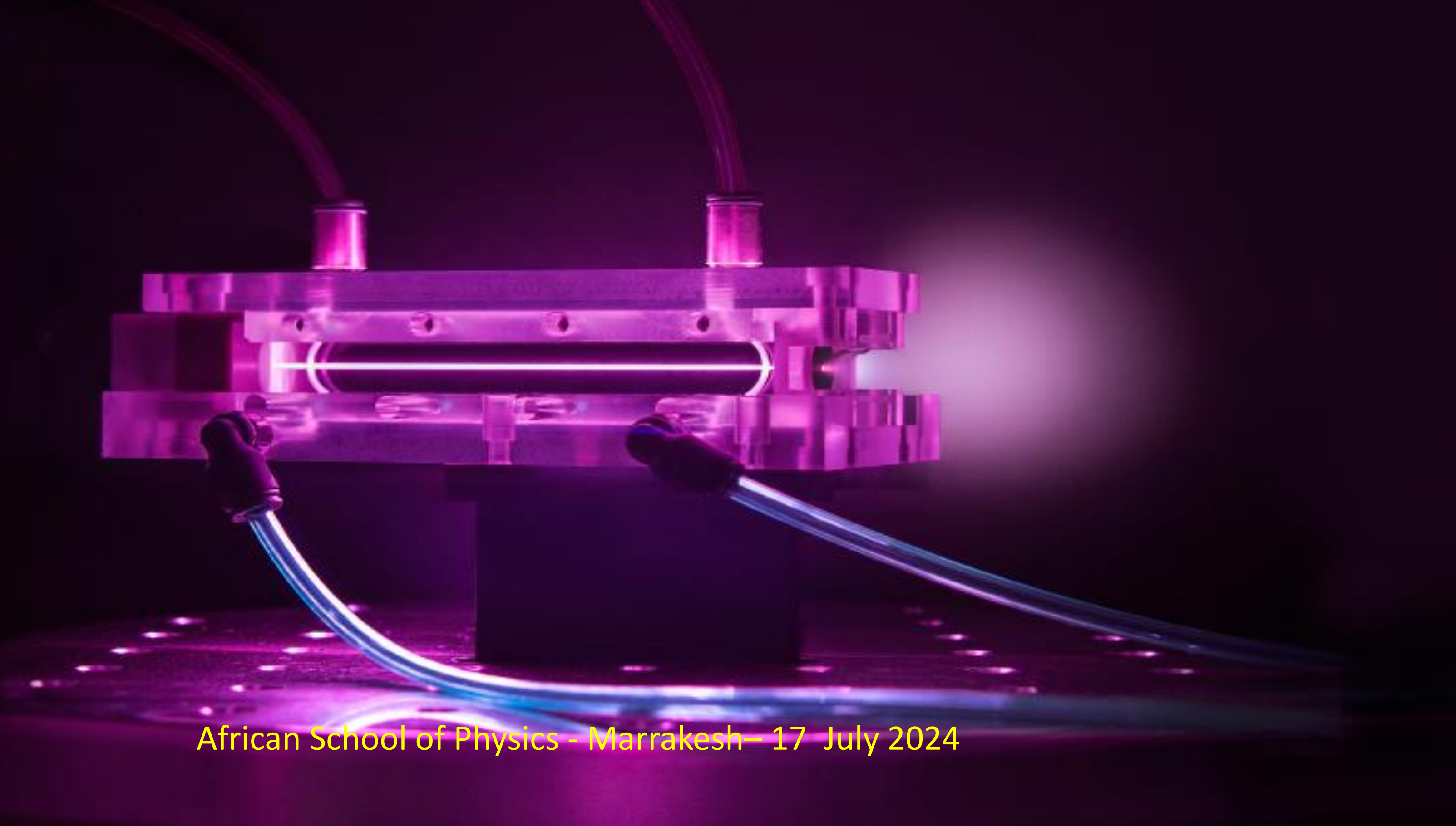
Advanced Accelerator Concepts

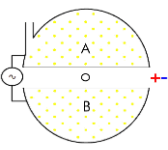
Massimo.Ferrario@lnf.infn.it

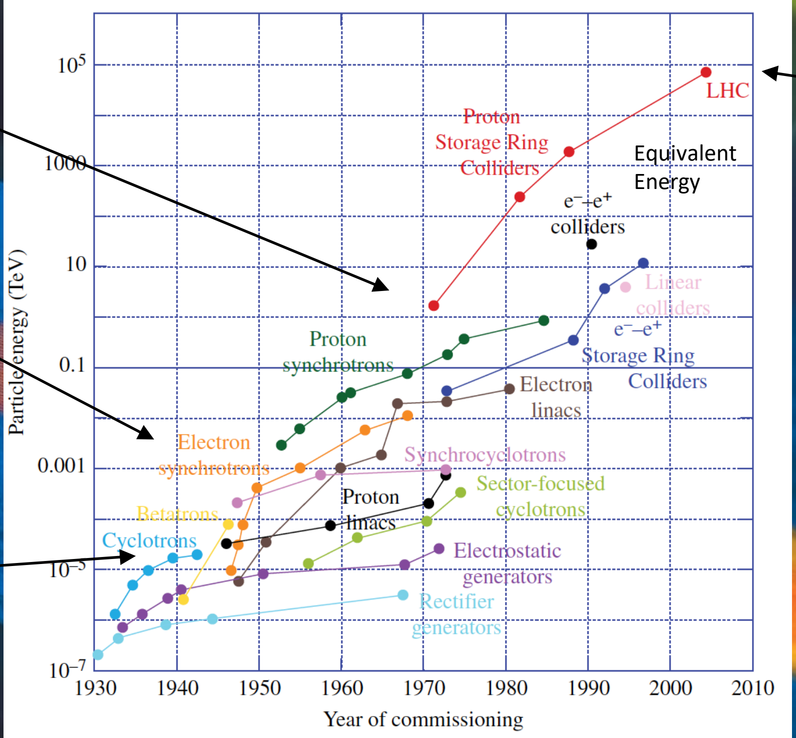


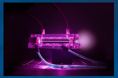
African School of Physics - Marrakesh– 17 July 2024

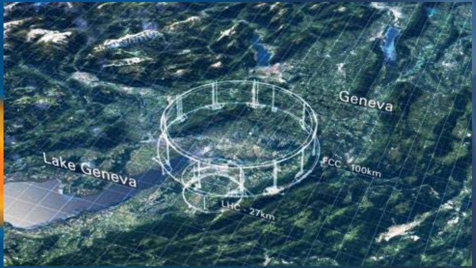
Livingstone Diagram

$$
\begin{cases}
\omega_L = \dfrac{q B_y}{\gamma m_0} \\
p_z = q B_y R
\end{cases}
$$









Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

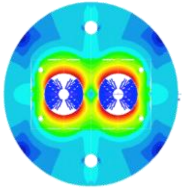
Options towards higher energies

Hadron (p) circular collider

$$p = e \cdot R \cdot B_y$$

Increase bending field
SC bend magnet work (FCC-hh)

Increase radius = size (FCC-hh)



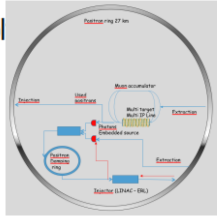
Lepton (e-,e+) circular collider

$$p \propto E_0 \cdot \sqrt[4]{\rho \cdot U_0}$$

Increase supplied RF vol
(FCC-ee)

Increase mass of acc. particle (muon)

Increase radius = size (FCC-ee)



Lepton (e-,e+) linear collider

$$p = L \cdot G_{acc}$$

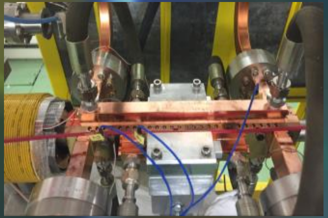
Increase length (ILC, CLIC)

Compact and Cost
Effective….

High Gradient Options

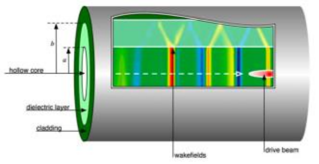
Metallic accelerating structures =>

100 MV/m < E_{acc}< 1 GV/m



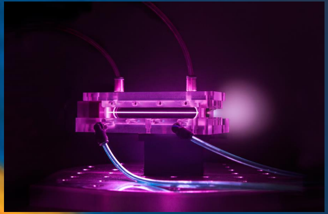
Dielectrict structures, laser or particle driven =>

E_{acc} < 10 GV/m



Plasma accelerator, laser or particle driven =>

E_{acc} < 100 GV/m



Related Issues: Power Sources and Efficiency, Stability, Reliability, Staging, Synchronization, Rep. Rate and short (fs) bunches with small (μm) spot to match high gradients

Beam Quality Requirements

Future accelerators will require also high quality beams :

==> High Luminosity & High Brightness,

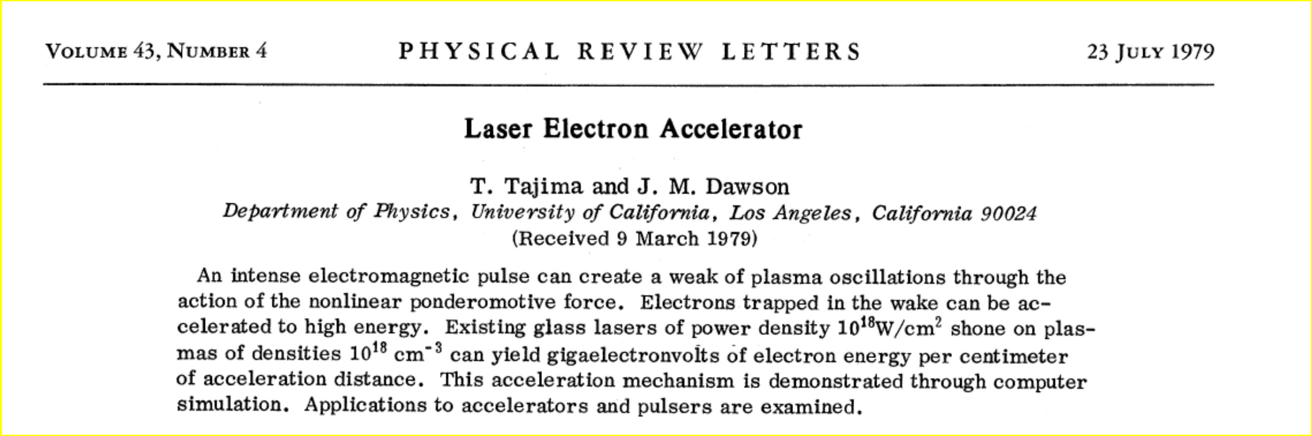
==> High Energy & Low Energy Spread

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

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

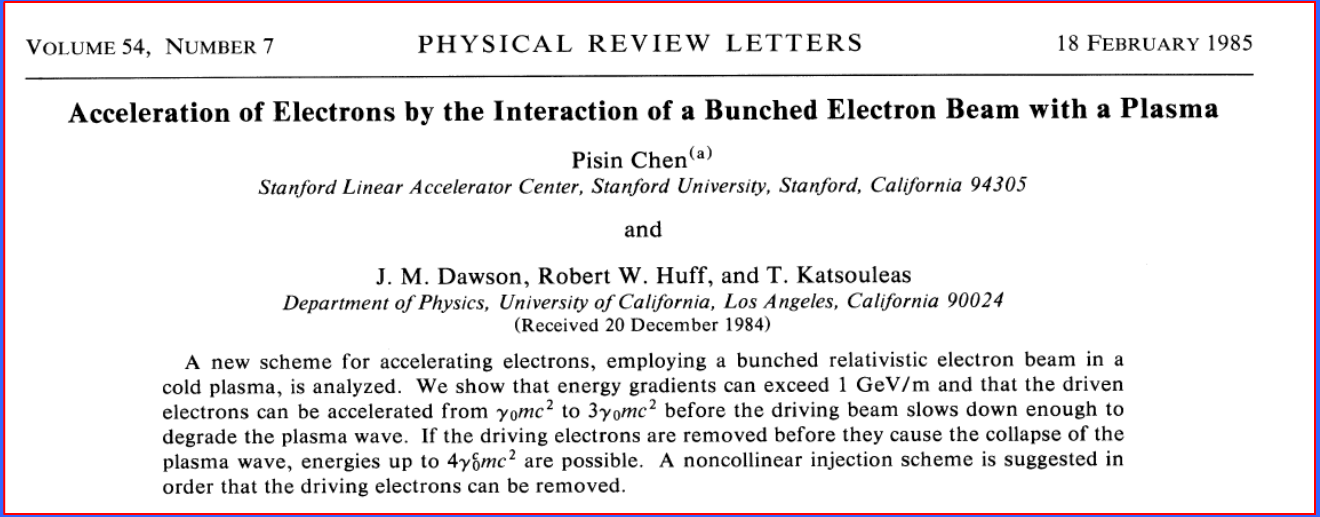


VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.



VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

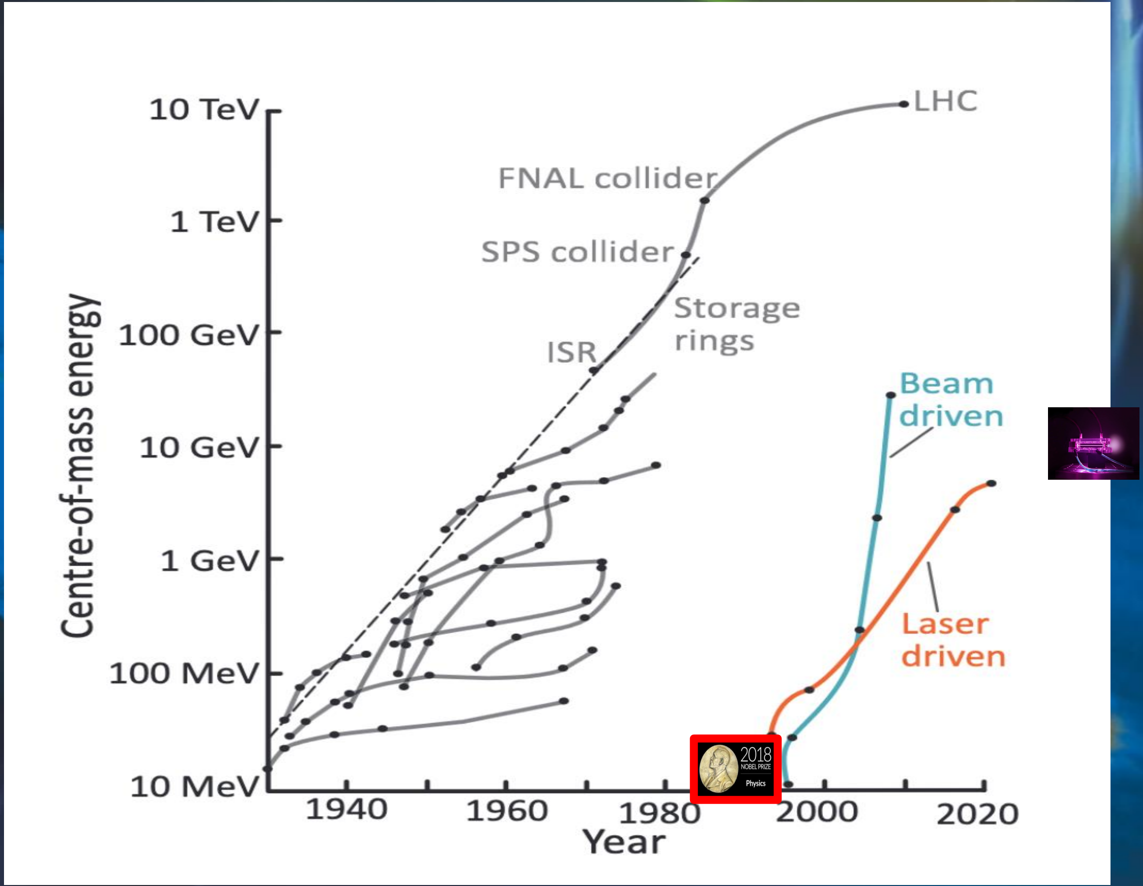
Pisin Chen[(a)]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024
(Received 20 December 1984)

A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma_0 mc^2$ to $3\gamma_0 mc^2$ before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to $4\gamma_0^c mc^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.

Livingstone Diagram with PWFA



Principles of plasma physics

Definition of Plasma: a quasi-neutral gas of charged particles showing collective behaviour

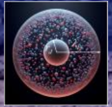
=> a plasma responds to external forces as a single entity

The Debye length is a fundamental property of nearly all plasmas of interest and depends equally on its temperature

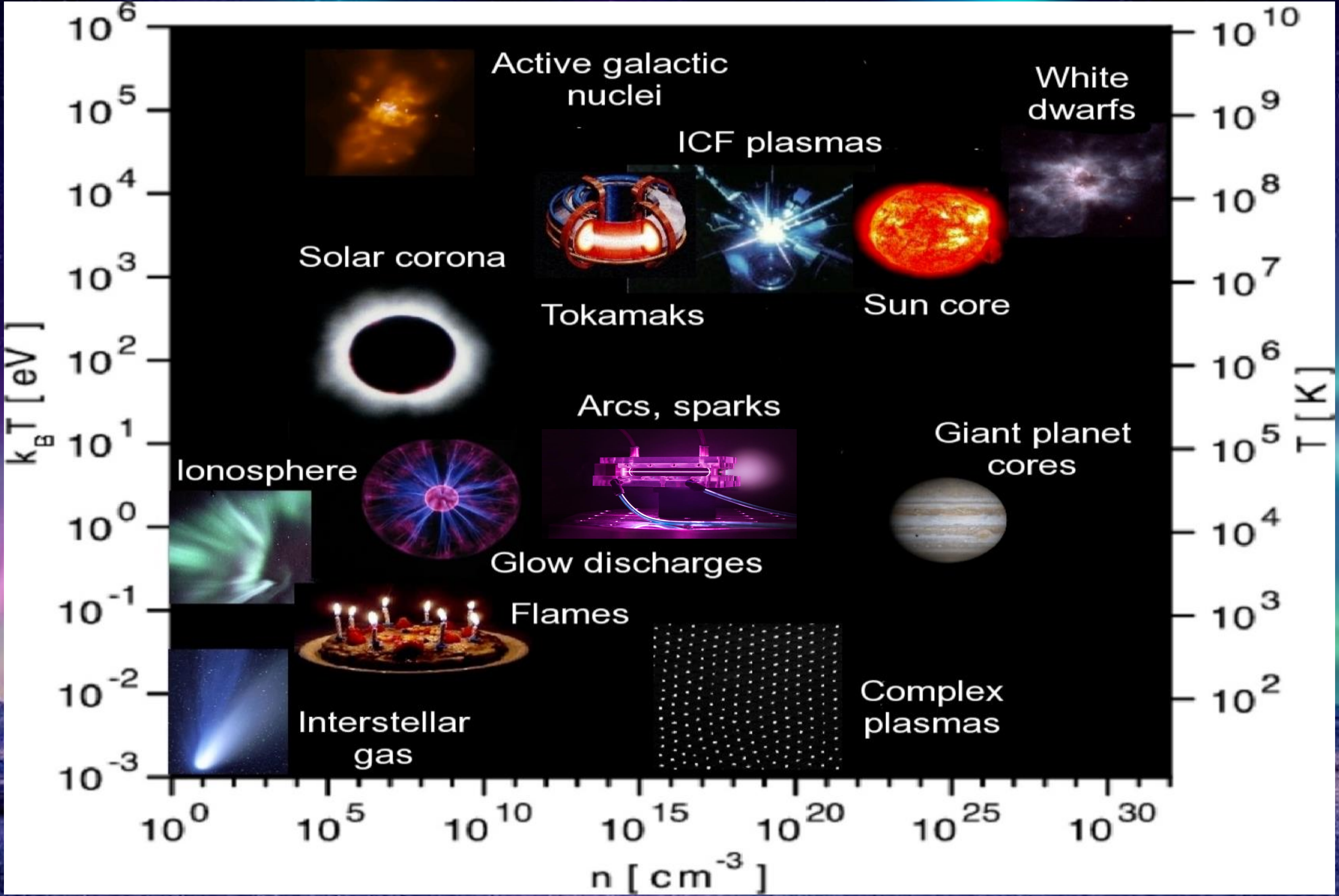
$$\lambda_D = \left(\frac{\varepsilon_0 k_B T_e}{e^2 n_e}\right)^{1/2} = 743\left(\frac{T_e}{\mathrm{eV}}\right)^{1/2}\left(\frac{n_e}{\mathrm{cm}^{-3}}\right)^{-1/2}\ \mathrm{cm}.$$

=> An ideal plasma has many particles per Debye sphere, a prerequisite for the collective behaviour:

$$N_D \equiv n_e \frac{4\pi}{3}\lambda_D^3 \gg 1$$

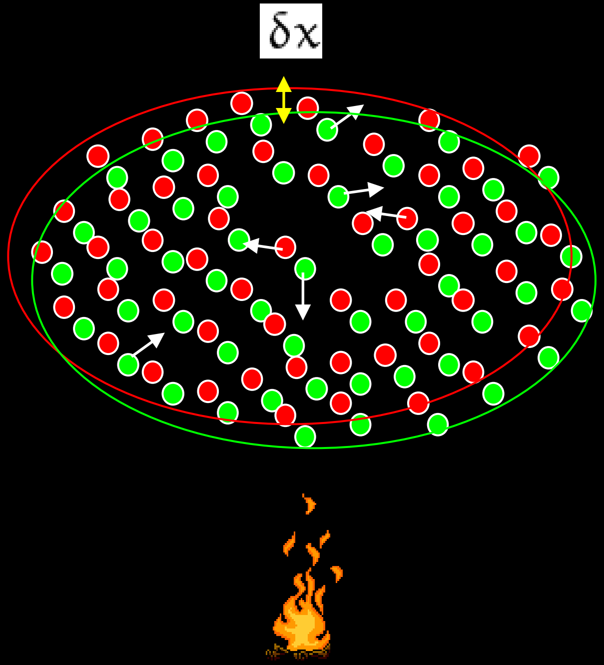


Plasma Temperature and Density



Surface charge density

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



Surface electric field

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

Restoring force

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

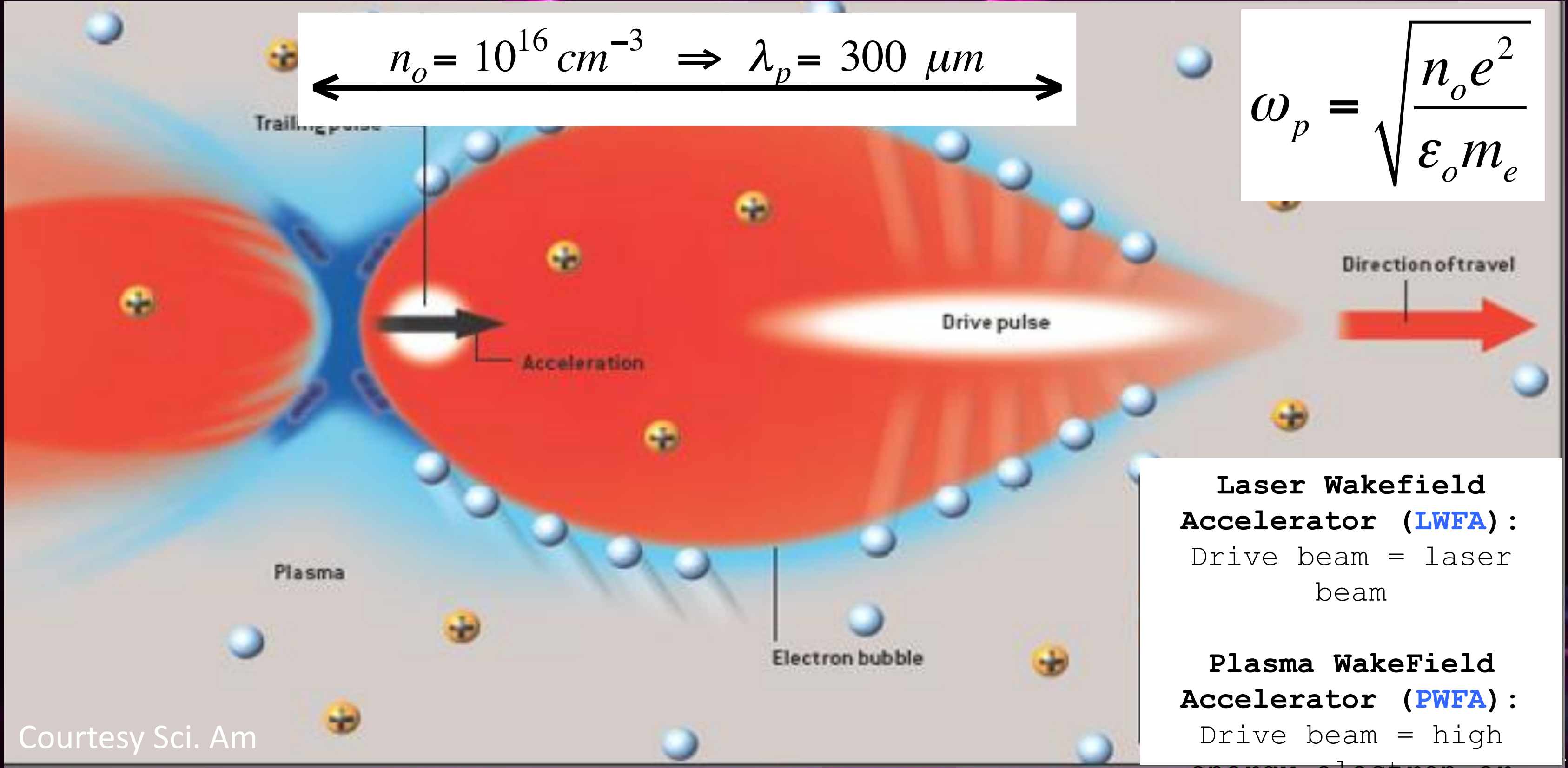
Plasma frequency

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

Plasma oscillations

$$\delta x = (\delta x)_0 \cos\left(\omega_p\, t\right)$$

Principle of plasma acceleration



$$n_o = 10^{16}\ cm^{-3} \Rightarrow \lambda_p = 300\ \mu m$$

$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$$

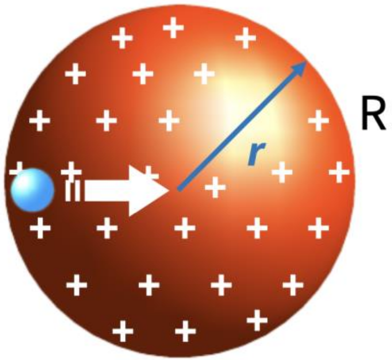
Courtesy Sci. Am

Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam

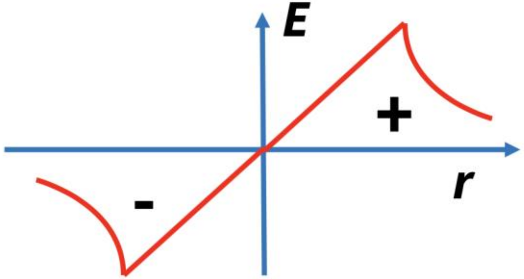
Principle of plasma acceleration

From Maxwell's equations, the electric field in a (positively) charged sphere with uniform density $\boldsymbol{n_i}$ at location **r** is



$$\vec{E}(r) = \frac{q_i n_i}{3\epsilon_0} r$$

The field is **increasing** inside the sphere



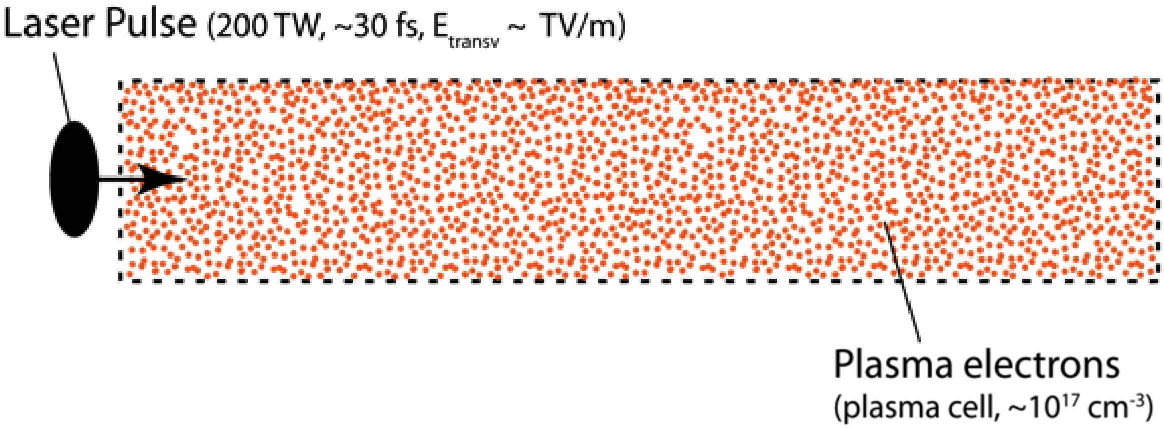
Let's put some numbers

$n_i = 10^{16}\ cm^{-3}$

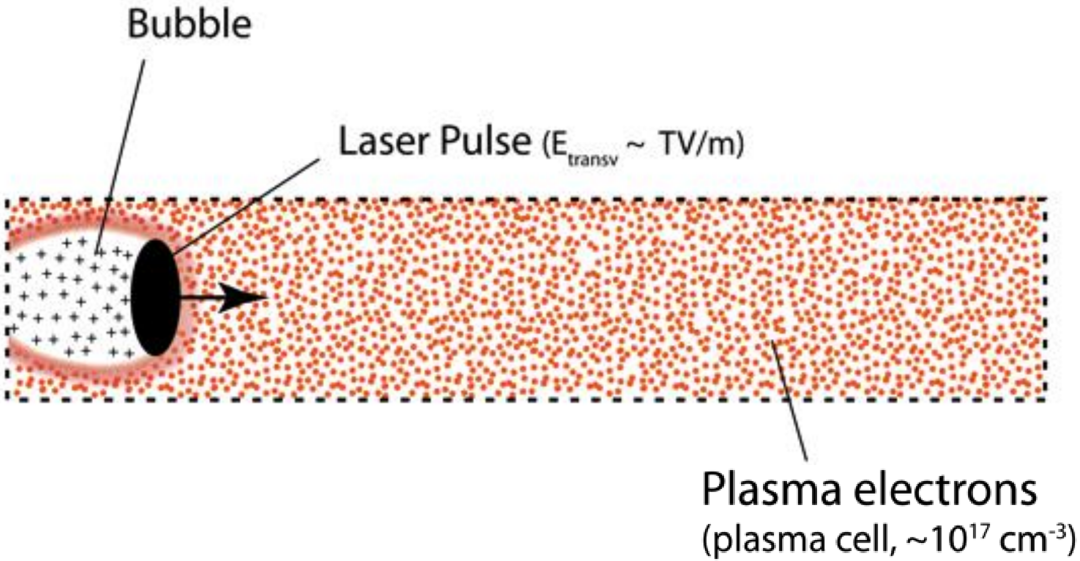
$R = 0.5$

➡ $$E \approx 10 \frac{GV}{m}$$

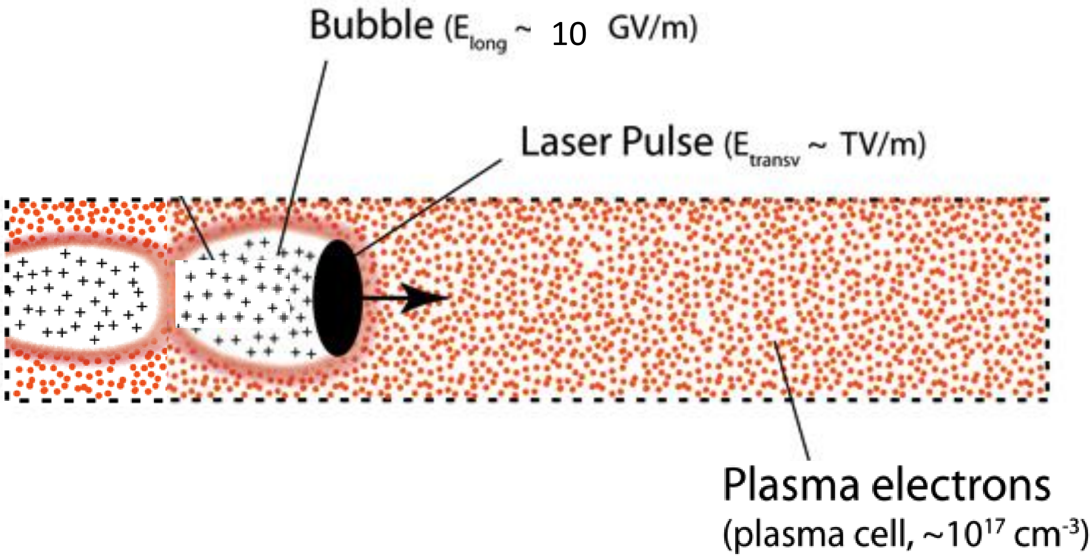
Plasma Wake-Acceleration



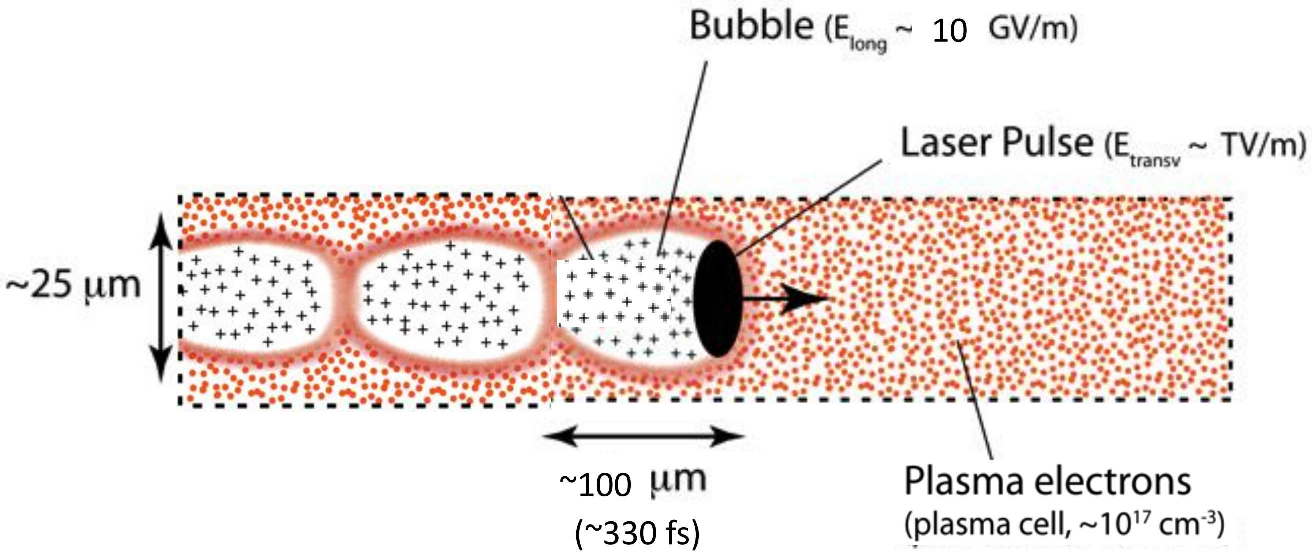
Plasma Wake-Acceleration



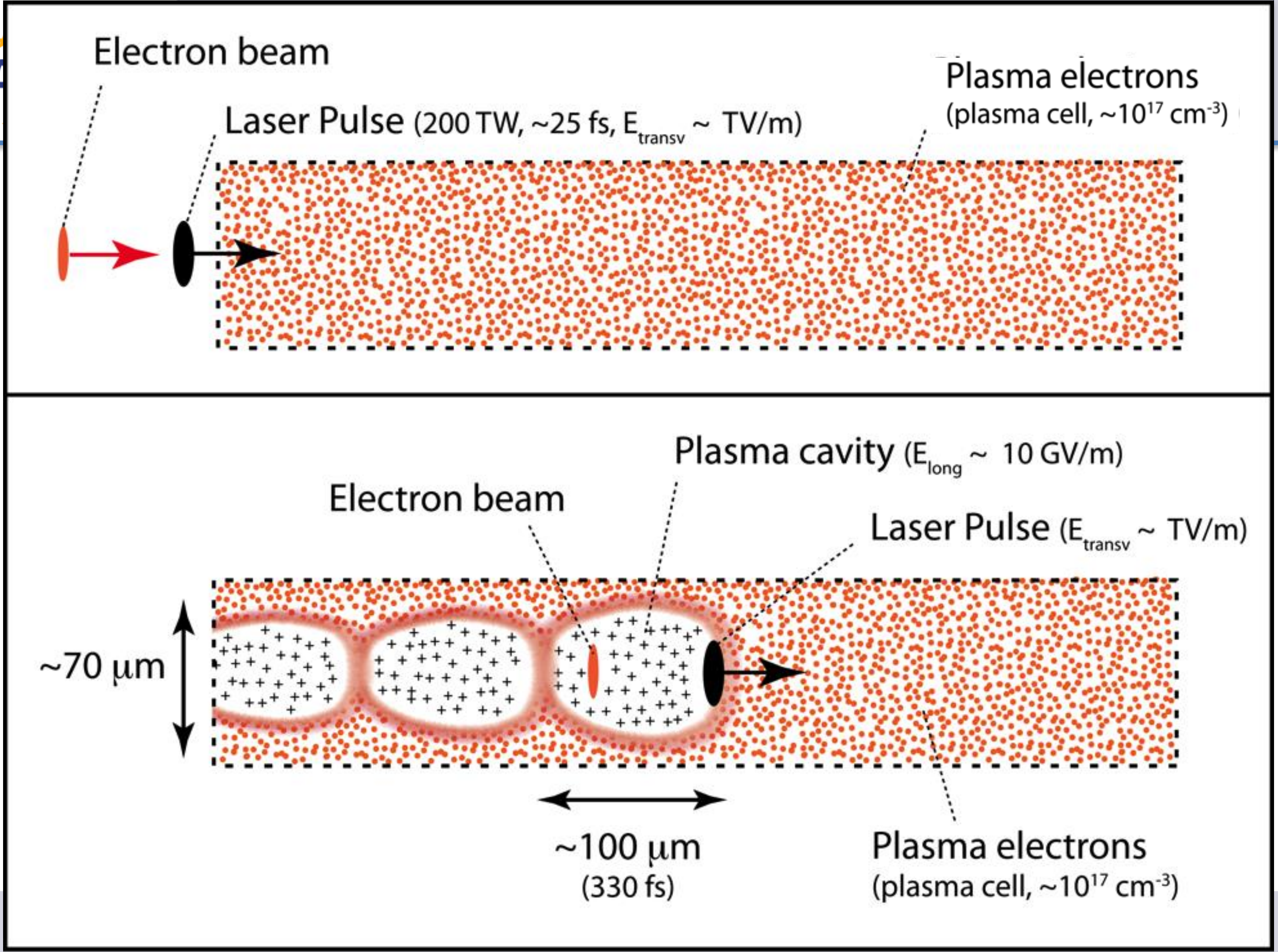
Plasma Wake-Acceleration



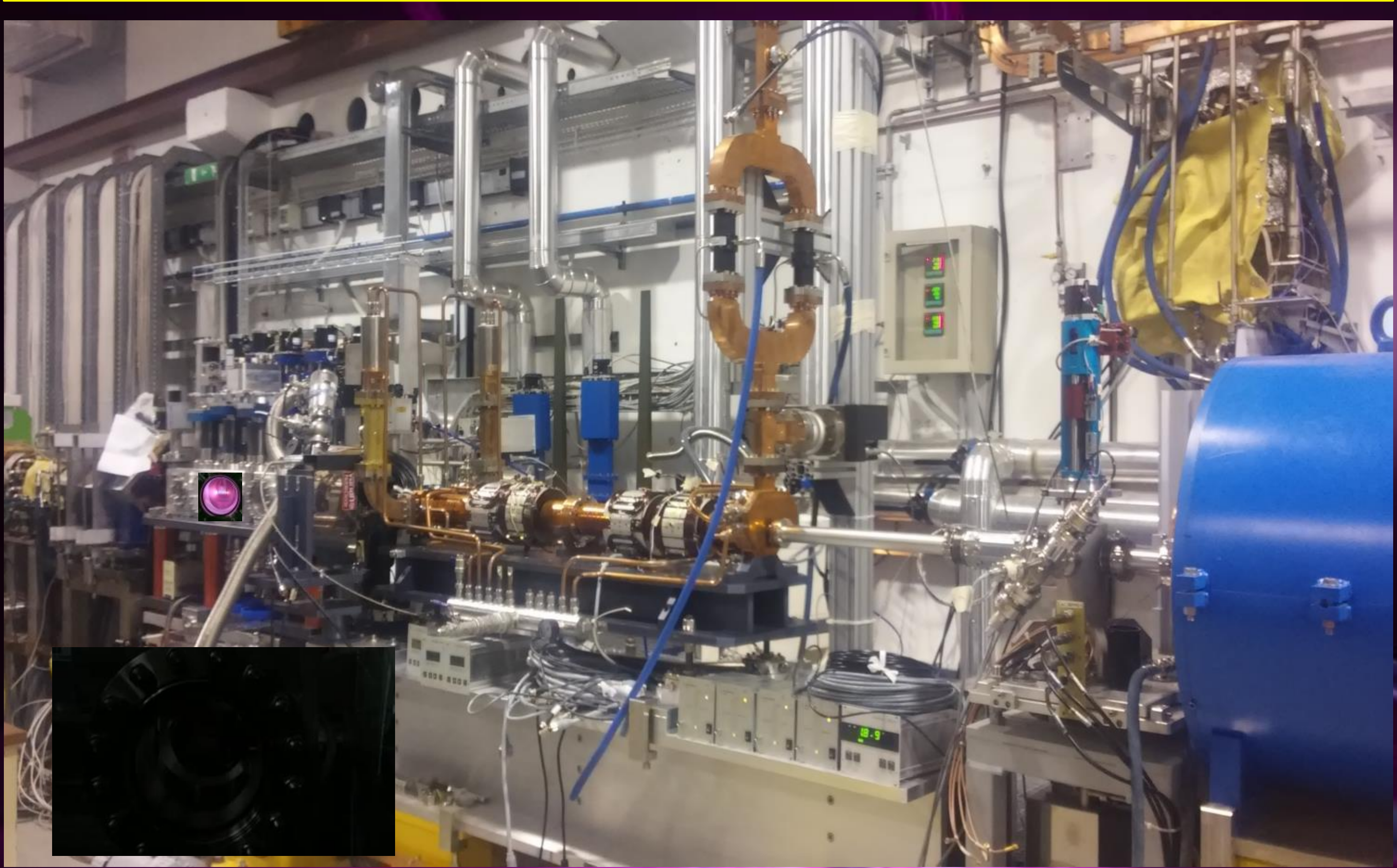
Plasma Wake-Acceleration

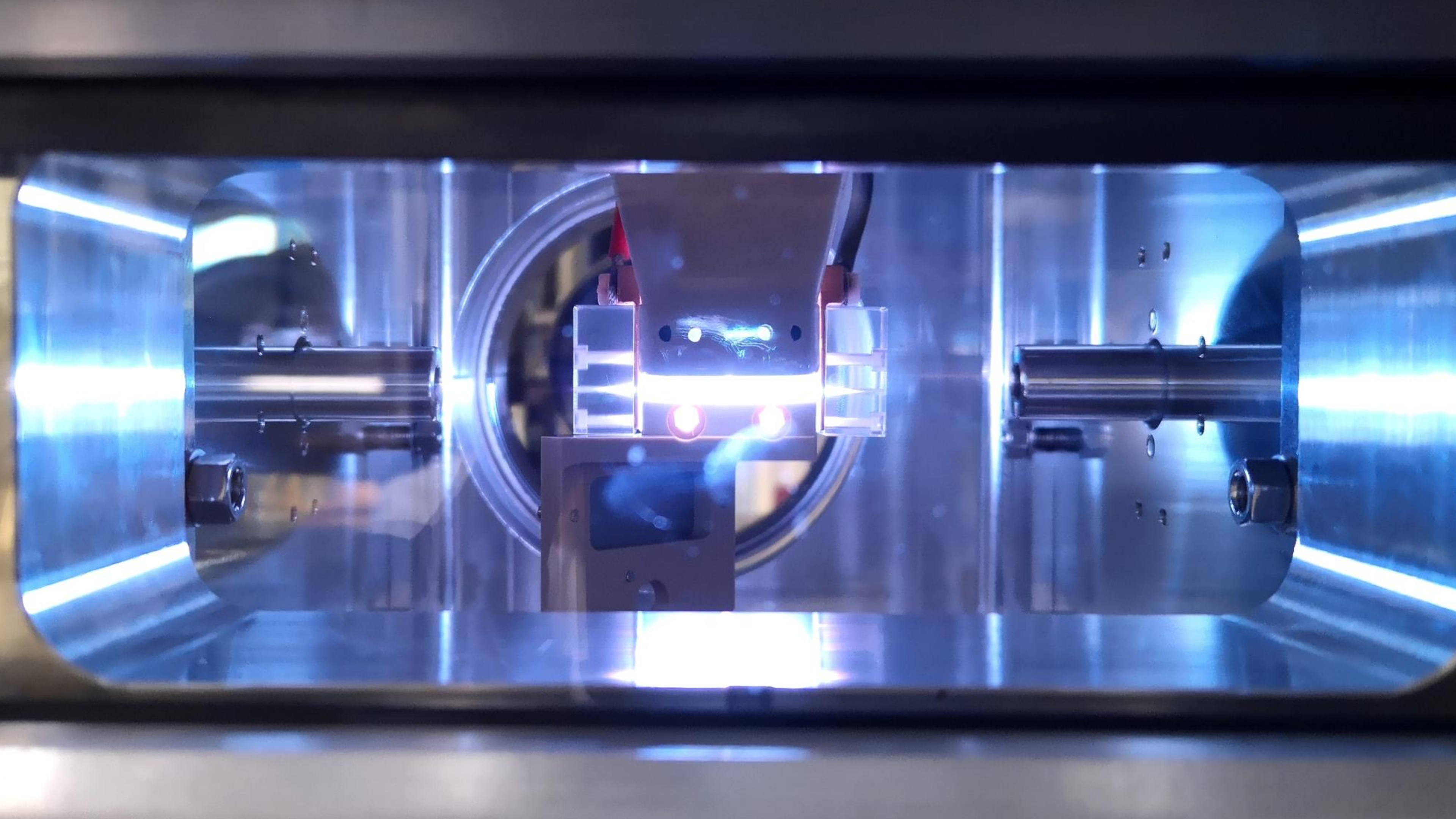


This accelerator fits into a human hair!

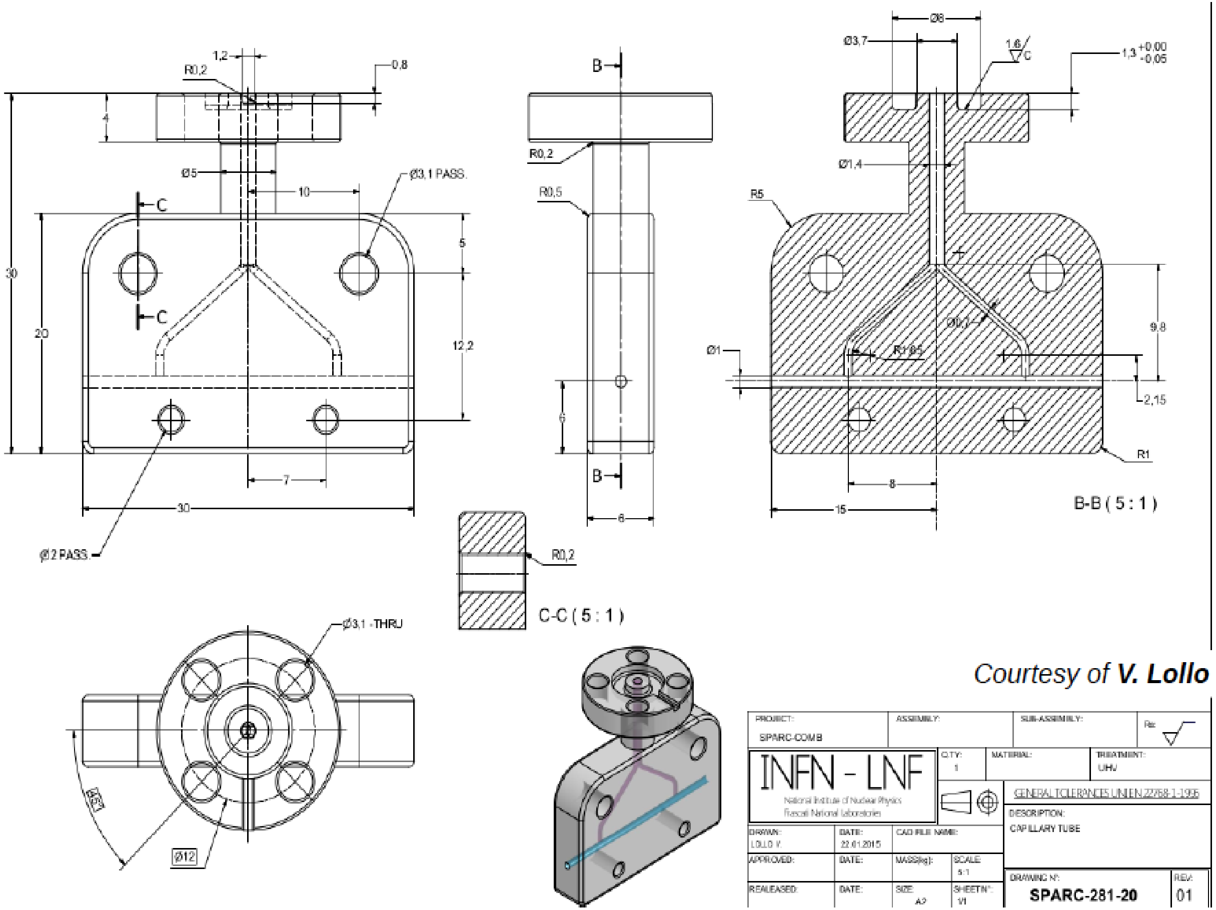

Electron beam
Laser Pulse (200 TW, ~25 fs, E_{transv} ~ TV/m)
Plasma electrons
(plasma cell, ~10^{17} cm^{-3})
Plasma cavity (E_{long} ~ 10 GV/m)
Electron beam
Laser Pulse (E_{transv} ~ TV/m)
~70 μm
~100 μm
(330 fs)
Plasma electrons
(plasma cell, ~10^{17} cm^{-3})

PWFA beam line at SPARC_LAB





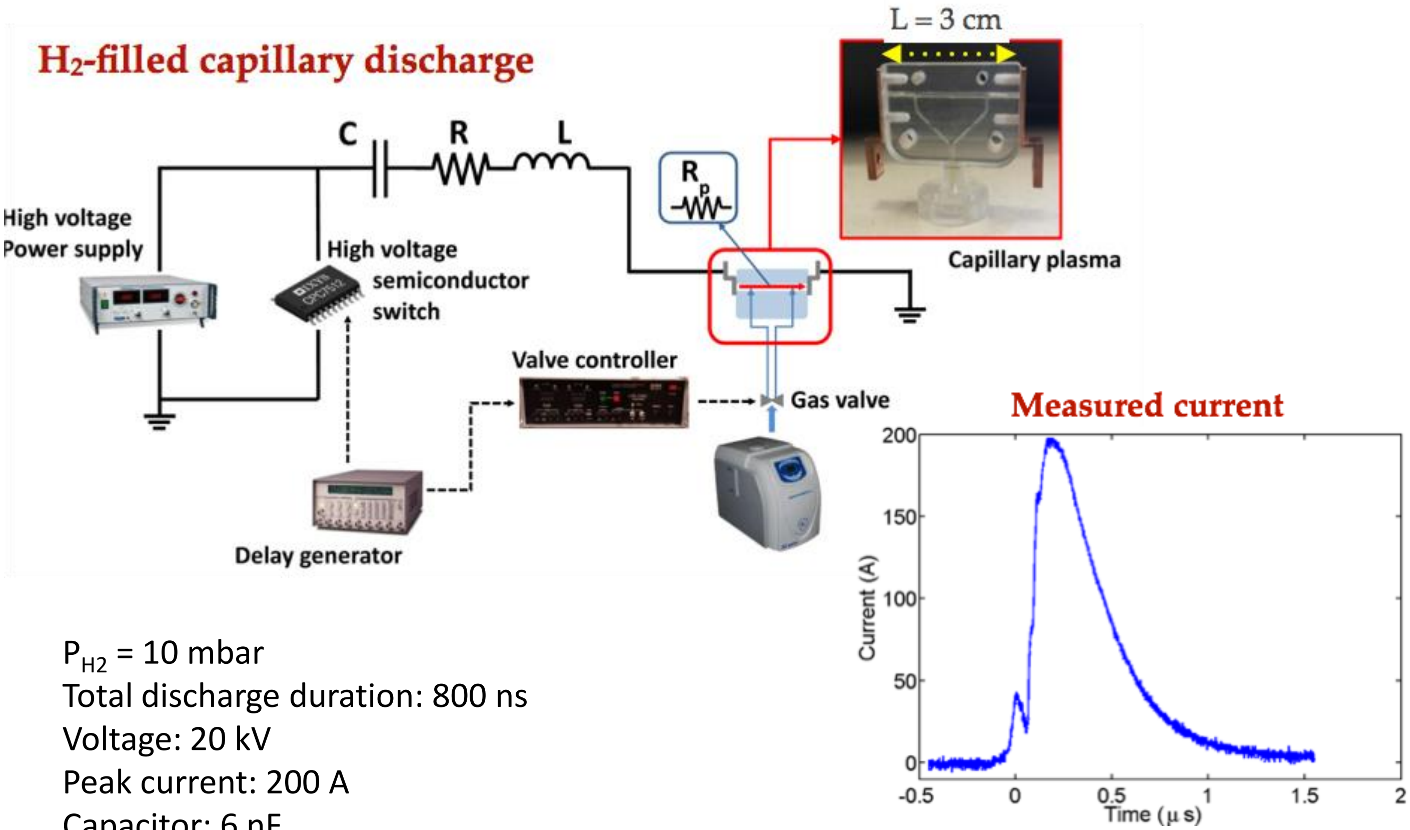
Plasma capillary



Courtesy of ***V. Lollo***

PROJECT: SPARC-COMB	ASSEMBLY:	SUB-ASSEMBLY:	Ra:
INFN - LNF National Institute of Nuclear Physics Frascati National Laboratories	Q.TY: 1	MATERIAL:	TREATMENT: UHV
		GENERAL TOLERANCES UNI EN 22768-1-1996	
DRAWN: LOLLO V.	DATE: 22.01.2015	CAD FILE NAME:	DESCRIPTION: CAPILLARY TUBE
APPROVED:	DATE:	MASS(kg):	SCALE: 5:1
RELEASED:	DATE:	SIZE: A2	SHEET N°: 1/1
DRAWING N°: **SPARC-281-20**	REV: 01		

Plasma Source

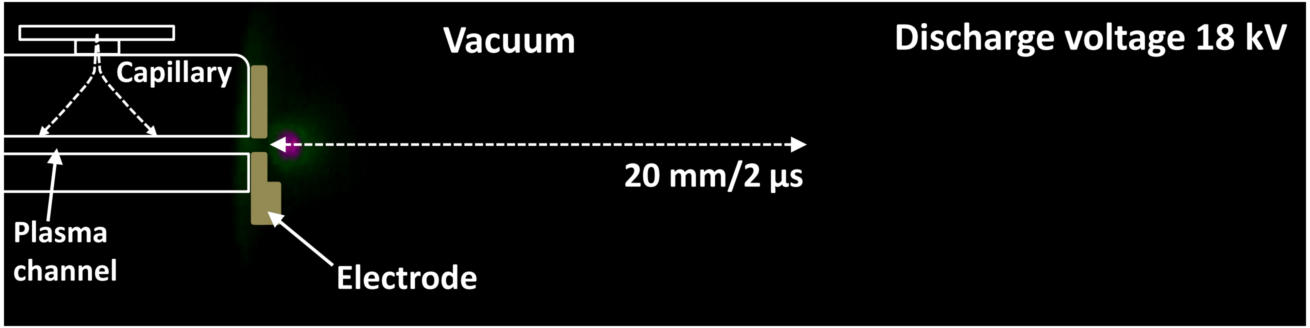


P_{H2} = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

Courtesy of M. P. Anania, A. Biagioni, D. Di Giovenale, F. Filippi, S. Pella

Plasma plumes

- **20 images separated by 100 ns, so 2 μs of total observation time of the plasma plumes**
- **The ICCD camera area is 1024 x 256 pixel**

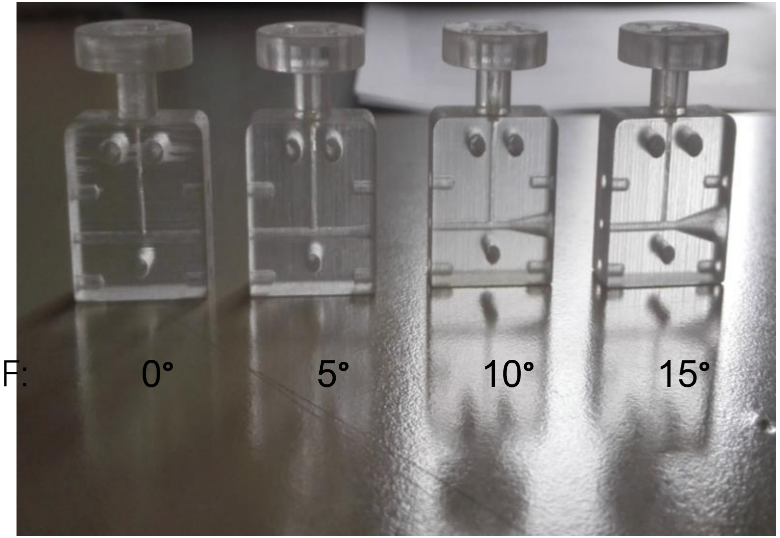


- Both plama plumes can reach a total expansion length around 40 mm (20 mm each one) that is comparable with the channel length of 30 mm, so they can strongly affect the beam properties that passes through the capillary
- Temperature, pressure and plasma density, inside and outside the gas-filled capillary plasma source, represent essential parameters that have to be investigated to understand the plasma evolution and how it can affect the electron beam.

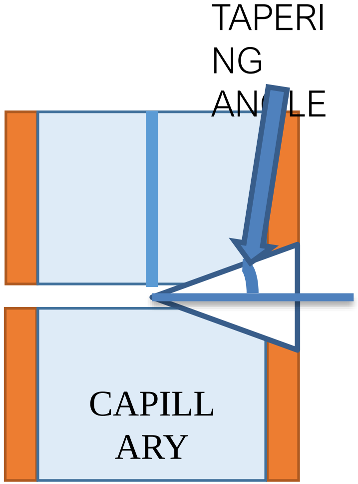
Angelo.Biagioni@lnf.infn.it

Tapered capillaries

Local control of the plasma density is required to match the laser/electron beam into the plasma.
Tapering the capillary diameter is the easiest way to change locally the density.



TAPERING OF: 0° 5° 10° 15°



TAPERING ANGLE

CAPILLARY

Principle of plasma acceleration

Driven by Radiation Pressure

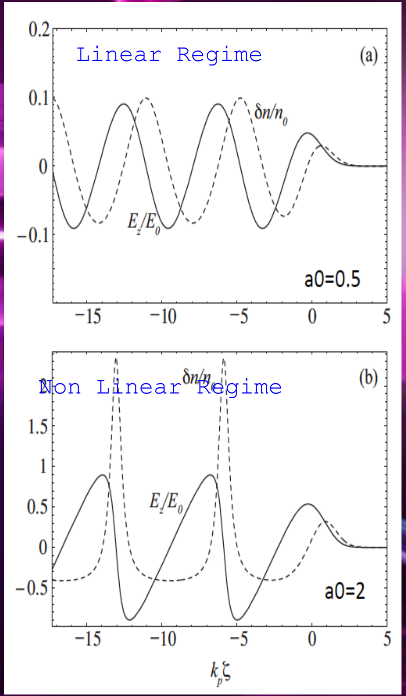
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=c^2\nabla^2\frac{a^2}{2}$$

$$a=\frac{eA}{mc^2}\propto\lambda J^{1/2}$$

Driven by Space Charge

$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=-\omega_p^2\frac{n_{beam}}{n_o}$$

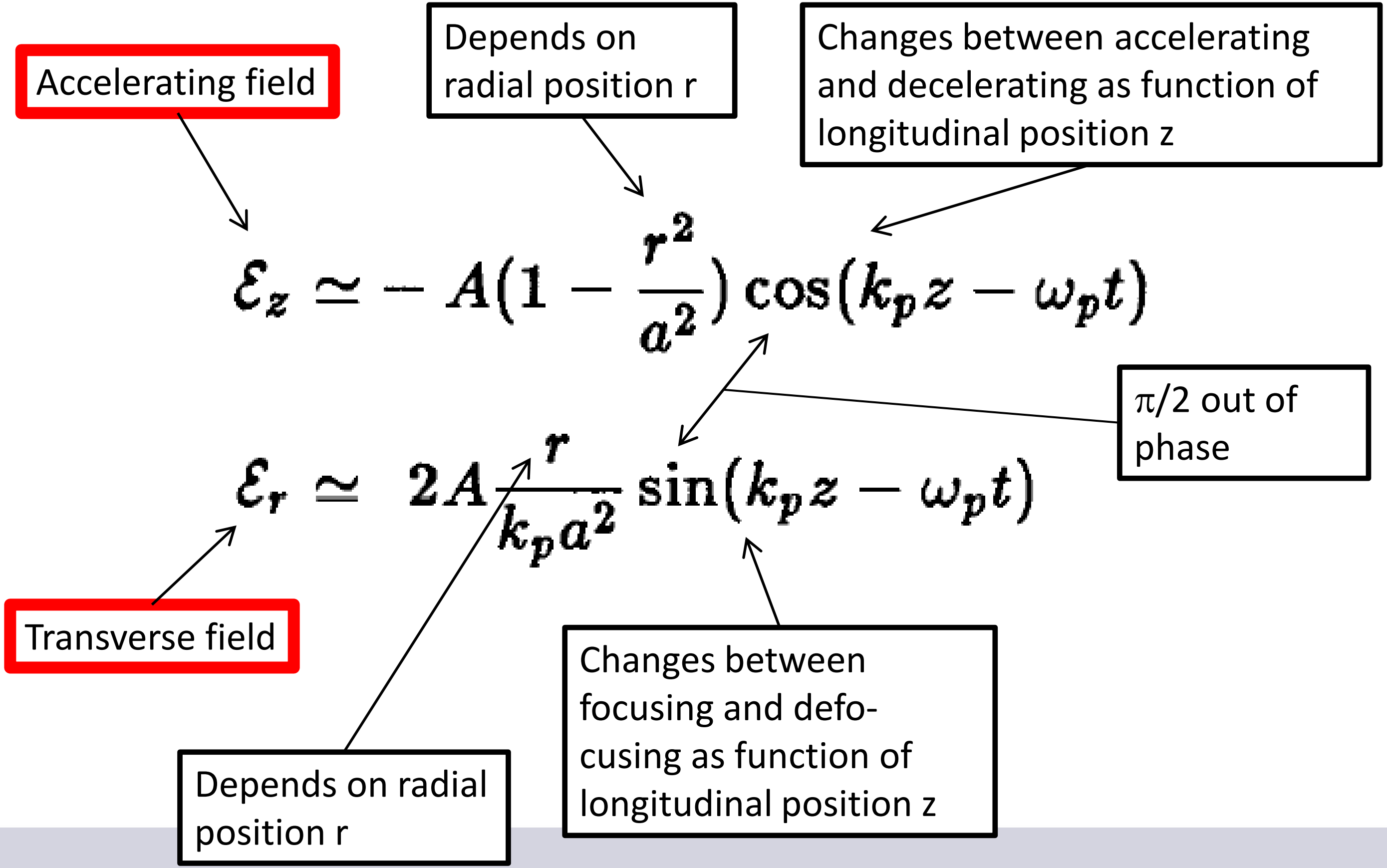
$$n_{beam}=\frac{N}{\sqrt{(2\pi)^3}\,\sigma_r^2\sigma_z}$$



LWFA limitations: Diffraction, Dephasing, Depletion

PWFA limitations: Head Erosion, Hose

Linear Wakefields
(R. Ruth / P. Chen 1986)



Accelerating field

Depends on radial position r

Changes between accelerating and decelerating as function of longitudinal position z

$$\mathcal{E}_z \simeq -A\left(1-\frac{r^2}{a^2}\right)\cos(k_p z - \omega_p t)$$

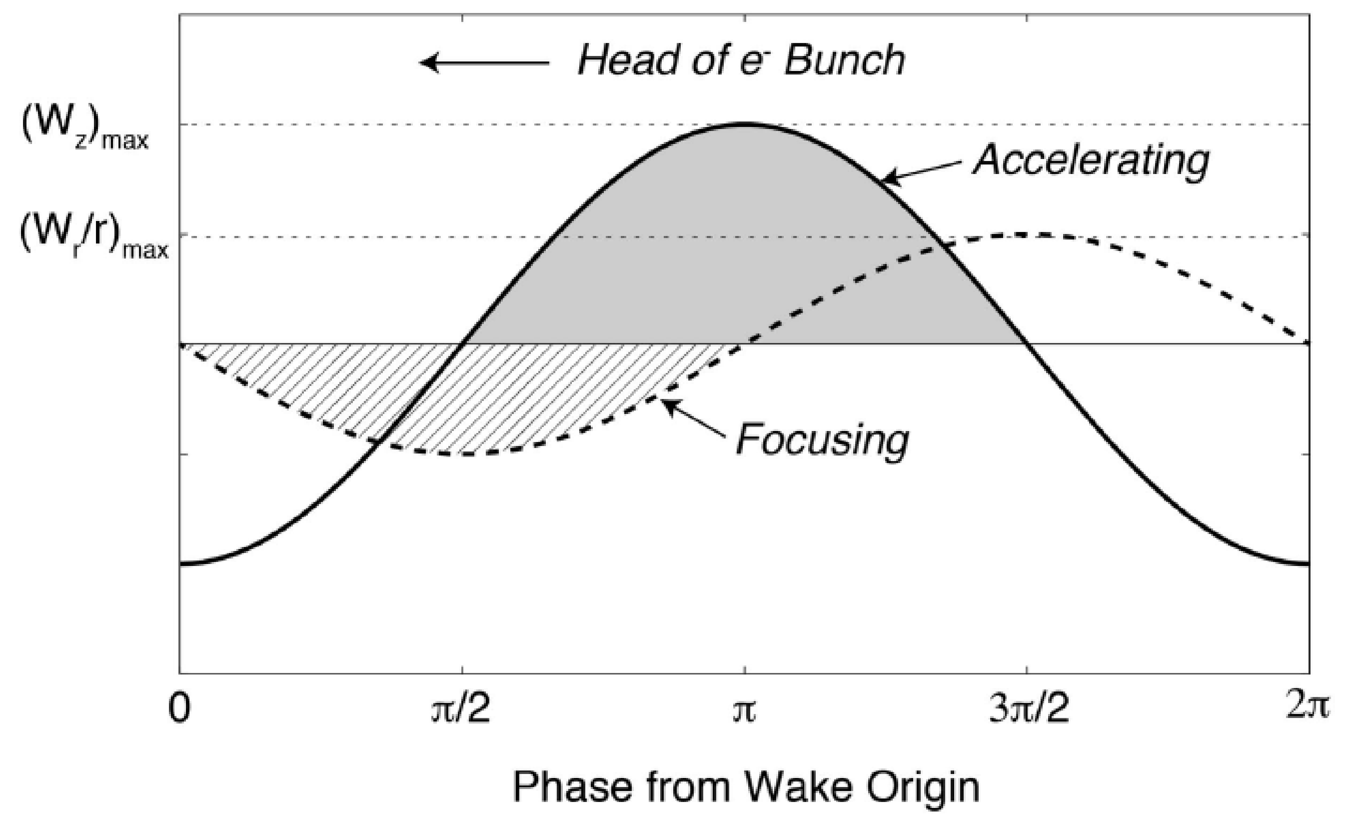
π/2 out of phase

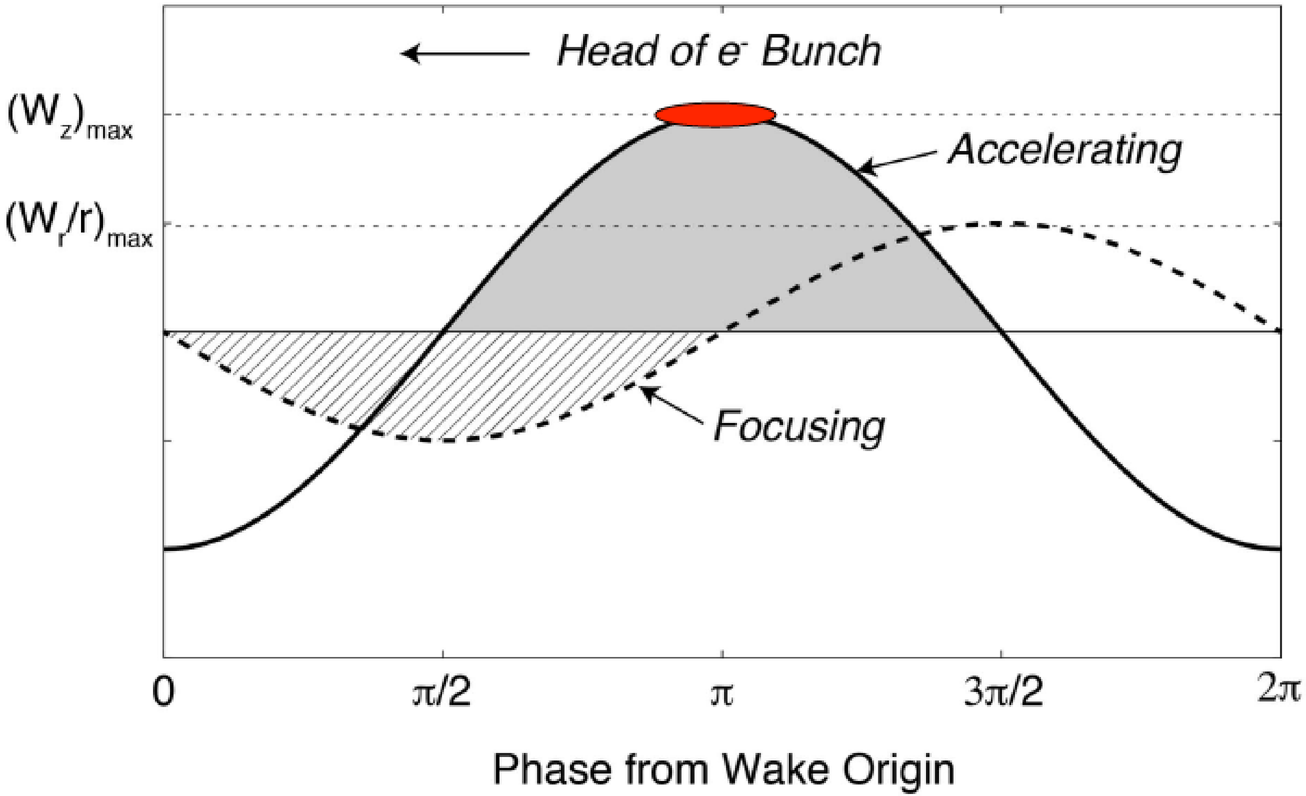
$$\mathcal{E}_r \simeq 2A\frac{r}{k_p a^2}\sin(k_p z - \omega_p t)$$

Transverse field

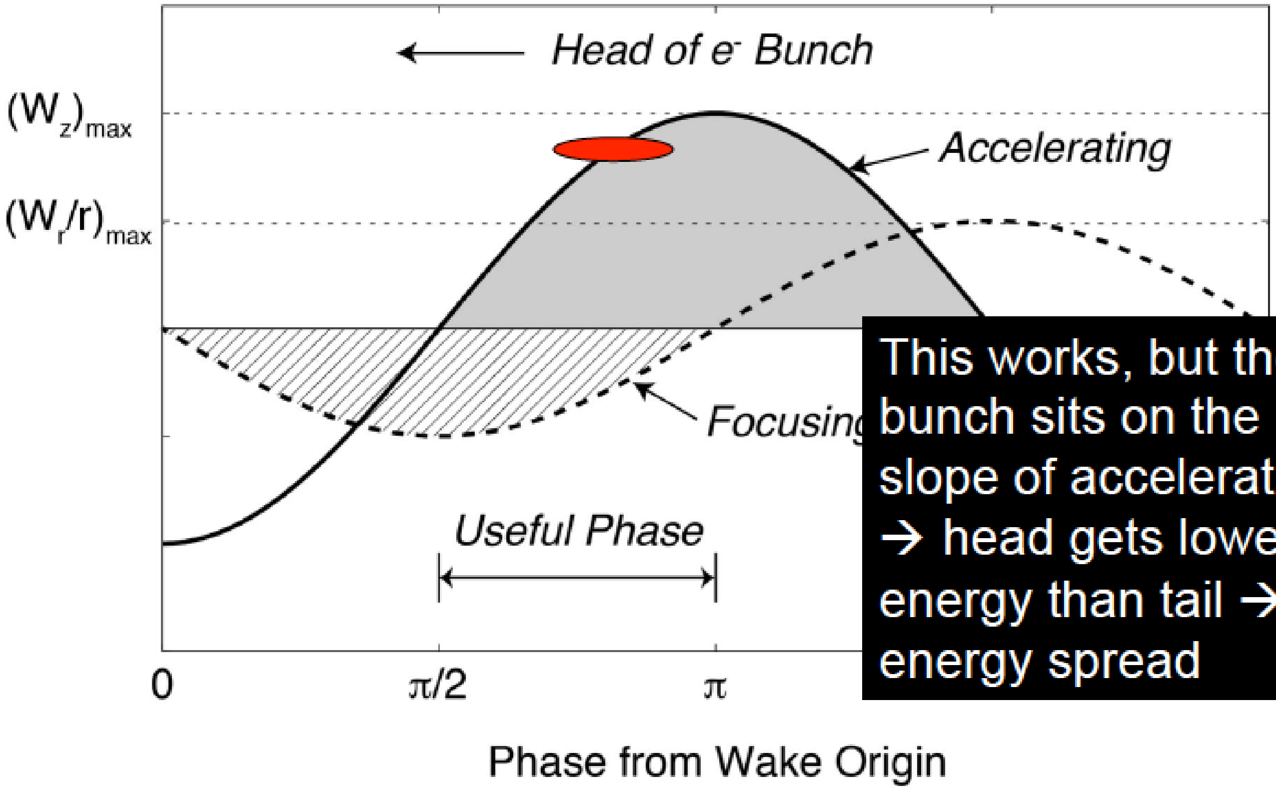
Depends on radial position r

Changes between focusing and defocusing as function of longitudinal position z


Head of e- Bunch
$(W_z)_{max}$
$(W_r/r)_{max}$
Accelerating
Focusing
0
π/2
π
3π/2
2π
Phase from Wake Origin

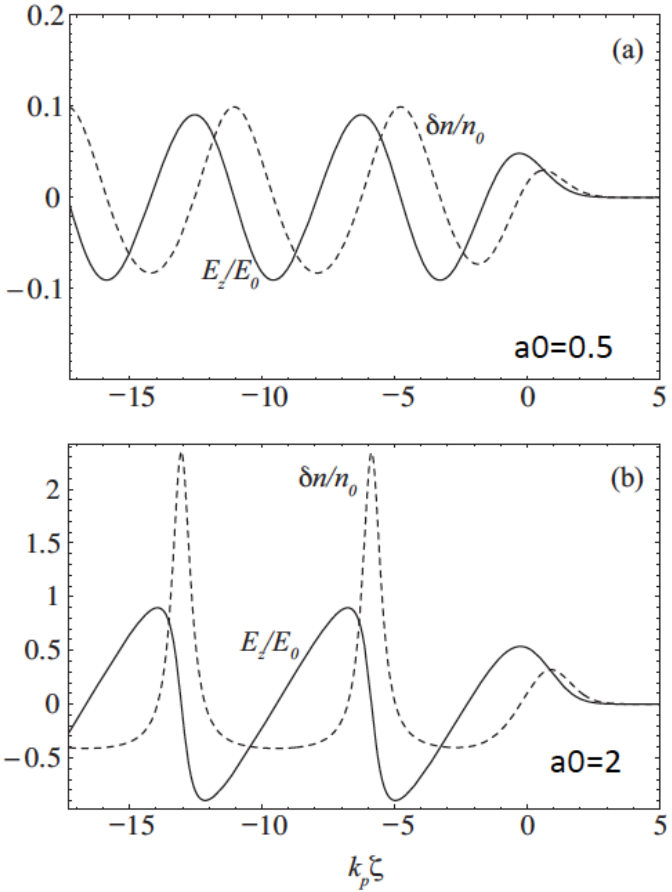


Head of e^- Bunch
$(W_z)_{max}$
$(W_r/r)_{max}$
Accelerating
Focusing
0
$\pi/2$
π
$3\pi/2$
2π
Phase from Wake Origin



This works, but the bunch sits on the slope of acceleration → head gets lower energy than tail → energy spread

Regimes: Linear & Non-Linear

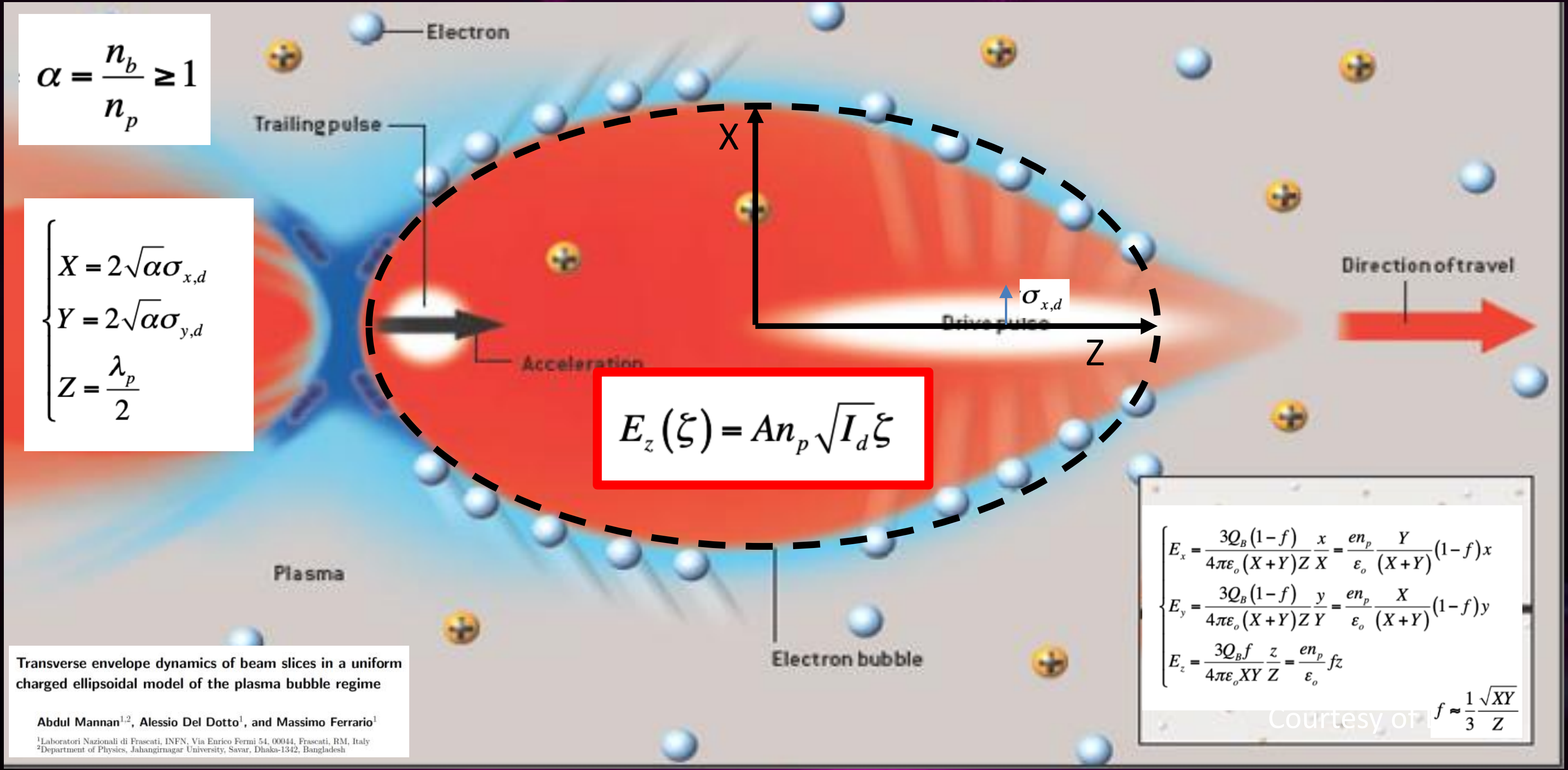


Linear

FIG. 8. Time-averaged density variation $\delta n/n_0$ (dashed curve) and axial electric field E_z/E_0 (solid curve) in an LWFA driven by a Gaussian laser pulse (pulse is moving to the right, centered at $k_p\zeta=0$ with rms intensity length $L_{\rm rms}=k_p^{-1}$) for (a) $a_0=0.5$ and (b) $a_0=2.0$.

Non-Linear

Non Linear Regime – Ellipsoidal Bubble Model



$$\alpha = \frac{n_b}{n_p} \geq 1$$

$$\begin{cases} X = 2\sqrt{\alpha}\sigma_{x,d} \\ Y = 2\sqrt{\alpha}\sigma_{y,d} \\ Z = \frac{\lambda_p}{2} \end{cases}$$

$$\boxed{E_z(\zeta) = An_p\sqrt{I_d}\zeta}$$

$$\begin{cases} E_x = \frac{3Q_B(1-f)}{4\pi\varepsilon_o(X+Y)Z}\frac{x}{X} = \frac{en_p}{\varepsilon_o}\frac{Y}{(X+Y)}(1-f)x \\ E_y = \frac{3Q_B(1-f)}{4\pi\varepsilon_o(X+Y)Z}\frac{y}{Y} = \frac{en_p}{\varepsilon_o}\frac{X}{(X+Y)}(1-f)y \\ E_z = \frac{3Q_Bf}{4\pi\varepsilon_o XY}\frac{z}{Z} = \frac{en_p}{\varepsilon_o}fz \end{cases}$$

$$f \approx \frac{1}{3}\frac{\sqrt{XY}}{Z}$$

Transverse envelope dynamics of beam slices in a uniform charged ellipsoidal model of the plasma bubble regime

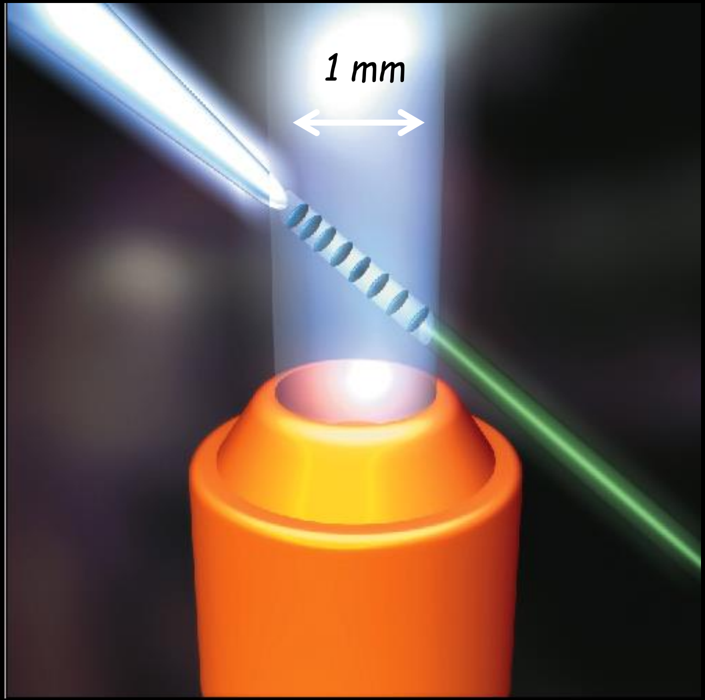
Abdul Mannan[1,2], Alessio Del Dotto[1], and Massimo Ferrario[1]

[1]Laboratori Nazionali di Frascati, INFN, Via Enrico Fermi 54, 00044, Frascati, RM, Italy
[2]Department of Physics, Jahangirnagar University, Savar, Dhaka-1342, Bangladesh

Laser Driven

LWFA

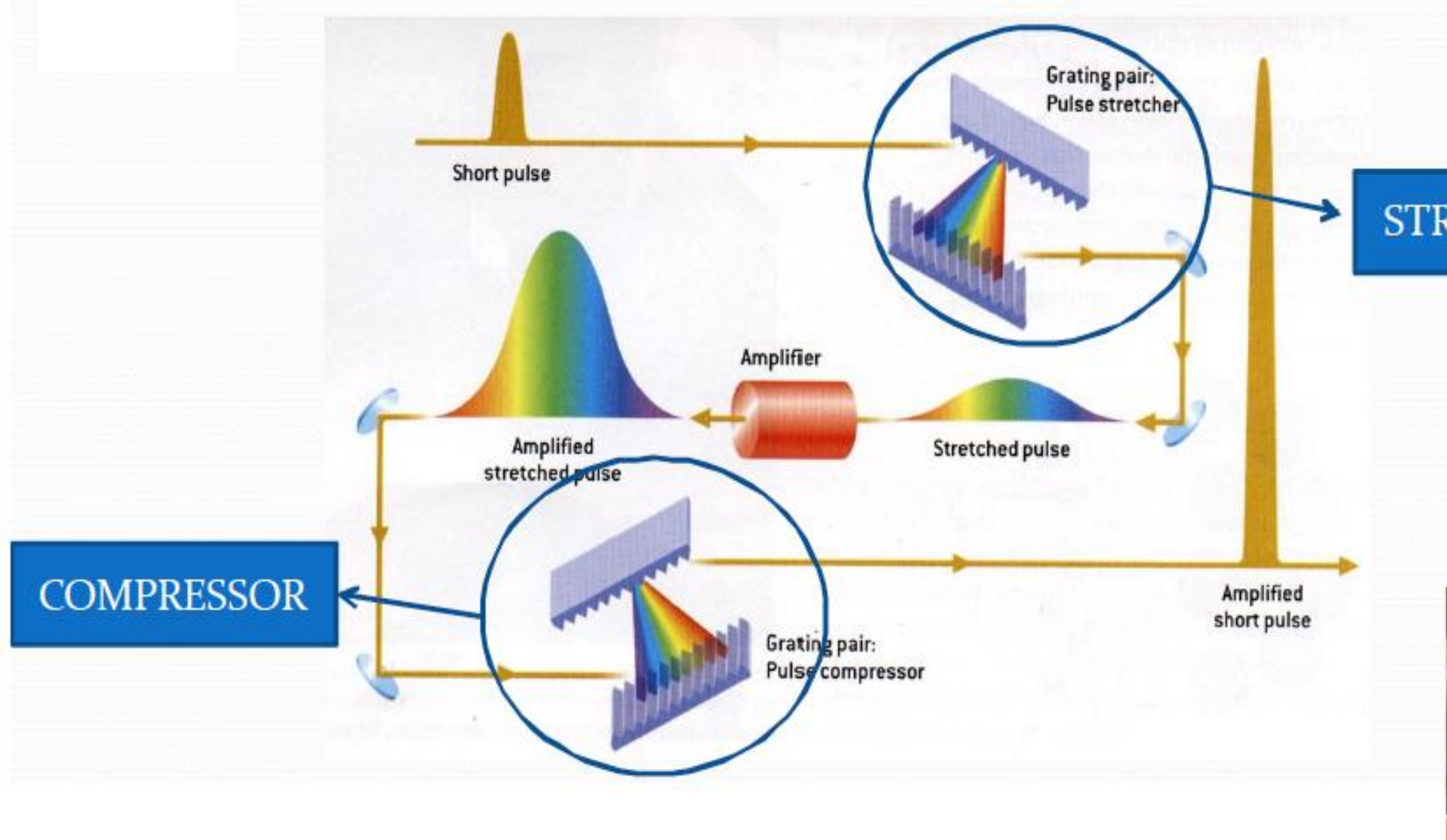
Direct production of e-beam



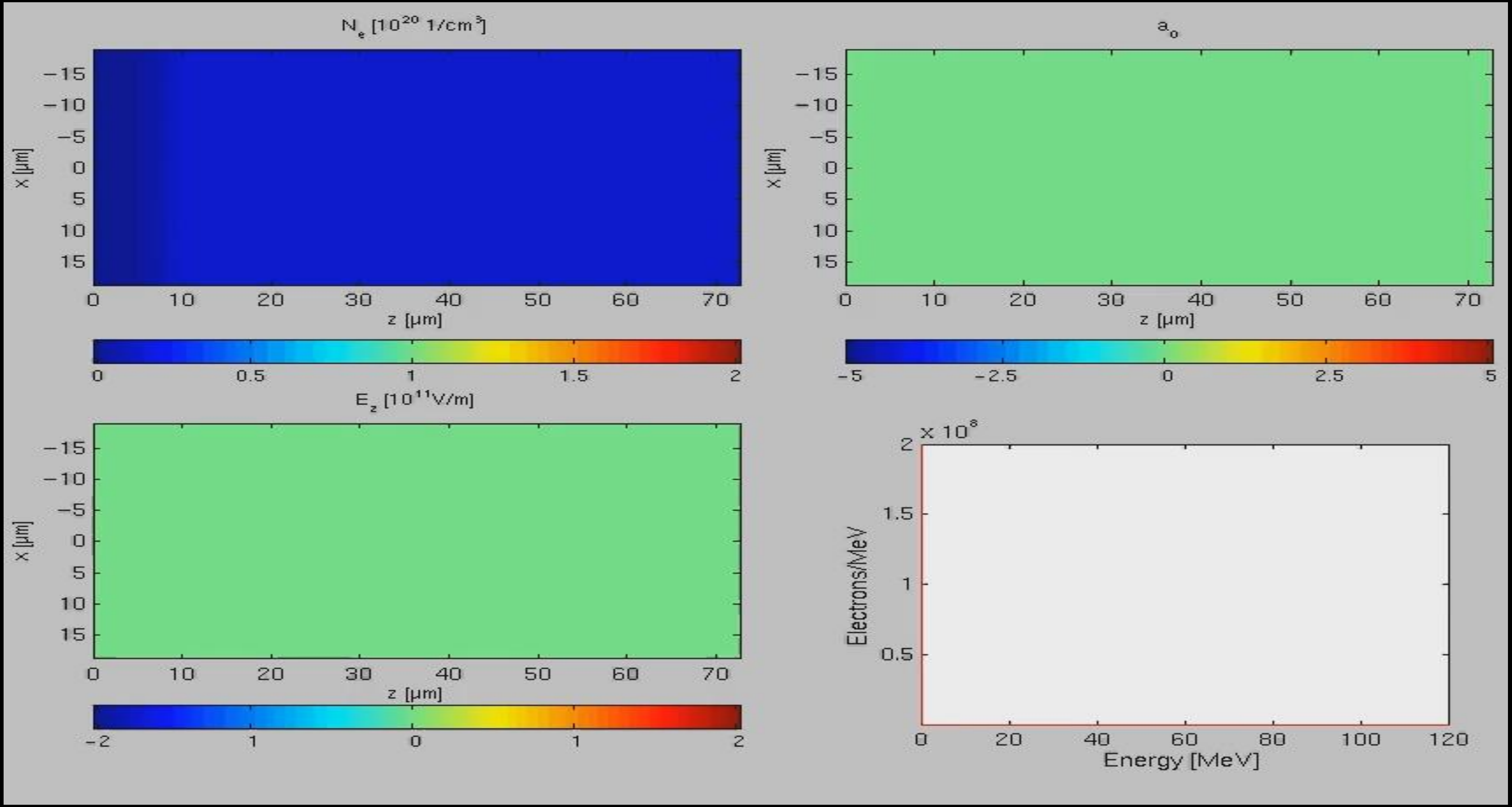
Electron beam

Chirped Pulse

2018
NOBEL PRIZE
Physics

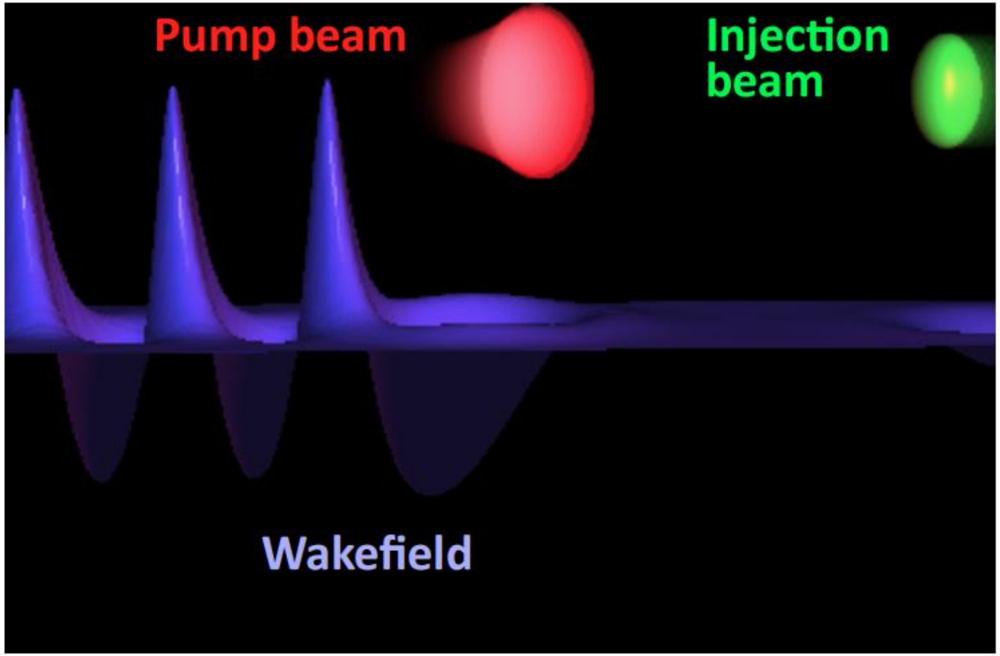


Diffraction - Self injection - Dephasing – Depletion



Colliding Laser Pulses Scheme

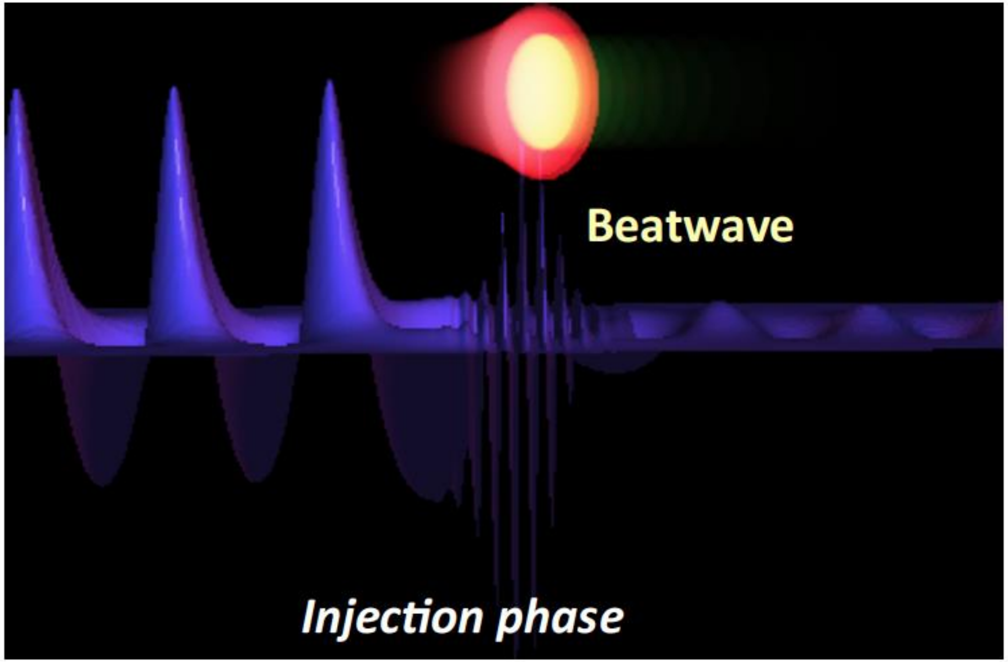
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

Colliding Laser Pulses Scheme

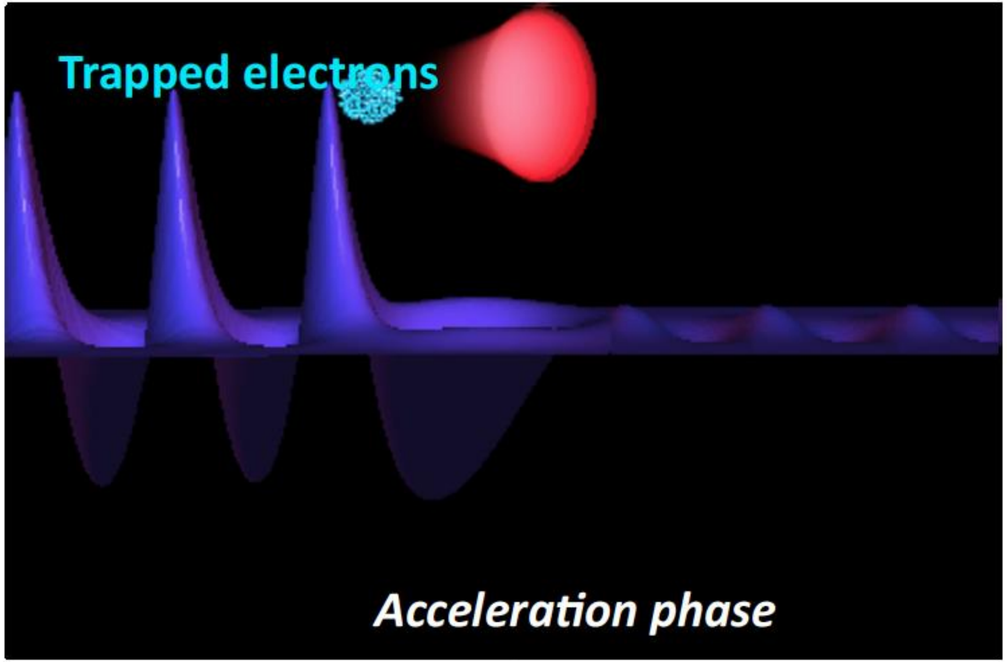
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

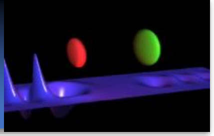
Colliding Laser Pulses Scheme

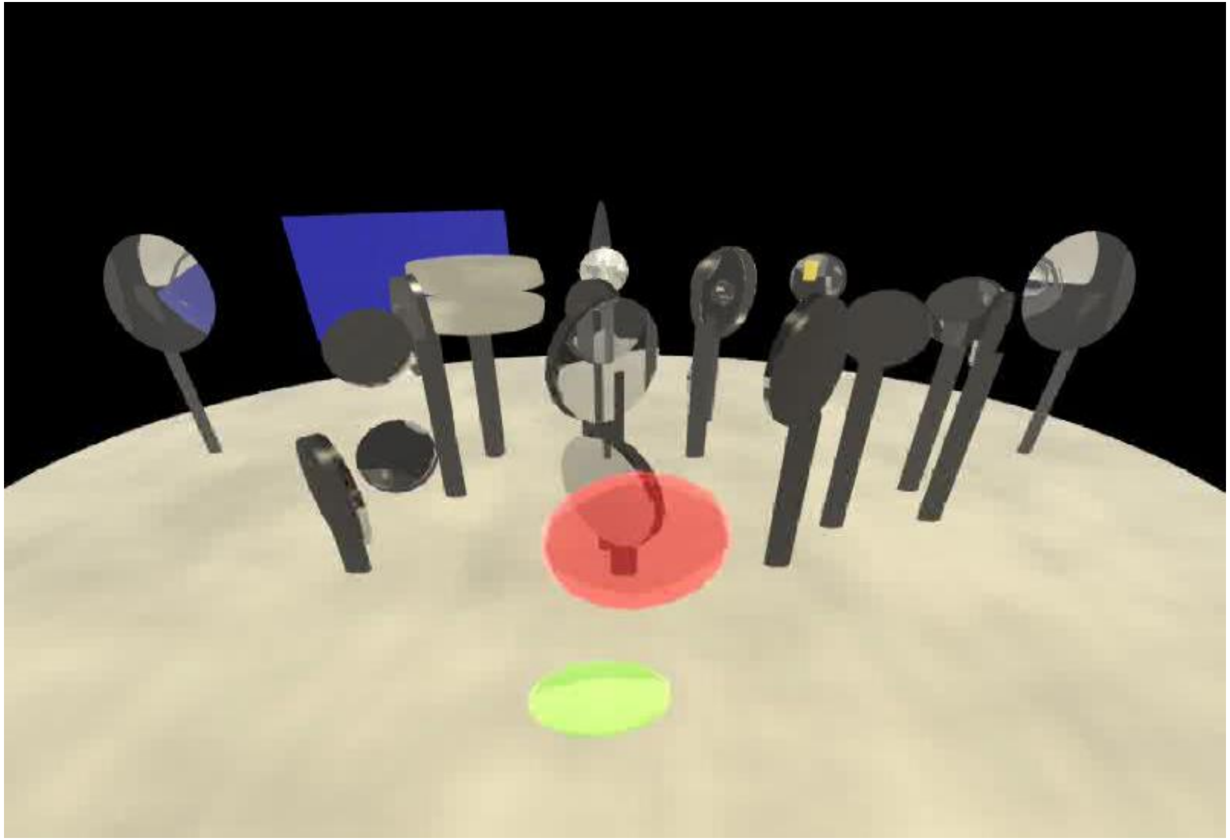
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



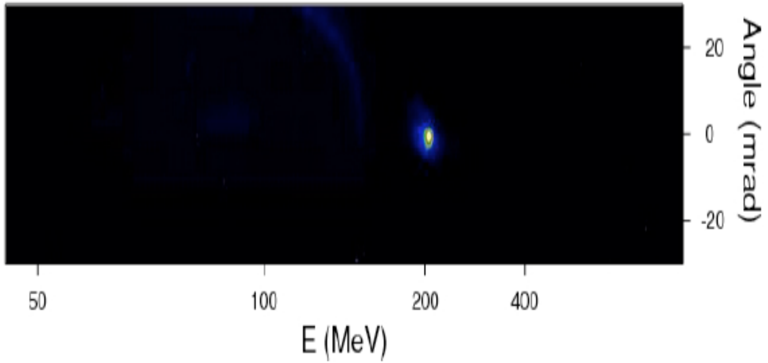
Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

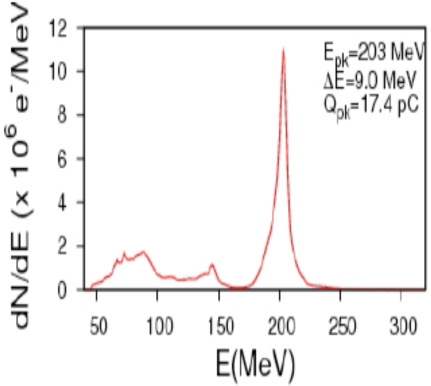
The colliding of two laser pulses



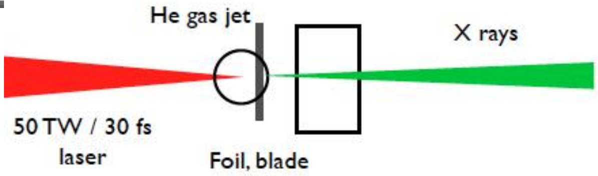


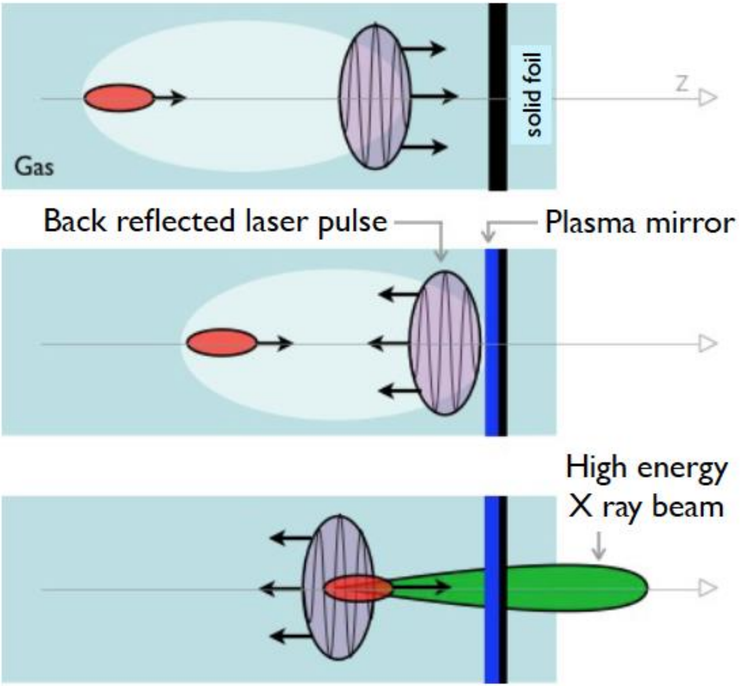
Stable Laser Plasma Accelerators





Inverse Compton Scattering : New scheme





A single laser pulse

A plasma mirror reflects the laser beam

The back reflected laser collides with the accelerated electrons

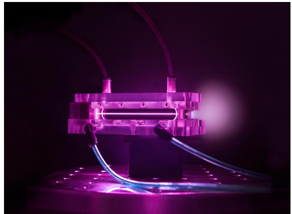
No alignment : the laser and the electron beams naturally overlap

Save the laser energy !

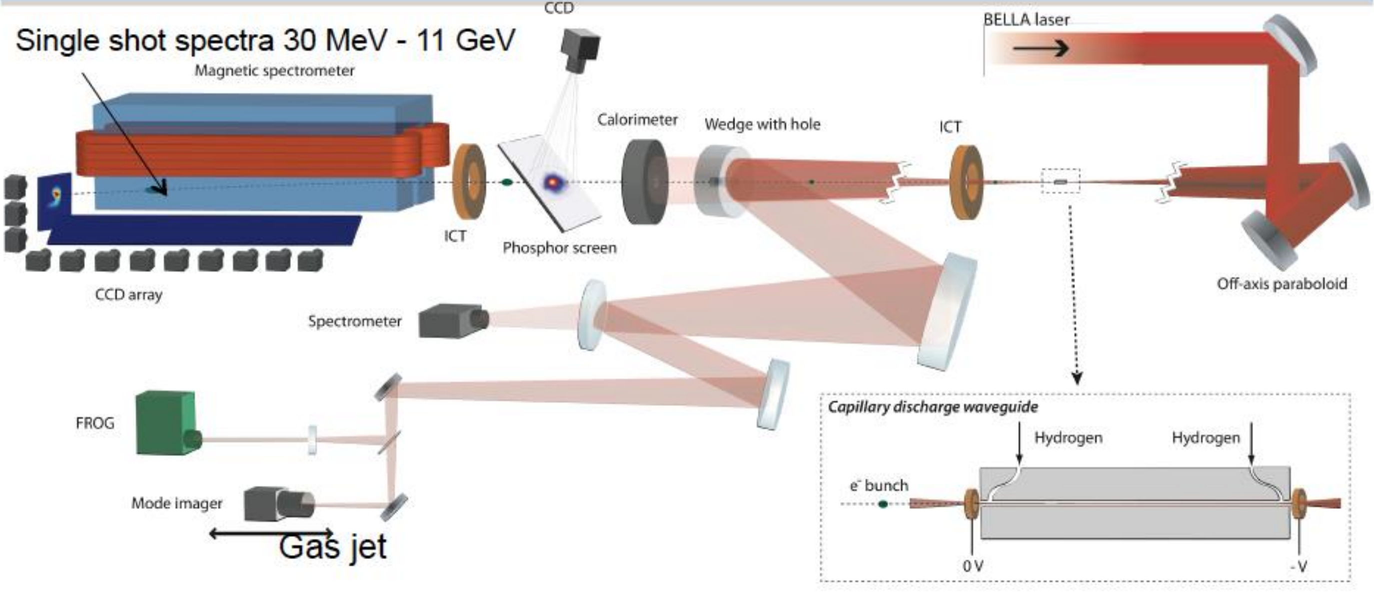
BELLA: BErkeley Lab Laser Accelerator

BELLA Facility: state-of-the-art 1.3 PW-laser for laser accelerator science:
>42 J in <40 fs (> 1PW) at 1 Hz laser and supporting infrastructure at LBNL

Critical HEP experiments:
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration

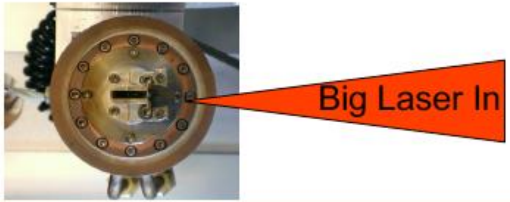


Experiments at LBNL use the BELLA laser focused by a 14 m focal length off-axis paraboloid onto gas jet or capillary discharge targets



Single shot spectra 30 MeV - 11 GeV

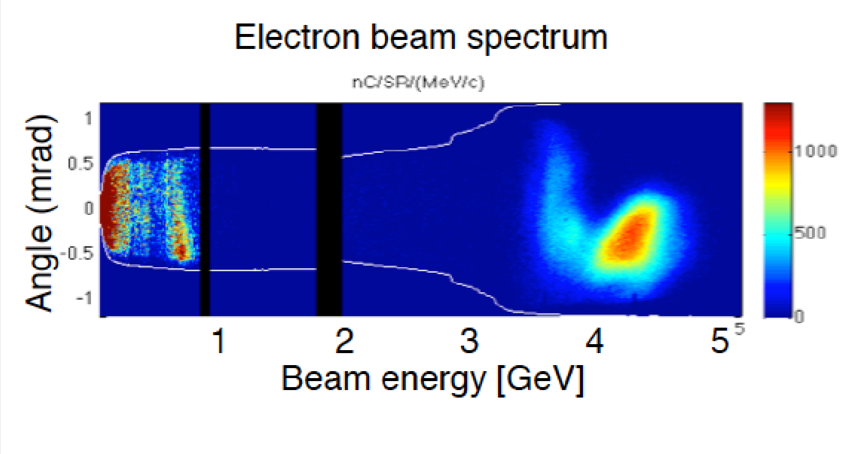
Gas jet

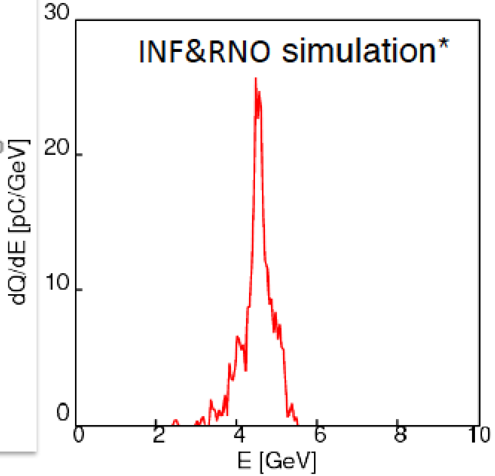


Capillary discharge

4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses (15 J)

*C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012





- **Laser** (E=15 J):
  - Measured) longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 μm)
- **Plasma:** parabolic plasma channel (length 9 cm, n_0~6-7x10^{17} cm^{-3})

	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

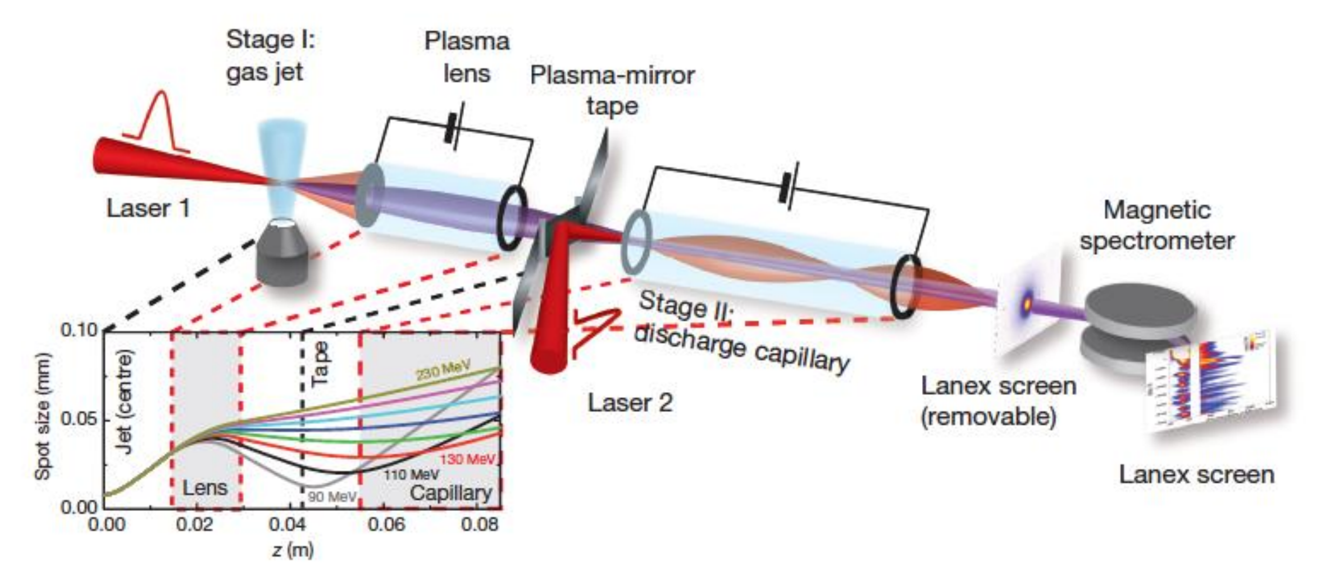
W.P. Leemans et al.,PRL 2014

LETTER

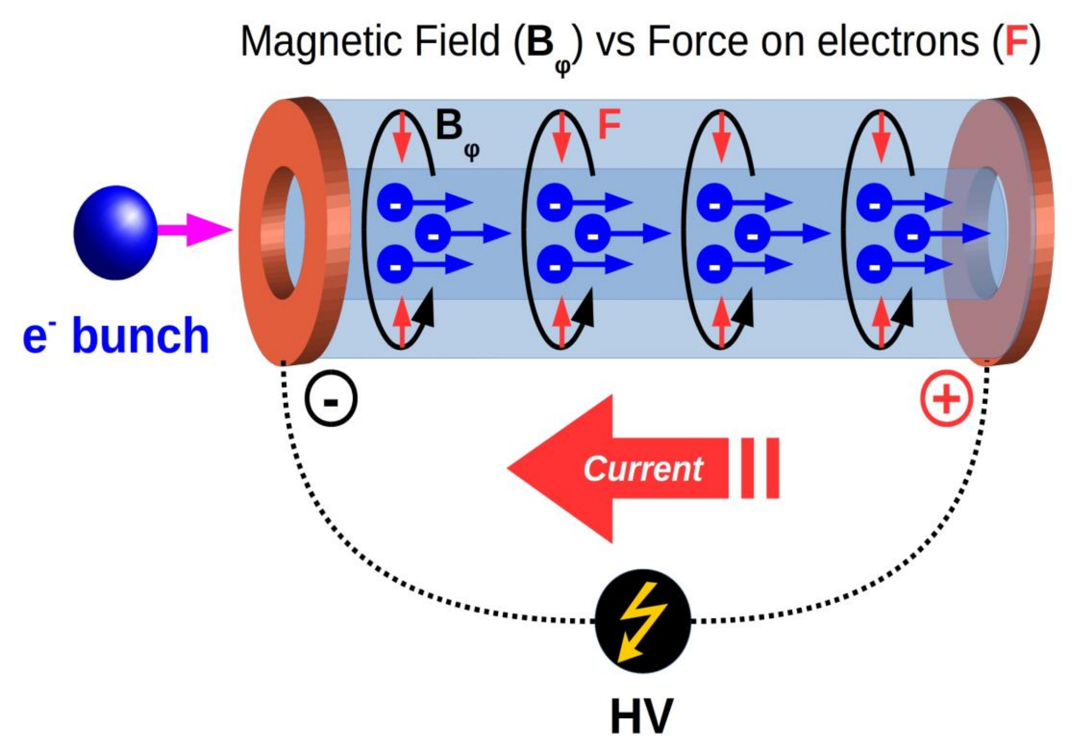
doi:10.1038/nature16525

Multistage coupling of independent laser–plasma accelerators

S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Daniels[1,3], K. K. Swanson[1,2], A. J. Gonsalves[1], K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]



Active Plasma Lens

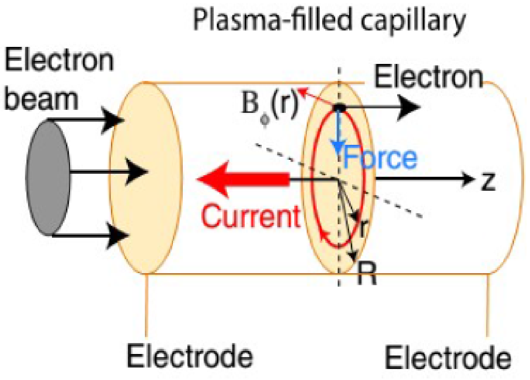


Active plasma lens

- Focusing field produced by electric discharge in a plasma-filled capillary
  - *Focusing field produced, according to Ampere's law, by the discharge current*

$$B_\phi(r)=\frac{1}{2}\int_0^r \mu_0 J(r')\,dr'$$

- ✓ Radial focusing
  - *X/Y planes are not dependent as in quads*
- ✓ Weak chromaticity
  - *Focusing force scales linearly with energy*
- ✓ Compactness
  - *Higher integrated field than quad triplets*
- ✓ Independent from beam distribution
  - *Not sensitive to longitudinal/transverse charge profile as in passive plasma lenses*

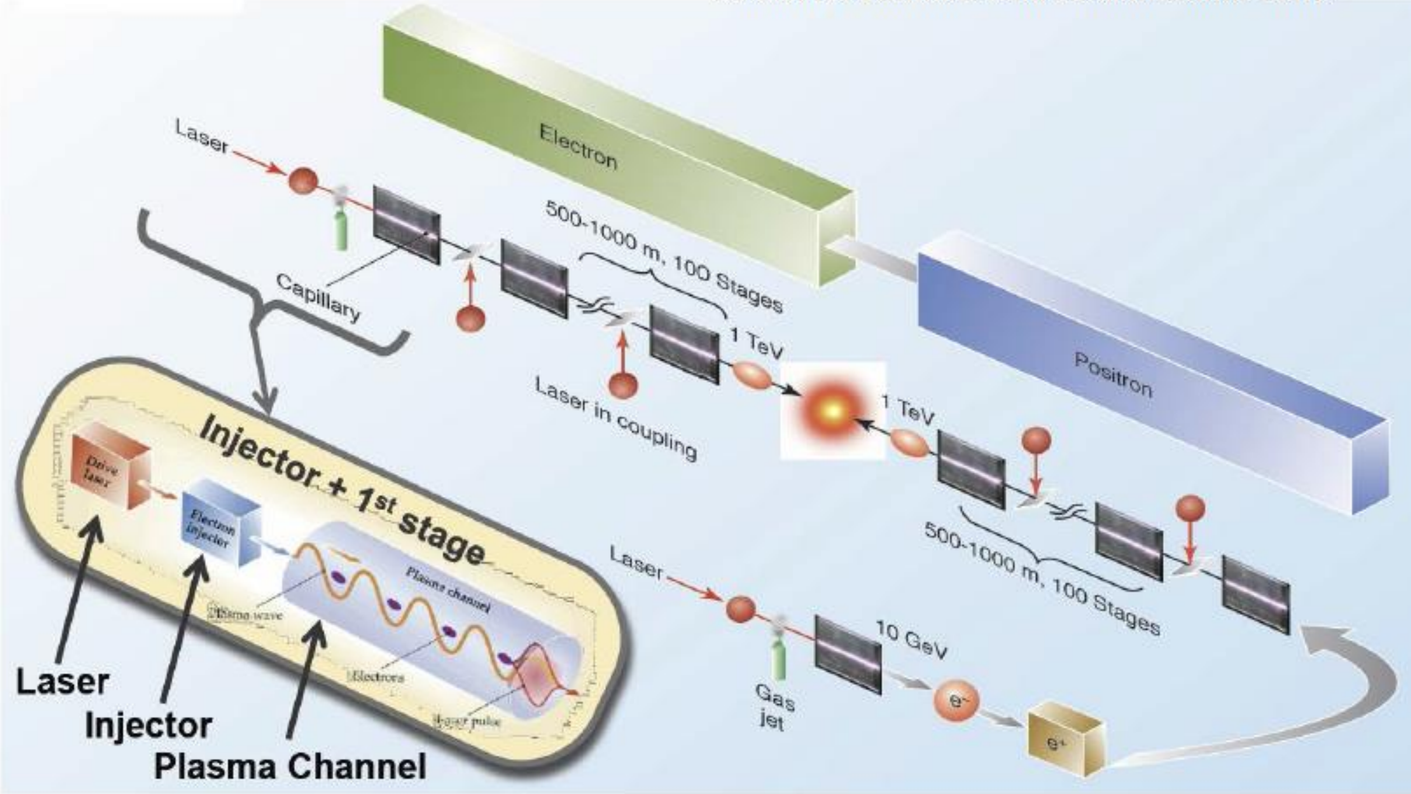


Van Tilborg, J., et al. "Active plasma lensing for relativistic laser-plasma-accelerated electron beams." Physical review letters 115.18 (2015): 184802.

Beam Manipulation

Laser-Plasma-Accelerator LC

Leemans & Esarey, Physics Today (March 2009)

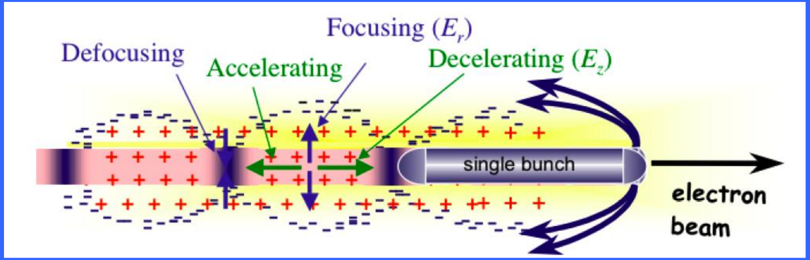


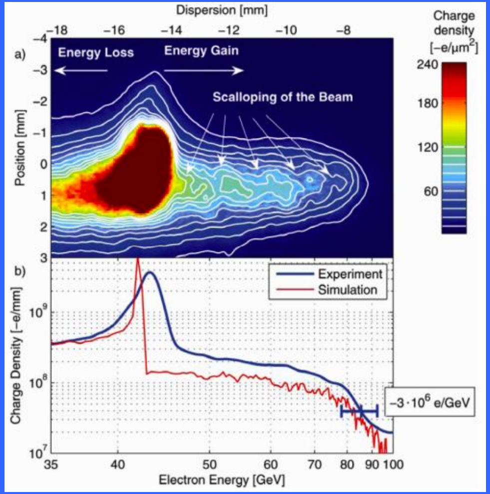
Parameter Set for LPWA LC

Case: CoM Energy (Plasma density)	**1 TeV** (10^{17} cm^{-3})	**1 TeV** (2×10^{15} cm^{-3})	**10 TeV** (10^{17} cm^{-3})	**10 TeV** (2×10^{15} cm^{-3})	
Energy per beam (TeV)	0.5	0.5	5	5	
Luminosity (10^{34} cm^{-2}s^{-1})	2	2	200	200	
Electrons per bunch ($\times10^{10}$)	0.4	2.8	0.4	2.8	
Bunch repetition rate (kHz)	15	0.3	15	0.3	☹
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	100	100	50	50	☹
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	100	100	50	50	☹
β^* (mm)	1	1	0.2	0.2	☹
Horizontal beam size at IP σ^*_x (nm)	10	10	1	1	
Vertical beam size at IP σ^*_y (nm)	10	10	1	1	
Disruption parameter	0.12	5.6	1.2	56	
Bunch length σ_z (μm)	1	7	1	7	
Beamstrahlung parameter Υ	180	180	18,000	18,000	
Beamstrahlung photons per e, n_γ	1.4	10	3.2	22	
Beamstrahlung energy loss δ_E (%)	42	100	95	100	☹
Accelerating gradient (GV/m)	10	1.4	10	1.4	☹
Average beam power (MW)	5	0.7	50	7	
Wall plug to beam efficiency (%)	6	6	10	10	
One linac length (km)	0.1	0.5	1.0	5	**×2+FF**

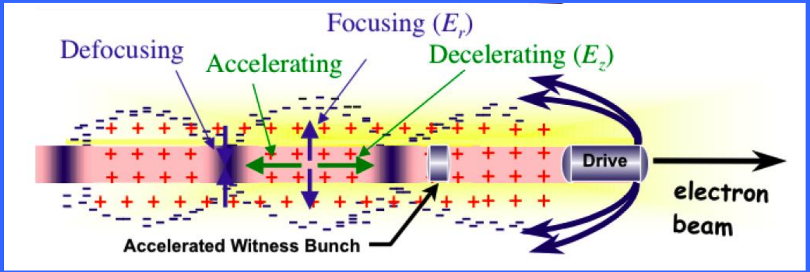
Beam Driven

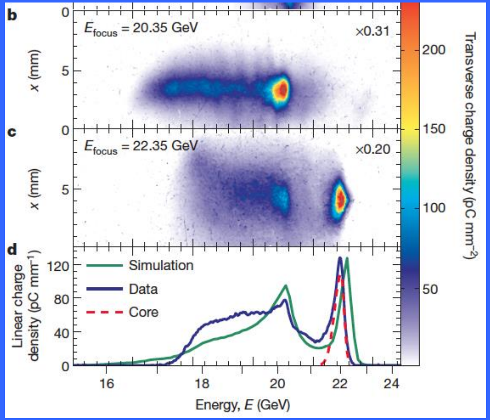
PWFA





Blumenfeld, I. et al. *Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator*. **Nature** 445, 741–744 (2007).

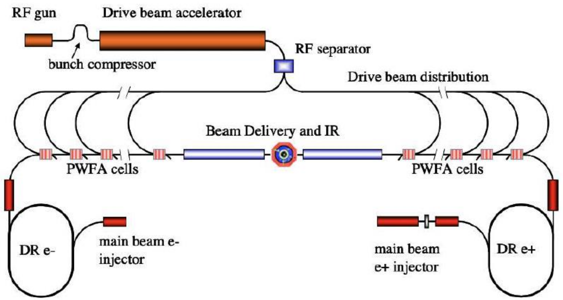




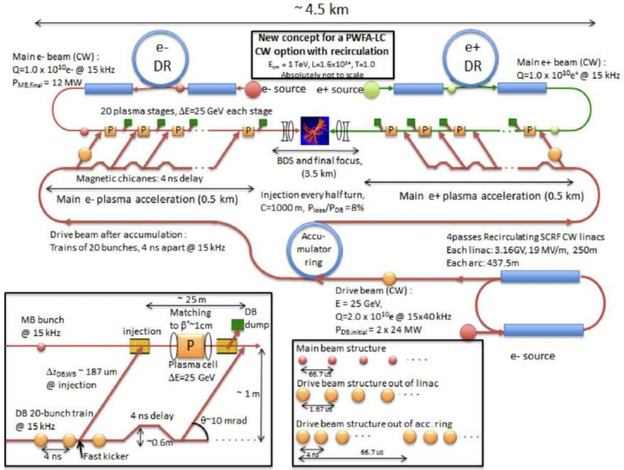
Litos, M. et al. *High-efficiency acceleration of an electron beam in a plasma wakefield accelerator*. **Nature** 515, 92–95 (2014).

Solution: **A plasma-based e⁺e⁻ collider?**

- Footprint of RF colliders dominated by main linacs:
  - Use plasma-based accelerators (GV/m)
- Several proposals over the past decades:
  - Rosenzweig *et al.* (1996)
  - Pei *et al.* (2009)
  - Schroeder *et al.* (2010)
  - Adli *et al.* (2013)
- **Simplistic, but useful exercises to focus the R&D**
- Some key challenges have been identified:
  - Positron acceleration
  - Energy efficiency



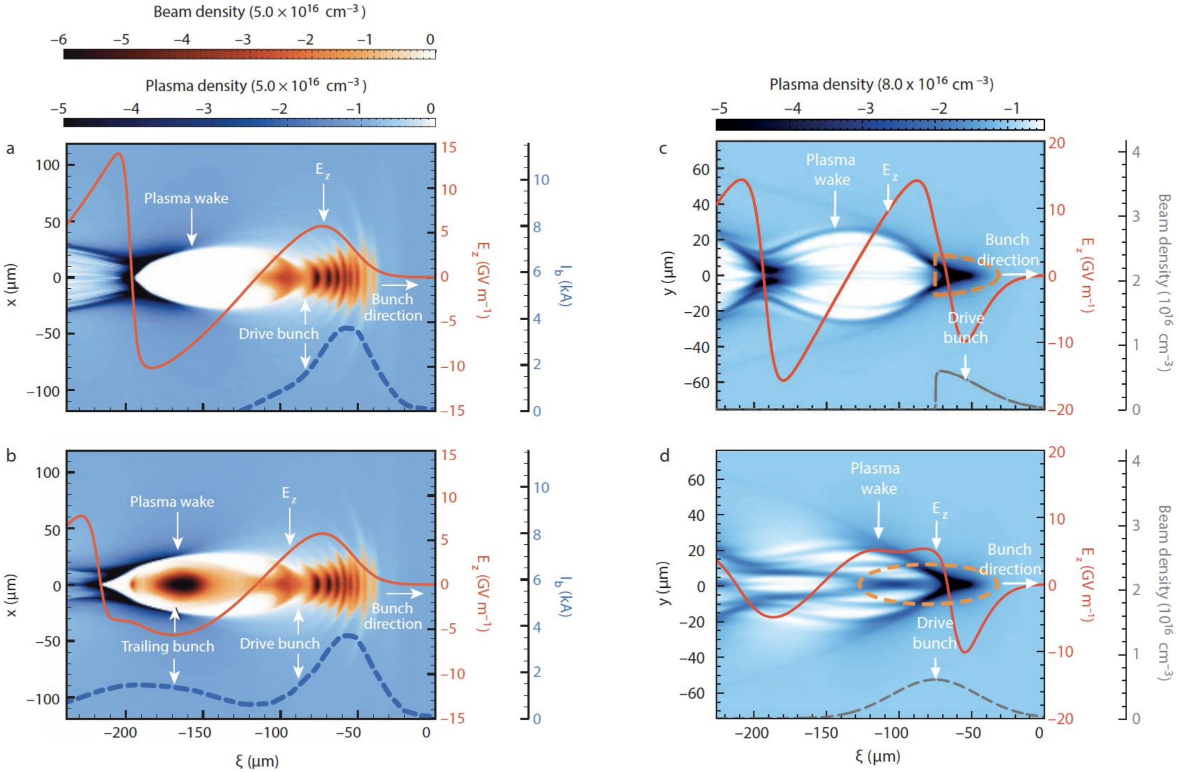
Source: Pei et al., Proc. PAC (2009)



Source: Adli et al., Proc. Snowmass (2013)

Main problem: **Positron acceleration in plasmas**

- Plasmas = charge asymmetric
    - No "blowout regime" for e^+
- Positron acceleration has been demonstrated.
    - Several schemes proposed to improve beam quality.
      — but lack of e^+ test facilities



Source: Litos et al. Nature 515, 92 (2014), Corde et al. Nature 524, 442 (2015).

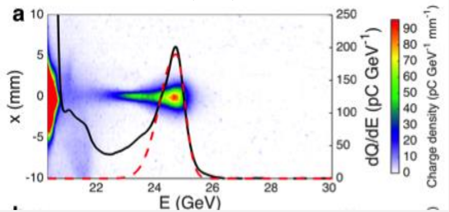
Positron Acceleration, FACET

First demonstration of positron acceleration in plasma (FFTB)

*B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (**2003**)*
M. J. Hogan et. al. Phys. Rev. Lett. 90 205002 (2003).

Energy gain of 5 GeV. Energy spread can be as low as 1.8%

S. Corde et al., Nature ***524****, 442 (2015)*

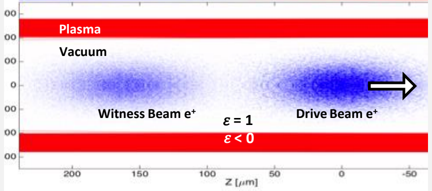


High-density, compressed positron beam for non-linear PWFA experiments. Energy transfer from the front to the back part of the bunch.

Two-bunch positron beam: First demonstration of controlled beam in positron-driven wake
S. Doche *et al.*, Nat. Sci. Rep. 7, 14180 (2017)

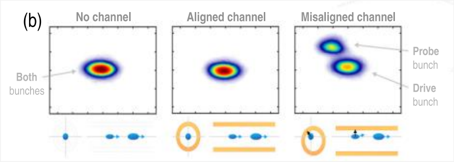
Hollow plasma channel: positron propagation, wake excitation, acceleration in 30 cm channel.

S. Gessner et. al. Nat. Comm. 7, 11785 (2016)



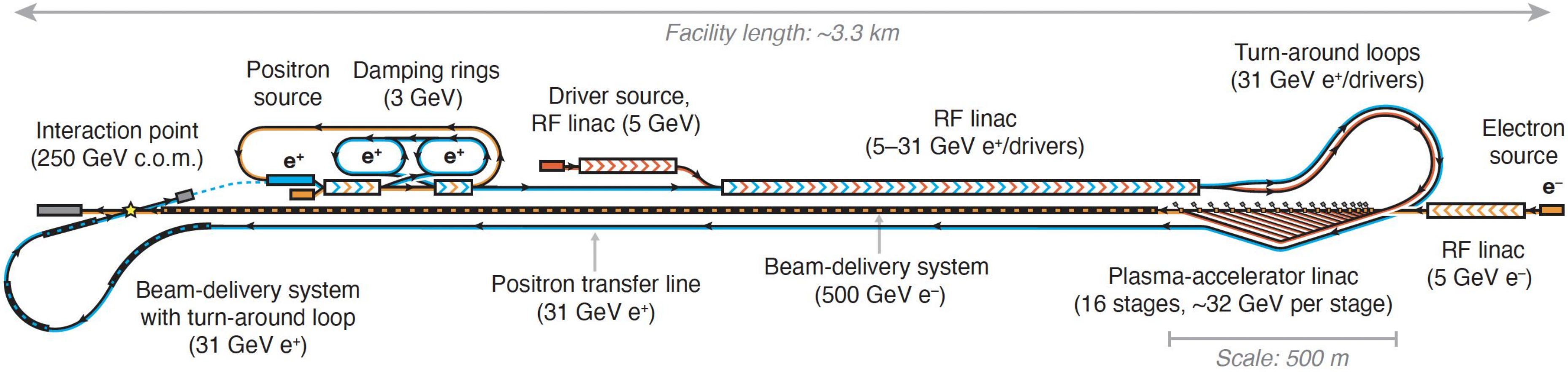
Measurement of **transverse wakefields in a hollow plasma** channel due to off-axis drive bunch propagation.

*C. A. Lindstrøm et. al. Phys. Rev. Lett. 120 124802 (**2018**).*



➔ **Emittance blow-up is an issue!** → Use hollow-channel, so no plasma on-axis, no complicated forces from plasma electrons streaming through the plasma → but then strong transverse wakefields when beams are misaligned.

HALHF: A Hybrid, Asymmetric, Linear Higgs Factory



Facility length: ~3.3 km

Positron source

Damping rings (3 GeV)

Driver source, RF linac (5 GeV)

Turn-around loops (31 GeV e^+/drivers)

Interaction point (250 GeV c.o.m.)

RF linac (5–31 GeV e^+/drivers)

Electron source

Beam-delivery system with turn-around loop (31 GeV e^+)

Positron transfer line (31 GeV e^+)

Beam-delivery system (500 GeV e^-)

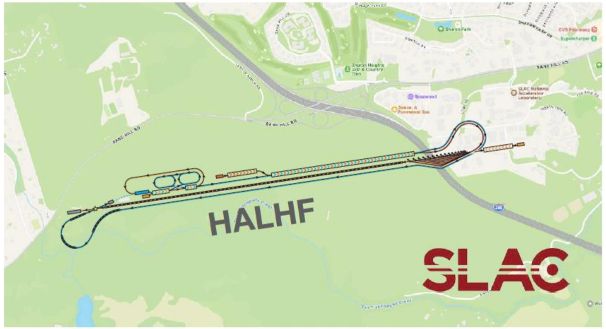
Plasma-accelerator linac (16 stages, ~32 GeV per stage)

RF linac (5 GeV e^-)

Scale: 500 m

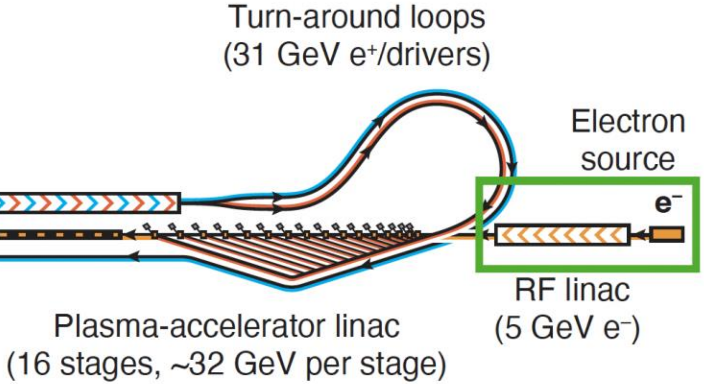
Source: Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)

- Beam-driven: Use e^+ RF linac for producing e^- drivers
- Overall footprint: ~3.3 km
  - Length dominated by e^- beam-delivery system
  - Fits in most major particle-physics laboratories



The novelty: **A multistage plasma-based linac**

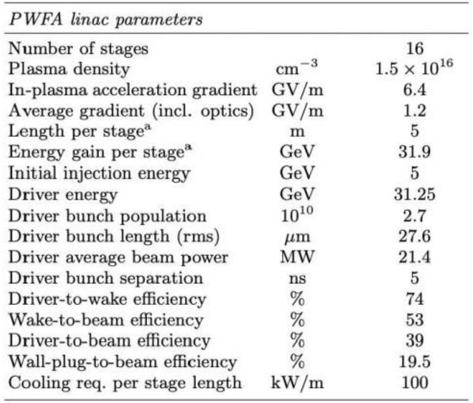
- Length: 16 PWFA stages (5-m long): ~400 m total length
- Gradient: 6.4 GV/m (in plasma)—1.2 GV/m (average)
- Efficiency: 38% = 72% depletion, 53% wake extraction
- No damping ring required due to high-emittance electrons


Turn-around loops
(31 GeV e+/drivers)

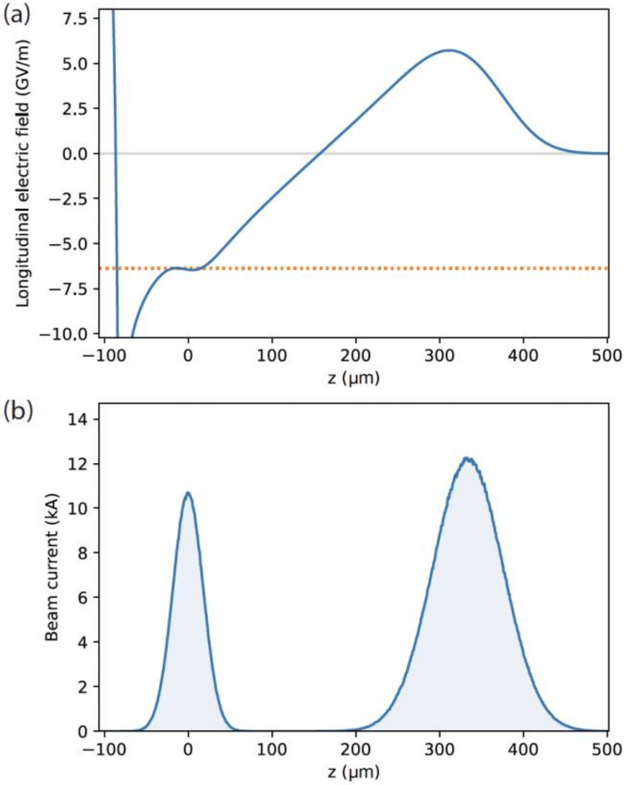
Electron source

RF linac
(5 GeV e−)

Plasma-accelerator linac
(16 stages, ~32 GeV per stage)


PWFA linac parameters

Number of stages		16
Plasma density	cm^{-3}	1.5×10^{16}
In-plasma acceleration gradient	GV/m	6.4
Average gradient (incl. optics)	GV/m	1.2
Length per stage[a]	m	5
Energy gain per stage[a]	GeV	31.9
Initial injection energy	GeV	5
Driver energy	GeV	31.25
Driver bunch population	10^{10}	2.7
Driver bunch length (rms)	μm	27.6
Driver average beam power	MW	21.4
Driver bunch separation	ns	5
Driver-to-wake efficiency	%	74
Wake-to-beam efficiency	%	53
Driver-to-beam efficiency	%	39
Wall-plug-to-beam efficiency	%	19.5
Cooling req. per stage length	kW/m	100



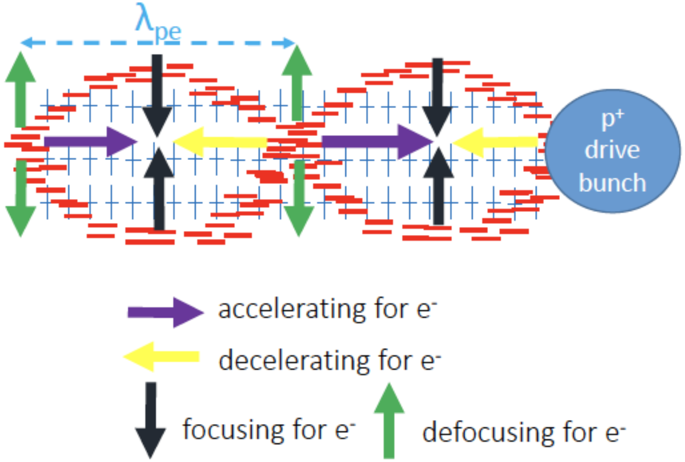
Simulated with Wake-T
Plasma density: 7 x 10^{15} cm^{-3}
Driver/witness charge: 4.3/1.6 nC

Proton-driven Plasma Wakefield Acceleration Collaboration: Accelerating e$^-$ on the wake of a p$^+$ bunch

Reasons for proton bunch driver

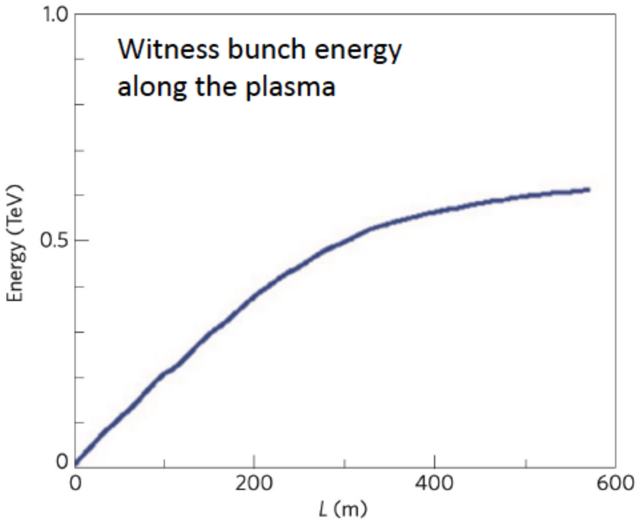
Available proton bunches carry large amounts of energy:

- CERN SPS proton bunch: $3 \cdot 10^{11}$ ppb at 400 GeV/c → 19.2 kJ
- CERN LHC proton bunch: $1 \cdot 10^{11}$ ppb at 7 TeV/c → 112 kJ



⇒ Overcome the need of staging!

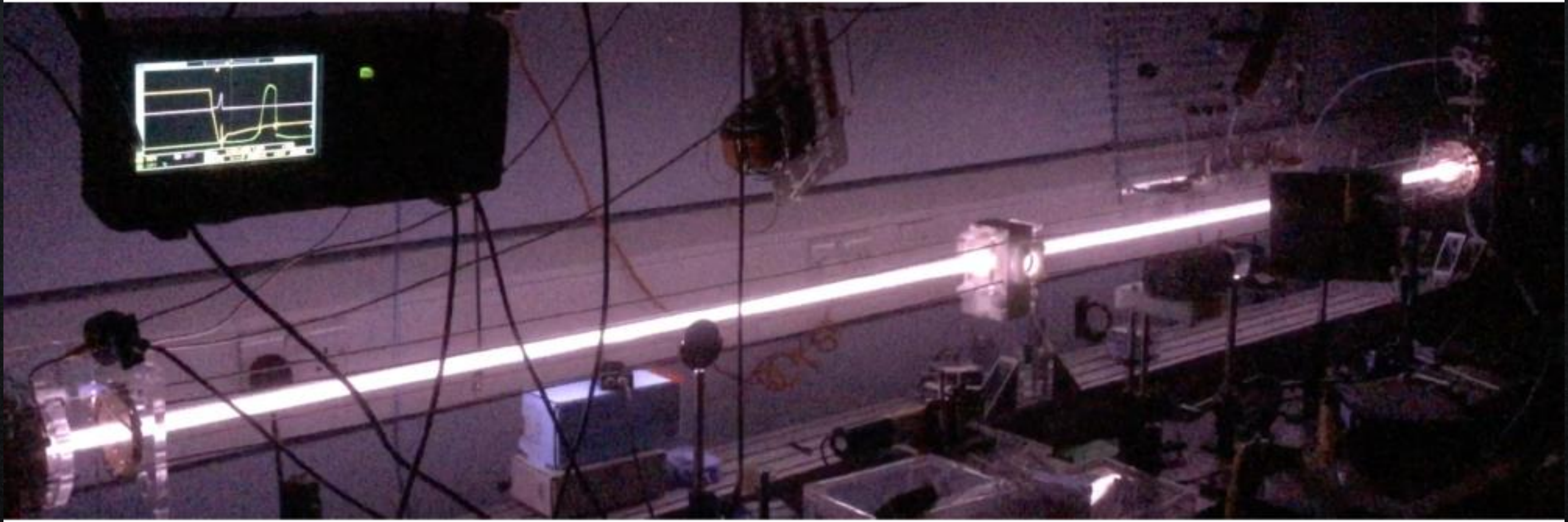
Parameters:
single proton bunch
σ_z = 100 µm,
E = 1 TeV,
population: $1 \cdot 10^{11}$ ppb



A. Caldwell et al., Nature Phys. 5, 363–367 (2009)

Discharge configuration II

preliminary tests with the AWAKE 3 meter test tube at IC - 2016



very promising results

… reliable, low jitter plasma formation

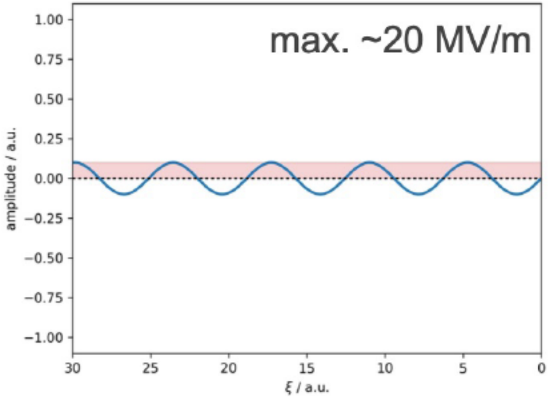
scalability of electric circuit for plasmas > 10 m seem achievable…

Self-modulation in plasma

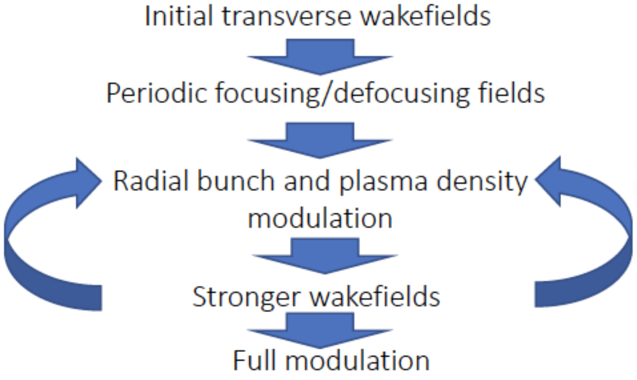
CERN SPS Proton bunch

$$\sigma_r \approx 200\ \mu m\ \rightarrow n_{pe} \approx 7 \cdot 10^{14} cm^{-3}$$

$$\sigma_z \approx 7\ cm \gg\ \lambda_{pe}$$



Growth mechanism



Initial transverse wakefields

Periodic focusing/defocusing fields

Radial bunch and plasma density modulation

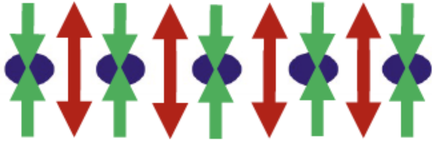
Stronger wakefields

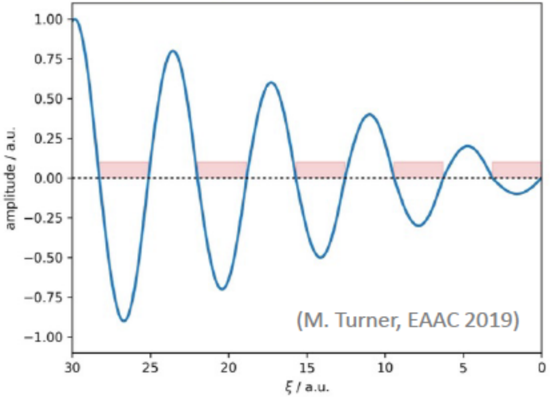
Full modulation

Self-Modulation instability (SMI)

→ resonant wakefield excitation

→ phase of the micro-bunch train and of the wakefields VARIES from event to event

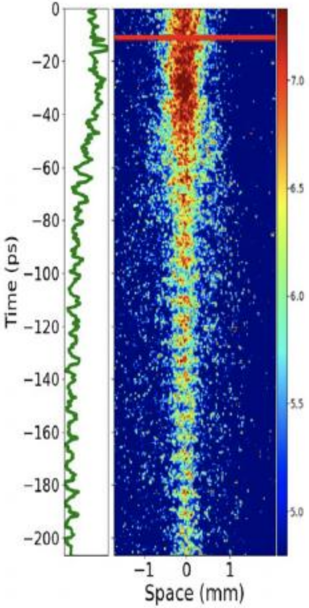




(M. Turner, EAAC 2019)

N. Kumar et al., Phys. Rev. Lett. 104 (25), 255003 (2010)
A. Pukhov et al., Phys. Rev. Lett. 107 (14), 145003 (2011)

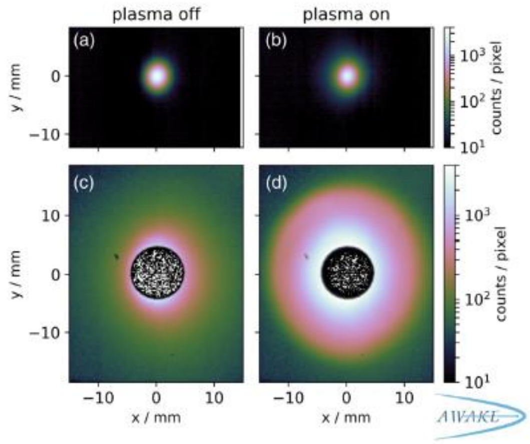
AWAKE Run 1 (2016-2018)



AWAKE Coll., Phys. Rev. Lett. 122, 054802 (2019)

time-resolved imaging:

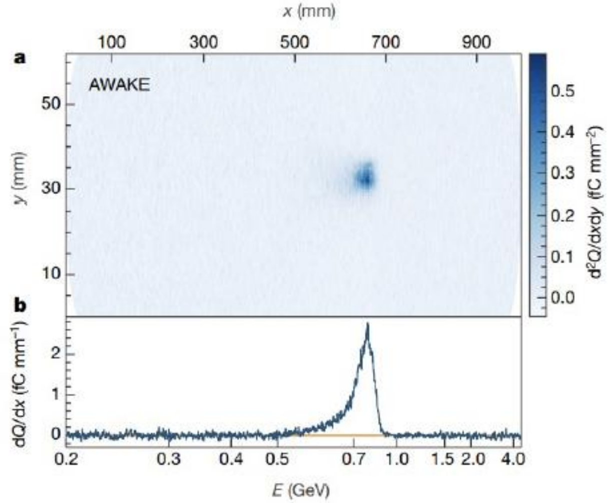
- the proton bunch self-modulates in plasma
- focusing phase → micro-bunches
- frequency of the modulation≈ ω_{pe}



M. Turner et al., Phys. Rev. Lett. 122, 054801 (2019)

time-integrated, transverse imaging:

- defocusing phase→ large halo
- wakefields grow along the plasma

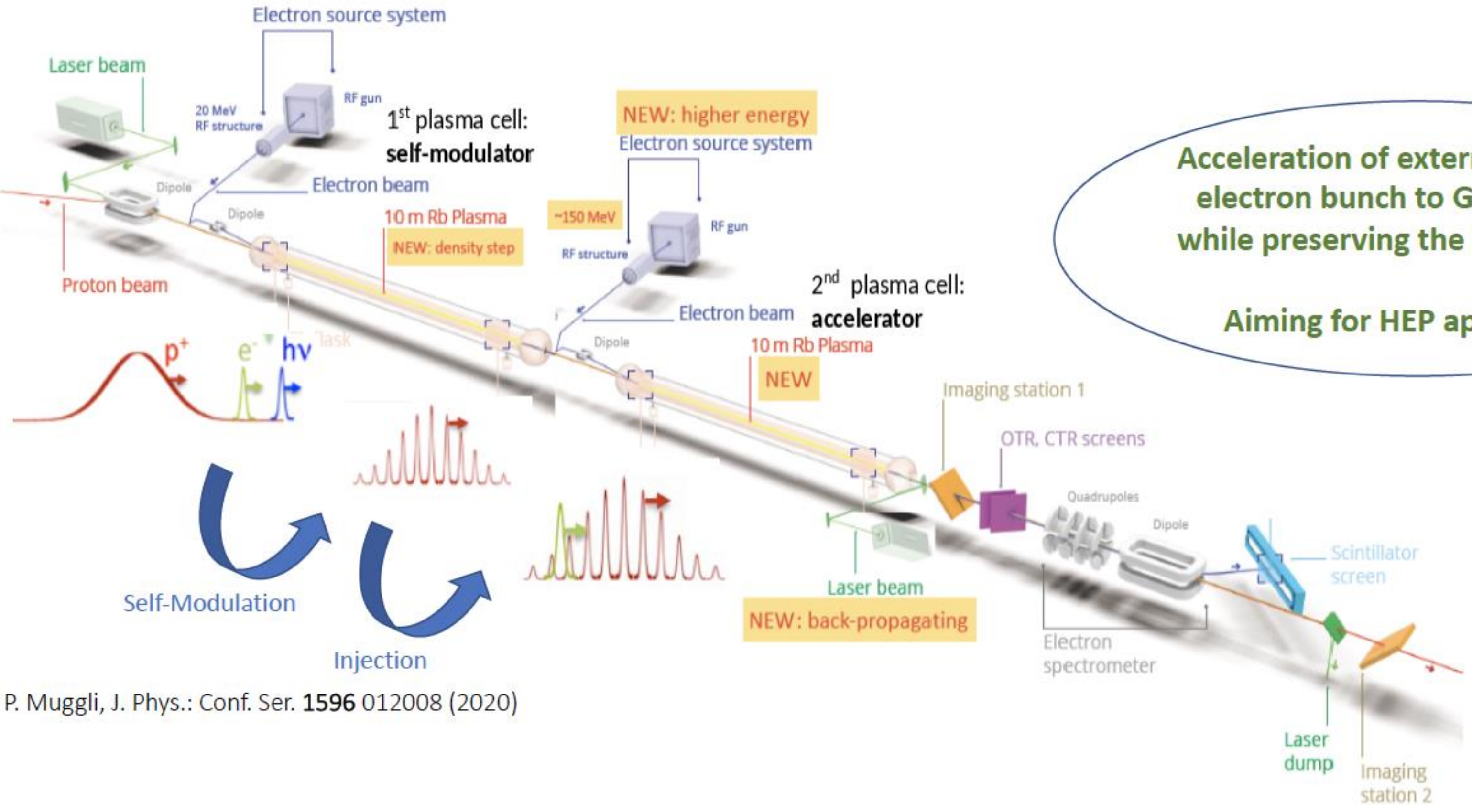


AWAKE Coll., Nature 561, 363-367 (2018)

19 MeV electrons can be injected into the wakefields and accelerated to GeV-energies

PROOF OF PRINCIPLE!

AWAKE Run 2 (2021→) setup &final goal



Acceleration of externally injected electron bunch to GeV-energies while preserving the initial quality

Aiming for HEP application!

P. Muggli, J. Phys.: Conf. Ser. **1596** 012008 (2020)

The near future

A New European High-Tech User Facility

Funded by the European Union

1

Building a facility with very high field plasma accelerators, driven by lasers or beams
1 – 100 GV/m accelerating field

Shrink down the facility size

2

Producing particle and photon pulses to support several urgent and timely science cases

Enable frontier science in new regions and parameter regimes

https://www.eupraxia-facility.org/

FEATURE EuPRAXIA

Surf's up *Simulation of electron-driven plasma wakefield acceleration, showing the drive electron beam (orange/purple), the plasma electron wake (grey) and wakefield-ionised electrons forming a witness beam (orange).*

EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

Ralph Assmann, Massimo Ferrario and Carsten Welsch describe the status of the ESFRI project EuPRAXIA, which aims to develop the first dedicated research infrastructure based on novel plasma-acceleration concepts.

Energetic beams of particles are used to explore the fundamental forces of nature, produce known and unknown particles such as the Higgs boson at the LHC, and generate new forms of matter, for example at the future FAIR facility. Photon science also relies on particle beams: electron beams that emit pulses of intense synchrotron light, including soft and hard X-rays, in either circular or linear machines. Such light sources enable time-resolved measurements of biological, chemical and physical structures on the molecular down to the atomic scale, allowing a diverse global community of users to investigate systems ranging from viruses and bacteria to materials science, planetary science, environmental science, nanotechnology and archaeology. Last but not least, particle beams for industry and health support many societal applications ranging from the X-ray inspection of cargo containers to food sterilisation, and from chip manufacturing to cancer therapy.

This scientific success story has been made possible through a continuous cycle of innovation in the physics and technology of particle accelerators, driven for many decades by exploratory research in nuclear and particle physics. The invention of radio-frequency (RF) technology in the 1920s opened the path to an energy gain of several tens of MeV per metre. Very-high-energy accelerators were constructed with RF technology, entering the GeV and finally the TeV energy scales at the Tevatron and the LHC. New collision schemes were developed, for example the mini "beta squeeze" in the 1970s, advancing luminosity and collision rates by orders of magnitudes. The invention of stochastic cooling at CERN enabled the discovery of the W and Z bosons 40 years ago.

However, intrinsic technological and conceptual limits mean that the size and cost of RF-based particle accelerators are increasing as researchers seek higher beam energies. Colliders for particle physics have reached a

THE AUTHORS

Ralph Assmann *DESY and INFN,* **Massimo Ferrario** *INFN,* **Carsten Welsch** *University of Liverpool/INFN.*

CERN COURIER MAY/JUNE 2023

25

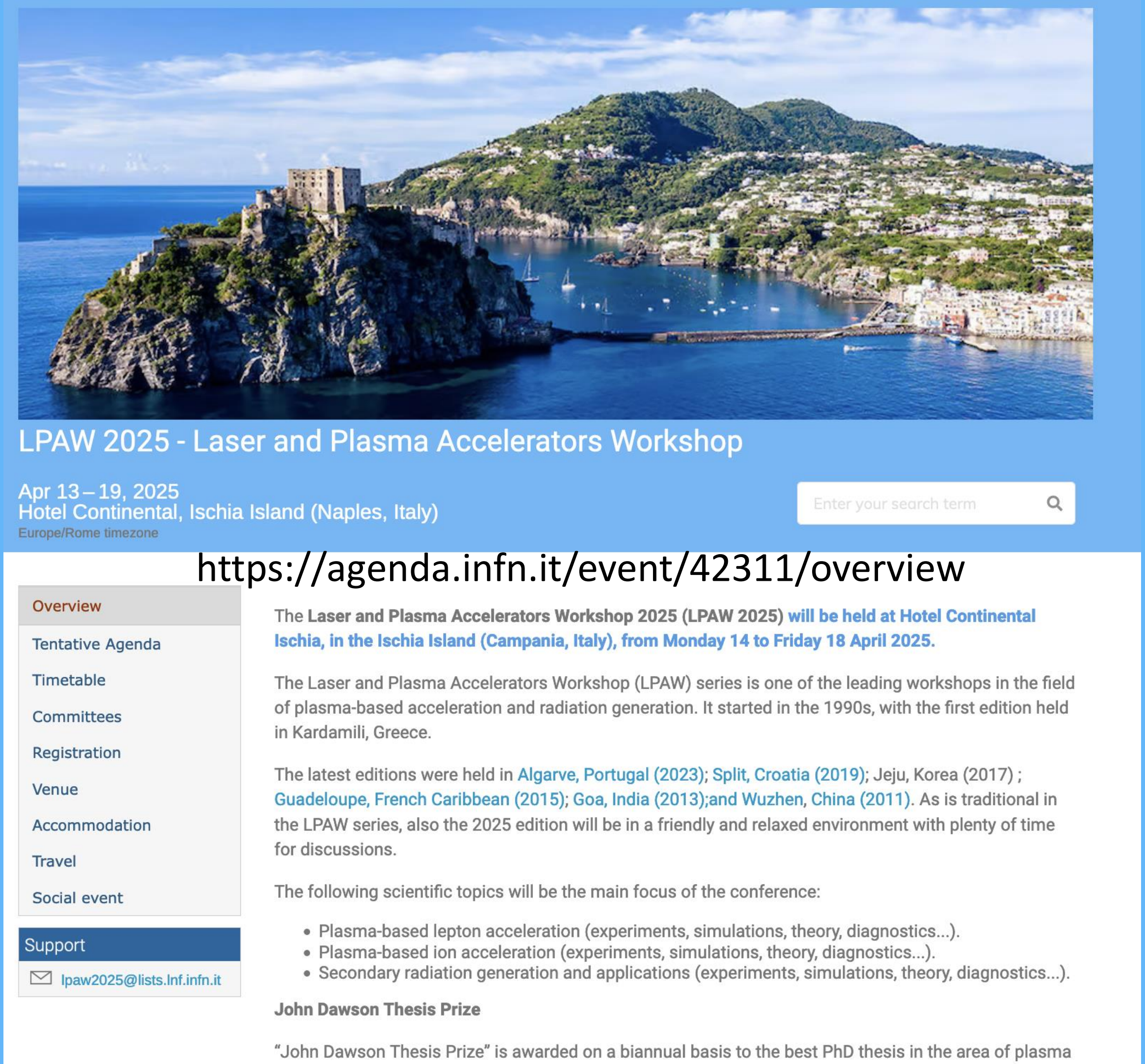
Conclusions

- Accelerator-based High Energy Physics will at some point become practically limited by the size and cost of the proposed e^+e^- colliders for the energy frontier.
- **Novel Acceleration Techniques like Plasma-based, high gradient accelerators open the realistic vision of very compact accelerators for scientific, commercial and medical applications.**

- The R&D now concentrates on **beam quality, stability, staging and continuous operation**. These are necessary steps towards various technological applications.
- The progress in advanced accelerators benefits from strong synergy with general advances in technology, for example in the laser and/or high gradient RF structures industry.

- **A major milestone is an operational, 1 GeV compact accelerator. Challenges in repetition rate and stability must be addressed. This unit could become a stage in a high-energy accelerator..**
- **➔ FIRST PLASMA BASED USER FACILITIES Under Construction (EuPRAXIA)**

Thank for your attention



LPAW 2025 - Laser and Plasma Accelerators Workshop

Apr 13 – 19, 2025
Hotel Continental, Ischia Island (Naples, Italy)
Europe/Rome timezone

https://agenda.infn.it/event/42311/overview

The **Laser and Plasma Accelerators Workshop 2025 (LPAW 2025)** **will be held at Hotel Continental Ischia, in the Ischia Island (Campania, Italy), from Monday 14 to Friday 18 April 2025.**

The Laser and Plasma Accelerators Workshop (LPAW) series is one of the leading workshops in the field of plasma-based acceleration and radiation generation. It started in the 1990s, with the first edition held in Kardamili, Greece.

The latest editions were held in Algarve, Portugal (2023); Split, Croatia (2019); Jeju, Korea (2017) ; Guadeloupe, French Caribbean (2015); Goa, India (2013);and Wuzhen, China (2011). As is traditional in the LPAW series, also the 2025 edition will be in a friendly and relaxed environment with plenty of time for discussions.

The following scientific topics will be the main focus of the conference:

- Plasma-based lepton acceleration (experiments, simulations, theory, diagnostics...).
- Plasma-based ion acceleration (experiments, simulations, theory, diagnostics...).
- Secondary radiation generation and applications (experiments, simulations, theory, diagnostics...).

John Dawson Thesis Prize

“John Dawson Thesis Prize” is awarded on a biannual basis to the best PhD thesis in the area of plasma