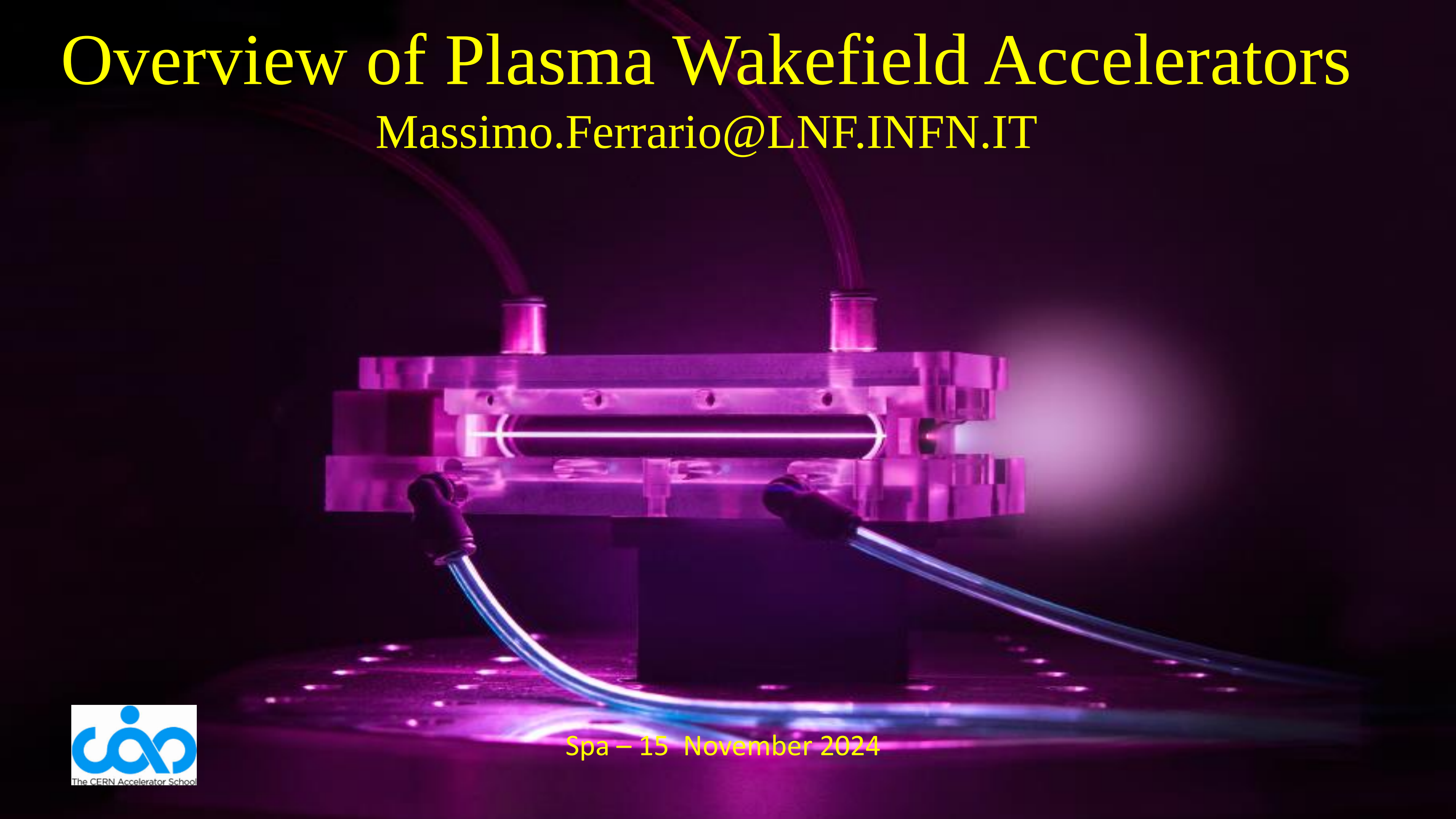
Overview of Plasma Wakefield Accelerators

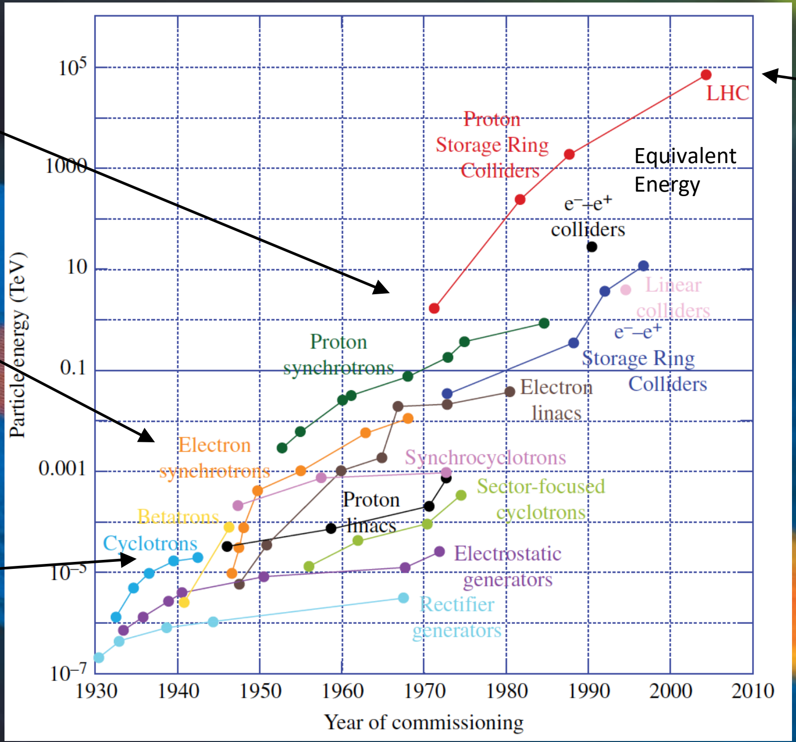
Massimo.Ferrario@LNF.INFN.IT

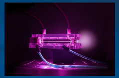


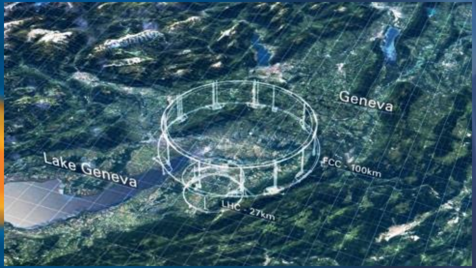
The CERN Accelerator School

Spa – 15 November 2024

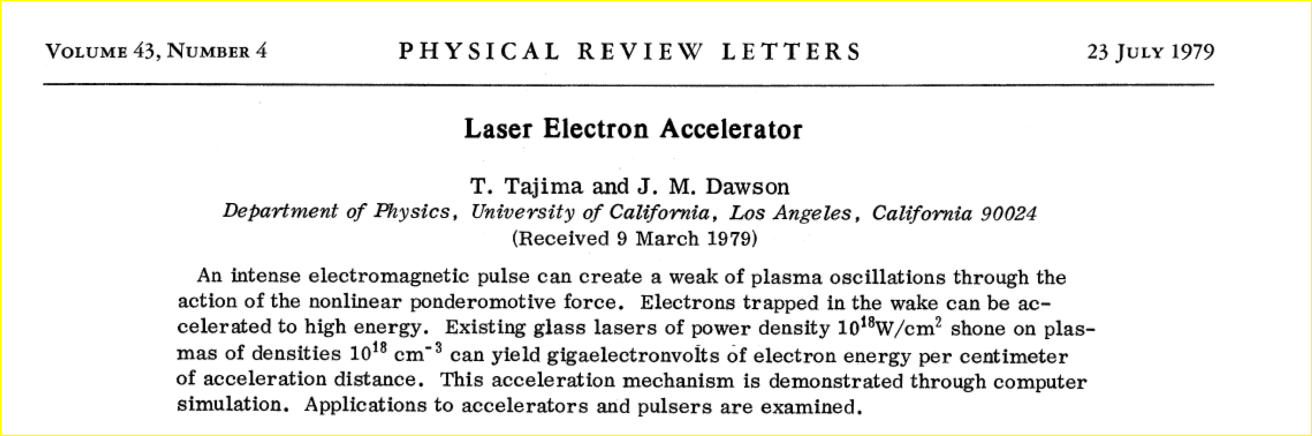
Livingstone Diagram







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.



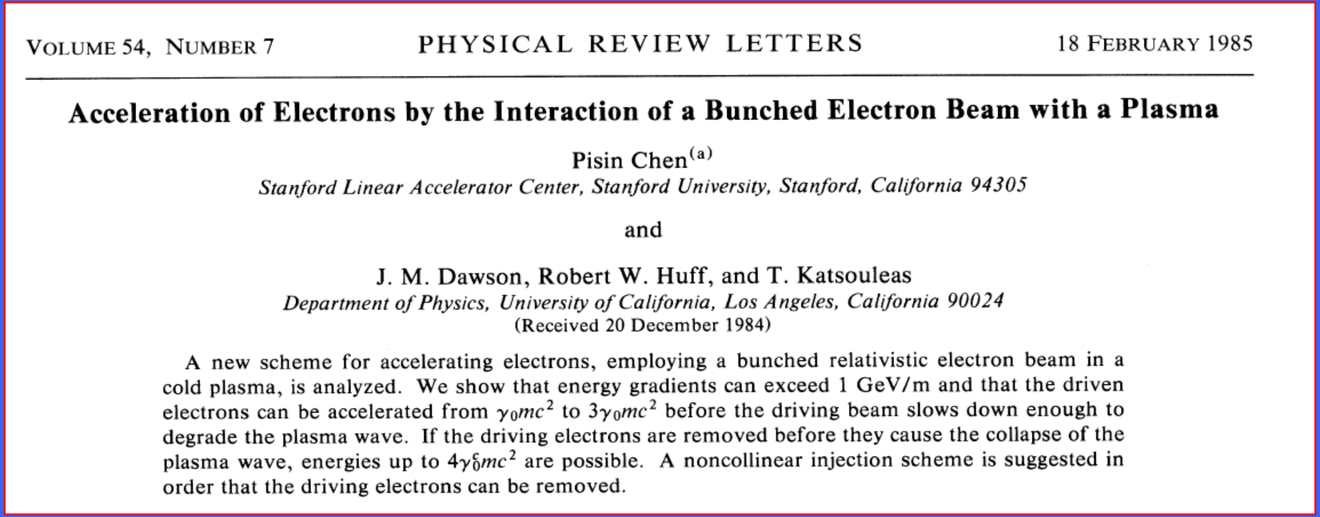
VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024

(Received 9 March 1979)

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



VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

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

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

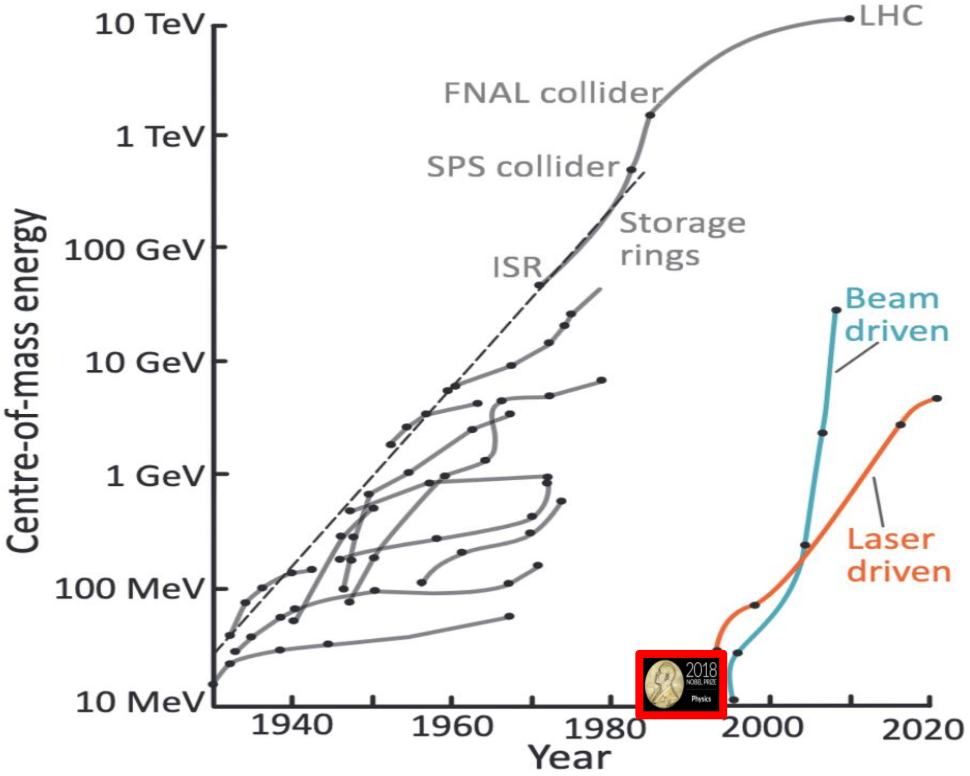
and

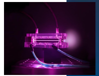
J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024

(Received 20 December 1984)

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

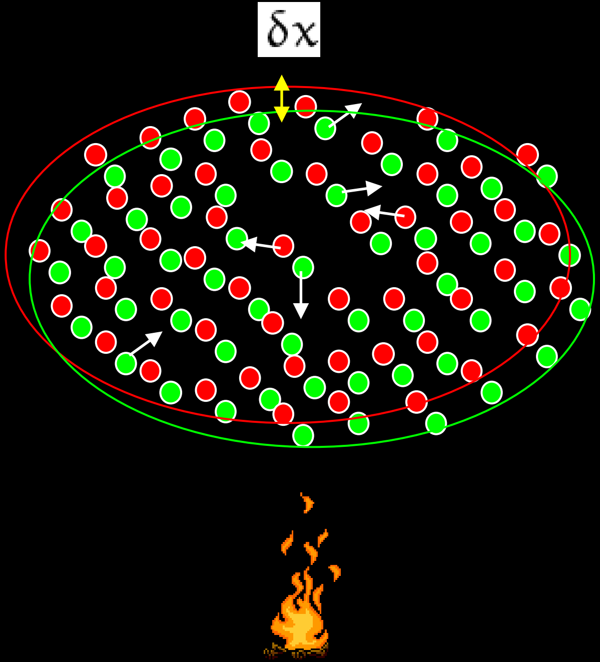
Livingstone Diagram with PWFA





Surface charge density

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



Surface electric field

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

Restoring force

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

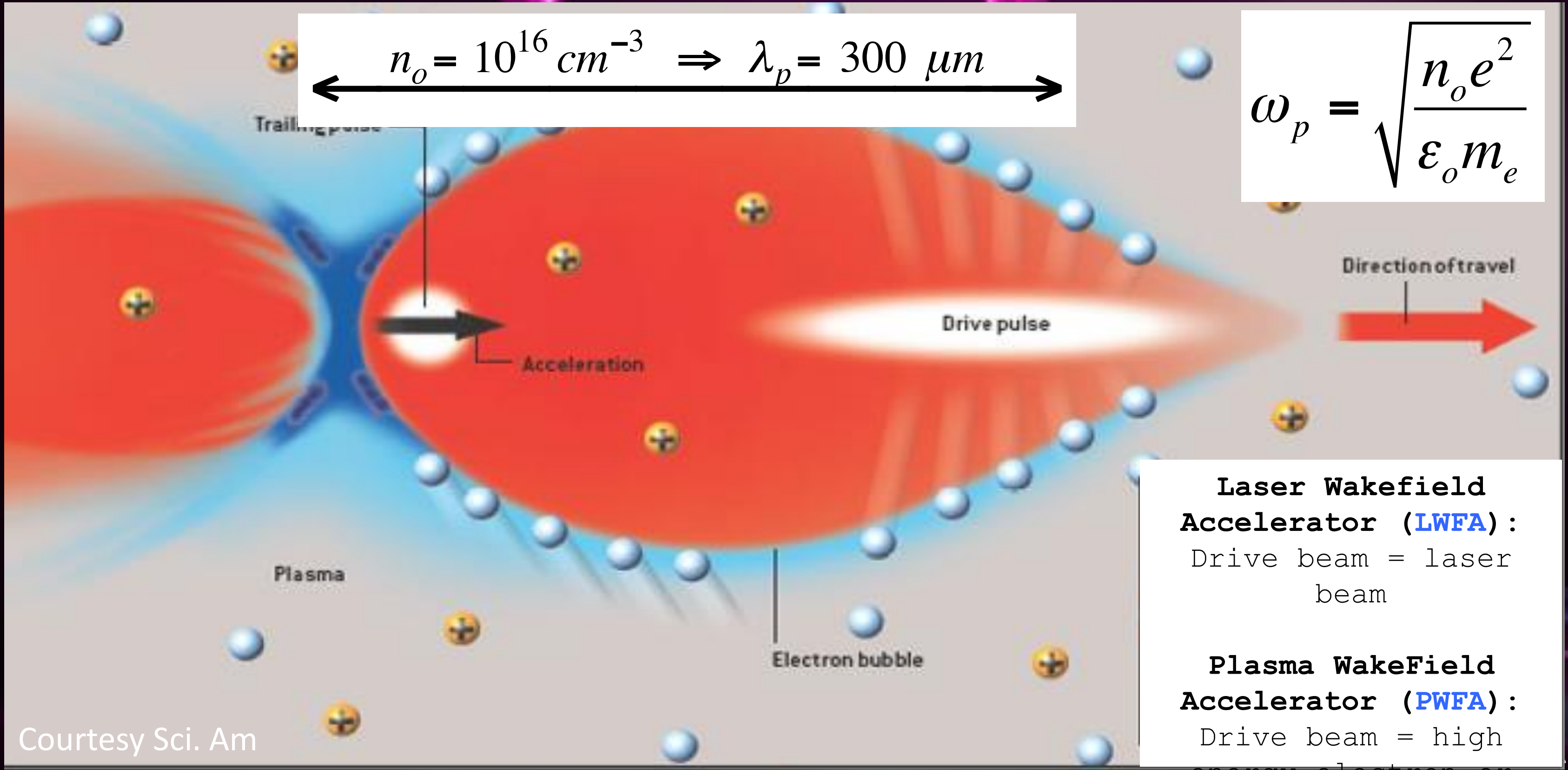
Plasma frequency

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

Plasma oscillations

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

Principle of plasma acceleration



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

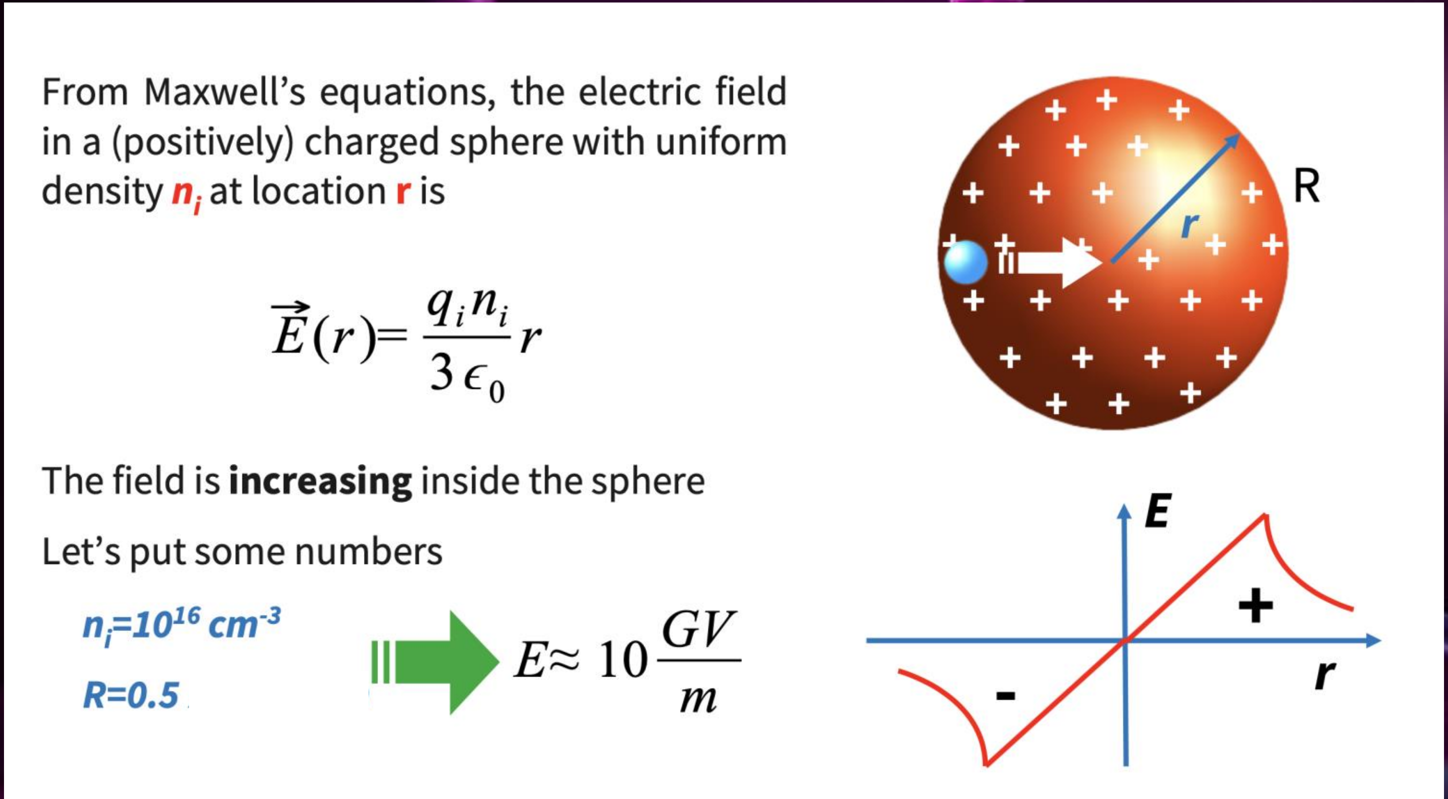
$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$$

Courtesy Sci. Am

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

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

Principle of plasma acceleration



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

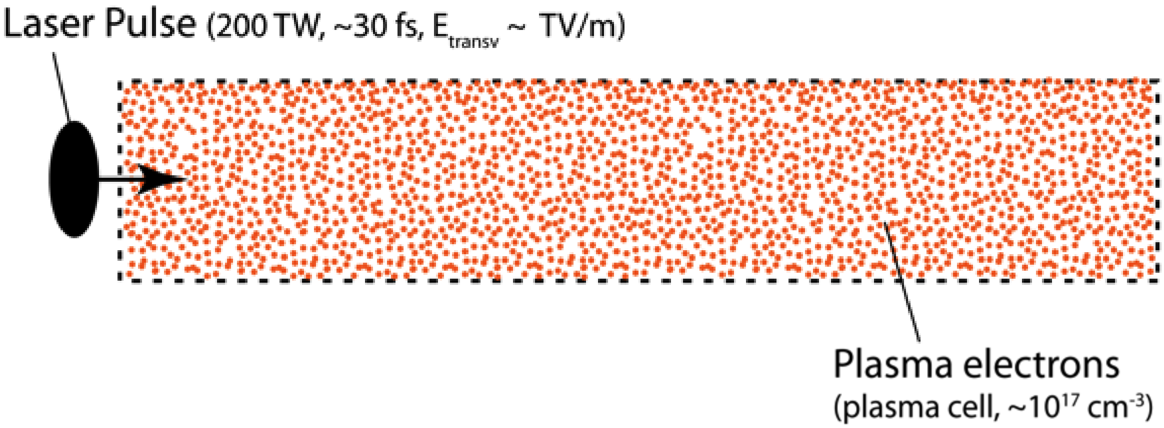
Let's put some numbers

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

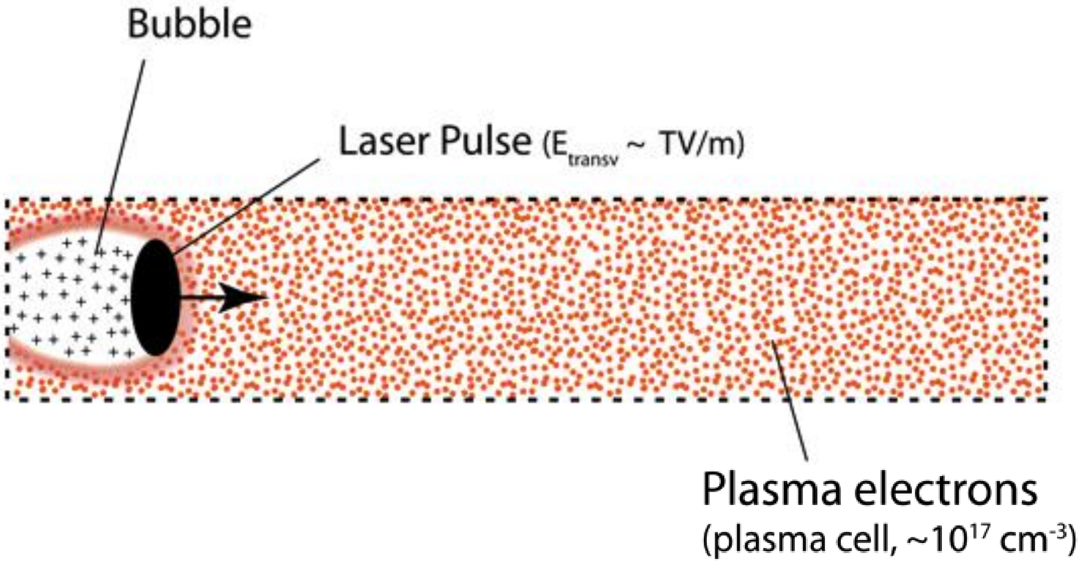
R=0.5

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

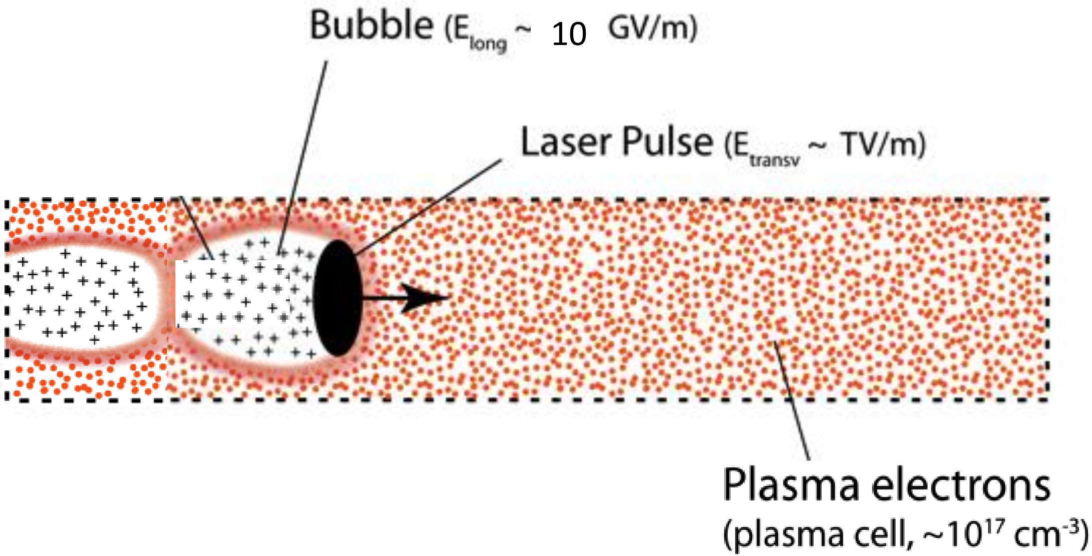
Plasma Wake-Acceleration



Plasma Wake-Acceleration

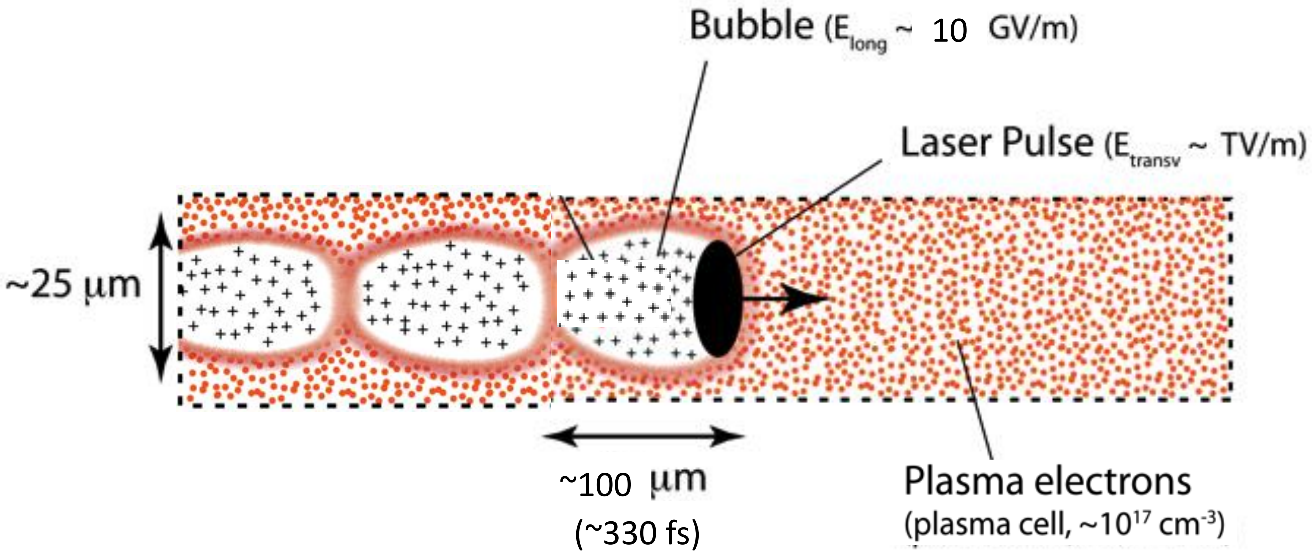


Plasma Wake-Acceleration

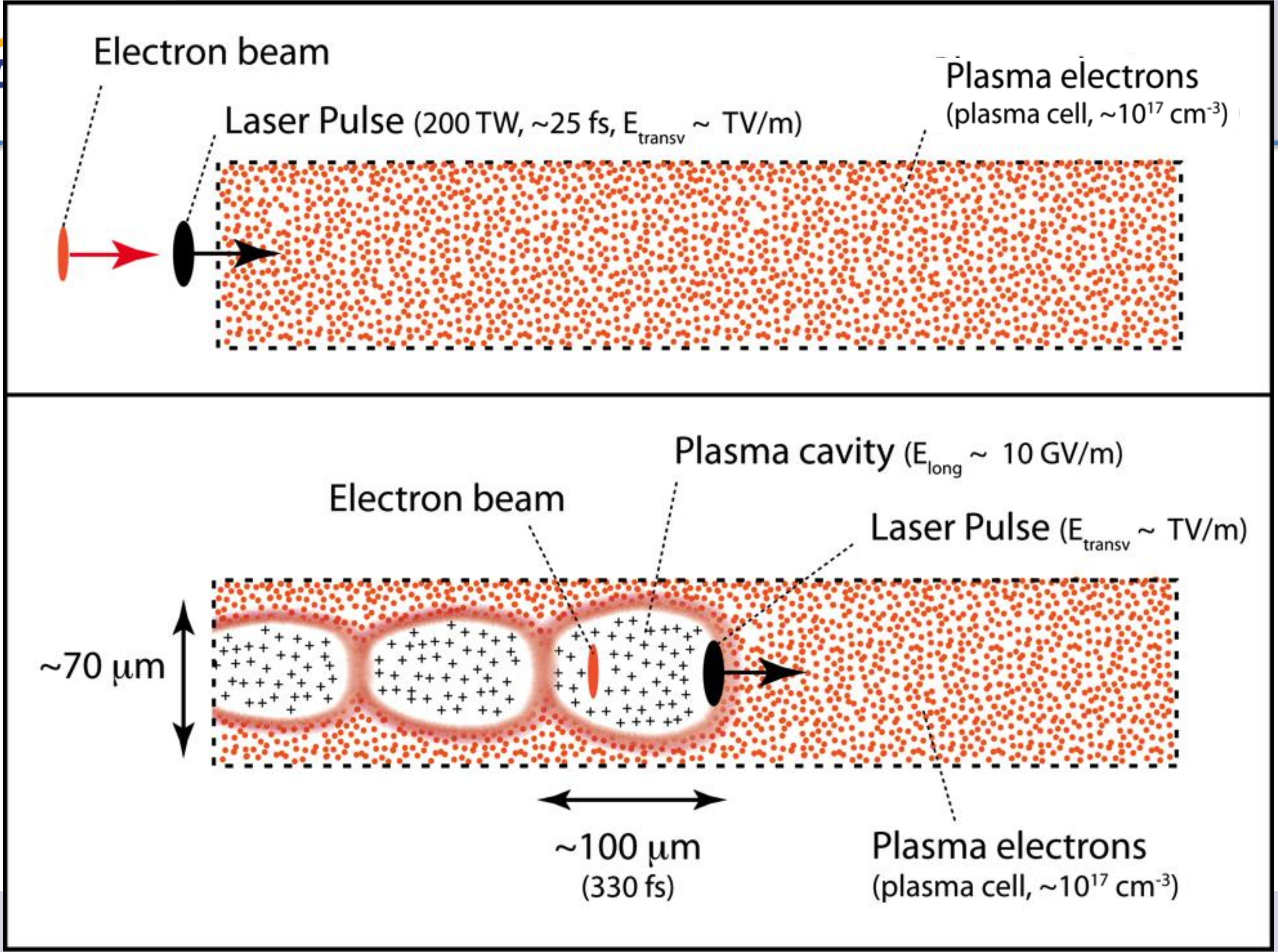


Plasma Wake-Acceleration

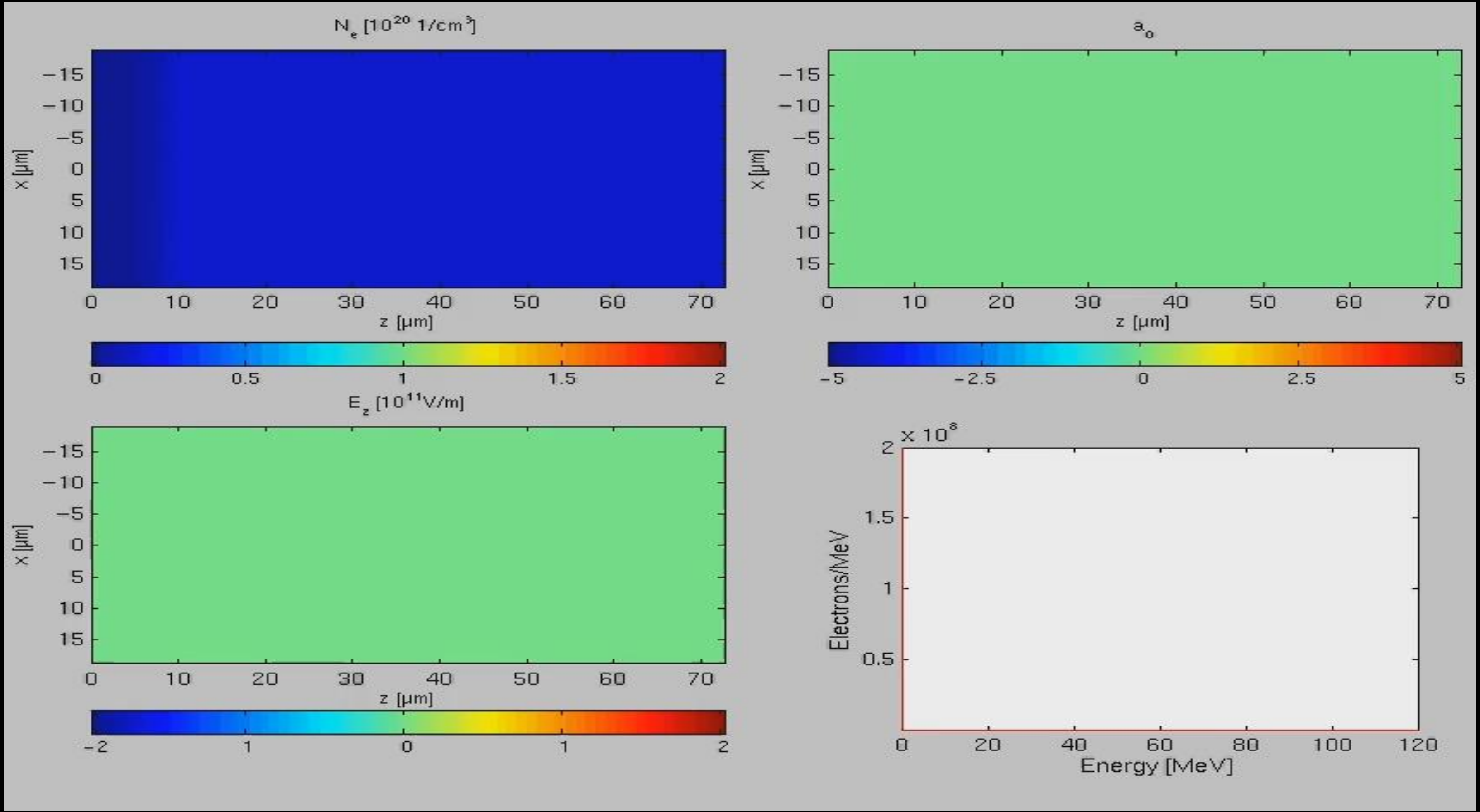
Horizon2020



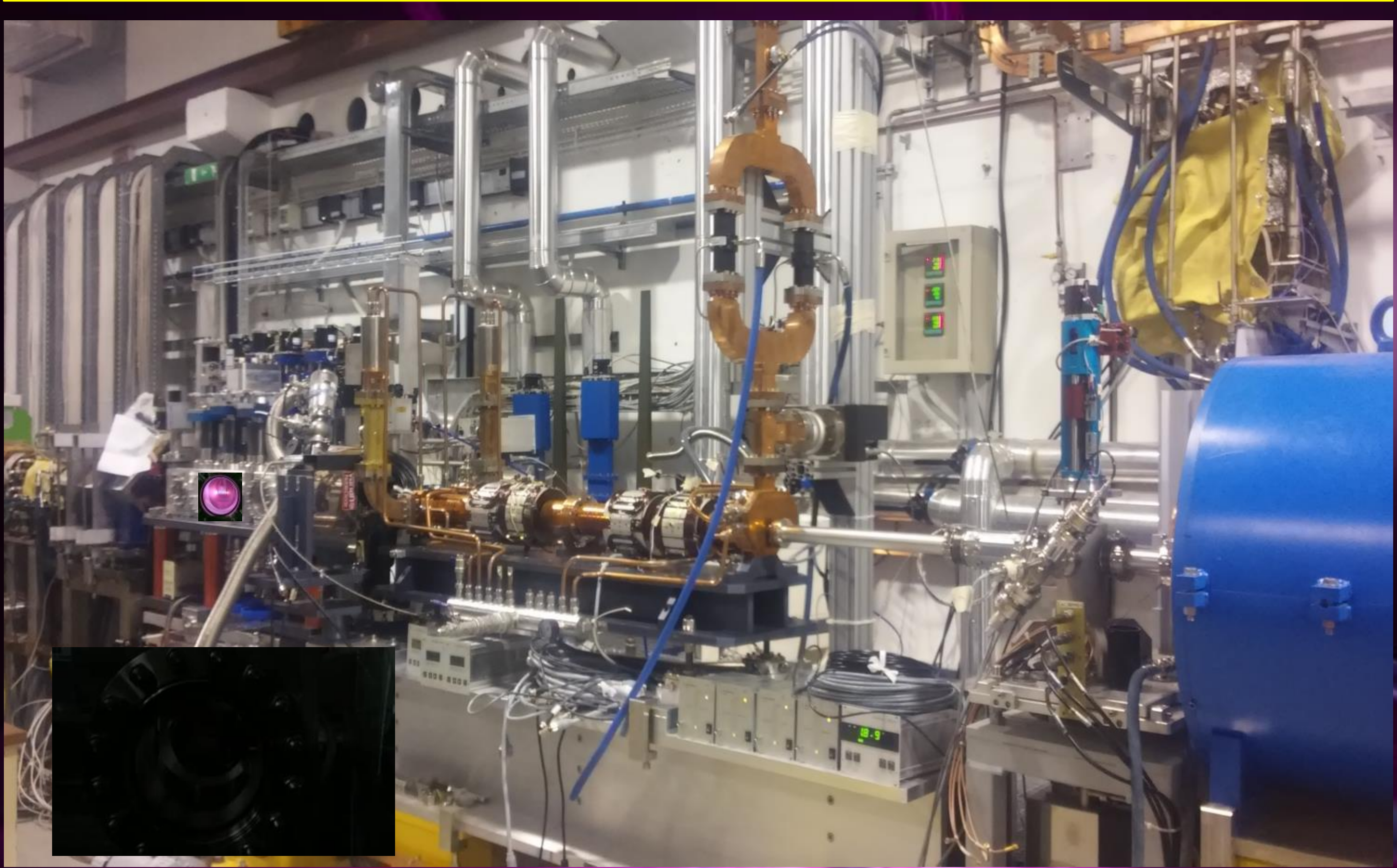
This accelerator fits into a human hair!

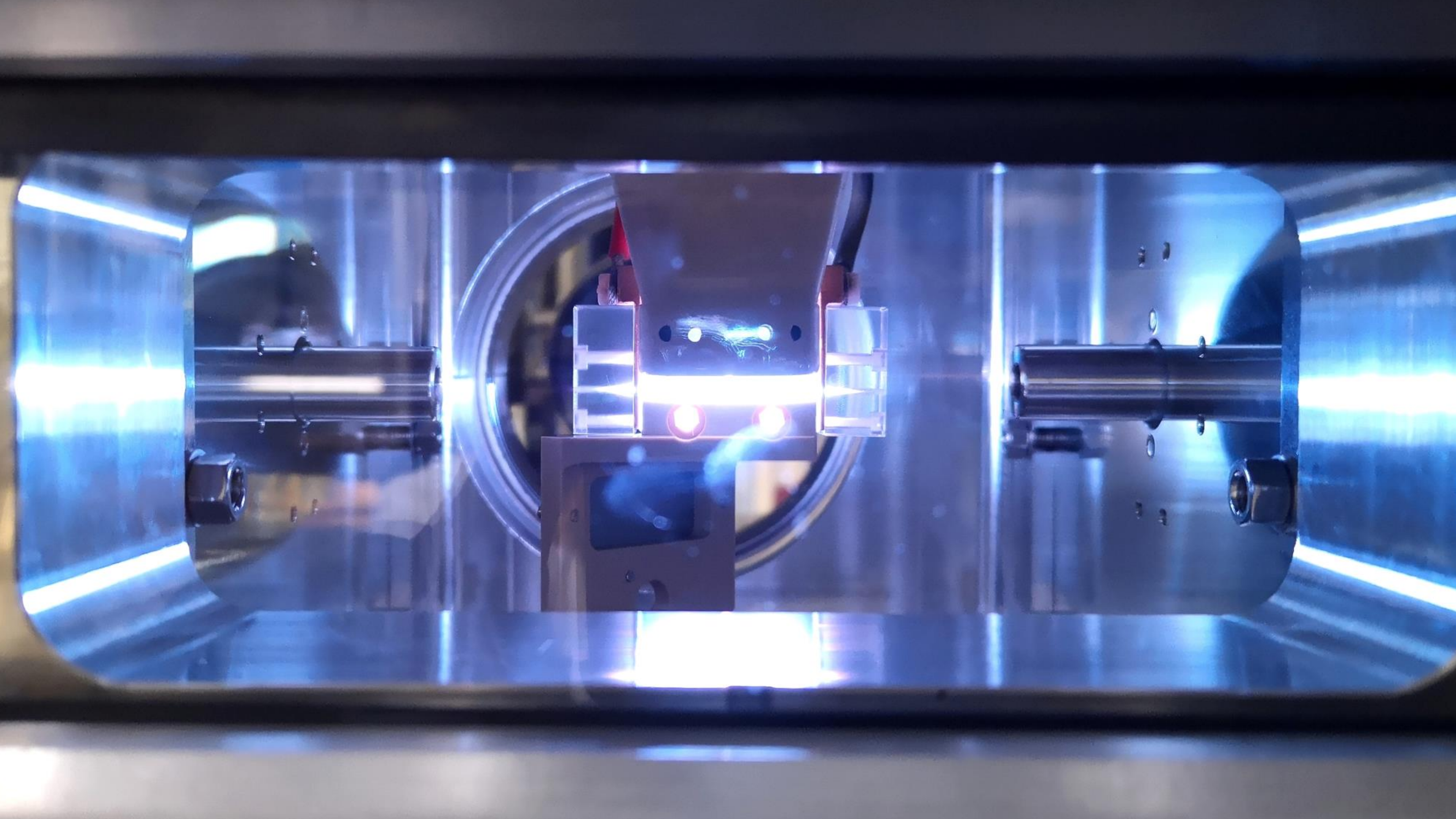

Electron beam
Laser Pulse (200 TW, ~25 fs, E_{transv} ~ TV/m)
Plasma electrons
(plasma cell, ~10^{17} cm^{-3})
Plasma cavity (E_{long} ~ 10 GV/m)
Electron beam
Laser Pulse (E_{transv} ~ TV/m)
~70 μm
~100 μm
(330 fs)
Plasma electrons
(plasma cell, ~10^{17} cm^{-3})

Diffraction - Self injection - Dephasing – Depletion

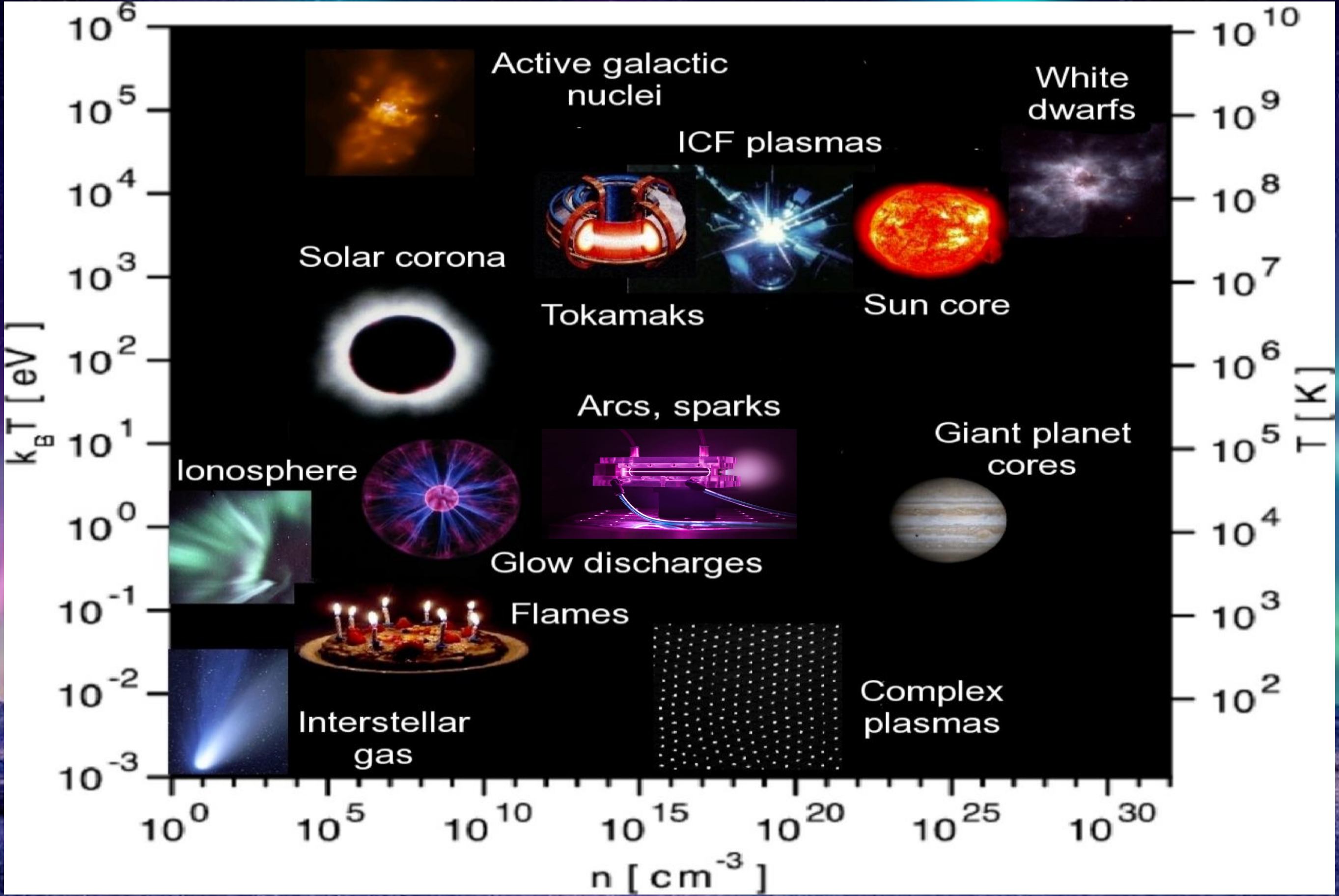


PWFA beam line at SPARC_LAB





Plasma Temperature and Density



Principle of plasma acceleration

Driven by Radiation Pressure

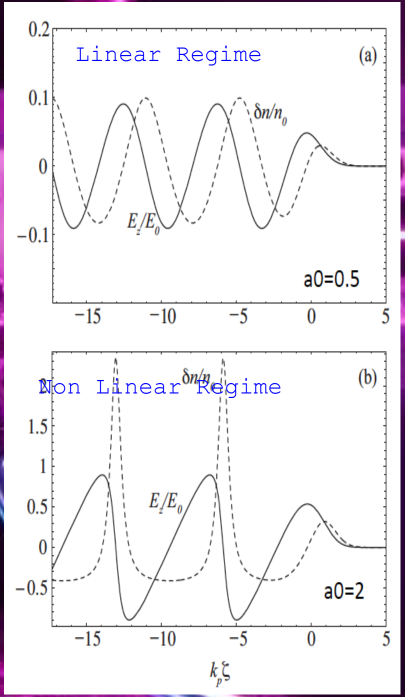
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=c^2\nabla^2\frac{a^2}{2}$$

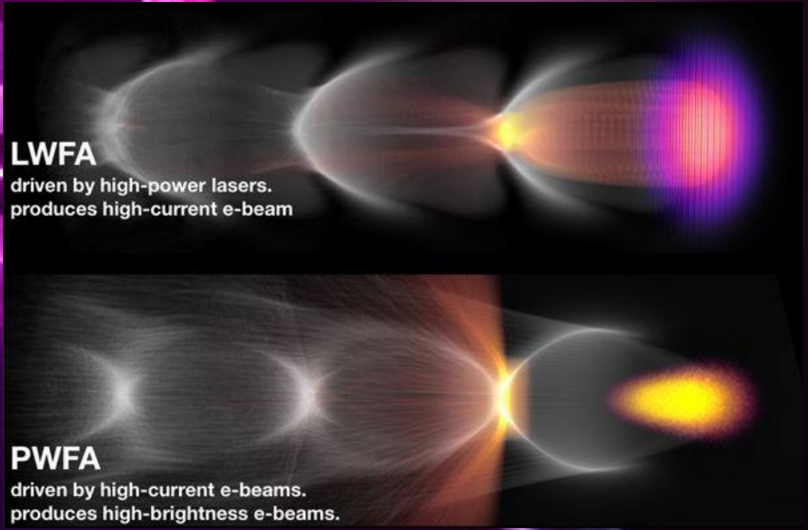
$$a=\frac{eA}{mc^2}\propto\lambda J^{1/2}$$

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

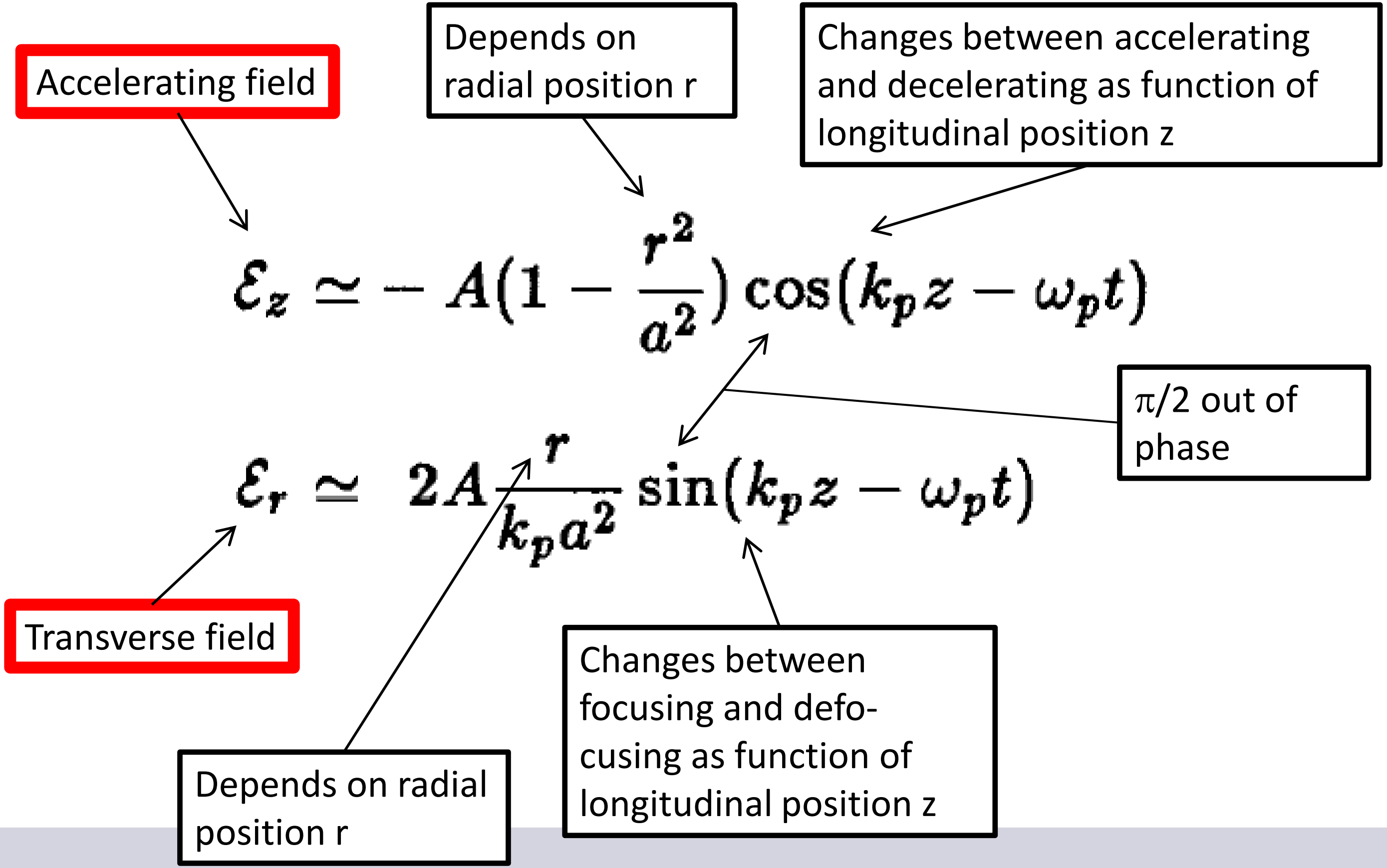
driven by high-power lasers.
produces high-current e-beam

PWFA

driven by high-current e-beams.
produces high-brightness e-beams.

LWFA limitations: Diffraction, Dephasing, Depletion
PWFA limitations: Head Erosion, Hose

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



Accelerating field

Depends on radial position r

Changes between accelerating and decelerating as function of longitudinal position z

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

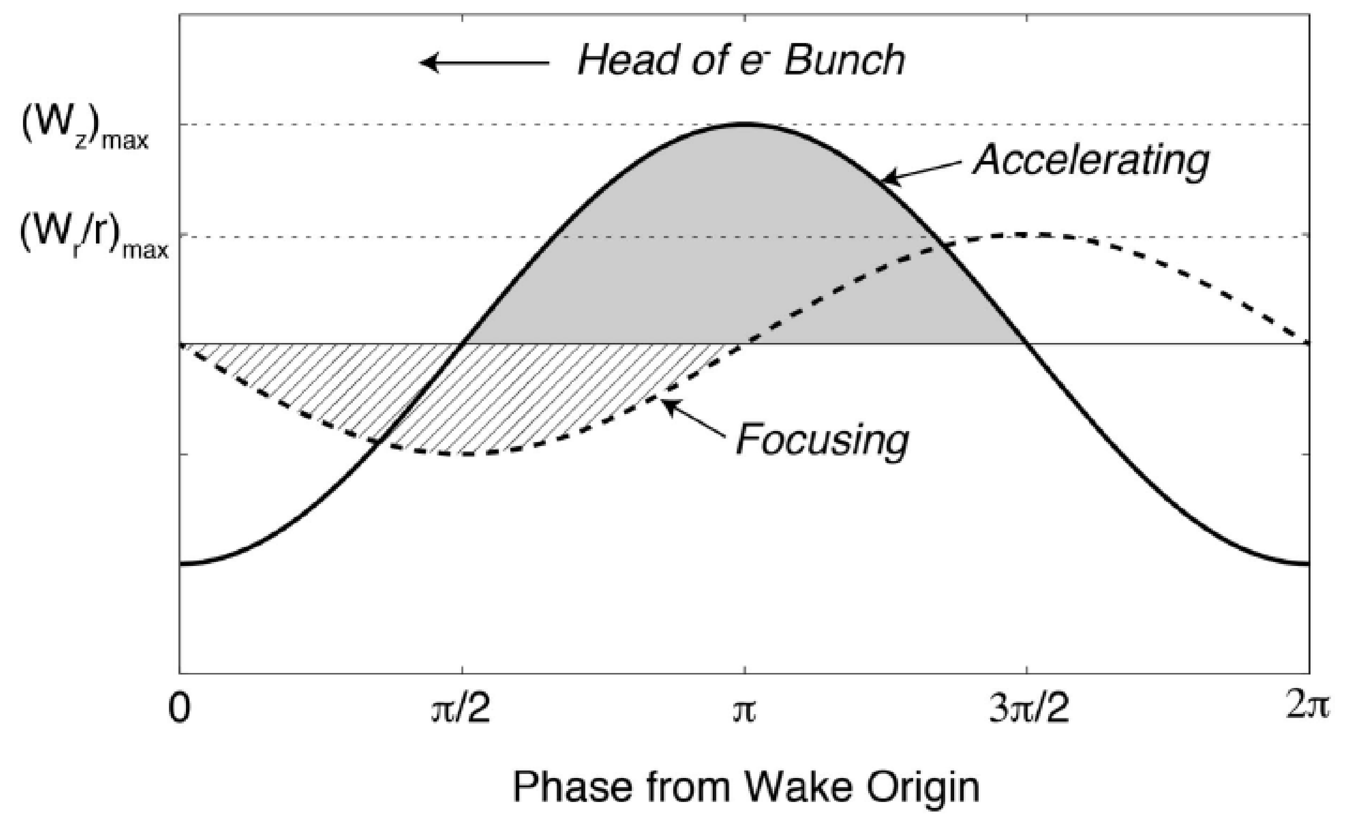
π/2 out of phase

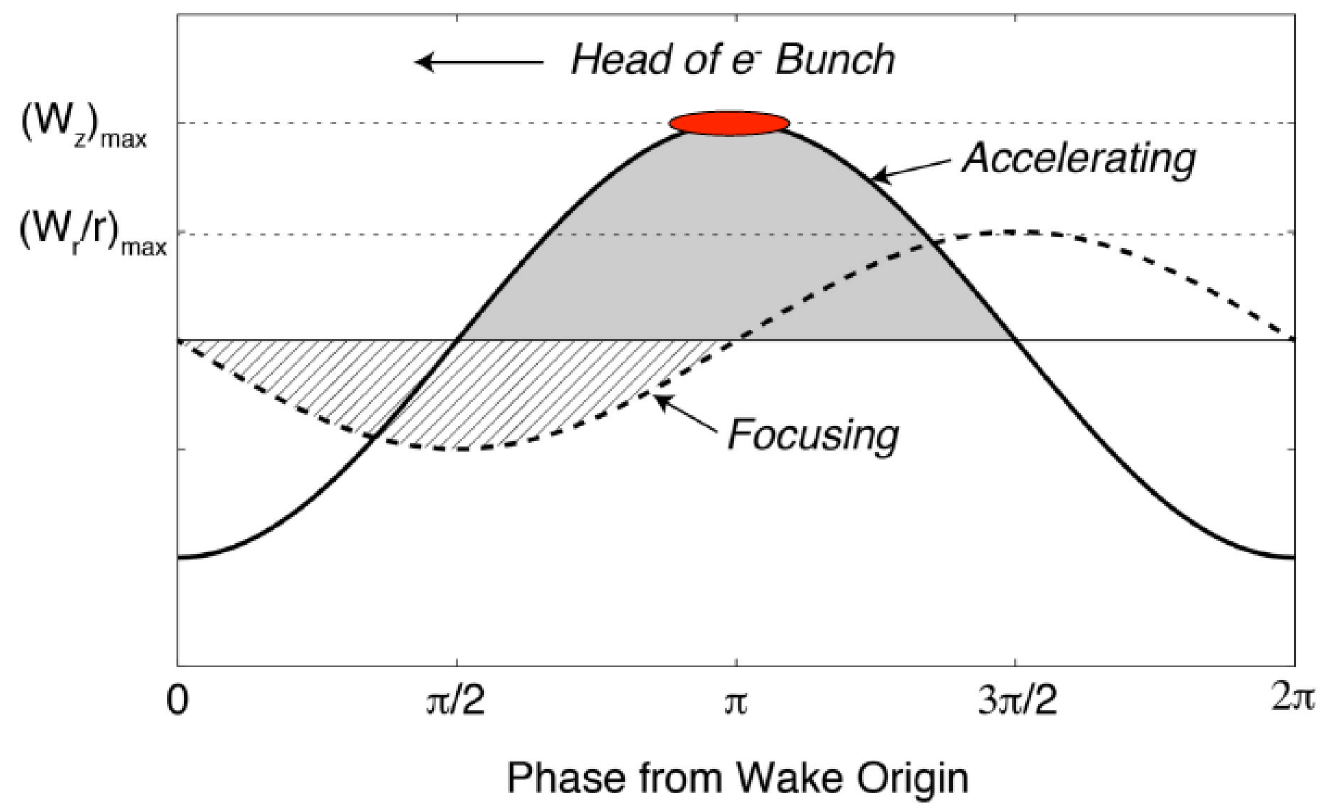
$$\mathcal{E}_r \simeq 2A\frac{r}{k_p a^2}\sin(k_p z-\omega_p t)$$

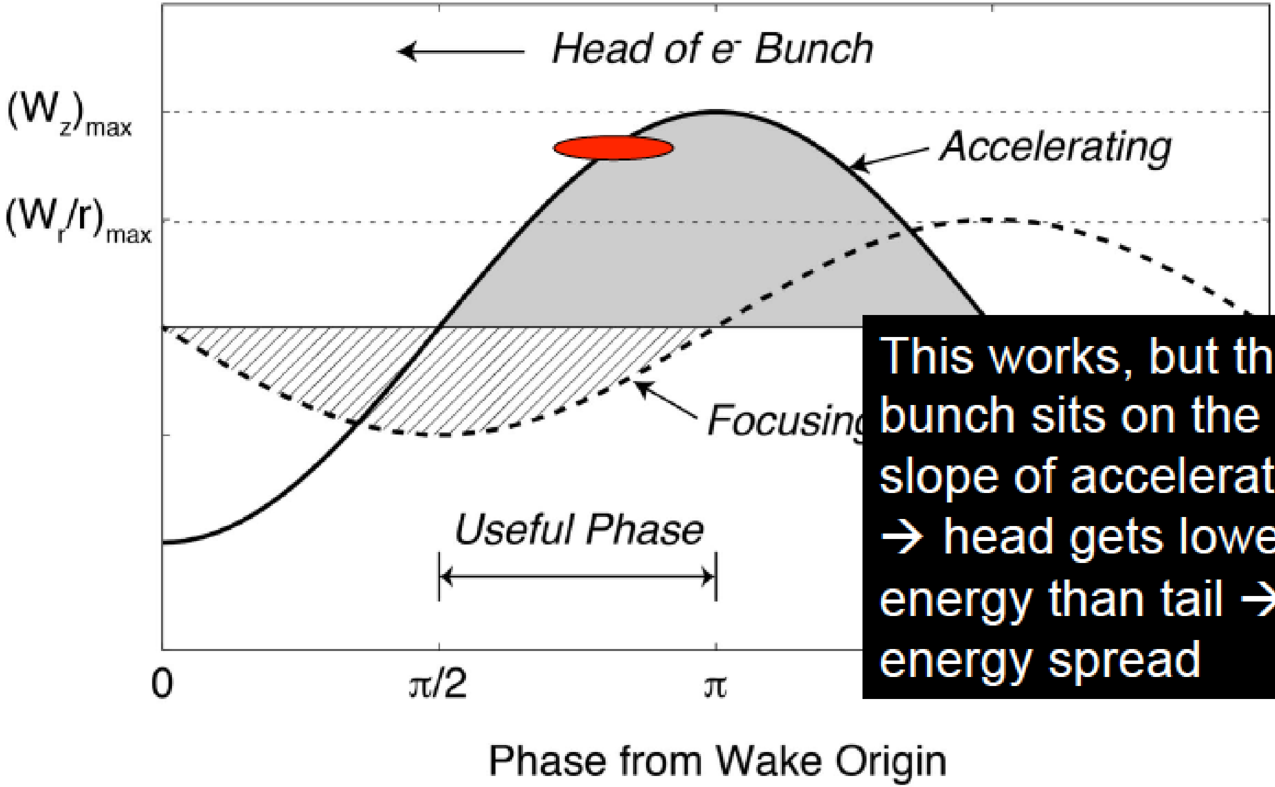
Transverse field

Depends on radial position r

Changes between focusing and defocusing as function of longitudinal position z

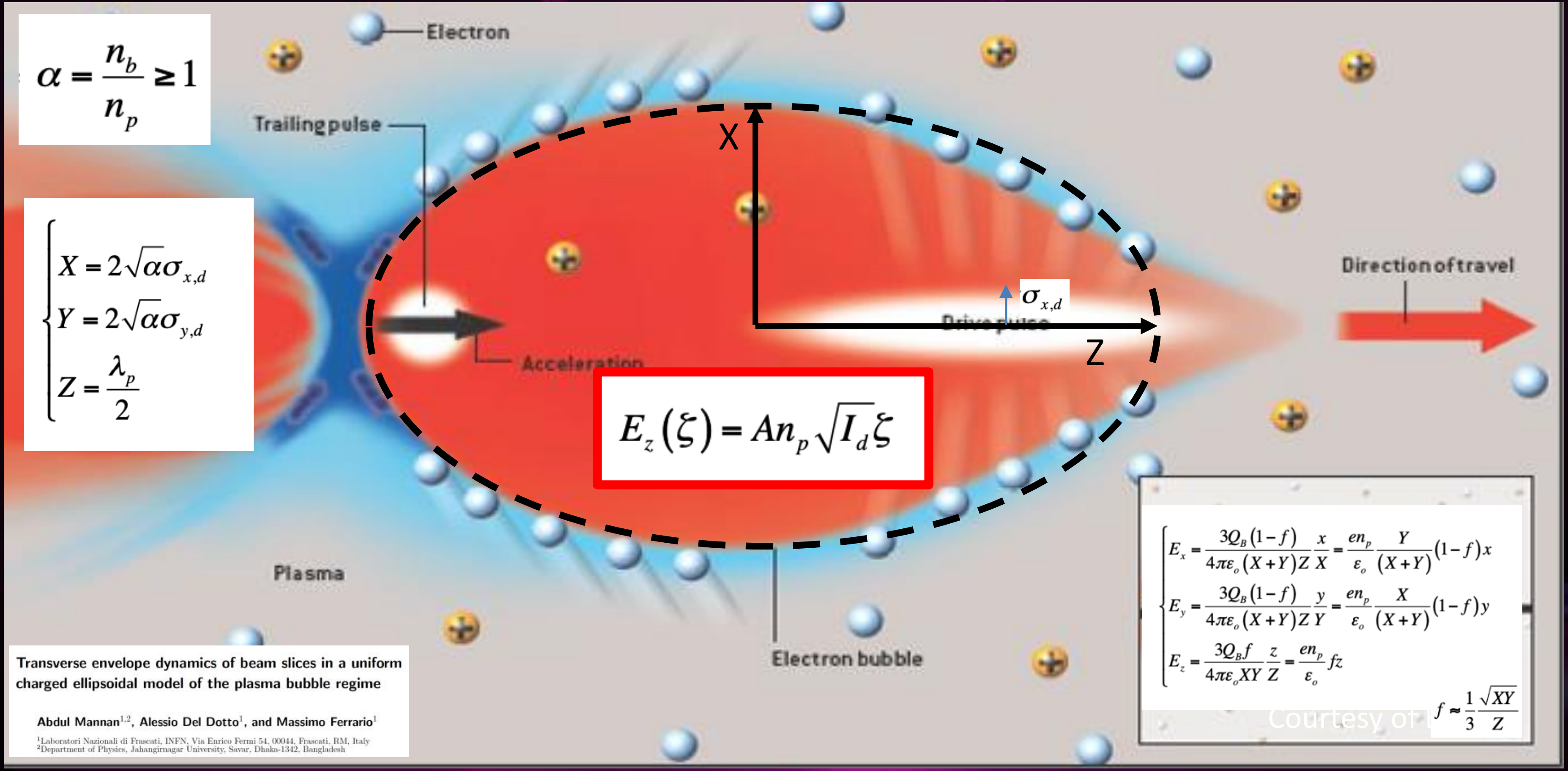

Head of e⁻ Bunch
$(W_z)_{max}$
$(W_r/r)_{max}$
Accelerating
Focusing
0
π/2
π
3π/2
2π
Phase from Wake Origin


Head of e⁻ Bunch
$(W_z)_{max}$
$(W_r/r)_{max}$
Accelerating
Focusing
0
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

Non Linear Regime – Ellipsoidal Bubble Model



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

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

$$\boxed{E_z(\zeta) = A n_p \sqrt{I_d}\,\zeta}$$

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

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

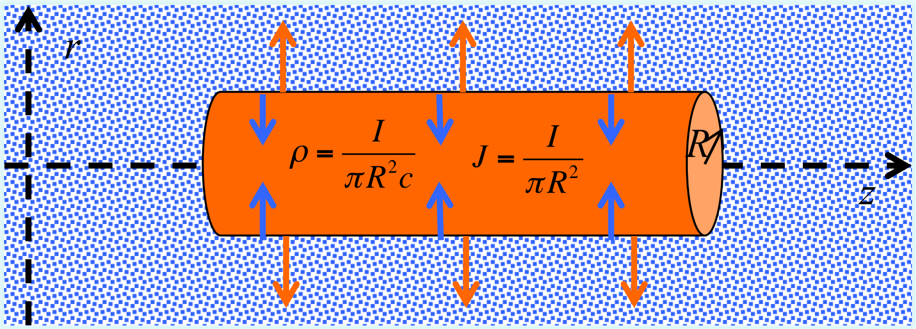
Courtesy of

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

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

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

Uniform Cylindrical Beam Model with ionized gas background



f_e : charge neutralisation factor

$$\begin{cases} E_r = \dfrac{I\left(1-f_e\right)}{2\pi\varepsilon_o a^2 c}\, r & \text{for} \quad r \leq a \\[2ex] E_r = \dfrac{I\left(1-f_e\right)}{2\pi\varepsilon_o c}\, \dfrac{1}{r} & \text{for} \quad r > a \end{cases}$$

f_m : current neutralisation factor

$$\begin{cases} B_\vartheta = \mu_o \dfrac{I\left(1-f_m\right)}{2\pi a^2}\, r & \text{for} \quad r \leq a \\[2ex] B_\vartheta = \mu_o \dfrac{I\left(1-f_m\right)}{2\pi a^2}\, \dfrac{a^2}{r} & \text{for} \quad r > a \end{cases}$$

Lorentz Force

$$F_r = e\left(E_r - \beta c B_\vartheta\right) = \frac{eE_r}{\gamma^2}\left(1 - \gamma^2 f_e + \beta^2 \gamma^2 f_m\right)$$

Generalized Envelope Equation

$$\sigma'' + \frac{(\beta\gamma)'}{\beta\gamma}\sigma' + \frac{K}{\beta\gamma}\sigma = \frac{2I\left(1 - \gamma^2 f_e + \beta^2\gamma^2 f_m\right)}{I_A\left(\beta\gamma\right)^3 \sigma} + \frac{\varepsilon_n^2}{\left(\beta\gamma\right)^2 \sigma^3}$$

Matching in a Plasma Accelerator with $f_e=n_p/n_e$ and $f_m=0$

$$\sigma'' + \frac{\gamma'}{\gamma}\sigma' + \frac{k_{ext}^2}{\gamma}\sigma = \frac{2I\left(1-\gamma^2 f_e + \gamma^2 f_m\right)}{I_A\gamma^3\sigma} + \frac{\varepsilon_n^2}{\gamma^2\sigma^3}$$

Let consider the charge screening effect of the plasma background with particle density n_p, by defining $f_e=n_p/n_e$, where n_e is the bunch particle density and $f_m=0$. We also do not include any external focusing element so that $k_{ext}=0$. The envelope equation can be recast as:

$$\sigma'' + \frac{\gamma'}{\gamma}\sigma' + \frac{2In_p}{I_A\gamma n_e\sigma} = \frac{2I}{I_A\gamma^3\sigma} + \frac{\varepsilon_n^2}{\gamma^2\sigma^3}$$

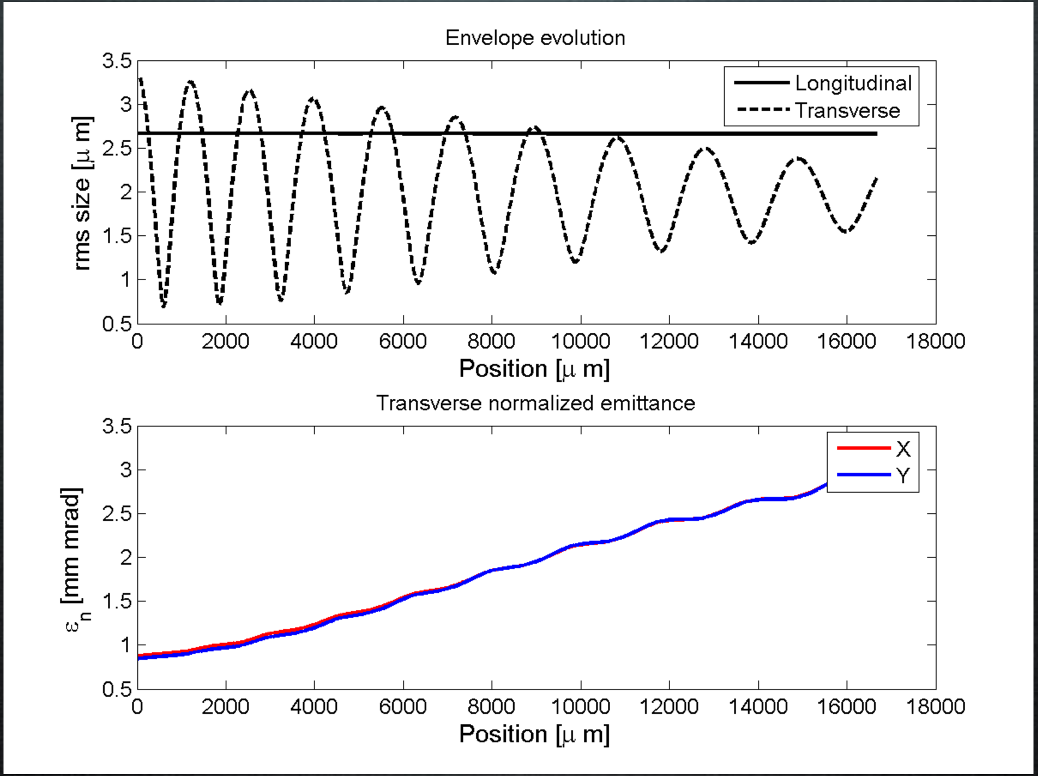
or by recalling the definition of the Alfven current I_A and of the beam current $I=ecn_e\pi\sigma^2$ it can be written in a more familiar form as:

$$I_A = \frac{4\pi\varepsilon_o m_o c^3}{e}$$

$$\sigma'' + \frac{\gamma'}{\gamma}\sigma' + \frac{k_p^2}{2\gamma}\sigma = \frac{2I}{I_A\gamma^3\sigma} + \frac{\varepsilon_n^2}{\gamma^2\sigma^3}$$

$$k_p^2 = \frac{e^2 n_p}{\varepsilon_o mc^2}$$

Transverse beam dynamics inside the plasma

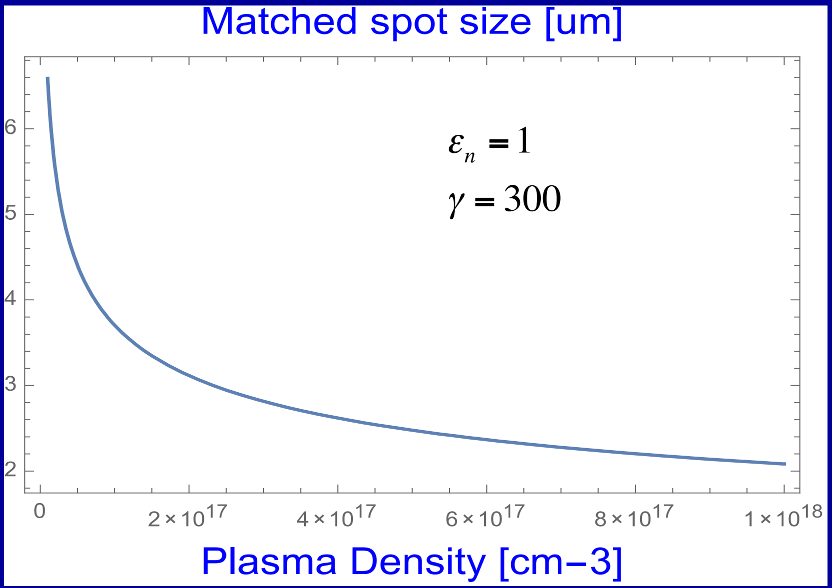


Courtesy P. Tomassini

With the typical beam parameters in a plasma accelerator: 1 kA peak current, 1 μm normalized emittance, injection energy γ_o=300 and spot size about 5 μm, the laminarity parameter (43) results to be ρ < 1, i.e. the beam is emittance dominated. We have also to neglect the adiabatic damping term, setting γ'=0 i.e. no acceleration. This approximation is quite strong but it will allow us to find at least a proper matching condition that holds at the entrance of the plasma column. It follows that the envelope equation can be approximated by the reduced expression:

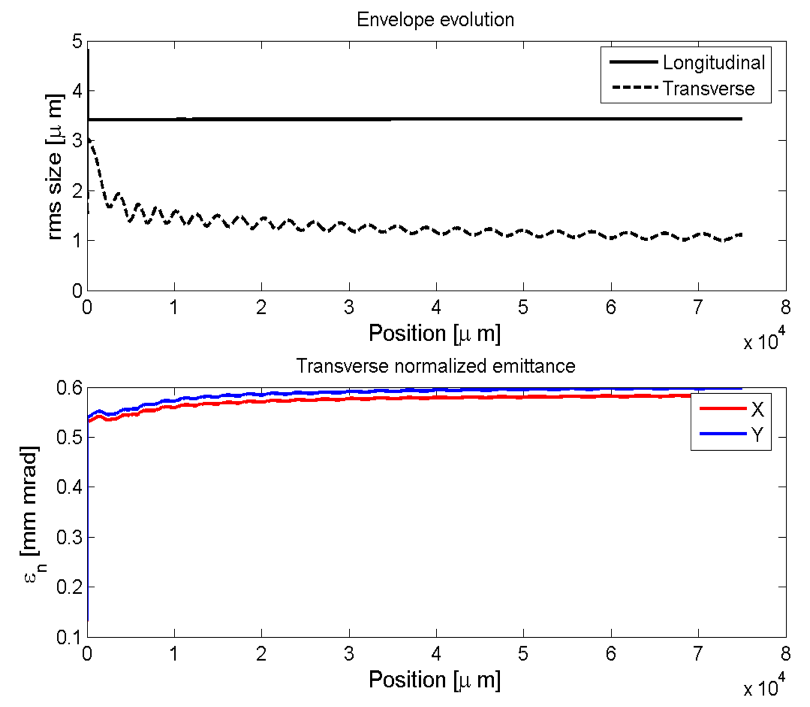
$$\sigma'' + \frac{k_p^2}{2\gamma}\sigma = \frac{\varepsilon_n^2}{\gamma^2\sigma^3}$$

$$\boxed{\sigma_{eq} = \sqrt[4]{\frac{2}{\gamma}}\sqrt{\frac{\varepsilon_n}{k_p}}}$$



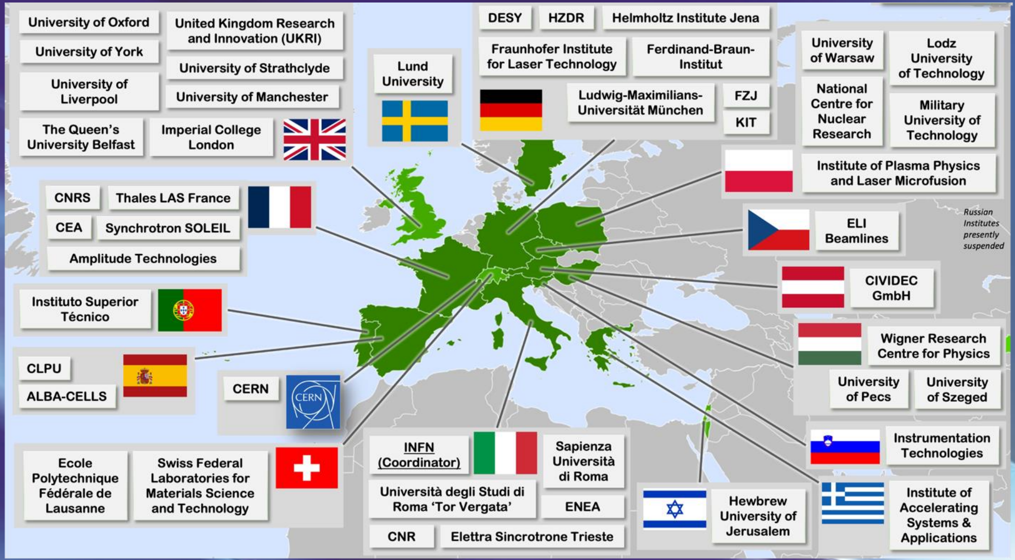
$\varepsilon_n = 1$

$\gamma = 300$


Envelope evolution
rms size [μ m]
Position [μ m]
x 10^4
Longitudinal
Transverse
0
1
2
3
4
5
6
7
8
Transverse normalized emittance
ε_n [mm mrad]
0.1
0.2
0.3
0.4
0.5
0.6
X
Y
Position [μ m]
x 10^4

The near future

EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS



University of Oxford
United Kingdom Research and Innovation (UKRI)
University of York
University of Strathclyde
University of Liverpool
University of Manchester
The Queen's University Belfast
Imperial College London

CNRS
Thales LAS France
CEA
Synchrotron SOLEIL
Amplitude Technologies

Instituto Superior Técnico

CLPU
ALBA-CELLS

CERN

Ecole Polytechnique Fédérale de Lausanne
Swiss Federal Laboratories for Materials Science and Technology

Lund University

DESY
HZDR
Helmholtz Institute Jena
Fraunhofer Institute for Laser Technology
Ferdinand-Braun-Institut
Ludwig-Maximilians-Universität München
FZJ
KIT

INFN (Coordinator)
Sapienza Università di Roma
Università degli Studi di Roma 'Tor Vergata'
ENEA
CNR
Elettra Sincrotrone Trieste

Hewbrew University of Jerusalem

University of Warsaw
Lodz University of Technology
National Centre for Nuclear Research
Military University of Technology
Institute of Plasma Physics and Laser Microfusion

ELI Beamlines

Russian Institutes presently suspended

CIVIDEC GmbH

Wigner Research Centre for Physics
University of Pecs
University of Szeged

Instrumentation Technologies

Institute of Accelerating Systems & Applications

A New European High-Tech User Facility

Funded by the European Union

EuPRAXIA is the first European project that develops a dedicated particle accelerator research infrastructure **based on novel plasma acceleration** concepts **driven by innovative laser and linac technologies**.

1

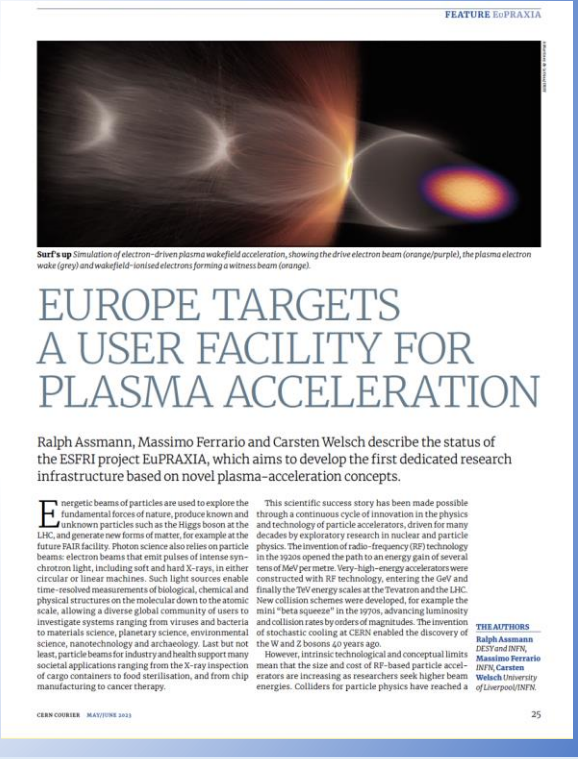
Building a facility with very high field plasma accelerators, driven by lasers or beams
1 – 100 GV/m accelerating field

Shrink down the facility size
Improve Sustainability

2

Producing particles and photons to support several urgent and timely science cases

Drive short wavelength FEL
Pave the way for future Linear Colliders



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.*

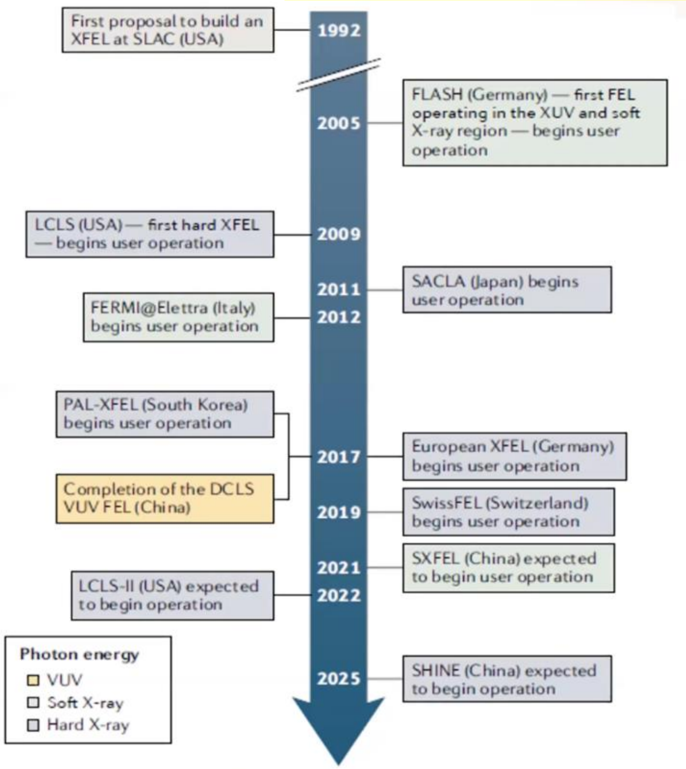
https://www.eupraxia-facility.org/

EuPRAXIA

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


1992 — First proposal to build an XFEL at SLAC (USA)

2005 — FLASH (Germany) — first FEL operating in the XUV and soft X-ray region — begins user operation

2009 — LCLS (USA) — first hard XFEL — begins user operation

2011 — SACLA (Japan) begins user operation

2012 — FERMI@Elettra (Italy) begins user operation

2017 — PAL-XFEL (South Korea) begins user operation

2017 — Completion of the DCLS VUV FEL (China)

2017 — European XFEL (Germany) begins user operation

2019 — SwissFEL (Switzerland) begins user operation

2021 — SXFEL (China) expected to begin user operation

2022 — LCLS-II (USA) expected to begin operation

2025 — SHINE (China) expected to begin operation

Photon energy
- ☐ VUV
- ☐ Soft X-ray
- ☐ Hard X-ray

New facilities are expected to begin operation in the next 5 years in the USA and China, and the UK is considering the scientific case for an XFEL.

Iulia Georgescu

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: $\epsilon_{x,y} < \dfrac{\lambda_0}{4\pi}$

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

Low emittances
Low energy spread
High current

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

Exponential growth

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

gain length

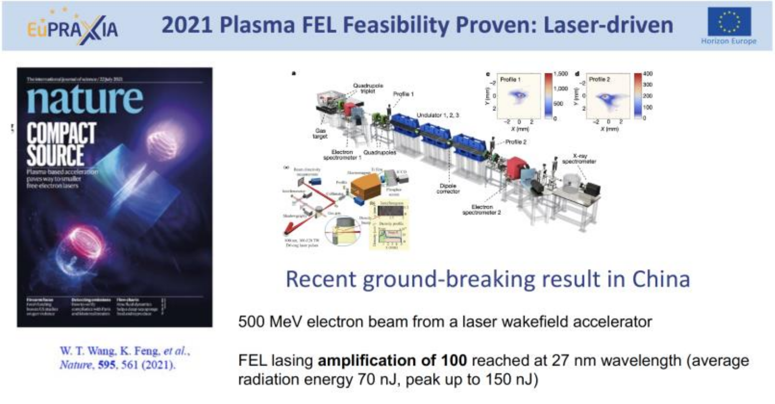
$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{fel}}$$

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

Basic beam quality achieved in pilot FEL experiments



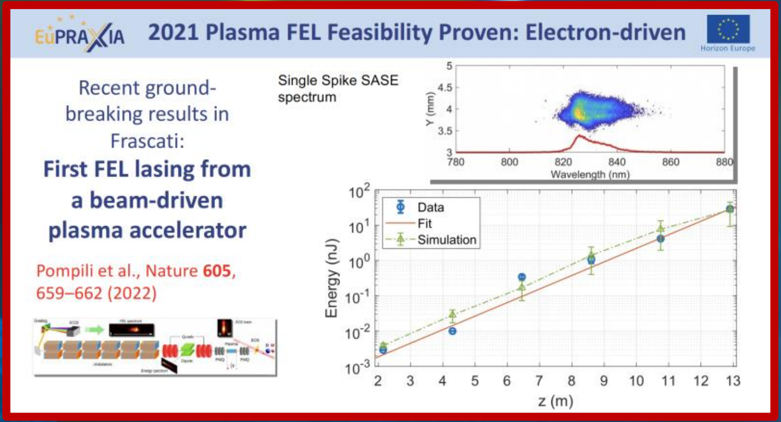
2021 Plasma FEL Feasibility Proven: Laser-driven

W. T. Wang, K. Feng, *et al.*, *Nature*, **595**, 561 (2021).

Recent ground-breaking result in China

500 MeV electron beam from a laser wakefield accelerator

FEL lasing **amplification of 100** reached at 27 nm wavelength (average radiation energy 70 nJ, peak up to 150 nJ)



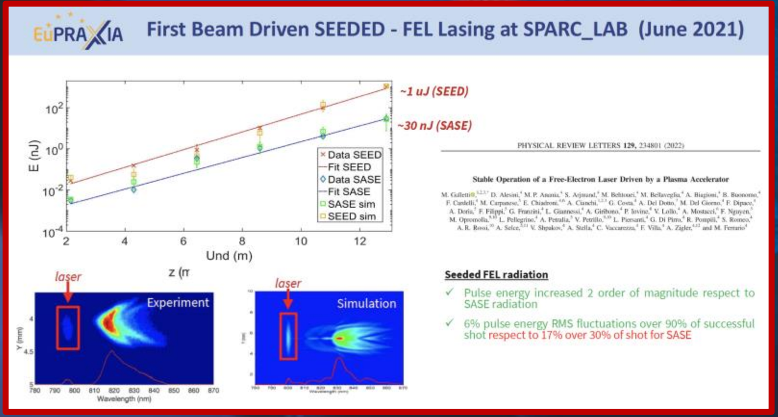
2021 Plasma FEL Feasibility Proven: Electron-driven

Recent ground-breaking results in Frascati:

First FEL lasing from a beam-driven plasma accelerator

Pompili et al., Nature **605**, 659–662 (2022)

Single Spike SASE spectrum



First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)

~1 uJ (SEED)

~30 nJ (SASE)

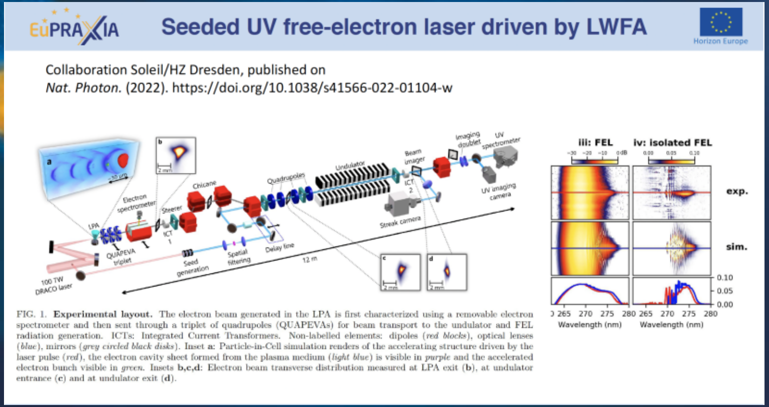
PHYSICAL REVIEW LETTERS **129**, 234801 (2022)

Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator

M. Galletti, D. Alesini, M. P. Anania, S. Arjmand, M. Behtouei, M. Bellaveglia, A. Biagioni, B. Buonomo, F. Cardelli, M. Carpanese, E. Chiadroni, A. Cianchi, G. Costa, A. Del Dotto, M. Del Giorno, F. Dipace, A. Doria, F. Filippi, G. Franzini, L. Giannessi, A. Giribono, P. Iovine, V. Lollo, A. Mostacci, F. Nguyen, M. Opromolla, L. Pellegrino, A. Petralia, V. Petrillo, L. Piersanti, G. Di Pirro, R. Pompili, S. Romeo, A. R. Rossi, A. Selce, V. Shpakov, A. Stella, C. Vaccarezza, F. Villa, A. Zigler, and M. Ferrario

Seeded FEL radiation

- ✓ Pulse energy increased 2 order of magnitude respect to SASE radiation
- ✓ 6% pulse energy RMS fluctuations over 90% of successful shot respect to 17% over 30% of shot for SASE



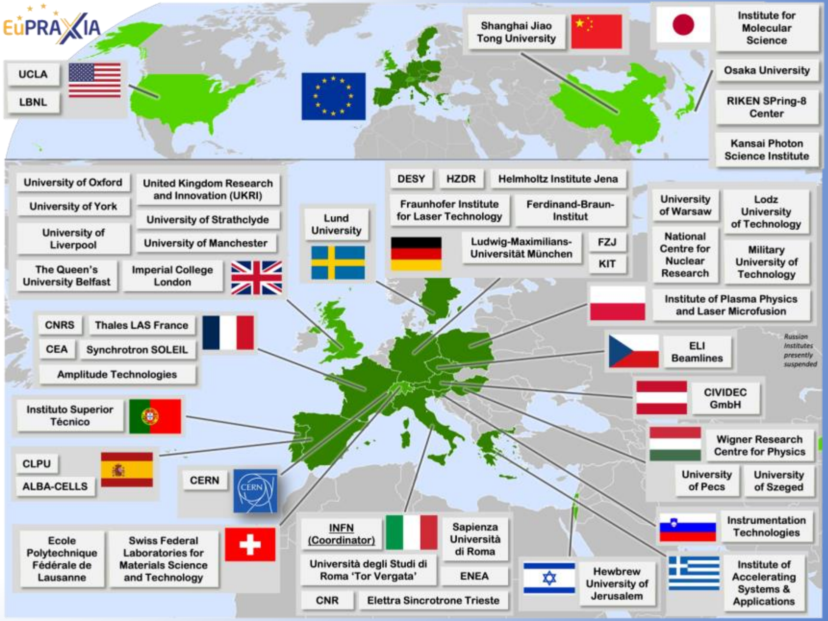
Seeded UV free-electron laser driven by LWFA

Collaboration Soleil/HZ Dresden, published on *Nat. Photon.* (2022). https://doi.org/10.1038/s41566-022-01104-w

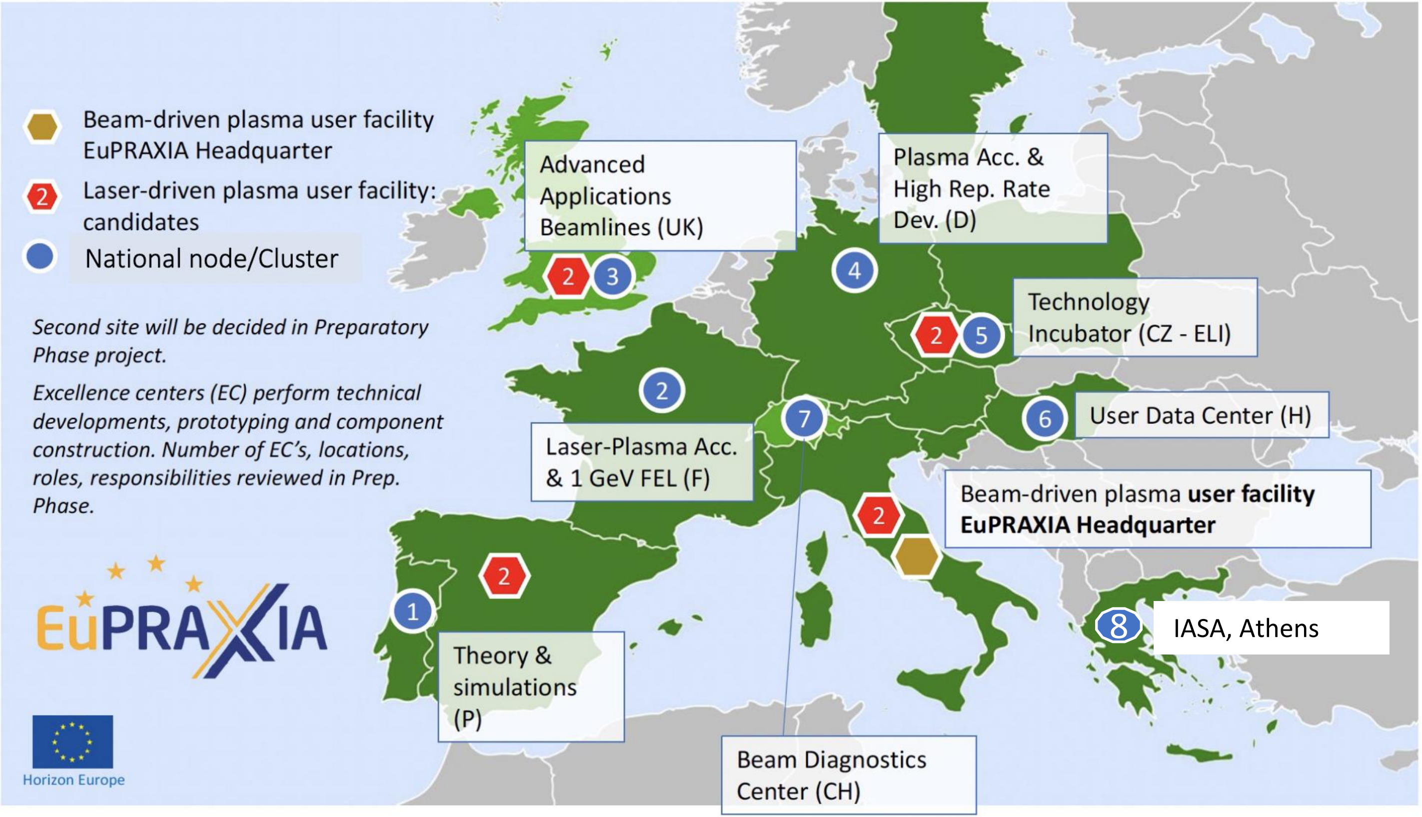
FIG. 1. **Experimental layout.** The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAs) for beam transport to the undulator and FEL radiation generation. ICTs: Integrated Current Transformers. Non-labelled elements: dipoles (*red blocks*), optical lenses (*blue*), mirrors (*grey circled black disks*). Inset **a**: Particle-in-Cell simulation renders of the accelerating structure driven by the laser pulse (*red*), the electron cavity sheet formed from the plasma medium (*light blue*) is visible in *purple* and the accelerated electron bunch visible in *green*. Insets **b,c,d**: Electron beam transverse distribution measured at LPA exit (**b**), at undulator entrance (**c**) and at undulator exit (**d**).

Wide International Collaboration

- **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)


EuPRAXIA
UCLA
LBNL
Shanghai Jiao Tong University
Institute for Molecular Science
Osaka University
RIKEN SPring-8 Center
Kansai Photon Science Institute
University of Oxford
University of York
University of Liverpool
The Queen's University Belfast
United Kingdom Research and Innovation (UKRI)
University of Strathclyde
University of Manchester
Imperial College London
Lund University
DESY
HZDR
Helmholtz Institute Jena
Fraunhofer Institute for Laser Technology
Ferdinand-Braun-Institut
Ludwig-Maximilians-Universität München
FZJ
KIT
University of Warsaw
Lodz University of Technology
National Centre for Nuclear Research
Military University of Technology
Institute of Plasma Physics and Laser Microfusion
CNRS
Thales LAS France
CEA
Synchrotron SOLEIL
Amplitude Technologies
ELI Beamlines
Russian Institutes presently suspended
CIVIDEC GmbH
Instituto Superior Técnico
Wigner Research Centre for Physics
University of Pecs
University of Szeged
CLPU
ALBA-CELLS
CERN
Instrumentation Technologies
Ecole Polytechnique Fédérale de Lausanne
Swiss Federal Laboratories for Materials Science and Technology
INFN (Coordinator)
Sapienza Università di Roma
Università degli Studi di Roma 'Tor Vergata'
ENEA
CNR
Elettra Sincrotrone Trieste
Hewbrew University of Jerusalem
Institute of Accelerating Systems & Applications

Distributed Research Infrastructure



⬢ Beam-driven plasma user facility EuPRAXIA Headquarter

2 Laser-driven plasma user facility: candidates

● National node/Cluster

Second site will be decided in Preparatory Phase project.

Excellence centers (EC) perform technical developments, prototyping and component construction. Number of EC's, locations, roles, responsibilities reviewed in Prep. Phase.

Horizon Europe

A large collection of the best European know-hows
in accelerators, lasers an
plasma technologies

Network organization
- **Sites (PWFA/LWFA)**
- **National nodes**
- **Technology clusters**

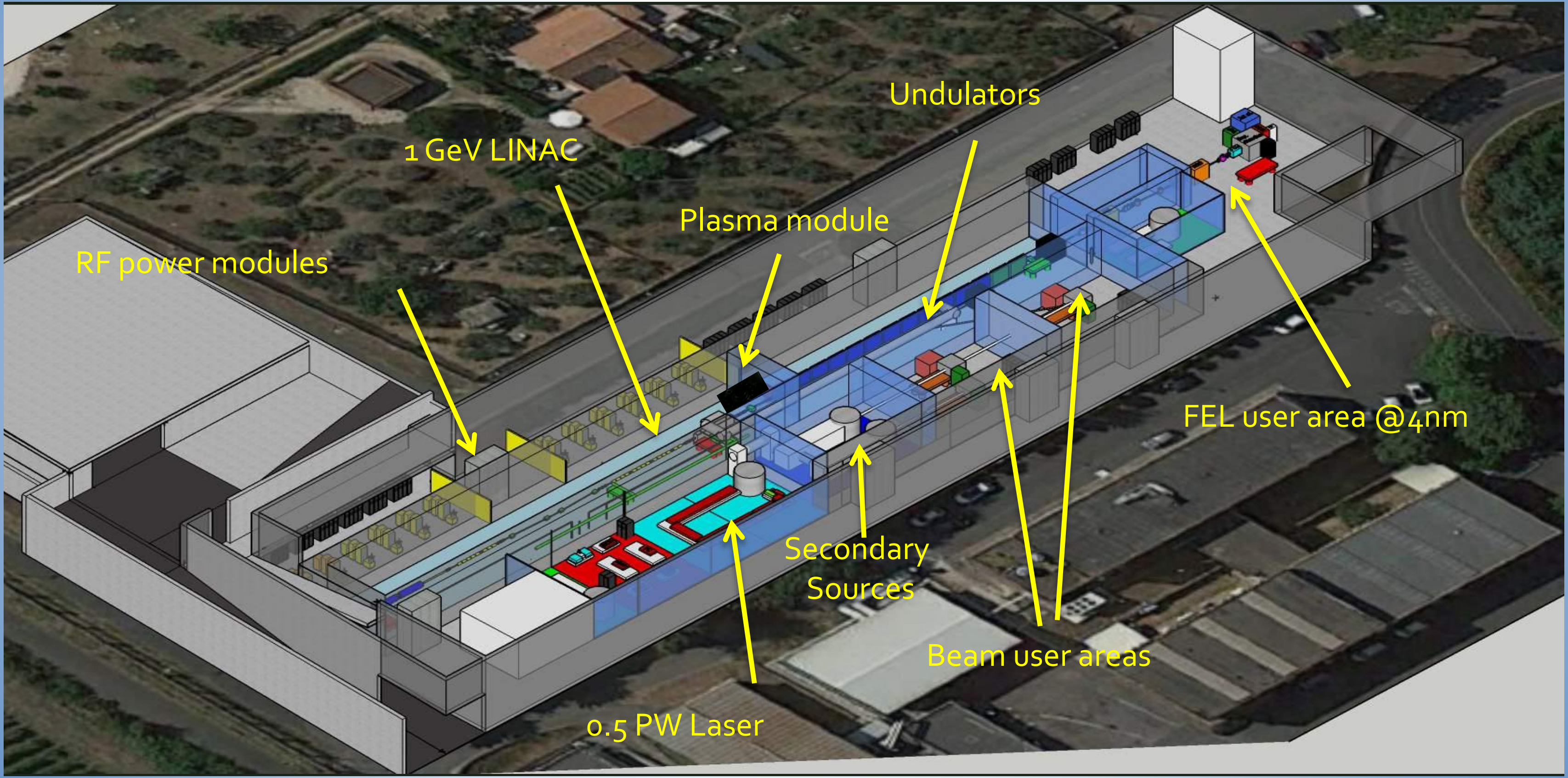
4 candidates for LWFA:
- CLPU, Salamanca
- CNR-INO, Pisa
- ELI ERIC, Prague
- EPAC-RAL, UK

Funded by the European Union

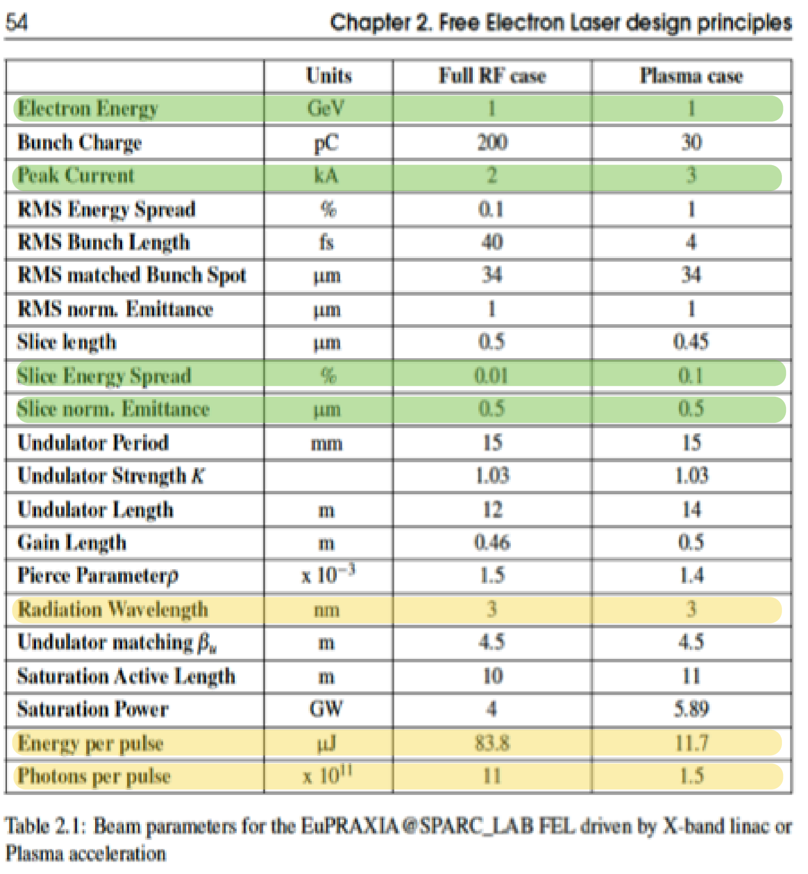
Headquarter and Site 1: EuPRAXIA@SPARC_LAB

- 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



Expected SASE FEL performances

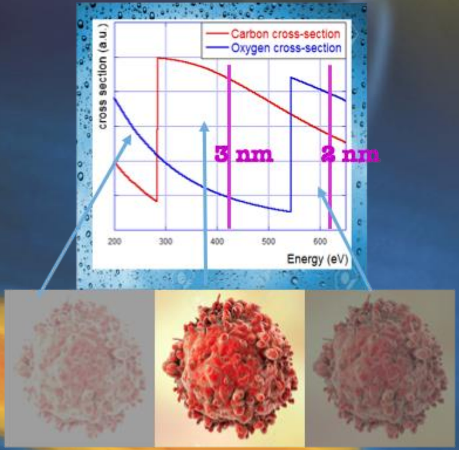


54 Chapter 2. Free Electron Laser design principles

	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	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

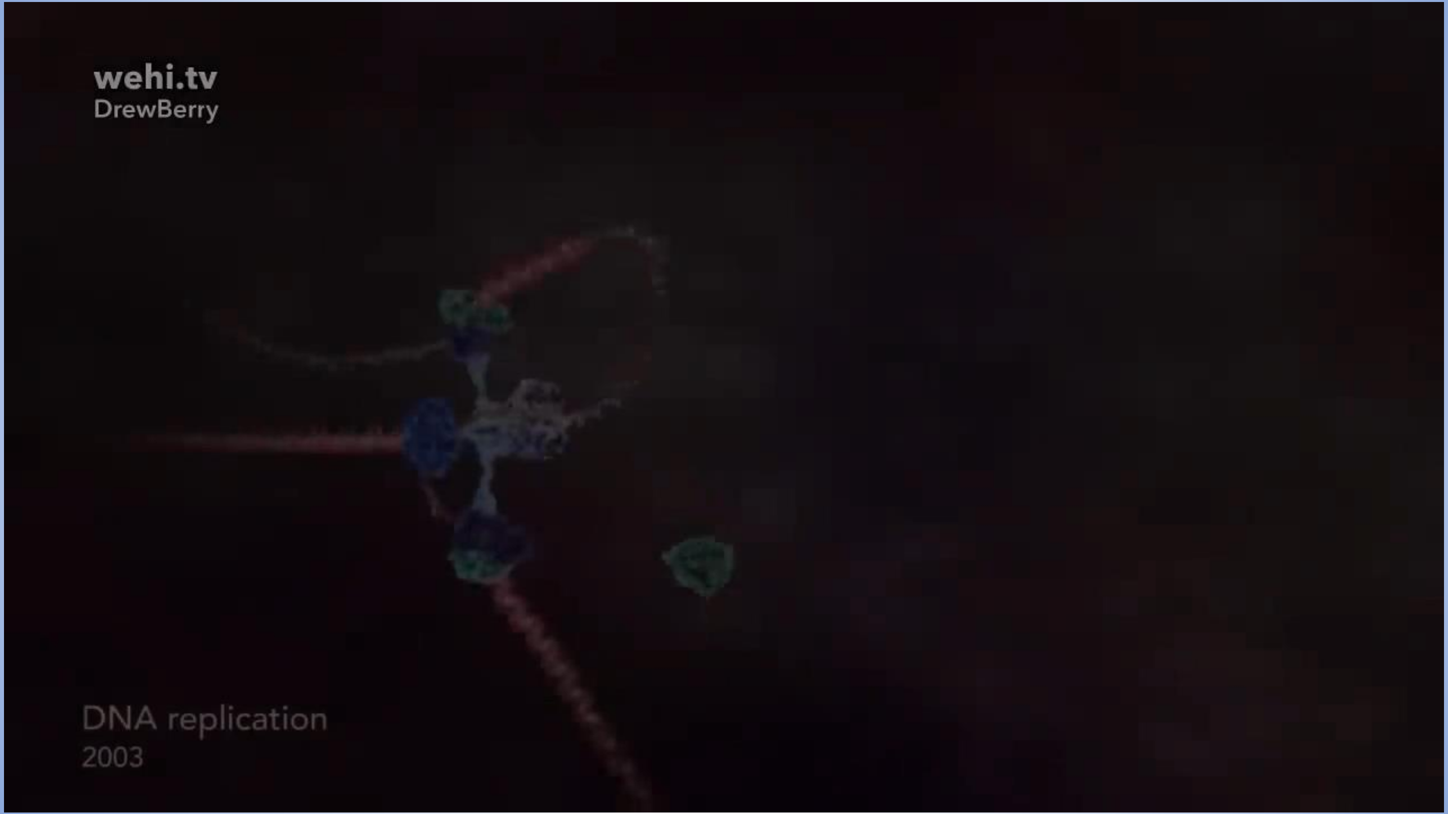
In the Energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV) water is almost transparent to radiation while nitrogen and carbon are absorbing (and scattering)



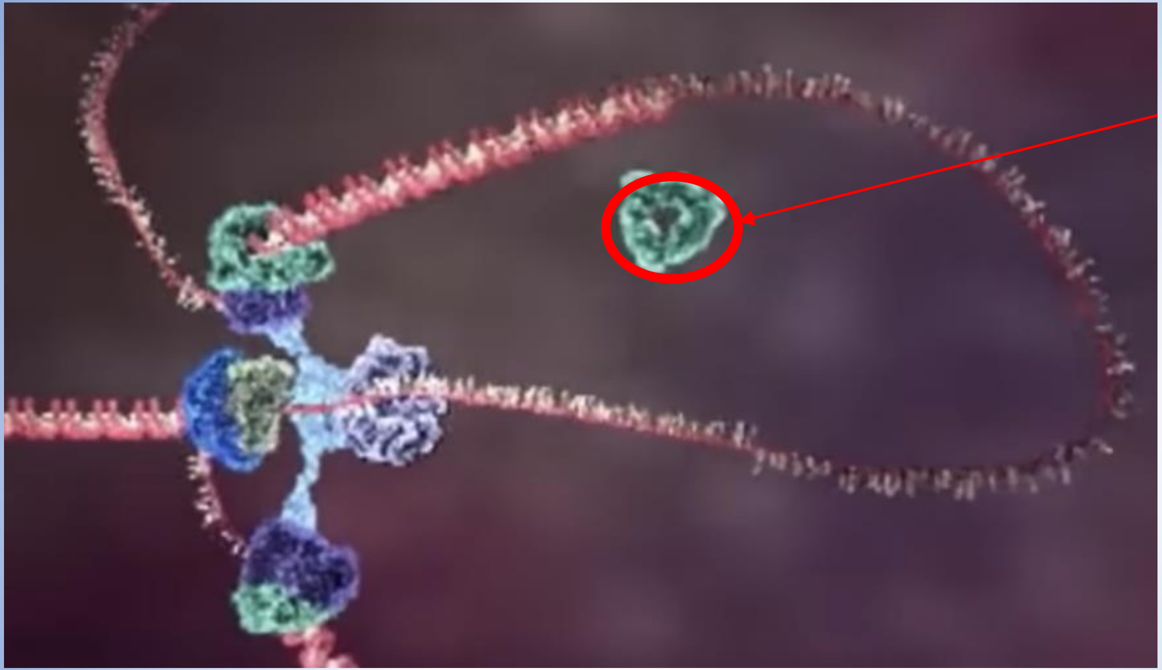
Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state
Possibility to study dynamics
~10^{11} photons/pulse needed

Courtesy F. Stellato, UniToV

Single Protein Imaging with hard x-rays



Single Protein Imaging with hard x-rays

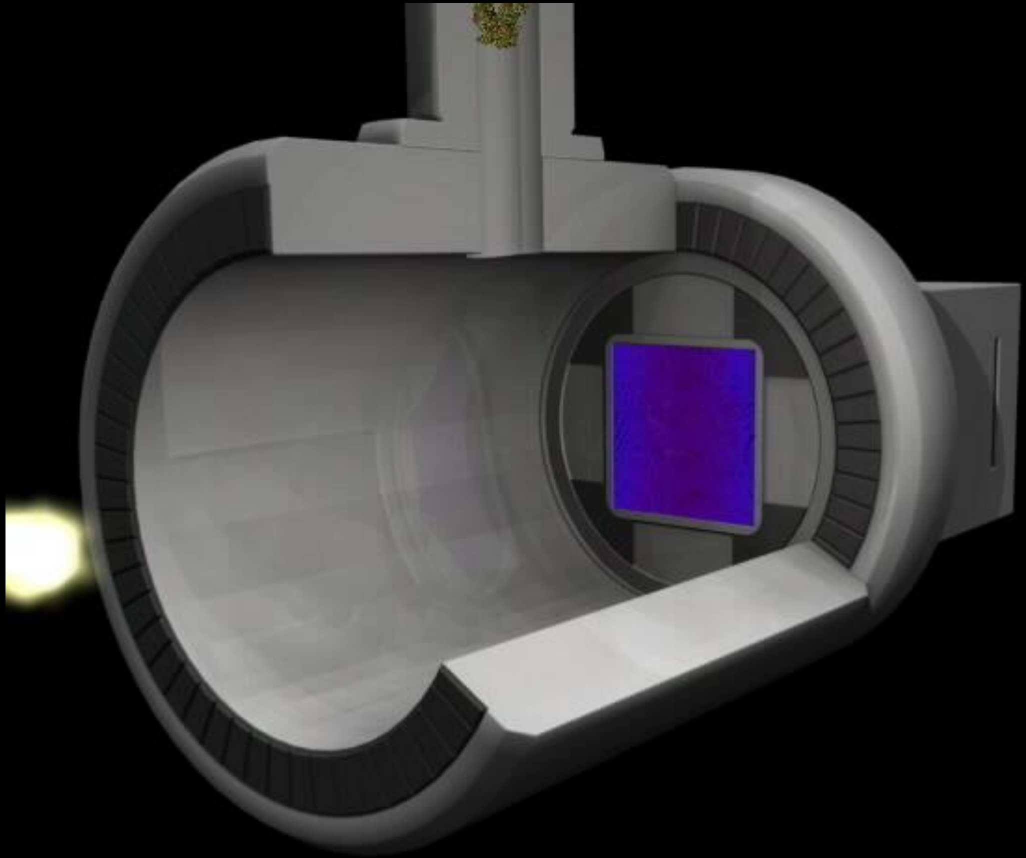


Static picture of a macro-molecule

Required properties

- Short wavelength (X-ray)
- High energy per pulse
- Ultra-short pulse (few femtoseconds)
- Coherence

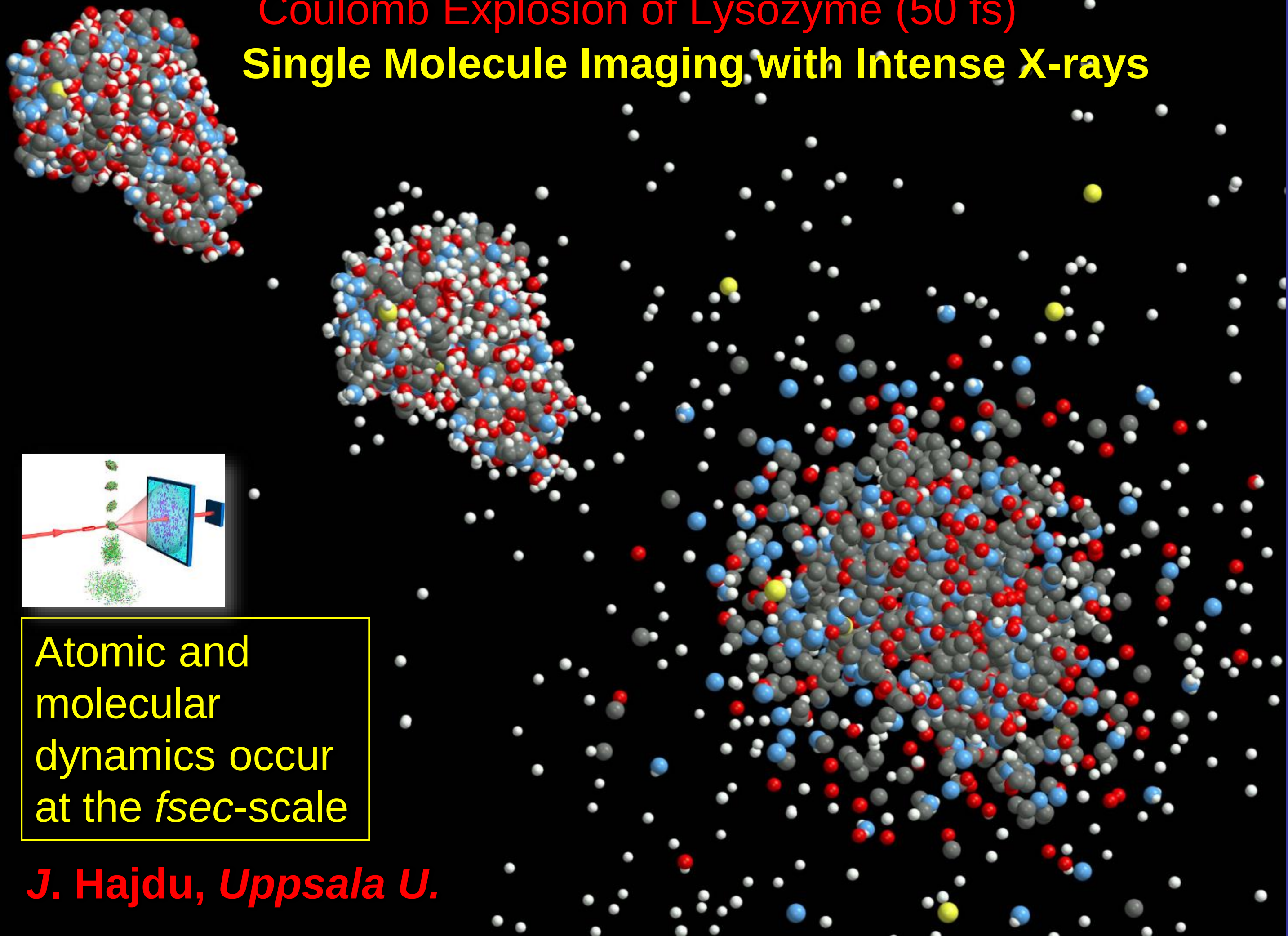
Single Protein Imaging



http://lcls.slac.stanford.edu/AnimationViewLCLS.asp

Coulomb Explosion of Lysozyme (50 fs)

Single Molecule Imaging with Intense X-rays



Atomic and molecular dynamics occur at the *fsec*-scale

***J. Hajdu**, Uppsala U.*

Plasma collider challenges

Beam delivery system

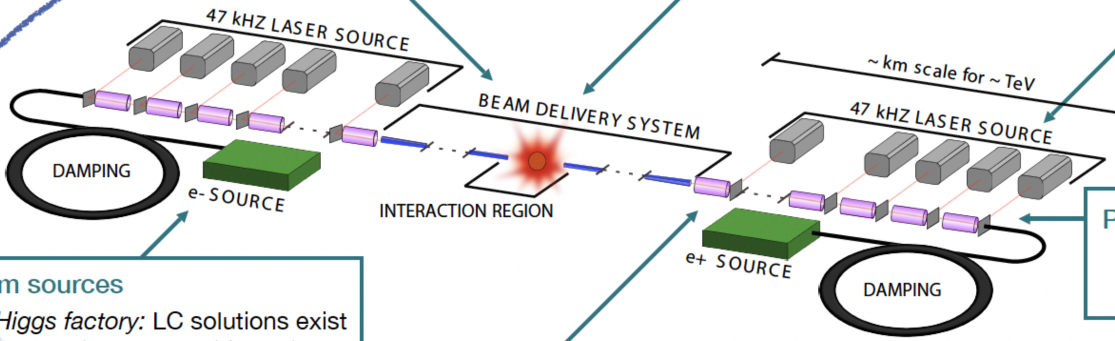
- *Higgs factory:* optimized LC designs exist
  optimizations for plasmas needed/possible?
- *10 TeV collider:* no design exists
  critical - HF designs scale poorly with energy (geo. gradient) → 20 (CLIC) to 90 (ILC) km

Interaction region

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

Driver technology

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



Beam sources

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

Positron acceleration

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

Plasma stages + coupling

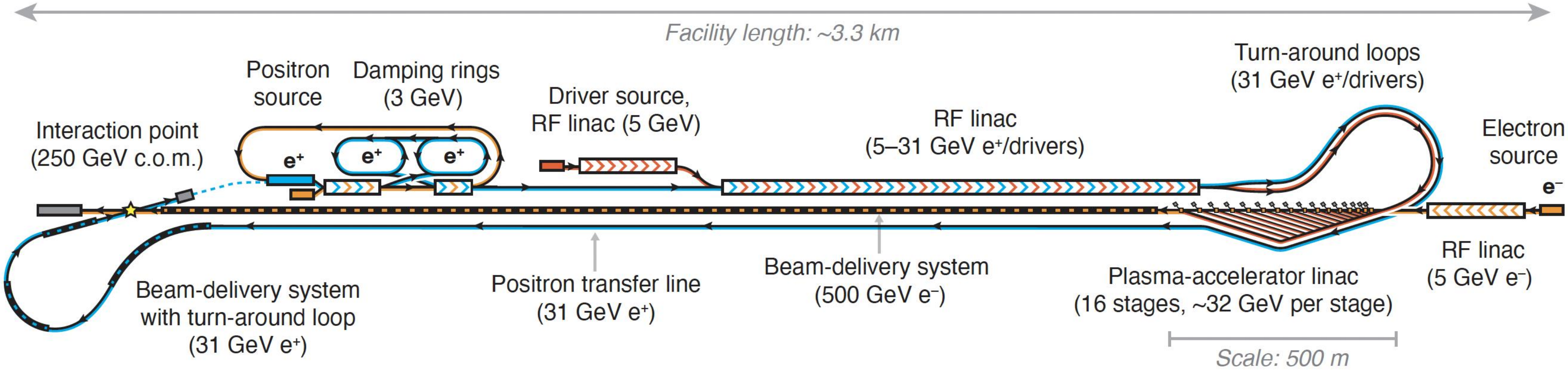
- Focus and key charge for our field, no roadblocks known
  critical - beam quality (incl. polarization), efficiency, stability, longevity, resilience to jitter (in time, space, and momentum), resilience to catastrophic errors (one bad shot)
- *Plasma stage:* requires demonstration of collider parameters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

Full system integration

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

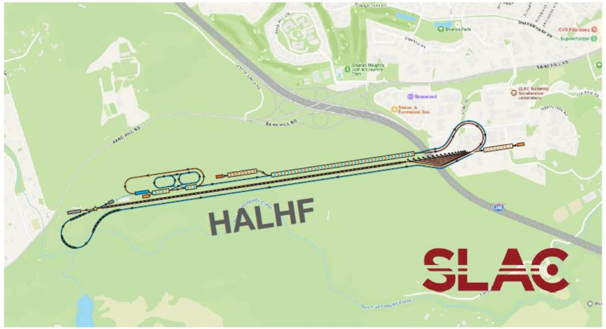
Courtesy J. Osterhoff

HALHF: A Hybrid, Asymmetric, Linear Higgs Factory



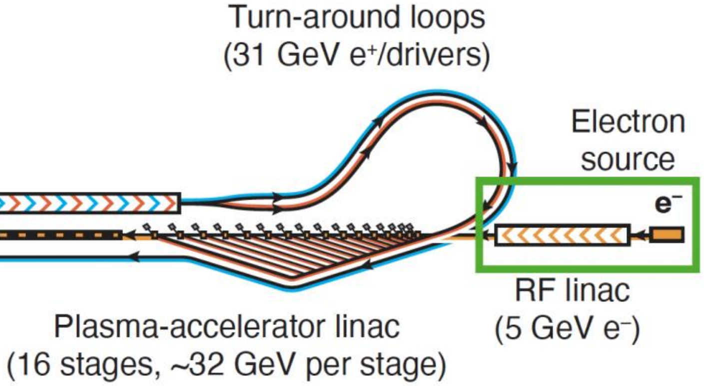
Source: Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)

- 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



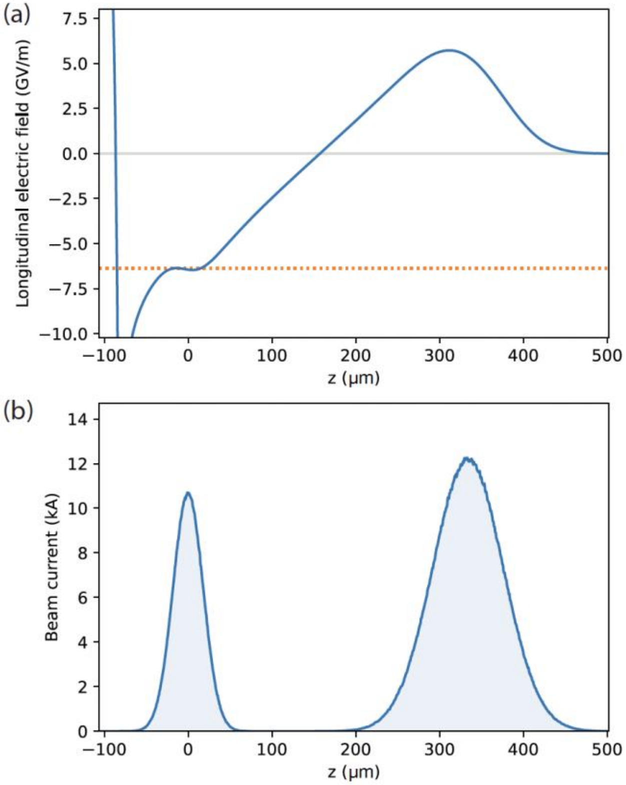
The novelty: **A multistage plasma-based linac**

- 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

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 (EuPRAXIA)**

LPAW 2025 – Ischia Island

Funded by the European Union

LPAW 2025

Laser and Plasma Accelerators Workshop 2025

14-18 April 2025, Ischia Island, Italy

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

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

The Laser and Plasma Accelerators Workshop (LPAW) series is one of the leading workshops in the field of plasma-based acceleration and radiation generation.

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

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

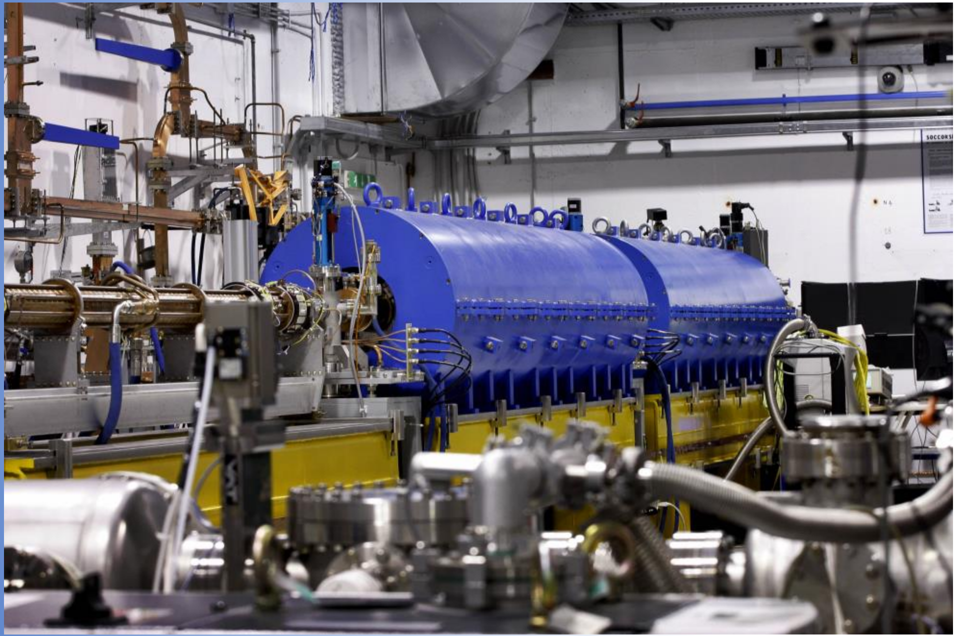
John Dawson Thesis Prize

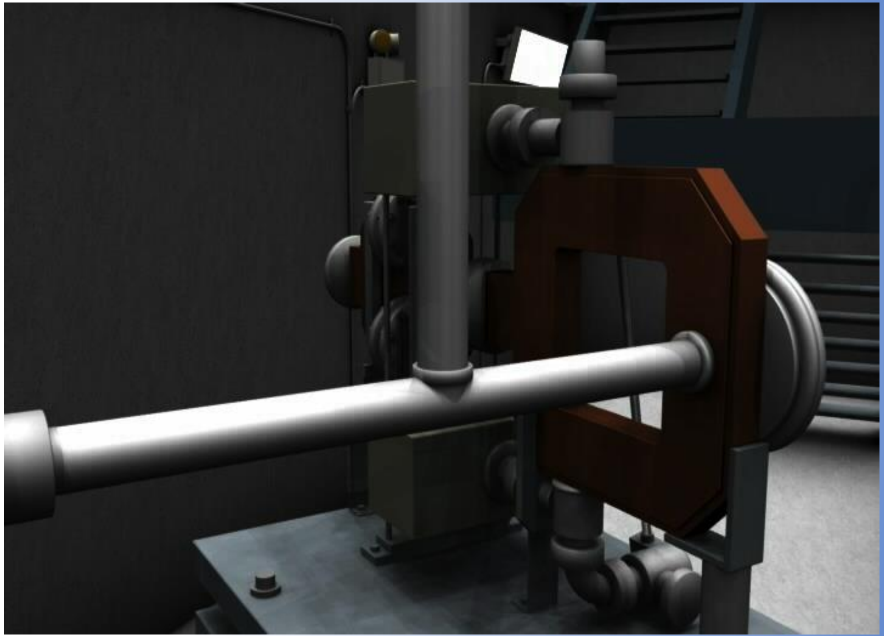
“John Dawson Thesis Prize” is awarded on a biannual basis to the best PhD thesis in the area of plasma accelerators driven by laser or particle beams. The prize will be awarded for fundamental (theoretical or experimental) or applied aspects.

Each prize winner will receive a certificate of merit, up to 500 Euros, and financial support to attend the “Laser and Plasma Accelerators Workshop,” where the prize will be awarded.

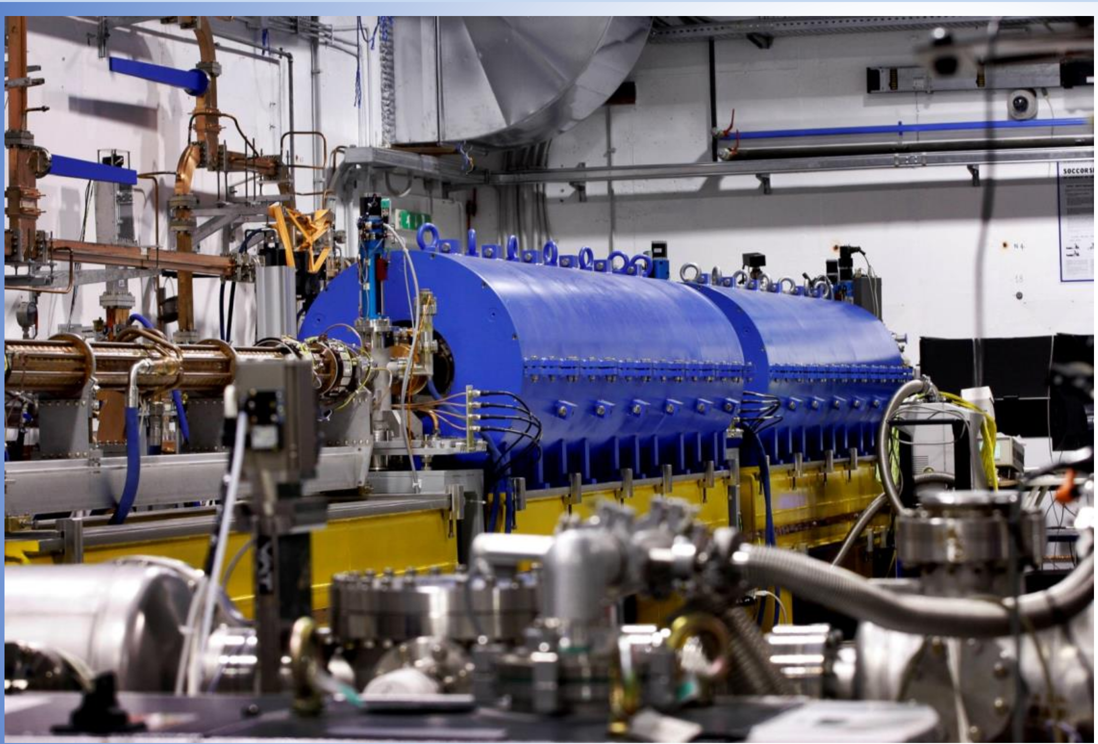
Thank for your attention

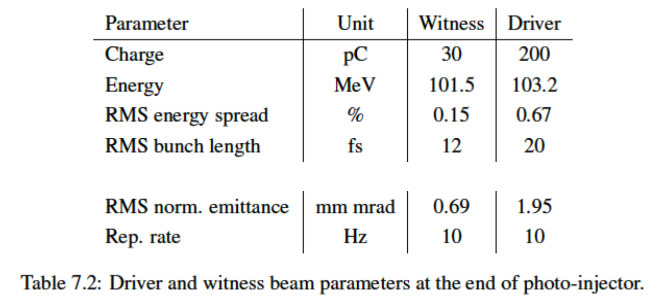
High Brightness Photo-injector with Velocity Bunching





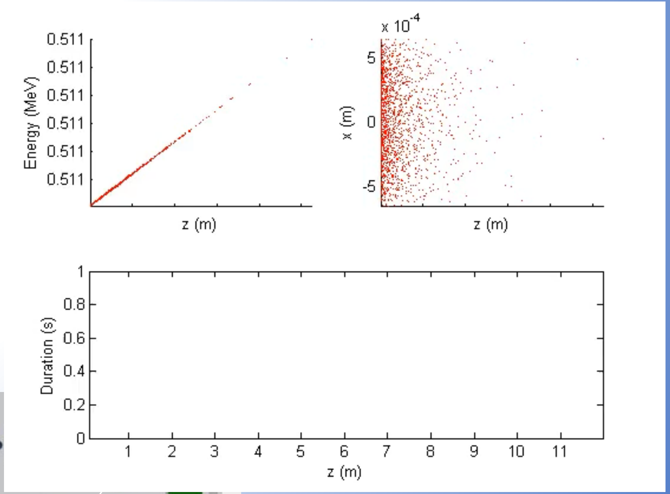
High Quality Electron Beams





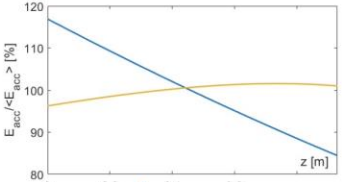
Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

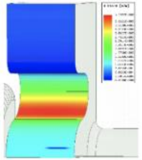
Table 7.2: Driver and witness beam parameters at the end of photo-injector.



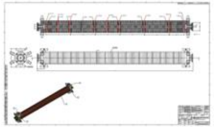
Courtesy E. Chiadroni

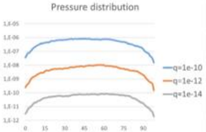
World`s Most Compact RF Linac: X Band

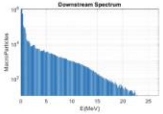




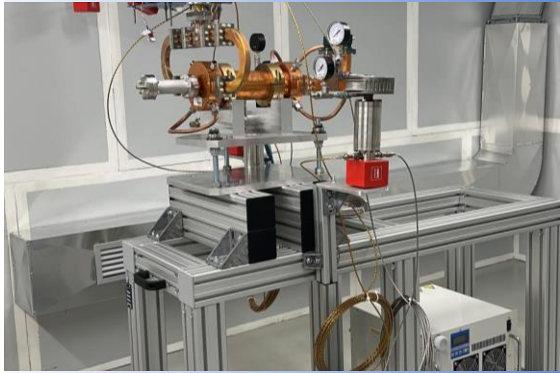
1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*

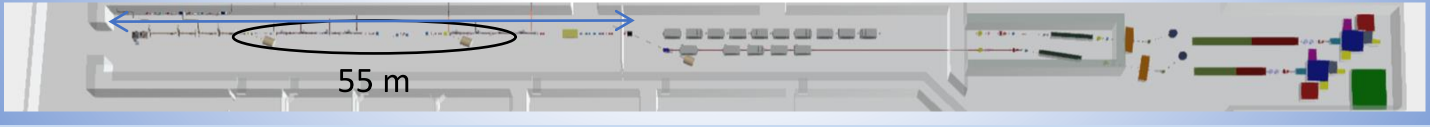






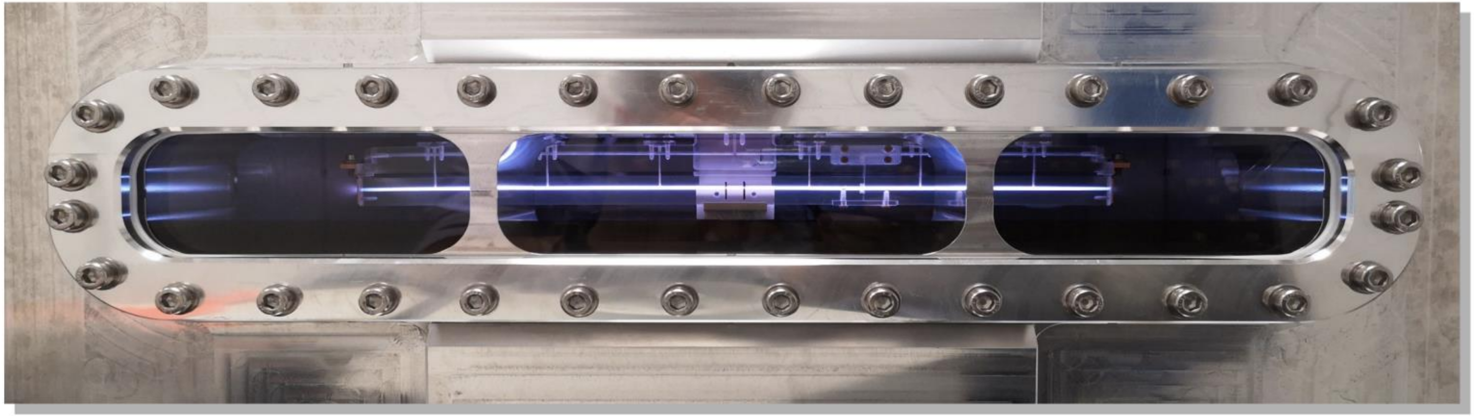
PARAMETER	Value with linear tapering	 w/o tapering
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85-3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length (flange-to-flange) [m]	**0.94 (1.05)**	
No. of cells	112	
Shunt impedance R [MΩ/m]	93-107	100
Effective shunt Imp. $R_{sh\ eff}$ [MΩ/m]	350	347
Peak input power per structure [MW]	70	
Input power averaged over the pulse [MW]	51	
Average dissipated power [kW]	1	
P_{out}/P_{in} [%]	25	
Filling time [ns]	130	
Peak Modified Poynting Vector [W/μm²]	3.6	4.3
Peak surface electric field [MV/m]	160	190
Unloaded SLED/BOC Q-factor Q_0	150000	
External SLED/BOC Q-factor Q_E	21300	20700
Required Kly power per module [MW]	**20**	
RF pulse [μs]	**1.5**	
Rep. Rate [Hz]	**100**	





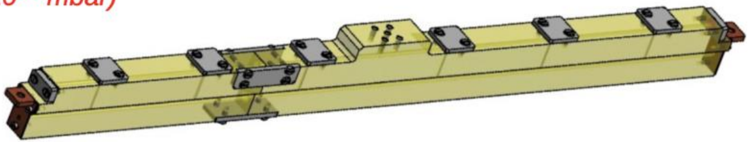
Courtesy D. Alesini

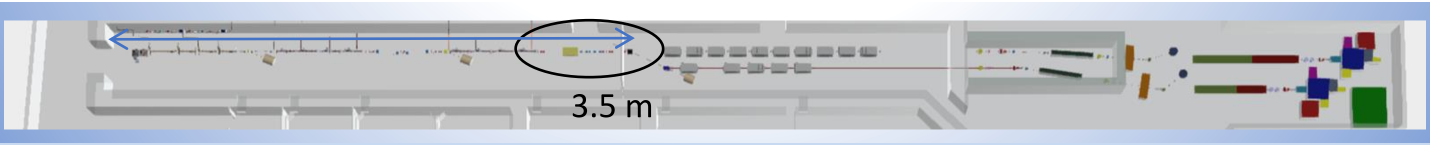
Plasma Module



A. Biagioni, V. Lollo

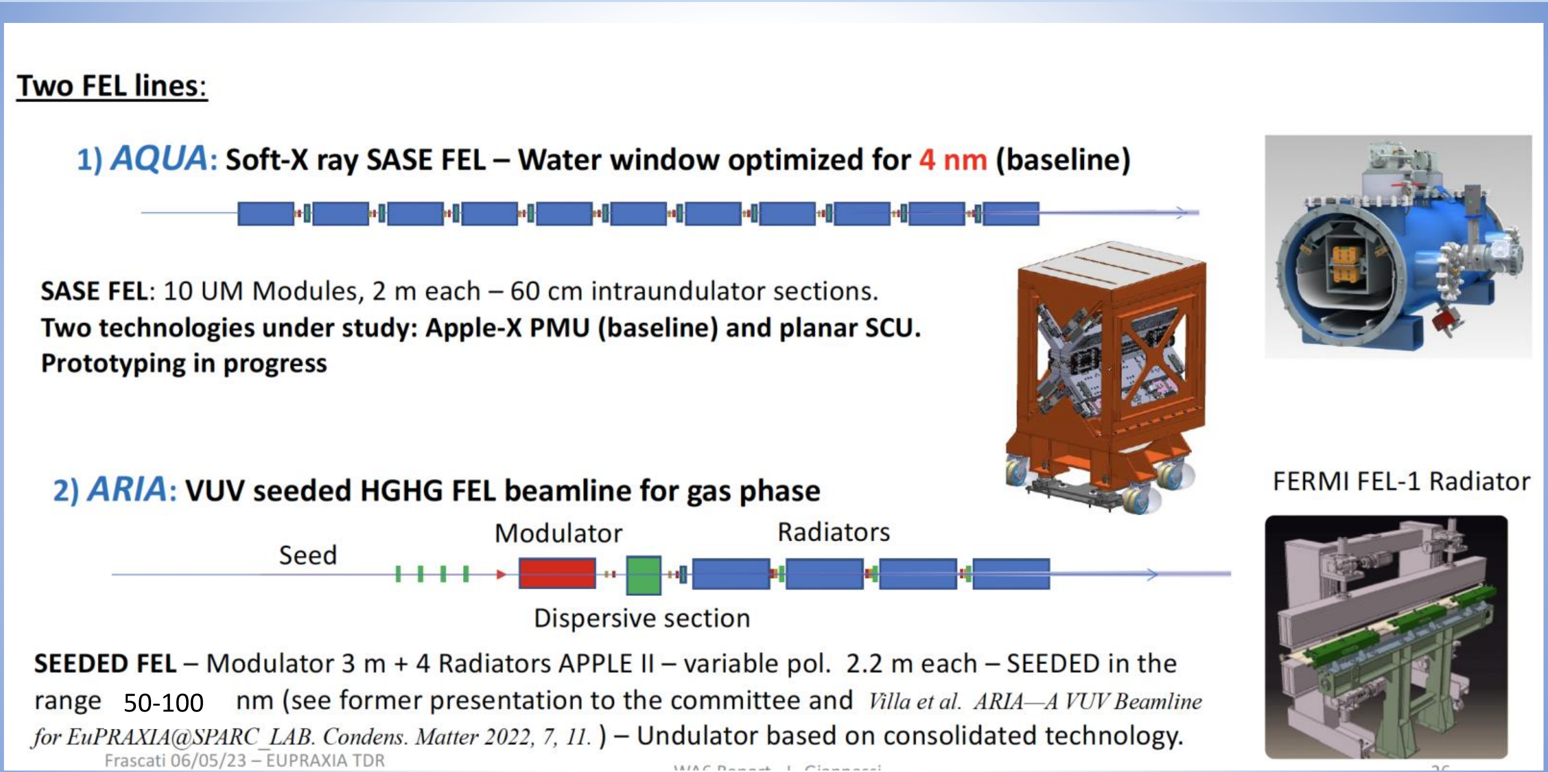
- 40 cm long capillary → 1^{st} prototype for the EuPRAXIA facility
  - *Made with special junction to allow negligible gas leaks ($<10^{-10}$ mbar)*
- Operating conditions
  - *1 Hz repetition rate (to be increased up to 100 Hz)*
  - *10 kV – 380 A minimum values for ionization*
  - *6 inlets for gas injection. Electro-valve aperture time 8-12 ms*





Courtesy A. Biagioni, R. Pompili

Radiation Generation: FEL



Two FEL lines:

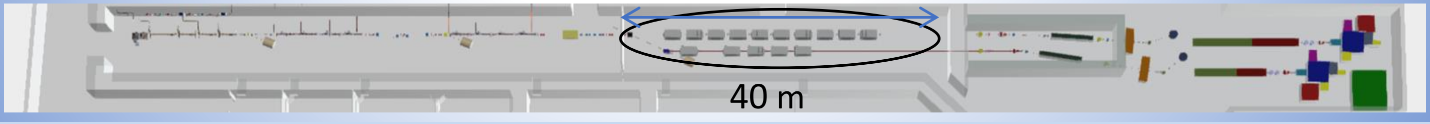
1) ***AQUA*: Soft-X ray SASE FEL – Water window optimized for 4 nm (baseline)**

SASE FEL: 10 UM Modules, 2 m each – 60 cm intraundulator sections.
Two technologies under study: Apple-X PMU (baseline) and planar SCU.
Prototyping in progress

2) ***ARIA*: VUV seeded HGHG FEL beamline for gas phase**

FERMI FEL-1 Radiator

SEEDED FEL – Modulator 3 m + 4 Radiators APPLE II – variable pol. 2.2 m each – SEEDED in the range 50-100 nm (see former presentation to the committee and *Villa et al. ARIA—A VUV Beamline for EuPRAXIA@SPARC_LAB. Condens. Matter 2022, 7, 11.*) – Undulator based on consolidated technology.



Courtesy L. Giannessi

Principle of plasma acceleration

Driven by Radiation Pressure

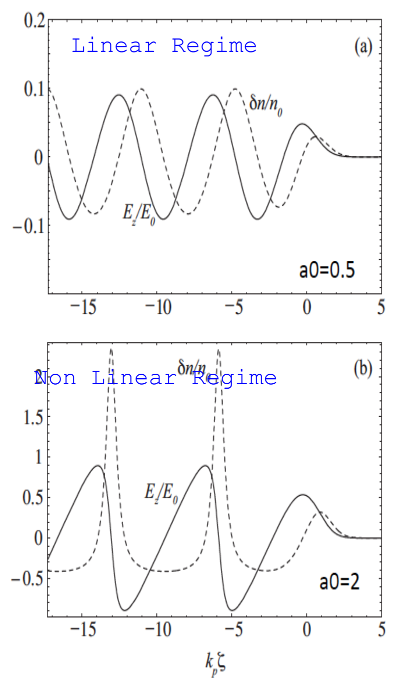
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=c^2\nabla^2\frac{a^2}{2}$$

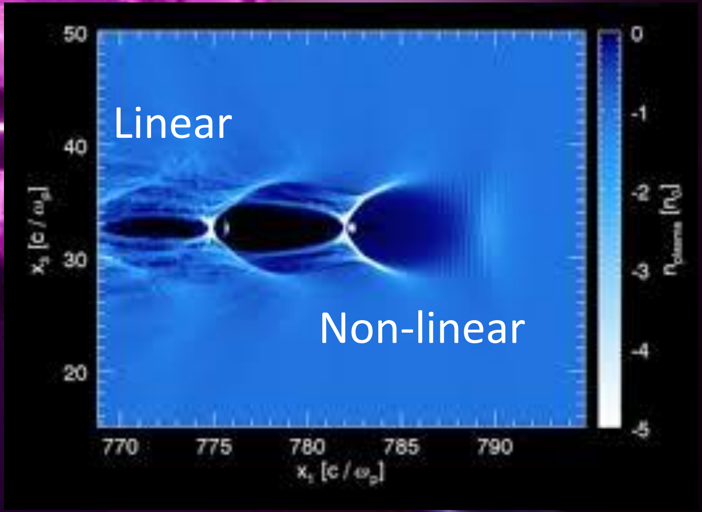
$$a=\frac{eA}{mc^2}\propto\lambda J^{1/2}$$

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