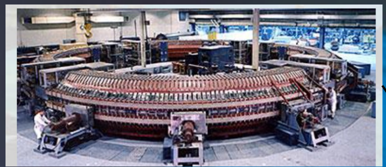
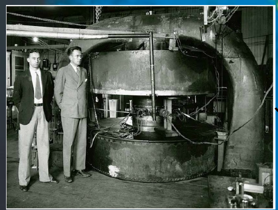
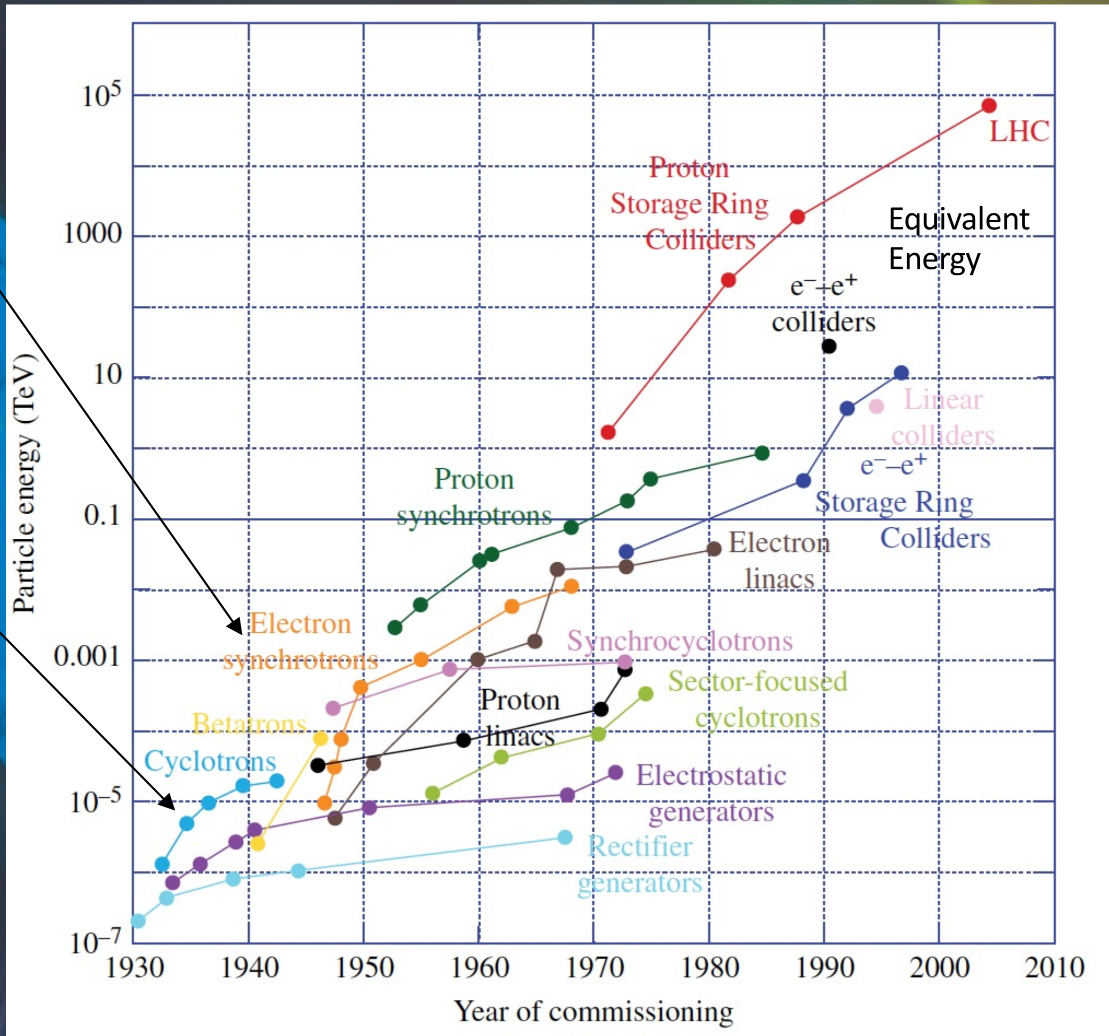
# Advanced Accelerator Concepts

Massimo.Ferrario@lnf.infn.it








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.

The CERN Accelerator School

SPARC LAB

Introduction to Accelerator Physics

Geneva – 29 Sept. 2021

# Advanced Accelerator Concepts

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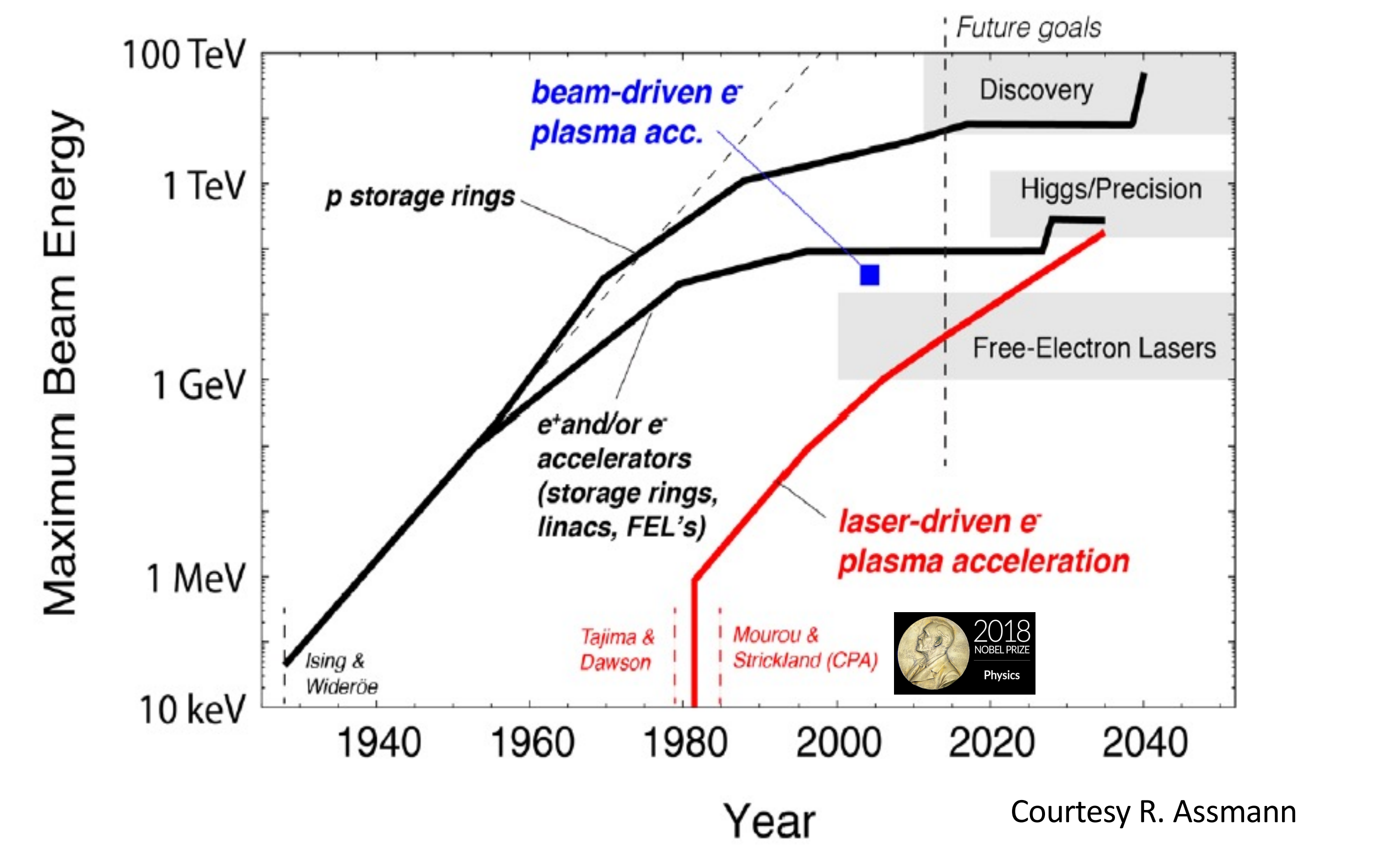


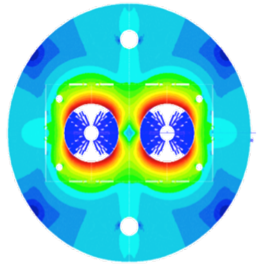

Courtesy R. Assmann

# Options towards higher energies

**Hadron (p) circular collider**

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

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

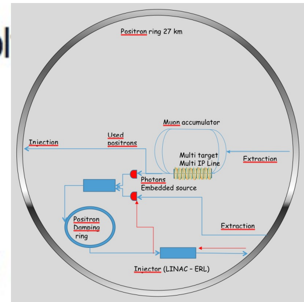


Increase radius = size (FCC-hh)

**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....

# 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

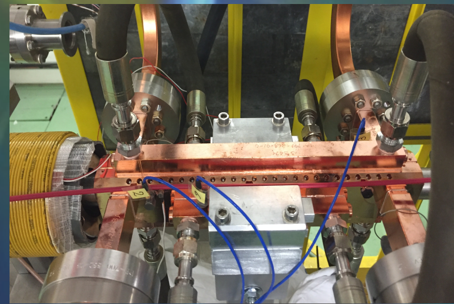
$$B_n \approx \frac{2I}{\varepsilon_n^2}$$

- Short pulse (ps => fs)
- Little spread in transverse momentum and angle => low emittance

# High Gradient Options

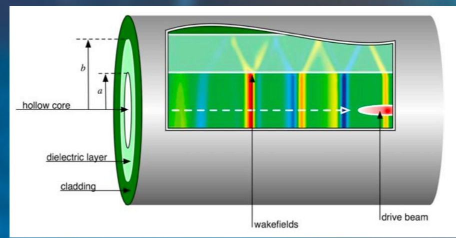
Metallic accelerating structures =>

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



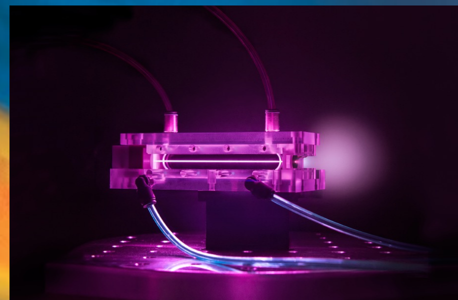
Dielectrict structures, laser or particle driven =>

$E_{acc}$ < 10 GV/m




Plasma accelerator, laser or particle driven =>

$E_{acc}$ < 100 GV/m



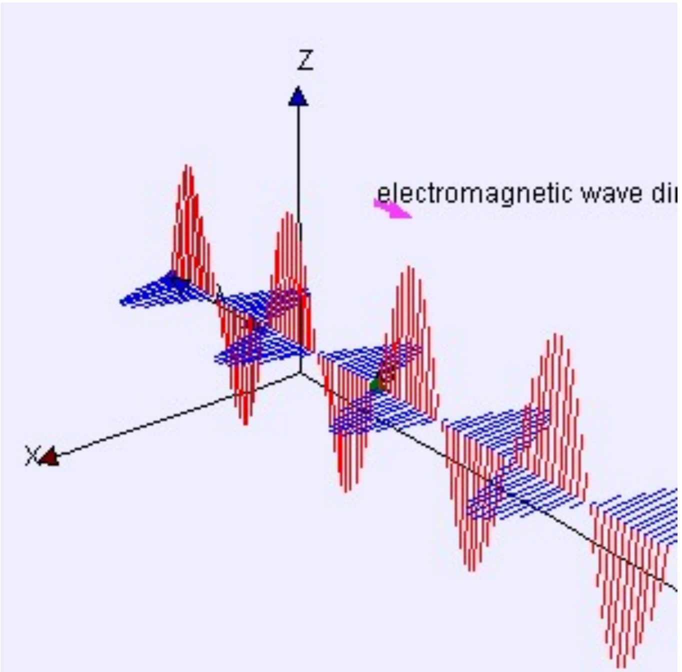
Related Issues: Power Sources and Efficiency, Stability, Reliability, Staging, Synchronization, Rep. Rate and short (fs) bunches with small (µm) spot to match high gradients

# Lawson-Woodward Theorem

(J.D. Lawson, IEEE Trans. Nucl. Sci. NS-26, 4217, 1979)

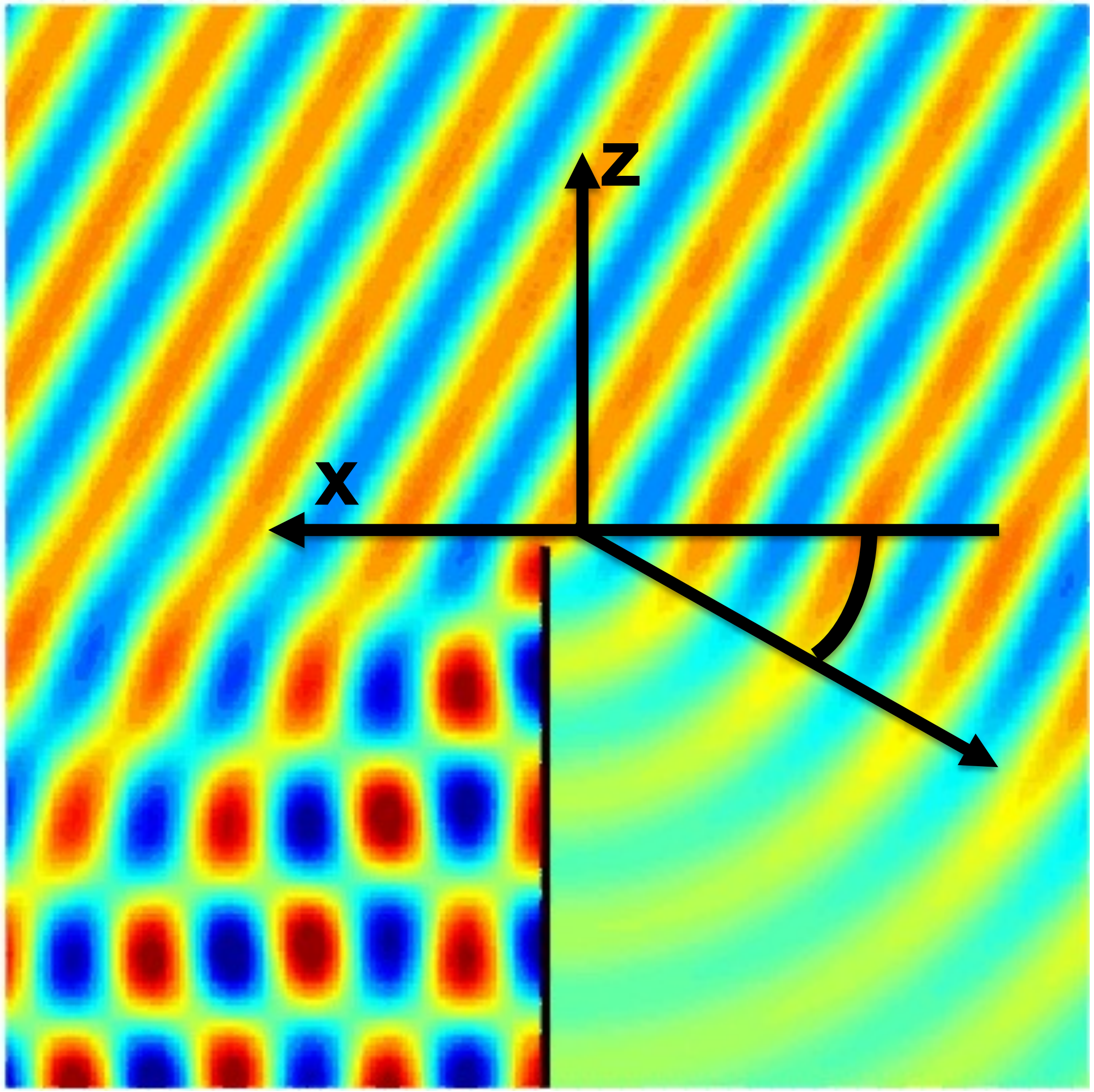
The net energy gain of a relativistic electron interacting with an electromagnetic field **in vacuum** is zero.

The theorem assumes that
(i) the laser field is in vacuum with no walls or boundaries present,
(ii) the electron is highly relativistic ($v \approx c$) along the acceleration path,
(iii) no static electric or magnetic fields are present,
(iv) the region of interaction is infinite,




$$F_{\perp} \cong \frac{eE_x}{\gamma^2} cos\left(\frac{\omega t}{2\gamma^2}\right)$$

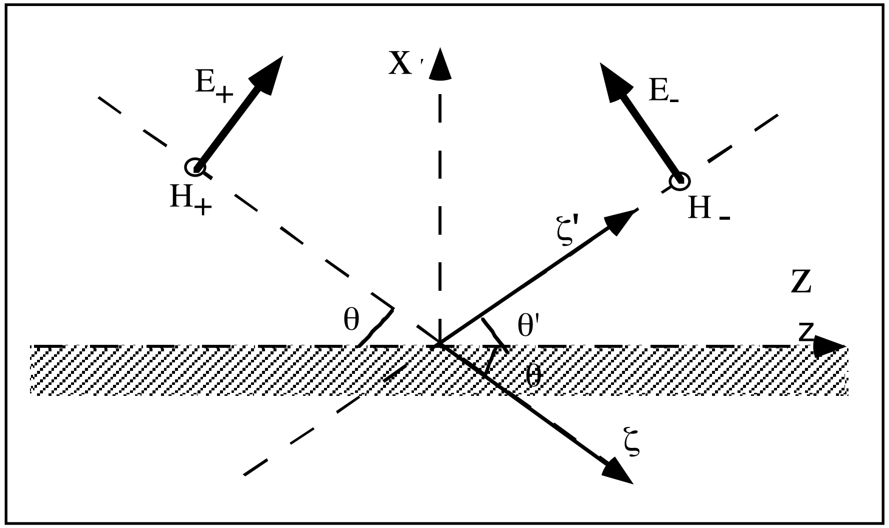
# Reflection of plane waves



# Reflection of plane waves

Plane wave reflected by a perfectly conducting plane

$$\sigma = \infty$$




In the plane xz the field is given by the superposition of the incident and reflected wave:

$$E(x,z,t) = E_+(x_o,z_o,t_o)e^{i\omega t - ik\zeta} + E_-(x_o,z_o,t_o)e^{i\omega t - ik\zeta'}$$

$$\zeta = z\cos\theta - x\sin\theta \qquad \zeta' = z\cos\theta' + x\sin\theta'$$

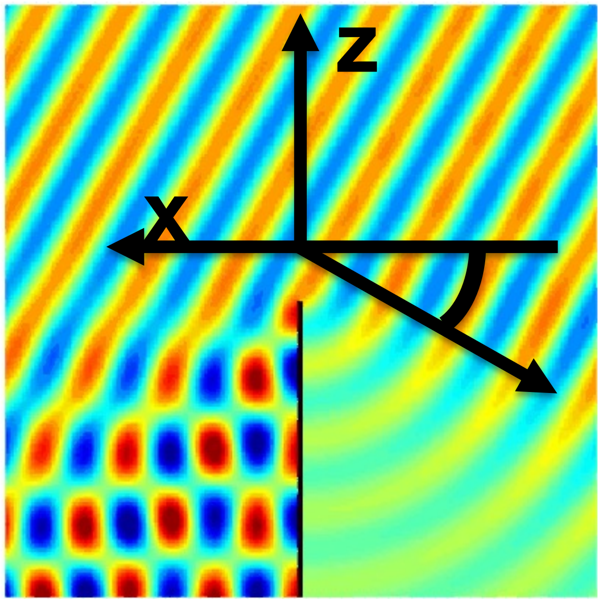
And it has to fulfill the boundary conditions: (no tangential E-field on the surface of the conducting plane)

# Reflection of plane waves (a first boundary value problem)

Taking into account the boundary conditions the longitudinal component of the field becomes:

$$E_z(x,z,t) = (E_+ \sin\theta)e^{i\omega t - ik(z\cos\theta - x\sin\theta)} - (E_+ \sin\theta)e^{i\omega t - ik(z\cos\theta + x\sin\theta)}$$

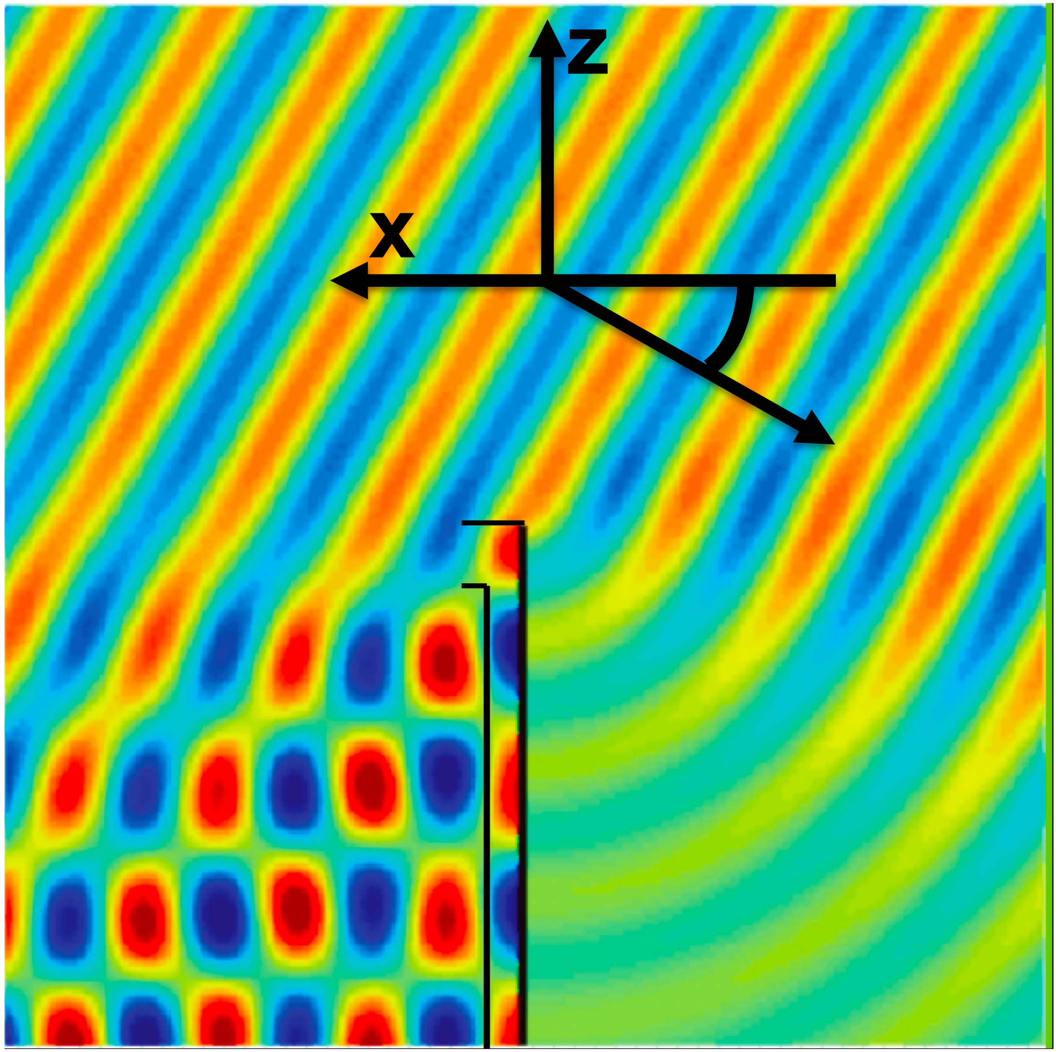
$$= 2iE_+ \sin\theta \sin(kx\sin\theta)e^{i\omega t - ikz\cos\theta}$$




Standing Wave pattern (along x)

Guided wave pattern (along z)

# From reflections to waveguides



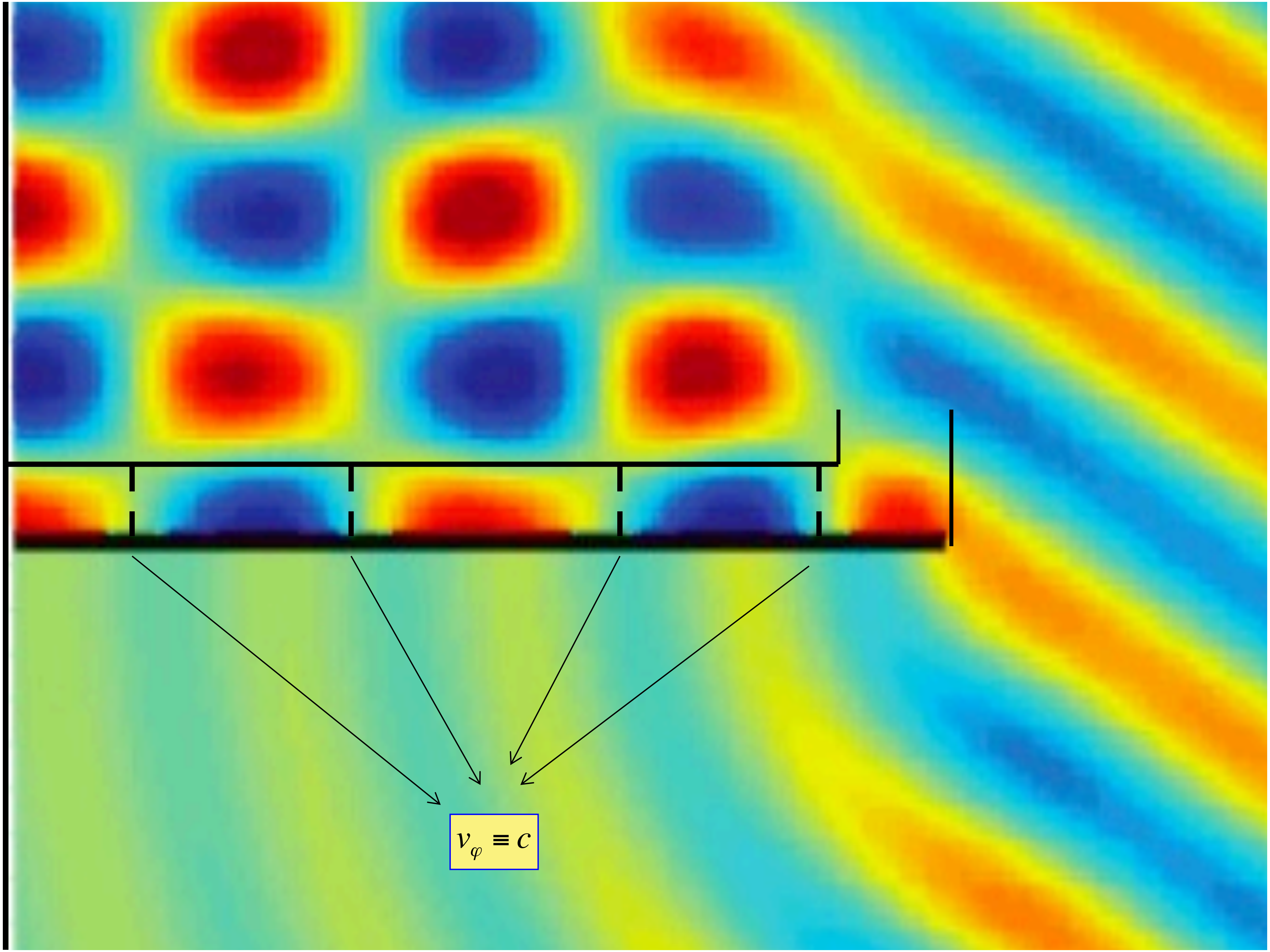

Put a metallic boundary where the field is zero at a given distance from the wall.

Between the two walls there must be an integer number of half wavelengths (at least one).

For a given distance, there is a maximum wavelength, i.e. there is **cut-off frequency**.

$$v_{\phi z} = \frac{\omega}{k_z} = \frac{\omega}{k\cos\theta} = \frac{c}{\cos\theta} > c$$

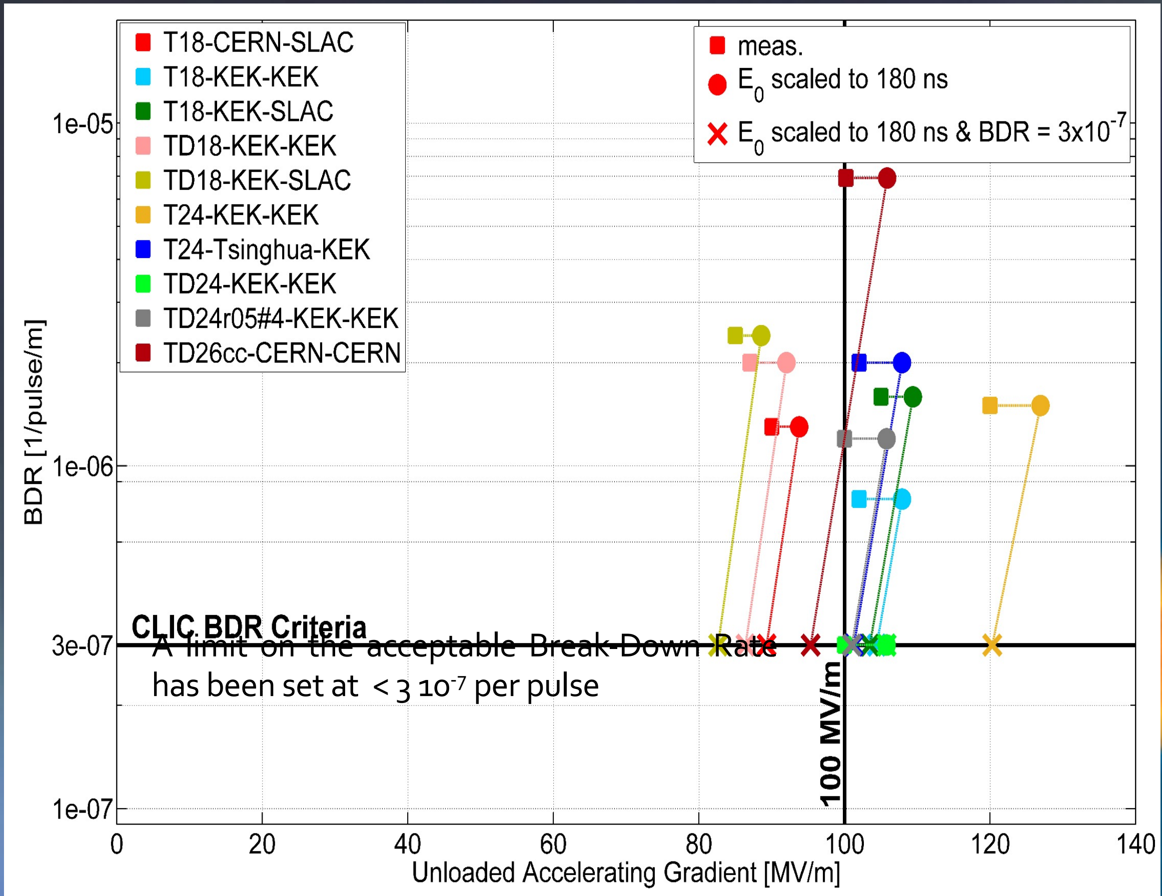
→ It can not be used as it is for particle acceleration

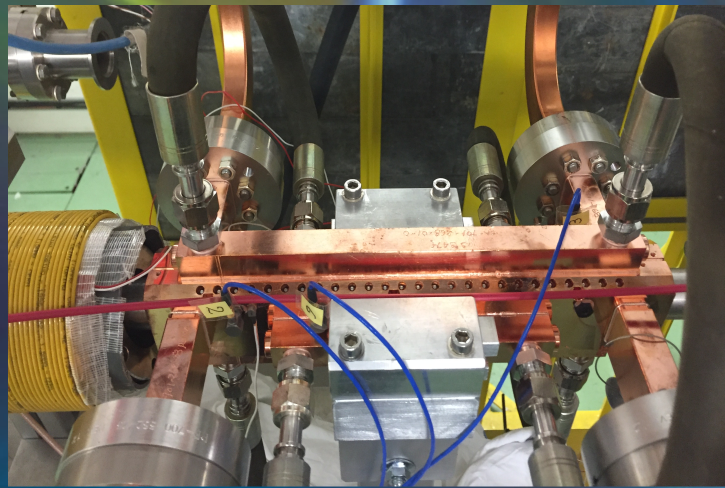

$v_\varphi \equiv c$

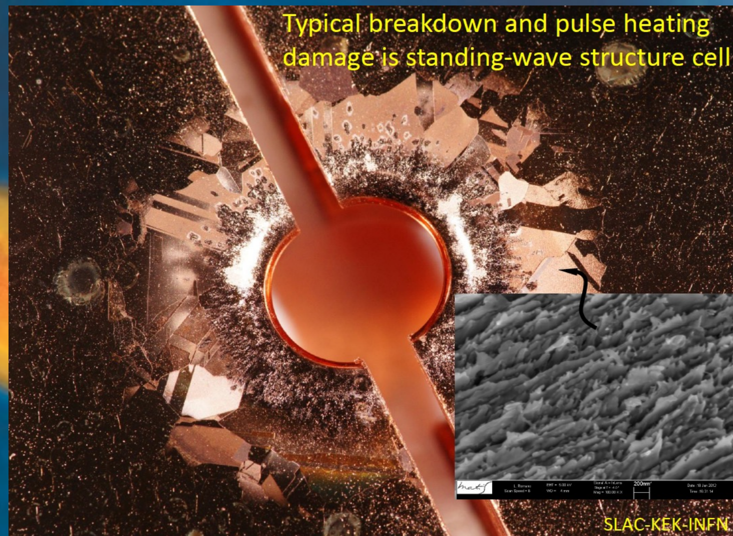
# Conventional RF accelerating structures

# X-band RF structures – State of the Art

Max accelerating field: $\tau_{rf}^{-1/6}$
Stored energy: $f^{-3}$



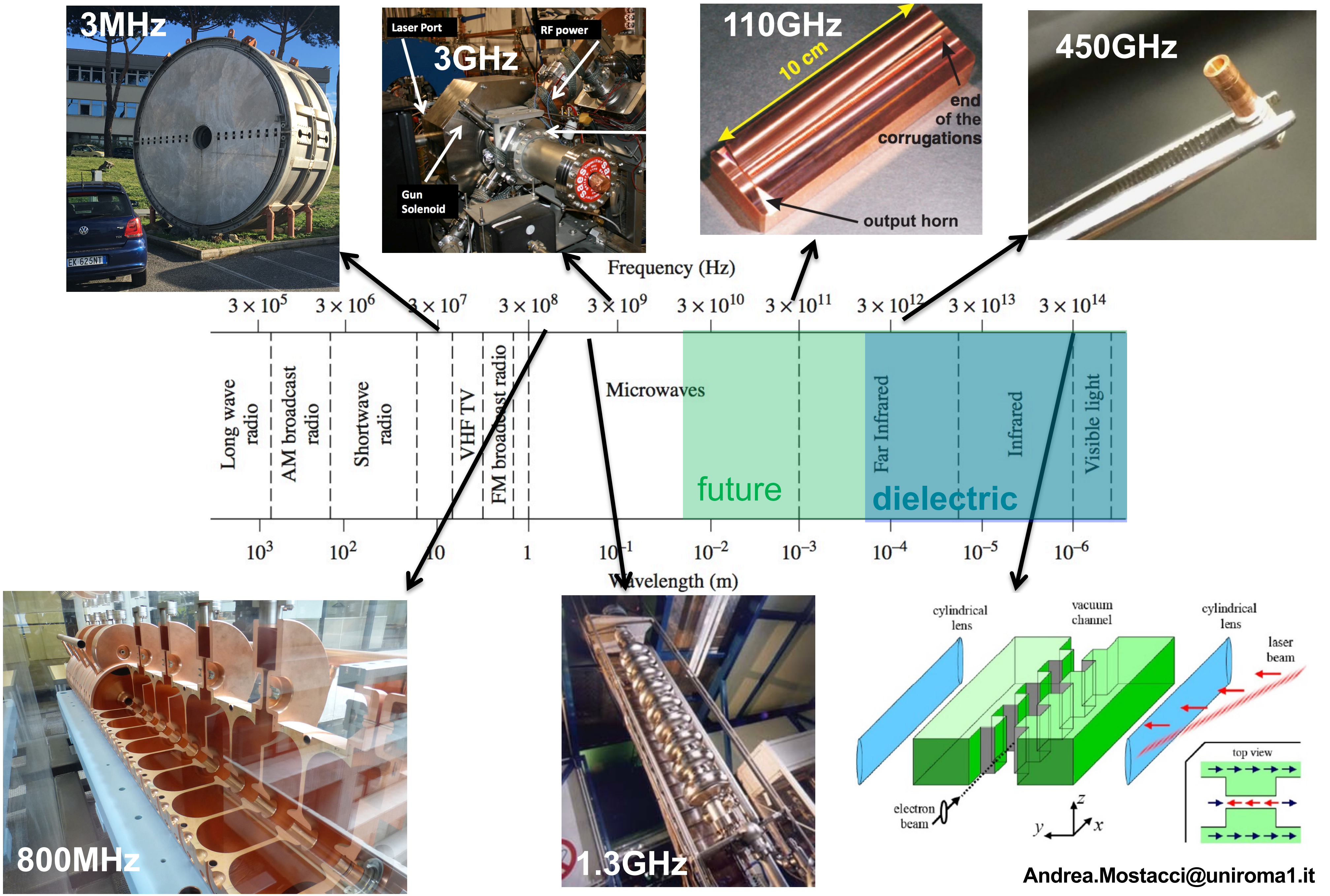







- Kilpatrick, W. D., Rev. Sci. Inst. 28, 824 (1957).
- *A. Grudiev et al, PRST-AB 12, 102001 (2009)*
- S. V. Dolgashev, et al. Appl. Phys. Lett. 97, 171501 2010.
- M. D. Forno, et al. PRAB. 19, 011301 (2016).

# The E.M. Spectrum of Accelerating Structures

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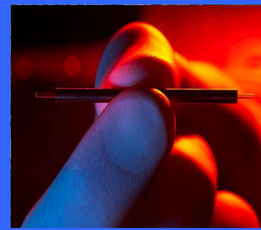
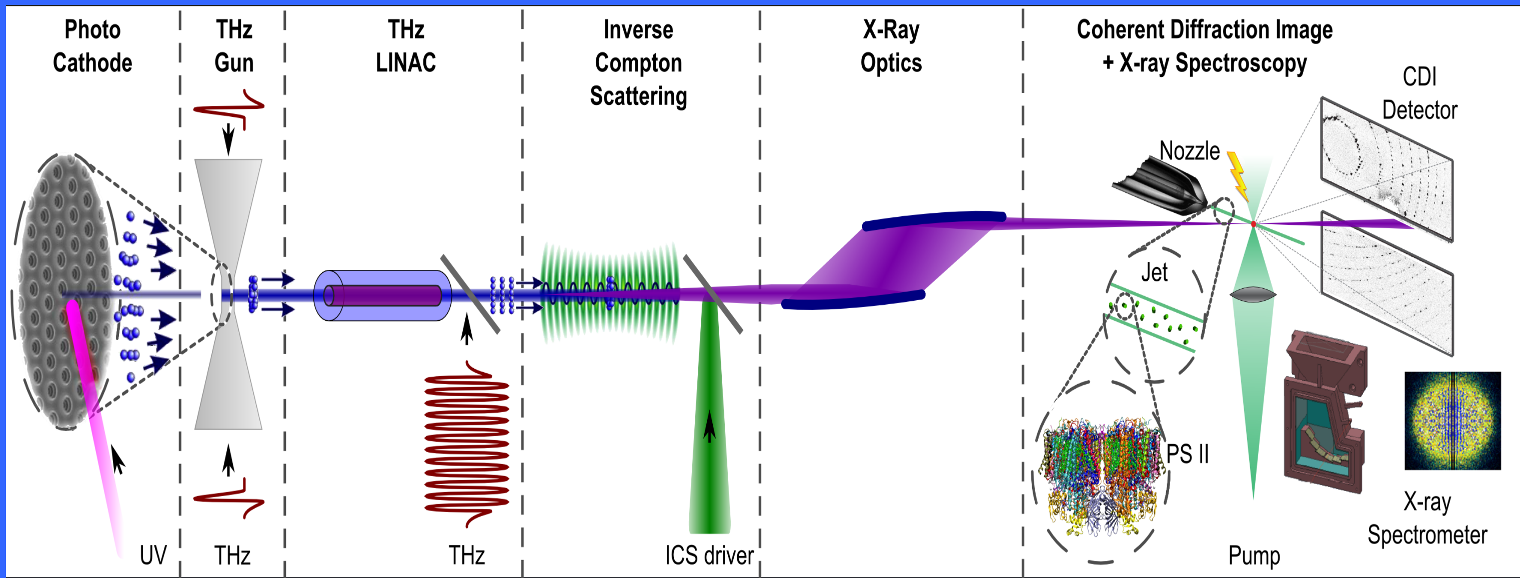
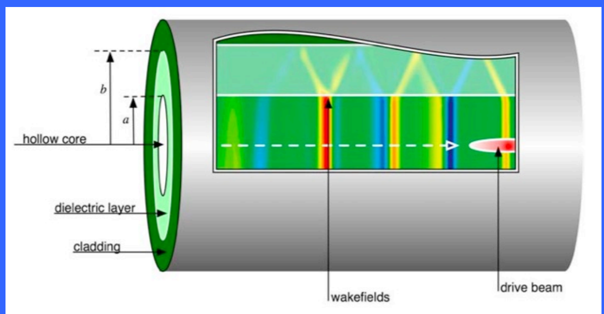
# Dielectric Structures

Attoseconds X-ray Science Imaging and Spectroscopy



F.X. Kärtner et al., NIM A 829, 24 (2016)



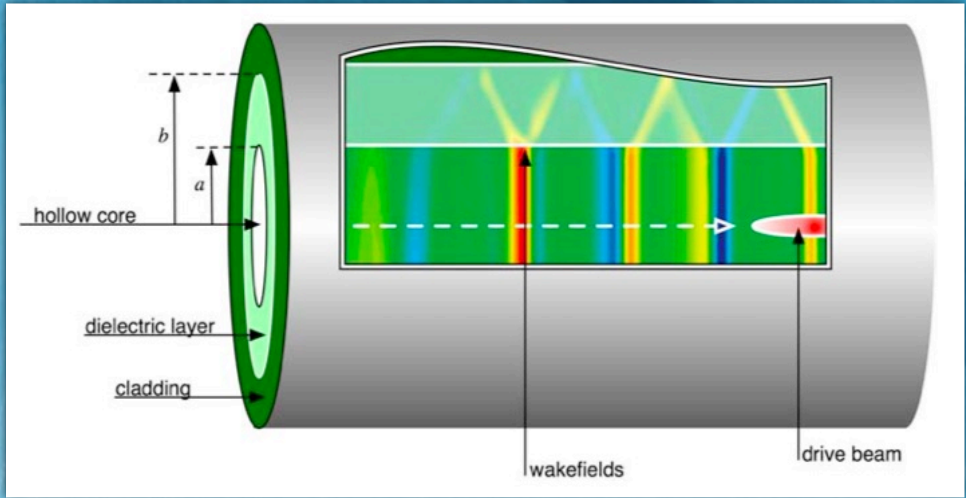

All laser driven => intrinsic attosecond synchr.,
1 Joule, 1 kHz Cryogenic Yb:YAG Laser
Laser-based THz generation
THz Linac, Optical undulator
Copper Inner Diameter = 940 µm
Fused Silica Inner Diameter = 400 µm

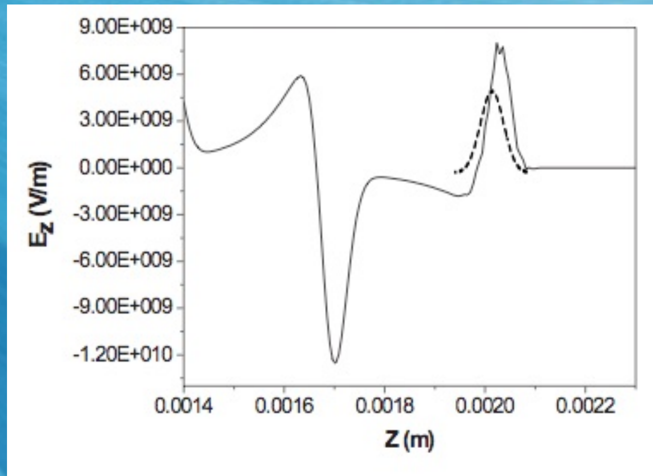
E. Nanni et al., Nat. Comm. 6, 8486 (2015)

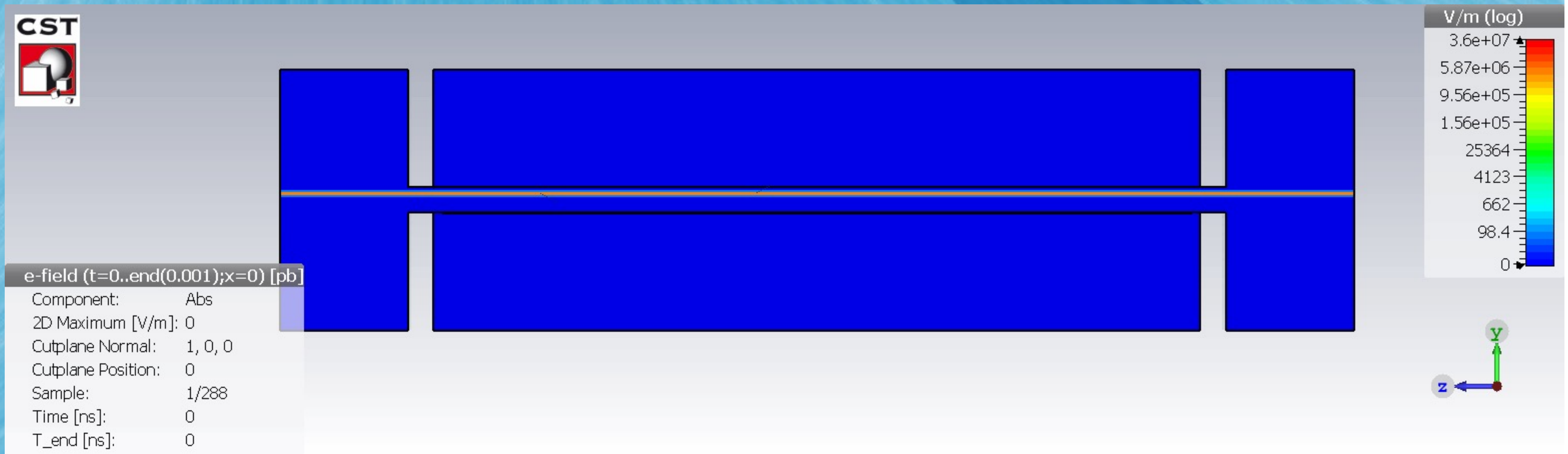
# Dielectric Wakefield Acceleration

DWA

# Dielectric Wakefield Accelerator

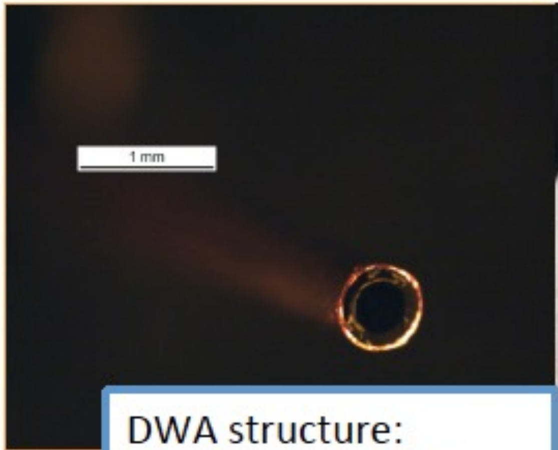


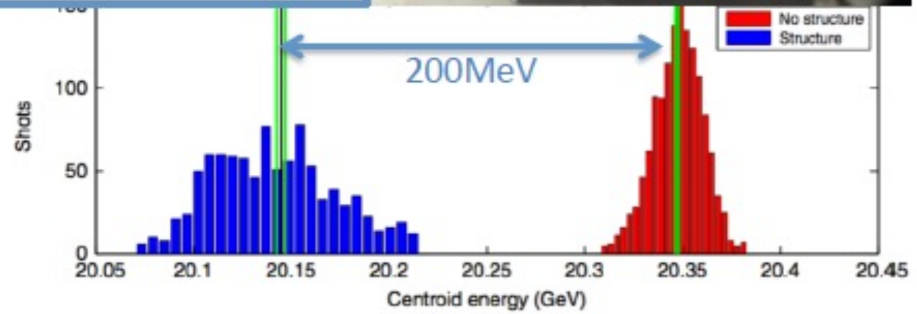
# GV/m fields in DWA

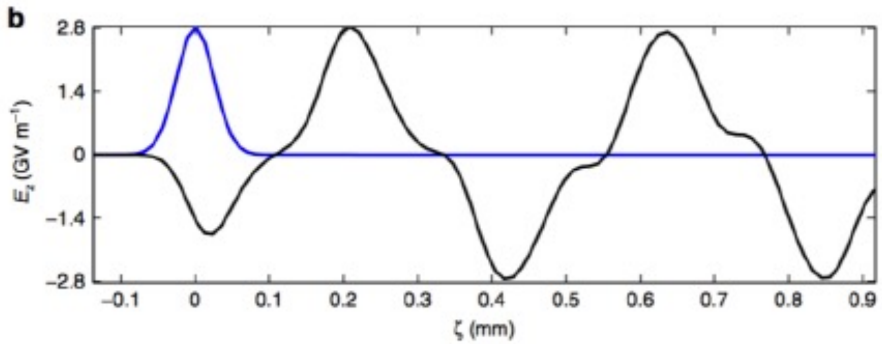
- High-fields with small ID structures
  - Compressed beam (<25µm)
  - High charge (3nC)
- Beam centroid data
  - Measured Energy loss of 200 MeV
  - 1.3 GeV/m deceleration
  - 2.6 GeV/m peak field
  - Strong agreement with PIC simulations
- Continuous operation of >28hours (>100k shots at 10 Hz rep)
- No signs of damage or performance deterioration

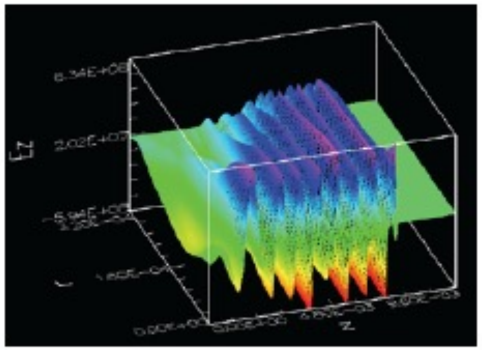



DWA structure:

- a/b = 150/200 µm
- L = 15cm
- Cylindrical, $SiO_2$

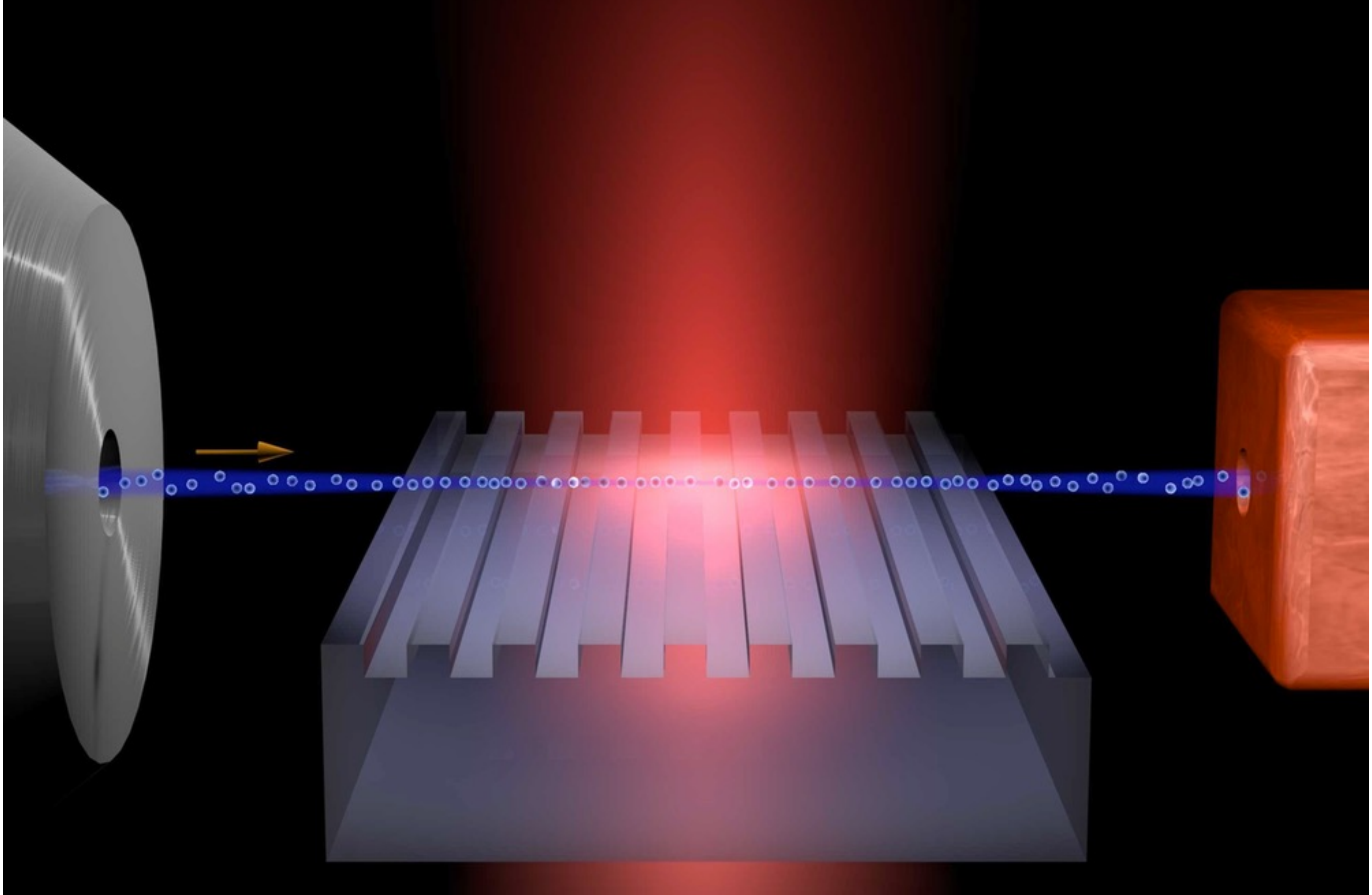


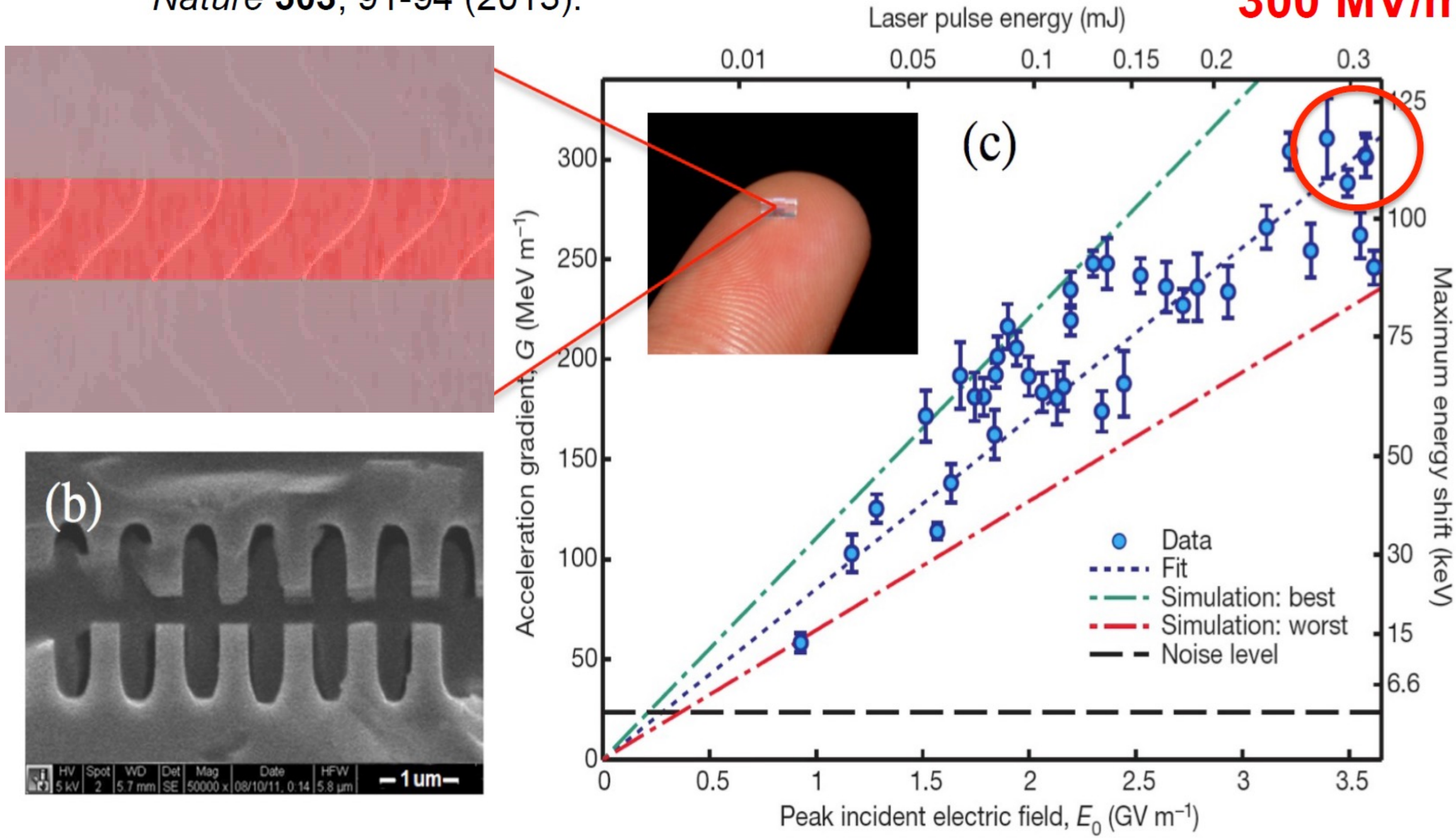
# Dielectric Laser Acceleration
DLA

# Laser based dielectric accelerator



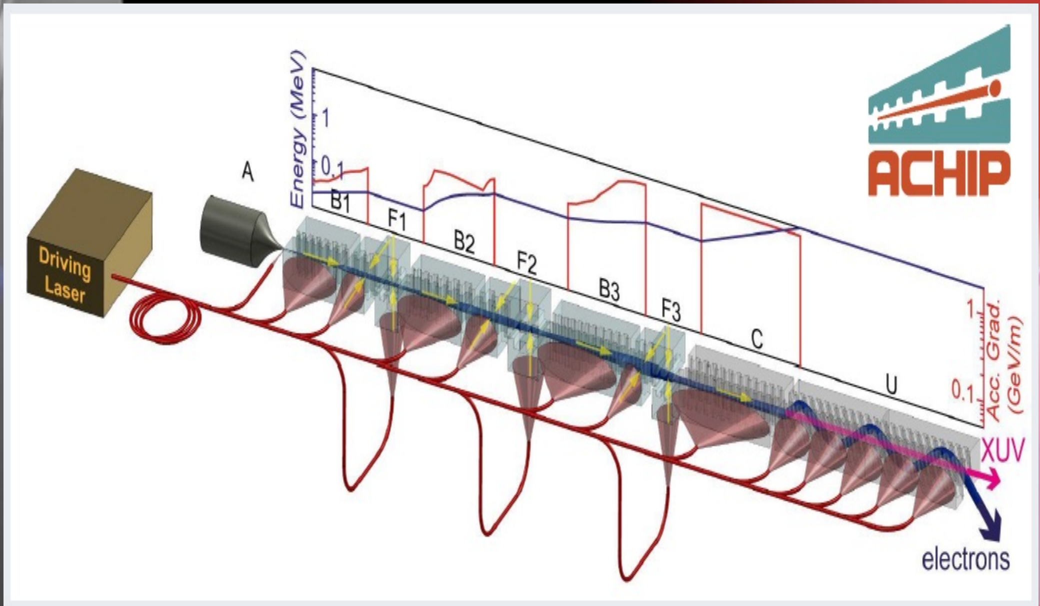
*Nature* **503**, 91-94 (2013).

**300 MV/m**

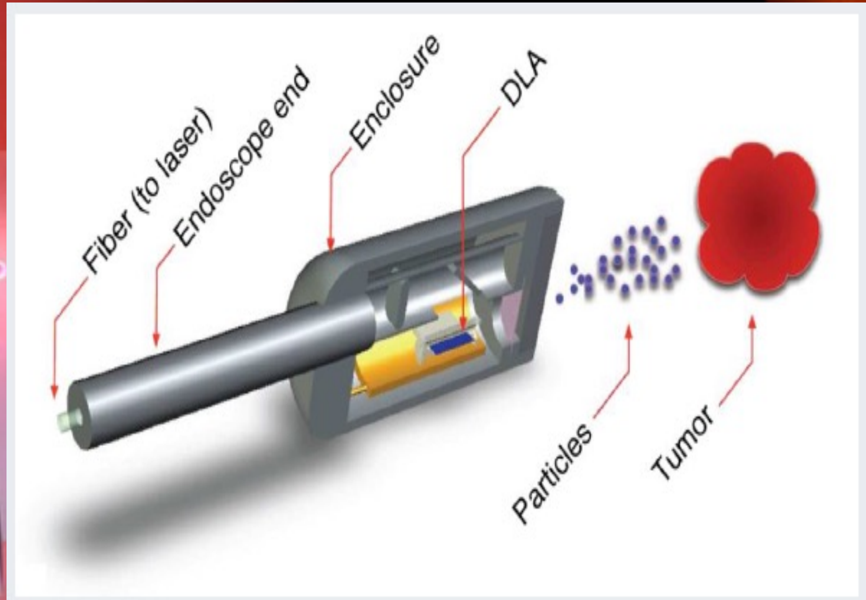


# Dielectric Structures Applications

A combination of DLA modules and optical undulator allows dreaming for a compact table top FEL




DLA module can be built onto the end of a fiber-optic catheter and attached to an endoscope, allowing to deliver controlled, high energy radiation directly to organs, tumors, or blood vessels within the body.



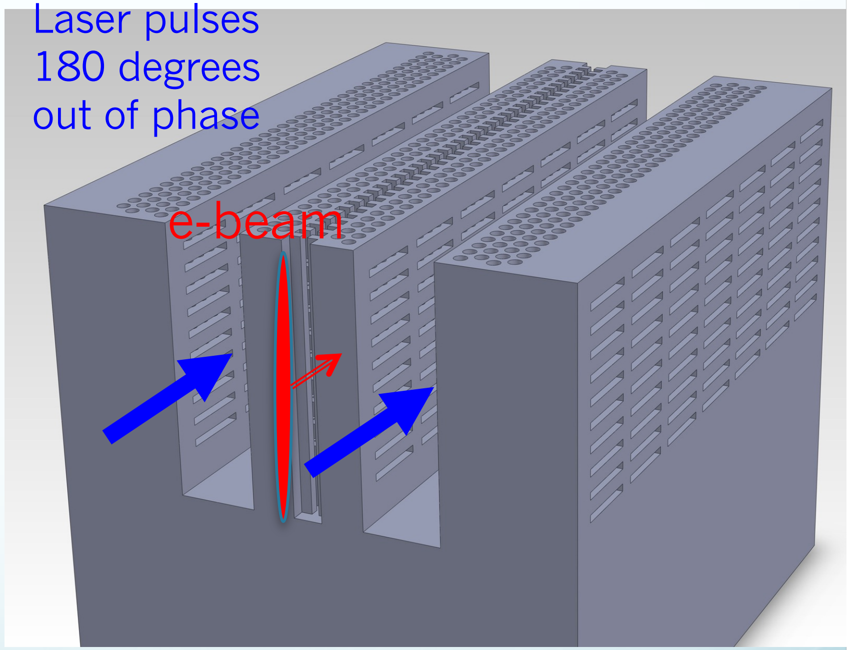

Electrons with 1-3MeV have a range of about a centimeter, allowing for irradiation volumes to be tightly controlled.

# Dielectric Photonic Structure

- Why photonic structures?
  - Natural in dielectric
  - Advantages of burgeoning field
    - design possibilities
    - Fabrication

- Dynamics concerns

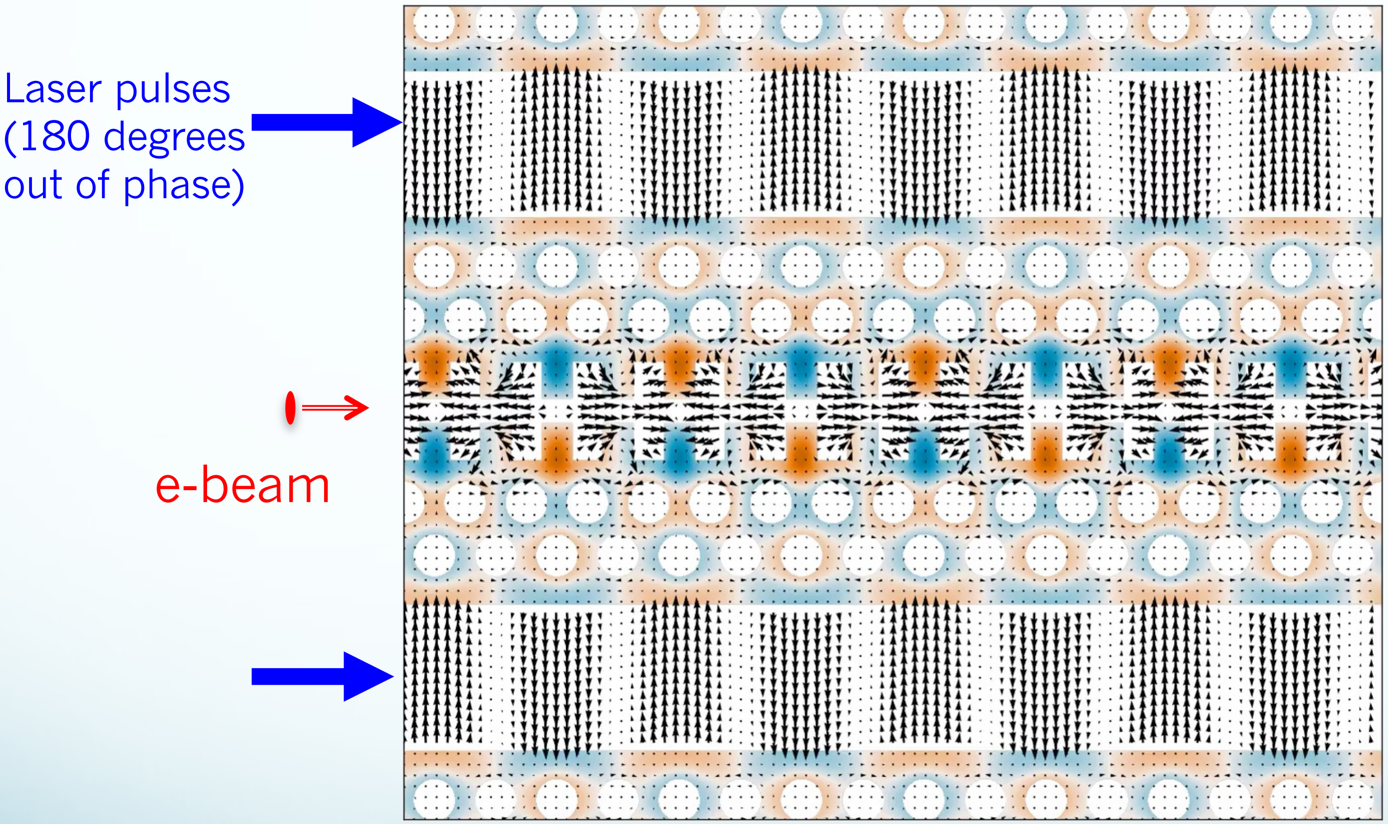
- External coupling schemes




Schematic of GALAXIE
monolithic photonic DLA

# Laser-Structure Coupling: TW

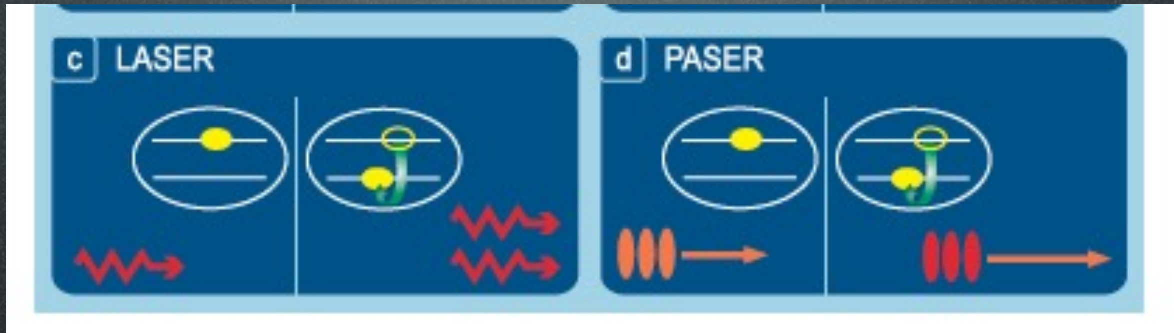
GALAXIE Dual laser drive structure, large reservoir of power recycles

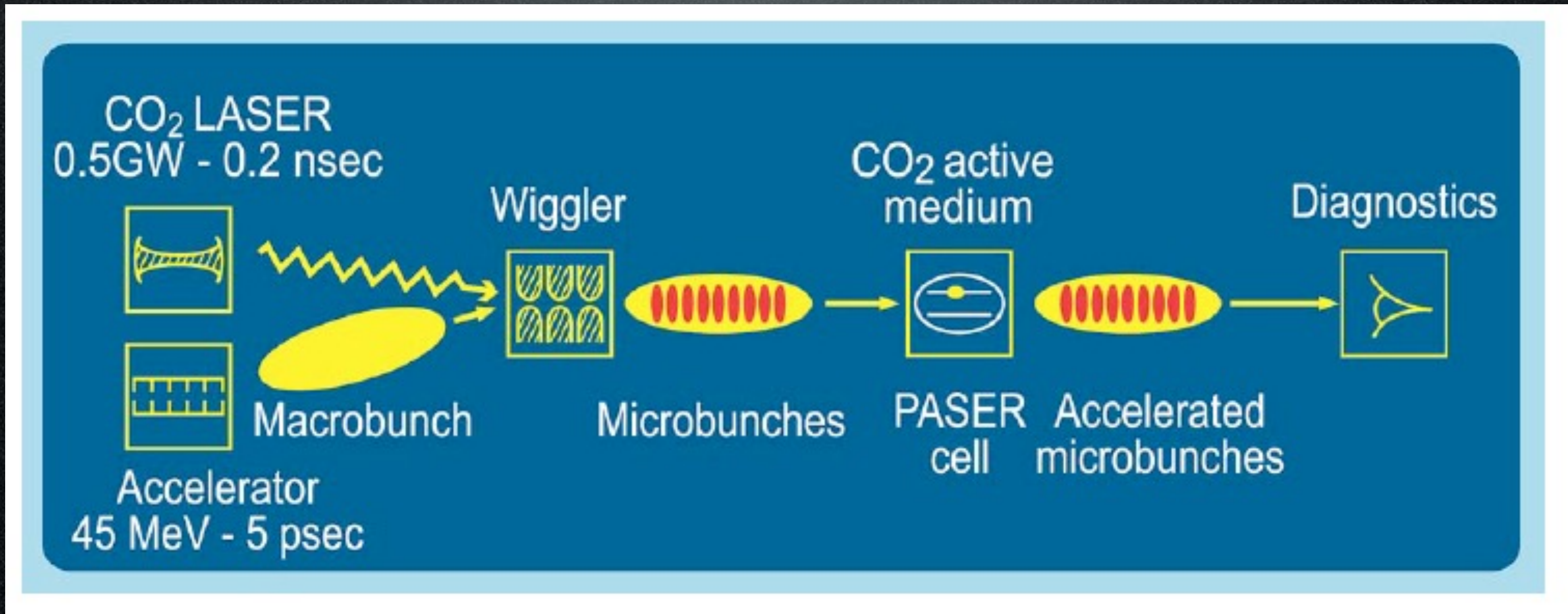


PHYSICAL REVIEW E **74**, 046501 (2006)

# Particle acceleration by stimulated emission of radiation: Theory and experiment

Samer Banna,* Valery Berezovsky, and Levi Schächter
*Department of Electrical Engineering, Technion, Israel Institute of Technology, Haifa 32000, Israel*
(Received 28 June 2006; published 23 October 2006)



PRL 97, 134801 (2006) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2006

# Experimental Observation of Direct Particle Acceleration by Stimulated Emission of Radiation

Samer Banna,* Valery Berezovsky, and Levi Schächter
*Department of Electrical Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel*
(Received 4 June 2006; published 28 September 2006)

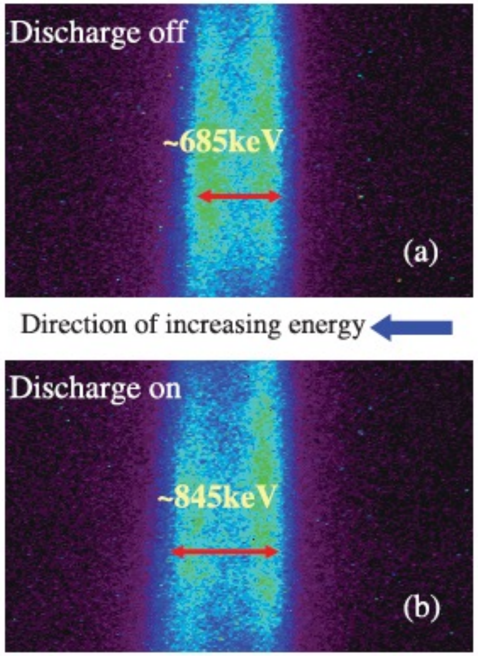



FIG. 3 (color). Raw video images from the electron energy spectrometer. Energy dispersion is in the horizontal direction. (a) Discharge is off in the PASER cell. (b) Discharge is on in the PASER cell. In both cases, ~1.5% peak-to-peak energy modulation was imparted.

# Plasma Wakefield Acceleration

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*

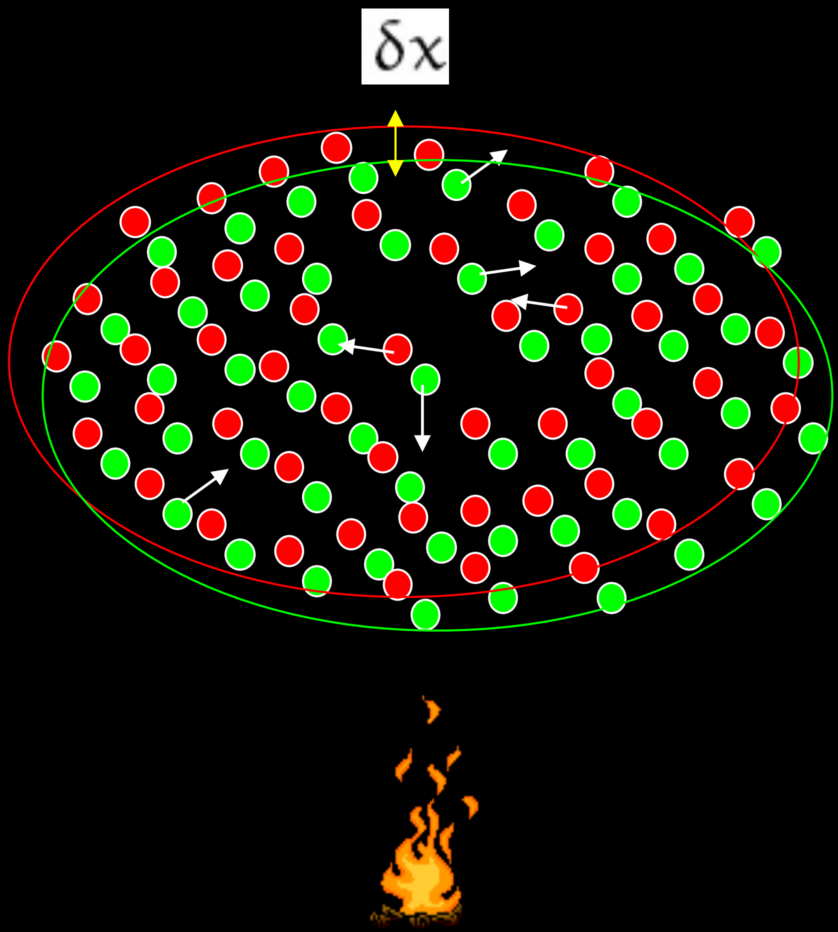
and

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.

Surface charge density

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




Surface electric field

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

Restoring force

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

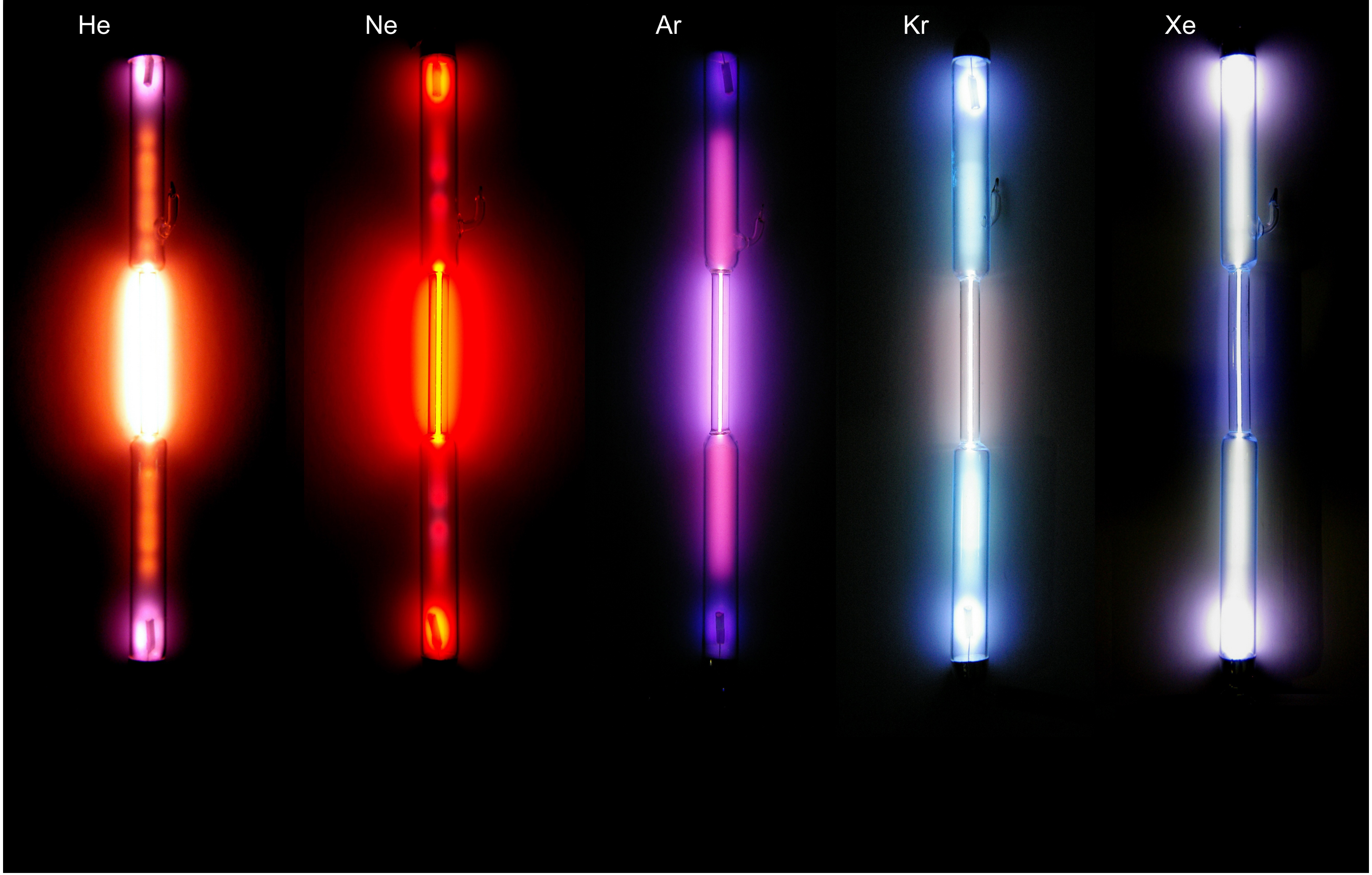
Plasma frequency

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

Plasma oscillations

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

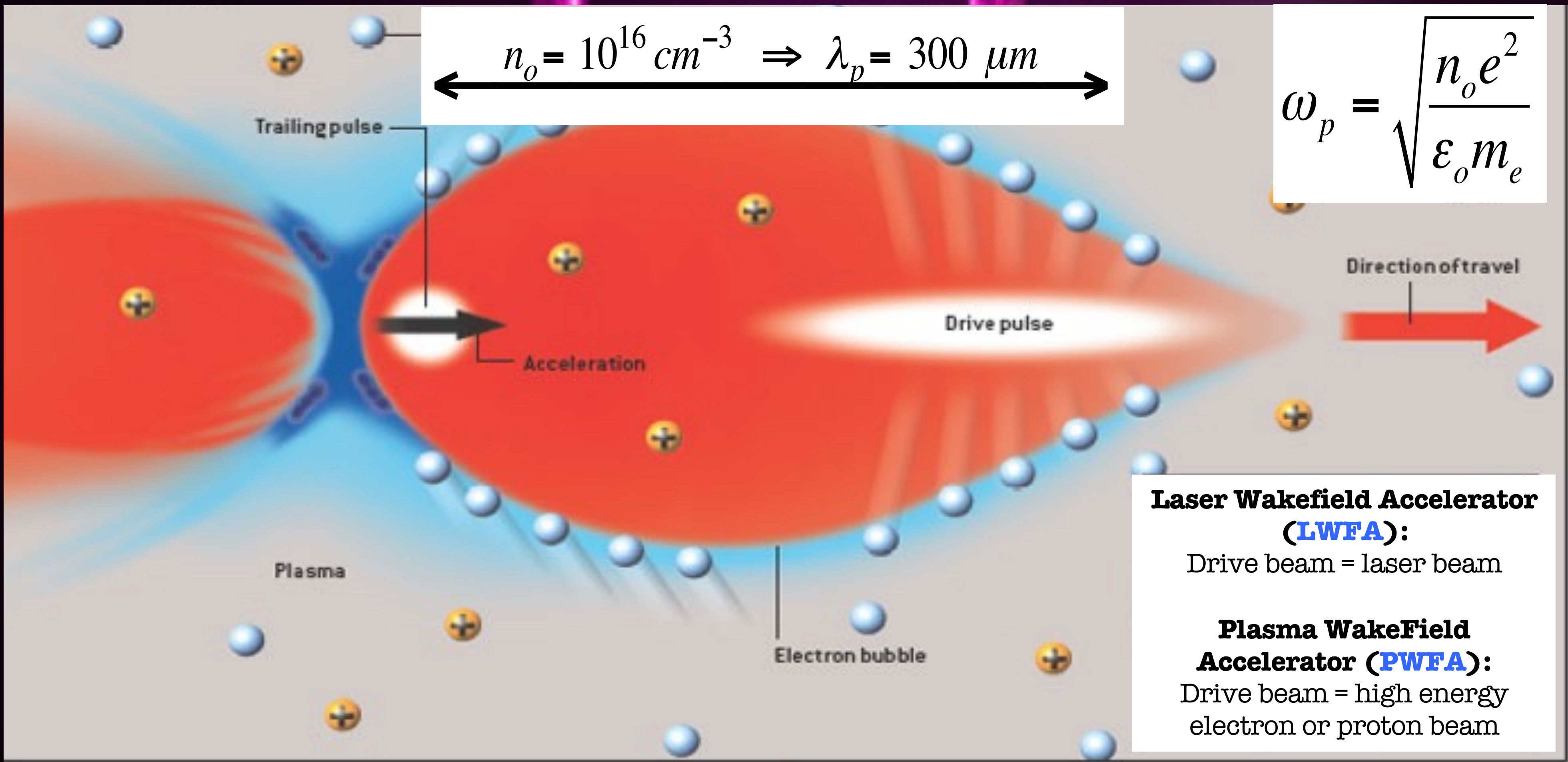
# Looking for a plasma target



# 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

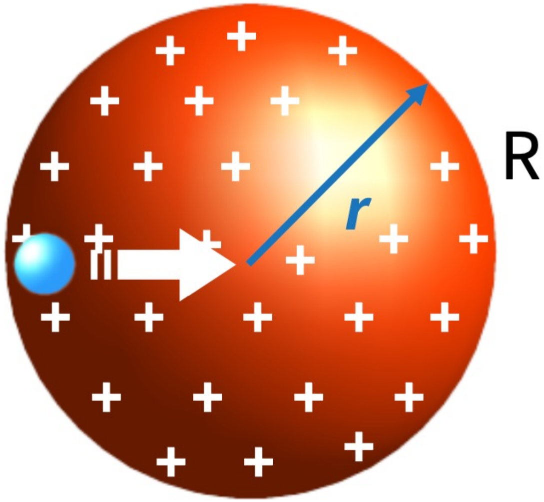
**Plasma WakeField Accelerator (PWFA):**
Drive beam = high energy electron or proton beam

Break-Down Limit?
⇒ Wave-Breaking field:

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

# Principle of plasma acceleration

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




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

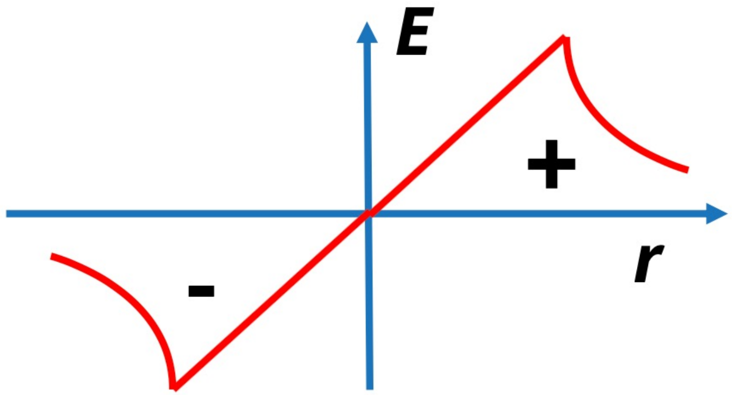
The field is **increasing** inside the sphere

Let's put some numbers

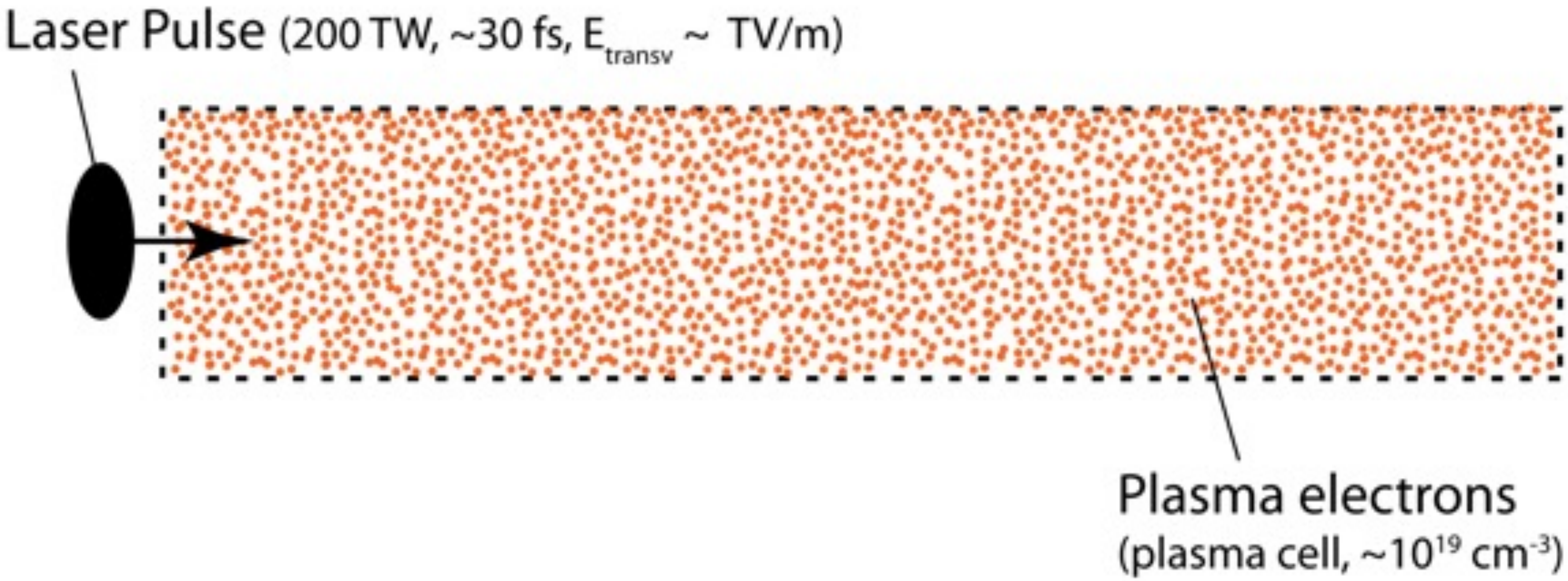
$n_i = 10^{16}\ cm^{-3}$

$R = 0.5$

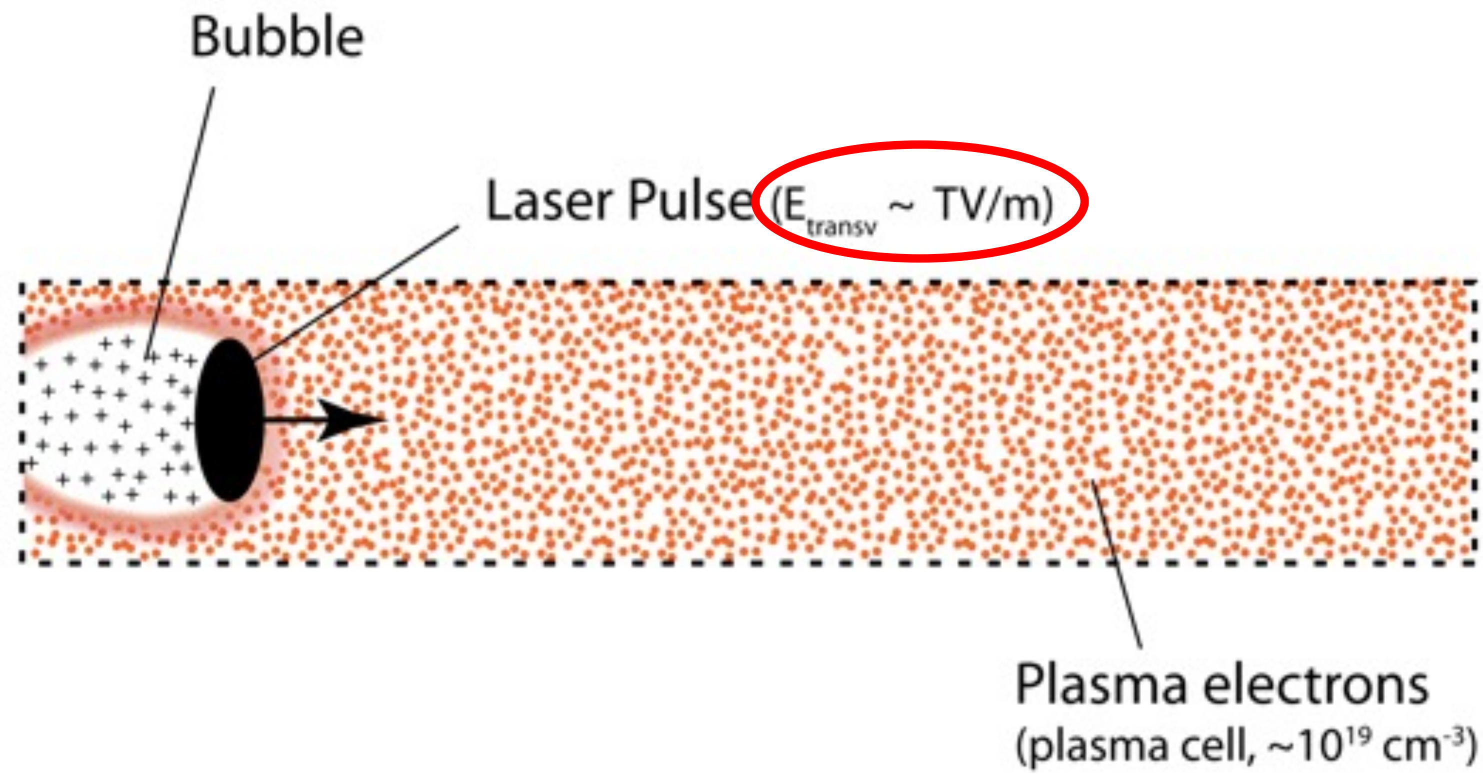
$$E \approx 10 \frac{GV}{m}$$



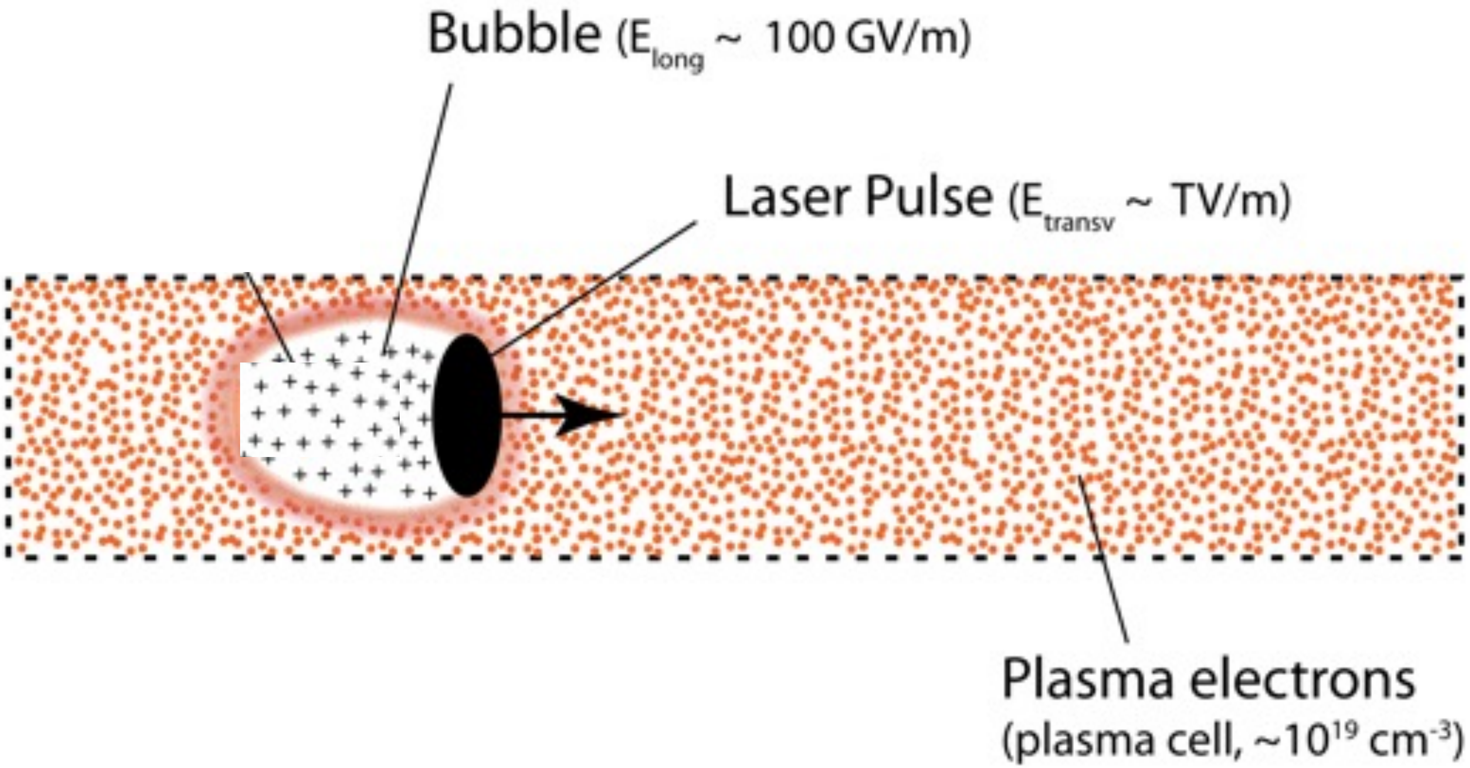
# Plasma Wake-Acceleration



# Plasma Wake-Acceleration

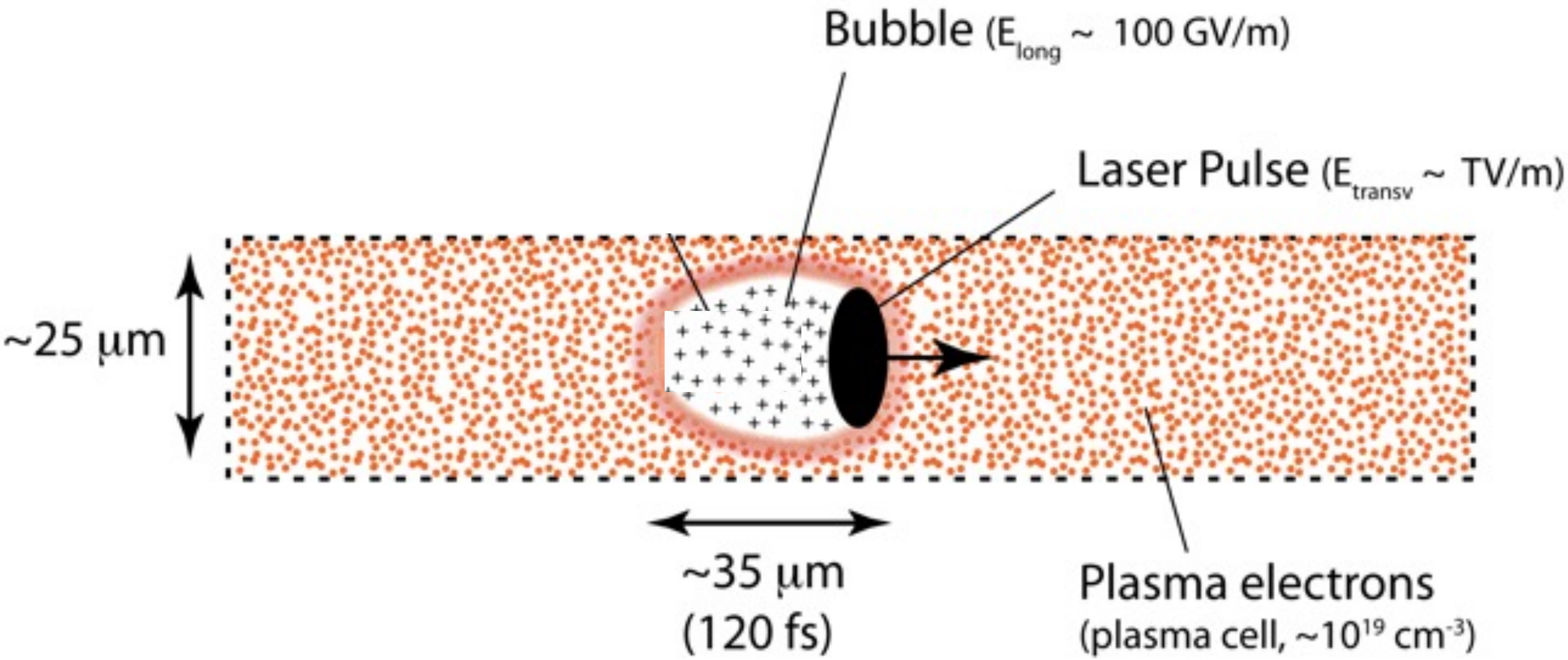


# Plasma Wake-Acceleration



# Plasma Wake-Acceleration






**This accelerator fits into a human hair!**

# Principle of plasma acceleration

Driven by Radiation Pressure

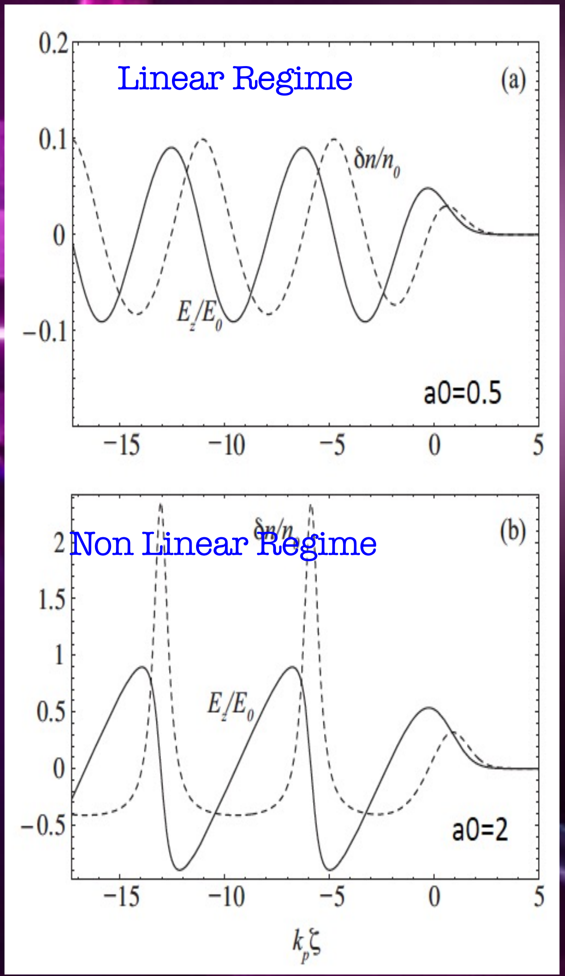
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=c^2\nabla^2\frac{a^2}{2}$$

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

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)

Accelerating field

Depends on radial position r

Changes between accelerating and decelerating as function of longitudinal position z

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

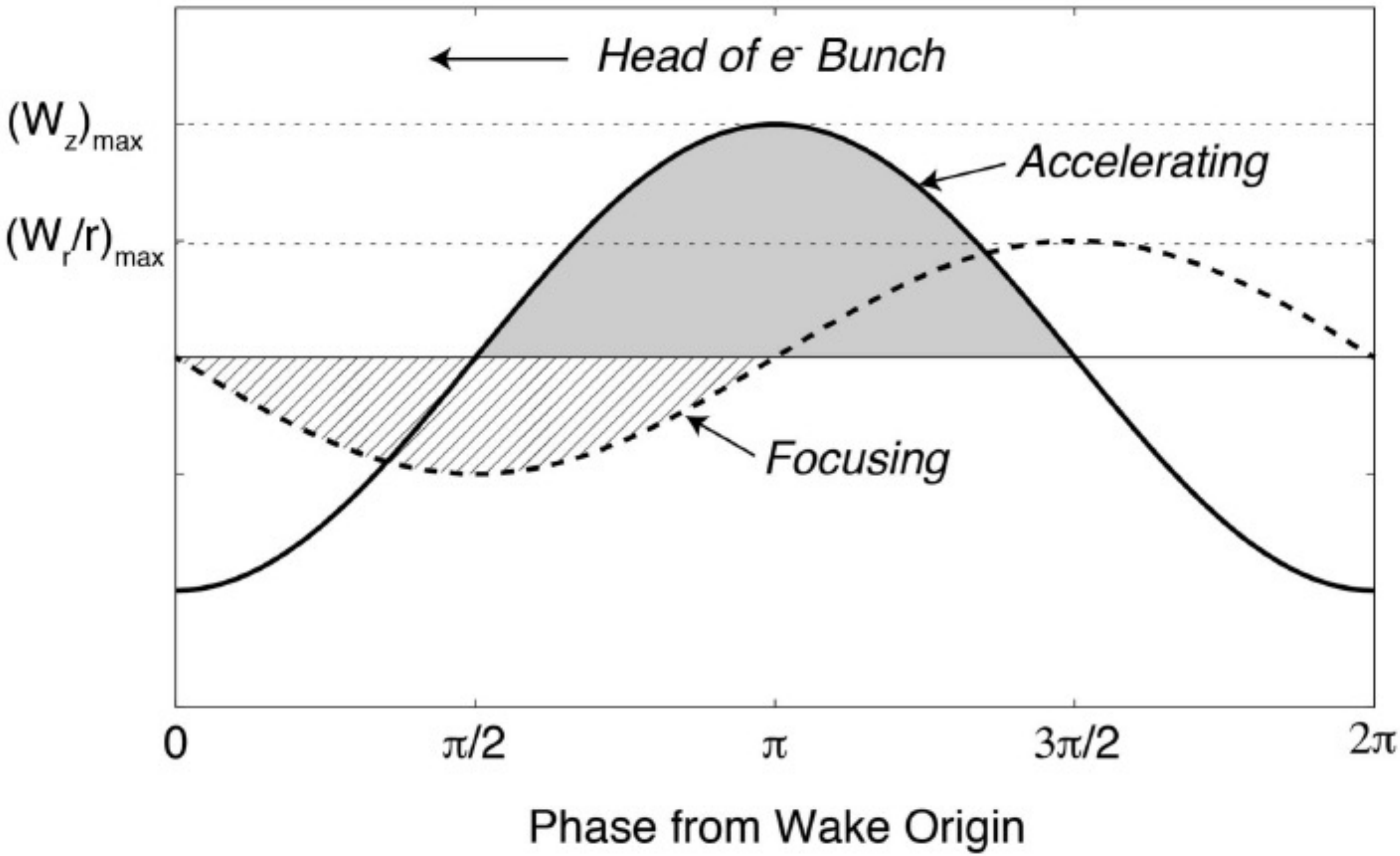
$\pi/2$ out of phase

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

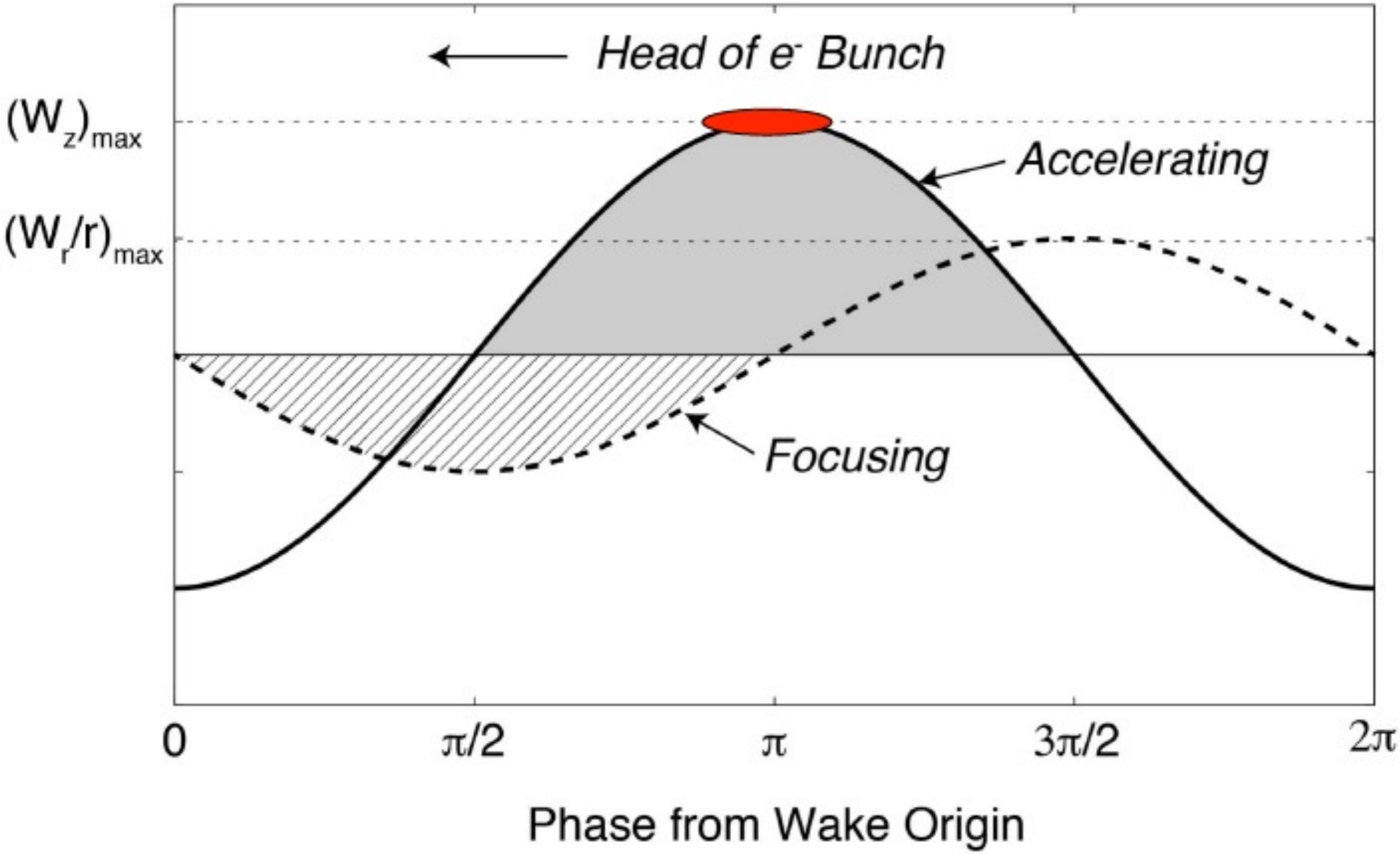
Transverse field

Depends on radial position r

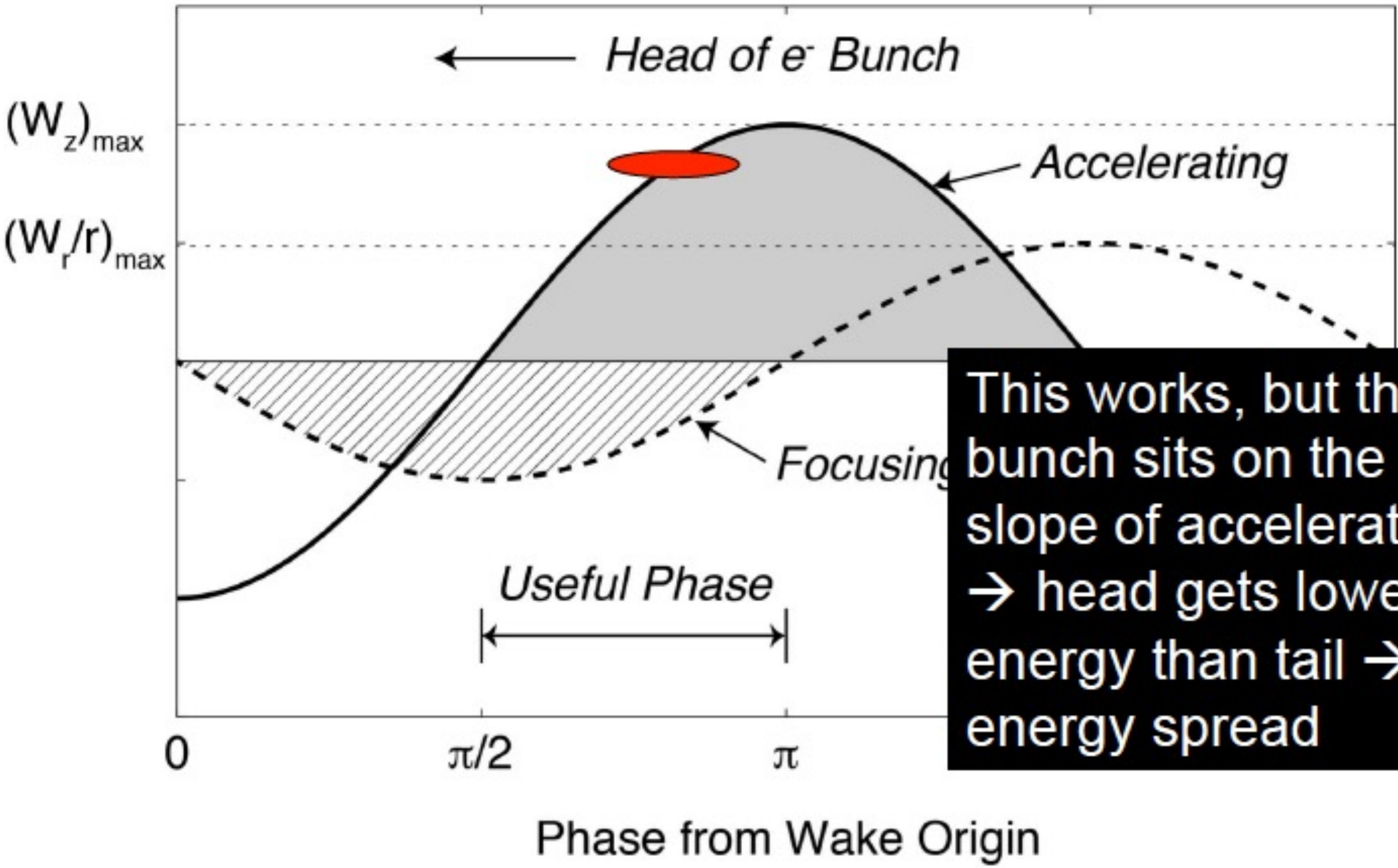
Changes between focusing and defocusing as function of longitudinal position z



Head of e⁻ Bunch
(W_z)_max
(W_r/r)_max
Accelerating
Focusing
0
π/2
π
3π/2
2π
Phase from Wake Origin

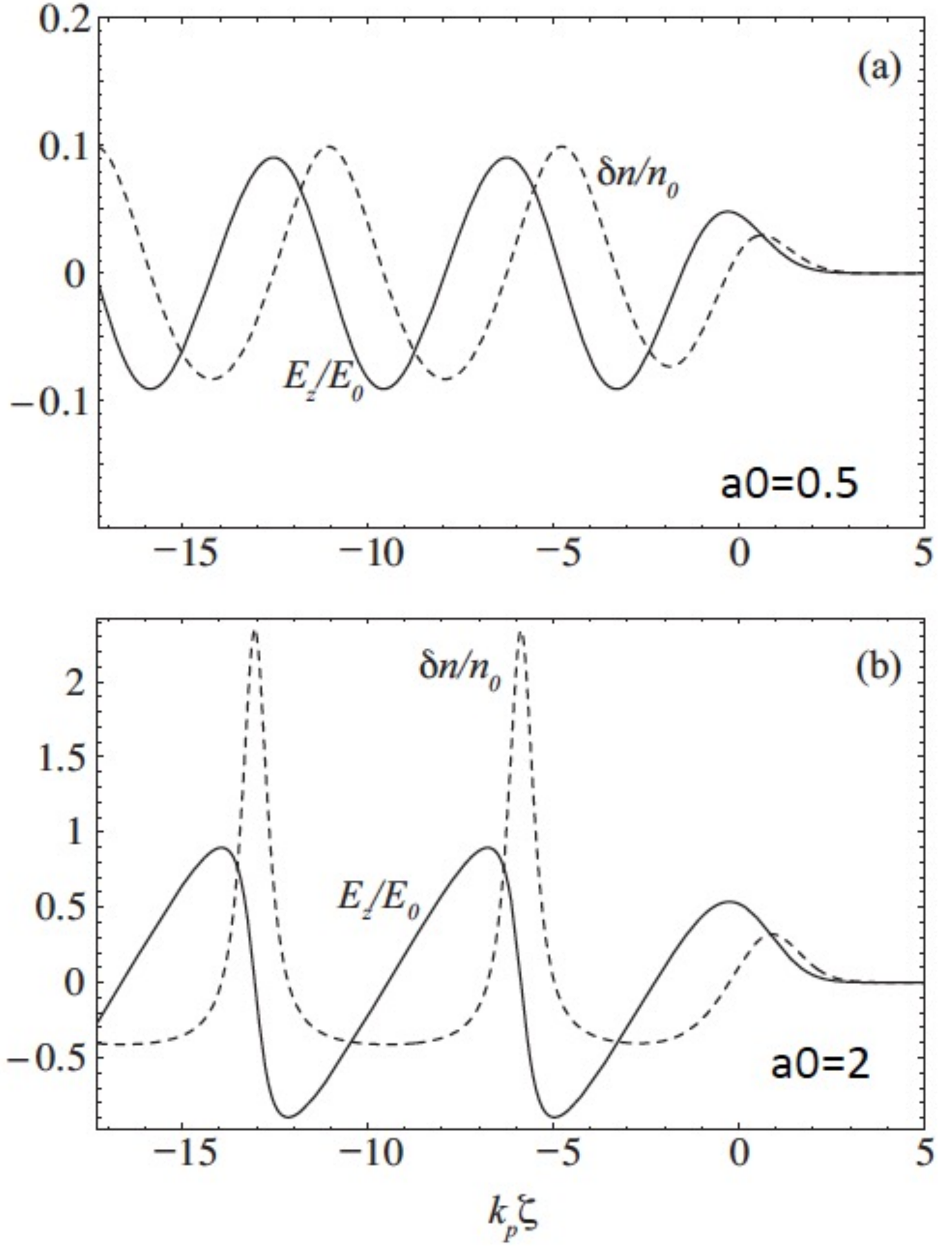


Head of e⁻ Bunch
$(W_z)_{max}$
Accelerating
$(W_r/r)_{max}$
Focusing
0
π/2
π
3π/2
2π
Phase from Wake Origin




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**

# Energy spread compensation with beam loading

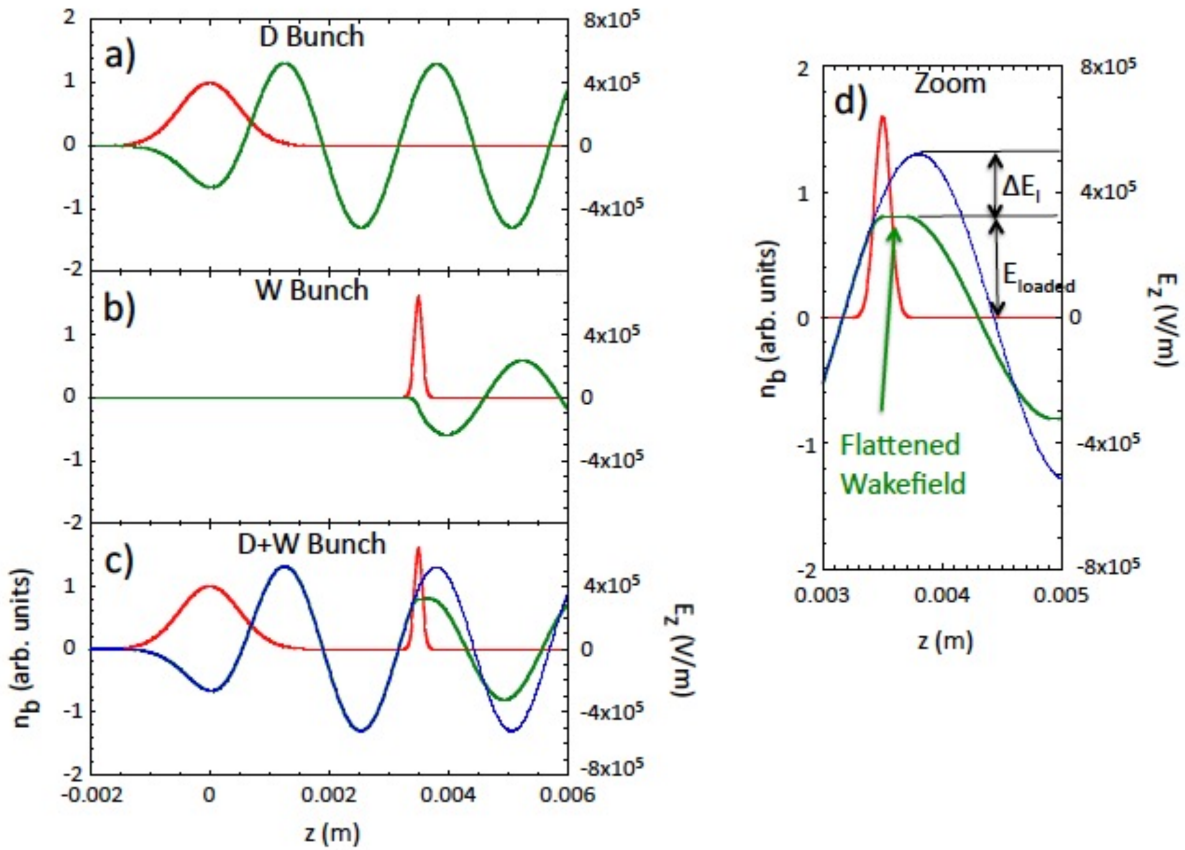
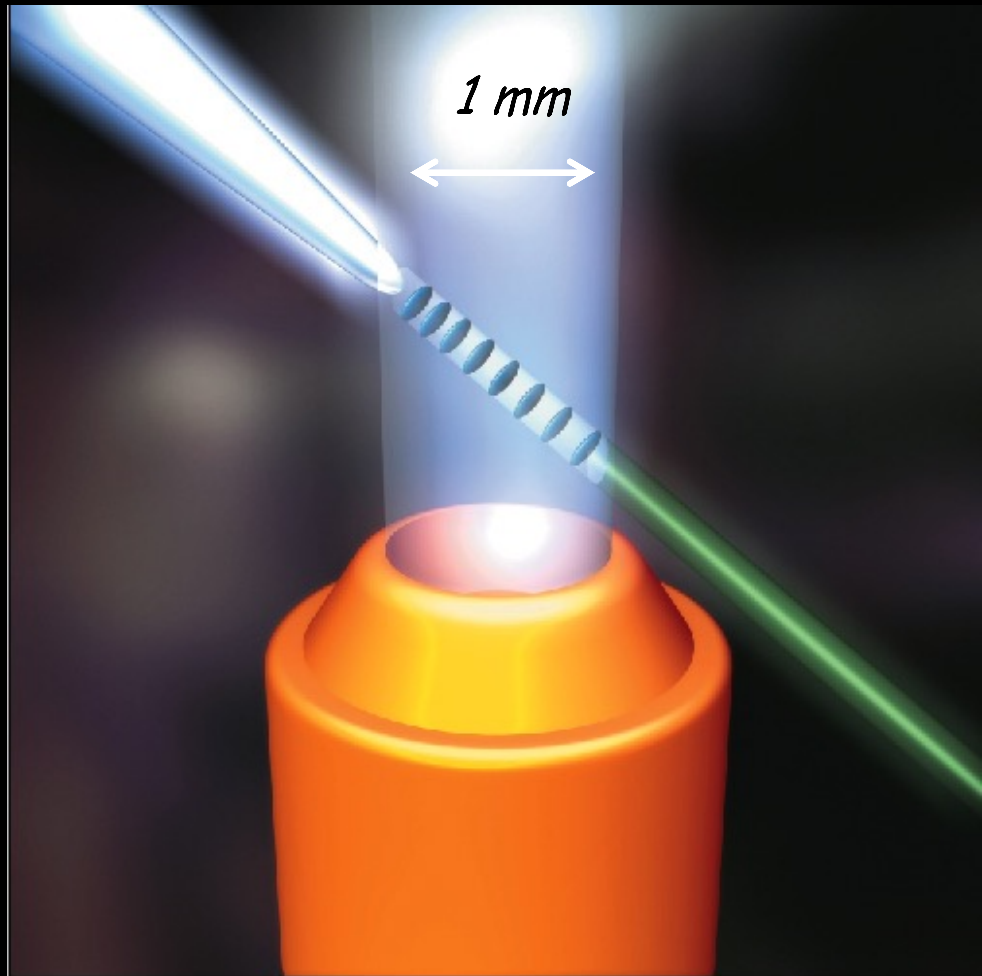



**Fig. 5:** Linear beam loading example: (a) drive bunch density profile (red line) and longitudinal wakefield $E_z$ (green line), (b) same for the witness bunch, (c) same for the drive and witness bunches together. The field of the drive bunch only is shown as the blue line in panel (c). A zoom around the witness bunch is shown in panel (d). The bunches move to the left.

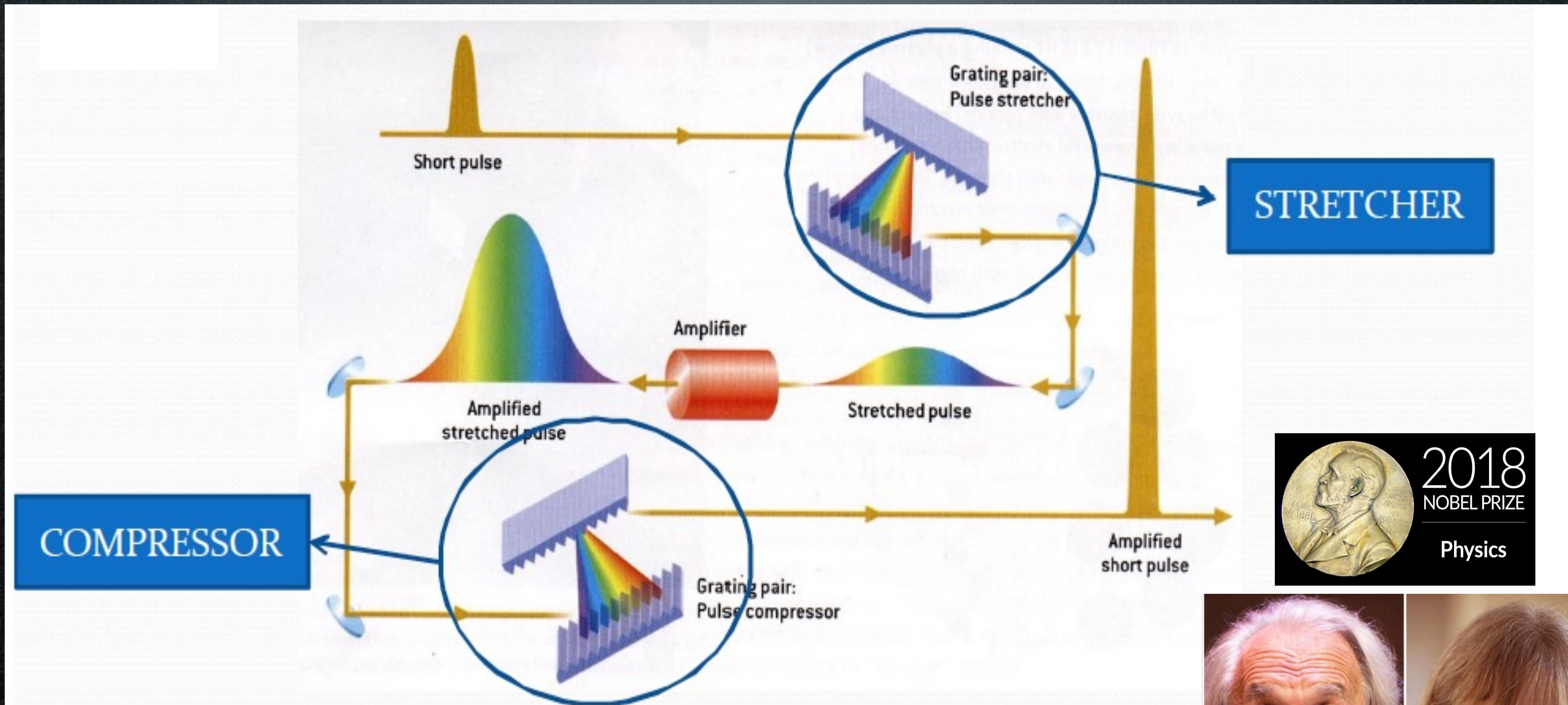
Laser Driven

LWFA

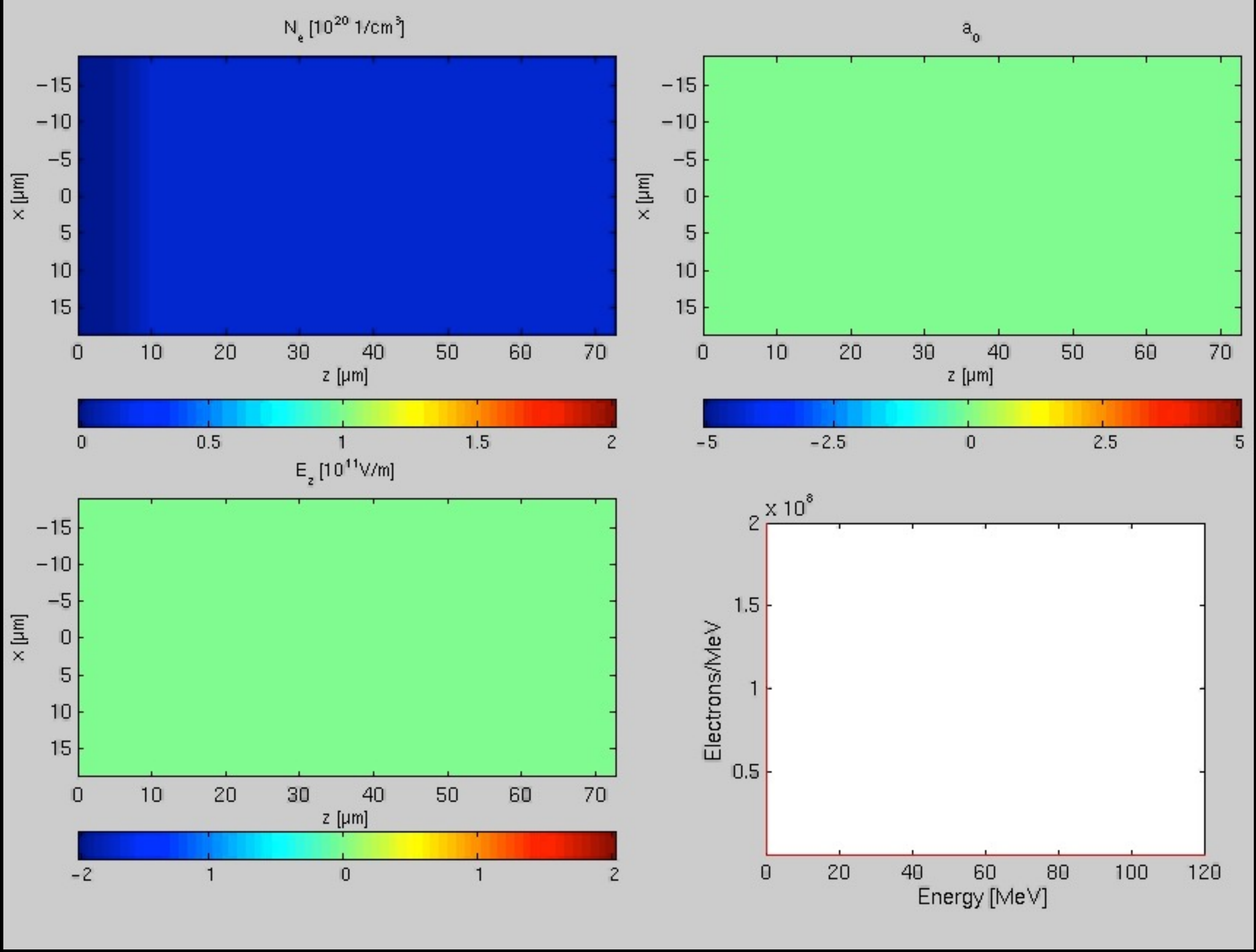
# Direct production of e-beam



# Chirped Pulse Amplification

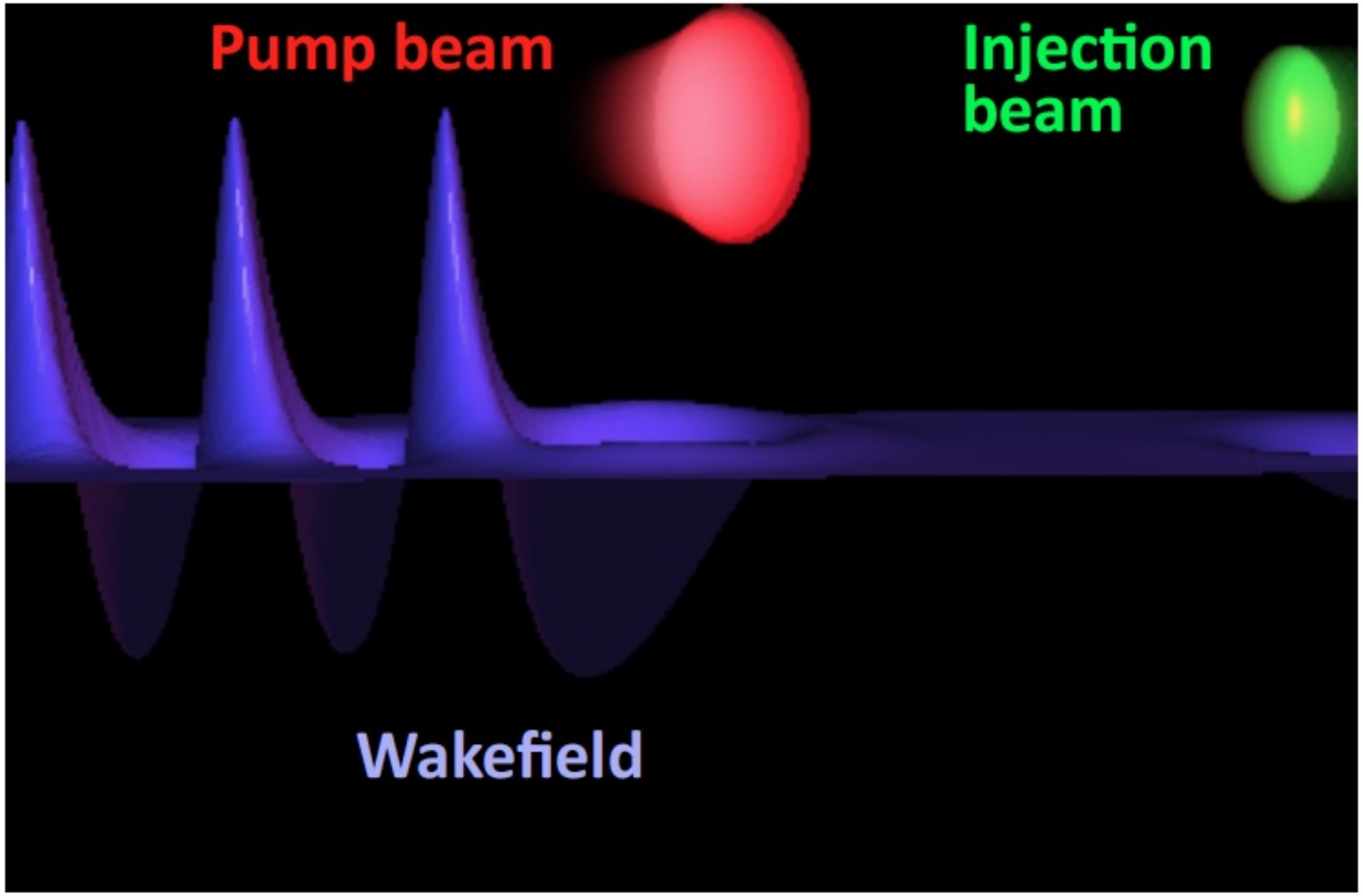



# Diffraction - Self injection - Dephasing – Depletion



# 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)

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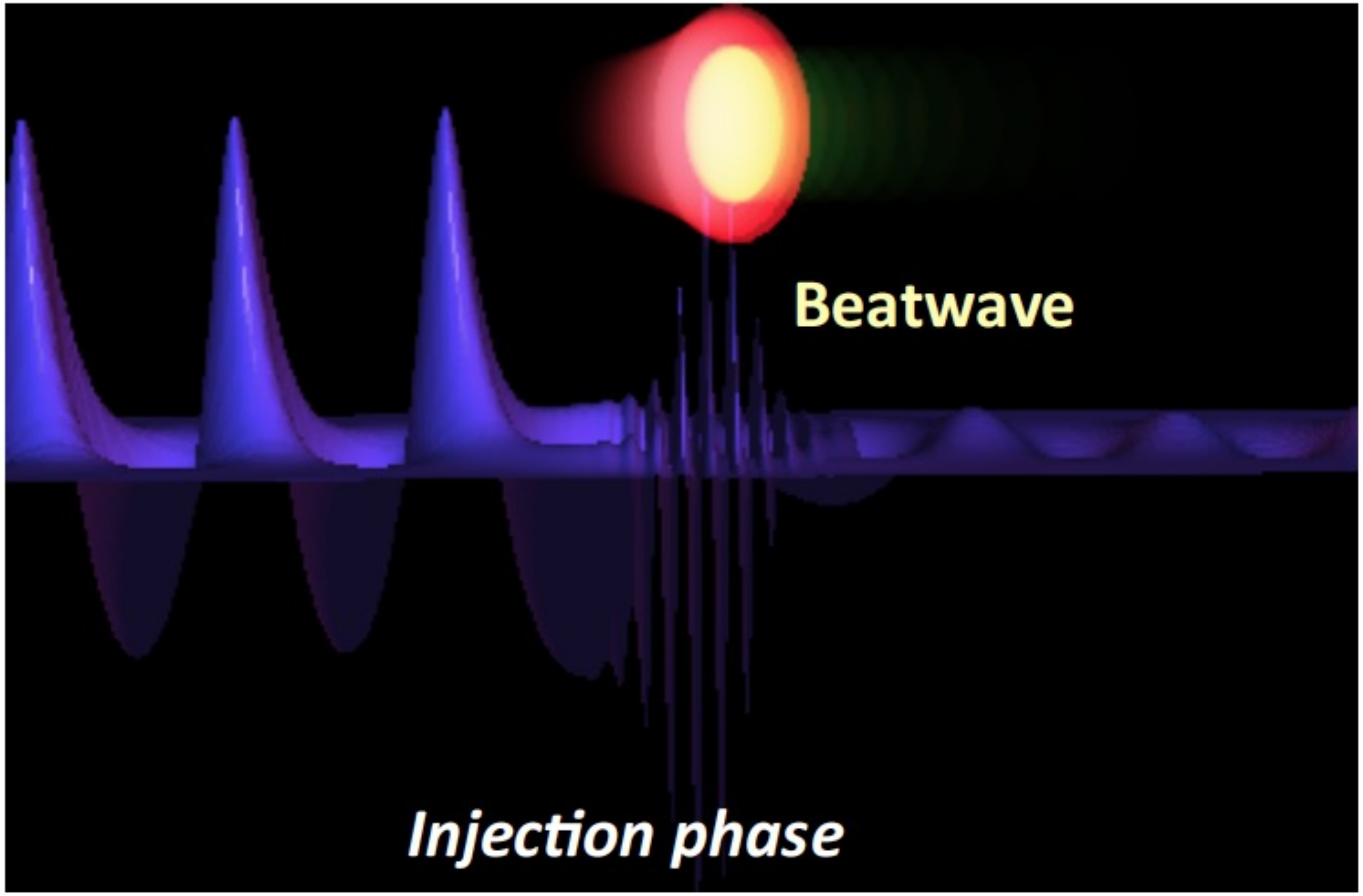


Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
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# Colliding Laser Pulses Scheme

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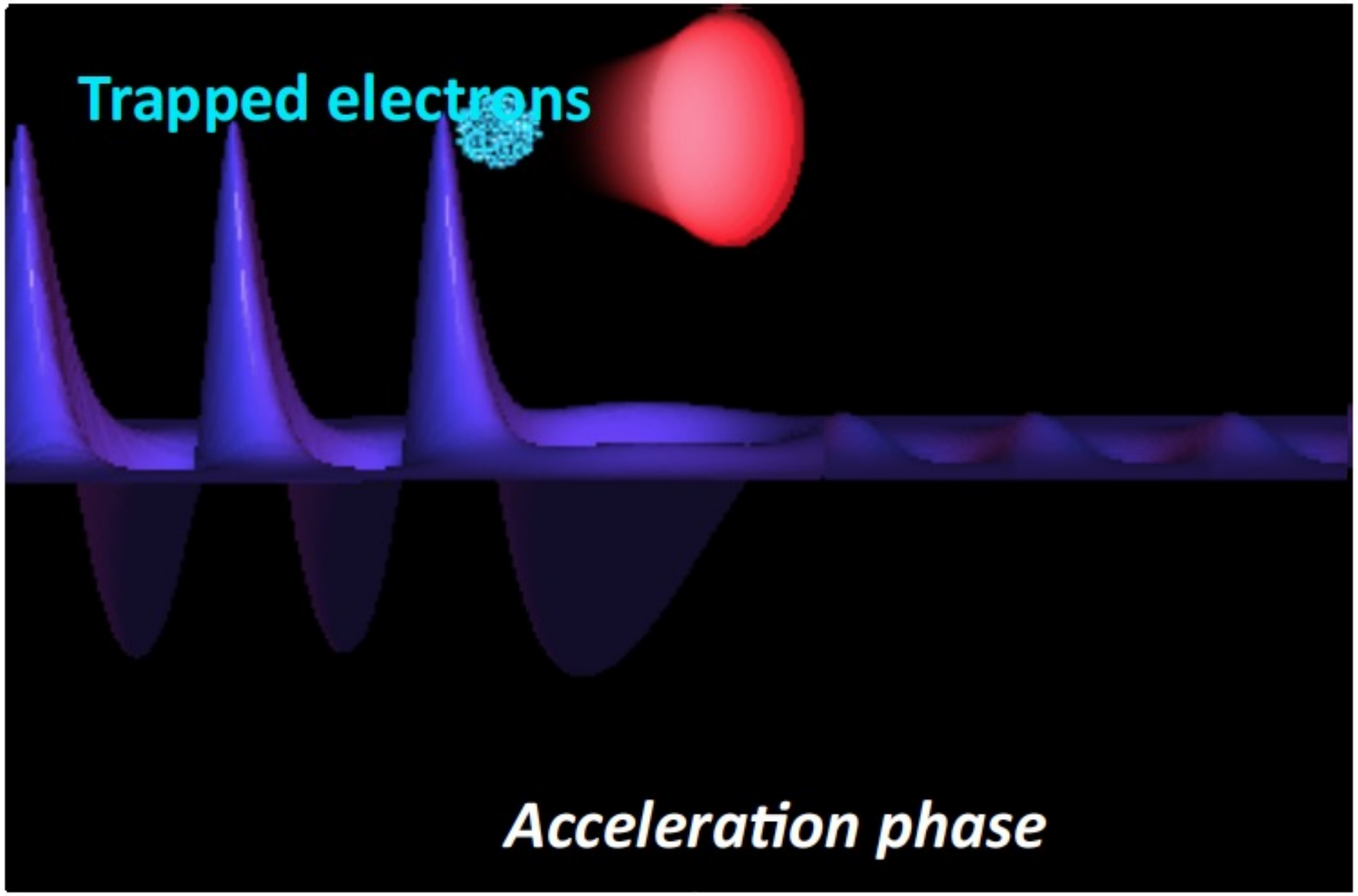
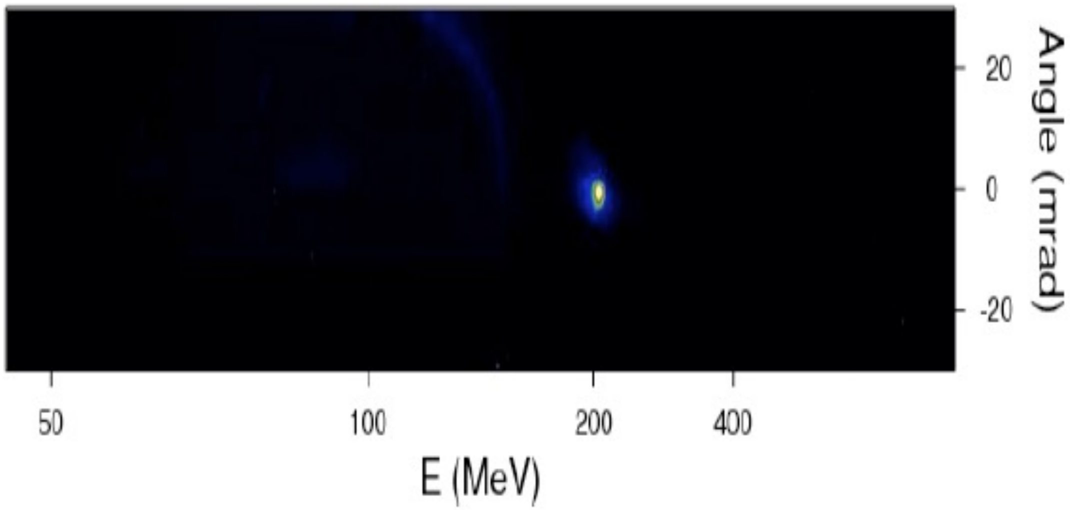
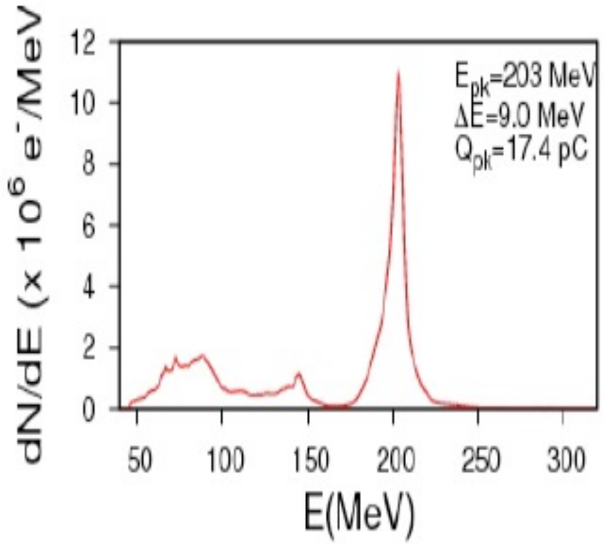


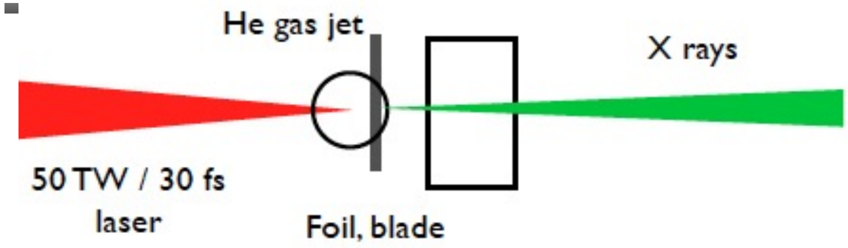

Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

# Stable Laser Plasma Accelerators



# Inverse Compton Scattering : New scheme



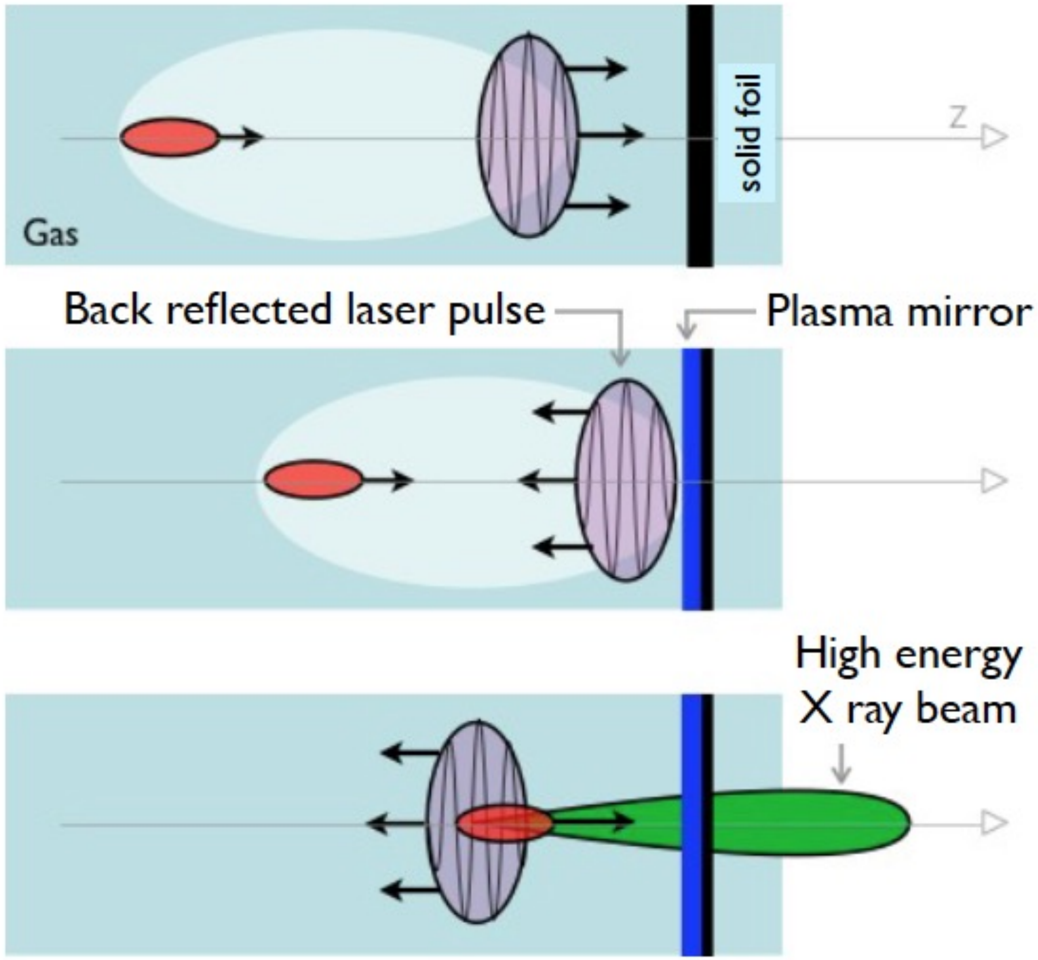

A single laser pulse

A plasma mirror reflects the laser beam

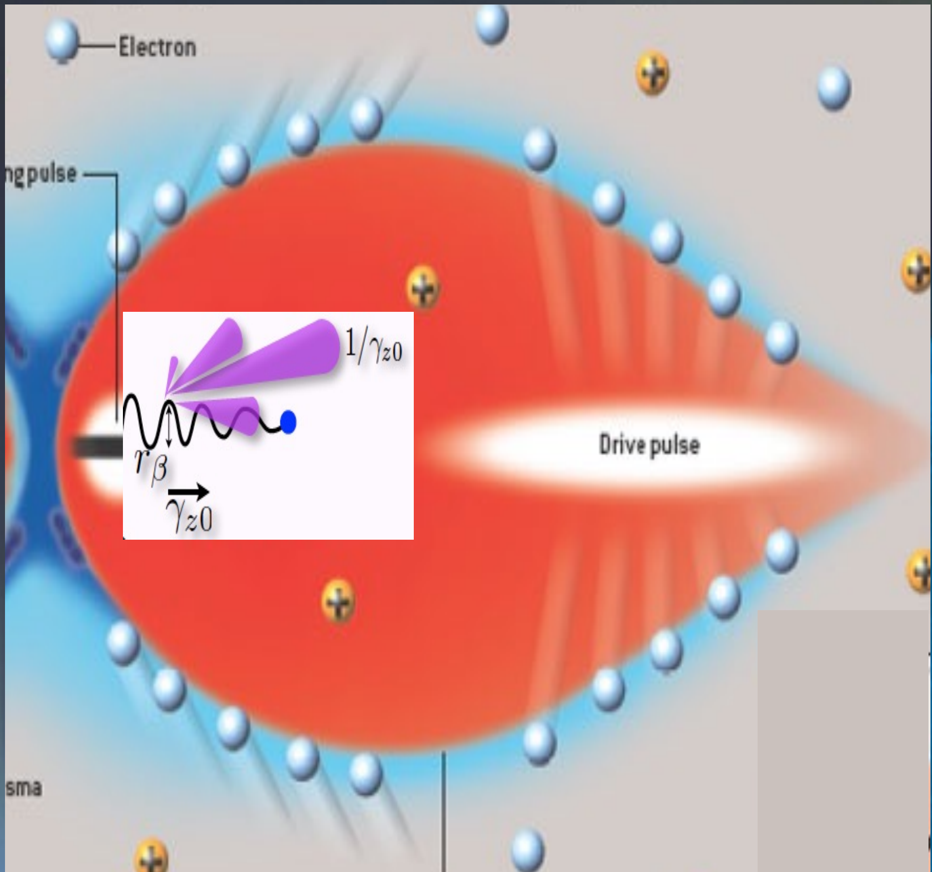
The back reflected laser collides with the accelerated electrons

No alignment : the laser and the electron beams naturally overlap

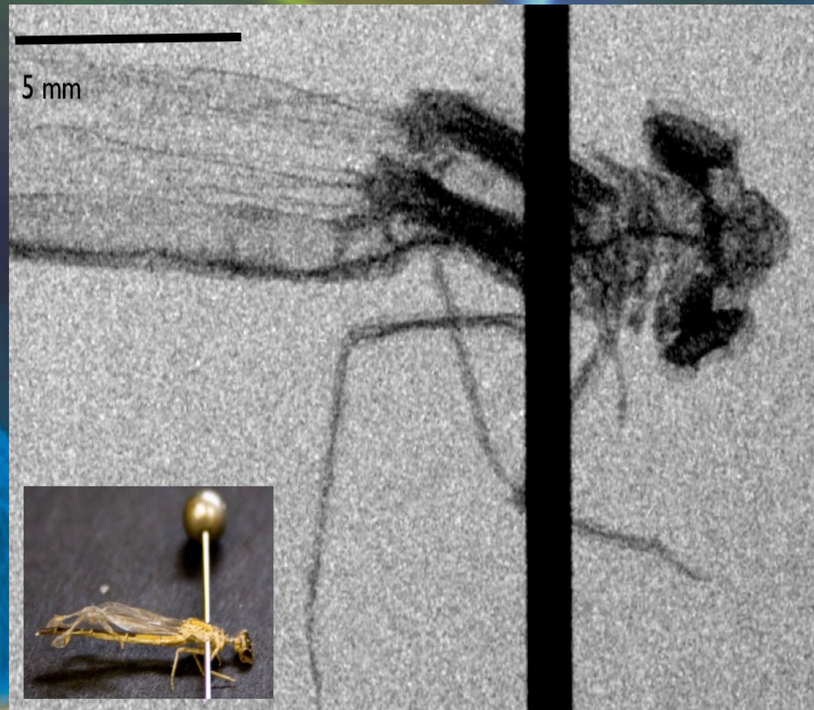
Save the laser energy !



# Betatron Radiation Source



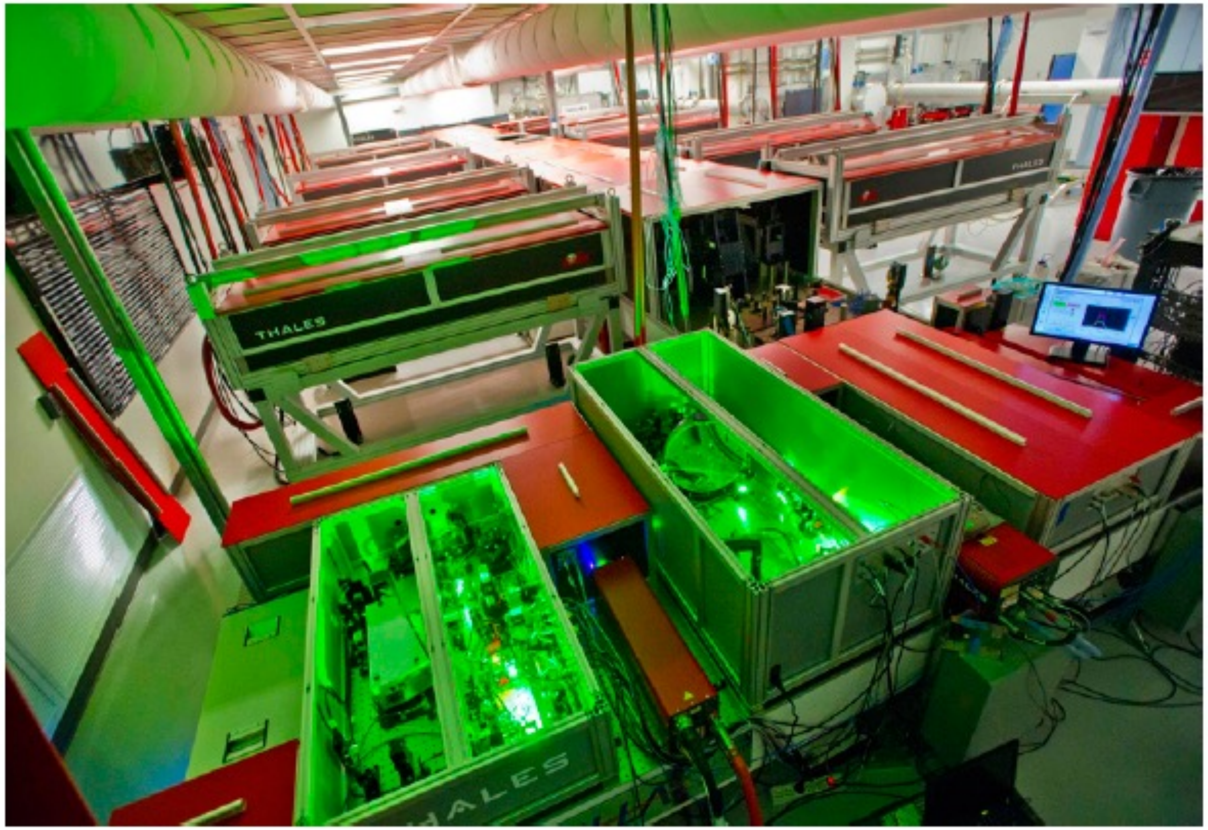

E Esarey PRE 65, 056505 (2002)
Kneip, Appl. Phys. Lett. 99, (2011).




Photon energy > 25 keV, investigating dense material, biological materials
Small source size (~ μm), intrinsically high resolution, exhibits spatial resolution
Small divergence (~ 10 mRad)
Short pulse (~10s fs), suitable for ultrafast dynamics
Bright (>109 photons per shot), suitable for single shot imaging

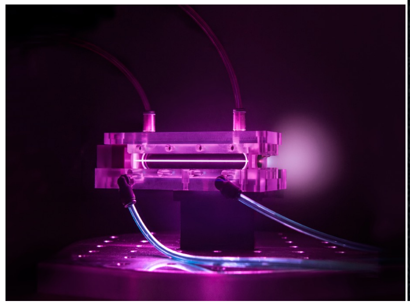
# BELLA: BErkeley Lab Laser Accelerator

***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:

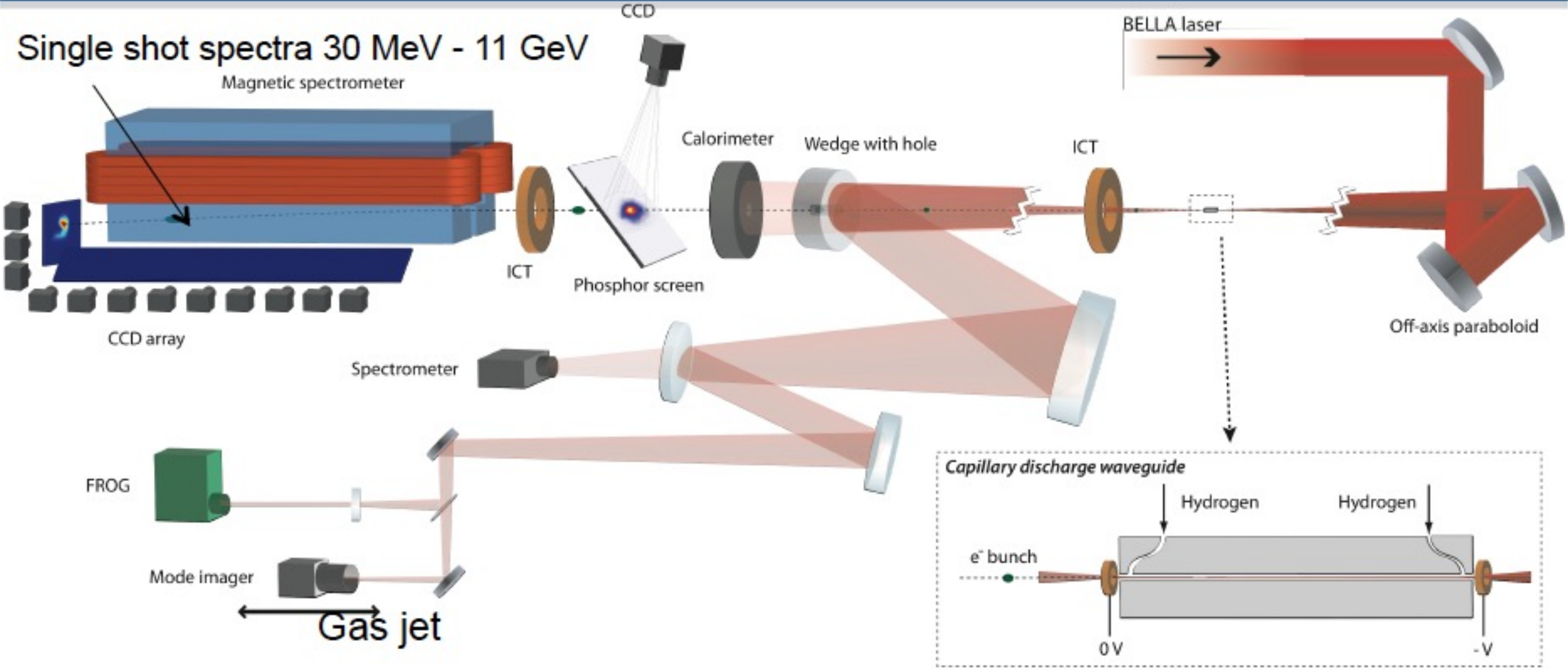
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration



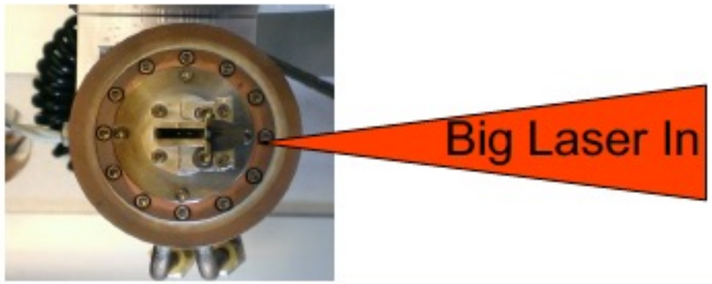
BELLA

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

Single shot spectra 30 MeV - 11 GeV



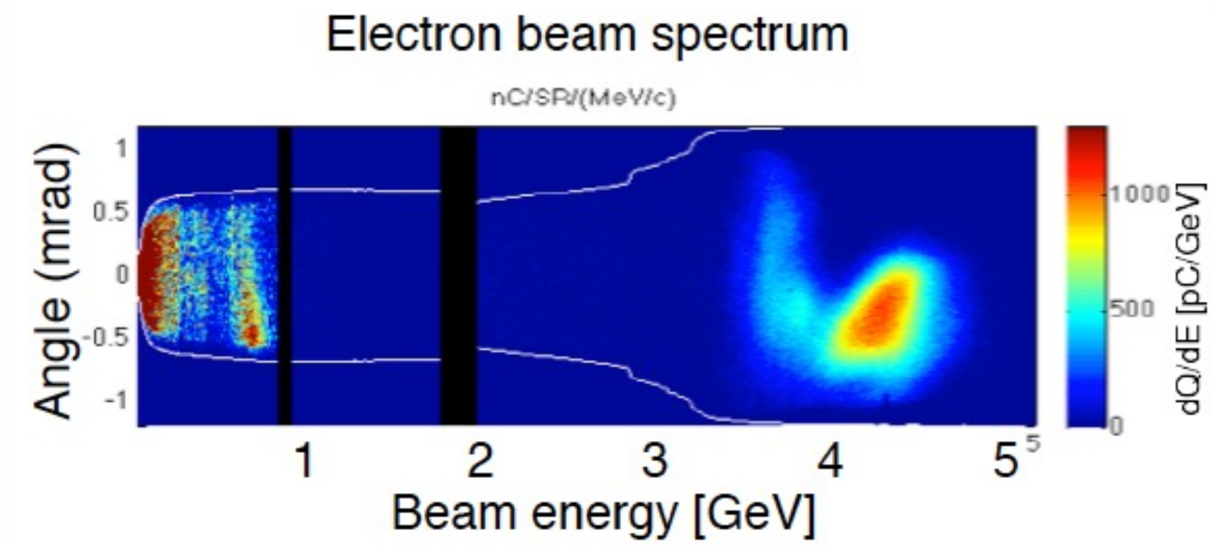

Gas jet

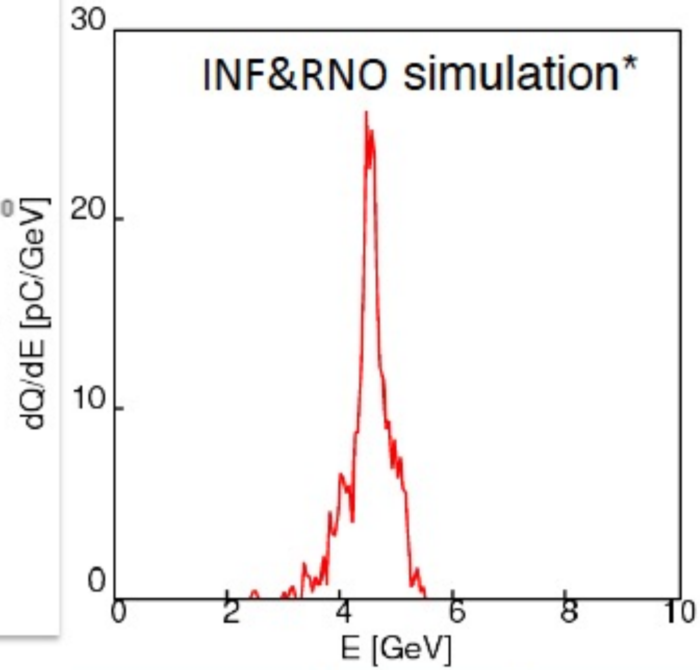



Capillary discharge

# 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, $n_0$~6-7x$10^{17}$ $cm^{-3}$)

| | 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 |

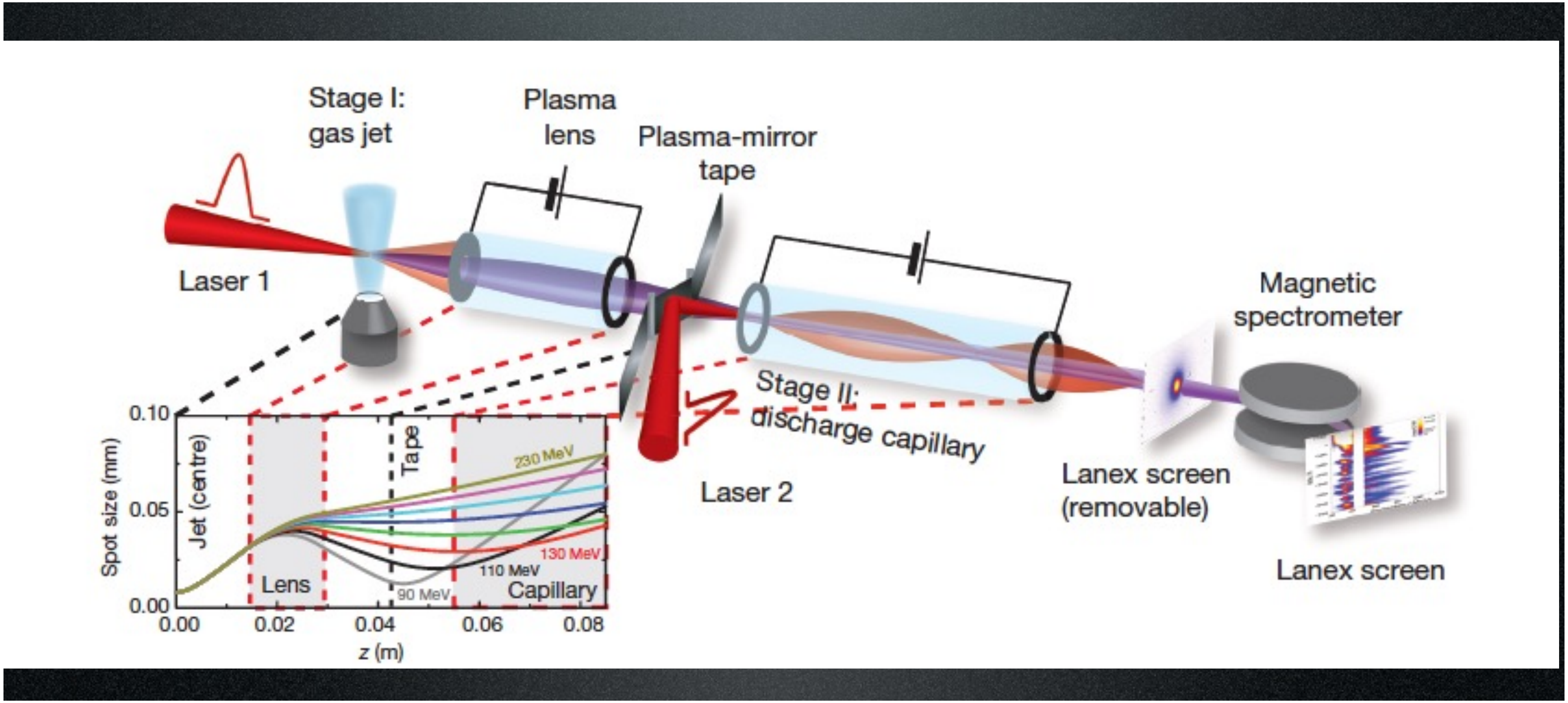
W.P. Leemans et al.,PRL 2014

# LETTER

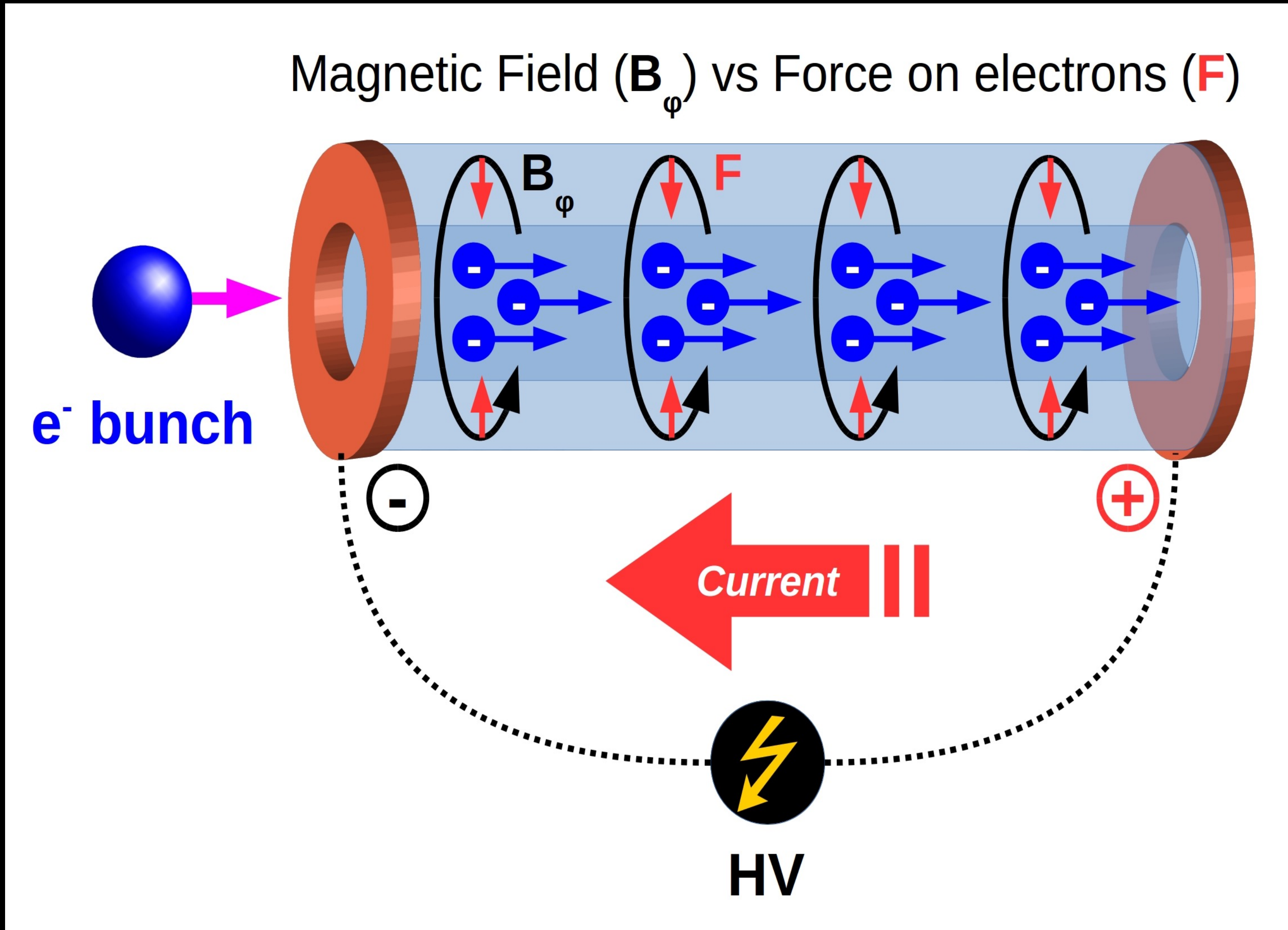
doi:10.1038/nature16525

# 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

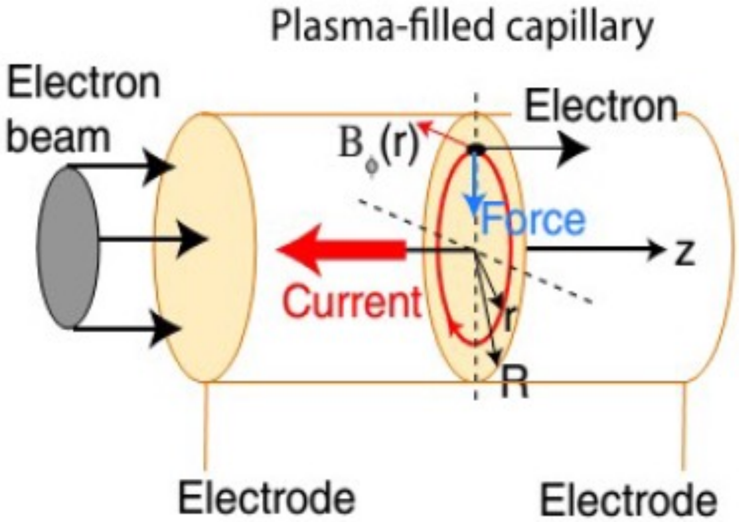


# Active plasma lens

- 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*

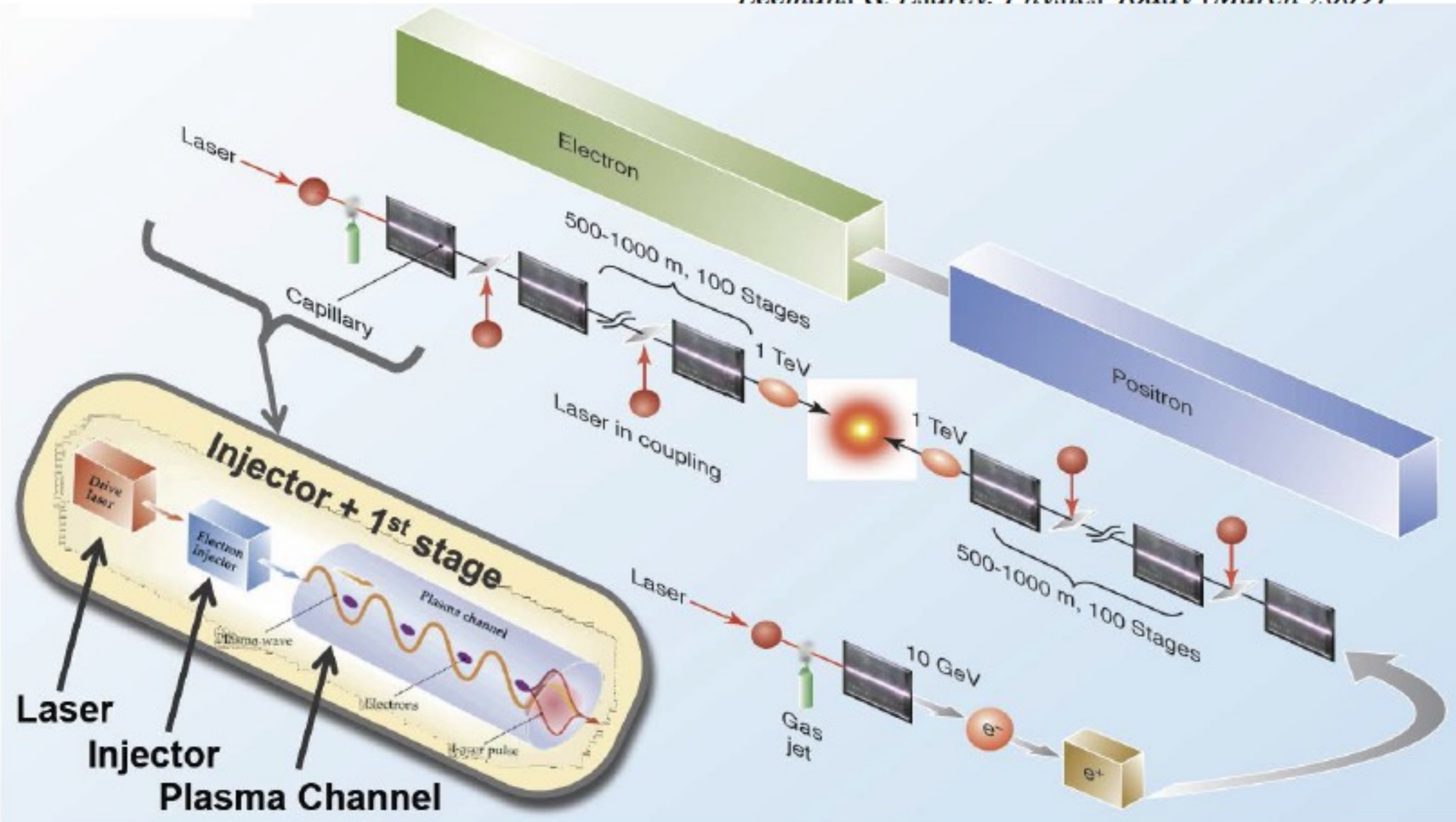



Van Tilborg, J., et al. "Active plasma lensing for relativistic laser-plasma-accelerated electron beams." Physical review letters 115.18 (2015): 184802.

# Beam Manipulation

# Laser-Plasma-Accelerator LC

*Leemans & Esarey, Physics Today (March 2009)*



# Parameter Set for LPWA LC

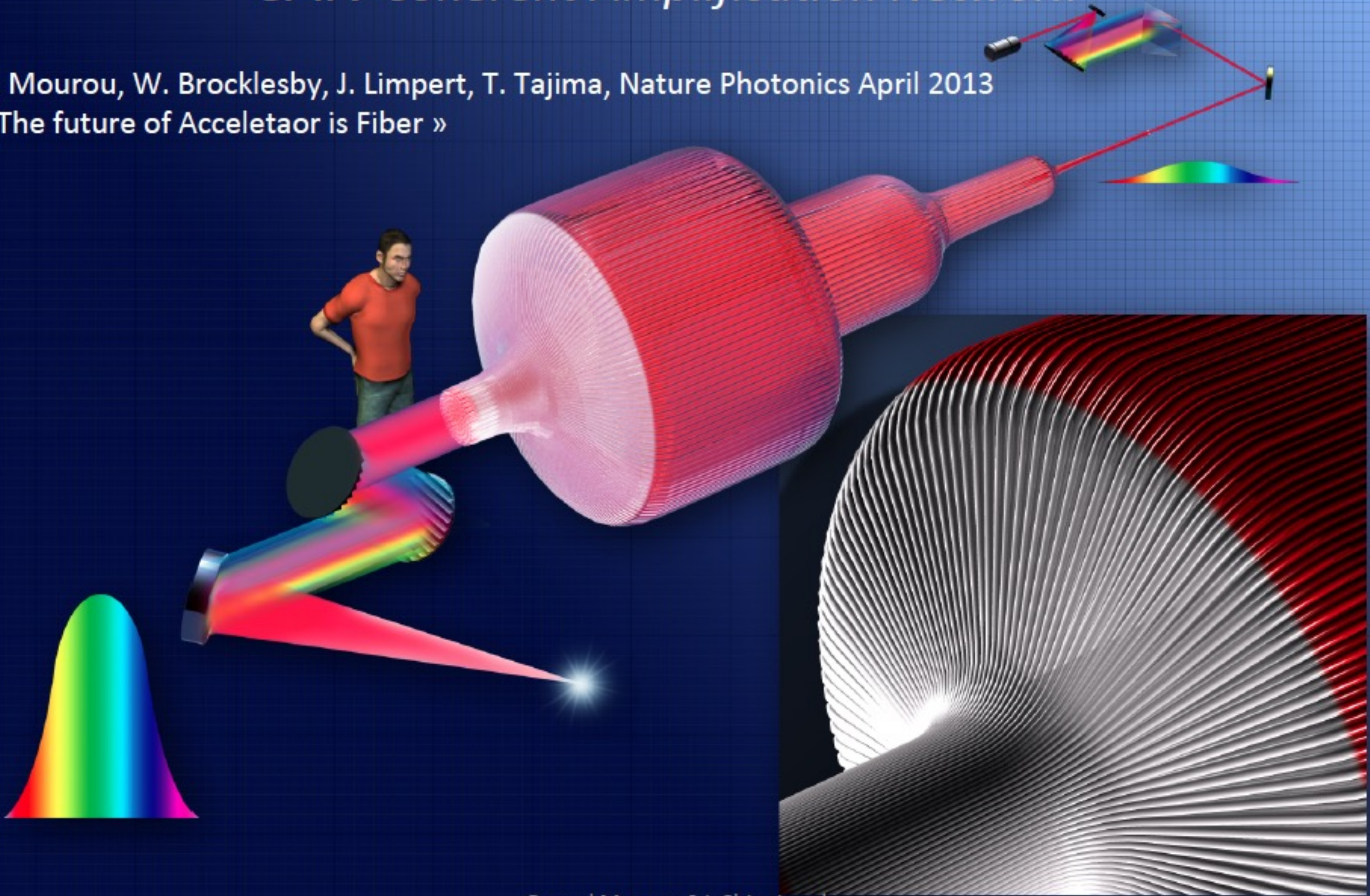
| Case: CoM Energy (Plasma density) | 1 TeV ($10^{17}$ cm$^{-3}$) | 1 TeV ($2\times10^{15}$ cm$^{-3}$) | 10 TeV ($10^{17}$ cm$^{-3}$) | 10 TeV ($2\times10^{15}$ cm$^{-3}$) |
|---|---|---|---|---|
| Energy per beam (TeV) | 0.5 | 0.5 | 5 | 5 |
| Luminosity ($10^{34}$ cm$^{-2}$s$^{-1}$) | 2 | 2 | 200 | 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 $\sigma^*_x$ (nm) | 10 | 10 | 1 | 1 |
| Vertical beam size at IP $\sigma^*_y$ (nm) | 10 | 10 | 1 | 1 |
| Disruption parameter | 0.12 | 5.6 | 1.2 | 56 |
| Bunch length $\sigma_z$ (μm) | 1 | 7 | 1 | 7 |
| Beamstrahlung parameter $\Upsilon$ | 180 | 180 | 18,000 | 18,000 |
| Beamstrahlung photons per e, $n_\gamma$ | 1.4 | 10 | 3.2 | 22 |
| Beamstrahlung energy loss $\delta_E$ (%) | 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

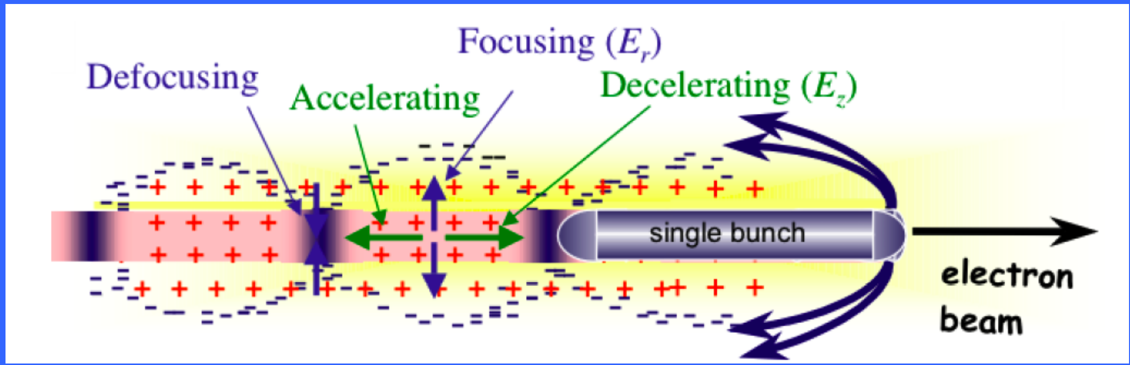
# ICAN (European Project)

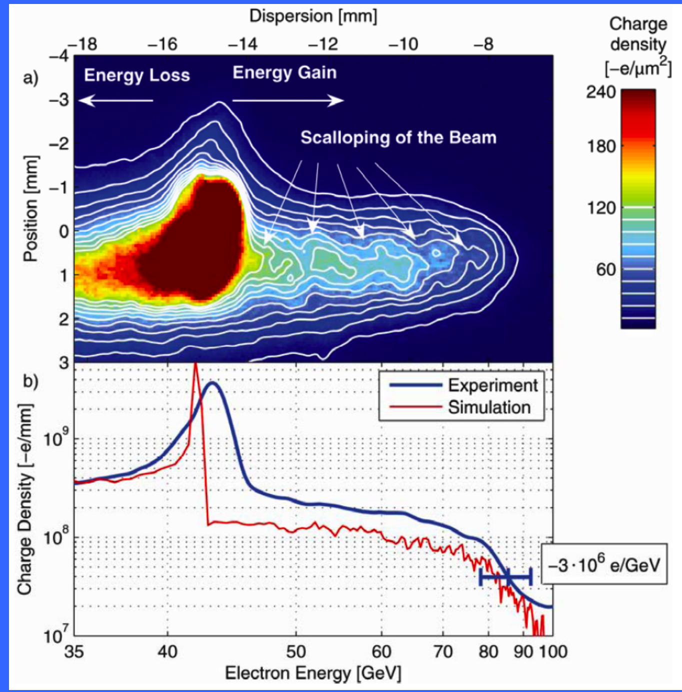
## CAN Coherent Amplification Network

G. Mourou, W. Brocklesby, J. Limpert, T. Tajima, Nature Photonics April 2013
« The future of Acceletaor is Fiber »

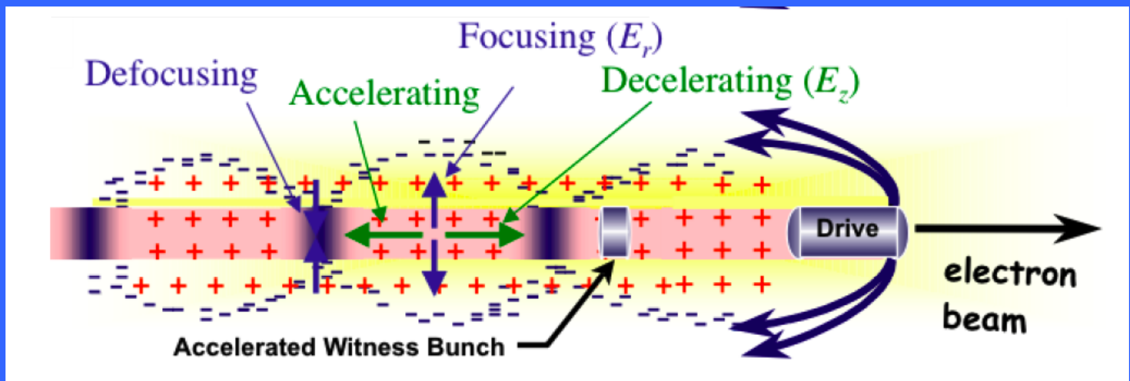


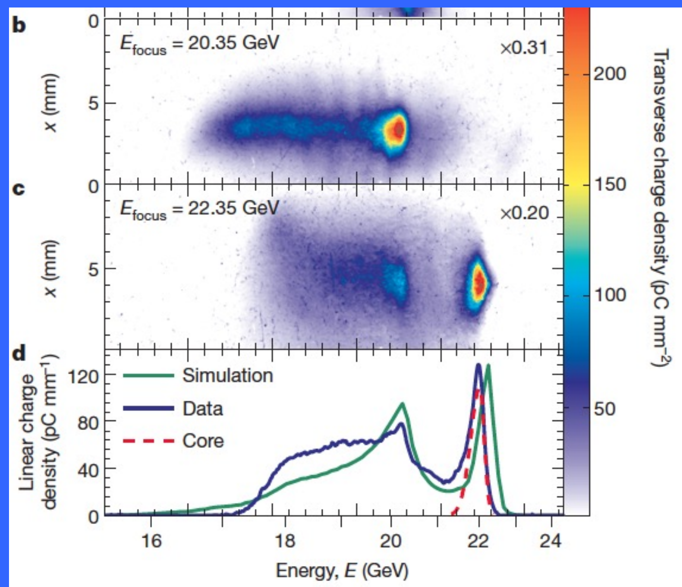
# Beam Driven
## PWFA




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).

# CONCEPTUAL DESIGN OF THE DRIVE BEAM FOR A PWFA-LC*

S. Pei#, M. J. Hogan, T. O. Raubenheimer, A. Seryi, SLAC, CA 94025, U.S.A.
H. H. Braun, R. Corsini, J. P. Delahaye, CERN, Geneva

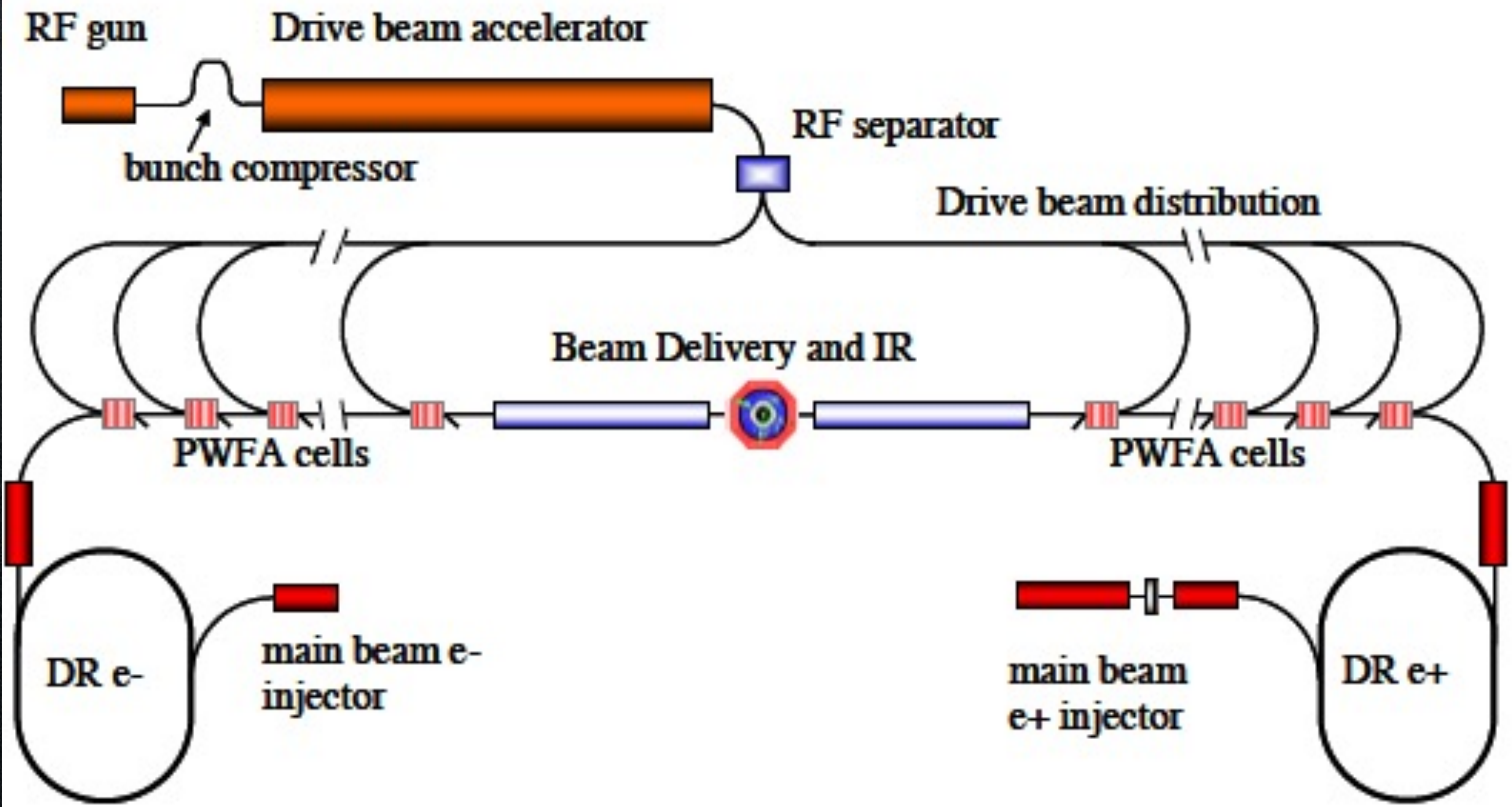



Fig. 1: Concept for a multi-stage PWFA Linear Collider.

Table 1: Key Parameters of the Conceptual Multi-Stage PWFA-based Linear Collider

| | |
|---|---|
| Main beam: bunch population, bunches per train, rate | $1\times10^{10}$, 125, 100 Hz |
| Total power of two main beams | 20 MW |
| Drive beam: energy, peak current and active pulse length | 25 GeV, 2.3 A, 10 μs |
| Average power of the drive beam | 58 MW |
| Plasma density, accelerating gradient and plasma cell length | $1\times10^{17}cm^{-3}$, 25 GV/m, 1 m |
| Power transfer efficiency drive beam=>plasma =>main beam | 35% |
| Efficiency: Wall plug=>RF=>drive beam | 50% × 90% = 45% |
| Overall efficiency and wall plug power for acceleration | 15.7%, 127 MW |
| Site power estimate (with 40MW for other subsystems) | 170 MW |
| Main beam emittances, x, y | 2, 0.05 mm-mrad |
| Main beam sizes at Interaction Point, x, y, z | 0.14, 0.0032, 10 μm |
| Luminosity | $3.5\times10^{34}$ $cm^{-2}s^{-1}$ |
| Luminosity in 1% of energy | $1.3\times10^{34}$ $cm^{-2}s^{-1}$ |

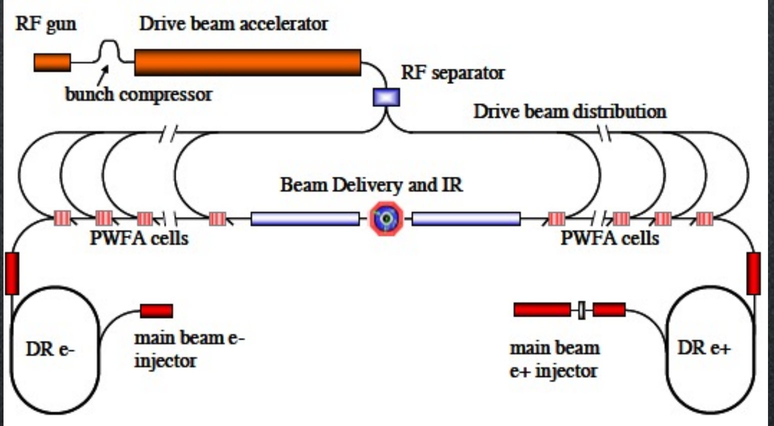



Fig. 1: Concept for a multi-stage PWFA Linear Collider.

# Positron Acceleration, FACET

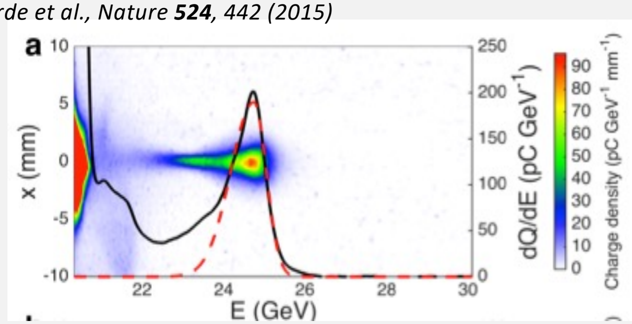
Positrons for high energy linear colliders: **high energy, high charge, low emittance**.

**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)*

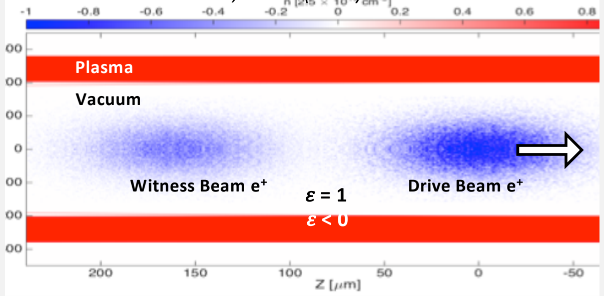



High-density, compressed positron beam for non-linear PWFA experiments. Energy transfer from the front to the back part of the bunch.

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

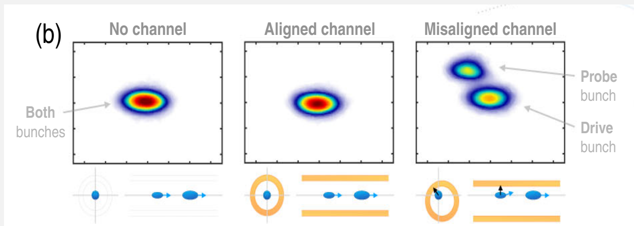
## Hollow plasma channel: positron propagation, wake excitation, acceleration in 30 cm channel.

*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**).*

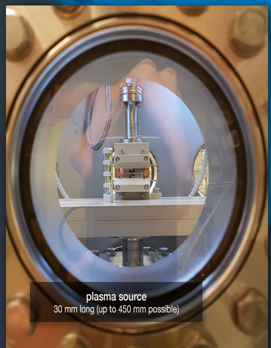


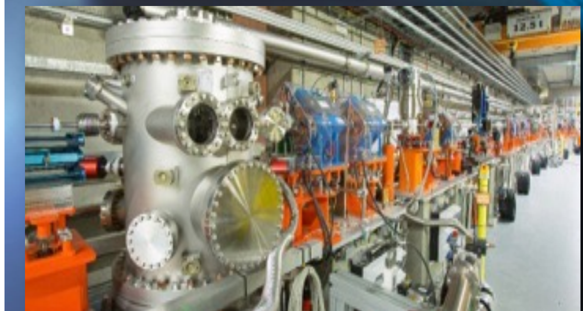

**➔ Emittance blow-up is an issue!** → Use hollow-channel, so no plasma on-axis, no complicated forces from plasma electrons streaming through the plasma → but then strong transverse wakefields when beams are misaligned.

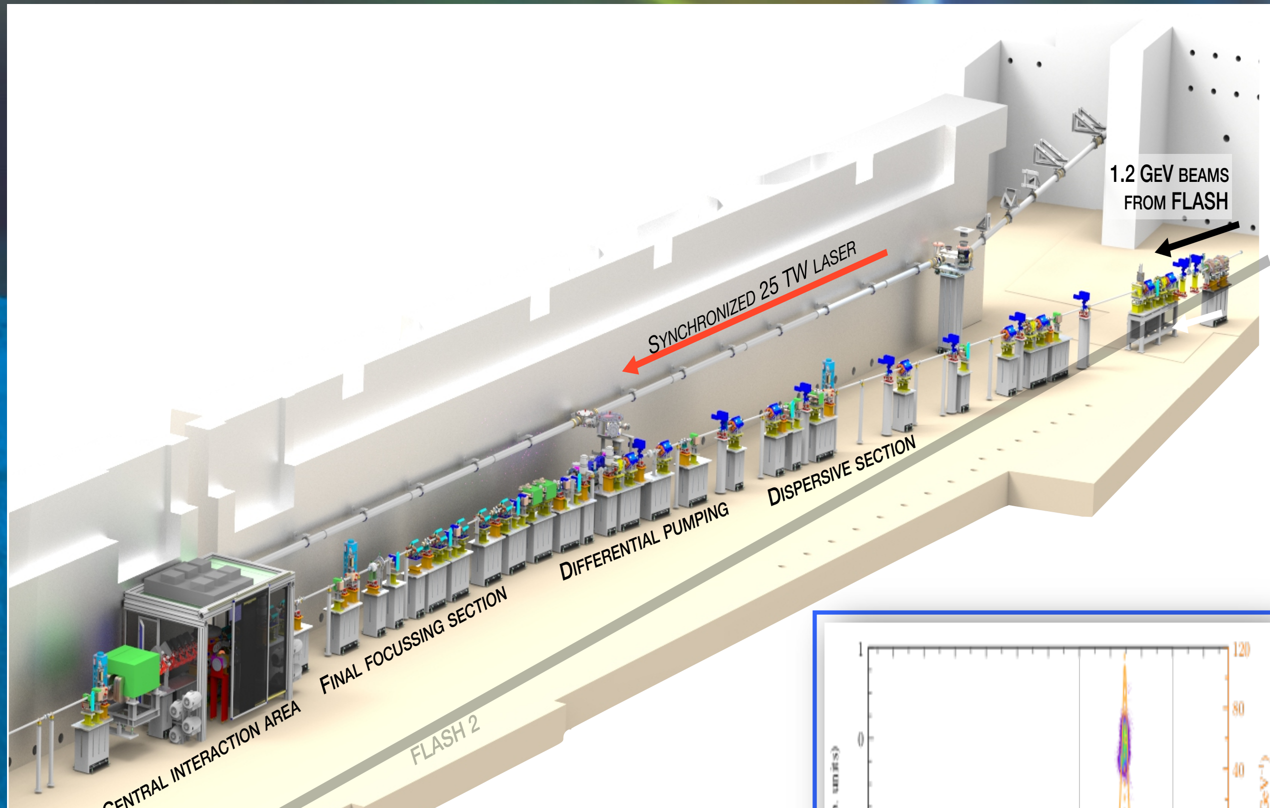
# FLASHForward>>, DESY

→ unique FLASH facility features for PWFA

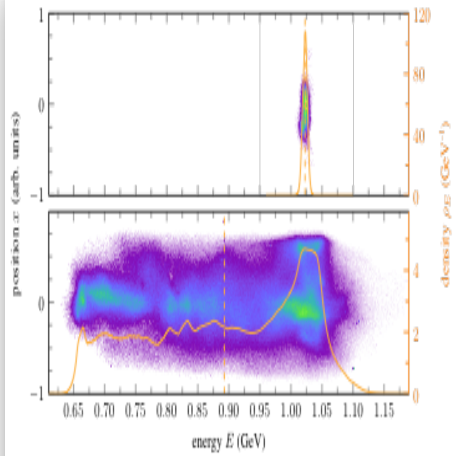
- FEL-quality drive and witness beams
- up to 1 MHz repetition rate
- 3rd harmonic cavity for phase-space linearization
  → tailoring of beam current profile
- differentially pumped, windowless plasma sources
- *2019*: X-band deflector of 1 fs resolution post-plasma (collaboration with FALSH 2, SINBAD, CERN & PSI)
- *Future:* up to 800 bunches (~MHz spacing) at 10 Hz macro-pulse rate, few 10 kW average power.






→ A. Aschikhin *et al.*, NIM A **806**, 175 (2016)




→ (12.3 ± 1.7) GV/m wakefield generated in 30 mm plasma cell

→ 12.7% total energy loss to plasma wakefield

# SPARC_LAB, Frascati, Italy

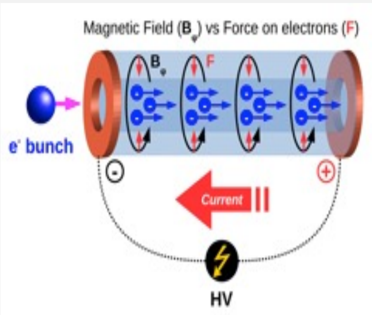
SPARC_LAB is the test and training facility for EuPRAXIA@SPARC_LAB

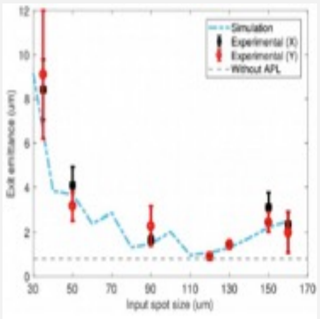

M. Ferrario et al., SPARC_LAB present and future, NIM B 309, (2013)

➔ **Main challenges addressed in this facility: beam quality, beam transport**

- 150 MeV drive/witness beam
- FEL experiments
- Resonant LWFA with 200 TW laser
- PWFA

## Active Plasma Lens Experiments:



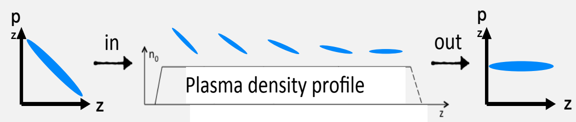




*R. Pompili et al., PRL 121 (2018), 174801*

***BELLA, LBNL:** J. van Tilborg et al., PRL 115 (2015), 184802*
***CLEAR, CERN**: C.A. Lindstrom et al., PRL 121 (2018), 194801*

## Plasma dechirper:

Longitudinal phase-space manipulation with the wakefield induced in plasma by the beam itself.





From 0.6% to 0.1% energy spread

*V. Shpakov et al., PRL 122 (2019), 114801*

***FLASHForward, DESY:** R. D'Arcy et al., PRL 122 (2019), 034801*

MAX-PLANCK-GESELLSCHAFT

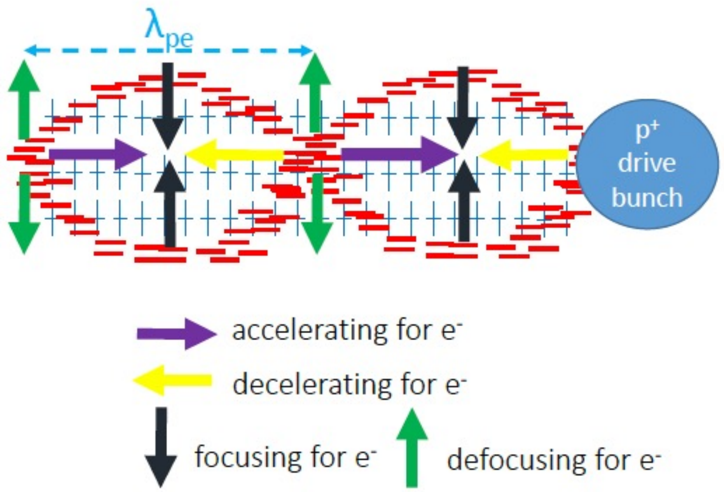
AWAKE

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

# Reasons for proton bunch driver

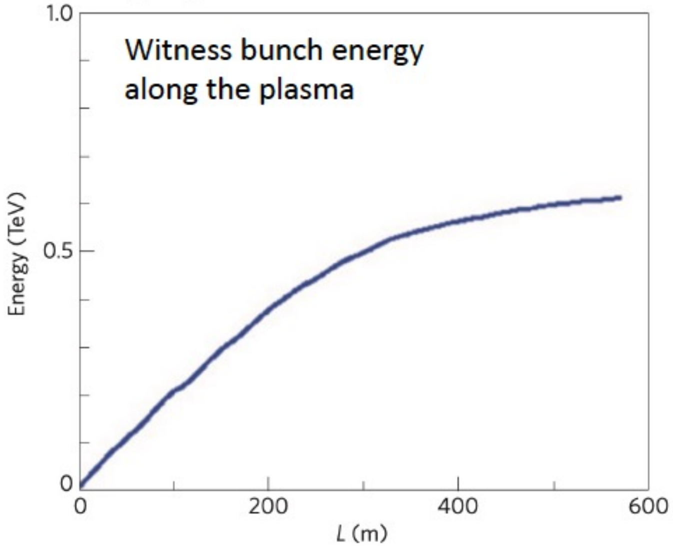
Available proton bunches carry large amounts of energy:

- 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!**

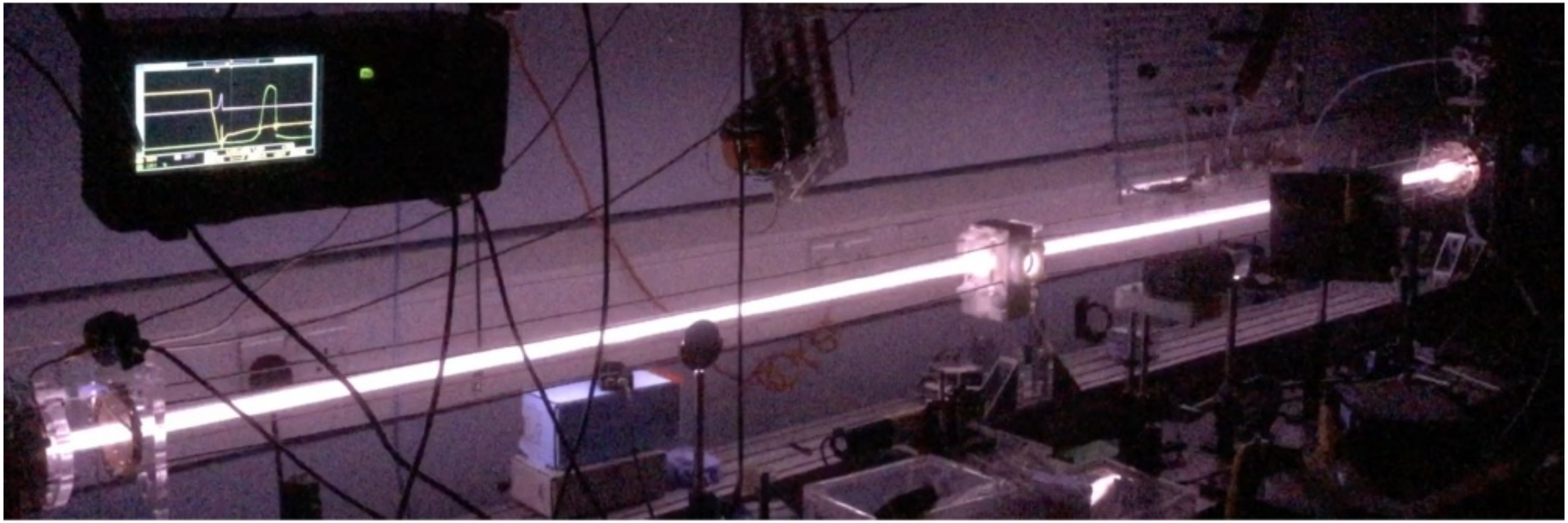
Parameters:
single proton bunch
$\sigma_z$ = 100 µm,
E = 1 TeV,
population: $1 \cdot 10^{11}$ ppb




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

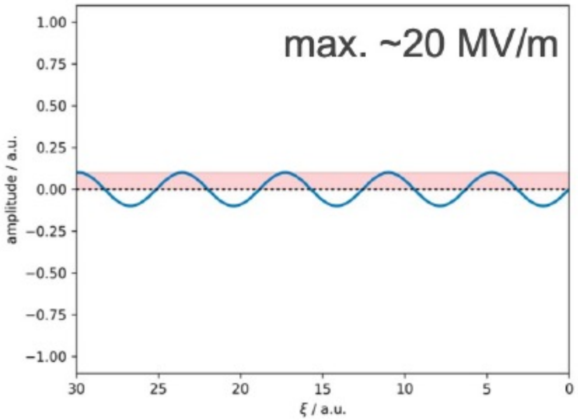
scalability of electric circuit for plasmas > 10 m seem achievable…

# Self-modulation in plasma

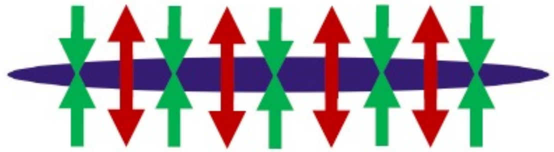
**CERN SPS Proton bunch**

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

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




**Growth mechanism**



Initial transverse wakefields

↓

Periodic focusing/defocusing fields

↓

Radial bunch and plasma density modulation

↓

Stronger wakefields

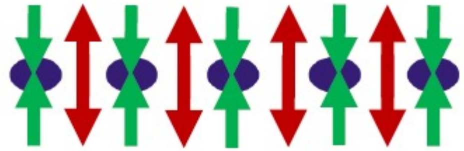
↓

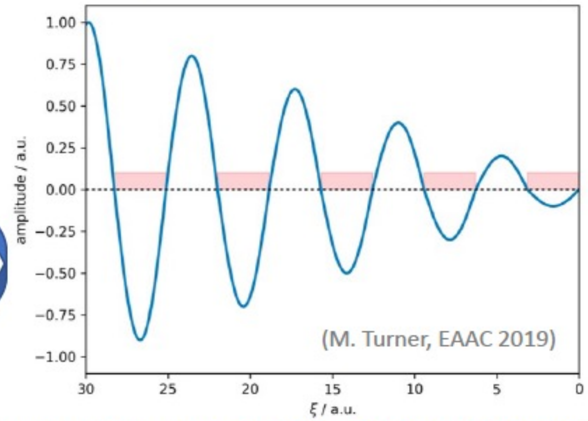
Full modulation

**Self-Modulation instability (SMI)**

→ resonant wakefield excitation

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

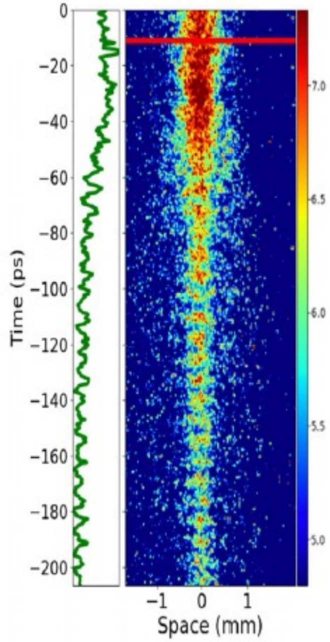





N. Kumar et al., Phys. Rev. Lett. 104 (25), 255003 (2010)

A. Pukhov et al., Phys. Rev. Lett. 107 (14), 145003 (2011)

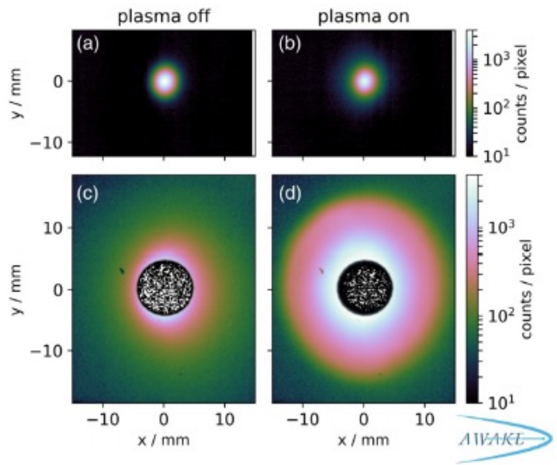
# AWAKE Run 1 (2016-2018)




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

time-resolved imaging:

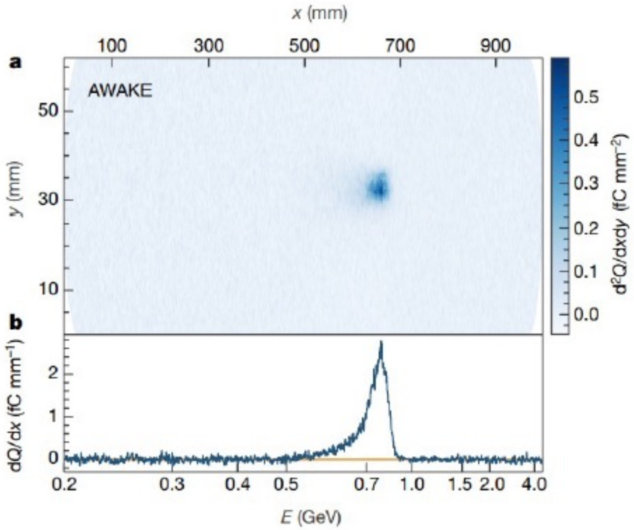
- the proton bunch self-modulates in plasma
- focusing phase → micro-bunches
- frequency of the modulation≈ $\omega_{pe}$




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

time-integrated, transverse imaging:

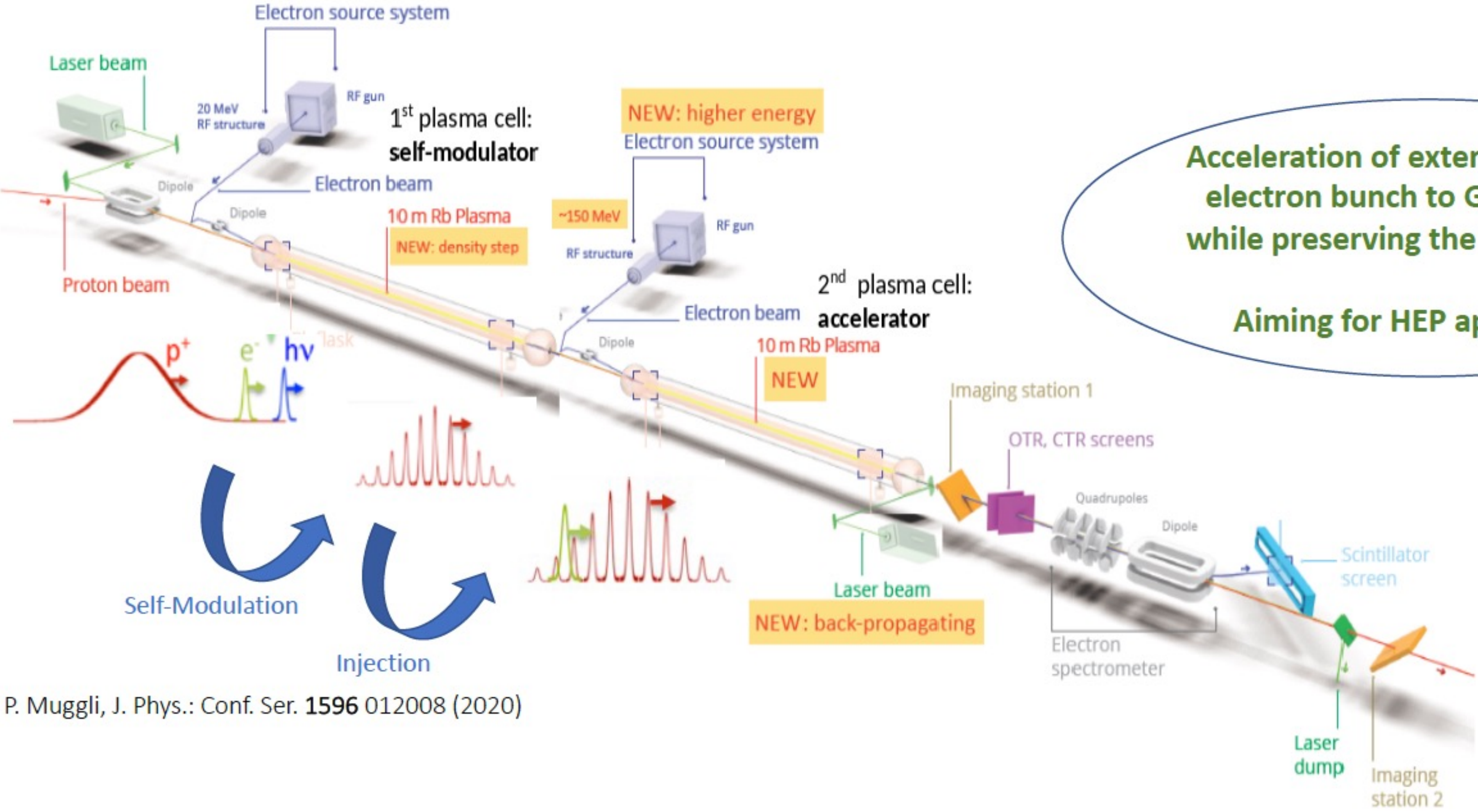
- defocusing phase→ large halo
- wakefields grow along the plasma




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)

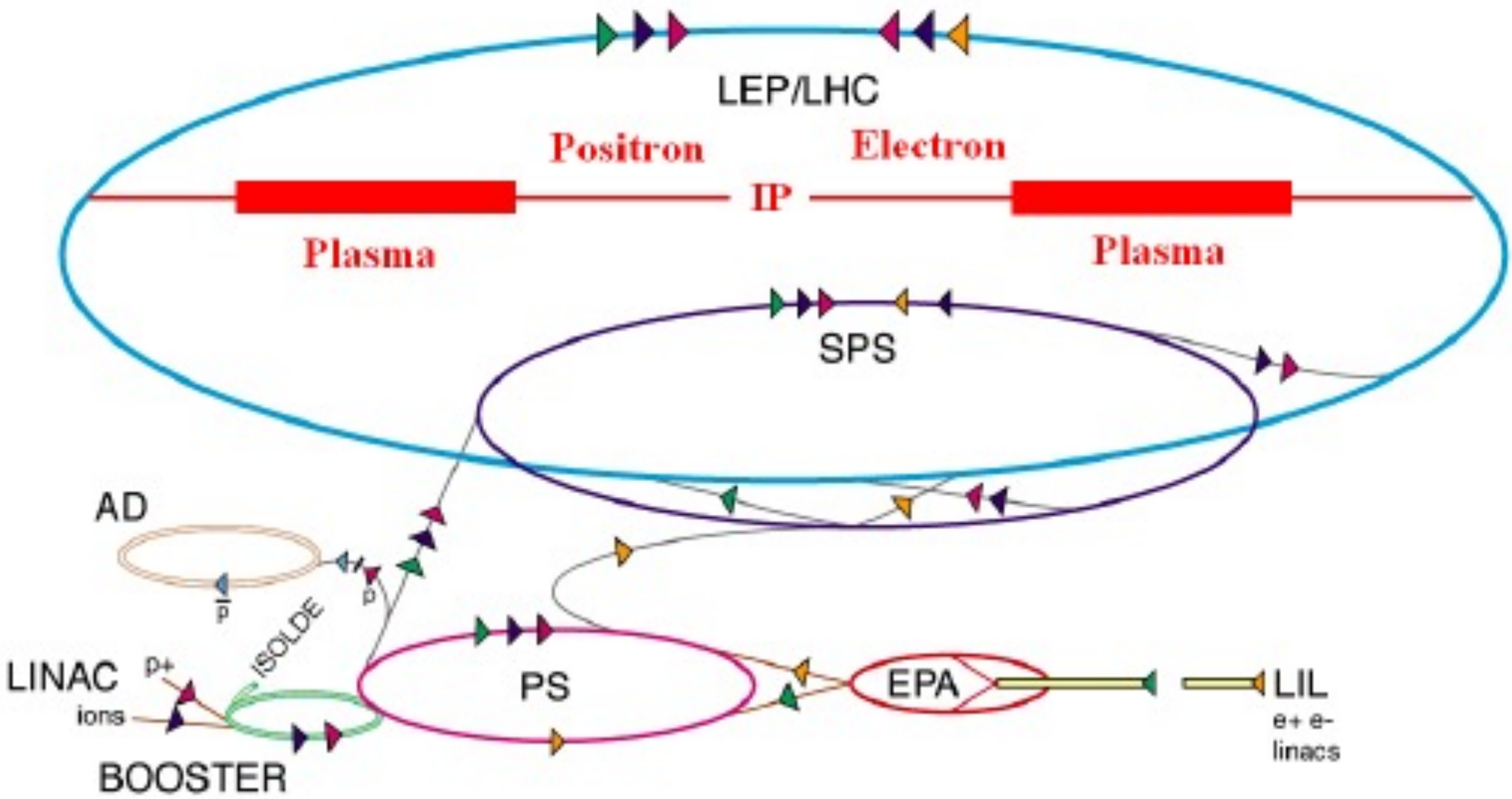
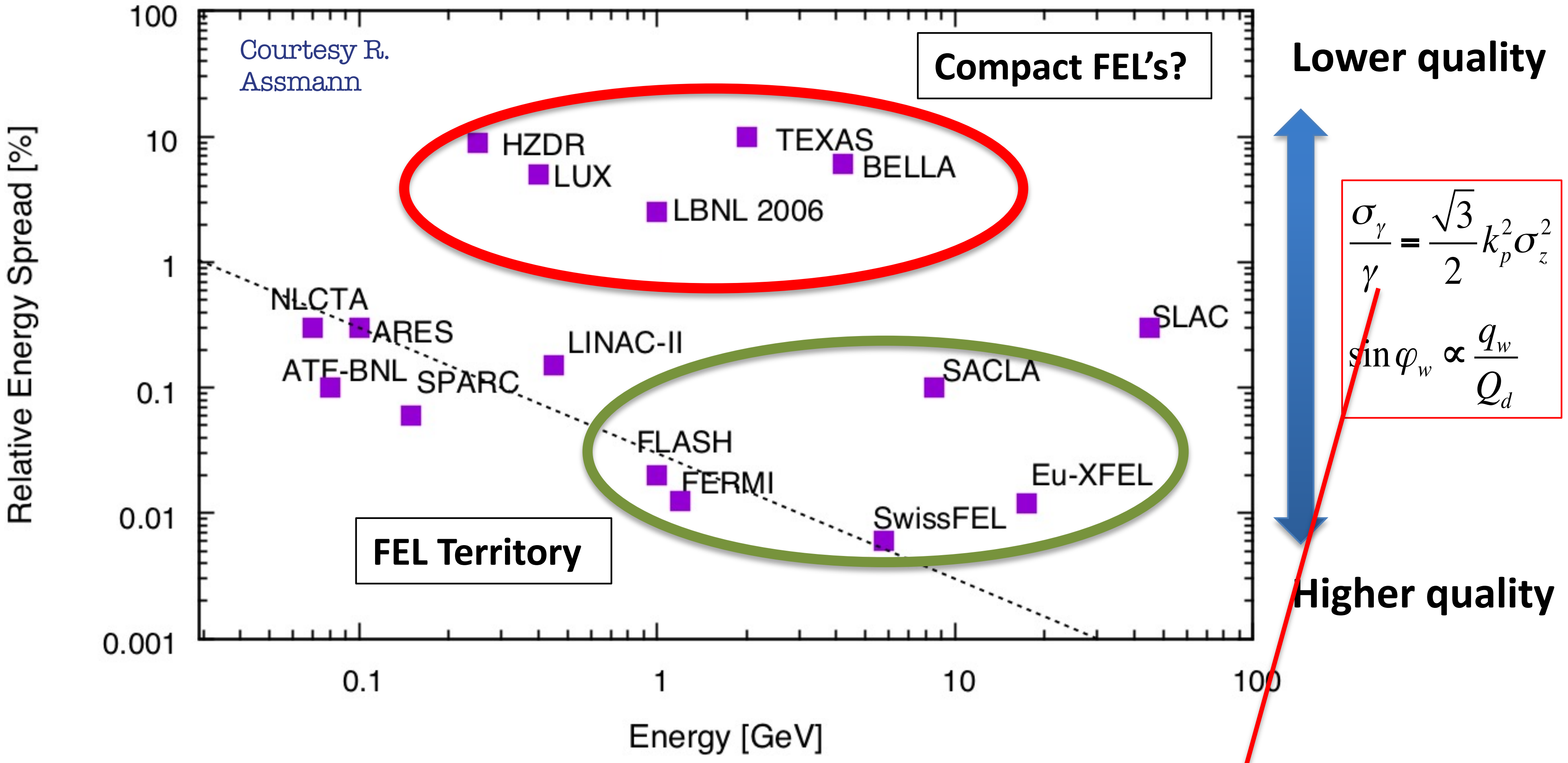



Figure 1: Schematic layout of a 2 TeV CoM electron-positron linear collider based on a modulated proton-driven plasma wakefield acceleration.

# The near future

# Quality: Example Energy Spread




$$\frac{\sigma_\gamma}{\gamma} = \frac{\sqrt{3}}{2} k_p^2 \sigma_z^2$$

$$\sin\varphi_w \propto \frac{q_w}{Q_d}$$

$$\varepsilon_{n,rms} = \sqrt{\langle \gamma^2 \rangle \left( \sigma_\gamma^2 \sigma_x^2 \sigma_{x'}^2 + \varepsilon_{rms}^2 \right)}$$

EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

EuPRAXIA Design Study started on Novemebr 2015

Approved as HORIZON 2020 INFRADEV, 4 years, 3 M€

Coordinator: Ralph Assmann (DESY)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

http://eupraxia-project.eu

# Motivations

Horizon2020

**PRESENT EXPERIMENTS**

- Demonstrating **100 GV/m** routinely
- Demonstrating **GeV** electron beams
- Demonstrating basic **quality**

**EuPRAXIA INFRASTRUCTURE**

- **Engineering a high quality, compact plasma accelerator**
- **5 GeV electron beam for the 2020's**
- **Demonstrating user readiness**
- **Pilot users from FEL, HEP, medicine, ...**

**PRODUCTION FACILITIES**

- Plasma-based **linear collider** in 2040's
- Plasma-based **FEL** in 2030's
- **Medical, industrial** applications soon

Courtesy R. Assmann

# The EuPRAXIA Project

http://www.eupraxia-project.eu/

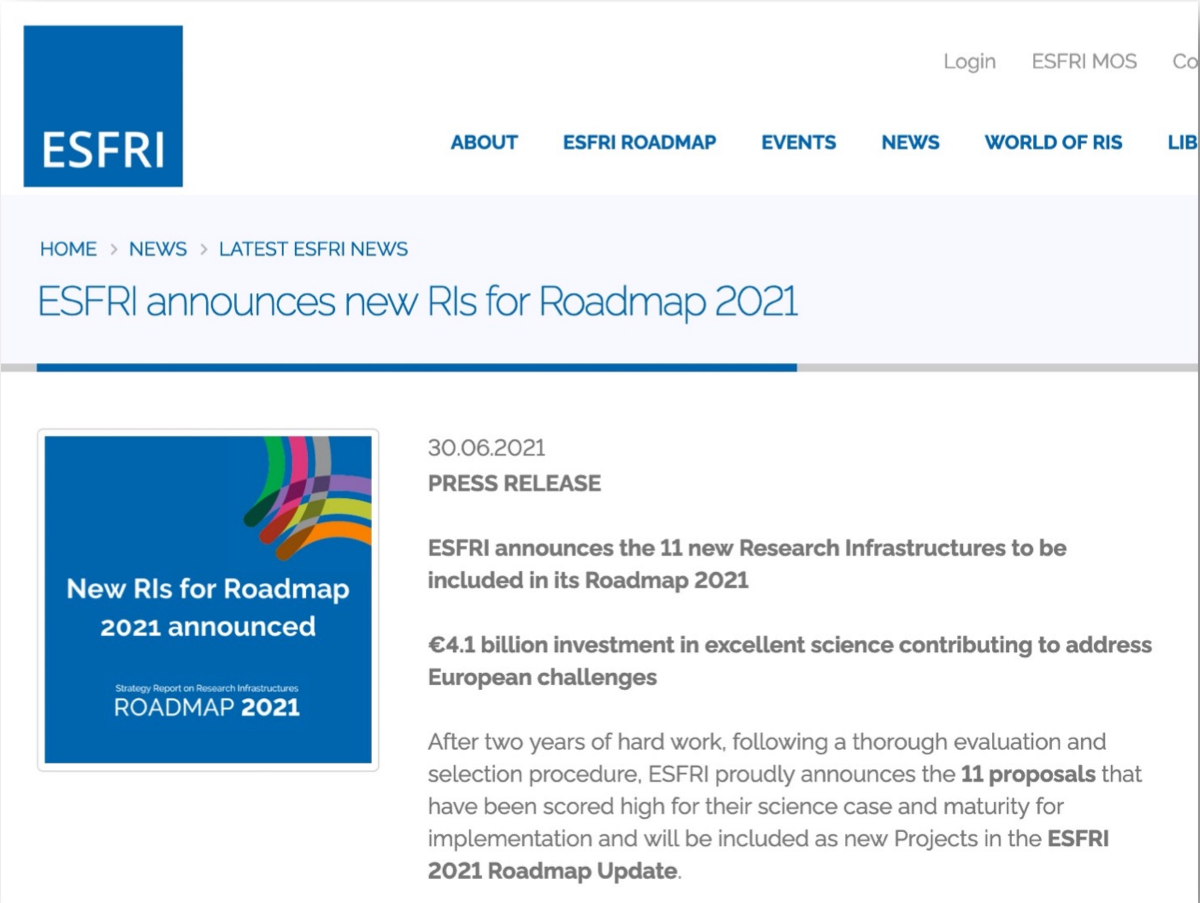
Horizon 2020

- First ever international design of a **plasma accelerator facility**.
- Challenges addressed by EuPRAXIA since 2015:
  - How **can plasma accelerators produce usable electron beams**?
  - **For what can we use those beams** while we increase the beam energy towards HEP and collider usages?
- **CDR for a distributed research infrastructure** funded by EU Horizon2020 program. Completed by 16+25 institutes.
- **Next phase consortium** with 40 partners, 10 observers.
- **Applied to ESFRI roadmap update 2021** with government support in Sep 2020.
- **Successful** and and placed on ESFRI roadma.


**653 page CDR,** 240 scientists contributed

# Great News 30.6.2021

## Building the first plasma accelerator facility



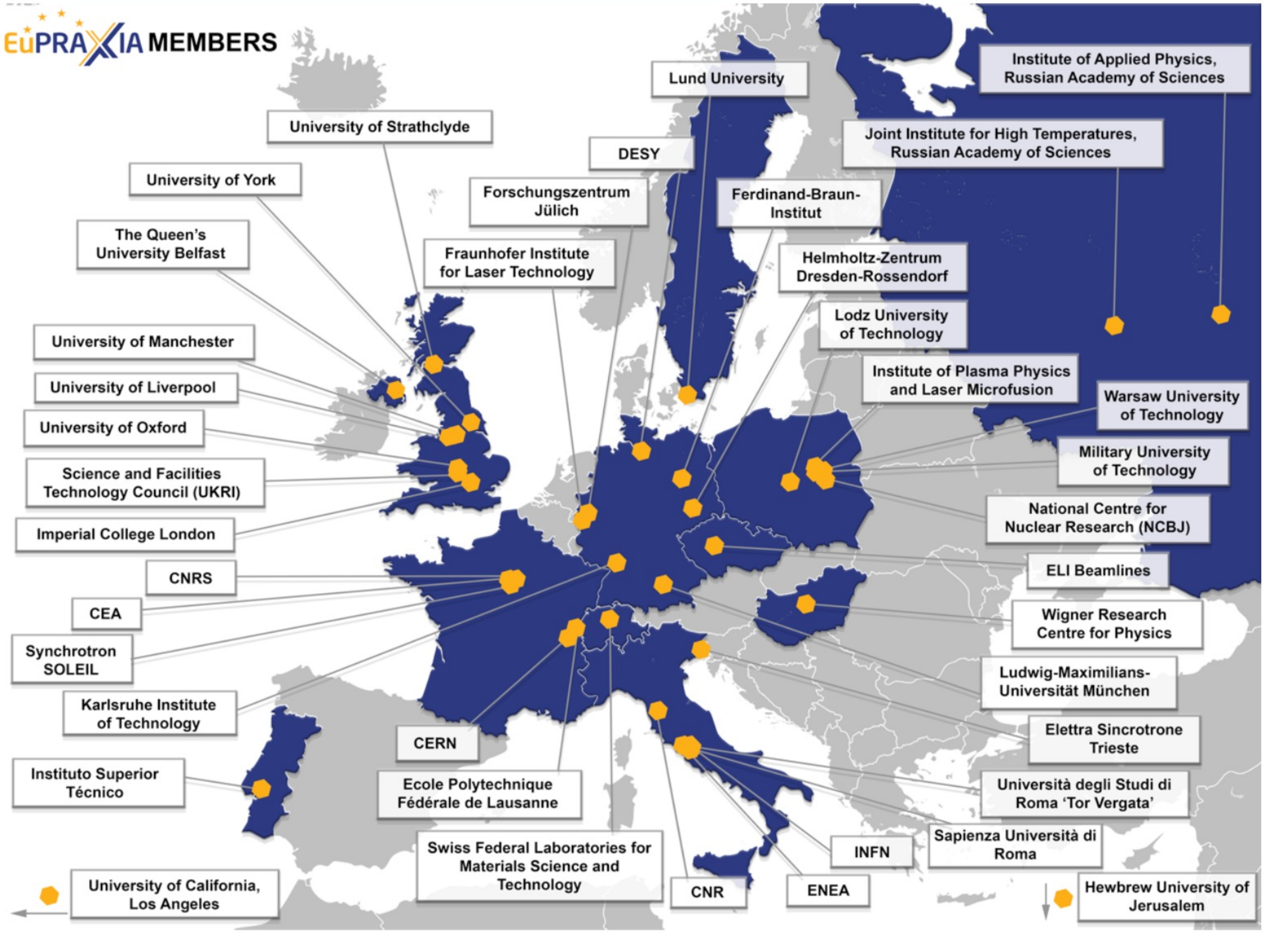

***About the ESFRI Roadmap***

*ESFRI has established a European Roadmap for Research Infrastructures (new and major upgrades, pan-European interest) for the next 10-20 years, stimulates the implementation of these facilities, and updates the roadmap as needed. The ESFRI Roadmap arguably contains the best European science facilities based on a thorough evaluation and selection procedure. It combines ESFRI Projects, which are new Research Infrastructures in progress towards implementation, and ESFRI Landmarks successfully implemented Research Infrastructures enabling excellent science.*

# The Consortium Members for the Next Phase

*(from 16 to 40)*

Horizon 2020



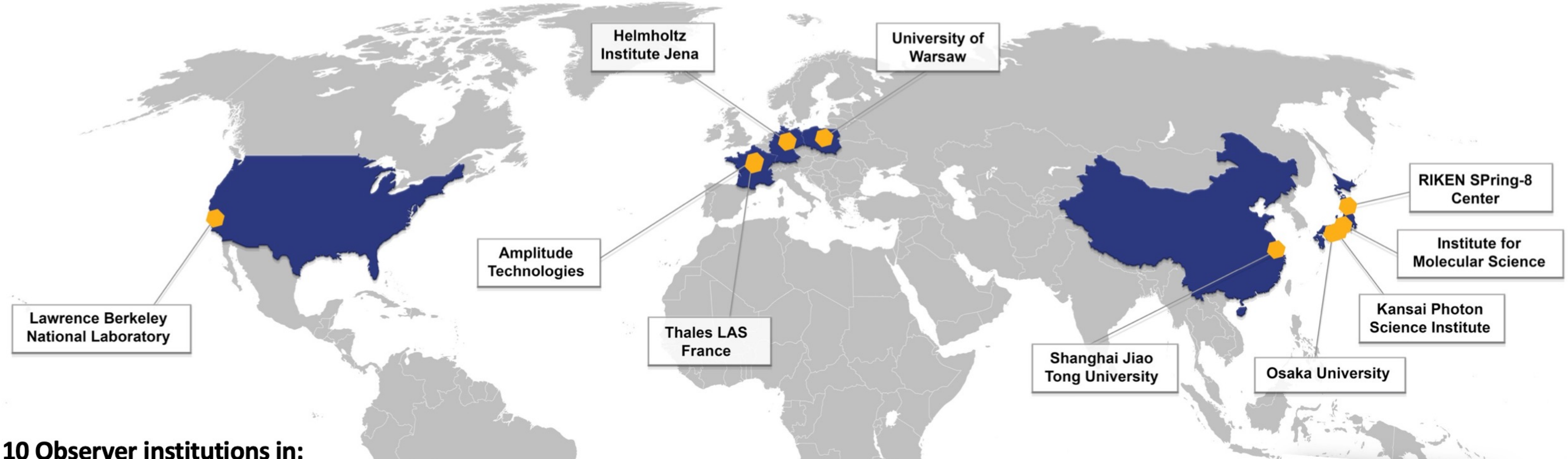

## 40 Member institutions in:

- **Italy** (INFN, CNR, Elettra, ENEA, Sapienza Università di Roma, Università degli Studi di Roma "Tor Vergata")
- **France** (CEA, SOLEIL, CNRS)
- **Switzerland** (EMPA, Ecole Polytechnique Fédérale de Lausanne)
- **Germany** (DESY, Ferdinand-Braun-Institut, Fraunhofer Institute for Laser Technology, Forschungszentrum Jülich, HZDR, KIT, LMU München)
- **United Kingdom** (Imperial College London, Queen's University of Belfast, STFC, University of Liverpool, University of Manchester, University of Oxford, University of Strathclyde, University of York)
- **Poland** (Institute of Plasma Physics and Laser Microfusion, Lodz University of Technology, Military University of Technology, NCBJ, Warsaw University of Technology)
- **Portugal** (IST)
- **Hungary** (Wigner Research Centre for Physics)
- **Sweden** (Lund University)
- **Israel** (Hebrew University of Jerusalem)
- **Russia** (Institute of Applied Physics, Joint Institute for High Temperatures)
- ***United States*** (UCLA)
- **CERN**
- **ELI Beamlines**

# The Consortium Observers for the Next Phase

*(from 25 to 10, Consortium Agreement signed)*

Horizon 2020




**10 Observer institutions in:**

- **France** (Amplitude Technologies, Thales LAS France SAS)
- **Germany** (Helmholtz-Institut Jena)
- **Poland** (University of Warsaw)
- **United States** (LBNL)
- **China** (Shanghai Jiao Tong University)
- **Japan** (Institute for Molecular Science, Osaka University, Kansai Photon Science Institute, RIKEN SPring-8 Center)

EuPRAXIA OBSERVERS


Consortium Agreement
between research institutions and organisations

# Location of possible sites within EU

Horizon 2020

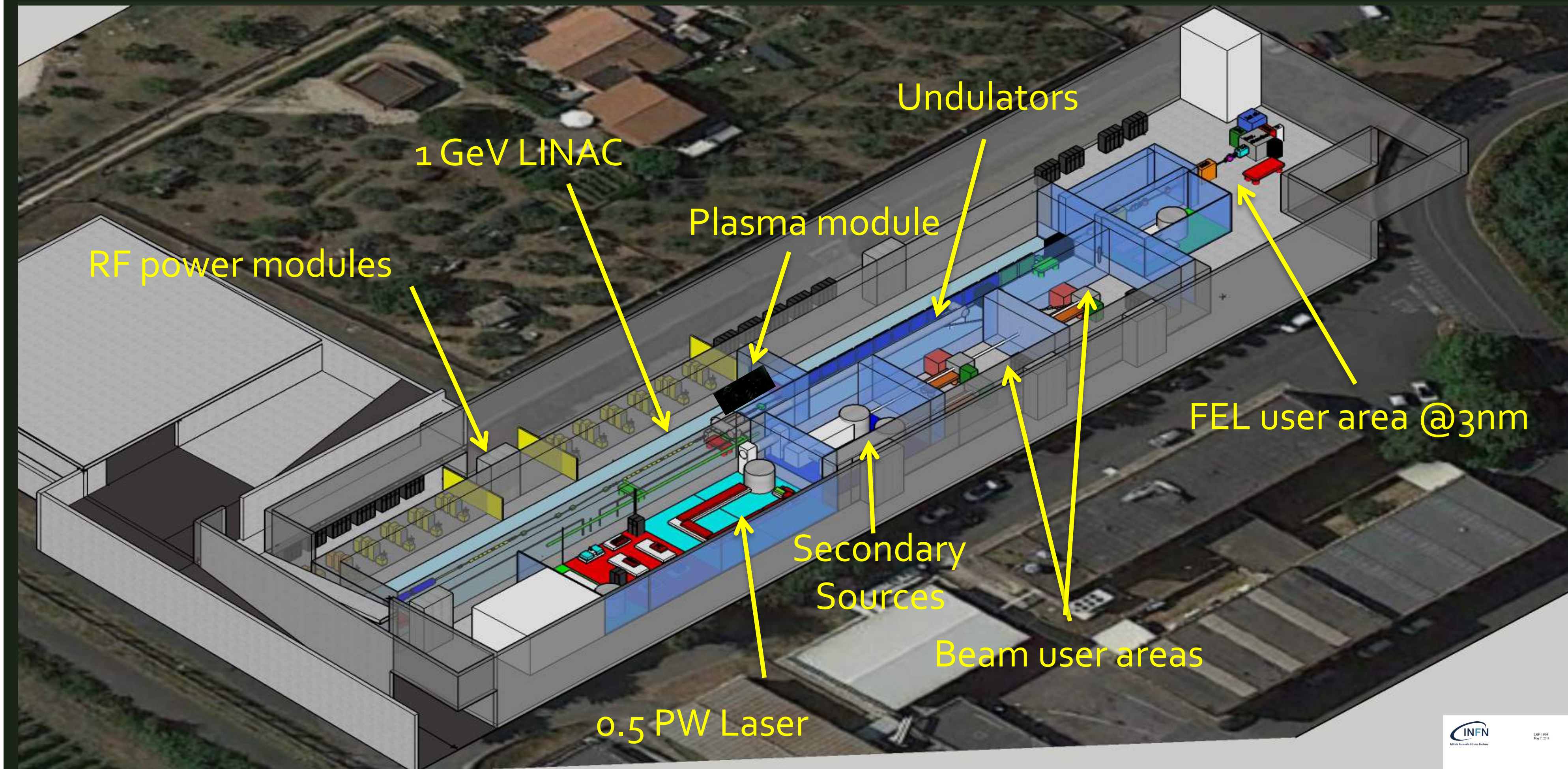
**EuPRAXIA site studies**:

- Design study is site independent
- Five possible sites have been discussed so far
- We invite the suggestions of additional sites





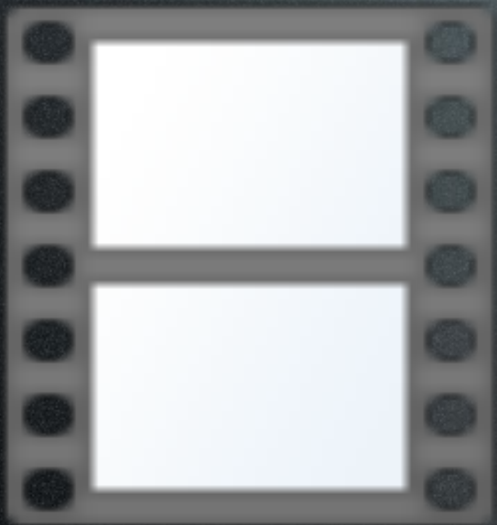

# EuPRAXIA@SPARC_LAB

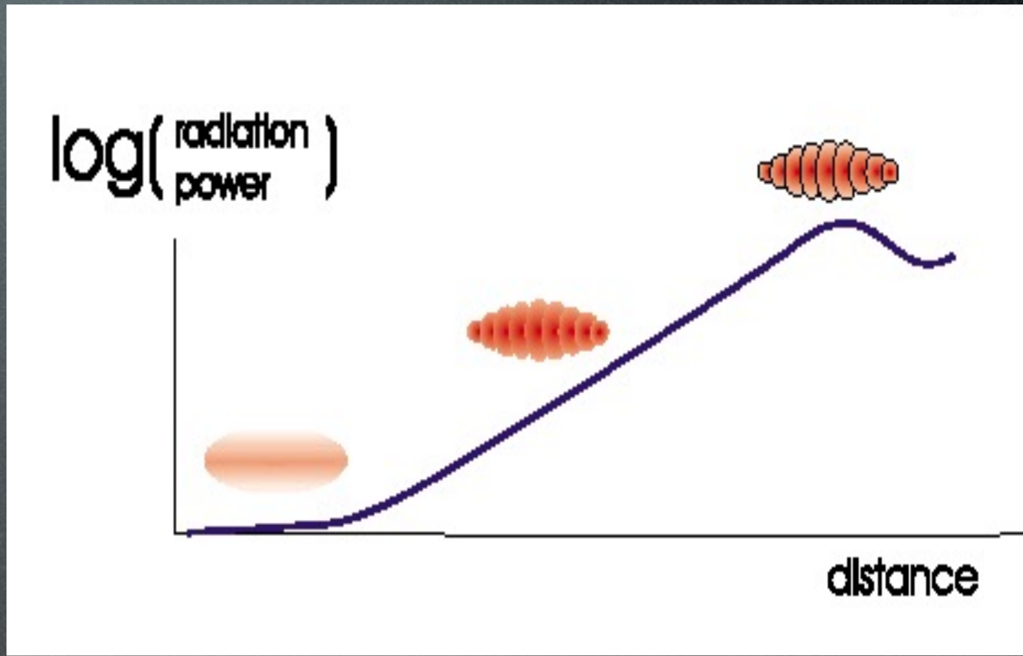




http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

## A Free Electron Laser is a device that converts a fraction of the electron kinetic energy into coherent radiation via a collective instability in a long undulator



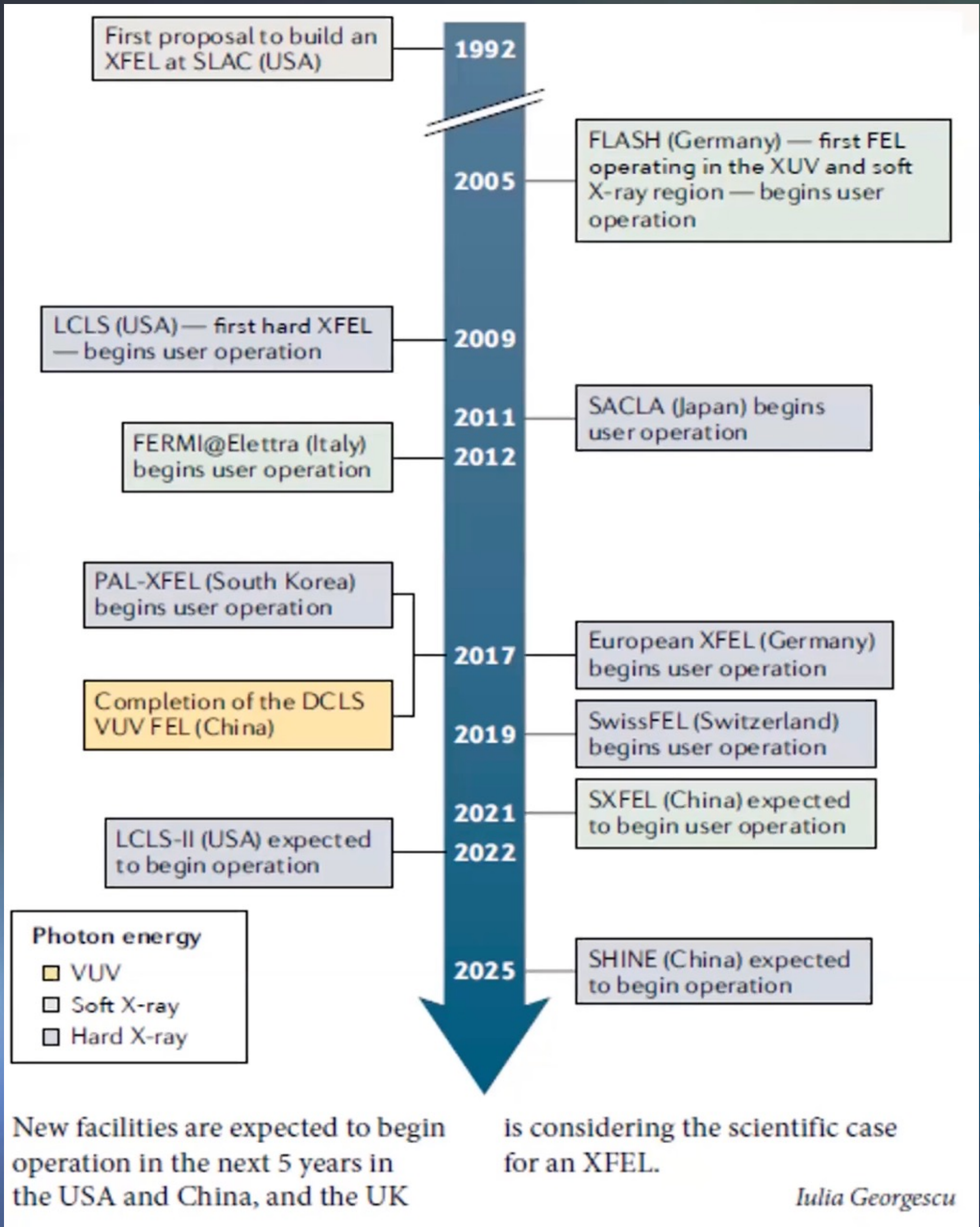


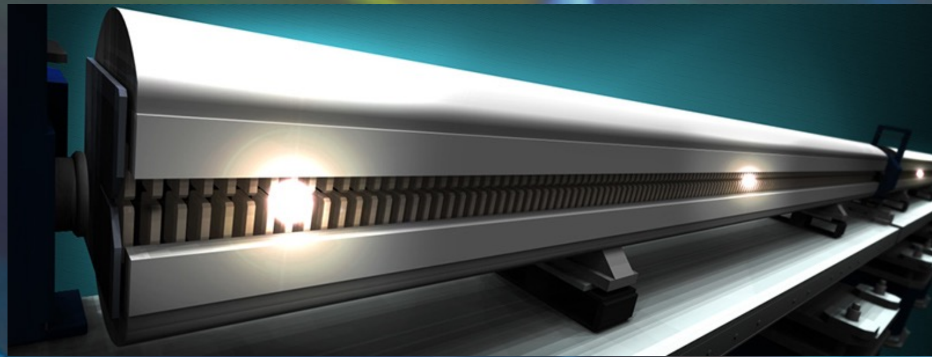

$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\vartheta^2\right)$$

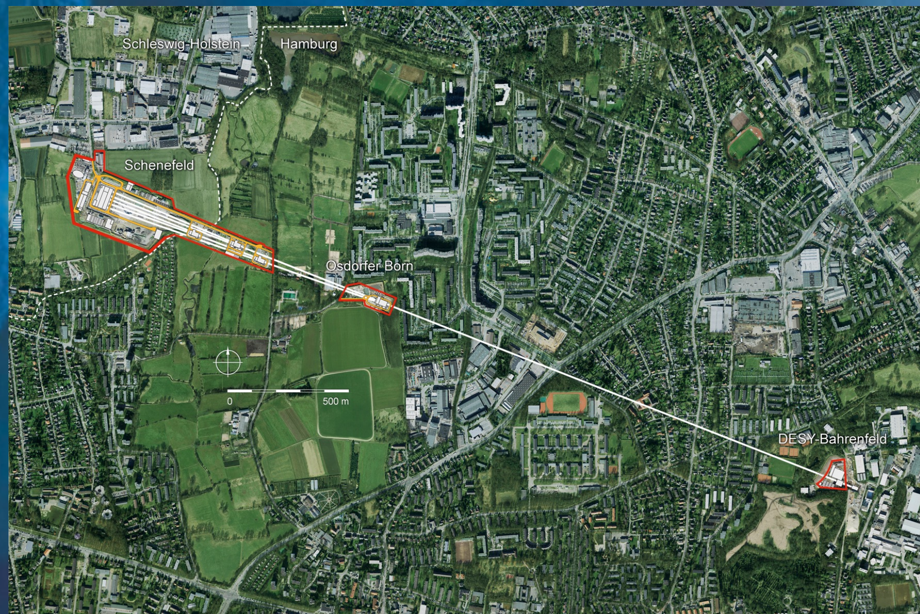
**(Tunability - Harmonics)**

# FEL is a well established technology

(But a widespread use of FEL is partially limited by its size and costs)





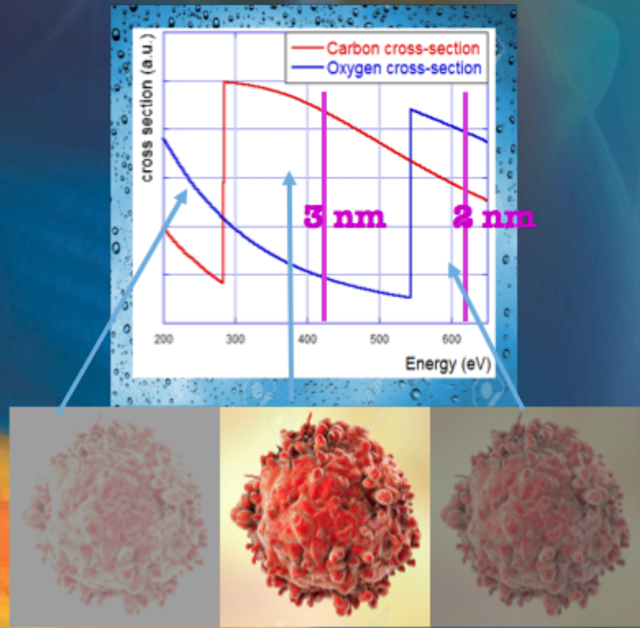
# Expected SASE FEL performances



| | Units | Full RF case | Plasma case |
|---|---|---|---|
| Electron Energy | GeV | 1 | 1 |
| Bunch Charge | pC | 200 | 30 |
| Peak Current | kA | 2 | 3 |
| RMS Energy Spread | % | 0.1 | 1 |
| RMS Bunch Length | fs | 40 | 4 |
| RMS matched Bunch Spot | µm | 34 | 34 |
| RMS norm. Emittance | µm | 1 | 1 |
| Slice length | µm | 0.5 | 0.45 |
| Slice Energy Spread | % | 0.01 | 0.1 |
| Slice norm. Emittance | µm | 0.5 | 0.5 |
| Undulator Period | mm | 15 | 15 |
| Undulator Strength $K$ | | 1.03 | 1.03 |
| Undulator Length | m | 12 | 14 |
| Gain Length | m | 0.46 | 0.5 |
| Pierce Parameter $\rho$ | x $10^{-3}$ | 1.5 | 1.4 |
| Radiation Wavelength | nm | 3 | 3 |
| Undulator matching $\beta_u$ | m | 4.5 | 4.5 |
| Saturation Active Length | m | 10 | 11 |
| Saturation Power | GW | 4 | 5.89 |
| Energy per pulse | µJ | 83.8 | 11.7 |
| Photons per pulse | x $10^{11}$ | 11 | 1.5 |

Table 2.1: Beam parameters for the EuPRAXIA@SPARC_LAB FEL driven by X-band linac or Plasma acceleration

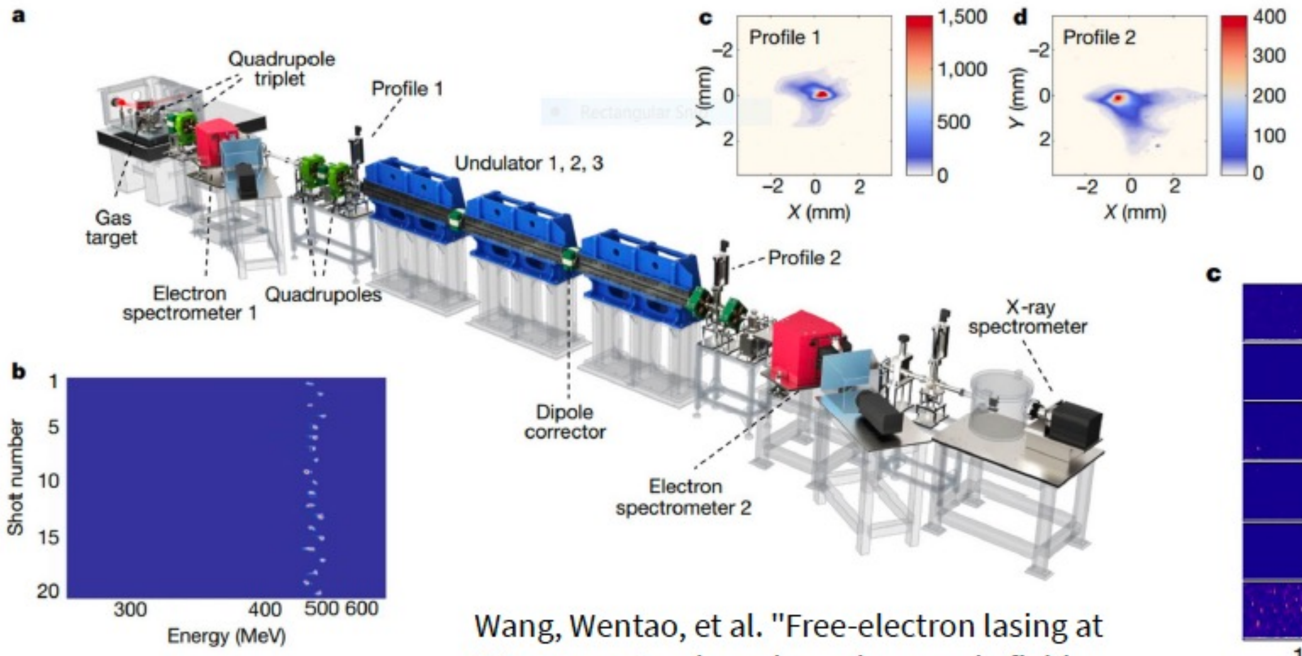
In the Energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV) water is almost transparent to radiation while nitrogen and carbon are absorbing (and scattering)

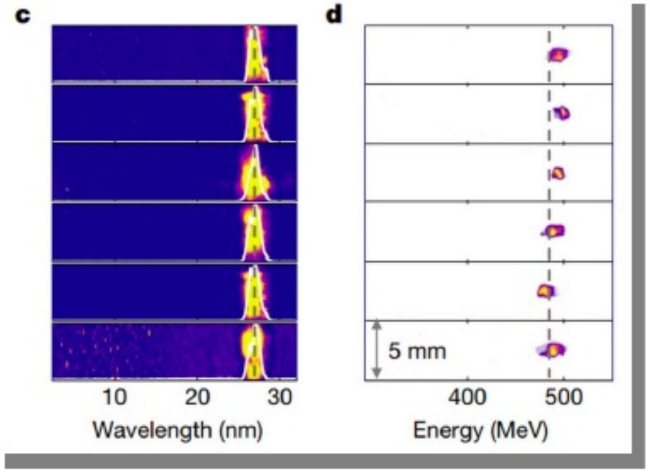



**Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state**
**Possibility to study dynamics**
**~$10^{11}$ photons/pulse needed**

Courtesy F. Stellato, UniToV

# First Lasing with LWFA at SIOM




Wang, Wentao, et al. "Free-electron lasing at 27 nanometres based on a laser wakefield accelerator." Nature 595.7868 (2021): 516-520.

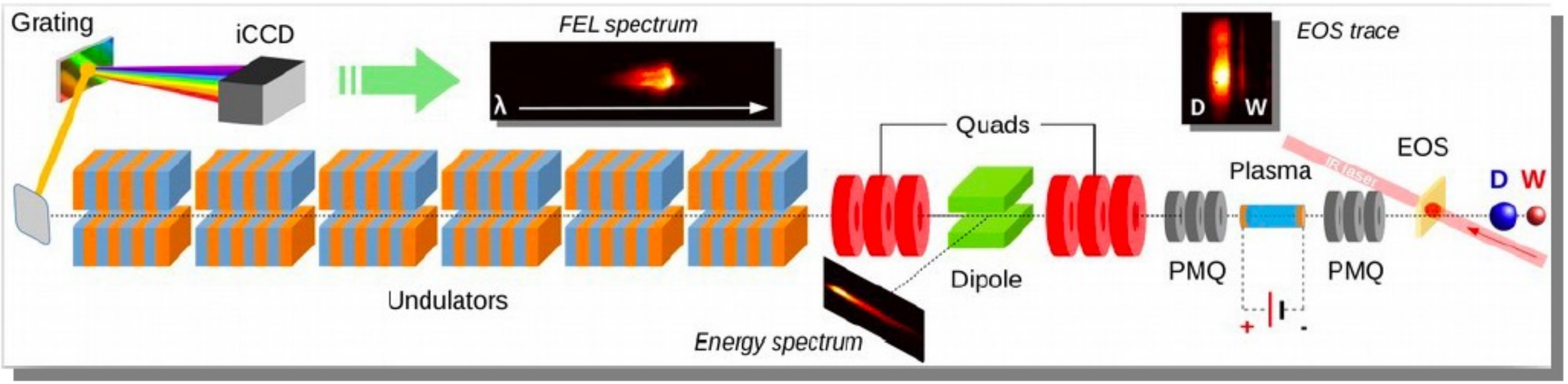
## Observation of FEL radiation @ 27 nm using LWFA

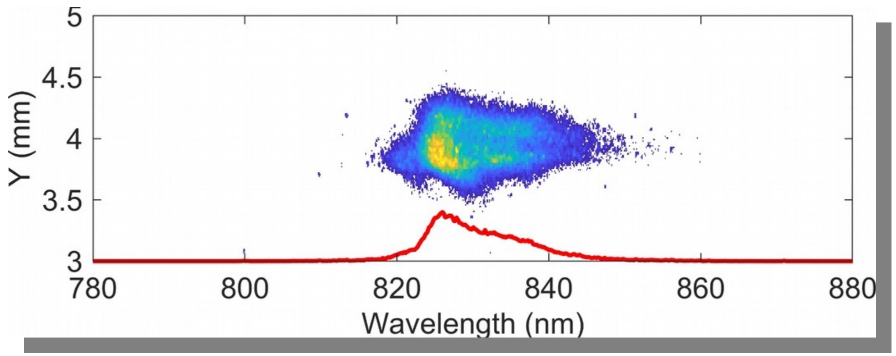
*Electron beam generated from a 200 TW (I~4x$10^{18}$ W/$cm^2$) laser focused on a gas-jet*

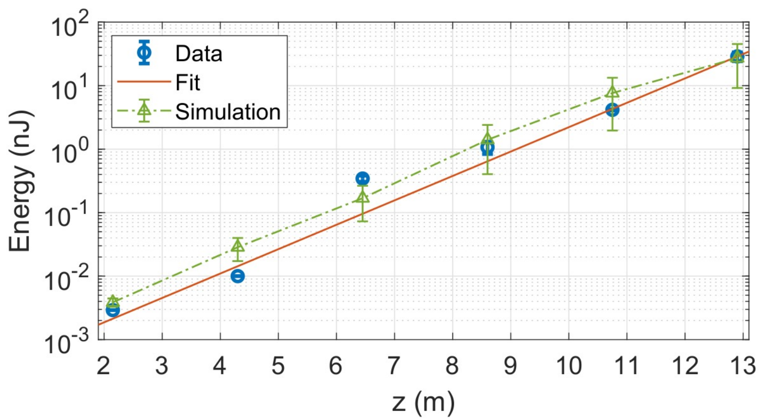
*Peak energy ~ 490 MeV, 0.5% spread (measured), emittance 0.5 um (estimated)*

*Radiation energy from 0.5 to 150 nJ*

# First Beam Driven SASE-FEL Lasing at SPARC_LAB (May 2021)




Submitted to Nature

# 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 and 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..**
- **➔ PILOT USER FACILITIES Under Constraction**