Dottorato in Fisica, Roma 3
Laboratori Nazionali di Frascati
13 - 14 giugno, 2016

Plasma Wakefield Acceleration

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Outline

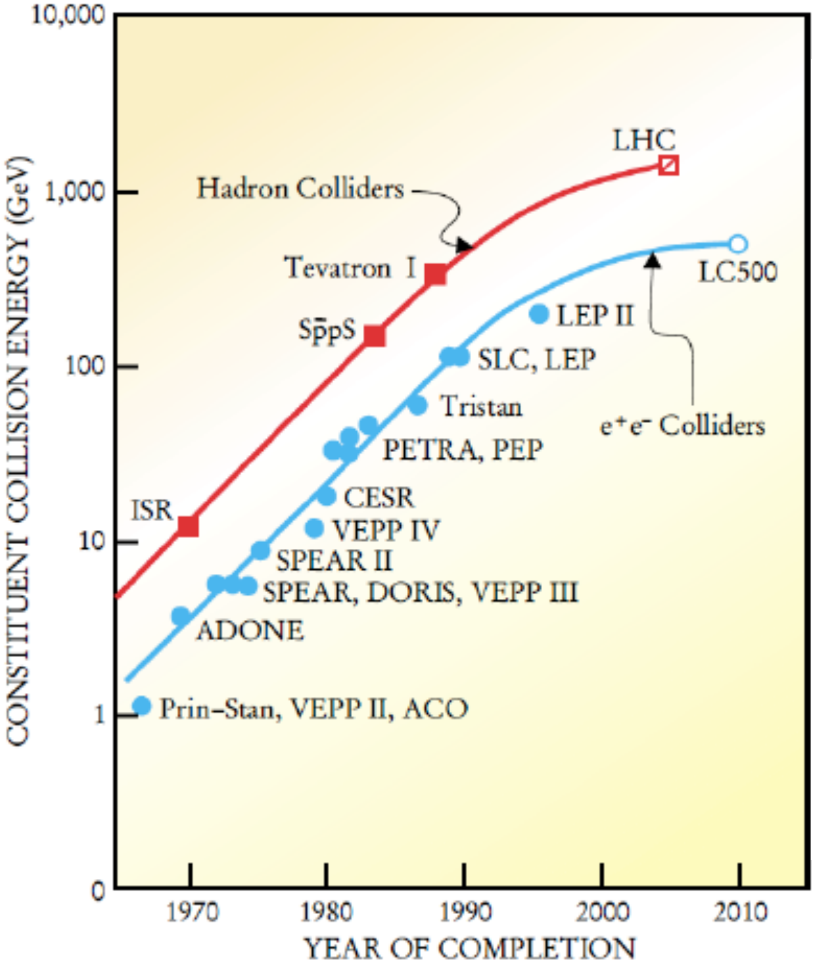
- Motivation and goals
  - Energy frontier accelerators
  - **Preservation of beam quality**
- Principle of plasma acceleration
- **External injection of high brightness electron bunches** (HBEBs) in both particle and laser driven plasma wakefield, PWFA and LWFA respectively

Motivation

- The quality of beams in particle accelerators is driven by applications
  - **Applied Science**
    - Novel sources (e.g. FELs, THz, Thomson, etc…) for material science, biology, …
  - Fundamental research
    - Particle physics: Build multi-stages **compact colliders**
- **The frontier in modern accelerator physics is based on R&D for the upgrade of existing machines and for the path towards compact accelerators**
- **Despite** the recent progresses in achieved **accelerating gradient performances, plasma-based accelerators** have **not yet** produced a beam quality really **competitive** with the existing RF particle accelerators **in terms of beam brightness, energy spread and repetition rate**
- The **main issue** is now on the **beam quality**
  - Acceleration of **high brightness electron beams (HBEB)**
    - The **development of** fast running **simulations codes and adequate beam and plasma diagnostics tools**, mandatory for a reliable characterization of the plasma accelerated beam **is also challenging**

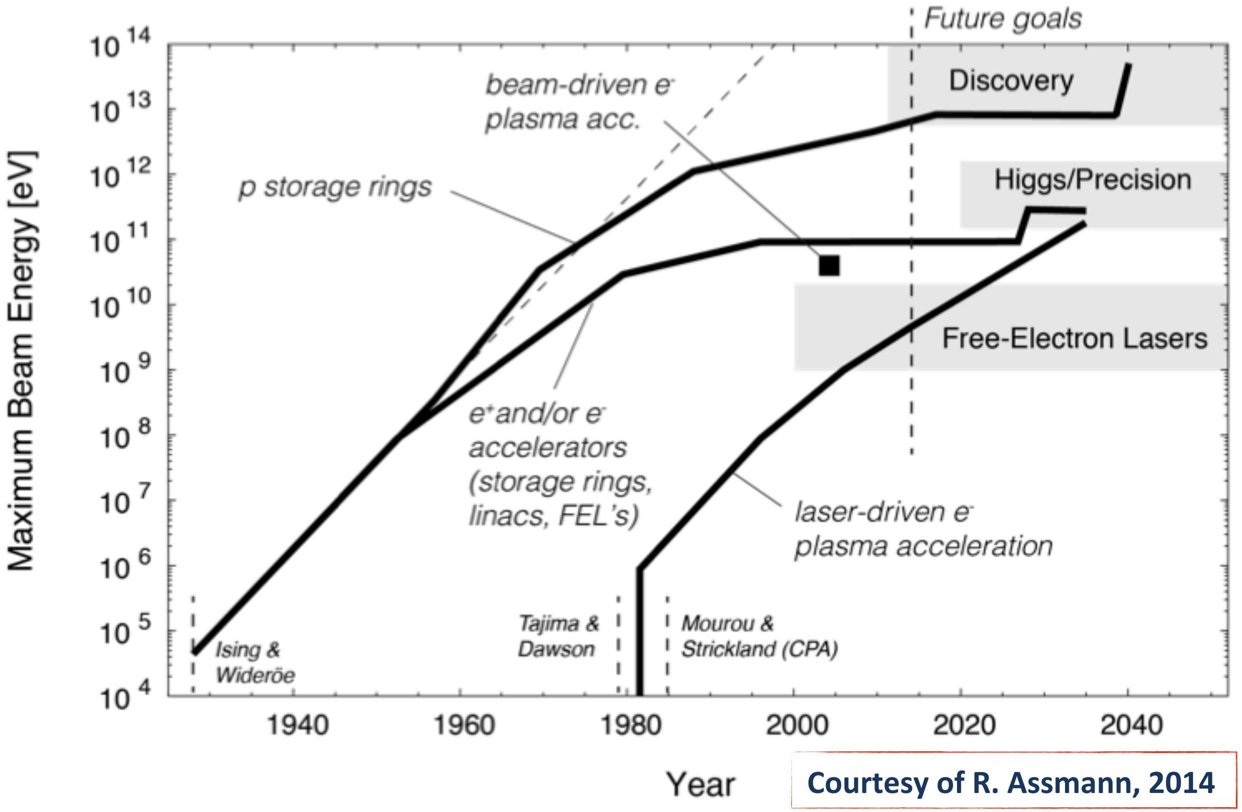
Energy frontier accelerators

Livingston Plot



M. Tigner, Phys. Today (2001)

Updated Livingston Plot

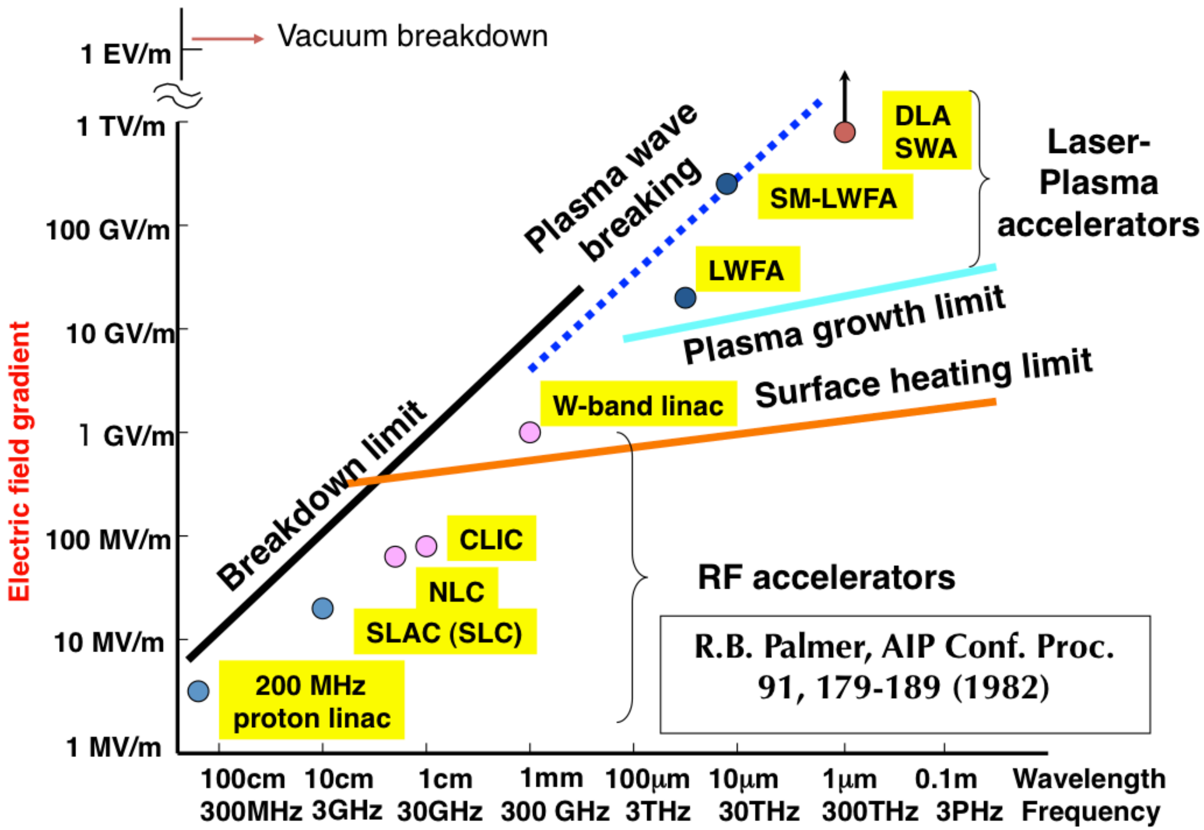


Courtesy of R. Assmann, 2014

Energy frontier accelerators

- **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

Saturation of accelerator technology



Principle of plasma acceleration

- **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

Acceleration in vacuum

In vacuum, the motion of an electron in a laser field

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

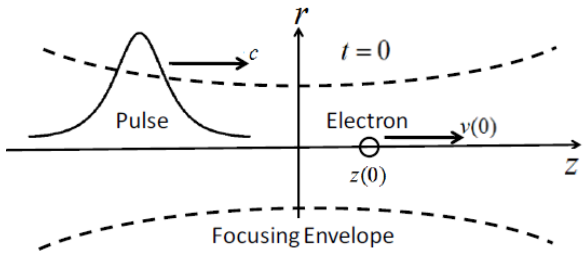
is determined by the Lorentz force equation,

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

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

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, i.e. 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

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

$$Z_R = \frac{kr_0^{\,2}}{2}$$ the Rayleigh length

The finite laser spot size implies the existence of an **axial component of the laser electric** field via $\nabla\cdot\vec{E}=0, \text{i.e. } E_z \approx \frac{1}{kr_0}E_\perp$

The amplitude of the axial field **can be very large** => the axial field might be directly used for laser acceleration

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

Since $v_{ph} > c$ **, electrons with** $\boxed{v_z < c}$ **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

The theorem assumes that

(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. **v** x **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 optics placed near the focus
    - 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 overcome
  - **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

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** => **Ponderomotive laser acceleration**
  - The <u>phase velocity of plasma wave</u> is <u>typically</u> equal to the group velocity of the laser pulse (and is <u>less than *c*</u>)
  - 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

Definition of plasma

- A partially or completely ionized gas, globally neutral, is a plasma if it exhibits a **collective behavior**
  - **Coulomb shielding**
    - dimensions >> **Debye length** $\lambda_D = \sqrt{\dfrac{kT\varepsilon_0}{ne^2}}$
  - **plasma oscillations**
    - temporal response >> ω_p^{-1}
- Potential energy (nearest neighbor) << kinetic energy
  - particles do not bind $e^2 n^{1/3} \ll k_B T_e$

Ponderomotive force

The non-linear response to the ***vxB*** force is responsible for "**ponderomotive**" **laser acceleration**

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

Let us consider a **charge q in an oscillating electric field with a non-uniform envelope** (e.g. a laser field, LWFA)

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

Hypotheses

1. Slowly varying envelope approximation (SVEA): $\vec{E}_s(\vec{r},t) \approx \vec{E}_s(\vec{r})$

2. 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

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

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

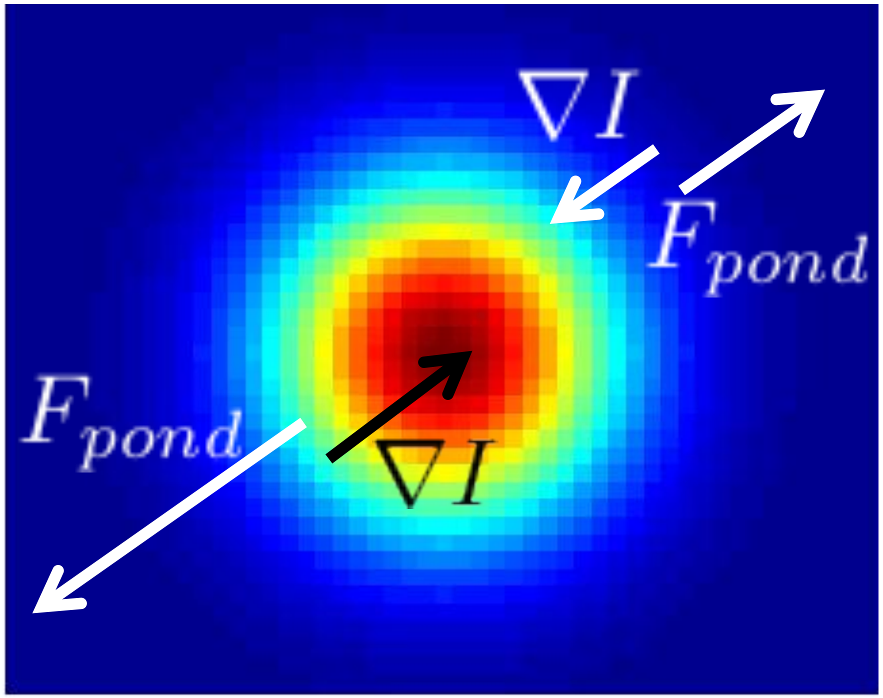
Ponderomotive force

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

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

Ponderomotive force per unit volume

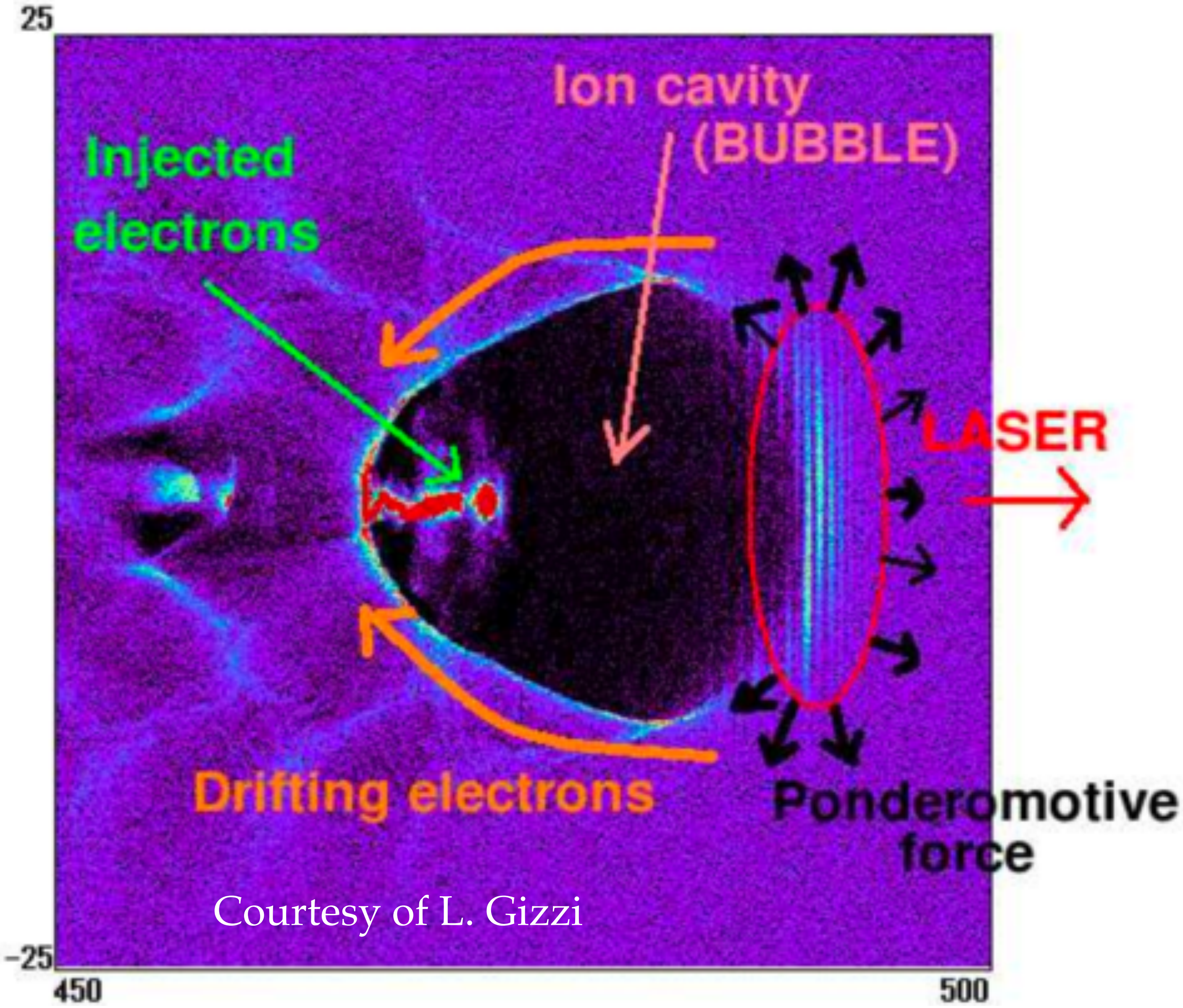
$$F_{pond} \propto -q^2\frac{\nabla(\text{wave intensity})}{m} = -q^2\frac{\nabla I}{m}$$



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

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

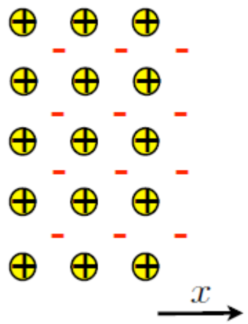
Ponderomotive force



Cold wave-breaking

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

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

Continuity equation:

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

Momentum equation:

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

- The natural frequency of oscillation is the plasma frequency $\boxed{\omega = \omega_p = \sqrt{\frac{4\pi n_0 e^2}{m_e}}}$
- The amplitude of plasma wave electric field is $\boxed{|E| = \left(\frac{m_e c \omega_p}{e}\right) \beta_p \frac{\delta n}{n_0}}$
- With $\beta_p = \frac{v_p}{c}$ and large density perturbation $\delta n \approx n_0$

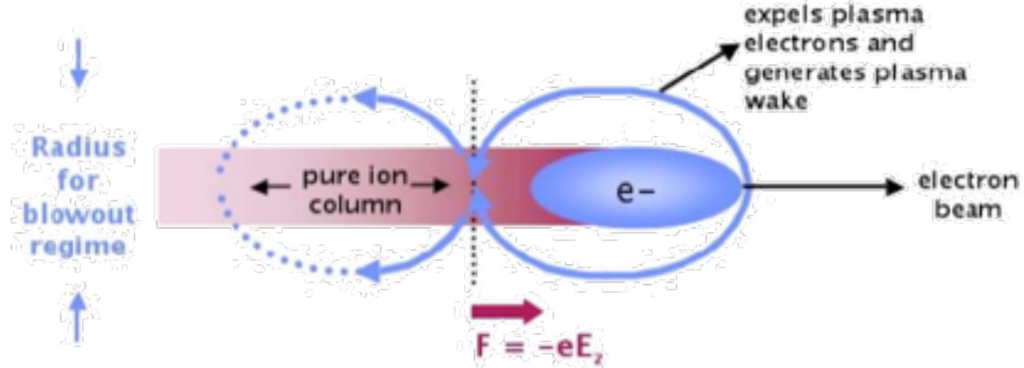
$$\boxed{E \sim E_0 = m_e c \omega_p / e \simeq 96\sqrt{n_0[\mathrm{cm}^{-3}]}}$$

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
  - $\boxed{L_{\mathrm{dephase}} = \lambda_p/2(1-\beta_p) \approx \lambda_p^3/\lambda^2}$ is the distance it takes a trapped electron to outrun a plasma wave that propagates at a sub-luminous 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 $\boxed{L_{\mathrm{deplete}} \propto n^{-3/2}\lambda^{-2}}$
    - **staging**

Particle-driven PWFA

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 peak acceleration gradient was just 1.6 MeV/m, however the experiment clearly showed the wakefield persisting for several plasma wavelengths.

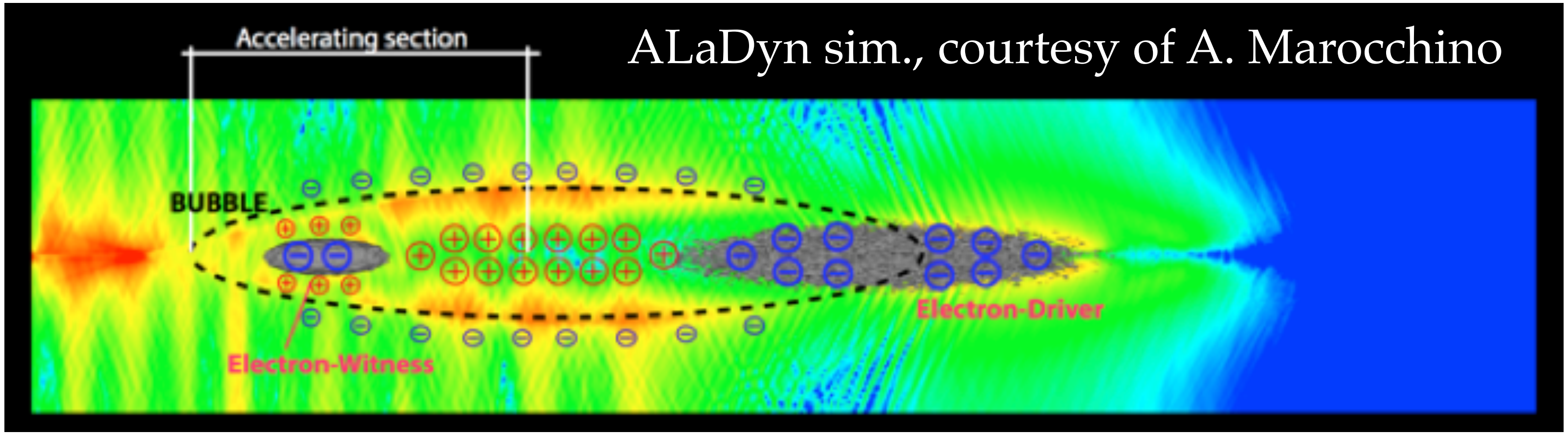


$$\boxed{\omega = \omega_p = \sqrt{\frac{4\pi n_0 e^2}{m_e}}}$$

- 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 plasma electrons which rush back in and overshoot** setting up a plasma oscillation

Single bunch for particle acceleration (**ΔE/E~1**)

Two-bunch train PWFA



- An **intense, high-energy charged particle beam** (**driver**) drives a **high-gradient wakefield** as it passes through the plasma

- The **space-charge** of the electron bunch **blows out plasma electrons**

- **Plasma electrons rush back in and overshoot** setting up a plasma density oscillation

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

- A second beam (**witness**), injected at the accelerating phase, is then accelerated by the wake

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

Limitation of PWFA

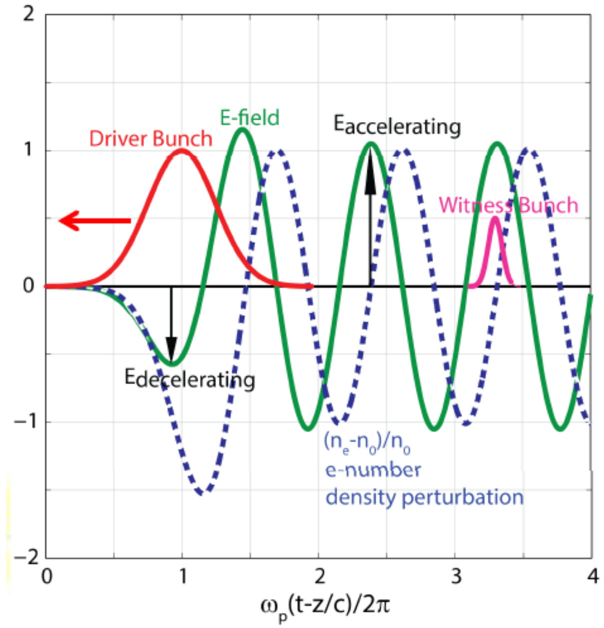
- **PWFA** acting as an **energy transformer** has the great potential to double beam energy in a single stage

- The energy transfer from the drive bunch to the plasma is optimized by maximizing the **transformer ratio**

$$R = \frac{|E_{+,max}|}{|E_{-,max}|}$$

Wakefield theorem*

- **Symmetric drive bunch current profile** in a single-mode structure: the **maximum accelerating field** behind the drive bunch **cannot exceed 2 times the maximum decelerating field** amplitude along the drive bunch



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

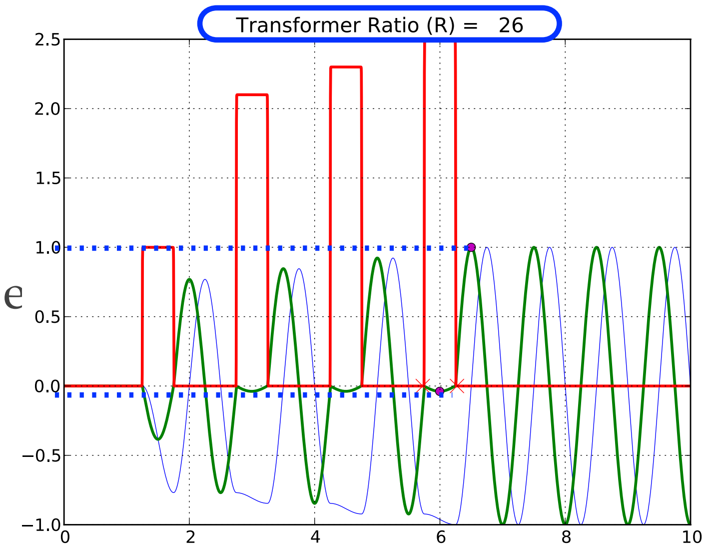
*V. V. Tsakanov, Nucl. Instrum. Methods Phys. Res., Sect. A 432, 202 (1999)

Enhancing Transformer Ratio

- By properly **tailoring the driver bunch shape**, the witness beam energy might be more than doubled when

*The maximum possible transformer ratio for a bunch with given length and total charge corresponds to that charge distribution which causes all particles in the bunch to see the same retarding field**

- Tailoring longitudinal current profile such that all longitudinal slices lose energy at the same rate
  - **Asymmetric drive bunch current profile,** i.e. triangular, double triangle, doorstep-like distributions, or **multiple ramped bunch trains**, overcome this limit (R.Ruth et al., PA 1985; W. Lu e PAC 2009)



*K. Bane, P. Chen, and P. B. Wilson, *SLAC-PUB-3662*,1985

Enhancing Transformer Ratio

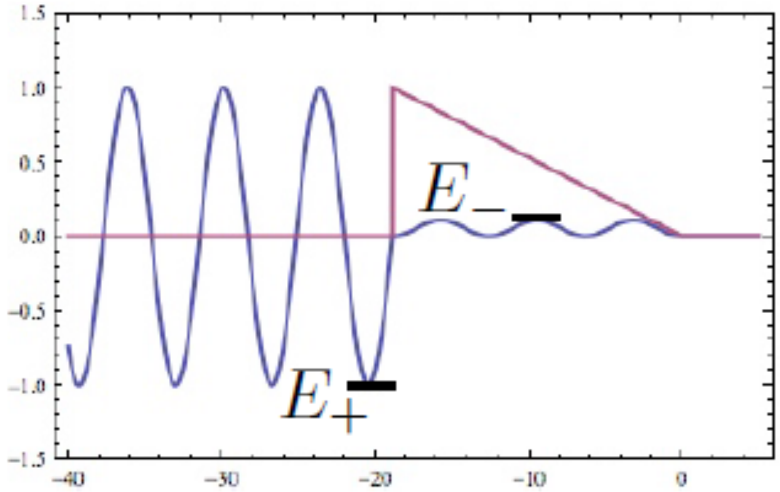
- Higher transformer ratios can be achieved using shaped (asymmetric) bunches:

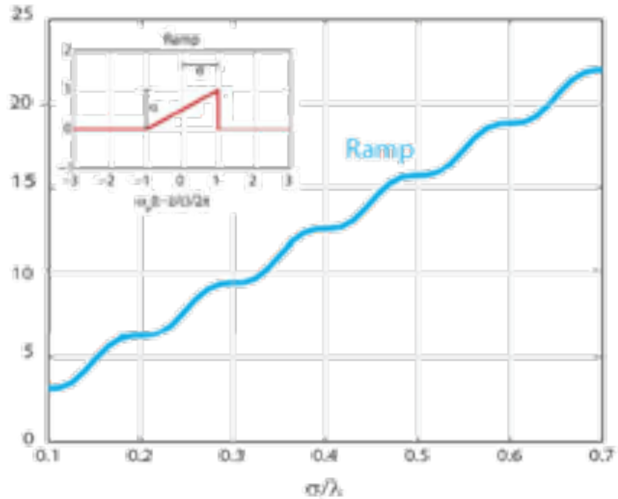
R. Ruth et al., PA (1985)

- 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)

Linear regime: $\boxed{\alpha = \frac{n_{driver,peak}}{n_0}}$ **= 10⁻⁴**

Plasma-based particle accelerators

Laser only

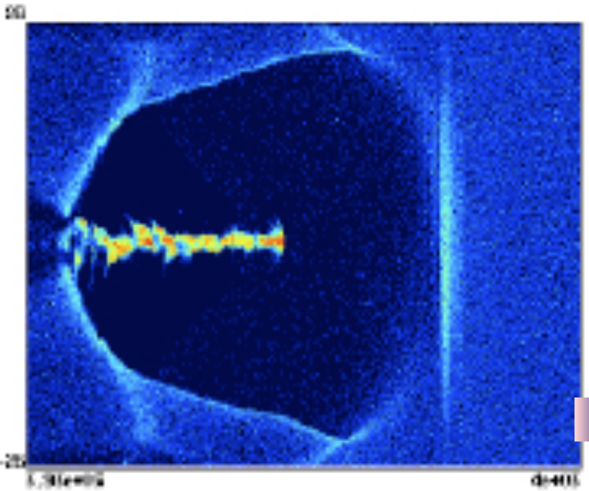
- The "easiest" to implement (requires "only" to tune the laser and the target)
- Difficult control over the whole process

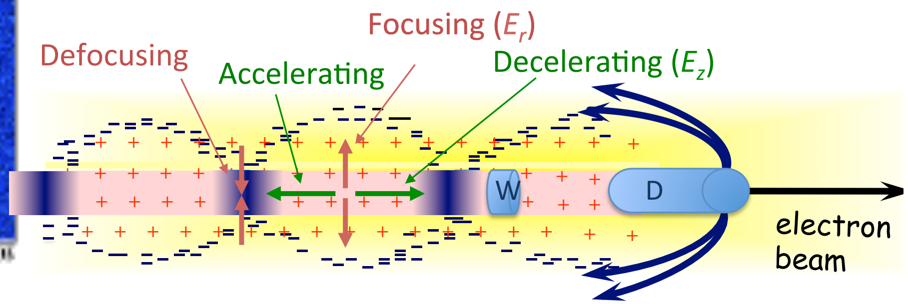
Electrons only

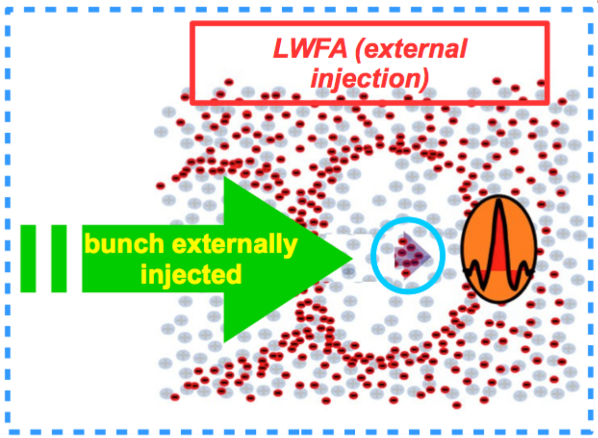
- Easier implementation than laser+electrons (no need for independent synchronization system and driver guiding)
- Produced e-beams quality and energy depends heavily on the ability to properly taylor the driver(s) and witness phase spaces

Laser and electrons

- In principle has the best potentialities in term of e-beam brightness and energy
- The hardest to implement (laser guiding, synchronization issues, ...)







Goals

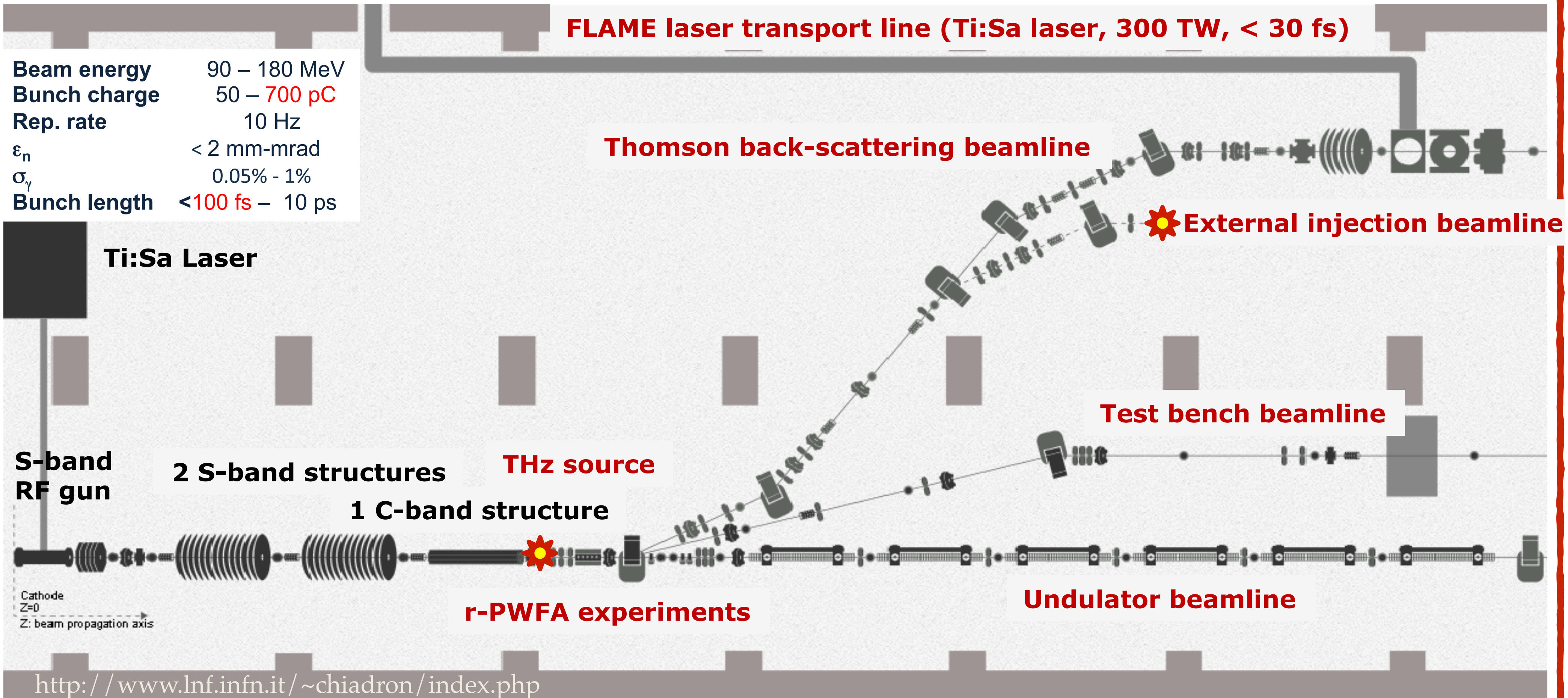
- Plasma-based acceleration has already proved the **ability to reach ultra-high, ~GV/m, accelerating gradients**
  - J. Rosenzweig et al., Phys. Rev. Lett. **61**, 98 (1988): *First experimental demonstration of PWFA*
  - Mangles, Geddes, Faure et al., Nature **431**, (2004): *The dream beam*
  - W. P. Leemans, Nature Physics vol. **2**, p.696-699 (2006): *GeV electron beams from a centimetre-scale accelerator*
  - I. Blumenfeld et al., Nature **445**, p. 741 (2007): *Doubling energy in a plasma wake*
  - P. Muggli et al, in Proc. of PAC 2011, TUOBN3*: Driving wakefields with multiple bunches*
- The **next step** is the extraction and transport of the beam, preserving its quality, i.e. 6D high brightness, stability and reliability to **drive a plasma-based user facility** (the EUPRAXIA Design Study has been funded from EU)
  - Litos, Nature 515, 92 (2014): *High efficiency acceleration in the driver-trailing bunches*
  - S. Steinke et al., Nature 000 (2016) doi:10.1038/nature16525: *Multi-stage coupling*

Our strategy

External injection of **high brightness electron beams (HBEBs)** in either particle-driven or laser-driven plasma wakefield

- resonant plasma wave excitation in a capillary discharge
  - Bunch trains generation with the *comb technique* based on RF Velocity Bunching (VB) to increase the transformer ratio
- laser-driven wakefield excitation in a plasma-filled guiding capillary
  - Hybrid compression, both VB and magnetic to deliver HBEBs
  - Synchronization issue

The SPARC_LAB Test Facility



Sources for Plasma Accelerators and Radiation Compton with Lasers And Beams

https://www.google.it/maps/@41.8231995,12.6743967,3a,69.7y,130.68h,76.68t/data=!3m6!1e1!3m4!1sYyB35yaBMxJgQ92-wp3oYQ!2e0!7i13312!8i6656?hl=en

FLAME Laser

Max Energy on Target: 5 J	
Min Pulse Duration: 23 fs	
Wavelength	800 nm
Bandwidth	60/80 nm
Spot @ focus	10 μm
Peak Power	300 TW
Contrast Ratio	10^{10}

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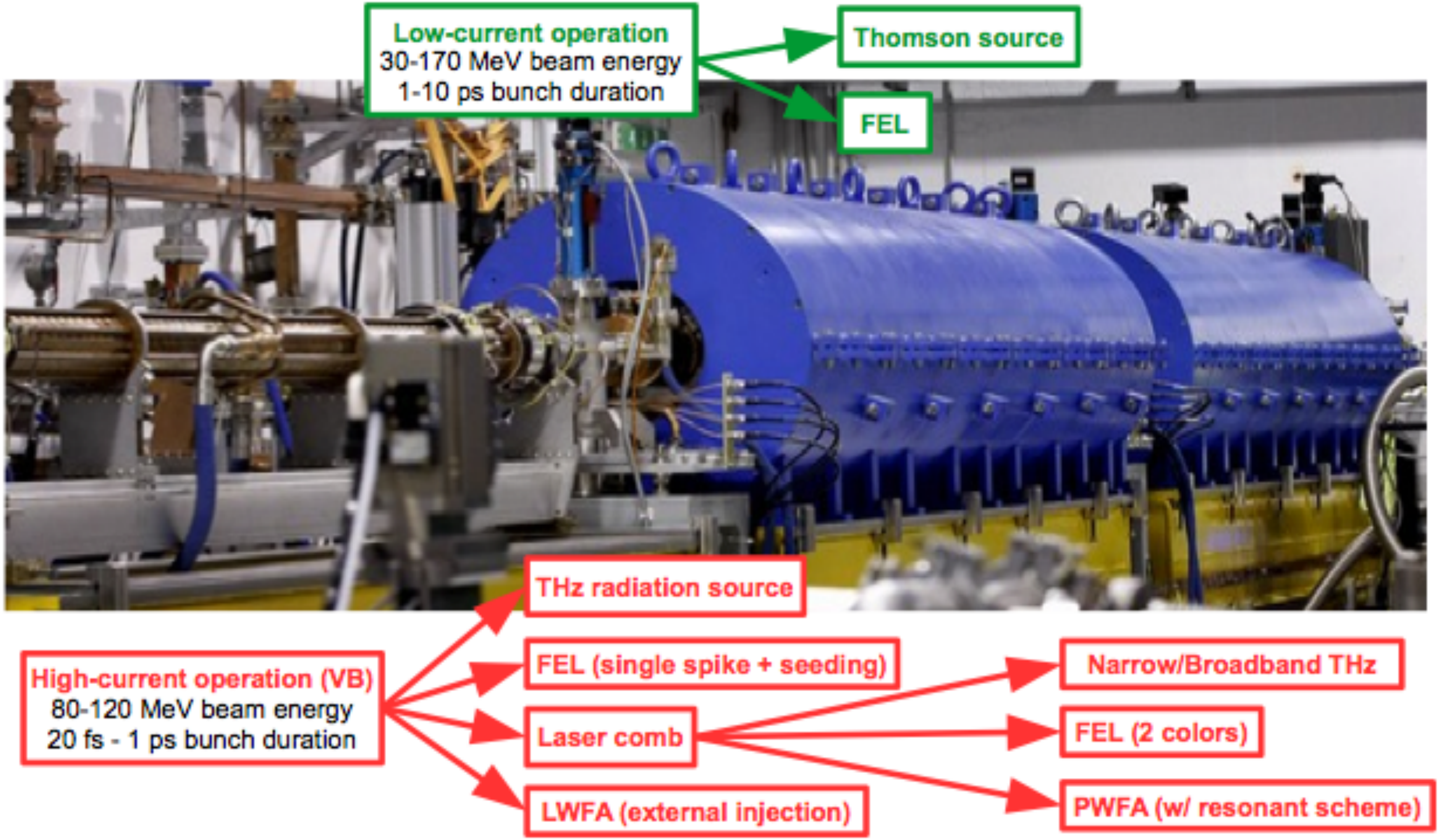
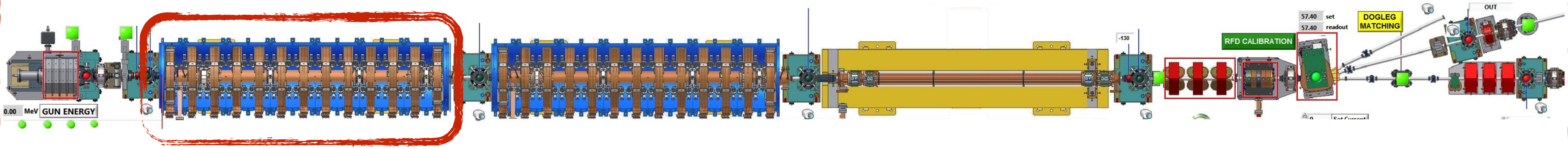
The SPARC_LAB Test Facility

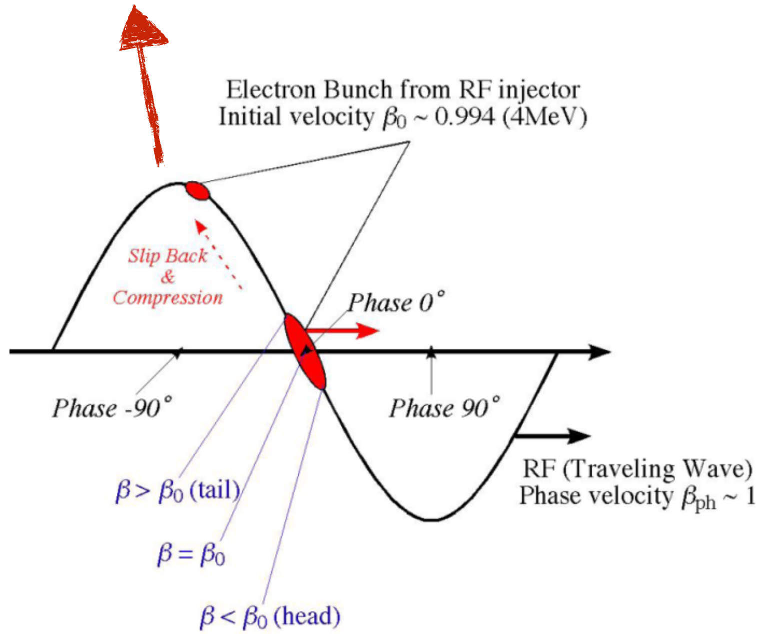
M. Ferrario et al., SPARC_LAB present and future, NIM B **309**, 183–188 (2013)

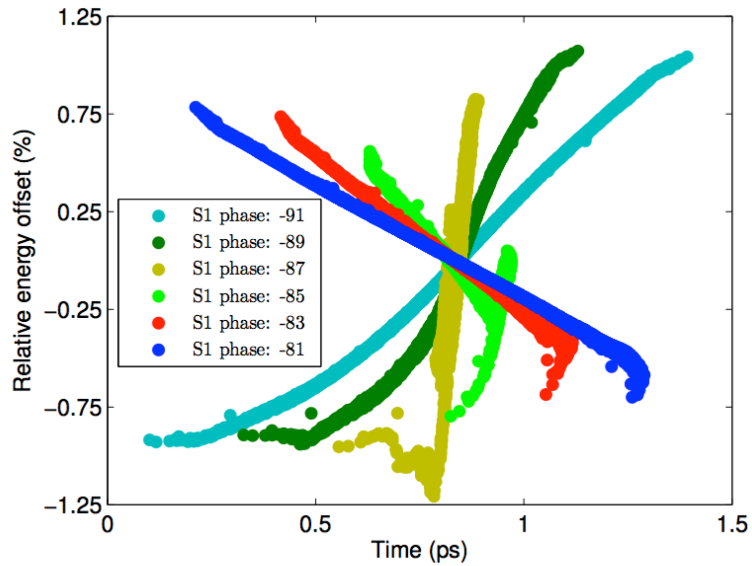


RF Compression: Velocity Bunching

Sub-relativistic electrons (β_c < 1) injected into a traveling wave cavity at zero crossing move more slowly than the RF wave (β_{RF} ~ 1). The electron bunch slips back to an accelerating phase and becomes simultaneously accelerated and compressed. Rectilinear trajectories => non coherent synchrotron radiation emission



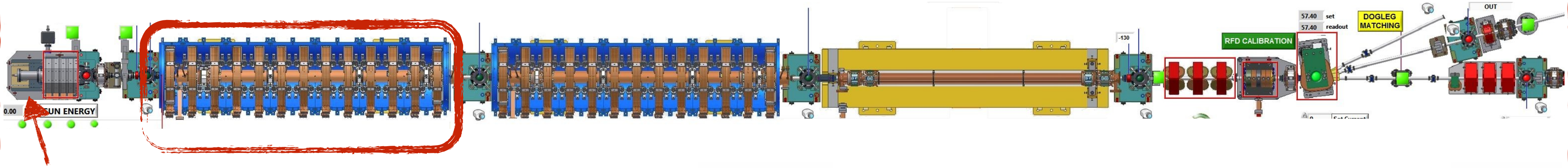


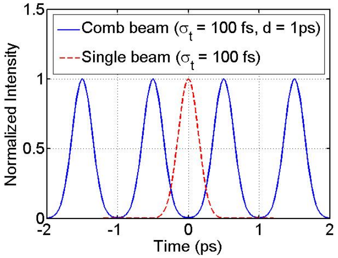


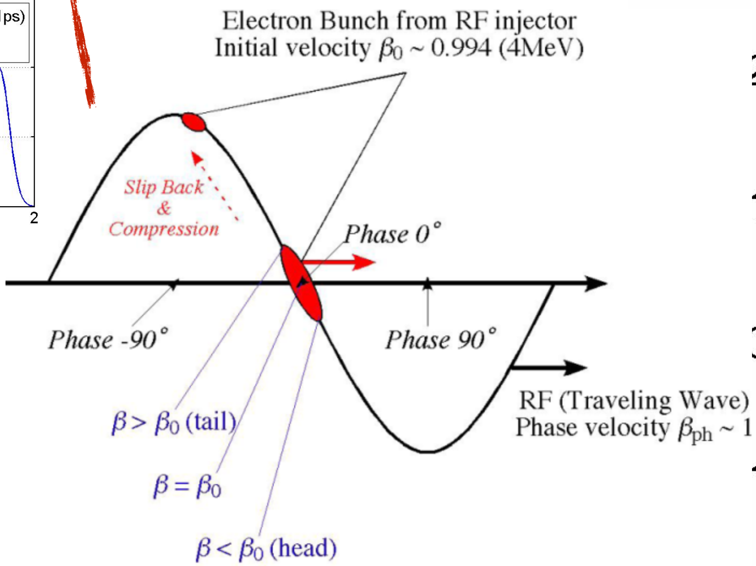
- **L. Serafini and M. Ferrario**, *Velocity Bunching in Photo-injectors*, Physics of, and Science with the X-Ray Free-Electron Laser, edited.by S. Chattopadhyay et al. © 2001 American Institute of Physics
- **M. Ferrario et al.**, *Experimental Demonstration of Emittance Compensation with Velocity Bunching,* Phys. Rev. Lett. **104**, 054801 (2010)

Multi-bunch trains

Generation and manipulation of bunch trains: *Laser comb technique*

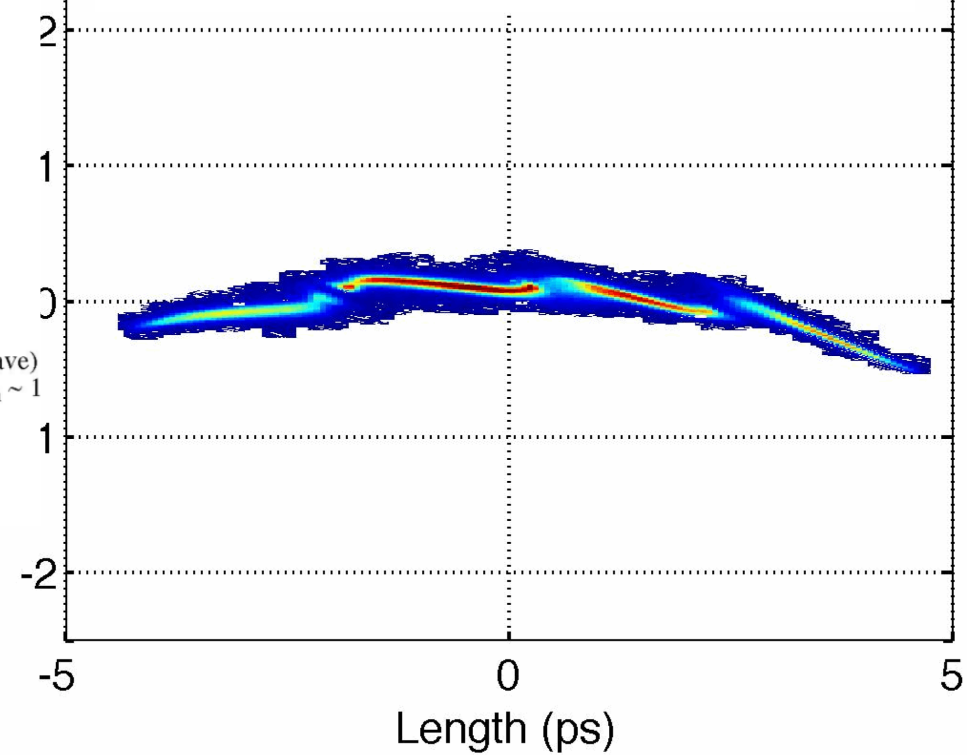




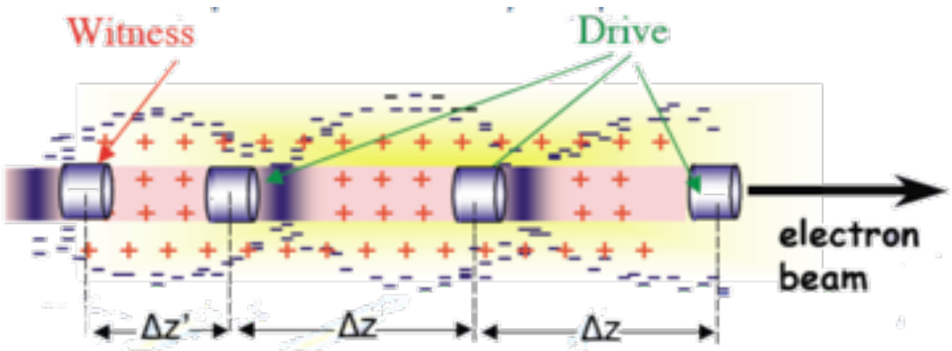


P. O. Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
M. Ferrario. M. Boscolo et al., Int. J. of Mod. Phys. B, 2006

Longitudinal Phase Space of a 4-bunches electron beam



Coherent plasma Oscillation by Multiple electron Bunches



- Bunch spacing depends on the plasma density

Driver $\Delta z = \lambda_p$

Witness $\Delta z' \approx \dfrac{\lambda_p}{2}$

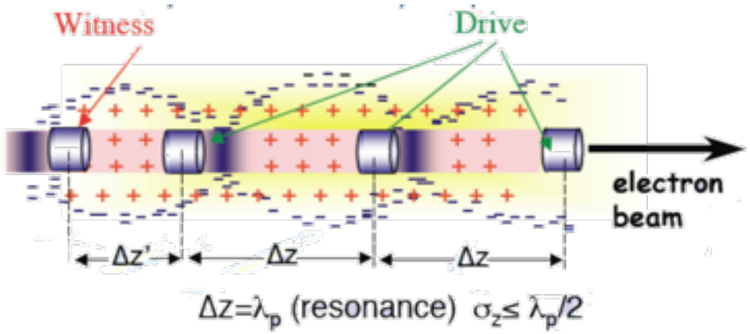
$\boxed{\lambda_p(\mu m) \approx 3.3 \cdot 10^4 \; n_e^{-1/2}(cm^{-3})}$ $= 330\ \mu\text{m} \ @ \ n_e = 10^{16}\ \text{cm}^{-3}$

- **Multi-bunch shaping is one of the most promising candidates**
  - Increase in energy of a trailing particle $\Delta\gamma = R\gamma$
  - Preservation of witness emittance and length
  - Better control of the energy spread

Coherent plasma Oscillation by Multiple electron Bunches

- 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, $n_0 \approx 10^{16}$ cm^{-3} at λ_p = 300 μm



$$\boxed{E_z \propto \left(\frac{N}{\sigma_z}\right)^2 N_T} \gtrsim GV/m$$

- **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

Quasi-non linear regime

- Condition for blowout $\frac{n_b}{n_p} > 1$
  - Bubble formation w/o wave-breaking, λ_p is constant
    - **resonant scheme in blowout**
  - Linear focusing force -> emittance is preserved
- A measure of non-linearity is the **normalized charge**

$$\tilde{Q} \equiv \frac{N_b k_p^3}{n_p} = 4\pi k_p r_e N_b \Rightarrow \begin{cases} \ll 1 & \text{linear regime} \\ > 1 & \text{blowout regime} \end{cases}$$

- Using low emittance, high brightness beam we have

$$\tilde{Q} < 1 \qquad \frac{n_b}{n_p} > 1$$

- These conditions define **quasi-non-linear regime**
  - $n_p = 10^{16}\,\mathrm{cm}^{-3}$, $Q_D = 200$ pC, $\sigma_t = 180$ fs, $\sigma_x = 5.5$ um → $n_b \sim 5 n_p$ and $\tilde{Q} \approx 0.8$

Conclusions

- Plasma-based ***acceleration*** provide ultra-high gradients
- Plasma-based ***accelerators*** demand high brightness beams
- Many potential applications possible for compact plasma-based accelerators, delivering ultra-short, high peak current electron beams (e.g. FEL, γ rays,...)
- Still some effort to guarantee stability and reliability needs to be done
- Accelerated electron beam diagnostics is challenging