EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

at SPARC_LAB

EuPRAXIA

The first **plasma-based** user-oriented high-energy accelerator

Livio Verra

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

1st ECFA-INFN Early Career Researchers Meeting

Outlook

I. EuPRAXIA : concept

II. Free-electron lasers

III. Plasma Wakefield Acceleration

IV. Previous Results and landscape
→ Requirements for applications (HEP Collider, FEL)

V. Results at Sparc

VI. Road to EuPRAXIA

EuPRAXIA

European Plasma Research Accelerator with Excellence in Applications

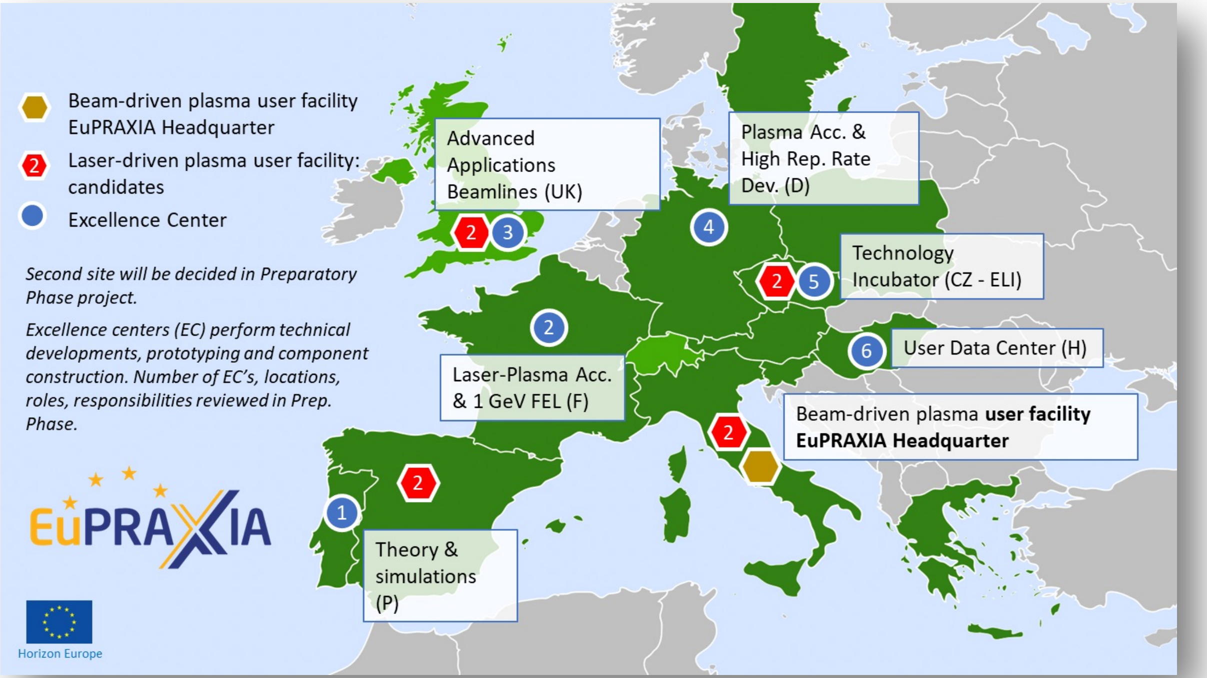
→ The first project developing user-oriented accelerators **based on plasma accelerator technology**

→ Distributed Research Infrastructure building TWO facilities driven by high-gradient plasma wakefield accelerator

   → > 1 GV/m accelerating field

   → Beam-driven and laser-driven facilities

→ Provide a practical path to more research facilities and ultimately to higher beam energies for the same investment in terms of size and cost



Included in 2021
European Roadmap For Research Infrastructure (ESFRI) Roadmap

EuPRAXIA

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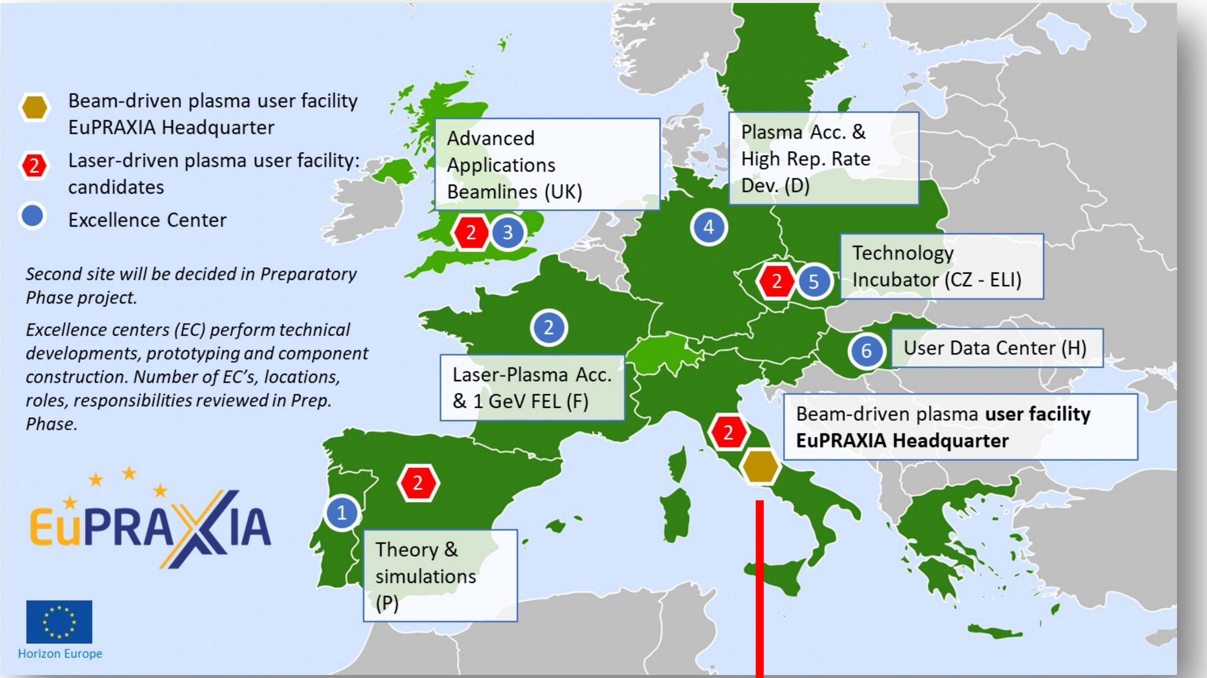

At LNF: the beam-driven facility: EuPRAXIA@SPARC_LAB

EuPRAXIA@SPARC_LAB

- Soft X-ray (2-4 nm) FEL based on Plasma Wakefield Acceleration (PWFA) at Frascati
- 500 MeV, 30 pC electron bunch boosted to 1 GeV in 60-cm-long plasma

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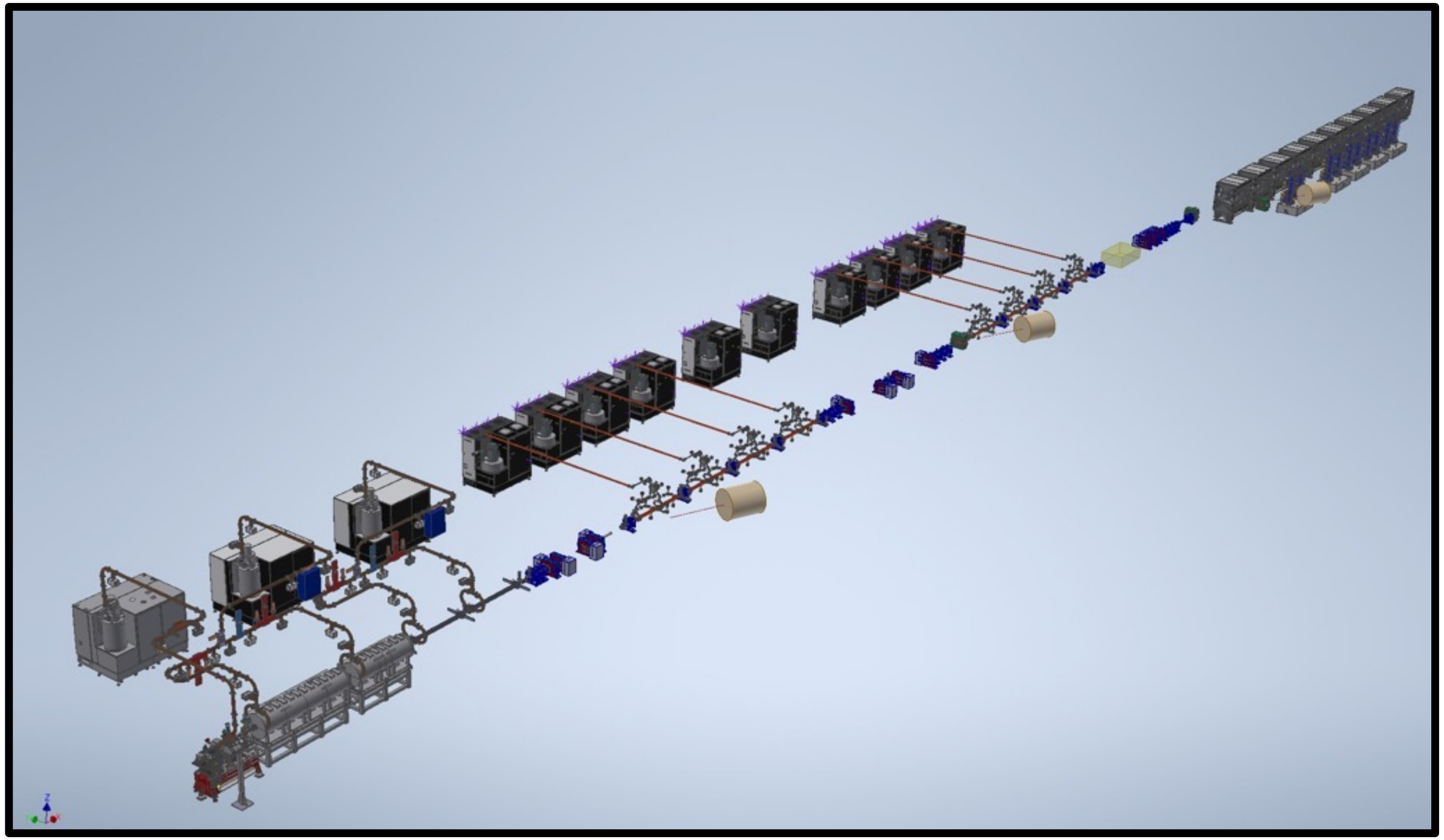

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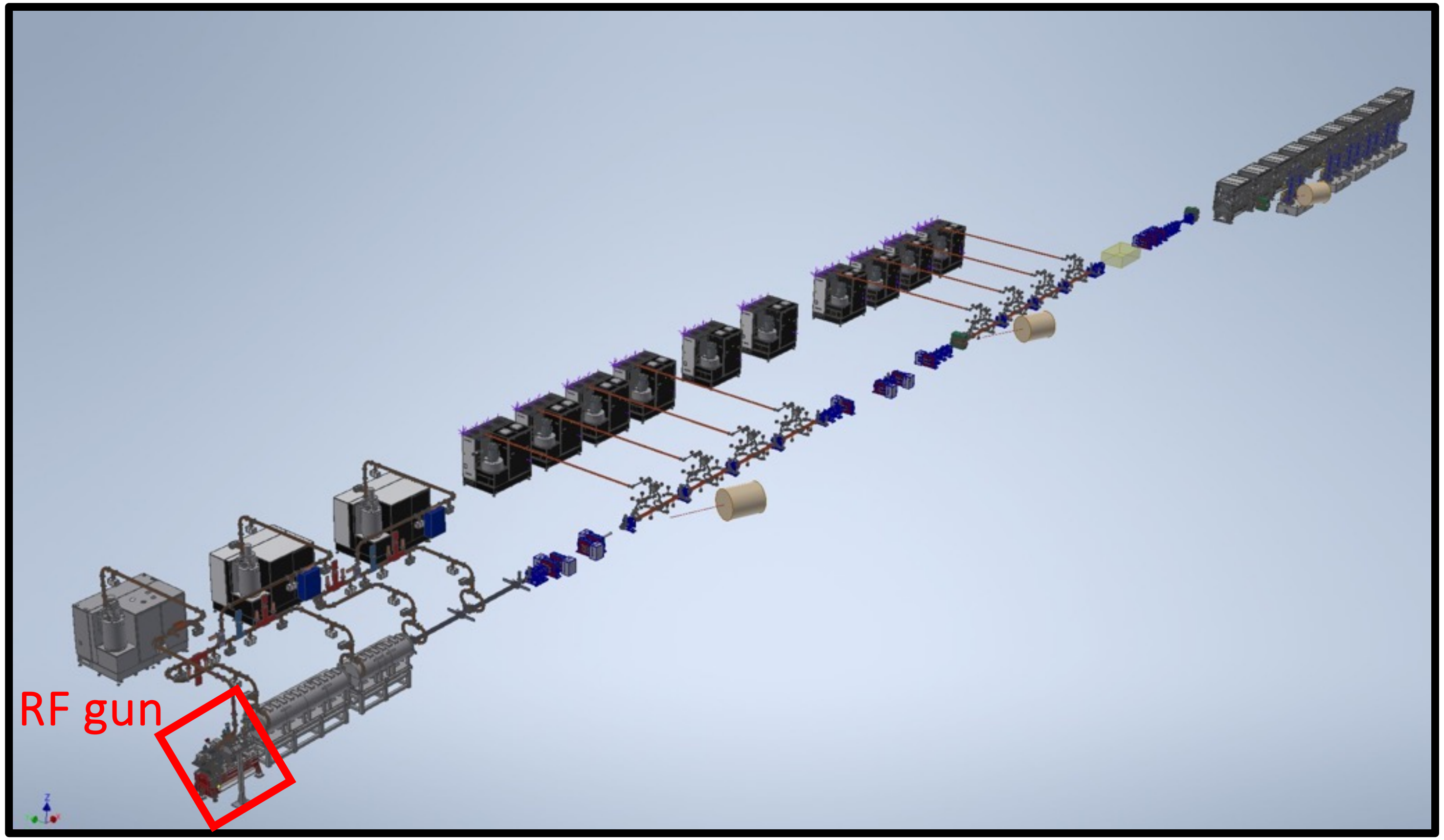

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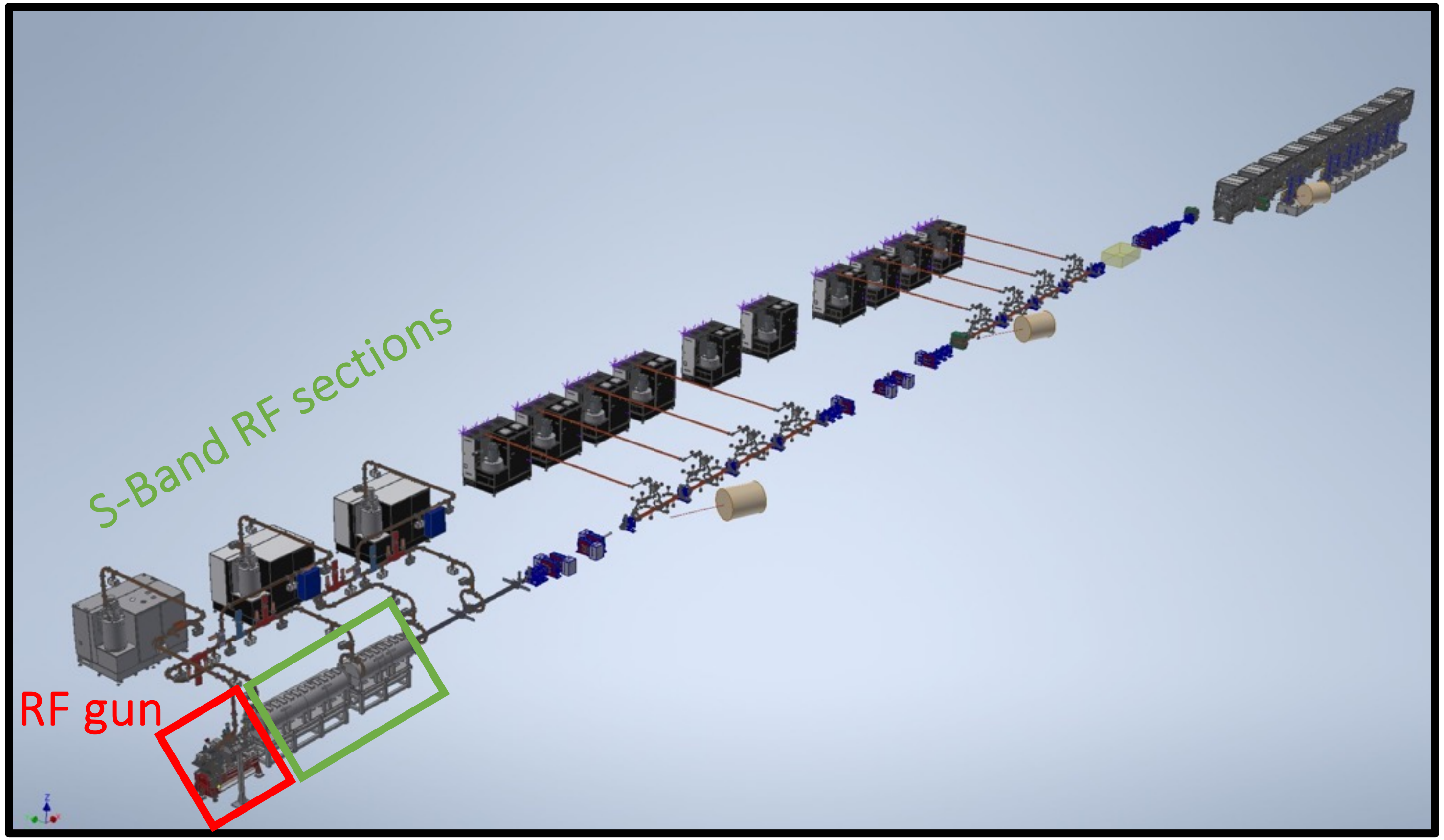

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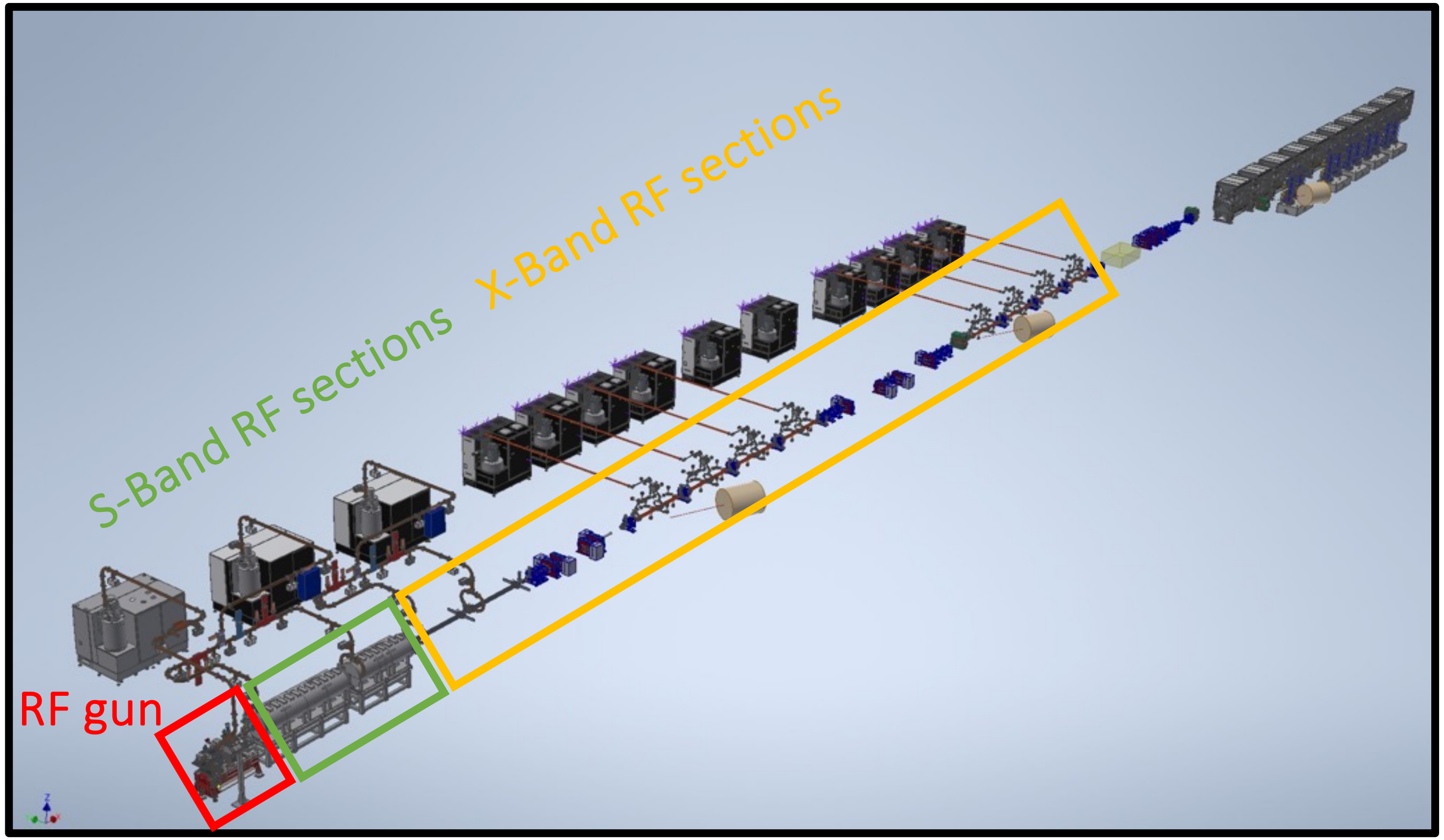

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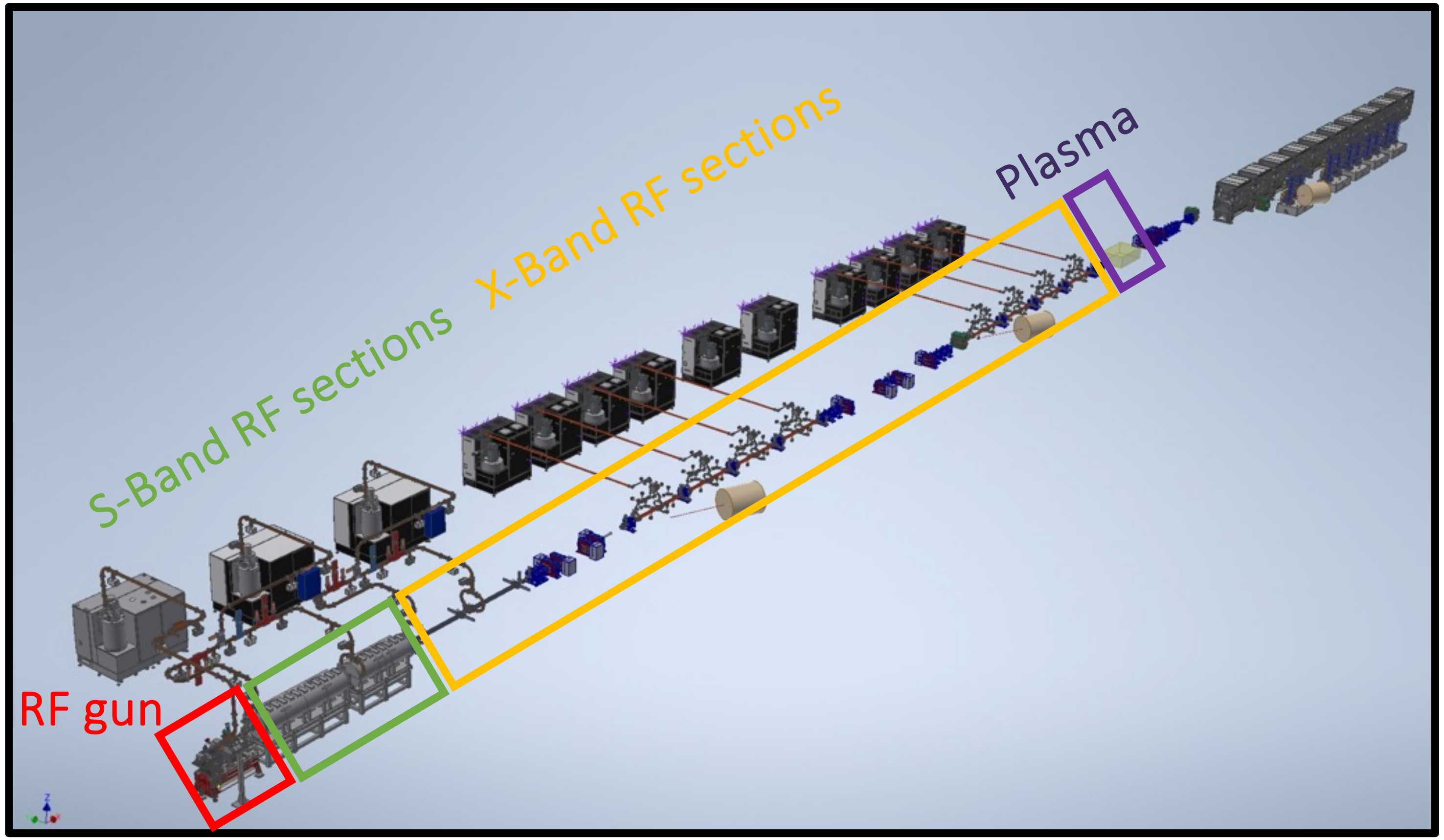

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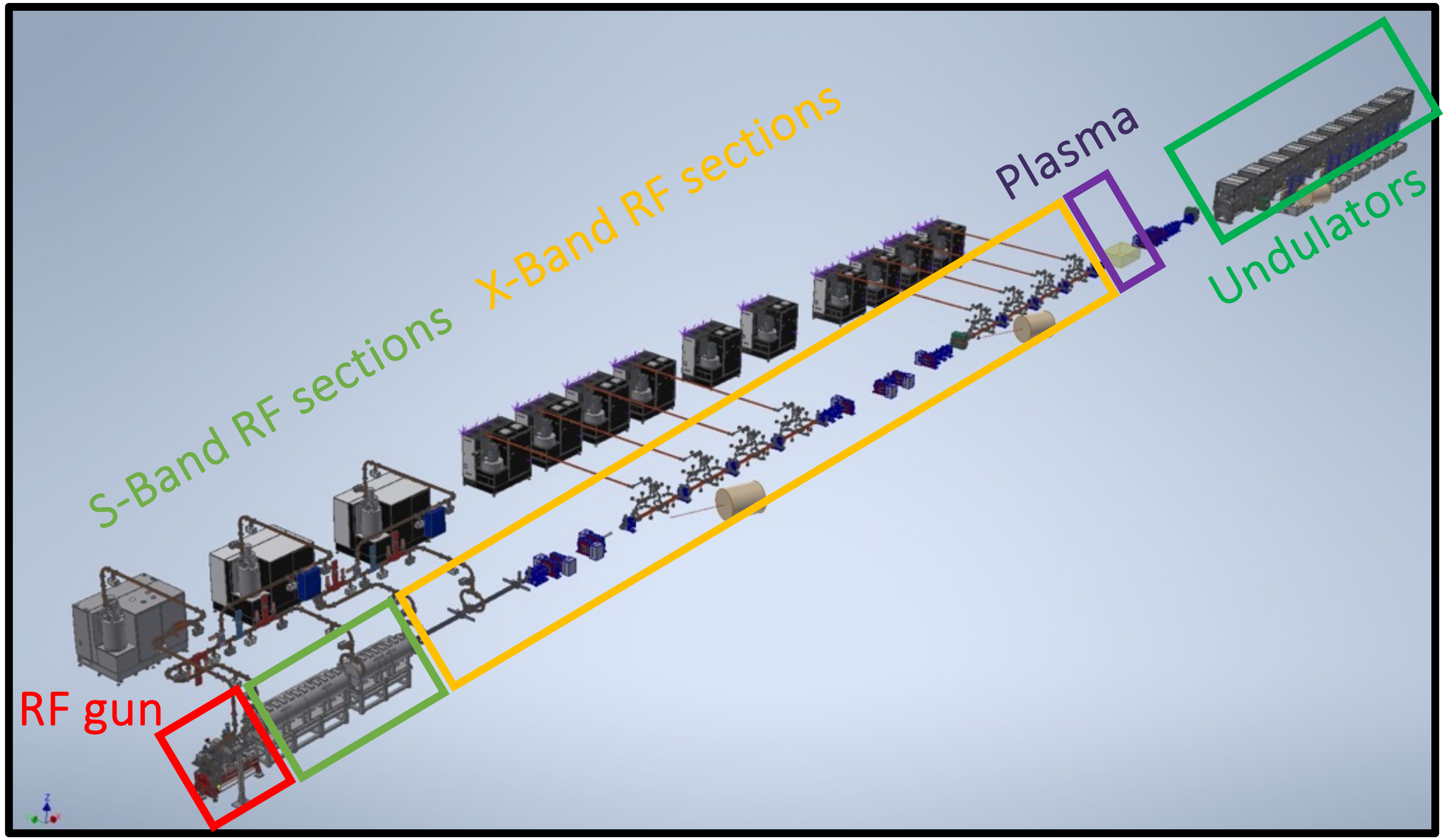

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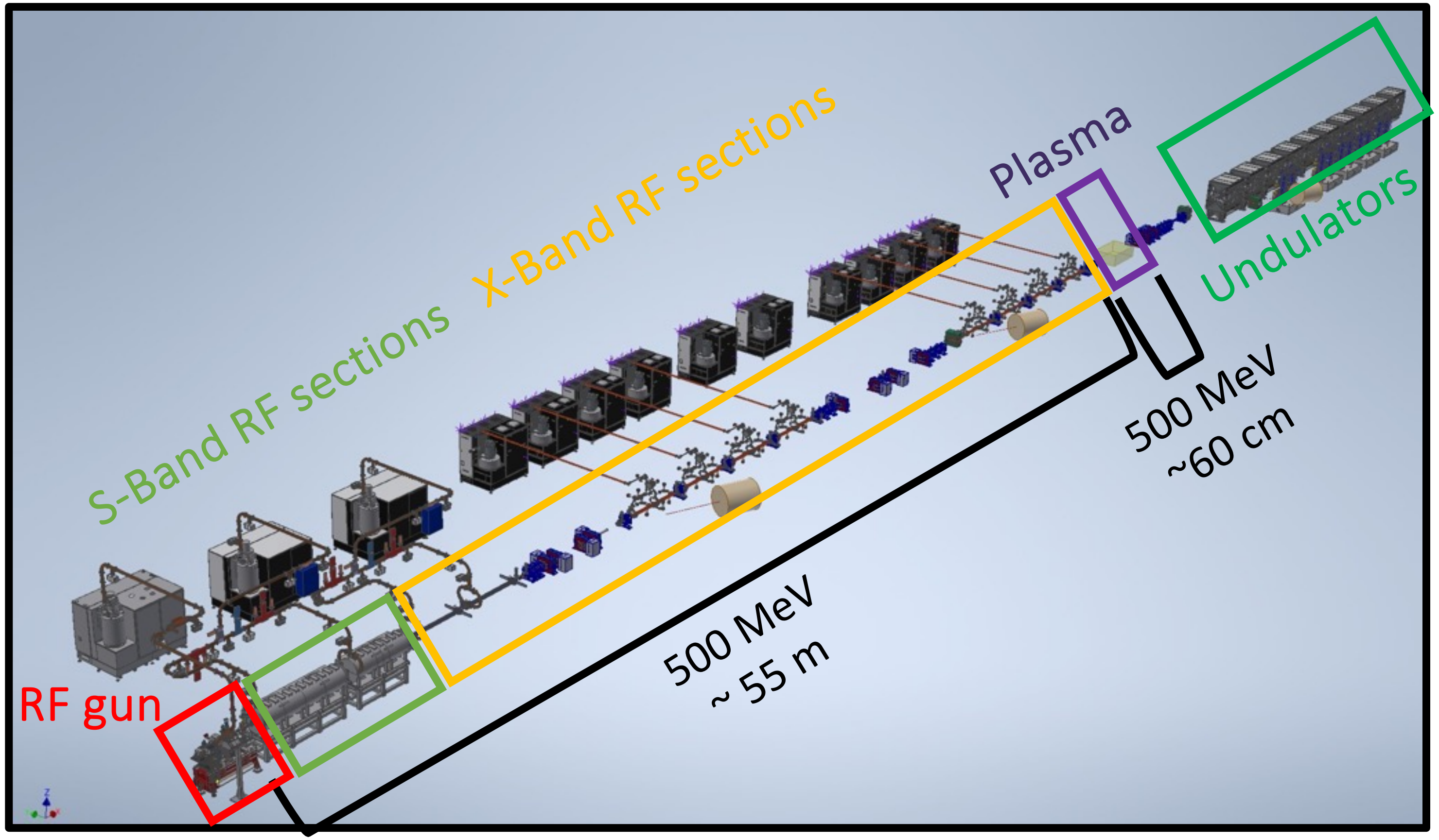

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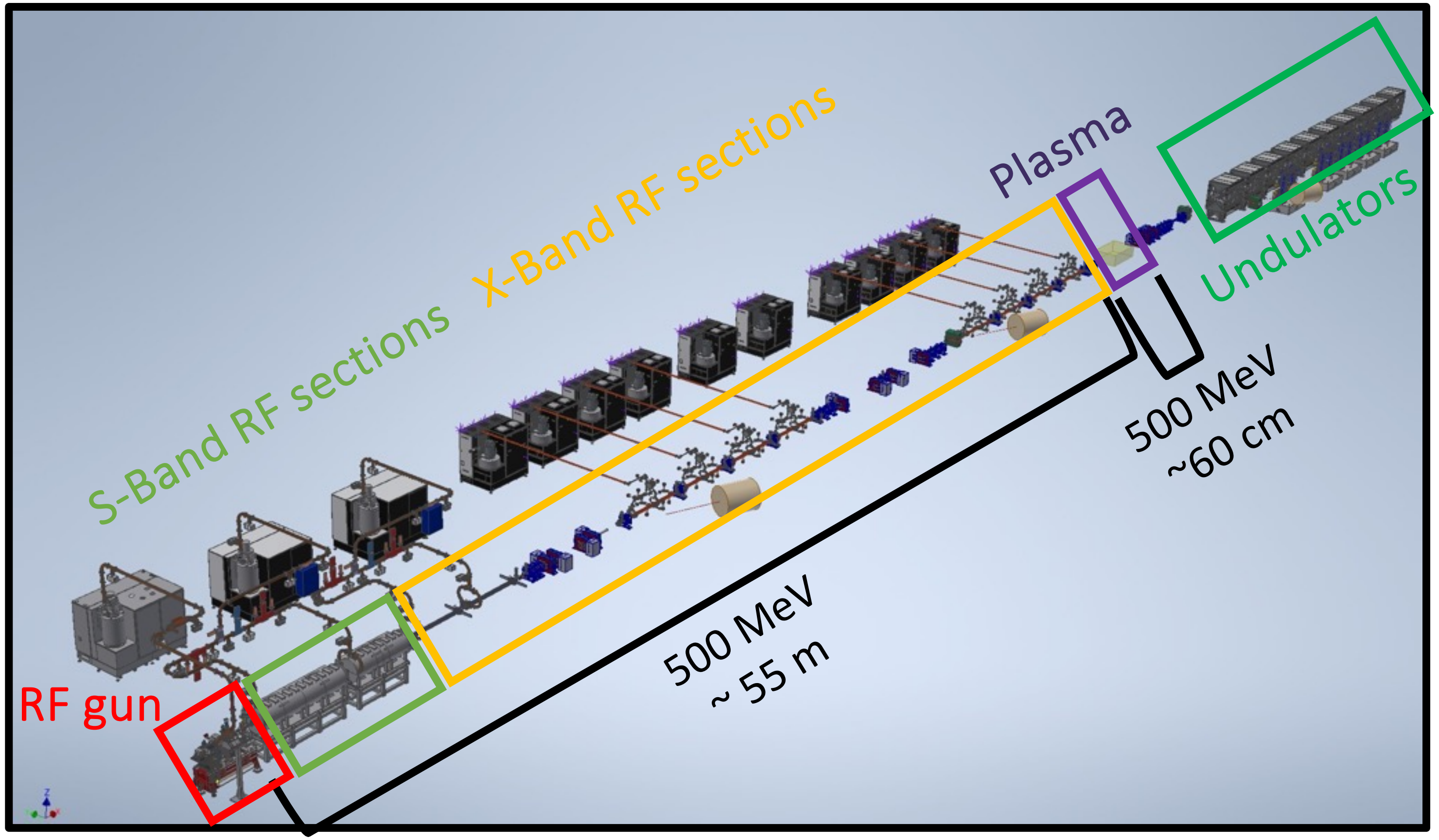

Key ingredients:

→ Free-electrons lasers

→ PWFA

Free-electron laser (FEL)

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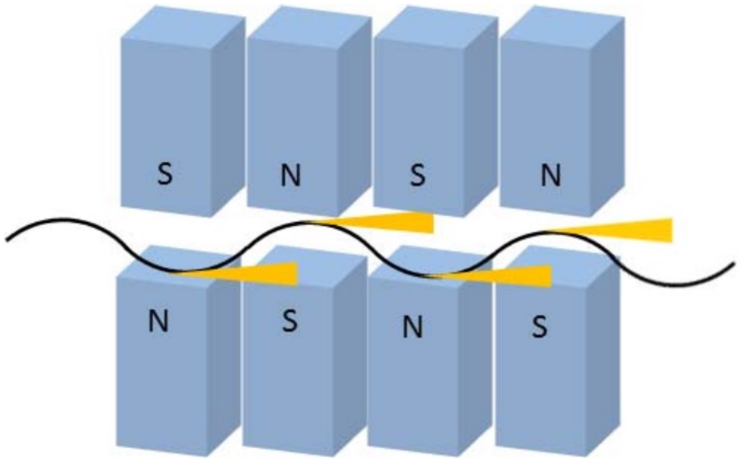
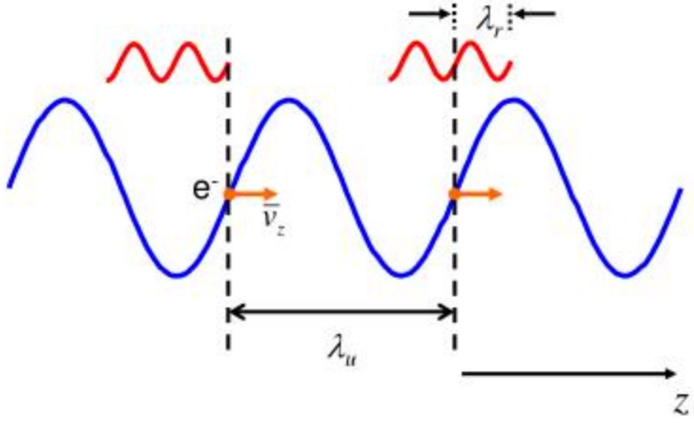
- Electrons propagating in oscillating magnetic field → emission of radiation



- Electrons emit COHERENTLY under resonance condition: radiation slips ahead by one wavelength per undulator period

- Fundamental wavelength: $\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$

$K = \frac{eB\lambda_u}{2\pi m_e c} \ll 1$ for undulators



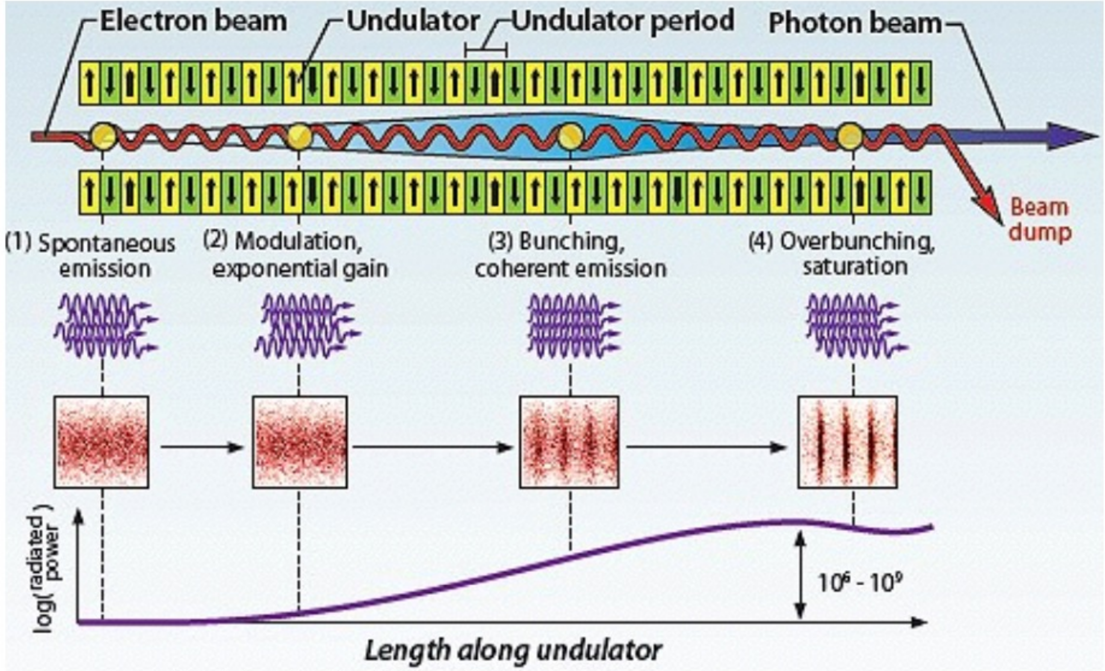
NUMERICAL EXAMPLES

$K \approx 1$ and $\lambda_u = 1$ cm:
Weakly relativistic beams: $\boldsymbol{\gamma = 3}$ **=>** $\boldsymbol{\lambda_r \approx 1}$ **mm** => Microwaves
Relativistic beams: $\boldsymbol{\gamma = 30}$ **=>** $\boldsymbol{\lambda_r \approx 10}$ **μm** => Infrared
Ultra-relativistic beams: $\boldsymbol{\gamma = 30000\ (E \sim 15GeV)}$ **=>** $\boldsymbol{\lambda_r \approx 0.1}$ **nm**
➔ X-rays

Further tunability is possible through B_u and λ_u as $K \propto B_u\lambda_u$

Free-electron laser (FEL)

- Coherent emission → $I \propto N^2$
  (as opposed to incoherent emission in synchrotrons $I \propto N$)
- Electron bunch is modulated into microbunches
  → Emitted power increases up to saturation within gain length L_g



https://www.lanl.gov/science/1663/june2010/story4b.shtml

Pierce parameter

$$\rho = \frac{1}{2\gamma}\left[\frac{I}{I_A}\left(\frac{\lambda_u K[JJ]}{\sqrt{8}\pi\sigma_x}\right)^2\right]^{1/3}$$

Fundamental FEL parameter

Gain length

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

Saturation power

$$P = P_{in} e^{\frac{z}{L_g}}$$

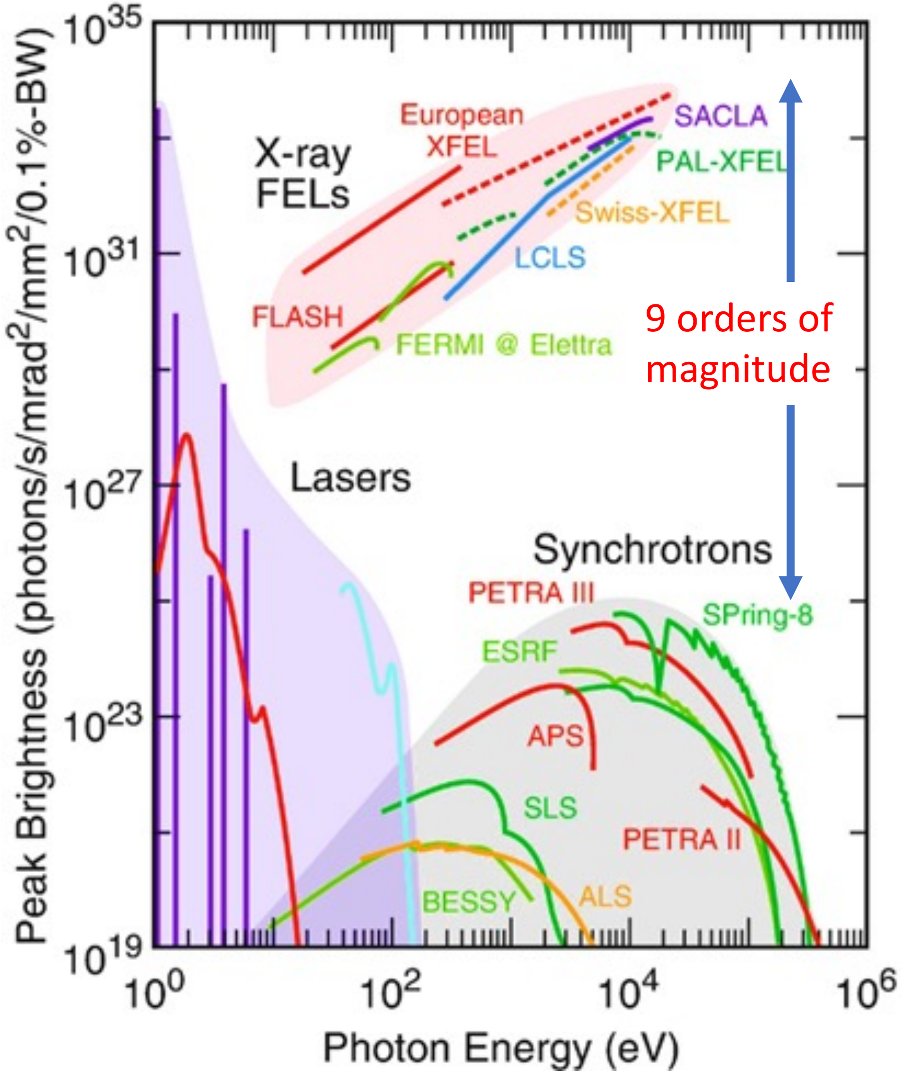
$$L_g \propto B_{5D}^{-\frac{1}{3}}$$

Free-electron laser (FEL)

- Applications: studies of dynamical properties of matter (soft x-rays: water window)

- Requests:
  - Short-wavelength (X-rays)
  - High-energy
  - Ultra-short (few femtoseconds, or less)
  - Transverse and longitudinal coherence
  - Monochromaticity
  - Tunability in wavelength (10 to 0.1 nm)
  - Defined polarization
  - Stability and reproducibility

- All potentially satisfied by FEL's



Plasma Wakefield Acceleration

- RF cavities are limited to ~ 100MV/m (but even less in operation)

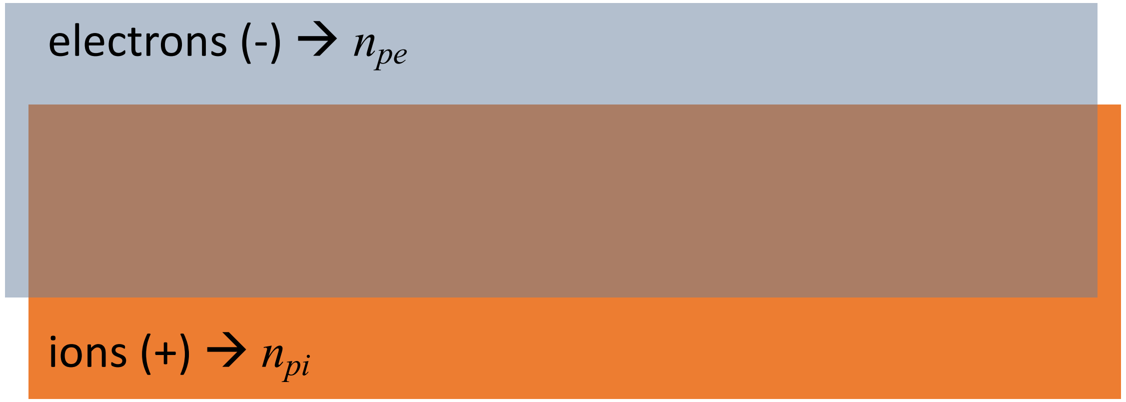
- Plasmas can sustain waves with amplitude up to:

$$E_{WB} \sim 100 \frac{V}{m} \sqrt{n_{pe}[\,cm^{-3}]}$$

E.g. for n_{pe} = (10^{14} – 10^{18}) cm^{-3}, $E_{WB} = (1 - 100)\ GV/m$

Plasma:

- Ionized gas
- Collisions can be (most of time) neglected
  → Electromagnetic interaction dominates
- Large number of particles ➔ **collective** behavior
- Quasi-neutral ($n_{pe} \sim n_{pi}$)



Plasma Wakefield Acceleration

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- Let's take a plasma with density n_{pe}

(inspired by P. Muggli's CAS lecture)

18

Plasma Wakefield Acceleration

- Let's take a plasma with density n_{pe}
- Let's take a relativistic charged bunch (e.g. e^-) or a high-intensity laser pulse

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Plasma Wakefield Acceleration

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- Let's take a plasma with density n_{pe}
- Let's take a relativistic charged bunch (e.g. e^-) or a high-intensity laser pulse

1. Transverse E field expels plasma electrons
2. Positively charged region behind the bunch head
   → restoring force

(inspired by P. Muggli's CAS lecture)

Longitudinal (accelerating – decelerating) wakefields

Transverse (focusing – defocusing) wakefields

20

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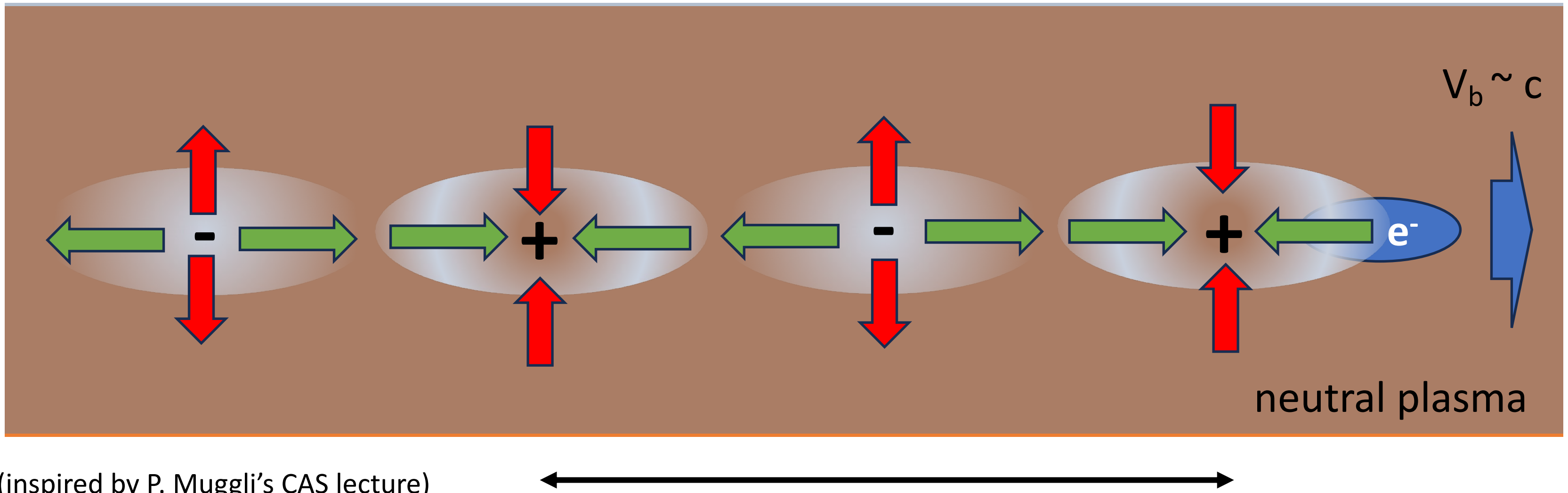

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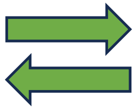
$$\lambda_{pe} = \frac{2\pi c}{\omega_{pe}}$$



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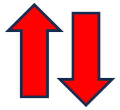

Transverse (focusing – defocusing) wakefields

1. Transverse E field expels plasma electrons
2. Positively charged region behind the bunch head
   → restoring force
3. Oscillation of plasma e^- with ω_{pe}
   → periodic density variation

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

→ Wakefields←

21

Plasma Wakefield Acceleration

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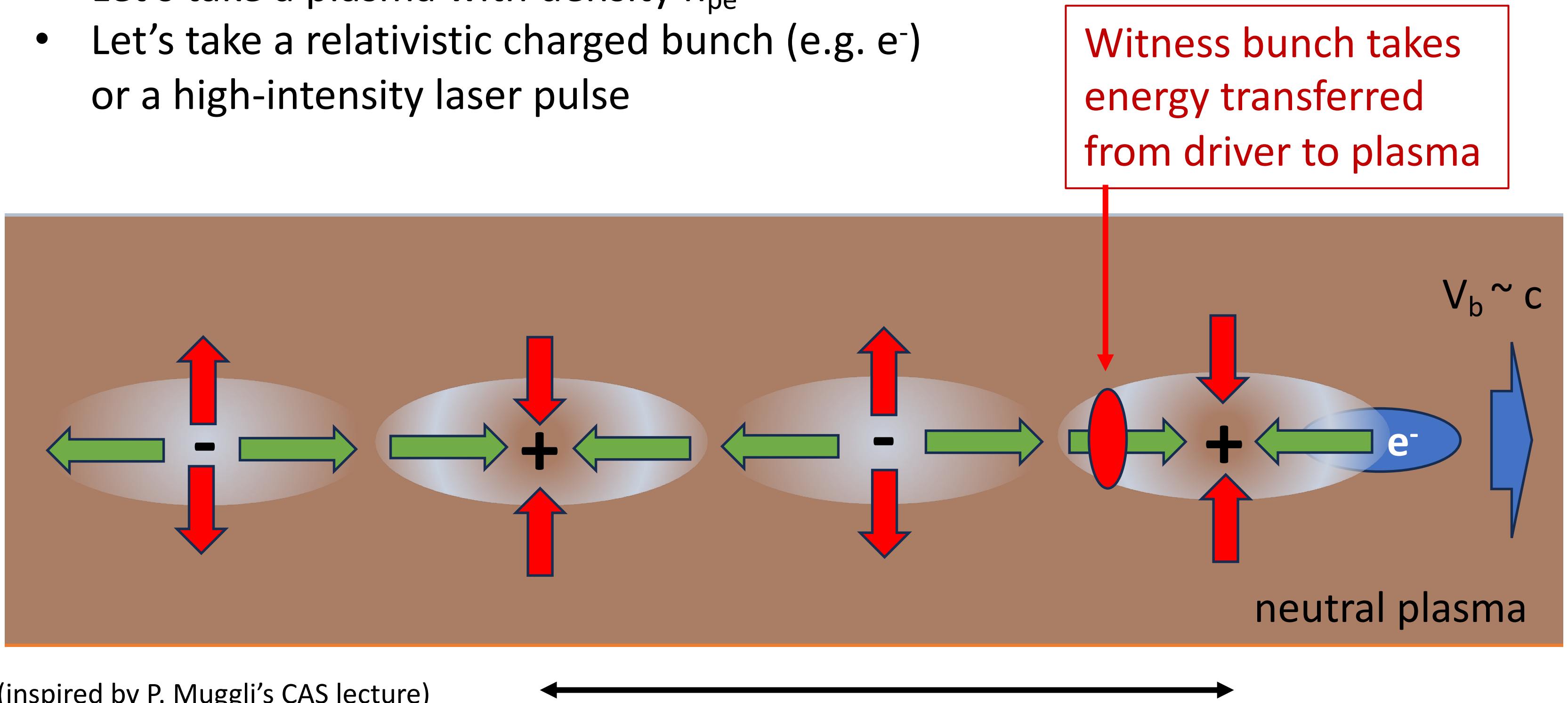

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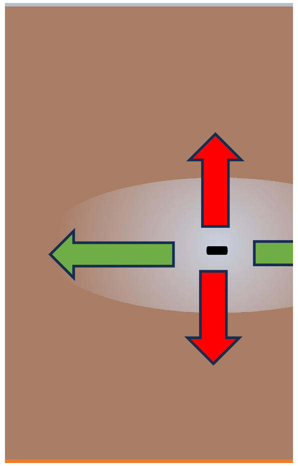

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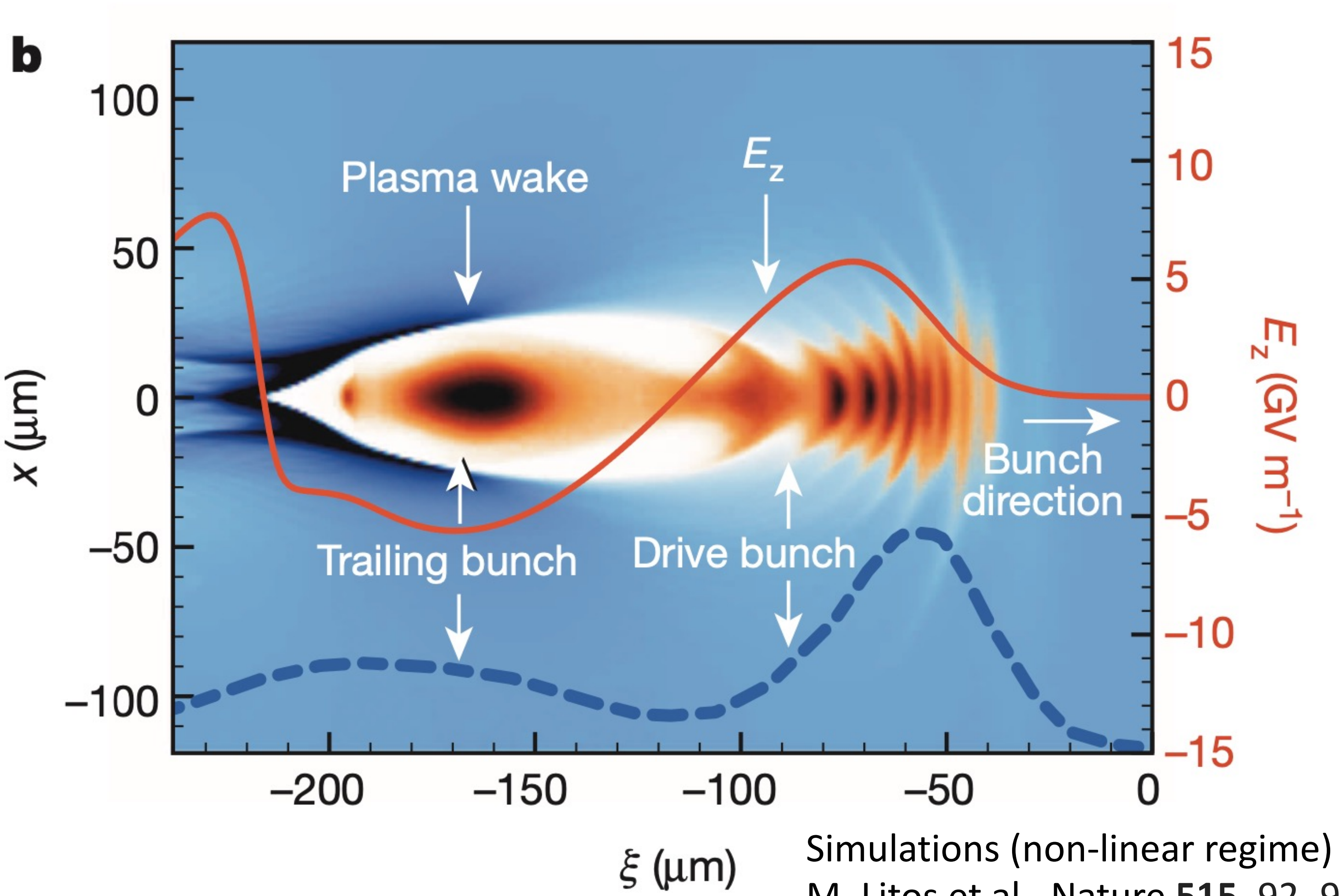

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Wakefields←

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Simulations (non-linear regime)
M. Litos et al., Nature **515**, 92–95 (2014)

23

Plasma Wakefield Acceleration

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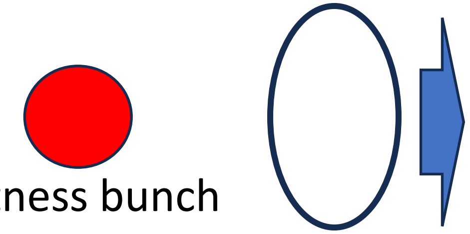
- Laser driven plasma wakefield acceleration (LWFA)



Advantages:

- Compact
- No need for photoinjector
- Extremely high gradients

Disadvantages:

- Light travels at v<c in medium → slower than particles
  → **DEPHASING**
- Pulses carry energy O(J)
  → fast **DEPLETION**
- Light is not focused by uniform plasma
  → need mitigation of **DIFFRACTION**

D's

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Funded by the European Union

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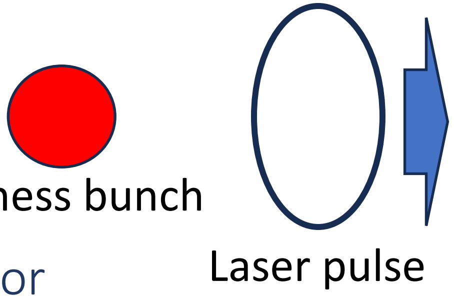

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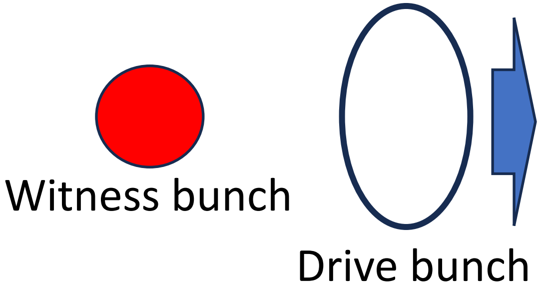

Advantages:

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- Witness bunch quality initially low from injector

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- **Intra-beam alignment issues**
- **Non-trivial bunch separation after plasma**

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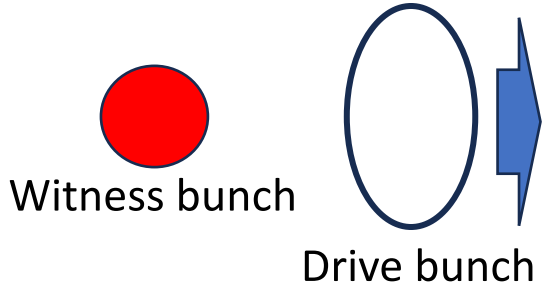

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PWFA Results

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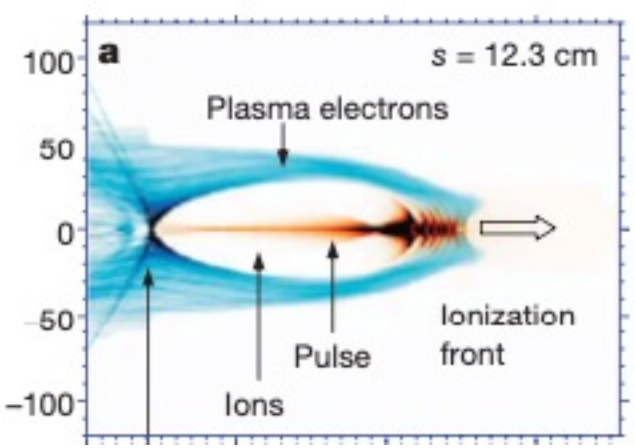
Vol 445|15 February 2007|doi:10.1038/nature05538 nature

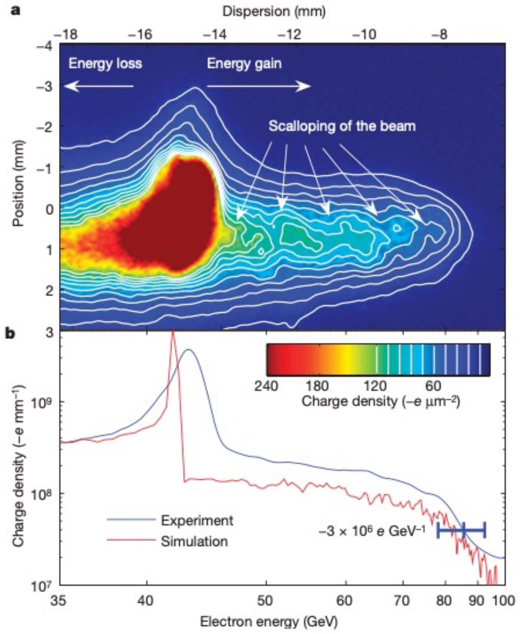
FFTB - SLAC

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]





~ 42 GeV in 85 cm

$n_{pe} = 2.8 \times 10^{17}\ cm^{-3}$

PWFA Results

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From bunch of electrons to electron bunch

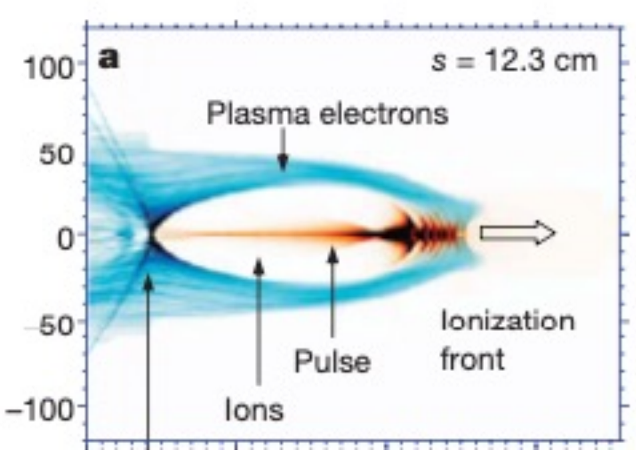
LETTER

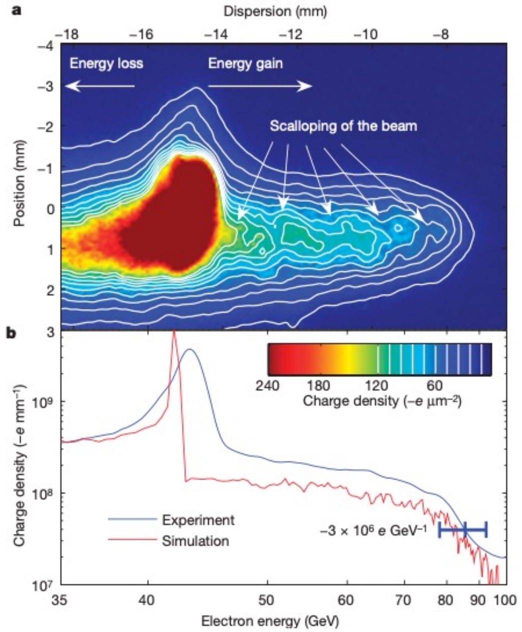
FACET - SLAC

doi:10.1038/nature13882

High-efficiency acceleration of an electron beam in a plasma wakefield accelerator

M. Litos[1], E. Adli[1,2], W. An[3], C. I. Clarke[1], C. E. Clayton[4], S. Corde[1], J. P. Delahaye[1], R. J. England[1], A. S. Fisher[1], J. Frederico[1], S. Gessner[1], S. Z. Green[1], M. J. Hogan[1], C. Joshi[4], W. Lu[5], K. A. Marsh[4], W. B. Mori[3], P. Muggli[6], N. Vafaei-Najafabadi[4], D. Walz[1], G. White[1], Z. Wu[1], V. Yakimenko[1] & G. Yocky[1]





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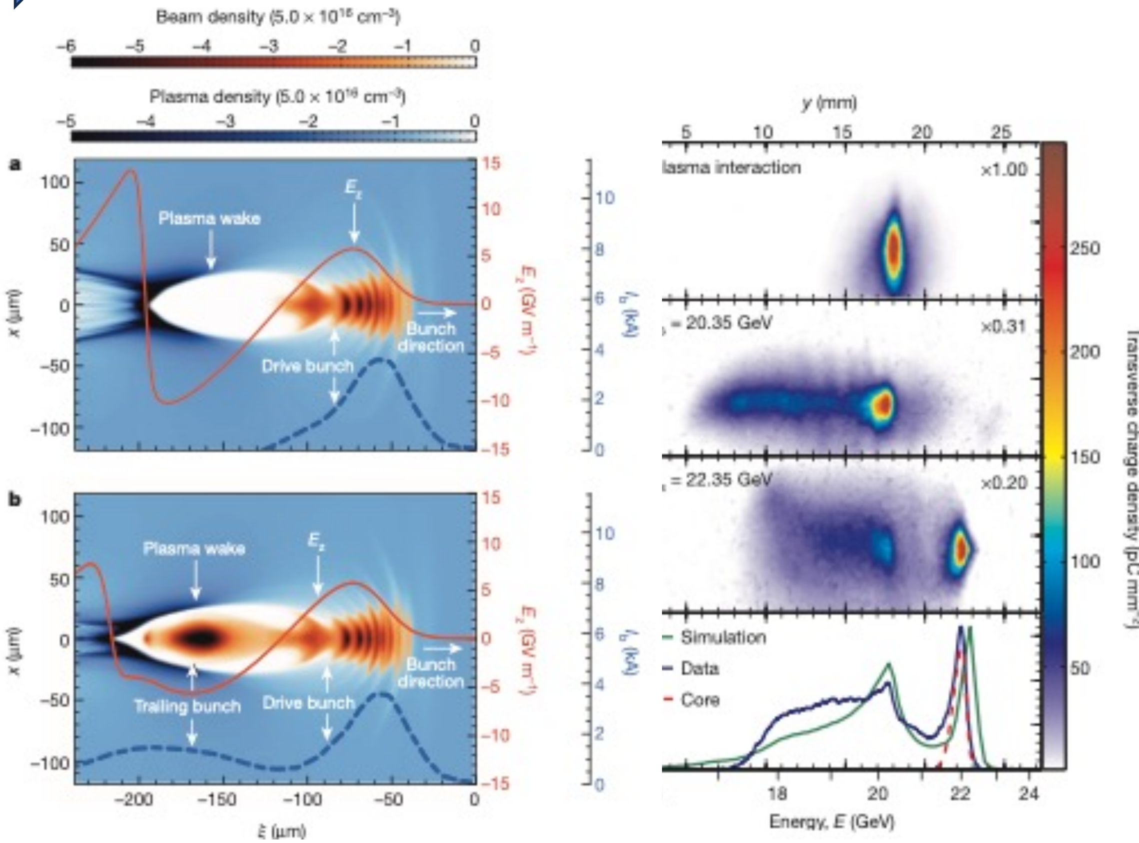

PWFA → FEL

Funded by the European Union

Beam Quality: Energy spread minimization

nature physics
LETTERS
https://doi.org/10.1038/s41567-020-01116-9
Check for updates

Energy spread minimization in a beam-driven plasma wakefield accelerator

R. Pompili[1]✉, D. Alesini[1], M. P. Anania[1], M. Behtouei[1], M. Bellaveglia[1], A. Biagioni[1], F. G. Bisesto[1], M. Cesarini[1,2], E. Chiadroni[1], A. Cianchi[3], G. Costa[1], M. Croia[1], A. Del Dotto[1], D. Di Giovenale[1], M. Diomede[1], F. Dipace[1], M. Ferrario[1], A. Giribono[1], V. Lollo[1], L. Magnisi[1], M. Marongiu[1], A. Mostacci[2], L. Piersanti[1], G. Di Pirro[1], S. Romeo[1], A. R. Rossi[4], J. Scifo[1], V. Shpakov[1], C. Vaccarezza[1], F. Villa[1] and A. Zigler[1,5]

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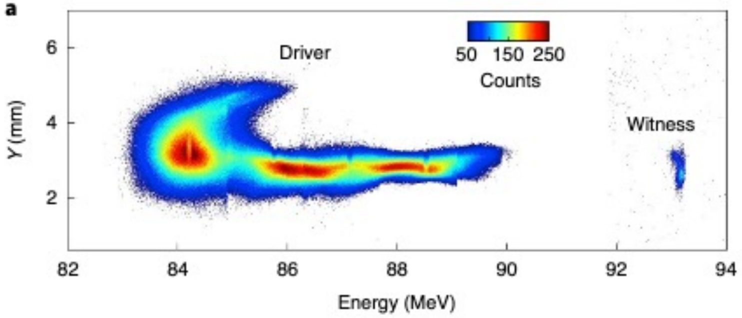

at SPARC_LAB

PWFA→ FEL

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Beam Quality: Energy spread minimization


nature physics

LETTERS

https://doi.org/10.1038/s41567-020-01116-9

Check for updates

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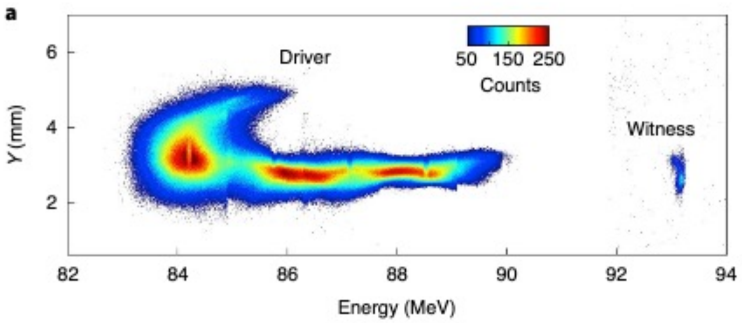
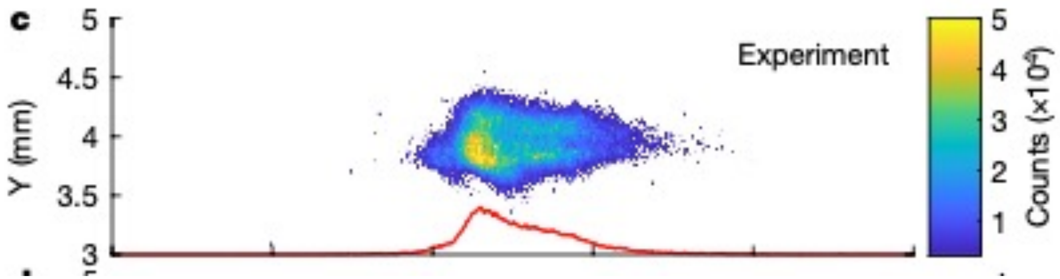


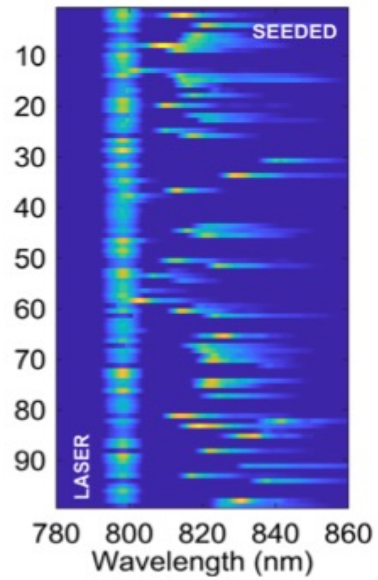
Good enough for lasing

Results building up expertise and paving the way towards EuPRAXIA

Lasing of PWFA witness bunch (SASE)



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



Galletti et al. PRL 129, 234801 (2022)

Lasing of PWFA witness bunch (Seeded)

Requirements for Applications

Free-electron Laser

Conditions for lasing:

$\sigma_E < \varrho \sim 10^{-3}$ → Cold electron beam

$\varepsilon \approx \lambda / 4\pi \sim 0.5$ mm-mrad → Electron-photon phase space matching

$Z_R / L_G > 1$ → Diffraction losses from the beam less than the gain length

Requirements for user facility:

- 1 Hz – 1kHz
- 24/7 operation
- Photon energy tunability
- Flux (high)
- Bandwidth (narrow)

e^+e^- collider

- Need to accelerate both species (positron acceleration being the most outstanding challenge so far)
- >kHz – MHz repetition rate
- Luminosity
  - Emittance << mm - mrad
  - Flat beams (beamstrahlung)
  - High charge per bunch
- Efficiency

Requirements for Applications

Free-electron Laser

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- Flux (high)
- Bandwidth (narrow)

Realizing a plasma-based FEL for users

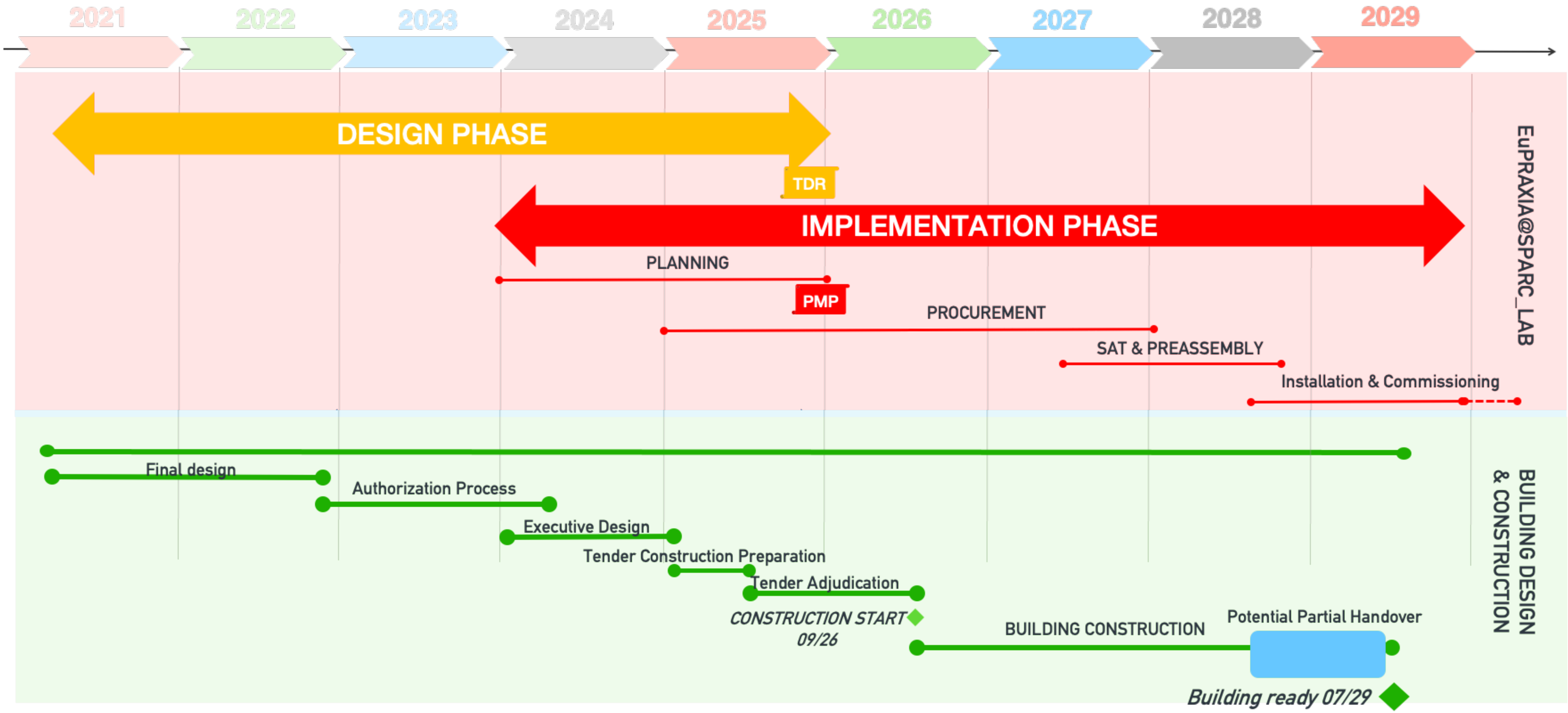
↓

step towards a collider

Plasma-Based Features:

- Compact
- Efficient
- Short Bunches (<fs)
- Large chirp (useful, if one knows how to use it..)
- Emission of Radiation (betatron radiation)

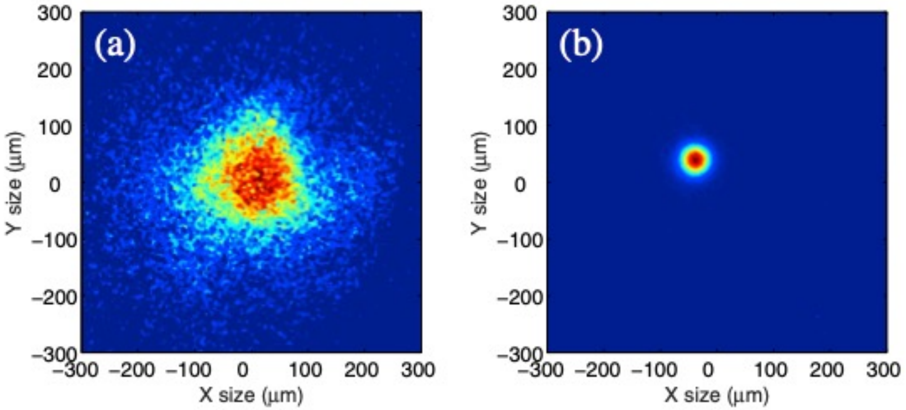
EuPRAXIA@SPARC_LAB - Timeline



Experimental Results (<2023)

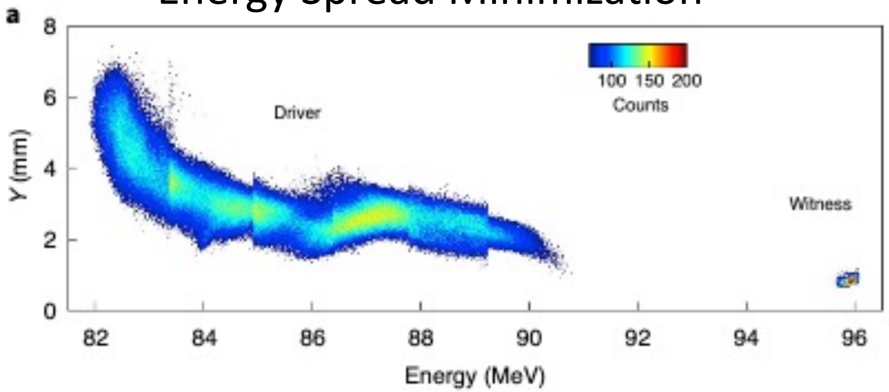
Funded by the European Union

Active Plasma Lens



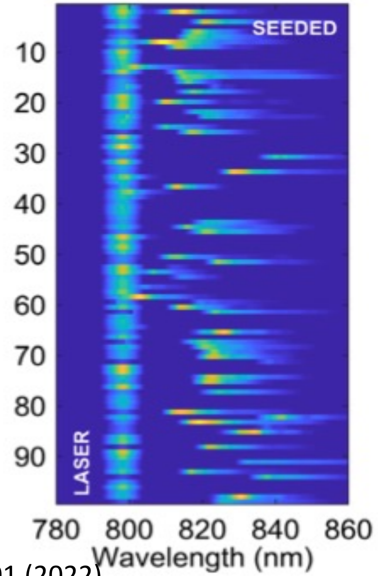
Pompili et al. PRL 121, 174801 (2018)

Energy Spread Minimization



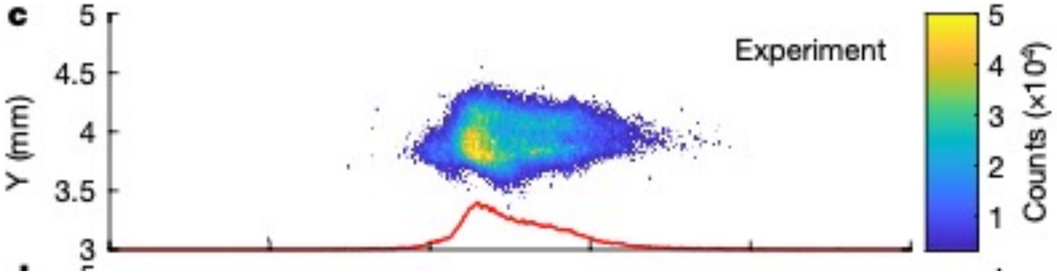
Pompili et al. Nat. Phys. 17, 499-503 (2021)

Lasing of PWFA witness bunch (Seeded)



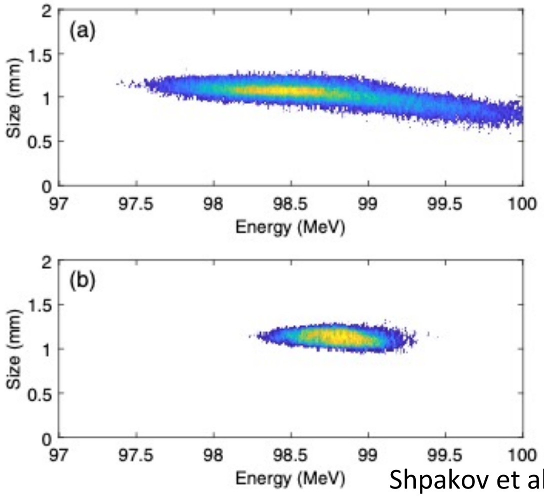
Galletti et al. PRL 129, 234801 (2022)

Lasing of PWFA witness bunch (SASE)



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

Plasma Dechirper

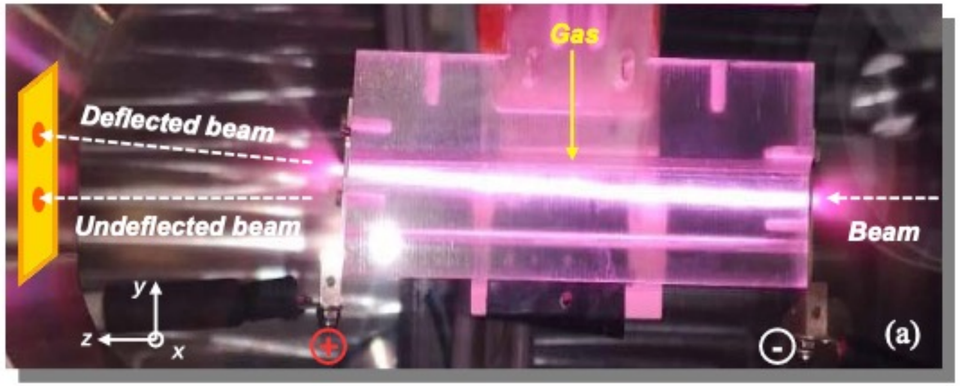


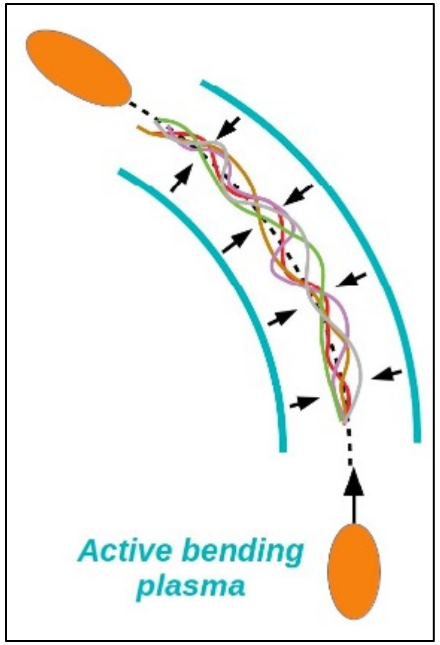
Shpakov et al. PRL 122, 114801 (2019)

Experimental Results (2023)

Funded by the European Union

Guiding of e- bunch in curved plasma

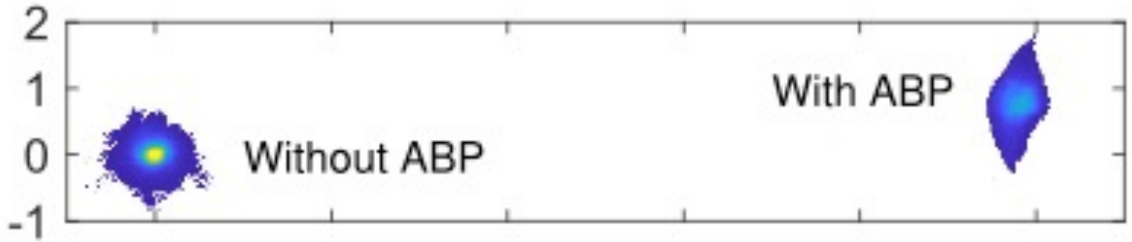




- Active Bending Plasma (ABP) acts as a curved active plasma lens

Azimuthal magnetic field $B_\phi = \frac{\mu_0}{r}\int_0^r J(r')r'dr'$

→ restoring force keeps bunch close to longitudinal axis



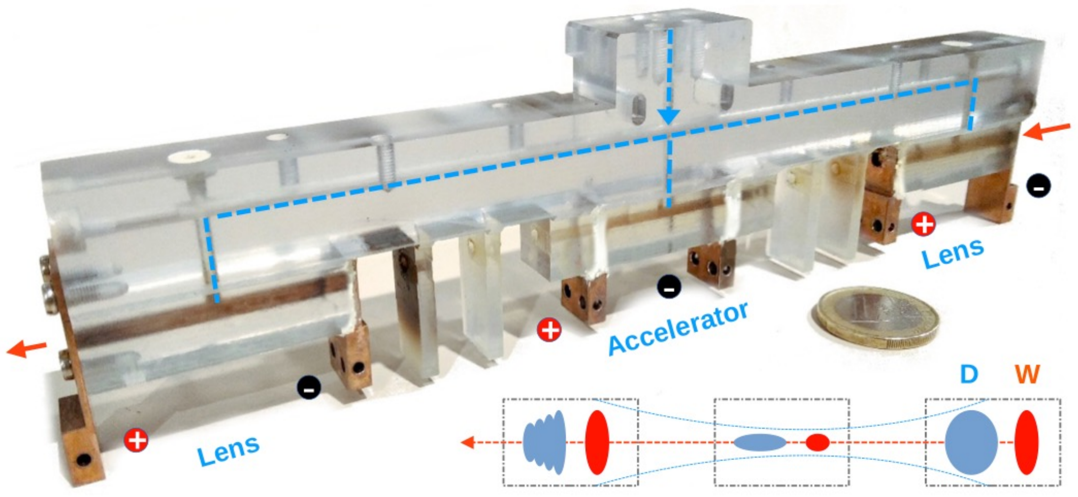
R. Pompili et al., PRL **132**, 215001 (2024)

Experimental Results (2023)

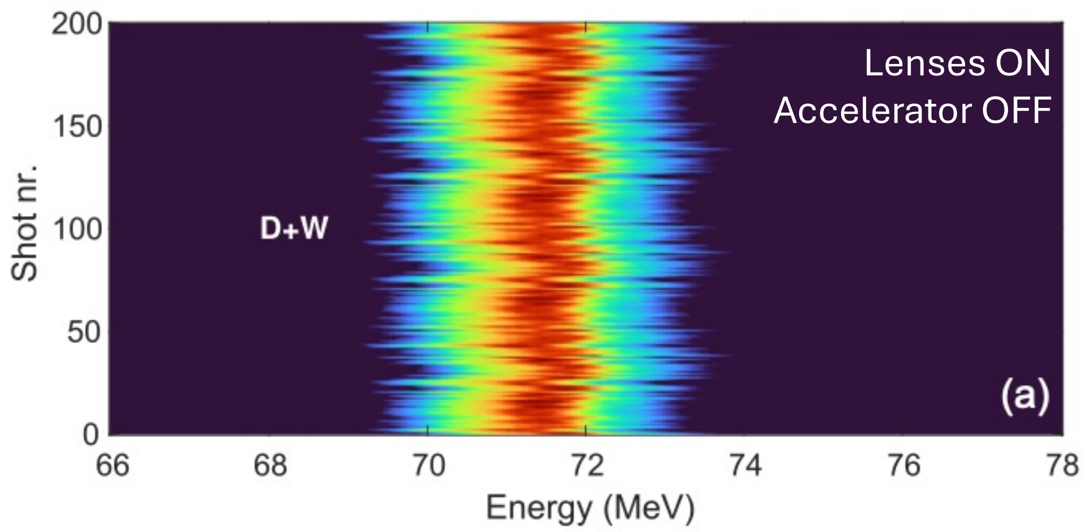
Funded by the European Union

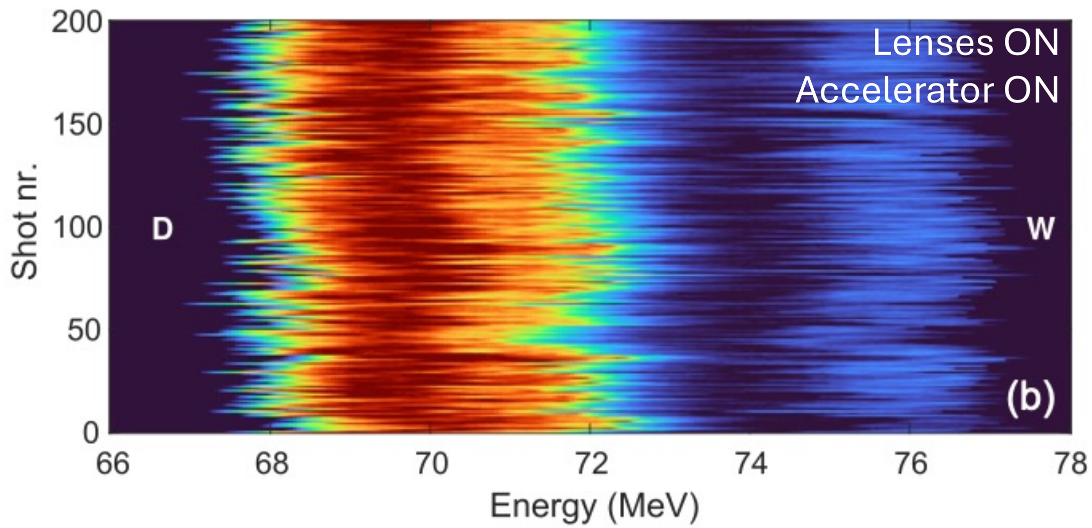
Acceleration and focusing in all-plasma device

- Single device:
  - Active plasma lens for injection
  - Accelerating section
  - Active plasma lens for extraction
- Common gas injection
- Independent discharge pulse circuit for each device



R. Pompili et al., PRE **109**, 055202 (2024)



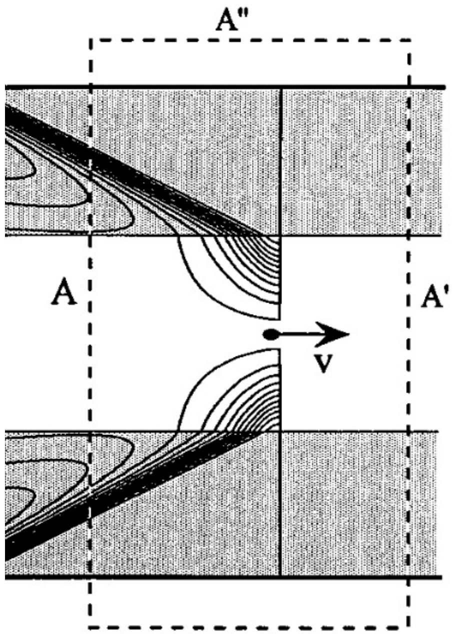


Experimental Results (2023)

Funded by the European Union

Direct observation of space-charge field of the electron bunch

- Space-charge field of relativistic bunches interacts with slow-wave structures
  → Cherenkov/Dielectric wakefields (DW)
  → Acting back on the drive bunch and on the witness bunch



S. S. Baturin, A. D. Kanareykin, PRL **113**, 214801 (2014)
S. Y. Park, J. L. Hirshfield, PRE **62**, 1 (2000)

Experimental Results (2023)

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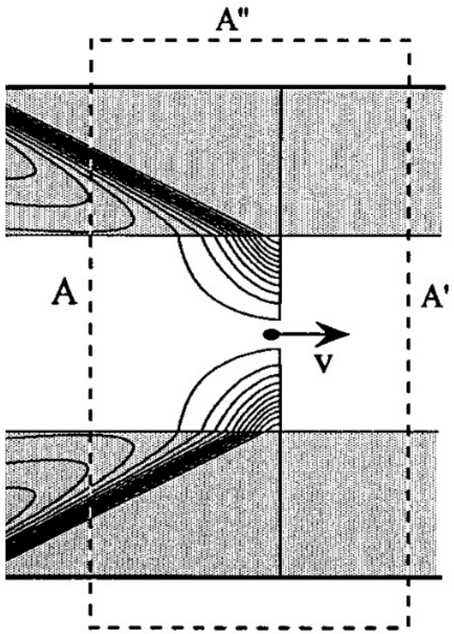
  → Cherenkov/Dielectric wakefields (DW)
  → Acting back on the drive bunch and on the witness bunch

- Beam couples with dipolar mode when traveling off-axis in a dielectric capillary
  → Transverse deflection in the misalignment direction
  → Head-to-tail correlation



S. S. Baturin, A. D. Kanareykin, PRL **113**, 214801 (2014)
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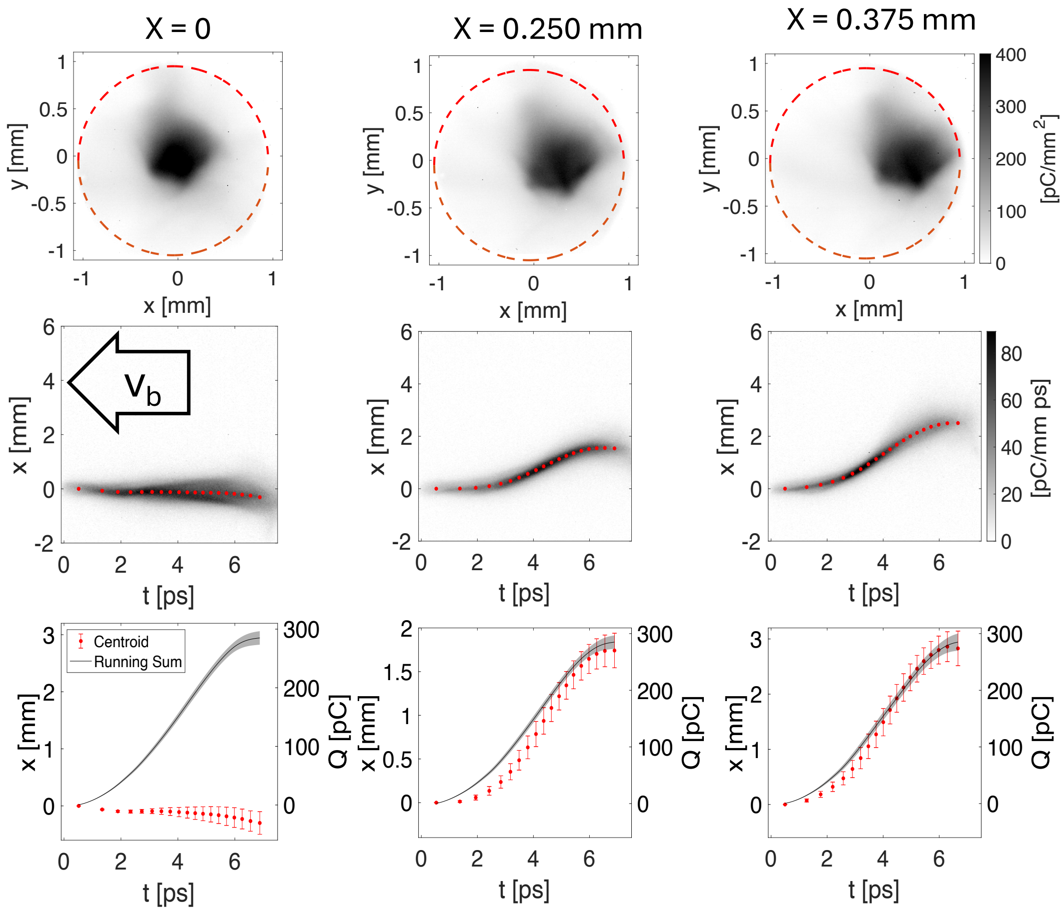


L. Verra et al., accepted PRL
https://arxiv.org/abs/2406.11314

Experimental Results (2023)

Funded by the European Union

Direct observation of space-charge field of the electron bunch

- Space-charge field of relativistic bunches has the same properties of an electromagnetic field
- Plasma screens electromagnetic fields as $E_r \propto e^{-\frac{r}{\delta}}$ ➔ full screening at r >> plasma skin depth $\delta = c\sqrt{\frac{m_e\epsilon_0}{n_{pe}^2 q}}$

L. Verra et al., accepted PRL
https://arxiv.org/abs/2406.11314

Experimental Results (2023)

Funded by the European Union

Direct observation of space-charge field of the electron bunch

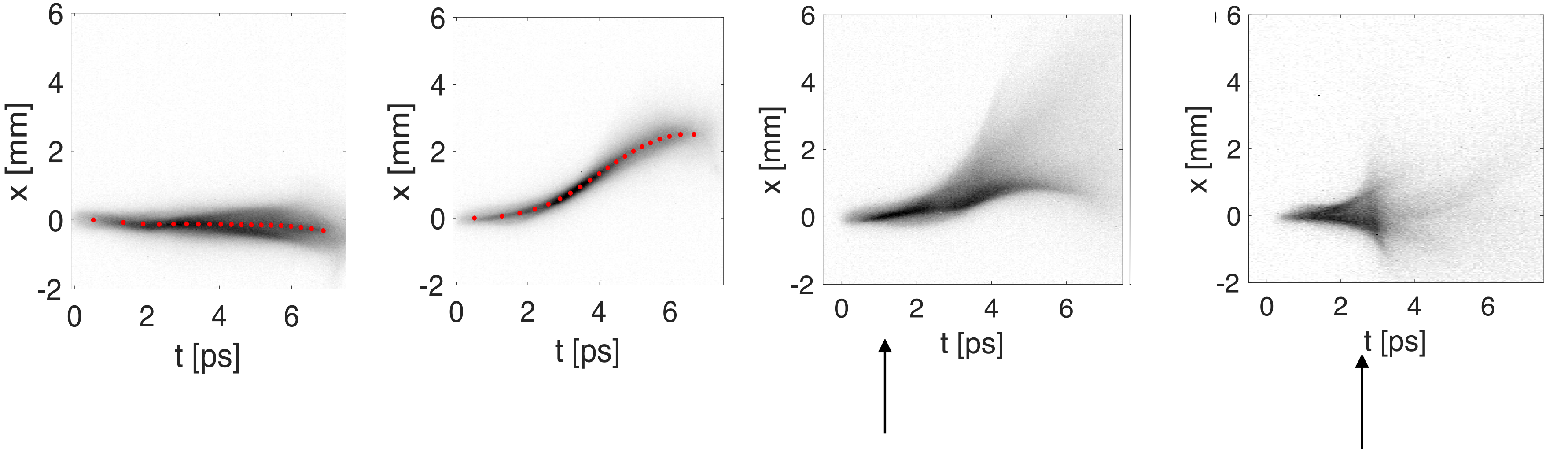
- Space-charge field of relativistic bunches has the same properties of an electromagnetic field
- Plasma screens electromagnetic fields as $E_r \propto e^{-\frac{r}{\delta}}$ ➔ full screening at r >> plasma skin depth $\delta = c\sqrt{\frac{m_e \epsilon_0}{n_{pe}^2 q}}$
- No dielectric wakefields when Beam-To-Capillary distance D >> δ

Aligned
No plasma

Misaligned
No plasma

Misaligned
$n_{pe} = 0.038 \cdot 10^{14}$ cm^{-3}

Misaligned
$n_{pe} = 1.0 \cdot 10^{14}$ cm^{-3}



Implications on alignment tolerances in PWFA → EuPRAXIA

Density too low
→ DW still present

Density high enough
→ DW suppressed

L. Verra et al., accepted PRL
https://arxiv.org/abs/2406.11314

Experimental Results (2023)

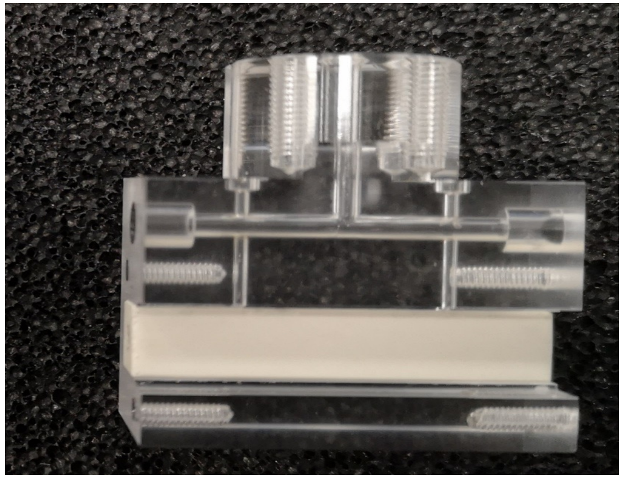
Funded by the European Union

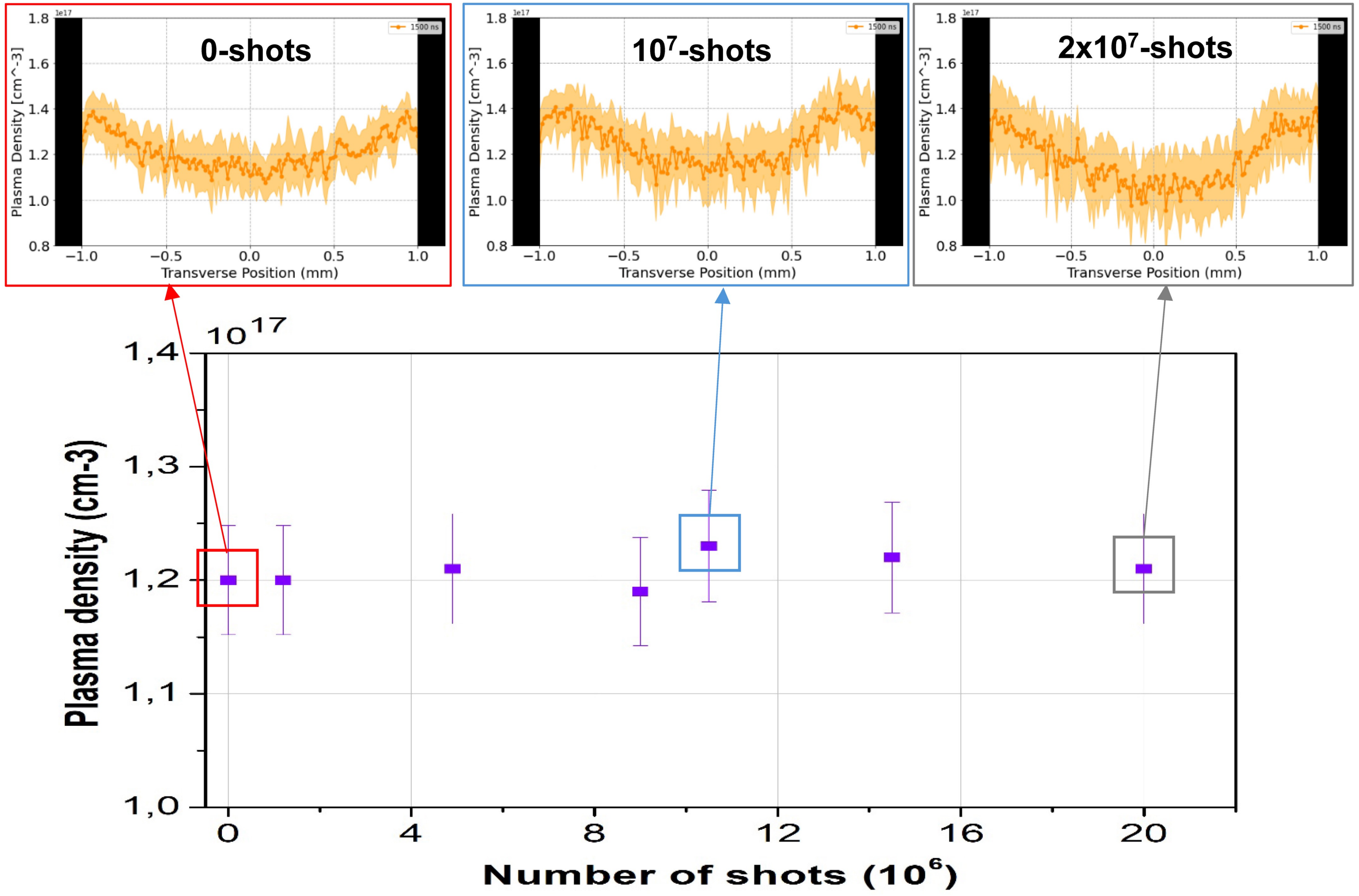
Development of high repetition rate plasma source

Intense activity to demonstrate:

- High repetition rate and material resistance
- High plasma density uniformity and repitability

Shapal → Ceramic material with high heat conductivity and melting temperature





Angelo Biagioni, Lucio Crincoli, Romain Demitra

Experimental Results (2023)

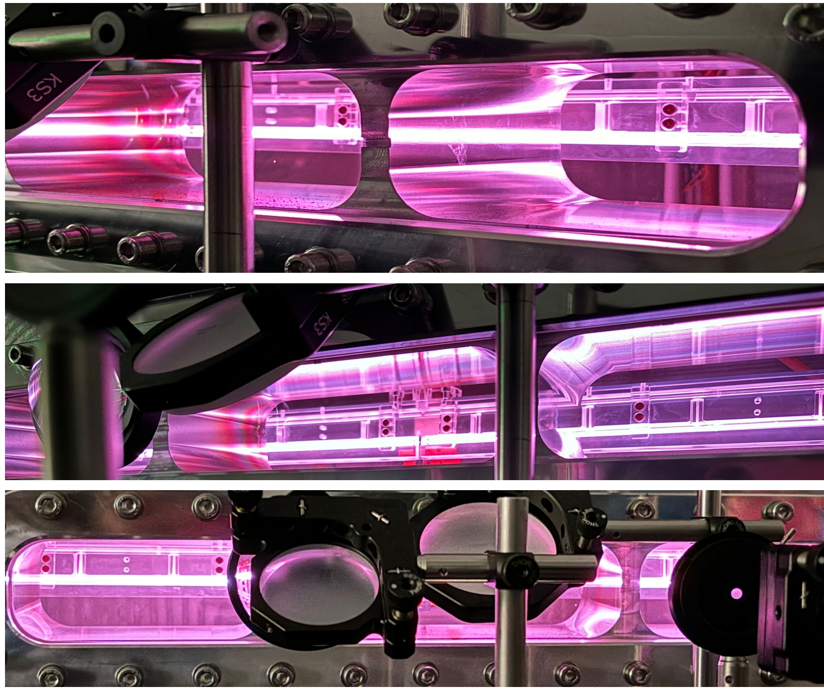
Funded by the European Union

Development of high repetition rate plasma source

Intense activity to demonstrate:

- High repetition rate and material resistance
- High plasma density uniformity and repitability

} Over a 60-cm-long capillary



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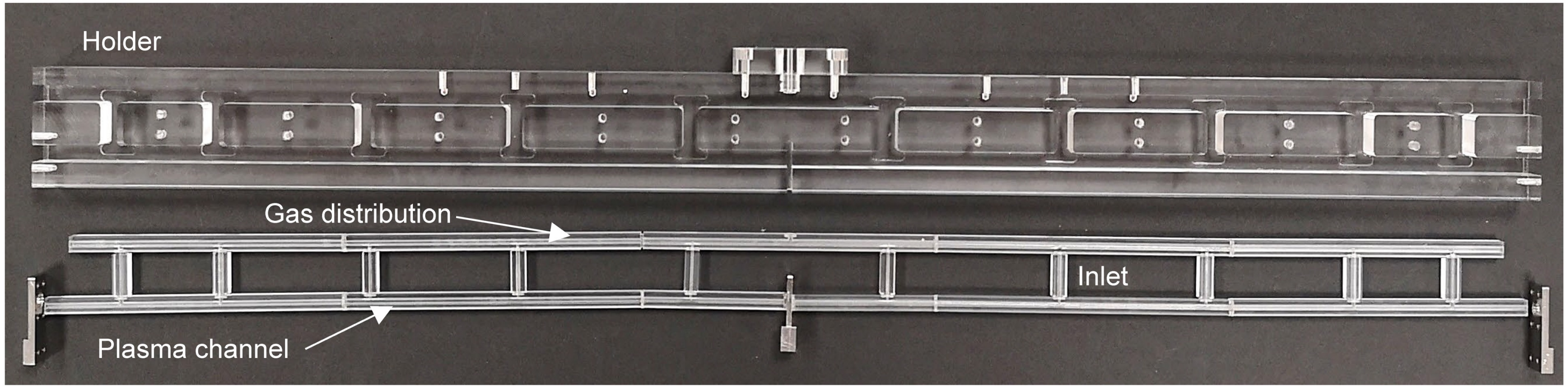


Angelo Biagioni, Lucio Crincoli, Romain Demitra

EuAPS Project

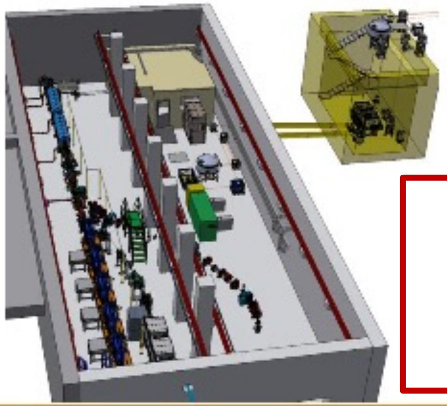
Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | EuPRAXIA Advanced Photon Sources

EuPRAXIA Advanced Photon Sources (EuAPS)

- Supported by PNRR funding
- Collaboration among INFN, CNR, University of Tor Vergata
- EuPRAXIA → *laser-driven betatron radiation source @SPARC_LAB*
  → development of high power (up to 1 PW at LNS) and high repetition rate (up to 100 Hz at CNR Pisa) laser
  → pre-cursor for user-facility

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).

Parameter	Value	unit
Electron beam Energy	100-500	MeV
Plasma Density	10^{18}-10^{19}	cm^{-3}
Photon Critical Energy	1 -10	keV
Number of Photons/pulse	10^{7}-10^{9}	
Repetition rate	1-5	Hz
Beam divergence	3-20	mrad



Good example of exploiting the unique features of plasma-based accelerators!

'EuPRAXIA Advanced Photon Sources PNRR_EuAPS Project', M. Ferrario et al. INFN-23-12-LNF (2023)

23

SABINA Project

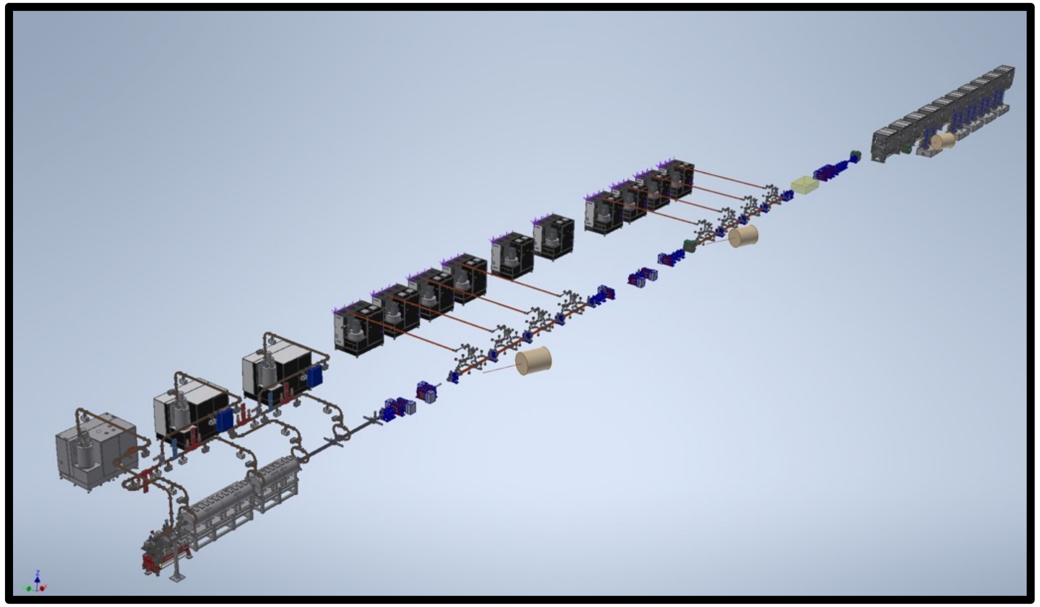
Upgrade of SPARC Linac + THZ FEL line

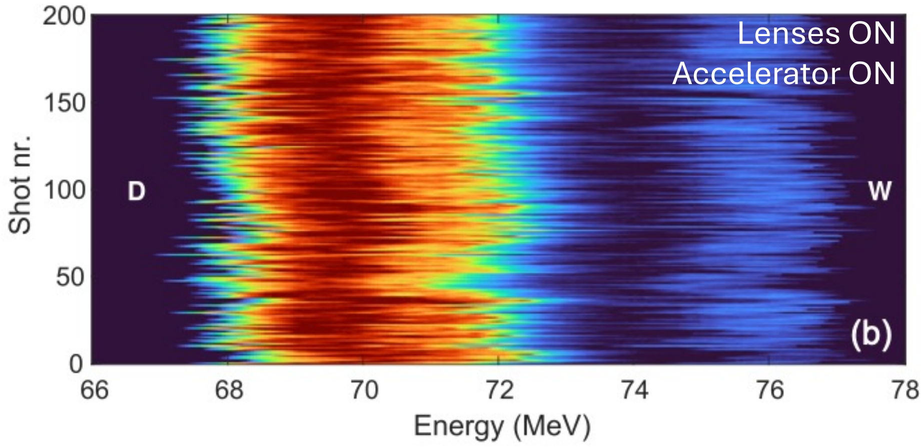
→ See Ilaria Balossino’s talk later!

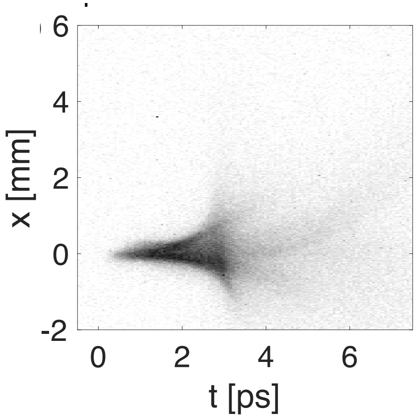
Conclusions

Funded by the European Union

- EuPRAXIA: distributed European facility within ESFRI
  → Goals: building 2 plasma-based FELs
- EuPRAXIA@SPARC_LAB will be the beam-driven FEL at LNF
- First ”real” plasma-based accelerator delivering beam to users
  - Step towards collider
- In the meantime, developments based on beautiful physics



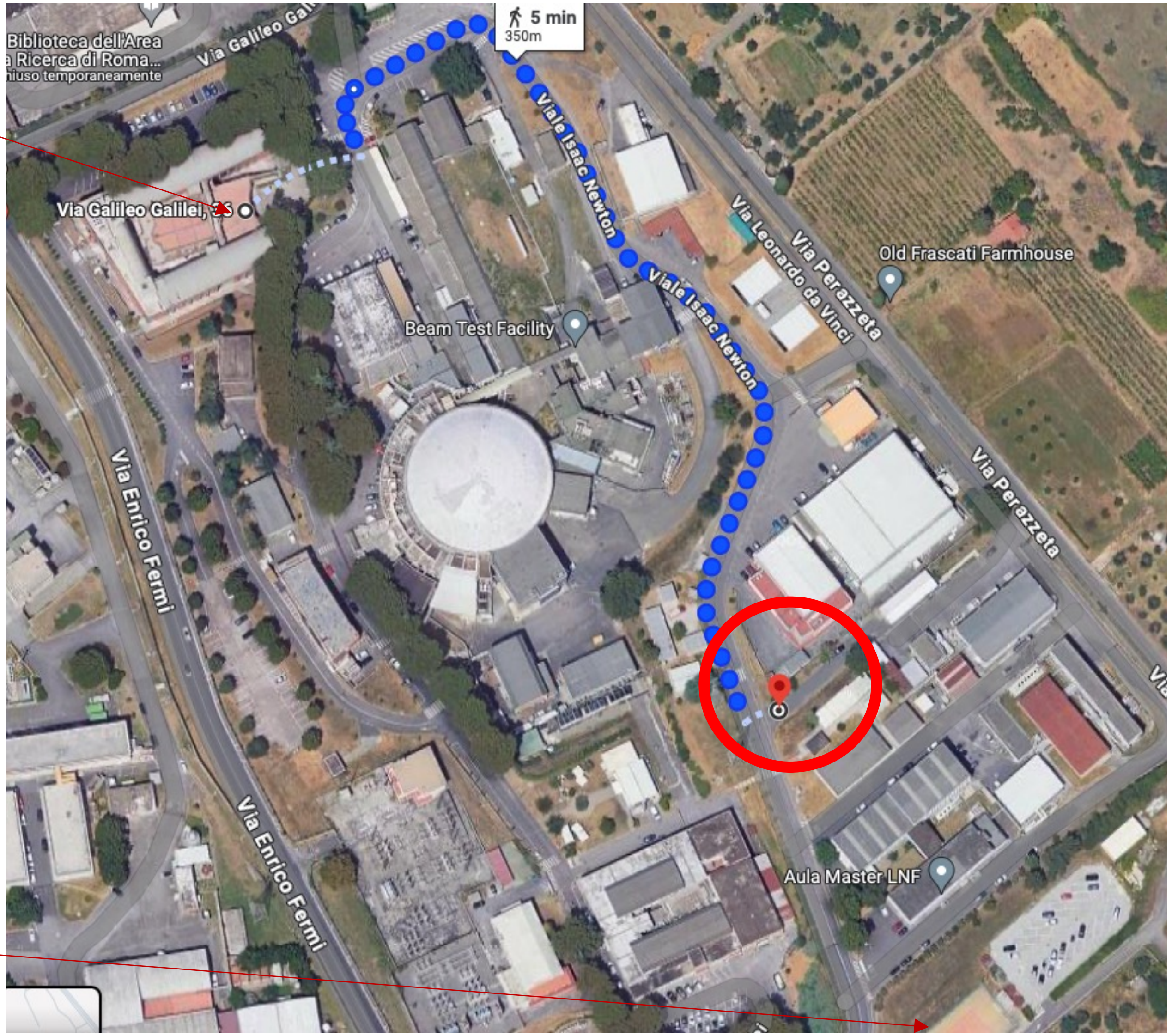




Guided tour at SPARC

WE ARE HERE

LUNCH



EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

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