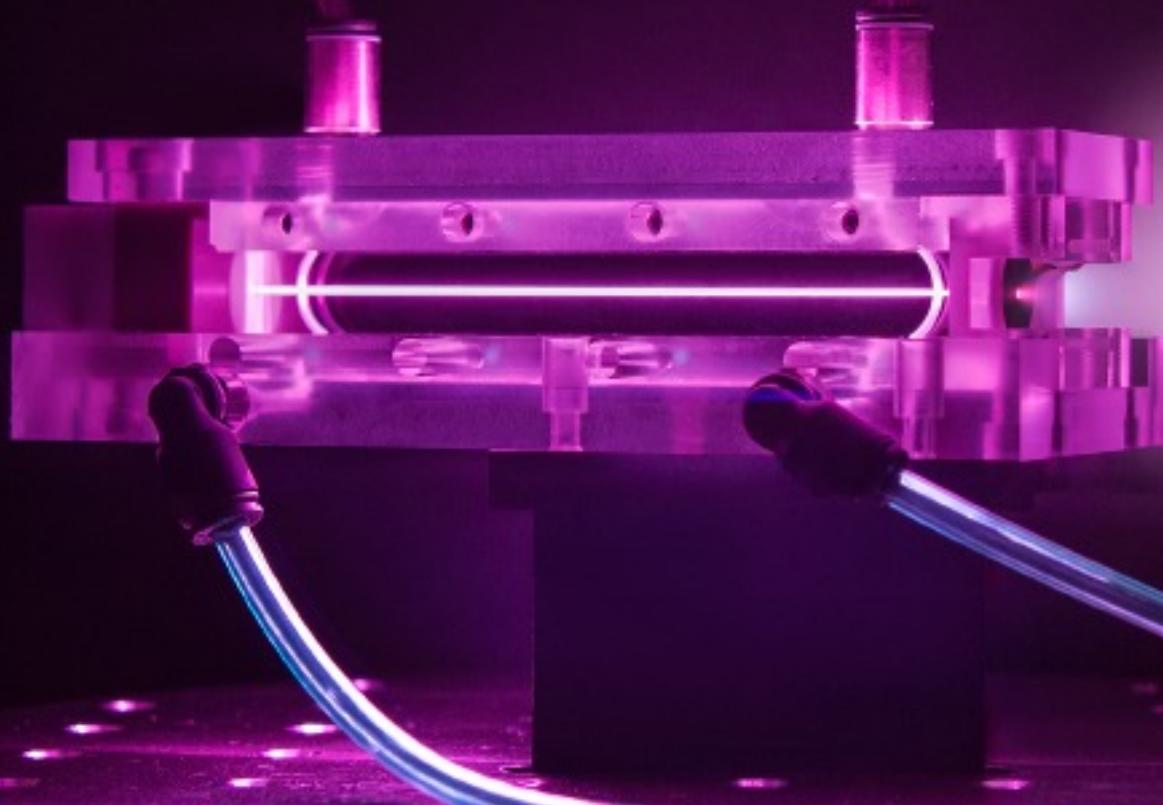


Advanced Accelerator Concepts

Massimo.Ferrario@lnf.infn.it

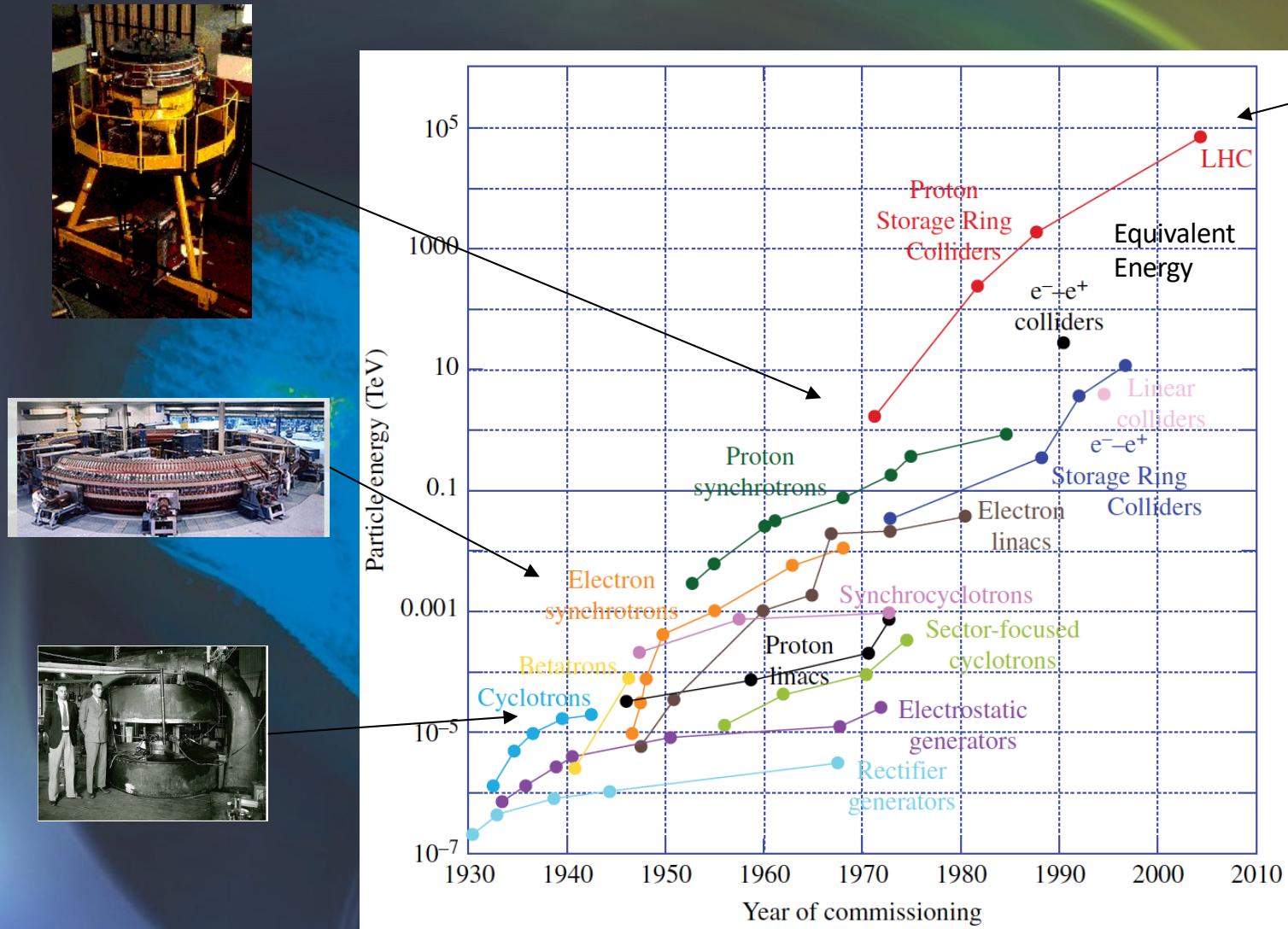


Introduction to Accelerator Physics

Kaunas – 29 Sept. 2022



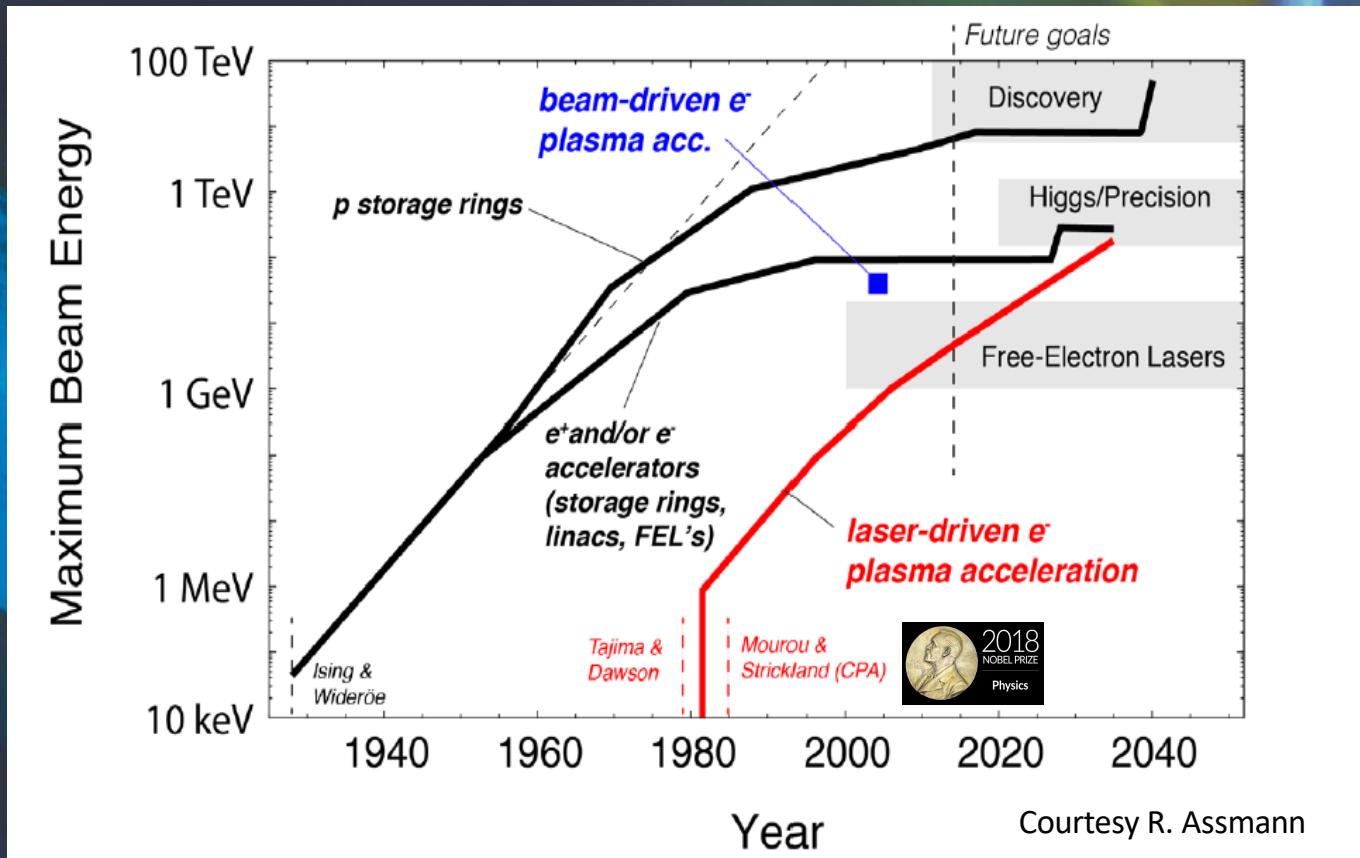
The Livingstone Diagram



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.

Advanced Accelerator Concepts

Massimo.Ferrario@lnf.infn.it



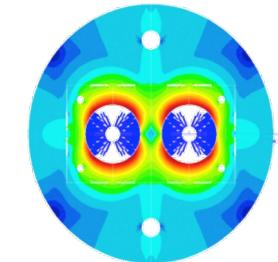
Options towards higher energies

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)



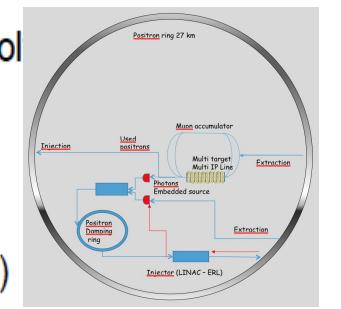
Lepton (e-,e+) circular collider

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

Increase mass of acc. particle (muon)

Increase supplied RF vol
(FCC-ee)

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



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



-Small spot size => low emittance

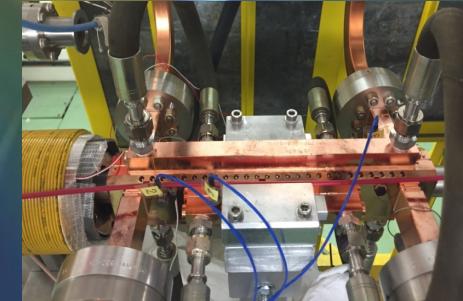
-Short pulse (ps => fs)

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

High Gradient Options

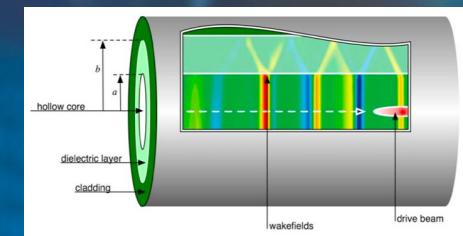
Metallic accelerating structures =>

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



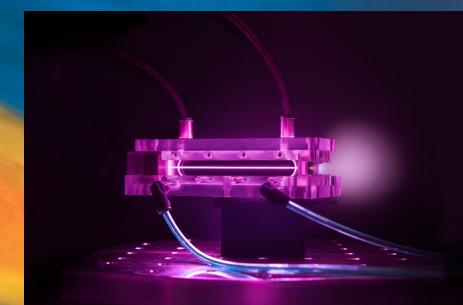
Dielectric structures, laser or particle driven =>

$$E_{\text{acc}} < 10 \text{ GV/m}$$



Plasma accelerator, laser or particle driven =>

$$E_{\text{acc}} < 100 \text{ GV/m}$$



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

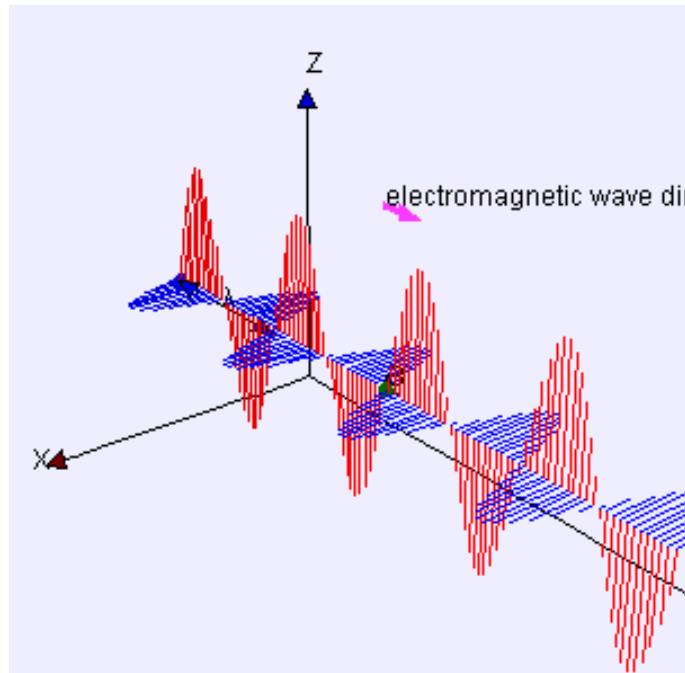
Lawson-Woodward Theorem

(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.

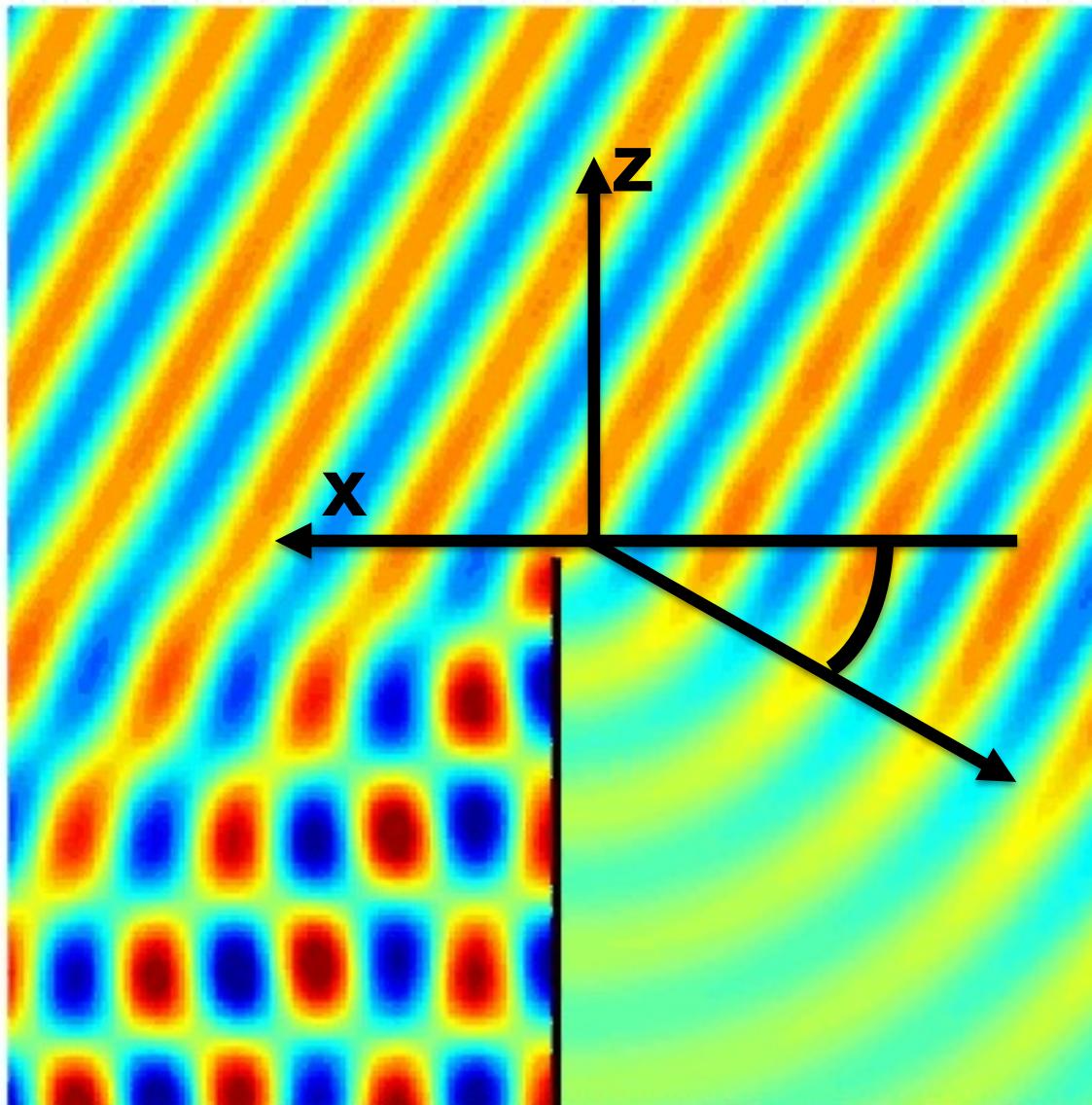
The theorem assumes that

- (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,



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

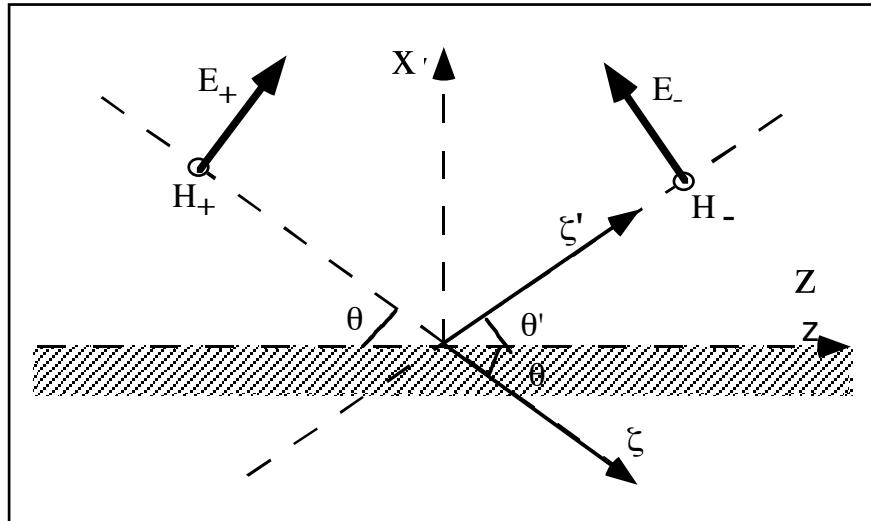
Reflection of plane waves



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:

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

$$\xi = z \cos \theta - x \sin \theta \quad \xi' = z \cos \theta' + x \sin \theta'$$

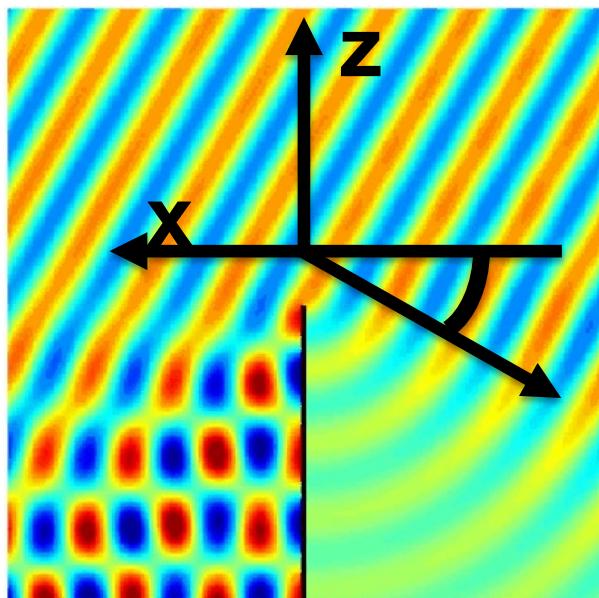
And it has to fulfill the boundary conditions: (no tangential E-field on the surface of the conducting plane)

Reflection of plane waves (a first boundary value problem)

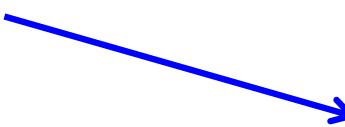
Taking into account the boundary conditions the longitudinal component of the field becomes:

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

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

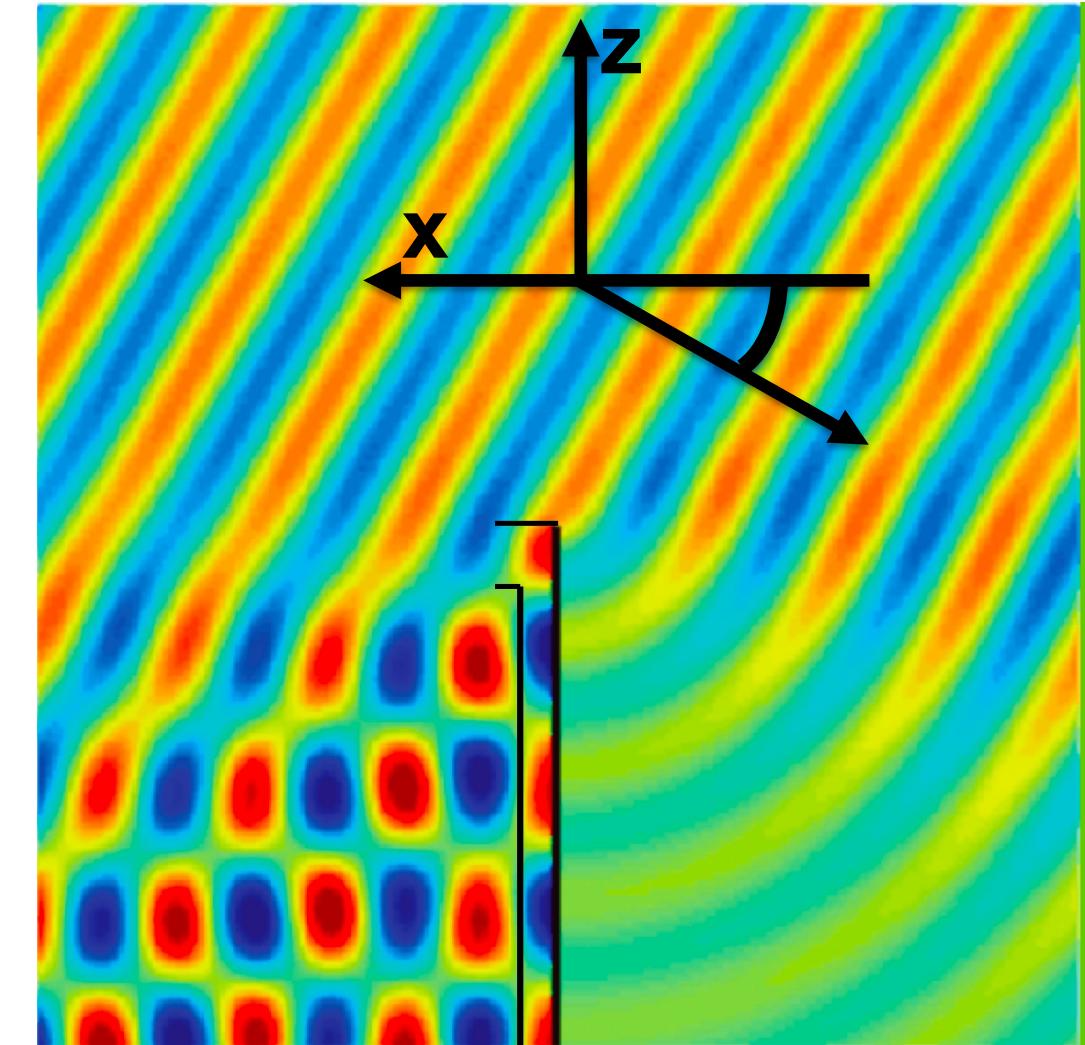


Standing Wave
pattern (along x)



Guided wave
pattern (along z)

From reflections to waveguides



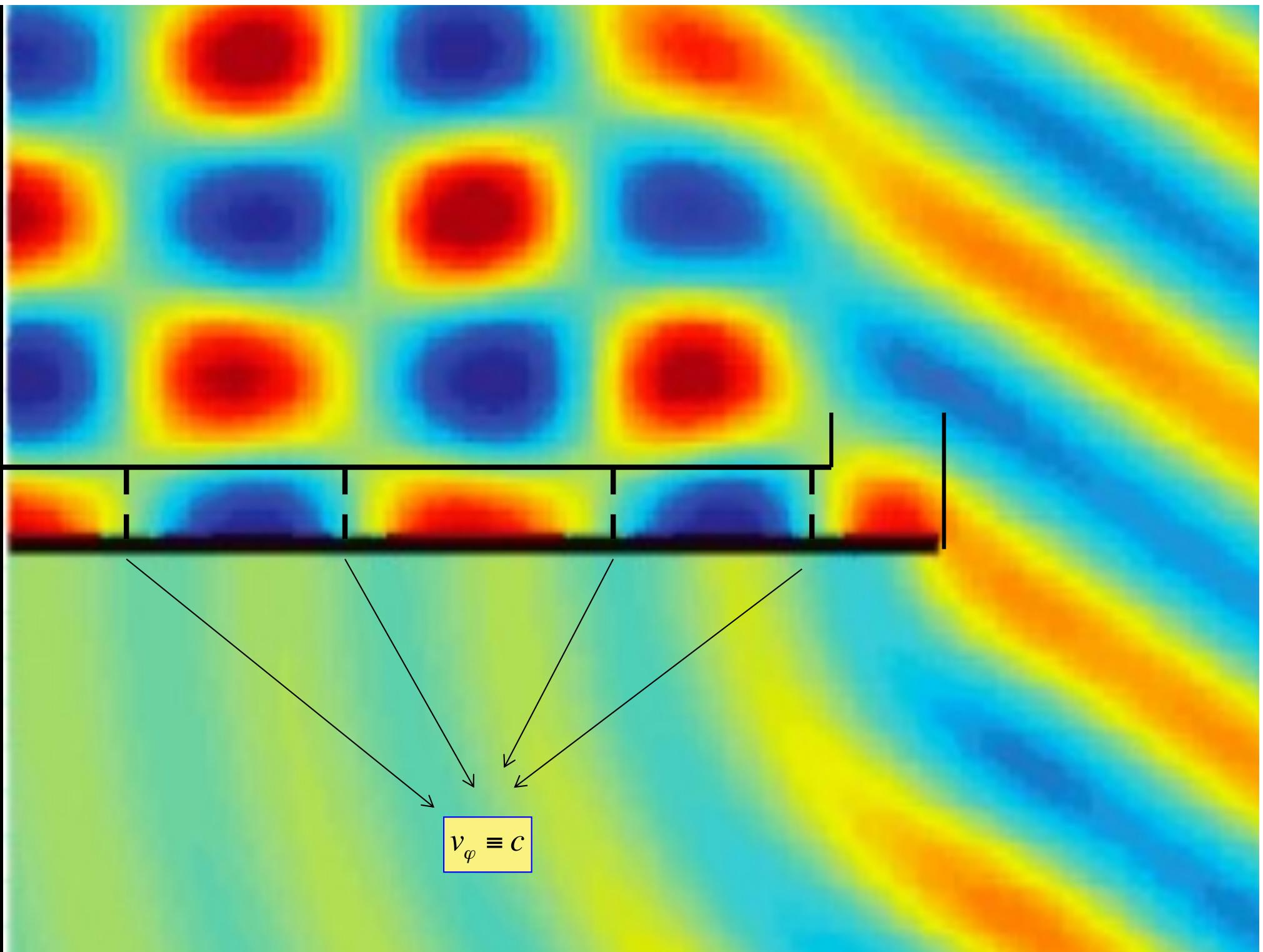
Put a metallic boundary where the field is zero at a given distance from the wall.

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

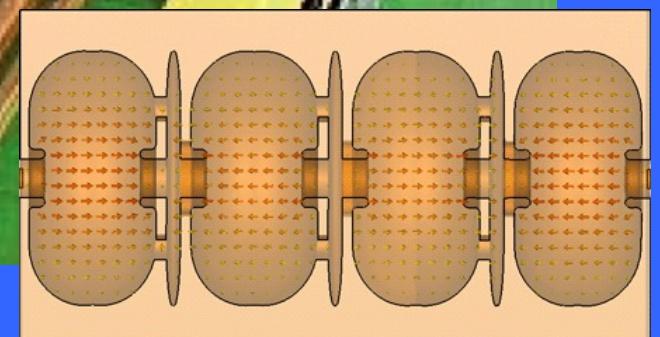
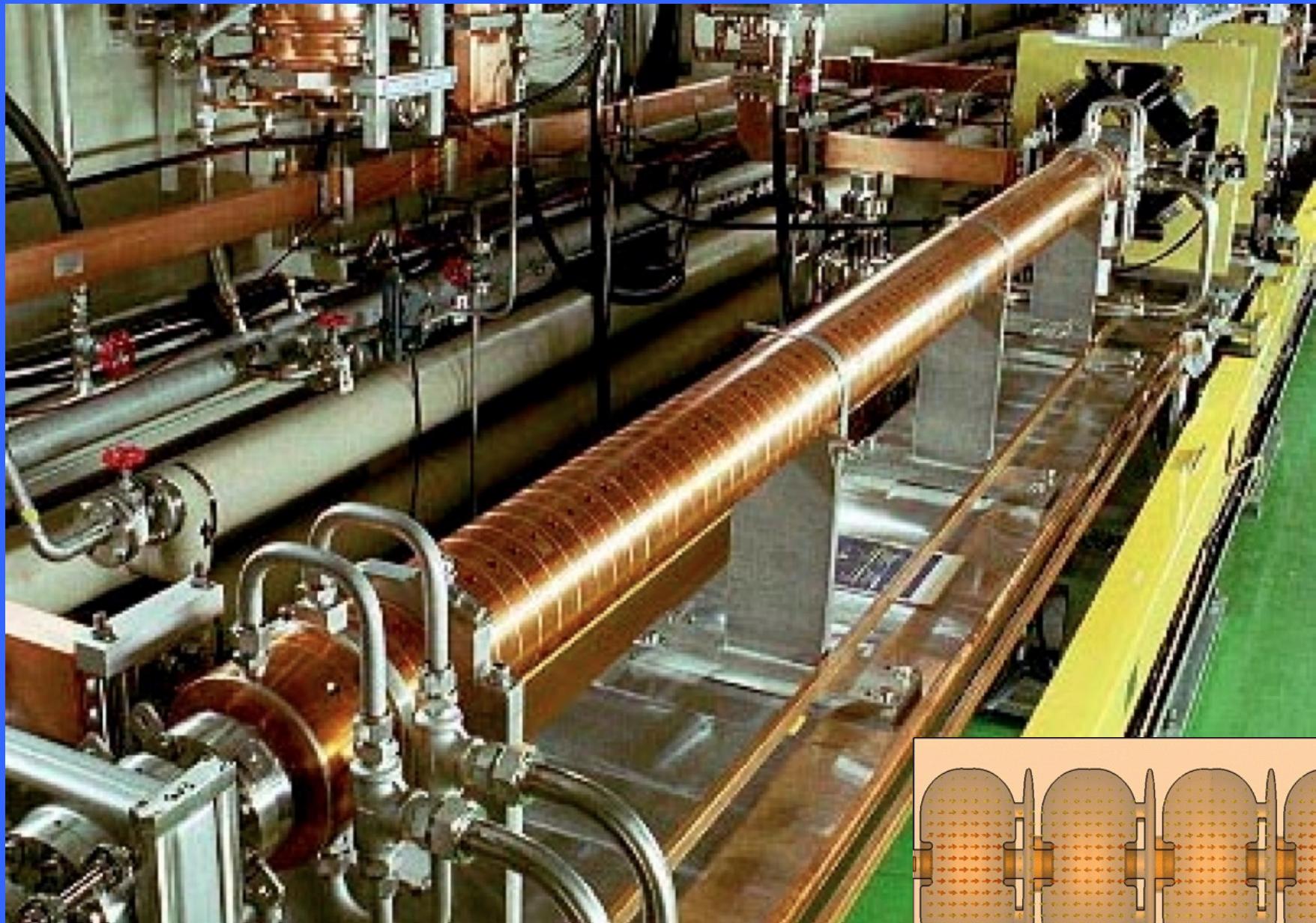
For a given distance, there is a maximum wavelength, i.e. there is **cut-off frequency**.

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

It can not be used as it is for particle acceleration

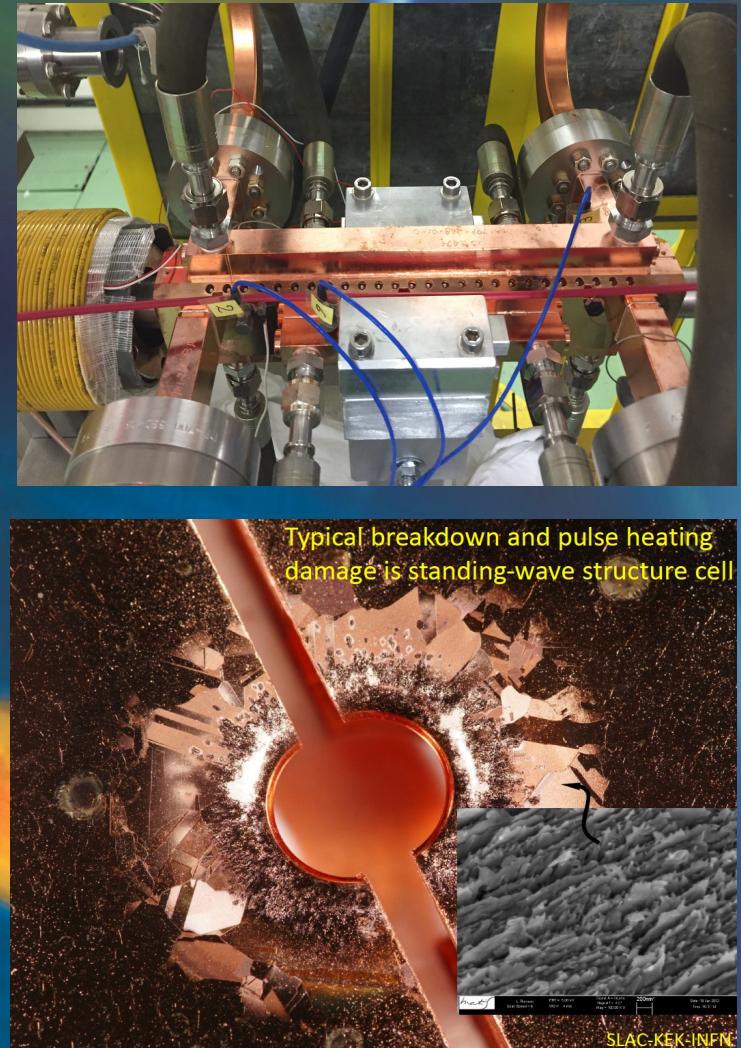
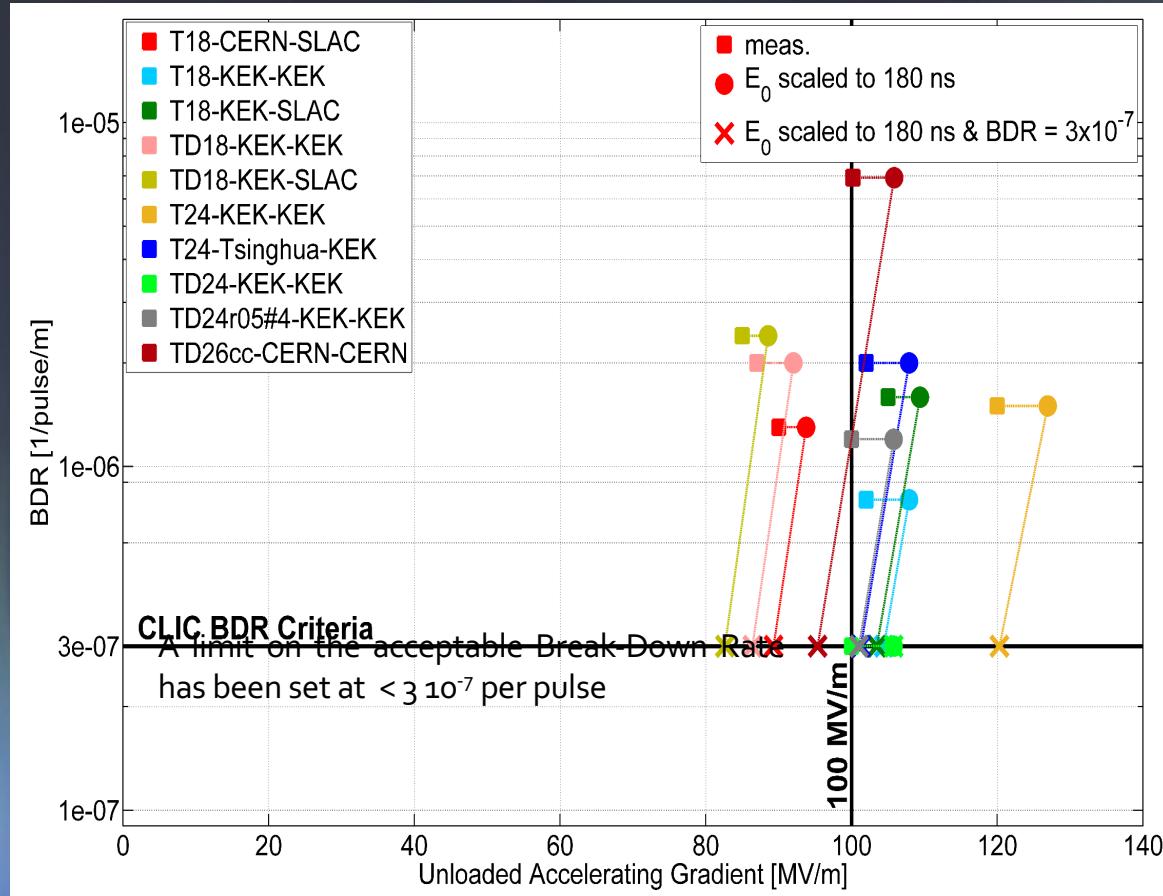


Conventional RF accelerating structures



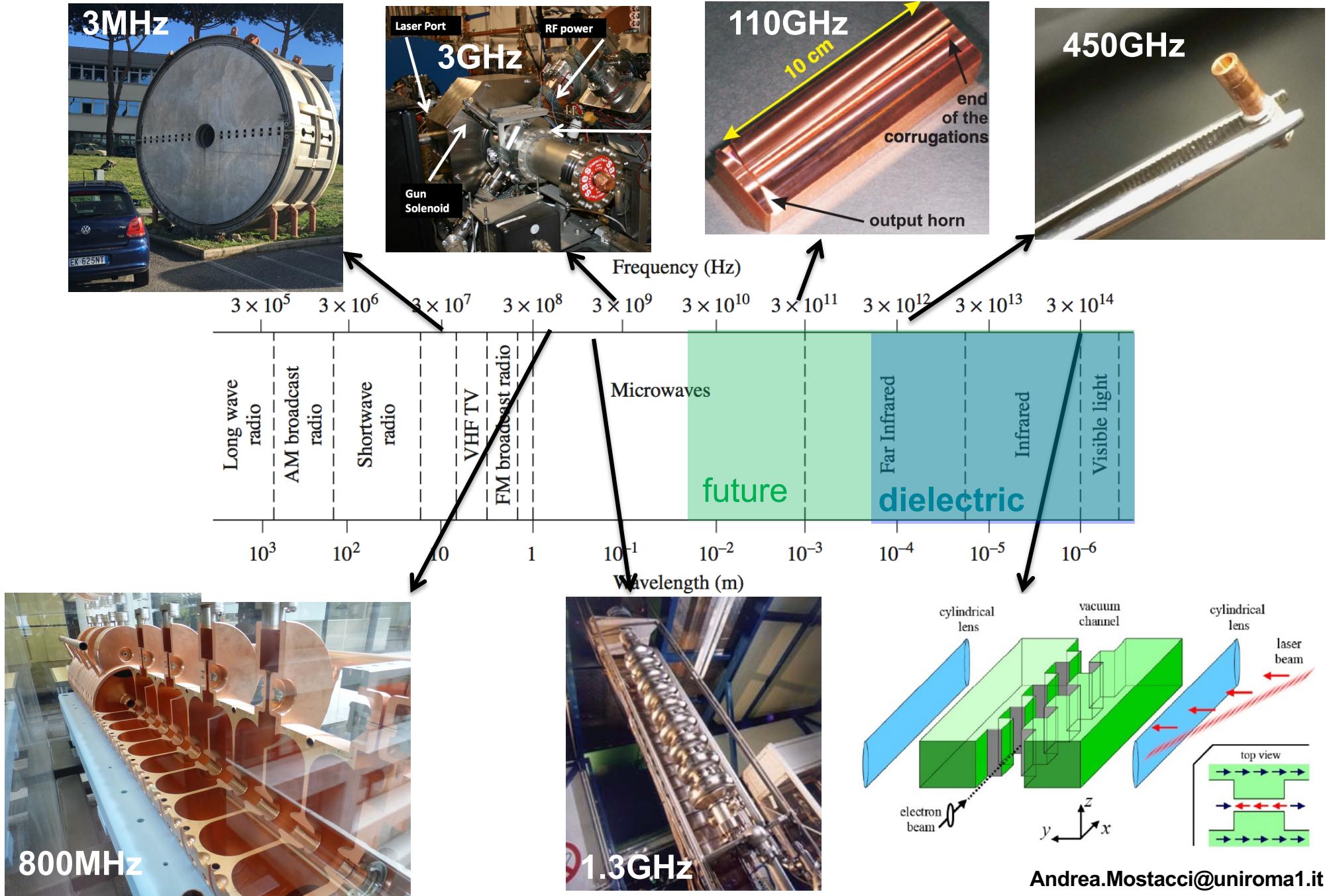
X-band RF structures – State of the Art

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

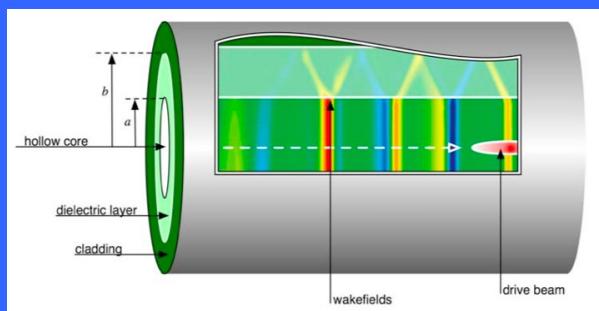
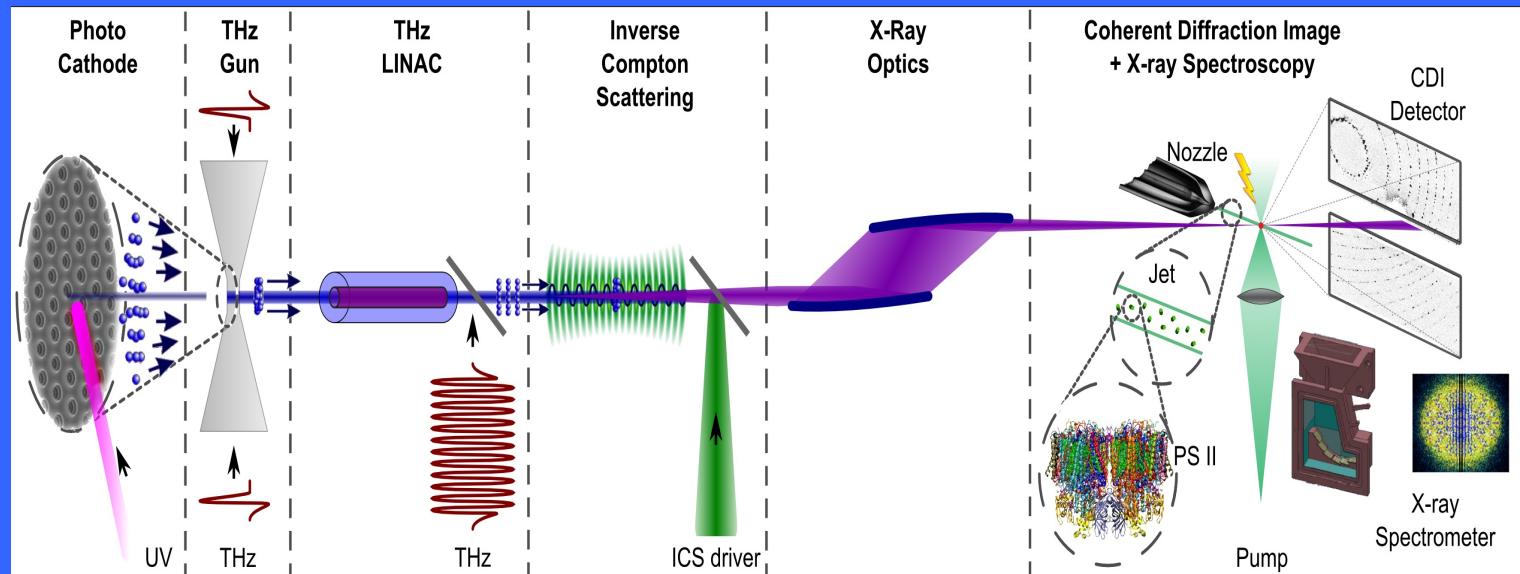


Dielectric Structures



Attoseconds X-ray Science Imaging and Spectroscopy

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



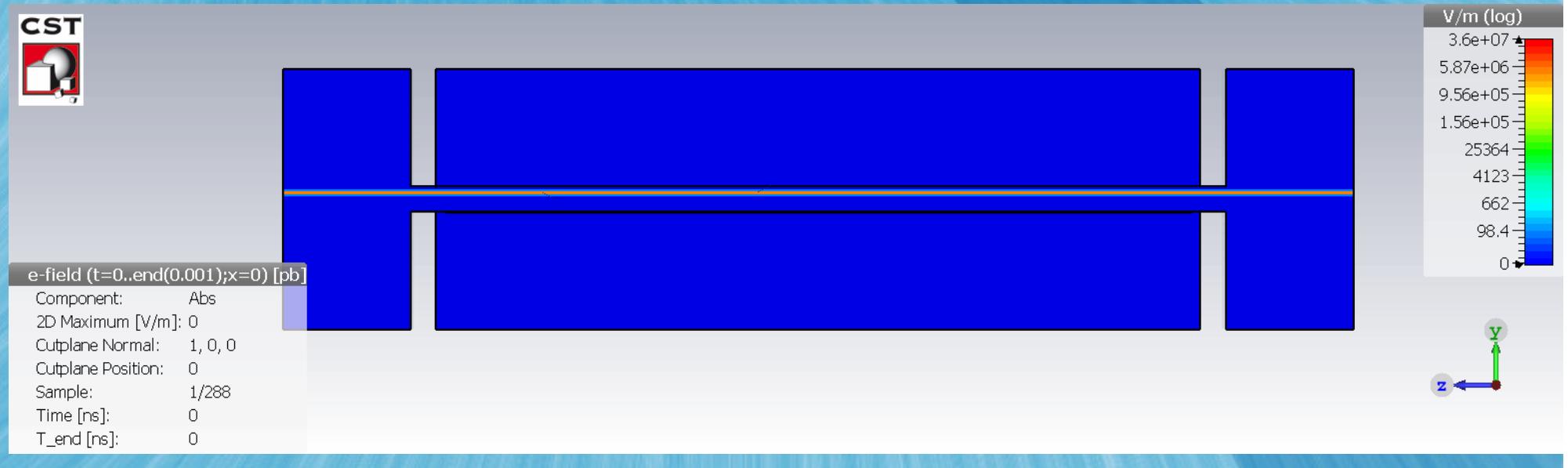
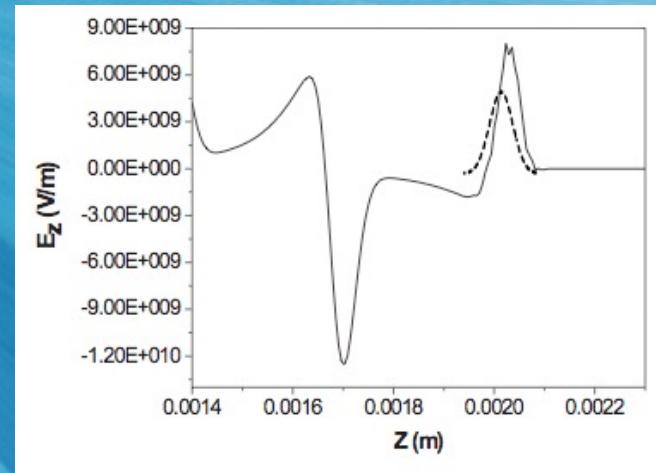
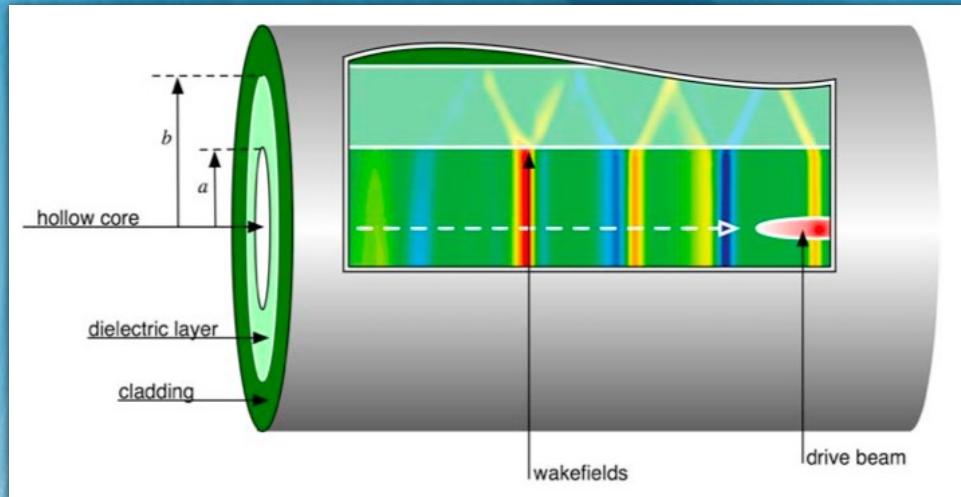
All laser driven => intrinsic attosecond synchr.,
1 Joule, 1 kHz Cryogenic Yb:YAG Laser
Laser-based THz generation
THz Linac, Optical undulator
Copper Inner Diameter = 940 μm
Fused Silica Inner Diameter = 400 μm

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

Dielectric Wakefield Acceleration

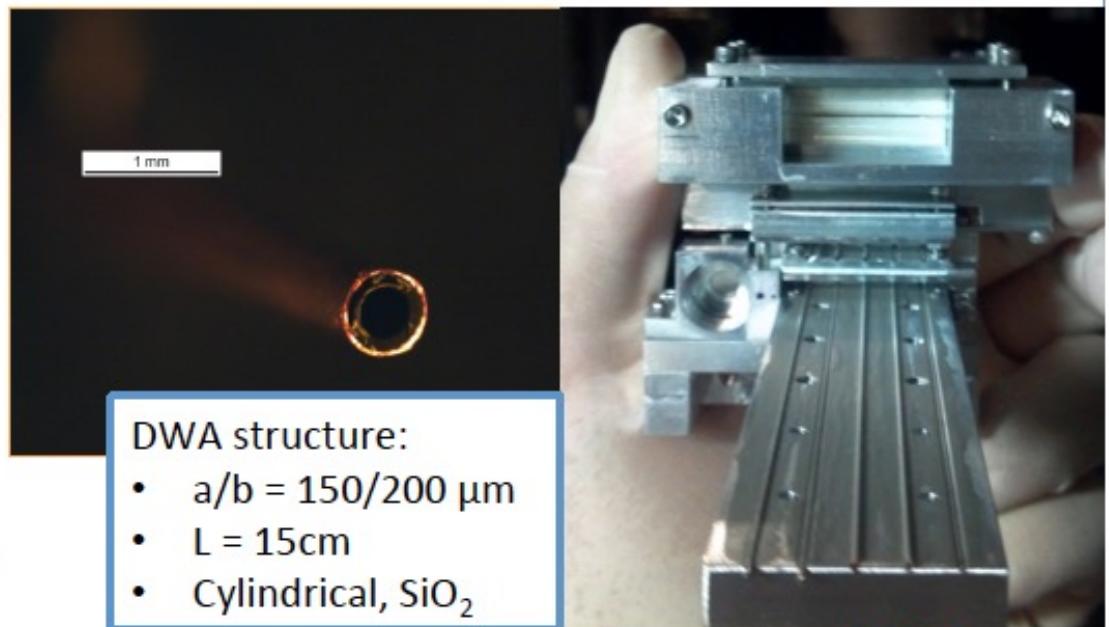
DWA

Dielectric Wakefield Accelerator



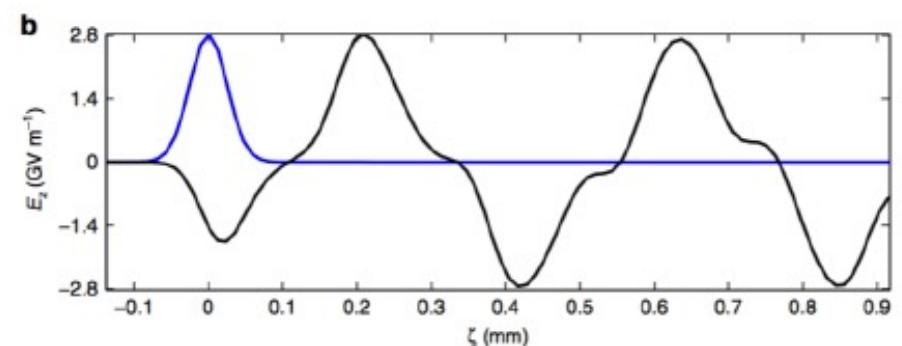
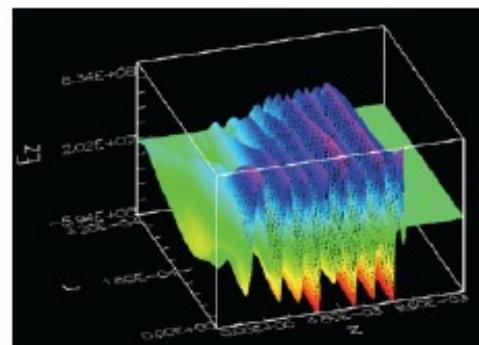
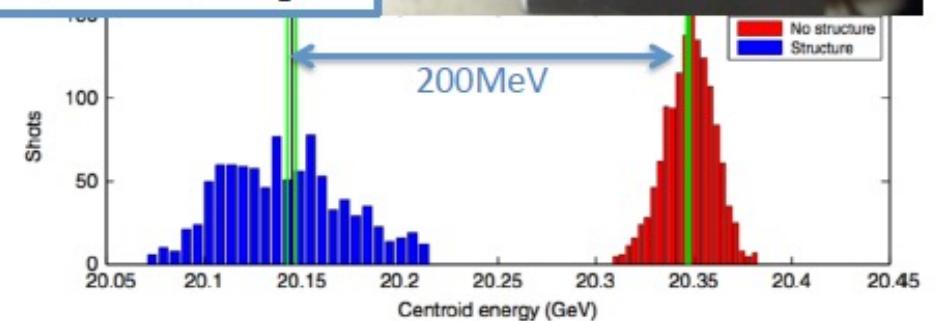
GV/m fields in DWA

- High-fields with small ID structures
 - Compressed beam ($<25\mu\text{m}$)
 - 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:

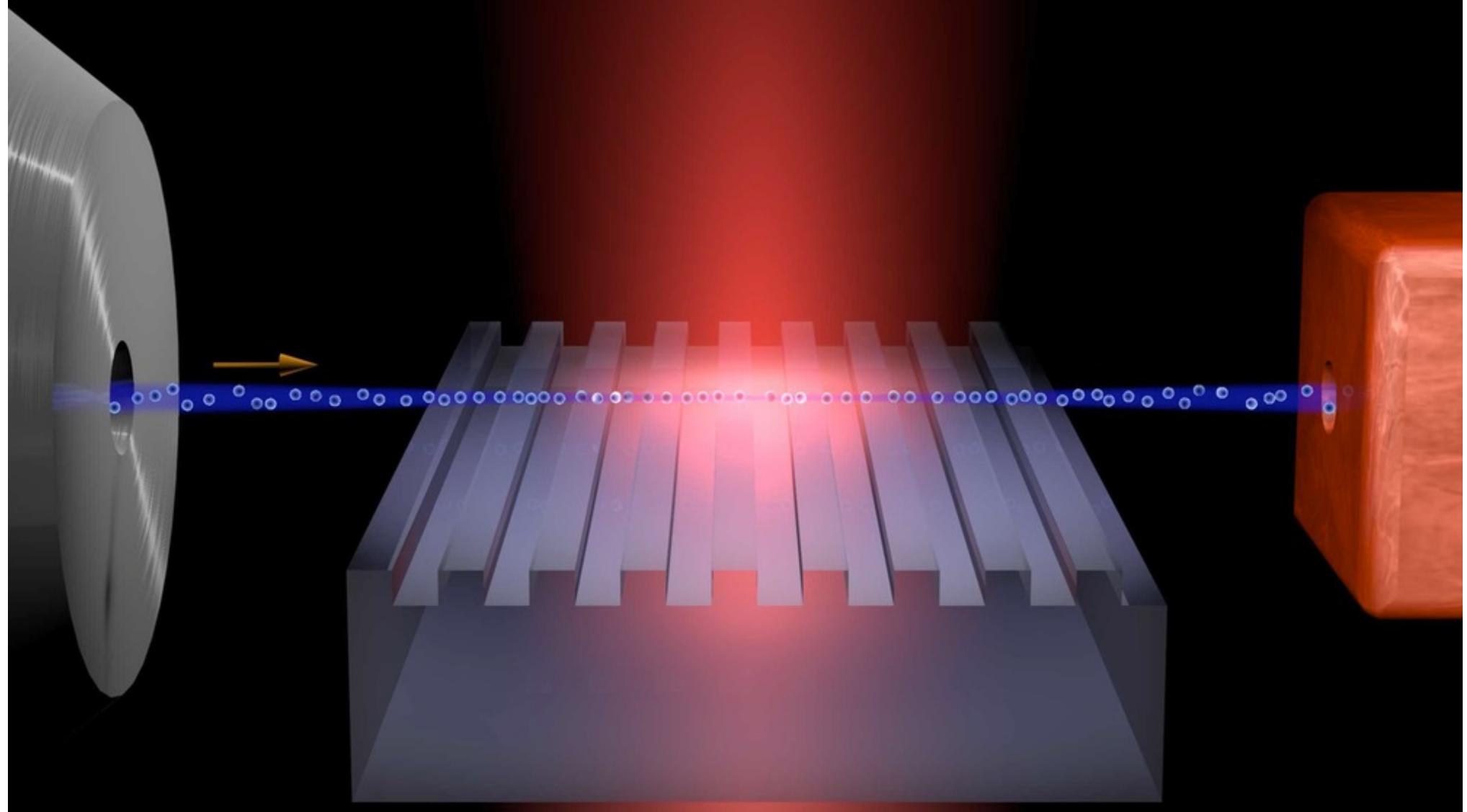
- $a/b = 150/200 \mu\text{m}$
- $L = 15\text{cm}$
- Cylindrical, SiO₂



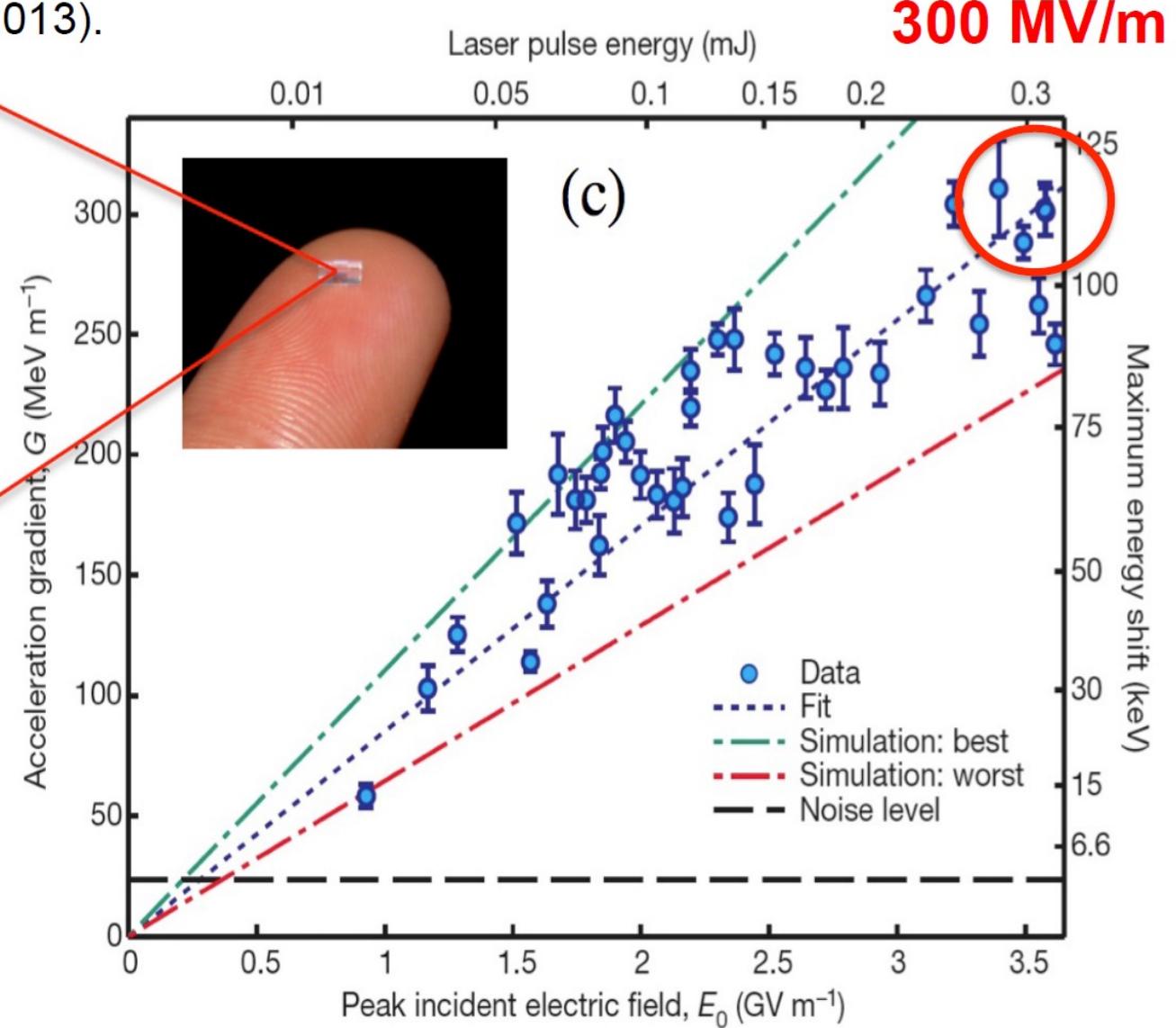
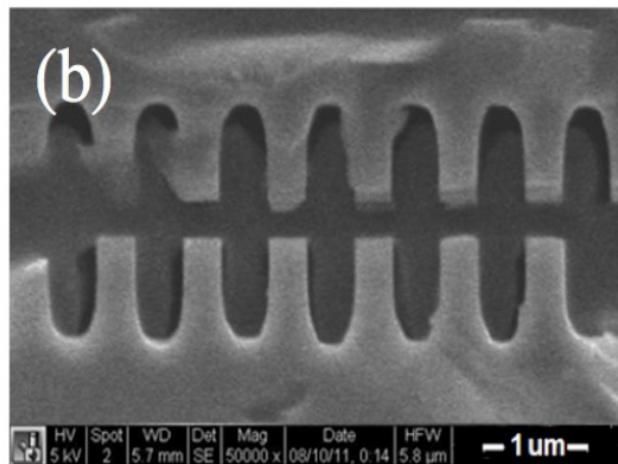
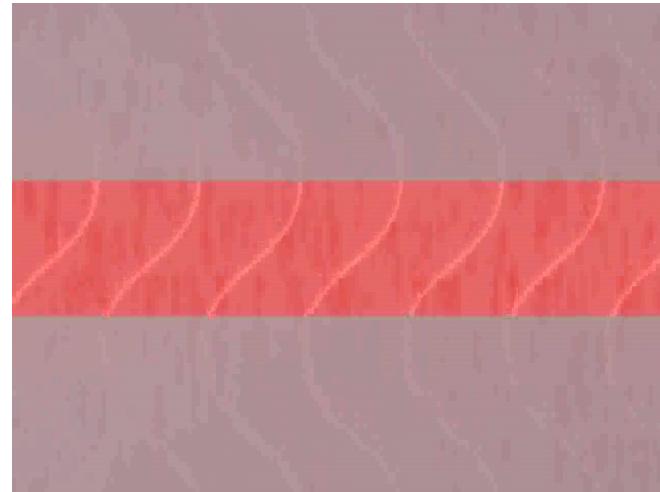
Dielectric Laser Acceleration

DLA

Laser based dielectric accelerator



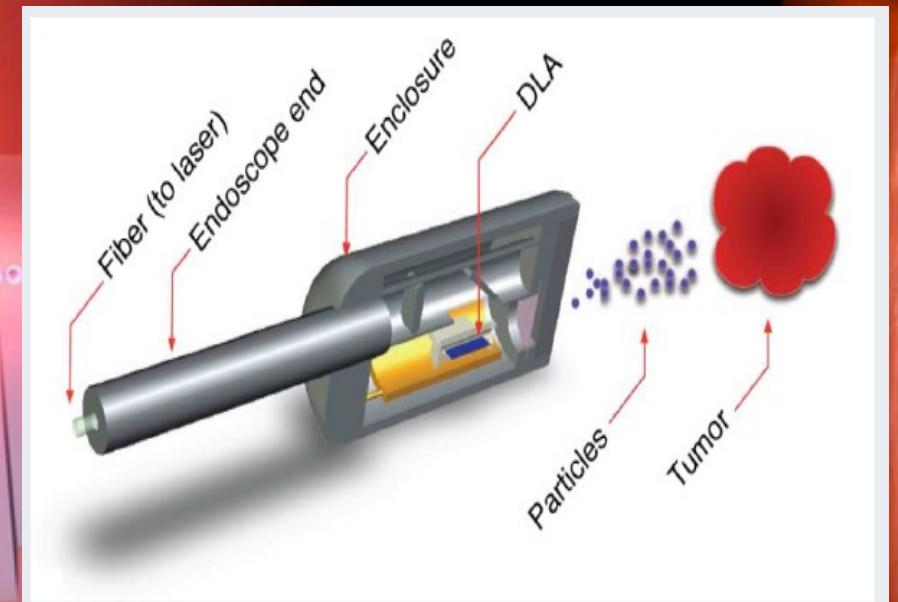
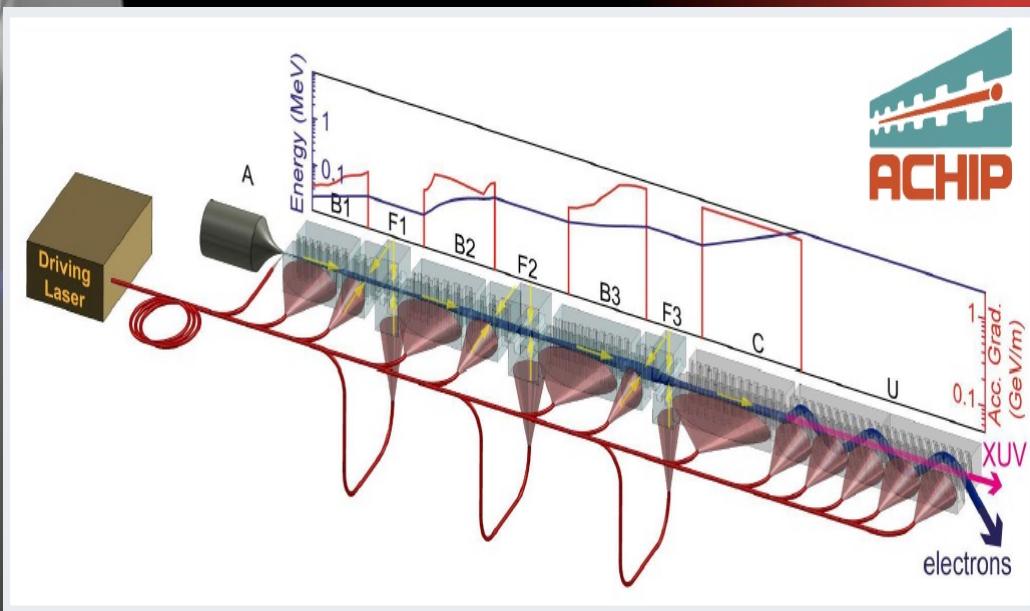
Nature **503**, 91-94 (2013).



Dielectric Structures Applications

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

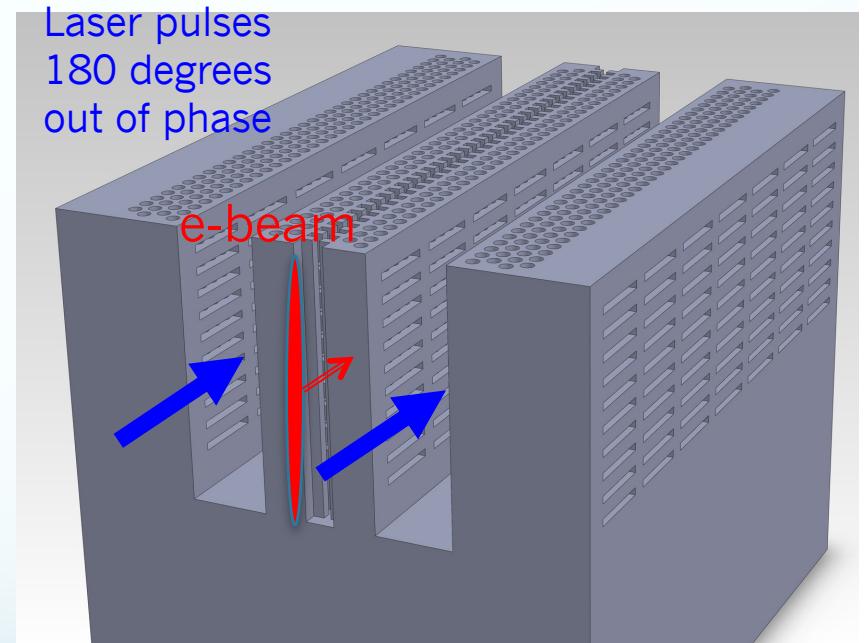
DLA module can be built onto the end of a fiber-optic catheter and attached to an endoscope, allowing to deliver controlled, high energy radiation directly to organs, tumors, or blood vessels within the body.



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

Dielectric Photonic Structure

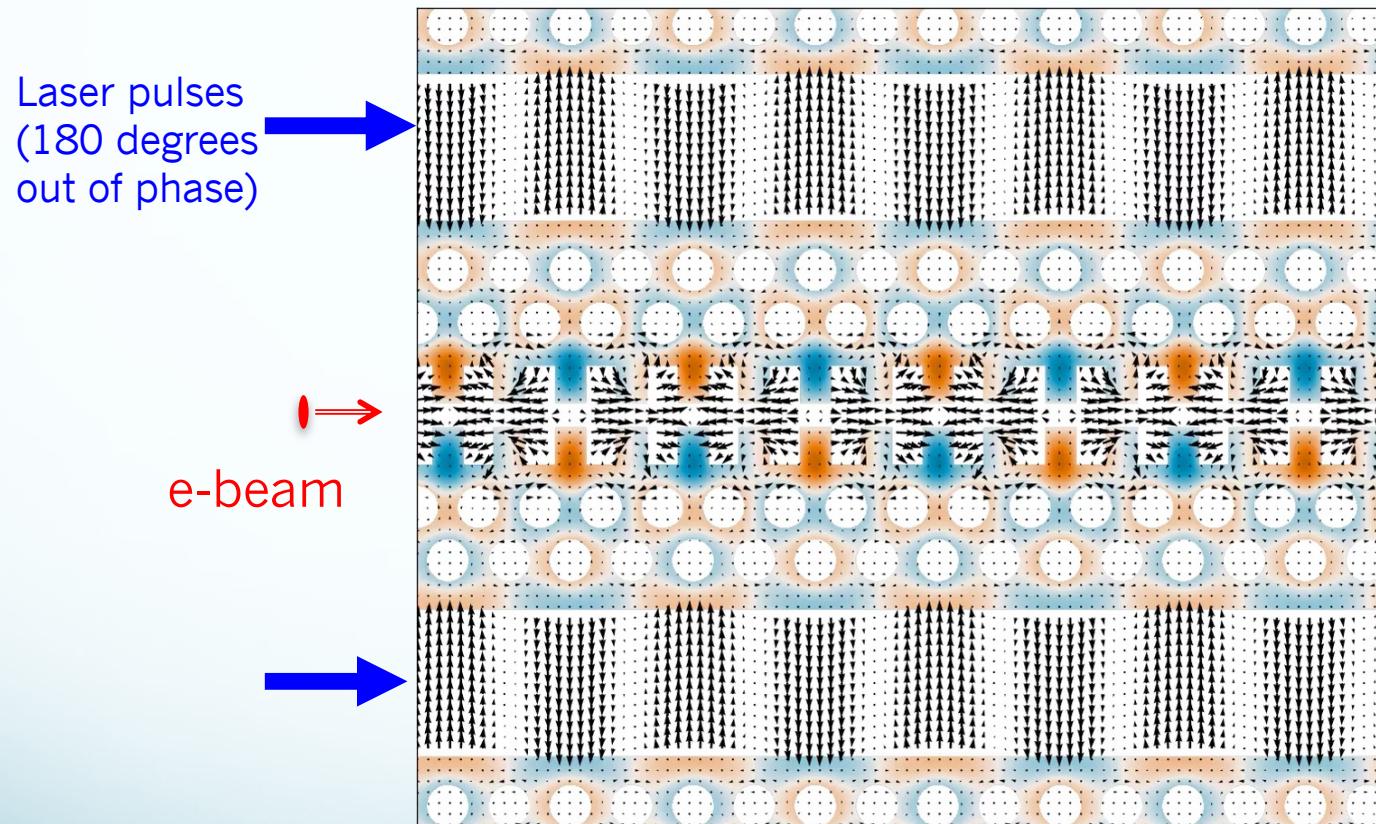
- Why photonic structures?
 - Natural in dielectric
 - Advantages of burgeoning field
 - design possibilities
 - Fabrication
- Dynamics concerns
- External coupling schemes



Schematic of GALAXIE
monolithic photonic DLA

Laser-Structure Coupling: TW

GALAXIE Dual laser drive structure, large reservoir of power recycles

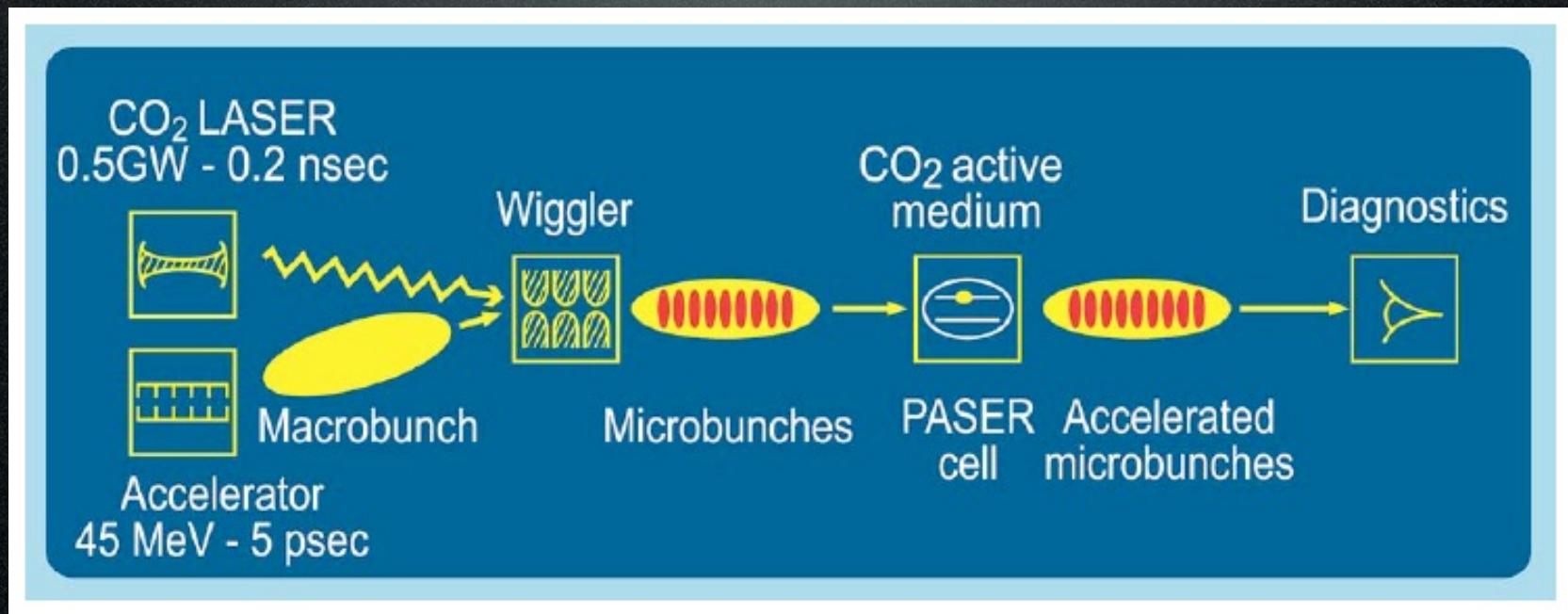
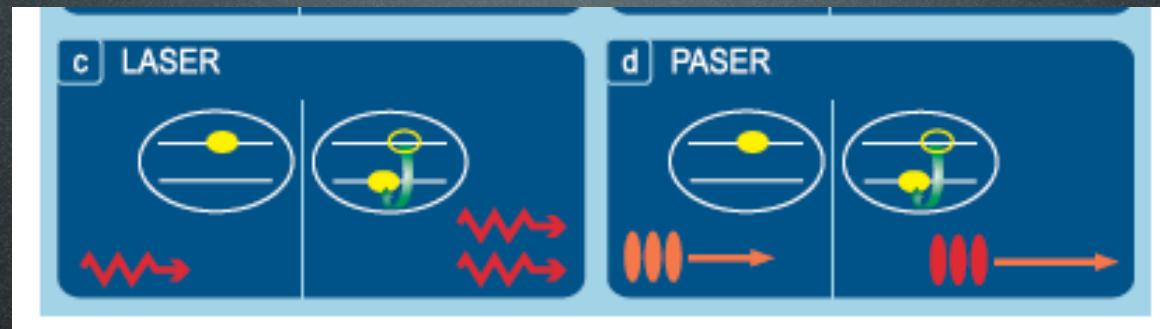


Particle acceleration by stimulated emission of radiation: Theory and experiment

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)



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)

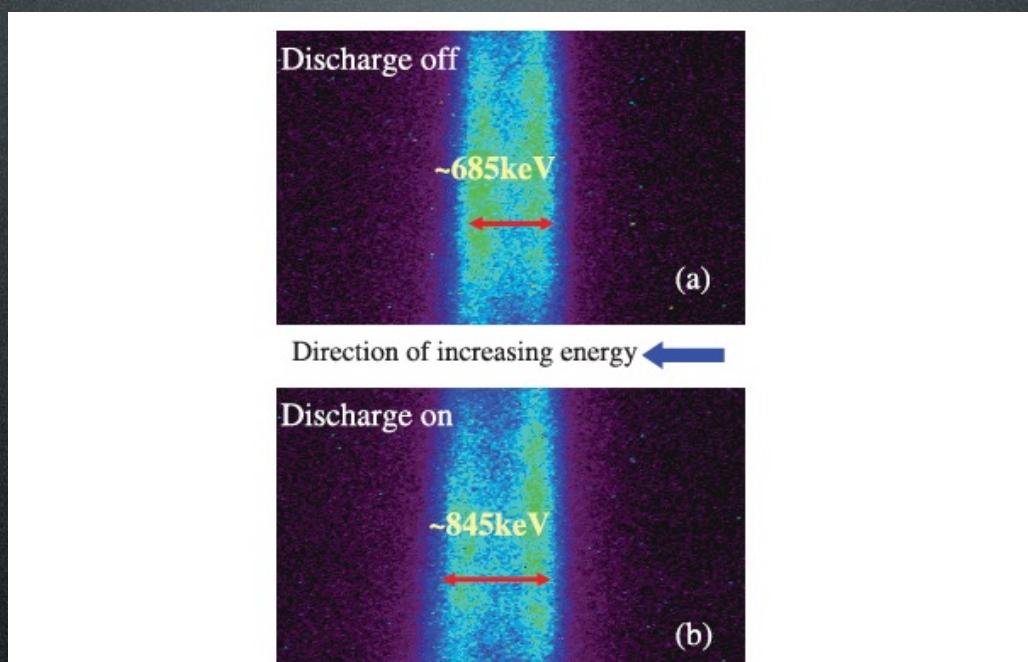


FIG. 3 (color). Raw video images from the electron energy spectrometer. Energy dispersion is in the horizontal direction. (a) Discharge is off in the PASER cell. (b) Discharge is on in the PASER cell. In both cases, $\sim 1.5\%$ peak-to-peak energy modulation was imparted.

Plasma Wakefield Acceleration

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.

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

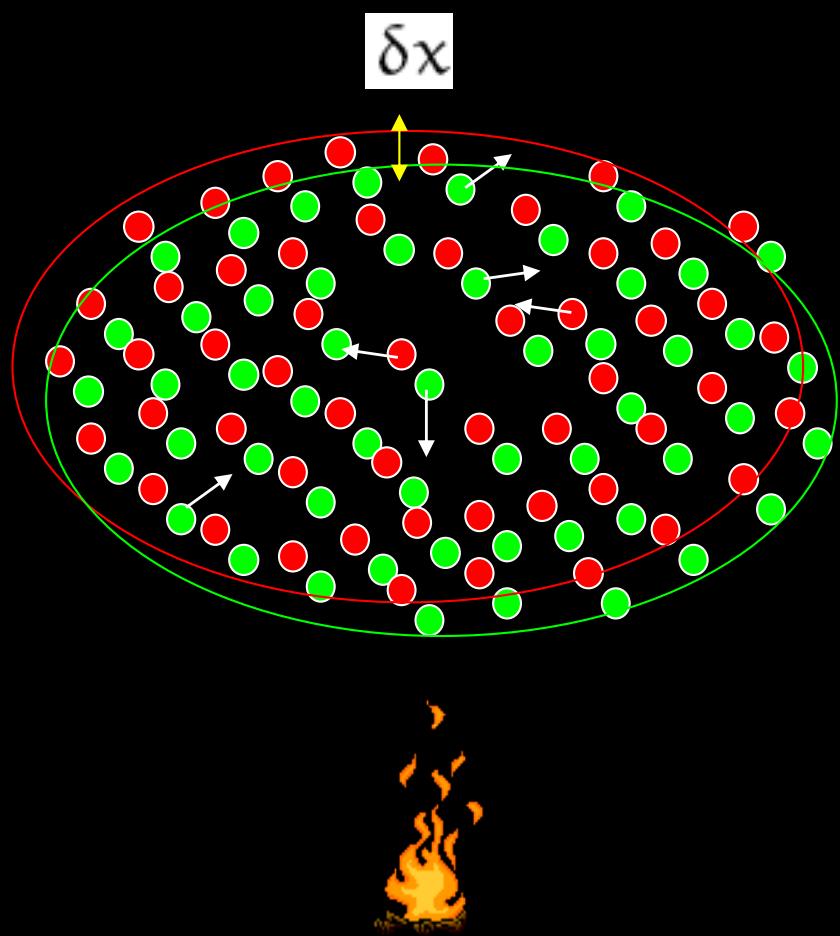
Department of Physics, University of California, Los Angeles, California 90024

(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 $4\gamma_0 mc^2$ 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

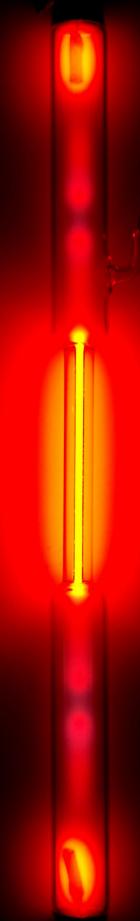
$$\delta x = (\delta x)_0 \cos(\omega_p t)$$

Looking for a plasma target

He



Ne



Ar



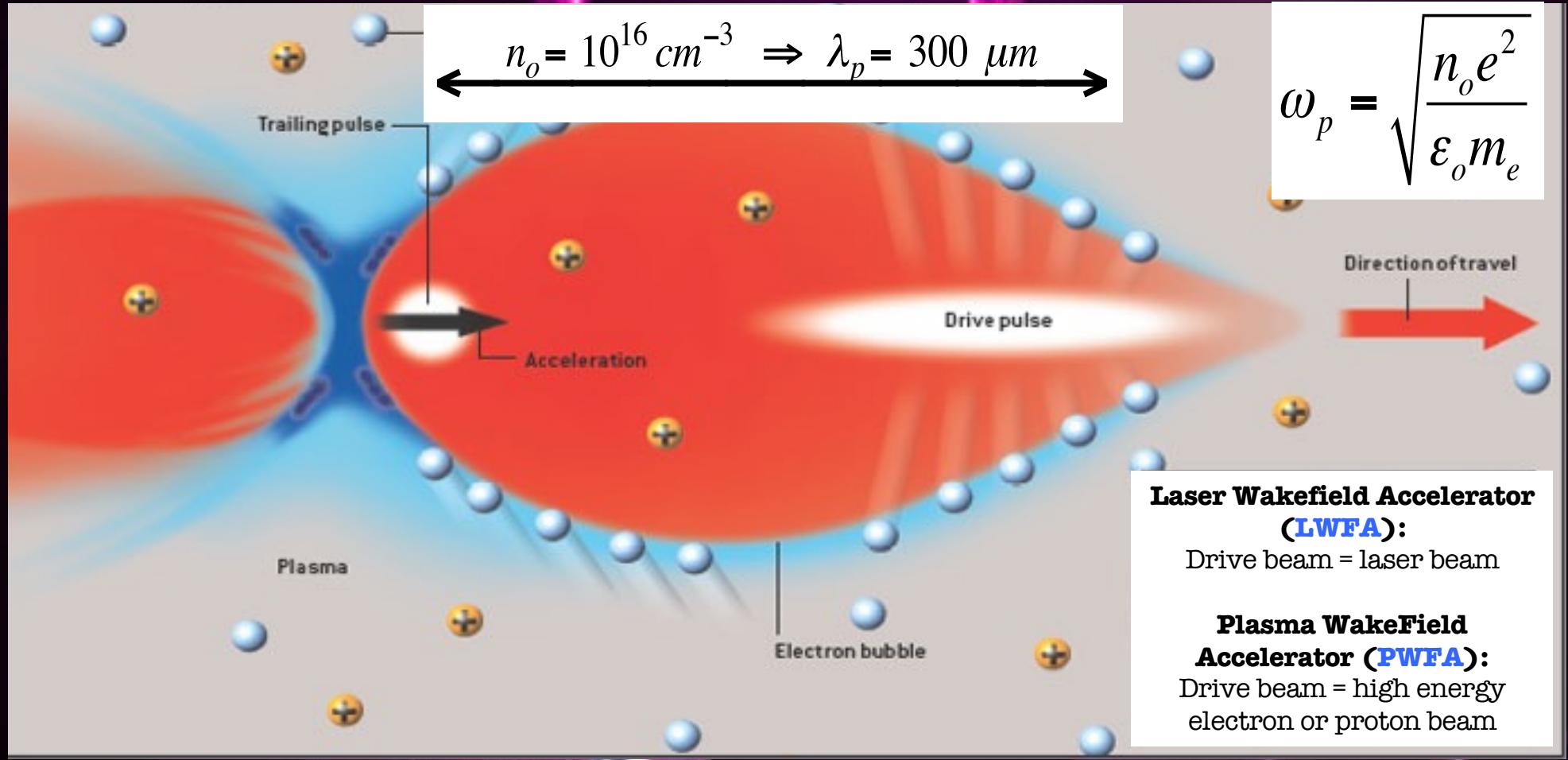
Kr



Xe



Principle of plasma acceleration



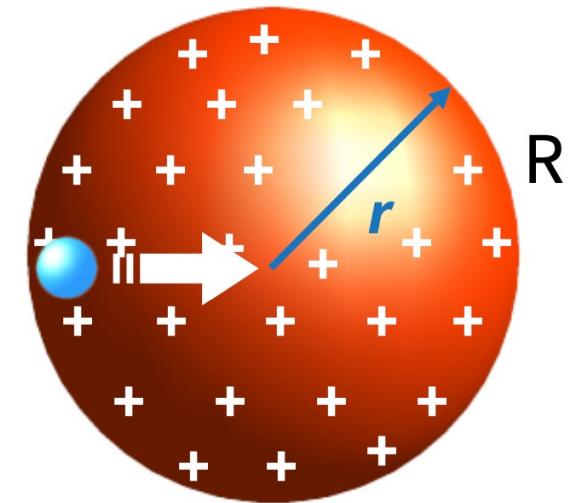
Break-Down Limit?
⇒ Wave-Breaking field:

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

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

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



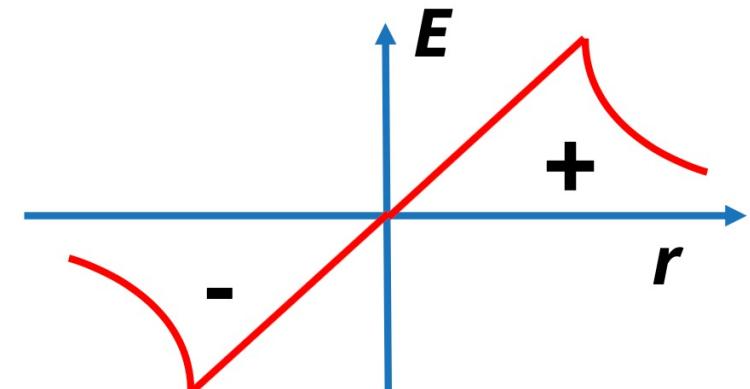
The field is **increasing** inside the sphere

Let's put some numbers

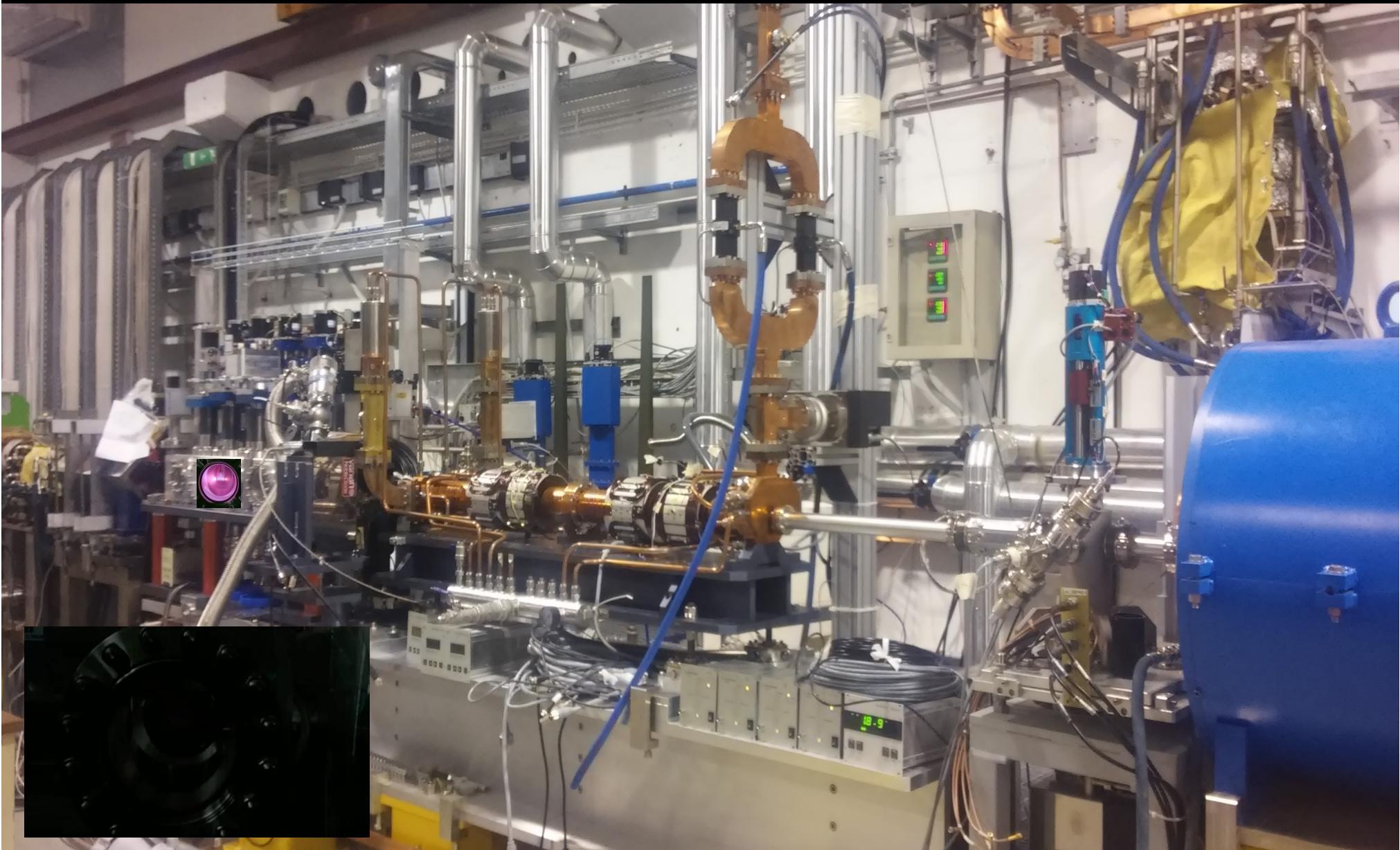
$$n_i = 10^{16} \text{ cm}^{-3}$$

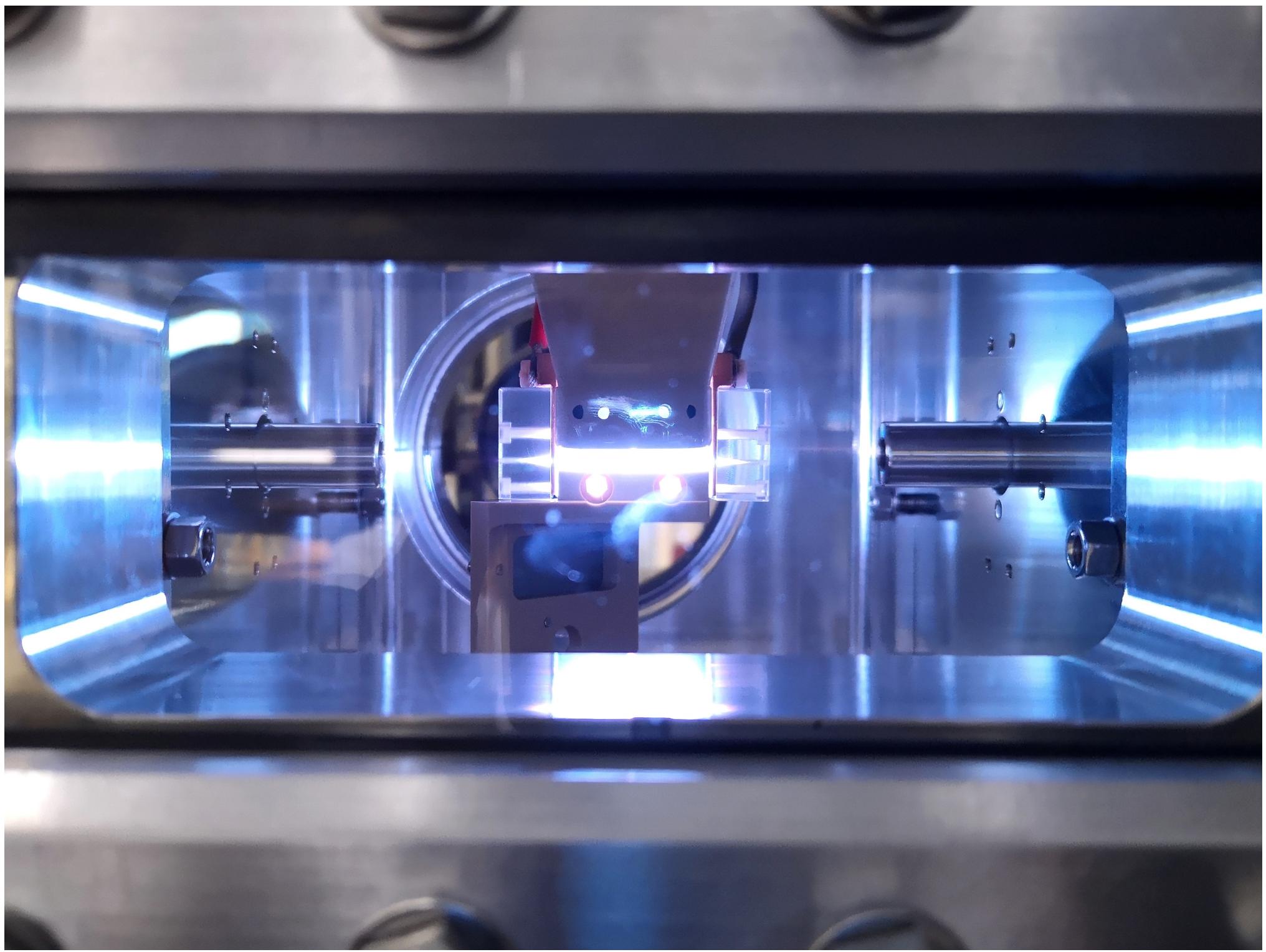
$$R = 0.5$$

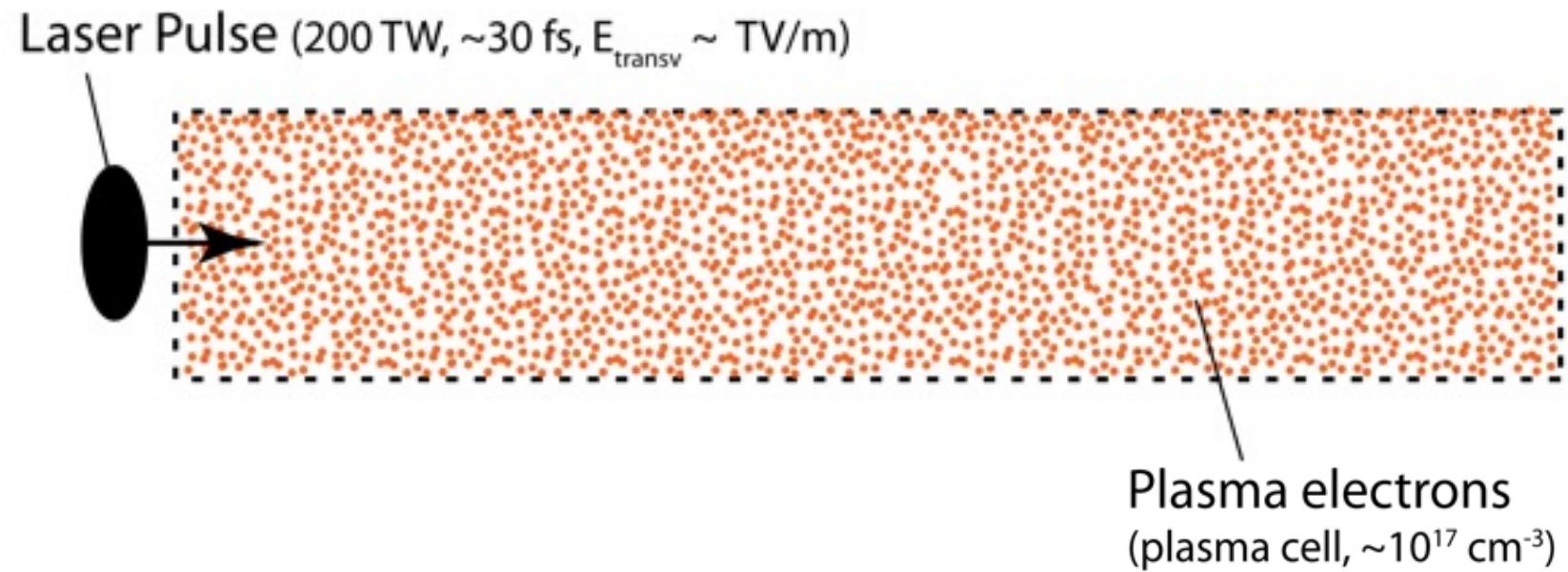
$$\Rightarrow E \approx 10 \frac{GV}{m}$$

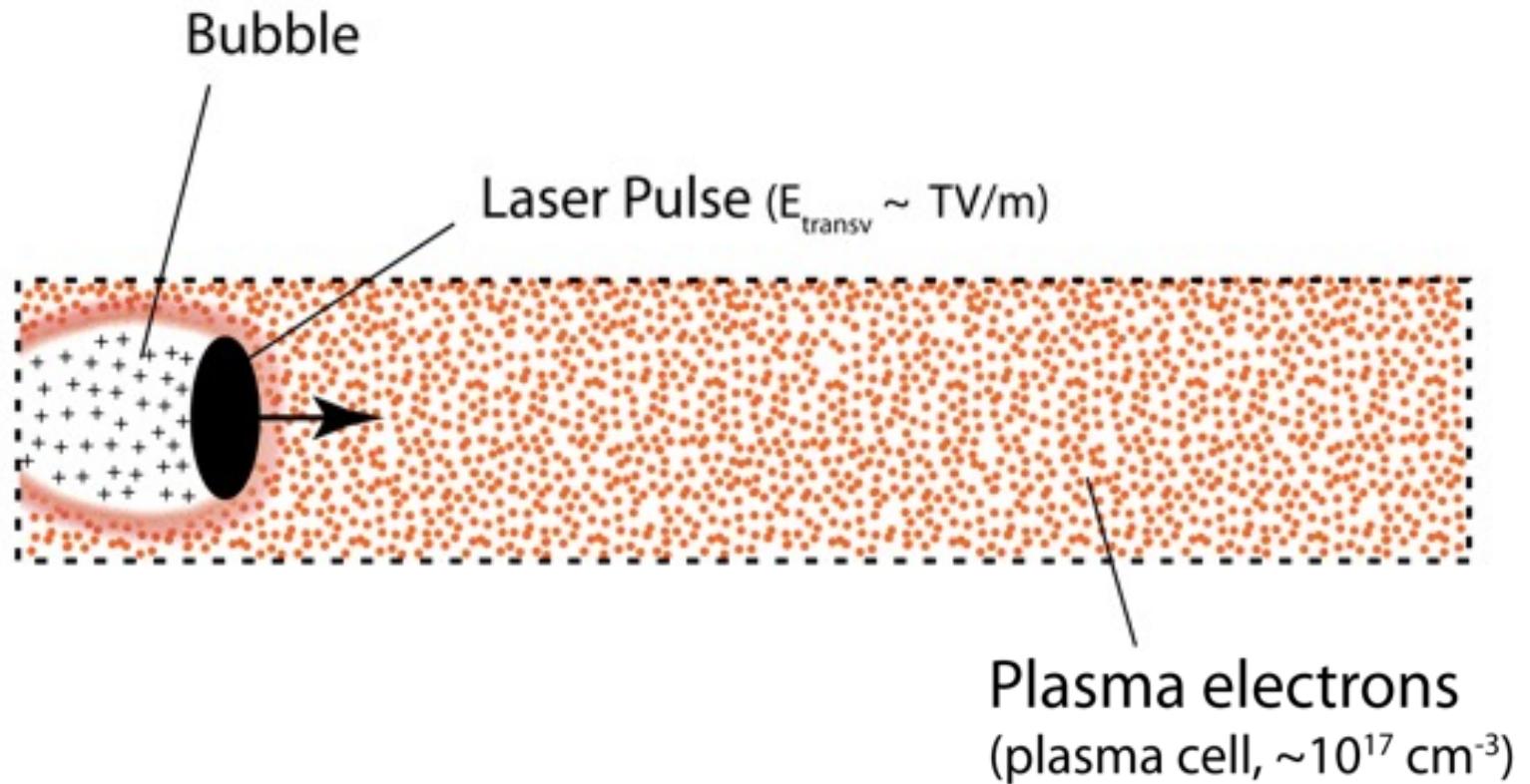


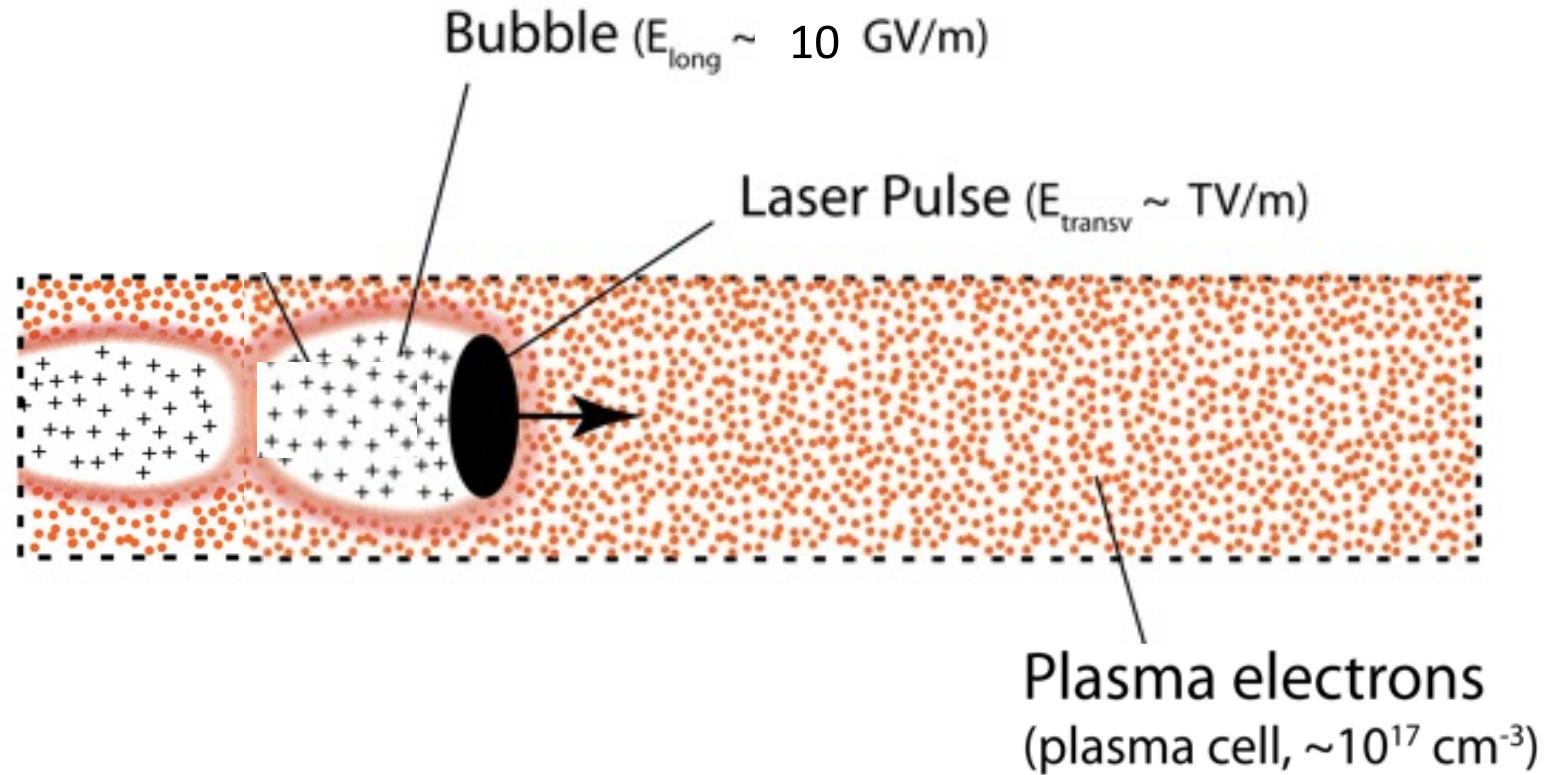
PWFA vacuum chamber at SPARC_LAB

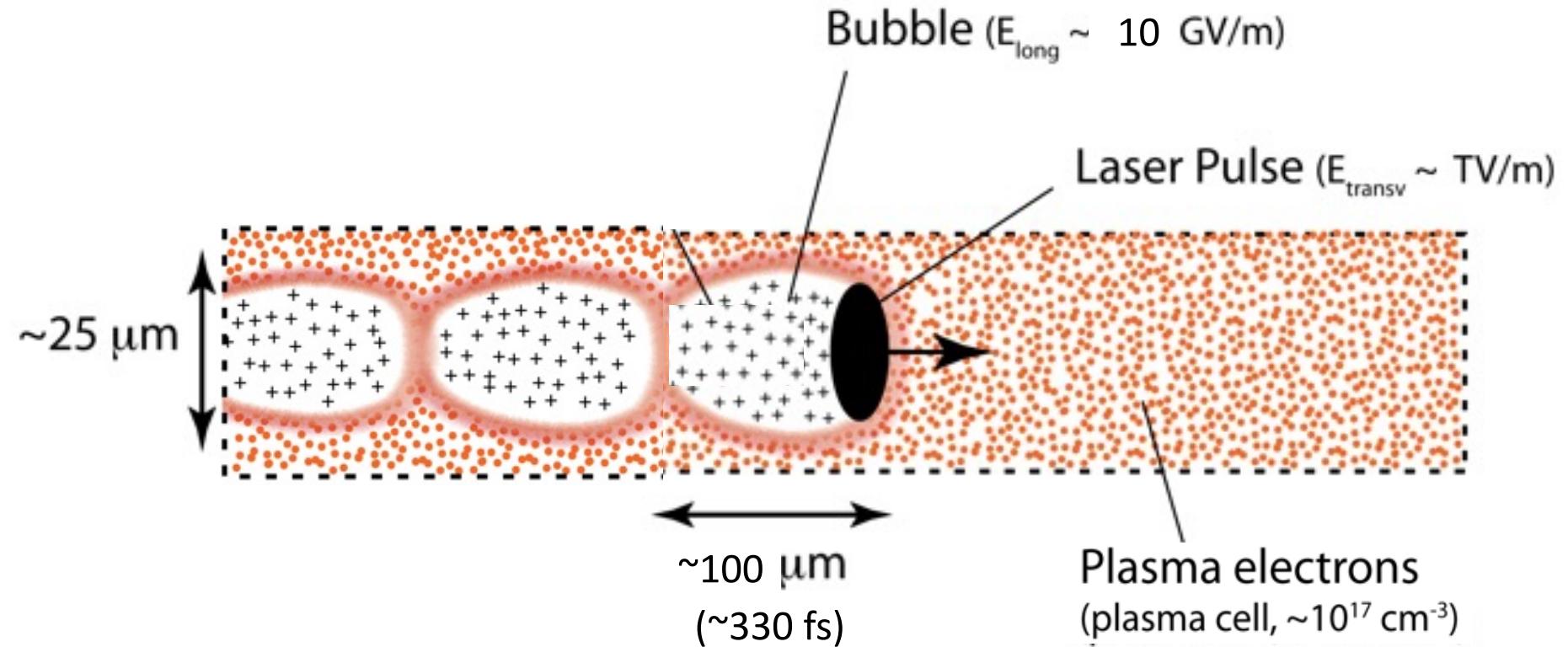




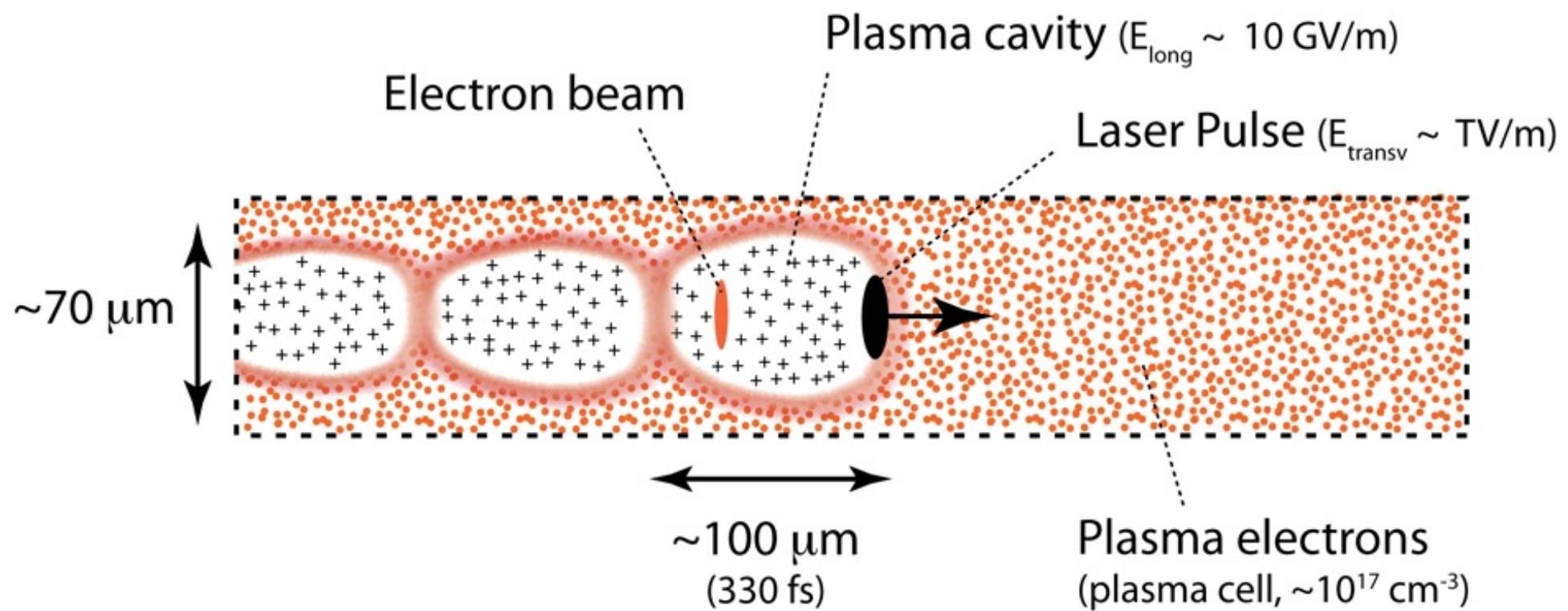
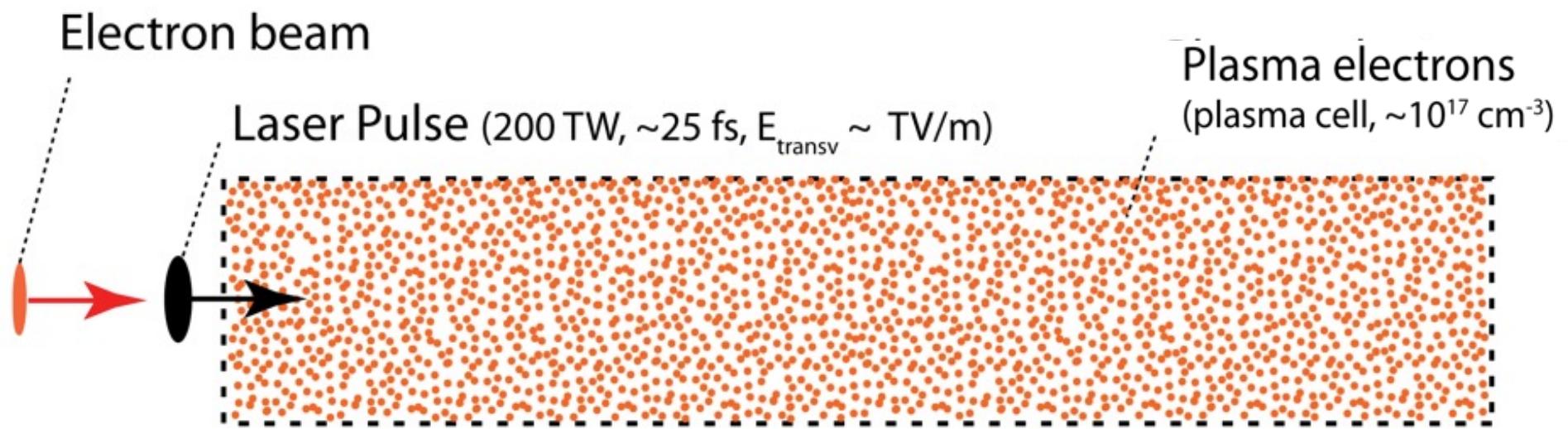








This accelerator fits into a human hair!



Principle of plasma acceleration

Driven by Radiation Pressure

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

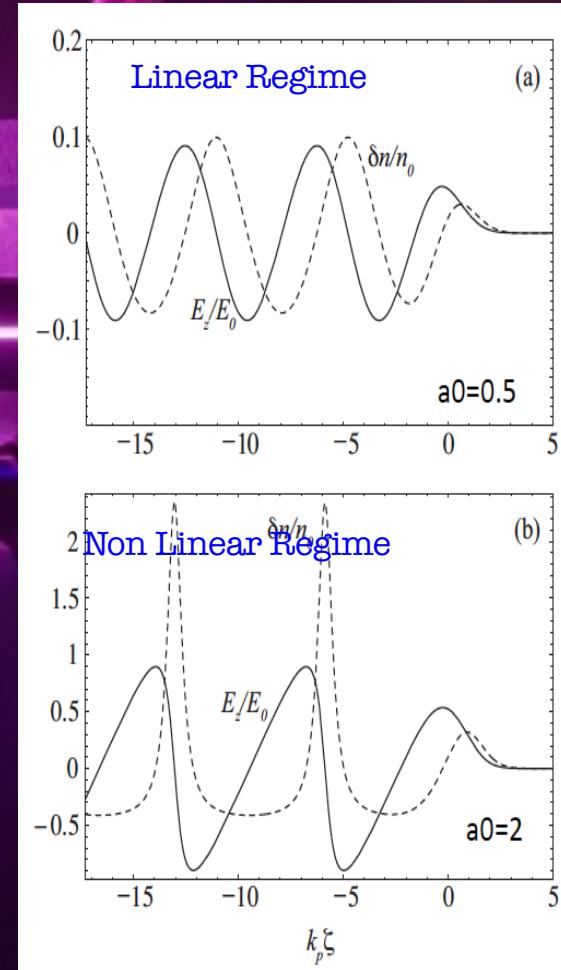
$$a = \frac{eA}{mc^2} \propto \lambda J^{1/2}$$



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

Accelerating field

Depends on
radial position r

Changes between accelerating
and decelerating as function of
longitudinal position z

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

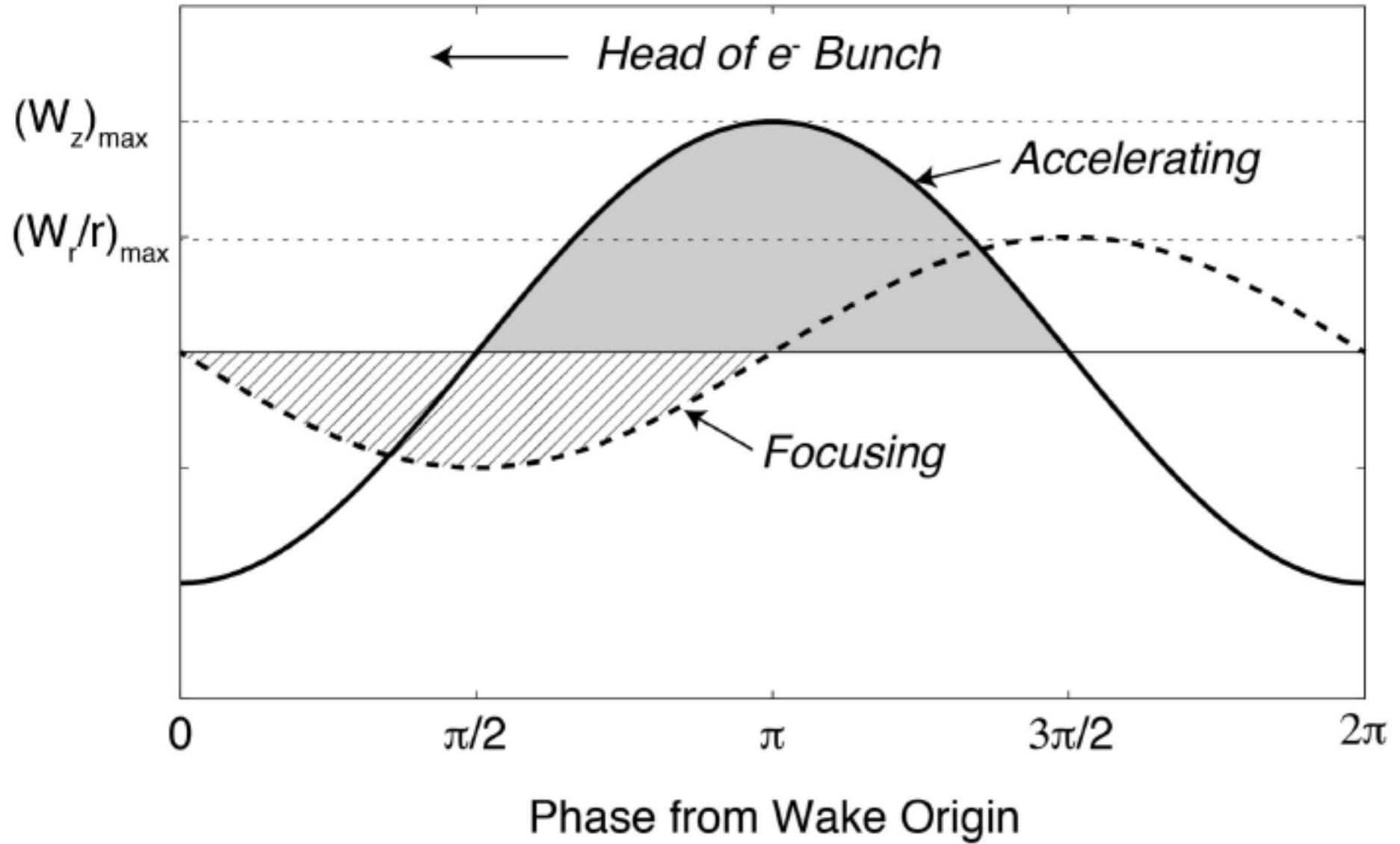
$$\mathcal{E}_r \simeq 2A \frac{r}{k_p a^2} \sin(k_p z - \omega_p t)$$

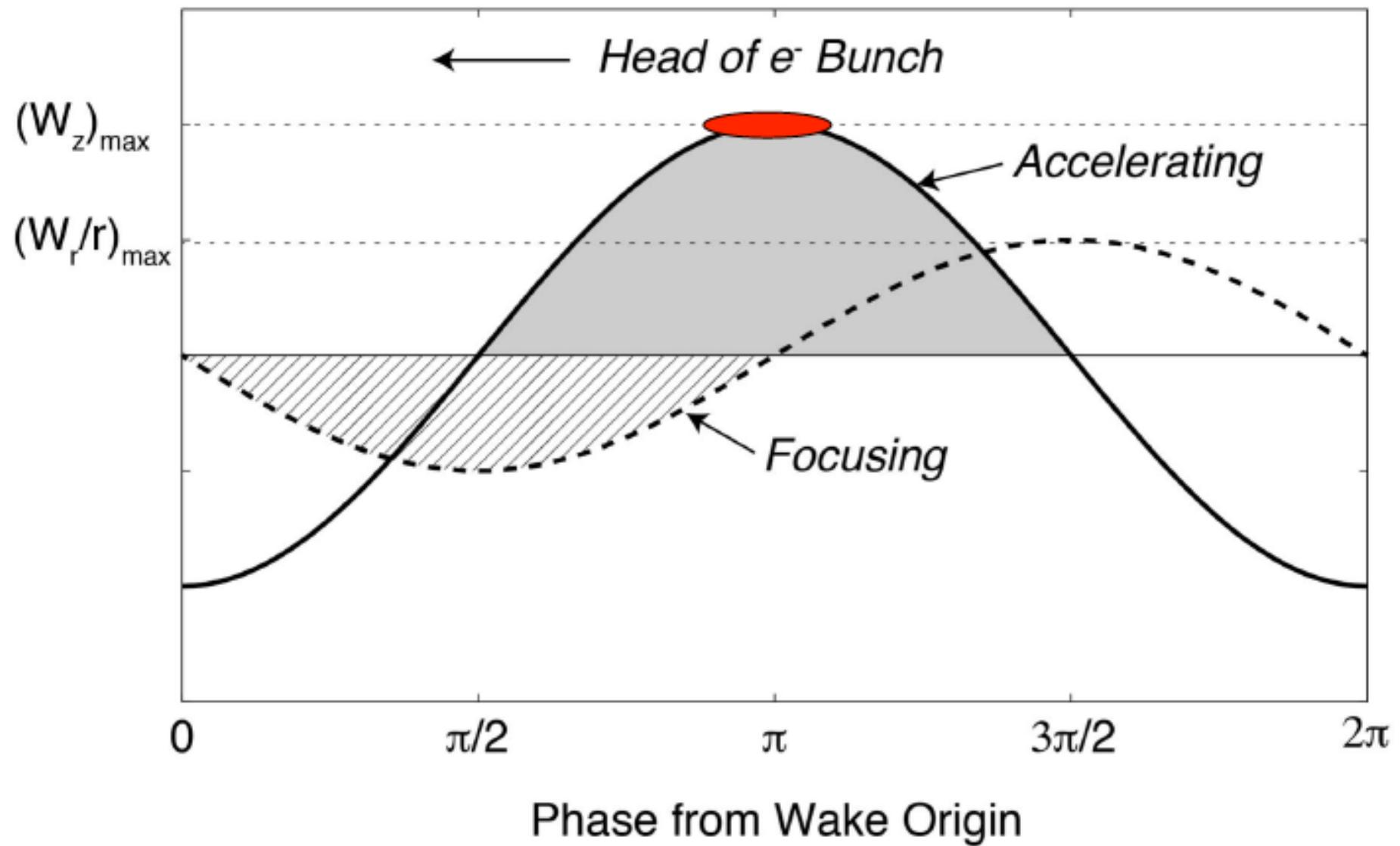
$\pi/2$ out of
phase

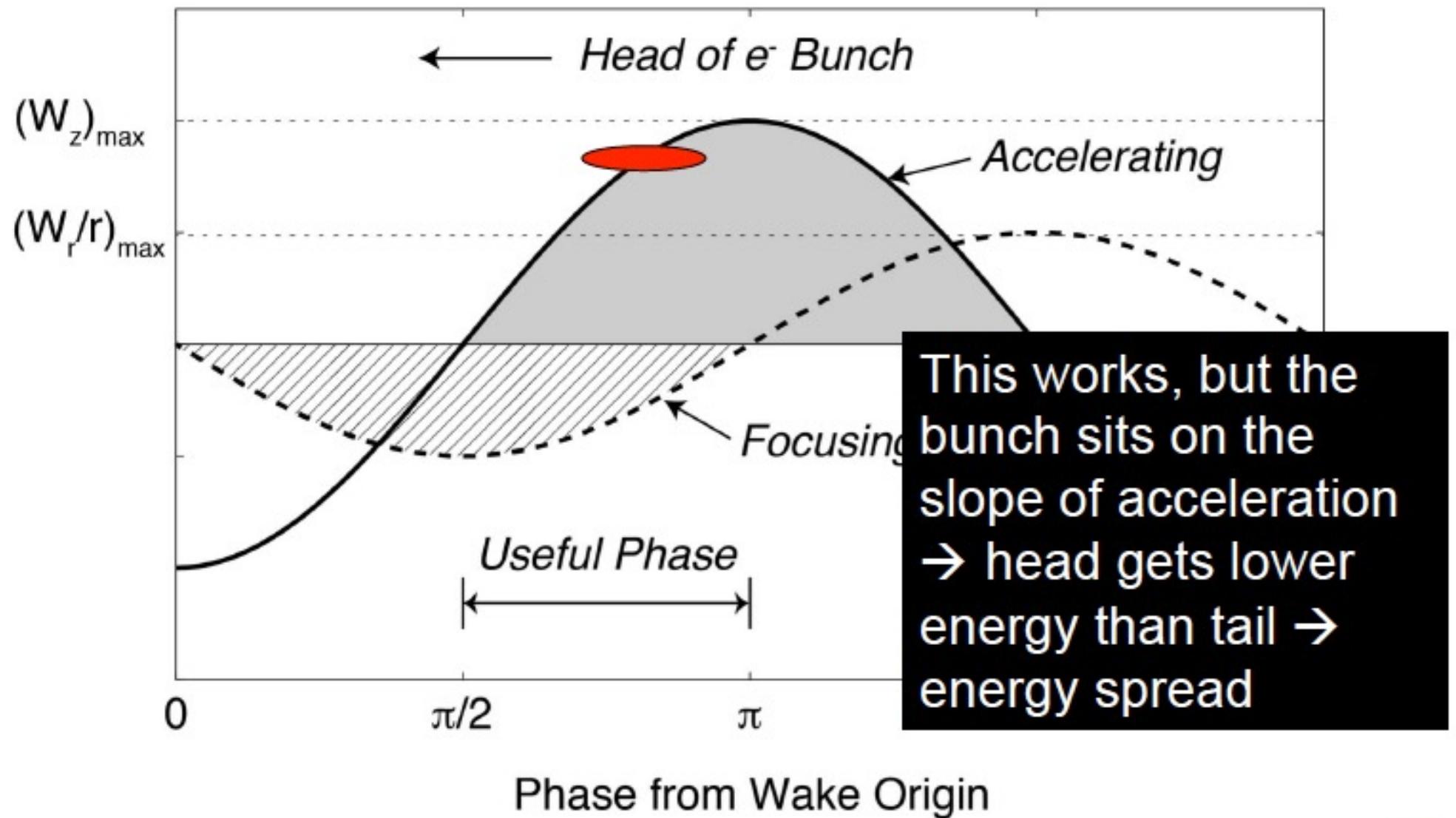
Transverse field

Depends on radial
position r

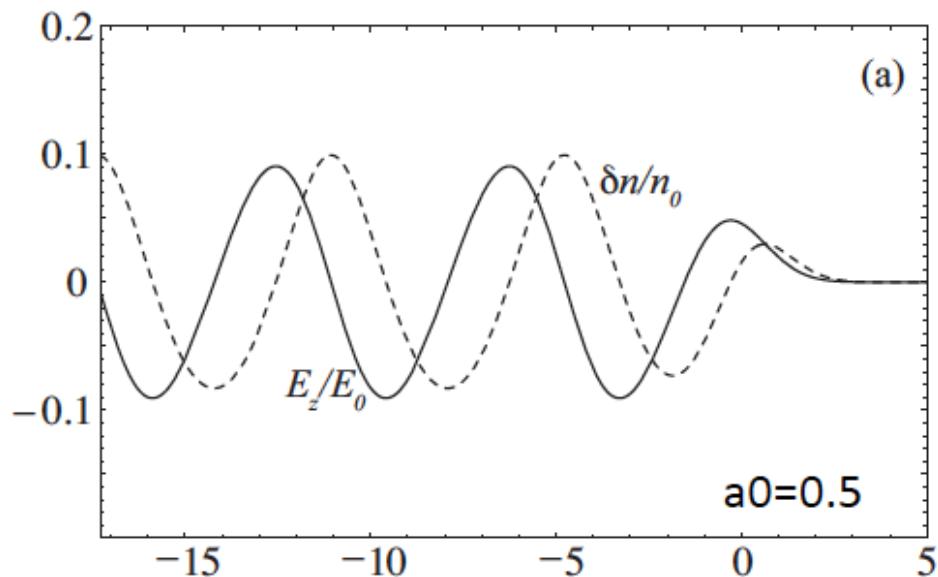
Changes between
focusing and defo-
cusing as function of
longitudinal position z



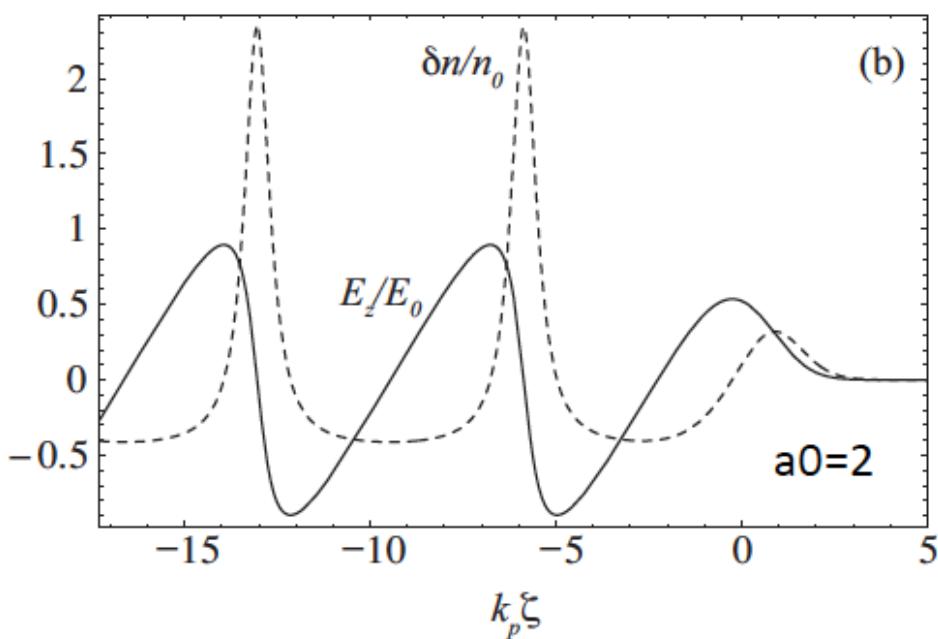




Regimes: Linear & Non-Linear



Linear

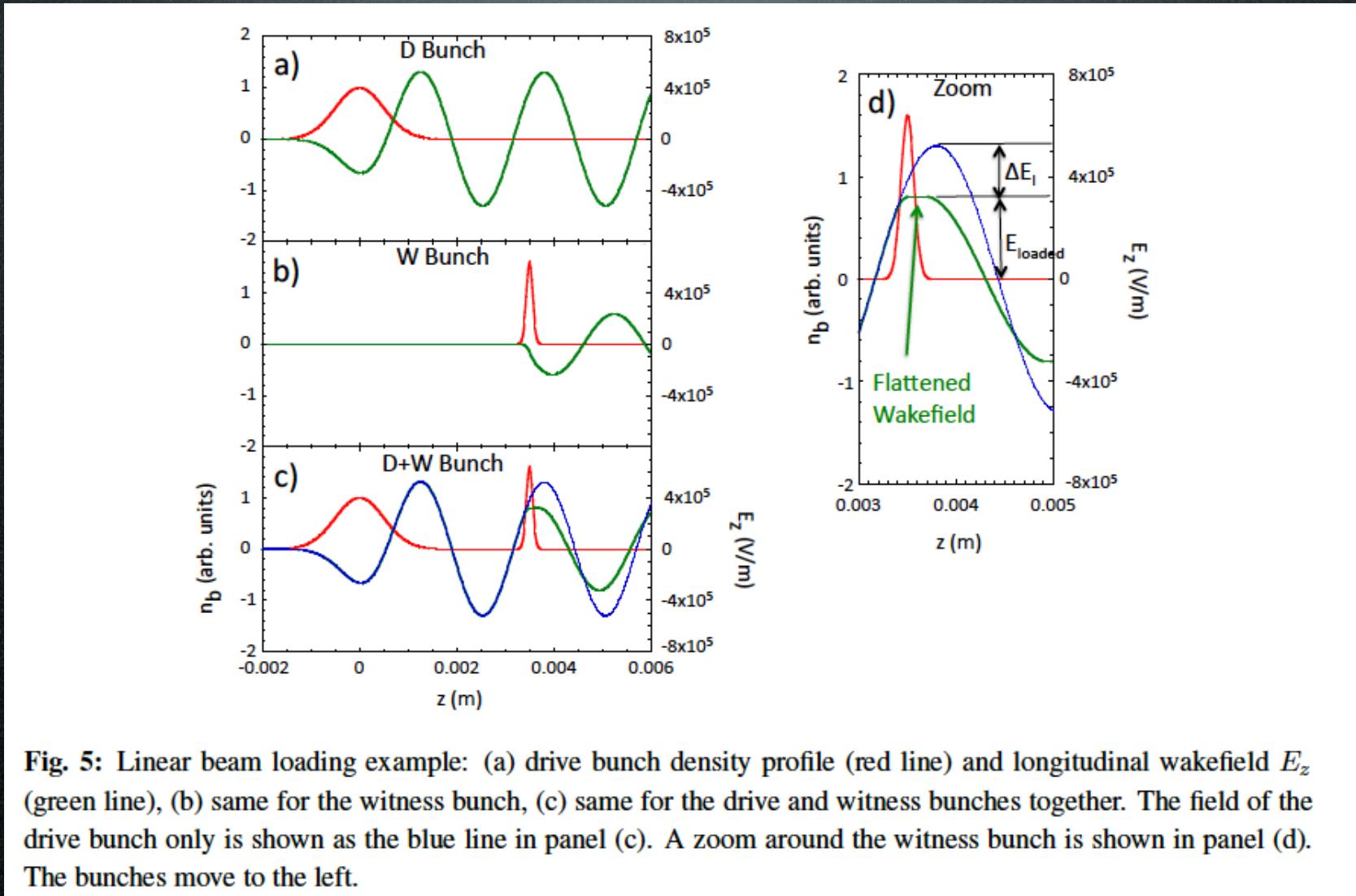


Non-Linear

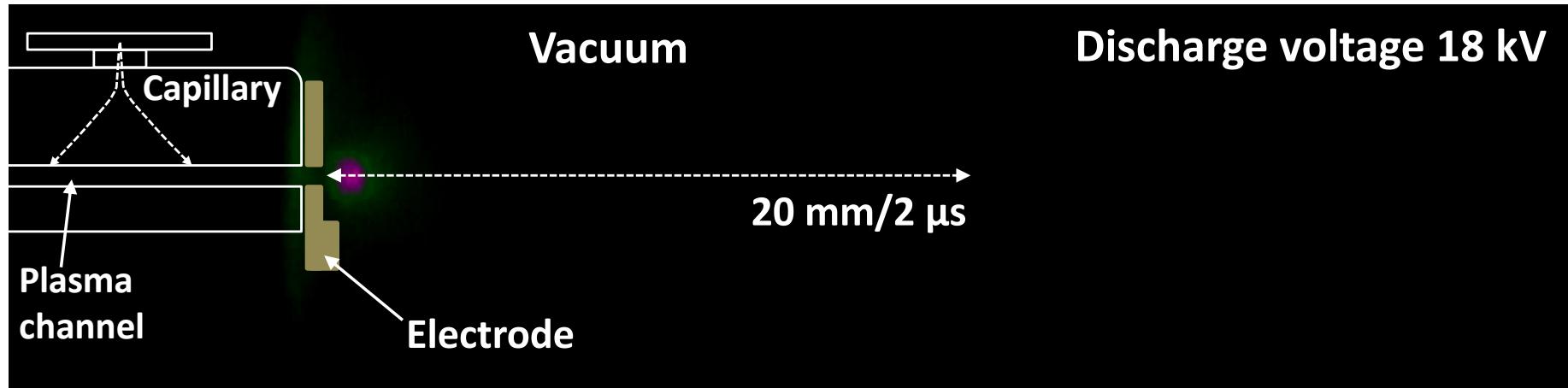


FIG. 8. Time-averaged density variation $\delta n/n_0$ (dashed curve) and axial electric field E_z/E_0 (solid curve) in an LWFA driven by a Gaussian laser pulse (pulse is moving to the right, centered at $k_p \zeta = 0$ with rms intensity length $L_{\text{rms}} = k_p^{-1}$) for (a) $a_0 = 0.5$ and (b)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

Energy spread compensation with beam loading



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



- Both plasma 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.

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.

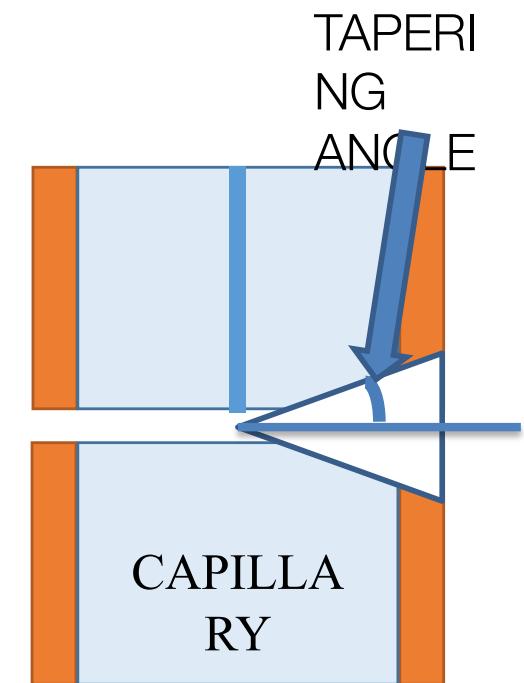
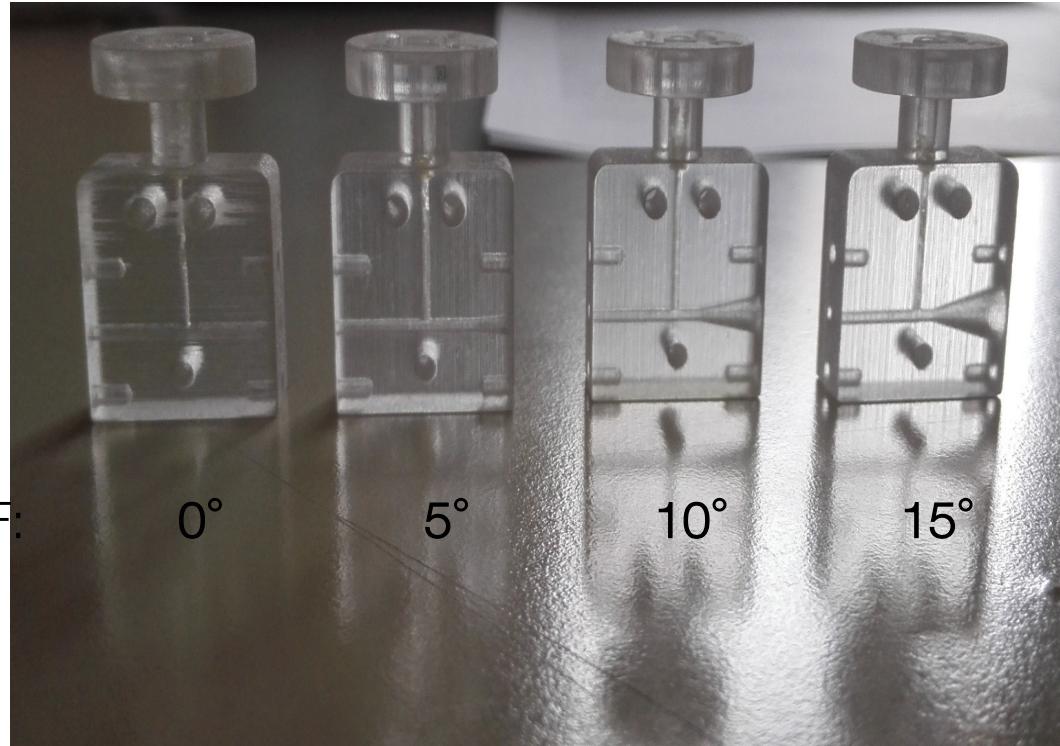
TAPERING OF:

0°

5°

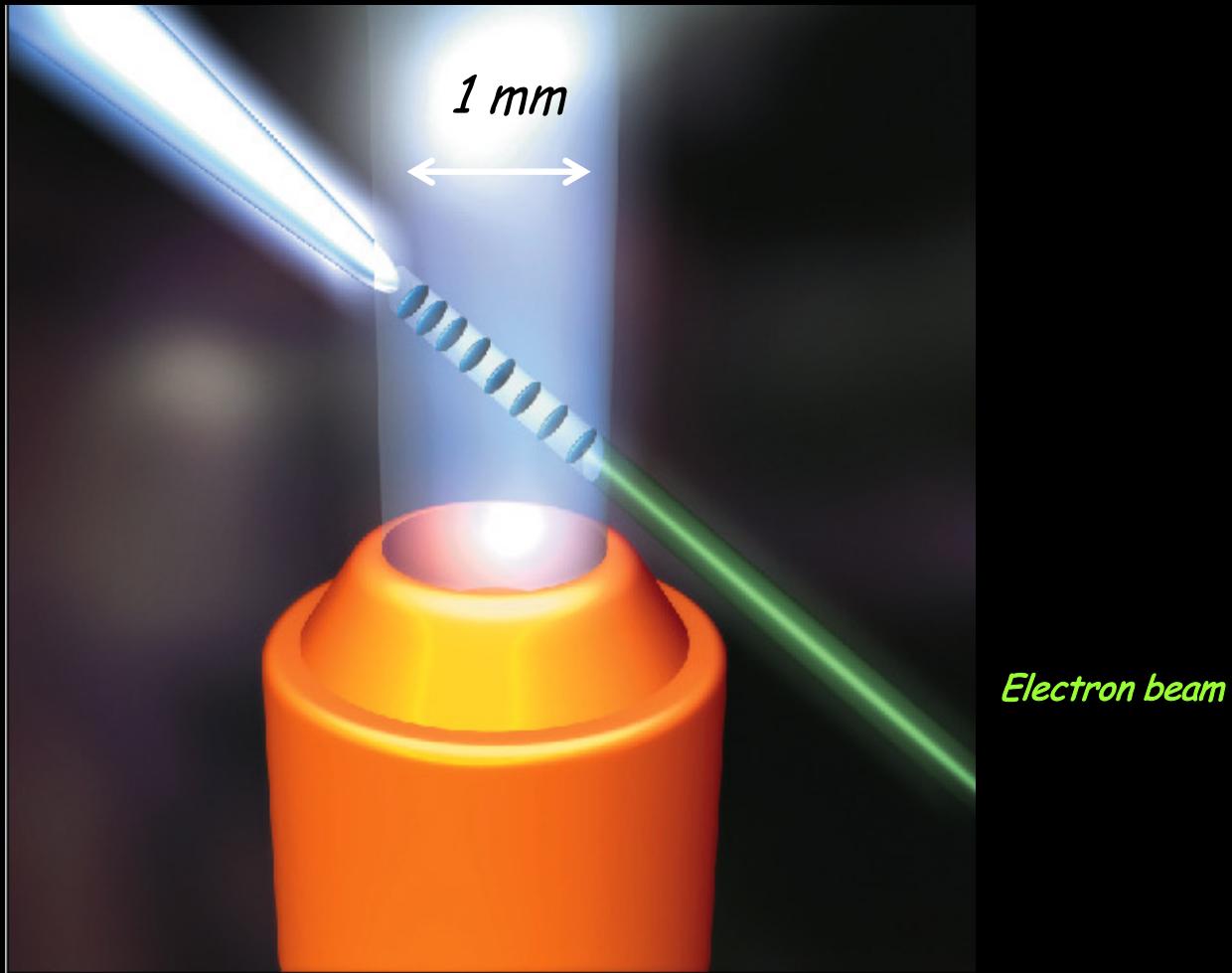
10°

15°

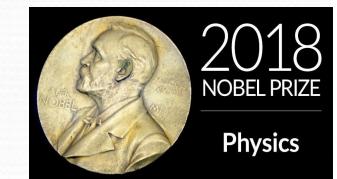
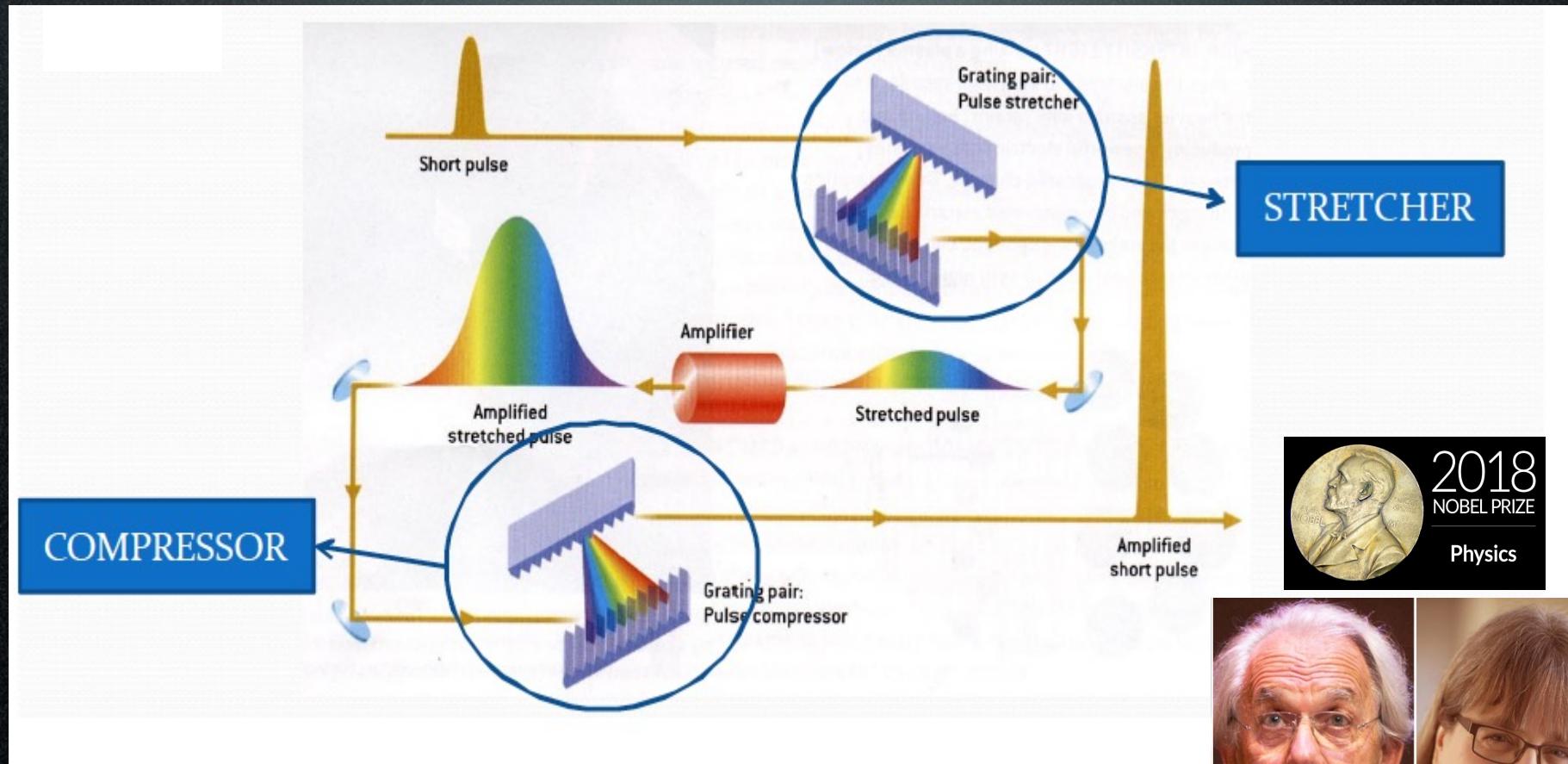


Laser Driven LWFA

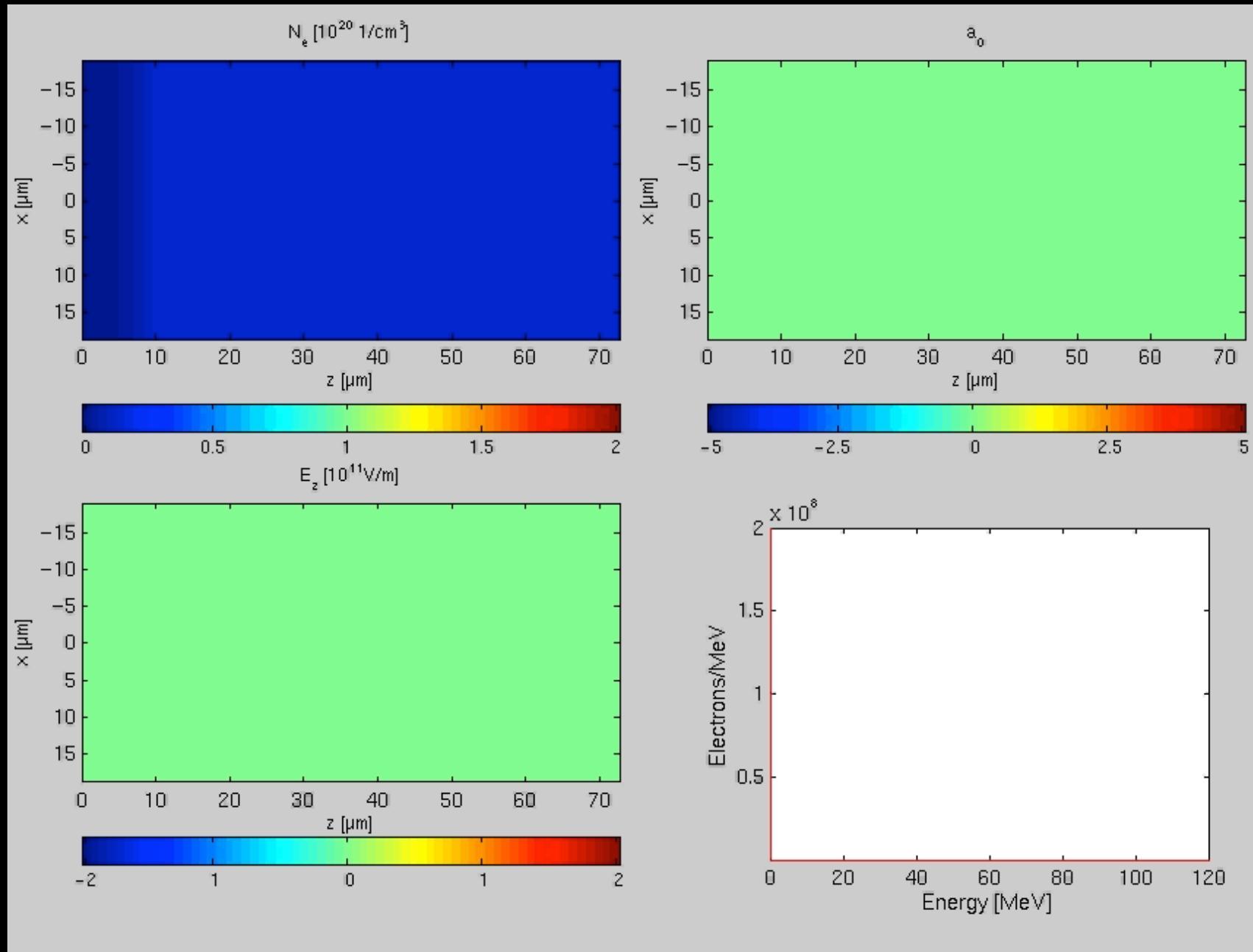
Direct production of e-beam



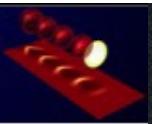
Chirped Pulse Amplification



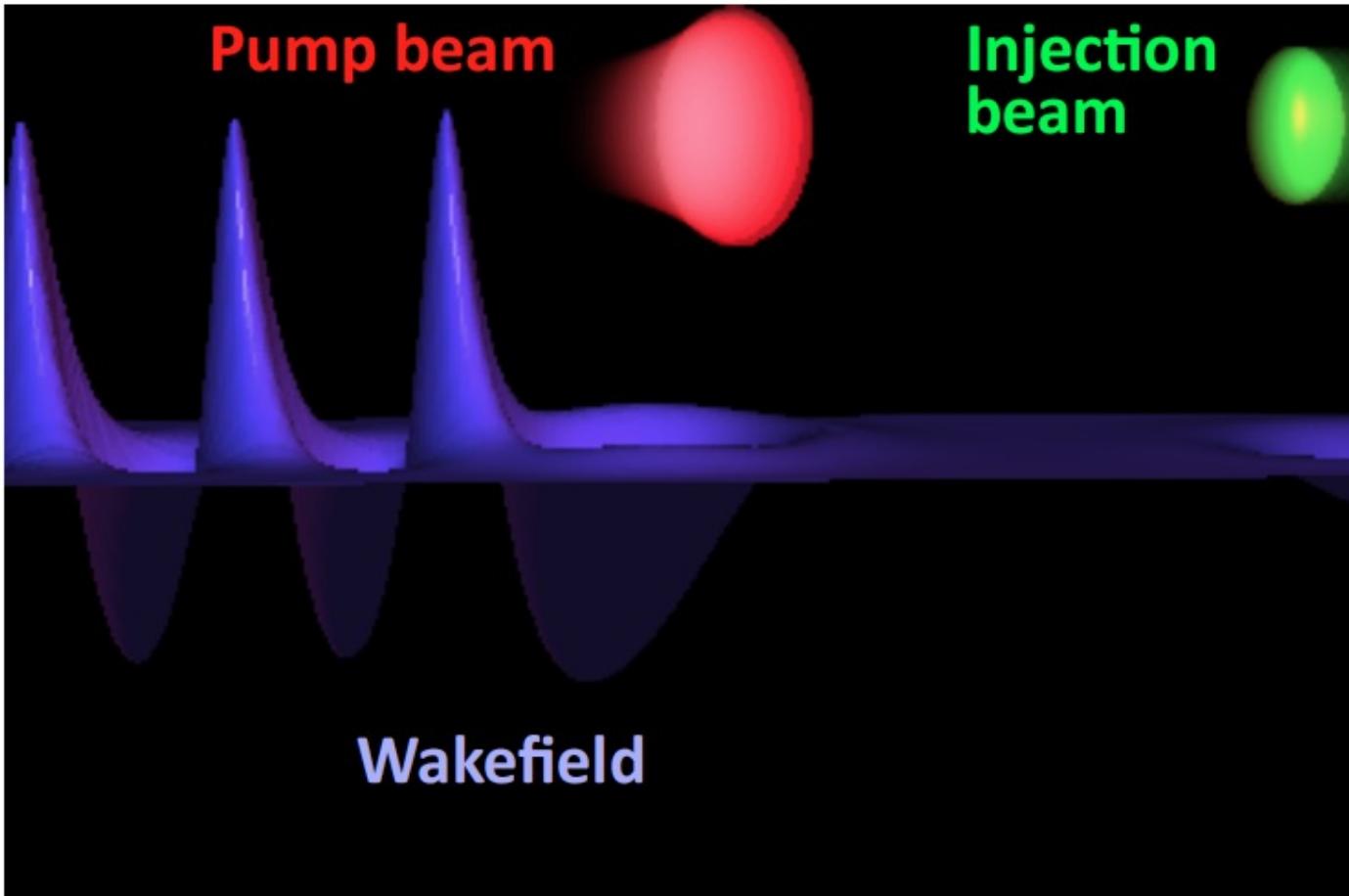
Diffraction - Self injection - Dephasing – Depletion



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)



<http://ioa.ensta.fr/>

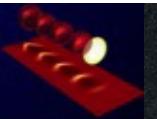
1st European Advanced Accelerator Concepts Workshop, La Biodola, Isola d'Elba - Italy, June 2-7 (2013)



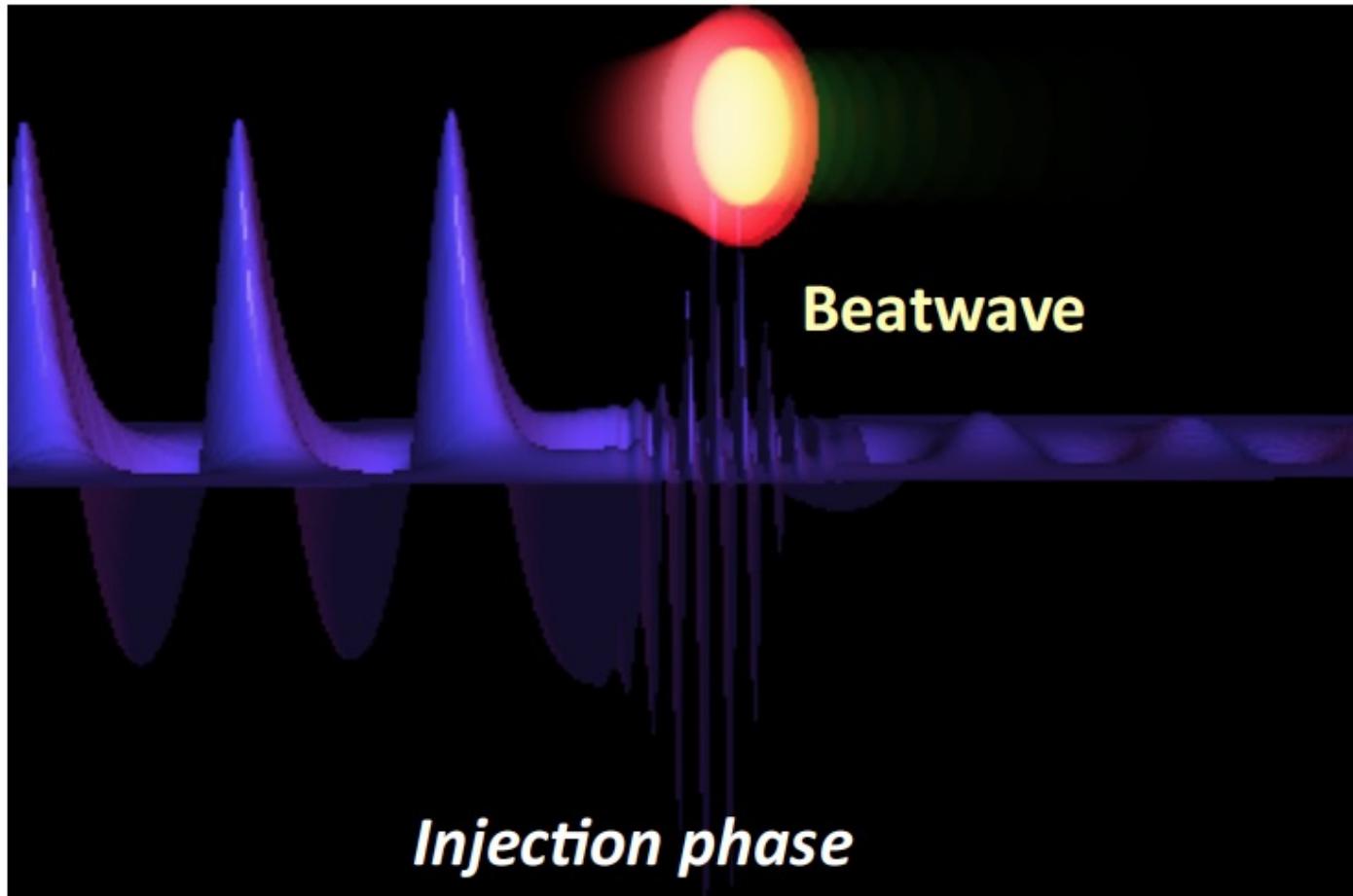
UMR 7639



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)



<http://loa.ensta.fr/>

lundi 3 juin 13

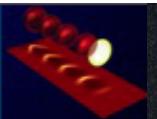
1st European Advanced Accelerator Concepts Workshop, La Biodola, Isola d'Elba - Italy, June 2-7 (2013)



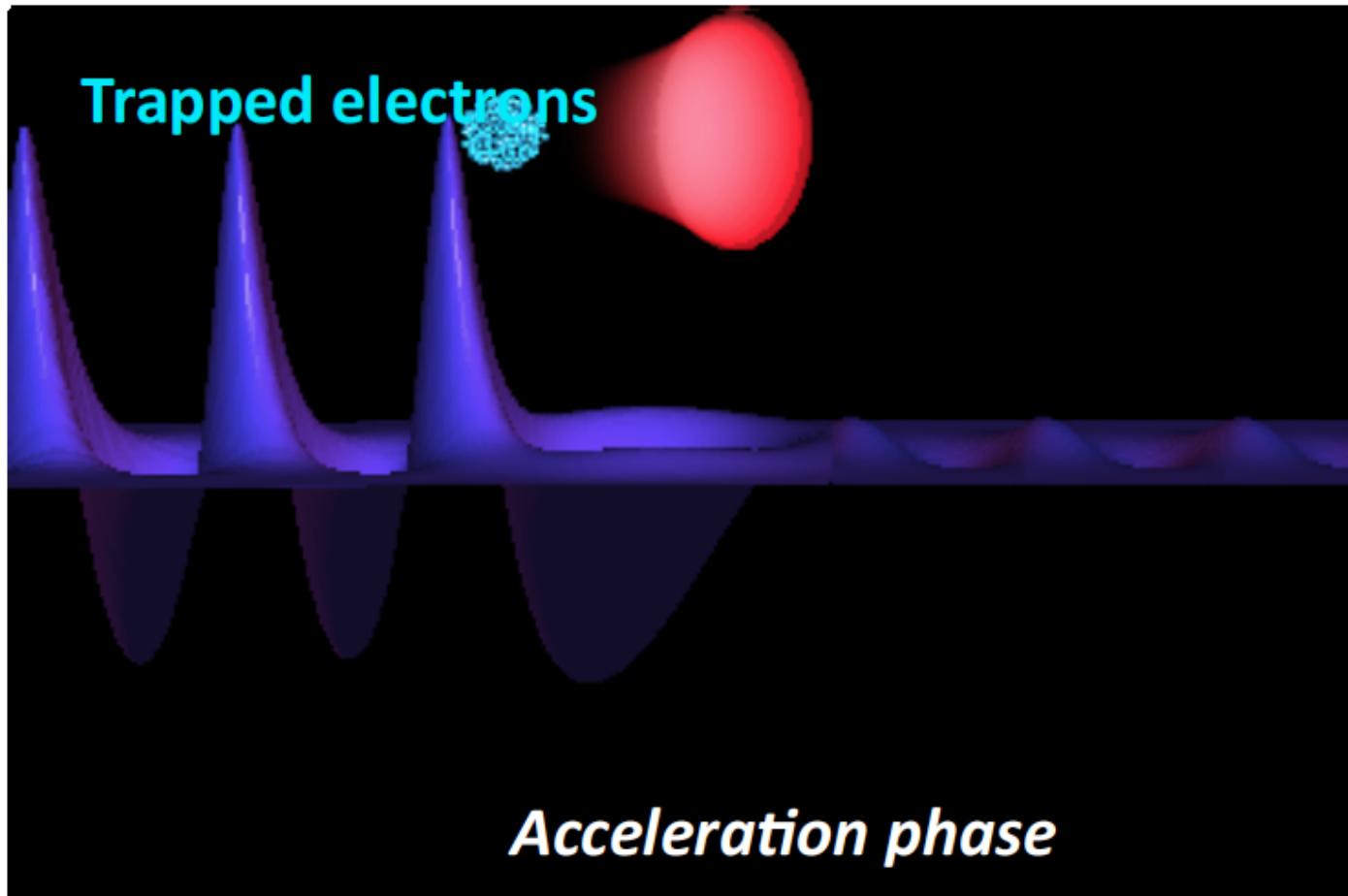
UMR 7639



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)



<http://loa.ensta.fr/>

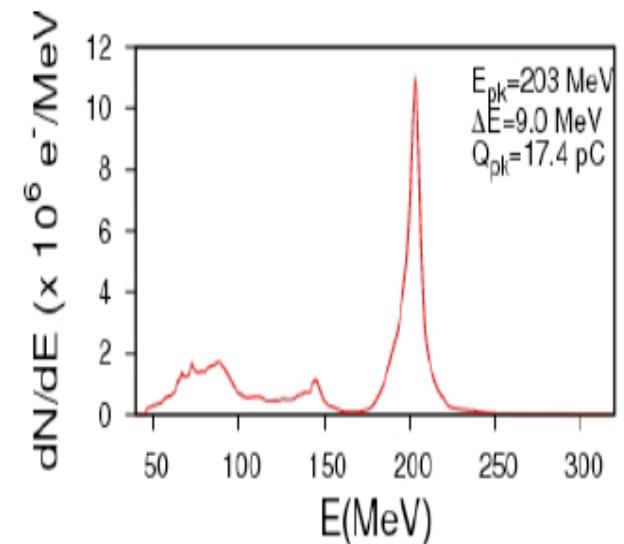
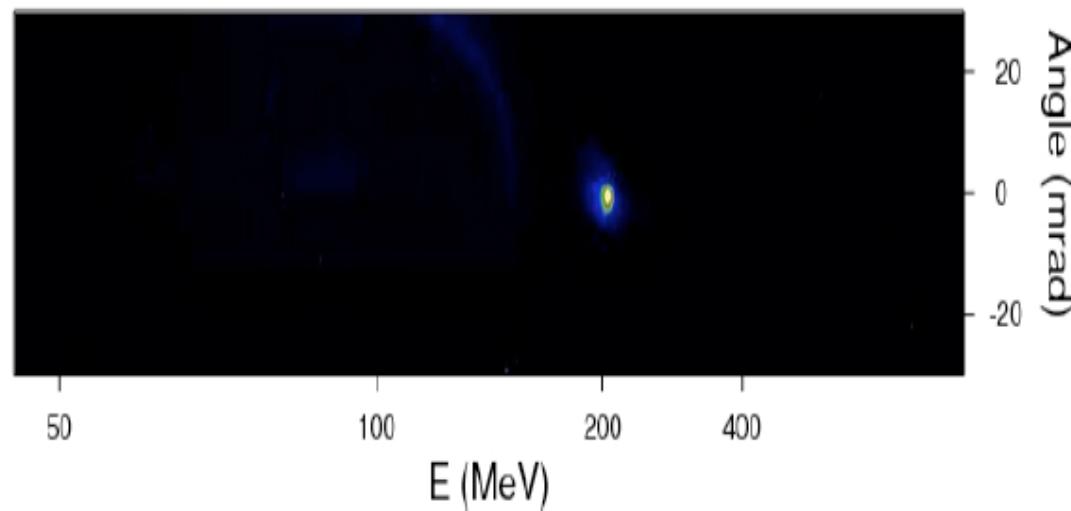
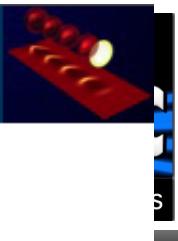
1st European Advanced Accelerator Concepts Workshop, La Biodola, Isola d'Elba - Italy, June 2-7 (2013)



UMR 7639



Stable Laser Plasma Accelerators



Ist European Advanced Accelerator Concepts Workshop, La Biodola, Isola d'Elba - Italy, June 2-7 (2013)

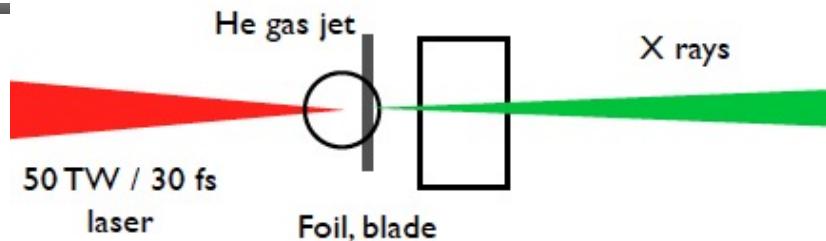
<http://loa.ensta.fr/>

lundi 3 juin 13

UMR 7639



Inverse Compton Scattering : New scheme



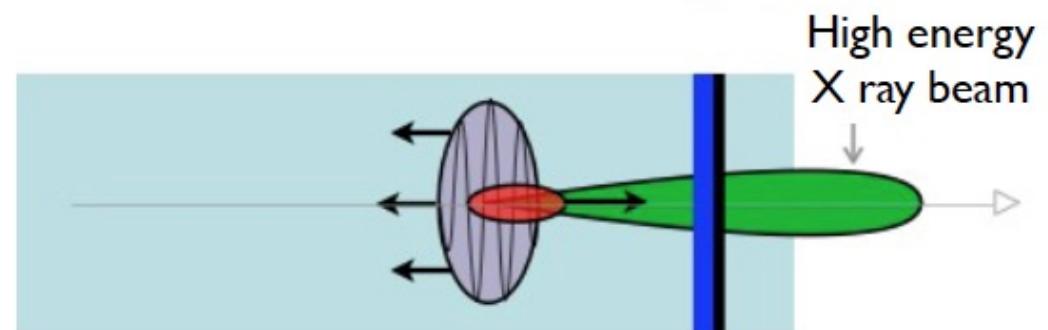
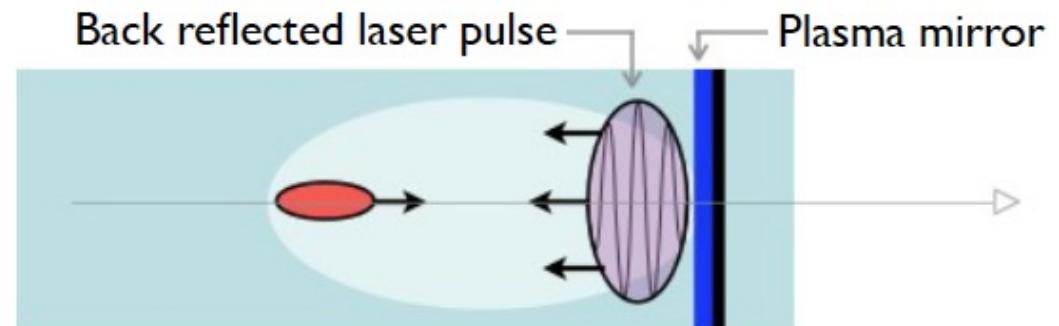
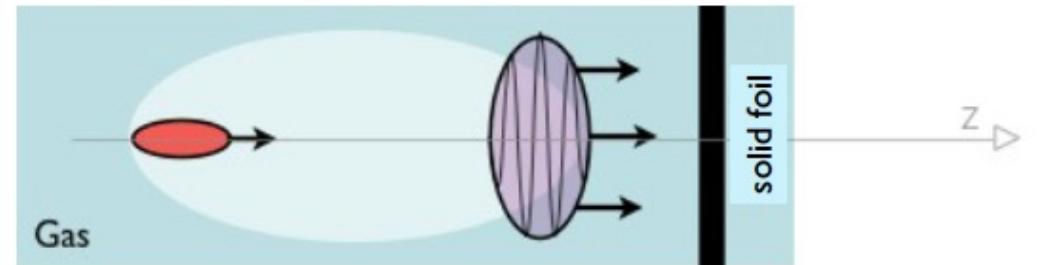
A single laser pulse

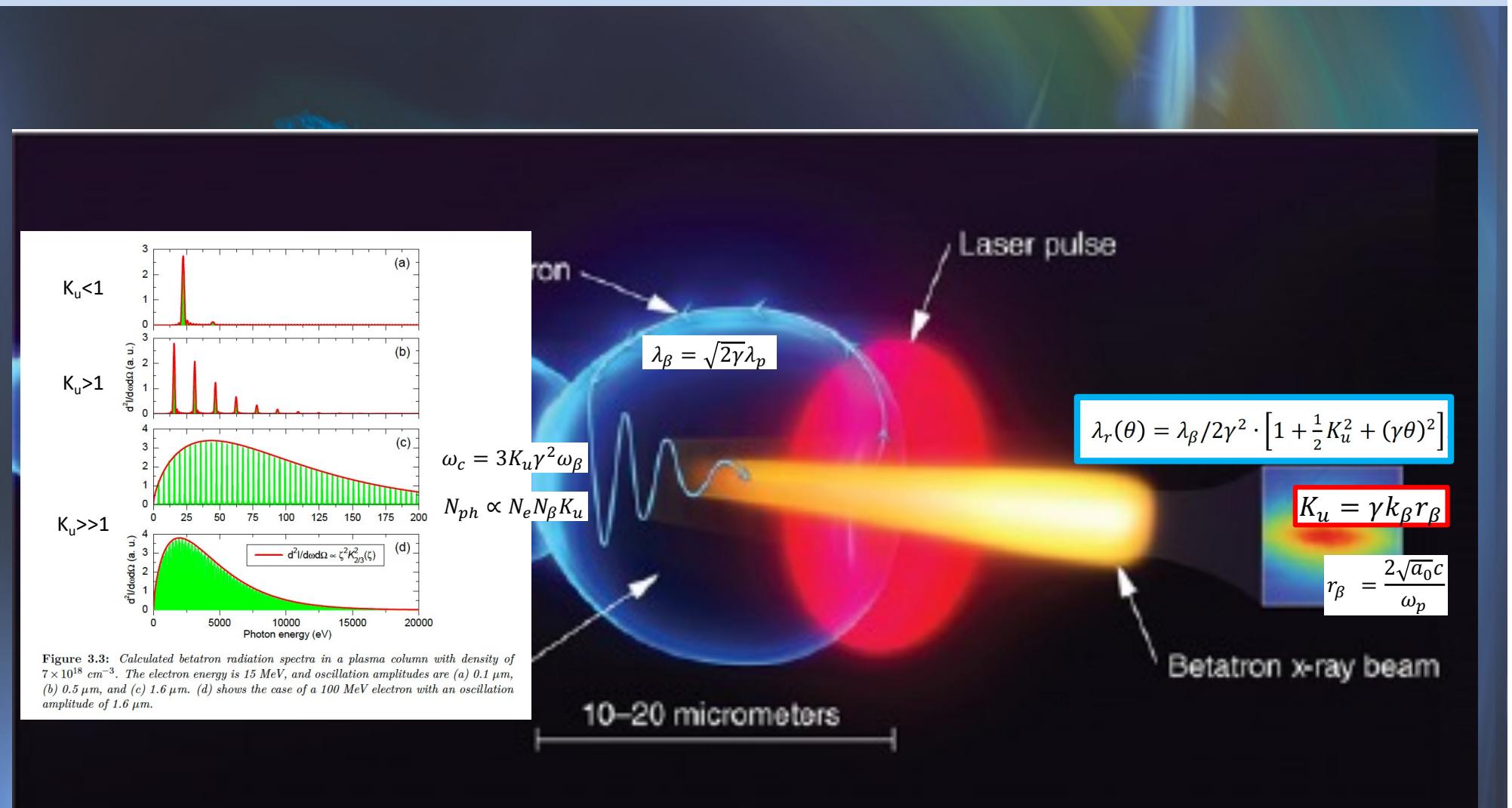
A plasma mirror reflects the laser beam

The back reflected laser collides with the accelerated electrons

No alignment : the laser and the electron beams naturally overlap

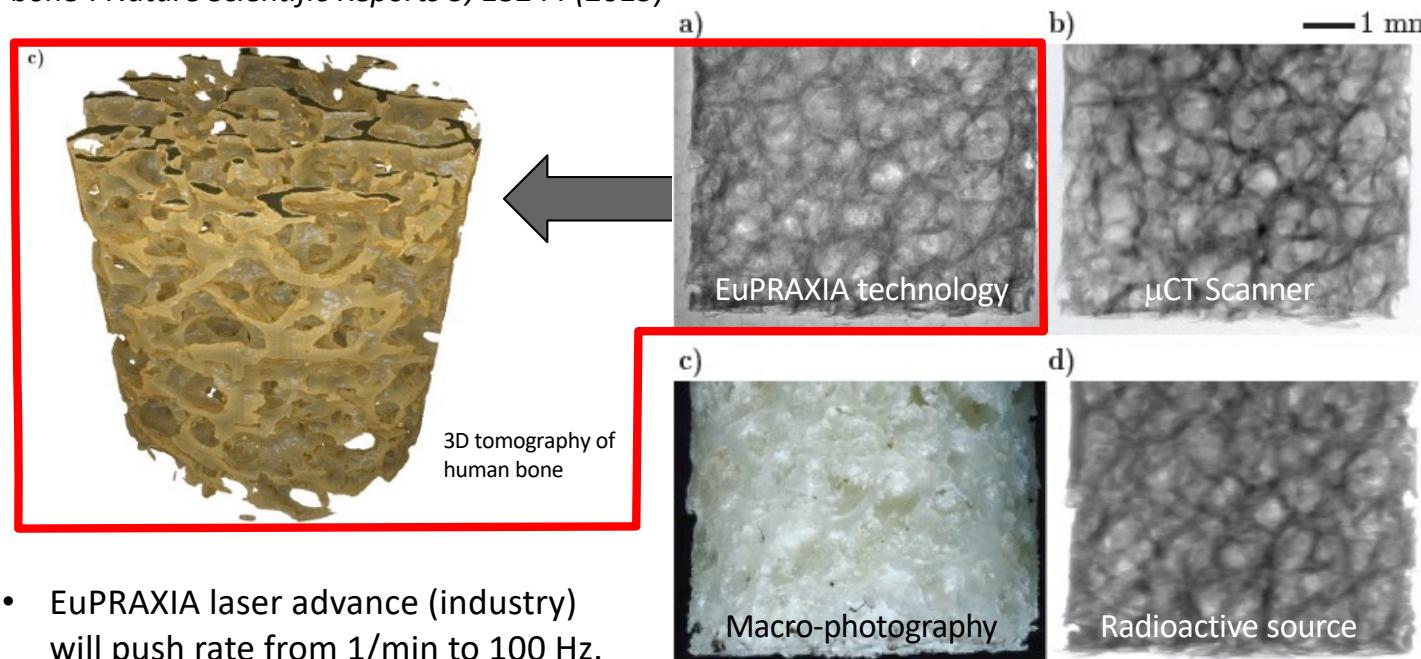
Save the laser energy !





Courtesy: Jinchuan Ju. Université Paris Sud - Paris XI, 2013

J.M. Cole et al, "Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone". *Nature Scientific Reports* 5, 13244 (2015)



- EuPRAXIA laser advance (industry) will push rate from 1/min to 100 Hz.
- **Ultra-compact source of hard X rays → exposing from various directions simultaneously is possible in upgrades**

Physics & Technology Background:

- Small EuPRAXIA accelerator → small emission volume for betatron X rays.
- **Quasi-pointlike** emission of X rays.
- **Sharper image from base optical principle.**
- Quality demonstrated and published, but takes a few hours for one image.
- Advancing flux rate with EuPRAXIA laser by factor > 1,000!

Added value

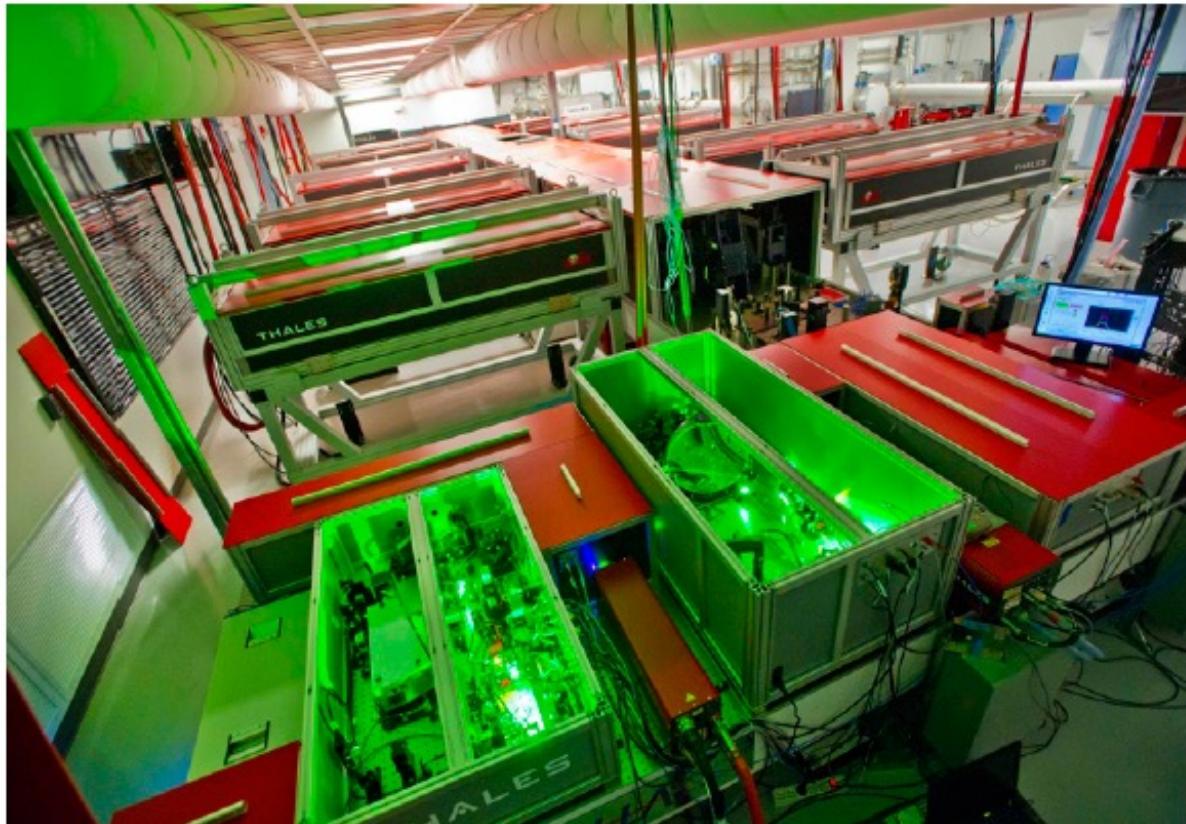
Sharper images with outstanding contrast

Identify smaller features (e.g. early detection of cancer at micron-scale – calcification)

Laser advance in EuPRAXIA → **fast imaging** (e.g. following moving organs during surgery)

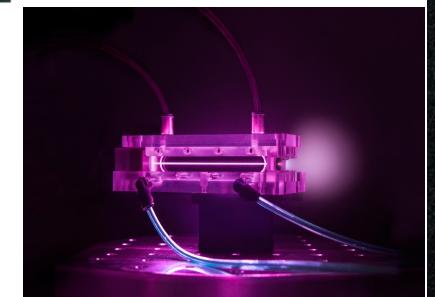
BELLA: BErkeley Lab Laser Accelerator

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

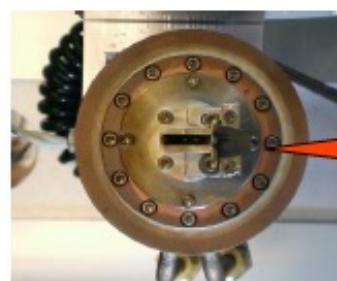
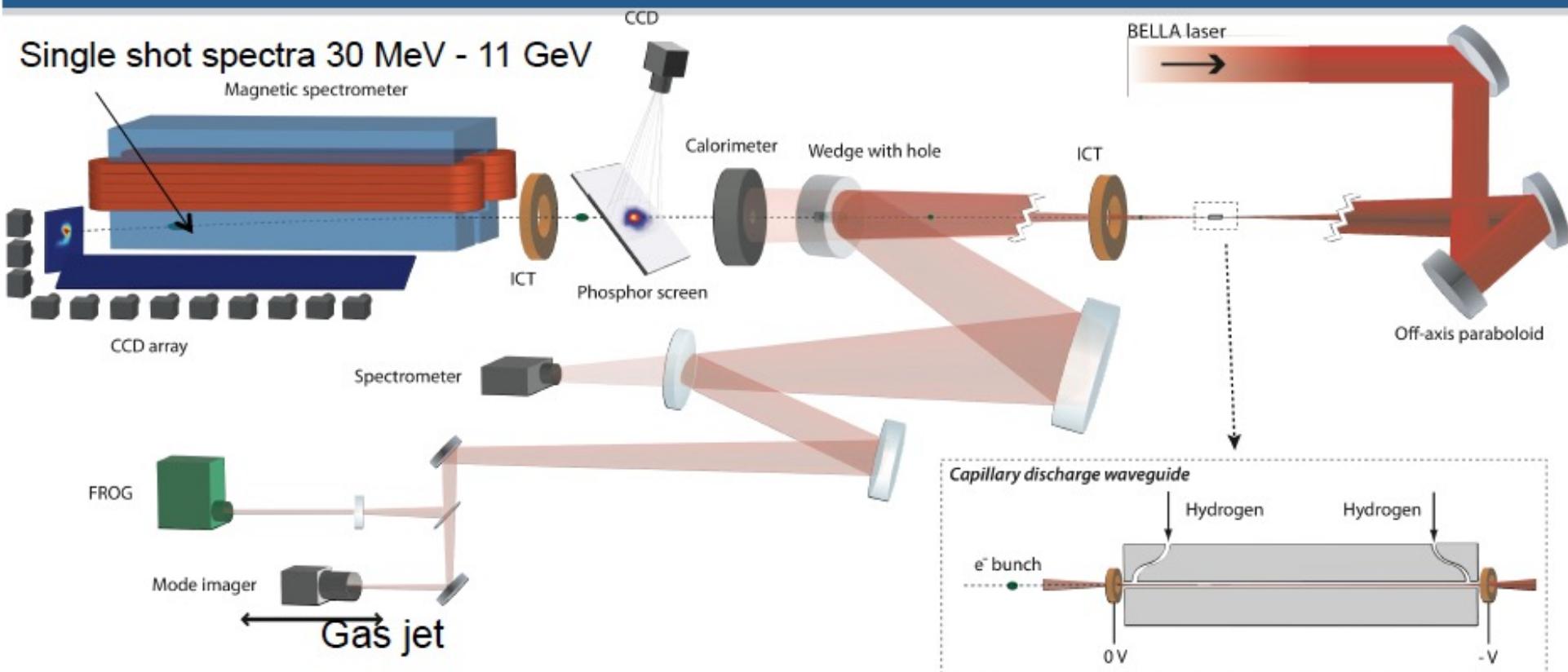


Critical HEP experiments:

- 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



Big Laser In

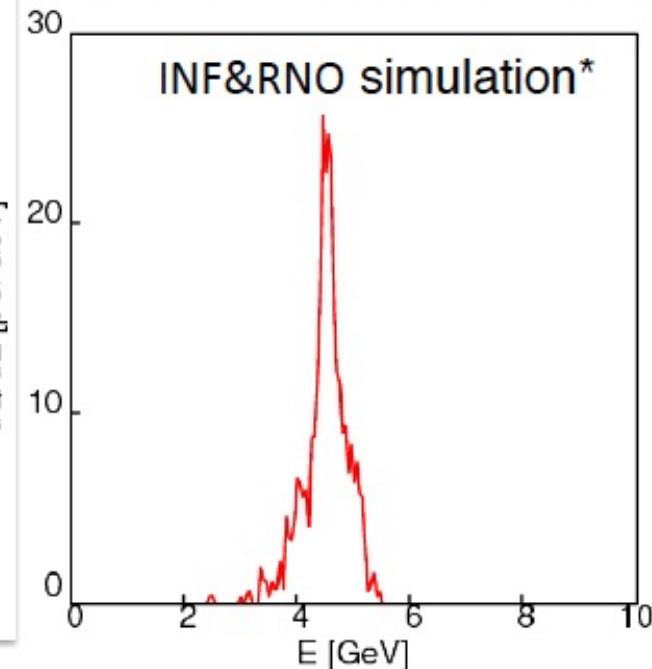
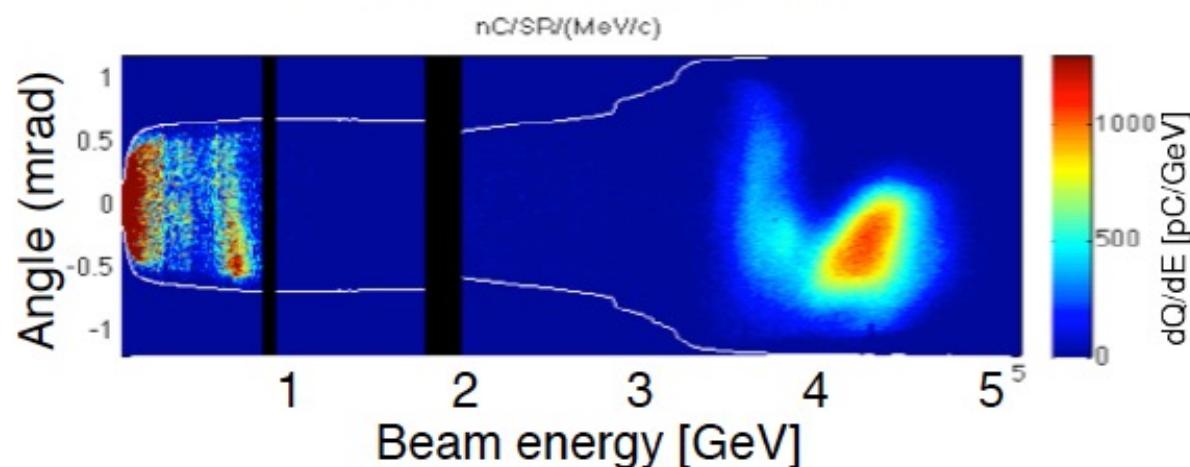


Capillary discharge

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

Electron beam spectrum



- **Laser ($E=15$ J):**
 - Measured longitudinal profile ($T_0 = 40$ fs)
 - Measured far field mode ($w_0 = 53 \mu\text{m}$)
- **Plasma:** parabolic plasma channel (length 9 cm, $n_0 \sim 6-7 \times 10^{17} \text{ cm}^{-3}$)

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

W.P. Leemans et al., PRL 2014



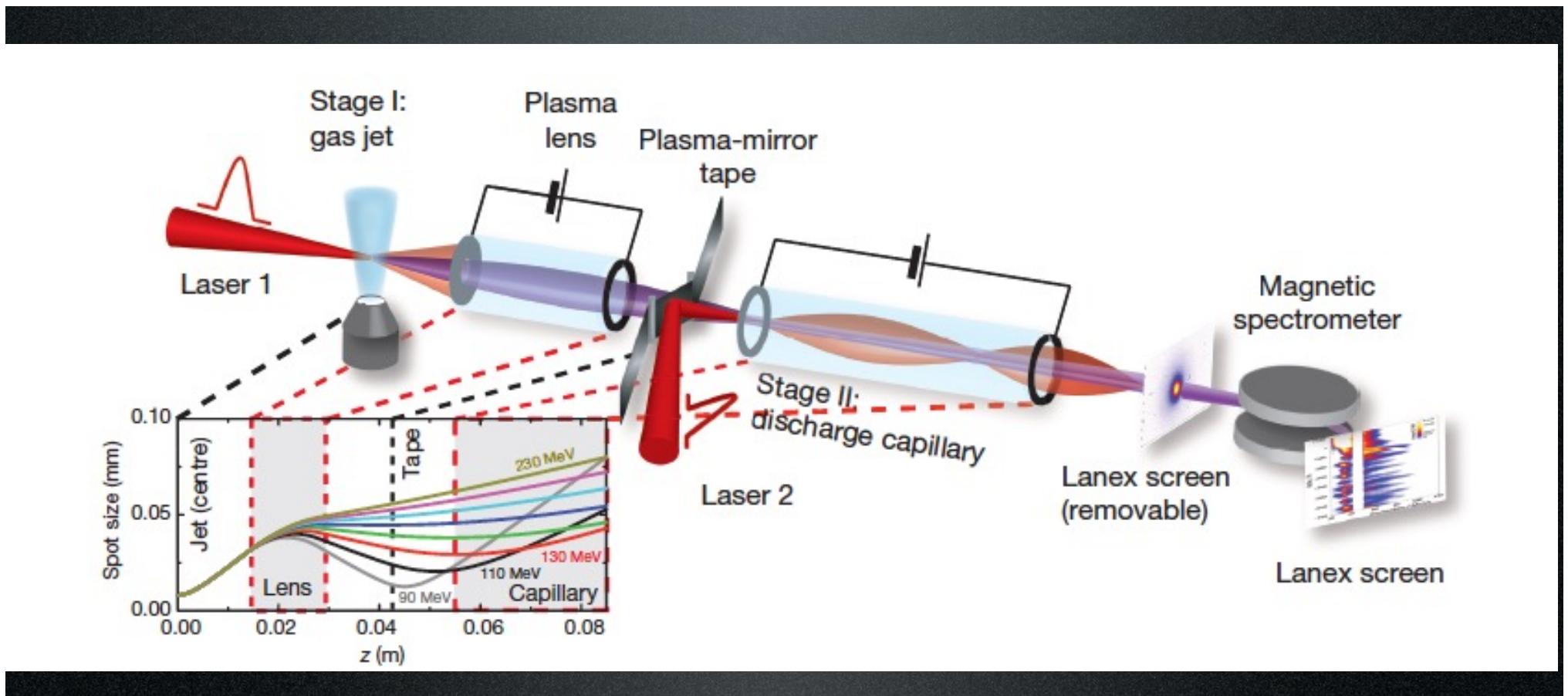
Office of
Science

ACCELERATOR TECHNOLOGY &
APPLIED PHYSICS DIVISION

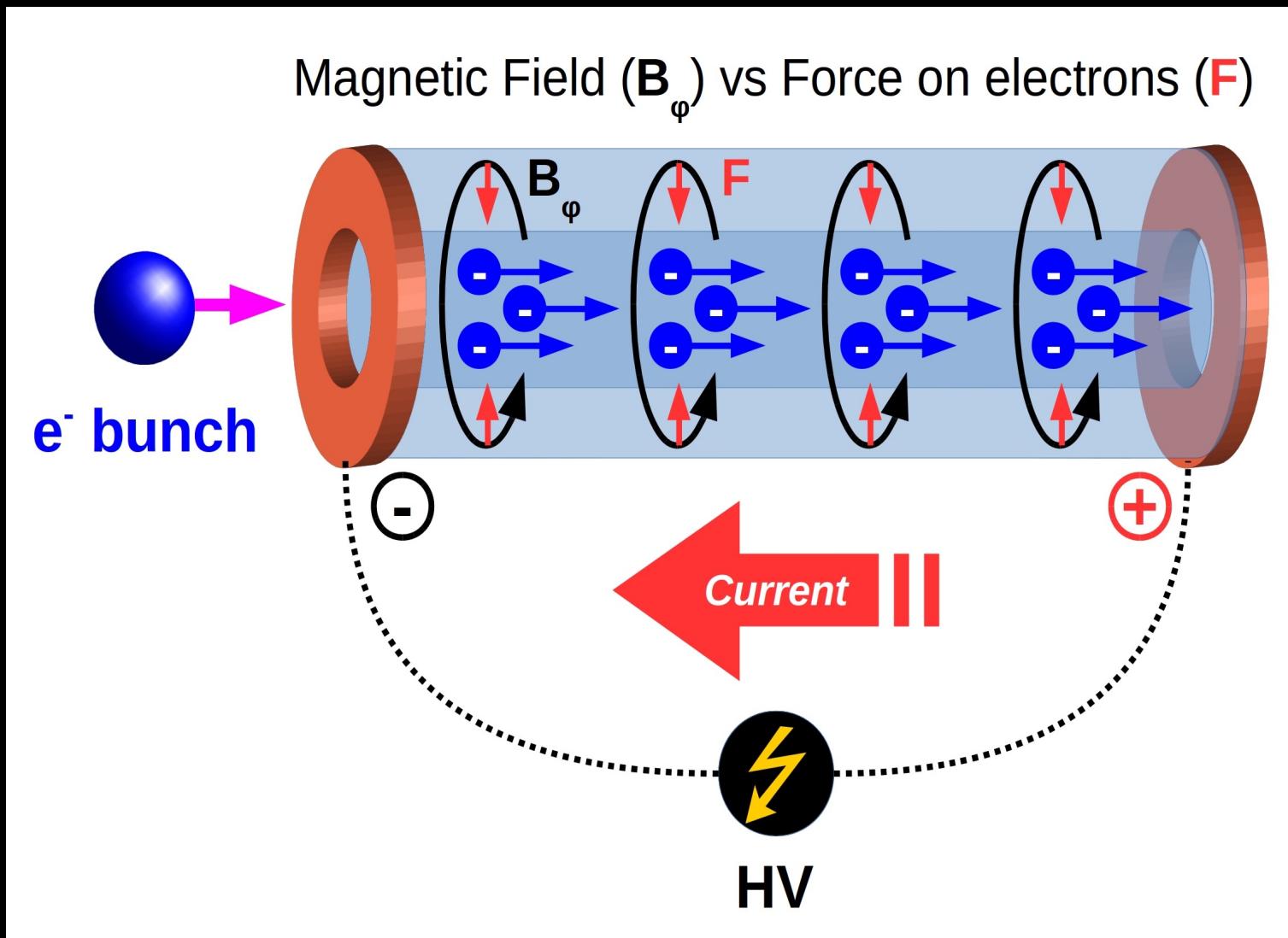


Multistage coupling of independent laser–plasma accelerators

S. Steinke¹, J. van Tilborg¹, C. Benedetti¹, C. G. R. Geddes¹, C. B. Schroeder¹, J. Daniels^{1,3}, K. K. Swanson^{1,2}, A. J. Gonsalves¹, K. Nakamura¹, N. H. Matlis¹, B. H. Shaw^{1,2}, E. Esarey¹ & W. P. Leemans^{1,2}



Active Plasma Lens

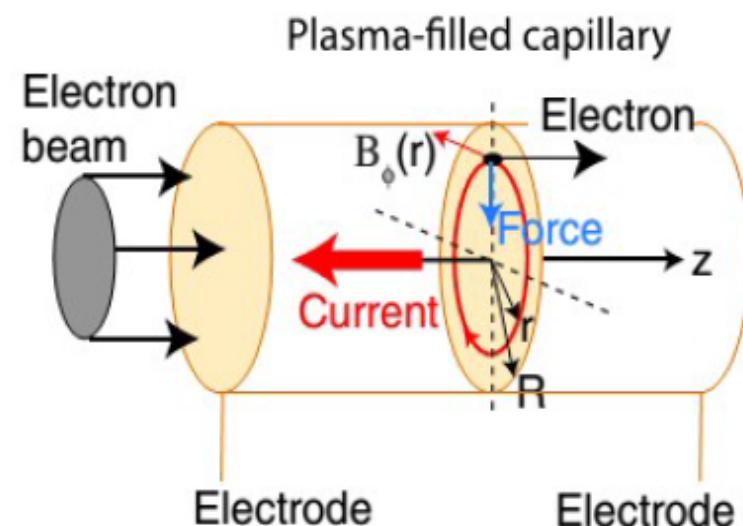


Active plasma lens

- 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.

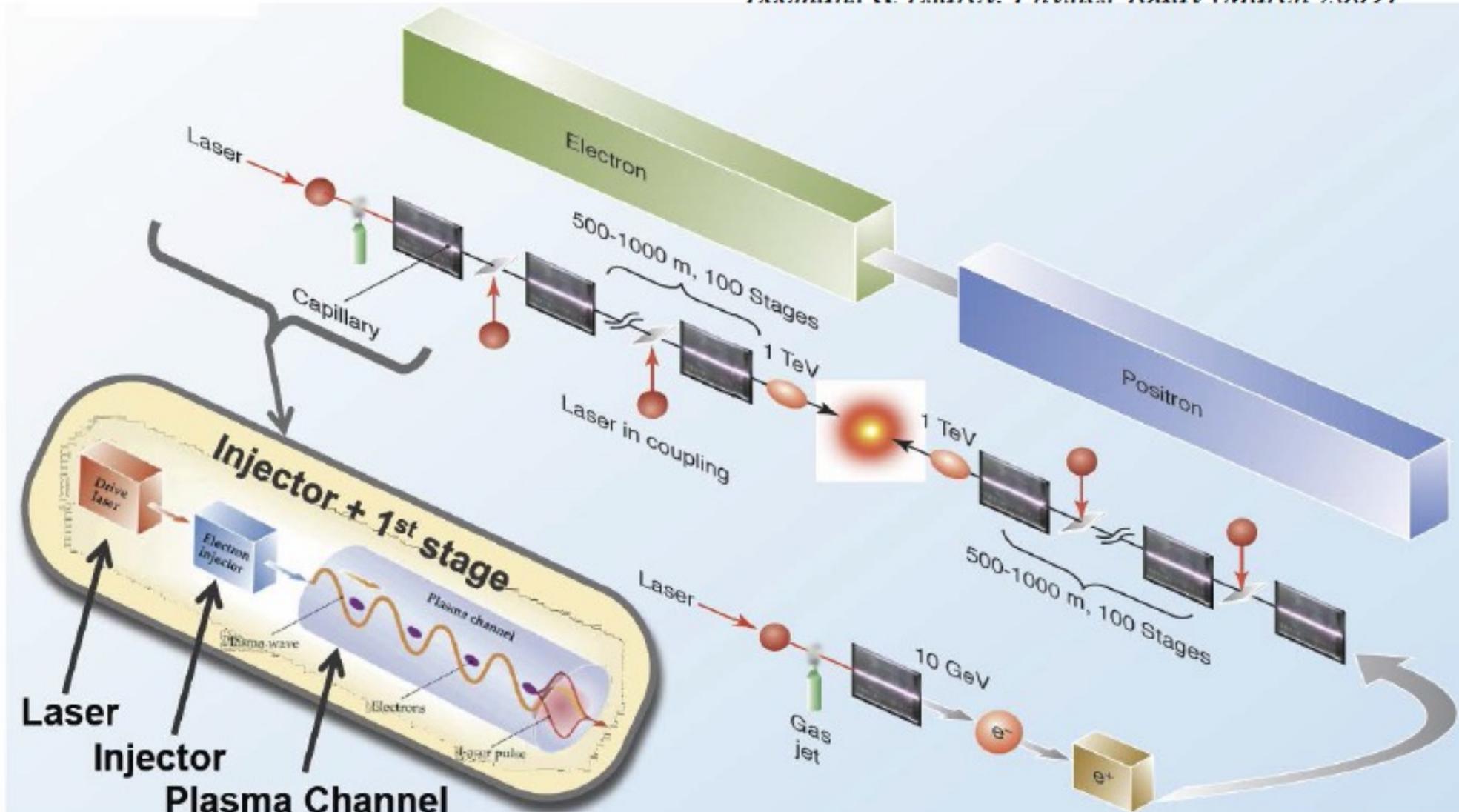
Beam Manipulation





Laser-Plasma-Accelerator LC

Leemans & Esarev. Physics Today (March 2009)





Parameter Set for LPWA LC

Case: CoM Energy (Plasma density)	1 TeV (10^{17} cm^{-3})	1 TeV ($2 \times 10^{15} \text{ cm}^{-3}$)	10 TeV (10^{17} cm^{-3})	10 TeV ($2 \times 10^{15} \text{ cm}^{-3}$)
Energy per beam (TeV)	0.5	0.5	5	5
Luminosity ($10^{34} \text{ cm}^{-2} \text{s}^{-1}$)	2	2	200	200
Electrons per bunch ($\times 10^{10}$)	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

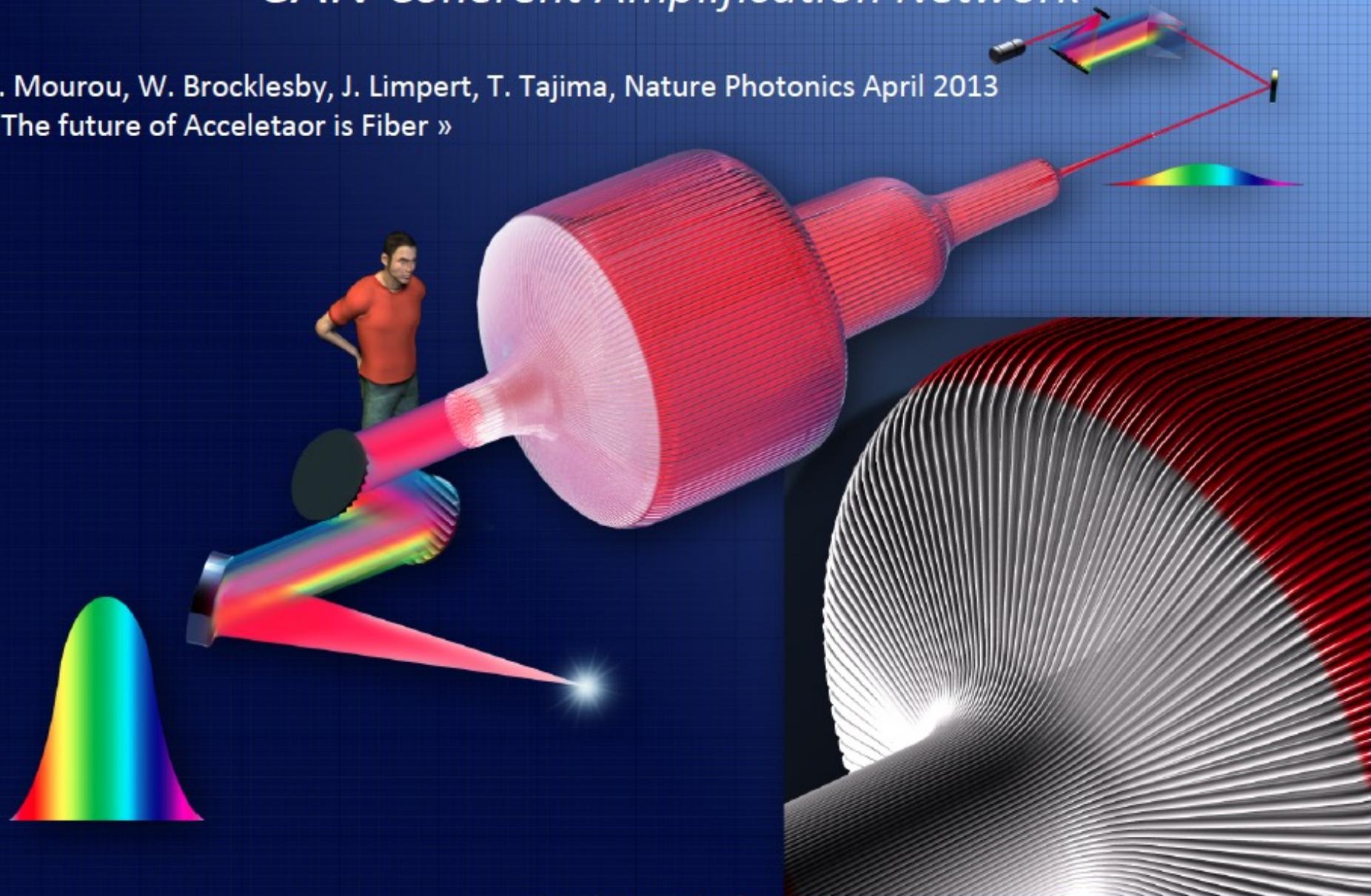


x2+FF

ICAN (European Project)

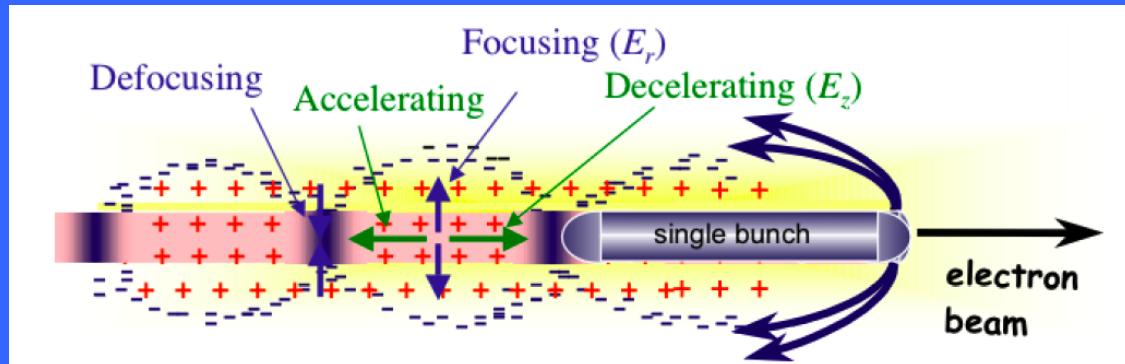
CAN Coherent Amplification Network

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

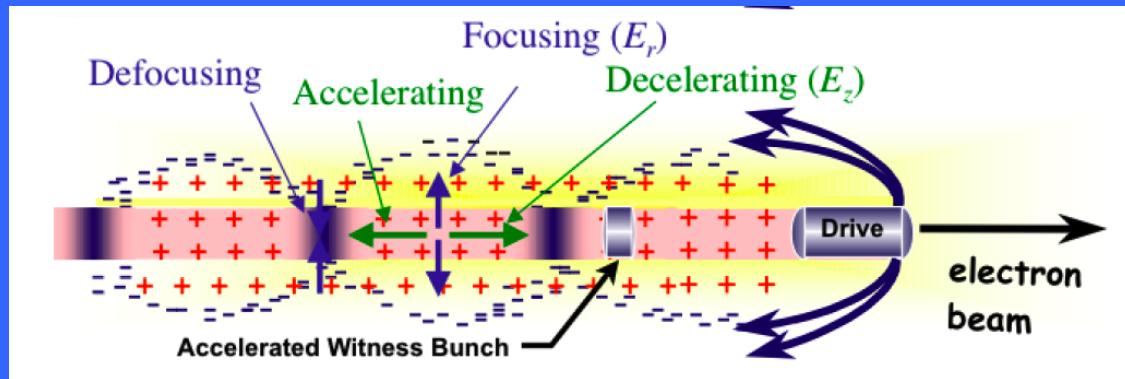


Gerard Mourou S.L Chin, Laval

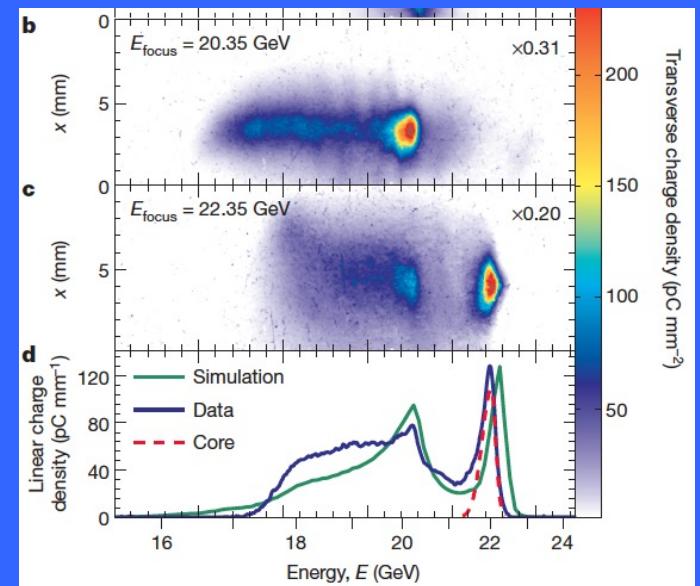
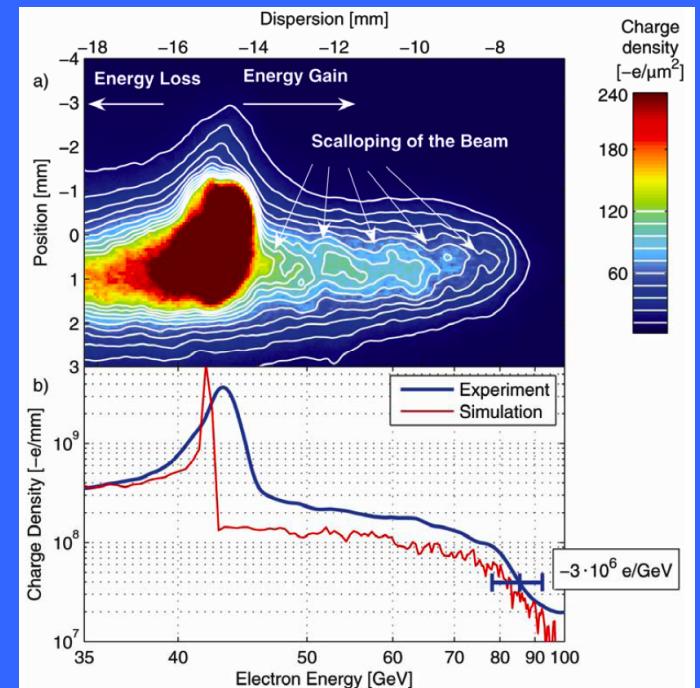
Beam Driven **PWFA**



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

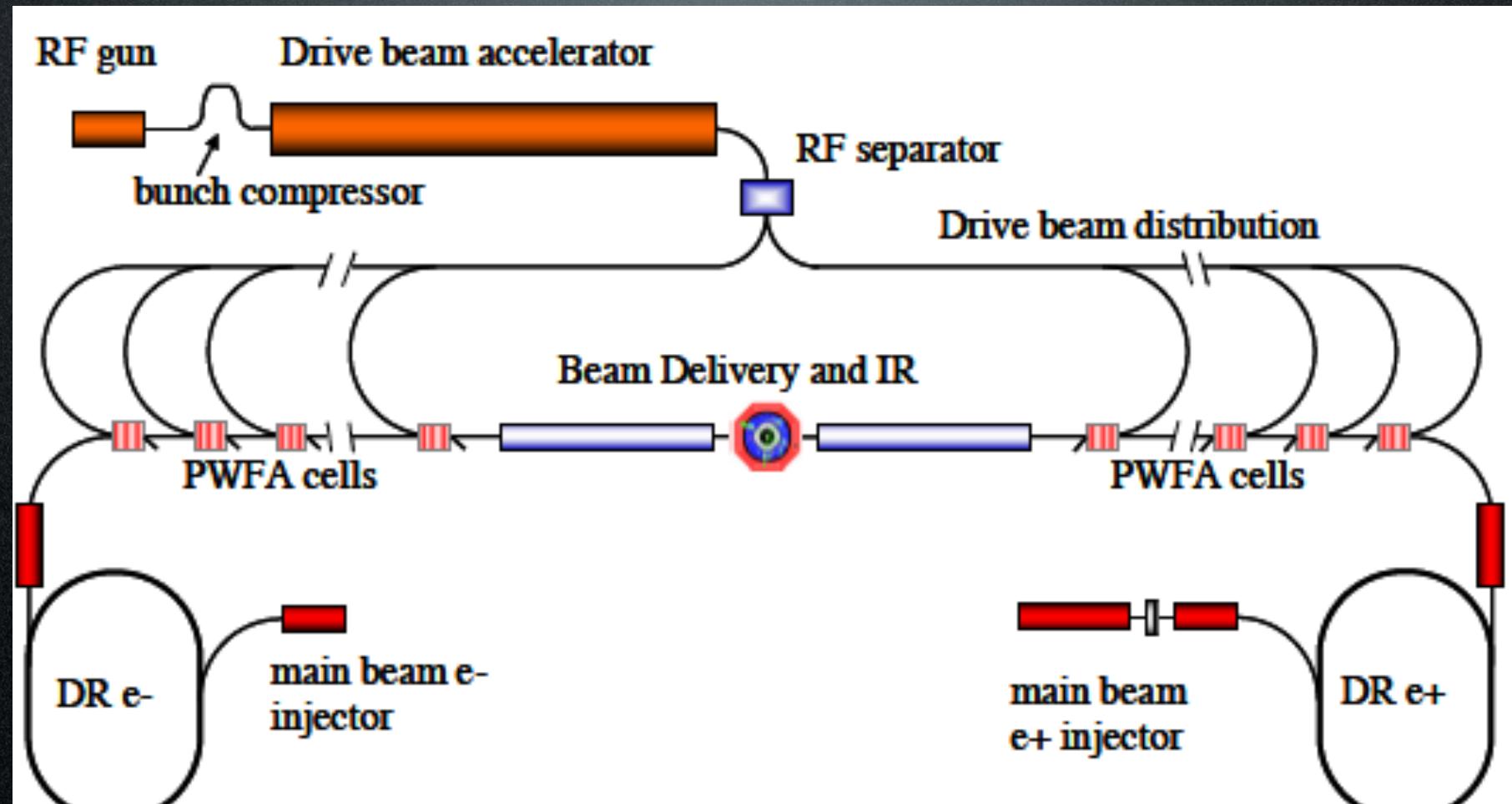


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

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

Main beam: bunch population, bunches per train, rate	1×10^{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 μ s
Average power of the drive beam	58 MW
Plasma density, accelerating gradient and plasma cell length	$1 \times 10^{17} \text{ cm}^{-3}$, 25 GV/m, 1 m
Power transfer efficiency drive beam=>plasma =>main beam	35%
Efficiency: Wall plug=>RF=>drive beam	$50\% \times 90\% = 45\%$
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 μ m
Luminosity	$3.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Luminosity in 1% of energy	$1.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

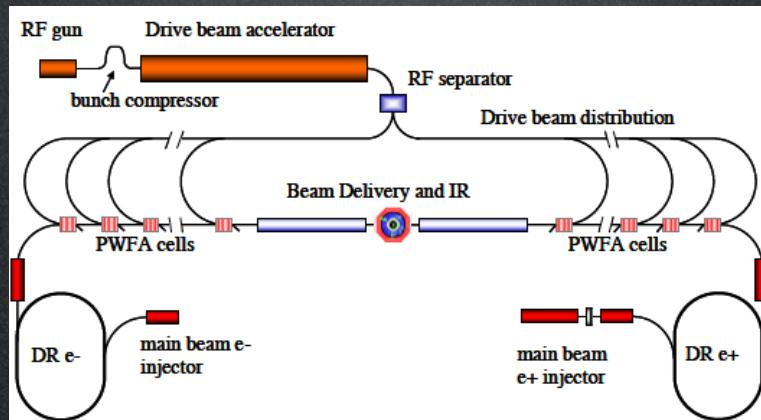


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

Positron Acceleration, FACET



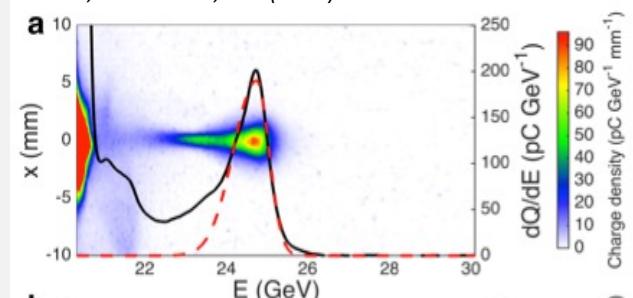
Positrons for high energy linear colliders: high energy, high charge, low emittance.

First demonstration of positron acceleration in plasma (FFTBB)

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)



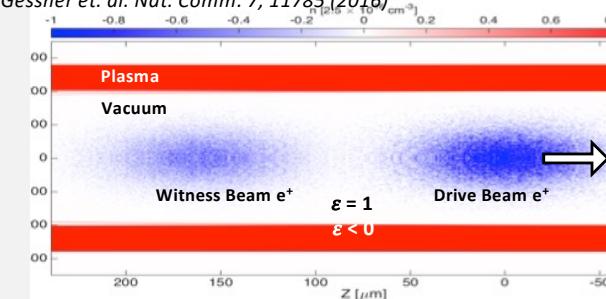
High-density, compressed positron beam for non-linear PWFA experiments. Energy transfer from the front to the back part of the bunch.

Two-bunch positron beam: First demonstration of

controlled beam in positron-driven wake
S. Doche et al., Nat. Sci. Rep. 7, 14180 (2017)

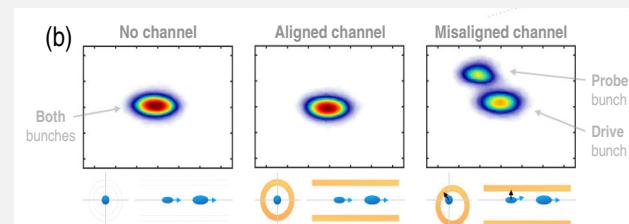
Hollow plasma channel: positron propagation, wake excitation, acceleration in 30 cm channel.

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

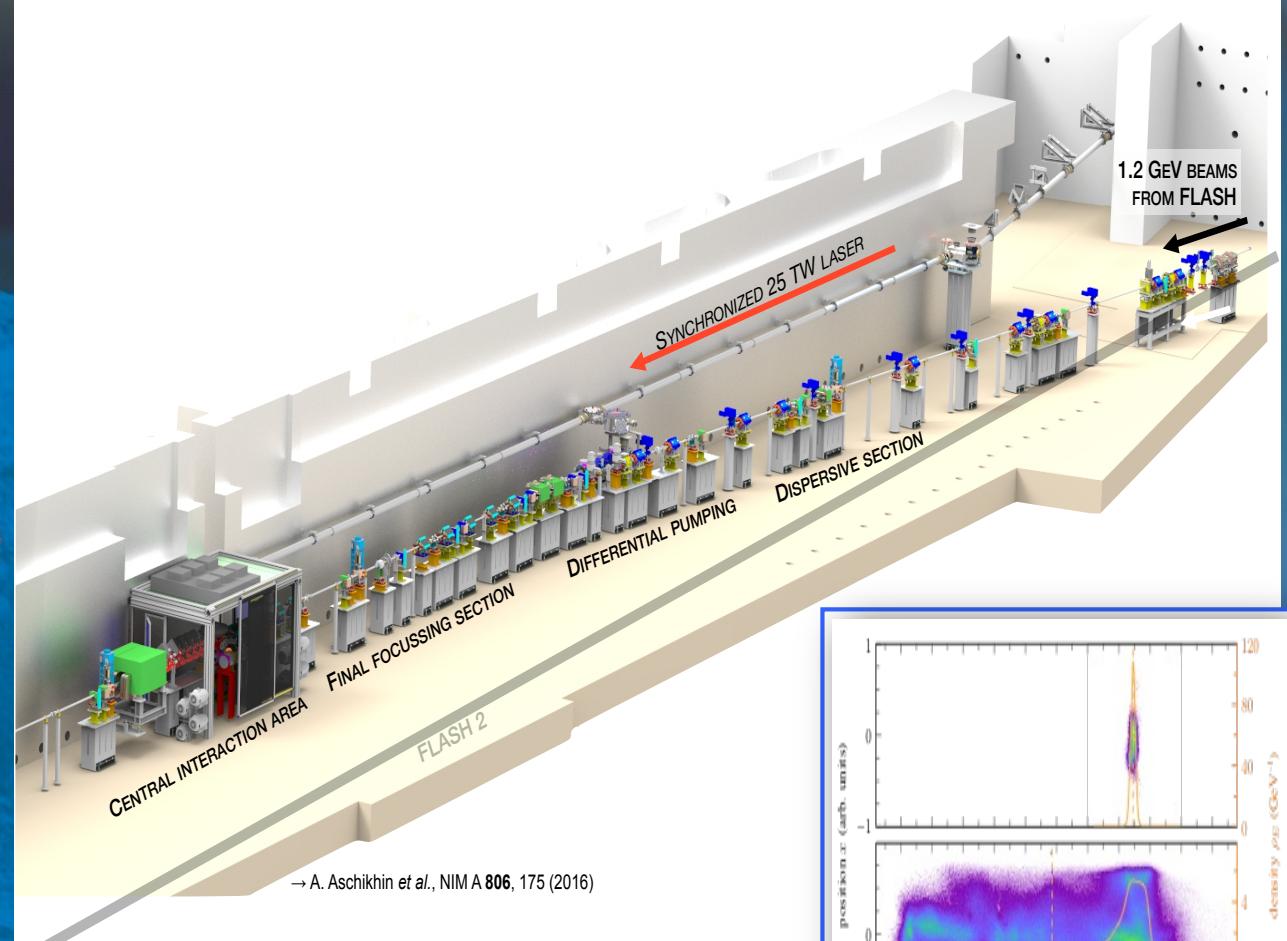
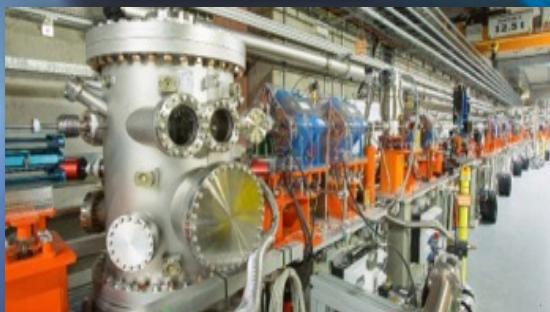


→ unique FLASH facility features for PWFA

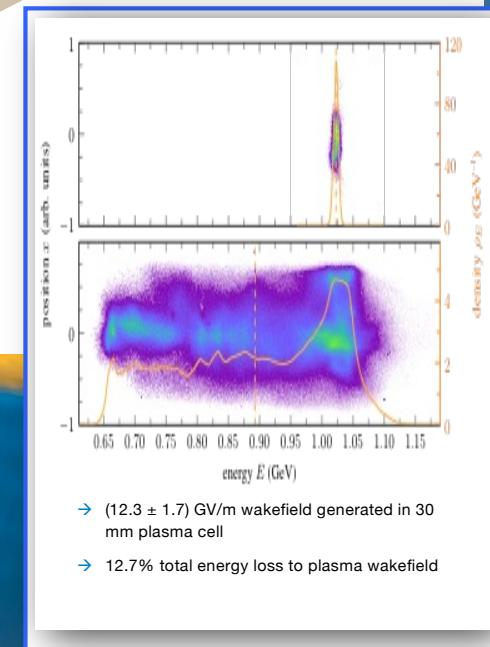
- FEL-quality drive and witness beams
- up to 1 MHz repetition rate
- 3rd harmonic cavity for phase-space linearization
→ tailoring of beam current profile
- differentially pumped, windowless plasma sources
- 2019: X-band deflector of 1 fs resolution post-plasma (collaboration with FLASH 2, SINBAD, CERN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



plasma source
30 mm long (up to 450 mm possible)



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



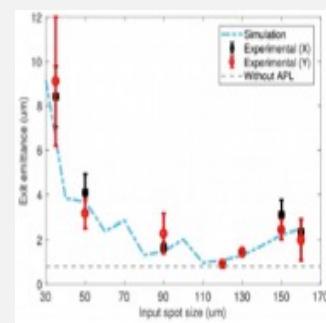
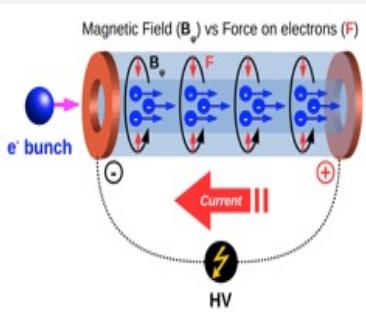
SPARC_LAB, Frascati, Italy



→ 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:

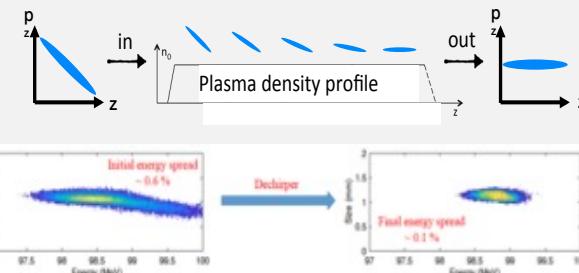


R. Pompili et al., PRL 121 (2018), 174801

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

P. Muggli, 06/04/2013, EAAC 2103

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



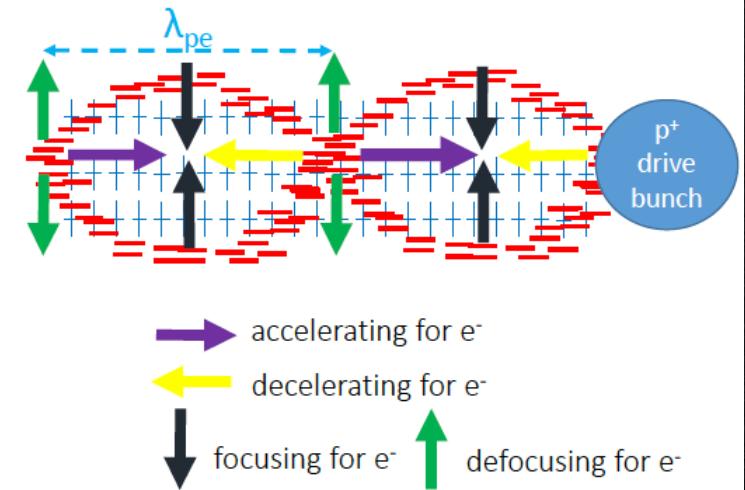
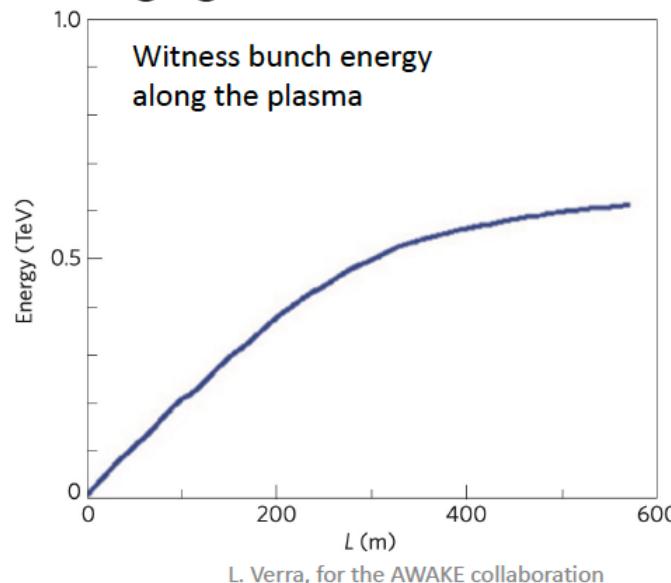
Reasons for proton bunch driver

Available proton bunches carry large amounts of energy:

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

⇒ Overcome the need of staging!

Parameters:
single proton bunch
 $\sigma_z = 100 \mu\text{m}$,
 $E = 1 \text{ TeV}$,
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

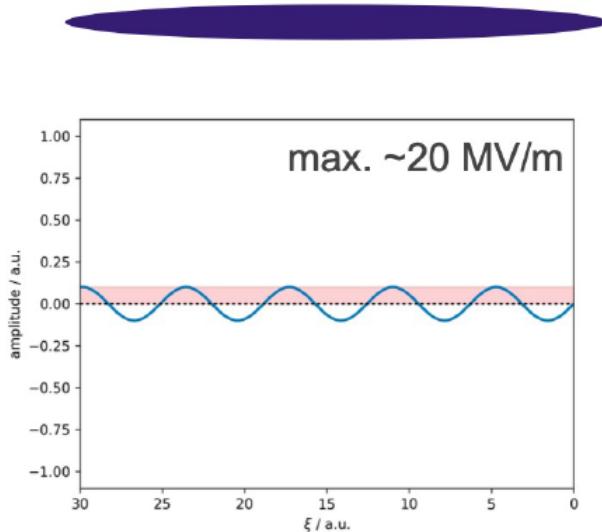
scalability of electric circuit for plasmas > 10 m seem achievable...

Self-modulation in plasma

CERN SPS Proton bunch

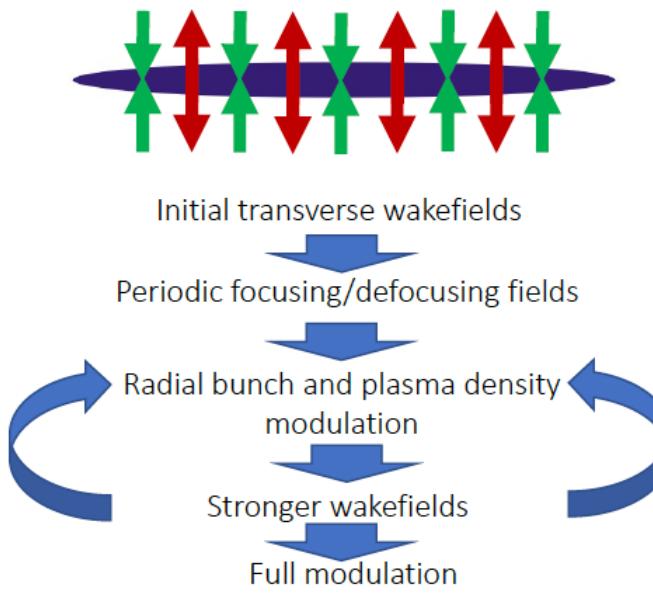
$$\sigma_r \approx 200 \mu\text{m} \rightarrow n_{pe} \approx 7 \cdot 10^{14} \text{ cm}^{-3}$$

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



21.09.2021

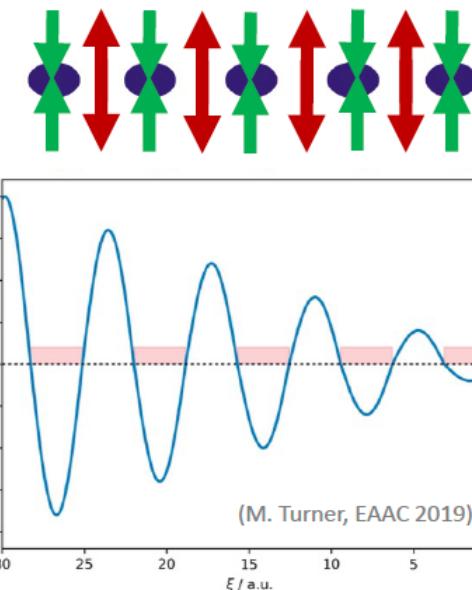
Growth mechanism



L. Verra, for the AWAKE collaboration

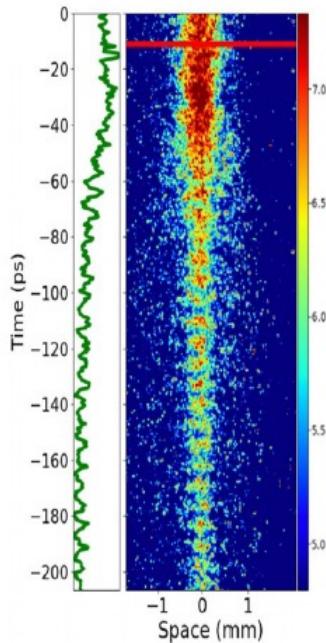
Self-Modulation instability (SMI)

- 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)

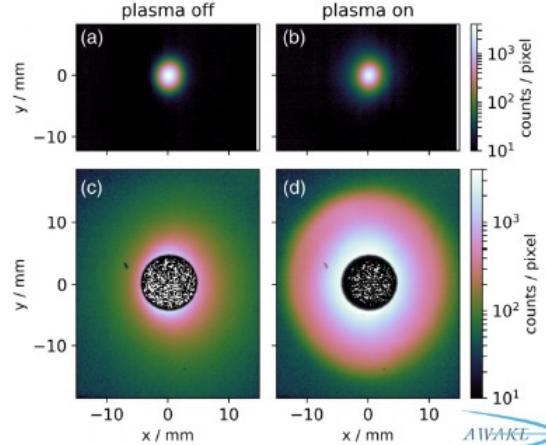
AWAKE Run 1 (2016-2018)



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

time-resolved imaging:

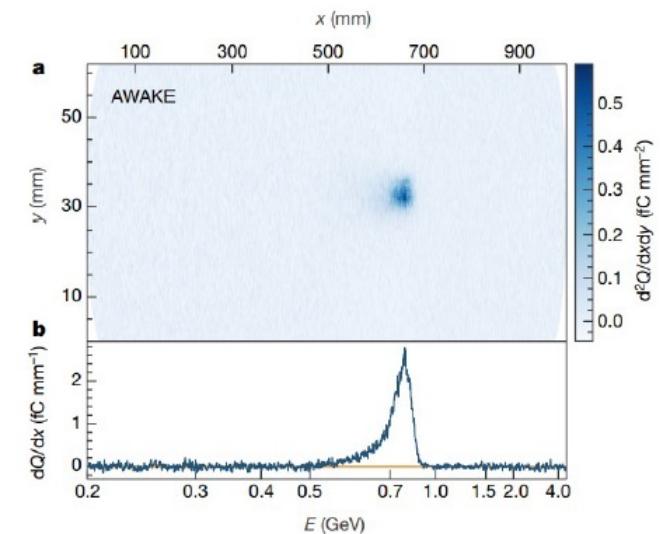
- the proton bunch self-modulates in plasma
- focusing phase → micro-bunches
- frequency of the modulation $\approx \omega_{pe}$



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

time-integrated, transverse imaging:

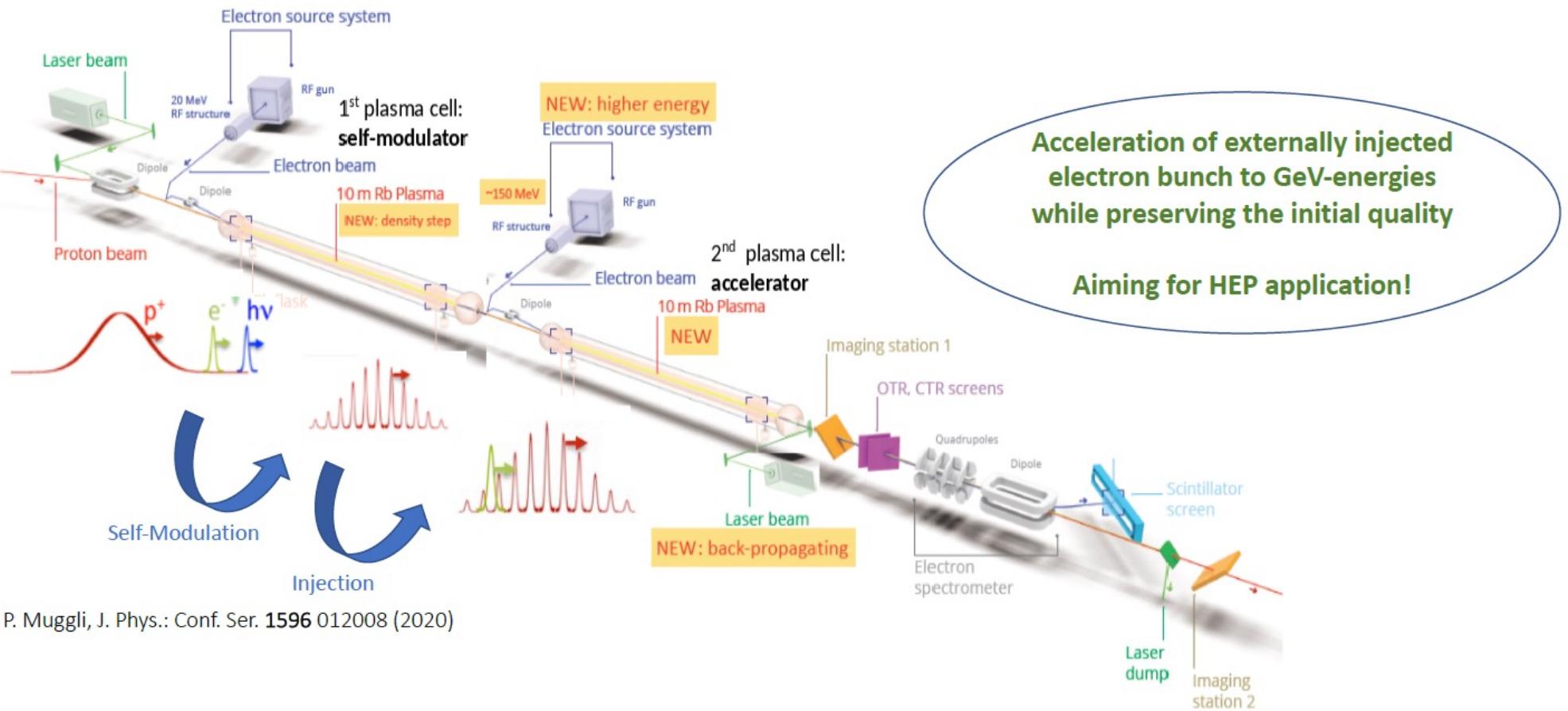
- defocusing phase → large halo
- wakefields grow along the plasma



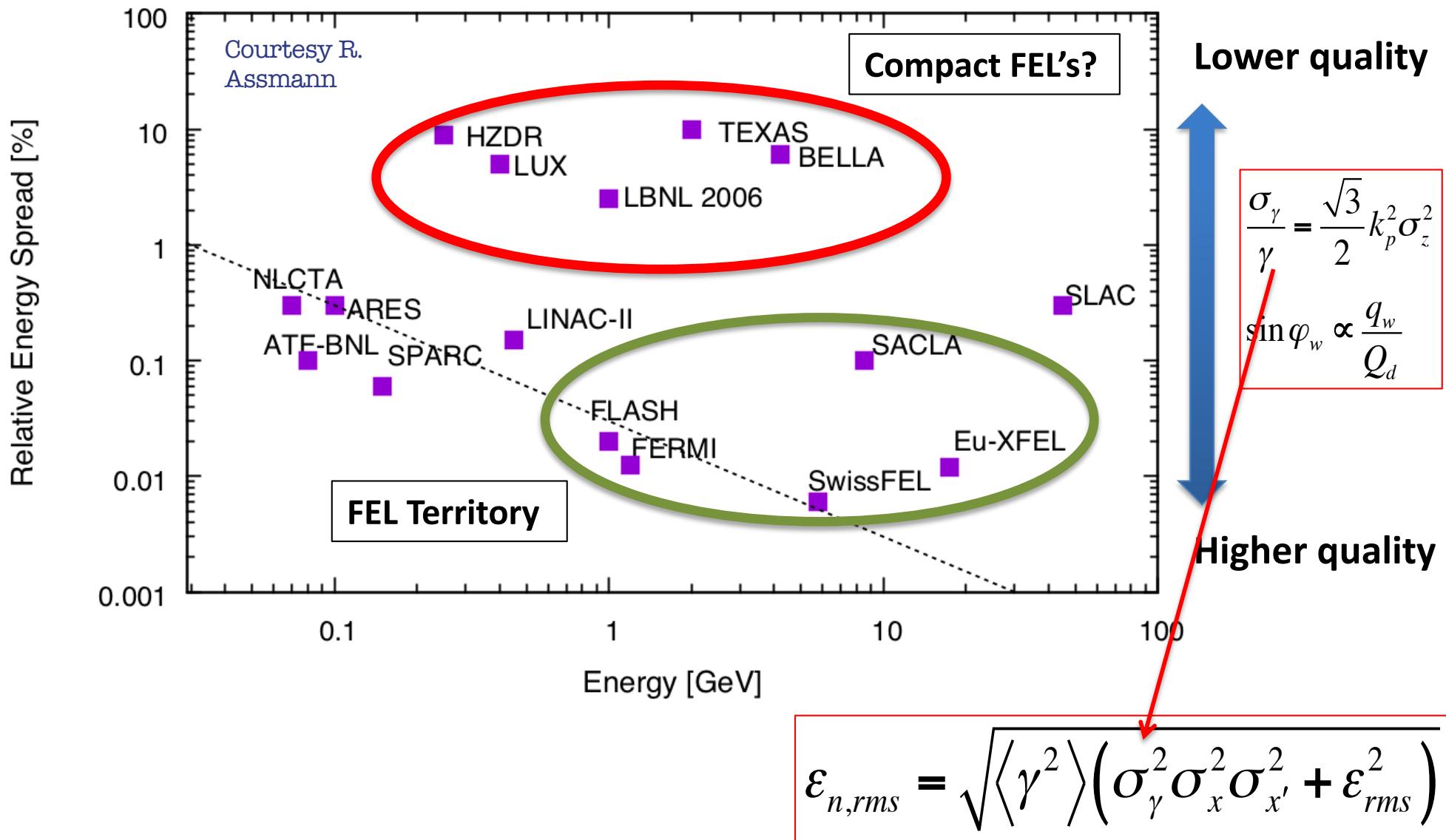
AWAKE Coll., Nature 561, 363-367 (2018)

19 MeV electrons can be injected into the wakefields and accelerated to GeV-energies
PROOF OF PRINCIPLE!

AWAKE Run 2 (2021→) setup & final goal



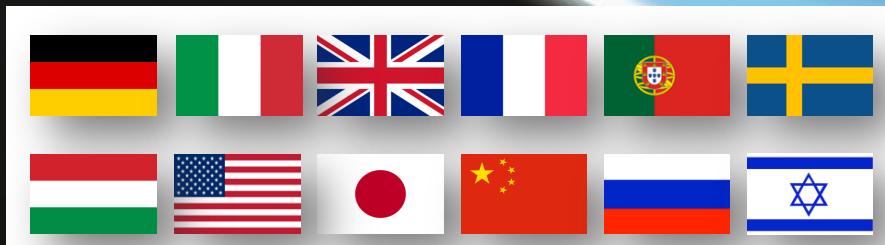
The near future



EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS



EuPRAXIA Design Study started on November 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>

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/>



- 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 placed on ESFRI roadma.



653 page CDR, 240 scientists contributed

Great News 30.6.2021

Building the first plasma accelerator facility

The screenshot shows the ESFRI website homepage. The top navigation bar includes links for Login, ESFRI MOS, and Co. Below the navigation is a secondary menu with links for ABOUT, ESFRI ROADMAP, EVENTS, NEWS, WORLD OF RIS, LIB, and CONTACT. The main content area features a blue banner with the text "New RIs for Roadmap 2021 announced" and "ROADMAP 2021". Below the banner, the date "30.06.2021" and the title "PRESS RELEASE" are displayed. The main text reads: "ESFRI announces the 11 new Research Infrastructures to be included in its Roadmap 2021" and "€4.1 billion investment in excellent science contributing to address European challenges". A detailed paragraph explains the selection process: "After two years of hard work, following a thorough evaluation and selection procedure, ESFRI proudly announces the 11 proposals that have been scored high for their science case and maturity for implementation and will be included as new Projects in the ESFRI 2021 Roadmap Update."

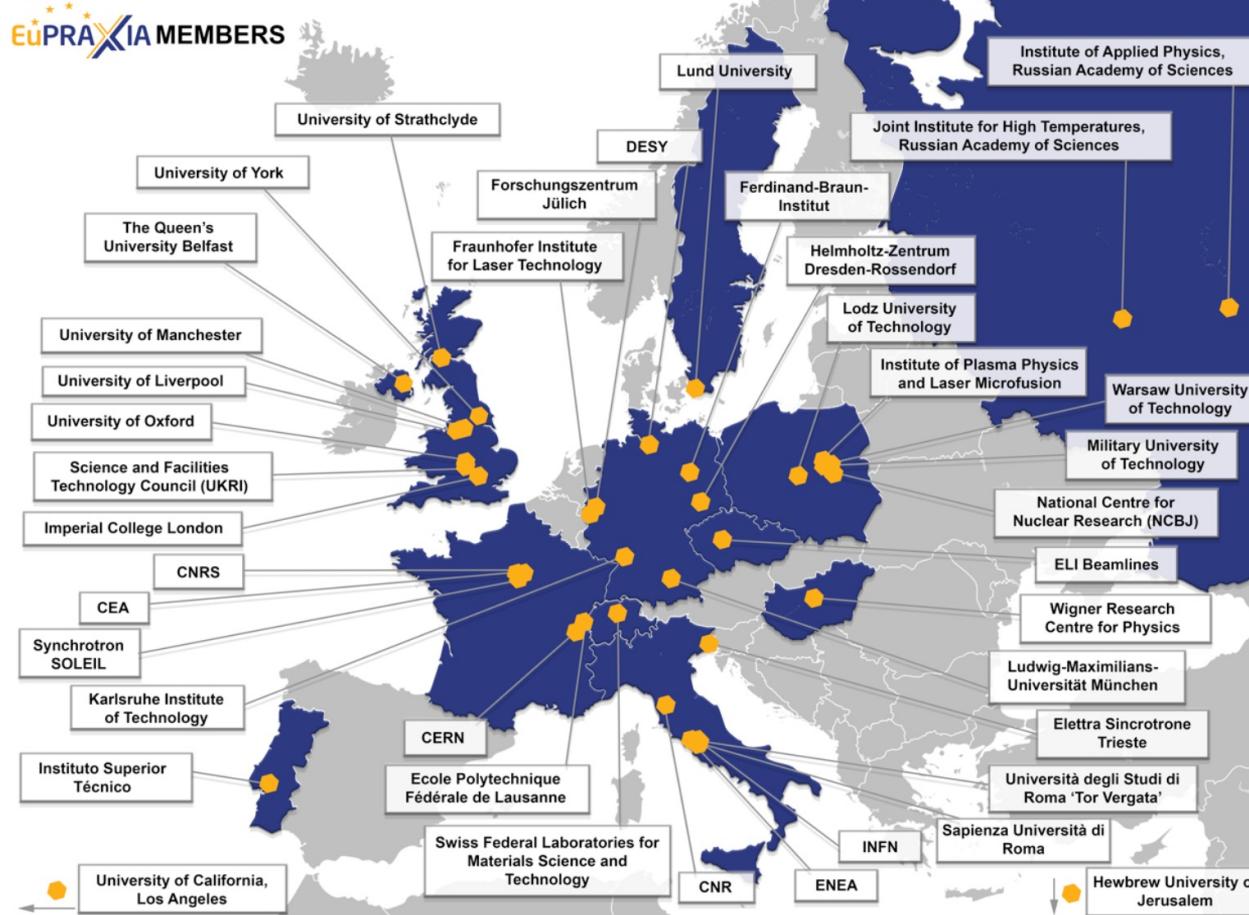
DESY. New Particle Acceleration Methods for High Energy Physics | Ralph Assmann | RWTH Seminar 07/2021

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)

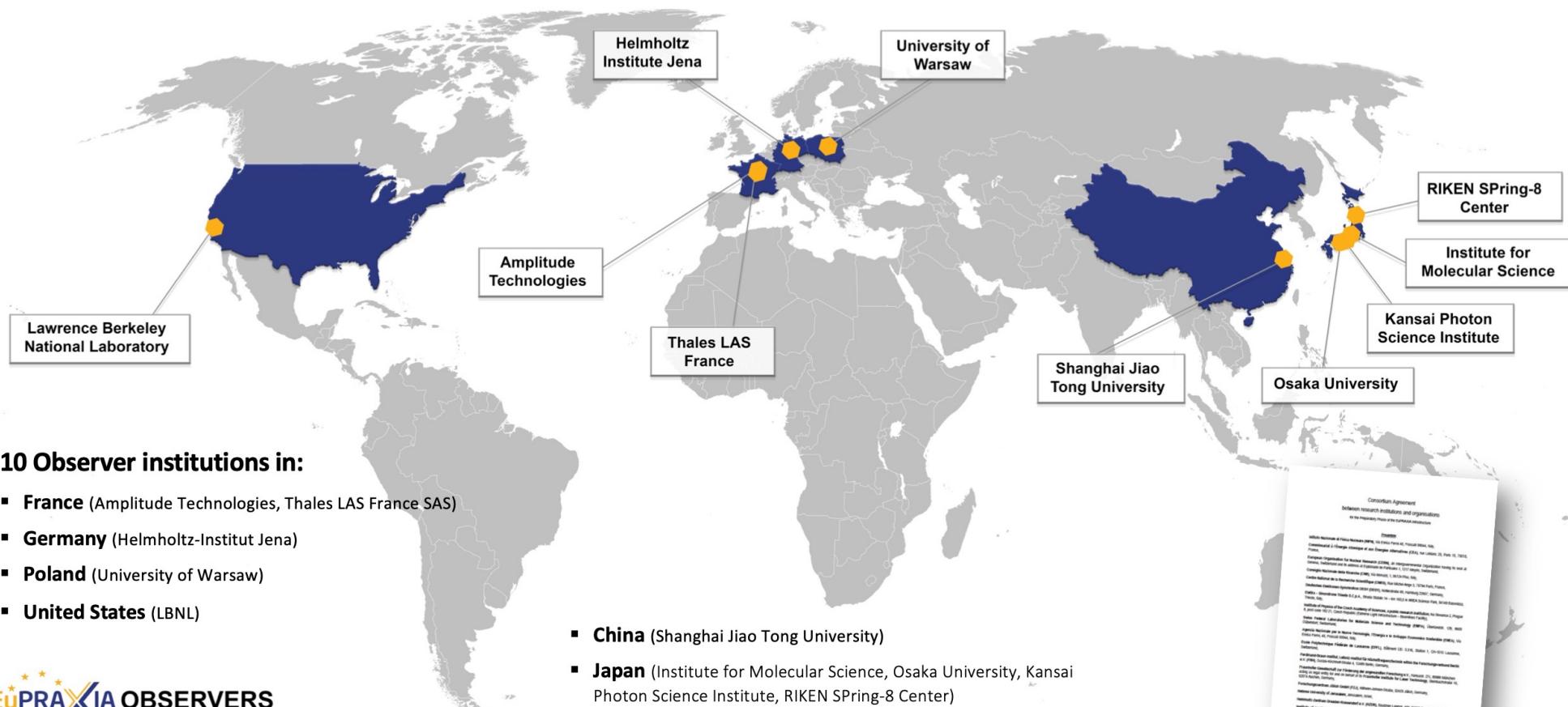


40 Member institutions in:

- **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)

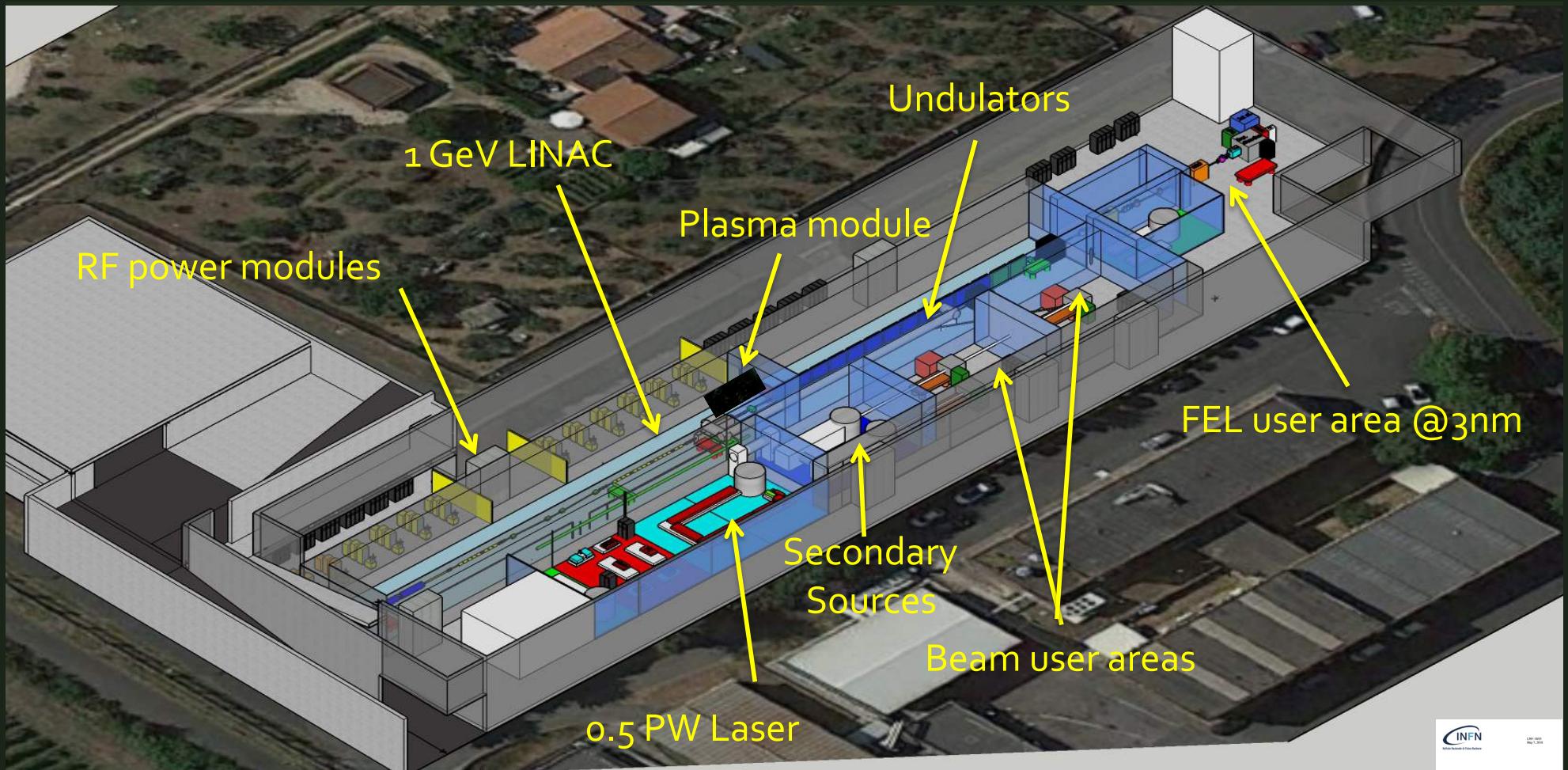


EuPRAXIA site studies:

- 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>



March 2022 - First discharge in EuPRAXIA @ SPARC_LAB
plasma acceleration module turned on

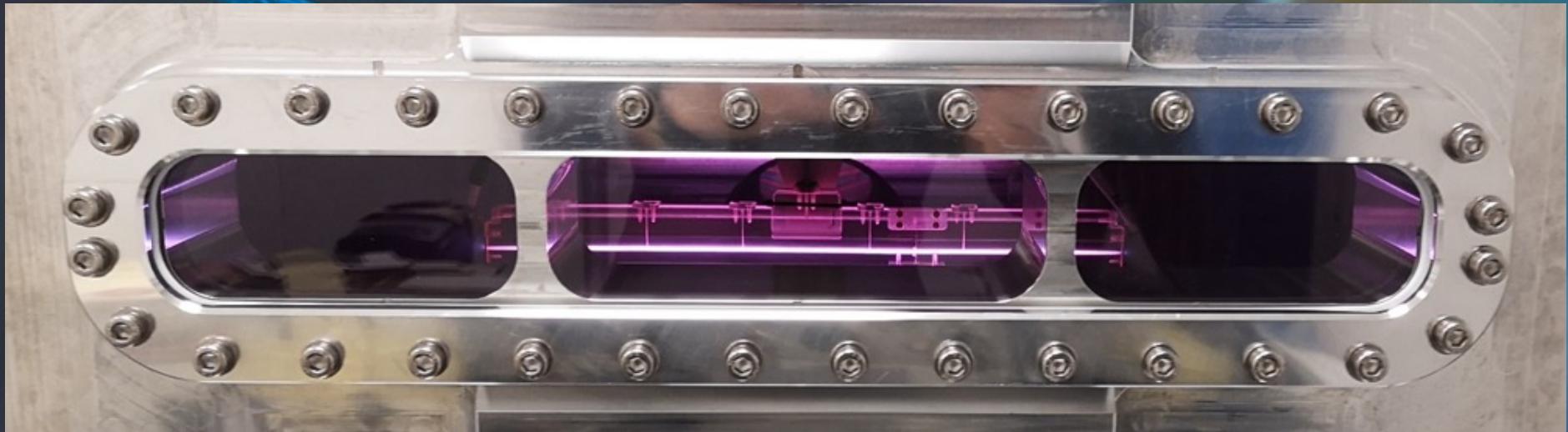
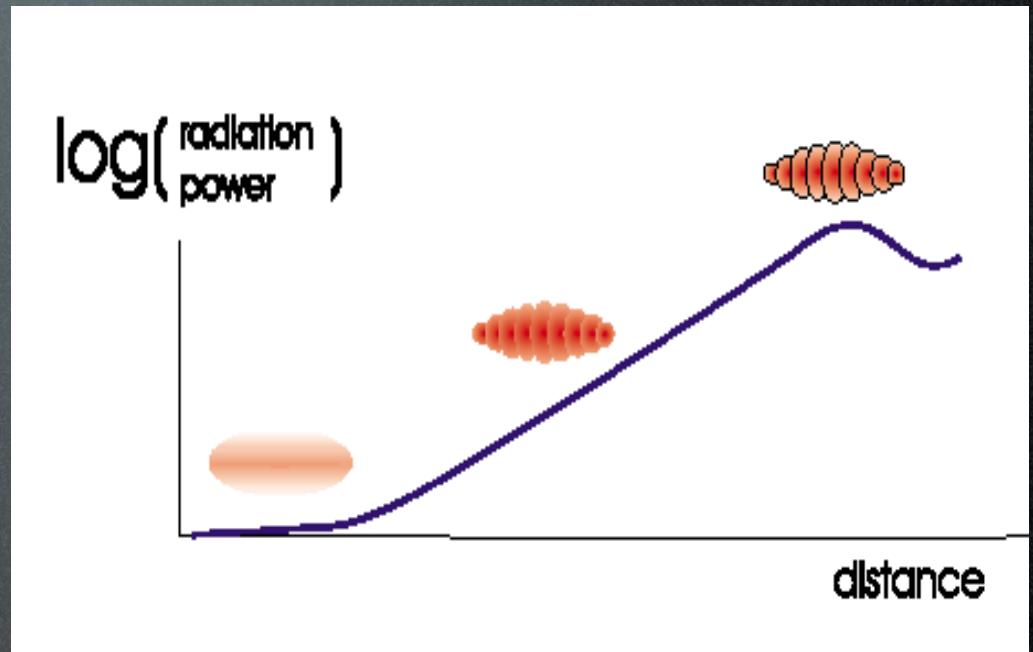
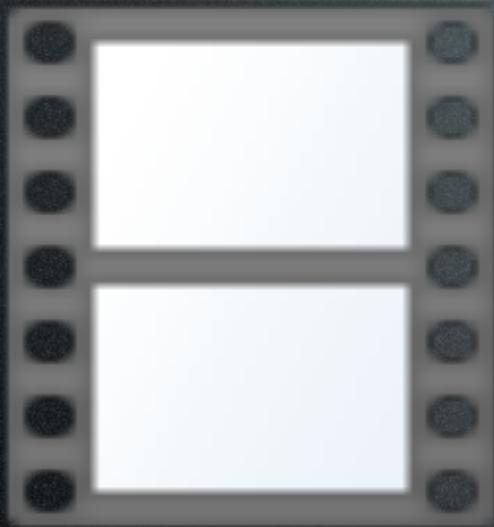


Image captured during the formation of plasma in the capillary 40 cm long and 2 mm in diameter, installed inside a vacuum chamber specially created to accommodate large plasma sources. The applied voltage pulse is 9 kV and the peak current reaches about 500 A.

Courtesy Angelo Biagioni

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

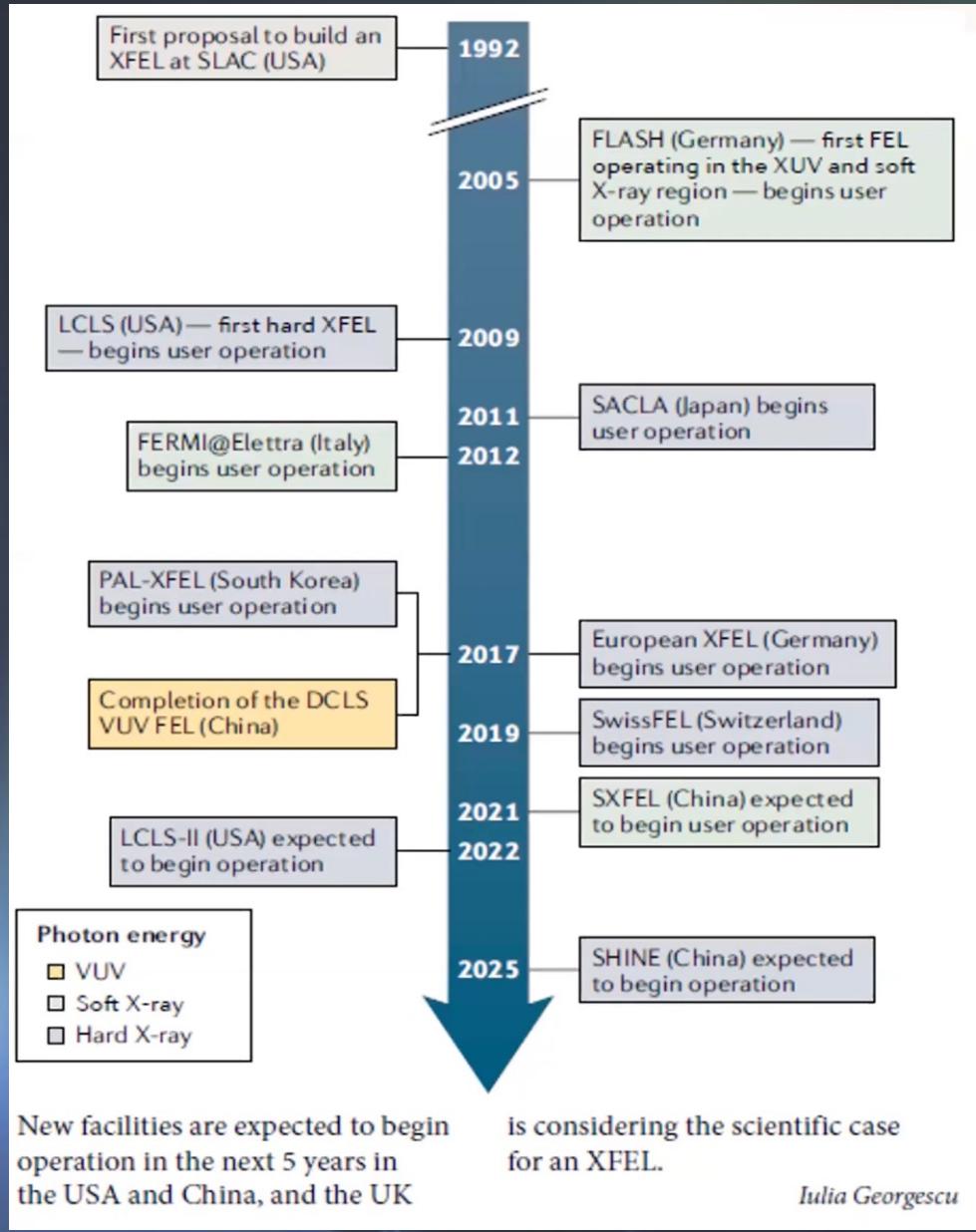


$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \vartheta^2 \right)$$

(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

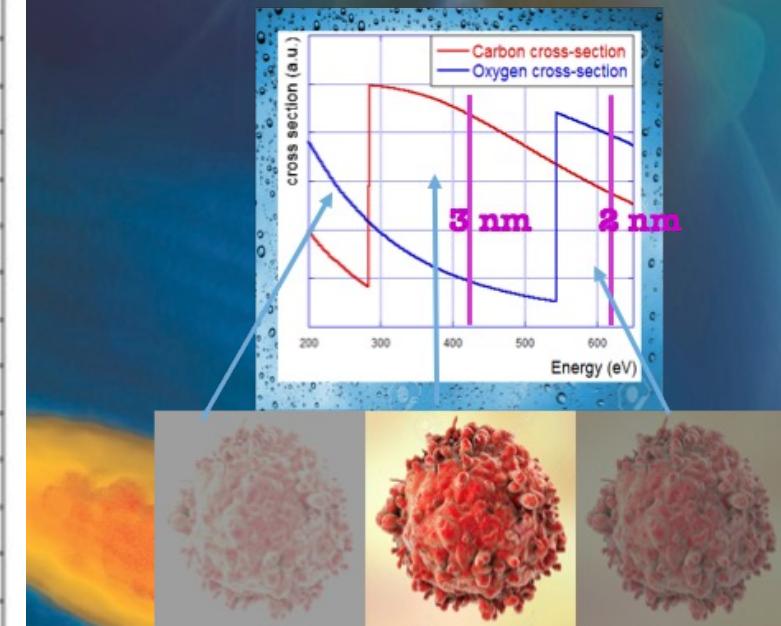
54

Chapter 2. Free Electron Laser design principles

	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 ρ	$\times 10^{-3}$	1.5	1.4
Radiation Wavelength	nm	3	3
Undulator matching β_w	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	$\times 10^{11}$	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)

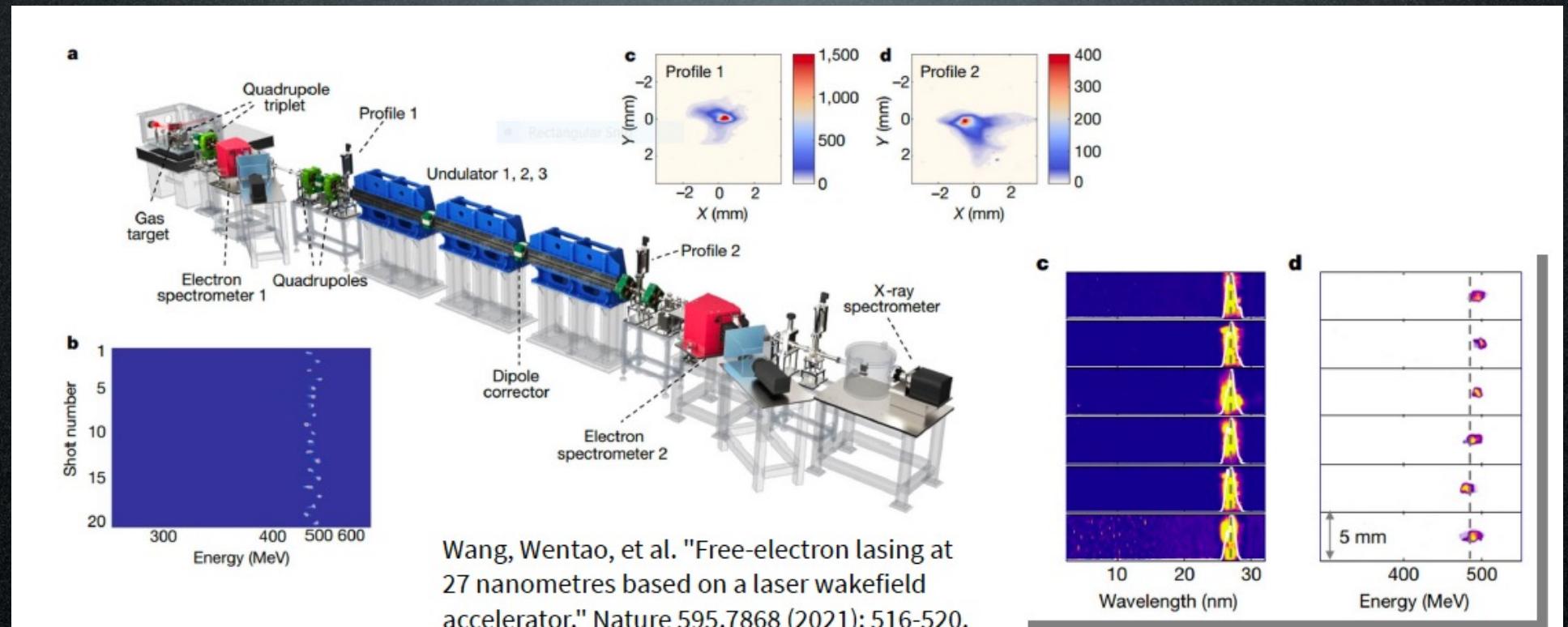


Coherent Imaging of biological samples
protein clusters, VIRUSES and cells
living in their native state

Possibility to study dynamics
 $\sim 10^{11}$ photons/pulse needed

Courtesy F. Stellato, UniToV

First Lasing with LWFA at SIOM



Observation of FEL radiation @ 27 nm using LWFA

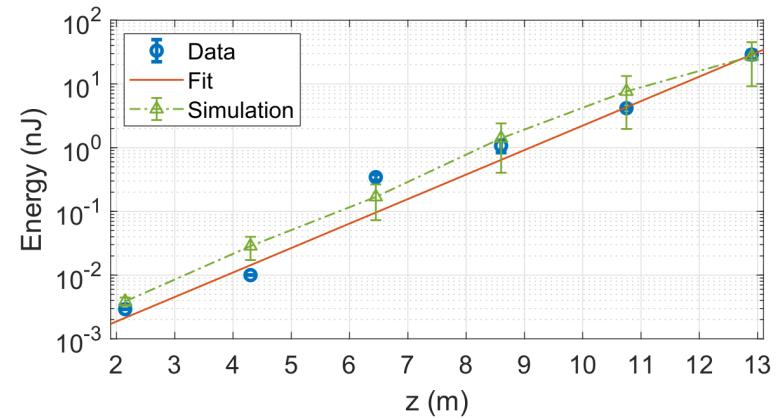
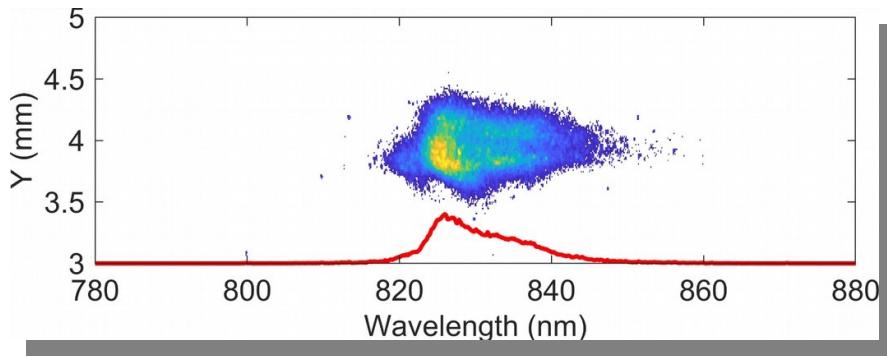
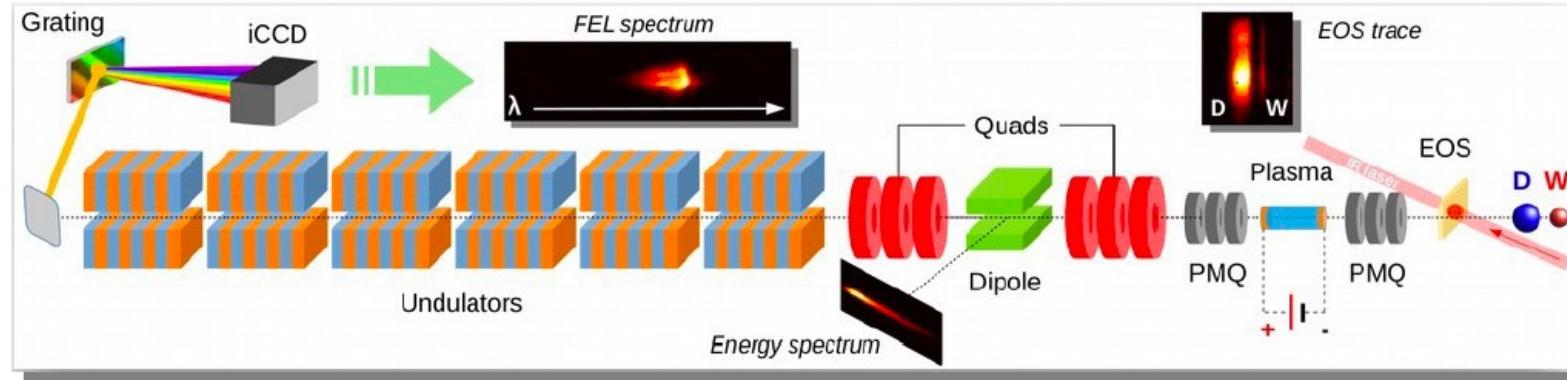
Electron beam generated from a 200 TW ($I \sim 4 \times 10^{18} \text{ W/cm}^2$) laser focused on a gas-jet

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)



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 Construction**



Doctoral Network

EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

Open positions in the EuPRAXIA Doctoral Network

EuPRAXIA is the first European project that develops a dedicated particle accelerator research infrastructure based on novel plasma acceleration concepts and laser technology. To fully exploit the potential of this breakthrough facility, advances are urgently required in plasma and laser R&D, studies into facility design and optimization, along a coordinated push for novel applications.

EuPRAXIA-DN is a new MSCA Doctoral Network for a cohort of students that will carry out an interdisciplinary and cross-sector plasma accelerator research and training program supporting this new research infrastructure.

Each student will benefit from a wide-ranging training between universities, research centers and industry that will take advantage of both local and network-wide activities.

Excellent salaries will be offered.

Application deadline:
31st January 2023

Contact and further detail:
Prof Dr Carsten P Welsch
Coordinator
INFN-LNF
Carsten.Welsch@lnf.infn.it

www.eupraxia-dn.org



This project has received funding from the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101073480.