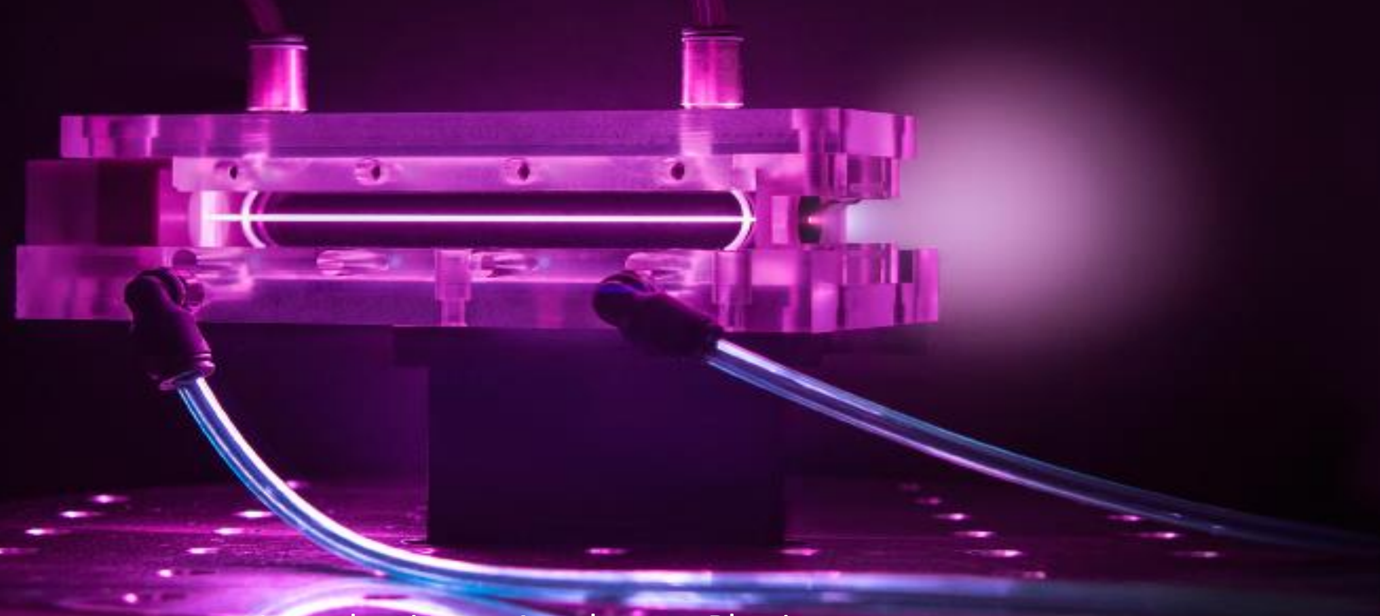
Advanced Accelerator Concepts II

Massimo.Ferrario@lnf.infn.it

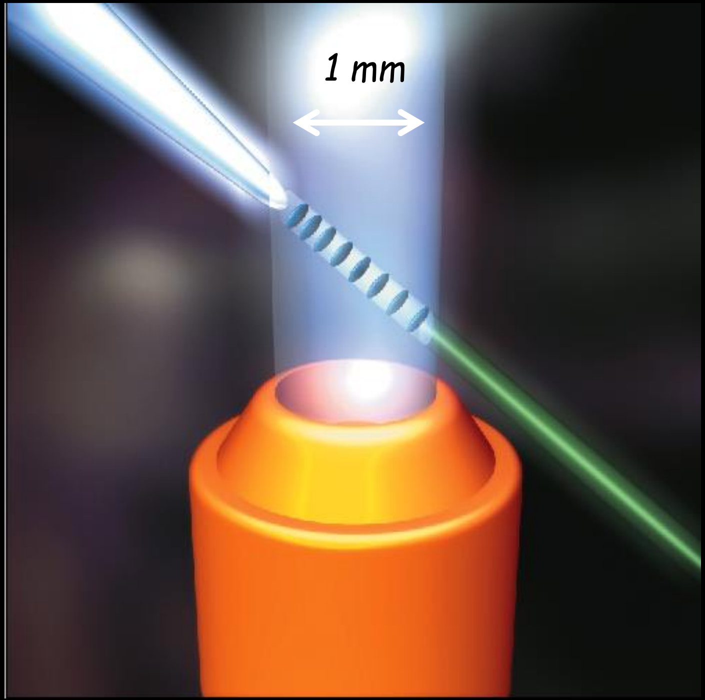


The CERN Accelerator School

Introduction to Accelerator Physics

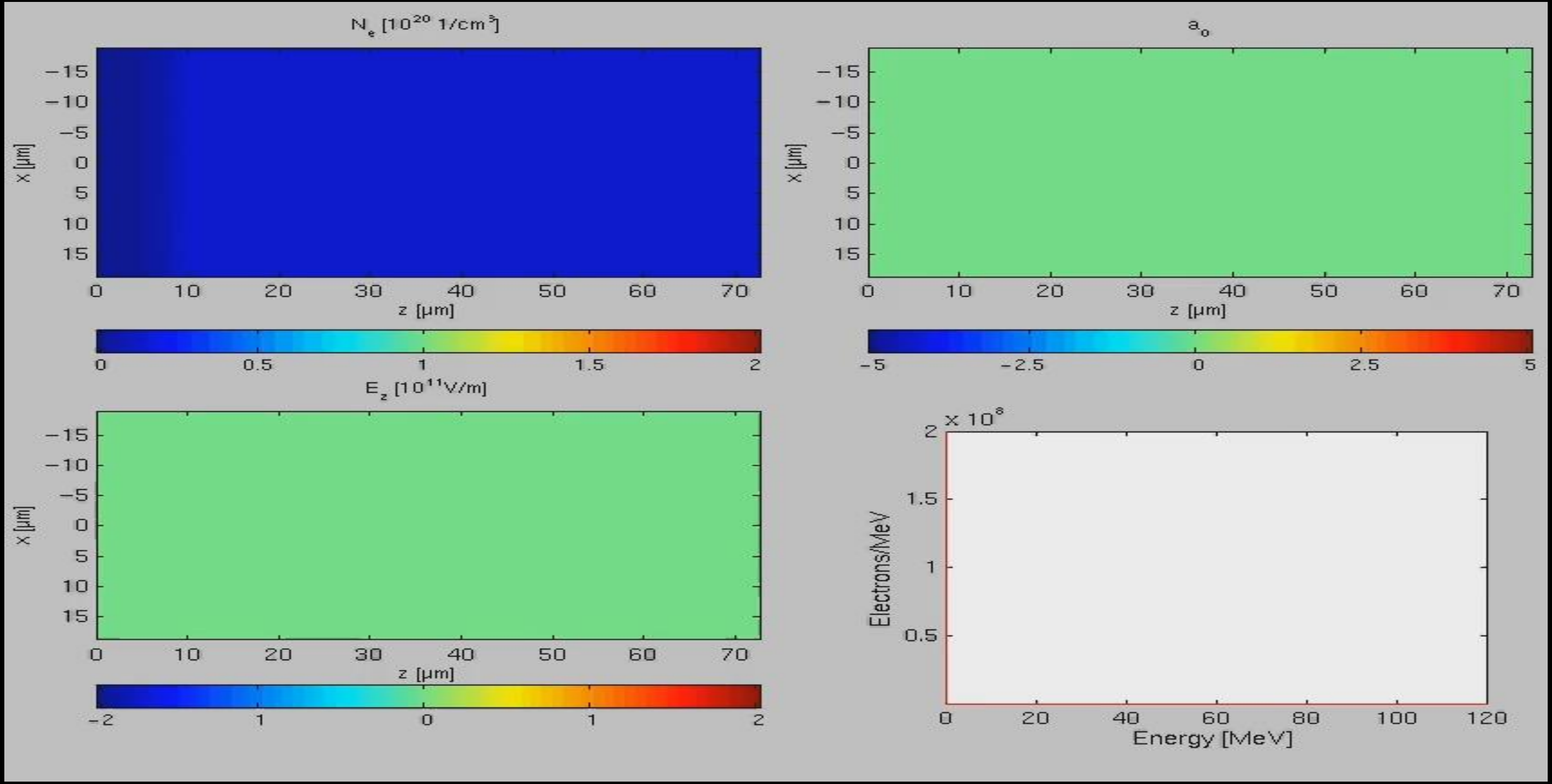
S. Susanna – 2 October 2024

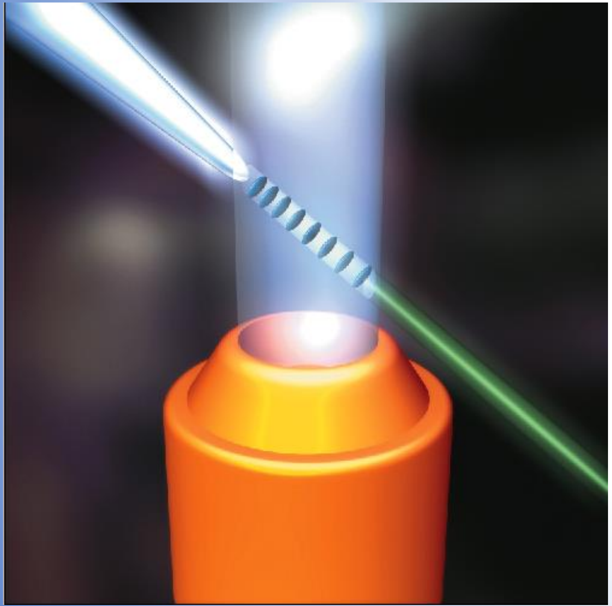
Direct production of e-beam



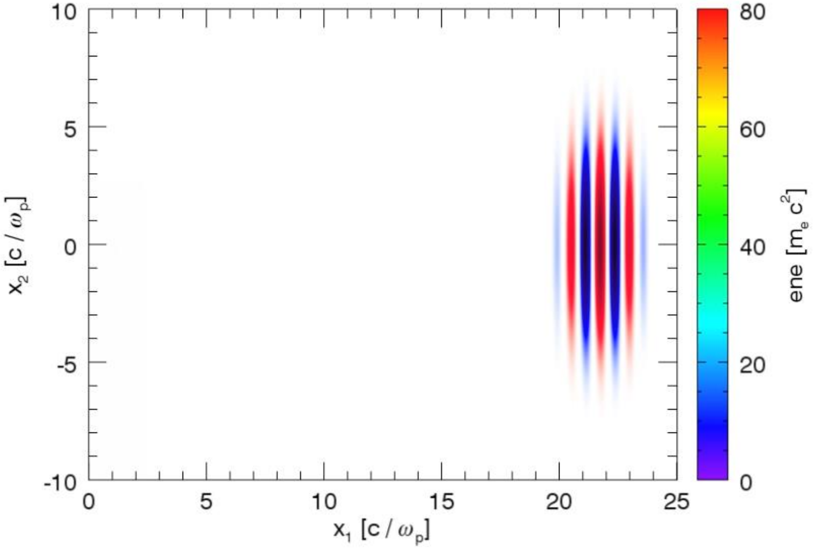
Electron beam

Diffraction - Self injection - Dephasing – Depletion





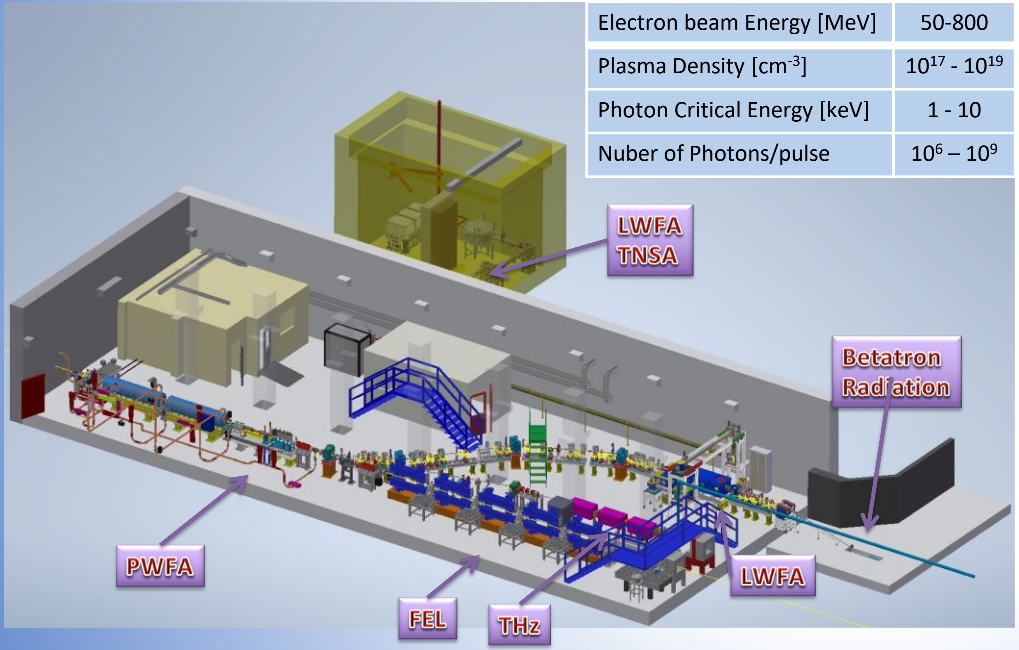
Example: a0 = 5; laser spot-size: 3 microns; laser duration: 12fs; plasma density = 6x10^19.



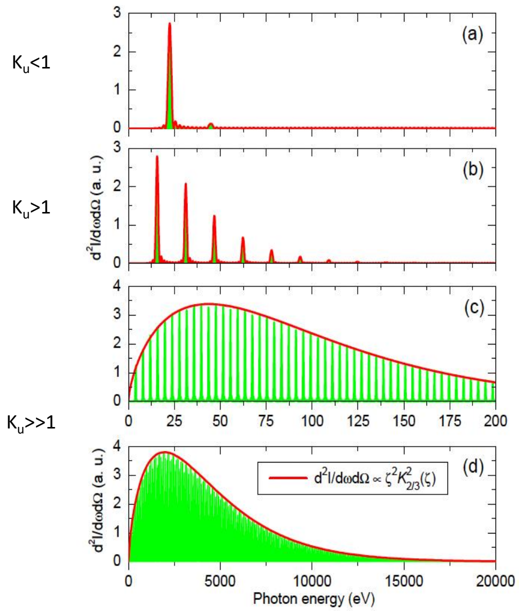
Courtesy J. Vieira, R. Fonseca/GoLP/IST Lisbon

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



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

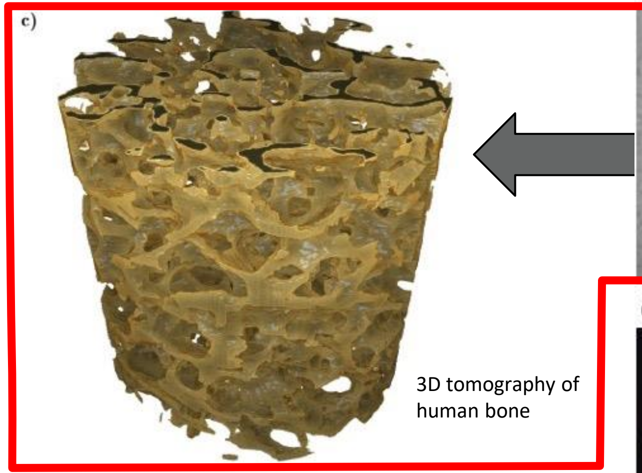
$$N_{ph} \propto N_e N_\beta K_u$$

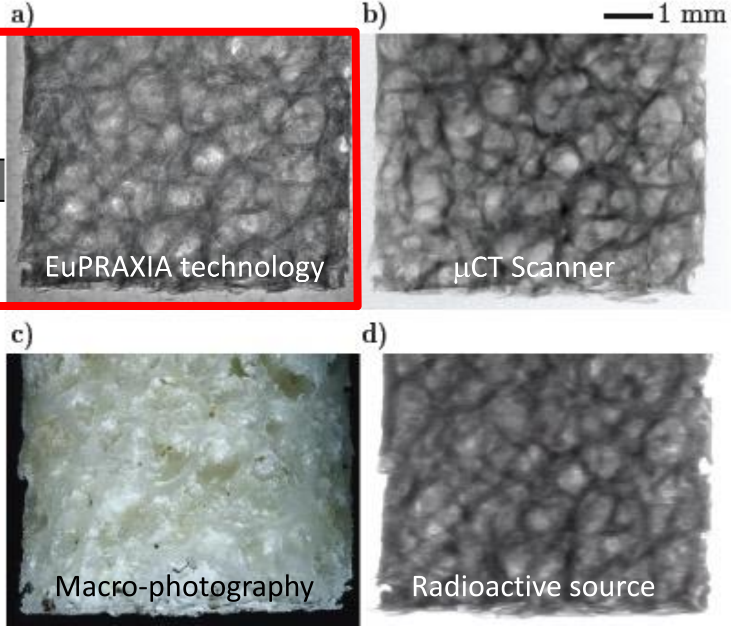
Figure 3.3: *Calculated betatron radiation spectra in a plasma column with density of 7×10^{18} cm^{-3}. The electron energy is 15 MeV, and oscillation amplitudes are (a) 0.1 μm, (b) 0.5 μm, and (c) 1.6 μm. (d) shows the case of a 100 MeV electron with an oscillation amplitude of 1.6 μm.*

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)

Plasma collider challenges

Beam delivery system

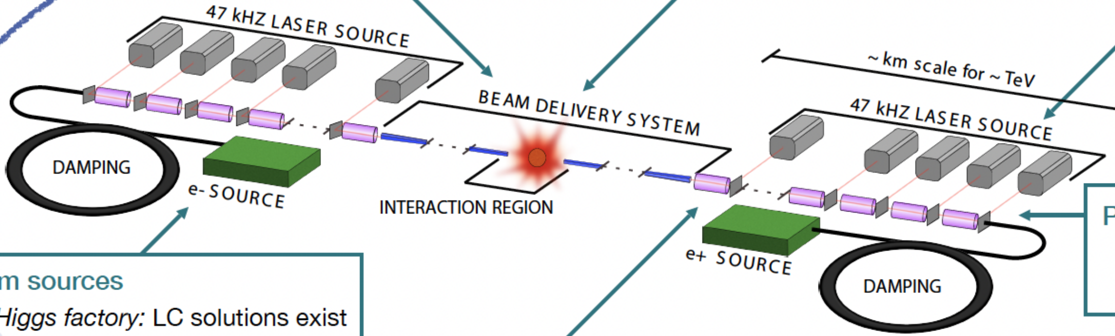
- *Higgs factory:* optimized LC designs exist
  optimizations for plasmas needed/possible?
- *10 TeV collider:* no design exists
  critical - HF designs scale poorly with energy (geo. gradient) → 20 (CLIC) to 90 (ILC) km

Interaction region

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

Driver technology

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



Positron acceleration

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

Beam sources

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

Plasma stages + coupling

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

Full system integration

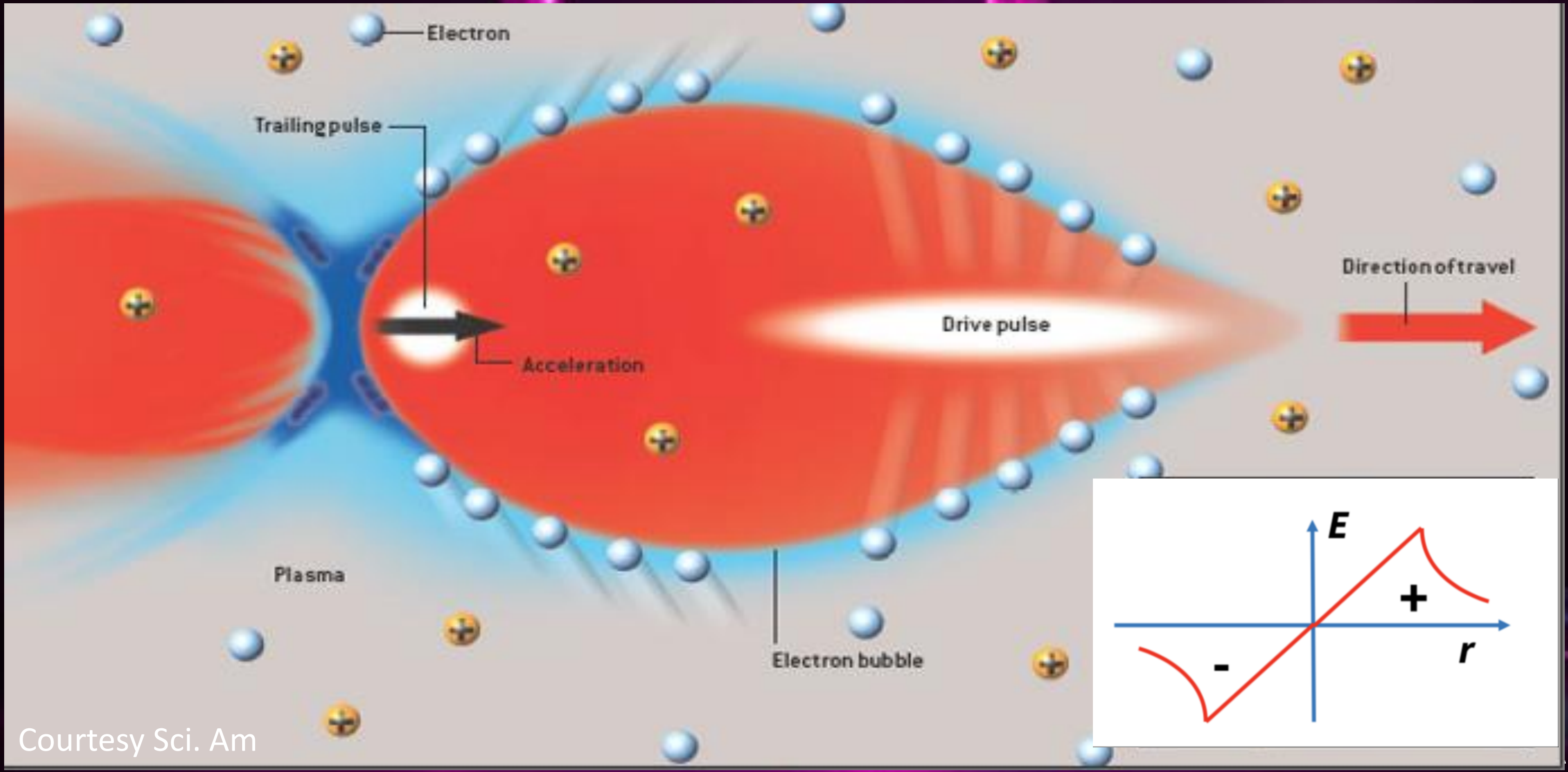
- Turn components into self-consistent machine
- Optimization of the system for cost, efficiency, environmental impact, physics performance, resiliency (jitter budget)

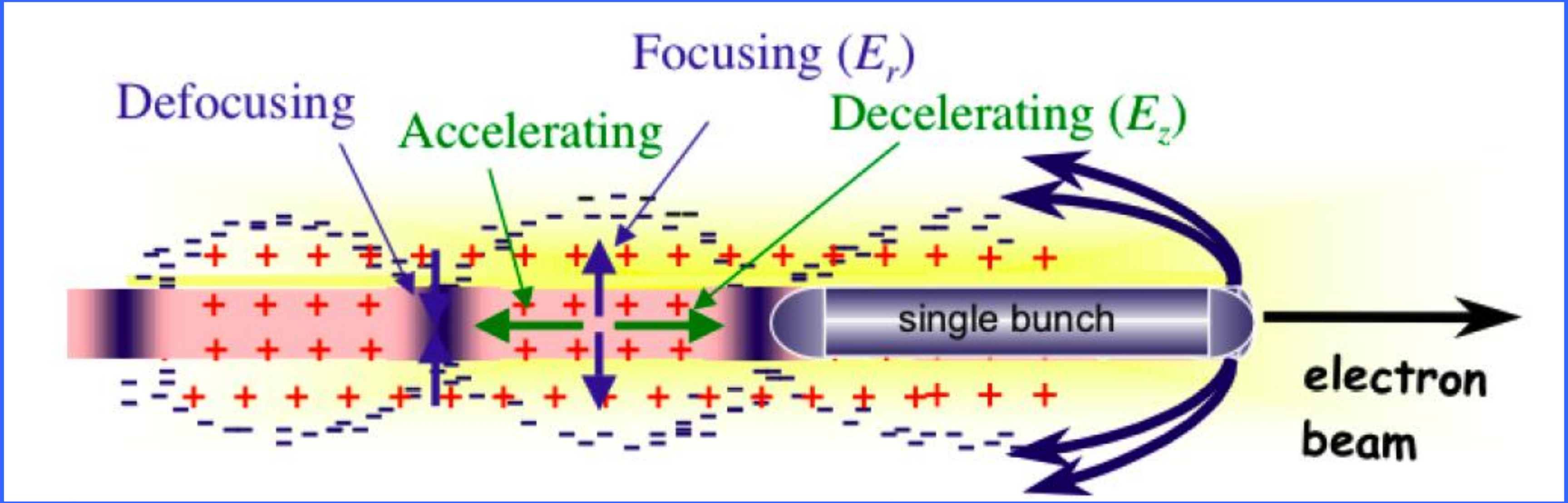
BERKELEY LAB

Courtesy J. Osterhoff

Beam Driven
PWFA

Principle of plasma acceleration




Focusing (E_r)
Defocusing
Accelerating
Decelerating (E_z)
single bunch
electron
beam

Beam Driven - Results

PRL 95, 054802 (2005) PHYSICAL REVIEW LETTERS week ending 29 JULY 2005

Multi-GeV Energy Gain in a Plasma-Wakefield Accelerator

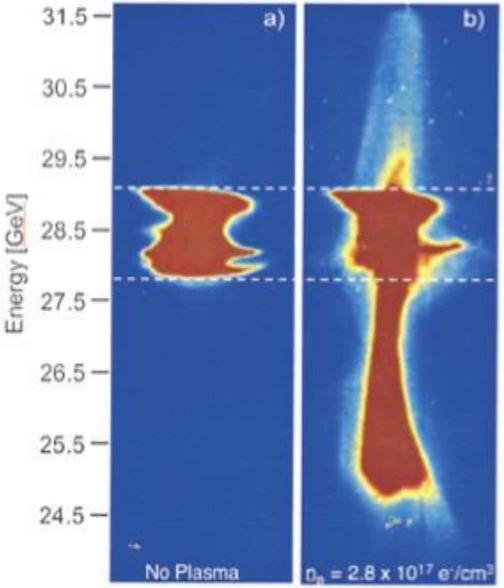
M. J. Hogan,[1] C. D. Barnes,[1] C. E. Clayton,[2] F. J. Decker,[1] S. Deng,[3] P. Emma,[1] C. Huang,[2] R. H. Iverson,[1] D. K. Johnson,[2] C. Joshi,[2] T. Katsouleas,[3] P. Krejcik,[1] W. Lu,[2] K. A. Marsh,[2] W. B. Mori,[2] P. Muggli,[3] C. L. O'Connell,[1] E. Oz,[3] R. H. Siemann,[1] and D. Walz[1]

Vol 445 | 15 February 2007 | doi:10.1038/nature05538 nature

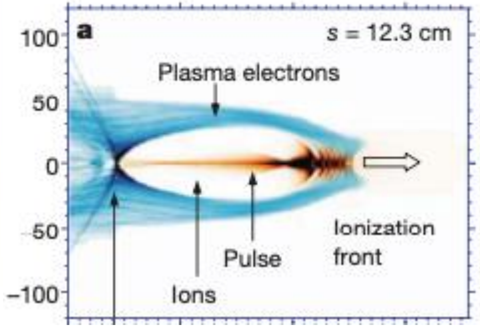
LETTERS

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

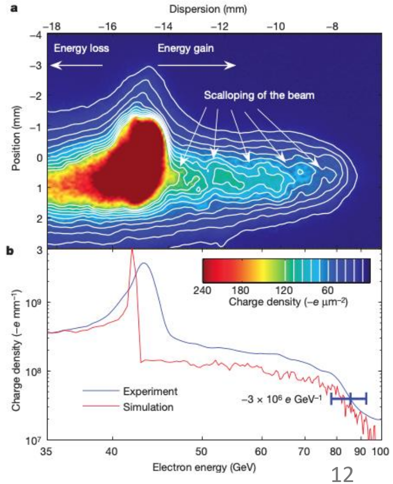
Ian Blumenfeld[1], Christopher E. Clayton[2], Franz-Josef Decker[1], Mark J. Hogan[1], Chengkun Huang[2], Rasmus Ischebeck[1], Richard Iverson[1], Chandrashekhar Joshi[2], Thomas Katsouleas[3], Neil Kirby[1], Wei Lu[2], Kenneth A. Marsh[2], Warren B. Mori[2], Patric Muggli[3], Erdem Oz[3], Robert H. Siemann[1], Dieter Walz[1] & Miaomiao Zhou[2]

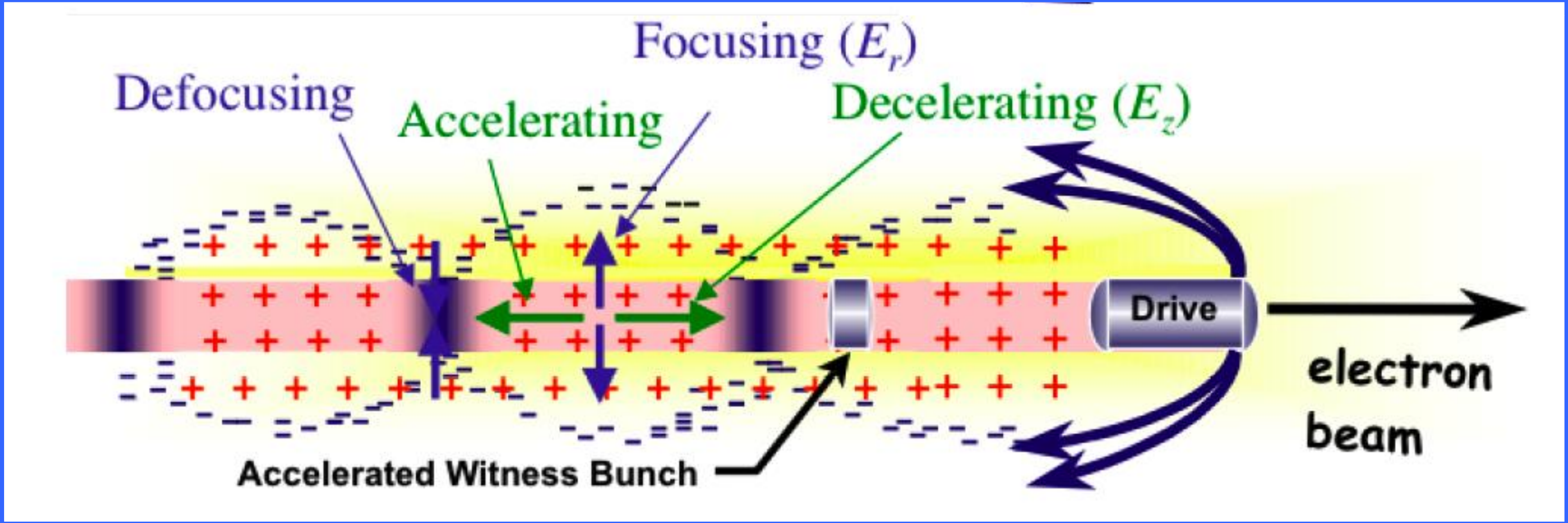


~ 2.7 GeV in 10 cm
$n_{pe} = 2.8 \times 10^{17}$ cm^{-3}



~ 42 GeV in 85 cm
$n_{pe} = 2.8 \times 10^{17}$ cm^{-3}



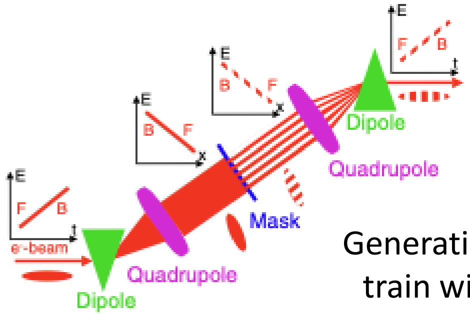

Focusing (E_r)
Defocusing
Accelerating
Decelerating (E_z)
Drive
electron
beam
Accelerated Witness Bunch

Beam Driven - Results

PRL 101, 054801 (2008) PHYSICAL REVIEW LETTERS week ending 1 AUGUST 2008

Generation of Trains of Electron Microbunches with Adjustable Subpicosecond Spacing

P. Muggli,[1] V. Yakimenko,[2] M. Babzien,[2] E. Kallos,[1] and K. P. Kusche[2]
[1]*University of Southern California, Los Angeles, California 90089, USA*
[2]*Brookhaven National Laboratory, Upton, Long Island, New York 11973, USA*
(Received 25 December 2007; published 29 July 2008)



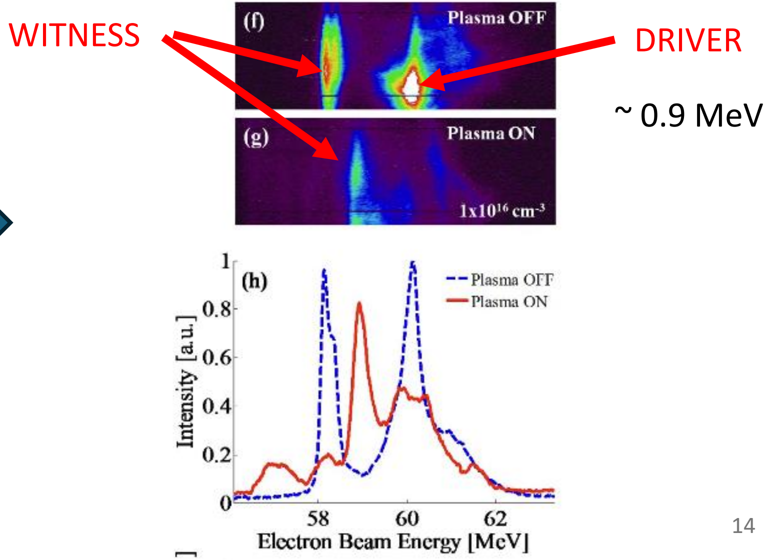
Generation of bunch train with mask in dispersive section (and chirped bunch)

then

PRL 100, 074802 (2008) PHYSICAL REVIEW LETTERS week ending 22 FEBRUARY 2008

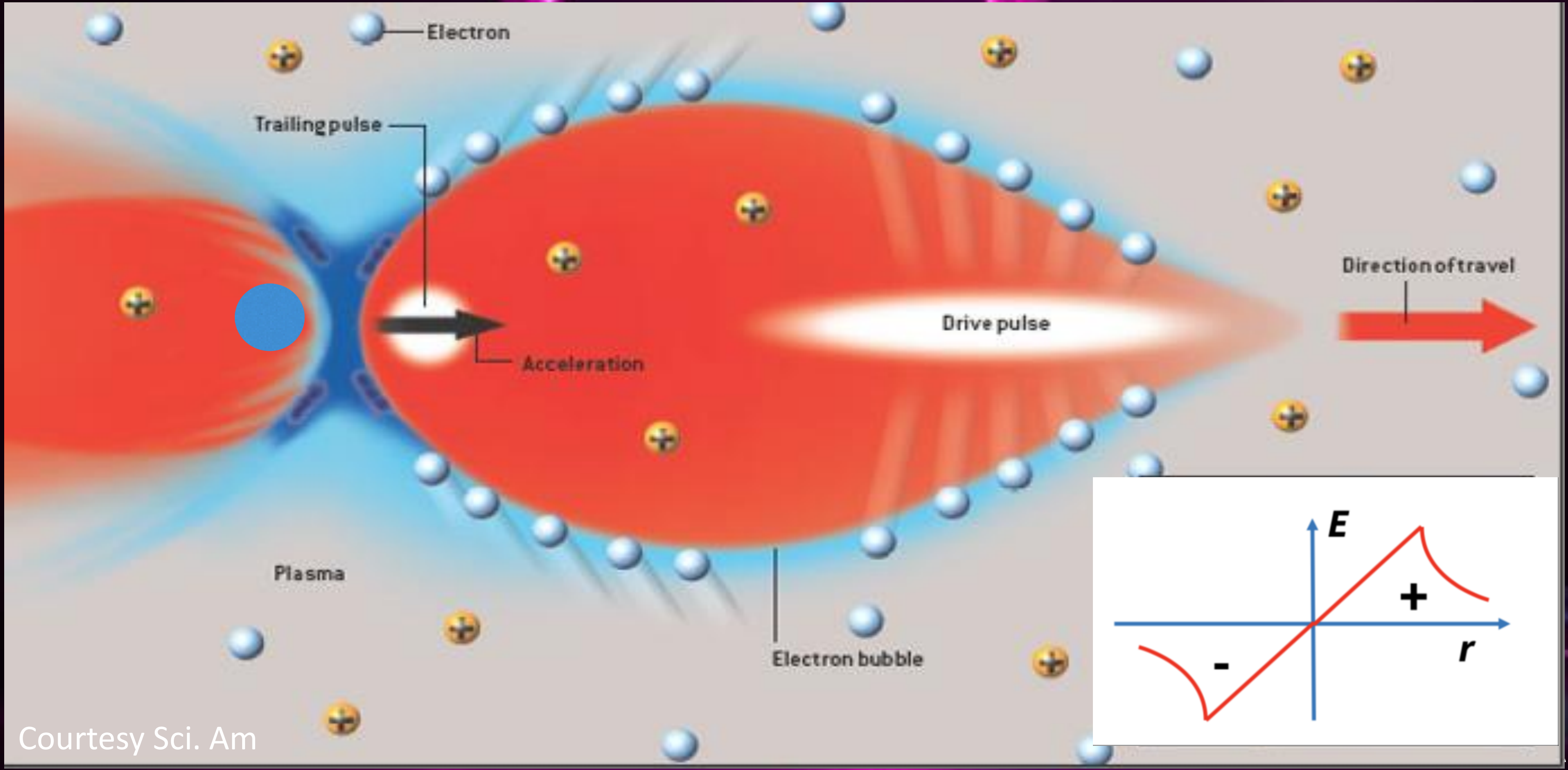
High-Gradient Plasma-Wakefield Acceleration with Two Subpicosecond Electron Bunches

Efthymios Kallos,[1] Tom Katsouleas,[1] Wayne D. Kimura,[2] Karl Kusche,[3] Patric Muggli,[1] Igor Pavlishin,[3] Igor Pogorelsky,[3] Daniil Stolyarov,[3] and Vitaly Yakimenko[3]



~ 0.9 MeV in 6 mm

Positron acceleration?



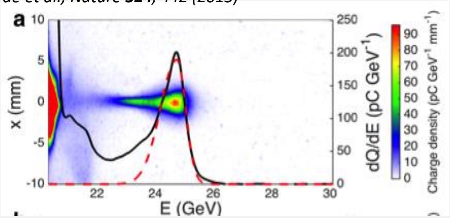
Positron Acceleration, FACET

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)*

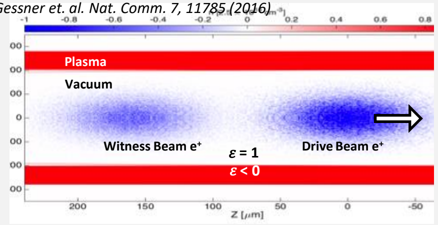


High-density, compressed positron beam for non-linear PWFA experiments. Energy transfer from the front to the back part of the bunch.

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

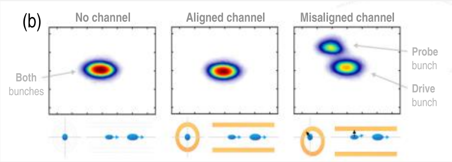
Hollow plasma channel: positron propagation, wake excitation, acceleration in 30 cm channel.

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



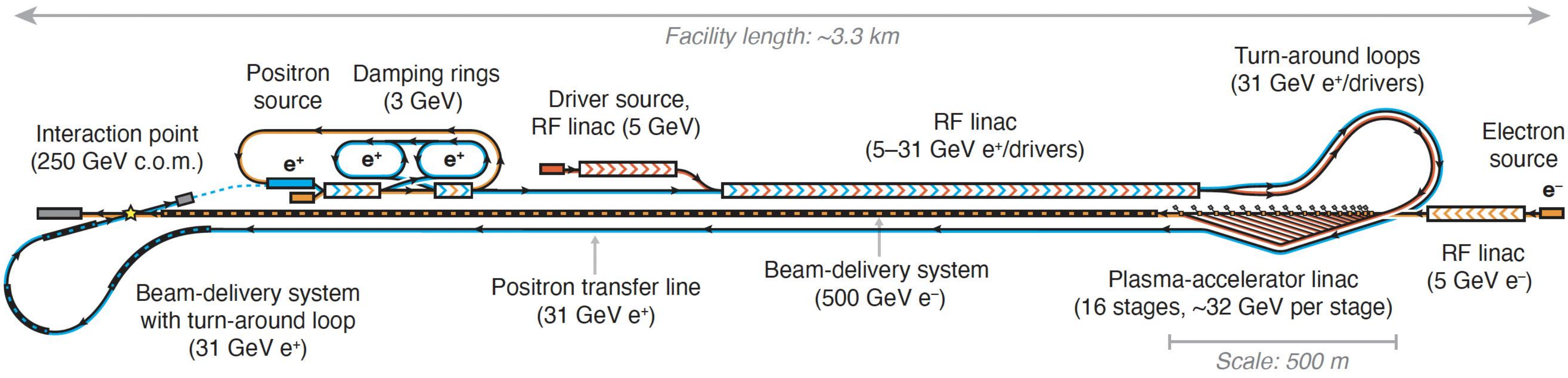
Measurement of **transverse wakefields in a hollow plasma** channel due to off-axis drive bunch propagation.

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



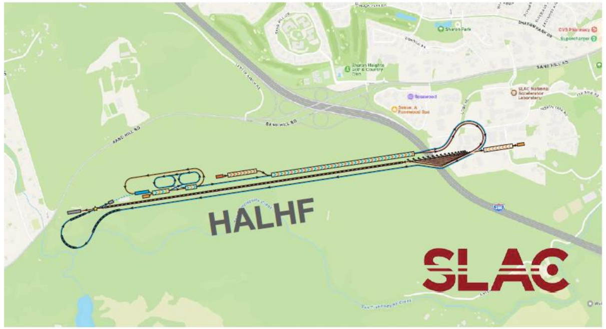
➔ **Emittance blow-up is an issue!** → Use hollow-channel, so no plasma on-axis, no complicated forces from plasma electrons streaming through the plasma → but then strong transverse wakefields when beams are misaligned.

HALHF: A Hybrid, Asymmetric, Linear Higgs Factory



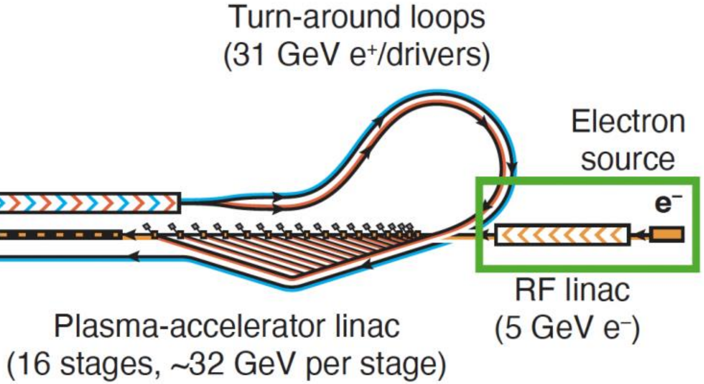
Source: Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)

- 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



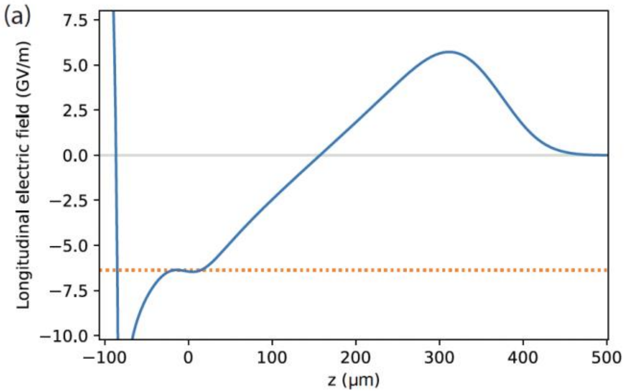
The novelty: **A multistage plasma-based linac**

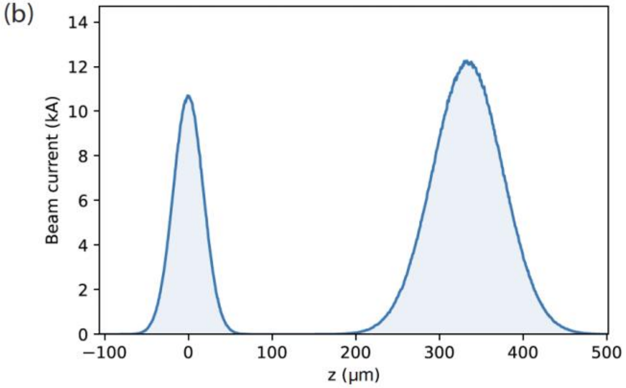
- Length: 16 PWFA stages (5-m long): ~400 m total length
- Gradient: 6.4 GV/m (in plasma) — 1.2 GV/m (average)
- Efficiency: 38% = 72% depletion, 53% wake extraction
- No damping ring required due to high-emittance electrons



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

AWAKE

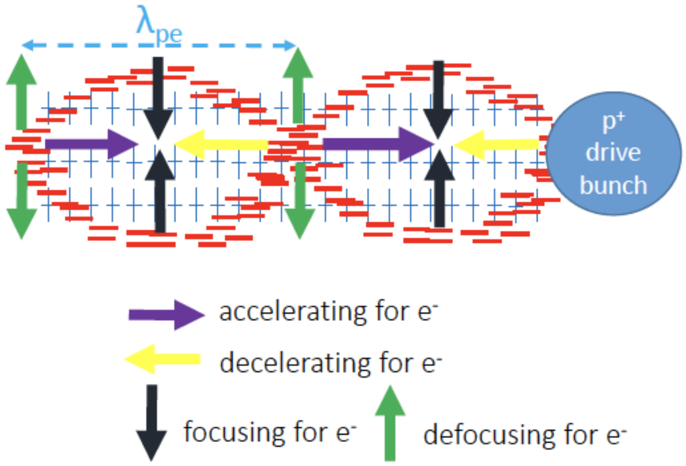
Proton-driven
Plasma Wakefield Acceleration
Collaboration:
Accelerating e^- on the wake of a p^+ bunch

© P. Muggli

Reasons for proton bunch driver

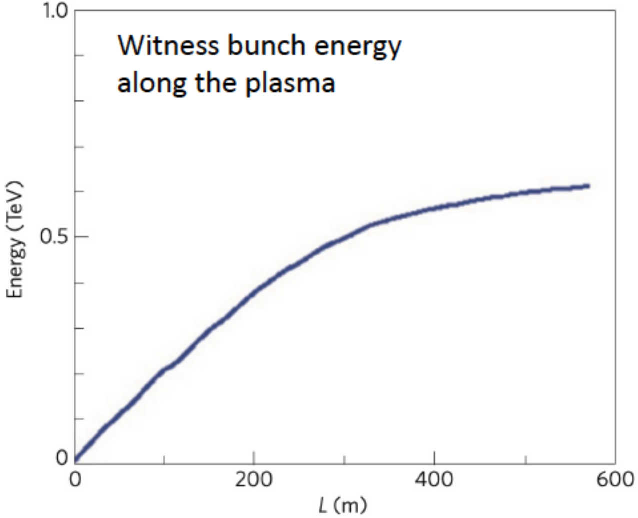
Available proton bunches carry large amounts of energy:

- 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!

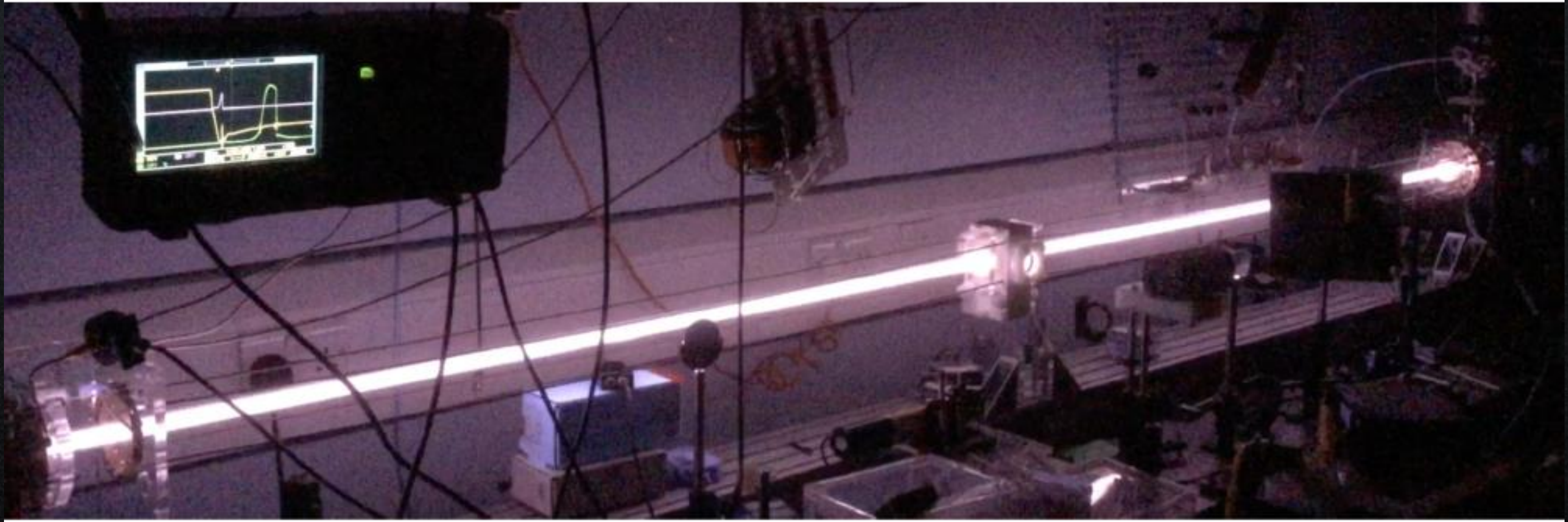
Parameters:
single proton bunch
σ_z = 100 µm,
E = 1 TeV,
population: $1 \cdot 10^{11}$ ppb



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

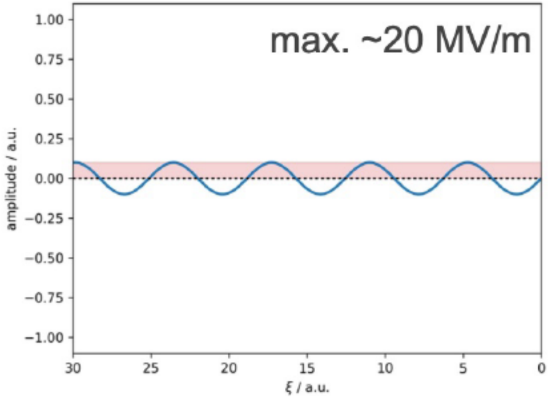
scalability of electric circuit for plasmas > 10 m seem achievable…

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

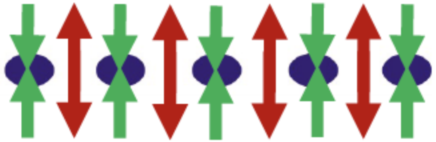
Stronger wakefields

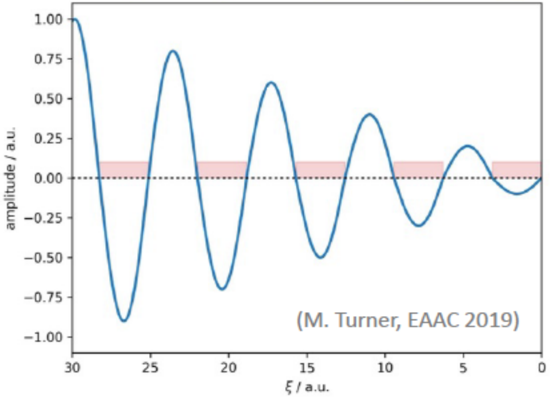
Full modulation

Self-Modulation instability (SMI)

→ resonant wakefield excitation

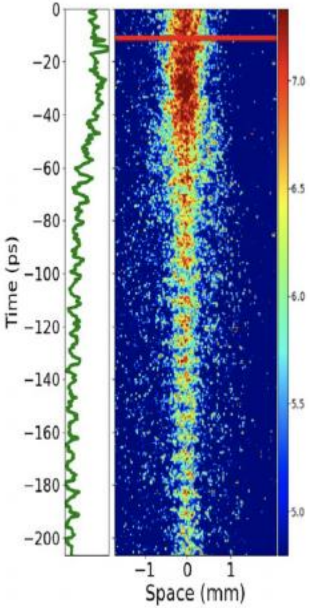
→ phase of the micro-bunch train and of the wakefields VARIES from event to event





N. Kumar et al., Phys. Rev. Lett. 104 (25), 255003 (2010)
A. Pukhov et al., Phys. Rev. Lett. 107 (14), 145003 (2011)

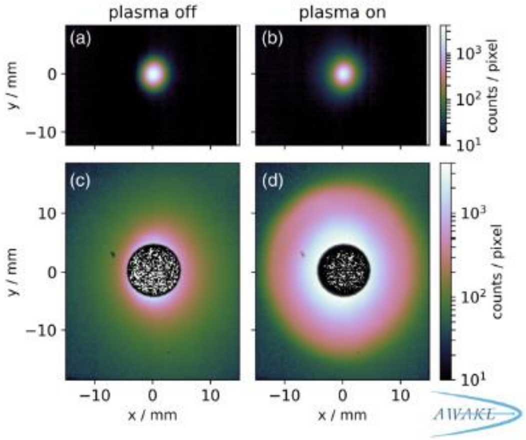
AWAKE Run 1 (2016-2018)



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

time-resolved imaging:

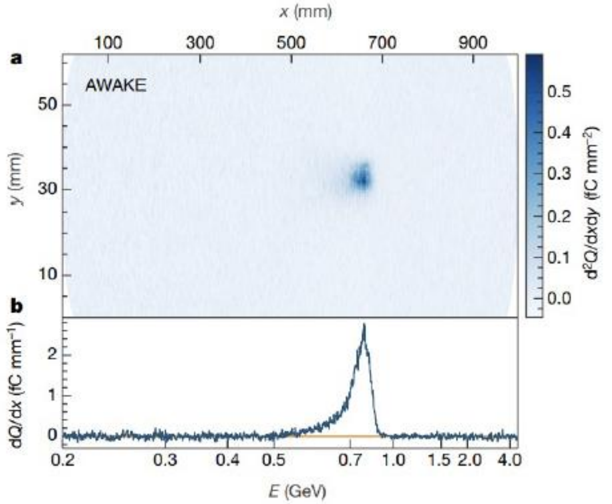
- the proton bunch self-modulates in plasma
- focusing phase → micro-bunches
- frequency of the modulation≈ ω_{pe}



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

time-integrated, transverse imaging:

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

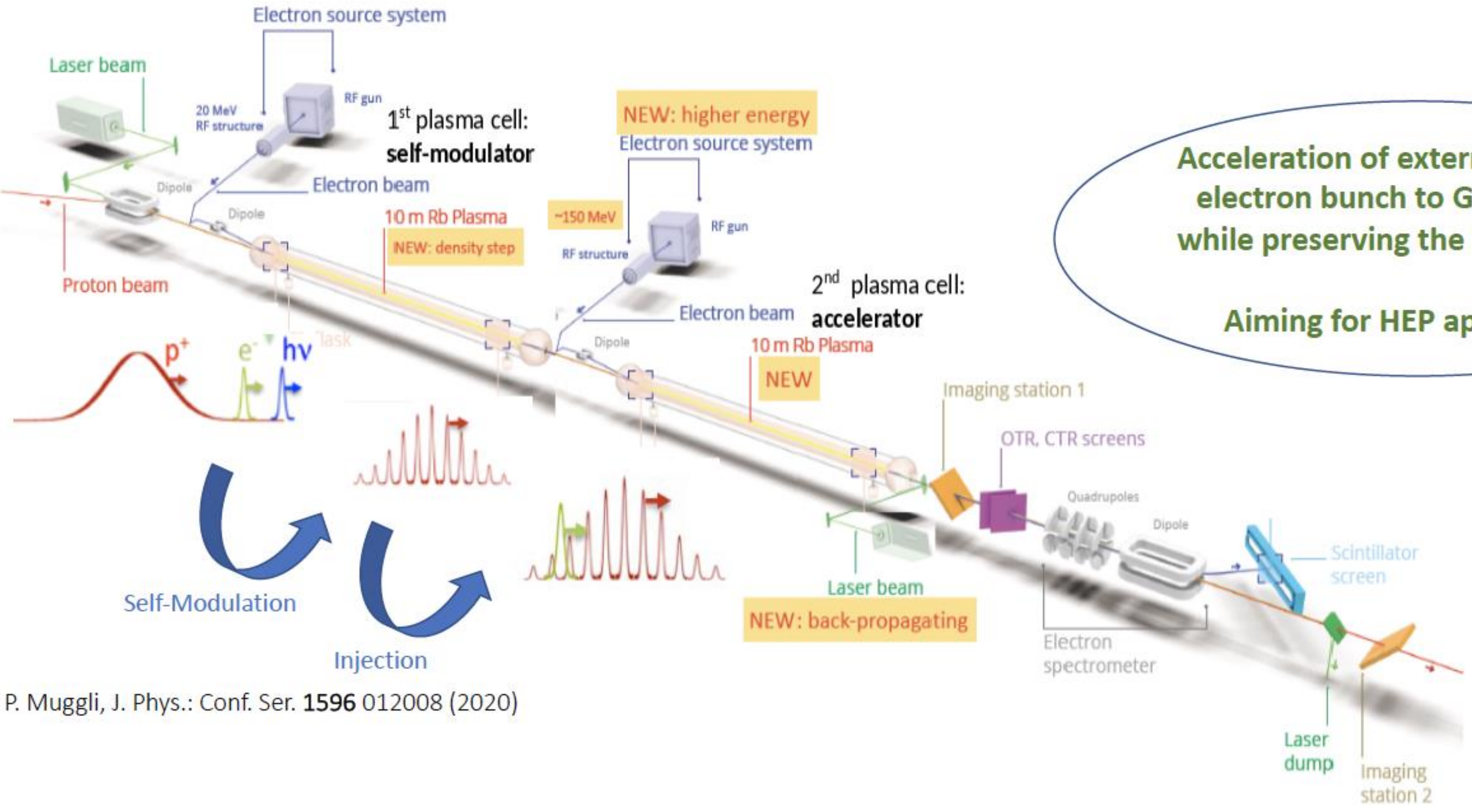


AWAKE Coll., Nature 561, 363-367 (2018)

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

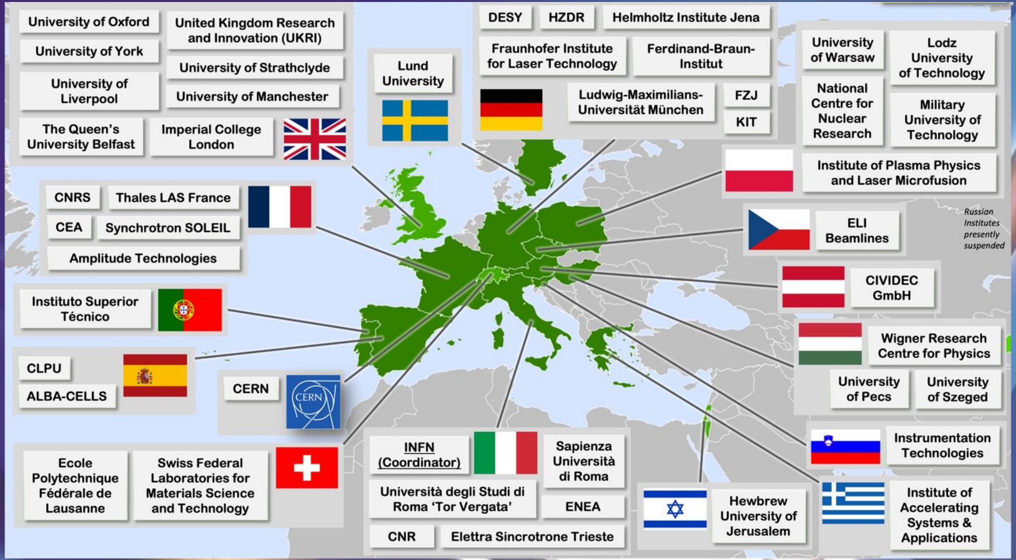
Aiming for HEP application!

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

The near future

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

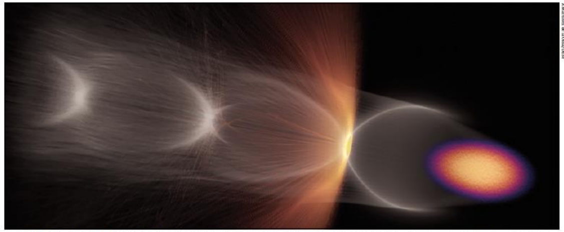
Shrink down the facility size
Improve Sustainability

2

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

Drive short wavelength FEL
Pave the way for future Linear Colliders

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



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.

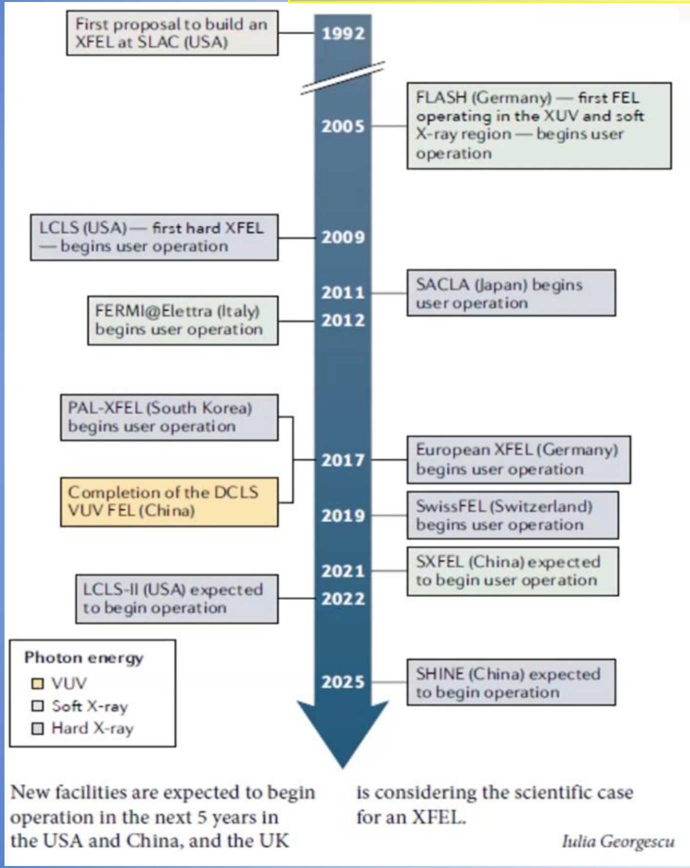
This scientific success story has been made possible through a continuous cycle of innovation in the physics and technology of particle accelerators, driven for many decades by exploratory research in nuclear and particle physics. The invention of radio-frequency (RF) technology in the 1920s opened the 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.*

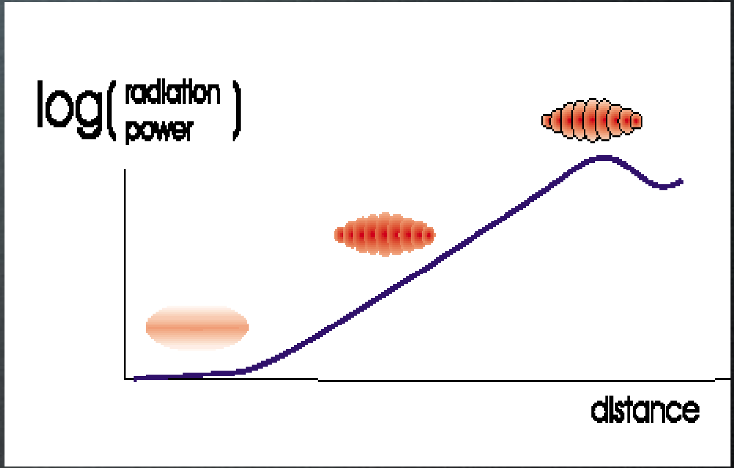
FEL is a well established technology

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



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

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)

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: $\sigma_\gamma < \frac{1}{2}\rho_{fel}$

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

Low emittances
Low energy spread
High current

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

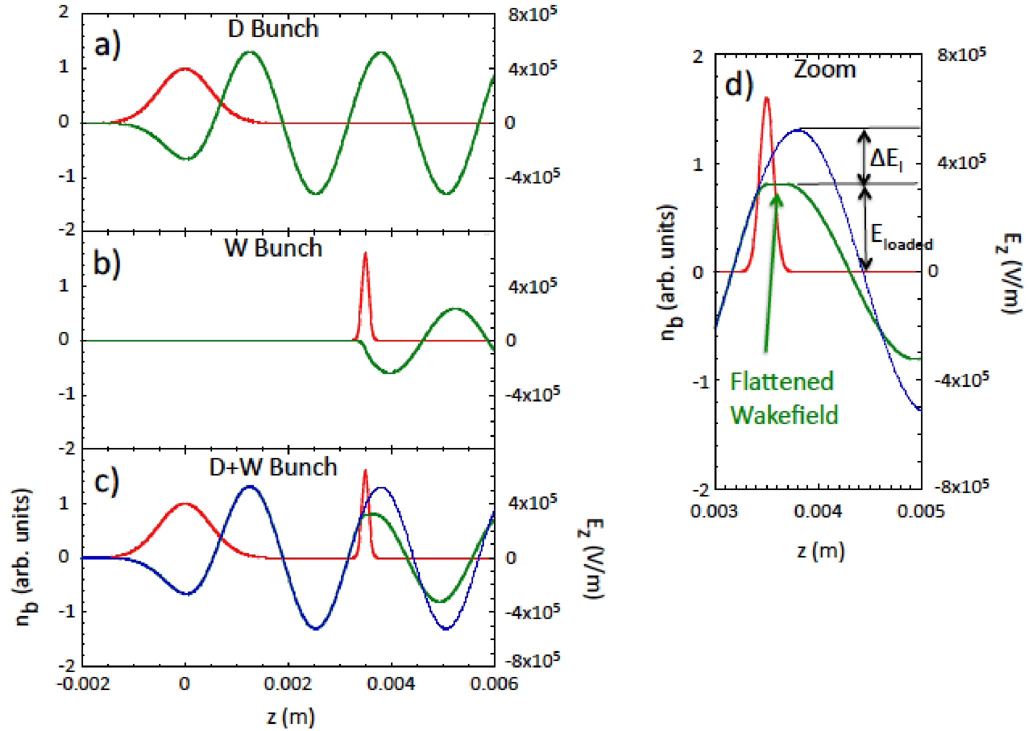
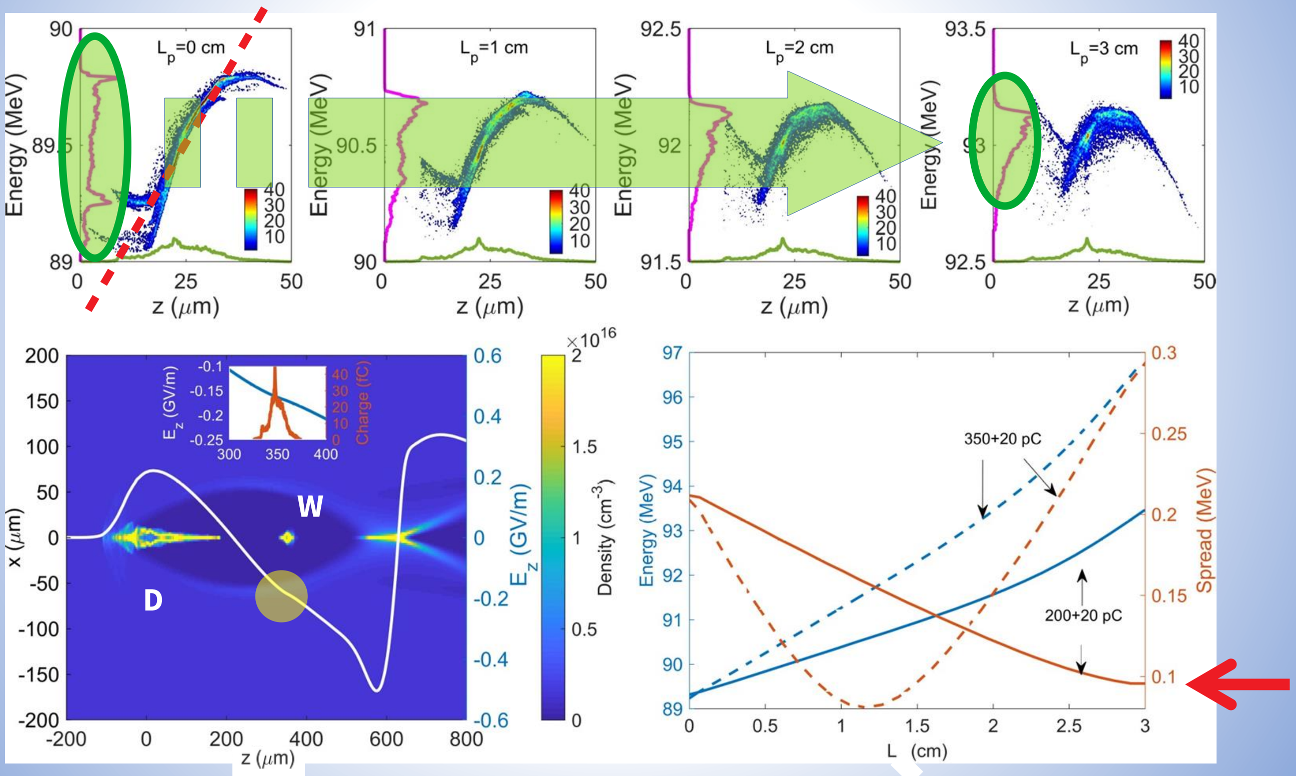


Fig. 5: Linear beam loading example: (a) drive bunch density profile (red line) and longitudinal wakefield E_z (green line), (b) same for the witness bunch, (c) same for the drive and witness bunches together. The field of the drive bunch only is shown as the blue line in panel (c). A zoom around the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

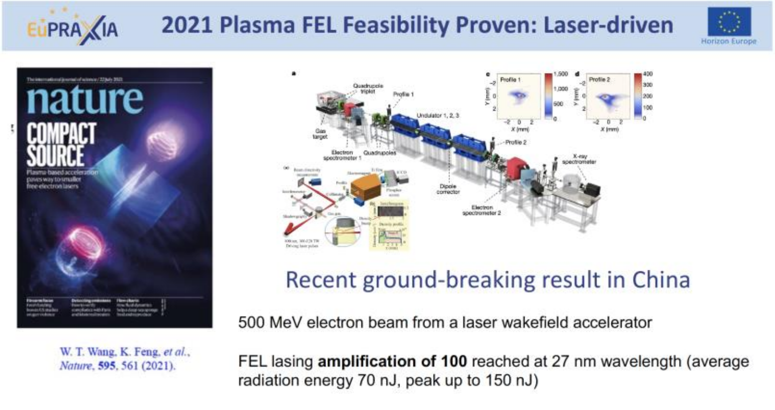
Assisted beam-loading technique

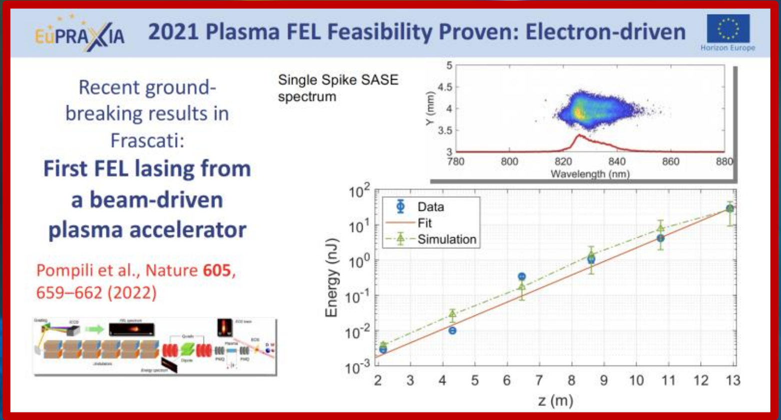
Pre-chirp to compensate wakefield slope

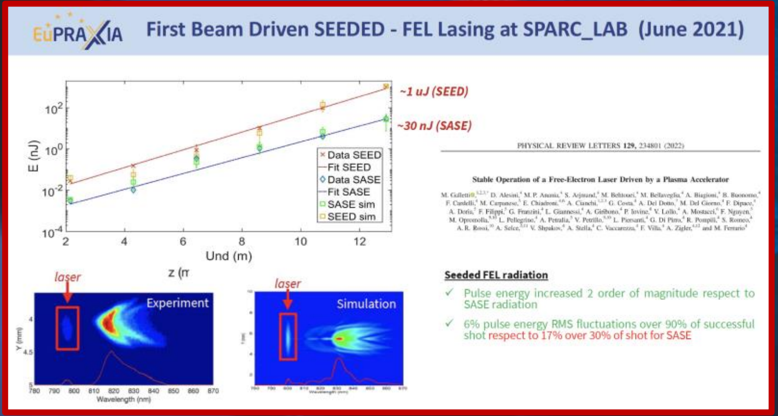


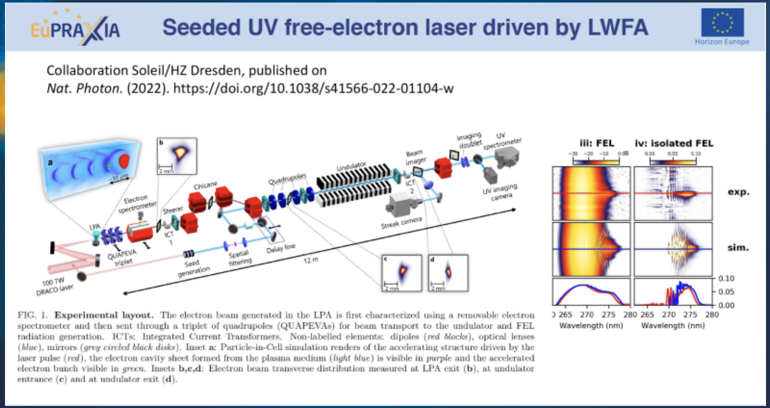
R. Pompili et al., Energy spread minimization in a beam-driven plasma wakefield accelerator, *Nature Physics* **volume 17**, pages 499–503 (2021)

Basic beam quality achieved in pilot FEL experiments

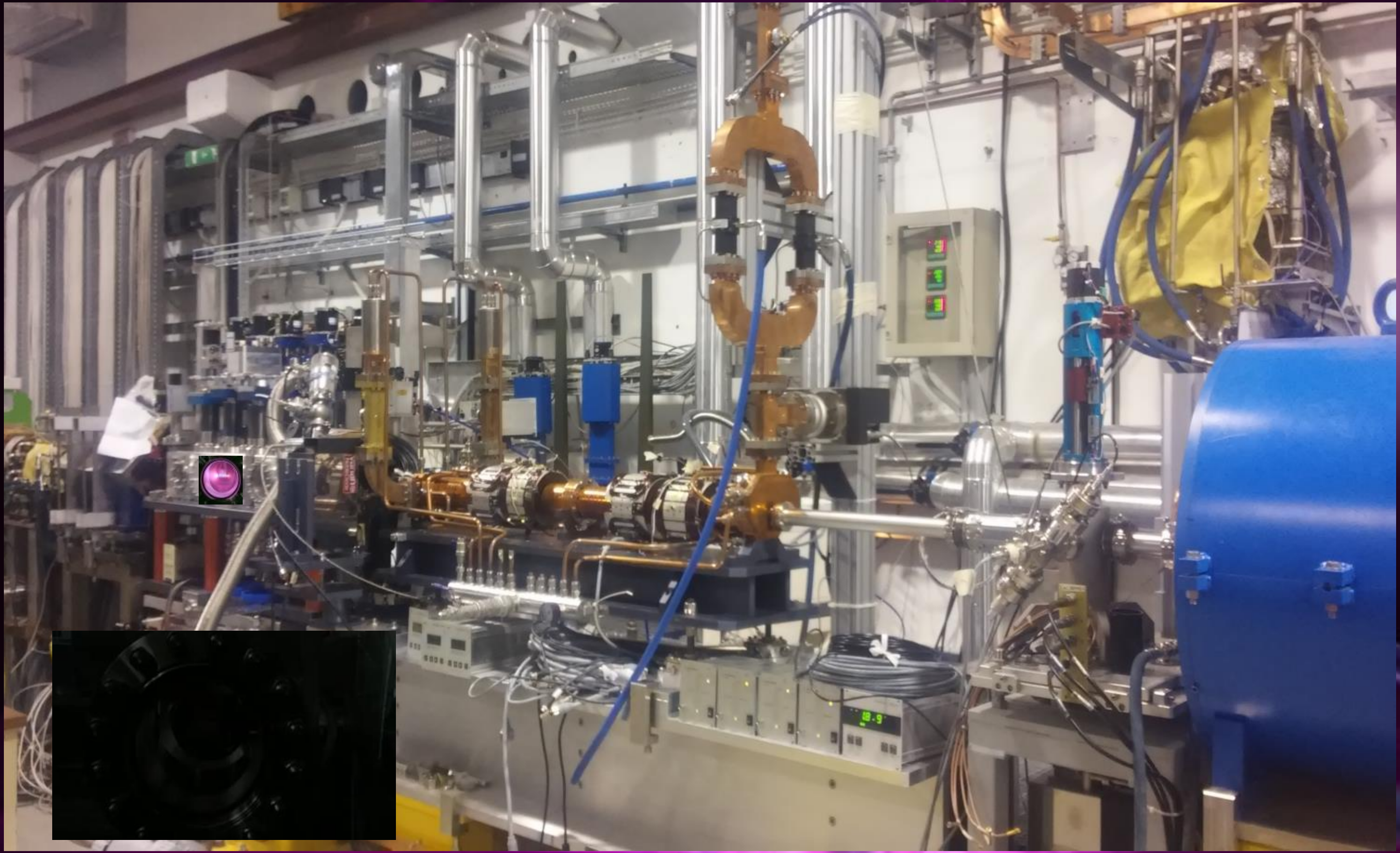








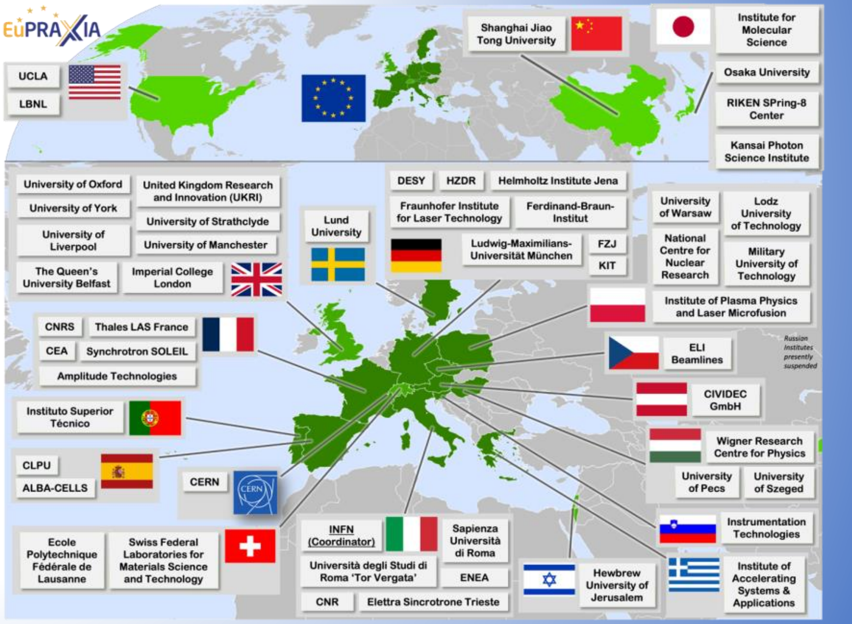
PWFA beam line at SPARC_LAB



Wide International Collaboration

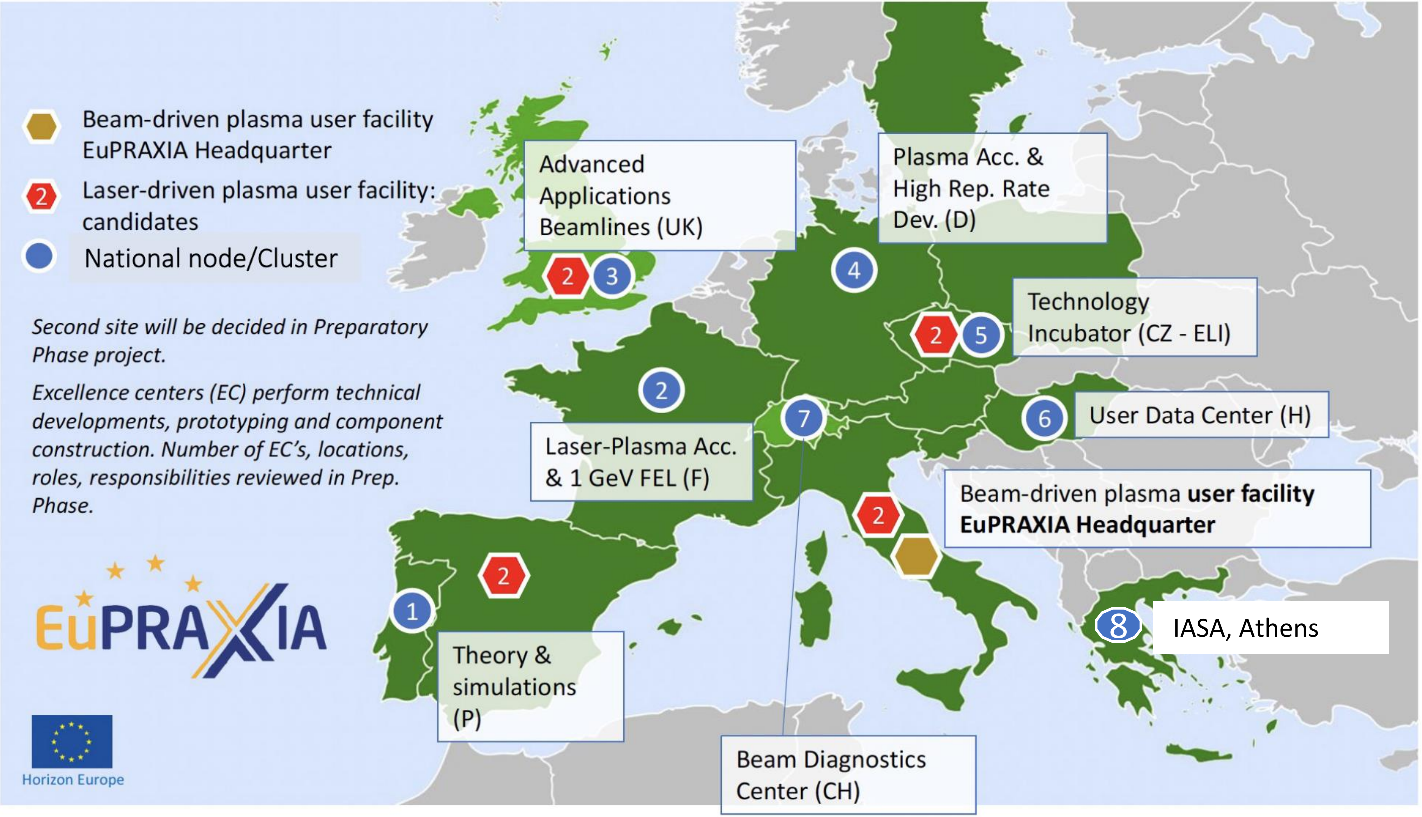
Funded by the European Union

- **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)



Distributed Research Infrastructure

Funded by the European Union



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

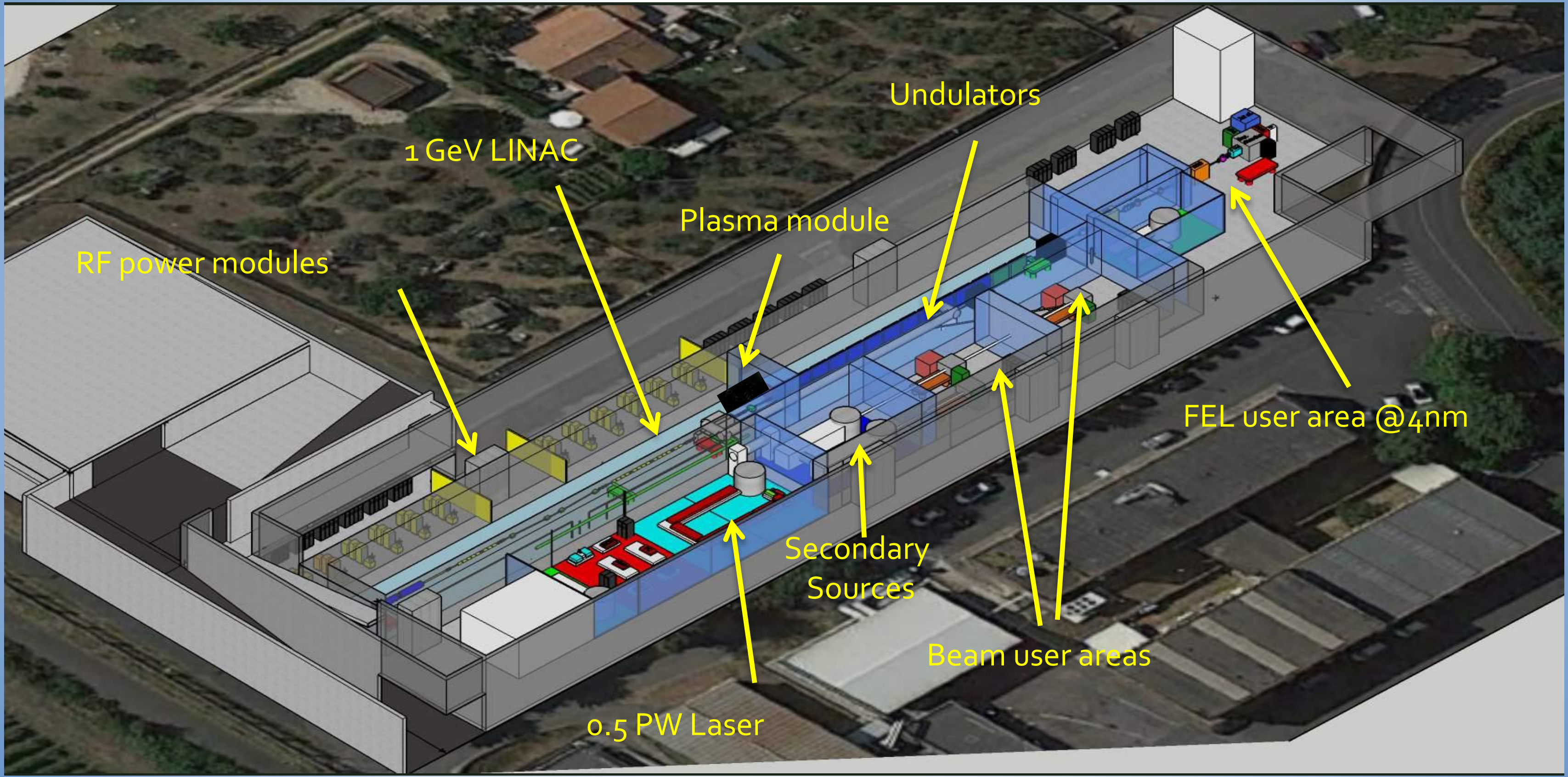
Network organization
- **Sites (PWFA/LWFA)**
- **National nodes**
- **Technology clusters**

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

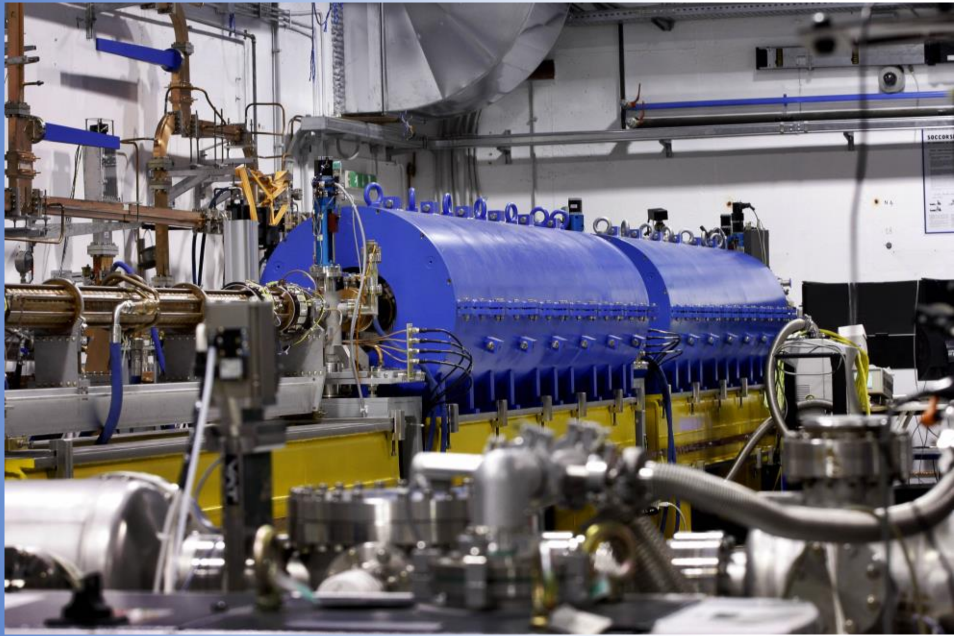
Headquarter and Site 1: EuPRAXIA@SPARC_LAB

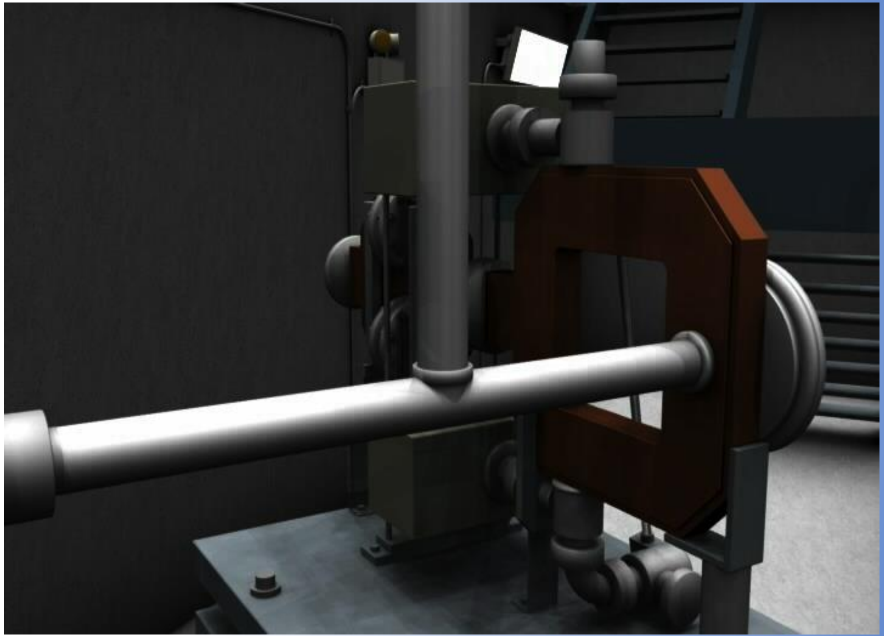
- Frascati`s future facility
- > 130 M€ invest funding
- Beam-driven plasma accelerator
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator (X band with CERN)

EuPRAXIA@SPARC_LAB



High Brightness Photo-injector with Velocity Bunching



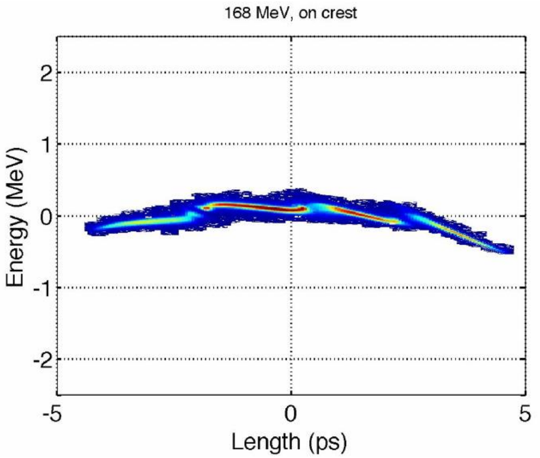


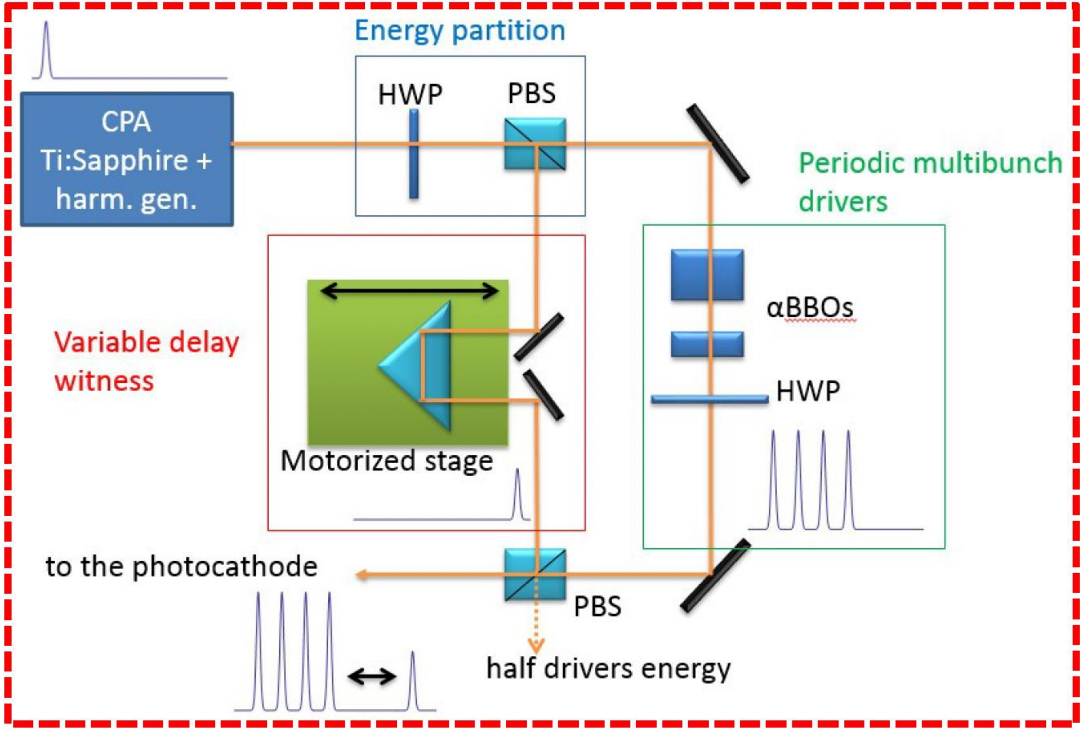
Generation of multiple bunches

Funded by the European Union

Ferrario, M., et al. "Laser comb with velocity bunching: Preliminary results at SPARC." NIM A 637.1 (2011): S43-S46.

Villa, F., et al. "Laser pulse shaping for multi-bunches photo-injectors." NIM A 740 (2014): 188-192.





Compression with velocity-bunching

Funded by the European Union

Velocity Bunching in Photo-Injectors

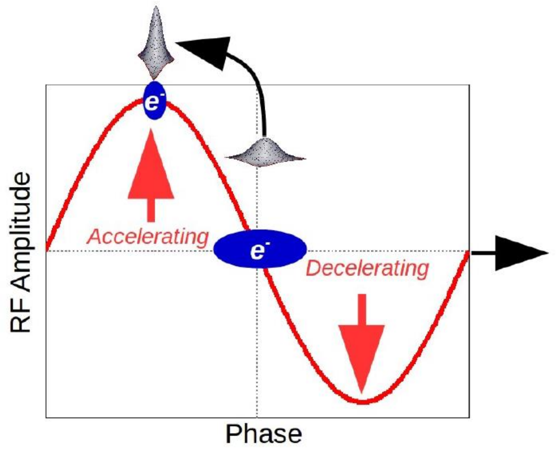
L. Serafini and M. Ferrario*

VB exploits the different fields felt by the beam head/tail to make compression

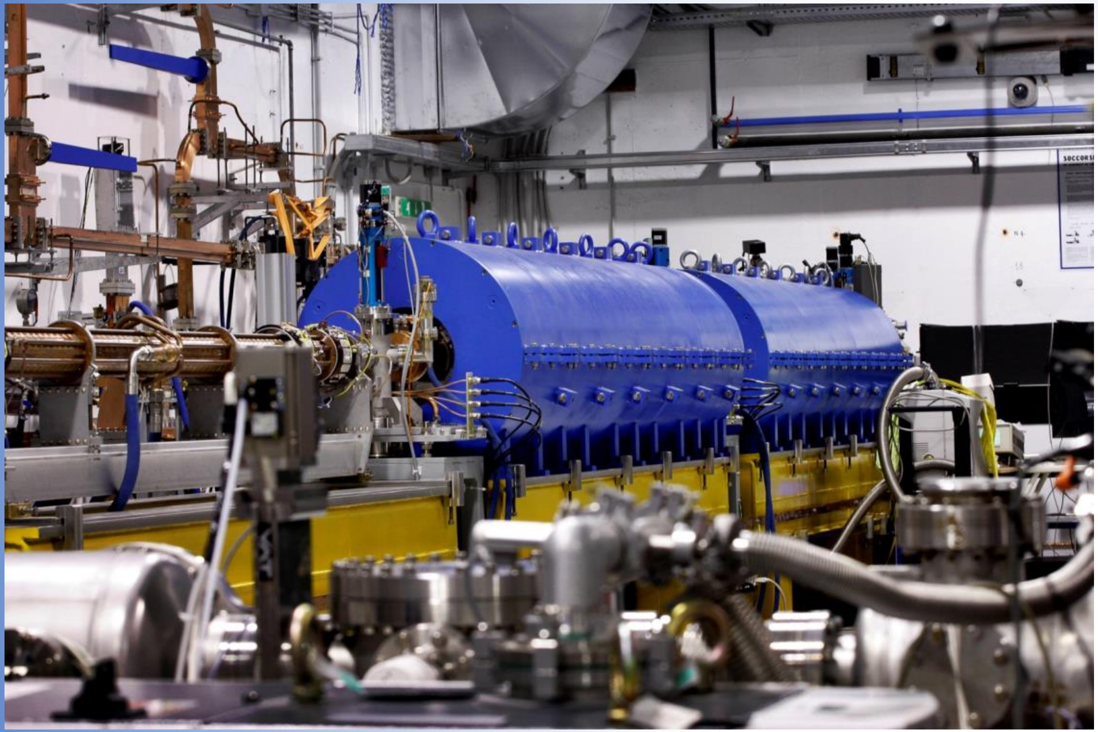
Simple, tunable and compact <u>but</u> can suffer from RF jitters (becoming intra-bunch jitters)

Compression is done in S1, where beams are not yet fully relativistic.

Shortest bunch measured @ SPARC was ~20 fs (20 pC). Largest peak current obtained for THz experiments (600 pC, 100 fs rms)

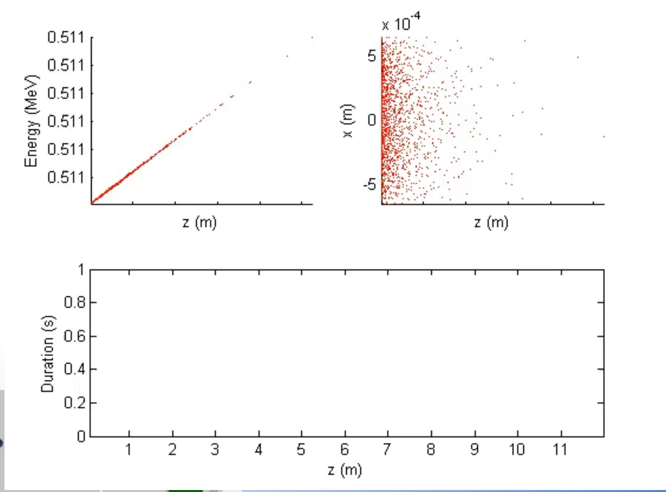


High Quality Electron Beams



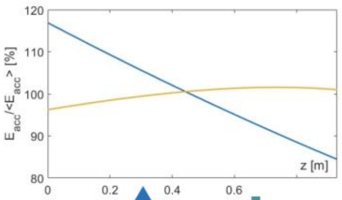
Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

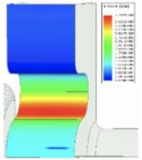
Table 7.2: Driver and witness beam parameters at the end of photo-injector.



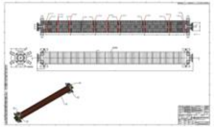
Courtesy E. Chiadroni

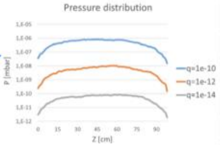
World`s Most Compact RF Linac: X Band

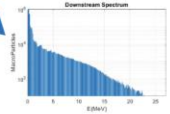




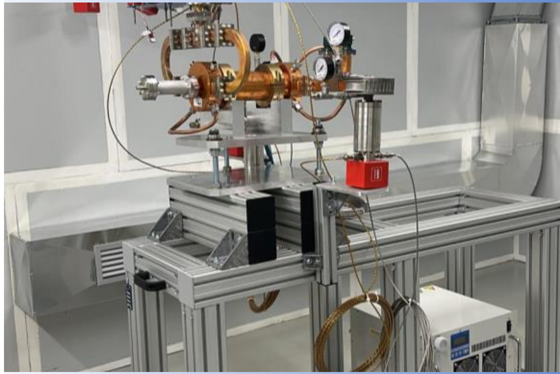
1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*

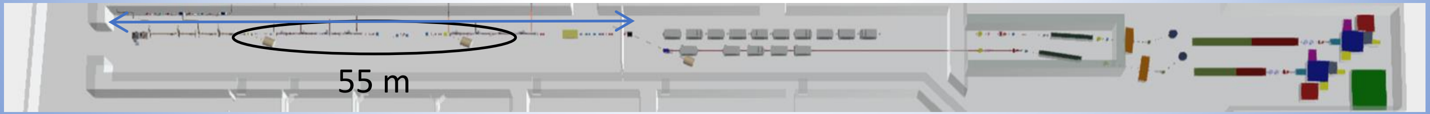






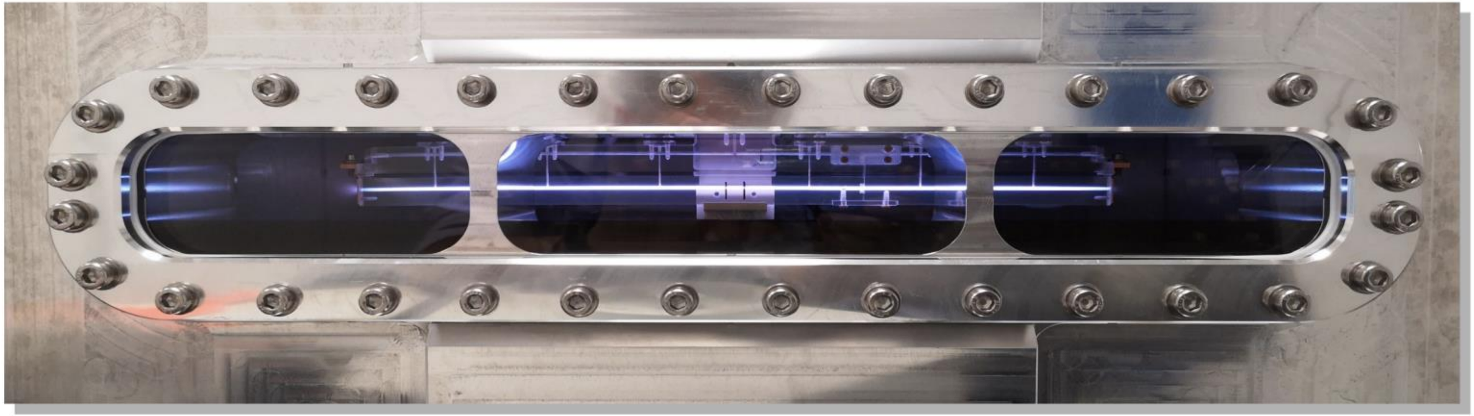
PARAMETER	Value	
	with linear tapering	w/o tapering
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85-3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length (flange-to-flange) [m]	**0.94 (1.05)**	
No. of cells	112	
Shunt 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**	





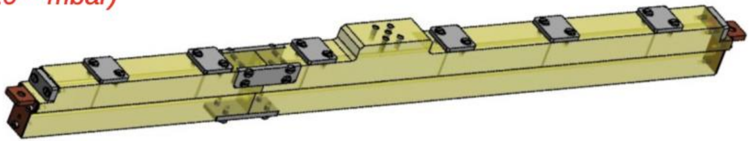
Courtesy D. Alesini

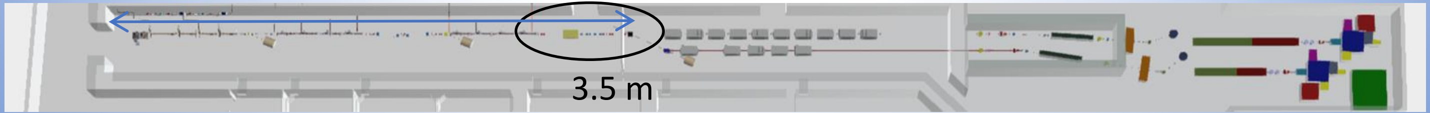
Plasma Module



- 40 cm long capillary → 1st 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*

A. Biagioni, V. Lollo





Courtesy A. Biagioni, R. Pompili

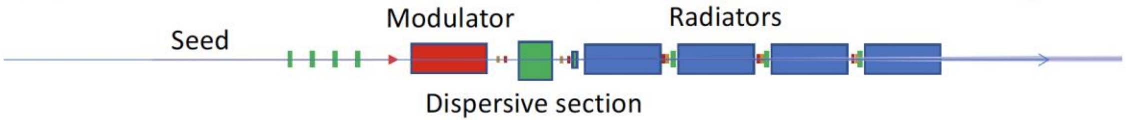
Radiation Generation: FEL

Two FEL lines:

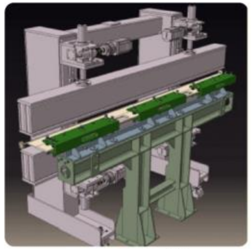
1) *AQUA*: Soft-X ray SASE FEL – Water window optimized for 4 nm (baseline)

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

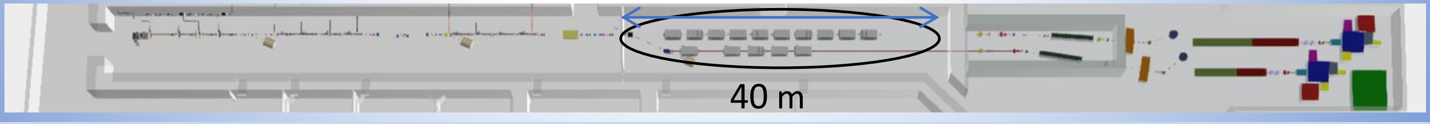
2) *ARIA*: VUV seeded HGHG FEL beamline for gas phase



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.



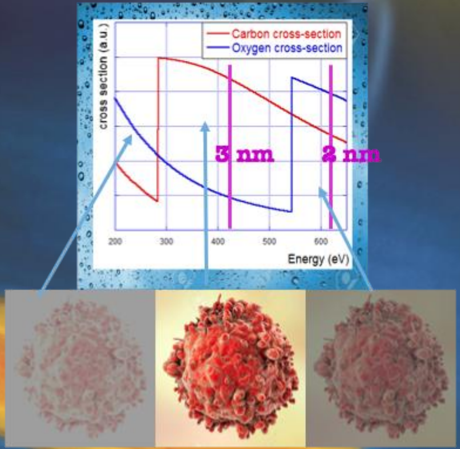
Courtesy L. Giannessi

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

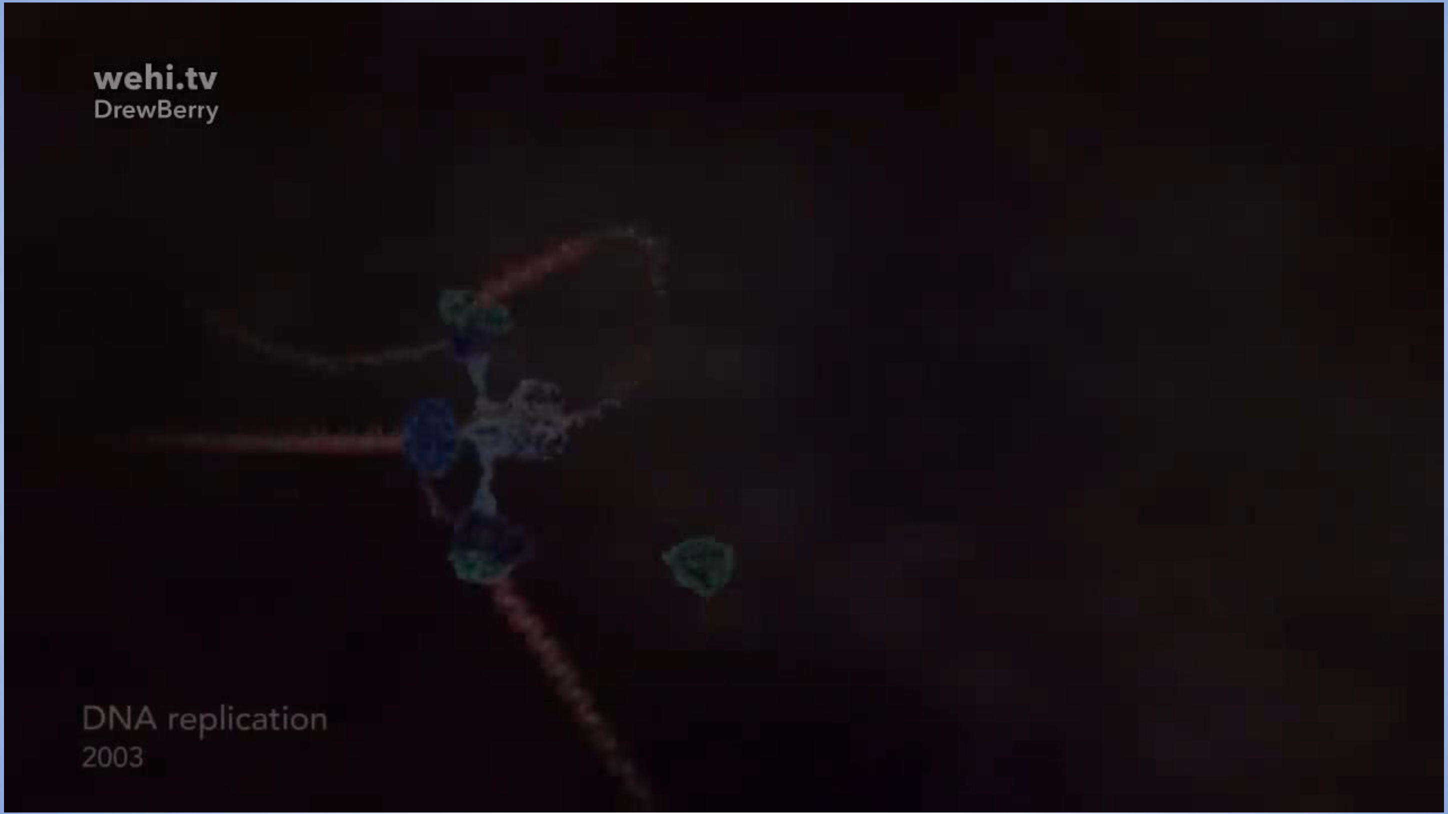
In the Energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV) water is almost transparent to radiation while nitrogen and carbon are absorbing (and scattering)



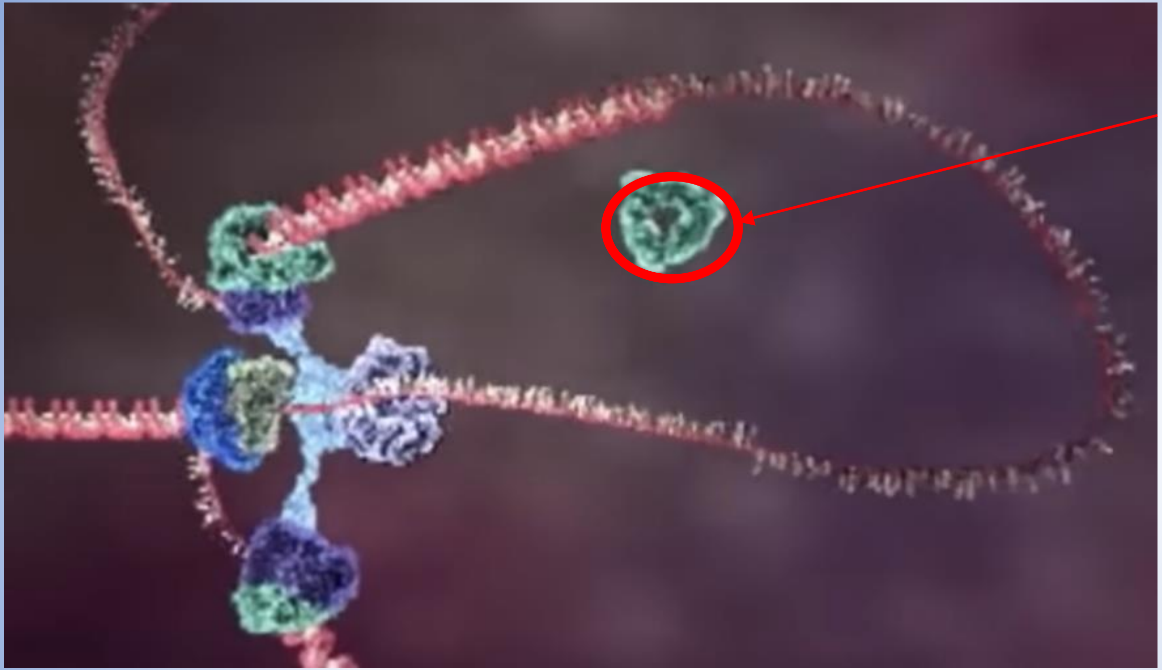
Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state
Possibility to study dynamics
~10^{11} photons/pulse needed

Courtesy F. Stellato, UniToV

Towards Single Protein Imaging with hard x-rays



Need light !

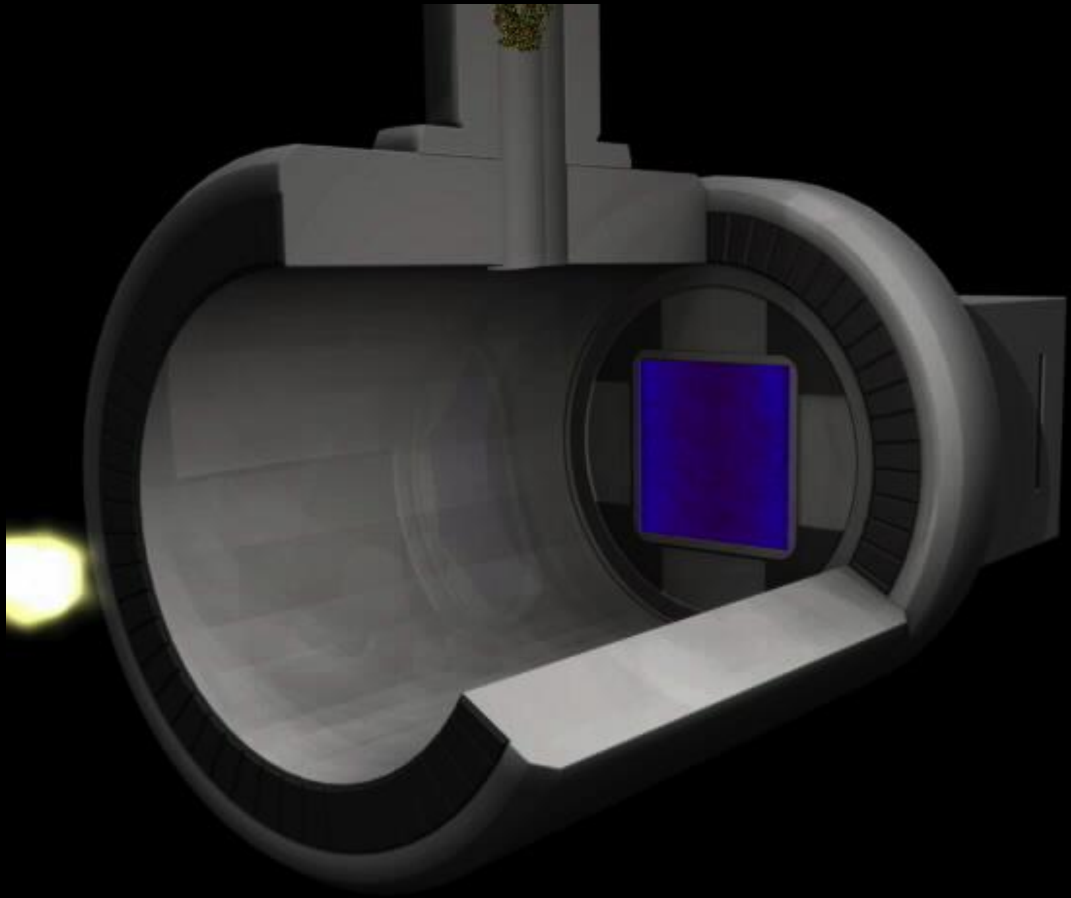


Static picture of a macro-molecule

Required properties

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

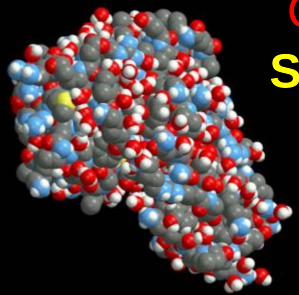
Single Protein Imaging

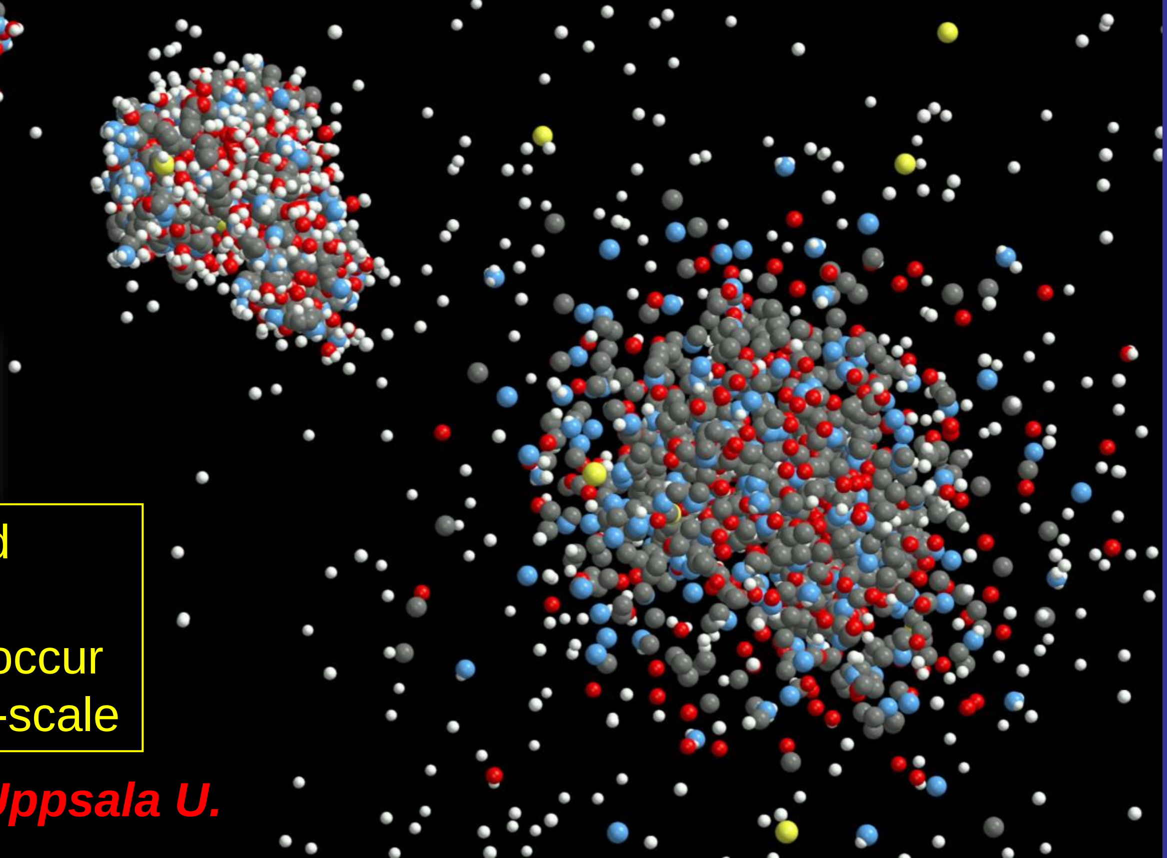


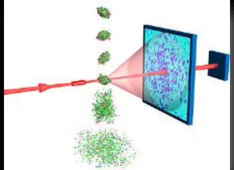
http://lcls.slac.stanford.edu/AnimationViewLCLS.asp

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.

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)**

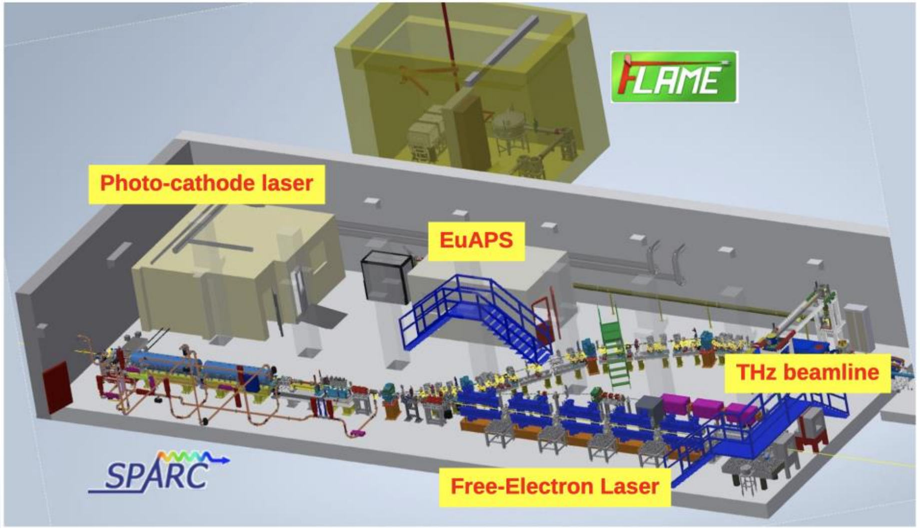
n. 20 POST-DOCTORAL SENIOR LEVEL 3 RESEARCH GRANT IN EXPERIMENTAL PHYSICS at INFN

Funded by the European Union

https://jobs.dsi.infn.it/dettagli_job.php?id=4180

DETTAGLIO DEL BANDO	
Numero :	27077
Anno :	2024
Titolo:	n. 20 POST-DOCTORAL SENIOR LEVEL 3 RESEARCH GRANT IN EXPERIMENTAL PHYSICS
Numero Posti:	20
Tipo:	Assegno di ricerca
Data bando:	12-09-2024
Data scadenza:	15-11-2024 **Dead line: November 15**
Bando:	27077.pdf

Istituto Nazionale di Fisica Nucleare



LPAW 2025 – Ischia Island

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.

Funded by the European Union


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