INFN ACCELERATORI ERICE Accelerator School

ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE
TO PAY A PERMANENT TRIBUTE TO ARCHIMEDES AND GALILEO GALILEI, FOUNDERS OF MODERN SCIENCE AND TO ENRICO FERMI, THE "ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

27 July 2023 - 2 August 2023
Ettore Majorana Center (Sicily, IT)

Plasma Accelerators

Overview of different schemes

Dipartimento di Scienze di Base e Applicate per l' Ingegneria

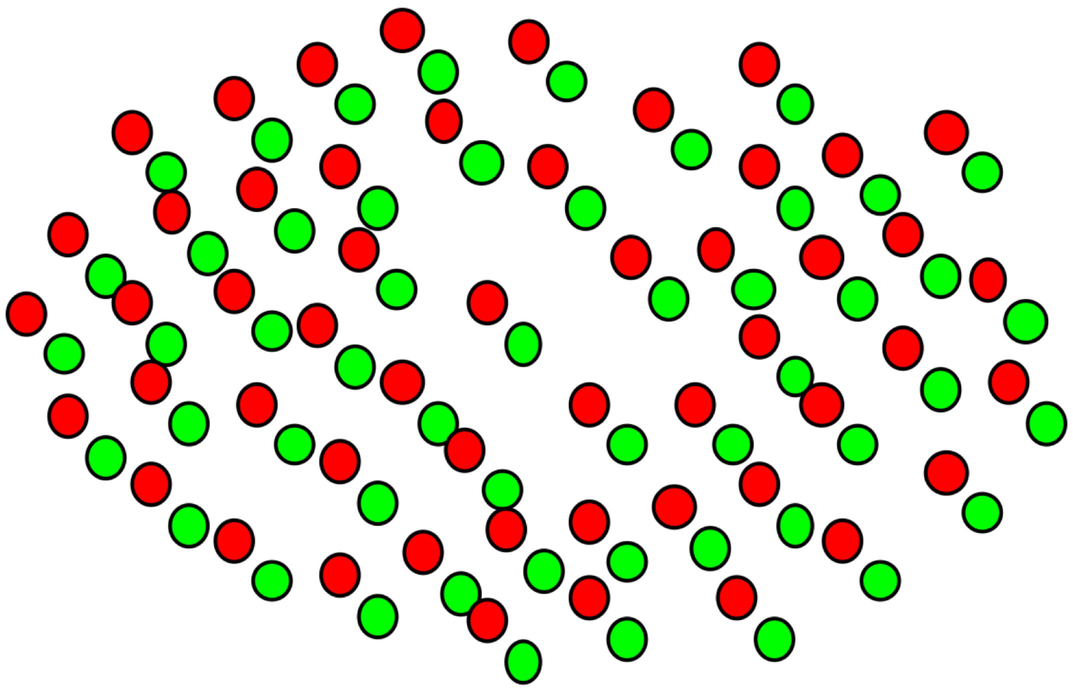
Enrica Chiadroni (Sapienza Univ. - SBAI Dept. and INFN - LNF

Sapienza Università di Roma

Outline

- Basic principle of plasma-based acceleration
  - Issues contributing to improving acceleration techniques
- Current research highlights
- Other uses for plasma in the accelerator field
  - Plasma lenses
  - Plasma wigglers/undulators
- Conclusions

Relativistic Plasma Waves



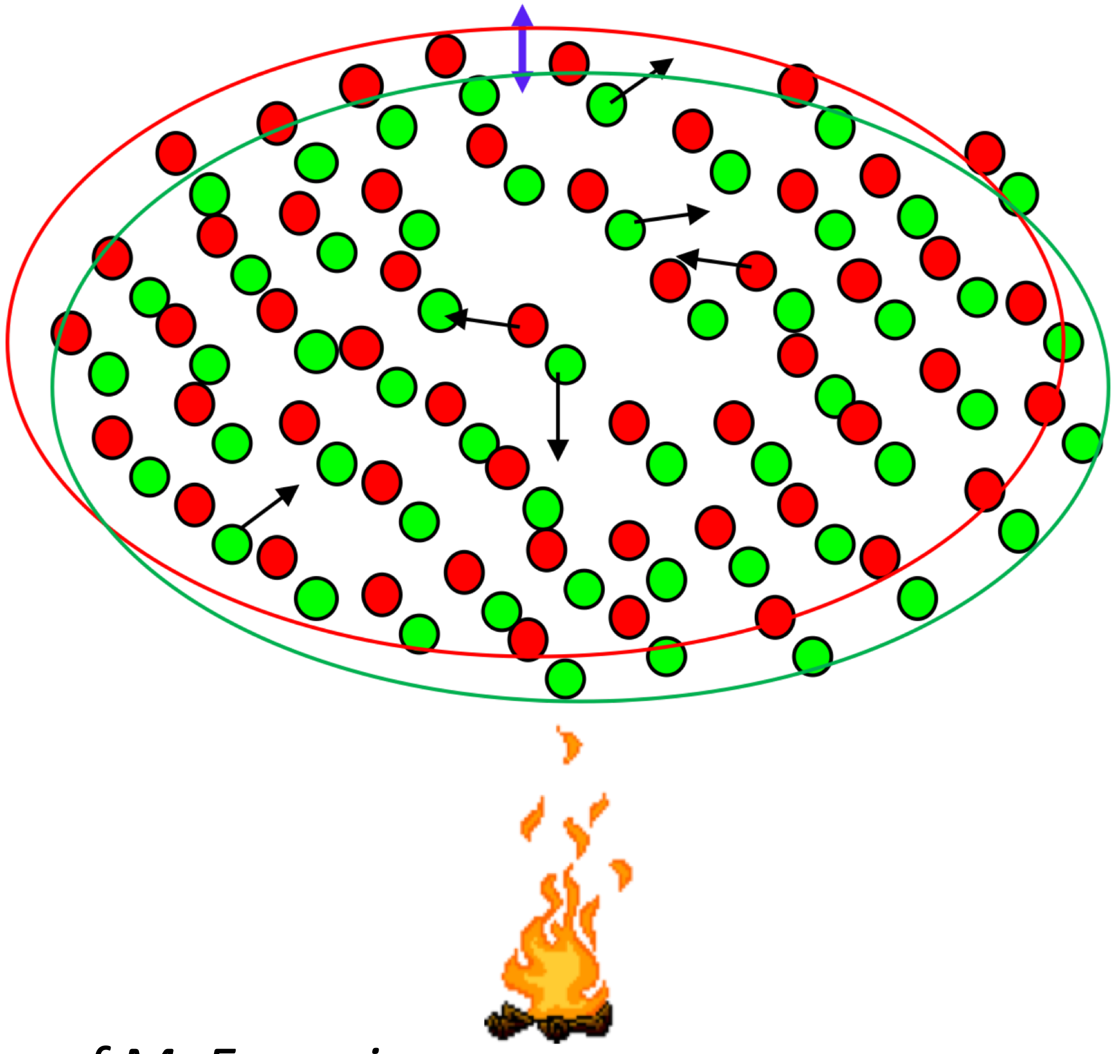
Courtesy of M. Ferrario

Relativistic Plasma Waves

Surface charge density

$$\sigma = e\,n\,\delta x$$

δx



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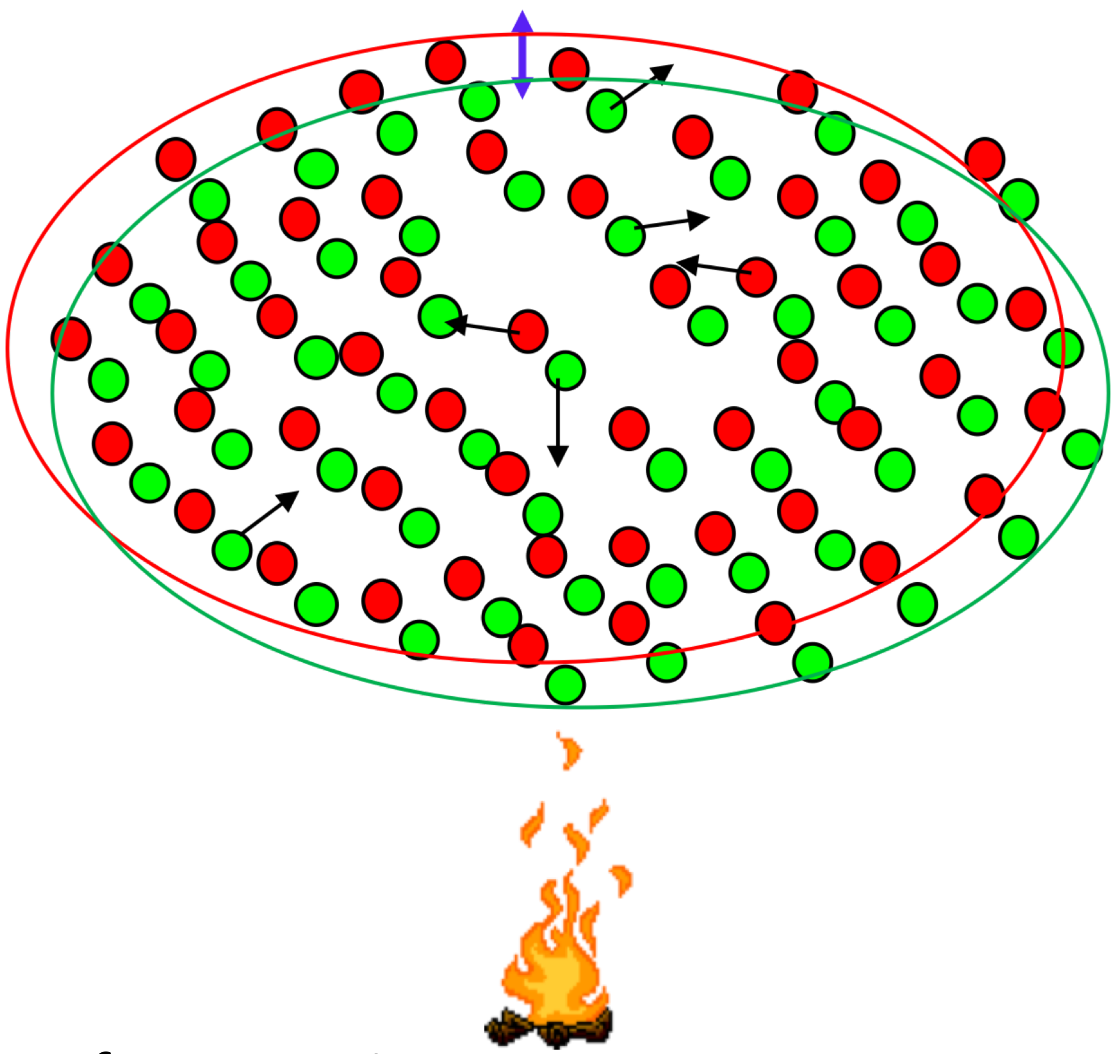


Courtesy of M. Ferrario

Surface electric field

$$E_x = -\sigma/\epsilon_0 = -e\,n\,\delta x/\epsilon_0$$

Restoring force

$$m\frac{d^2\delta x}{dt^2} = e\,E_x = -m\,\omega_p^{\,2}\,\delta x$$

Plasma oscillations

$$\delta x = (\delta x)_0 \cos(\omega_p t)$$

Plasma frequency

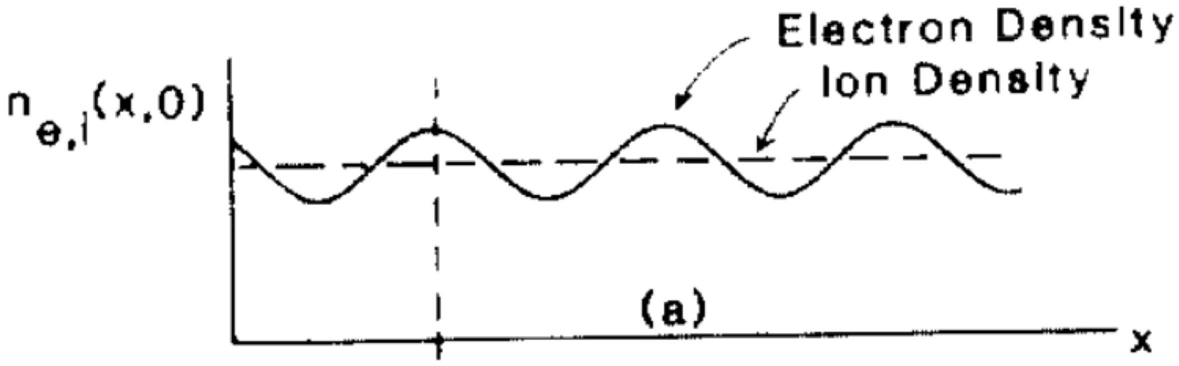
$$\omega_p^{\,2} = \frac{n\,e^2}{\epsilon_0\,m}$$

Collective behavior !!

Relativistic Electron Electrostatic Plasma Wave

$\omega_p = \sqrt{\frac{n_0 e^2}{m_e \varepsilon_0}}$ Plasma angular frequency/regular frequency $f_p = \frac{\omega_p}{2\pi} \approx 9\sqrt{n_0}$

- The oscillations lead to local compression (bunching) and rarefaction in the electron density
  - Electron oscillations are fast, ions are regarded as stationary



- The disturbance does not propagate as a wave
  - Plasma oscillation is purely an electrostatic oscillation

Acceleration in Plasma Waves

- When electrons are disturbed by a suitable phase relation, their oscillations consist of a traveling wave whose $\boldsymbol{v}_p$ can range from a few times the electron thermal velocity to infinity

- The basic equation for waves propagation in the **cold plasmas** is the Klein-Gordon equation:

$$\vec{\nabla} \times (\vec{\nabla} \times \vec{E}) + \frac{1}{c^2}\left[\frac{\partial^2 \vec{E}}{\partial t^2} + \omega_p^2 \vec{E}\right] = 0$$

- Plane wave solution $\vec{E} = \vec{E}_0 e^{i(\vec{k}\cdot\vec{r} - \omega t)}$ $\vec{k} \equiv$ wave vector

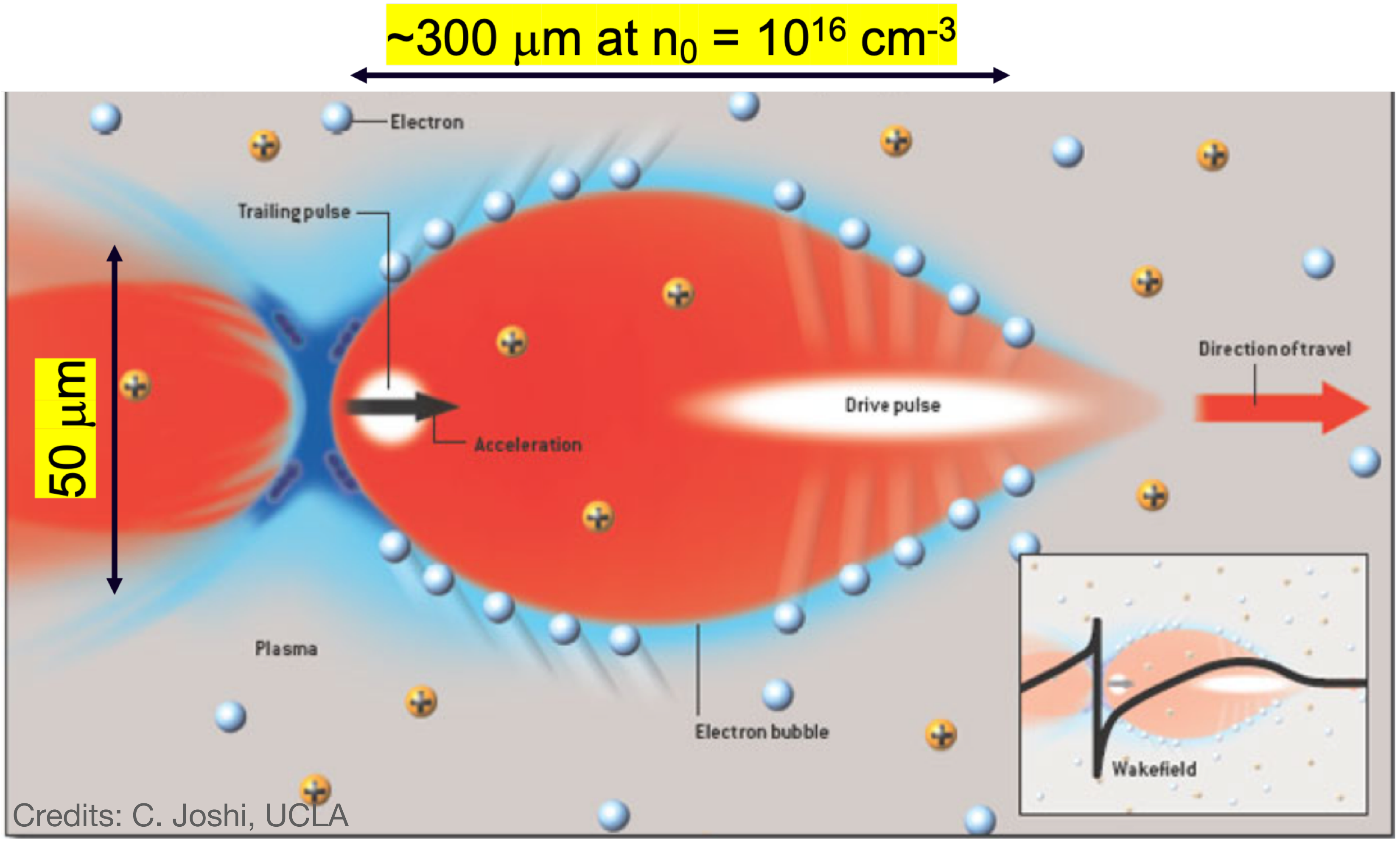
$$\frac{\partial}{\partial t} = -i\omega \qquad \vec{\nabla} \equiv i\vec{k}$$

$$i\vec{k} \times (i\vec{k} \times \vec{E}) + \frac{1}{c^2}(-\omega^2 + \omega_p^2)\vec{E} = 0$$

New Klein-Gordon equation

If **E** and **k** are in the same direction => longitudinal wave with $\omega = \omega_p$

Cold Wavebreaking Field



Credits: C. Joshi, UCLA

Characteristic scale length of the accelerating field, i.e. the plasma wake, is the plasma wavelength $\boldsymbol{\lambda_p}$

$$\lambda_p[\mu m] \approx \frac{3.3 \cdot 10^{10}}{\sqrt{n_0[cm^{-3}]}}$$

- The **ionized plasma can sustain** accelerating gradient 2-3 orders of magnitude larger than in conventional RF-based accelerators

- Maximum accelerating field a plasma can sustain: **Cold wave breaking field**

$$E_{Max}[V/m] = \frac{m_e c \omega_p}{e} \approx 100\sqrt{n_0[cm^{-3}]} \qquad n_0 = 10^{16} \div 10^{18} cm^{-3}$$

Plasma Definition

- A partially or completely ionized gas, globally neutral, is a plasma if it exhibits a **collective behavior**
  - Coulomb shielding
    - Dimensions >> Debye length

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

  - Plasma Oscillations
    - Temporal response >> ω_p^{-1}

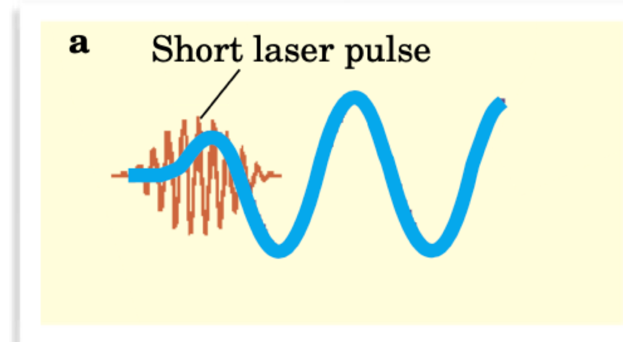
$$\omega_p = \sqrt{\frac{ne^2}{m\varepsilon_0}}$$

- The large electric fields a plasma can sustain are supported by collective motion of plasma electrons, forming a **space charge disturbance** moving at a speed slightly smaller than *c*

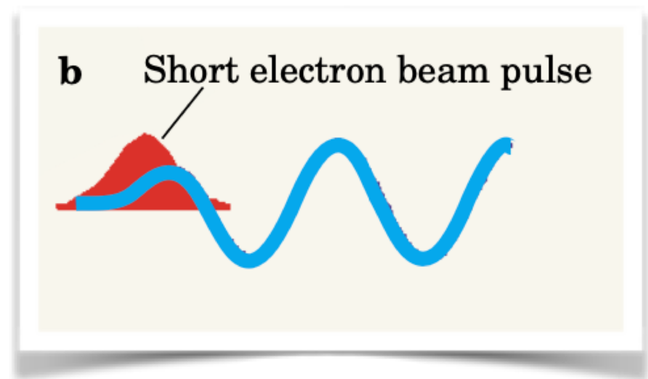
Collective Fields to Accelerate Charged Particles

First Ideas

- 1956, G I Budker and V I Veksler of the (then) USSR (Budker G I 1986 Proc. CERN Symp. on High Energy Accelerators vol 1 (Geneva: CERN) pp 68–80)
    - Use of the fields generated in a plasma by the passage of a medium-energy electron beam to accelerate ions to high energy
- Toshi Tajima and John Dawson of UCLA (Phys. Rev. Lett. 43 267 (1979))
    - Use of a relativistically propagating disturbance or a wake created in a plasma by the passage of a short laser pulse to accelerate electrons to ultrahigh energies in a short distance → **Laser Wakefield Accelerator**



- Pisin Chen at al., (Phys. Rev. Lett. 54 693 (1985))
    - instead of a laser pulse, one can use a high-current bunch of electrons to generate very high electric fields in a plasma that can be used to accelerate particles extremely rapidly → **Plasma Wakefield Accelerator**



The plasmas does not only provide high acceleration gradients, ~GV/m, but they also serve to focus accelerated beam to micrometer scale spot size

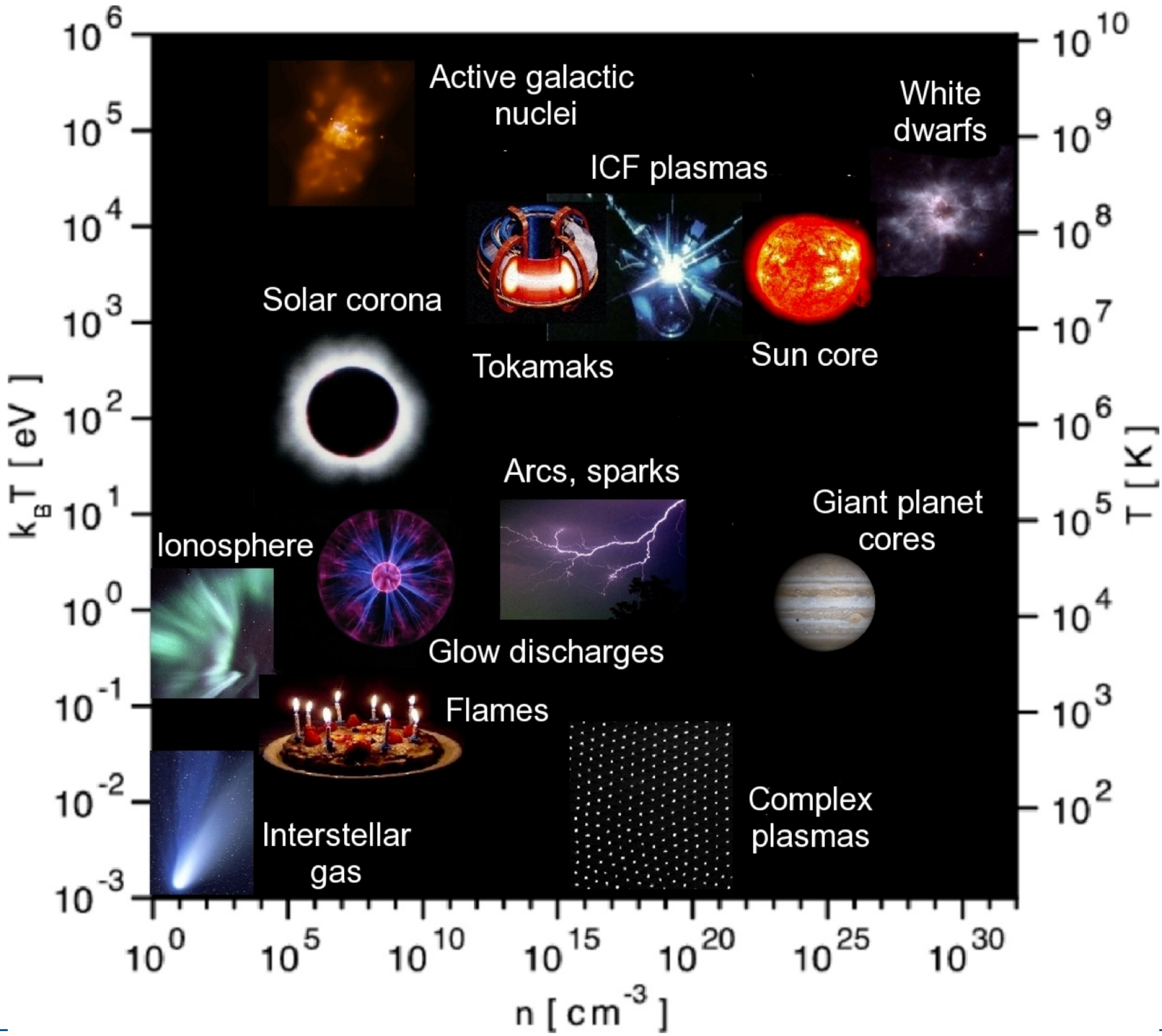
Credits: C. Joshi and T. Katsouleas, AIP Physics Today 2003

Basic Assumptions

- Upstream from the laser or beam driver, each fluid can be treated as at rest or cold
- For **underdense plasmas**, the phase velocity of the excited wakefields is roughly the speed of light, *c*
    - Compared with this speed, all the initial thermal velocities of plasma particles can be treated as zero
- Wavelike assumption
    - Fields in the wake depend on the variable $ct-z$, where the phase velocity of the wave is essentially *c*
- Quasi-static approximation
    - The driver evolves on a time scale much longer than the plasma response
        - **the driver can be consider as non-evolving when calculating the plasma response.** Therefore, the wake depends weakly on the distance the driver has moved into the plasma

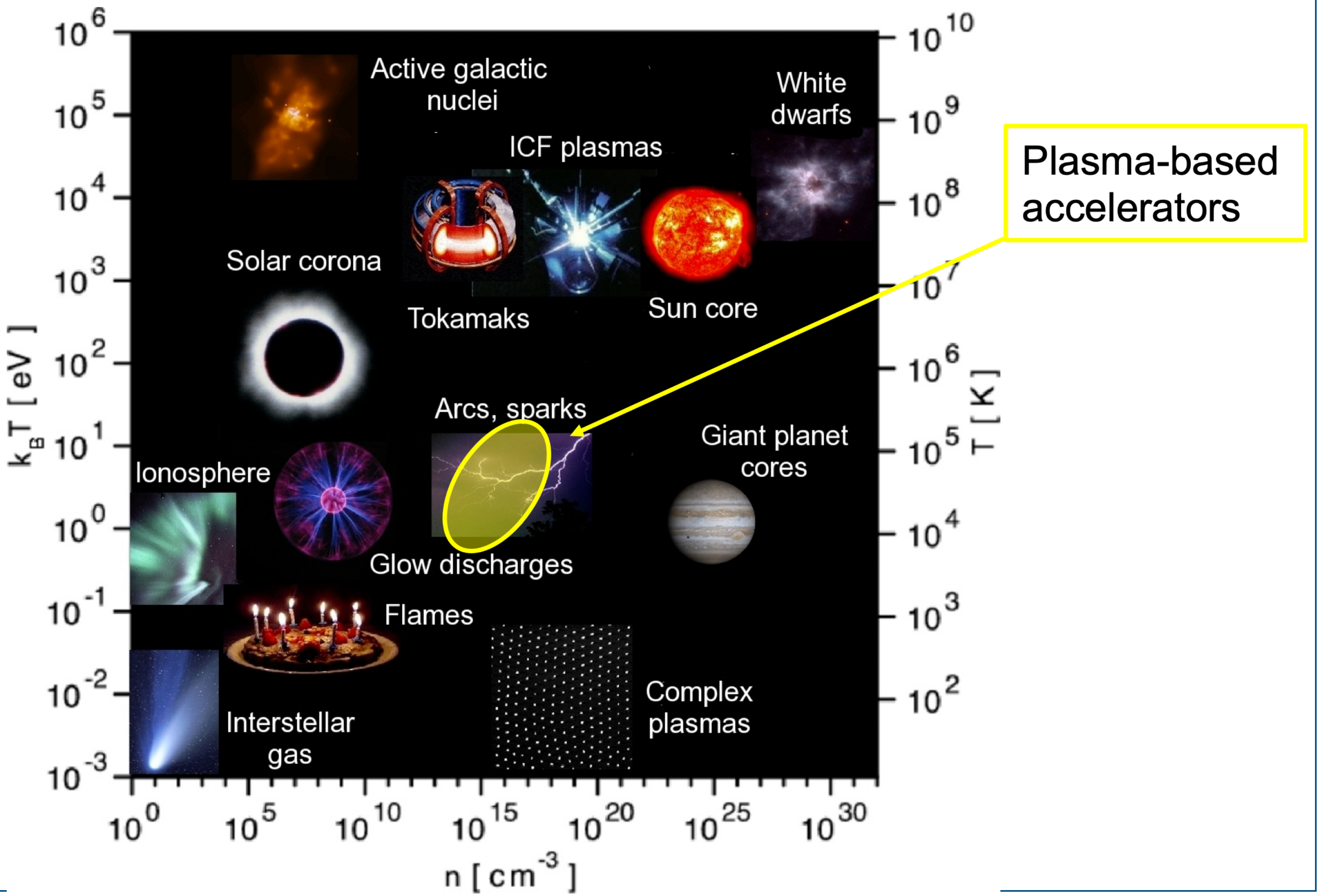
Plasma States

In Nature and in Laboratory



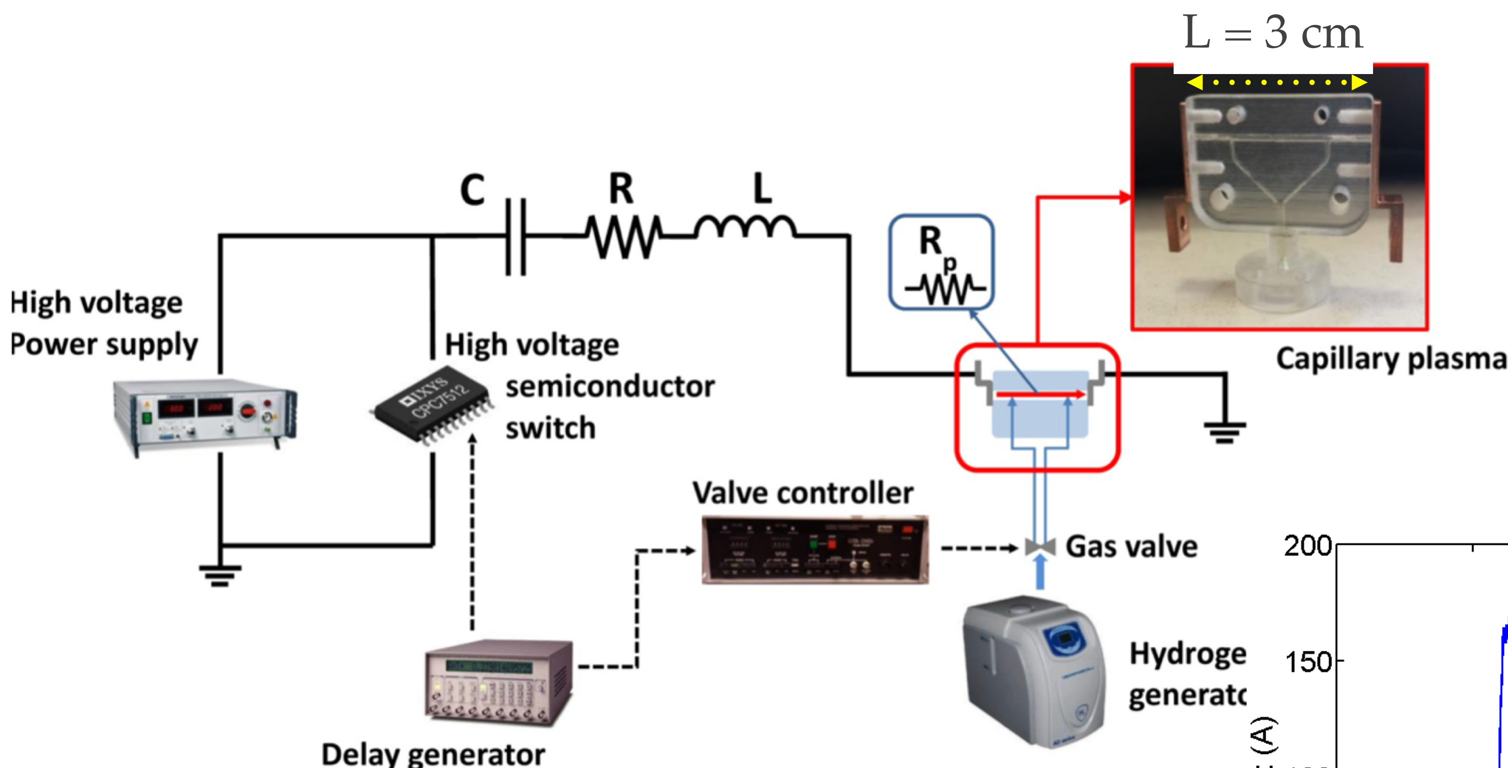
Plasma States

In Nature and in Laboratory



Plasma Source

Gas-filled capillary



P_{H2} = 10 mbar

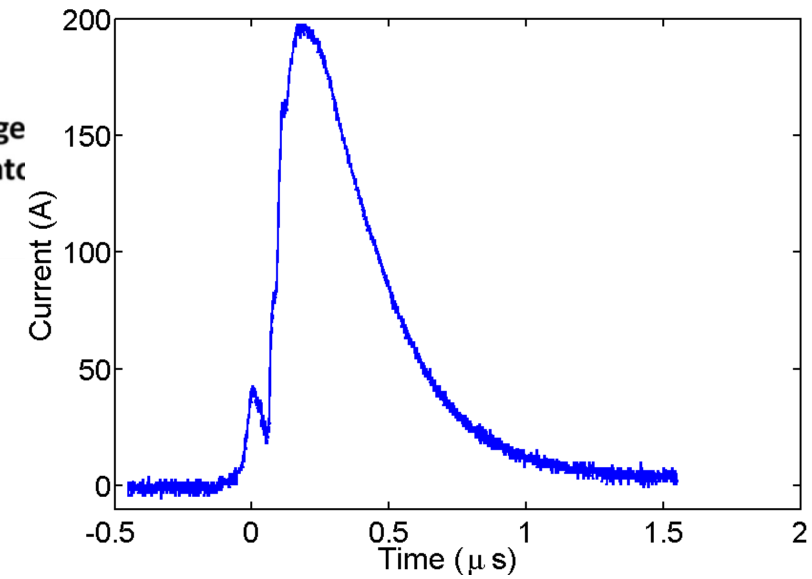
Total discharge duration :800 ns

Voltage : 20 kV

Peak current : 200 A

Capacitor : 6 nF

H_2-filled capillary discharge



Courtesy of A. Biagioni (INFN - LNF)

Response of a homogeneous plasma to a high frequency field

- Let's consider a 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

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

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

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

Fast Oscillations of Electrons

- 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

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

$$\int$$

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

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

From III Maxwell equation:

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

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

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

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

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

Ponderomotive Force

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

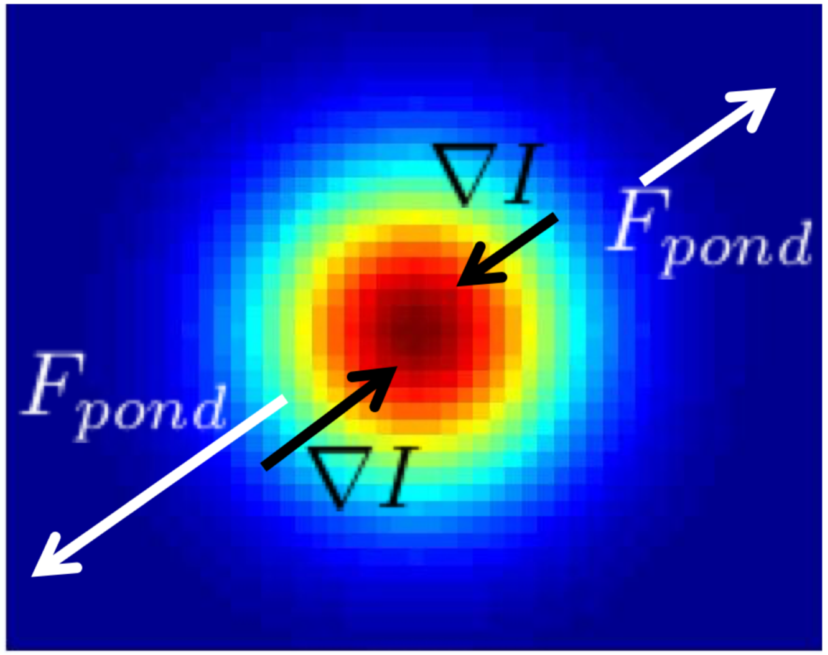
$$\left\langle m\frac{d\vec{v}}{dt}\right\rangle_T = \left\langle m\frac{d\vec{v}_0}{dt}\right\rangle_T = \frac{-q^2}{4m\omega^2}\nabla\left[\vec{E}_s(\vec{r}_0)^2\right]$$

Ponderomotive force

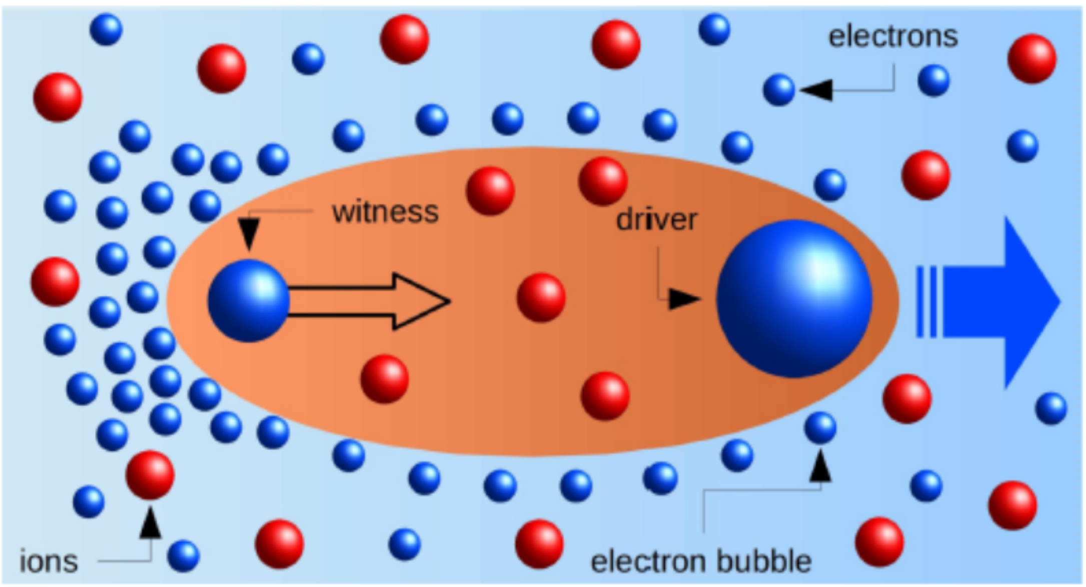
Ponderomotive force per unit volume

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

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



Acceleration Mechanism



- The **driver**, creating the bubble, can be either a
  - **dense relativistic particle beam** (**PWFA**) of sub-ps duration and kA level peak current
  - **ultra-intense laser pulse** (**LWFA**), ~10^{18} W/cm^2, of few 10s fs duration
- The **witness** can be either **self-injected** or **externally injected**

- Rapid acceleration of injected electrons to ultra-relativistic energies, inside the micrometer-sized structured plasma environment
  - the trapped electron beam remains short, dense, and free of significant space-charge driven emittance degradation

The Dawn of Compact Accelerators

September 2004

Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

S. P. D. Mangles[1], C. D. Murphy[1,2], Z. Najmudin[1], A. G. R. Thomas[1], J. L. Collier[2], A. E. Dangor[1], E. J. Divall[2], P. S. Foster[2], J. G. Gallacher[3], C. J. Hooker[2], D. A. Jaroszynski[3], A. J. Langley[2], W. B. Mori[4], P. A. Norreys[2], F. S. Tsung[4], R. Viskup[3], B. R. Walton[1] & K. Krushelnick[1]

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

C. G. R. Geddes[1,2], Cs. Toth[1], J. van Tilborg[1,3], E. Esarey[1], C. B. Schroeder[1], D. Bruhwiler[4], C. Nieter[4], J. Cary[4,5] & W. P. Leemans[1]

A laser–plasma accelerator producing monoenergetic electron beams

J. Faure[1], Y. Glinec[1], A. Pukhov[2], S. Kiselev[2], S. Gordienko[2], E. Lefebvre[3], J.-P. Rousseau[1], F. Burgy[1] & V. Malka[1]

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High-quality electron beam… laser wakefield acce… plasma-chann…

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A … plasma accelerator producing monoenergetic electron beams

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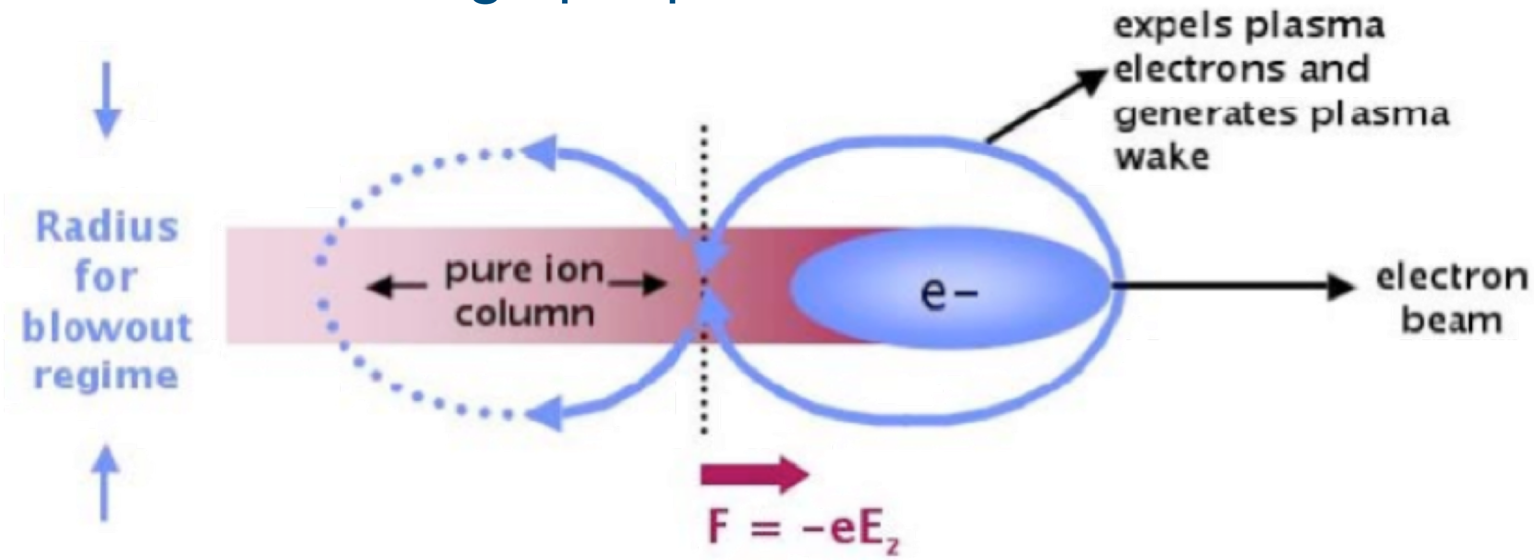
See Malka's talk for an insight on Laser Wakefield Acceleration

Particle-driven Plasma Wakefield Acceleration

Single bunch

- 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

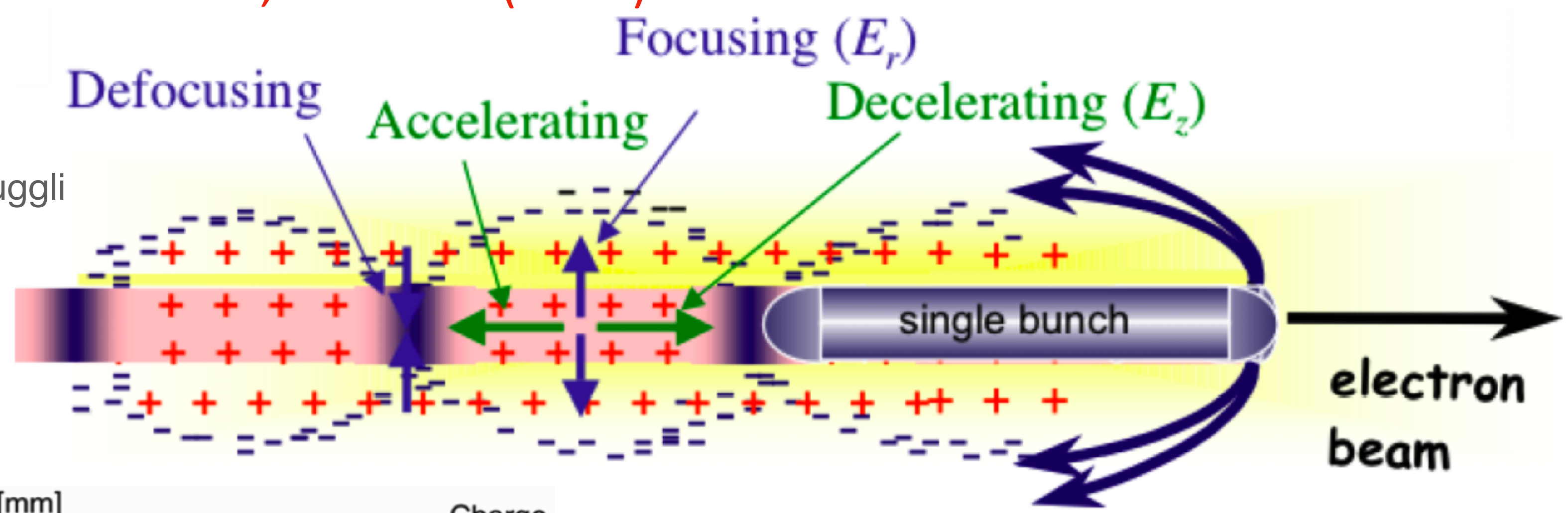


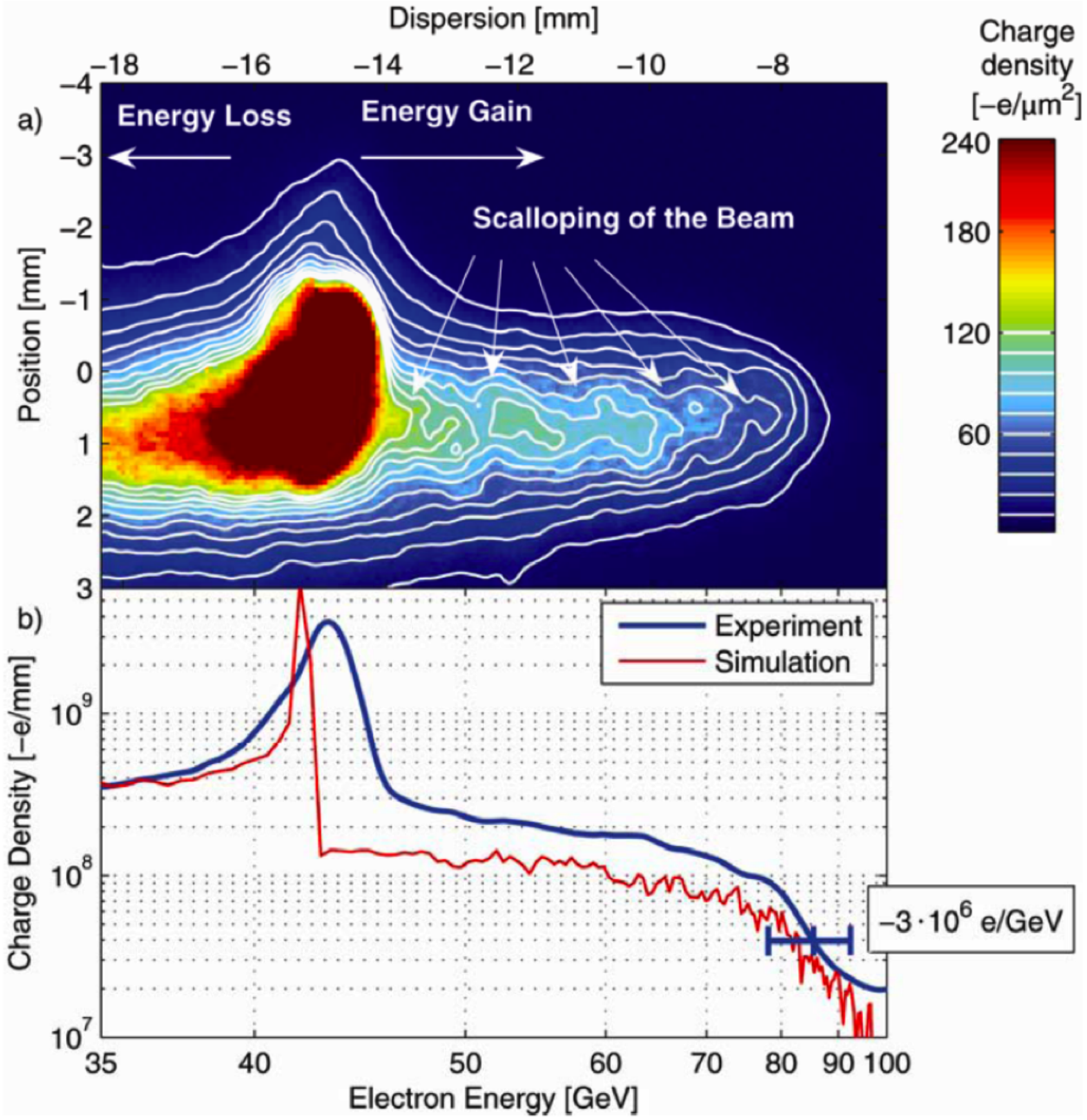
- First demonstration of the excitation of a wakefield by a relativistic beam in the linear regime, i.e. beam density typically less than the plasma density => J. Rosenzweig et al., Phys. Rev. Lett. 61, 98 (**1988**)
- Peak acceleration gradient ~ 1.6 MeV/m, but the experiment clearly showed the wakefield persisting for several plasma wavelengths

PWFA: Energy doubling in a meter scale

Blumenfeld, I. et al. **Nature** 445, 741–744 (2007)

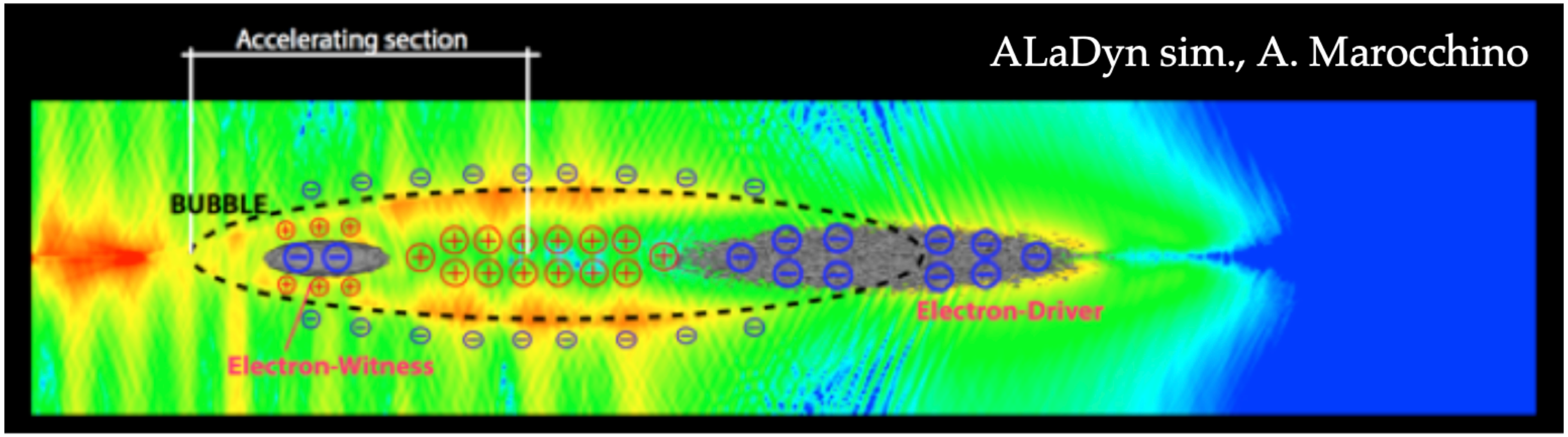
Credits: P. Muggli





- Gaussian electron beam with 42 GeV, 3nC @ 10 Hz, sx = 10µm, 50 fs
- 85cm Lithium vapour source, 2.7×10^{17} cm^{-3}
  - ☑ Accelerated electrons **from 42 GeV to 85 GeV in 85 cm**
  - ☑ Reached **accelerating gradient of 52 GeV/m**
    - Energy gain of the 3 km-long SLAC linac
- Single bunch
  - **ΔE/E** >> 1%

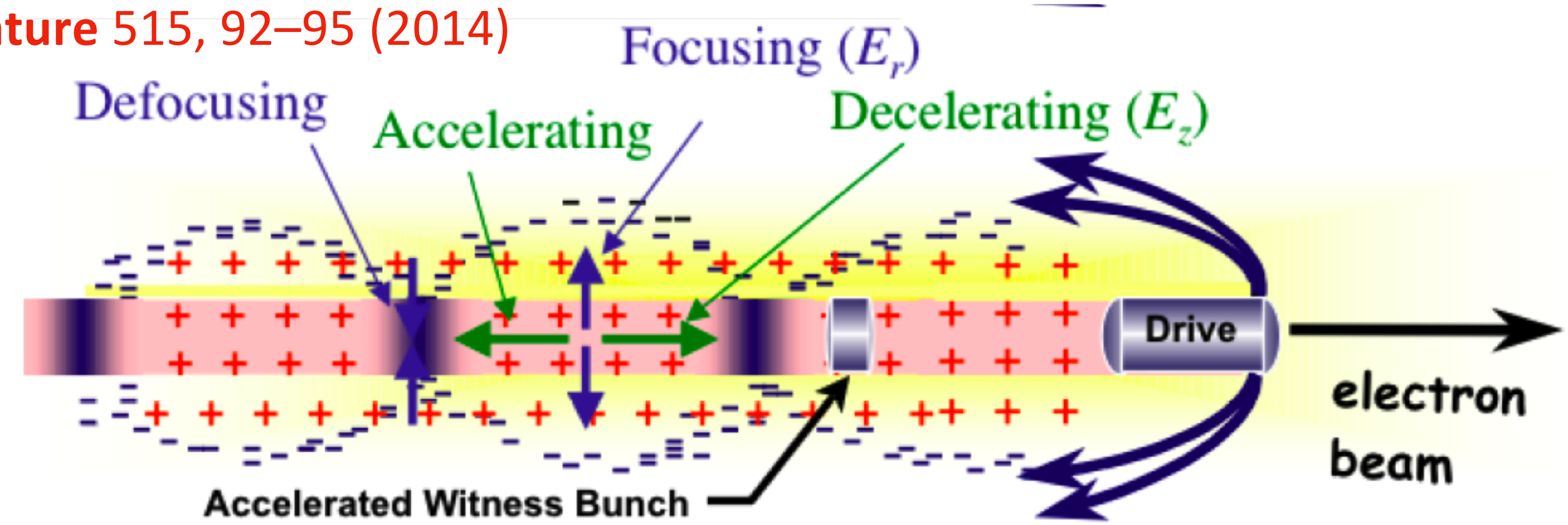
Two-bunch Train PWFA

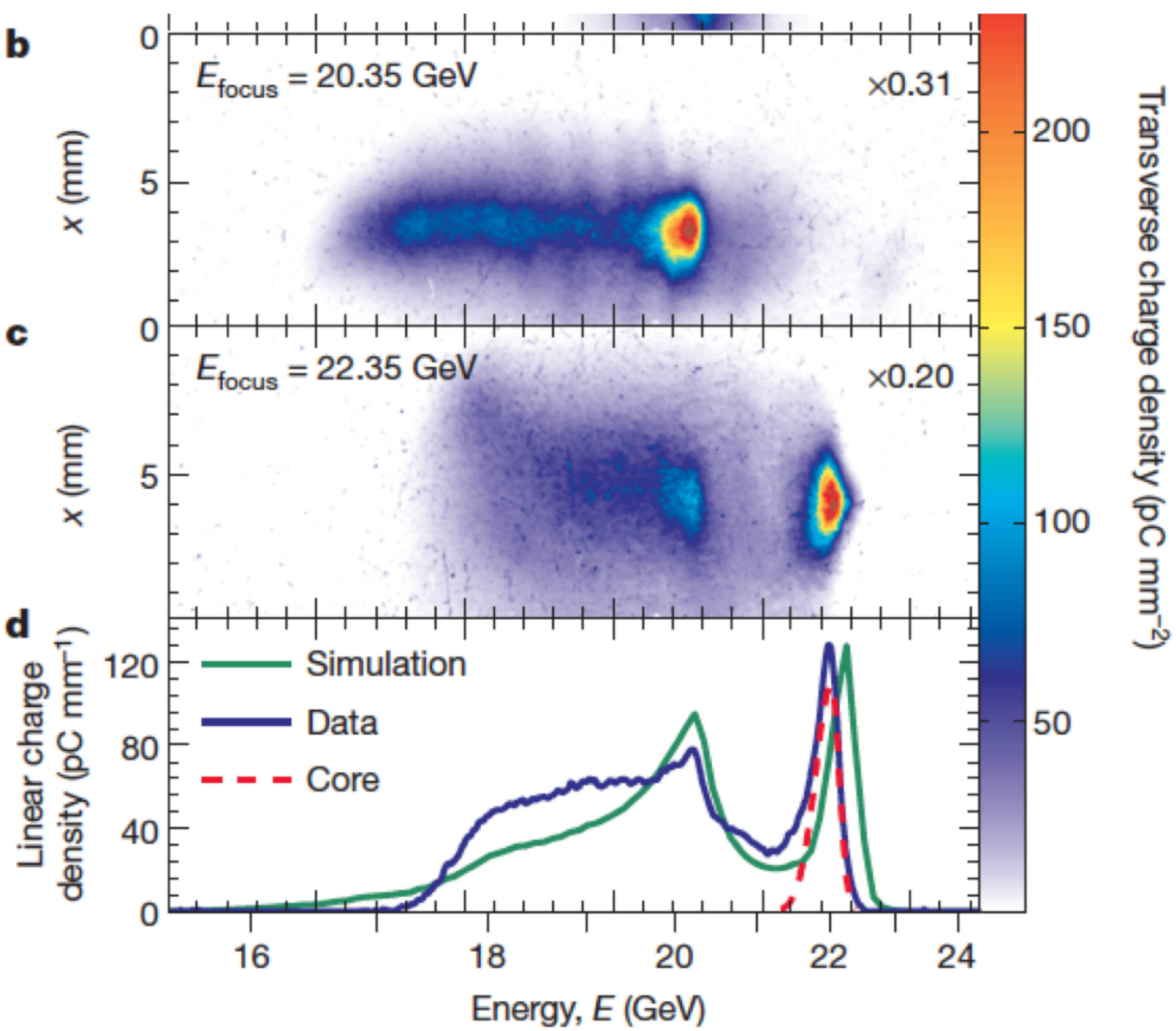


- Bunch length of tens of fs down to **fs scale**
  - A second, appropriately phased accelerating beam (**witness beam**), containing fewer particles than the **drive beam**, is then accelerated by the wake
    - Bunch train (D+W) for bunch acceleration (**ΔE/E<<1**)

PWFA: High-efficiency acceleration

Litos, M. et al. **Nature** 515, 92–95 (2014)





- Injection of two beams into the plasma
    - One drives the wake, *driver*, one samples the wake, *witness*
- Beam loading is key for
    - Narrower energy spread, **ΔE/E** <<1%, and high efficiency

Limitation of PWFA

Energy gain

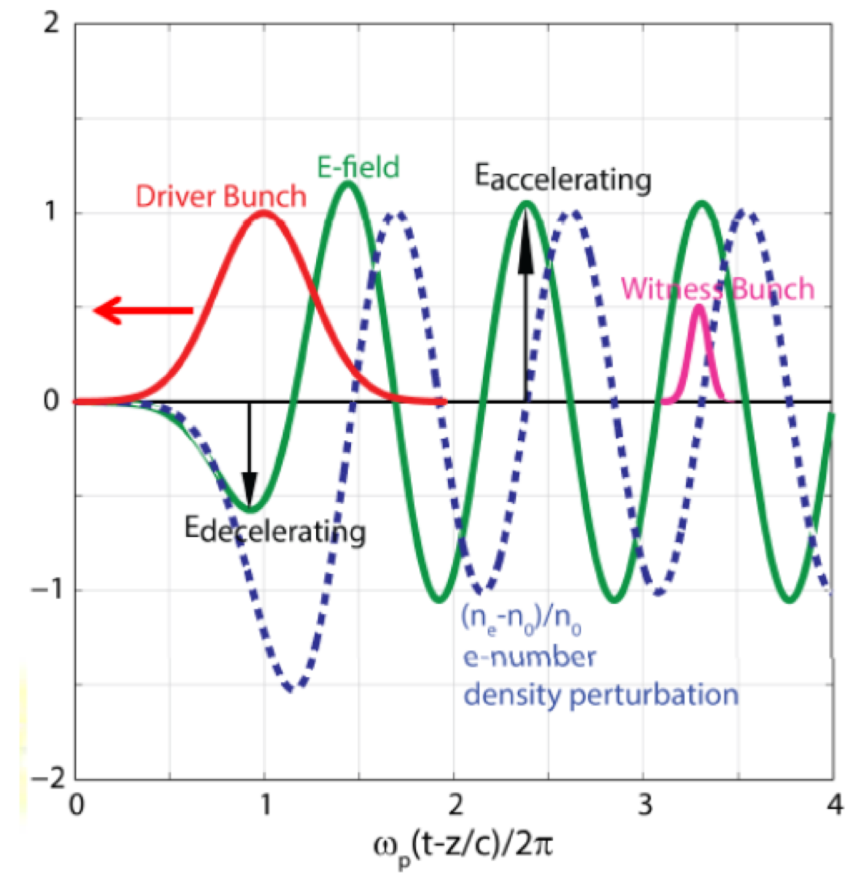
- **PWFA** acting as an **energy transformer** has the great potential to double beam energy in a single stage

- 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)

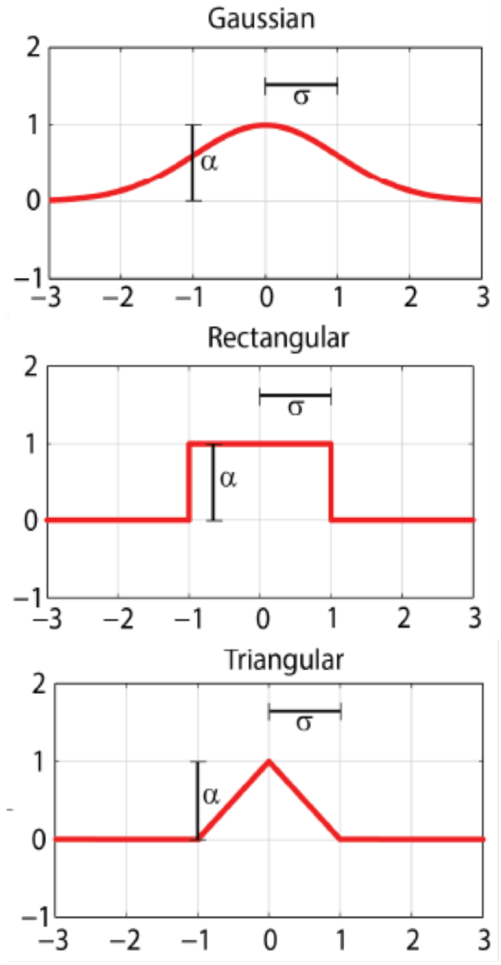
*V. V. Tsakanov, Nucl. Instrum. Methods Phys. Res., Sect. A 432, 202 (1999)

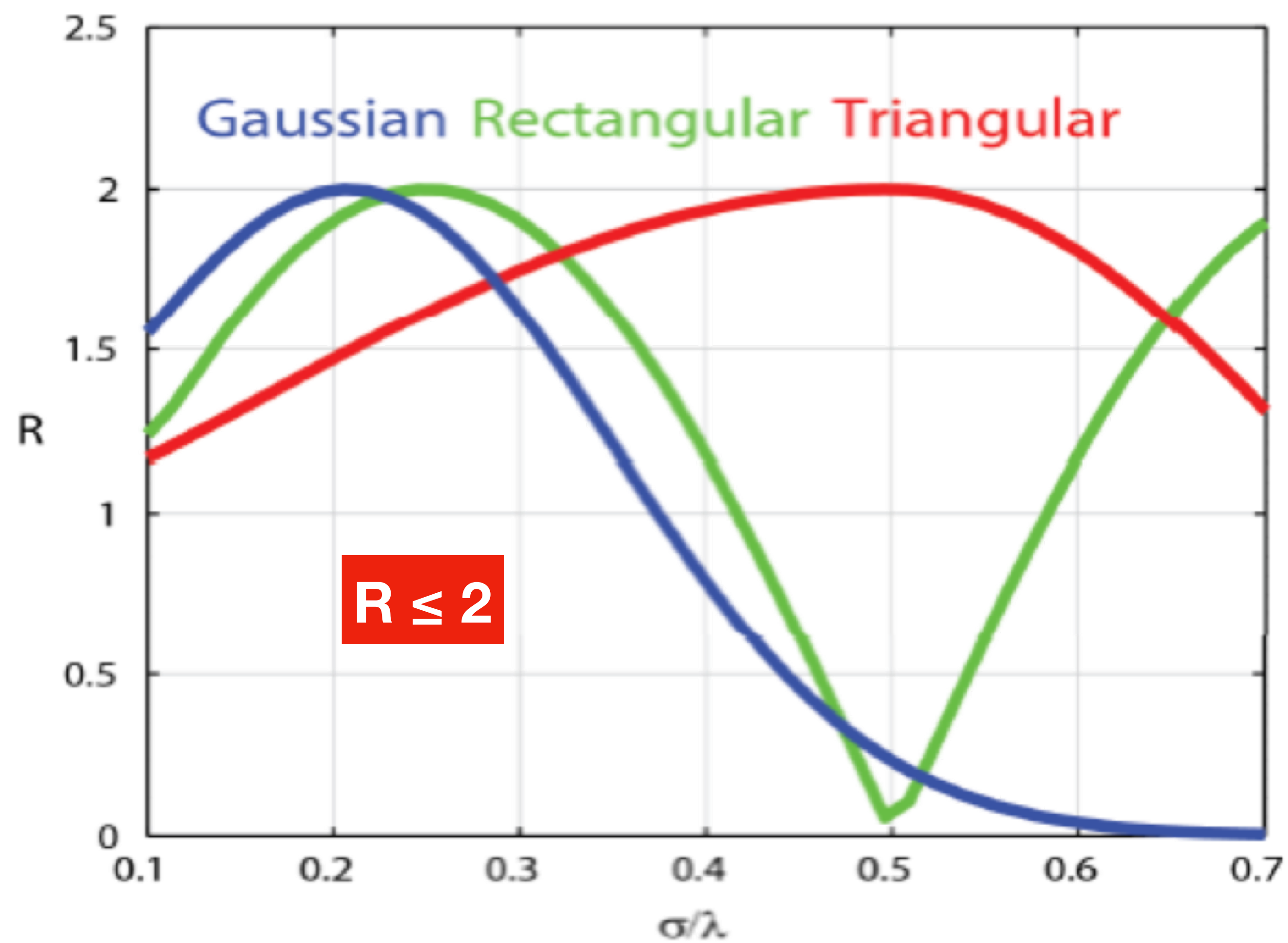
Limitation of PWFA

Energy gain

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** << 1





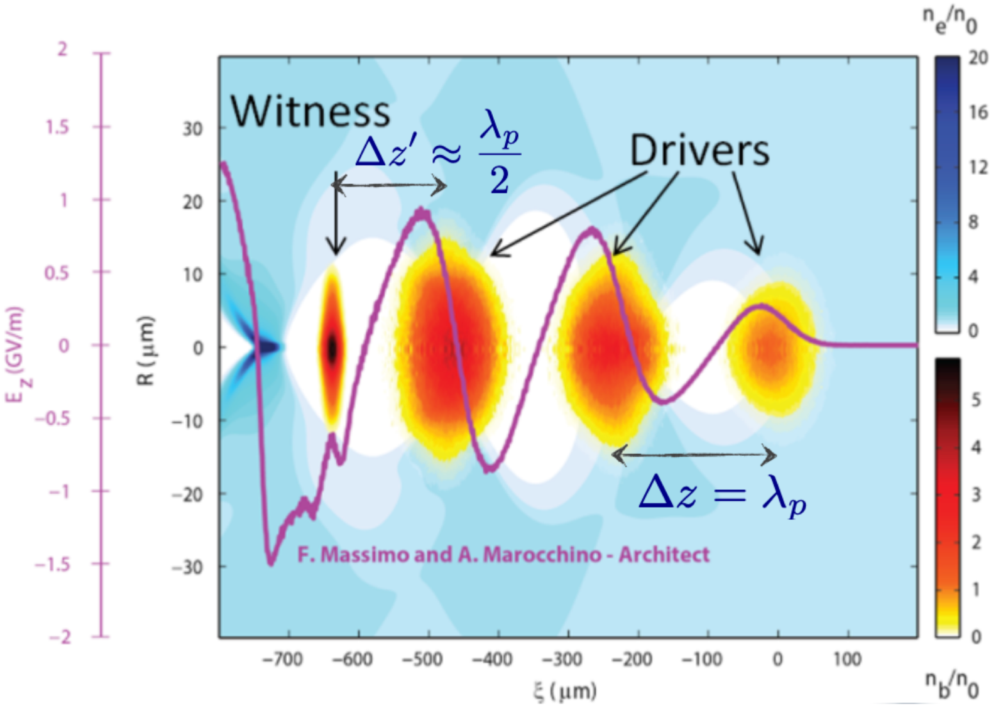
F. Massimo et al., NIM A **740**, 242–245 (2014)

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**

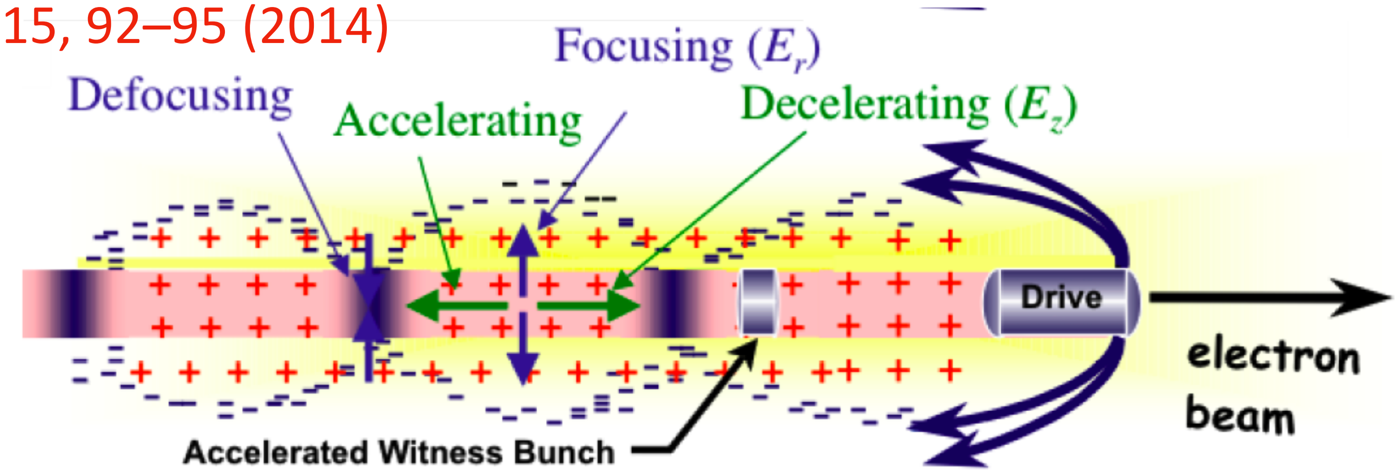
- Tailoring longitudinal current profile such that all longitudinal slices lose energy at the same rate
    - **Asymmetric drive bunch current profile**, i.e. triangular, double triangle, doorstep-like distributions, or **multiple ramped bunch trains**, overcome this limit (R.Ruth et al., PA 1985; W.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

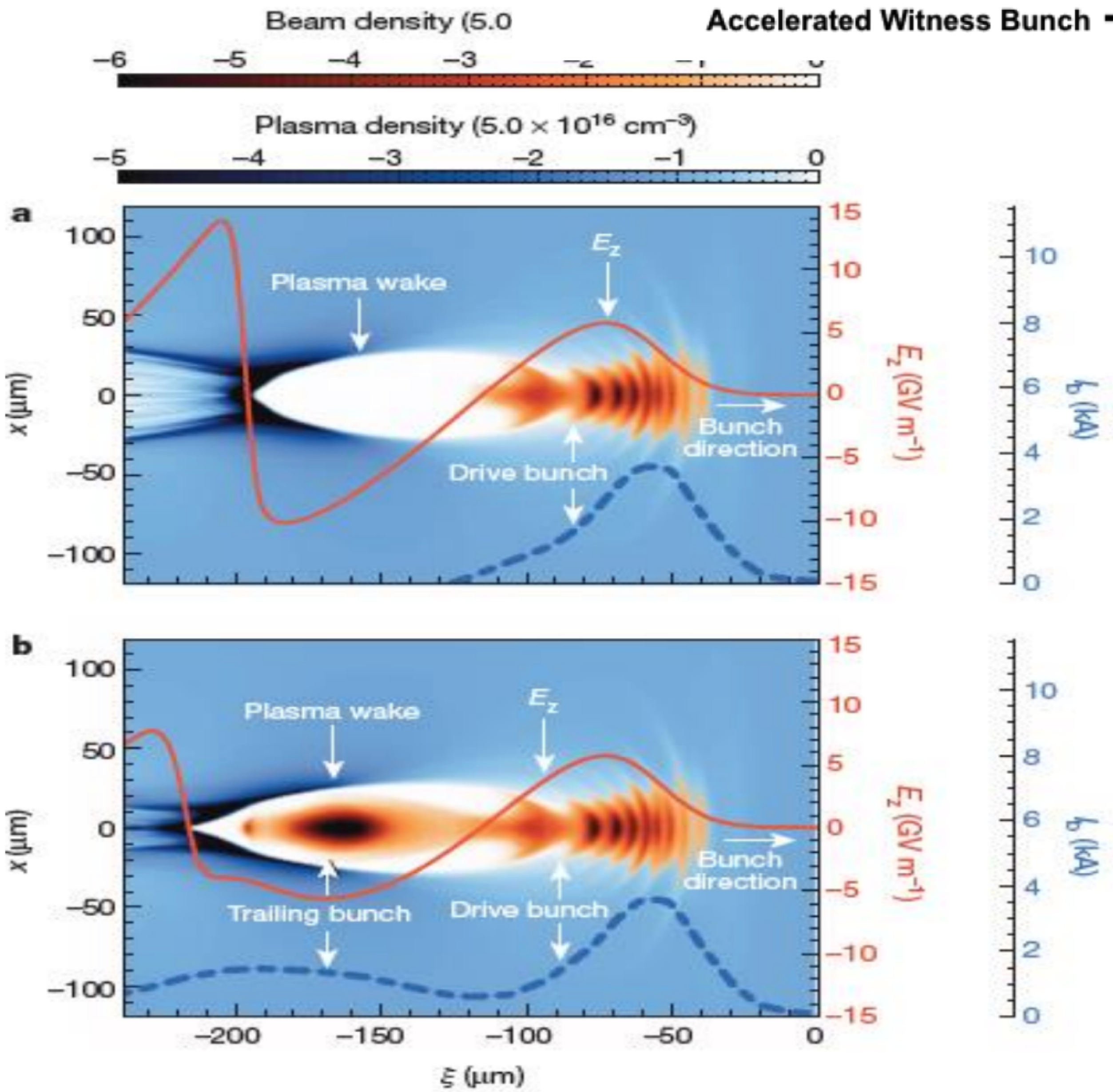


*K. Bane, P. Chen, and P. B. Wilson, *SLAC-PUB-3662*,1985

PWFA: High-efficiency acceleration

Litos, M. et al. **Nature** 515, 92–95 (2014)





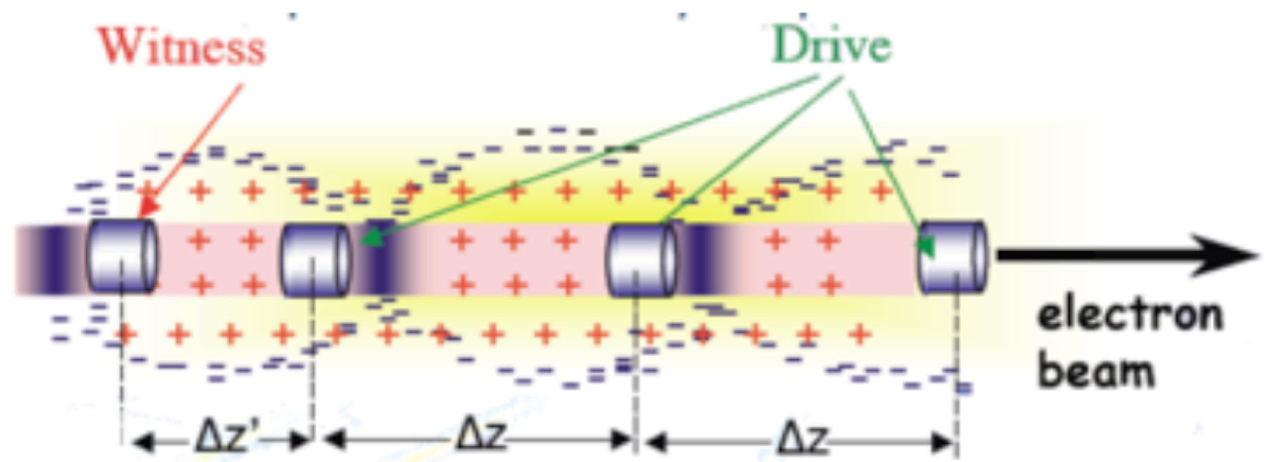
- Electric field in plasma wake is loaded by presence of trailing bunch
- Allows efficient energy extraction from the plasma wake

Resonant PWFA

Multi-bunch shaping

Driver $\Delta z = \lambda_p$

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



- Bunch spacing depends on the plasma density

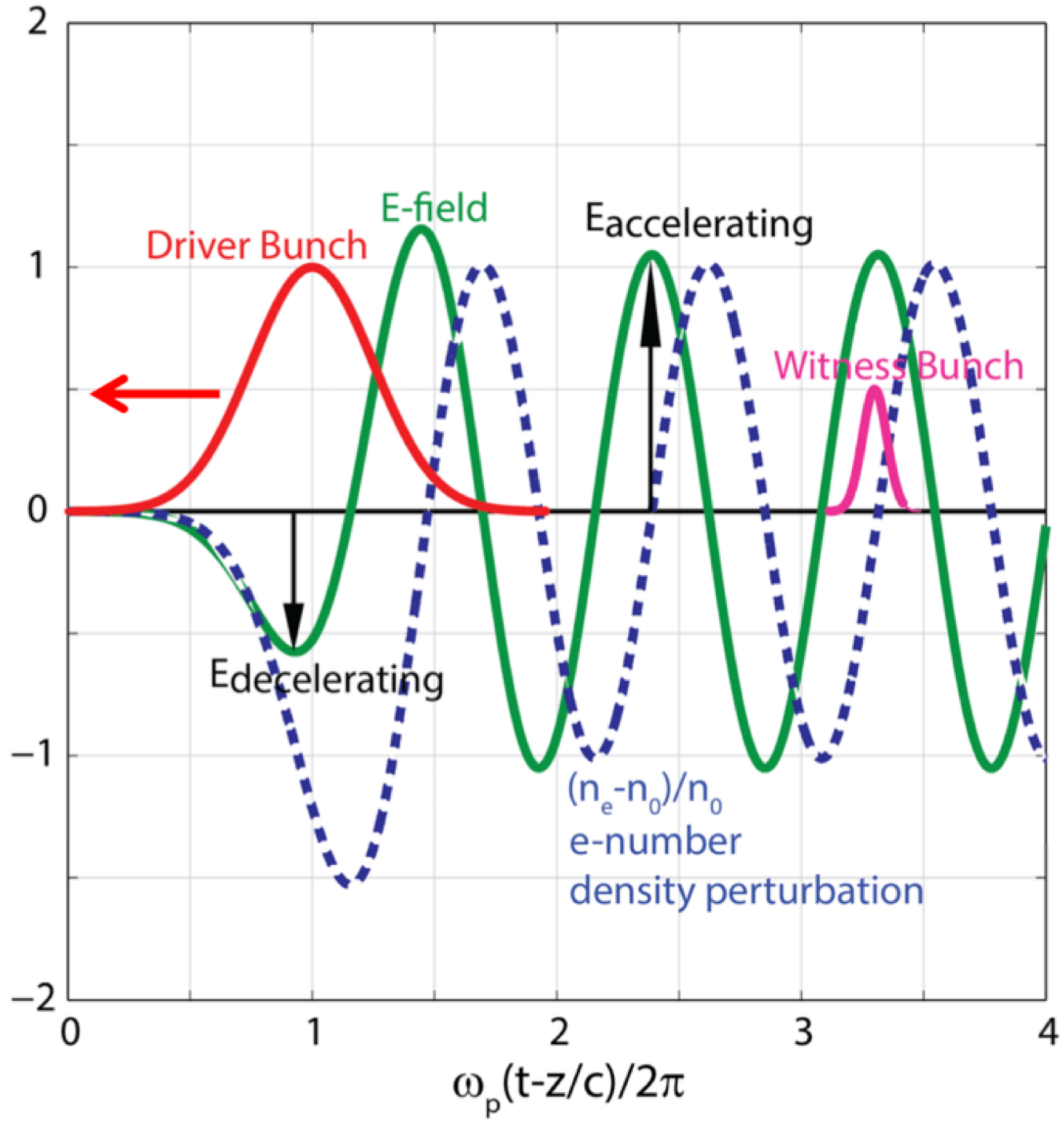
Scale length of the plasma wake $\lambda_p[\mu m] \approx \dfrac{3.3 \cdot 10^{10}}{\sqrt{n_0[cm^{-3}]}}$

Accelerating gradient $E_z \propto \left(\dfrac{N}{\sigma_z}\right)^2 N_T \gtrsim GV/m$

- Increase in energy of a trailing particle $\Delta\gamma mec^2 \sim eE+,maxLd = R\gamma bmec^2$
- Preservation of witness emittance and length
- Better control of the energy spread

From Linear Regime: $n_b << n_0$

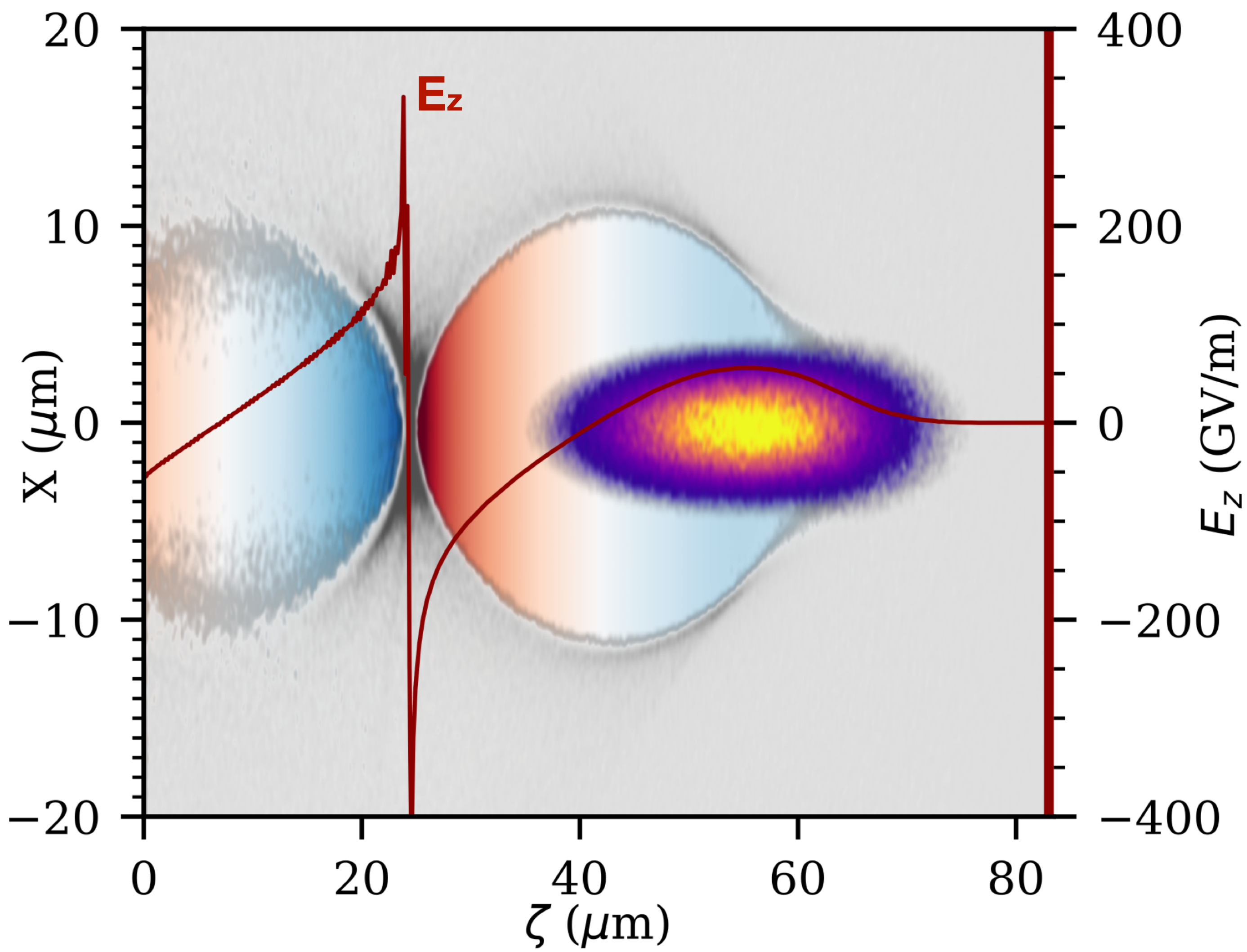
Focusing force is sinusoidal



- Lower wakefields
- Transverse forces not linear in *r*
- Symmetric for positive and negative witness bunches
- Well described by theory

to Quasi-Linear and Non-Linear Regime

The wake structure depends on the driver pulse «intensity»



- Higher wakefields
- transverse forces linear in r (emittance preservation)
- High charge witness acceleration possible
- Requires more intense drivers
- Not ideal for positron acceleration

Quasi-non Linear Regime

- Condition for blow-out $\frac{n_b}{n_p} > 1$
  - Bubble formation w/o wavebreaking, λ_p is constant
    - Resonant scheme in blowout
  - Linear focusing force => emittance preservation
- A measure of non-linearity is the normalised charge

$$\tilde{Q} \equiv \frac{N_b k_p^3}{n_p} = 4\pi k_p r_e N_b$$

<<1 linear regime
>1 blowout regime

- Using low emittance, high brightness beams

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

  - **Quasi-non Linear Regime**

$$n_p = 10^{16} cm^{-3}, Q_b = 200pC, \sigma_t = 180fs, \sigma_x = 5.5\mu m => \mathbf{n_b} \approx \mathbf{5n_p} and \tilde{\mathbf{Q}} \approx \mathbf{0.8}$$

High Quality Beams

$$L = \frac{N_{e+} N_{e-} f_r}{4\pi\sigma_x\sigma_y}$$

- N of particles per pulse => 10^9
- **High rep. rate** f_r => bunch trains

- Small spot size => **low emittance**

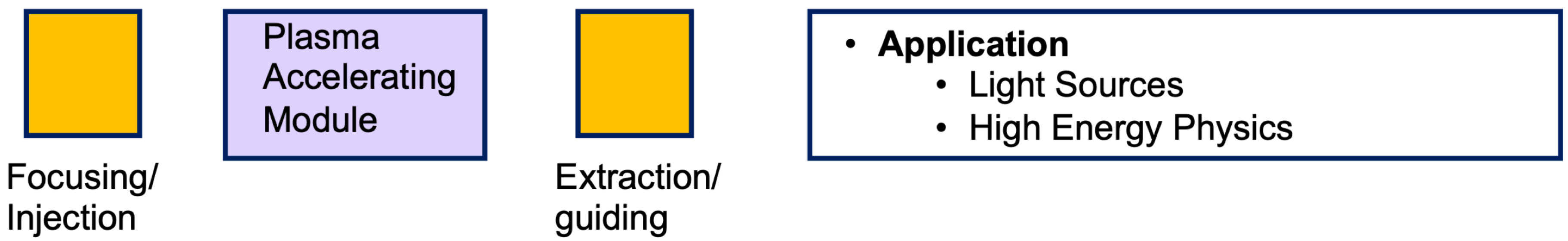
$$B_n \approx \frac{2I}{\varepsilon_n^2}$$

- **Short pulse** (ps to fs)

- Little spread in transverse momentum and angle => **low emittance**

Towards the Applications

- Multi-GeV acceleration of high brightness electron beams in cm-scale plasma structures



- Injection and matching to plasma accelerating module
  - The beam has to be focused to the matching spot to prevent envelope oscillations that may cause emittance growth
    - ***Blow-out regime***

$$\beta_{matching} = \frac{\sqrt{2\gamma}}{k_p} \qquad \alpha_{matching} = 0$$

Typical numbers

$$k_p = \frac{2\pi}{\lambda_p} \qquad \gamma = 1000$$

$$\lambda_p(\mu m) \approx \frac{3.3 \cdot 10^{10}}{\sqrt{n_0(cm^{-3})}} \qquad n_0 = 10^{16} cm^{-3}$$

$$\varepsilon_n = 1 mmmrad$$

Matching condition

$$\sigma_{matching} = \sqrt{\frac{\beta_{matching}\varepsilon_n}{\gamma}} \approx \mu m$$

Towards the Applications

- Extraction from plasma accelerating module
  - plasma fields stronger than in conventional accelerators

$$G(MT/m) = \frac{F_r}{ecr} \approx 3n(10^{17}\ cm^{-3})$$

- beams experience huge transverse size variation when propagating from the plasma outer surface to the conventional focusing optics

$$\sigma_x \sim \mu m \qquad\qquad \sigma_{x'} \sim mrad$$

- the particle transverse motion becomes extremely sensitive to energy spread
  - the beam angular divergence has to be reduced and the transverse spot size increased to limit the chromatic induced emittance degradation in vacuum

$$\varepsilon_n^2 = <\gamma>^2 \left(\sigma_E^2 \sigma_x^2 \sigma_{x'}^2 + \varepsilon^2\right) \approx <\gamma>^2 \left(\sigma_E^2 \sigma_{x'}^4 s^2 + \varepsilon^2\right)$$

M. Migliorati et al., PRST AB ***16****, 011302 (2013)*

Active Plasma Lenses

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 21, NUMBER 5 MAY, 1950

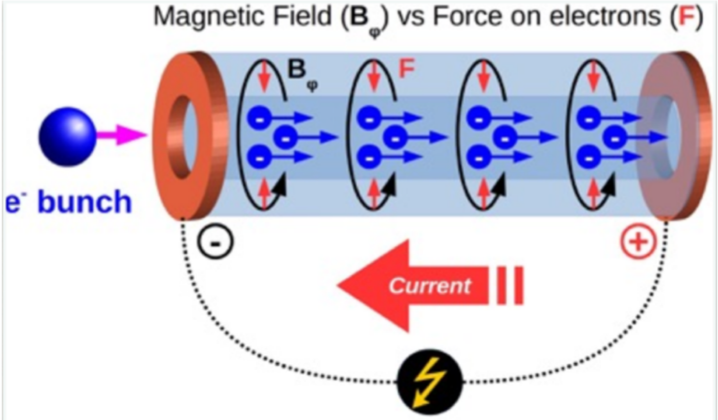
A Focusing Device for the External 350-Mev Proton Beam of the 184-Inch Cyclotron at Berkeley

W. K. H. PANOFSKY AND W. R. BAKER
Department of Physics, Radiation Laboratory, University of California, Berkeley, California
(Received January 11, 1950)

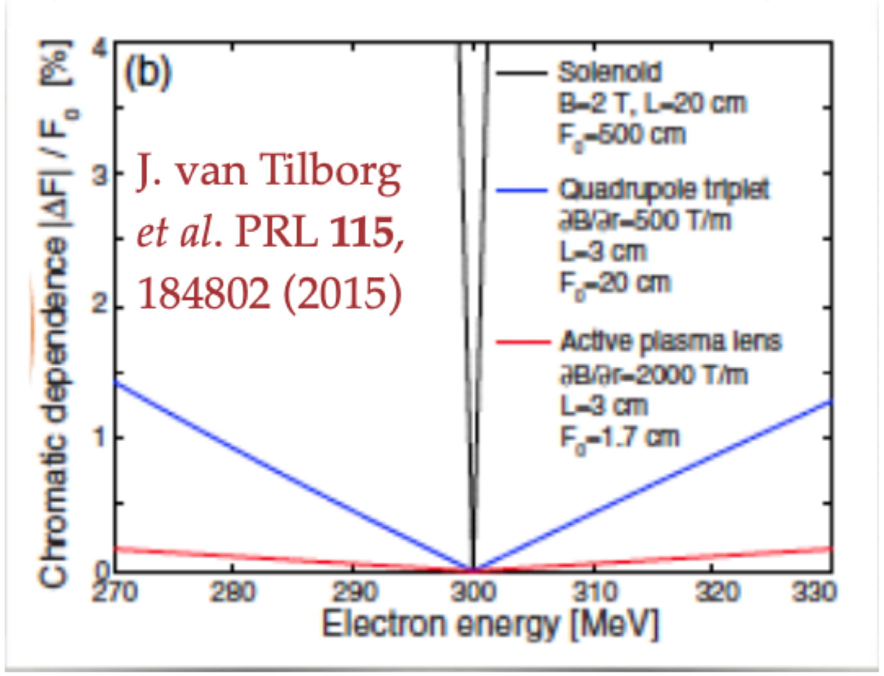
A device has been constructed to focus the external beam of the 184-in. cyclotron at Berkeley. The device consists of a cylindrical tube 4 ft. in length and 3 in. in diameter, which contains a longitudinal arc of nearly uniform current density. Such a device will focus any beam of cylindrical symmetry. Owing to the large power requirements of such a device it is applicable only to very short pulsed beams.

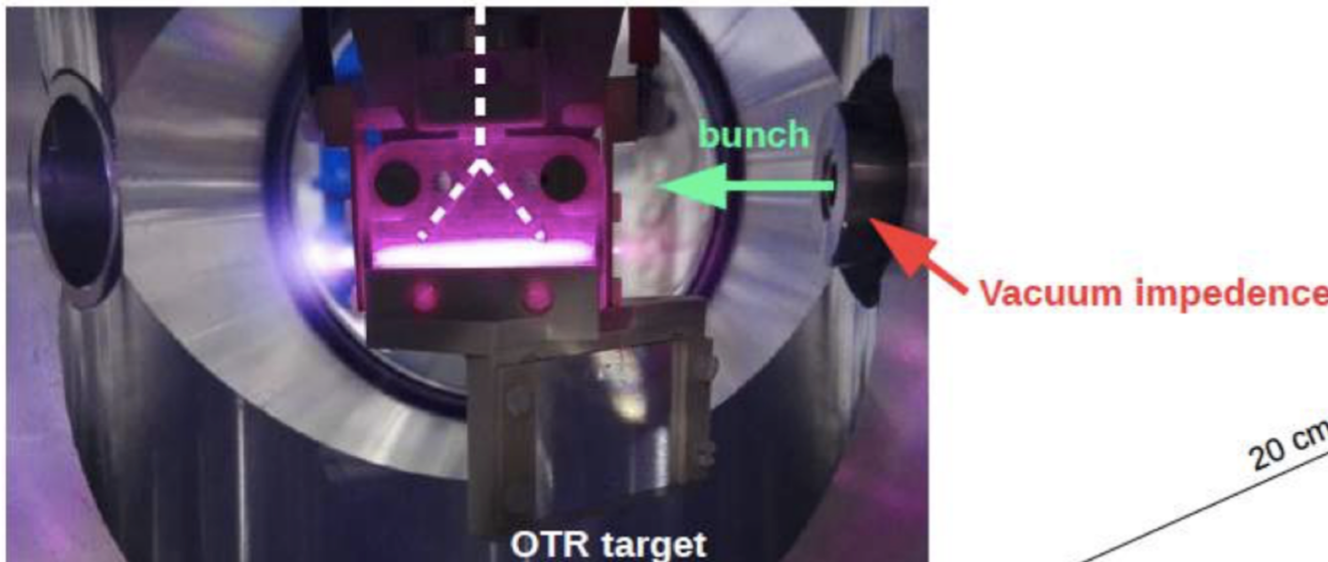
- Discharge current in gas-filled capillary

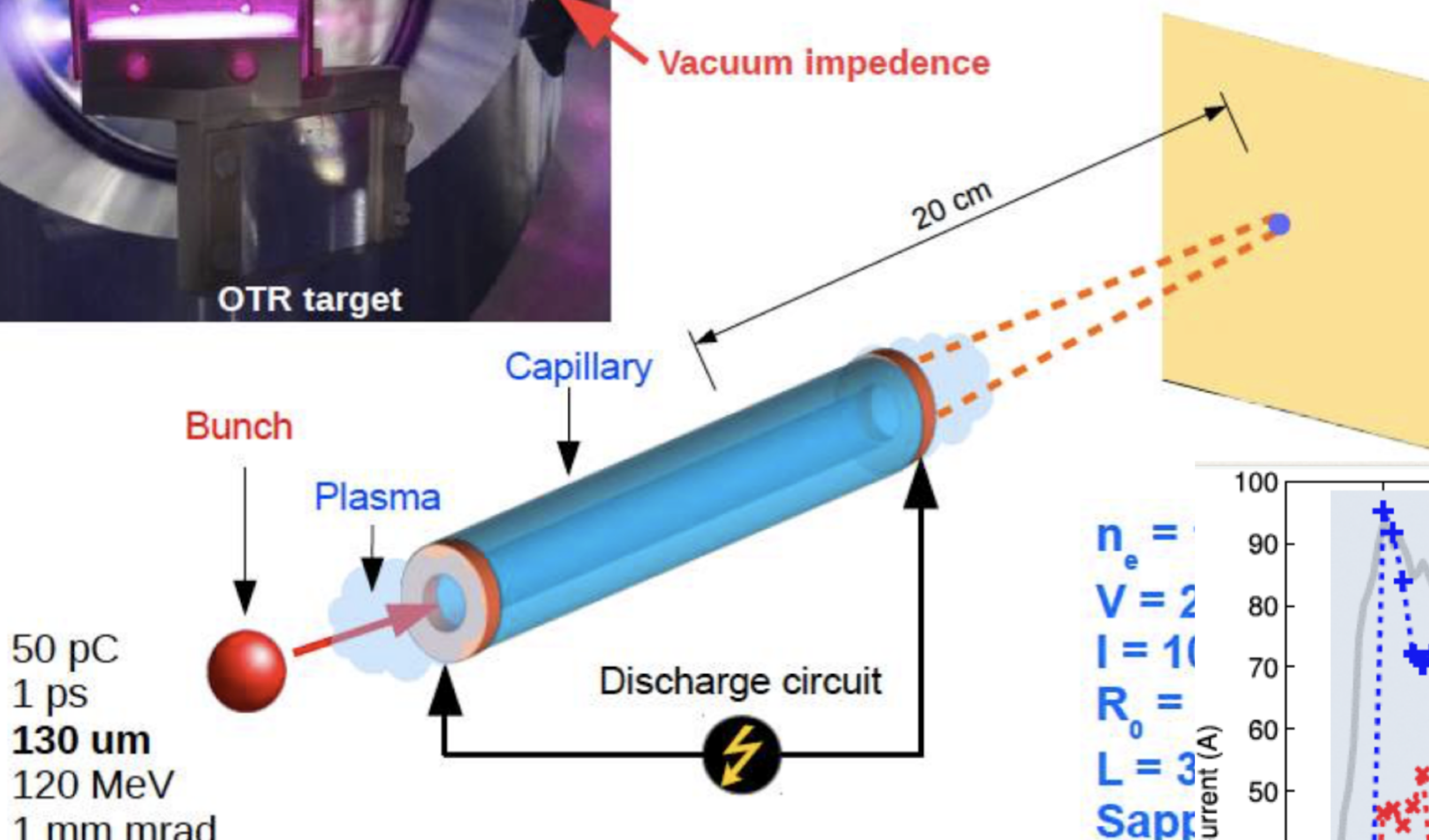
$$B_\phi(r) = \frac{\mu_0}{r}\int_0^r J(r')r'dr'$$

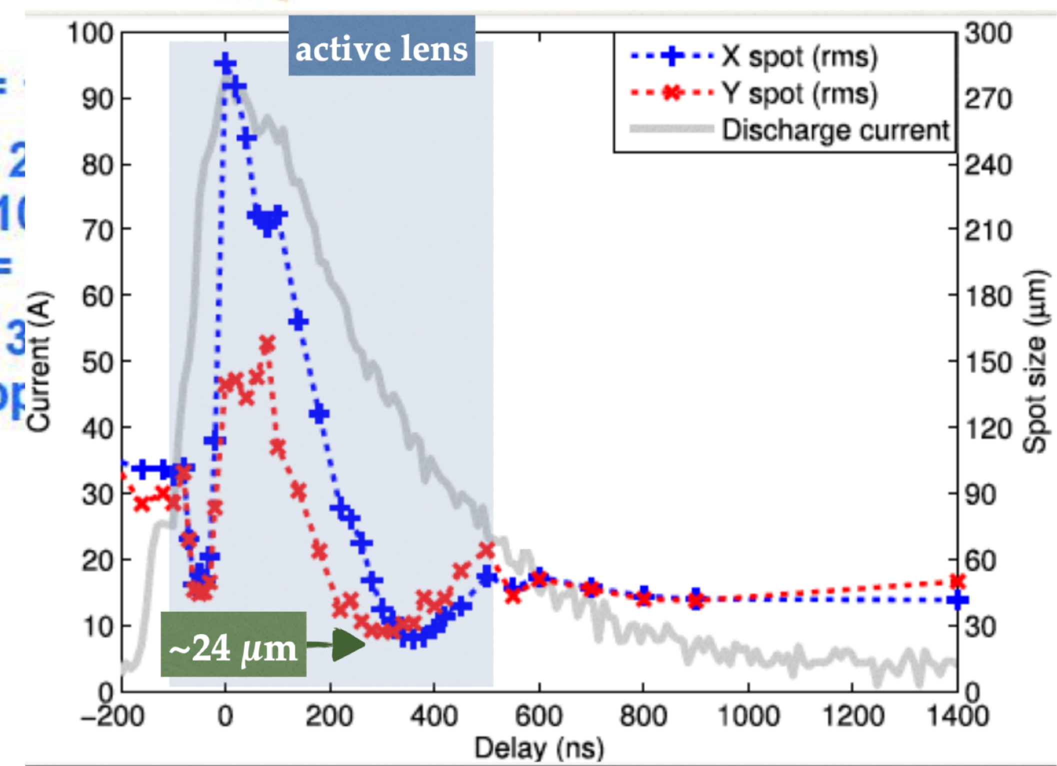


- Cylindrical symmetry
  - purely radial focusing effect
- Tunability
- Focusing strength $k \propto \gamma^{-1}$
- High focusing gradient ~ kT/m
  - short focal length
  - weak chromaticity



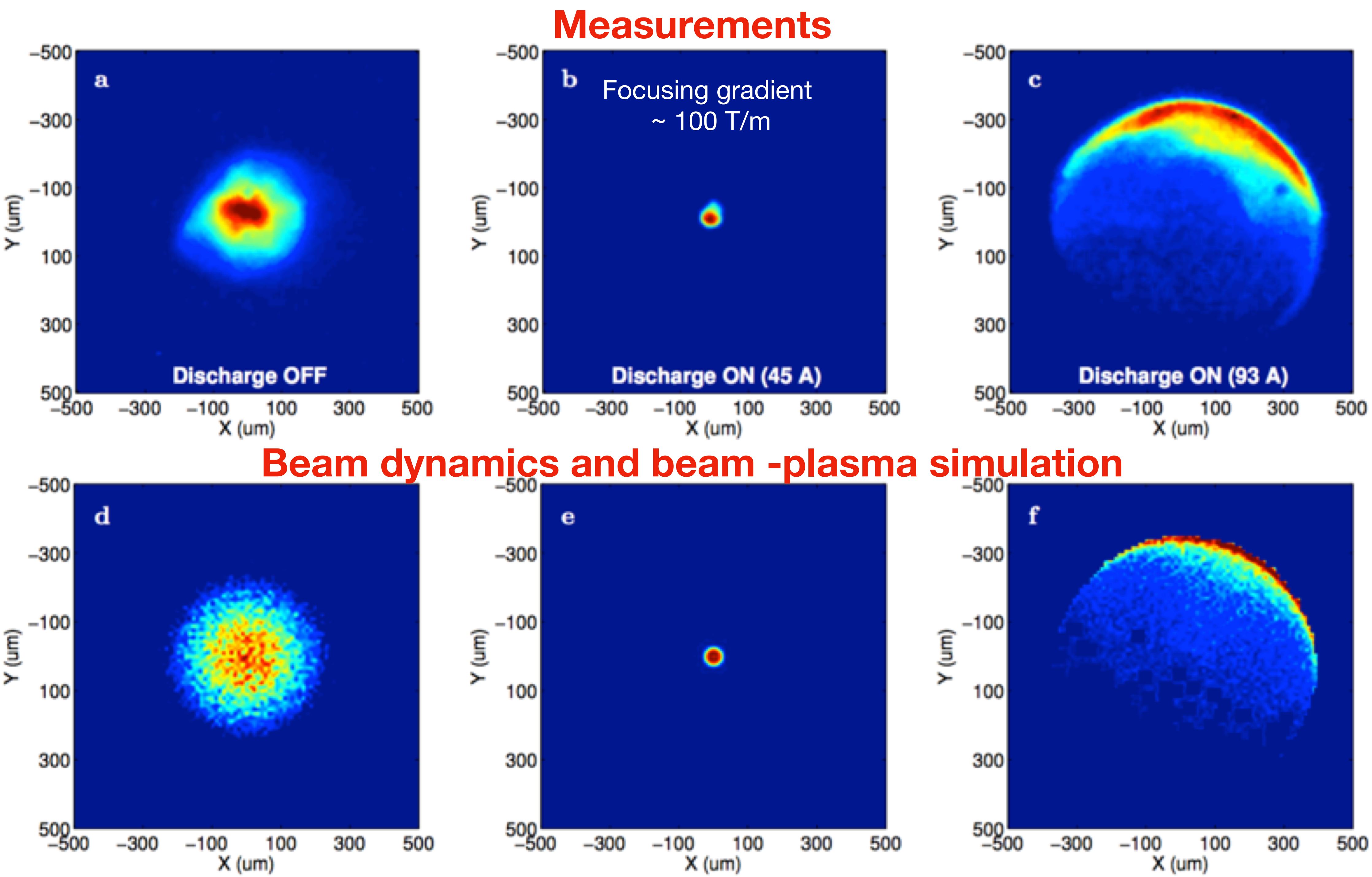

bunch
Vacuum impedence
OTR target


20 cm
Capillary
Bunch
Plasma
50 pC
1 ps
130 um
120 MeV
1 mm mrad
Discharge circuit


active lens
X spot (rms)
Y spot (rms)
Discharge current
Current (A)
Spot size (µm)
Delay (ns)
~24 µm

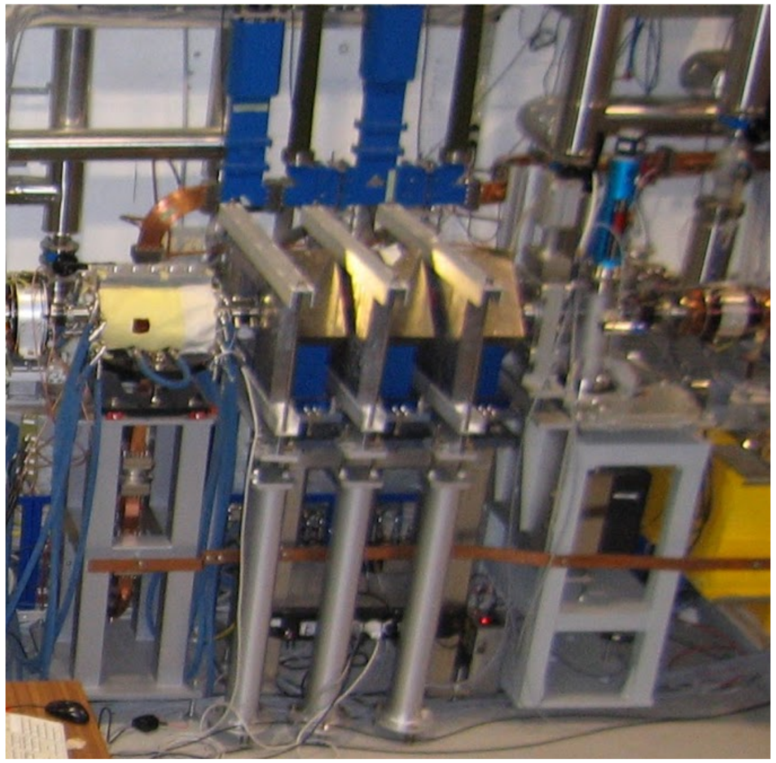
Active Plasma Lens

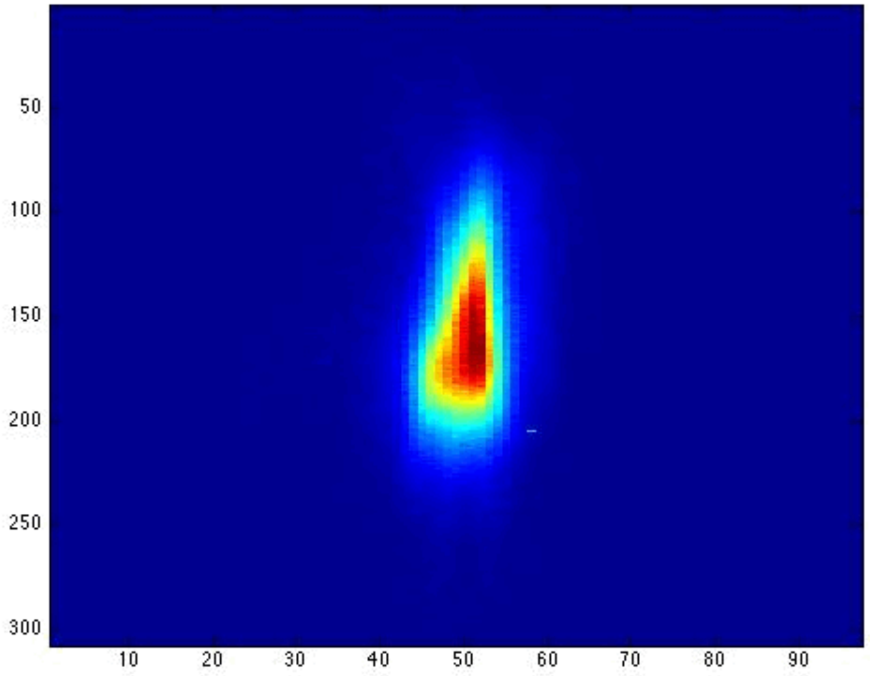
Measurements at SPARC_LAB



Plasma lens vs conventional focusing

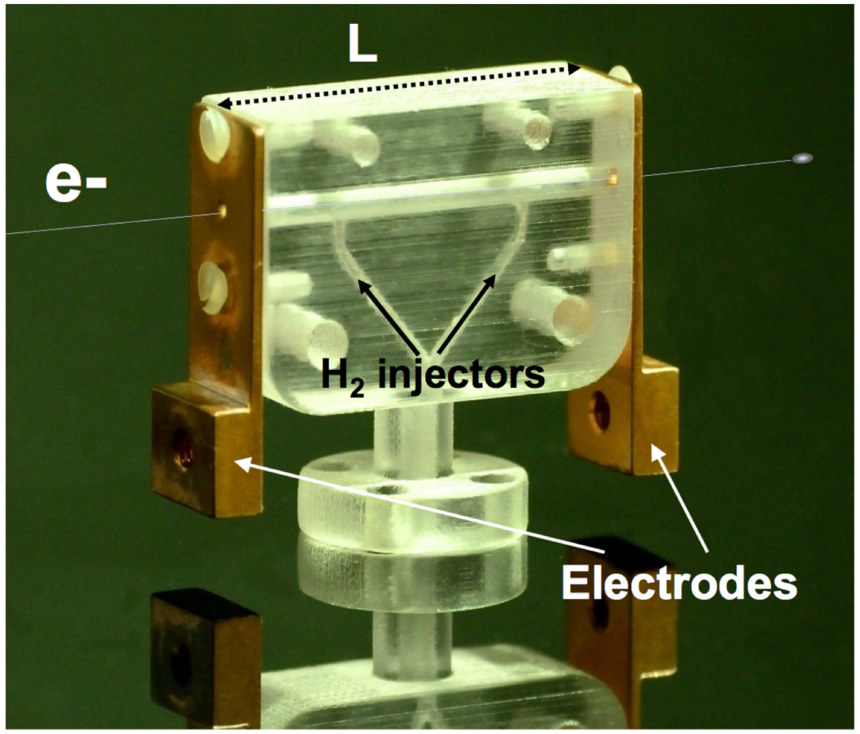
Single Quadrupole Magnet

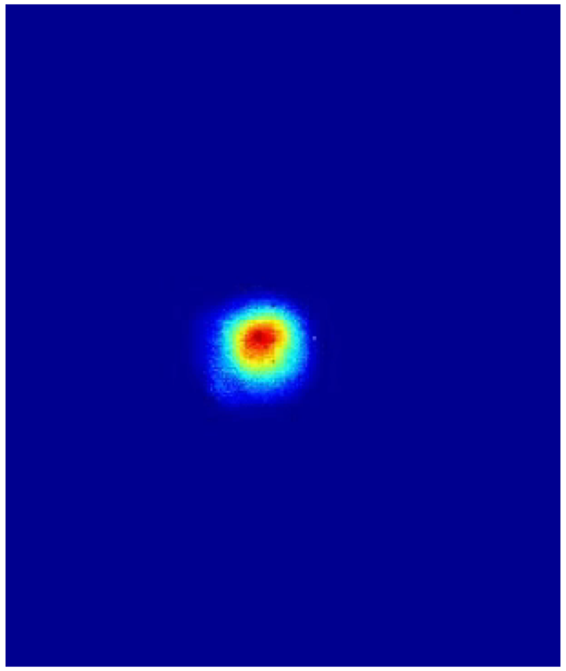




Experimental measurements at SPARC_LAB (INFN-LNF)

Single Plasma Lens

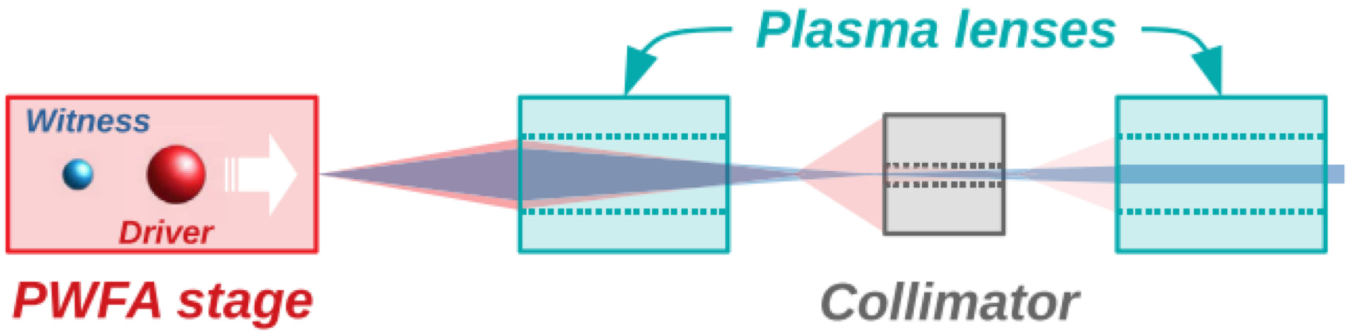




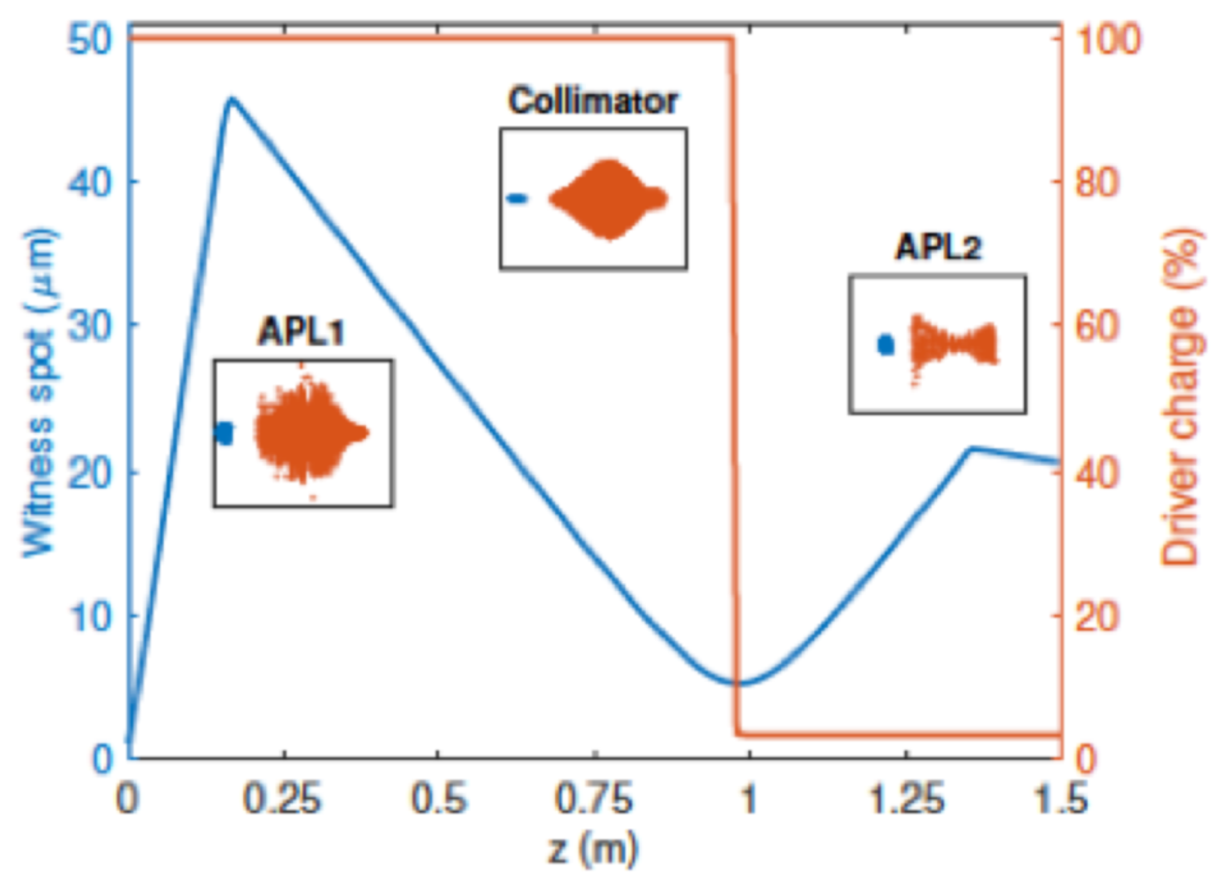
Extraction Beamline

EuPRAXIA@SPARC_LAB Case

	Driver	Witness
Charge (pC)	200	30
Energy (GeV)	0.460	1
Energy spread (%)	16	0.73
Normalized emittance (mm mrad)	5	0.6
RMS Spot size (μm)	7	1.2
RMS Duration (fs)	160	11.5
Peak current (kA)	1.2	2.6



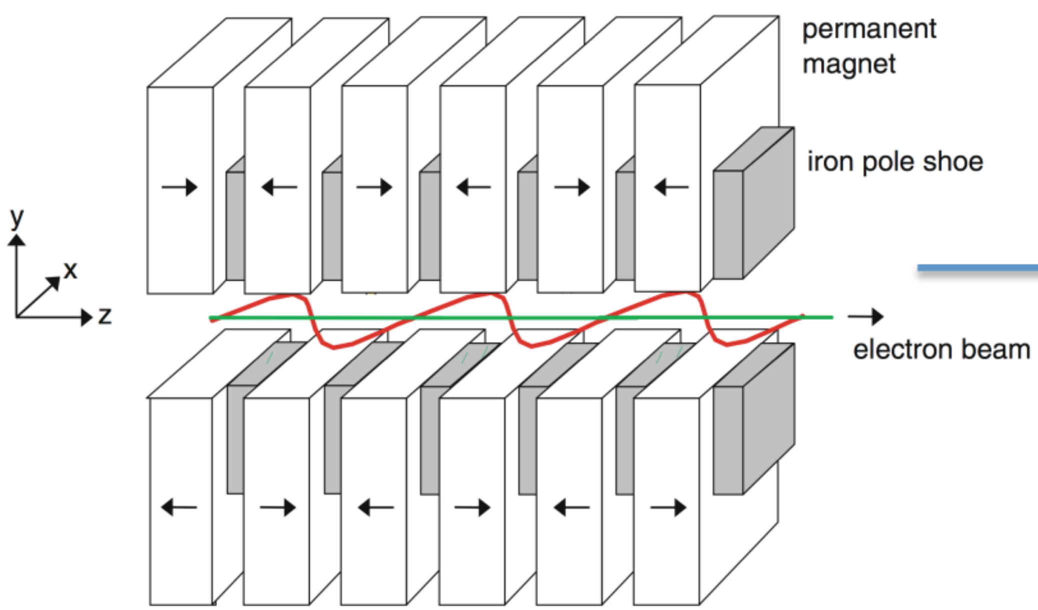
The witness is preserved in charge and quality and the driver is almost completely removed

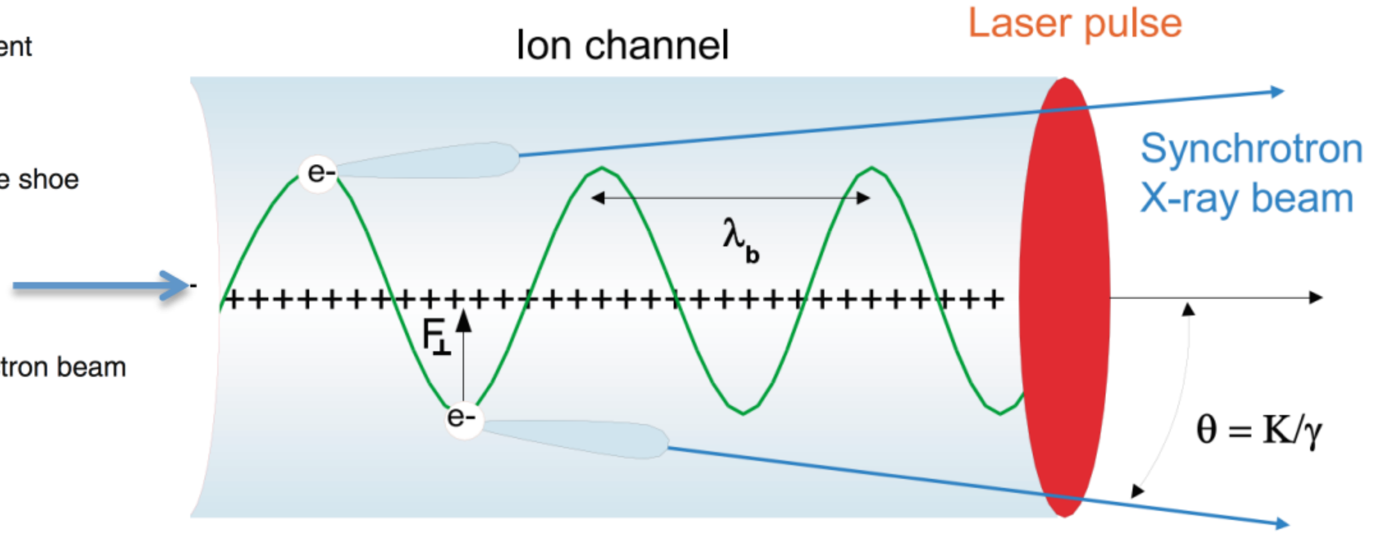


R. Pompili et al., Phys. Rev. AB **22**, 121302 (2019)

Plasma Wigglers

Betatron radiation based radiator





Betatron oscillation $k_\beta = \sqrt{2\pi r_e n_0 / \gamma} = k_p / \sqrt{2\gamma}$

A. Rousse *et al.,* Phys. Rev. Lett. **93**, 135005 (2004).

$$K = \frac{2\pi\gamma x_0}{\lambda_\beta} \simeq 1.33 \times 10^{-10}\, \gamma^{0.5}\, n_e^{0.5}\left[cm^{-3}\right] x_0\,[\mu m]$$

<u>Amplitude dependent</u>

K **can reach ~100 (Requires large offset, $k_p x_0$ ~1)**

$$E_c[eV] = 5 \times 10^{-21}\, \gamma^2\, n_e\left[cm^{-3}\right] x_0\,[\mu m]$$

Photon energy up to

Can reach up to 100 MeV with dense plasma.

Plasma wigglers can give magnet field equivalent B_u>100 T with sub-cm wavelength

Courtesy of J. Rosenzweig

S. Kiselev et al., PRL **93**, 135004 (2004)

Conclusions

- Plasma-based acceleration techniques have demonstrated accelerating gradients up to 3 orders of magnitudes beyond presently used RF technologies
- Plasma-based acceleration techniques have provided solid feasibility proofs of FEL lasing paving the way to applications
- Successful efforts on improving beam quality
- R&D on **beam stability, staging and continuous operation**, as necessary steps towards the realization of compact plasma-based accelerator facilities
    - Challenges in high repetition rate
- Plasma-based, ultra-high gradient accelerators therefore open the realistic vision of very compact accelerators for scientific, commercial and medical applications