Introduzione alla Fisica degli Acceleratori di Particelle
2

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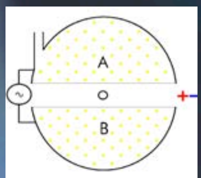
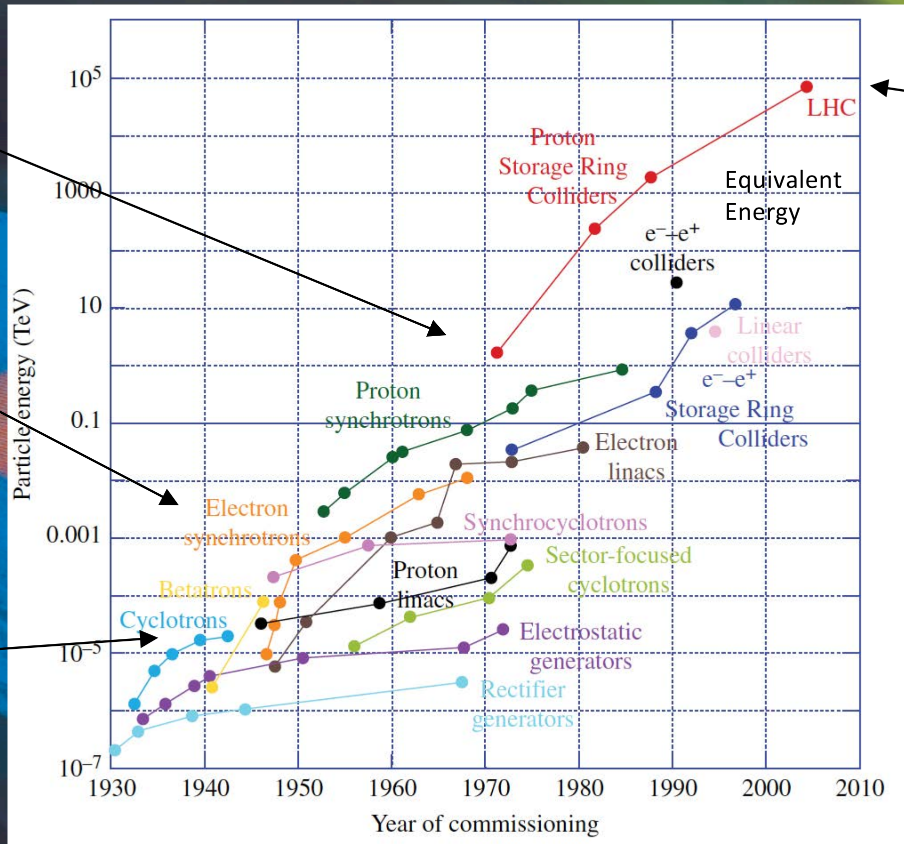
Livingstone Diagram

$$\begin{cases} \omega_L = \dfrac{qB_y}{\gamma m_0} \\ p_z = qB_yR \end{cases}$$





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.

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

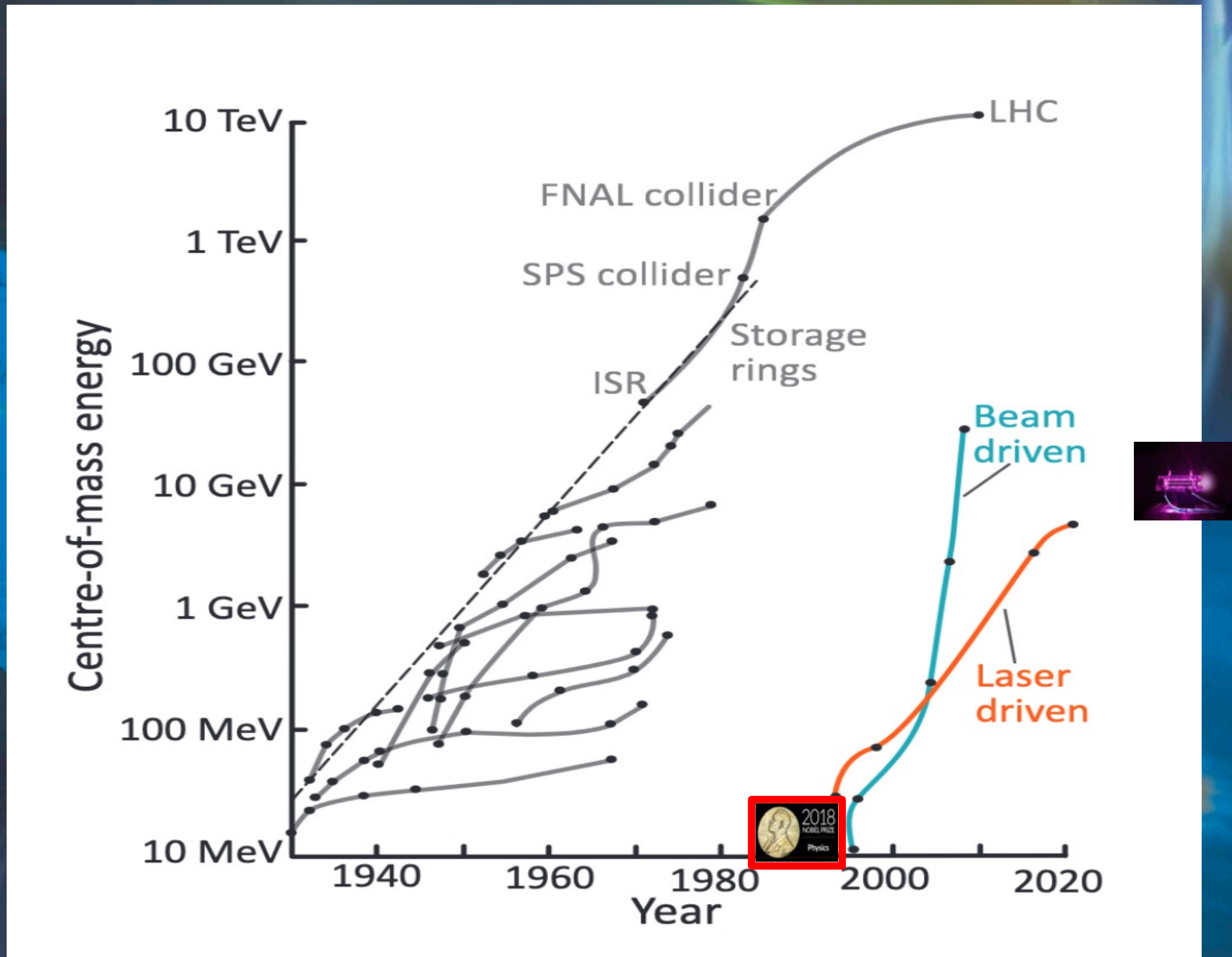
Pisin Chen[a]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

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 $4\gamma_0^3 mc^2$ 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

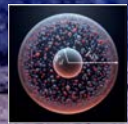
=> a plasma responds to external forces as a single entity

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

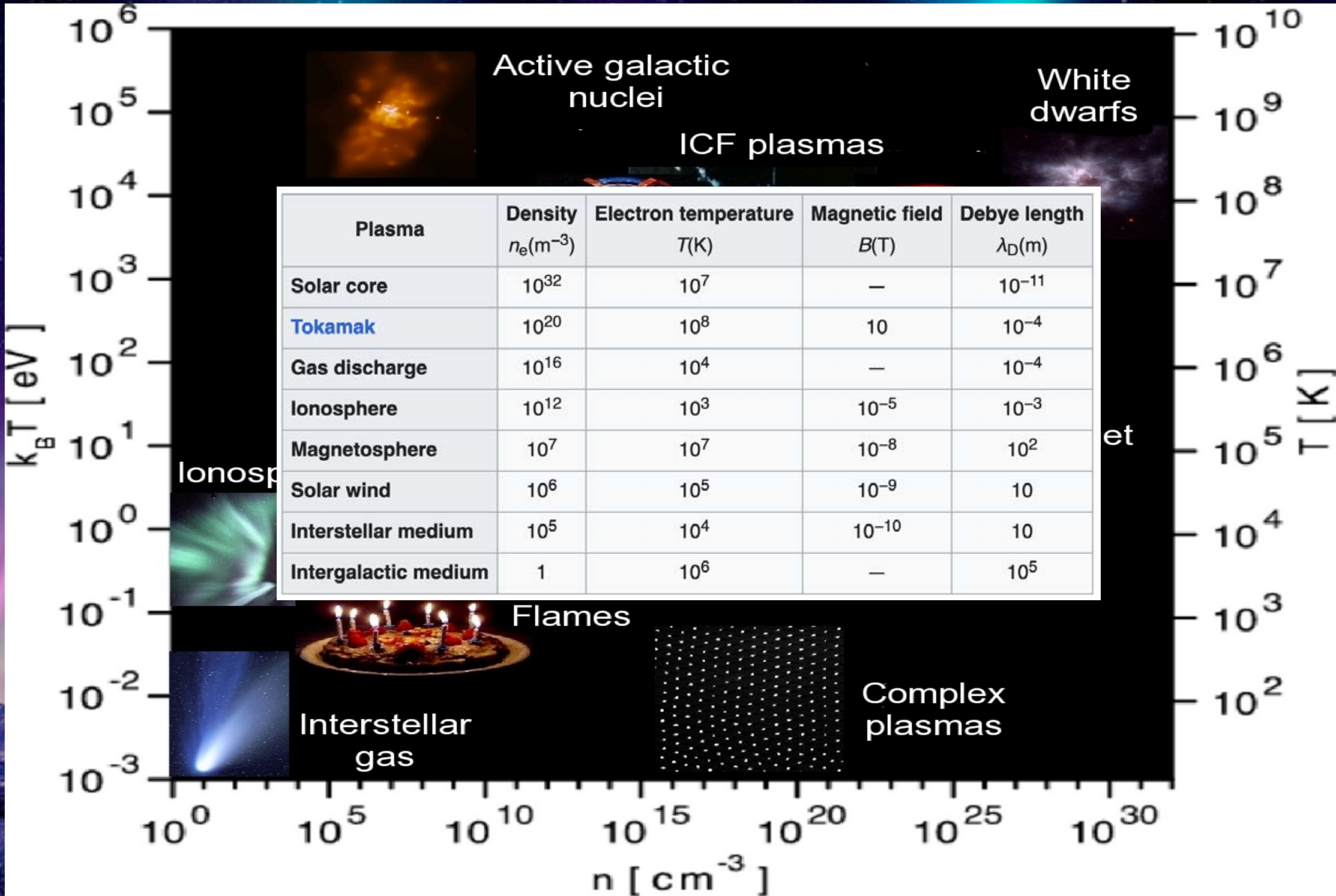
$$\lambda_D = \left(\frac{\varepsilon_0 k_B T_e}{e^2 n_e}\right)^{1/2} = 743 \left(\frac{T_e}{\mathrm{eV}}\right)^{1/2} \left(\frac{n_e}{\mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{cm}.$$

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

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



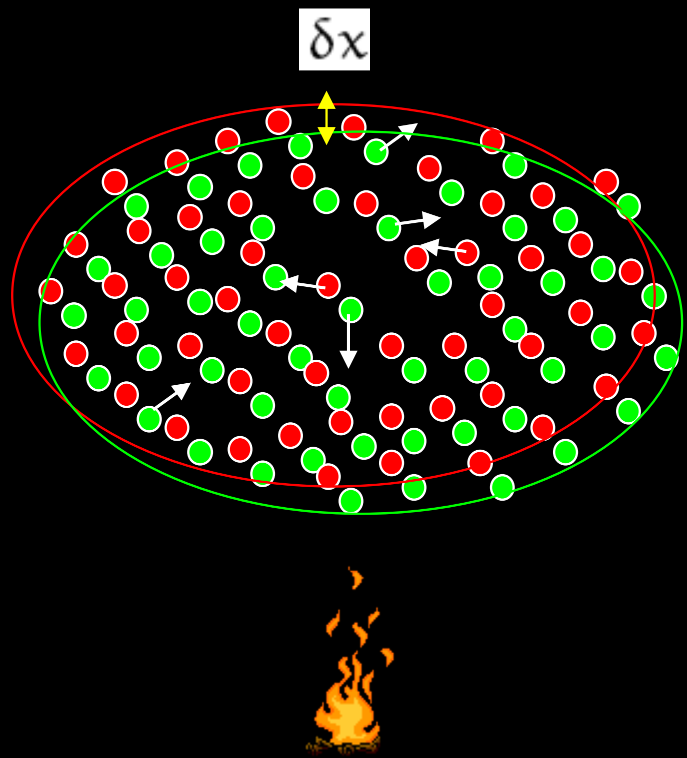
Plasma Temperature and Density



Plasma	Density n_e(m^{-3})	Electron temperature T(K)	Magnetic field B(T)	Debye length λ_D(m)
Solar core	10^{32}	10^{7}	—	10^{-11}
Tokamak	10^{20}	10^{8}	10	10^{-4}
Gas discharge	10^{16}	10^{4}	—	10^{-4}
Ionosphere	10^{12}	10^{3}	10^{-5}	10^{-3}
Magnetosphere	10^{7}	10^{7}	10^{-8}	10^{2}
Solar wind	10^{6}	10^{5}	10^{-9}	10
Interstellar medium	10^{5}	10^{4}	10^{-10}	10
Intergalactic medium	1	10^{6}	—	10^{5}

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

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

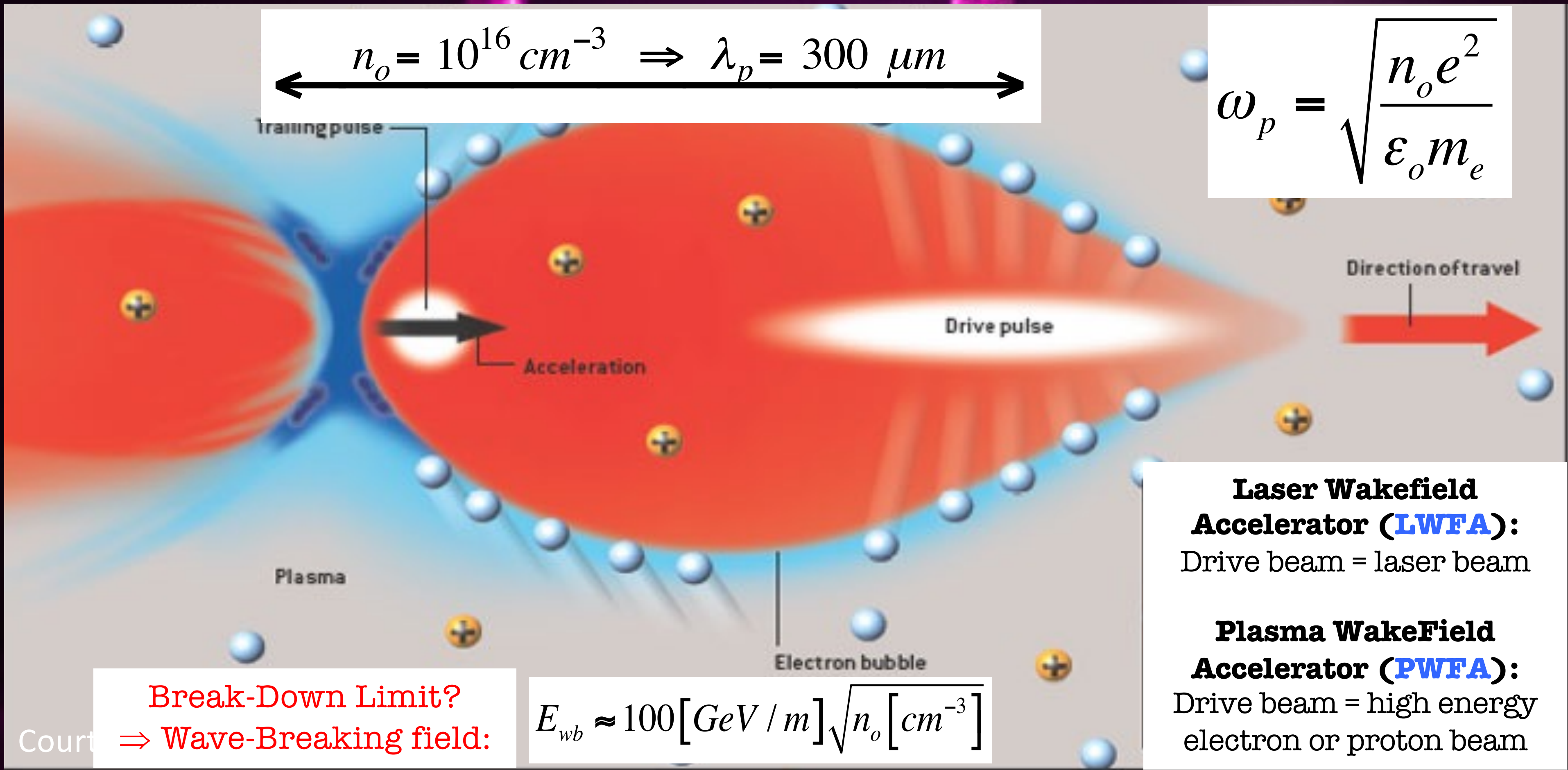
Plasma oscillations

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

Principle of plasma acceleration

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

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



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

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

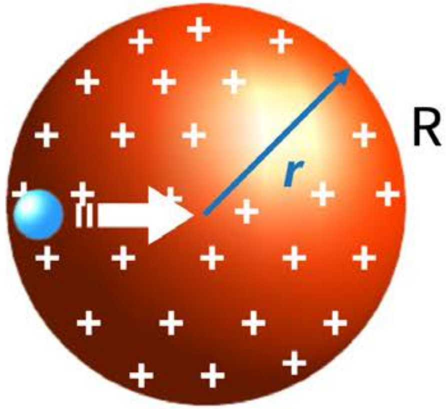
Break-Down Limit?
⇒ Wave-Breaking field:

$$E_{wb} \approx 100\left[GeV/m\right]\sqrt{n_o\left[cm^{-3}\right]}$$

Court

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



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

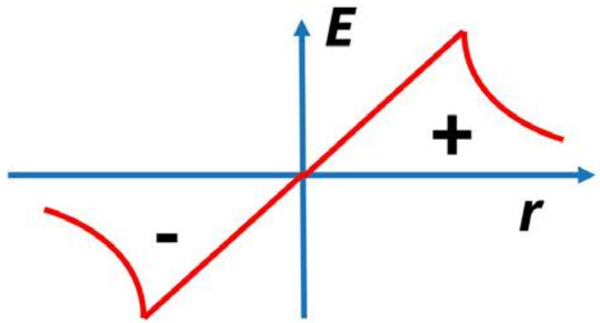
The field is **increasing** inside the sphere

Let's put some numbers

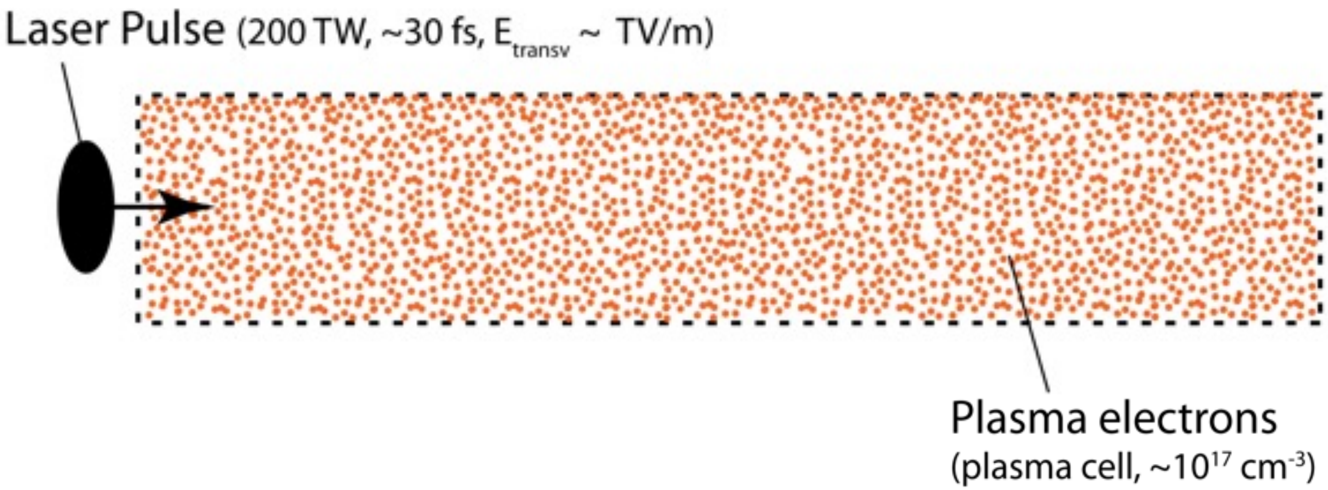
$n_i = 10^{16}\ cm^{-3}$

$R = 0.5$

$$E \approx 10 \frac{GV}{m}$$

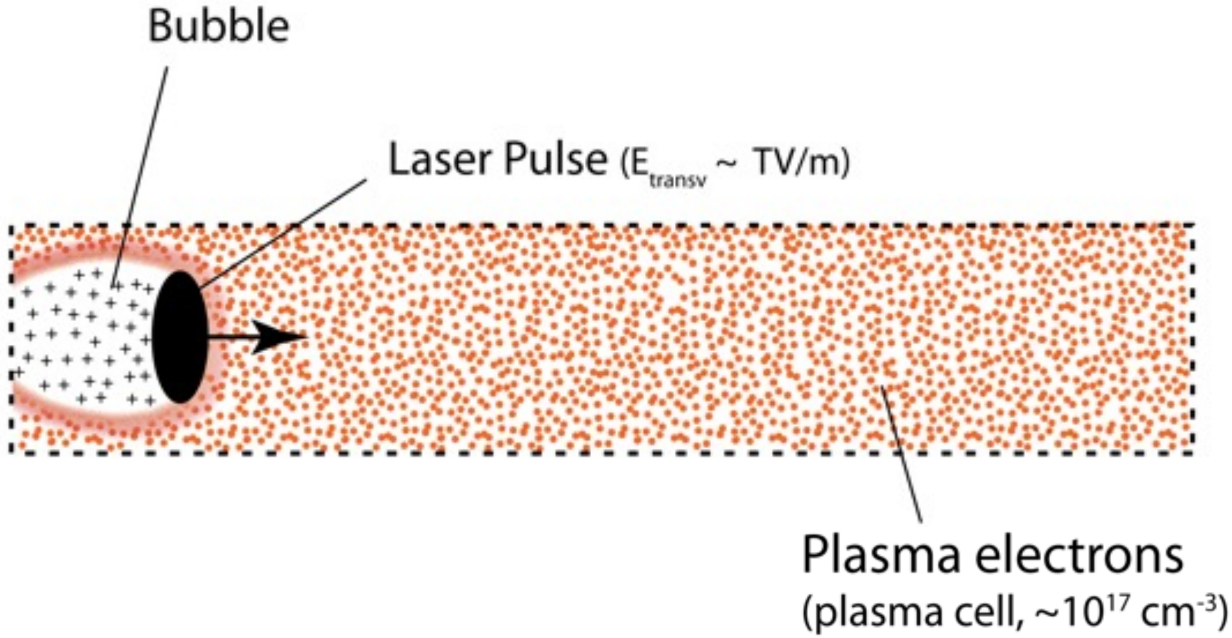


Plasma Wake-Acceleration



Plasma Wake-Acceleration

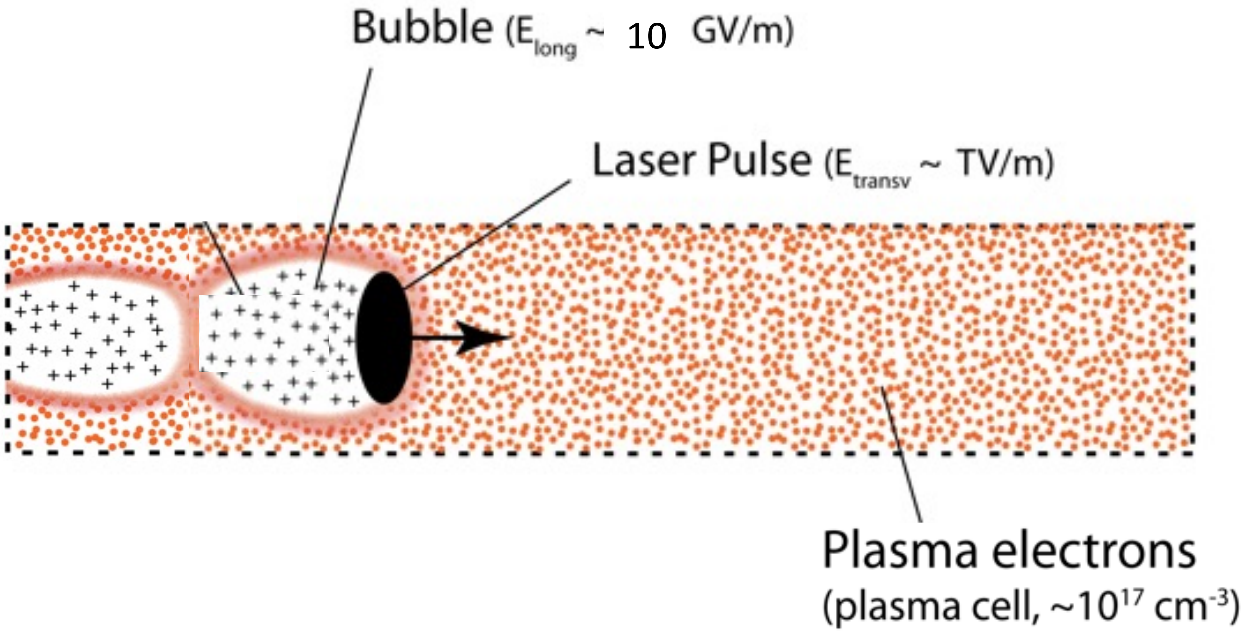
Horizon2020



EuPRAXIA

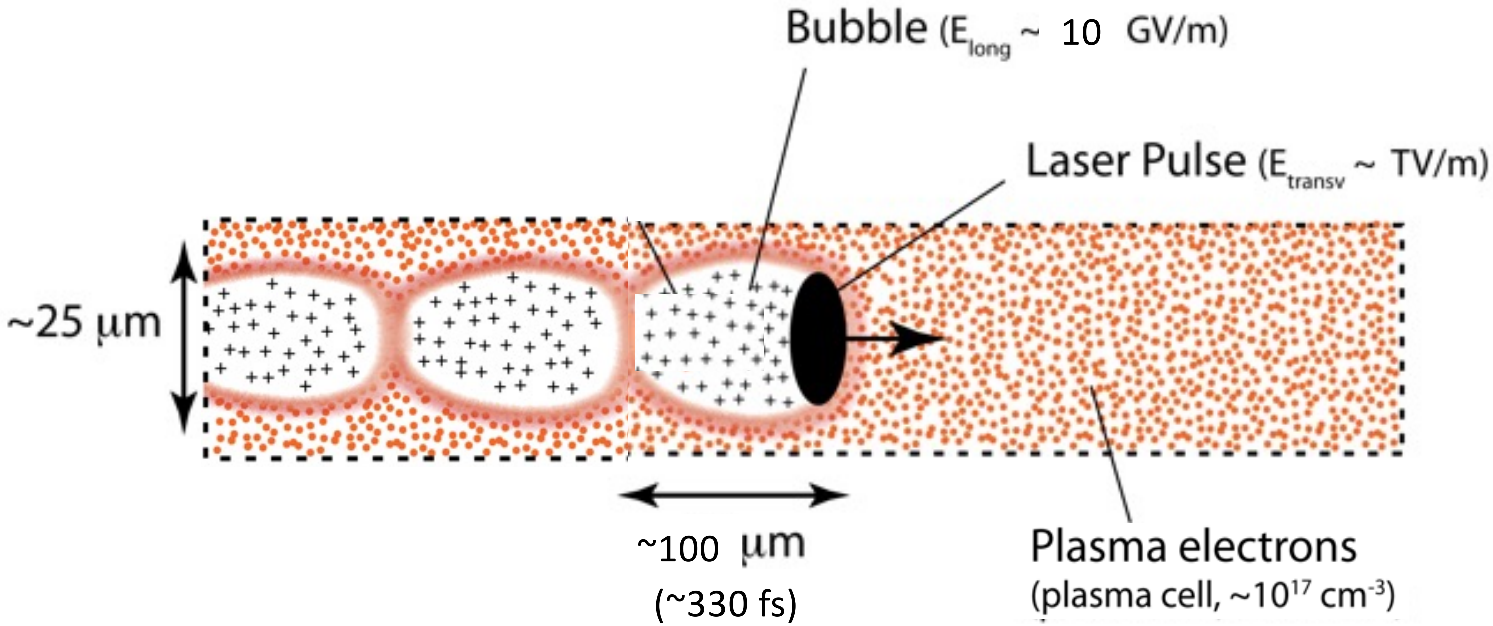
Plasma Wake-Acceleration

Horizon2020

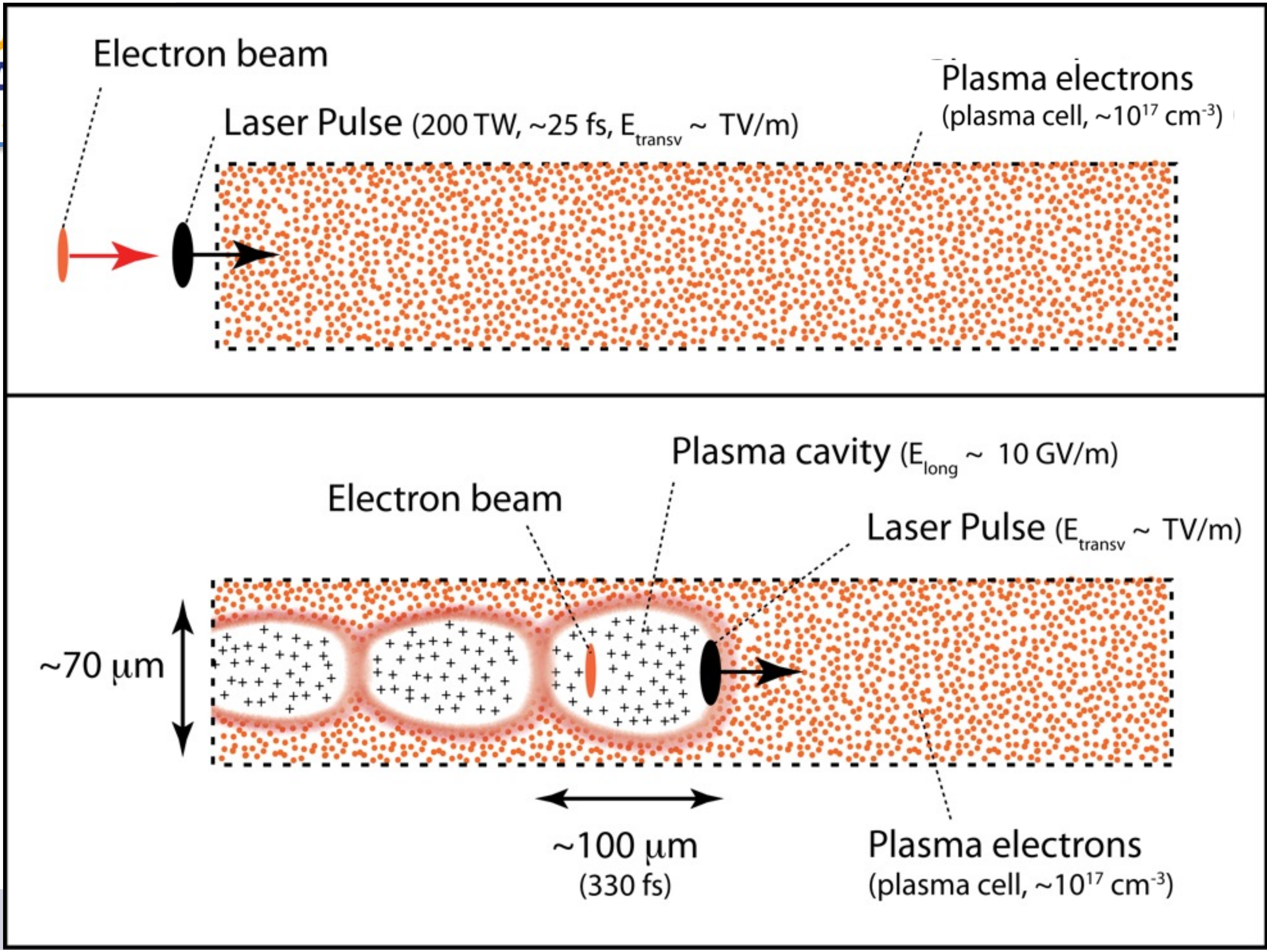


Plasma Wake-Acceleration

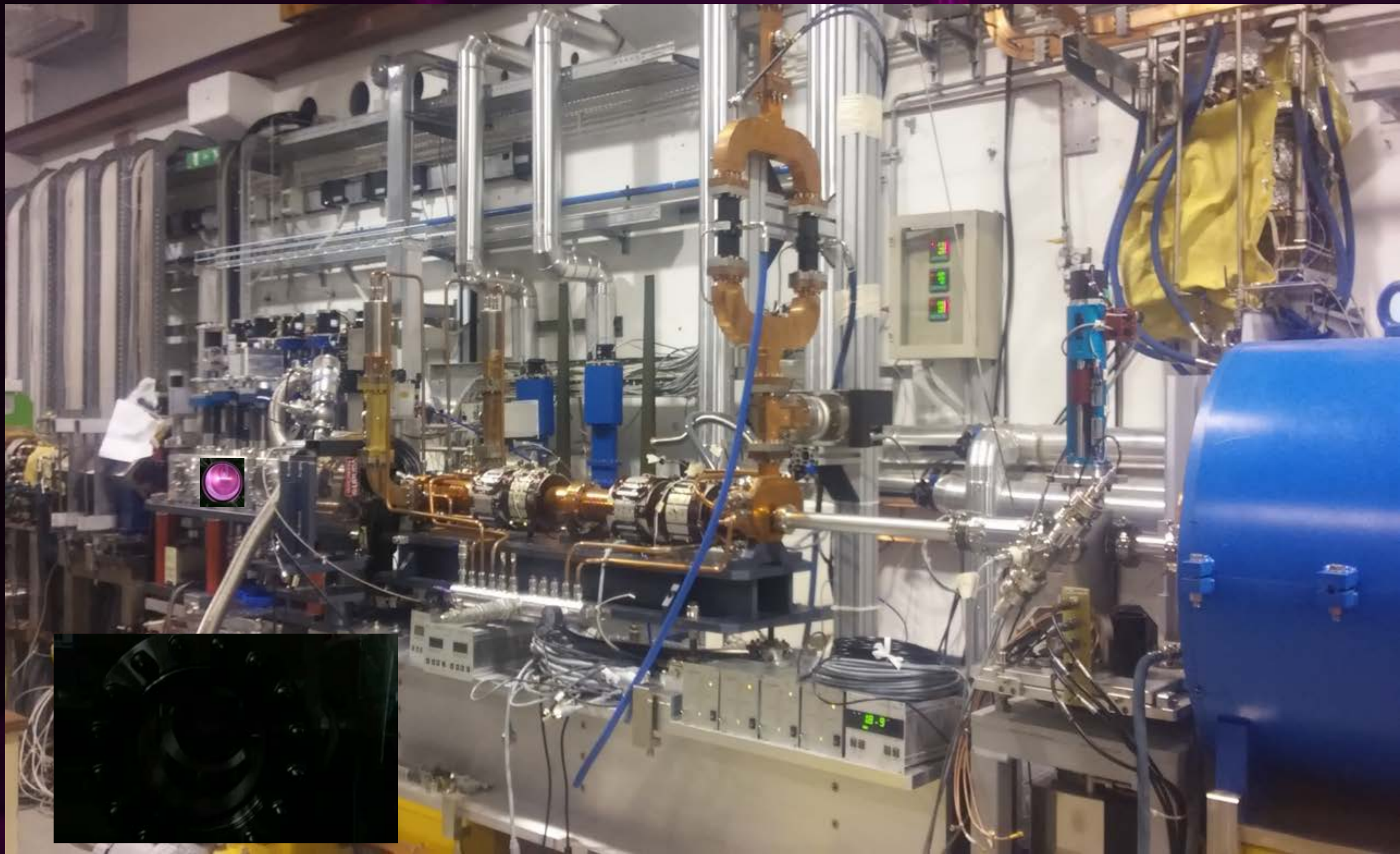
Horizon2020

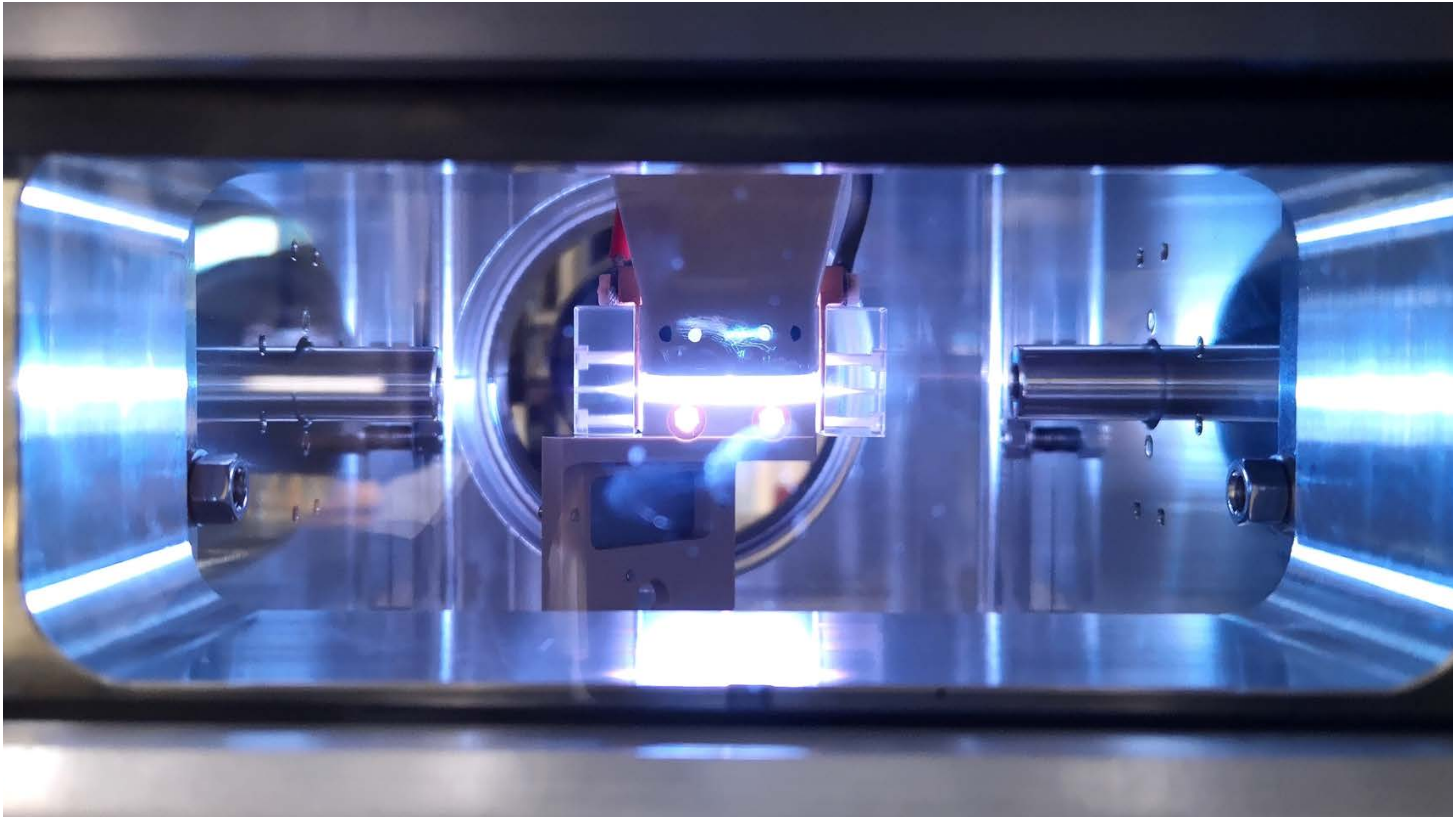


This accelerator fits into a human hair!

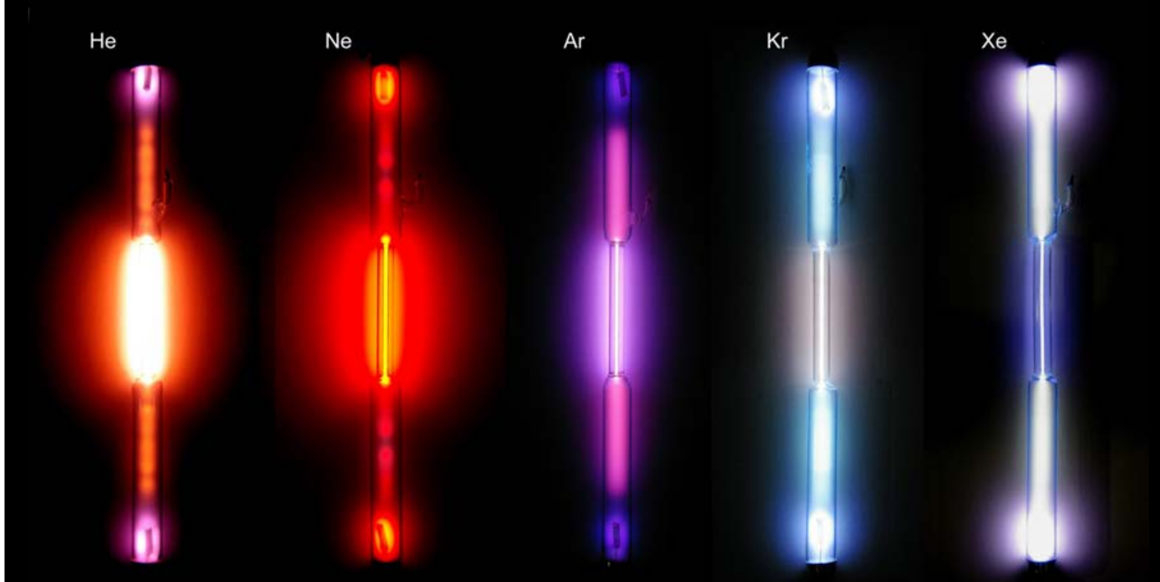

Electron beam
Laser Pulse (200 TW, ~25 fs, E_transv ~ TV/m)
Plasma electrons
(plasma cell, ~10^17 cm^-3)
Plasma cavity (E_long ~ 10 GV/m)
Electron beam
Laser Pulse (E_transv ~ TV/m)
~70 μm
~100 μm
(330 fs)
Plasma electrons
(plasma cell, ~10^17 cm^-3)

PWFA beam line at SPARC_LAB



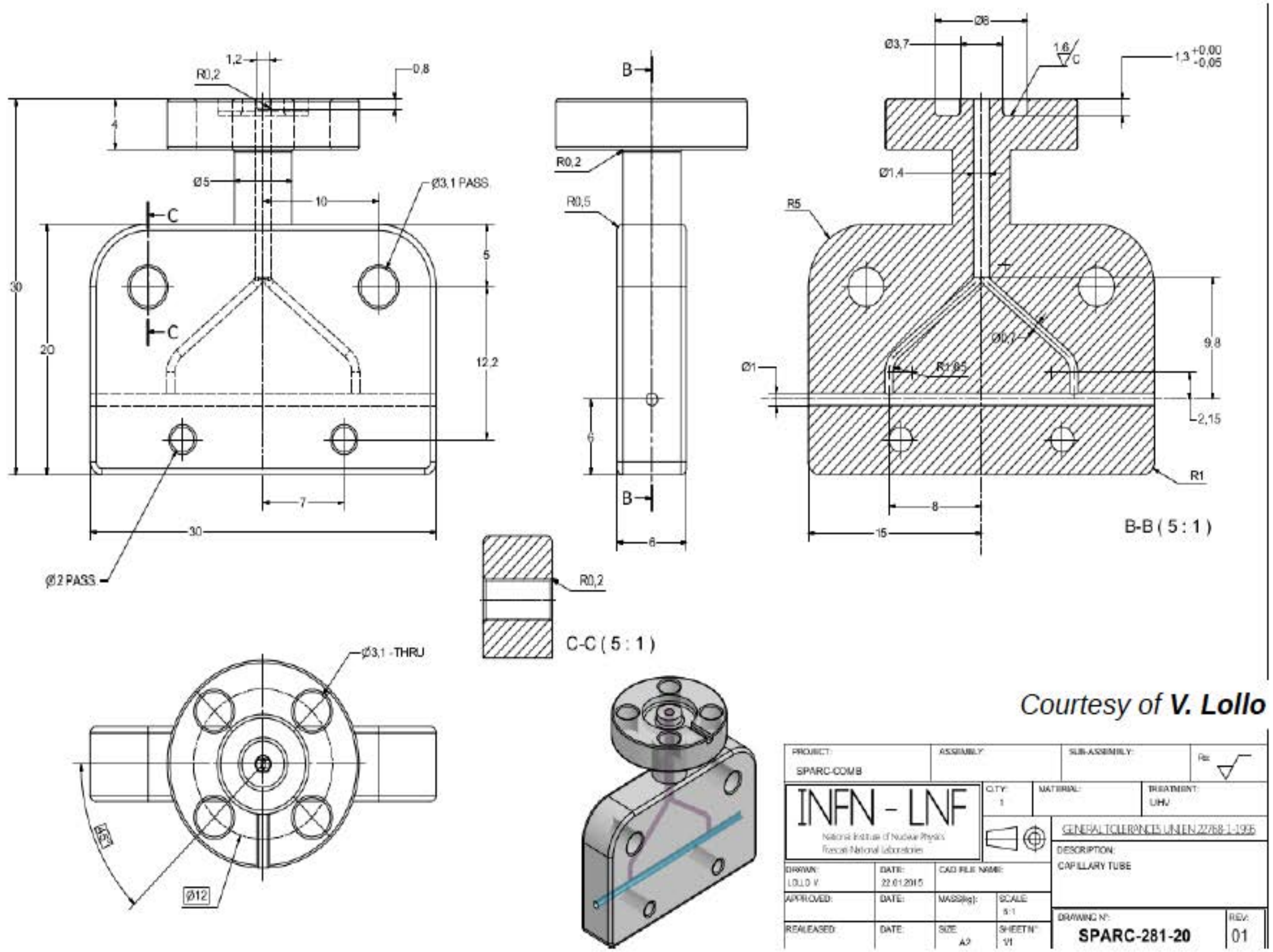


Gas Choices for Capillary Discharge Plasma Acceleration



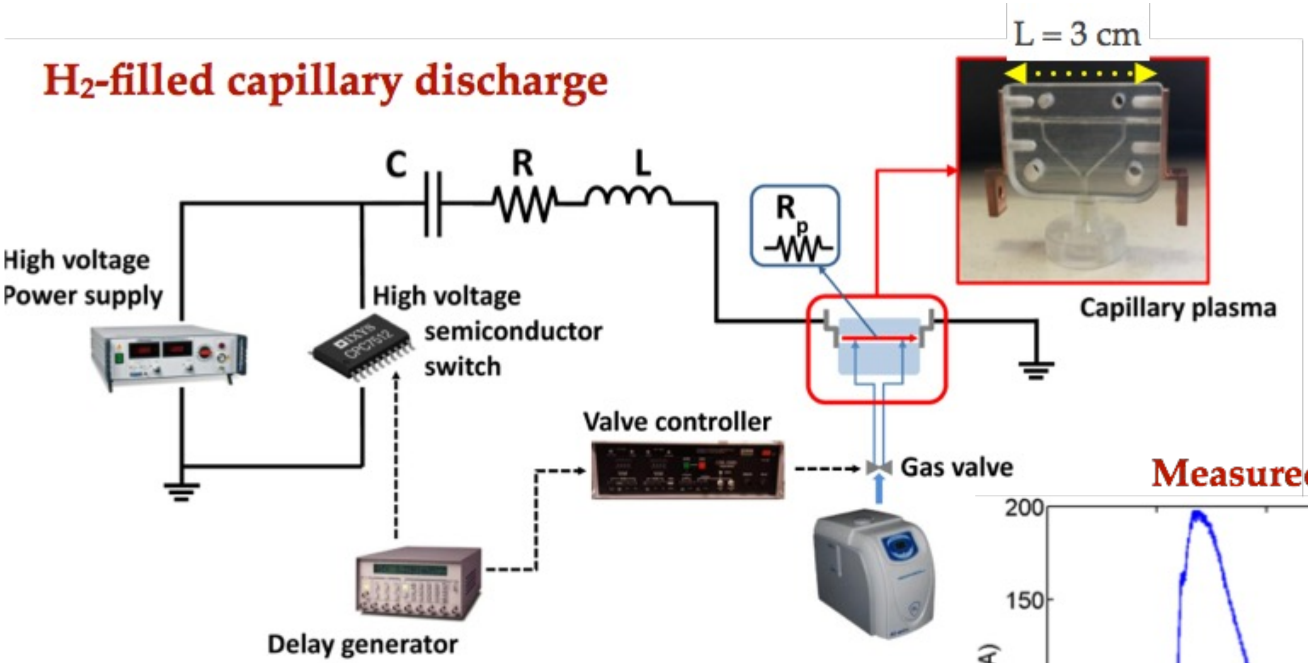
Gas	Advantages	Disadvantages	First Ionization Energy (eV)	Typical Recombination Time (ns)	Emission Wavelength (nm)
Hydrogen (H_2)	Low mass, easy ionization, good channel formation	Flammable, explosive risk	13.6	~10–100	~656.3 (Hα), 486.1 (Hβ)
Helium (He)	Inert, stable channels, low ion mass	More expensive, slightly harder to ionize	24.6	~100–500	587.6, 667.8, 706.5
Argon (Ar)	Multiple ionization stages, good for high densities	Heavy ions, wall heating, non-uniform channels	15.8	~1–10	696.5, 706.7, 750.4
Nitrogen (N_2)	Available, moderate Z, some molecular benefits	Chemically reactive, complex ionization paths	15.6	~1–10	337.1
Oxygen (O_2)	Similar to nitrogen, easy availability	Highly reactive, can erode capillary	13.6	~1–10	777.4, 844.6

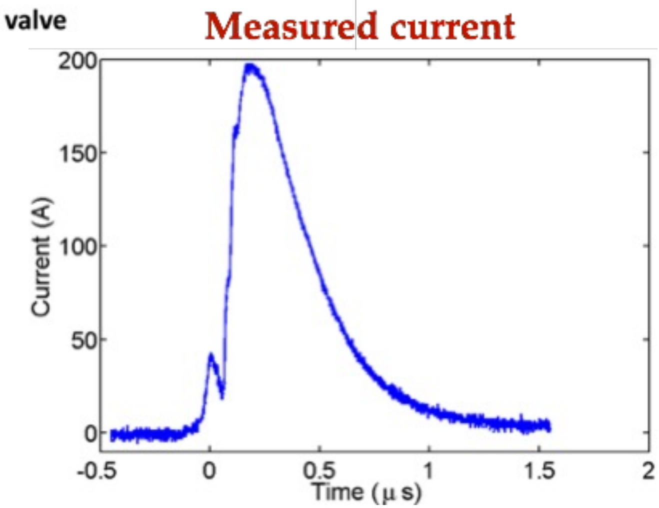
Plasma capillary



Courtesy of ***V. Lollo***

Plasma Source





P_{H2} = 10 mbar

Total discharge duration: 800 ns

Voltage: 20 kV

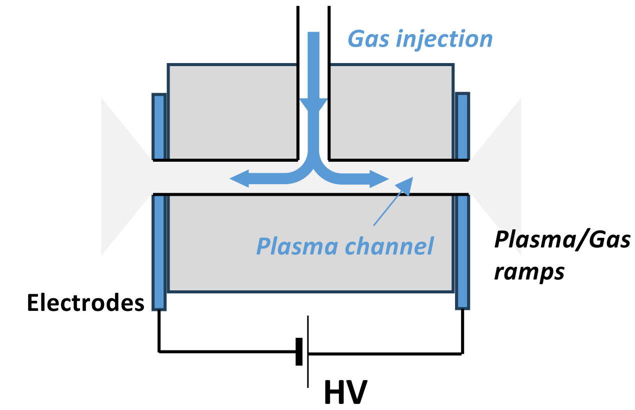
Peak current: 200 A

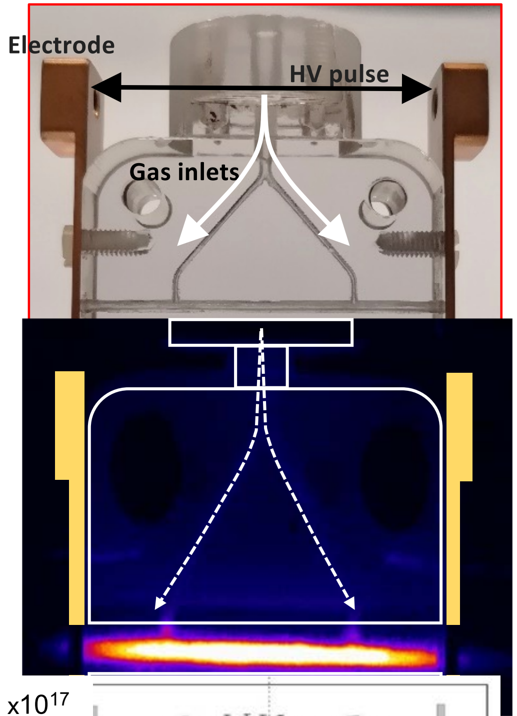
Capacitor: 6 nF

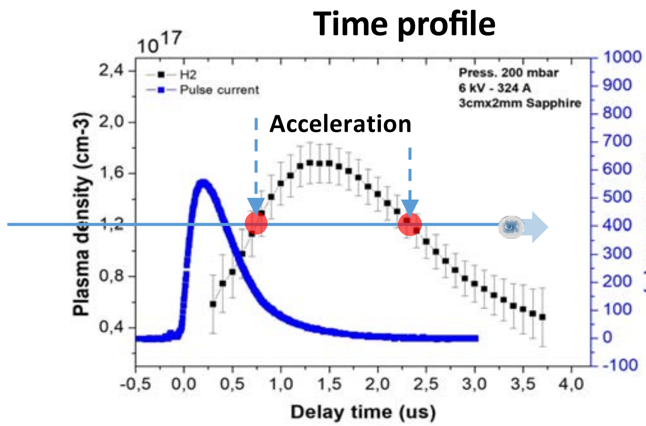
Courtesy of M. P. Anania, A. Biagioni, D. Di Giovenale, F. Filippi, S. Pella

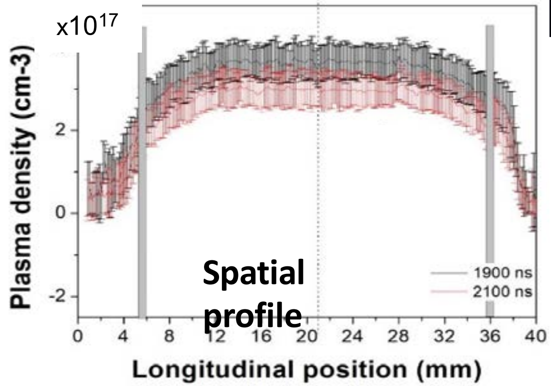
Discharge Plasma sources properties

- Region of uniform neutral gas contained by differential pumping at two input/output extremities and realized by a thin capillary
- Modulation of longitudinal gas distribution by special geometric shapes
- Small gas flow to operate in steady state regime with continuous flow (*P* < 1 bar)
- There is no movable parts
- Small dimension of the HV source to produce plasma
- Plume of gas from front and back of cell, plasma ramps to be controlled
- Density easily adjusted by controlling gas flow, geometry or voltage in the range: 10^{15} - 10^{19} cm^{-3}
- Erosion of the plasma channel due to the electrical discharges to form plasma



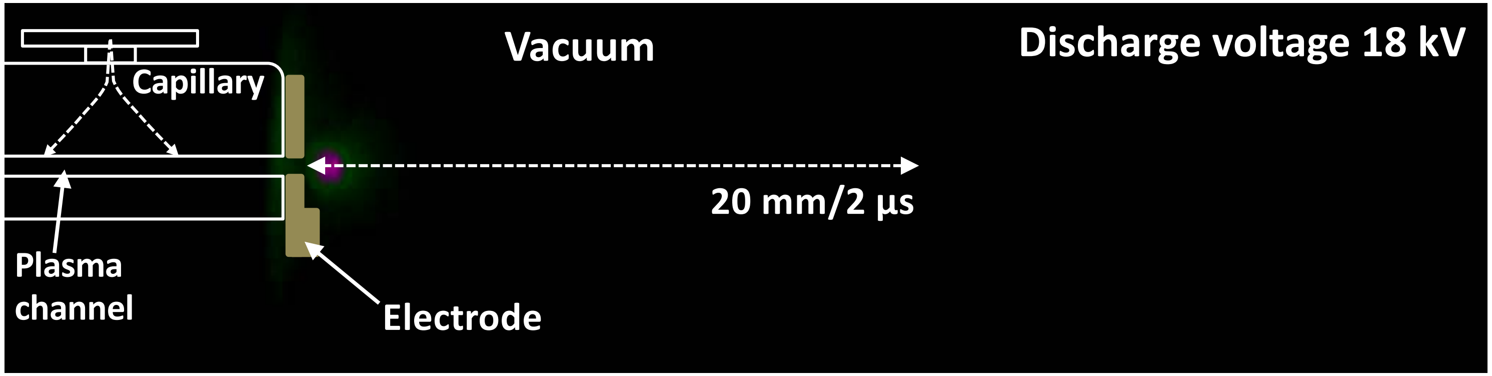






Plasma plumes

- **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.

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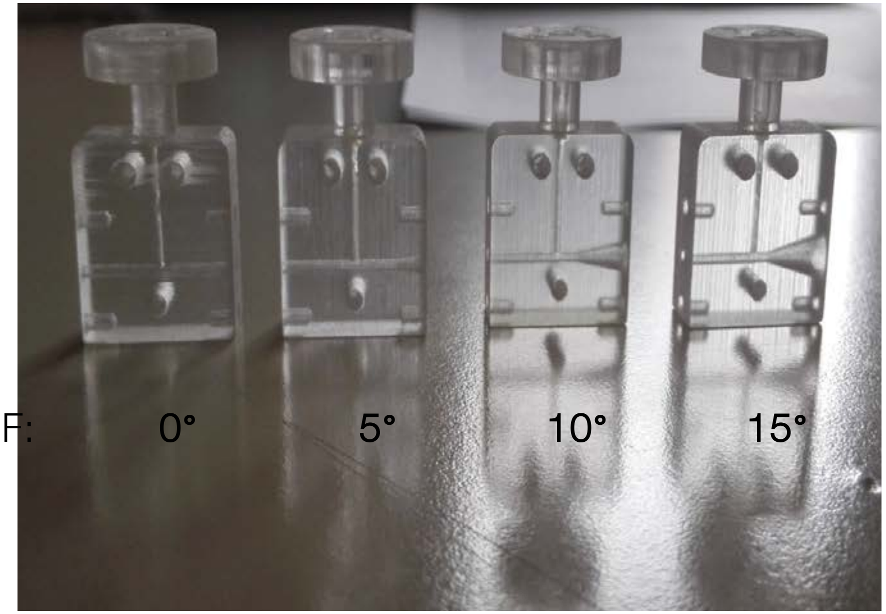
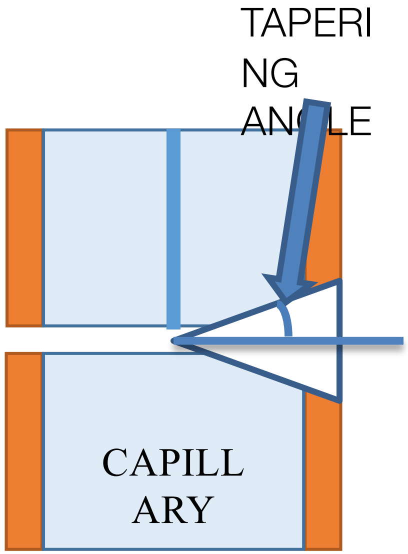
Tapered capillaries

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°



Principle of plasma acceleration

Driven by Radiation Pressure

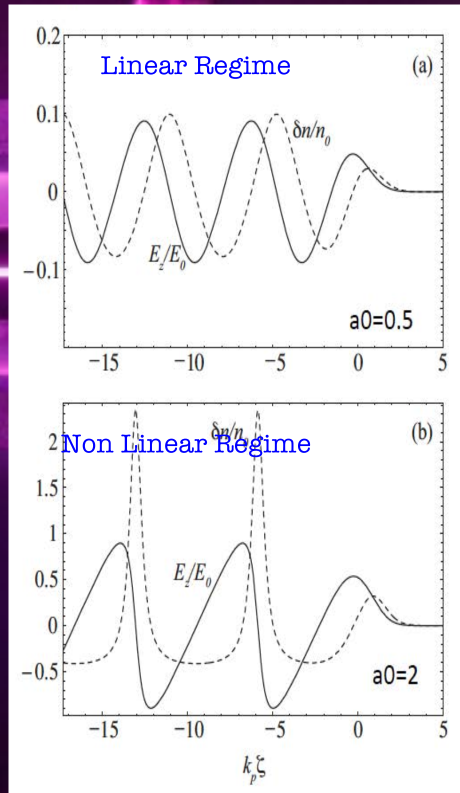
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=c^2\nabla^2\frac{a^2}{2}$$

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

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 Instability

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

Horizon2020

Accelerating field

Depends on radial position r

Changes between accelerating and decelerating as function of longitudinal position z

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

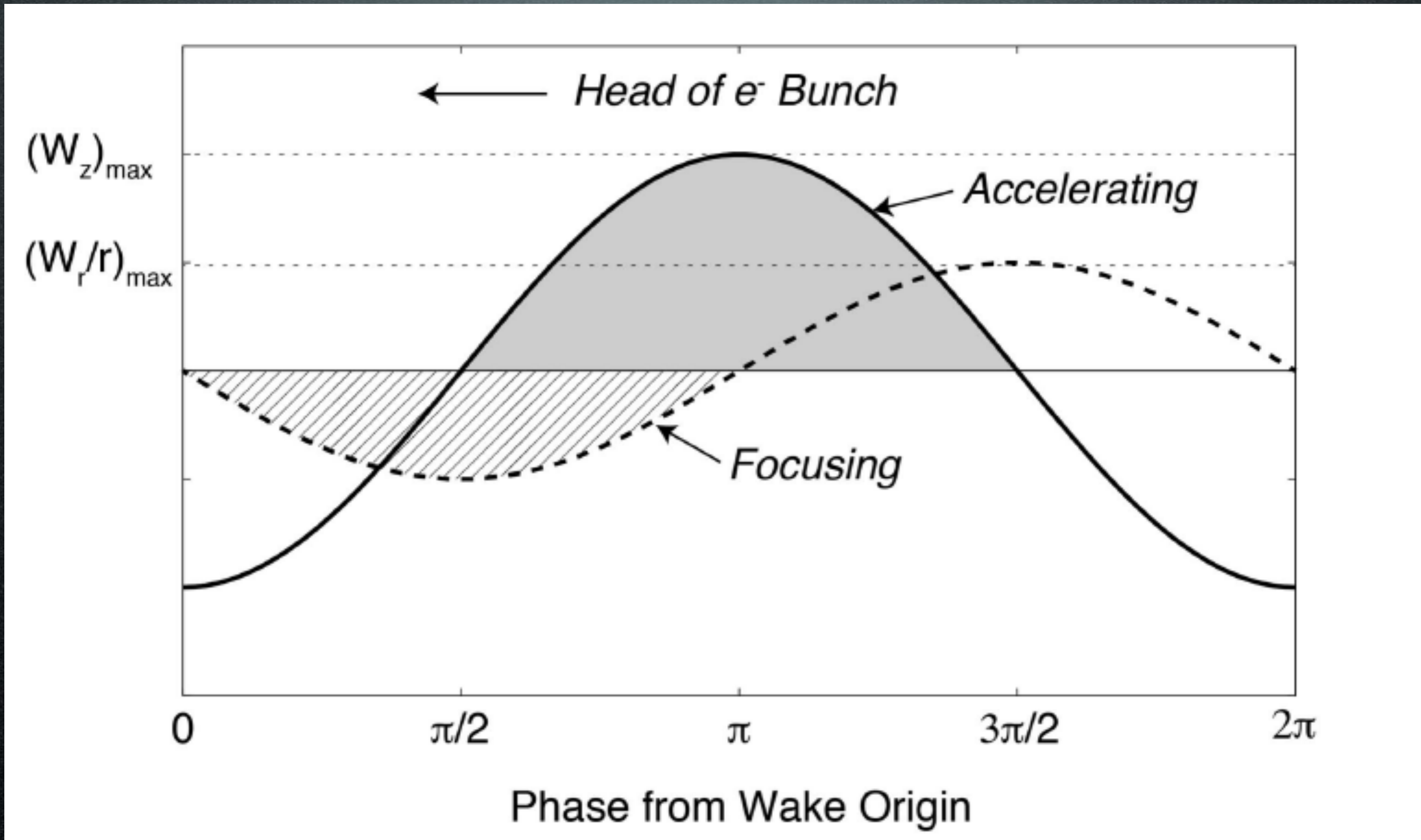
π/2 out of phase

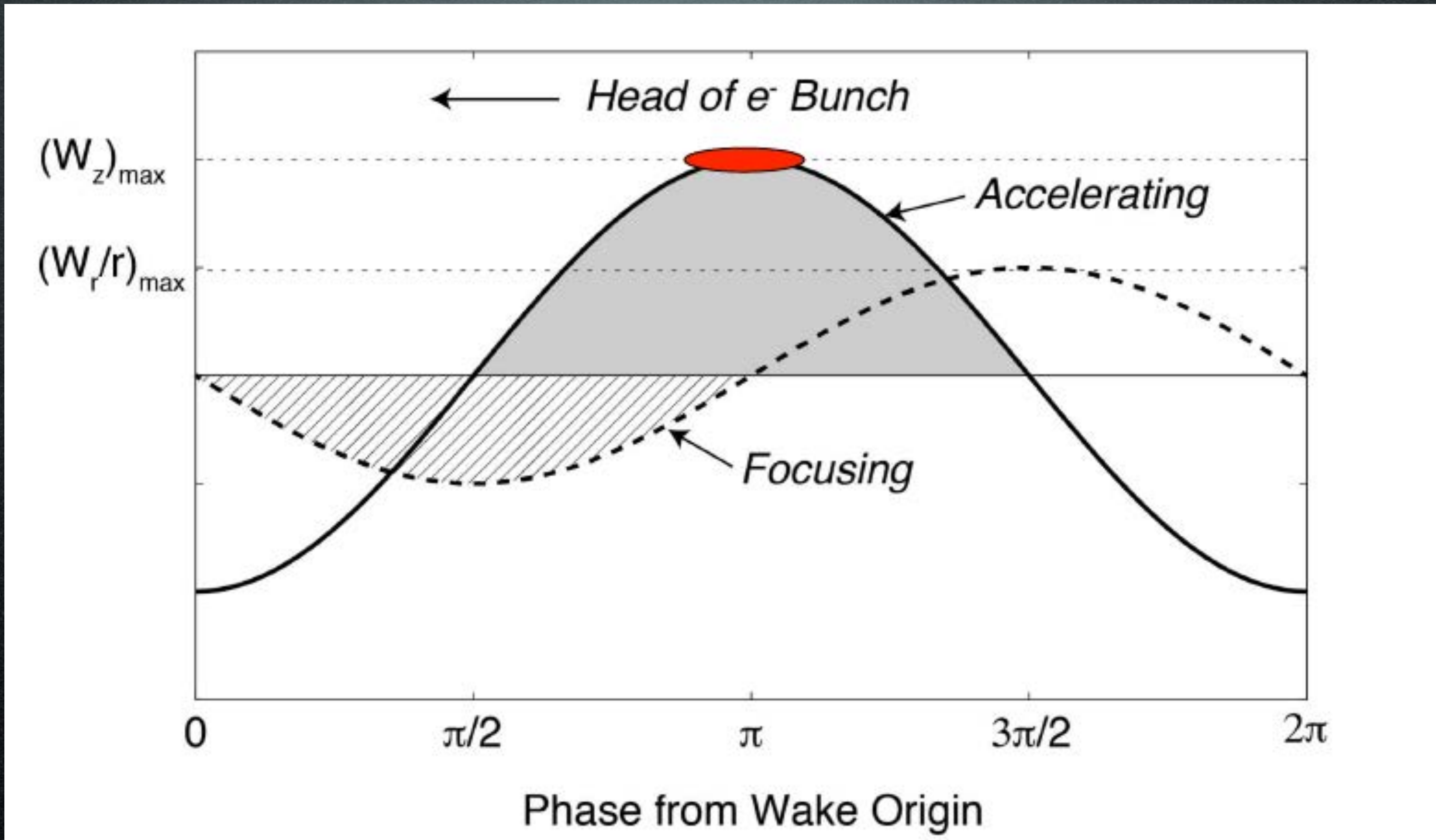
$$\mathcal{E}_r \simeq 2A\frac{r}{k_p a^2}\sin(k_p z-\omega_p t)$$

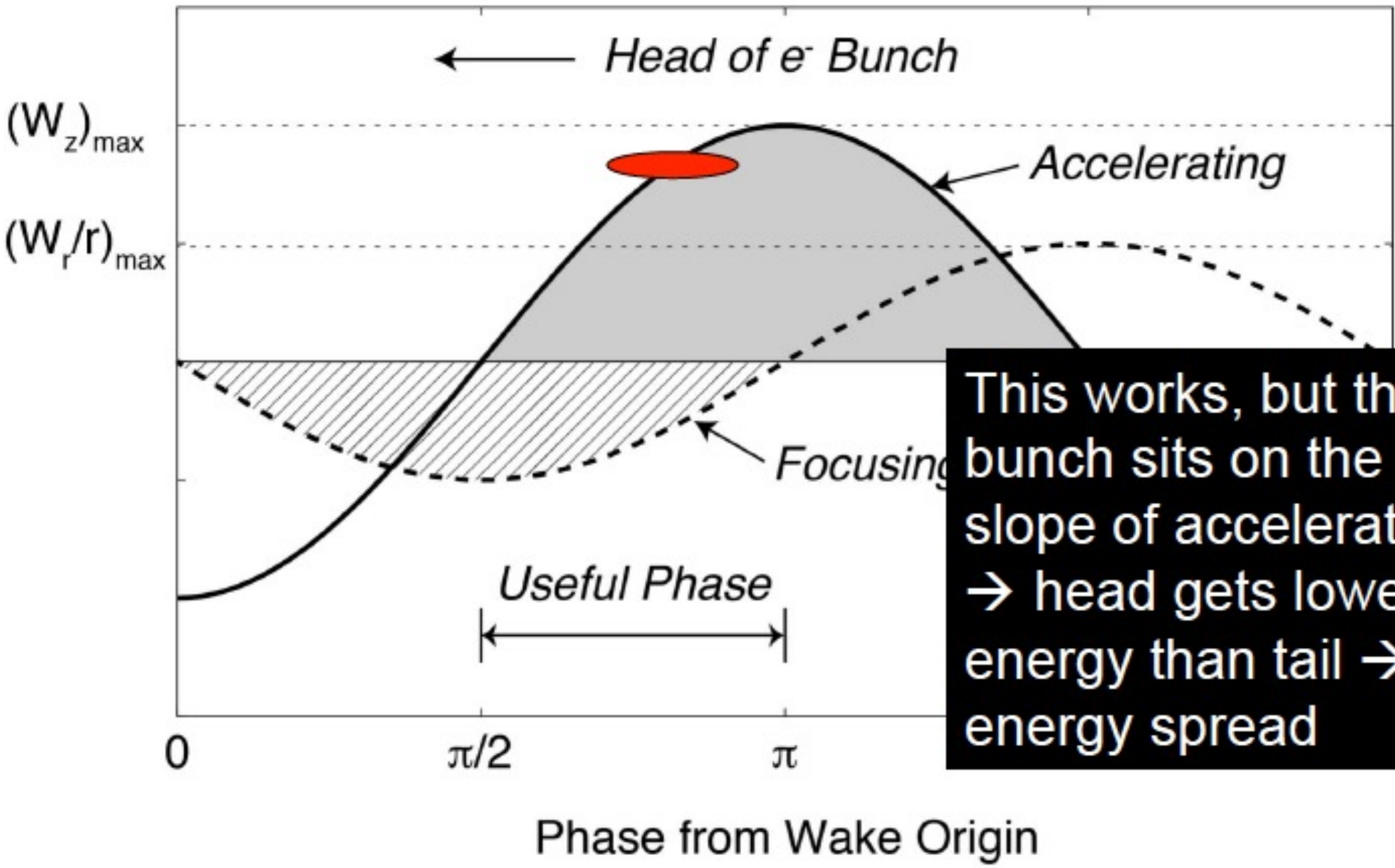
Transverse field

Depends on radial position r

Changes between focusing and defocusing as function of longitudinal position z

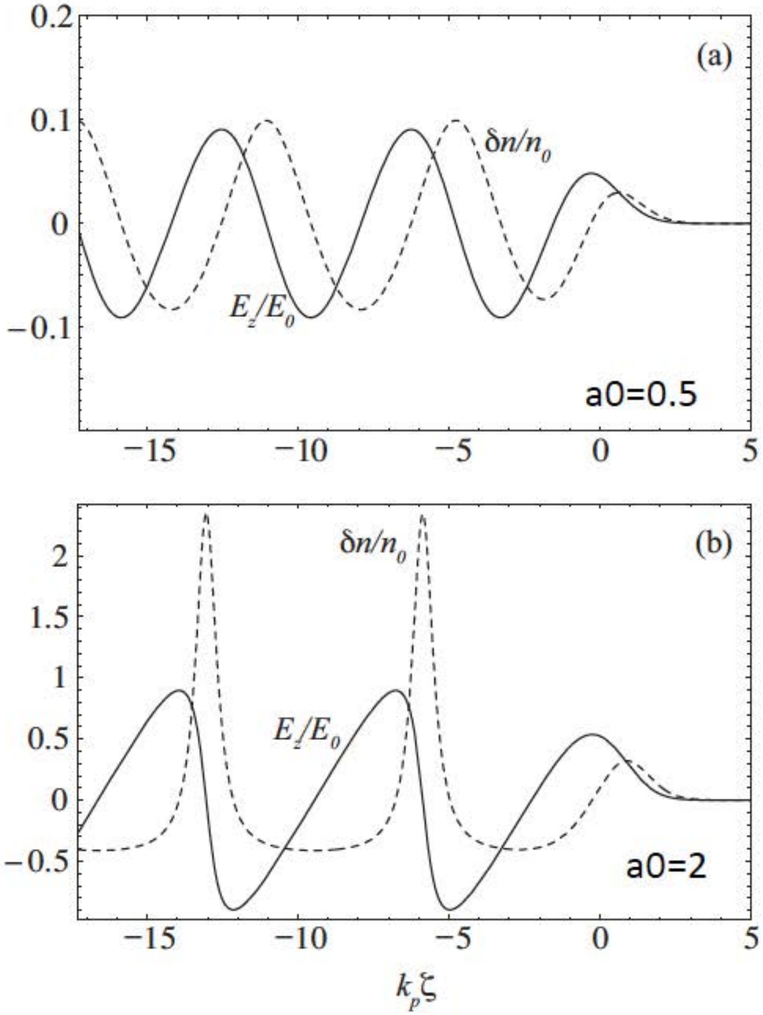

Head of e⁻ Bunch
$(W_z)_{max}$
$(W_r/r)_{max}$
Accelerating
Focusing
0
π/2
π
3π/2
2π
Phase from Wake Origin


Head of e⁻ Bunch
$(W_z)_{max}$
Accelerating
$(W_r/r)_{max}$
Focusing
0
π/2
π
3π/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) $a_0=2.0$.

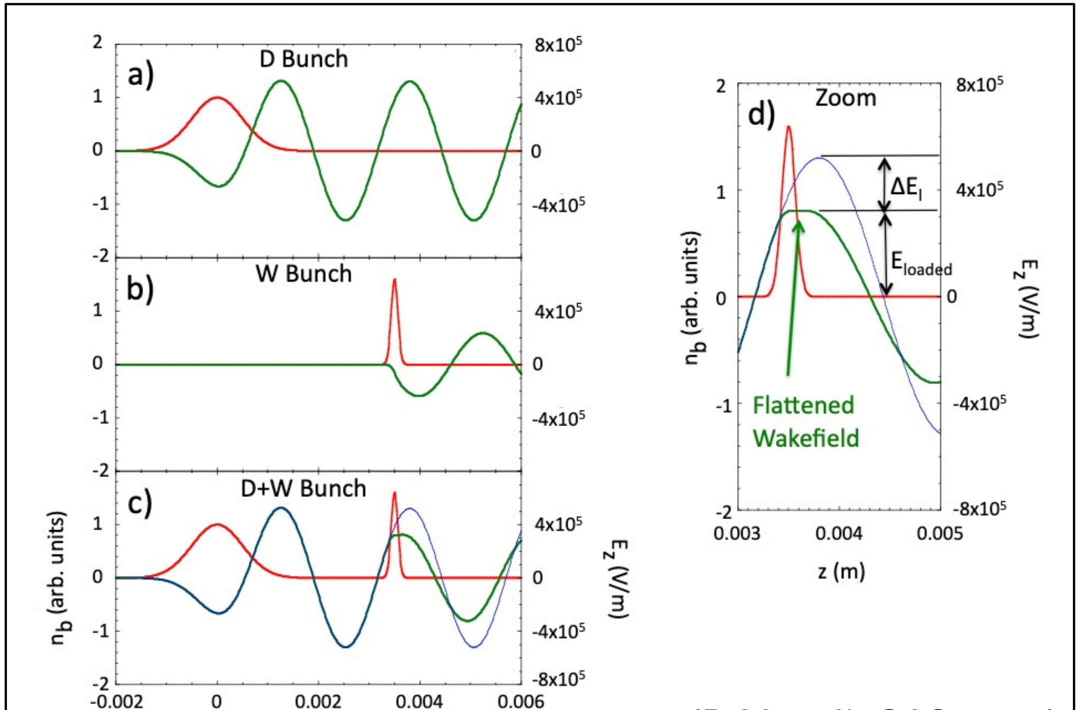
Non-Linear

Beam Loading

➔ BEAM LOADING:

The presence of the witness bunch affects the wakefields

Linear regime



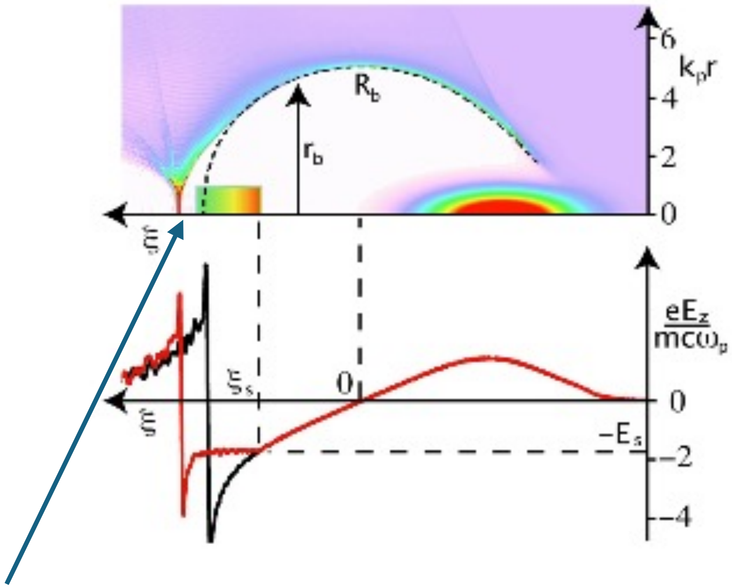
(P. Muggli, CAS 2014)

Non-linear regime


PRL 101, 145002 (2008) PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2008

Beam Loading in the Nonlinear Regime of Plasma-Based Acceleration

M. Tzoufras,[1] W. Lu,[1] F. S. Tsung,[2] C. Huang,[2] W. B. Mori,[1,2] T. Katsouleas,[3] J. Vieira,[4] R. A. Fonseca,[4] and L. O. Silva[4]

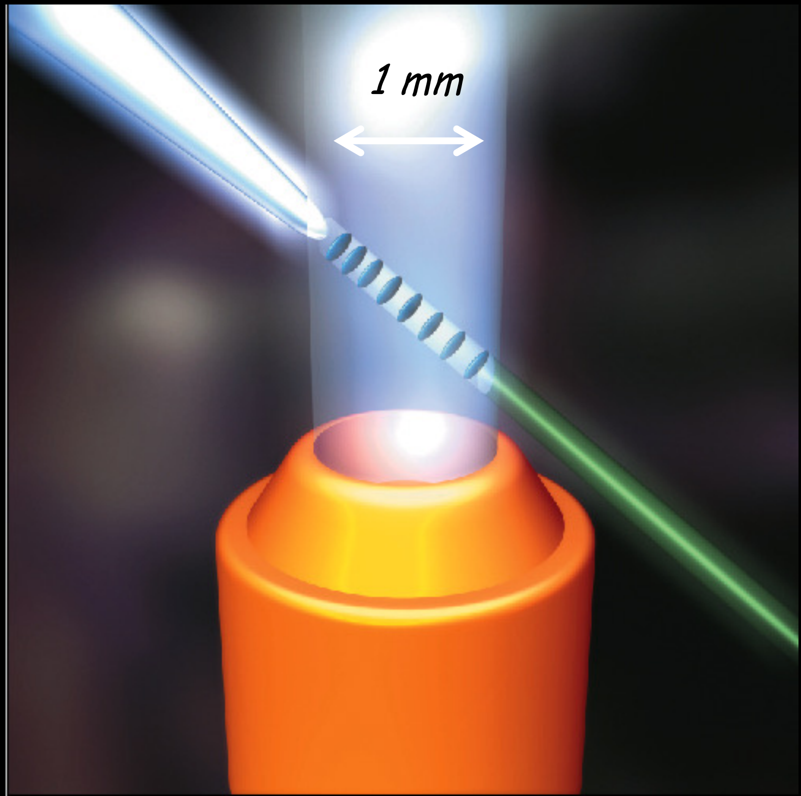


The bubble closes later

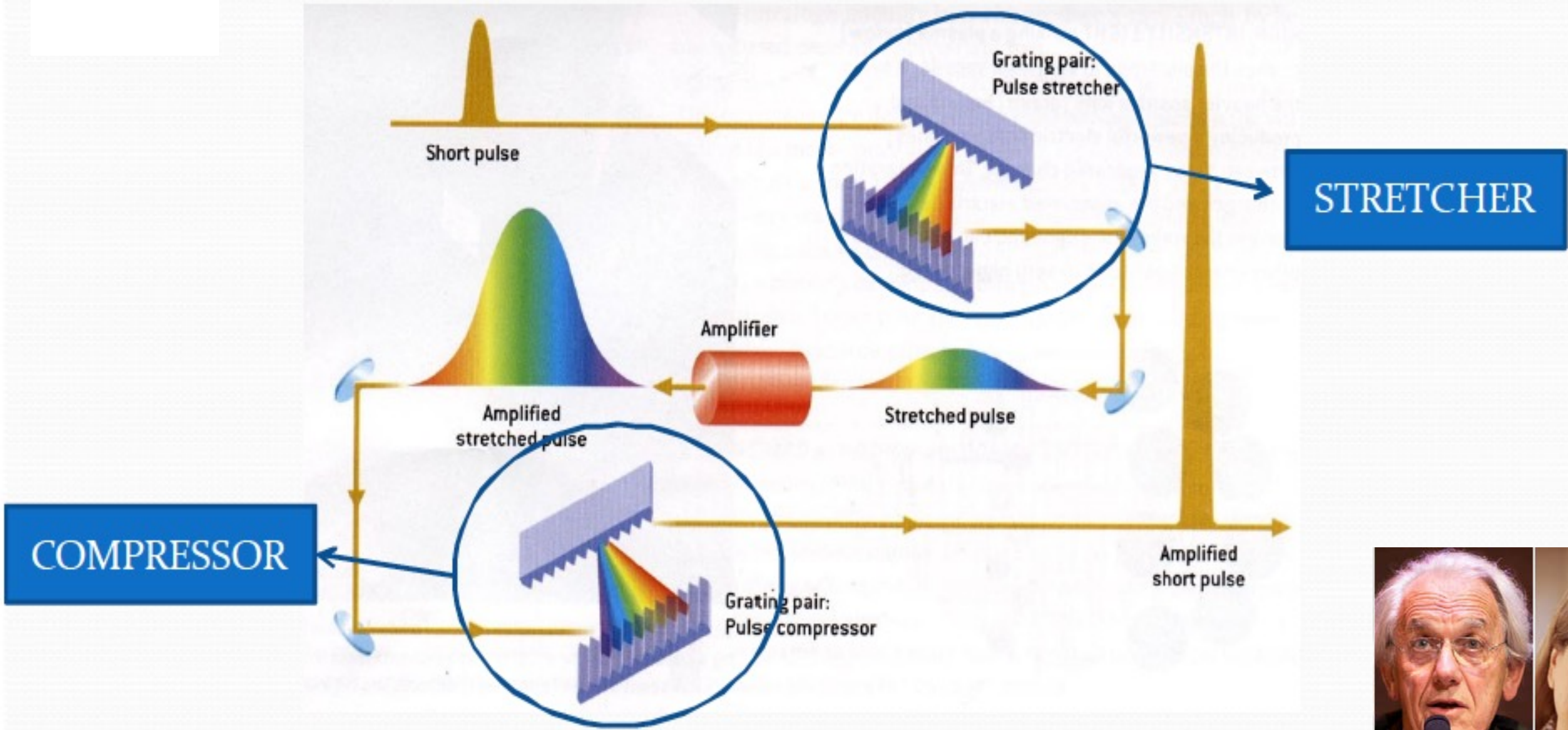
Laser Driven

LWFA

Direct production of e-beam

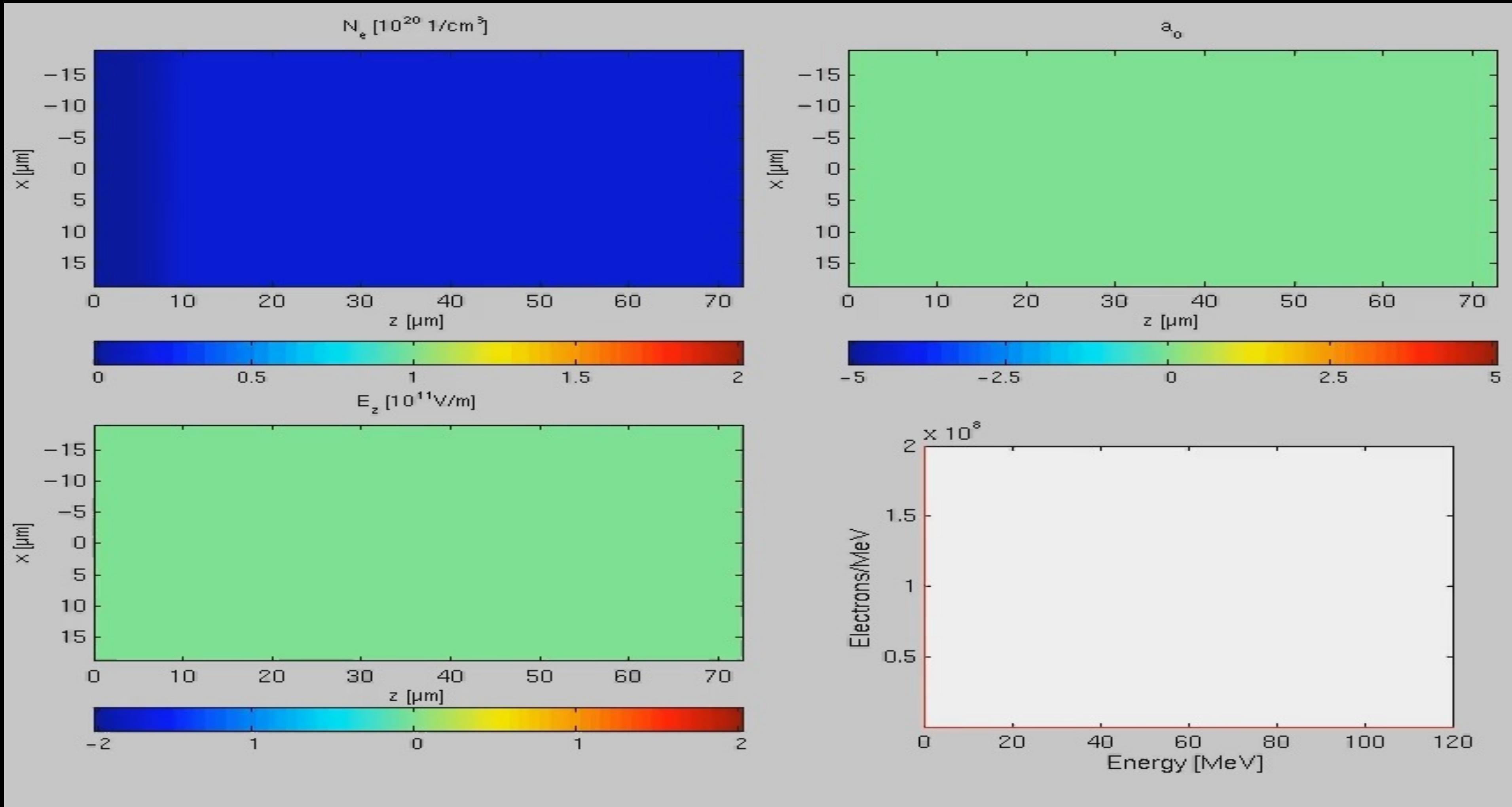


Chirped Pulse Amplification



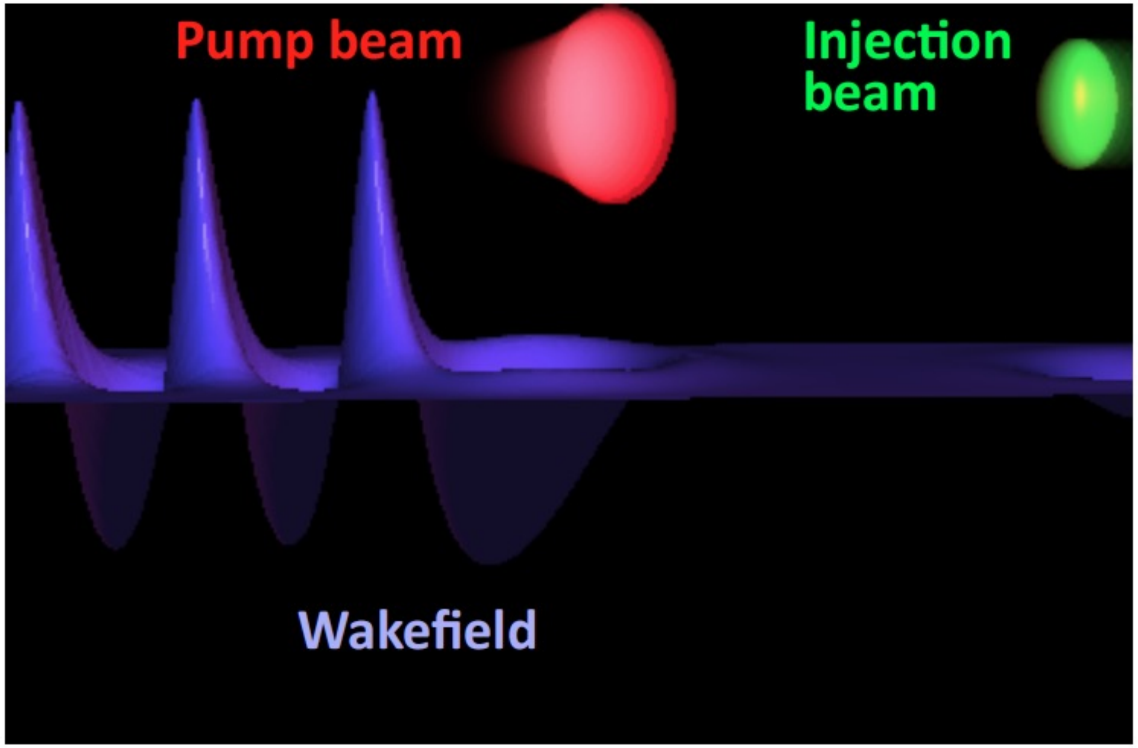
2018
NOBEL PRIZE
Physics

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

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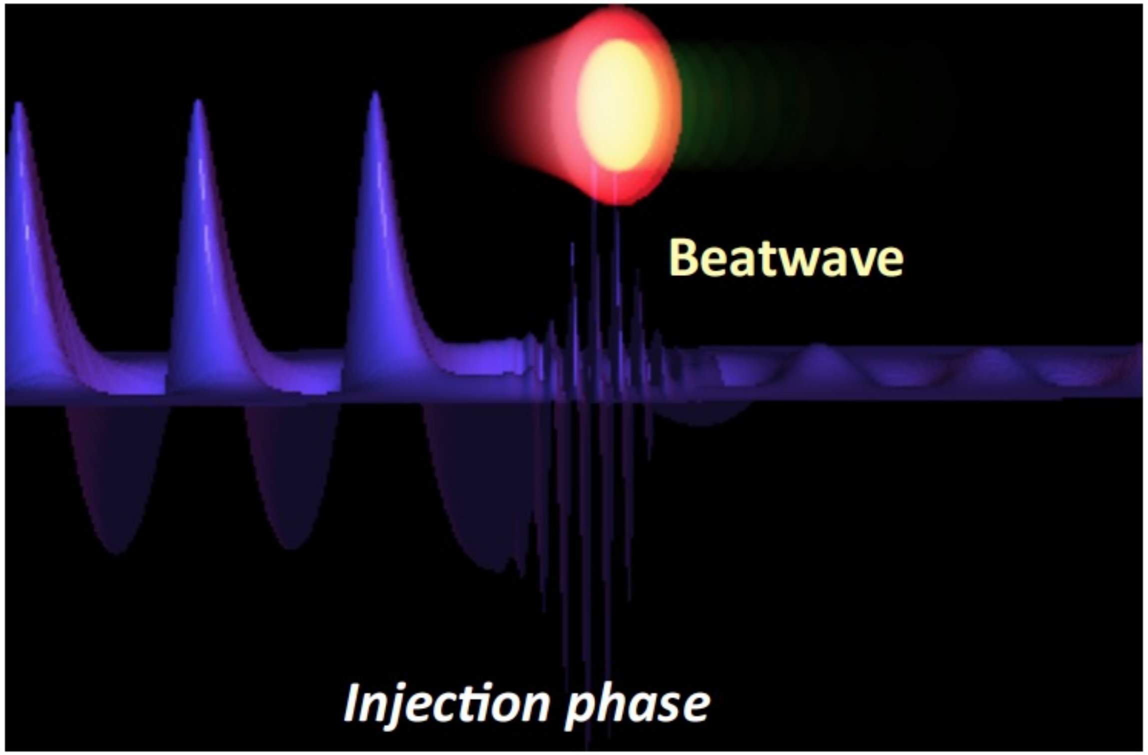

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Colliding Laser Pulses Scheme

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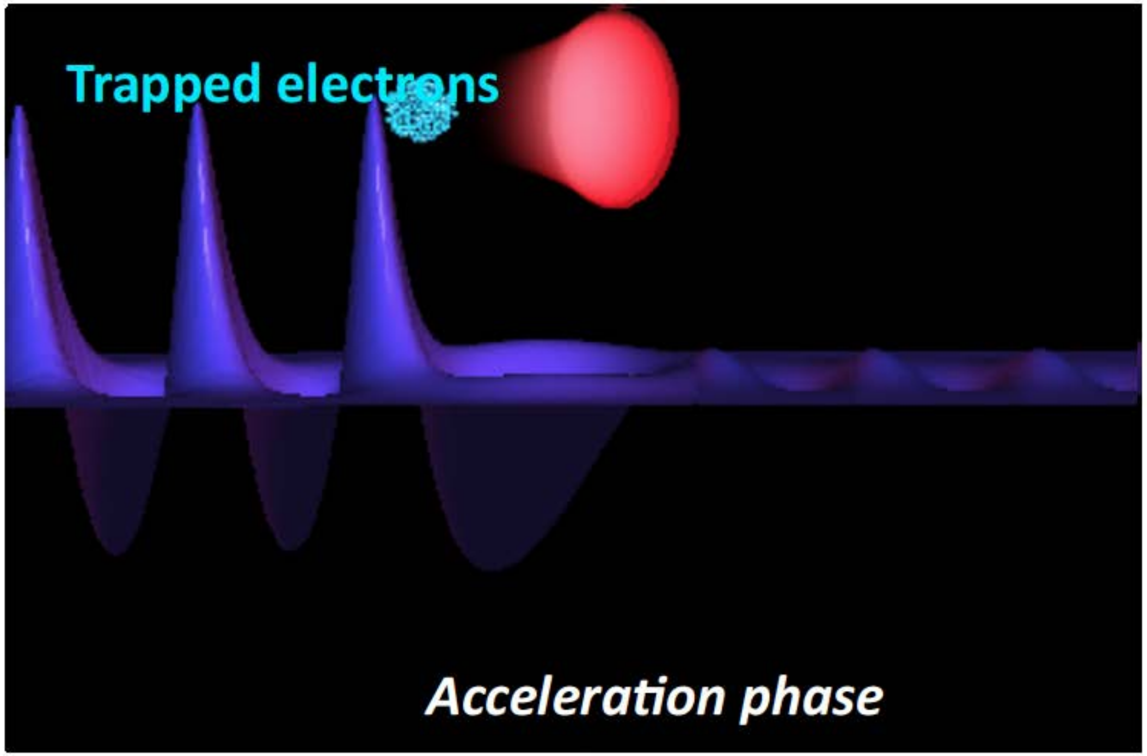
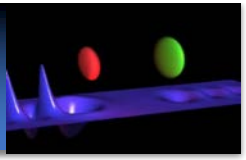
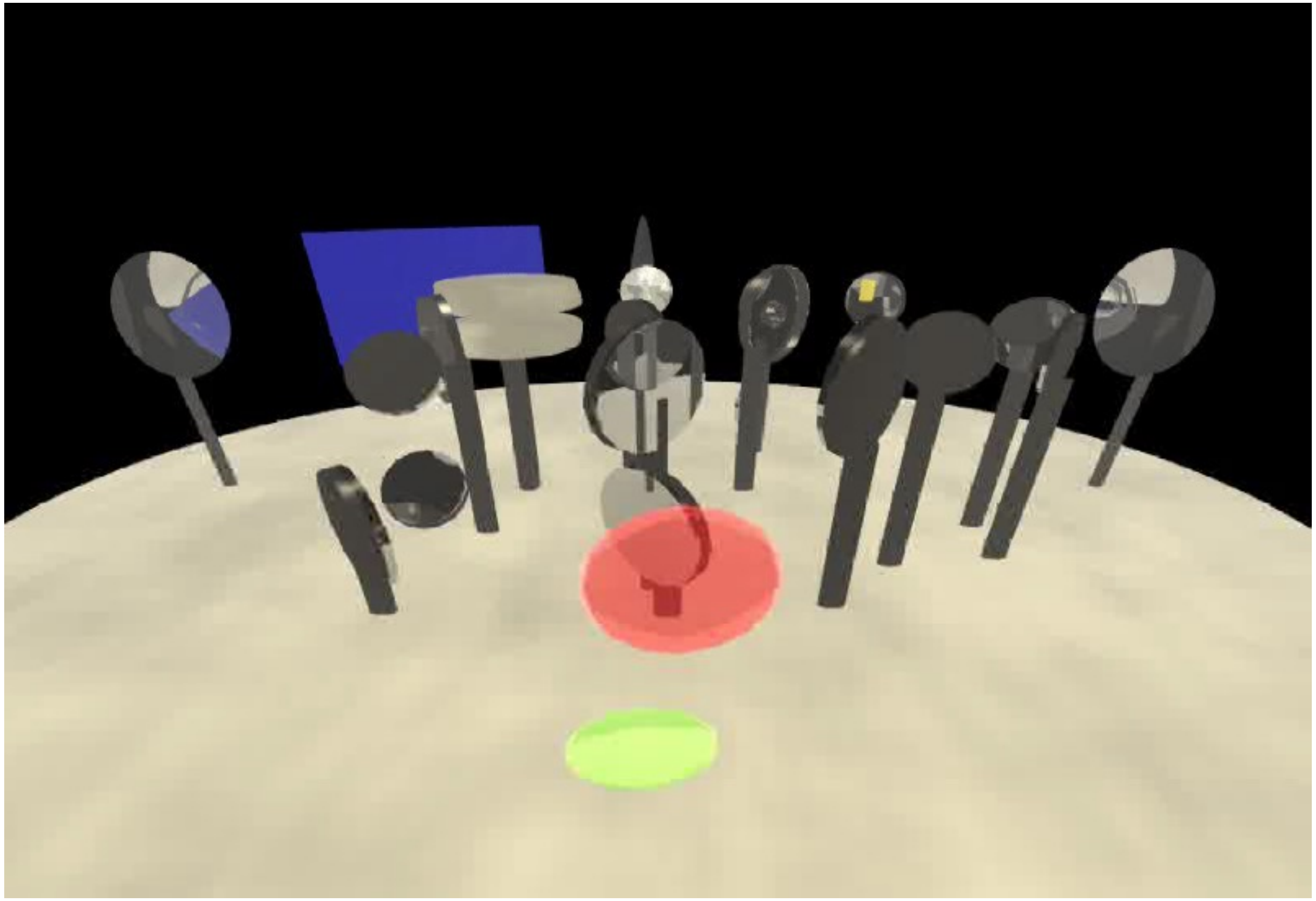


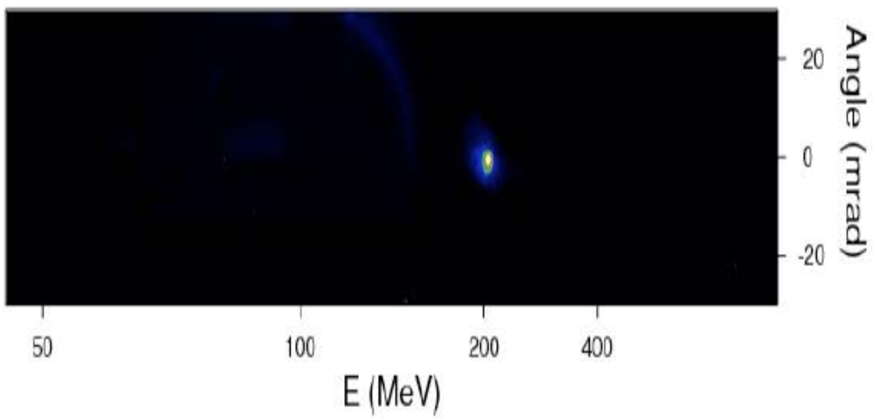
Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

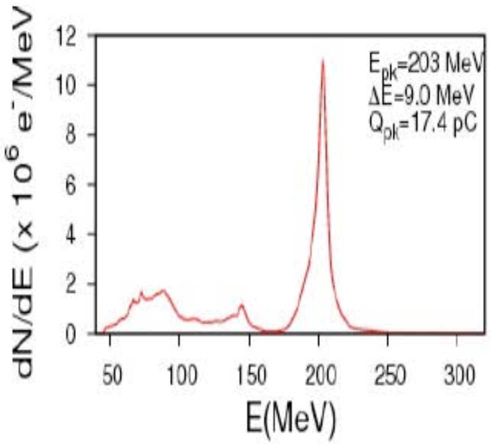
The colliding of two laser pulses



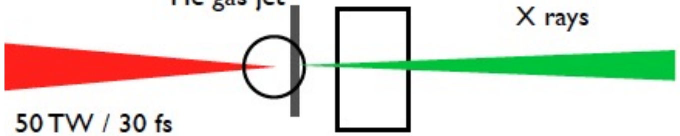


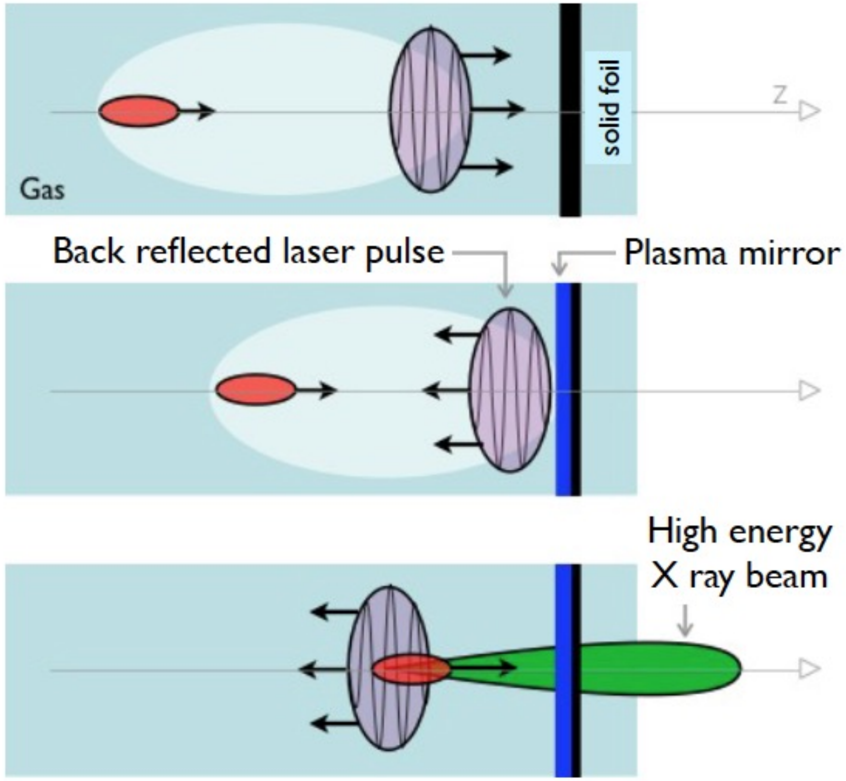
Stable Laser Plasma Accelerators





Inverse Compton Scattering : New scheme





A single laser pulse

A plasma mirror reflects the laser beam

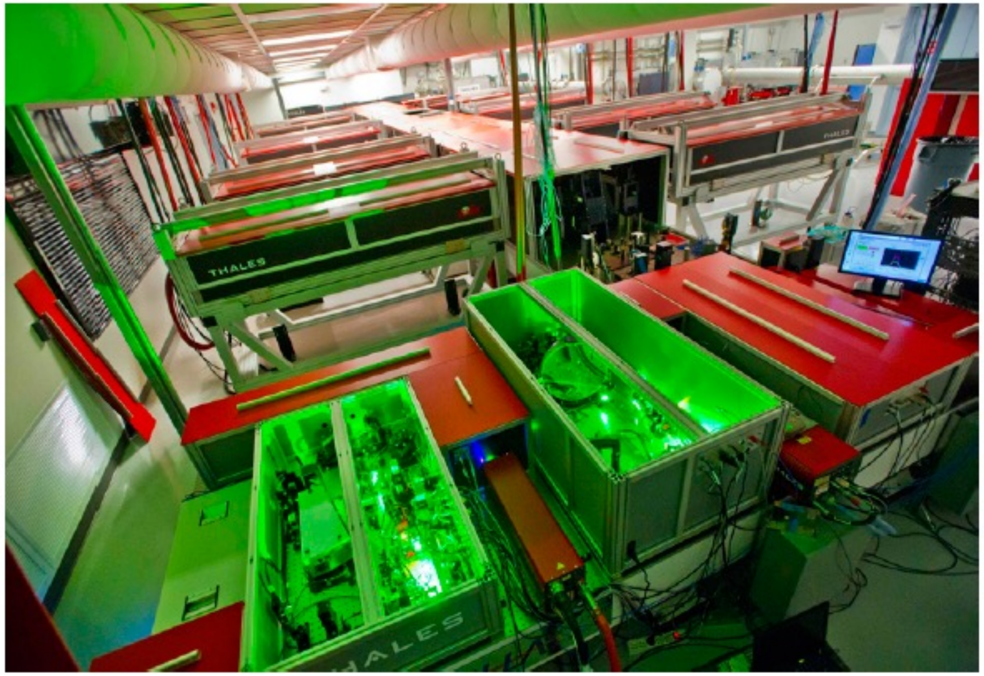
The back reflected laser collides with the accelerated electrons

No alignment : the laser and the electron beams naturally overlap

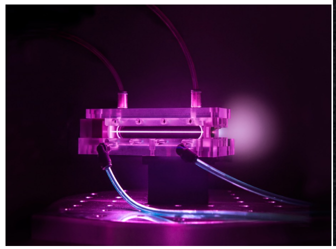
Save the laser energy !

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

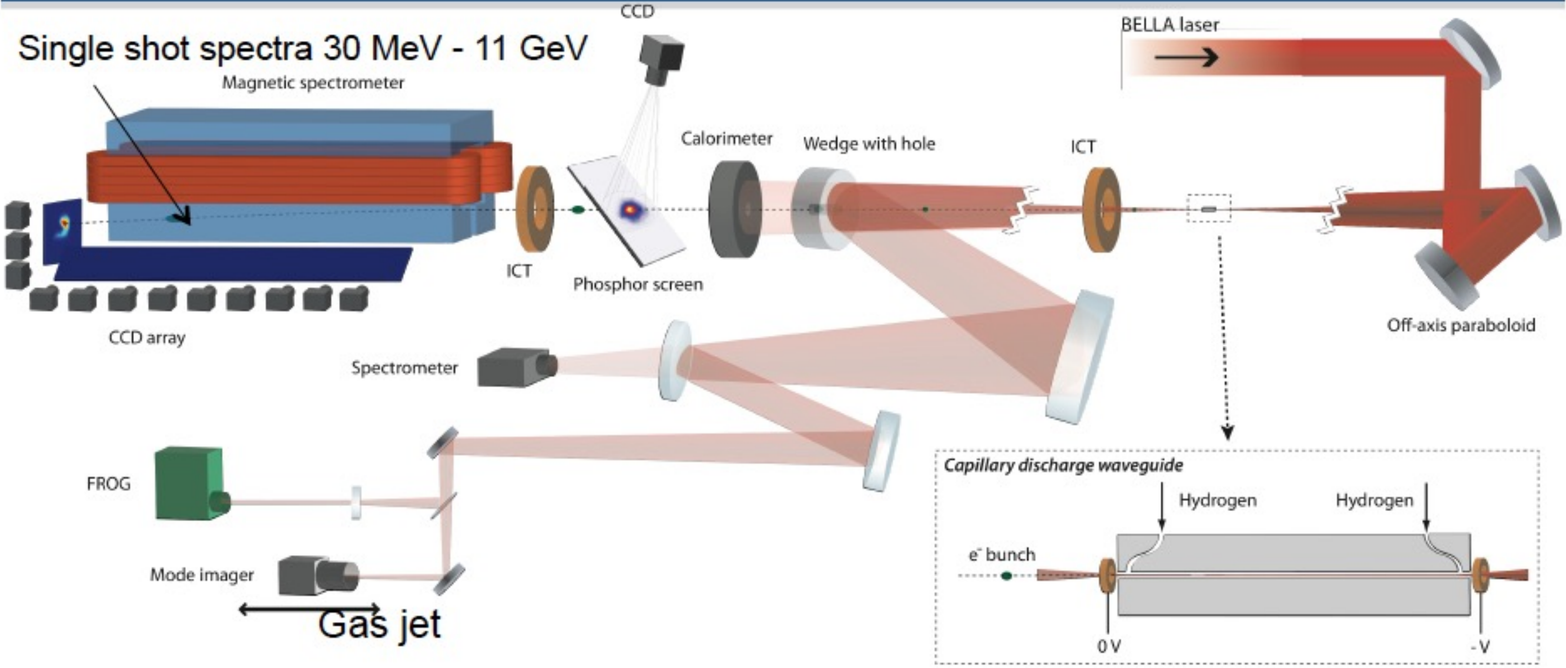


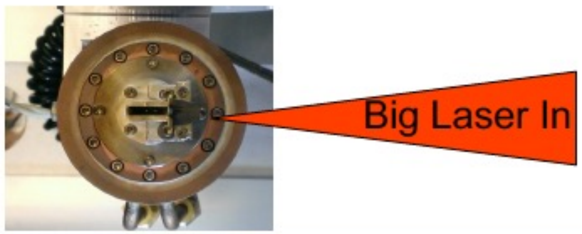
Critical HEP experiments:
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration



BELLA

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

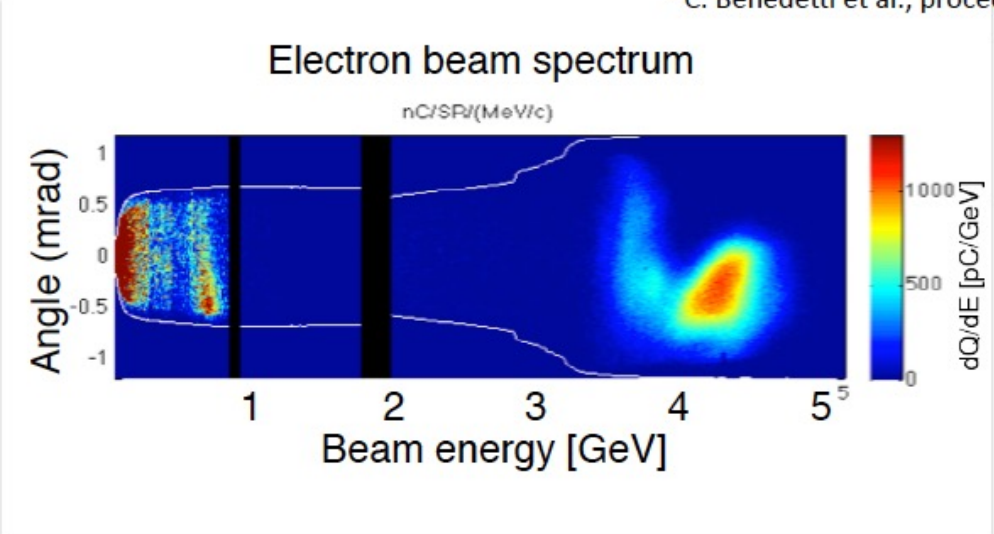


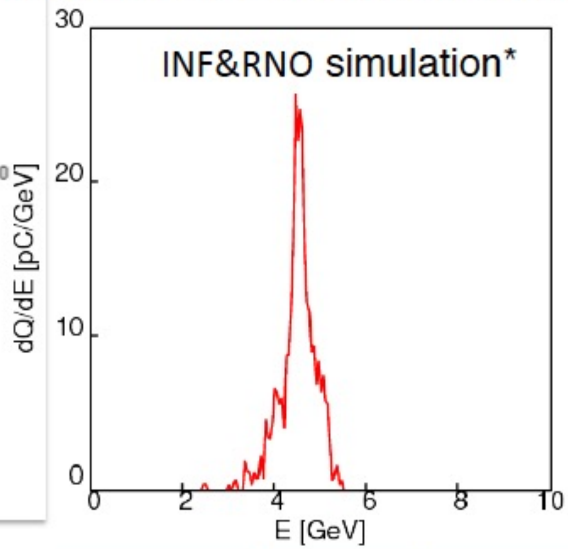


Capillary discharge

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





	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

- **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})

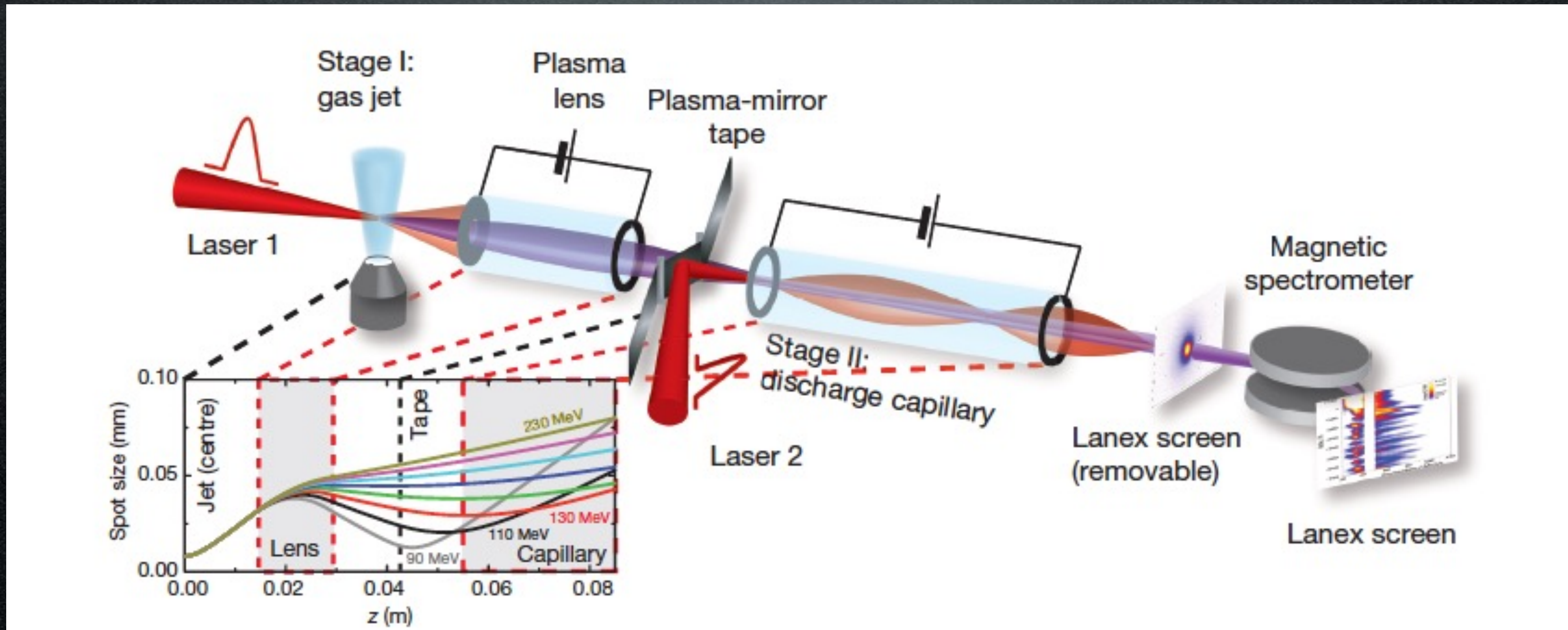
W.P. Leemans et al.,PRL 2014

LETTER

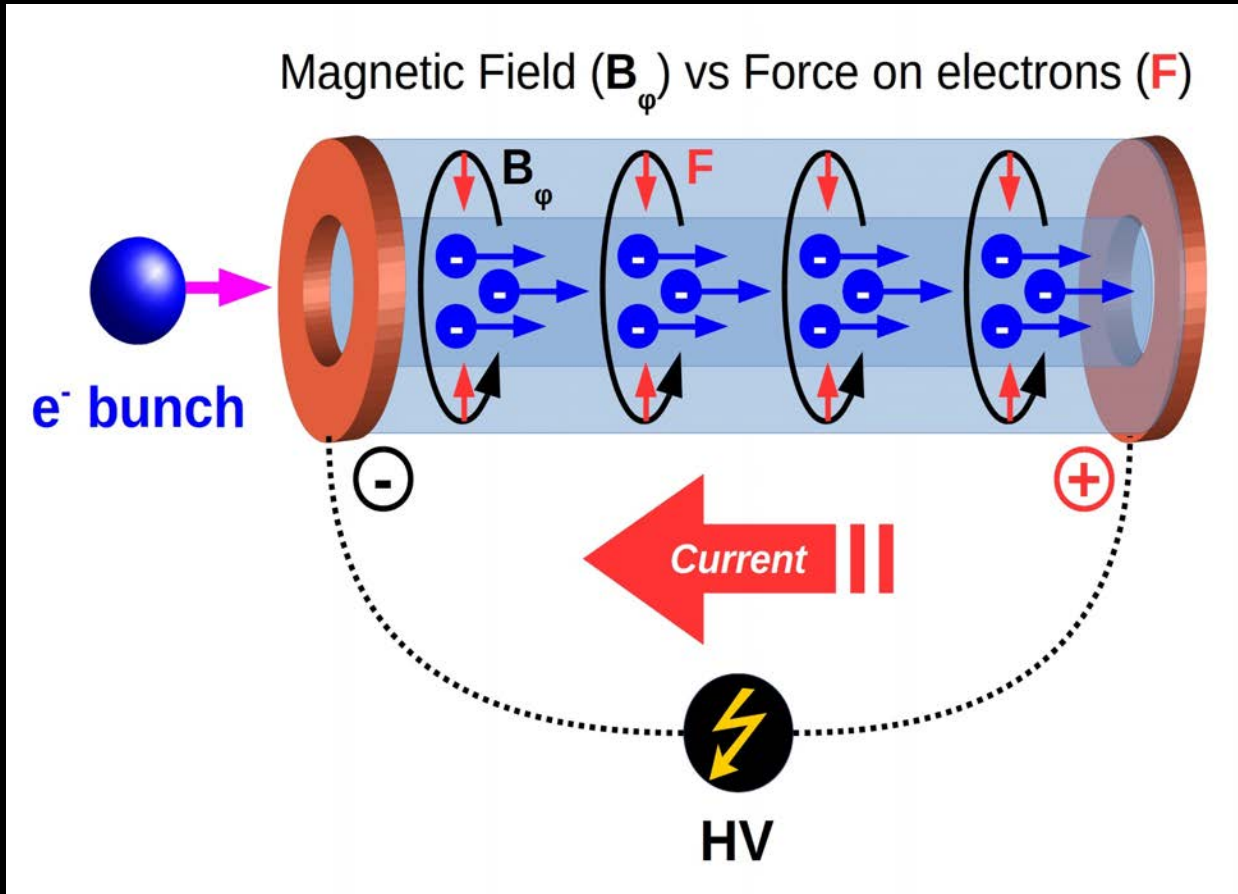
doi:10.1038/nature16525

Multistage coupling of independent laser–plasma accelerators

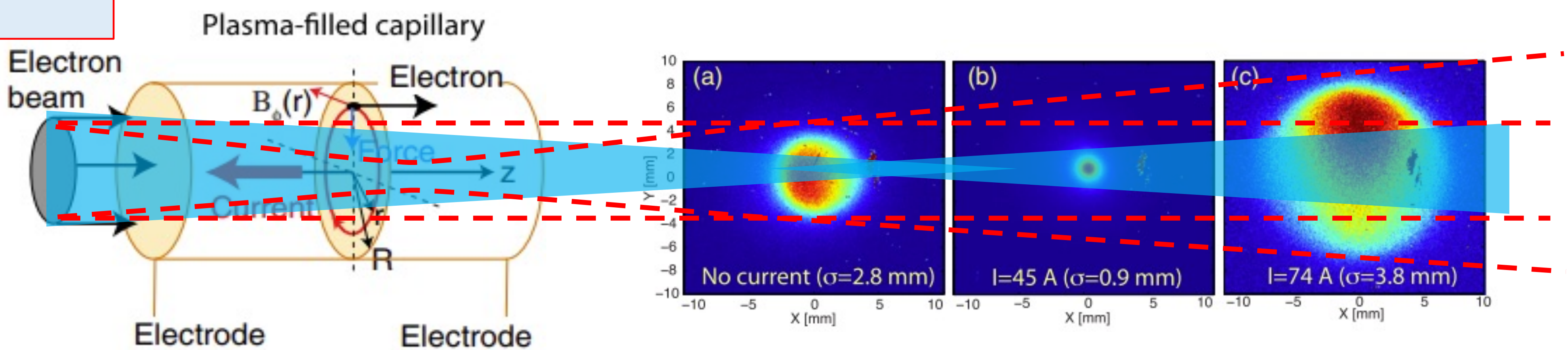
S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Daniels[1,3], K. K. Swanson[1,2], A. J. Gonsalves[1], K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]



Active Plasma Lens



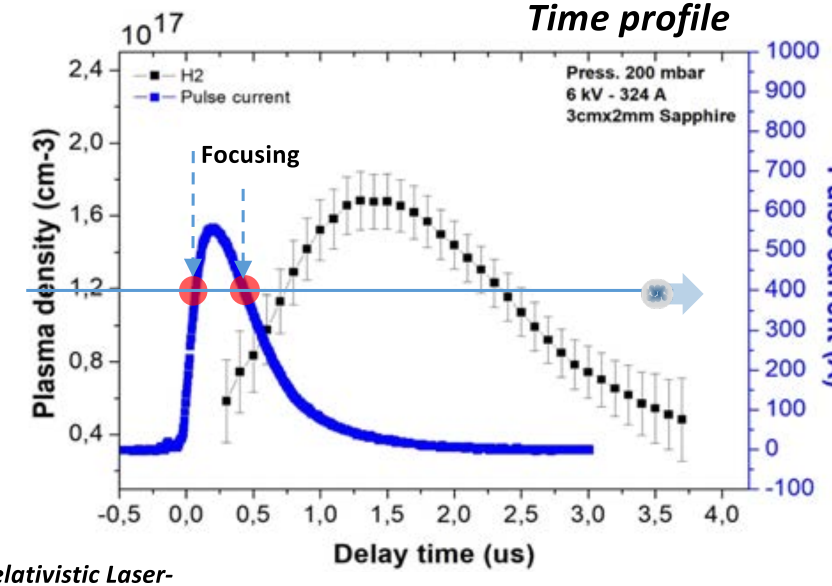
Active PlasmA alens (APL)

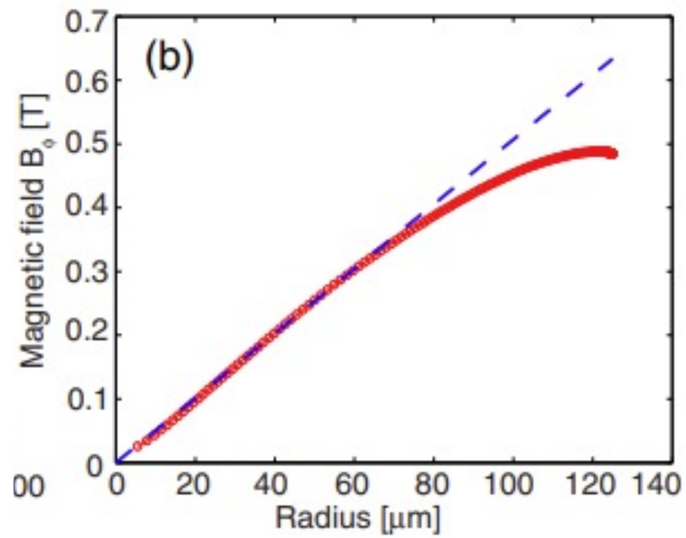


$$\partial B_\phi/\partial r = \mu_0 I_0/(2\pi R^2)$$

- ***R*** capillary radius
- ***I_0*** peak current

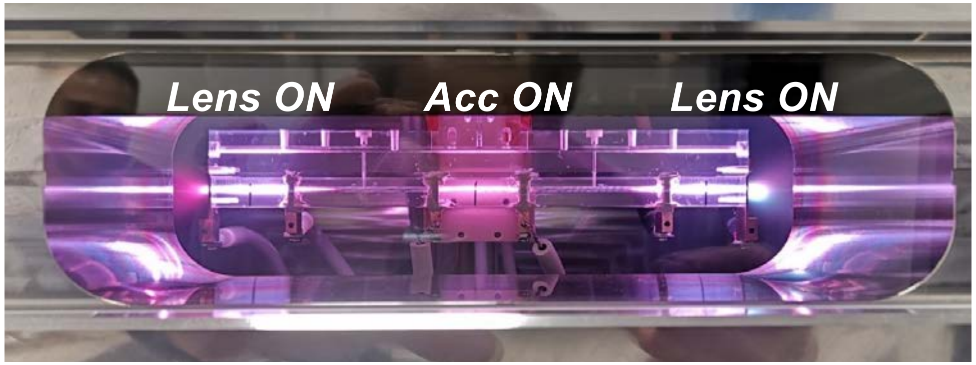
Time profile

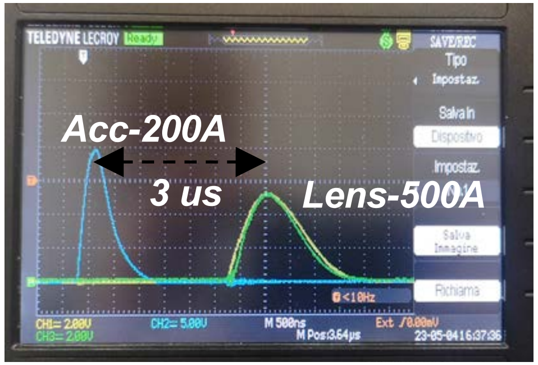




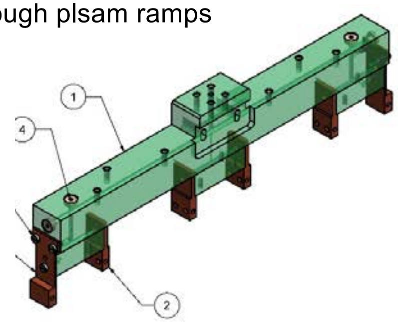
J. van Tilborg et Al, ***Active Plasma Lensing for Relativistic Laser-Plasma-Accelerated Electron Beams***, **PRL 115, 184802 (2015)**

Integrated capillary

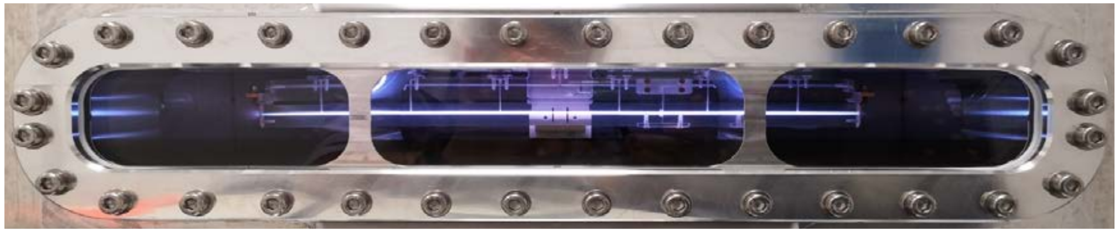




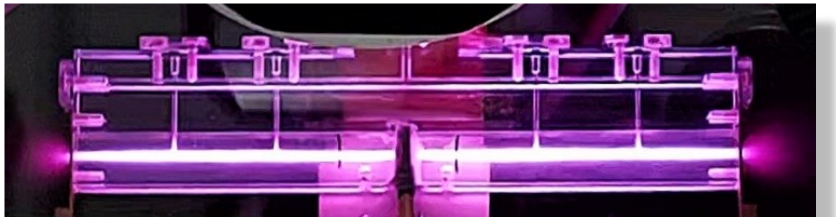
Studies on cross-talk effects:
Design of electrodes and HV-circuits to reduce the interaction among discharges through plsam ramps



Very long capillary

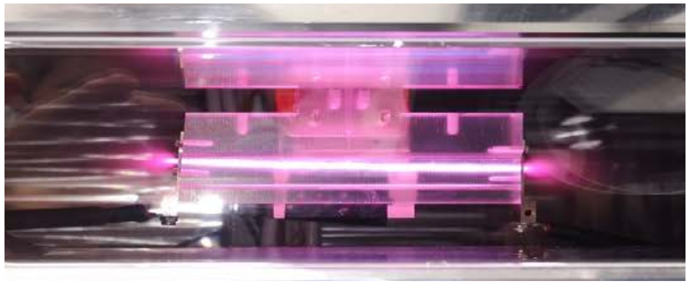


Design of m-scale capillaries for EuPRAXIA project by using segmented capillaries: design of HV-voltage circuits and discharge synchronization



Segmented capillary

Curved capillary for APD



Design of new geometries for curved channels: HV-circuits to allow high current pulses

Pompili, Riccardo, et Al, Guiding of charged particle beams in curved capillary-discharge waveguides, AIP Advances 8.1 (2018)

Plasma collider challenges

Beam delivery system

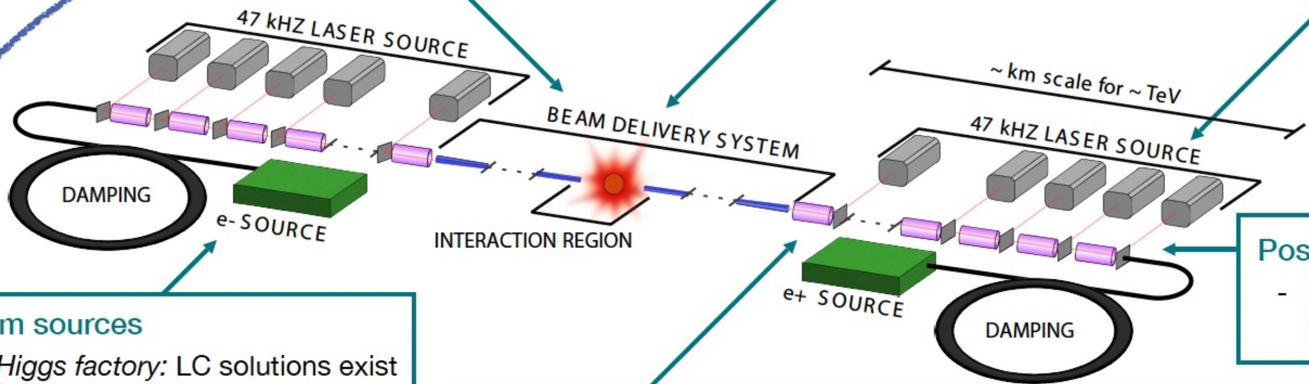
- *Higgs factory:* optimized LC designs exist
  optimizations for plasmas needed/possible?
- *10 TeV collider:* no design exists
  critical - HF designs scale poorly with energy (geo. gradient) → 20 (CLIC) to 90 (ILC) km

Interaction region

- *Higgs factory:* designed for other LCs
- *10 TeV collider:* studies critical to define collider type and machine parameters
  critical - valid codes for beam/beam studies

Driver technology

- *Beams:* technology exists in principle
  cost, gradient, efficiency, distribution optimization
- *Lasers:* do not exist, R&D paths identified
  critical - rep. rate & power, efficiency, robustness, cost
  opportunity - simple energy recovery (photovoltaics)



Positron acceleration

- No concept exists (yet) that fulfills needs
  critical - beam quality, efficiency, resilience

Beam sources

- *Higgs factory:* LC solutions exist
  opportunity - compact (cheaper) sources from plasmas
- *10 TeV collider:* undefined, potentially a key issue

Plasma stages + coupling

- Focus and key charge for our field, no roadblocks known
  critical - beam quality (incl. polarization), efficiency, stability, longevity, resilience to jitter (in time, space, and momentum), resilience to catastrophic errors (one bad shot)
- *Plasma stage:* requires demonstration of collider parameters
  + critical - rep. rates & bunch structure (CW vs. burst), power handling
- *Staging:* requires detailed concepts, additional test facilities
  + critical - driver in-/out-coupling, geometric gradient

Full system integration

- Turn components into self-consistent machine
- Optimization of the system for cost, efficiency, environmental impact, physics performance, resiliency (jitter budget)

BERKELEY LAB

Courtesy J. Osterhoff

Erice Accelerator School, Nov. 26 – Dec. 1, 2025

Funded by the European Union

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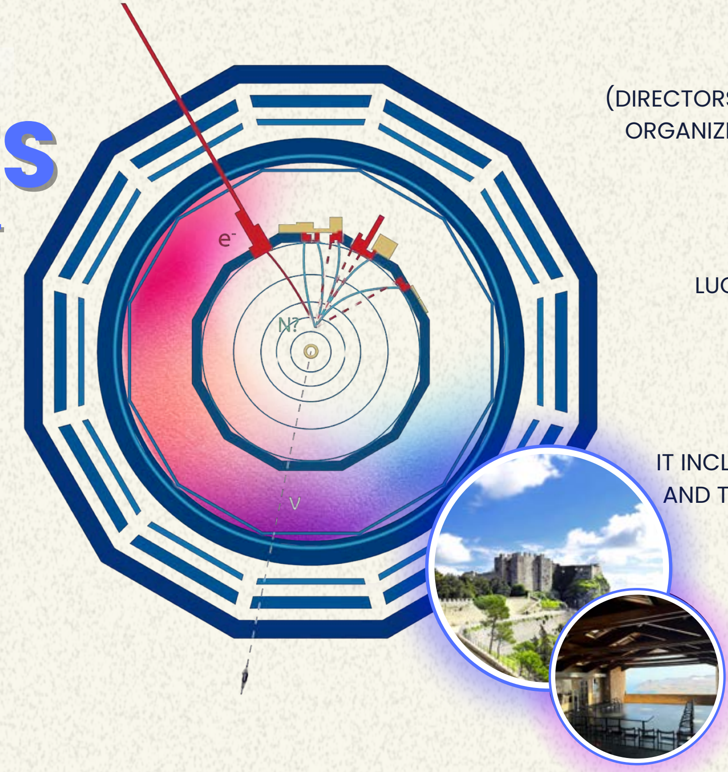

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