Advanced Accelerator Concepts I

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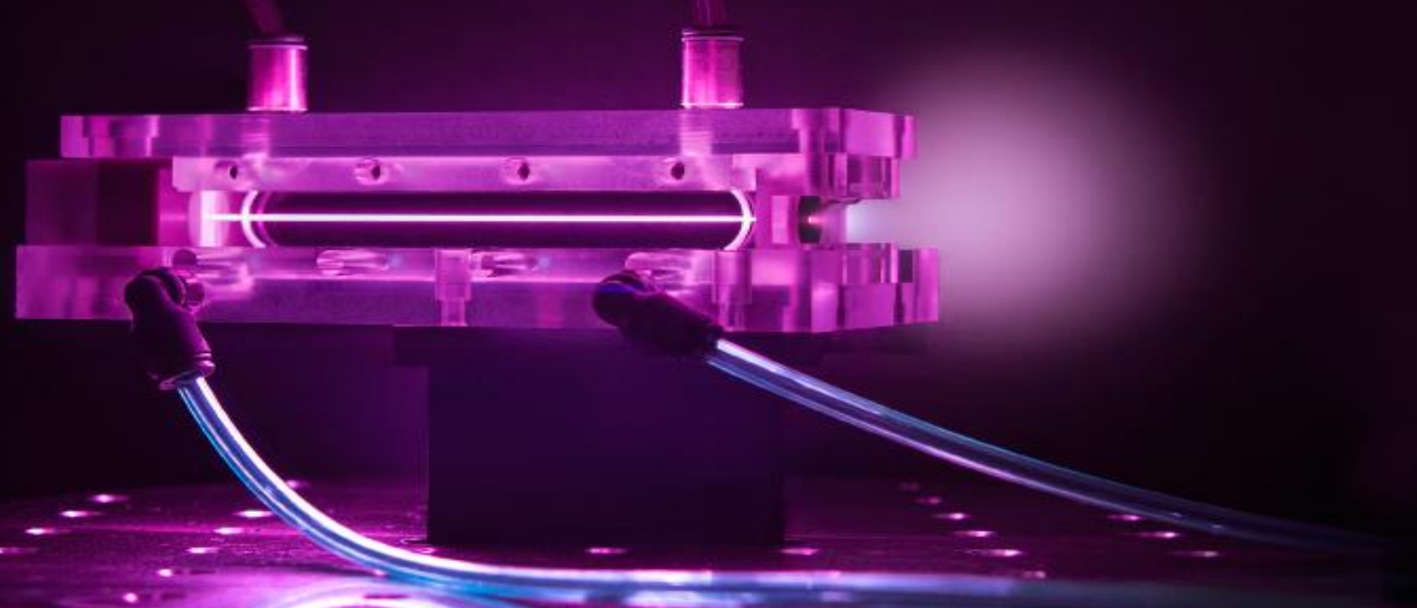
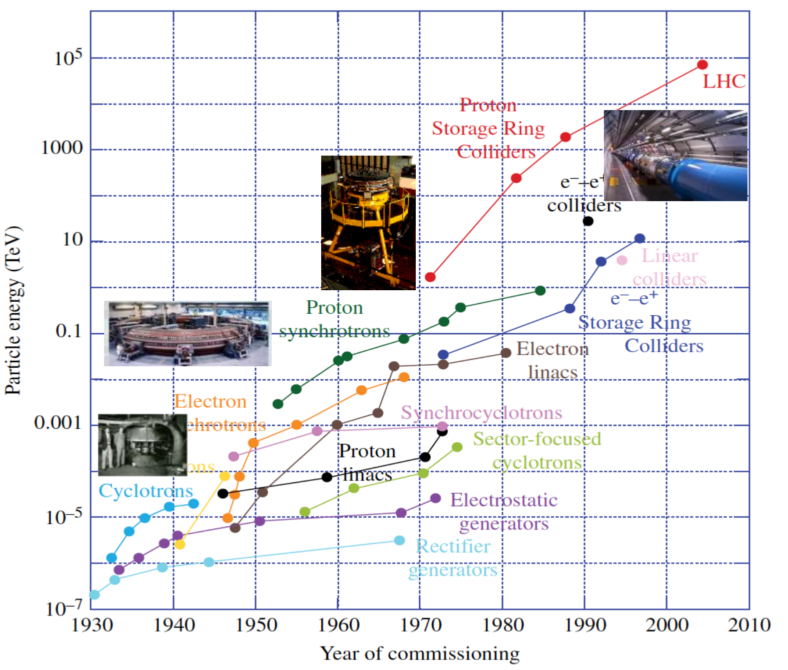


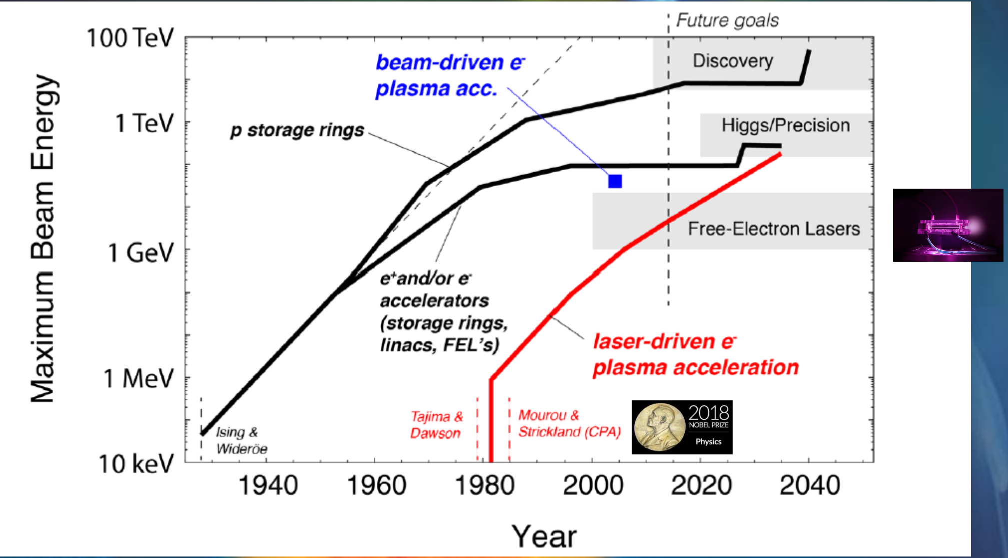
The CERN Accelerator School

Introduction to Accelerator Physics

S. Susanna – 6 October 2023

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.)

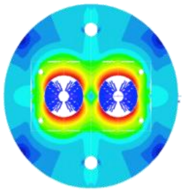
Options towards higher energies

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)



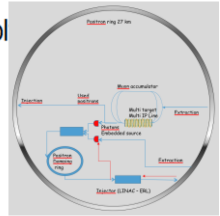
Lepton (e-,e+) circular collider

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

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

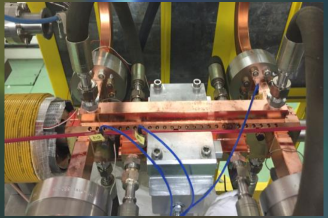
$$B_n \approx \frac{2I}{\epsilon_n^2}$$

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

High Gradient Options

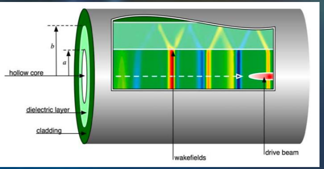
Metallic accelerating structures =>

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



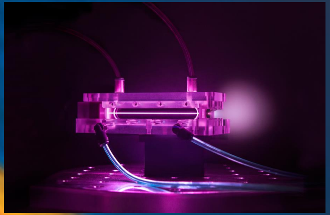
Dielectrict structures, laser or particle driven =>

E_{acc} < 10 GV/m



Plasma accelerator, laser or particle driven =>

E_{acc} < 100 GV/m



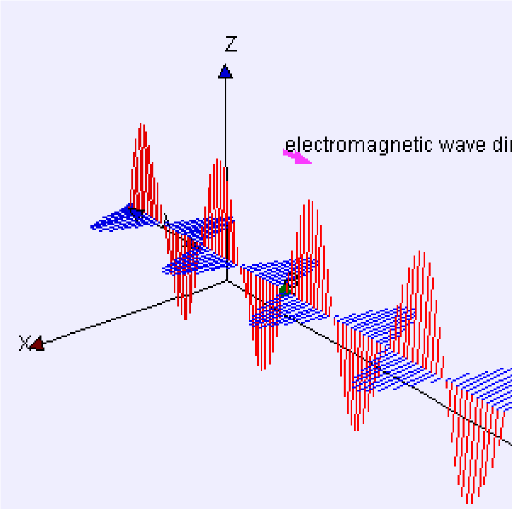
Related Issues: Power Sources and Efficiency, Stability, Reliability, Staging, Synchronization, Rep. Rate and short (fs) bunches with small (μm) spot to match high gradients

Lawson-Woodward Theorem

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

<u>The theorem assumes that</u>

(i) the em 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
(v) ponderomotive effects (nonlinear forces, e.g. **v** x **B** force) are neglected

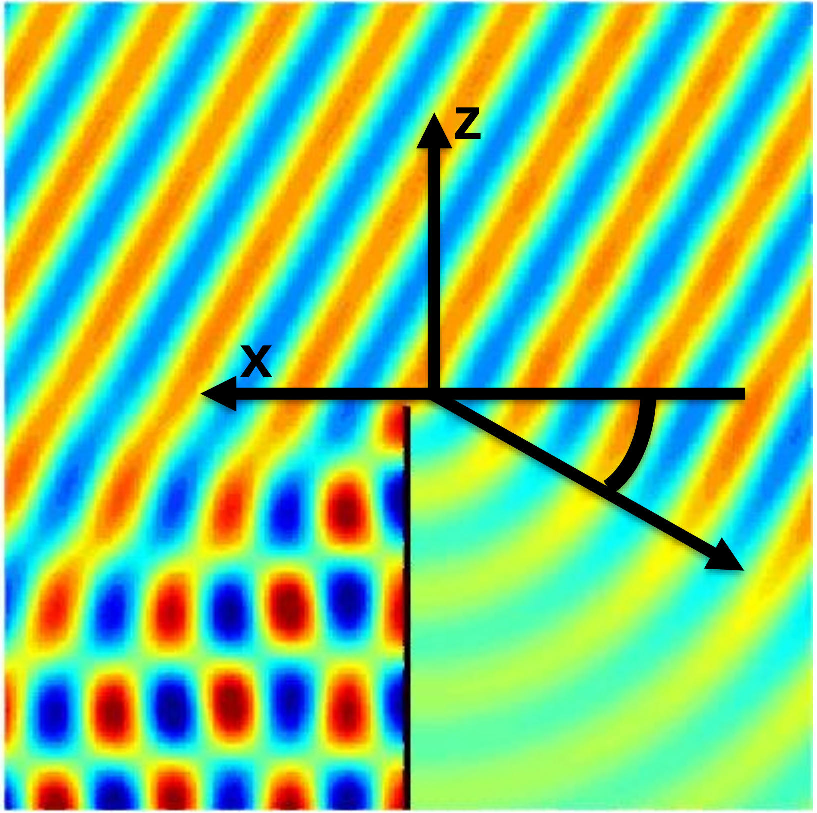


Acceleration mechanism must violate the Lawson-Woodward theorem

J.D. Lawson, IEEE Trans. Nucl. Sci. NS-26, 4217, 1979
P.M. Woodward, J. Inst. Electr. Eng. 93, 1554, 1947

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

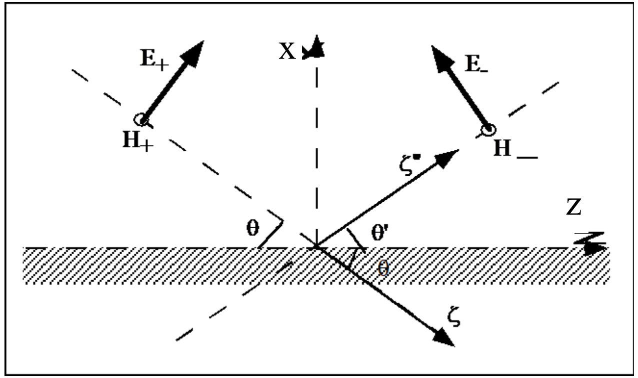
Reflection of plane waves



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:

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

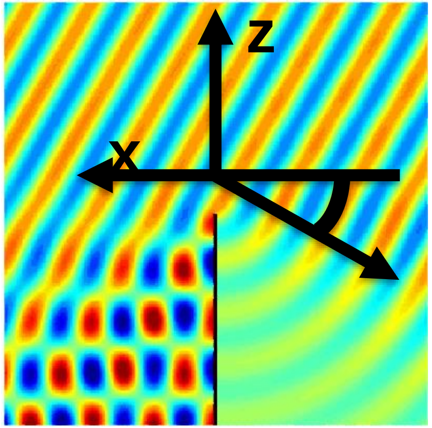
$$\zeta = z\cos\theta - x\sin\theta \qquad \zeta' = z\cos\theta' + x\sin\theta'$$

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

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

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

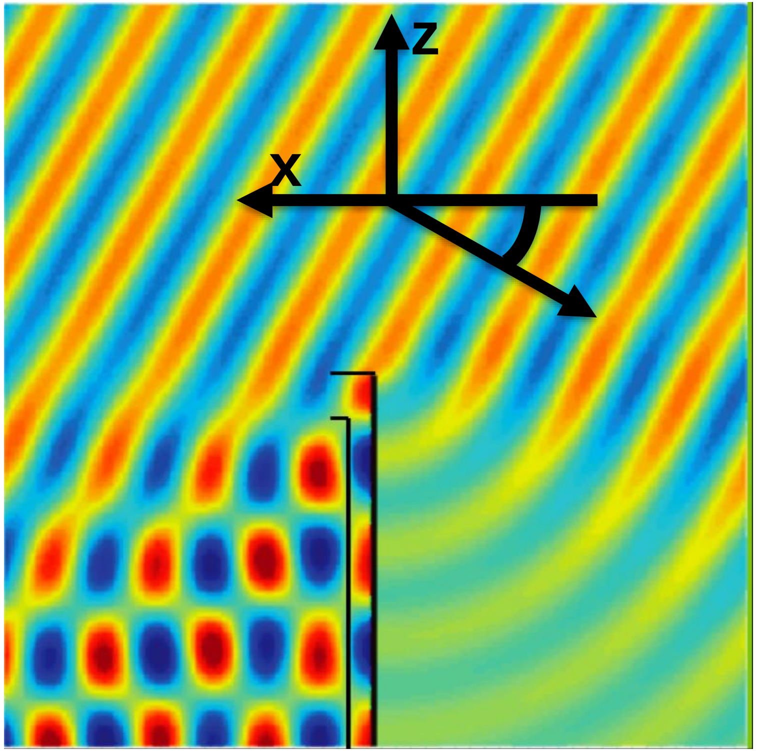
$$= 2iE_+ \sin\theta \sin(kx\sin\theta)e^{i\omega t - ikz\cos\theta}$$



Standing Wave pattern (along x)

Guided wave pattern (along z)

From reflections to waveguides



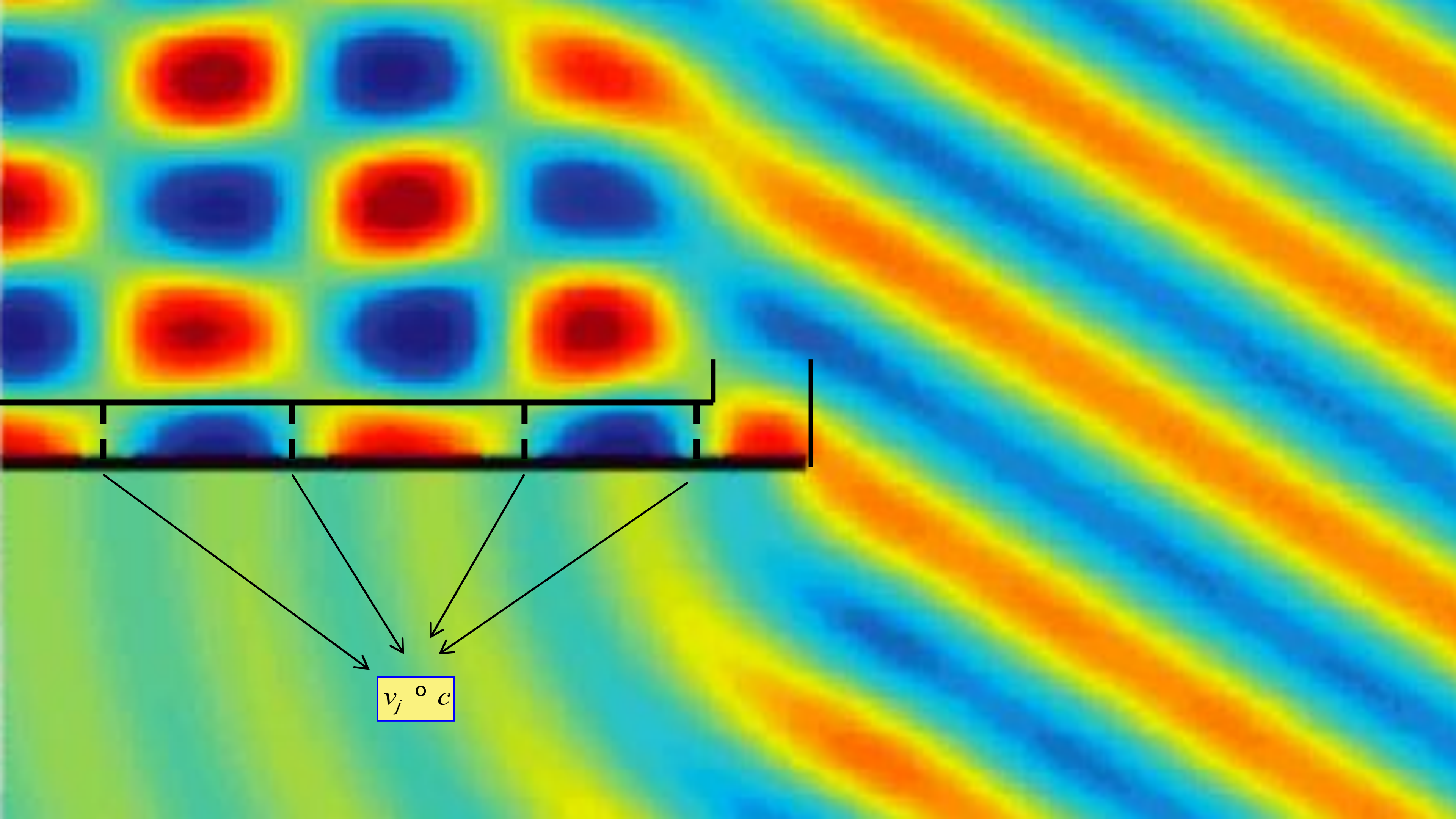
Put a metallic boundary where the field is zero at a given distance from the wall.

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

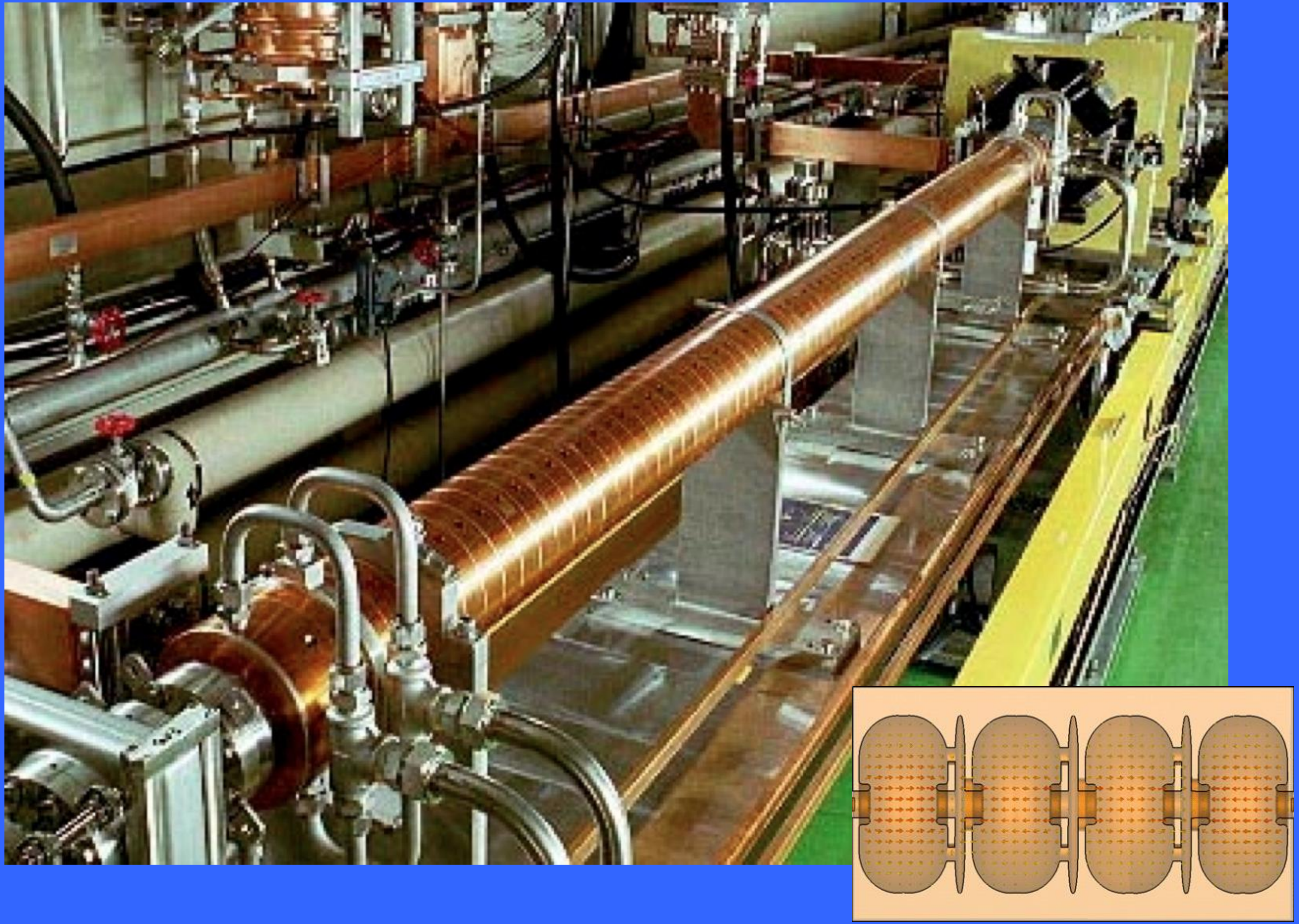
For a given distance, there is a maximum wavelength, i.e. there is **cut-off frequency**.

$$v_{fz} = \frac{W}{k_z} = \frac{W}{k\cos q} = \frac{c}{\cos q} > c$$

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

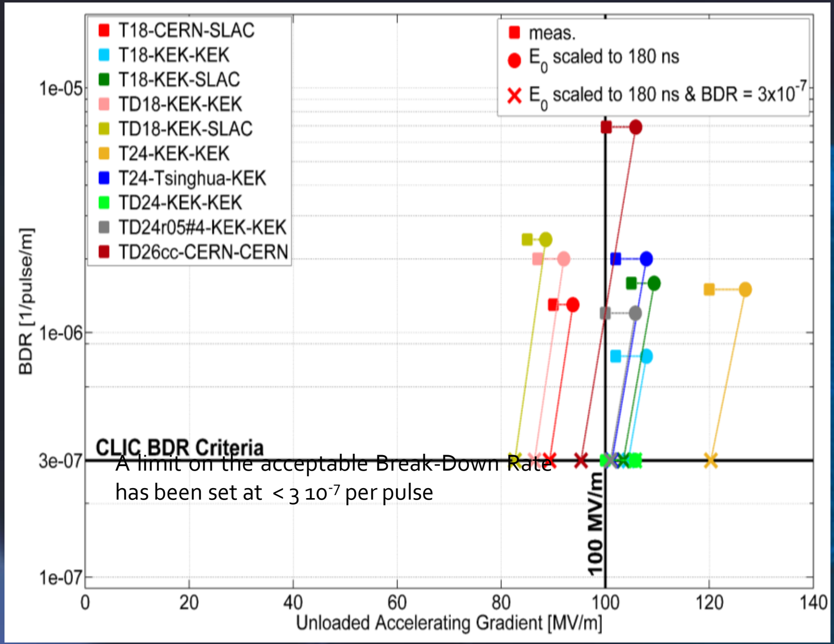

v_j o c

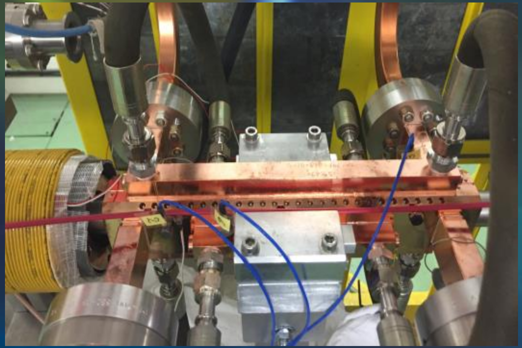
Conventional RF accelerating structures

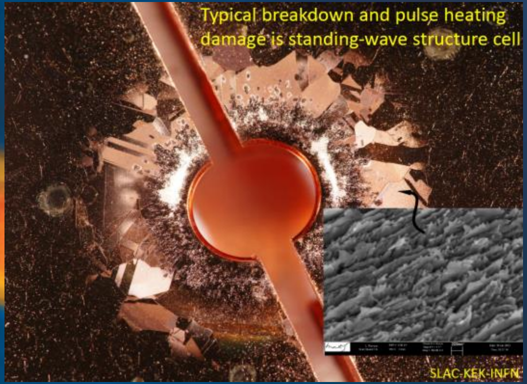


X-band RF structures – State of the Art

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

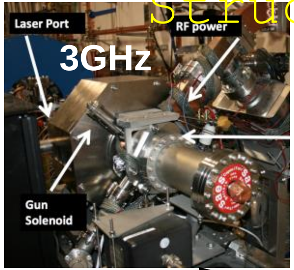


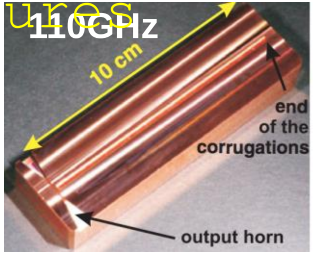


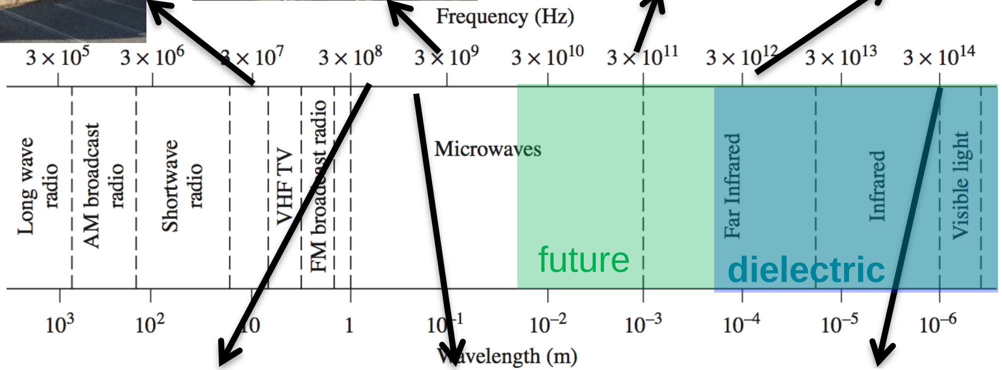


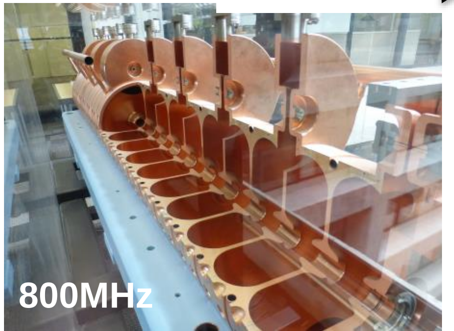
- Kilpatrick, W. D., Rev. Sci. Inst. 28, 824 (1957).
- *A. Grudiev et al, PRST-AB 12, 102001 (2009)*
- S. V. Dolgashev, et al. Appl. Phys. Lett. 97, 171501 2010.
- M. D. Forno, et al., PRAB, 19, 011301 (2016)

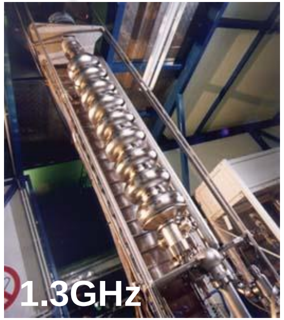
The E.M. Spectrum of Accelerating Structures

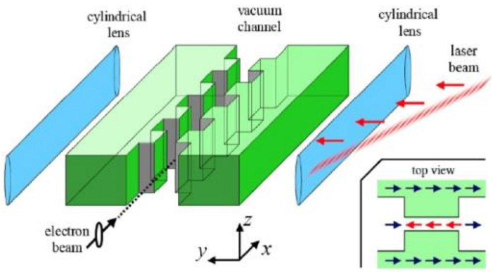












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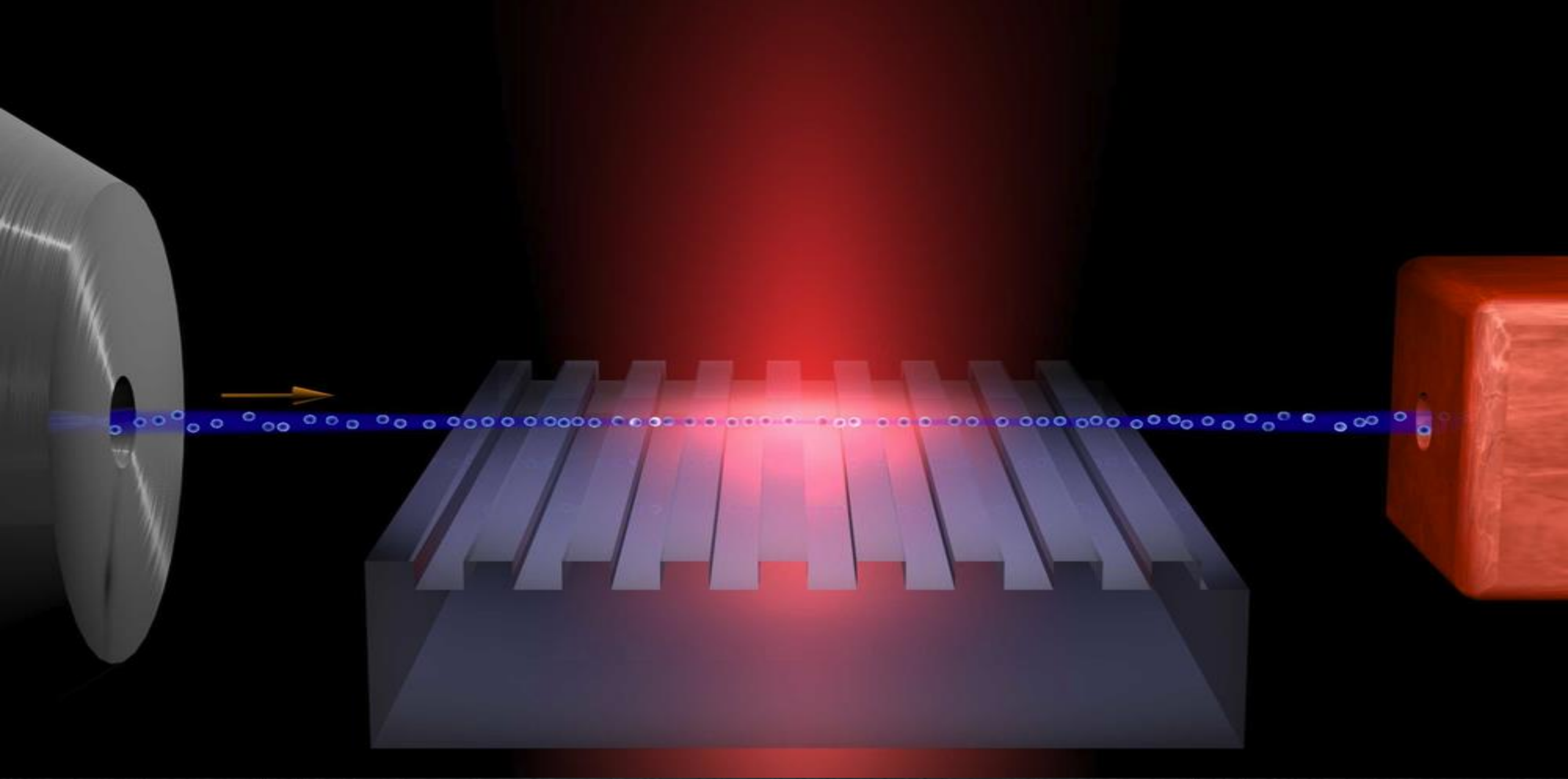
Dielectric Laser Acceleration

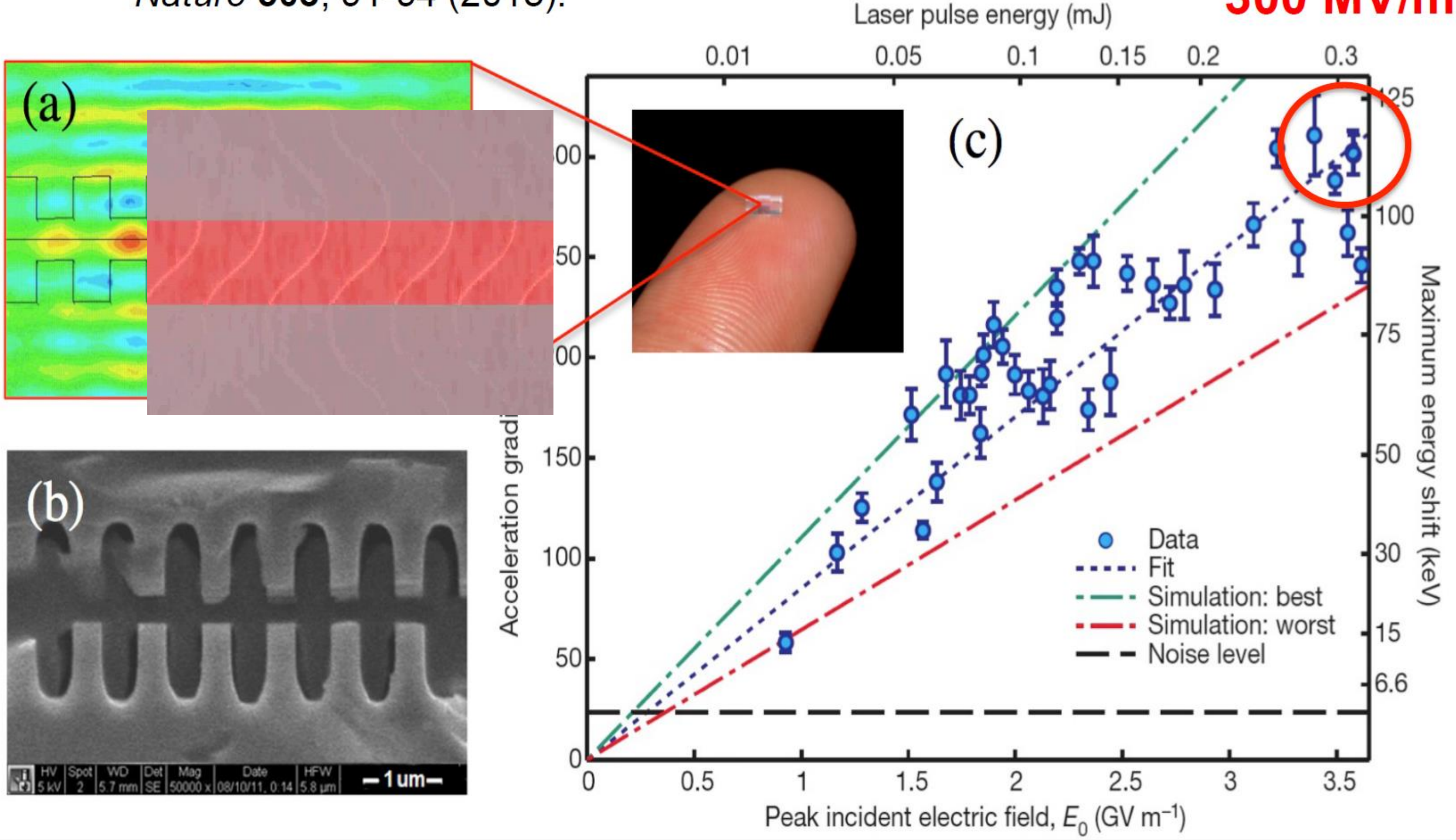
DLA

Laser based dielectric accelerator



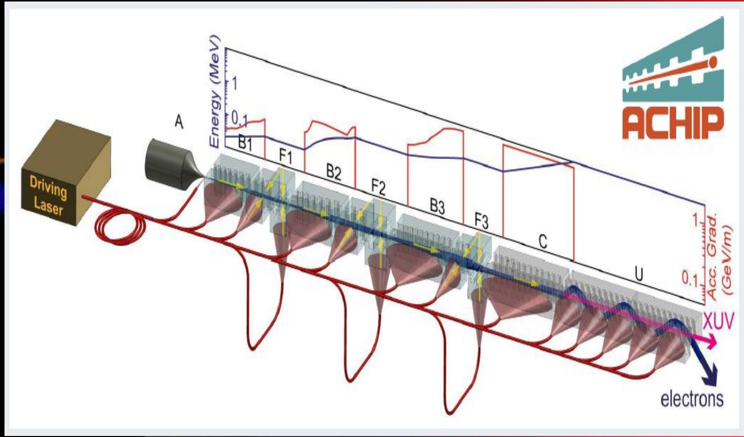
Nature **503**, 91-94 (2013).

300 MV/m

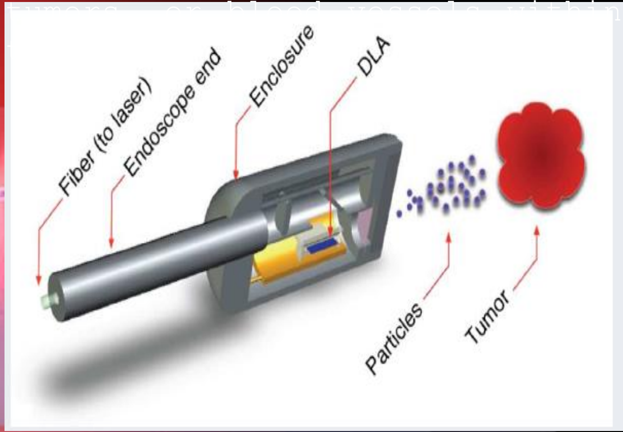


Dielectric Structures Applications

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



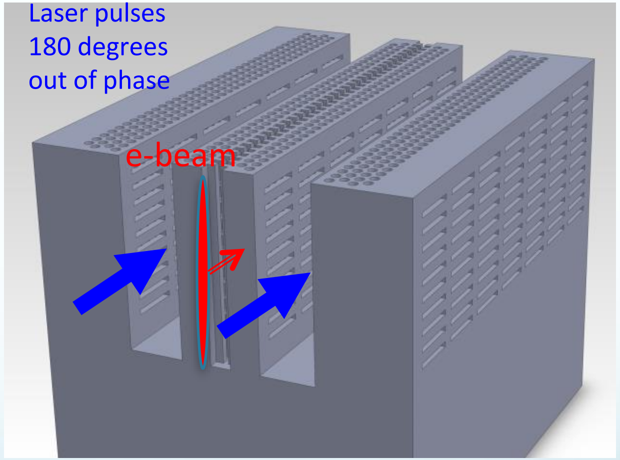
DLA module can be built onto the end of a fiber-optic catheter and attached to an endoscope, allowing to deliver controlled, high energy radiation directly to organs,



Electrons with 1-3MeV have a range of about a centimeter, allowing for irradiation

Dielectric Photonic Structure

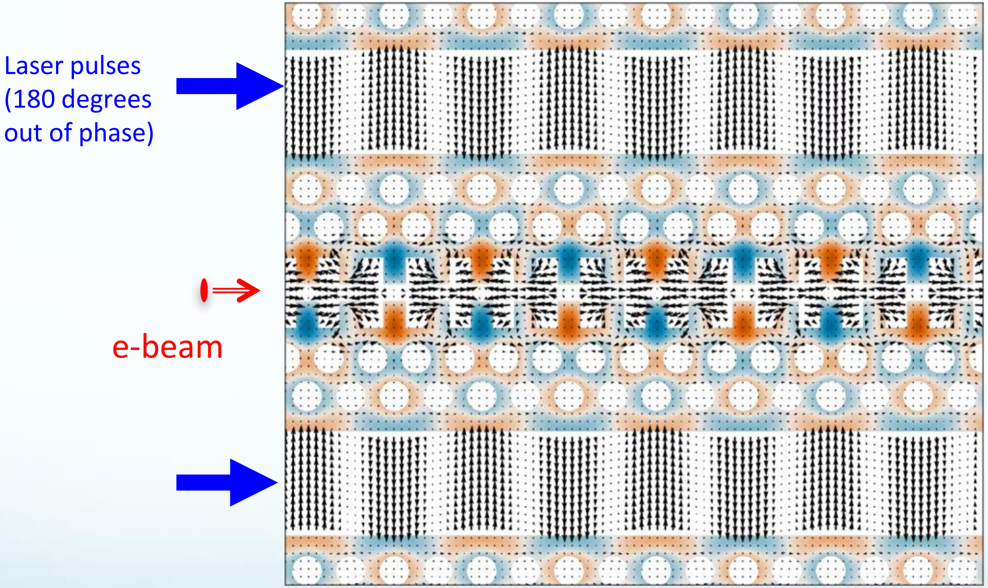
- Why photonic structures?
  - Natural in dielectric
  - Advantages of burgeoning field
    - design possibilities
    - Fabrication
- Dynamics concerns
- External coupling schemes



Schematic of GALAXIE monolithic photonic DLA

Laser-Structure Coupling: TW

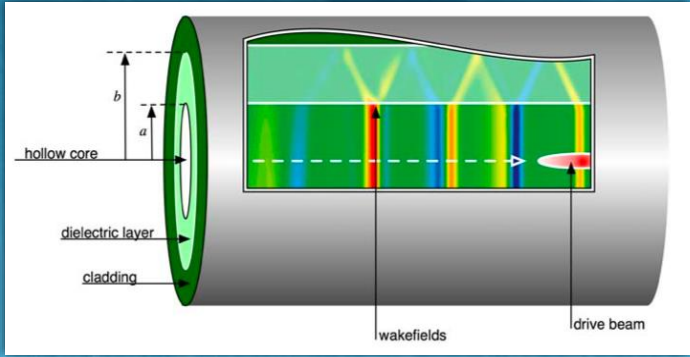
GALAXIE Dual laser drive structure, large reservoir of power recycles

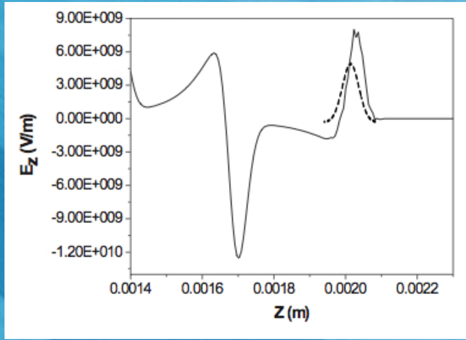


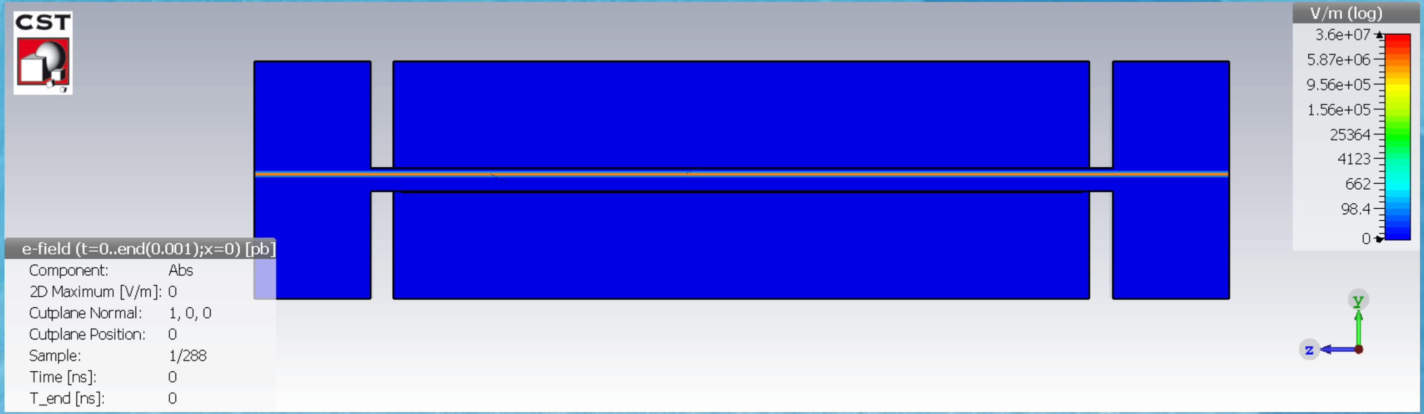
Dielectric Wakefield Acceleration

DWA

Dielectric Wakefield Accelerator

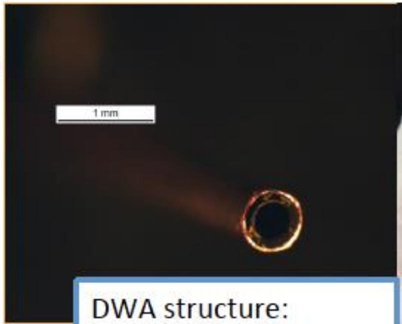




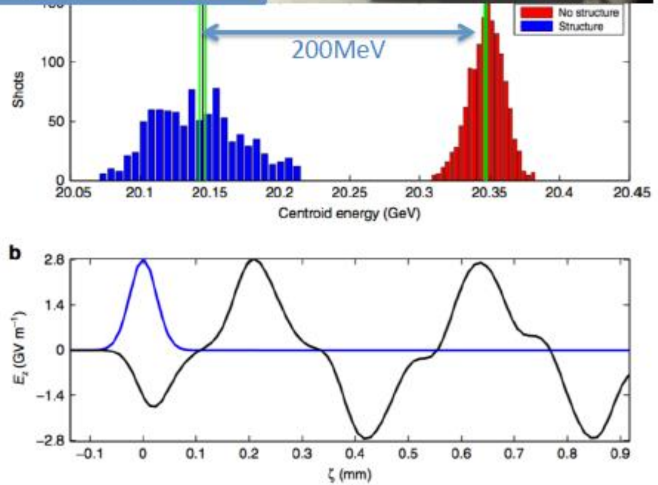


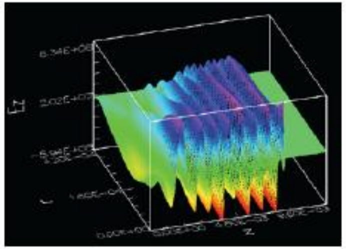
GV/m fields in DWA

- 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





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

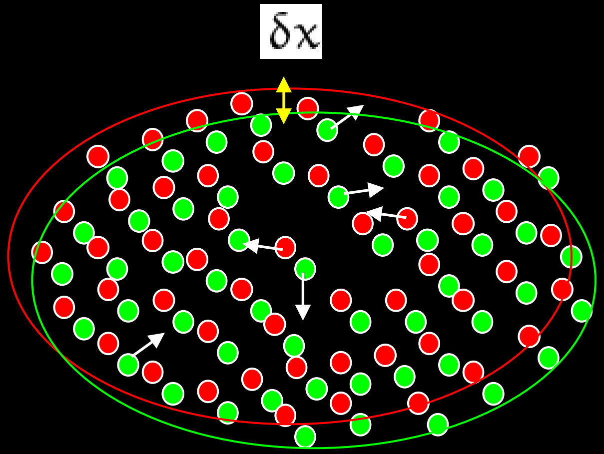
and

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

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

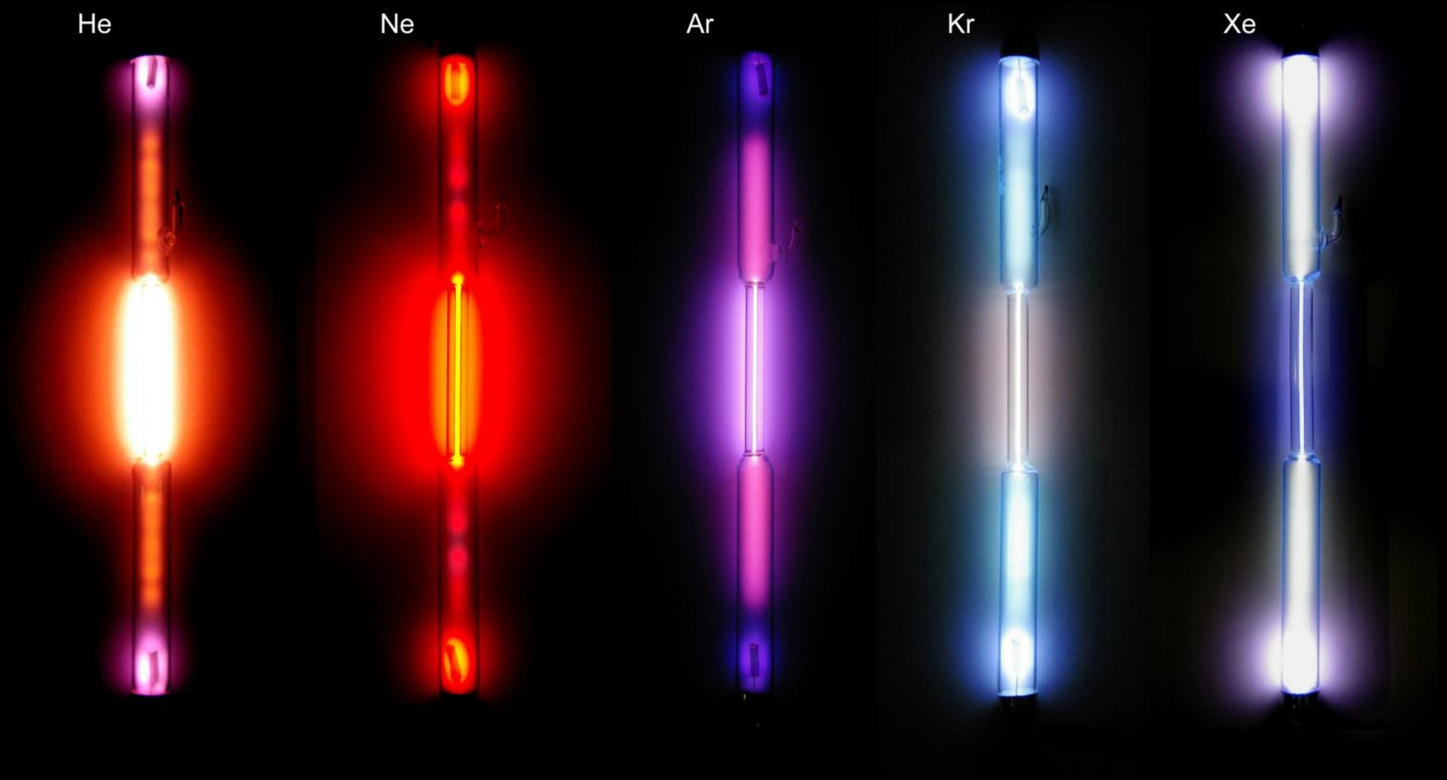
Plasma frequency

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

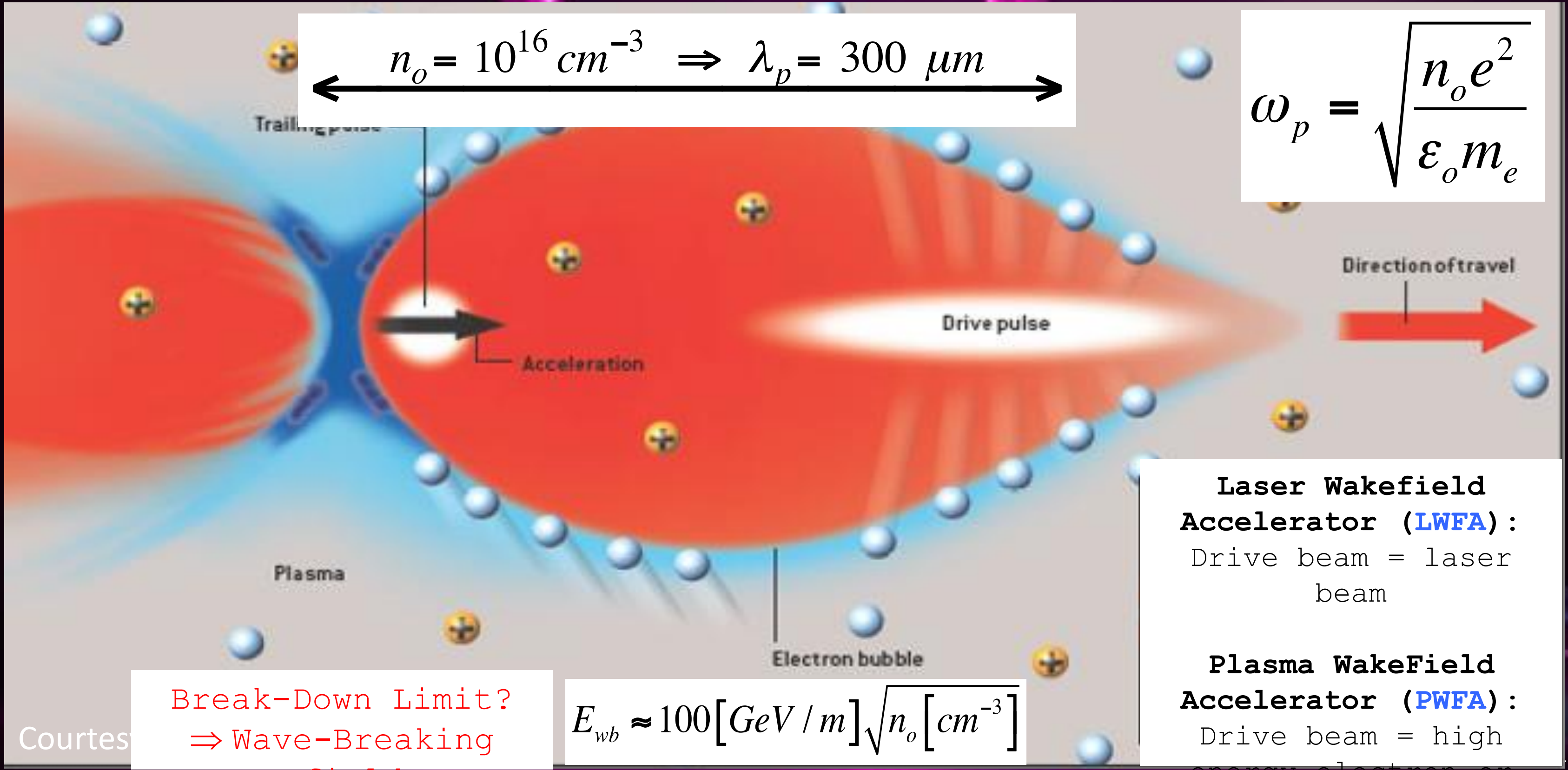
Plasma oscillations

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

Looking for a plasma target



Principle of plasma acceleration



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

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

Break-Down Limit?
⇒ Wave-Breaking field:

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

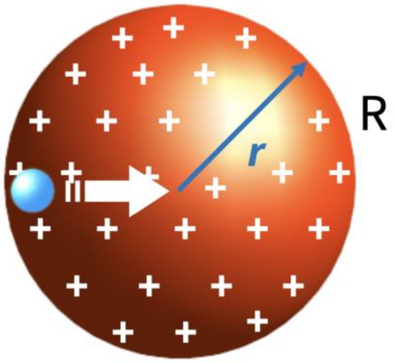
Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

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

Principle of plasma acceleration

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

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



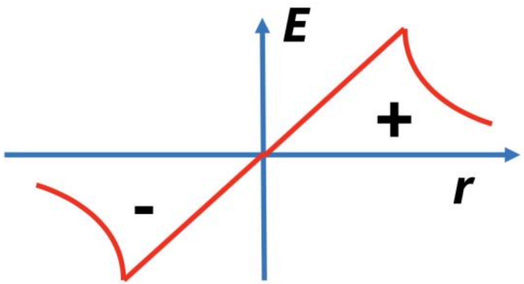
The field is **increasing** inside the sphere

Let's put some numbers

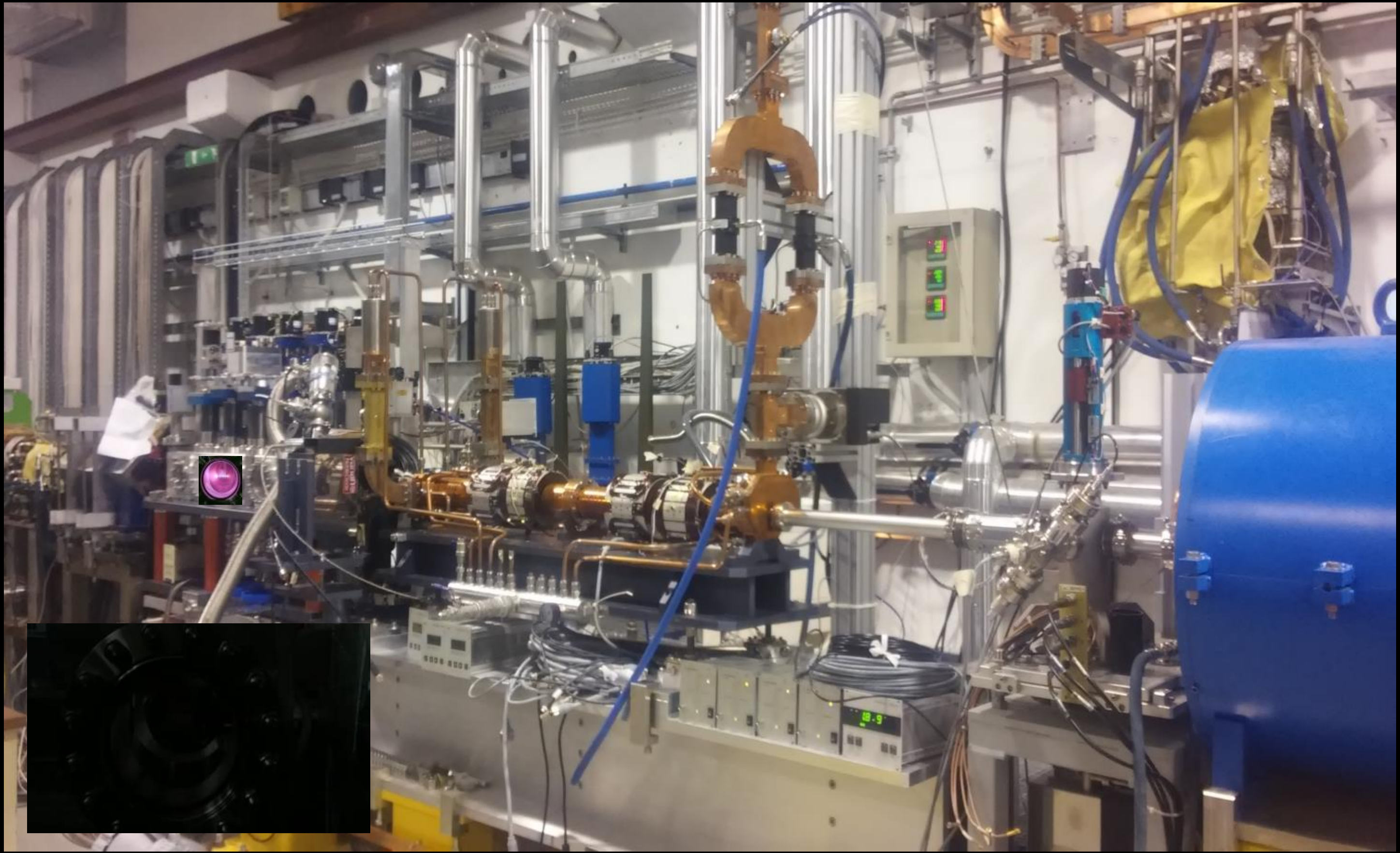
$n_i = 10^{16}\ cm^{-3}$

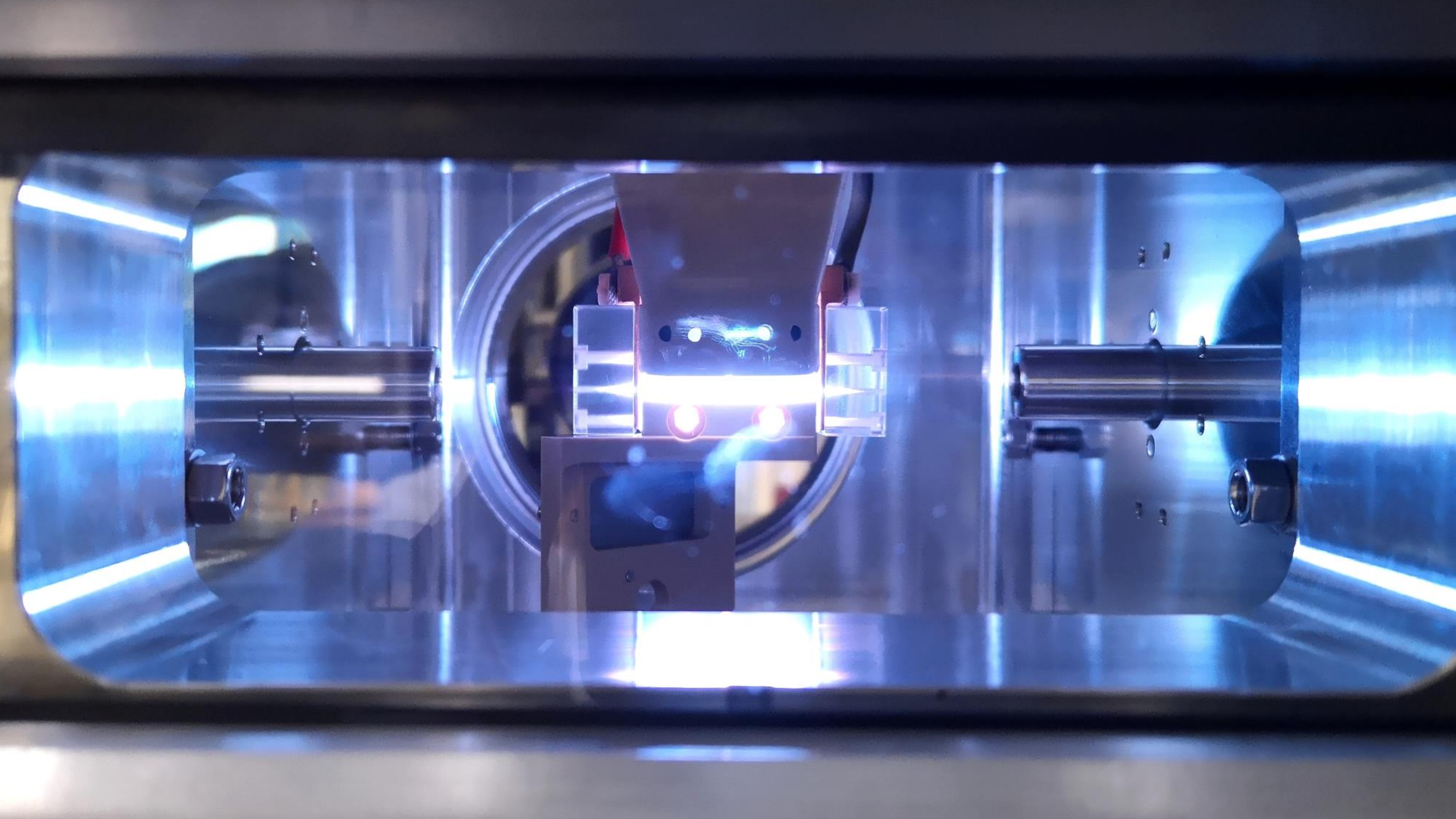
$R = 0.5$

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

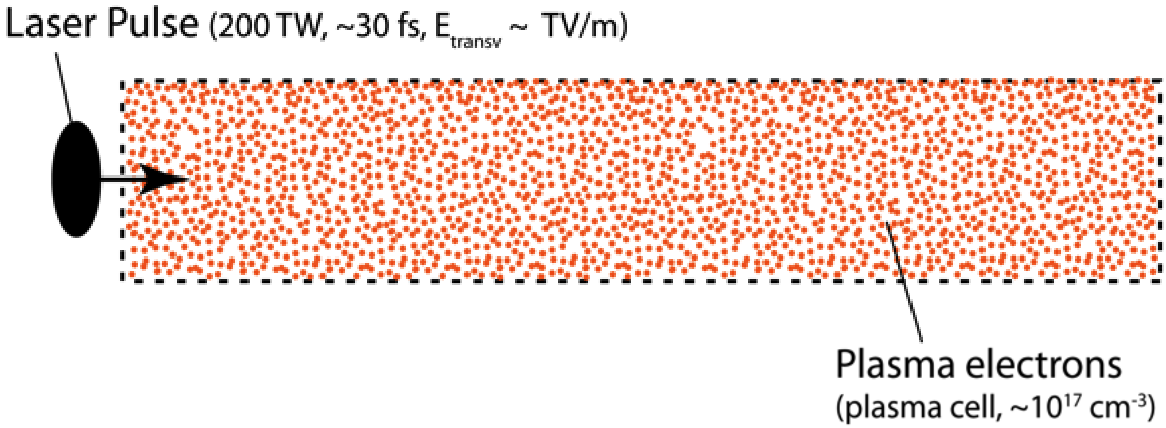


PWFA vacuum chamber at SPARC_LAB

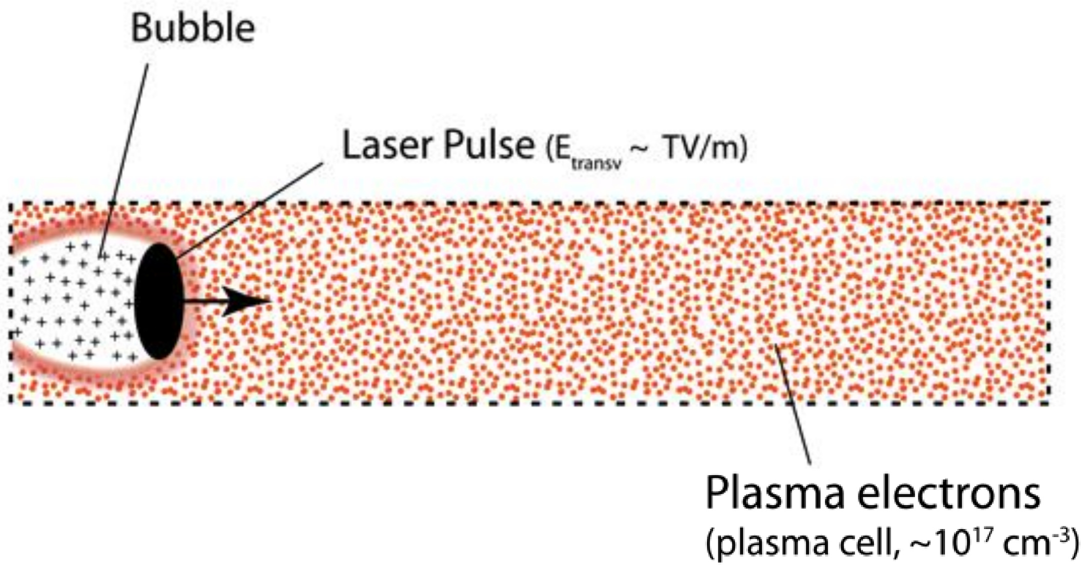




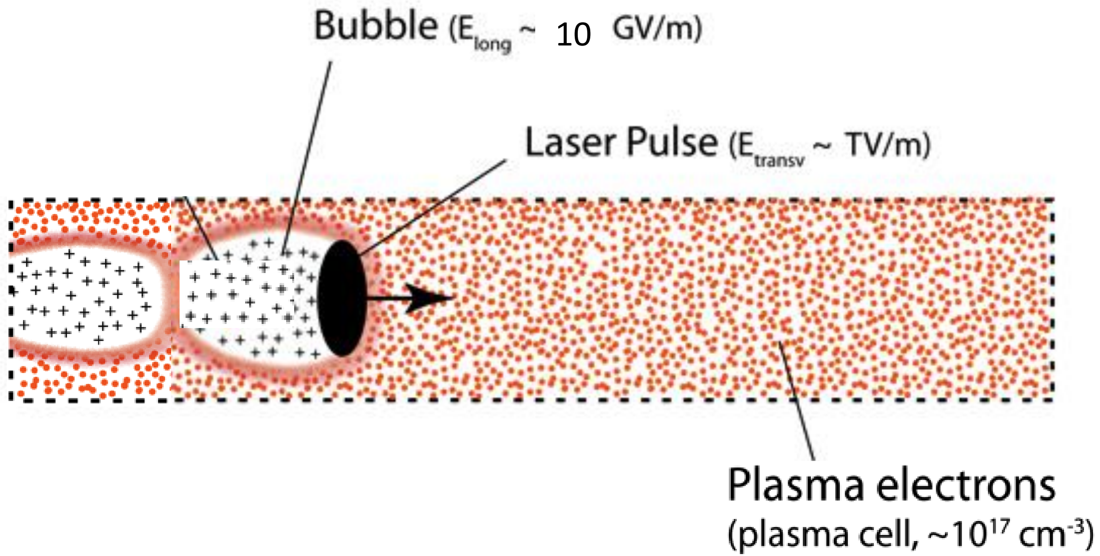
Plasma Wake-Acceleration



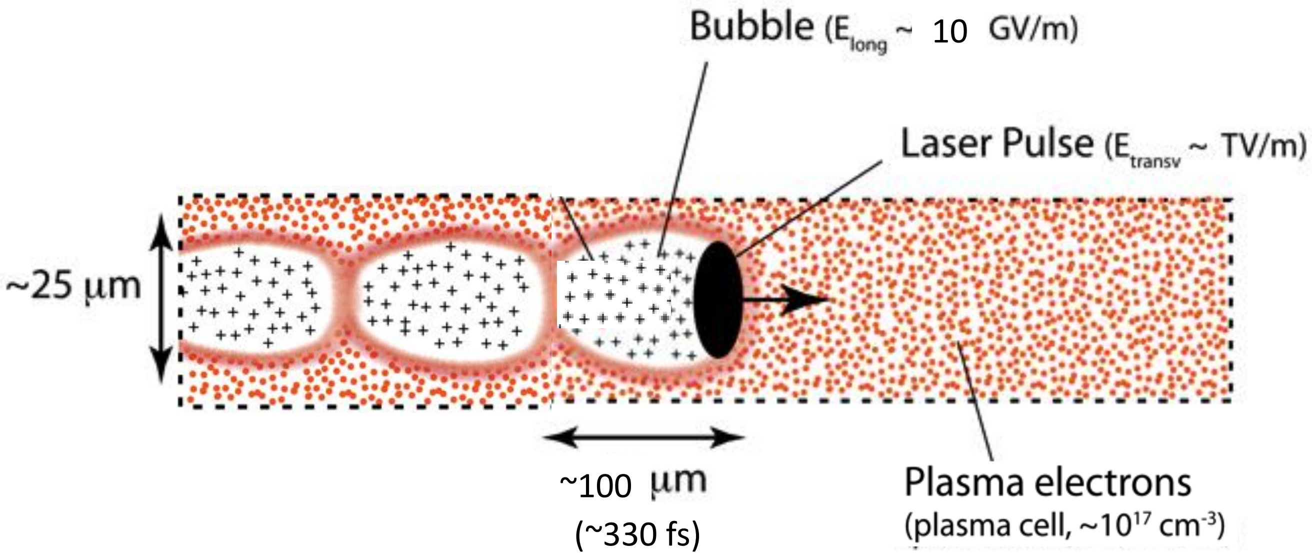
Plasma Wake-Acceleration



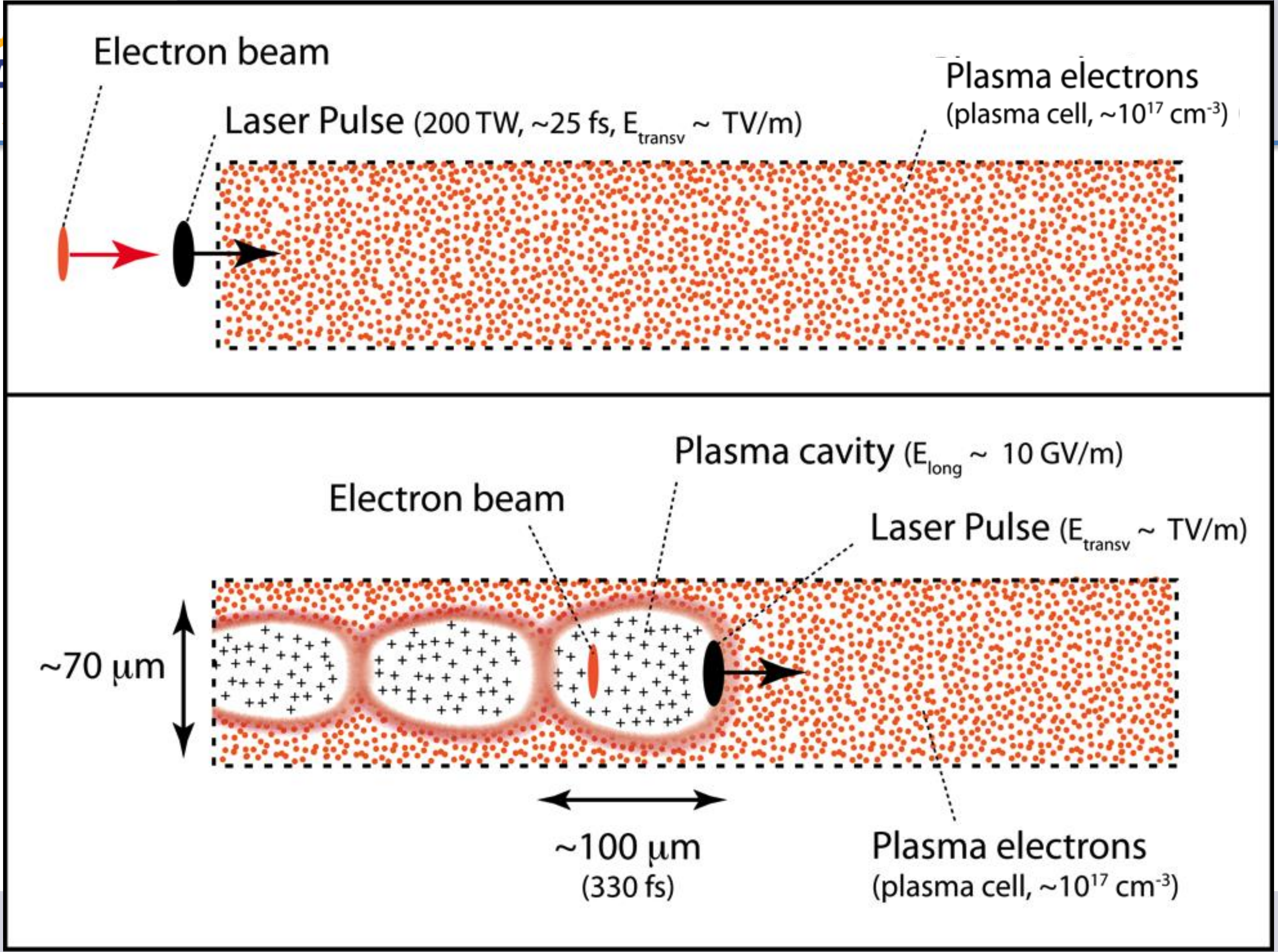
Plasma Wake-Acceleration



Plasma Wake-Acceleration



This accelerator fits into a human hair!



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

Advanced Accelerator Concepts I

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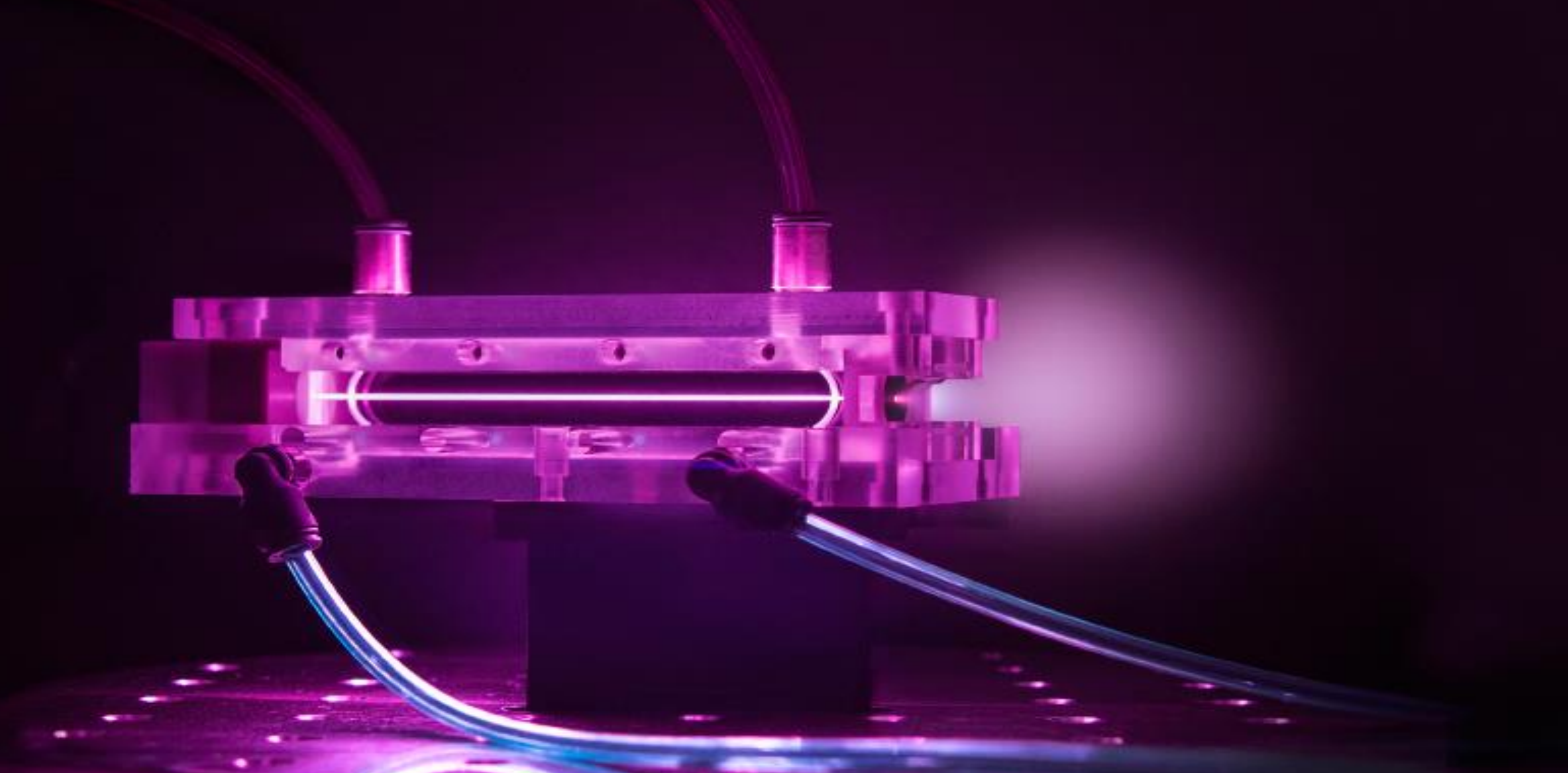


Introduction to Accelerator Physics

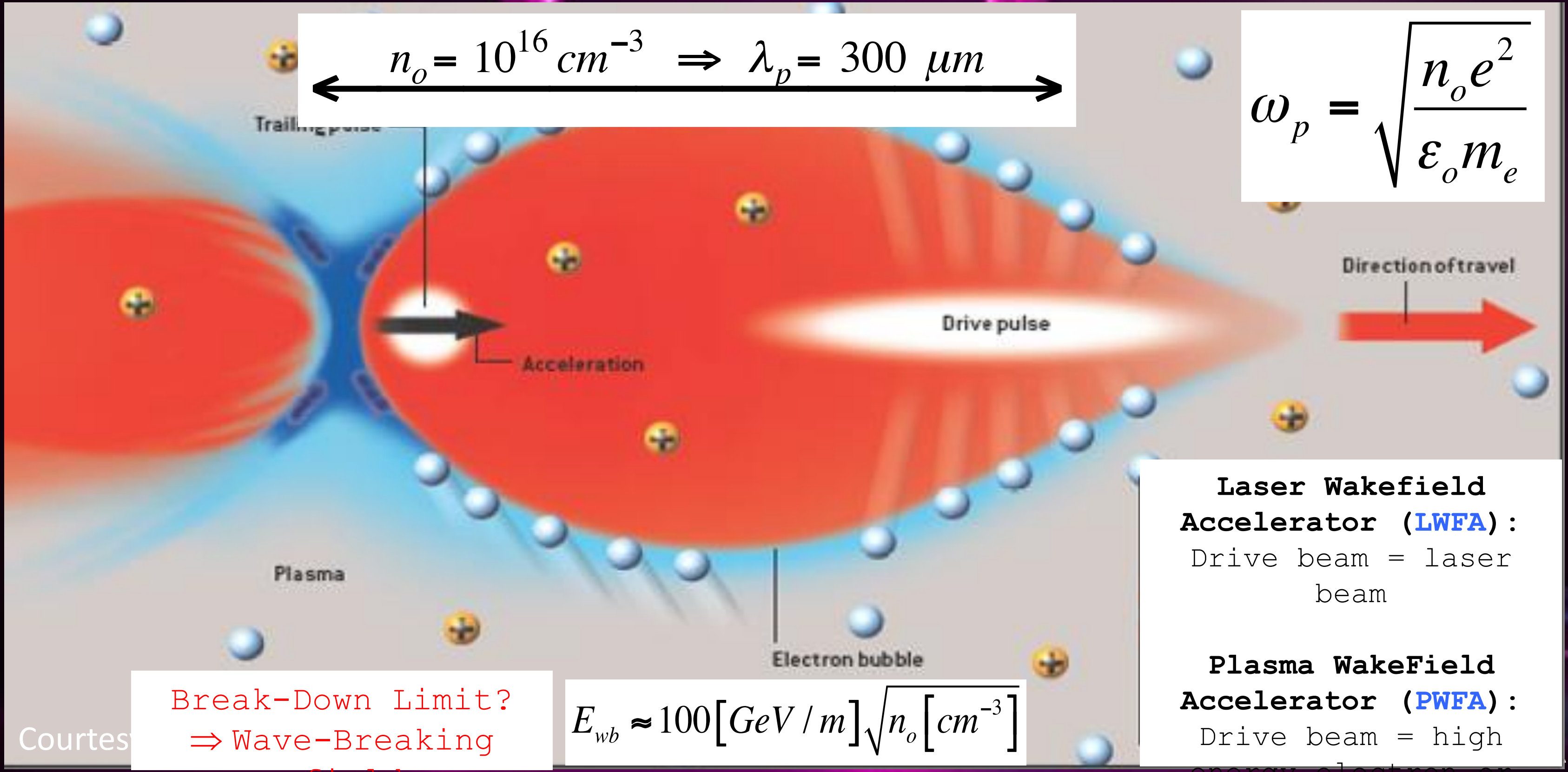
S. Susanna – 6 October 2023

The CERN Accelerator School

Principle of plasma acceleration

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

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



Break-Down Limit?
⇒ Wave-Breaking field:

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

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

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

Principle of plasma acceleration

Driven by Radiation Pressure

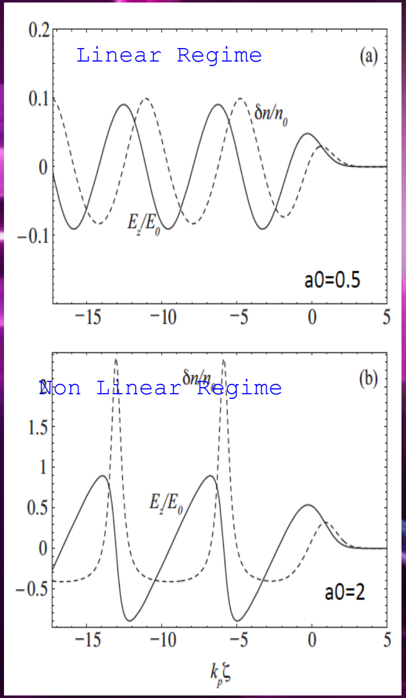
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=c^2\nabla^2\frac{a^2}{2}$$

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

Driven by Space Charge

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

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



LWFA limitations: Diffraction, Dephasing, Depletion

PWFA limitations: Head Erosion, Hose

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

Horizon2020

Accelerating field

Depends on radial position r

Changes between accelerating and decelerating as function of longitudinal position z

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

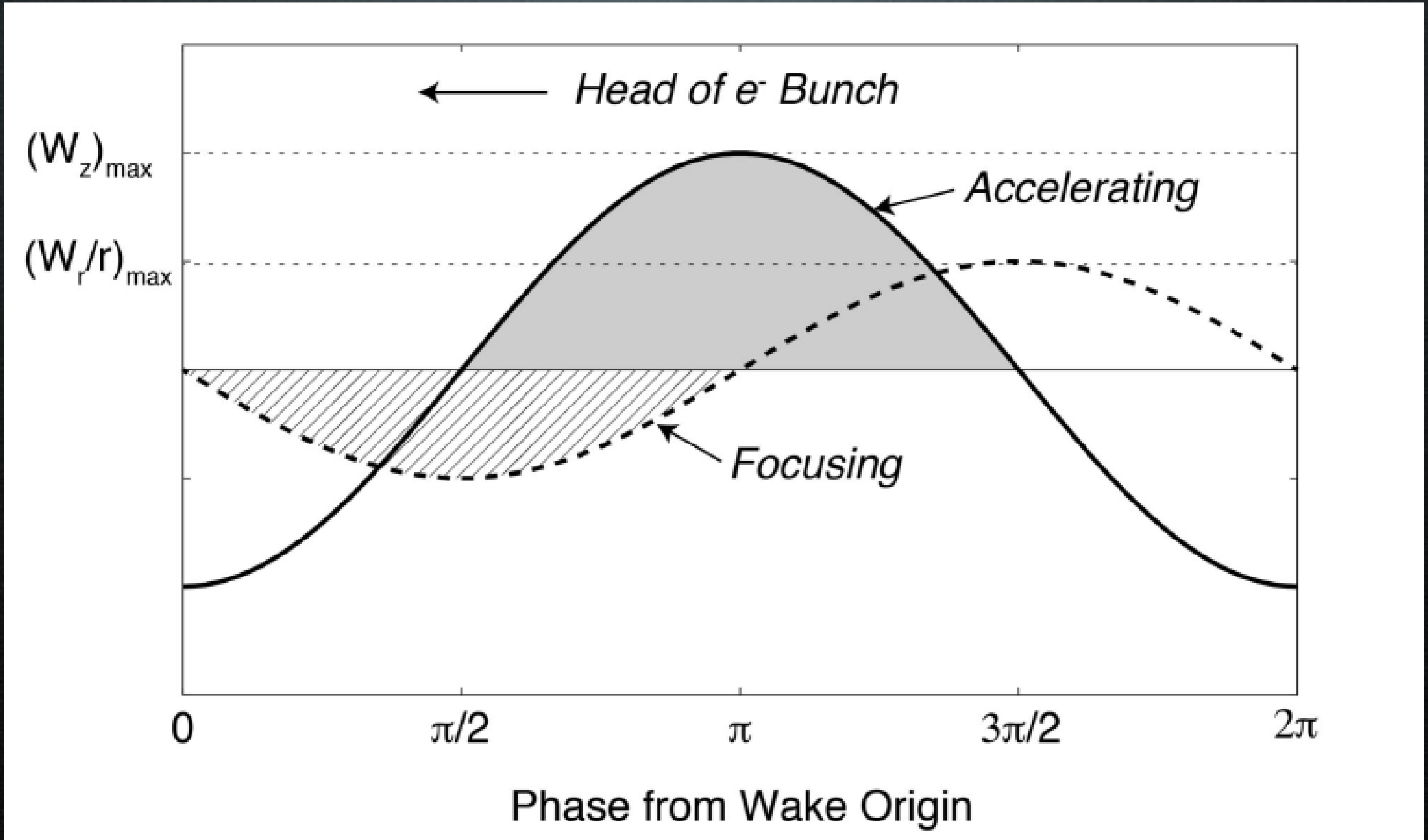
$\pi/2$ out of phase

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

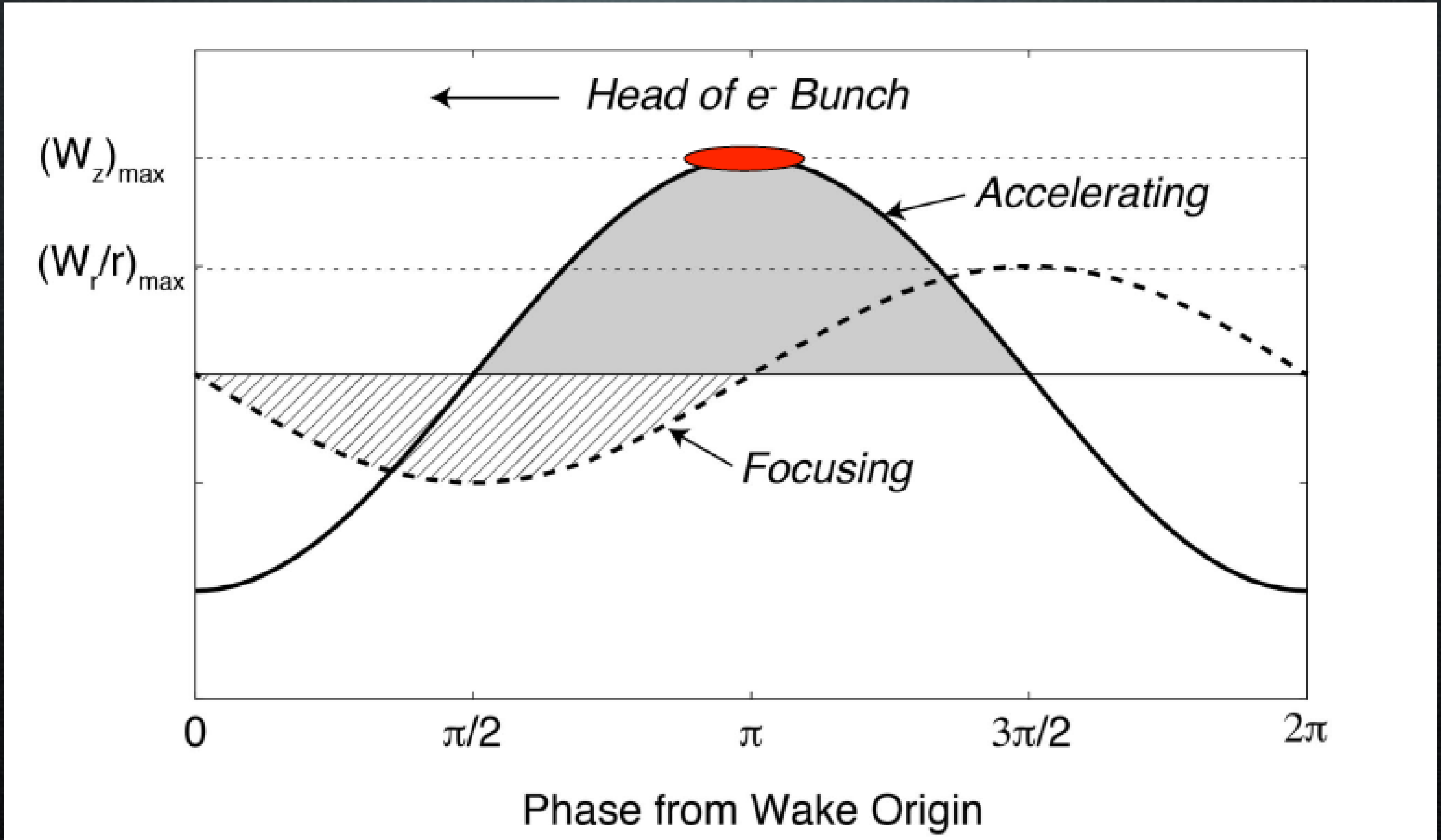
Transverse field

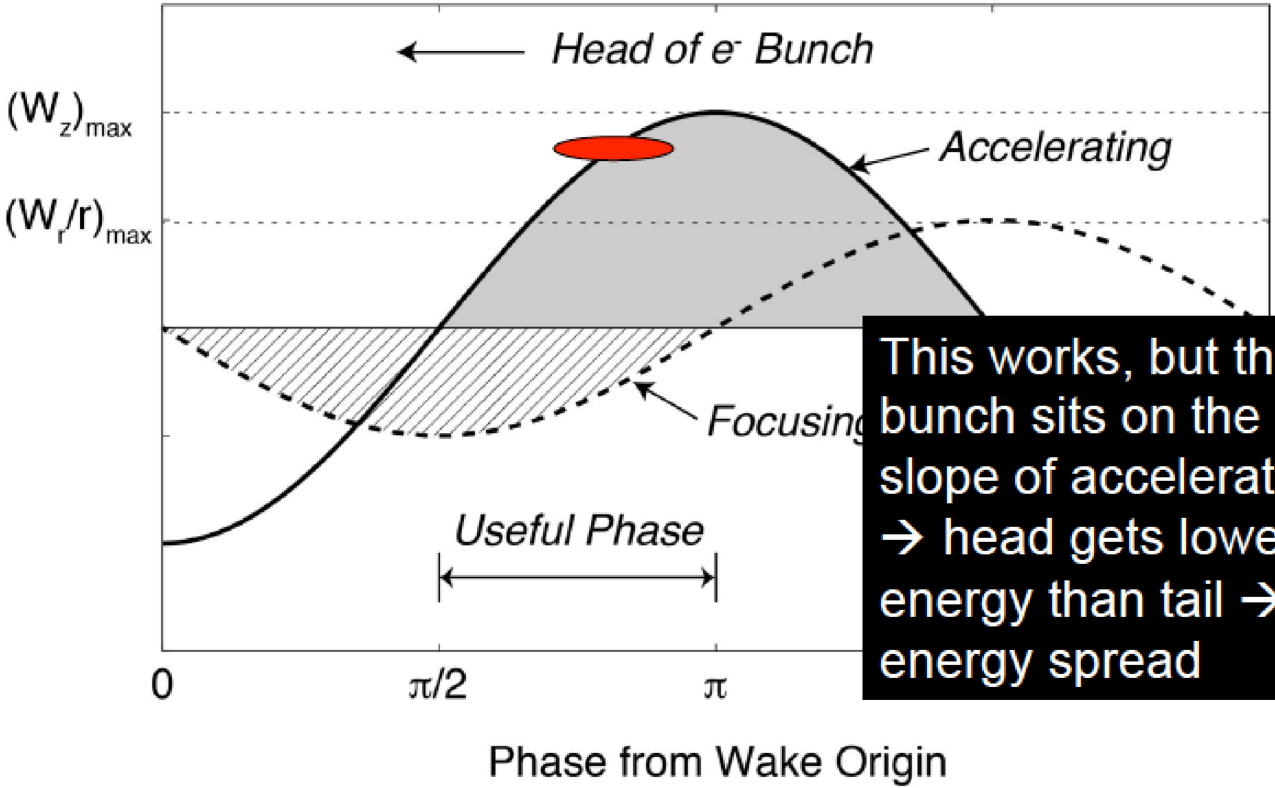
Depends on radial position r

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
$(W_z)_{max}$
$(W_r/r)_{max}$
Accelerating
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

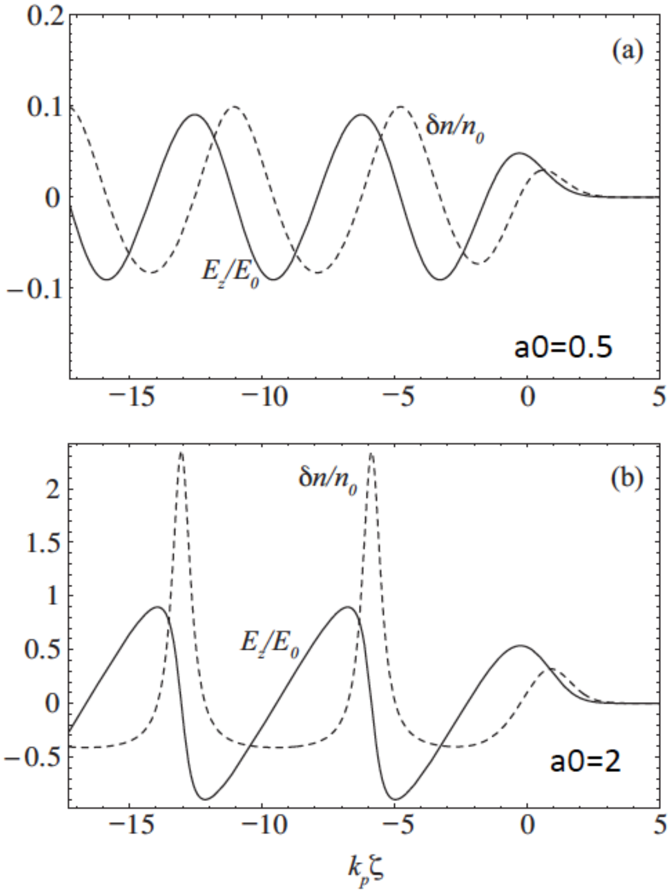
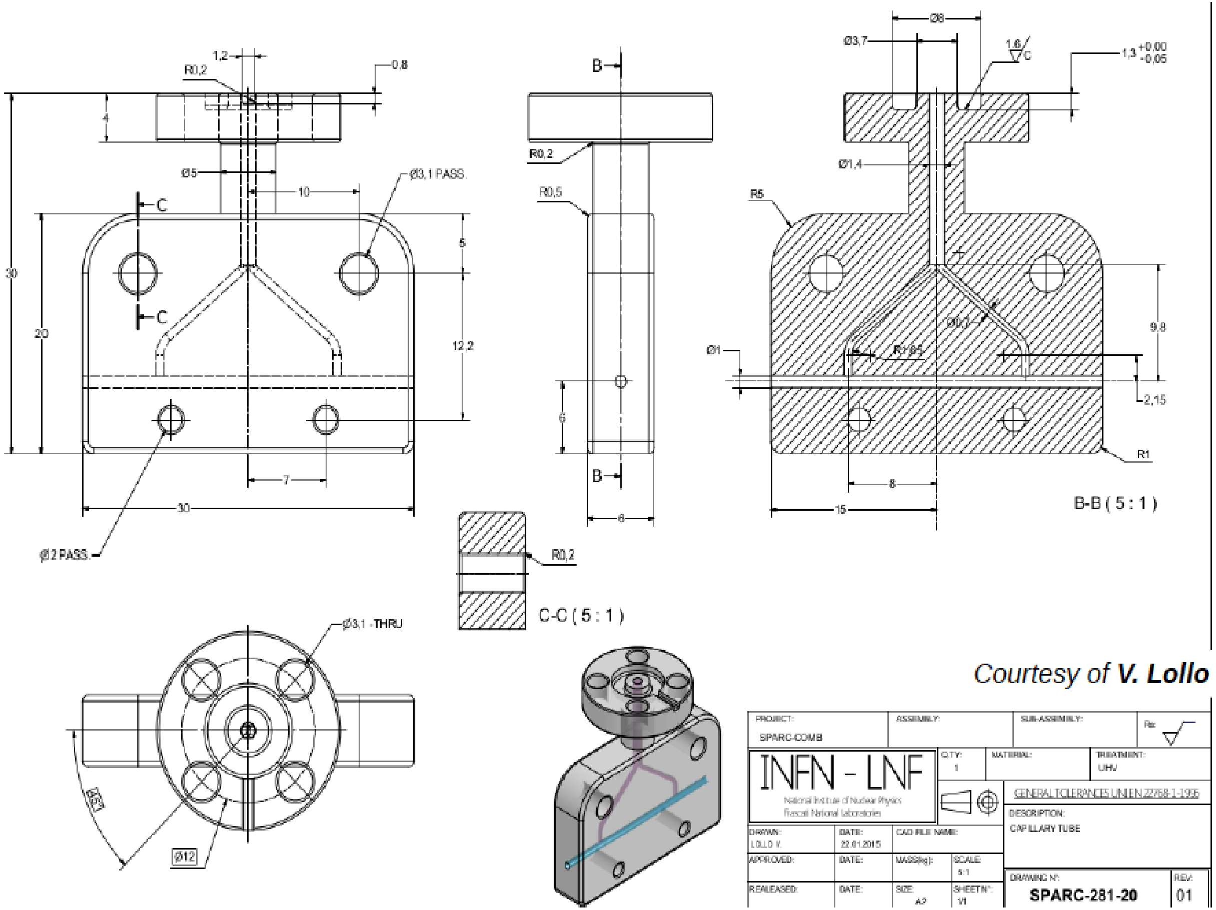


FIG. 8. Time-averaged density variation $\delta n/n_0$ (dashed curve) and axial electric field E_z/E_0 (solid curve) in an LWFA driven by a Gaussian laser pulse (pulse is moving to the right, centered at $k_p\zeta=0$ with rms intensity length $L_{\mathrm{rms}}=k_p^{-1}$) for (a) $a_0=0.5$ and (b) $a_0=2.0$.

Linear

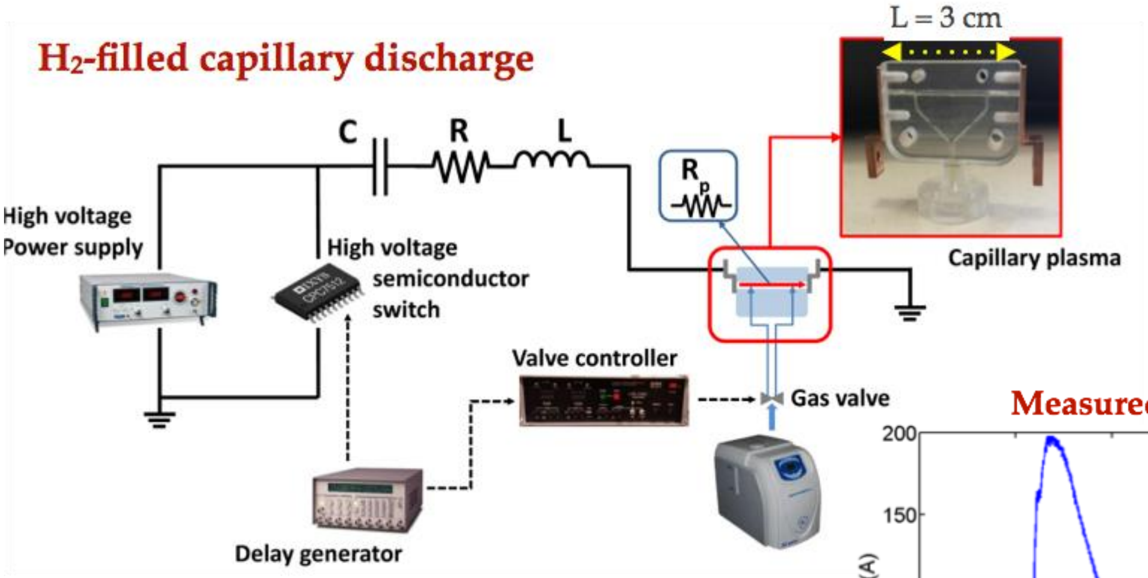
Non-Linear

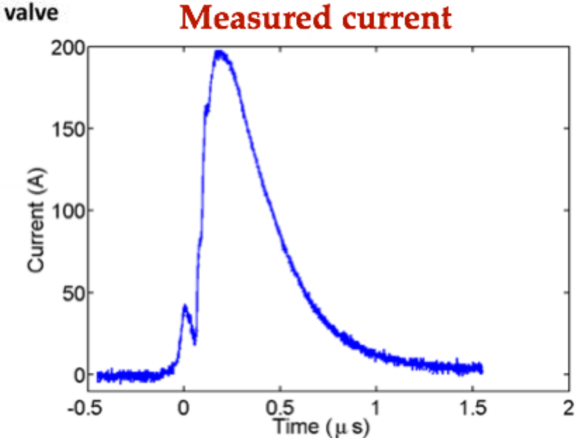
Plasma capillary



*Courtesy of **V. Lollo***

Plasma Source



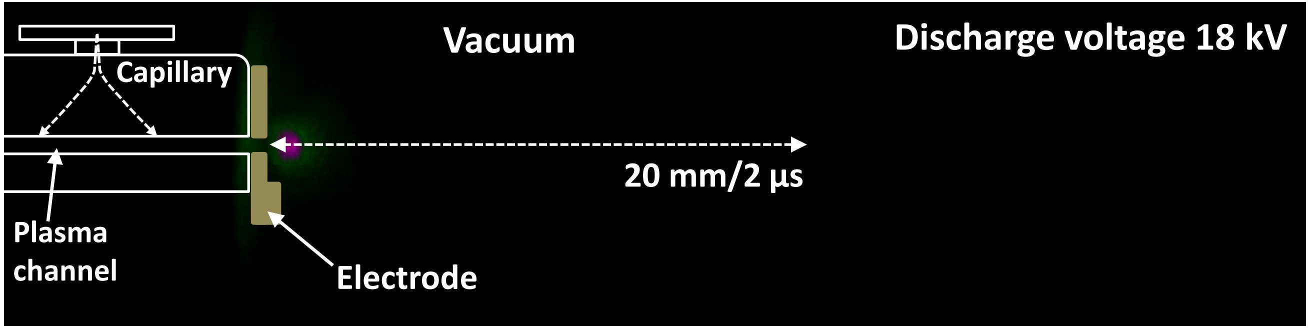


P_{H2} = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

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

Plasma plumes

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



- Both plama plumes can reach a total expansion length around 40 mm (20 mm each one) that is comparable with the channel length of 30 mm, so they can strongly affect the beam properties that passes through the capillary

- Temperature, pressure and plasma density, inside and outside the gas-filled capillary plasma source, represent essential parameters that have to be investigated to understand the plasma evolution and how it can affect the electron beam.

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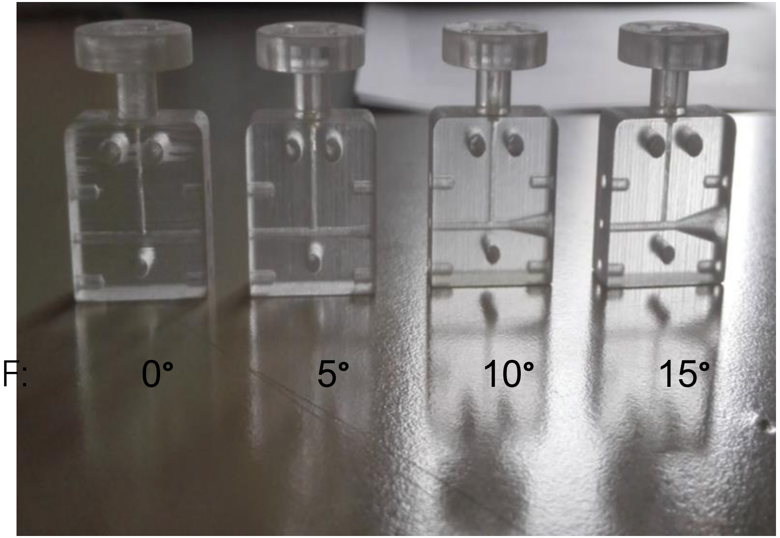
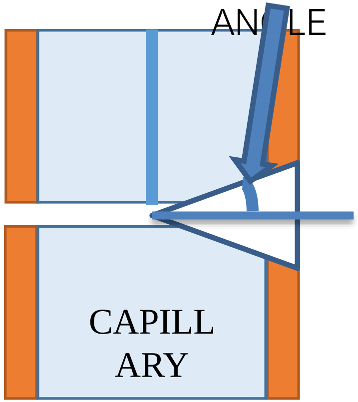
Tapered capillaries

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

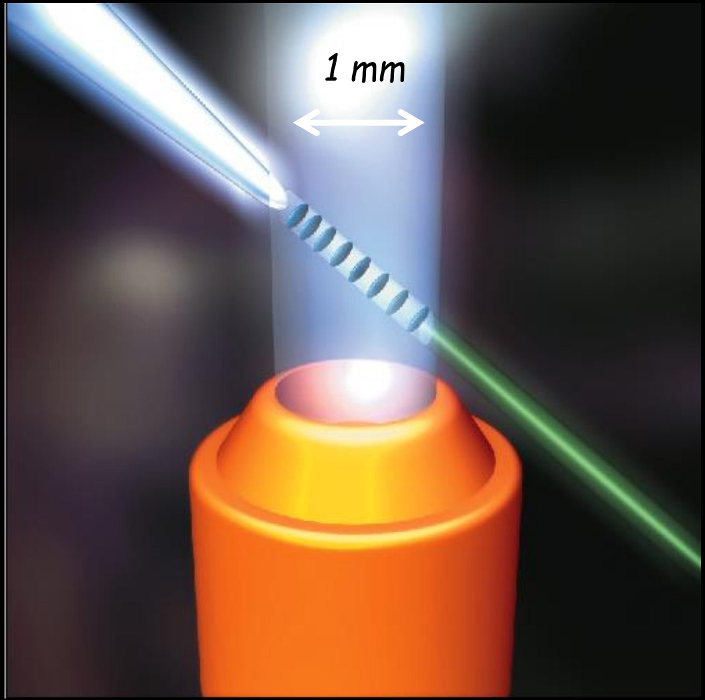




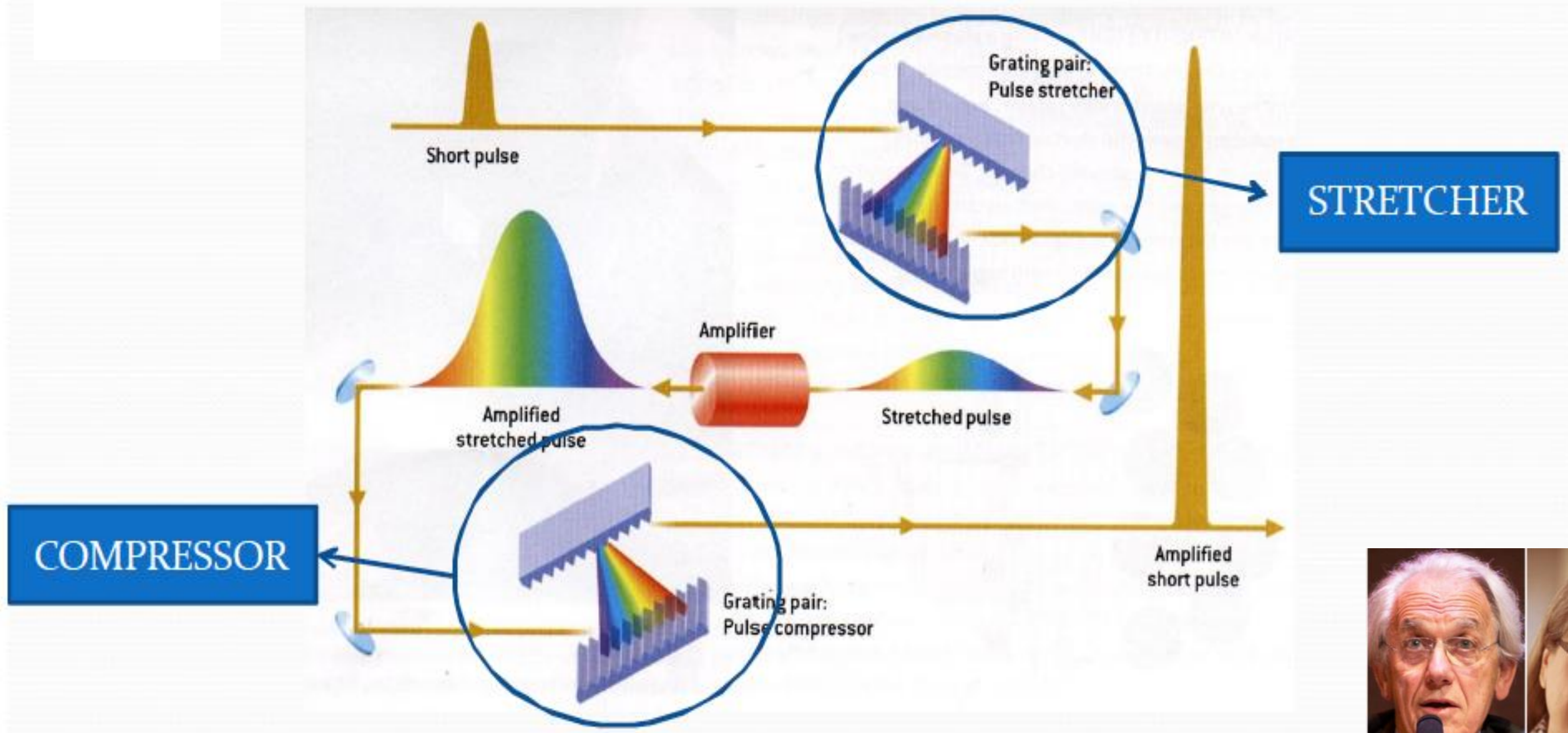
Laser Driven

LWFA

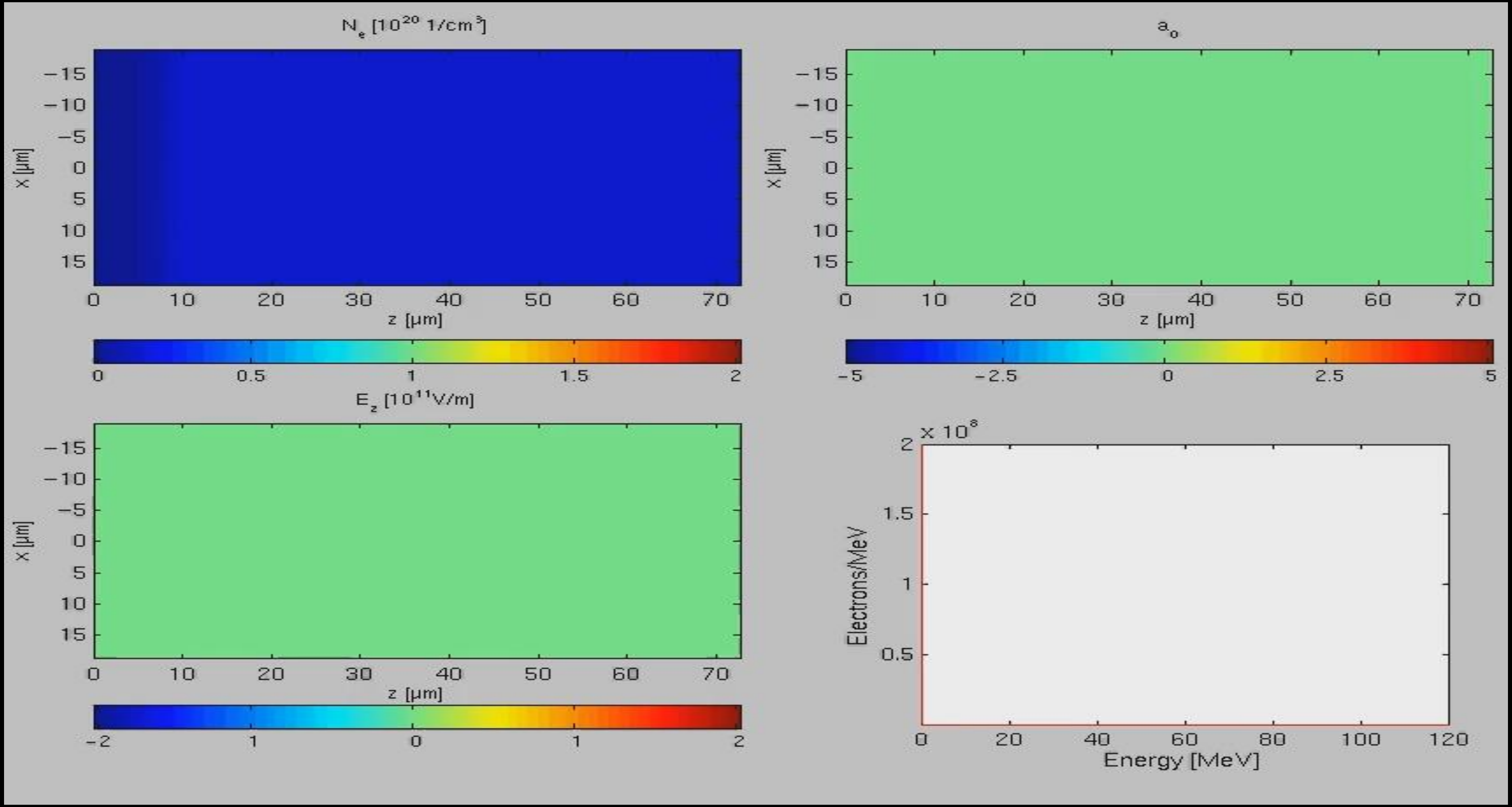
Direct production of e-beam



Chirped Pulse

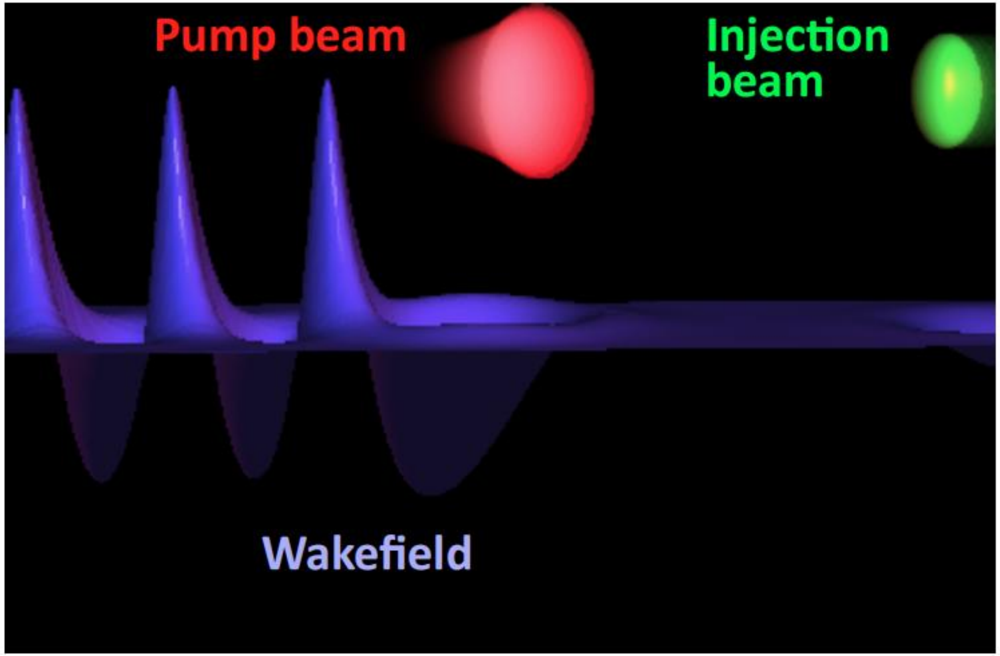


Diffraction - Self injection - Dephasing – Depletion



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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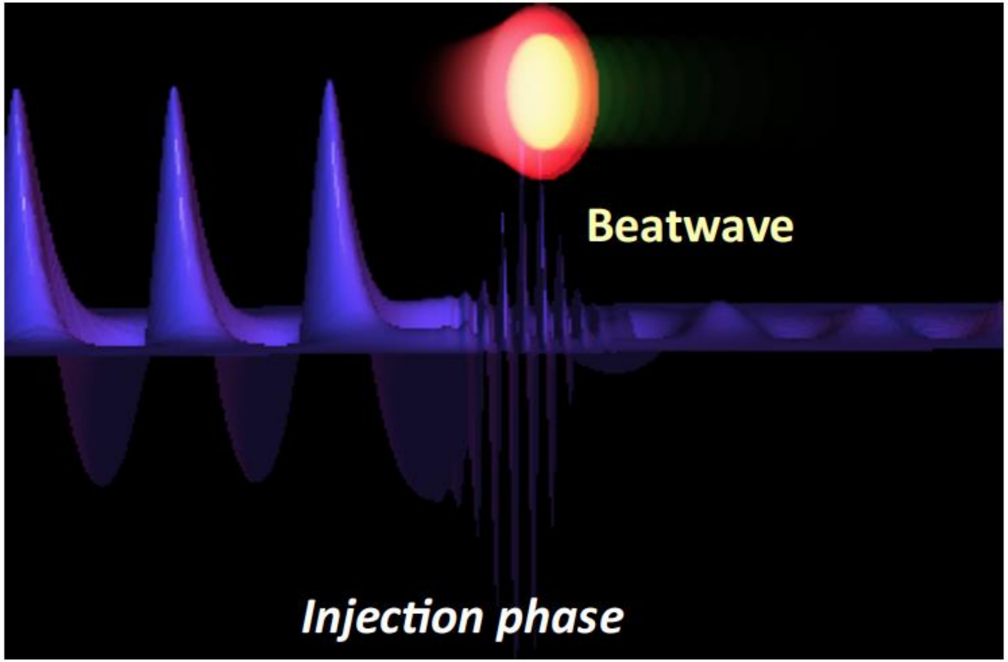

Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
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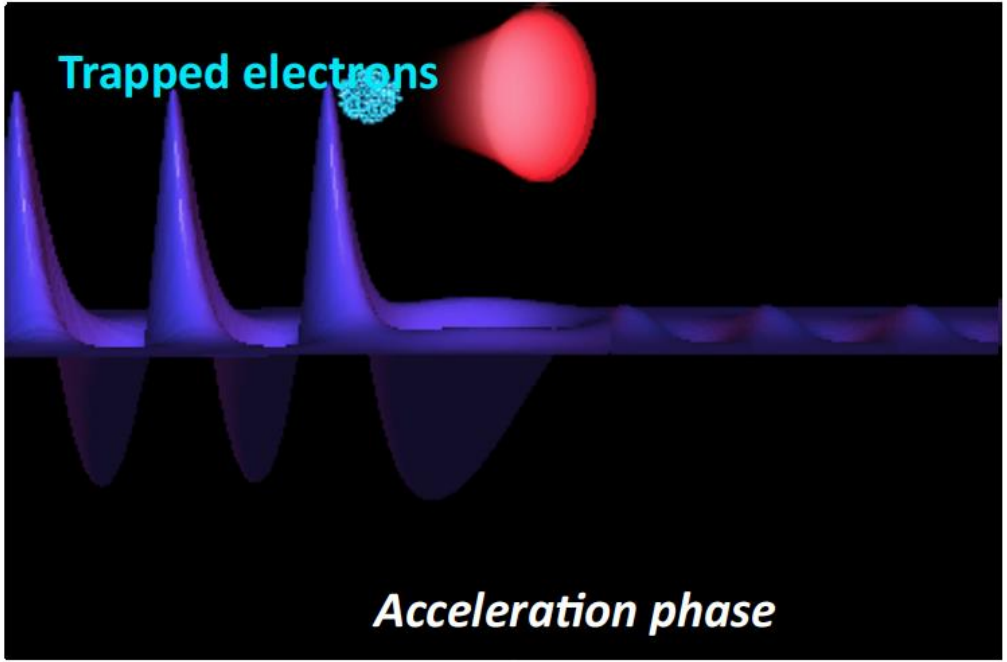
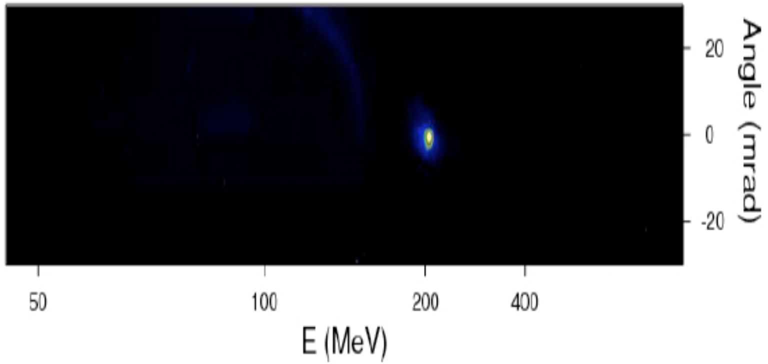
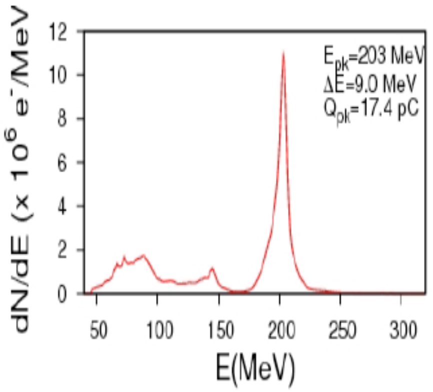


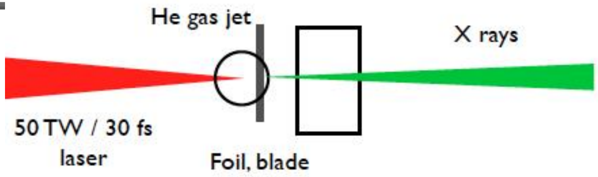
Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

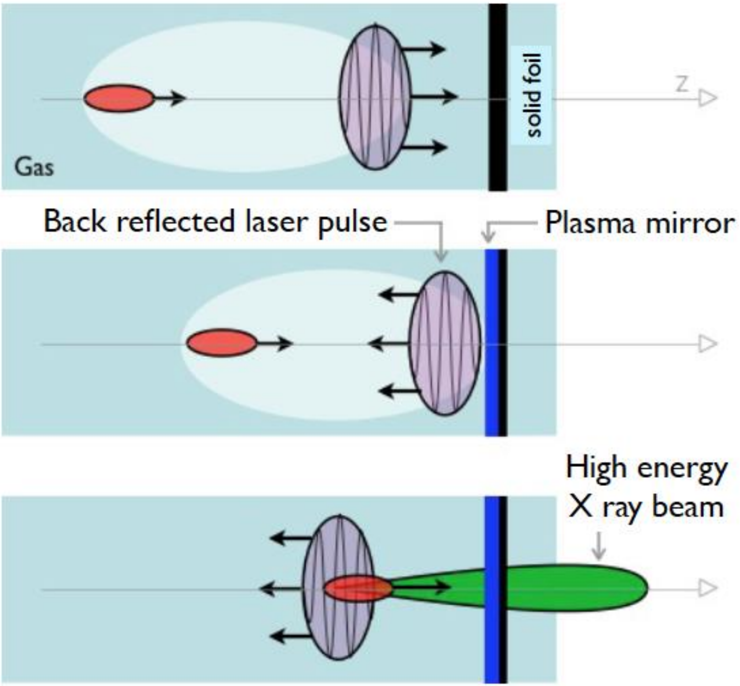
Stable Laser Plasma Accelerators





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

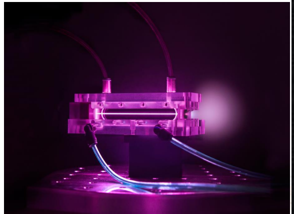
Save the laser energy !

BELLA: BErkeley Lab Laser Accelerator

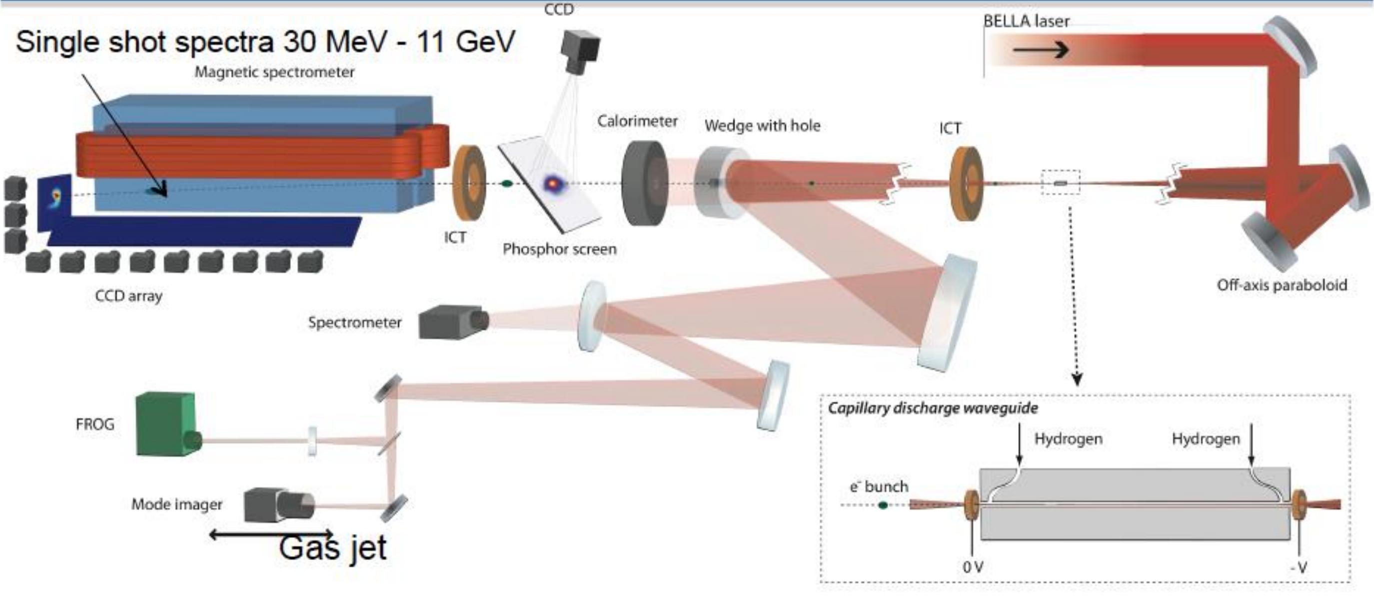
BELLA Facility: state-of-the-art 1.3 PW-laser for laser accelerator science:
>42 J in <40 fs (> 1PW) at 1 Hz laser and supporting infrastructure at LBNL

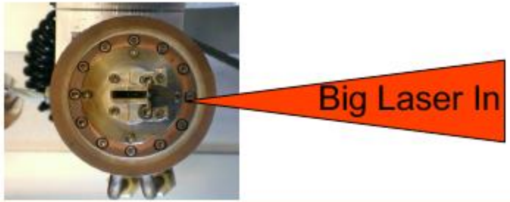
Critical HEP experiments:

- 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

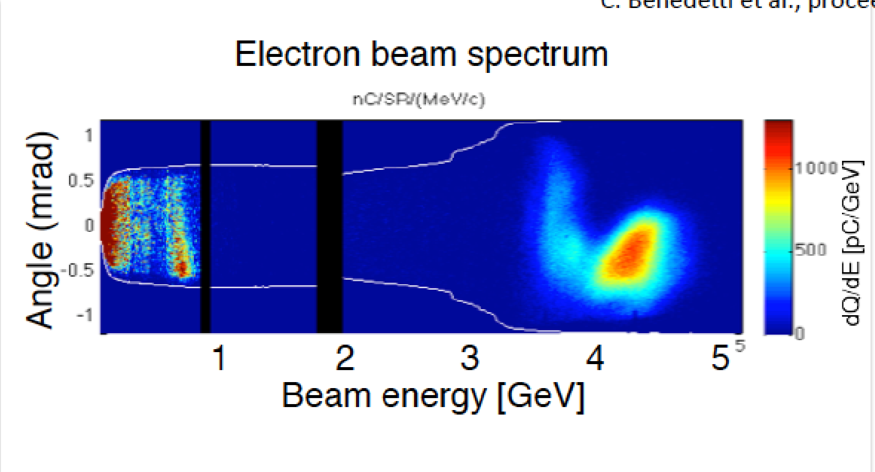


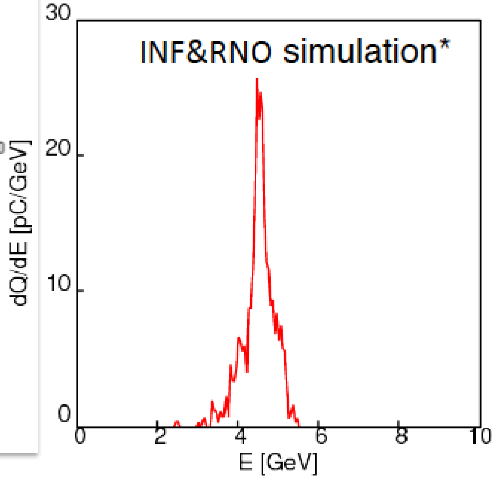


Capillary discharge

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

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





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

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

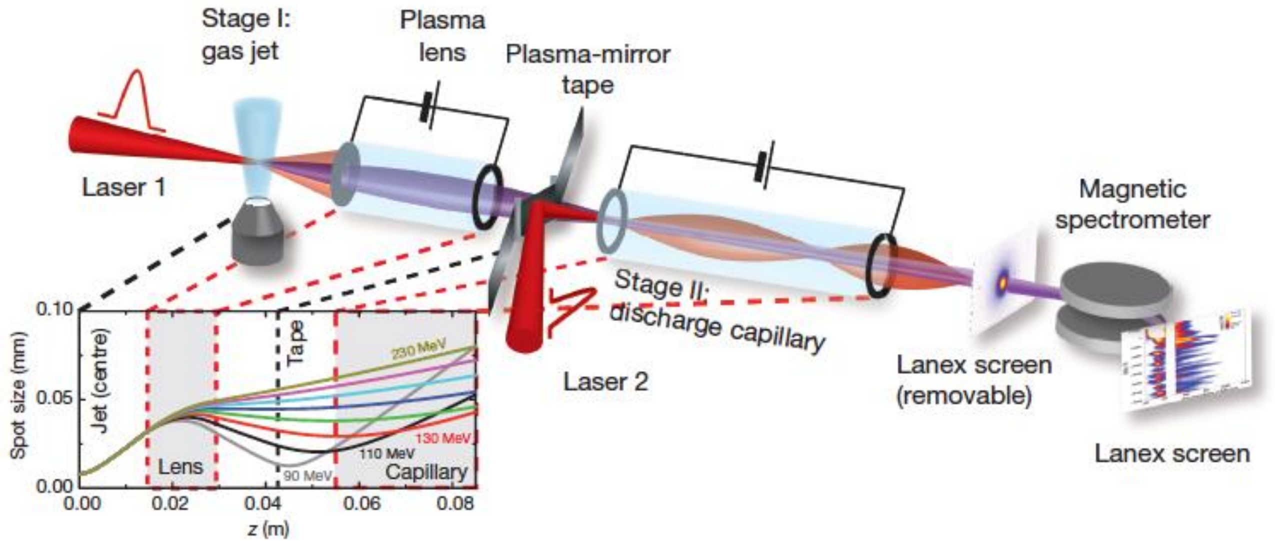
W.P. Leemans et al.,PRL 2014

LETTER

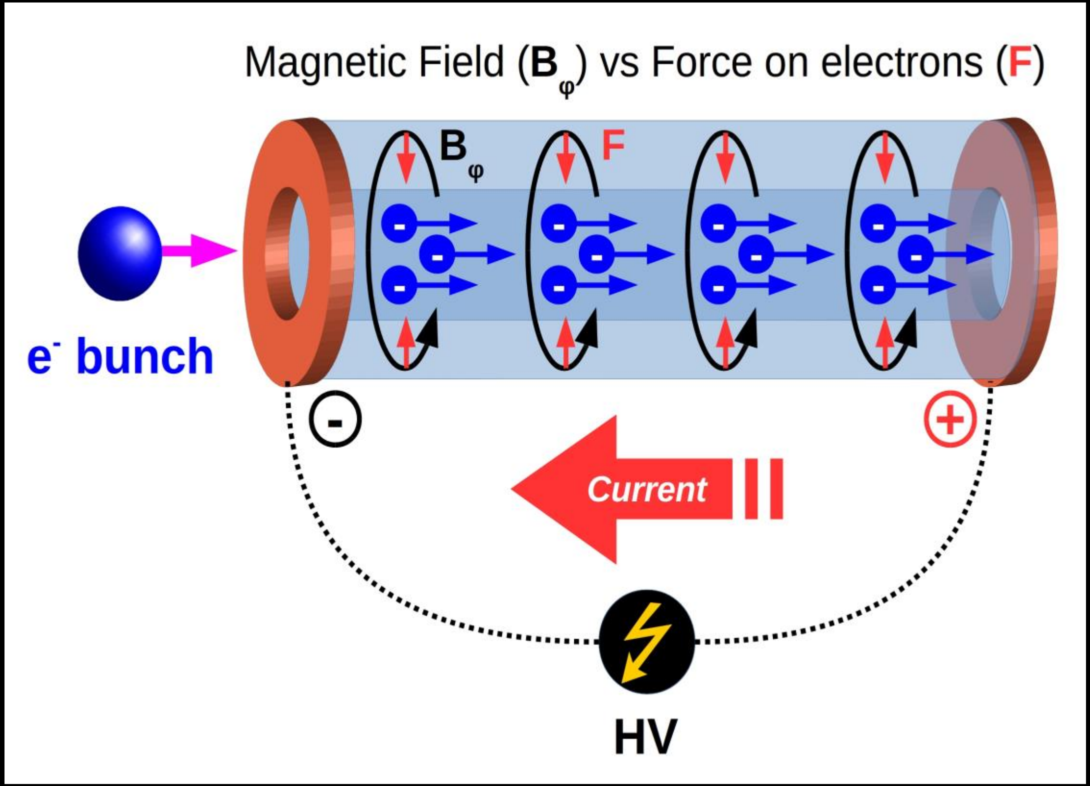
doi:10.1038/nature16525

Multistage coupling of independent laser–plasma accelerators

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



Active Plasma Lens

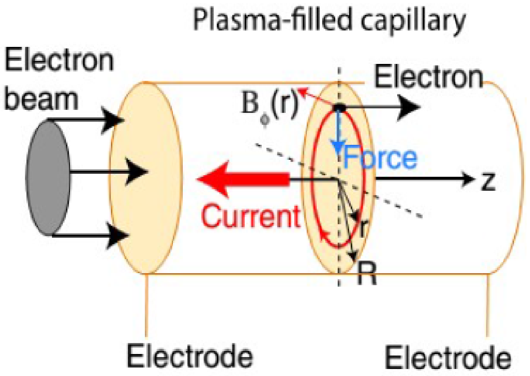


Active plasma lens

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

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

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

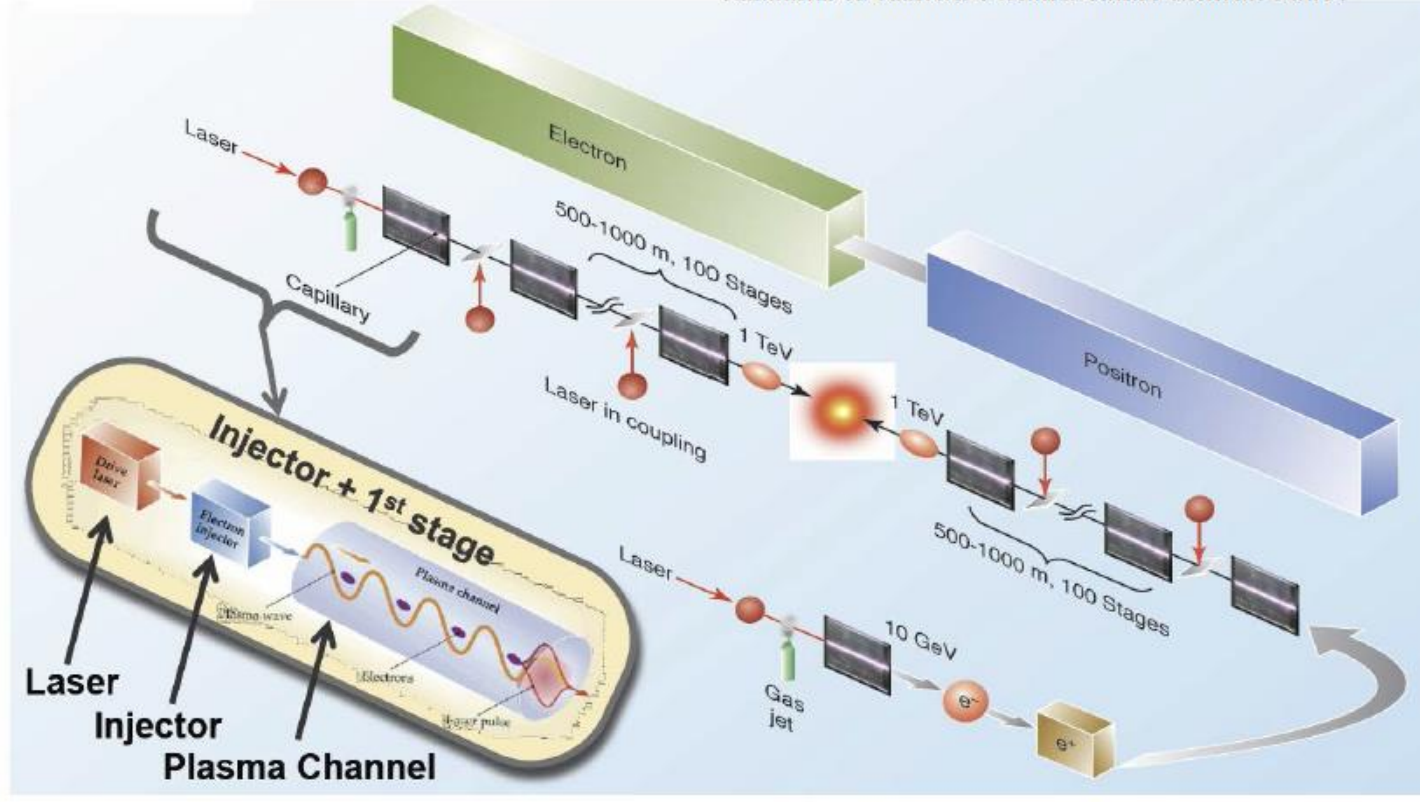


Van Tilborg, J., et al. "Active plasma lensing for relativistic laser-plasma-accelerated electron beams." Physical review letters 115.18 (2015): 184802.

Beam Manipulation

Laser-Plasma-Accelerator LC

Leemans & Esarey, Physics Today (March 2009)



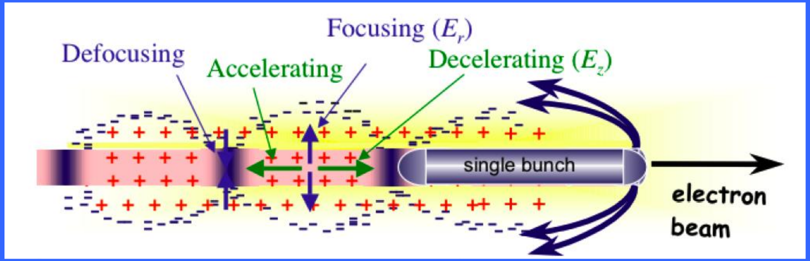
Parameter Set for LPWA LC

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

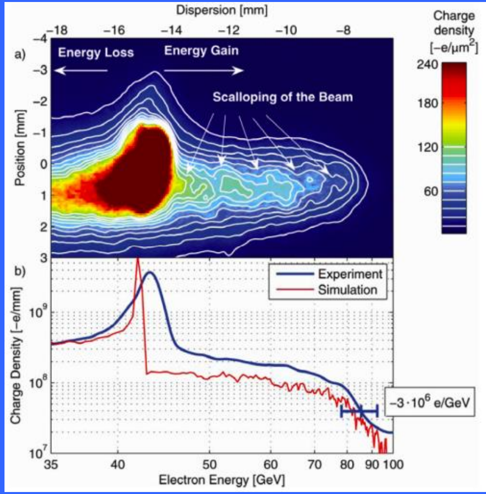
×2+FF

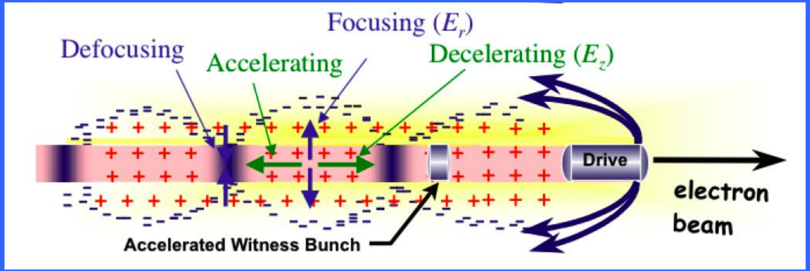
Beam Driven

PWFA

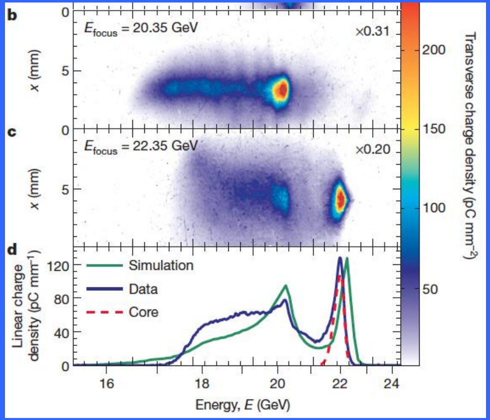


Blumenfeld, I. et al. *Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator*. **Nature** 445, 741–744 (2007).



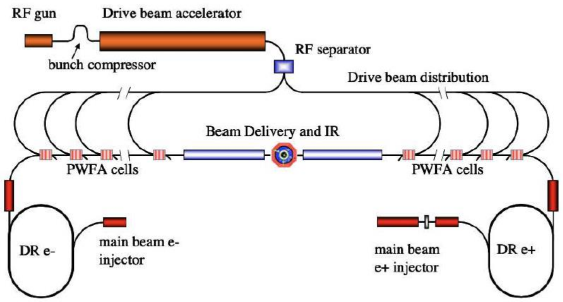


Litos, M. et al. *High-efficiency acceleration of an electron beam in a plasma wakefield accelerator*. **Nature** 515, 92–95 (2014).

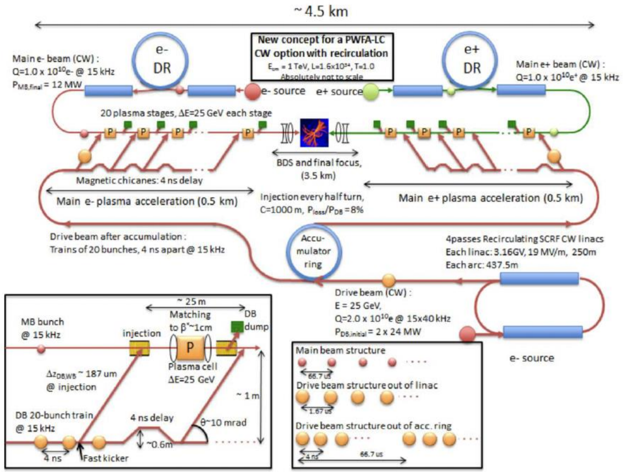


Solution: **A plasma-based e+e− collider?**

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



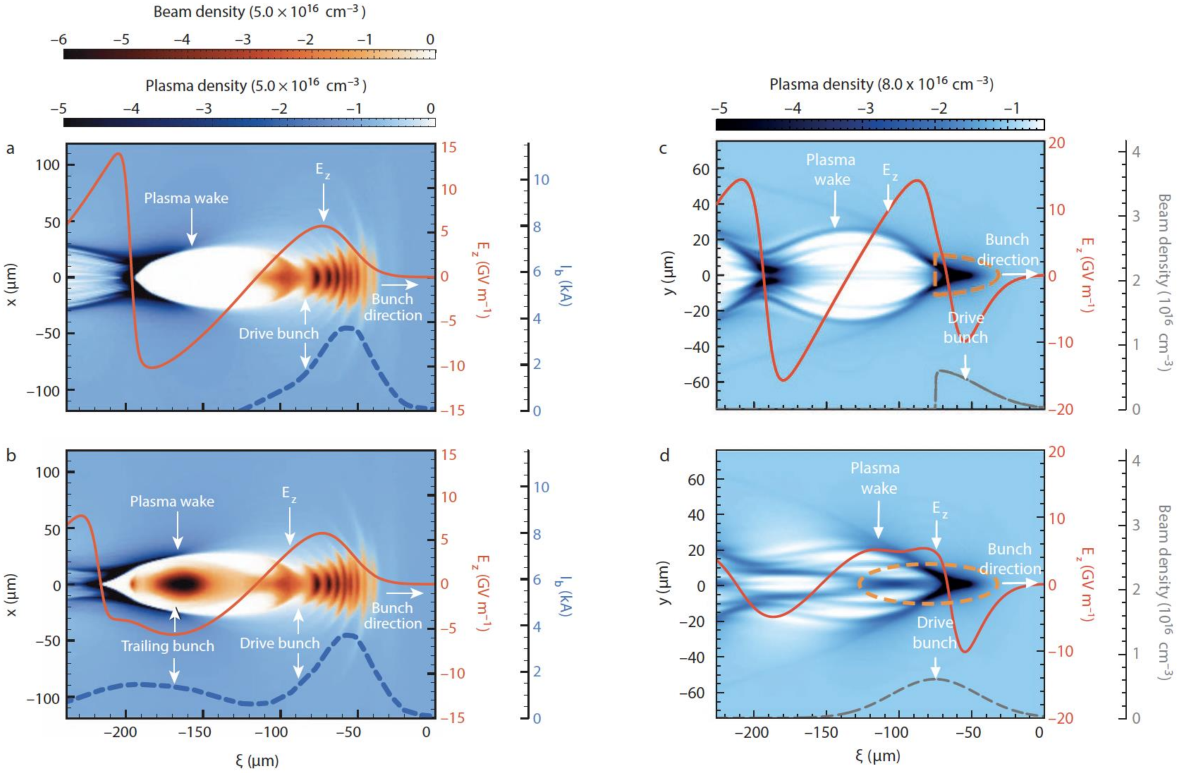
Source: Pei et al., Proc. PAC (2009)



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

Main problem: **Positron acceleration in plasmas**

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



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

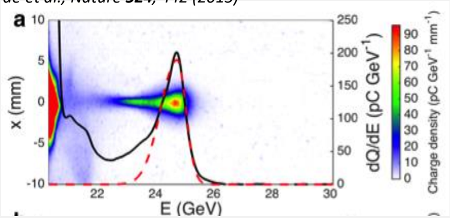
Positron Acceleration, FACET

First demonstration of positron acceleration in plasma (FFTB)

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

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

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

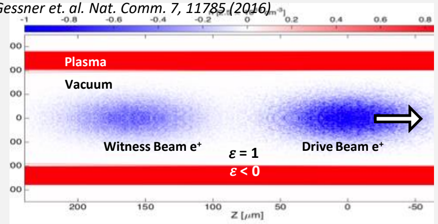


High-density, compressed positron beam for non-linear PWFA experiments. Energy transfer from the front to the back part of the bunch.

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

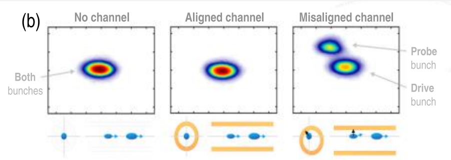
Hollow plasma channel: positron propagation, wake excitation, acceleration in 30 cm channel.

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



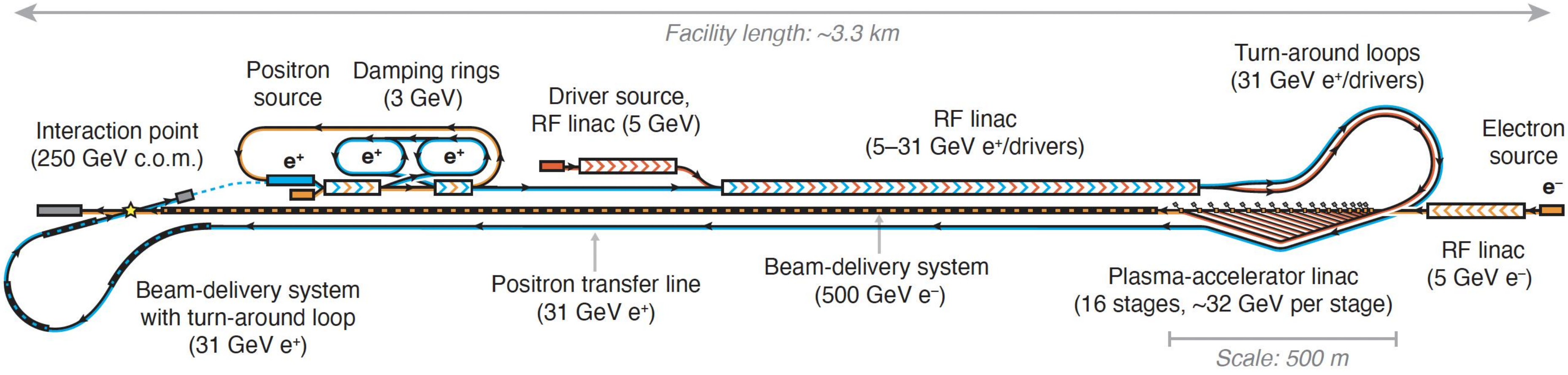
Measurement of **transverse wakefields in a hollow plasma** channel due to off-axis drive bunch propagation.

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



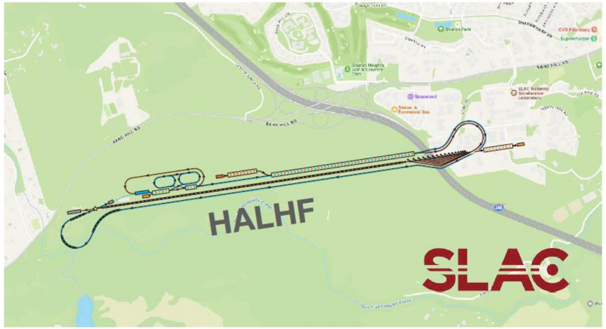
→ Emittance blow-up is an issue! → Use hollow-channel, so no plasma on-axis, no complicated forces from plasma electrons streaming through the plasma → but then strong transverse wakefields when beams are misaligned.

HALHF: A Hybrid, Asymmetric, Linear Higgs Factory



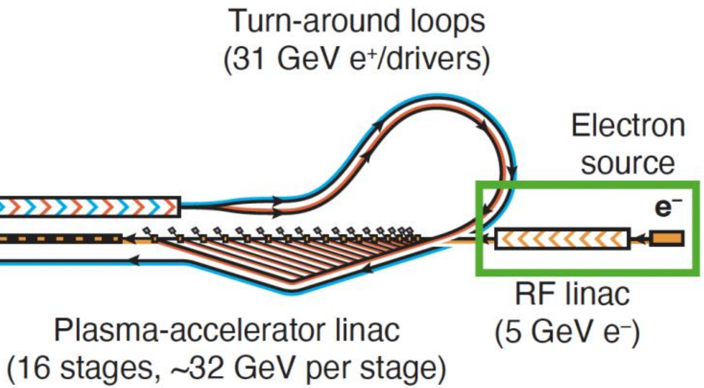
Source: Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)

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

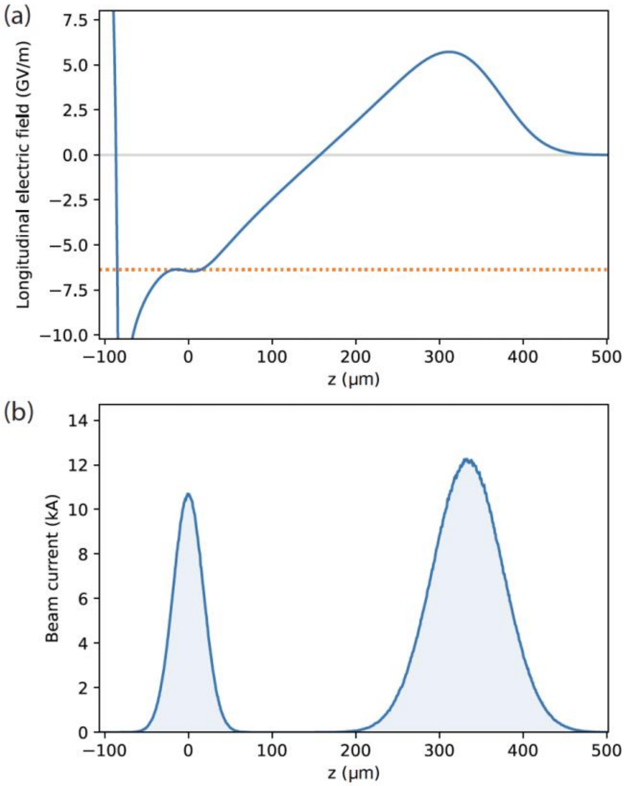


The novelty: **A multistage plasma-based linac**

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



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

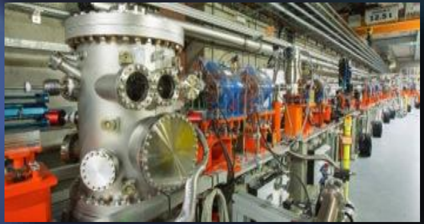


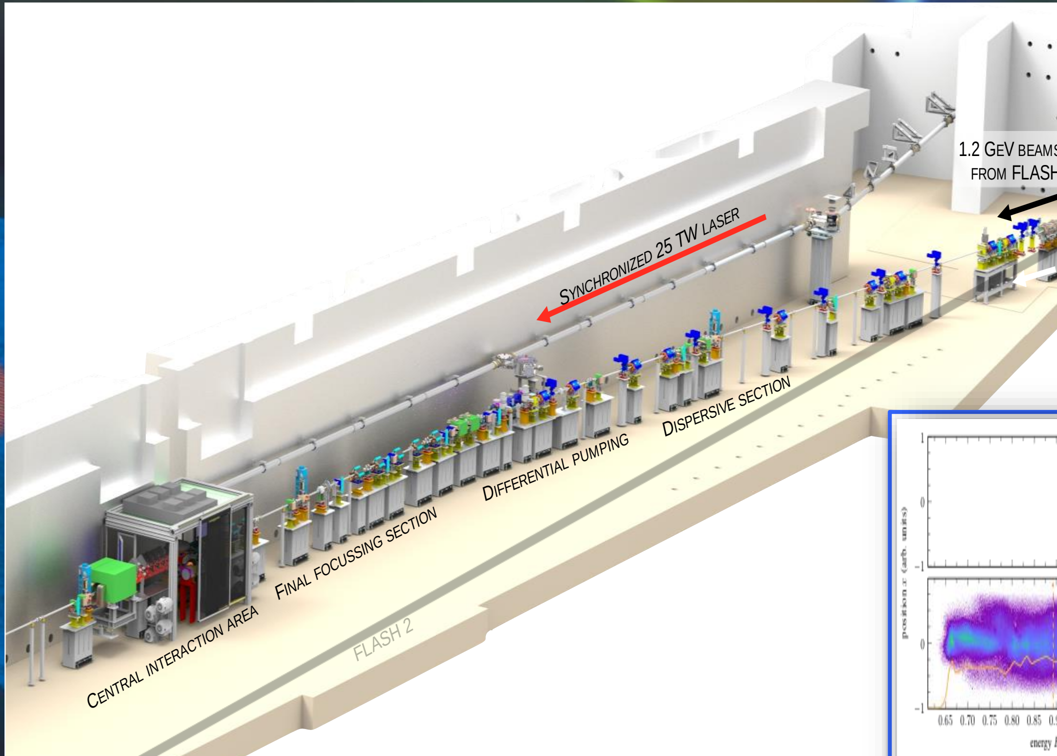
Simulated with Wake-T
Plasma density: 7 x 10^{15} cm^{-3}
Driver/witness charge: 4.3/1.6 nC

FLASHForward>>, DESY

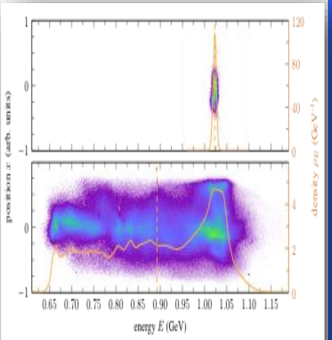
→ unique FLASH facility features for PWFA

- 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

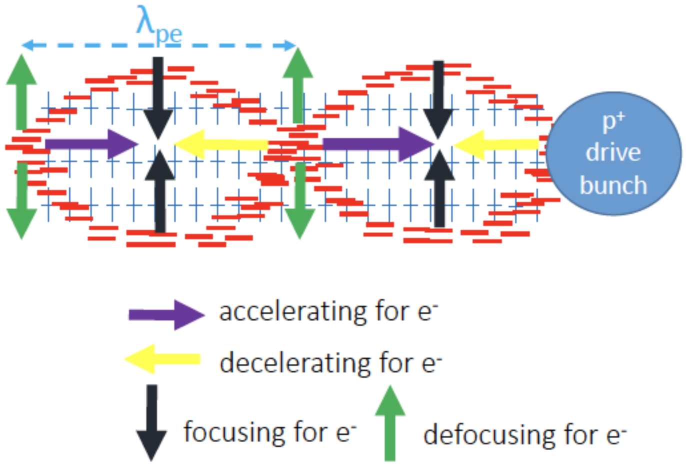
→ 12.7% total energy loss to plasma wakefield

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

Reasons for proton bunch driver

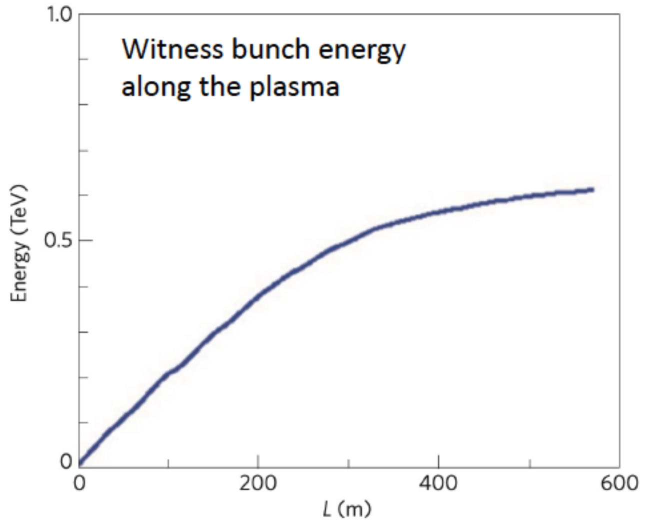
Available proton bunches carry large amounts of energy:

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



⇒ Overcome the need of staging!

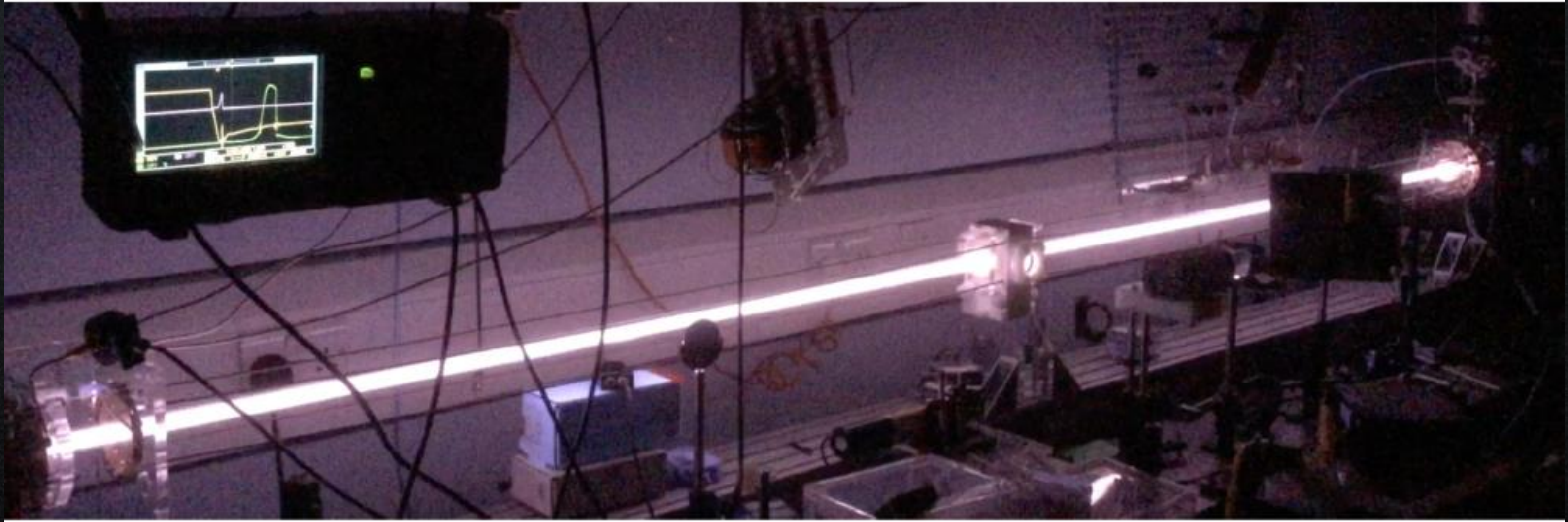
Parameters:
single proton bunch
σ_z = 100 µm,
E = 1 TeV,
population: $1 \cdot 10^{11}$ ppb



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

Discharge configuration II

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



very promising results

… reliable, low jitter plasma formation

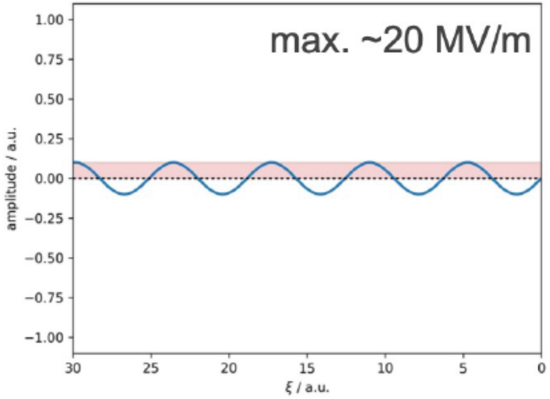
scalability of electric circuit for plasmas > 10 m seem achievable…

Self-modulation in plasma

CERN SPS Proton bunch

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

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



Growth mechanism

Initial transverse wakefields

Periodic focusing/defocusing fields

Radial bunch and plasma density modulation

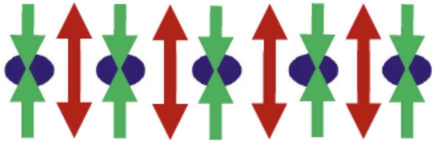
Stronger wakefields

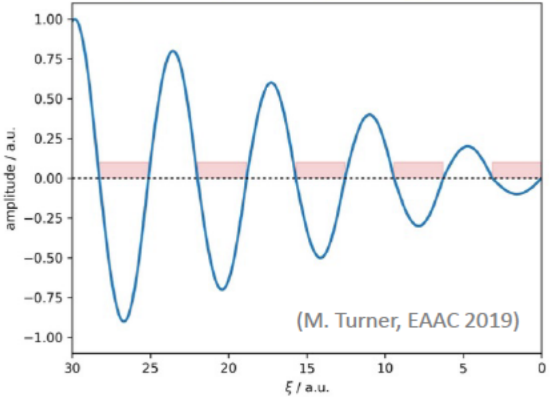
Full modulation

Self-Modulation instability (SMI)

→ resonant wakefield excitation

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

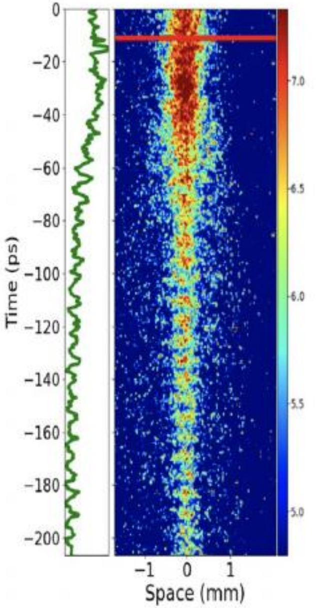




N. Kumar et al., Phys. Rev. Lett. 104 (25), 255003 (2010)

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

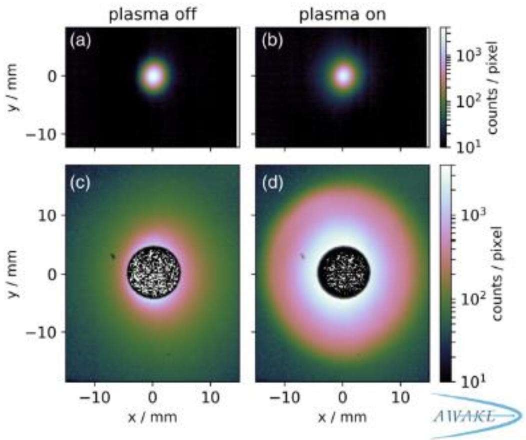
AWAKE Run 1 (2016-2018)



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

time-resolved imaging:

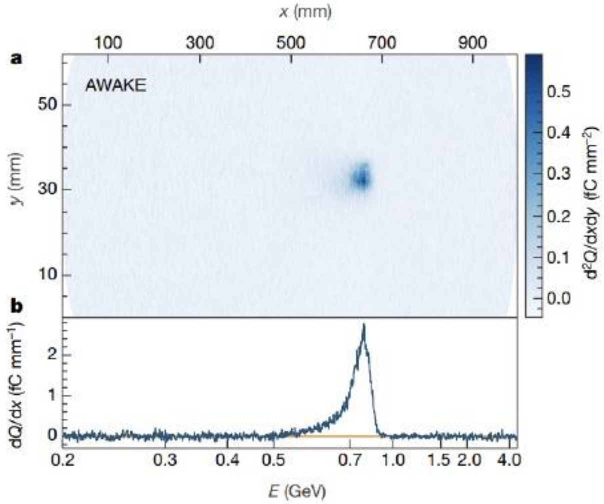
- the proton bunch self-modulates in plasma
- focusing phase → micro-bunches
- frequency of the modulation≈ ω_{pe}



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

time-integrated, transverse imaging:

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

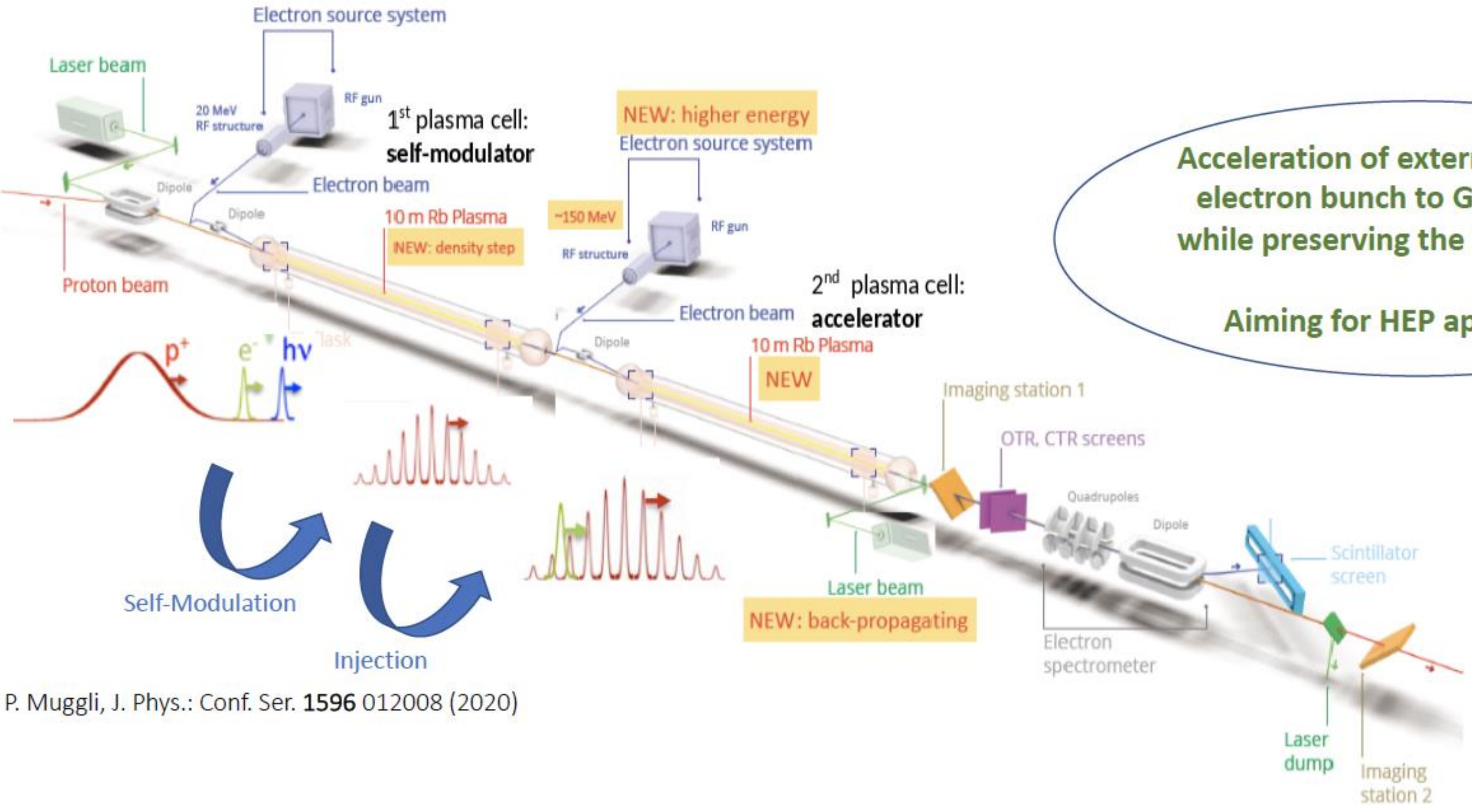


AWAKE Coll., Nature 561, 363-367 (2018)

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

PROOF OF PRINCIPLE!

AWAKE Run 2 (2021→) setup &final goal



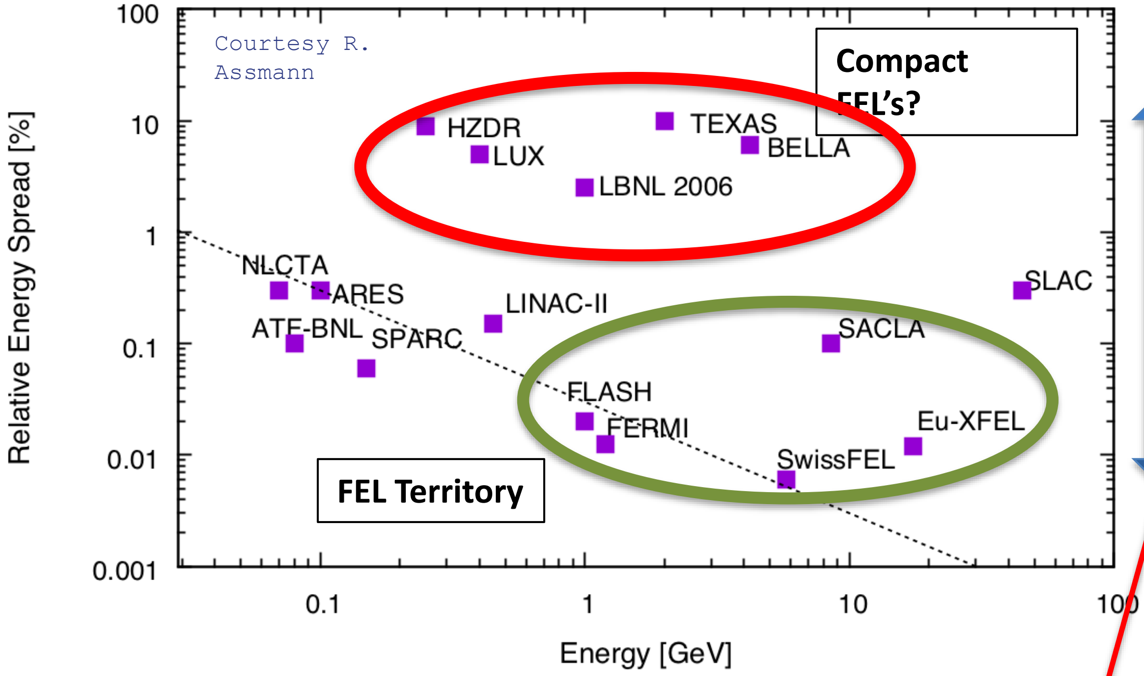
Acceleration of externally injected electron bunch to GeV-energies while preserving the initial quality

Aiming for HEP application!

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

The near future

Quality: Example Energy Spread



Lower quality

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

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

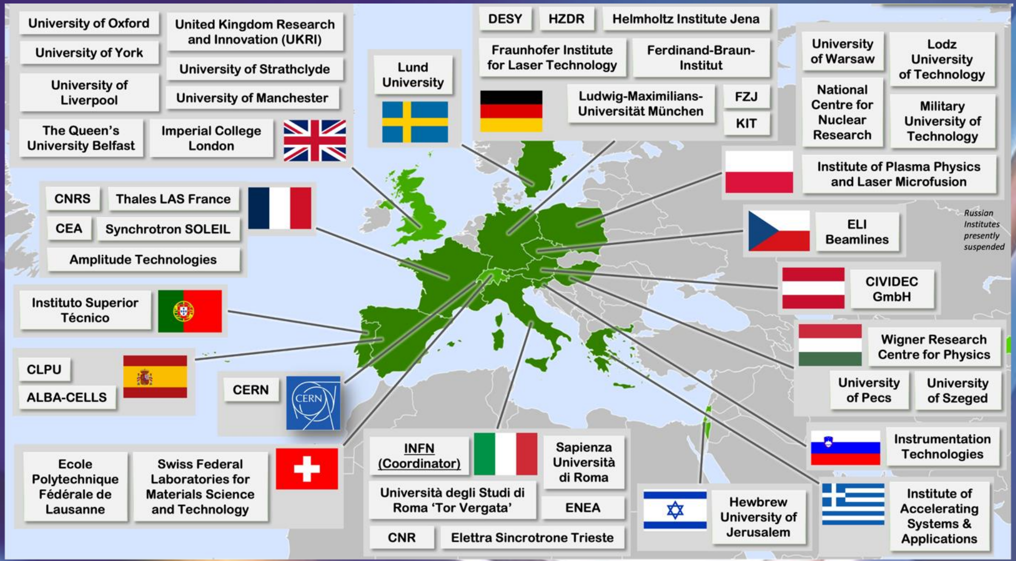
Higher quality

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

M. Migliorati et al, Physical Review Special Topics,Accelerators and Beams 16, 011302 (2013)
K. Floettmann, PRSTAB,6, 034202 (2003)

EUROPEAN
PLASMA RESEARCH
ACCELERATOR
WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA



This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

A New European High-Tech User Facility

Funded by the European Union

1

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

Shrink down the facility size

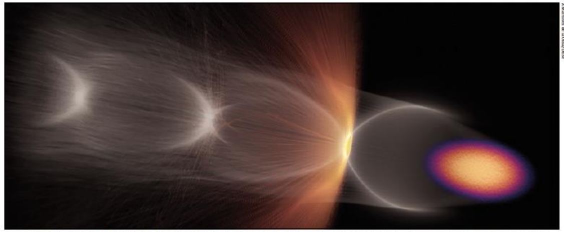
2

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

Enable frontier science in new regions and parameter regimes

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

FEATURE EuPRAXIA



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

EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

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

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

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

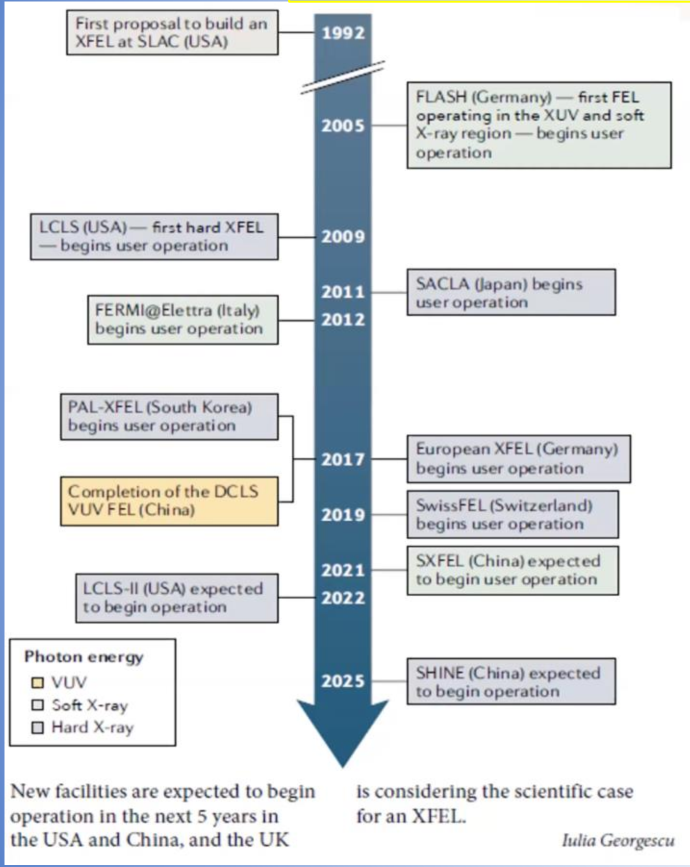
However, intrinsic technological and conceptual limits mean that the size and cost of RF-based particle accelerators are increasing as researchers seek higher beam energies. Colliders for particle physics have reached a

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

FEL is a well established technology

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

Funded by the European Union



Linac Coherent Light Source (LCLS) Conceptual Design Report - SLAC–R–593 April 2002 UC-414

Plasma accelerated beam driven FEL

It's a CHALLENGE: **the FEL is extremely sensitive to the beam quality.**

Low (geometric) emittances: $\epsilon_{x,y} < \frac{\lambda_0}{4\pi}$

Low relative energy spread σ_γ: $\sigma_\gamma < \frac{1}{2}\rho_{fel}$

Low emittances
Low energy spread
High current

where $$\rho_{fel} = \frac{1}{4\pi}\left[\frac{2\pi^2}{\gamma^3}\left(\lambda_u K\,[JJ]\right)^2 \frac{I_{peak}}{\Sigma_e I_A}\right]^{1/3}$$

Exponential growth

$$P(z) = \frac{1}{9}P_0 e^{z/L_g}$$

gain length

$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{fel}}$$

saturation

$$P_F \sim 1.6\,\rho_{fel} P_{beam}$$

=> A poor beam quality causes an increase of L_g and a reduction of P_F

Energy spread compensation with beam loading

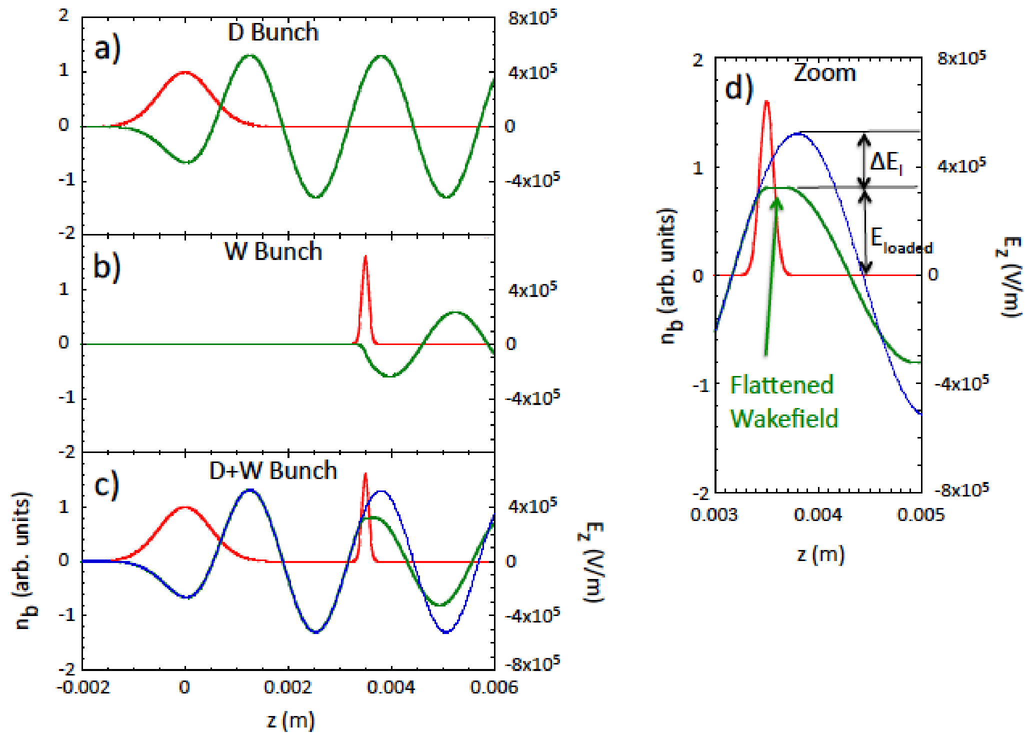
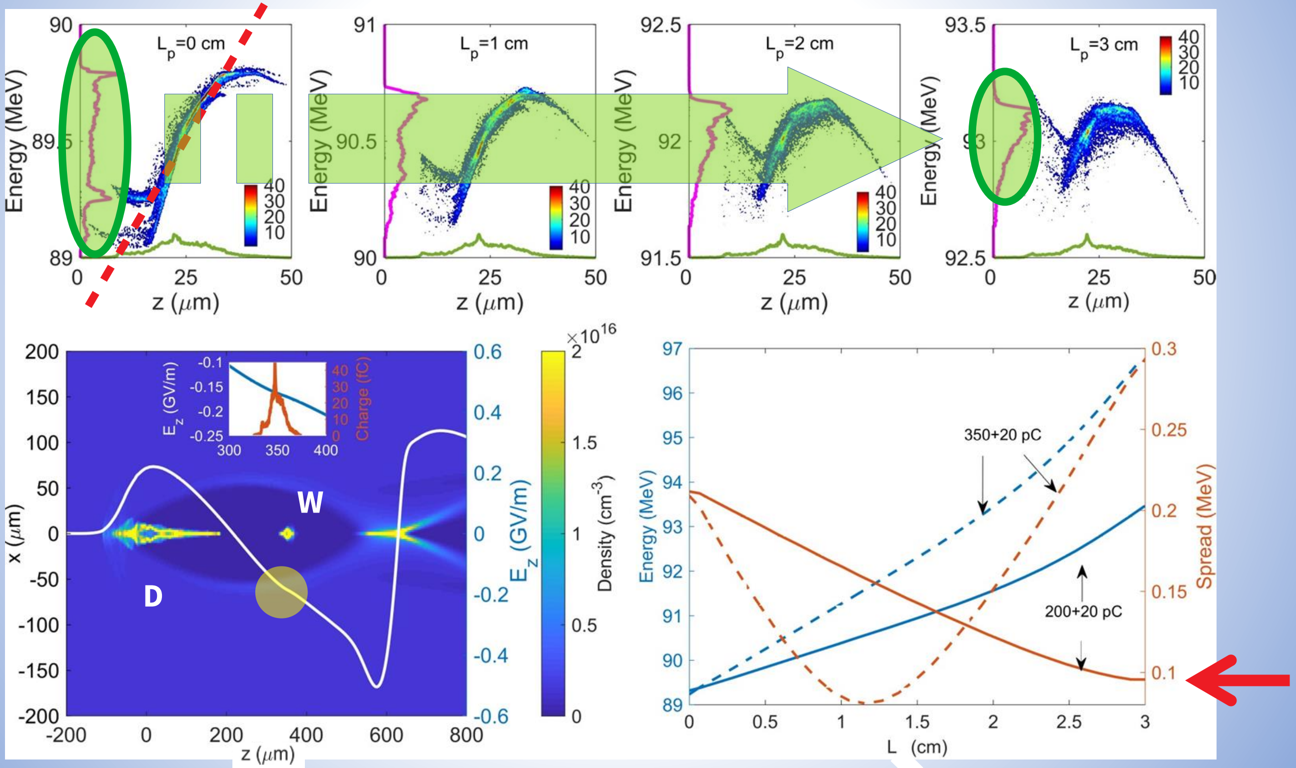


Fig. 5: Linear beam loading example: (a) drive bunch density profile (red line) and longitudinal wakefield E_z (green line), (b) same for the witness bunch, (c) same for the drive and witness bunches together. The field of the drive bunch only is shown as the blue line in panel (c). A zoom around the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

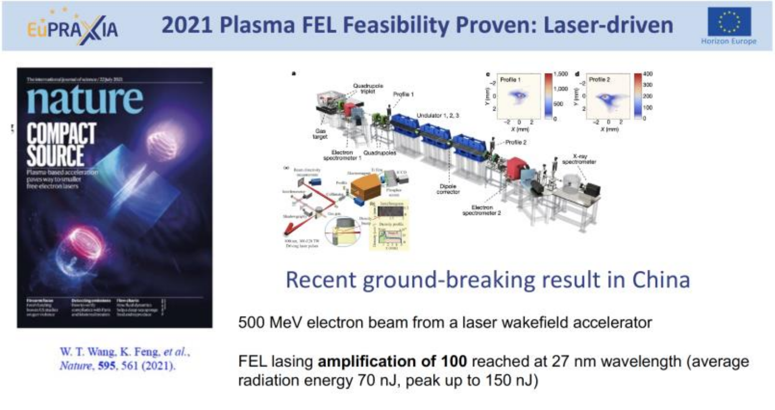
Assisted beam-loading technique

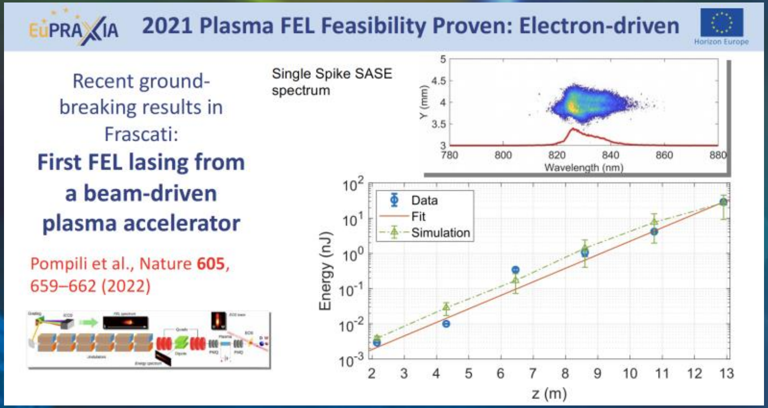
Pre-chirp to compensate wakefield slope

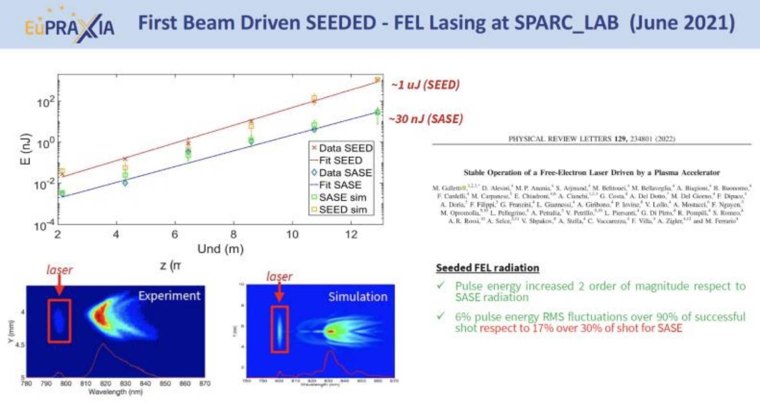


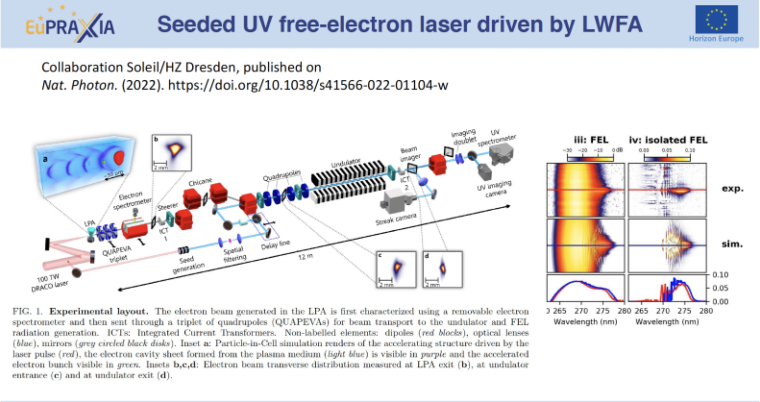
R. Pompili et al., Energy spread minimization in a beam-driven plasma wakefield accelerator, *Nature Physics* **volume 17**, pages 499–503 (2021)

Basic beam quality achieved in pilot FEL experiments

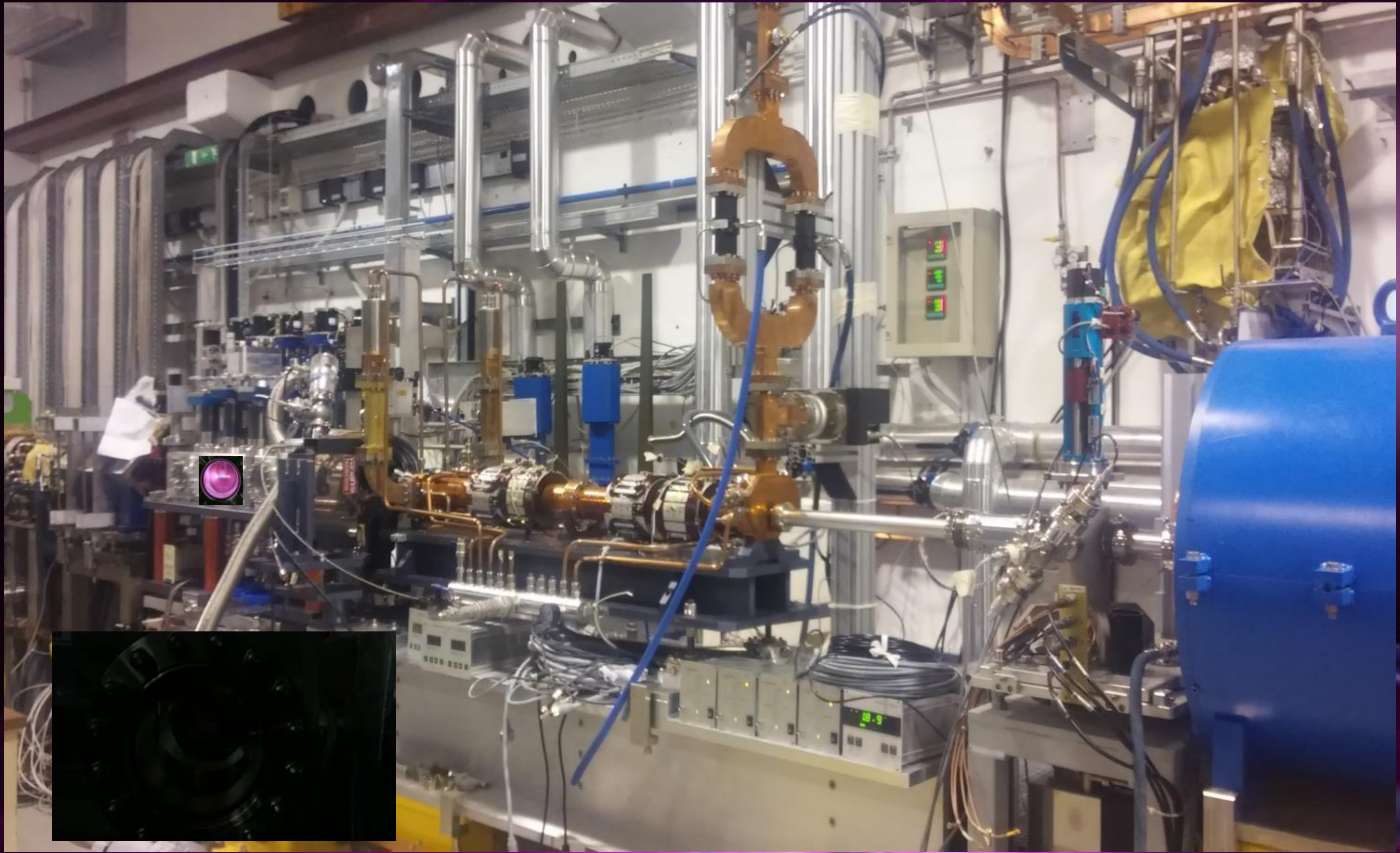








PWFA beam line at SPARC_LAB



Required Bunch Energy Stability

$$\frac{\Delta\lambda}{\lambda} \propto \frac{\Delta E}{E} \propto \rho \approx 10^{-3}$$

FEL requirement

$$E_z\left(\frac{\lambda_p}{2}\right) = \tilde{A}\sqrt{n_p I_d}$$

$$\left.\frac{\Delta E}{E}\right|_p = \frac{\Delta n_p}{n_p}$$

Plasma density

$$\left.\frac{\Delta E}{E}\right|_Q = \frac{\Delta I_d}{2\left(I_d\right)} + \frac{\Delta I_w}{2\left(I_w\right)}$$

Bunch charge/length

$$\left.\frac{\Delta E}{E}\right|_{DW} = \frac{a\omega_p}{2\pi}\Delta t_{DW}$$

$$2 \leq a \leq 4$$

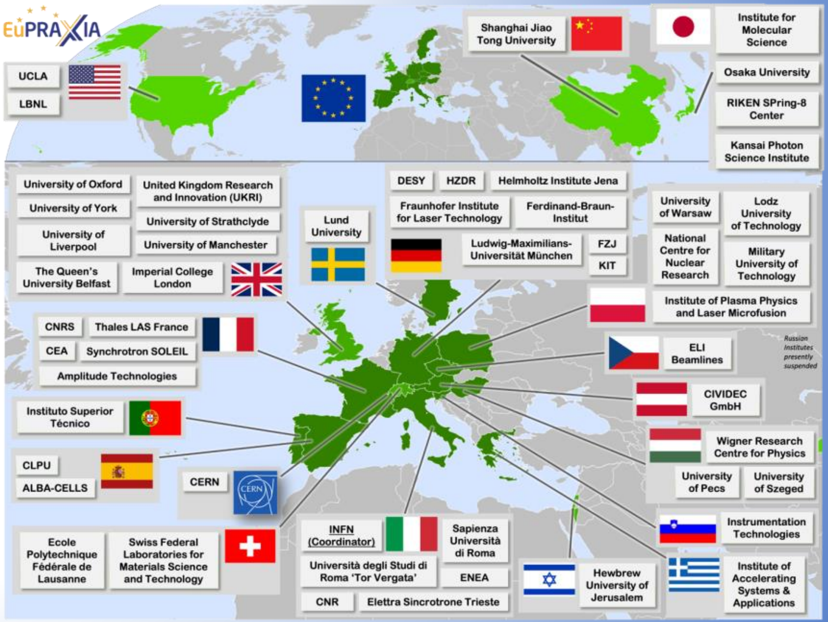
Driver/Witness separation

Wide International Collaboration

Funded by the European Union

- **The EuPRAXIA Consortium today: 54 institutes** from **18 countries** plus CERN
- Included in the **ESFRI** Road Map

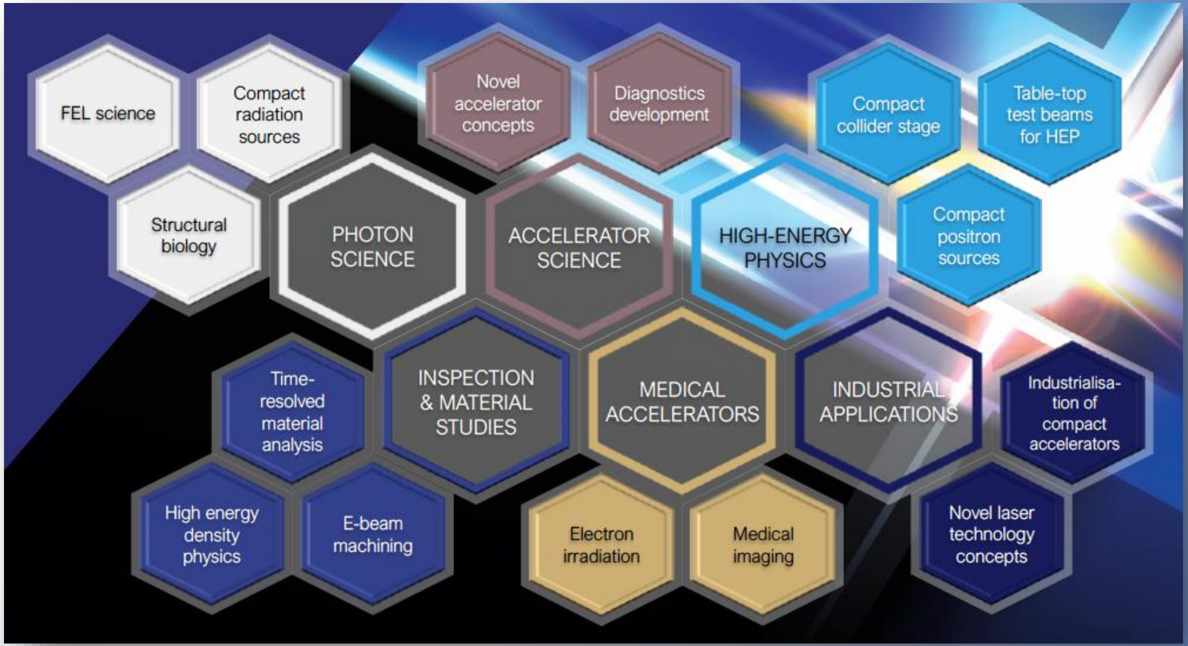
- **Efficient fund raising:**
  - –**Preparatory Phase** consortium (funding EU, UK, Switzerland, in-kind)
  - –**Doctoral Network** (funding EU, UK, in-kind)
  - –**EuPRAXIA@SPARC_LAB** (Italy, in-kind)
  - –**EuAPS Project** (Next Generation EU)



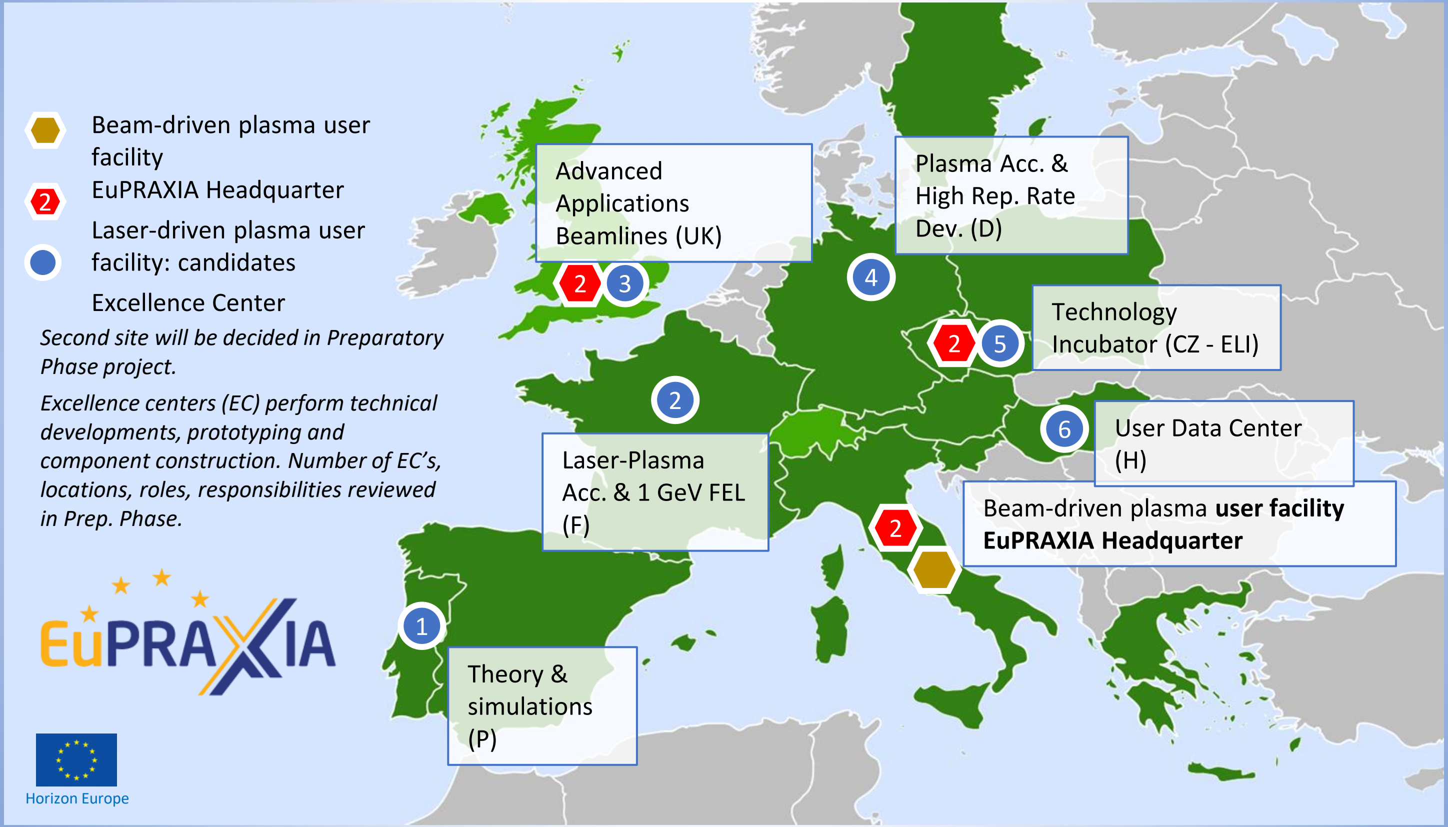
Intense R&D Program on critical components

Funded by the European Union

- **Electrons**
  (0.1-5 GeV, 30 pC)
- **Positrons**
  (0.5-10 MeV, 10^6)
- **Positrons** (GeV source)
- **Lasers**
  (100 J, 50 fs, 10-100 Hz)
- **X-band RF Linac**
  (60 MV/m , up to 400 Hz)
- **Plasma Targets**
- **Betatron X rays**
  (1-10 keV, 10^{10})
- **FEL light**
  (0.2-36 nm, 10^9-10^{13})

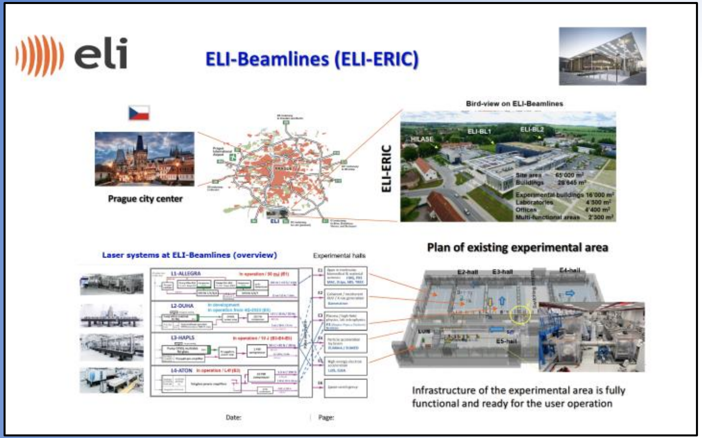


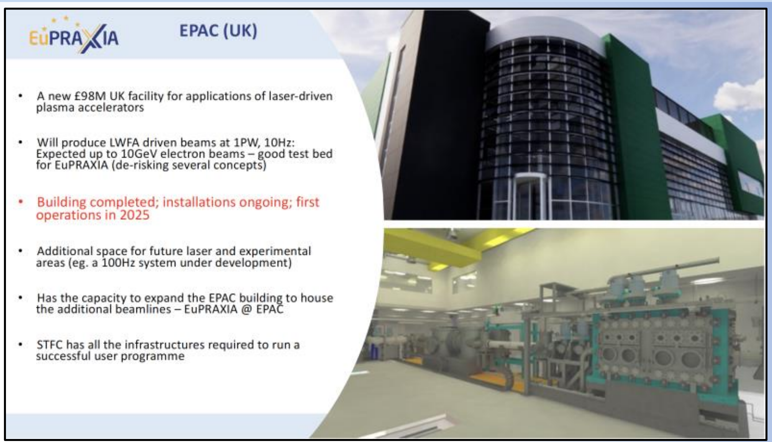
Distributed Research Infrastructure

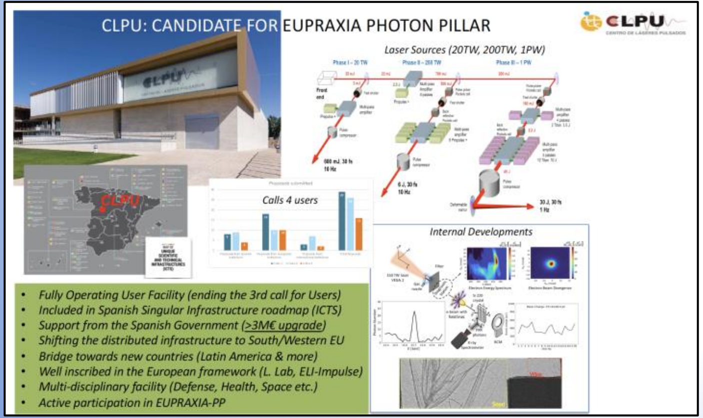


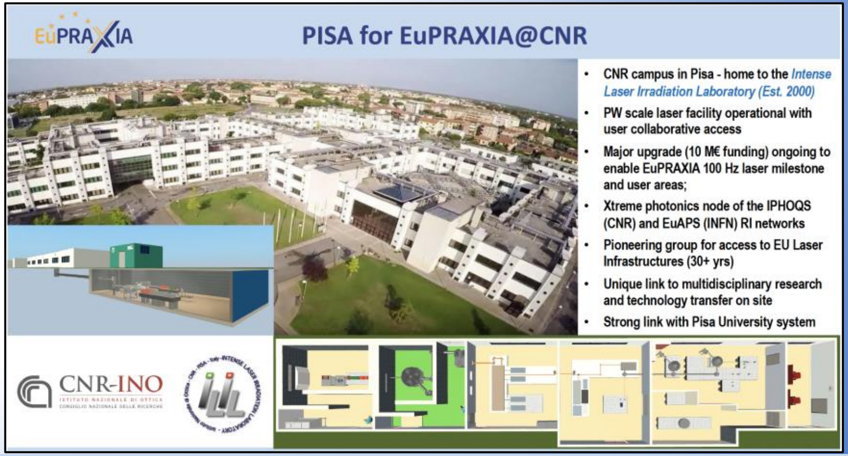
Funded by the European Union

Current Candidates for EuPRAXIA Laser Site





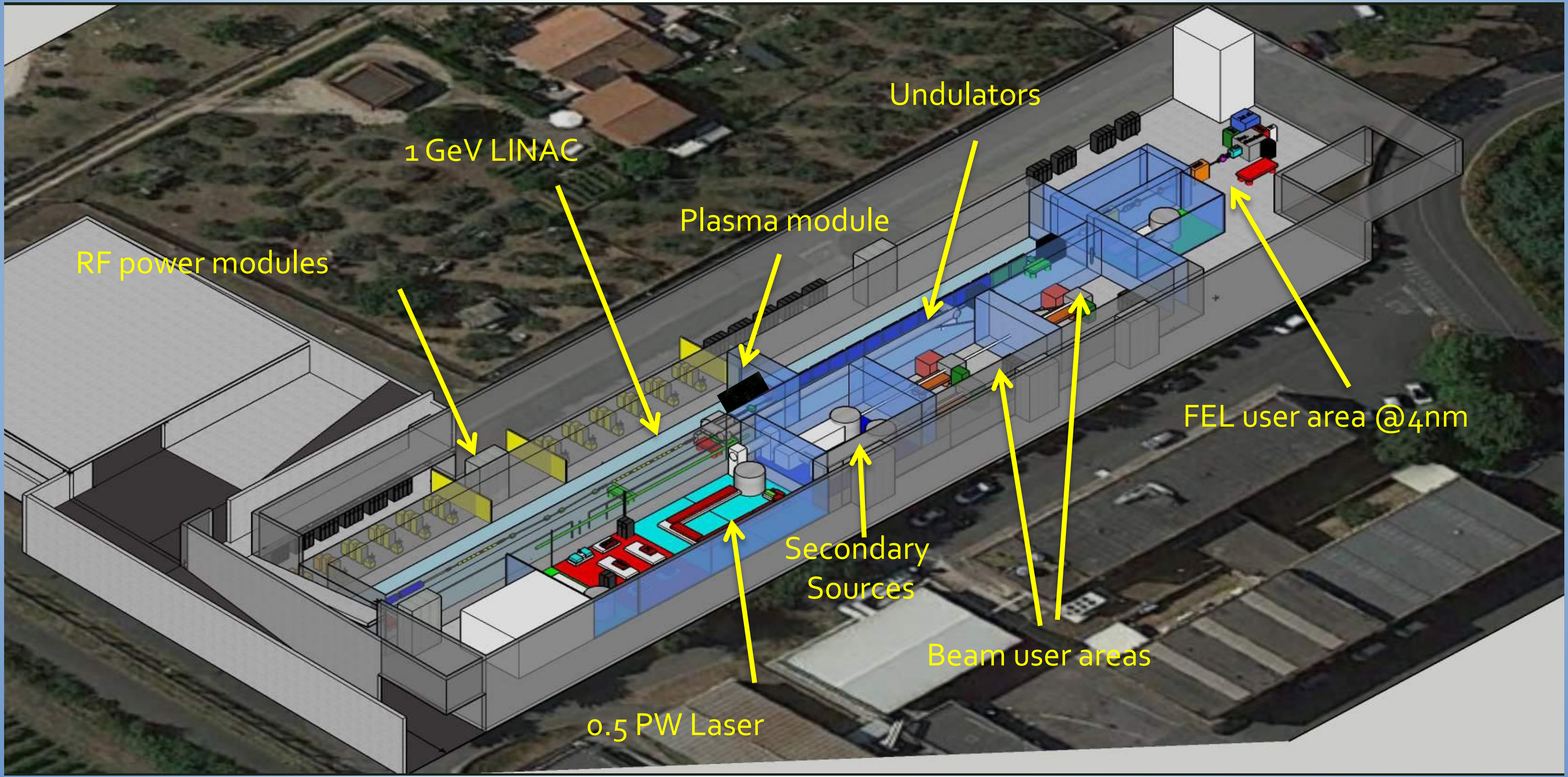




Headquarter and Site 1: EuPRAXIA@SPARC_LAB

- Frascati`s future facility
- > 130 M€ invest funding
- Beam-driven plasma accelerator
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator (X band with CERN)

EuPRAXIA@SPARC_LAB



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

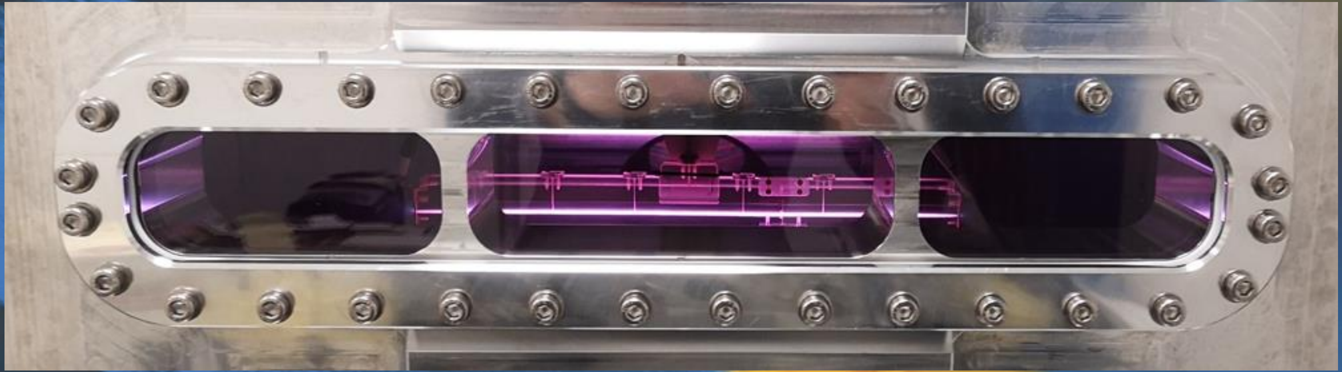
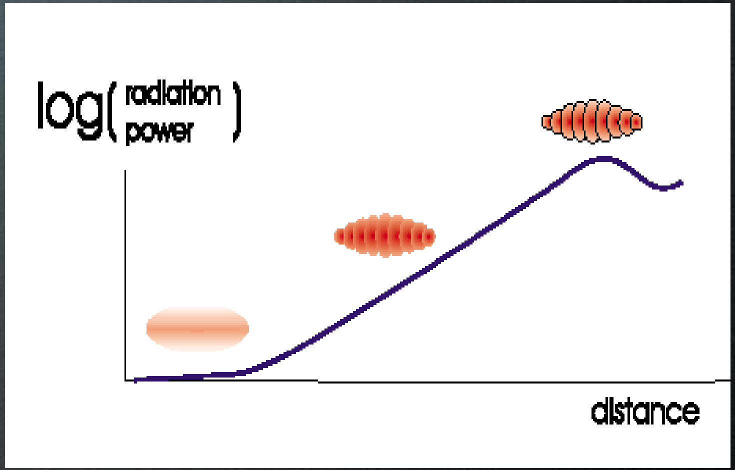


Image captured during the formation of plasma in the capillary 40 cm long and 2 mm in diameter, installed inside a vacuum chamber specially created to accommodate large plasma sources. The applied voltage pulse is 9 kV and the peak current reaches about 500 A.

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



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

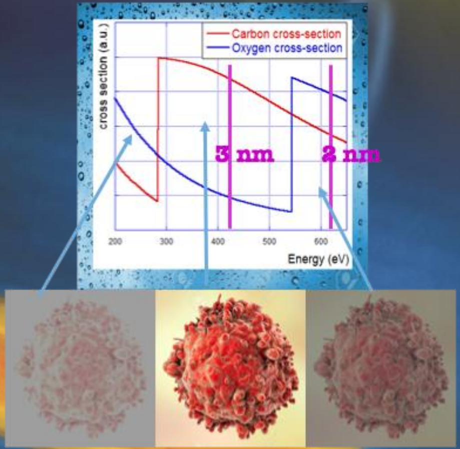
(Tunability - Harmonics)

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 ρ	x 10^{-3}	1.5	1.4
Radiation Wavelength	nm	3	3
Undulator matching β_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)

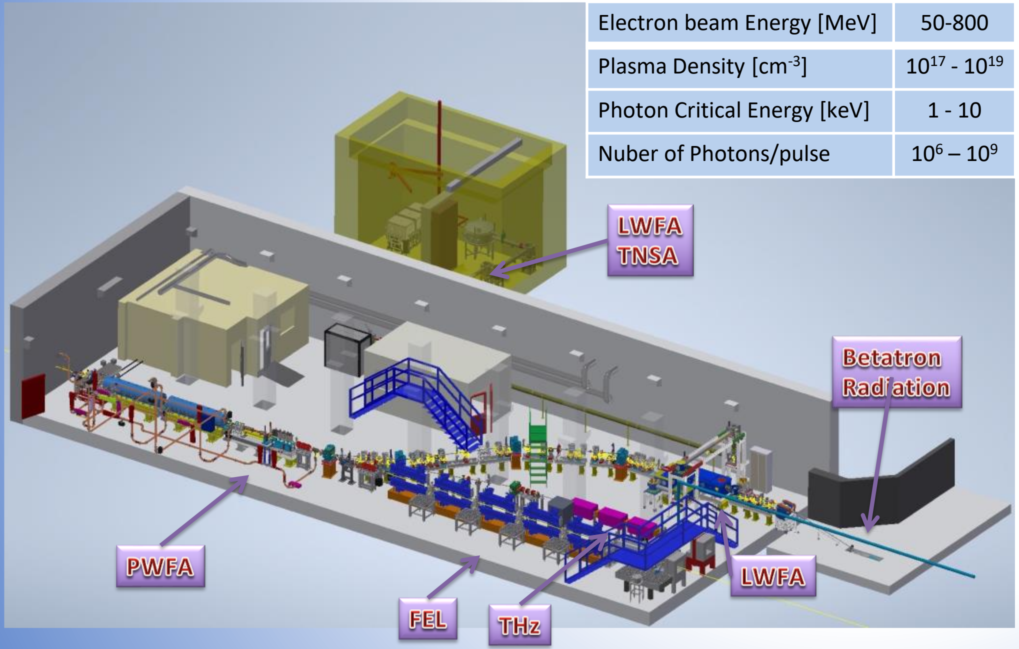


Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state
Possibility to study dynamics
~10^{11} photons/pulse needed

Courtesy F. Stellato, UniToV

Betatron Radiation Source at SPARC_LAB

Electron beam Energy [MeV]	50-800
Plasma Density [cm^{-3}]	10^{17} - 10^{19}
Photon Critical Energy [keV]	1 - 10
Nuber of Photons/pulse	10^{6} – 10^{9}



- Supported by PNRR funding
- Collaboration among INFN, CNR, University of Tor Vergata
- Operational facility at SPAClab by end of 2025
- EuPRAXIA pre-cursor for users

Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | EuPRAXIA Advanced Photon Sources

$K_u<1$

$K_u>1$

$K_u>>1$

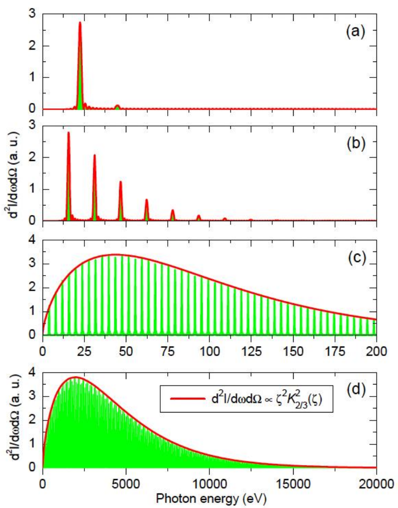


Figure 3.3: *Calculated betatron radiation spectra in a plasma column with density of 7×10^{18} cm^{-3}. The electron energy is 15 MeV, and oscillation amplitudes are (a) 0.1 μm, (b) 0.5 μm, and (c) 1.6 μm. (d) shows the case of a 100 MeV electron with an oscillation amplitude of 1.6 μm.*

$$\omega_c = 3K_u\gamma^2\omega_\beta$$

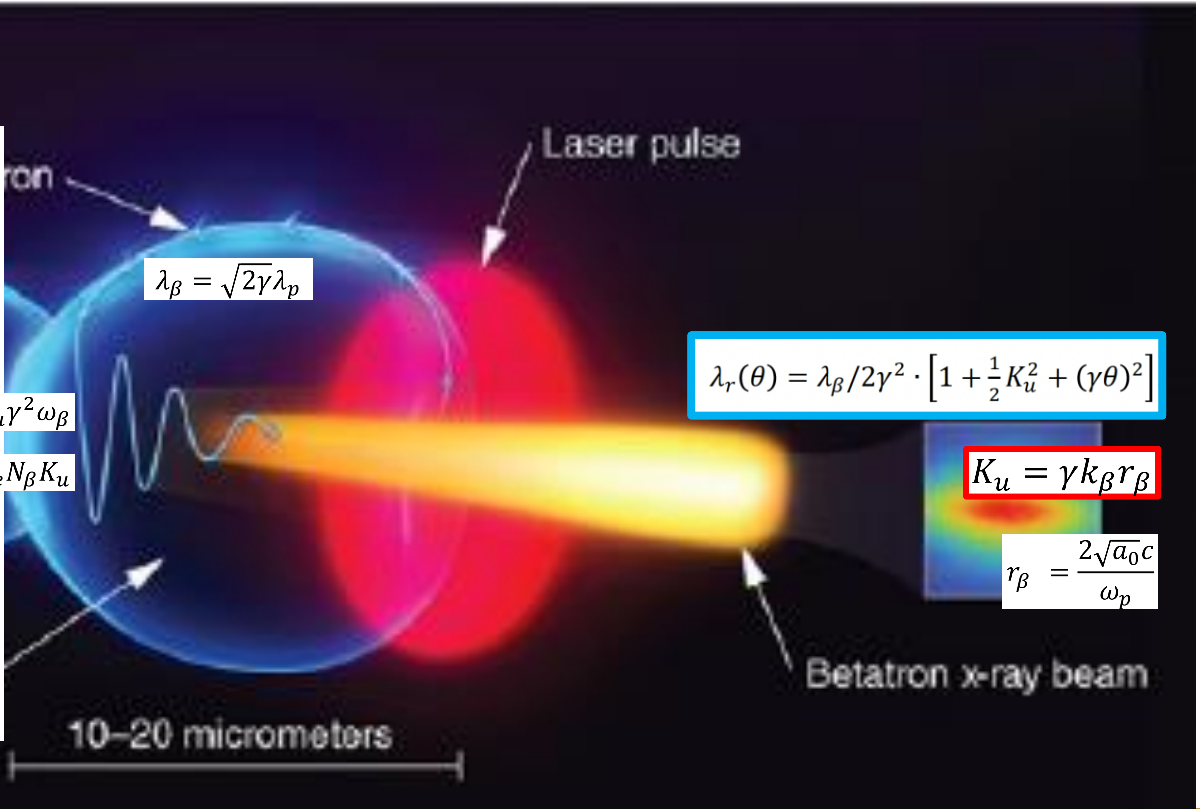
$$N_{ph} \propto N_e N_\beta K_u$$

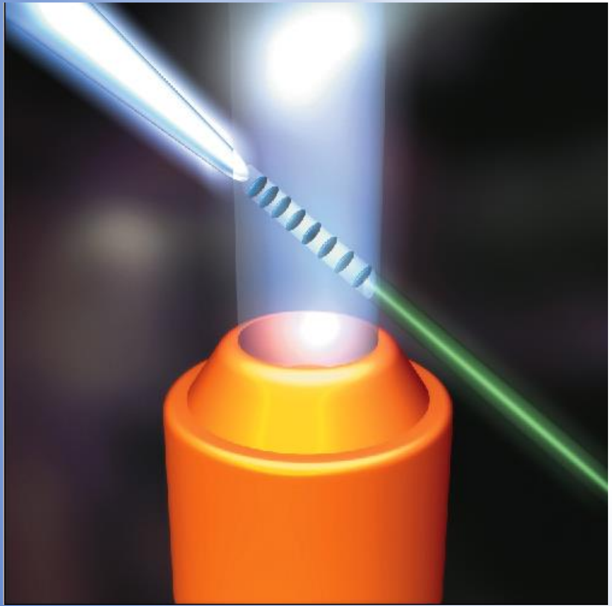
$$\lambda_\beta = \sqrt{2\gamma}\lambda_p$$

$$\lambda_r(\theta) = \lambda_\beta/2\gamma^2 \cdot \left[1 + \tfrac{1}{2}K_u^2 + (\gamma\theta)^2\right]$$

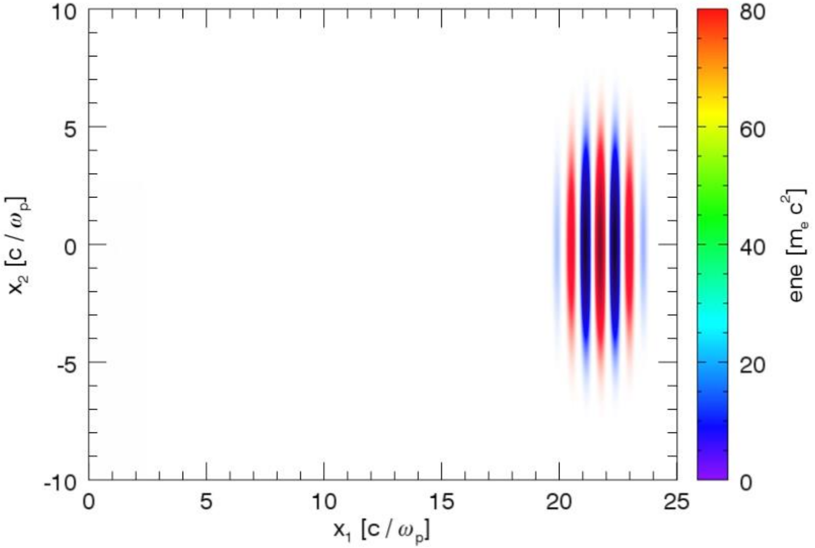
$$K_u = \gamma k_\beta r_\beta$$

$$r_\beta = \frac{2\sqrt{a_0}c}{\omega_p}$$

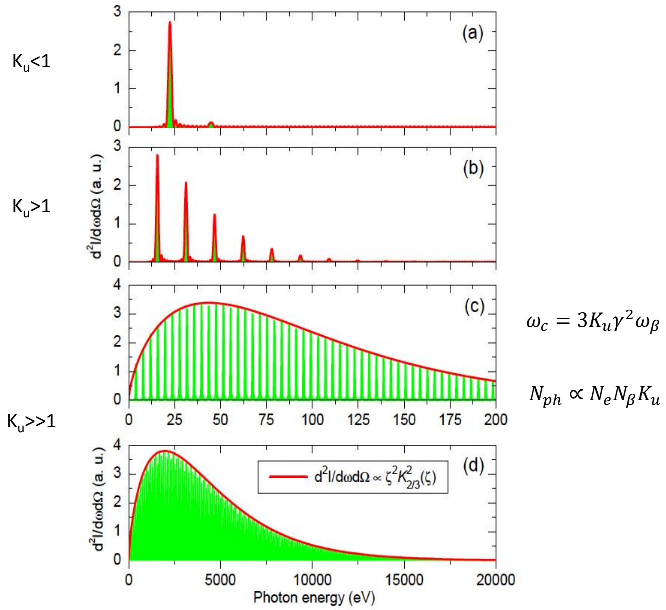




Example: a0 = 5; laser spot-size: 3 microns; laser duration: 12fs; plasma density = 6x10^19.



Courtesy J. Vieira, R. Fonseca/GoLP/IST Lisbon



$\omega_c = 3K_u\gamma^2\omega_\beta$

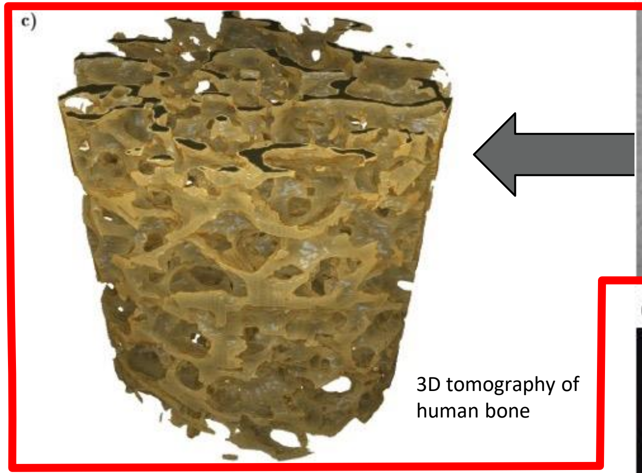
$N_{ph} \propto N_e N_\beta K_u$

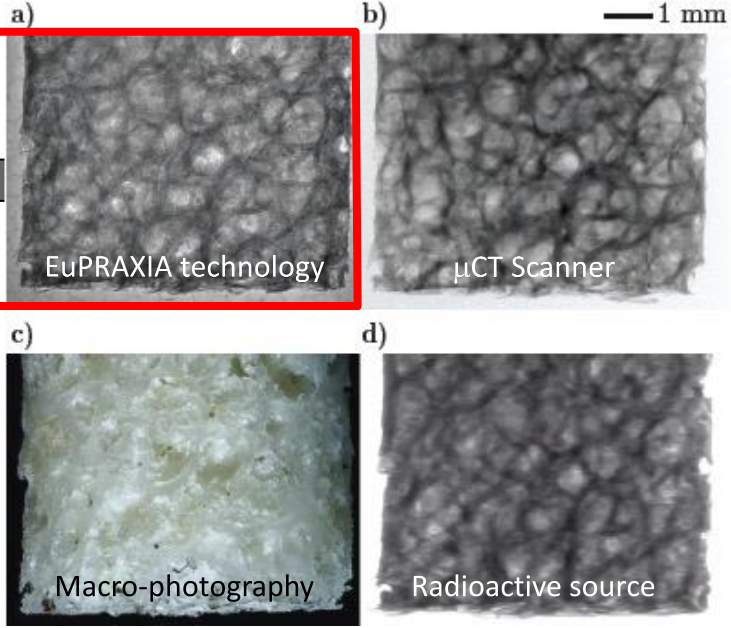
Figure 3.3: *Calculated betatron radiation spectra in a plasma column with density of 7×10^{18} cm^{-3}. The electron energy is 15 MeV, and oscillation amplitudes are (a) 0.1 μm, (b) 0.5 μm, and (c) 1.6 μm. (d) shows the case of a 100 MeV electron with an oscillation amplitude of 1.6 μm.*

1) **Ultrafast** - laser pulse duration tens of fs useful for **time resolved experiments** (XFEL tens of fs, synchrotron tens to 100 ps).
2) **Broad energy spectrum -** important for **X-ray spectroscopy**.
3) **High brightness** - small source size and high photon flux for **fast processes**.
4) **Large market** - 50 synchrotron light sources worldwide, 6 hard XFEL's and 3 soft-ray ones (many accelerators operational and some under construction).

Betatron X Rays: Compact Medical Imaging

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)

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 (EuPRAXIA)**

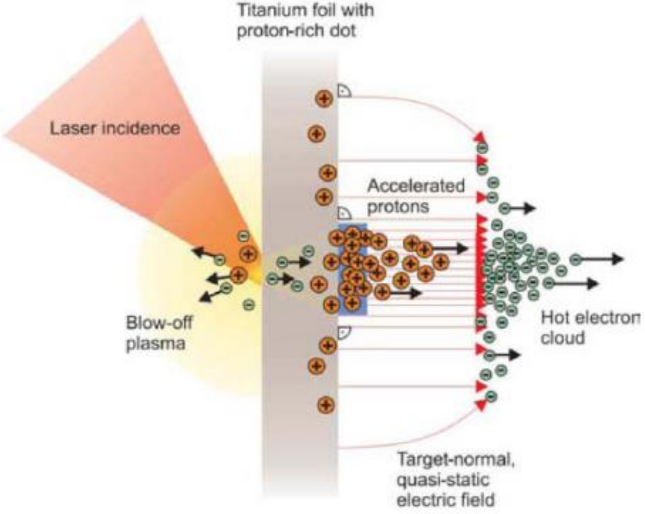

Thank for your attention

Protons and ions are too slow to catch the wave
- only indirect acceleration via electrons

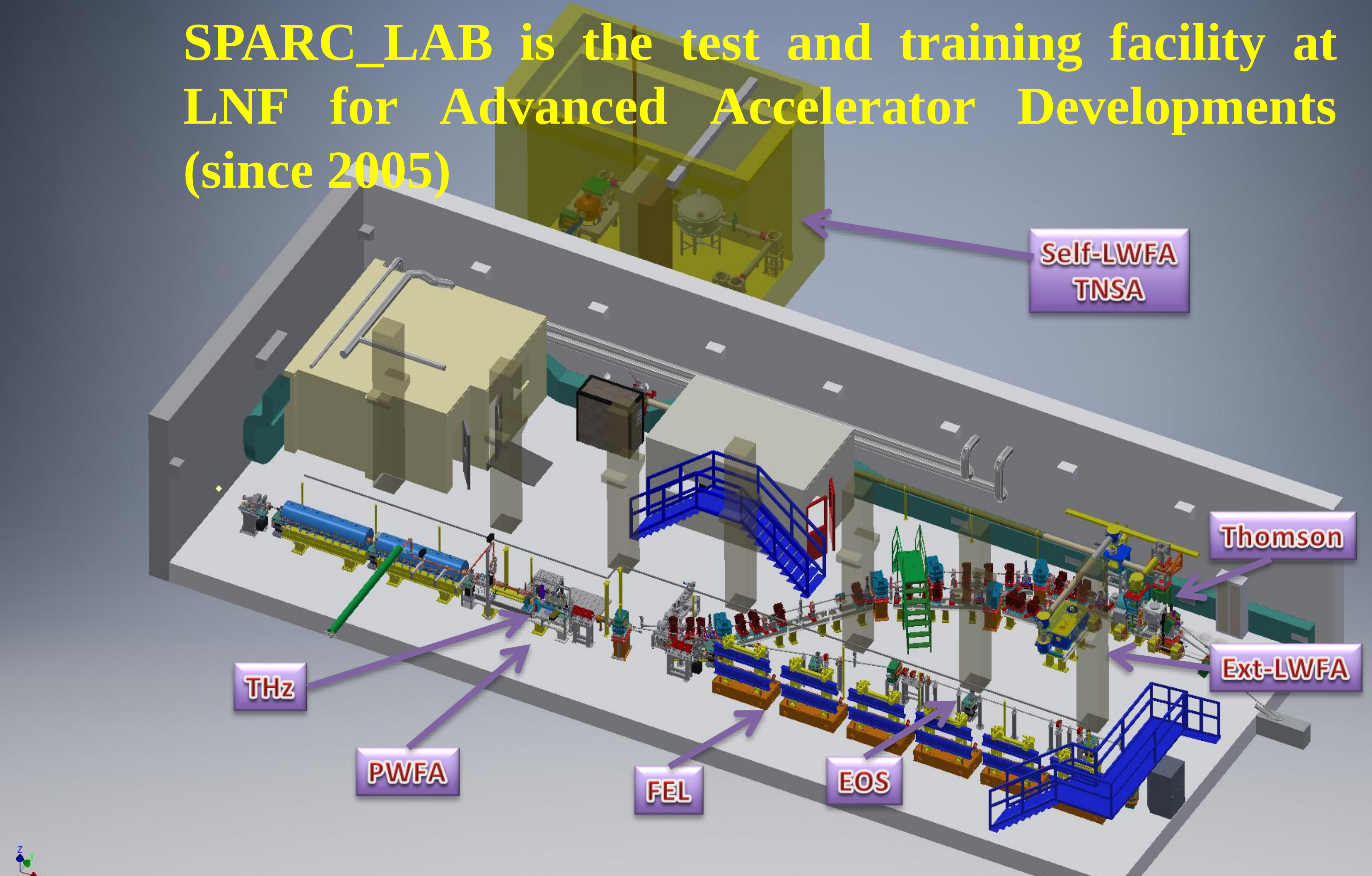
Laser Driven Acceleration of Protons
- Direct acceleration in laser field > 10^{25} W/cm² far beyond current lasers
- Plasma wakefield phase velocity too fast for protons & ions
- → only indirect ways

Need typically:
50 J 500 fs → 100 TW
30 μm radius → 10^{19} W/cm²

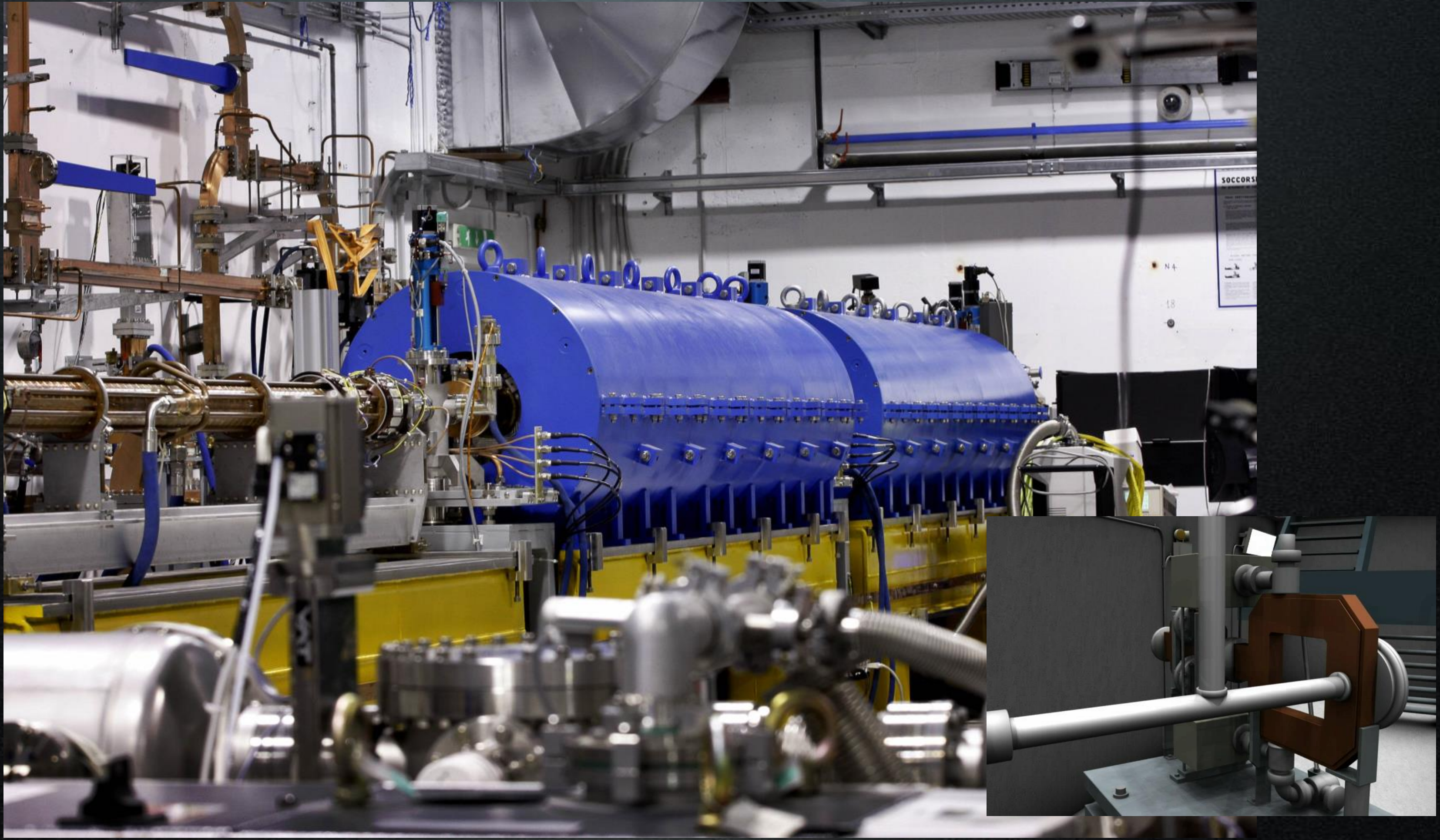
Target Normal Sheath Acceleration
"best understood" candidate:
- laser creates blow-off plasma on front surface
- backside expansion accelerated electrons ionize hydrogen
- hot electrons create electric field (by space charge)
- causes acceleration of protons (electrons slowing down – end of acceleration)
- neutralized bunch of comoving p and e generated



SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)

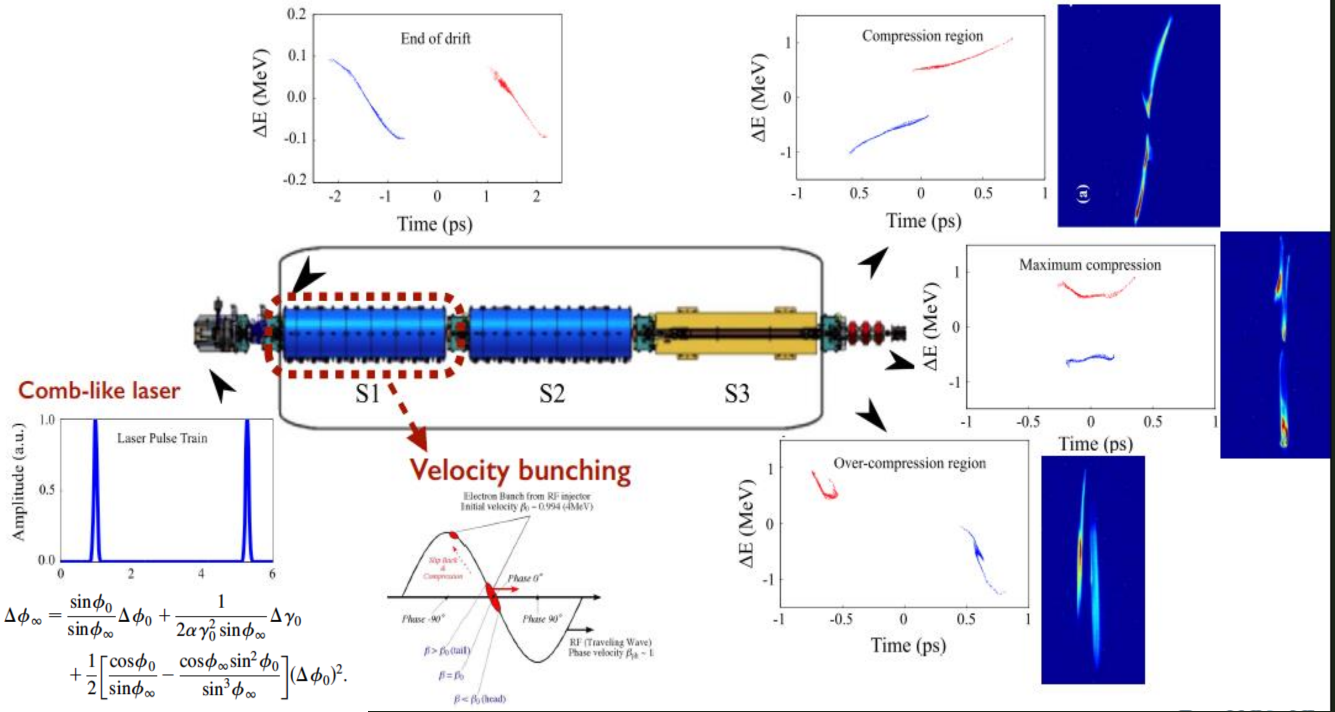


High Brightness Photo-injector with Velocity Bunching

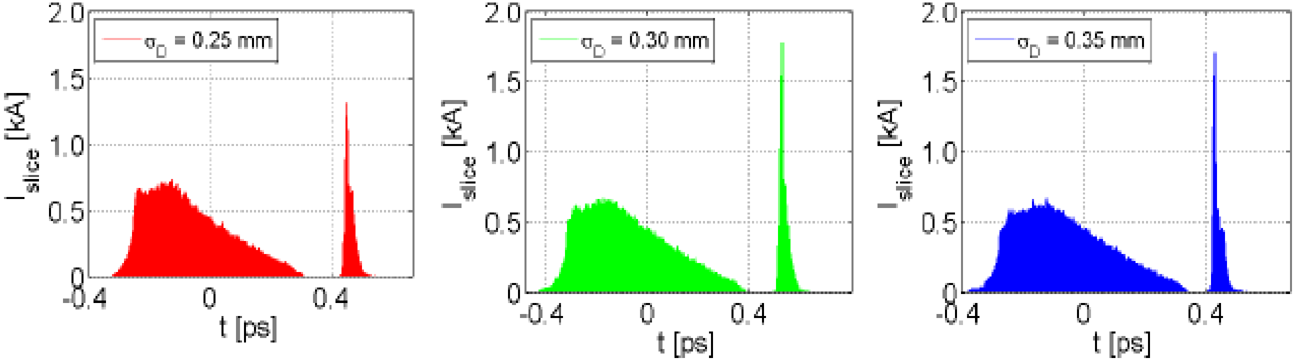


Generation of multi-bunch trains

Sub-relativistic electrons ($\beta_c < 1$) injected into a traveling wave cavity at zero crossing move more slowly than the RF wave ($\beta_{RF} \sim 1$). The electron bunch slips back to an accelerating phase and becomes simultaneously accelerated and compressed.



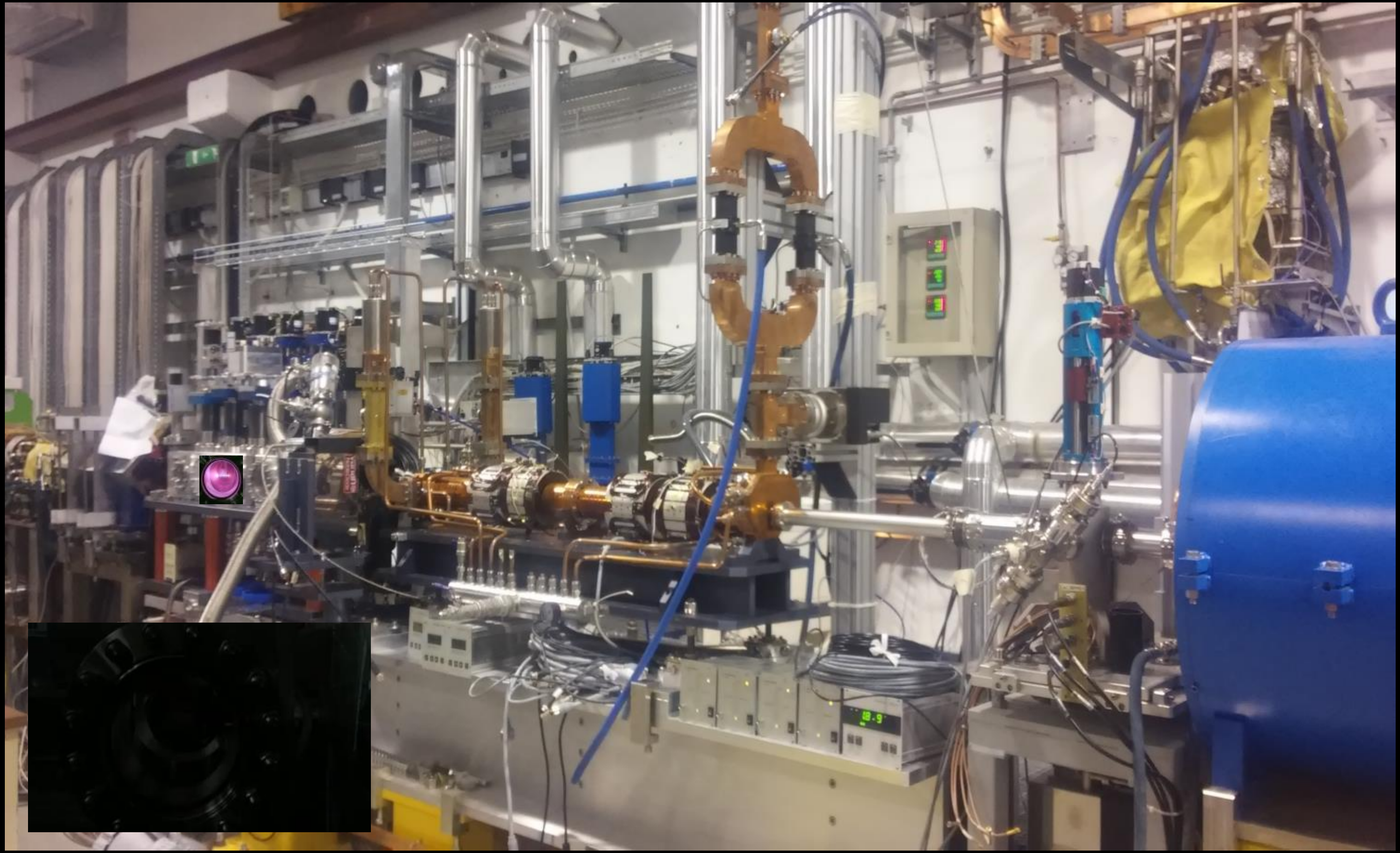
$$\Delta\phi_\infty = \frac{\sin\phi_0}{\sin\phi_\infty}\Delta\phi_0 + \frac{1}{2\alpha\gamma_0^2\sin\phi_\infty}\Delta\gamma_0 + \frac{1}{2}\left[\frac{\cos\phi_0}{\sin\phi_\infty} - \frac{\cos\phi_\infty\sin^2\phi_0}{\sin^3\phi_\infty}\right](\Delta\phi_0)^2.$$



Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

Table 7.2: Driver and witness beam parameters at the end of photo-injector.

PWFA vacuum chamber at SPARC_LAB



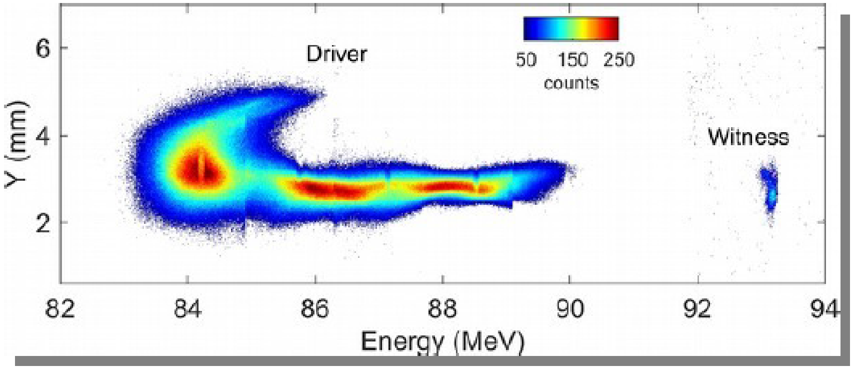
Assisted Beam Loading Energy Spread Compensation

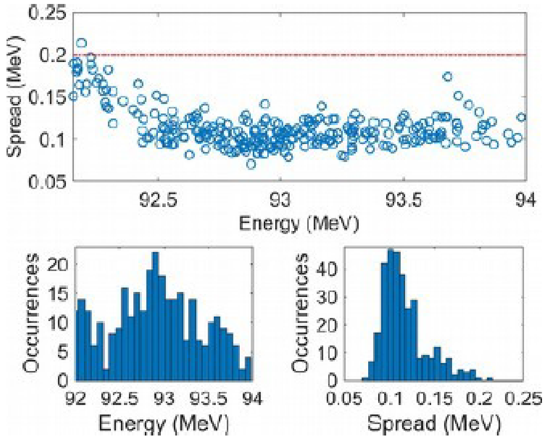
Achieved 4 MeV acceleration in 3 cm plasma with 200 pC driver

- *~133 MV/m accelerating gradient*
- *2x10^{15} cm^{-3} plasma density*

→ demonstration of energy spread compensation during acceleration

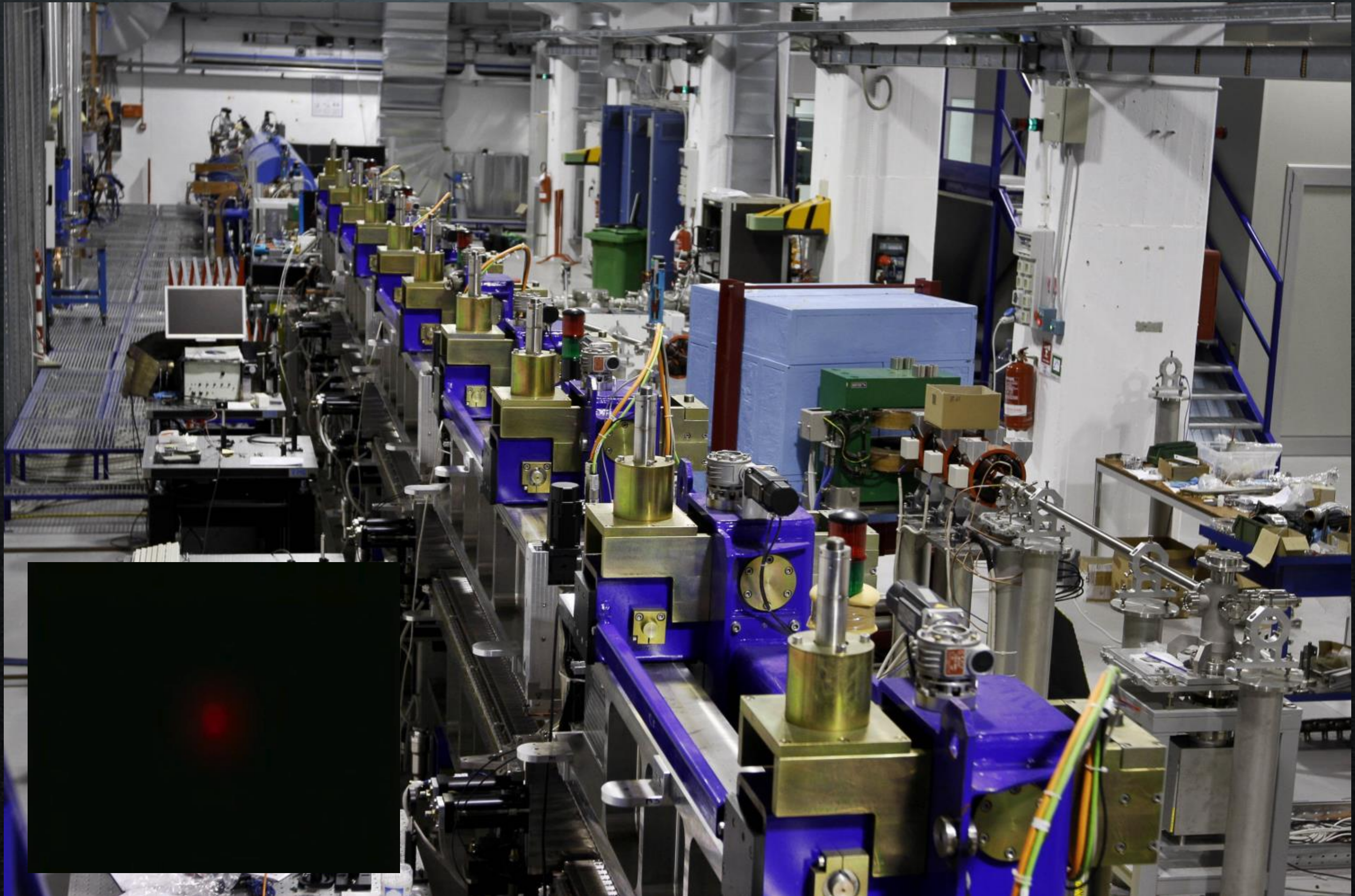
- *Energy spread reduced from 0.2% to 0.12%*
- *99.5% energy stability*



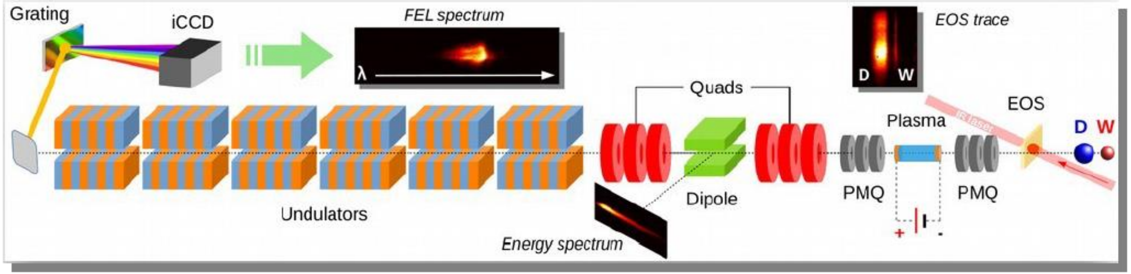


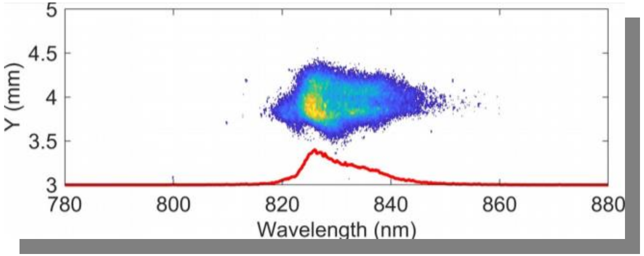
Pompili, R., et al. "Energy spread minimization in a beam-driven plasma wakefield accelerator." Nature Physics (2020): 1-5.

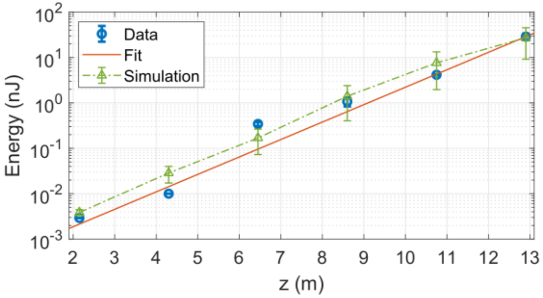
Free Electron Laser



at SPARC_LAB (May 2021)

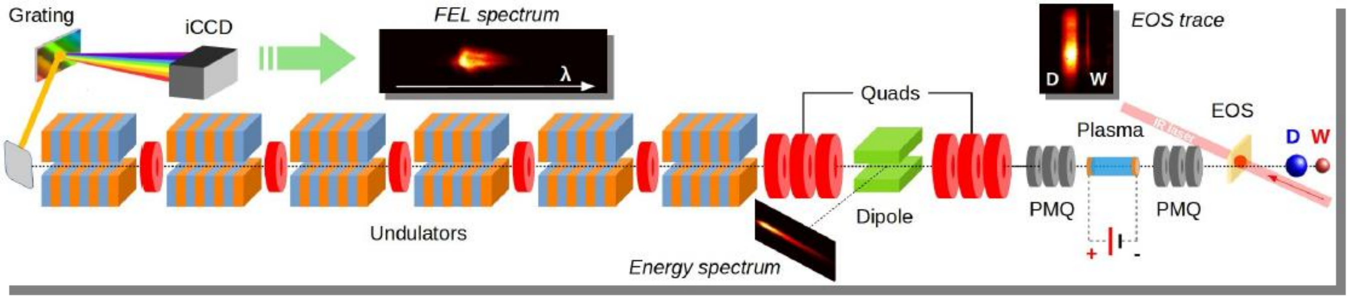






Submitted to Nature

Proof of SASE FEL driven by PWFA



Proof-of-principle experiment to demonstrate high-quality PWFA acceleration able to drive a Free-Electron Laser

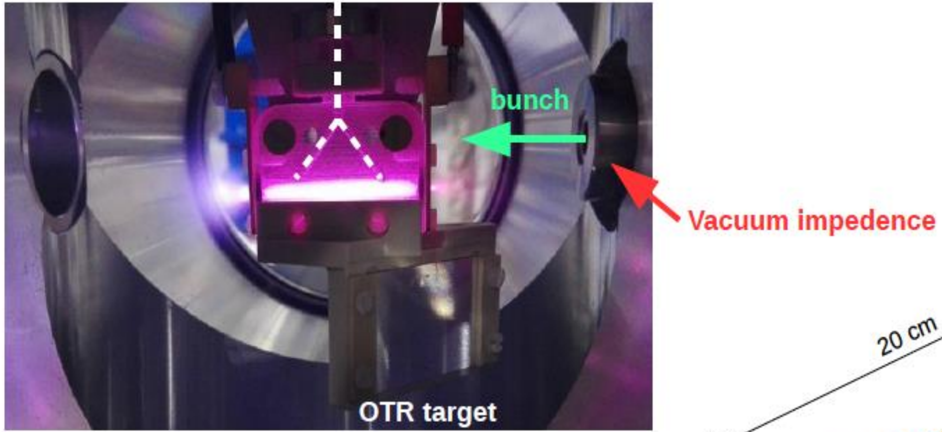
Witness is completely characterized (energy, spread, X/Y emittance) allowing to match it into the undulators beamline

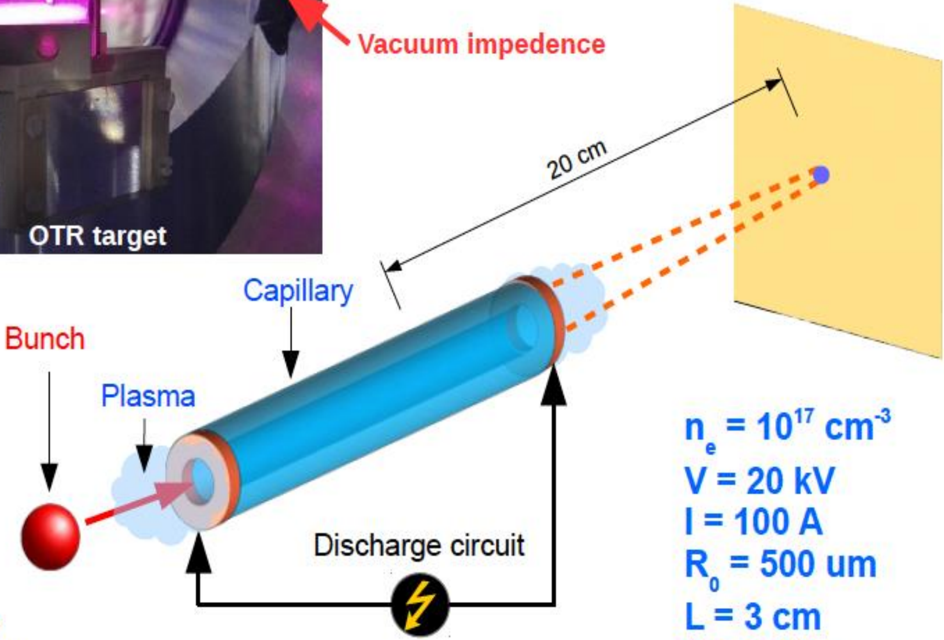
Jitter is online monitored with Electro-Optical Sampling (EOS) diagnostics

Imaging spectrometer with iCCD used to detect FEL radiation

In collaboration with

Experimental layout

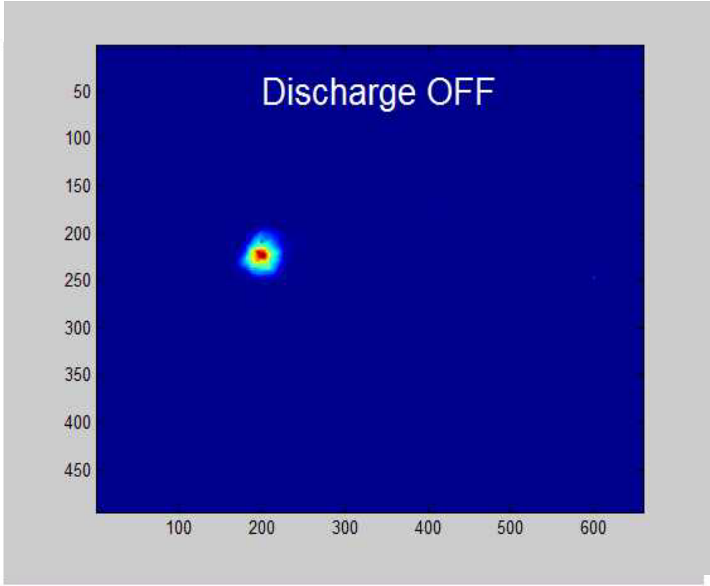


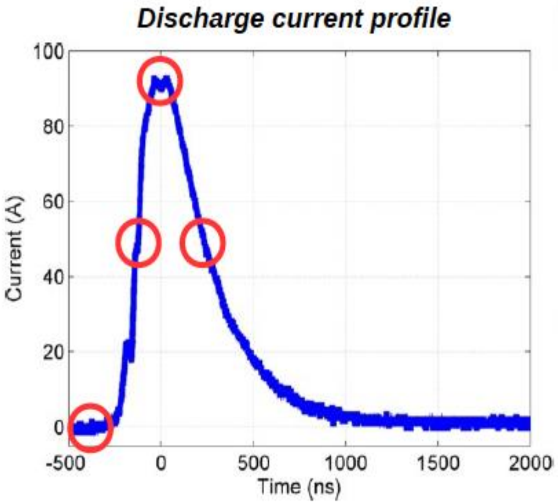


50 pC
1 ps
130 um
120 MeV
1 mm mrad

$n_e = 10^{17}$ cm^{-3}
V = 20 kV
I = 100 A
R_0 = 500 um
L = 3 cm
Sapphire

Preliminary results





Ig Nobel Prize 2022 in Physics

n_{e0}=2.1x10^{14}cm^{-3}

Wave-riding and wave-passing by ducklings in formation swimming

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