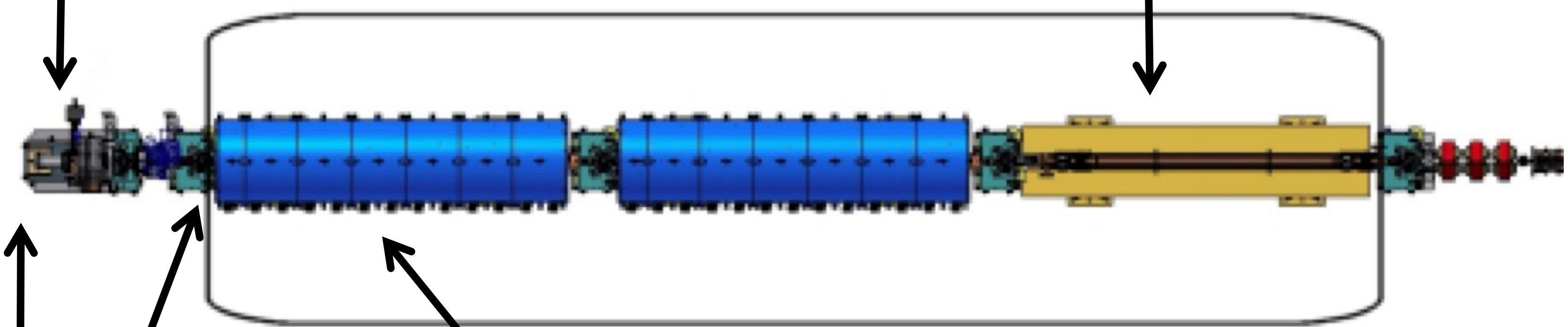
Fig. 1. Evolution of a six bunches electron beam train: the columns from left refer, respectively, to (a) the cathode, (b) the end of the drift at 150 cm and (c) the end of linac at 12 m far from cathode. The rows from top refer, respectively, to longitudinal profile and to energy modulation ΔE (MeV).



Manipulation of Bunch Trains

Gun focusing field (~3kG)
Emittance
Bunches current, length

Accelerating field
Energy separation



Injection phase
Bunch spacing
Train length

TW focusing field (~300G)
Emittance
Bunches current, length and their max compression phase

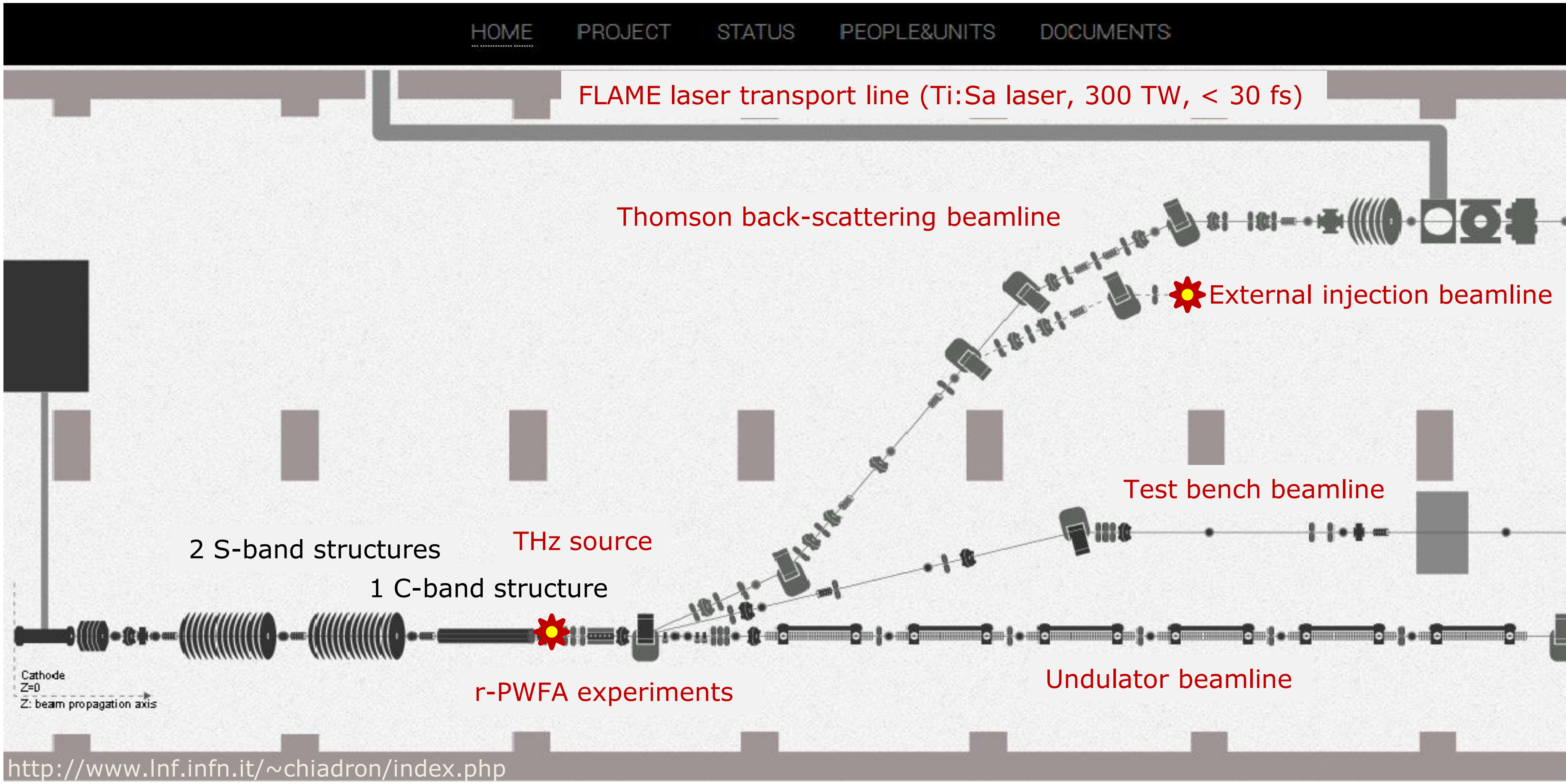
Gun exit energy
Beam brightness

Compression phase stability
Bunch separation stability

Gun injection phase and space charge
Bunches distance at the linac entrance

The SPARC_LAB Test Facility

Next Future

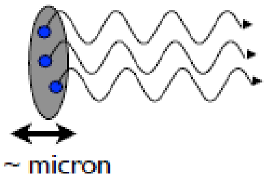


Conclusions

- Plasma accelerators provide ultra-high gradients (compact accelerators) generating short beams (high peak current)
- Many potential applications possible for compact plasma-based accelerators, delivering ultra-short, high peak current electron beams (e.g. FEL, γ rays,…)
  - LPA are intrinsically sources of fs bunches: the accelerated electron bunches are intrinsically synchronized to the laser pulses, enabling a wide variety of pump-probe applications

Conclusions

- High field THz generation
  - Coherent Transition/Diffraction radiation from short bunches



- Thomson scattering
  - scattering electron bunch from laser => compact γ ray source
- Betatron radiation
  - Synchrotron radiation from beam in transverse field of plasma wave => fs, broadband source of hard x-rays
- Undulator radiation
  - fs source of soft x-rays
- LPA-driven FEL
  - high peak power, coherent radiation

Grazie