Plasma Wakefield Acceleration

The long and winding road from proof-of-principle experiments to colliders

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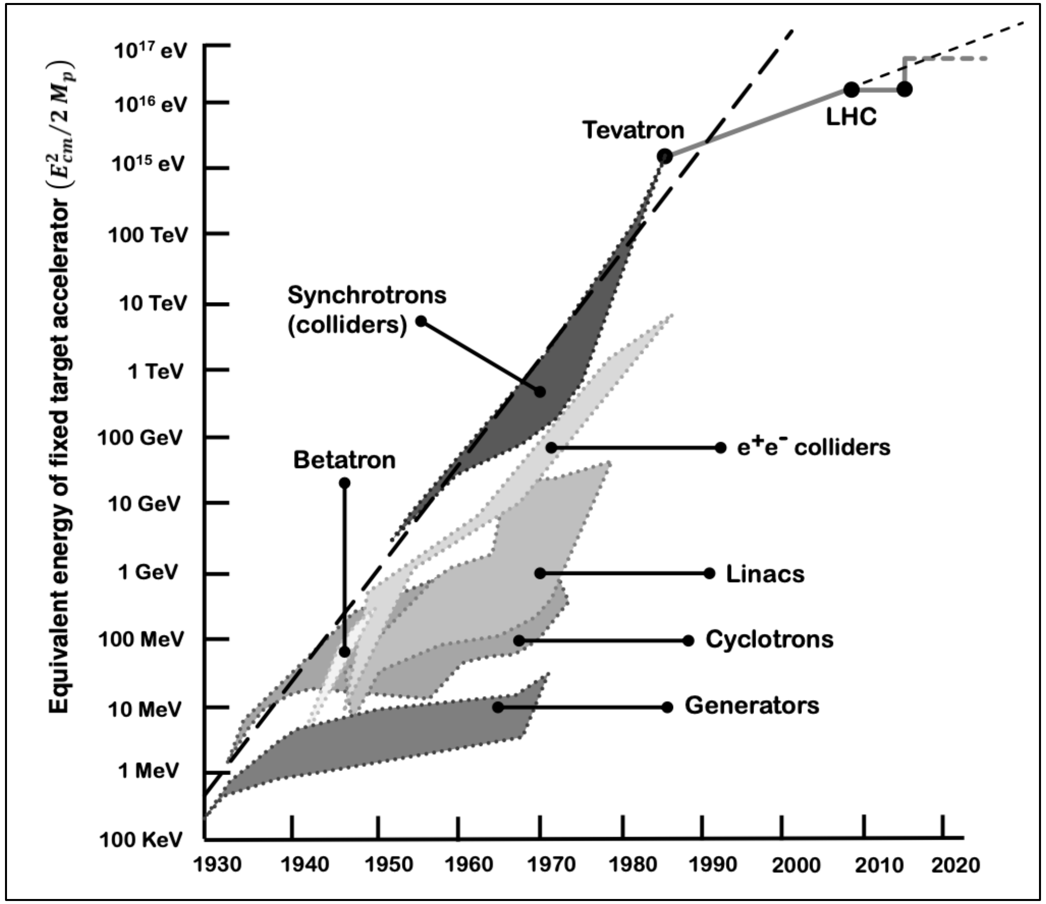
Particle Accelerators

"Livingston" plot of evolution of accelerators



A. Seryi, Unifying physics of accelerators, lasers and plasma

→ New technology allows for a jump in energy and in applications

→ Have we reached saturation of RF technology?

→ Can we reach higher energies in shorter distance?

Next HEP machine will probably be:

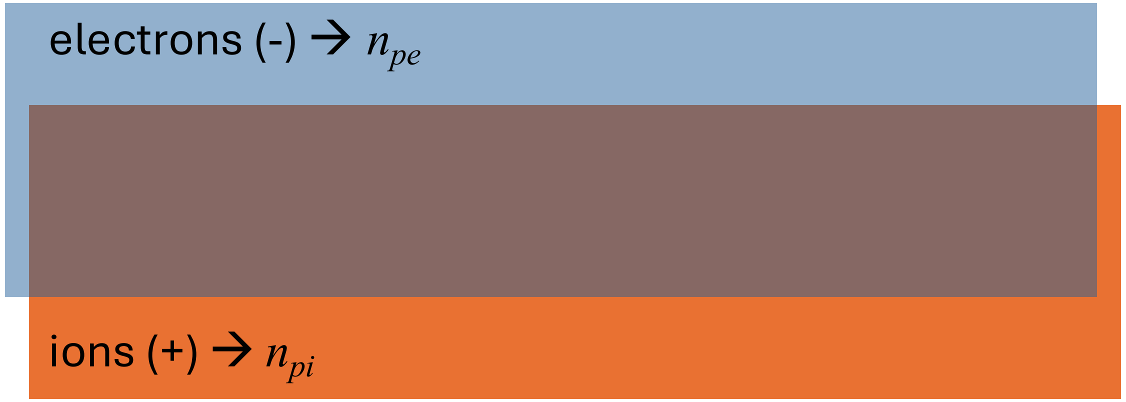
- Higgs factory (center of mass>250 GeV)
- Discovery machine with center of mass >>TeV

→ **This is where plasma comes into play!**

Plasma

What we talk about, when we talk about **plasma**:

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



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Plasma – Space Charge Screening

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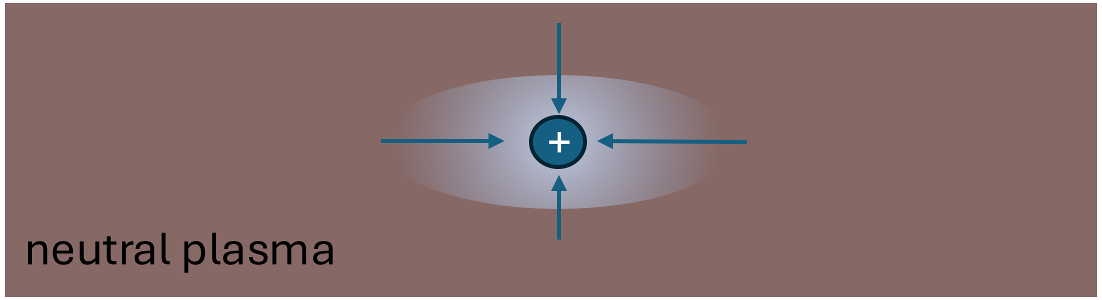
  → It tends to keep the charge and current neutrality:
  Plasma electrons (m_{pi}>>m_{pe}) move to compensate for the disturbance
  → Plasma screens electromagnetic fields



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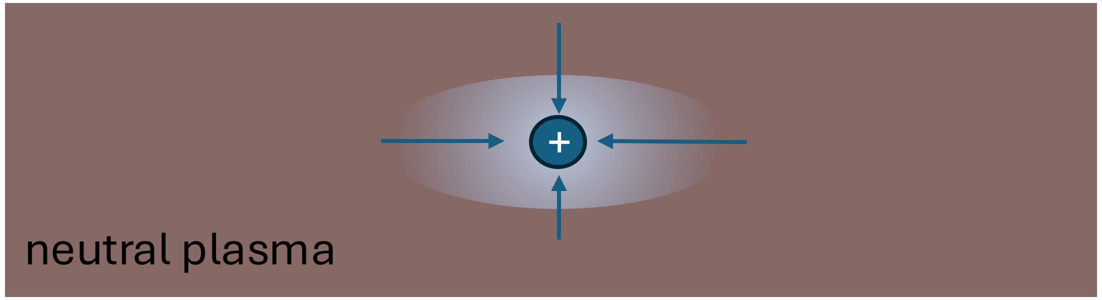

When the equilibrium is perturbed:

- Electrons oscillate with angular frequency $\omega_{pe} = \sqrt{\frac{n_{pe}e^2}{m_e \varepsilon_0}}$

- Ions with $\omega_{pi} = \sqrt{\frac{n_{pi}e^2}{m_i \varepsilon_0}} \ll \omega_{pe}$ (ions considered immobile for short time-scales)

Plasma Wakefields Excitation

- Let's take a plasma with density n_{pe}
- Let's take a relativistic charged bunch (e.g. e^-) with density $n_b << n_{pe}$ (roughly the same for laser pulses)

1. Transverse E field expels plasma electrons

(inspired by P. Muggli's CAS lecture)

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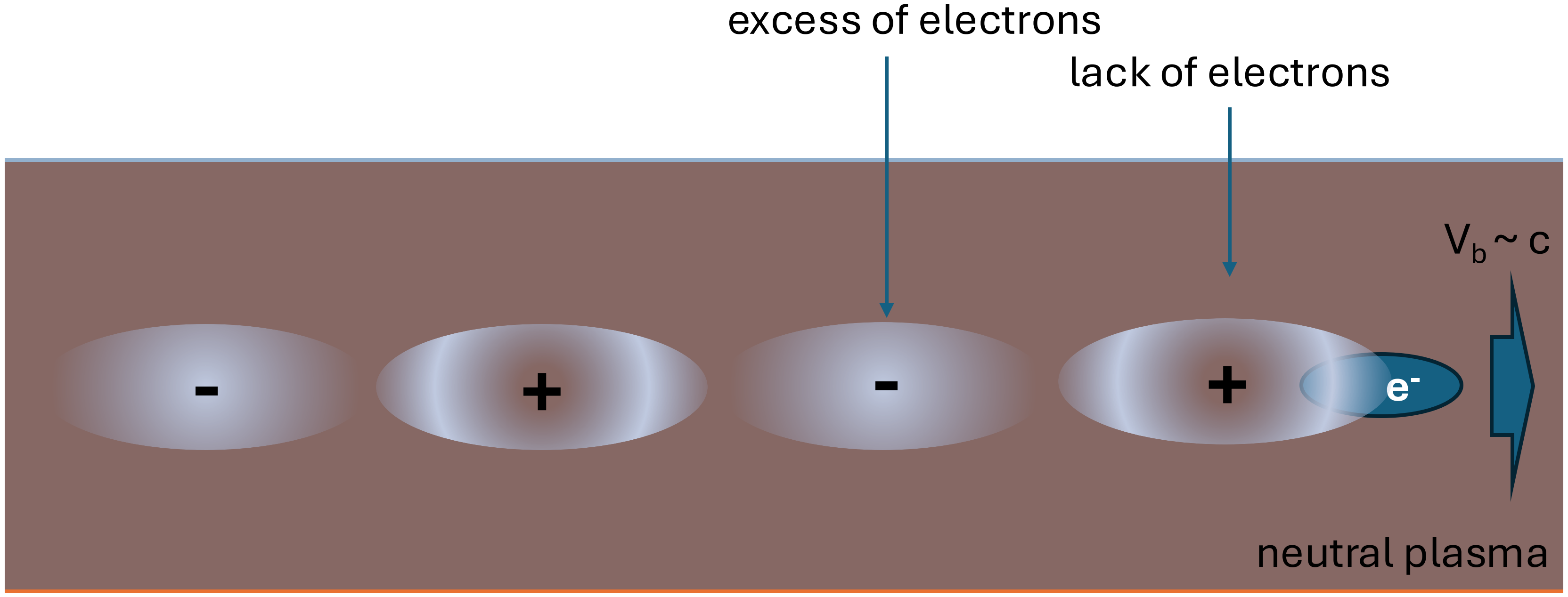

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1. Transverse E field expels plasma electrons
2. Positively charged region behind the bunch head
   → restoring force

Linear regime: plasma electrons DO NOT cross longitudinal axis: PERTURBATION!!
Blowout (non-linear) regime: electrons DO cross the axis

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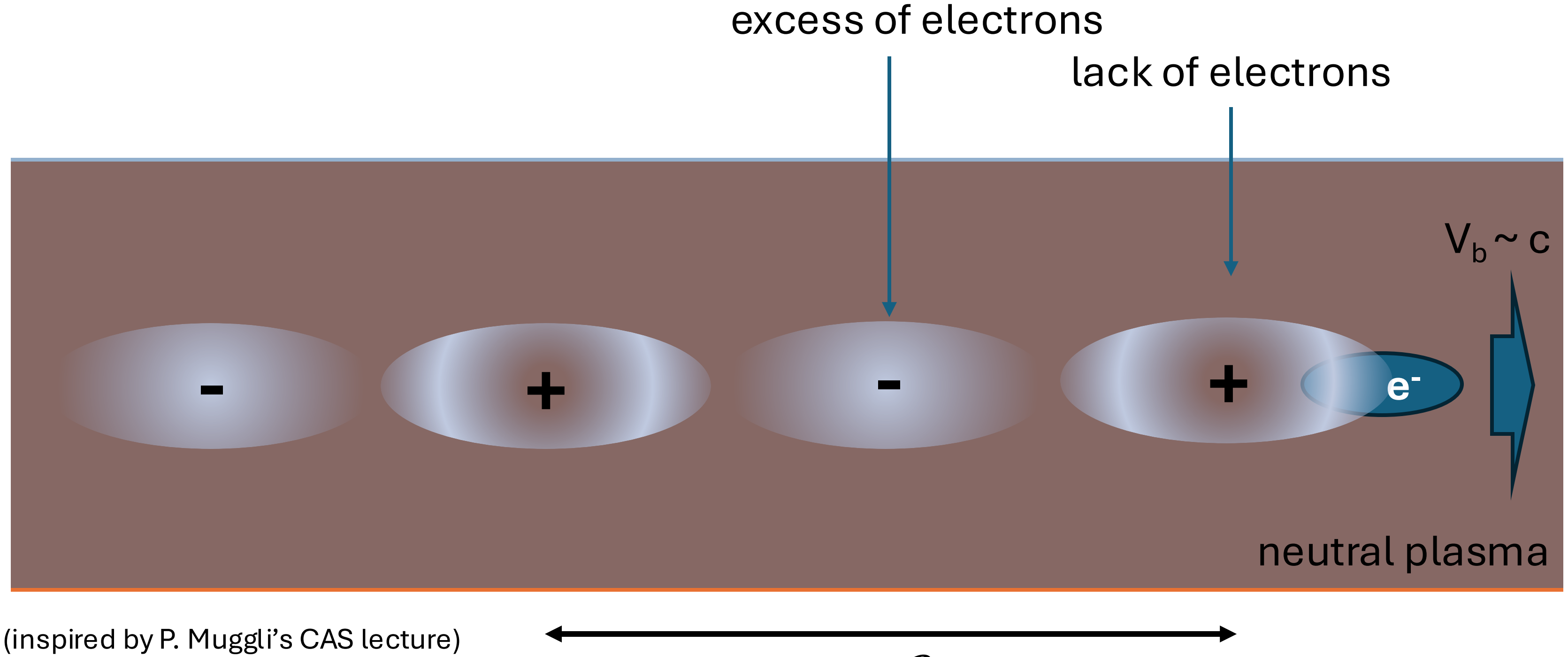

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$$\lambda_{pe} = \frac{2\pi c}{\omega_{pe}}$$

1. Transverse E field expels plasma electrons
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3. Oscillation of plasma e^- with ω_{pe}
   → periodic density variation

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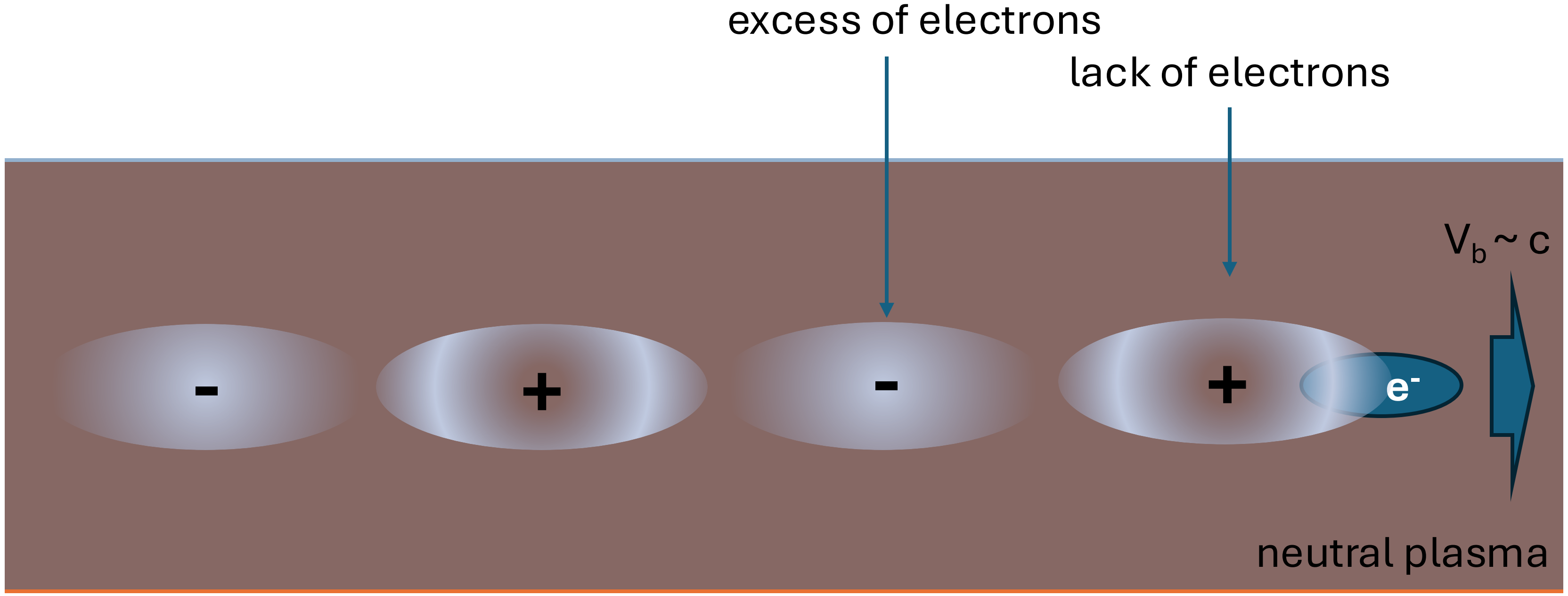

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$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

→ Wakefields ←

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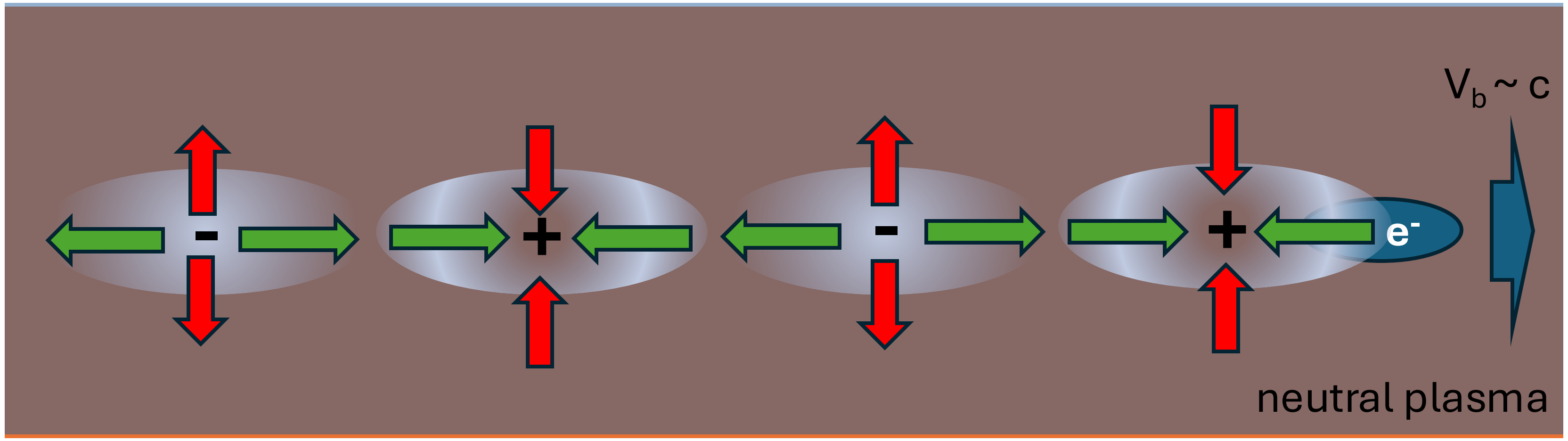
- **Wake travels at driver's velocity (no dephasing using relativistic bunches)**



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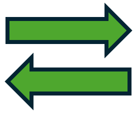
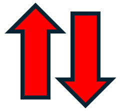
 Longitudinal (accelerating – decelerating) wakefields

$$E_z(\xi, r) = \frac{n_{b0} q}{\varepsilon_0} \int_{-\infty}^{\xi} n_{b||}(\xi') cos(k_{pe}(\xi - \xi')) d\xi' \cdot R(r)$$

 Transverse (focusing – defocusing) wakefields

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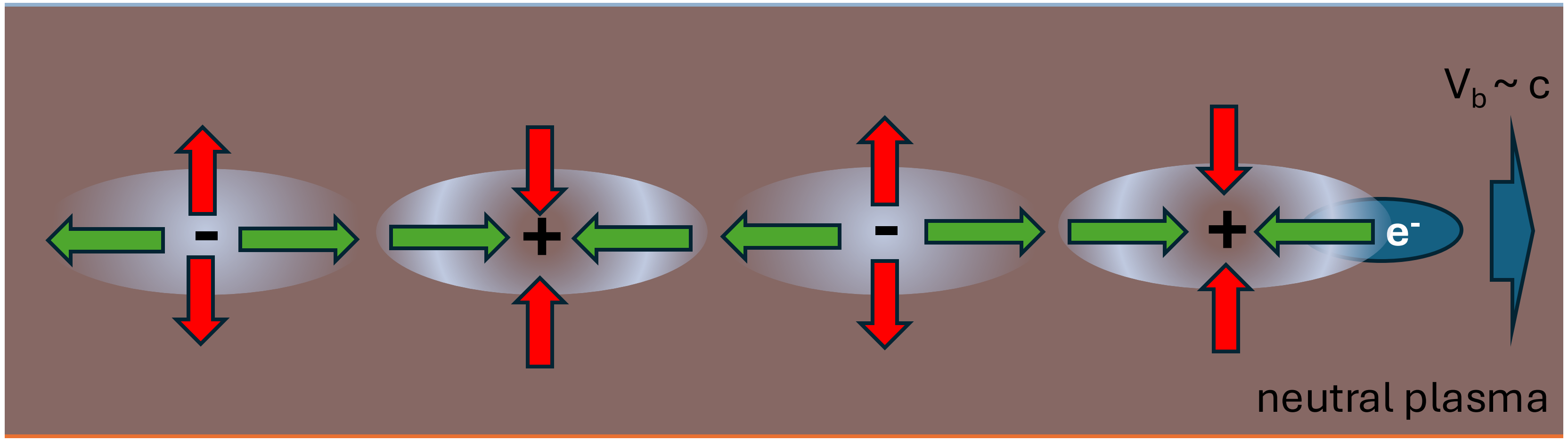

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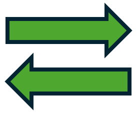
→ Wakefields ←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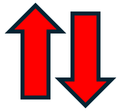
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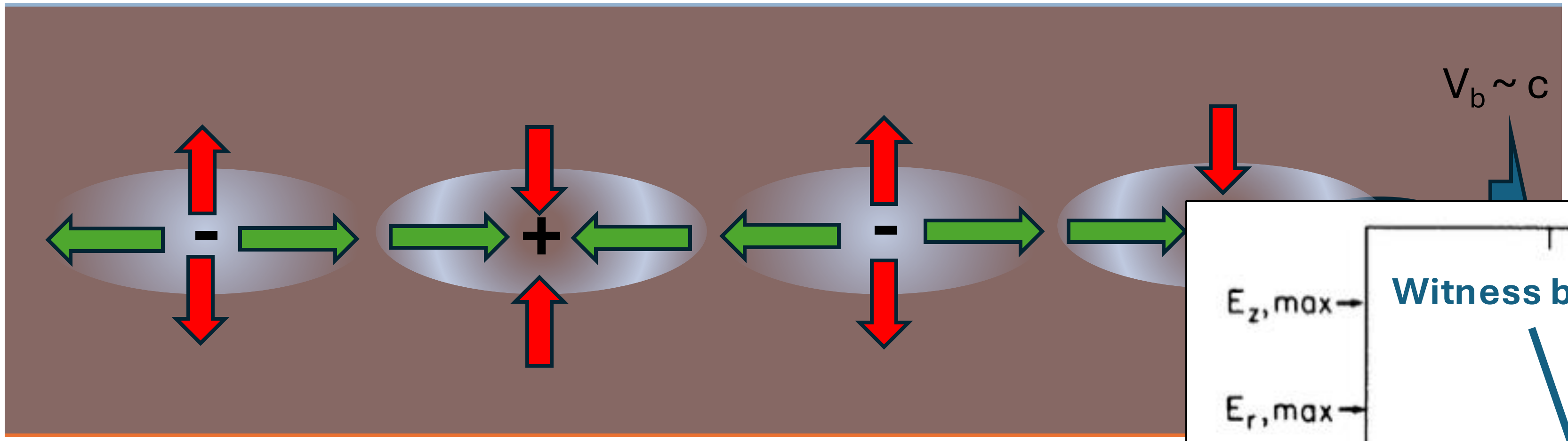

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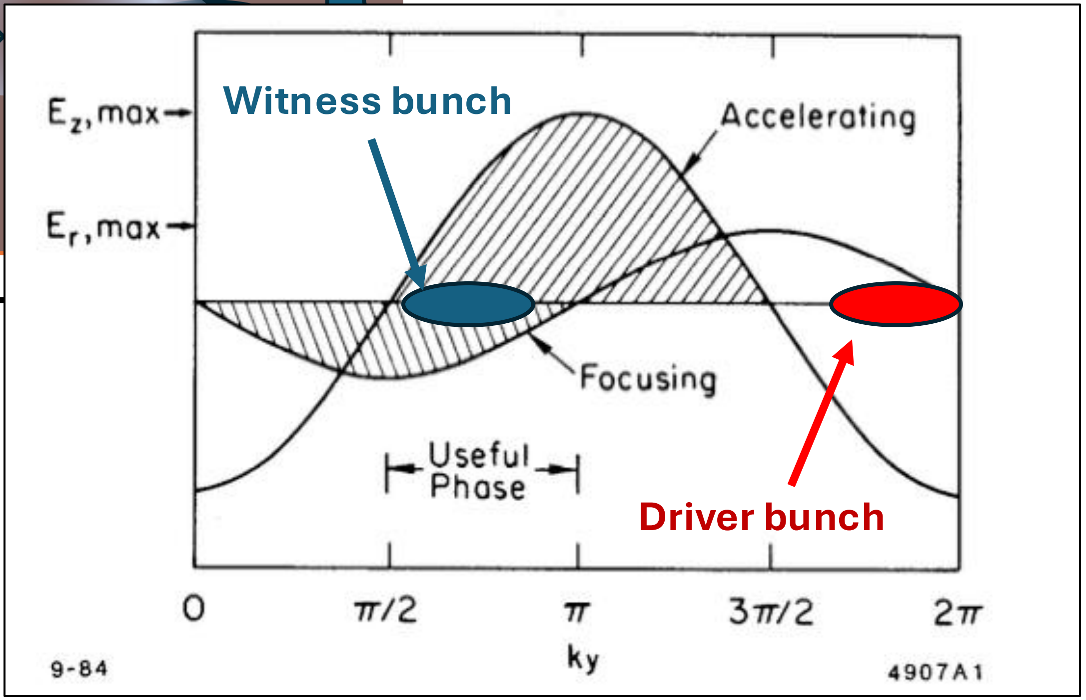
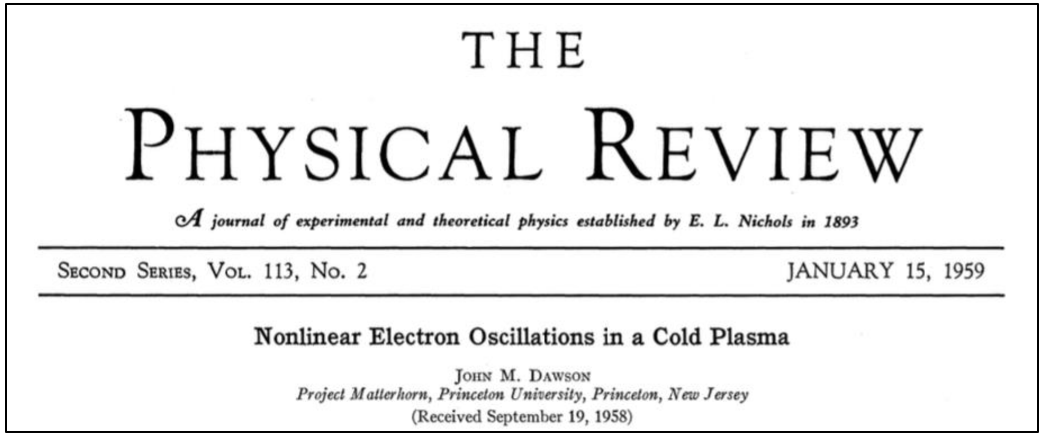


Longitudinal (accelerating – decelerating) wakefields

Transverse (focusing – defocusing) wakefields

Accelerating Gradient

- Fields in plasmas are sustained by the charge separation
  - As high as the cold wave-breaking field: $E_{WB} = \frac{m_e\, c\, \omega_{pe}}{q}$ → oscillation length cannot exceed plasma wavelength
  - E.g. for n_{pe} = (10^{14} – 10^{18}) cm^{-3}, $E_{WB} \sim 100 \frac{V}{m} \sqrt{n_{pe}[\,cm^{-3}]}$ = (1 – 100 GV /m)


THE

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SECOND SERIES, VOL. 113, No. 2 JANUARY 15, 1959

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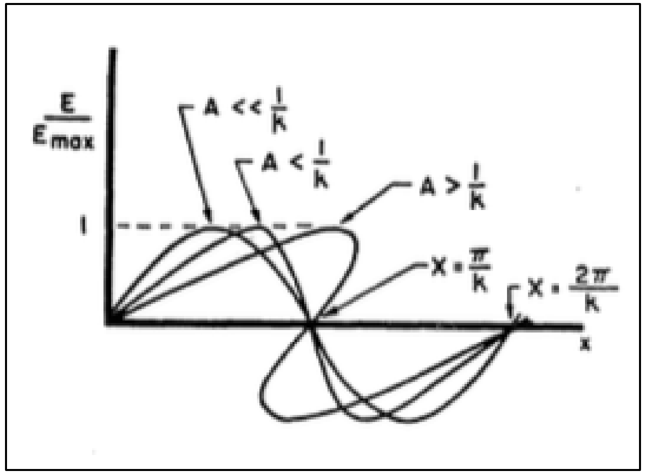

Wave «breaks» when the maximum amplitude is reached

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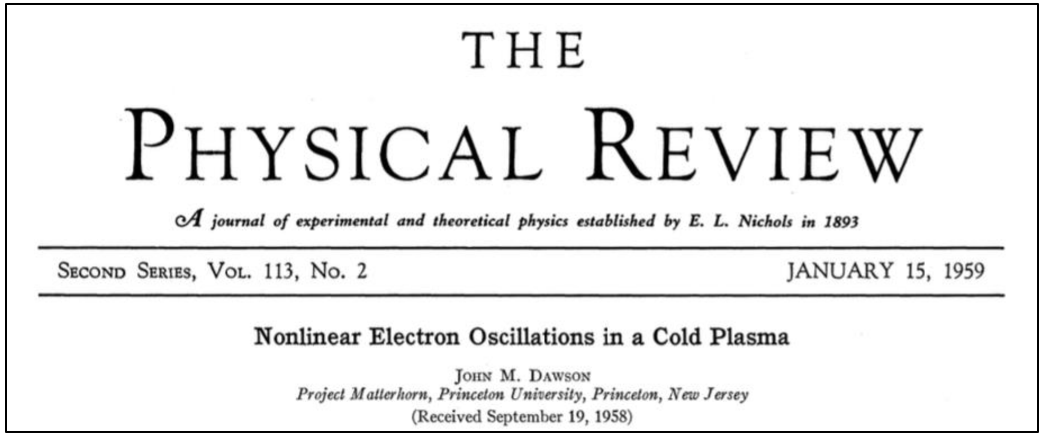
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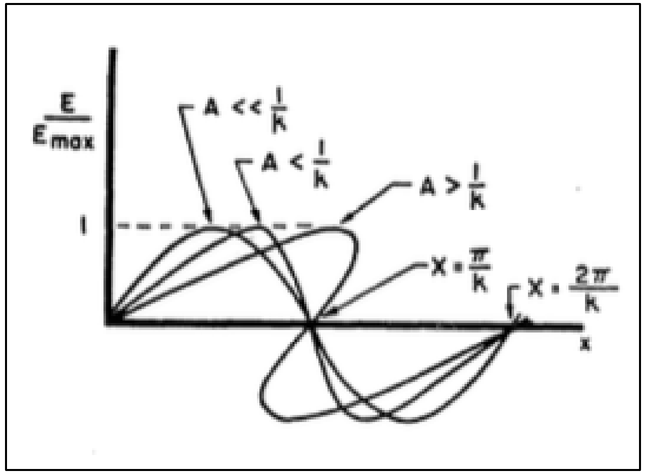

Wave «breaks» when the maximum amplitude is reached

- RF cavities limited to 100MV/m by breakdown, caused e.g. by fatigue, pulse heating, etc..

➔ one could dream of shrinking down the size of accelerators by orders of magnitude

Accelerating Gradient – Experimental Results

Laser Wakefield Acceleration (LWFA)

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

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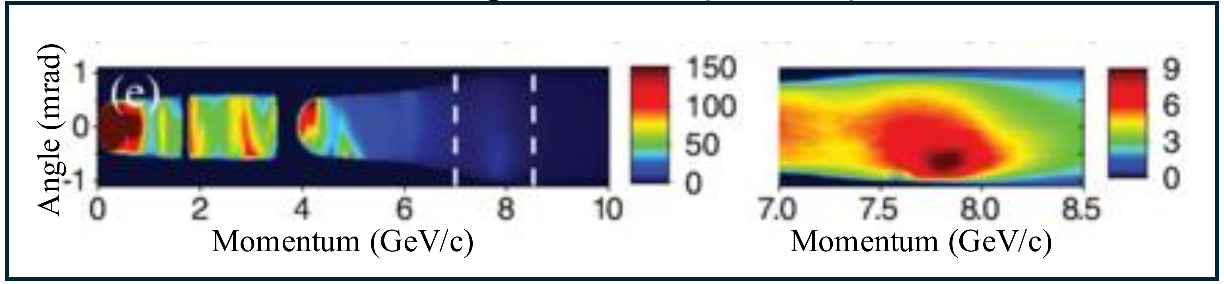

~ 8 GeV in 20 cm → ~40GV/m
n_{pe} = 3.4 x 10^{17} cm^{-3}

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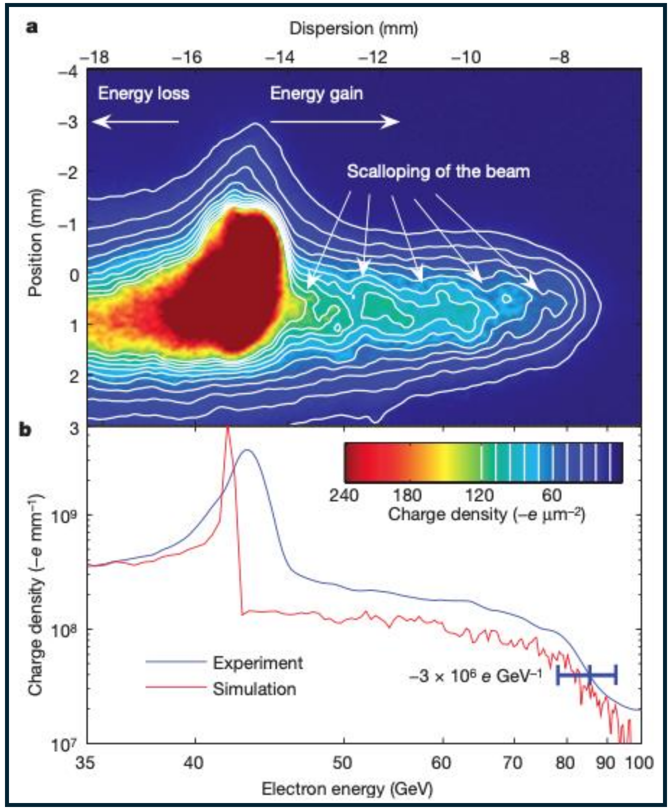

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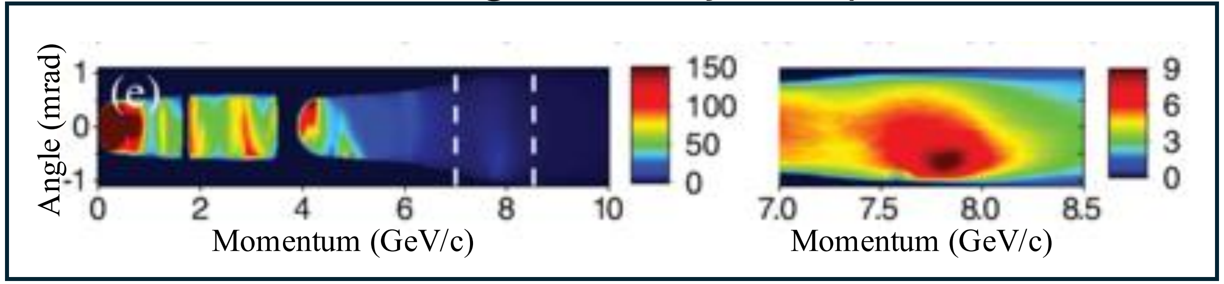

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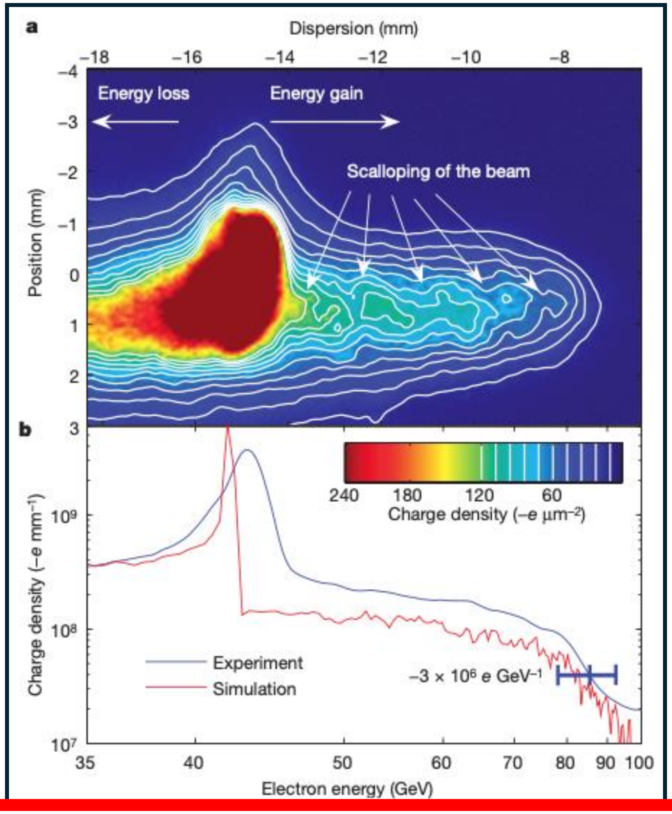

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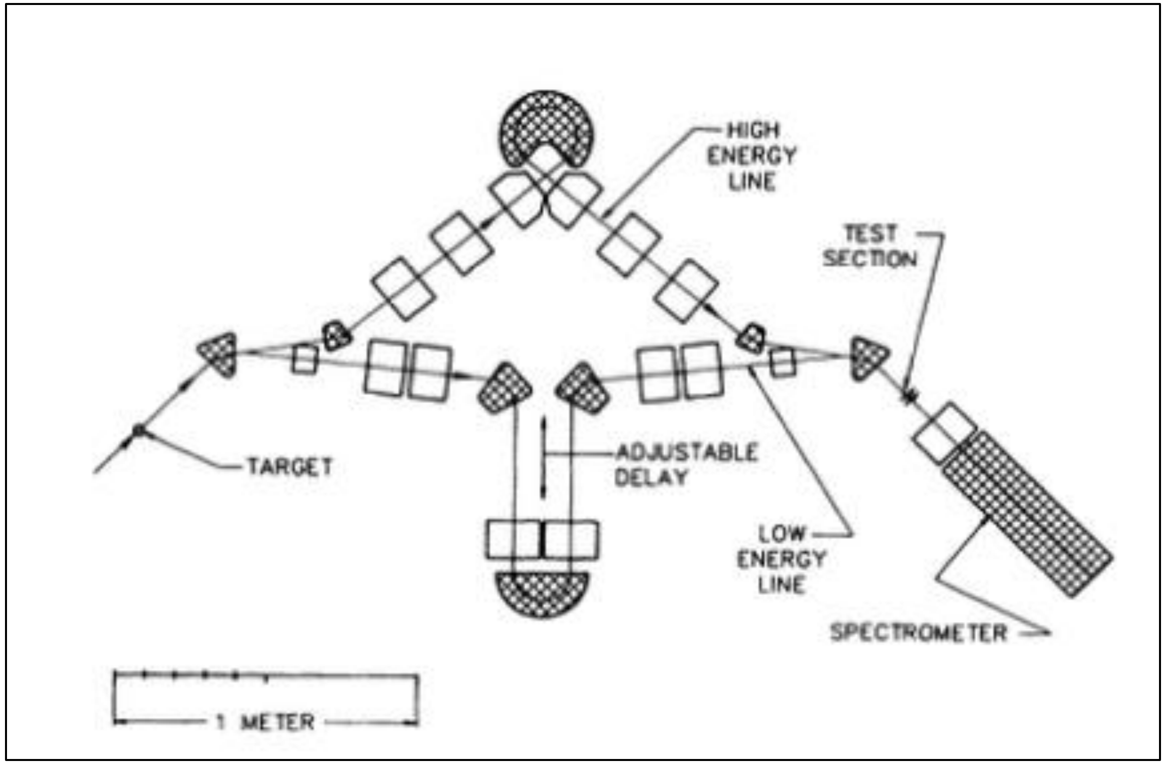
First experimental demonstration: 1988, Argonne National Laboratory (US)



VOLUME 61, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1988

Experimental Observation of Plasma Wake-Field Acceleration

J. B. Rosenzweig, D. B. Cline,[a] B. Cole,[b] H. Figueroa,[c] W. Gai, R. Konecny, J. Norem, P. Schoessow, and J. Simpson
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 21 March 1988)

We report the first experimental test of the physics of plasma wake-field acceleration performed at the Argonne National Laboratory Advanced Accelerator Test Facility. Megavolt-per-meter plasma wake fields are excited by a intense 21-MeV, multipiscosecond bunch of electrons in a plasma of density $n_e \simeq 10^{13}$ cm^{-3}, and probed by a low-intensity 15-MeV witness pulse with a variable delay time behind the intense bunch. Accelerating and deflecting wake-field measurements are presented, and the results compared to theoretical predictions.

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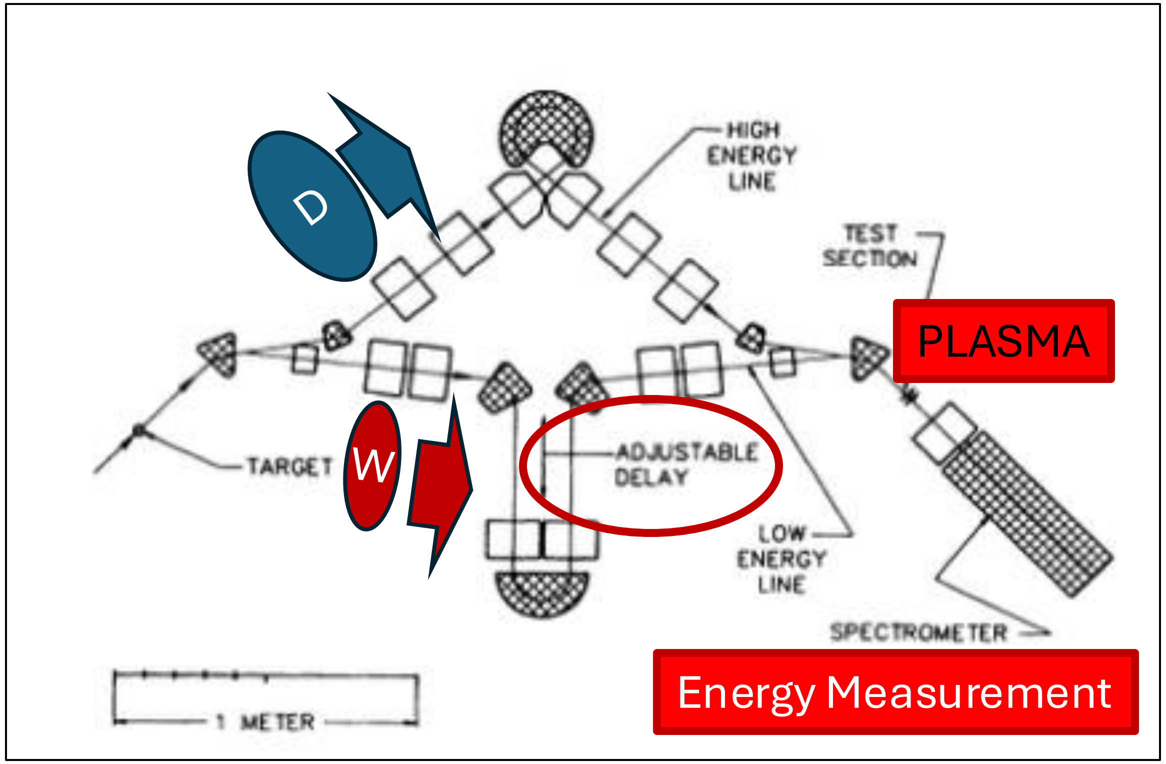

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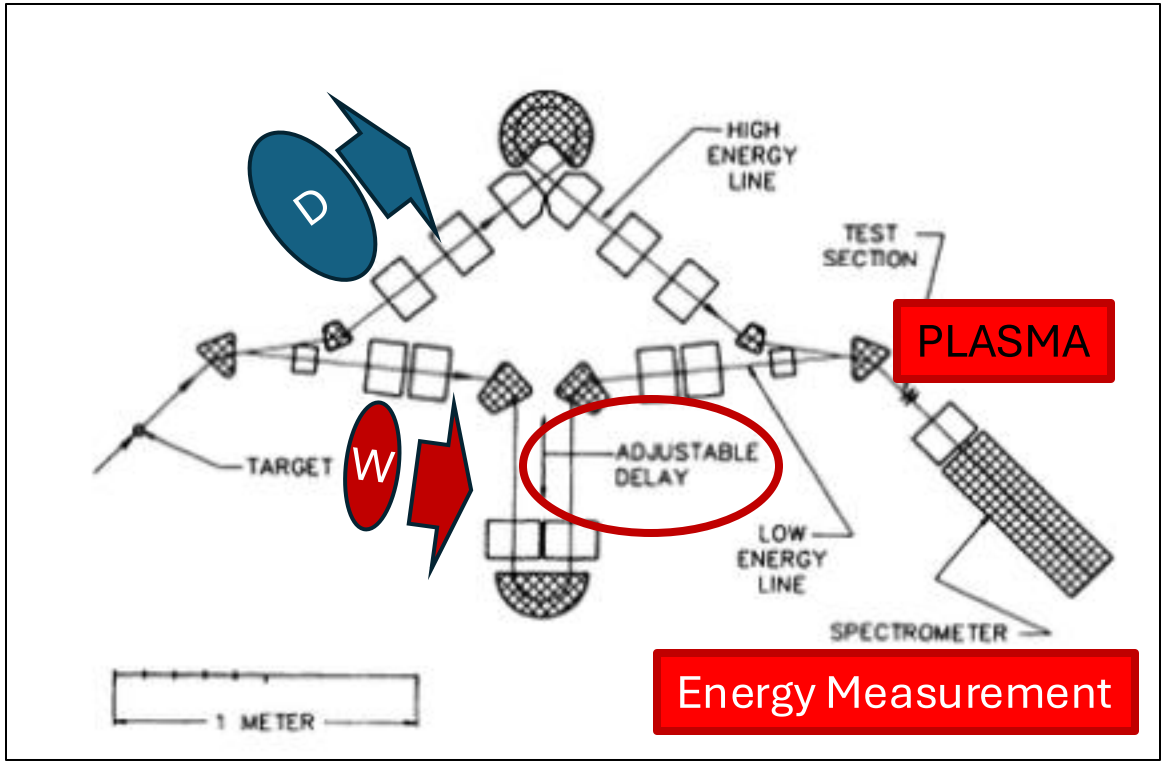
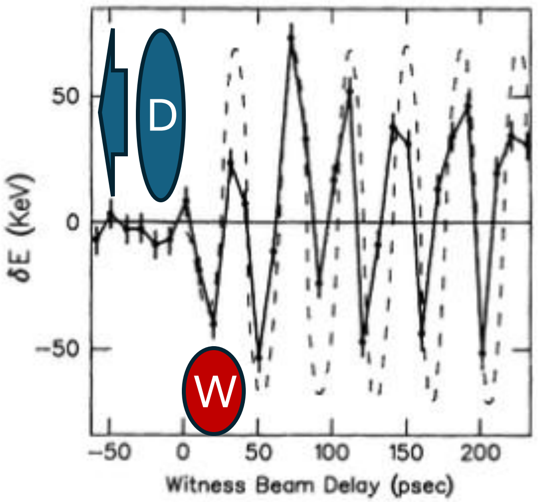
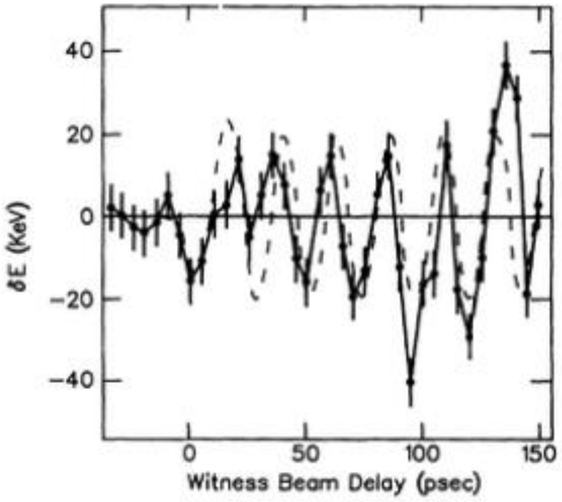


n_{pe} = 8.6 x 10^{12} cm^{-3}



n_{pe} = 2.3 x 10^{13} cm^{-3}



- Measurement of Witness energy as a function of delay
- Sinusoidal

- Linear regime
  → small gradient
  → hard to preserve beam quality

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PWFA — Non-linear Regime

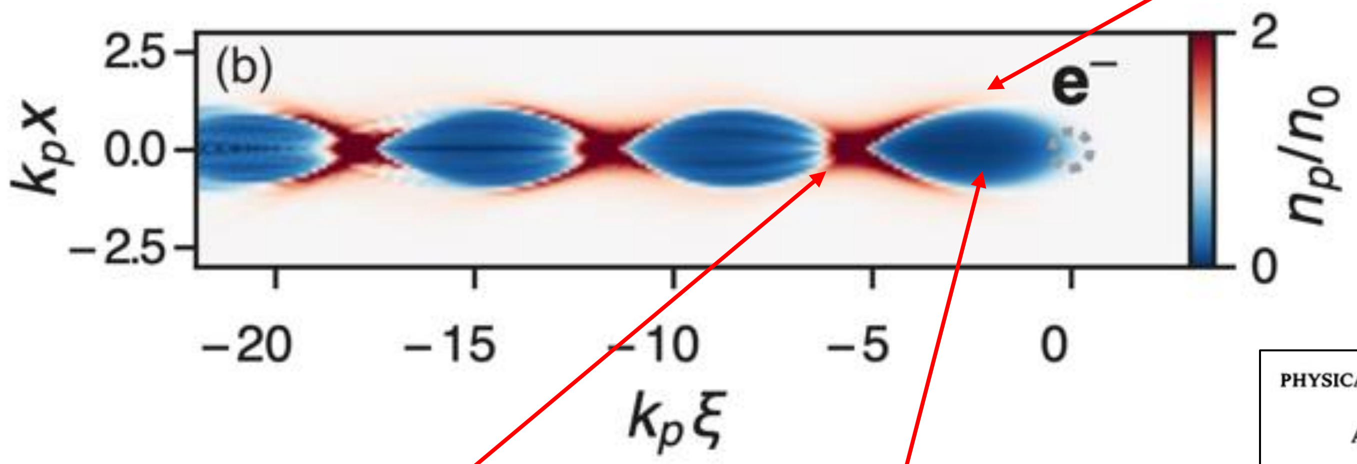
Most of PWFA's work in the non-linear *blowout* regime:

- High gradient
- Linear focusing force

Requirement:

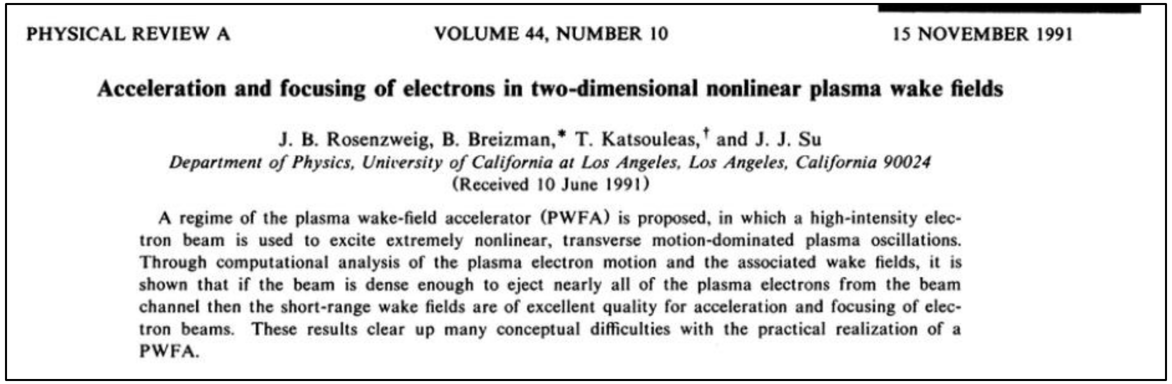
$$n_b \gg n_{pe}$$

Plasma electrons are pushed out



They cross the axis after ~λ_{pe}
→ Singularity
→ Non-linearities

No electrons on axis
(blowout)



PHYSICAL REVIEW A VOLUME 44, NUMBER 10 15 NOVEMBER 1991

Acceleration and focusing of electrons in two-dimensional nonlinear plasma wake fields

J. B. Rosenzweig, B. Breizman,* T. Katsouleas,† and J. J. Su

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

(Received 10 June 1991)

A regime of the plasma wake-field accelerator (PWFA) is proposed, in which a high-intensity electron beam is used to excite extremely nonlinear, transverse motion-dominated plasma oscillations. Through computational analysis of the plasma electron motion and the associated wake fields, it is shown that if the beam is dense enough to eject nearly all of the plasma electrons from the beam channel then the short-range wake fields are of excellent quality for acceleration and focusing of electron beams. These results clear up many conceptual difficulties with the practical realization of a PWFA.

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Most of PWFA's work in the non-linear *blowout* regime:

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→ Main challenge: beam quality preservation (vital for applications)

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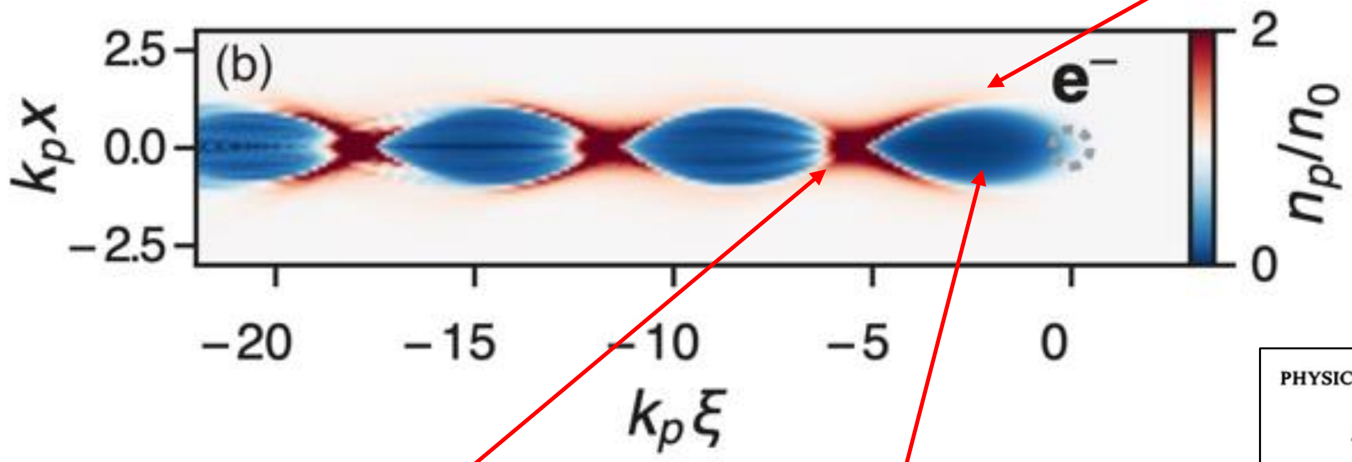

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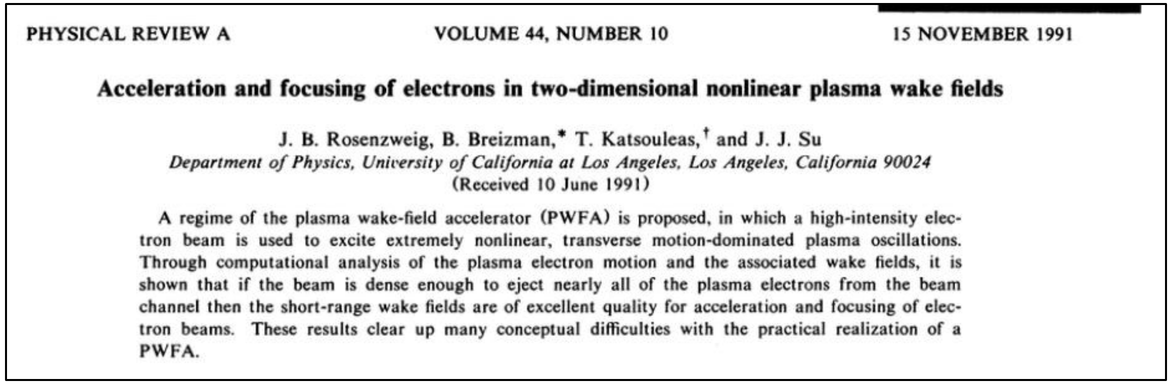
→ Non-linearities

No electrons on axis (blowout)



PHYSICAL REVIEW A VOLUME 44, NUMBER 10 15 NOVEMBER 1991

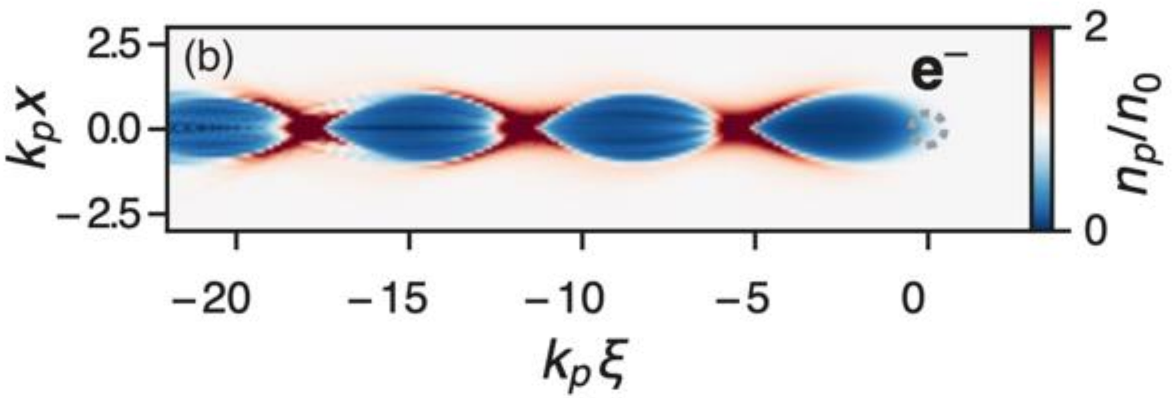
Acceleration and focusing of electrons in two-dimensional nonlinear plasma wake fields

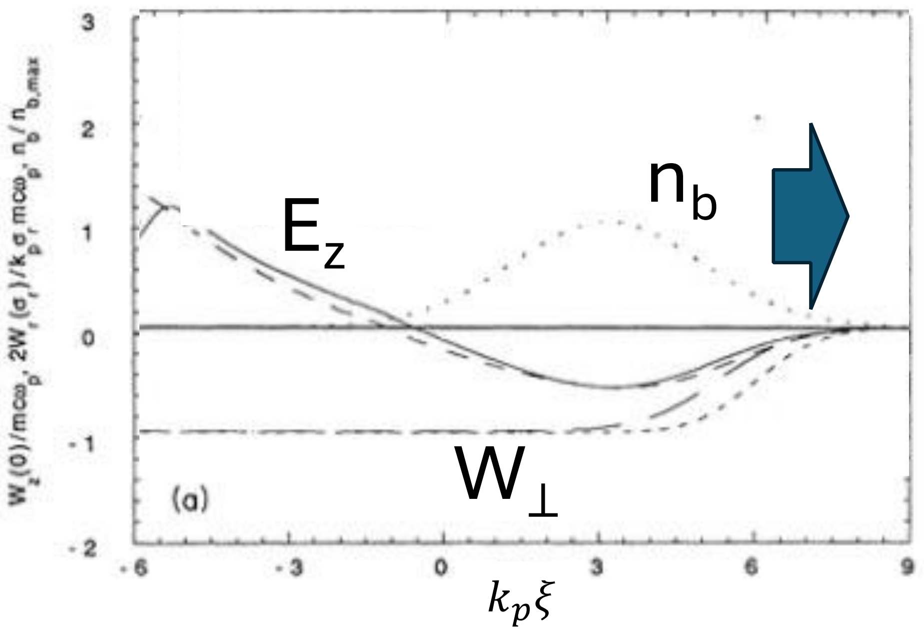
J. B. Rosenzweig, B. Breizman,* T. Katsouleas,† and J. J. Su
Department of Physics, University of California at Los Angeles, Los Angeles, California 90024

(Received 10 June 1991)

A regime of the plasma wake-field accelerator (PWFA) is proposed, in which a high-intensity electron beam is used to excite extremely nonlinear, transverse motion-dominated plasma oscillations. Through computational analysis of the plasma electron motion and the associated wake fields, it is shown that if the beam is dense enough to eject nearly all of the plasma electrons from the beam channel then the short-range wake fields are of excellent quality for acceleration and focusing of electron beams. These results clear up many conceptual difficulties with the practical realization of a PWFA.

Main challenge – Energy spread (*longitudinal* quality)

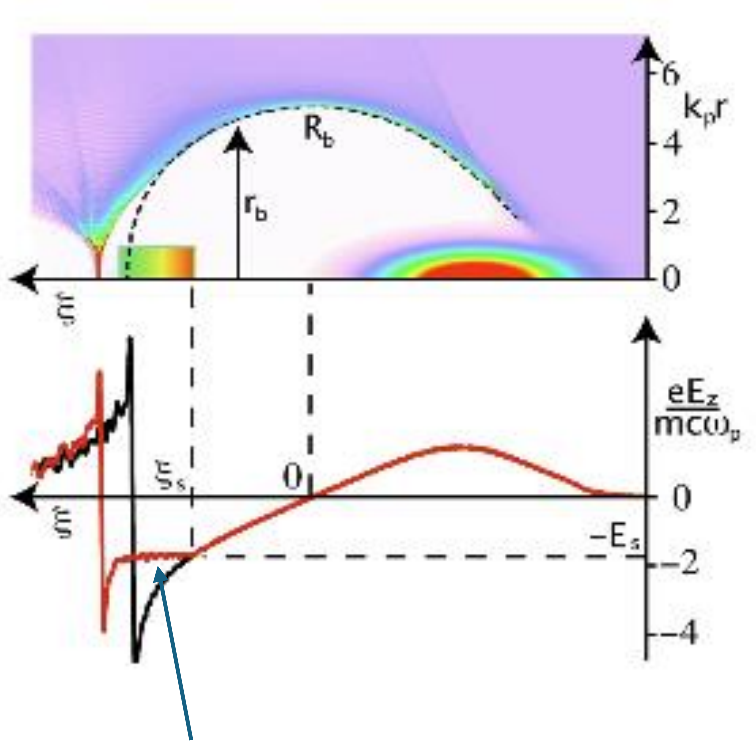




J. B. Rosenzweig et al., Phys. Rev. A 44, R6189(R) (1991)

- Accelerating field not uniform along the bubble
  → Energy spread increasing upon acceleration

- Solution: "*loading*" the wake with the presence of the witness bunch itself



Uniform accelerating field within the witness bunch

M. Tzoufras et al., PRL **101**, 145002 (2008)

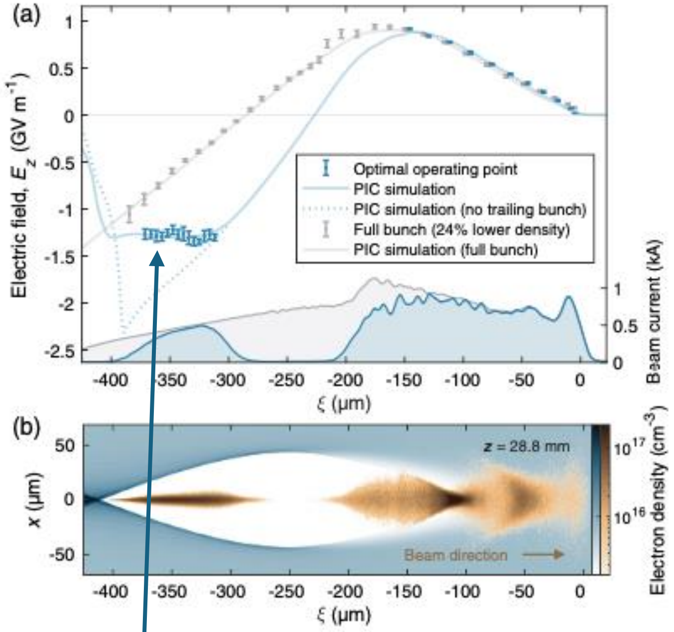
Main challenge – Energy spread (*longitudinal* quality)

➔Experimental Demonstrations:

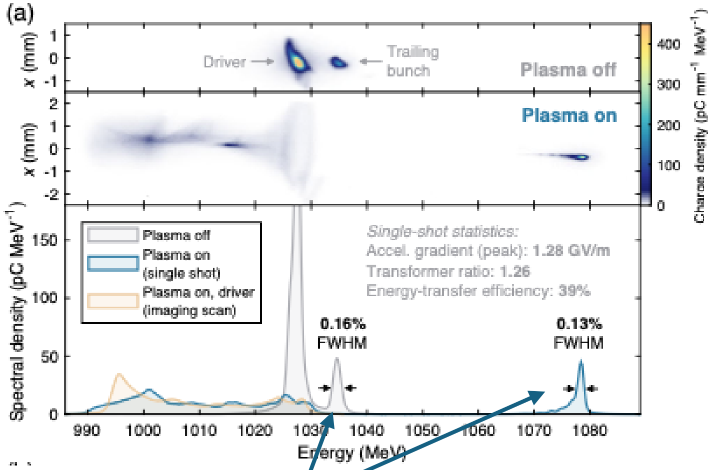
PHYSICAL REVIEW LETTERS 126, 014801 (2021)

Energy-Spread Preservation and High Efficiency in a Plasma-Wakefield Accelerator

C. A. Lindstrøm,[1,*] J. M. Garland,[1] S. Schröder,[1,2] L. Boulton,[1,3,4] G. Boyle,[1] J. Chappell,[5] R. D'Arcy,[1] P. Gonzalez,[1,2] A. Knetsch,[1,†] V. Libov,[1] G. Loisch,[1] A. Martinez de la Ossa,[1] P. Niknejadi,[1] K. Põder,[1] L. Schaper,[1] B. Schmidt,[1] B. Sheeran,[1,2] S. Wesch,[1] J. Wood,[1] and J. Osterhoff[1]



Flattened, loaded wake

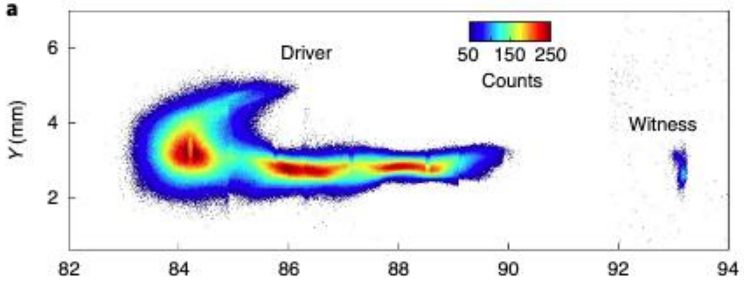


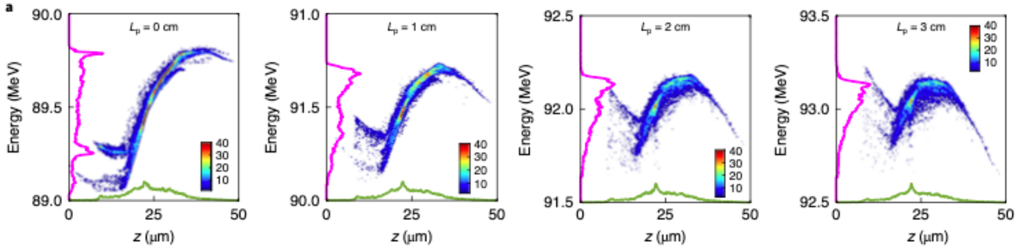
~GV/m acceleration
Preserved relative energy spread

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]





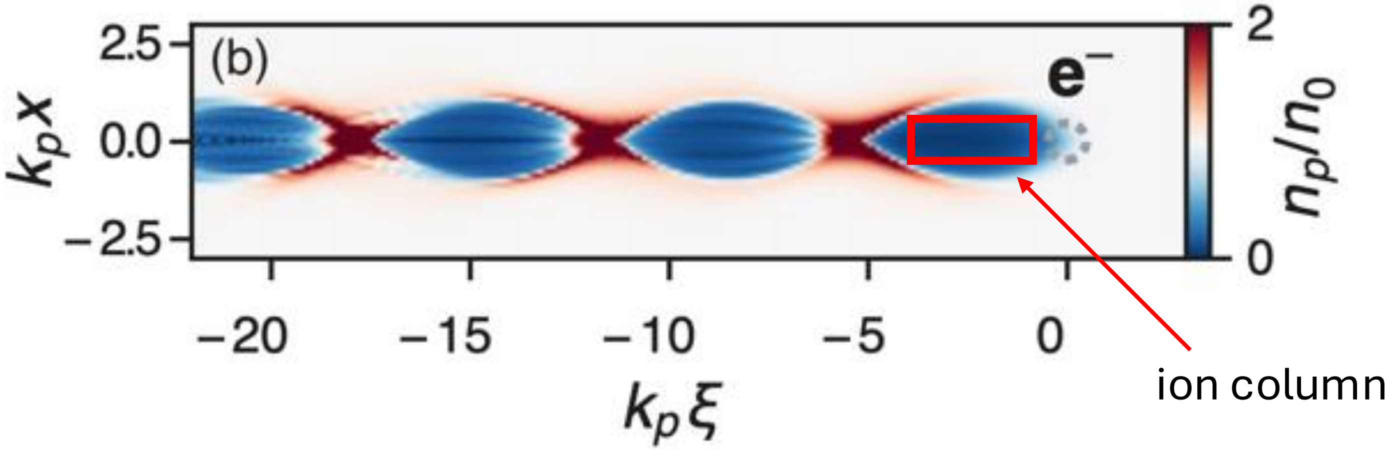
Combination of beam loading and initial chirp to obtain final small energy spread

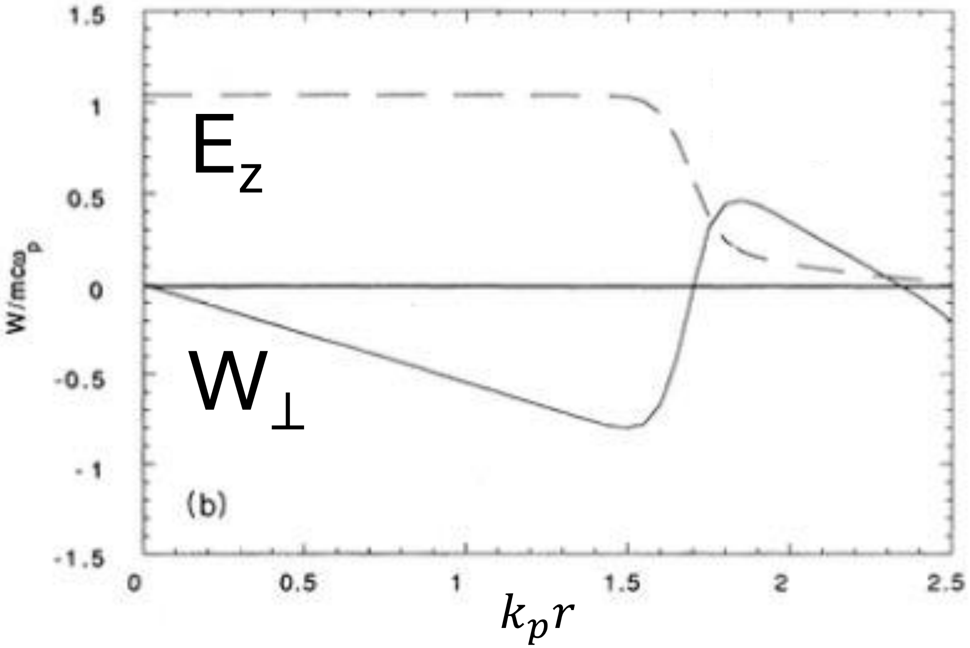
Main challenge – Emittance Preservation (*transverse* quality)

➔Ion column provides linear focusing force

Radial electric field: $E_r(r) = \frac{e n_{pe}}{2\varepsilon_0}\ r$

(Gauss' law on cylinder of ions)





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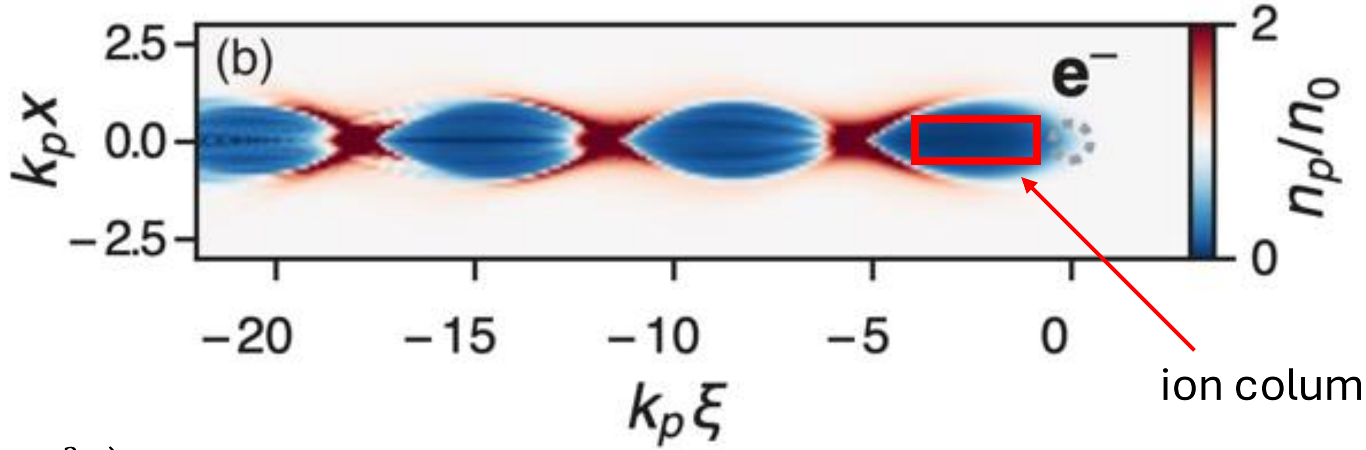

ion column

→ Plug it in envelope equation: $\sigma_r''(z) + \sigma_r(z)\underbrace{\left(K - \frac{\epsilon_g^2}{\sigma_r^4(z)}\right)}_{=0:} = 0$

Matching condition

Equilibrium between focusing force and emittance

Main challenge – Emittance Preservation (*transverse* quality)

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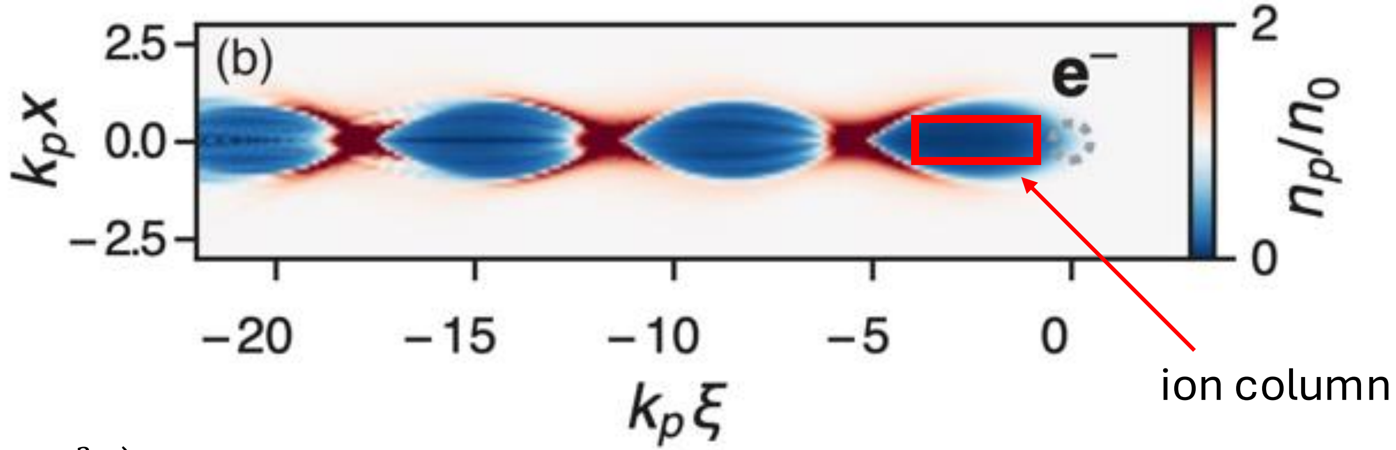
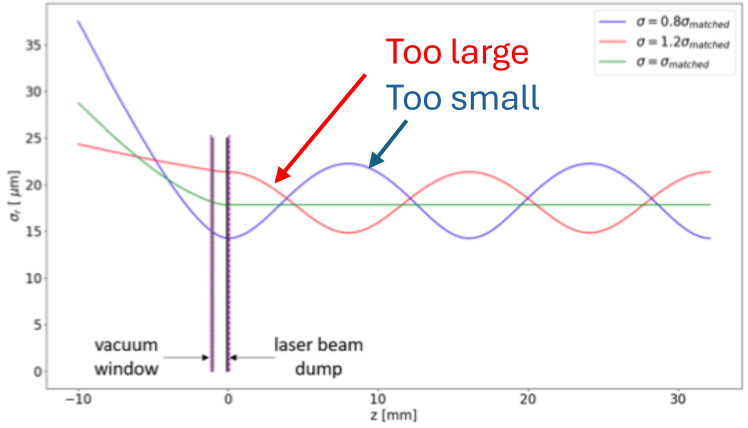


→ Plug it in envelope equation: $\sigma_r''(z) + \sigma_r(z)\underbrace{\left(K - \frac{\epsilon_g^2}{\sigma_r^4(z)}\right)}_{=0:} = 0$

Equilibrium between focusing force and emittance ← Matching condition

Matching Conditions:

- $\beta = \frac{\sigma^2(0)}{\epsilon_g} = \sqrt{\frac{2\varepsilon_0 m_e c^2 \gamma}{n_{pe} e^2}}$
- Injection at waist: $\sigma'(z=0) = 0$



if: beam envelope is *matched* to the focusing force (which is extremely strong!)

→ Possible emittance preservation

else: different energy slices rotate at different rates in transverse phase space

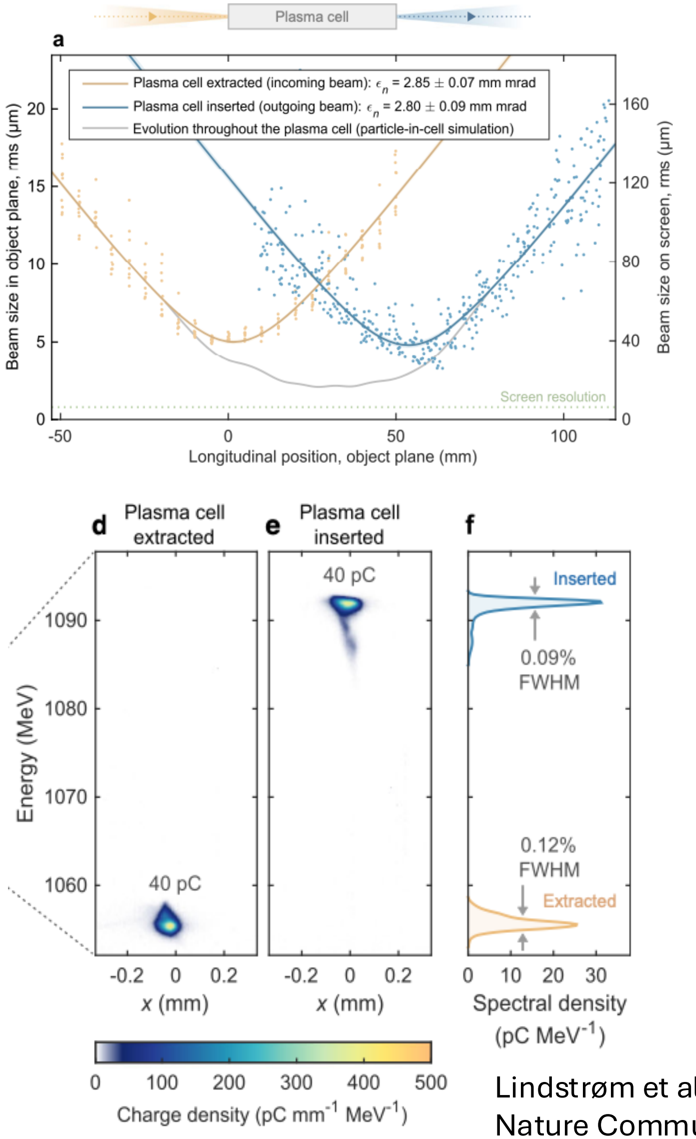
→ slice emittance preserved (linear focusing)

→ projected (i.e., overall) emittance grows!

(L. Verra *et al* 2020 *J. Phys.: Conf. Ser.* **1596** 012007)

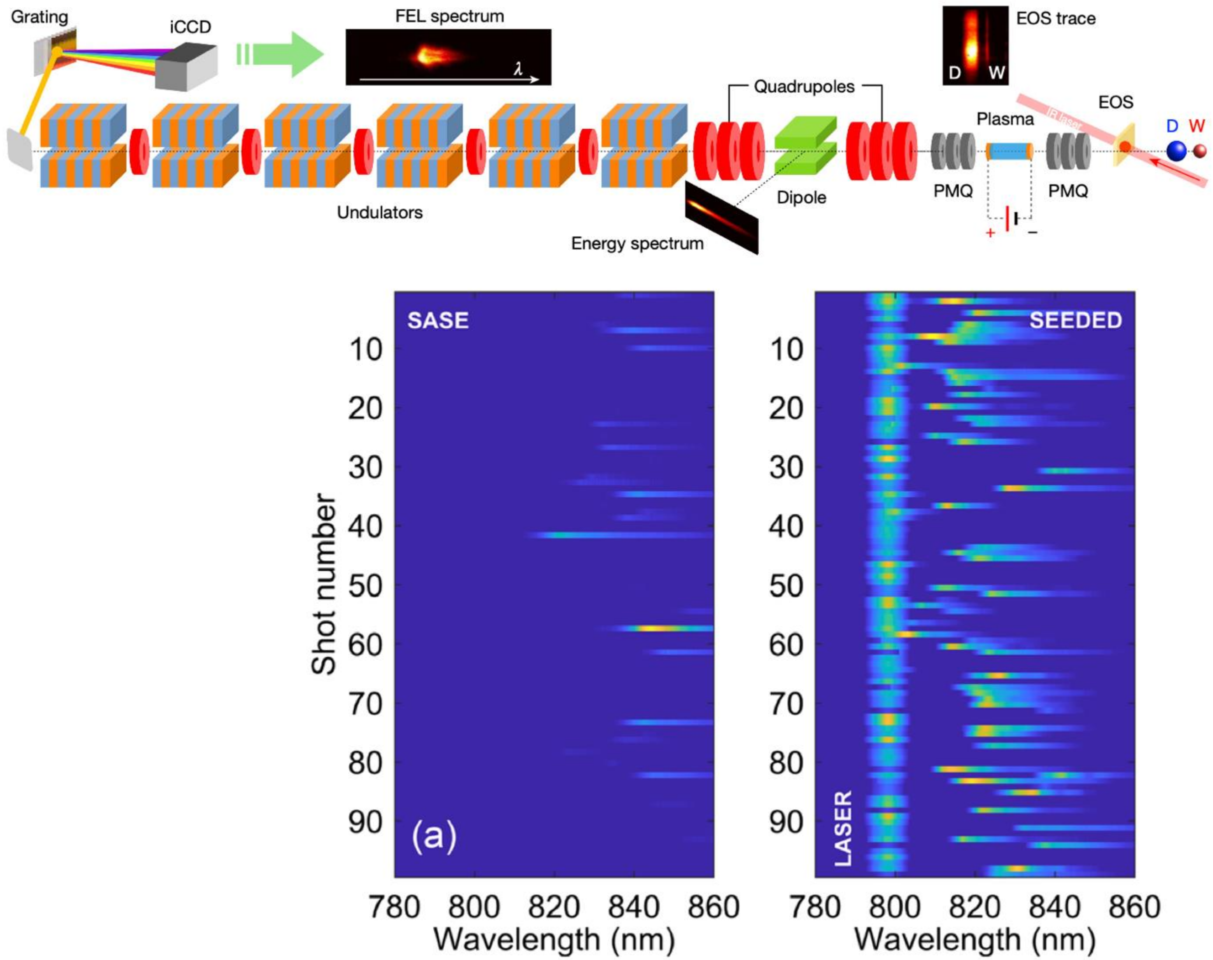
Main challenge – Emittance Preservation (*transverse* quality)

- Direct experimental demonstration:



Lindstrøm et al.,
Nature Communications 15, 6097 (2024)

- "Indirect" experimental proof:
Quality good enough for free-electron lasing

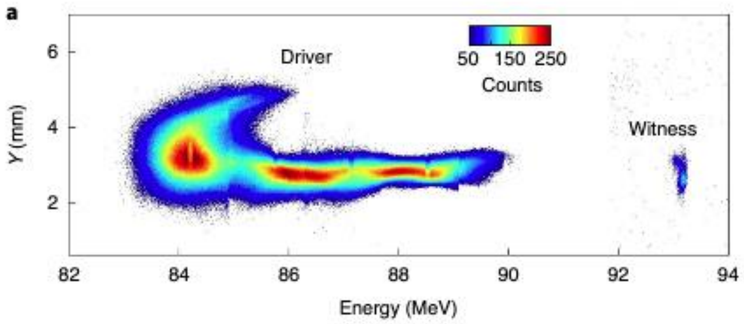


Galletti et al., PRL 129, 234801 (2022)
Pompili et al. Nature 605, 659–662 (2022)

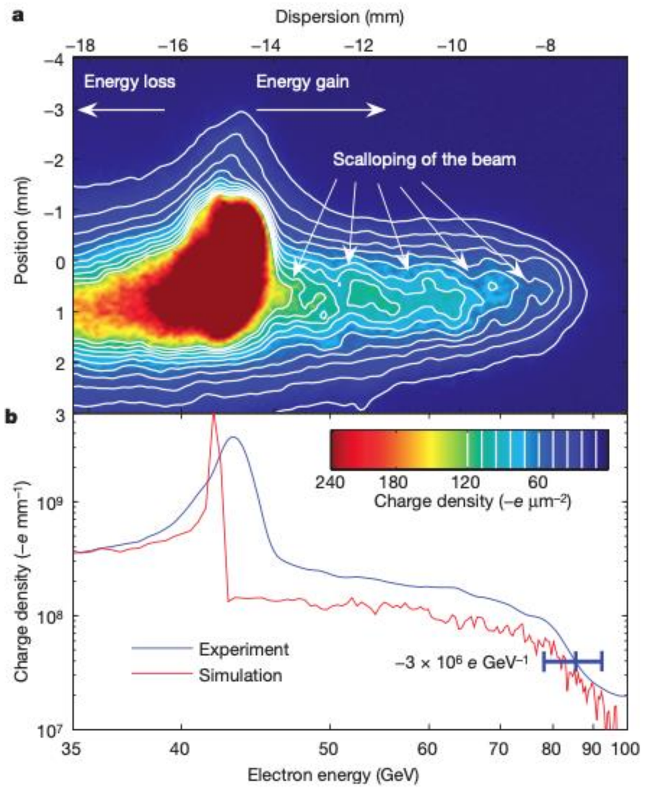
Main Challenges

The main challenge remains:
- Do everything at the same time

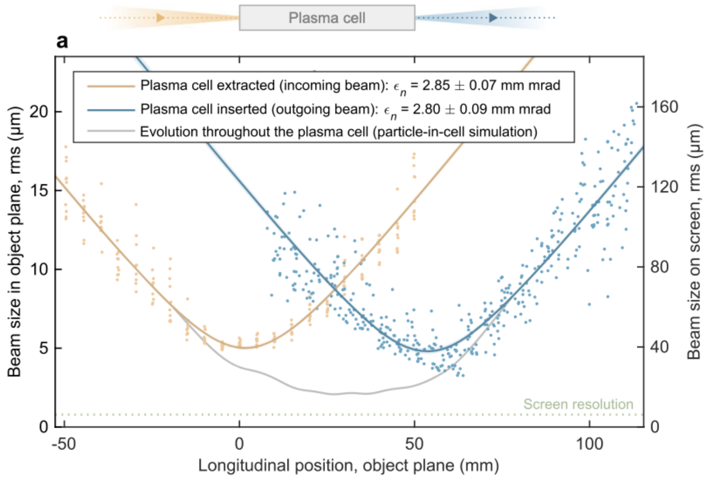
Energy spread minimization



Extremely high gradient



Emittance preservation



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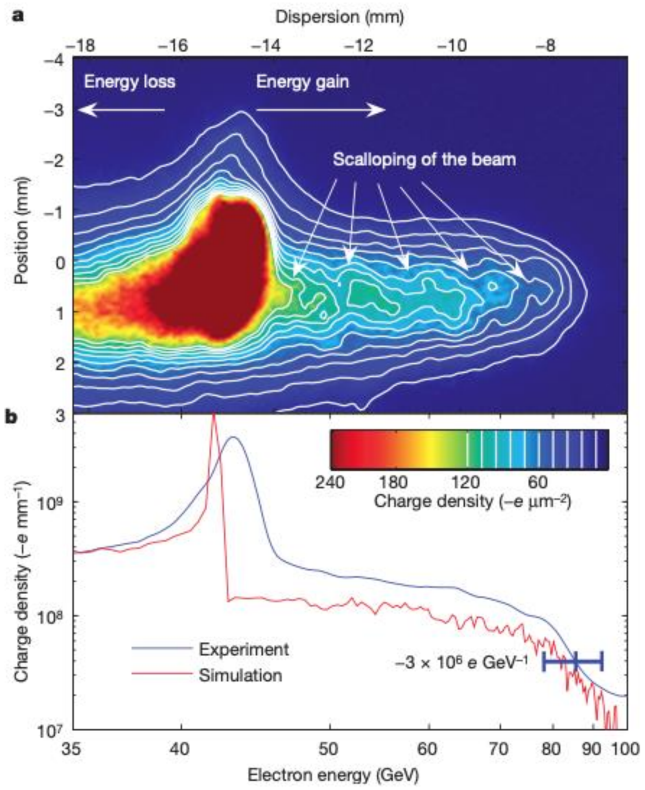

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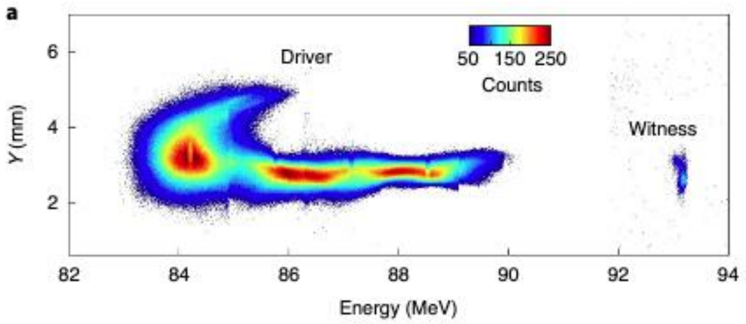
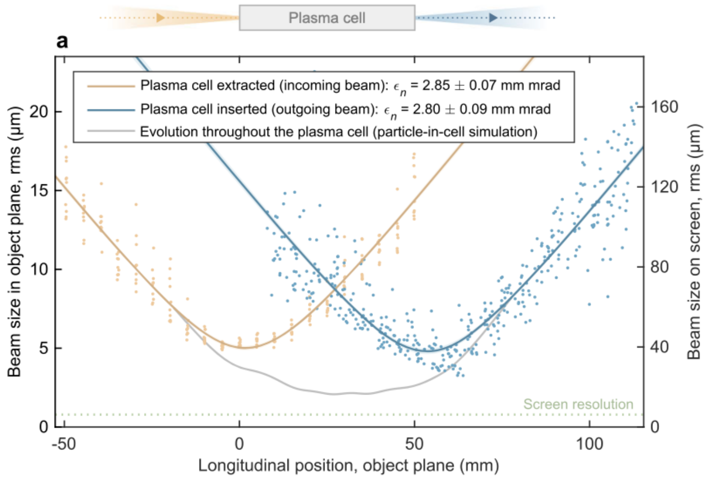
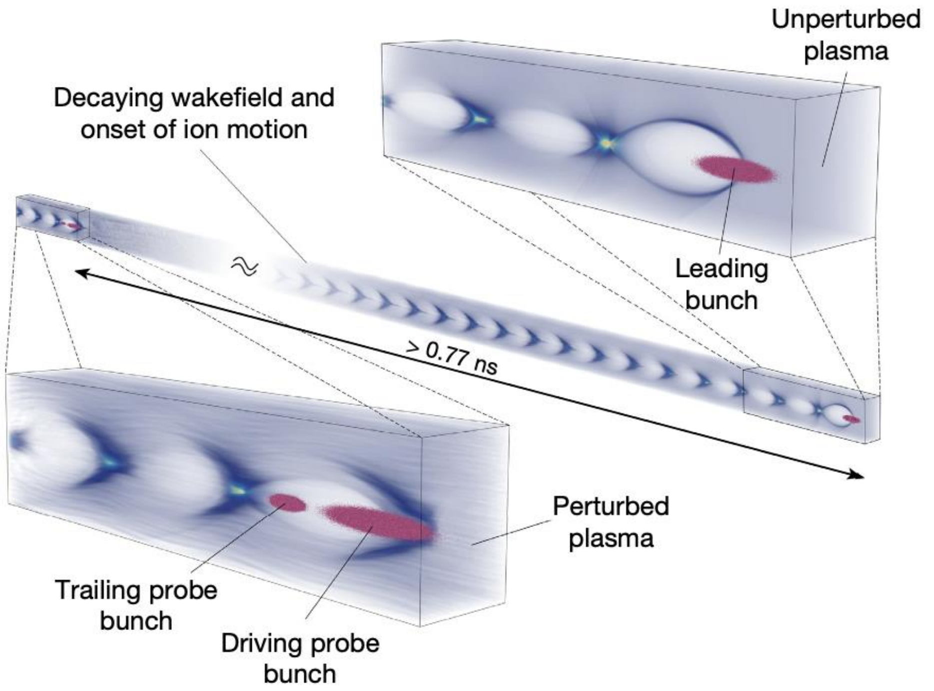


Emittance preservation



- Do it many times → high repetition rate



Plasma was shown to recover at ns time-scale

R. D'Arcy et al., Nature **603**, 58–62 (2022)

R. Pompili et al., Comm. Phys. 7, 241 (2024)

Still a technological challenge:

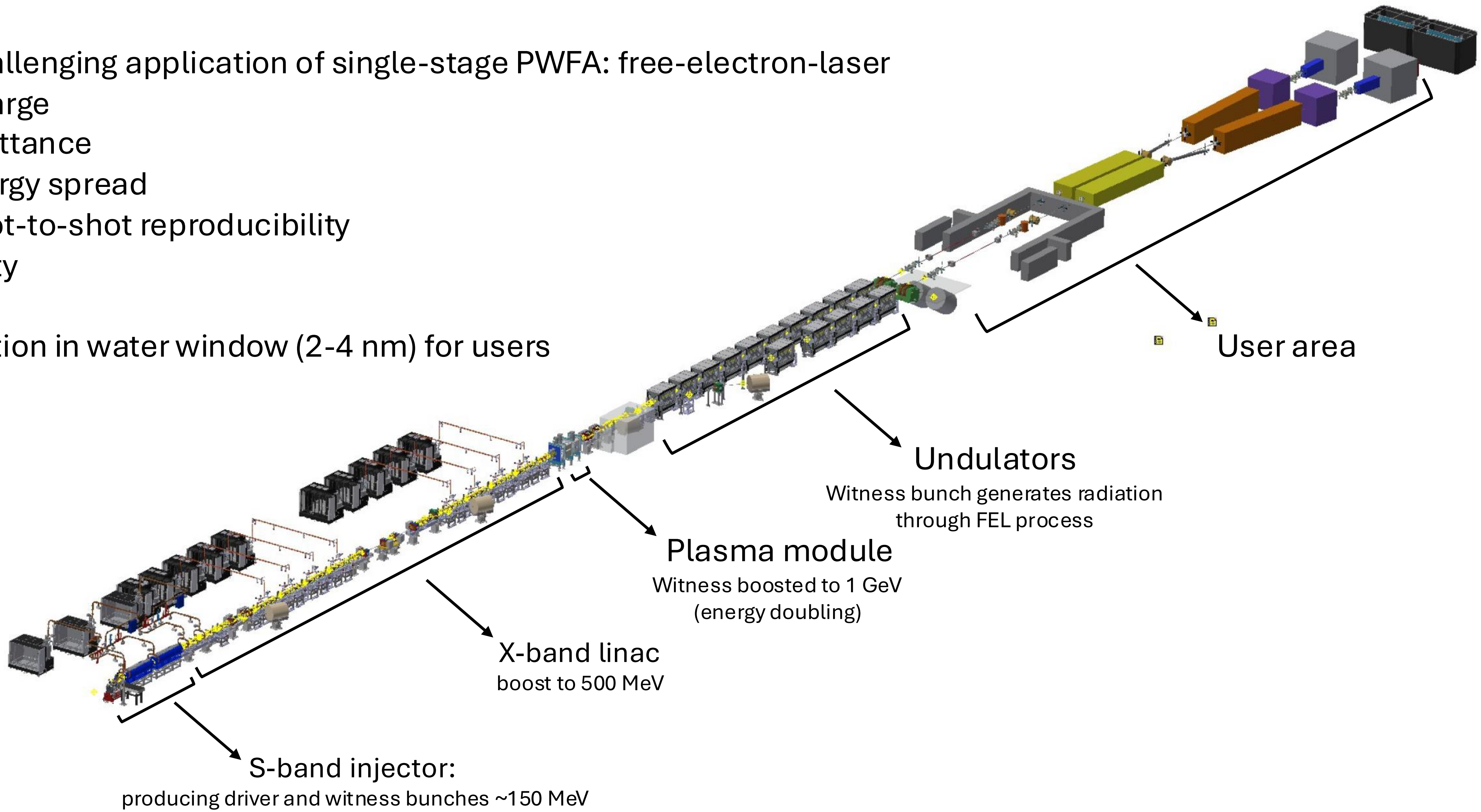
- Plasma generation
- Heat deposition
- etc..

EuPRAXIA@SPARC_LAB

Single-stage high-quality high energy gain, high repetition rate PWFA

- The most challenging application of single-stage PWFA: free-electron-laser
  - High charge
  - Low emittance
  - Low energy spread
  - High shot-to-shot reproducibility
  - Tunability

- Deliver radiation in water window (2-4 nm) for users



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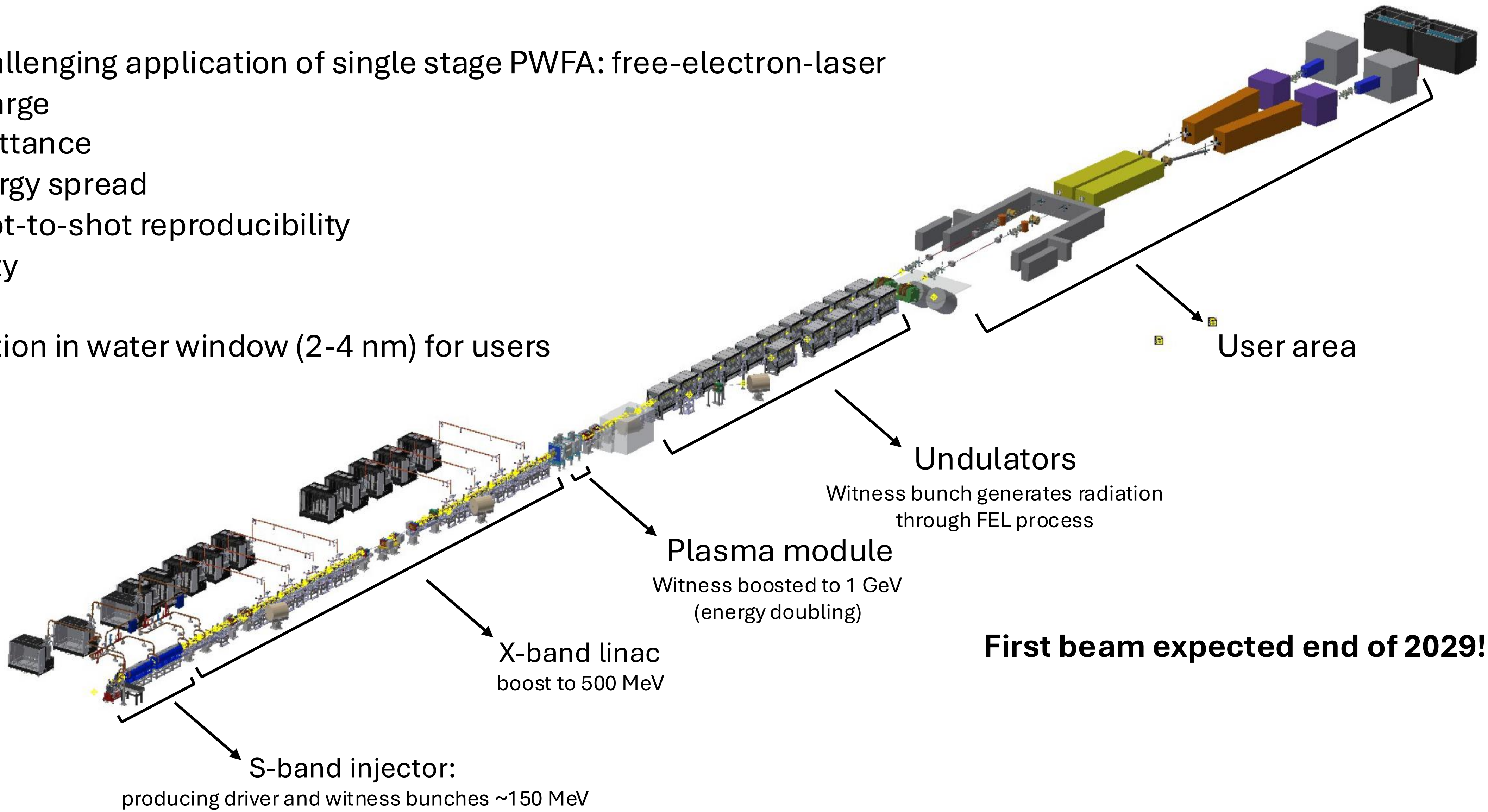
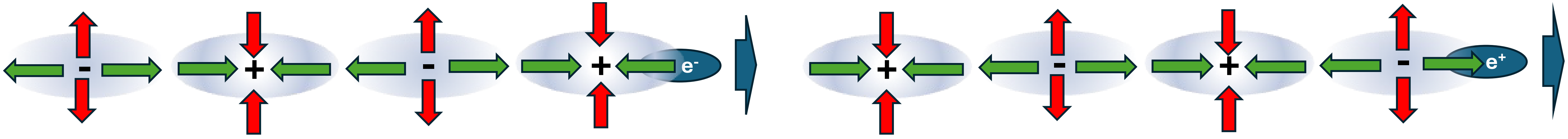


First beam expected end of 2029!

PWFA — Positrons

→ Positrons may be needed for future lepton colliders
In principle, just a π phase difference in the wakefields



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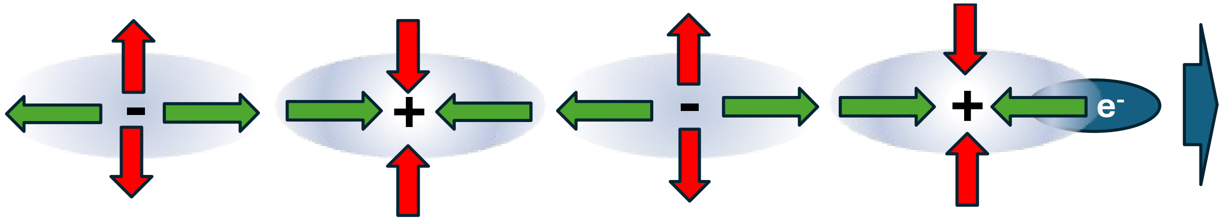
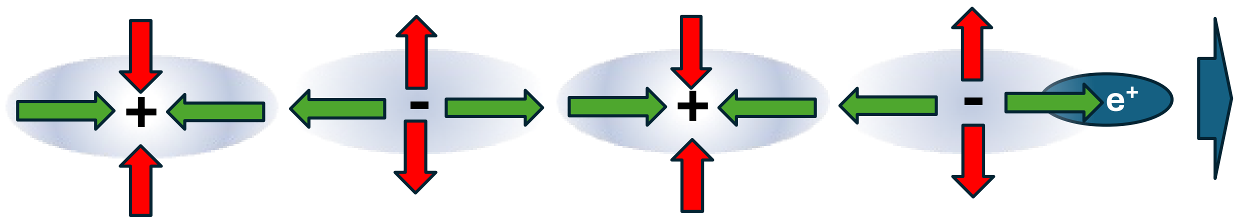
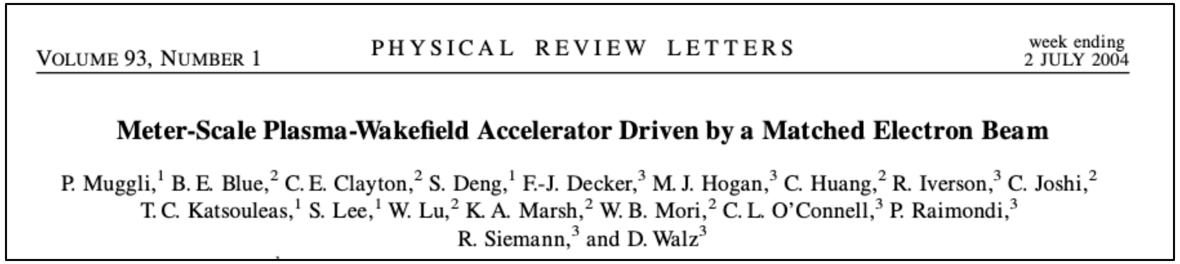





VOLUME 93, NUMBER 1 PHYSICAL REVIEW LETTERS week ending 2 JULY 2004

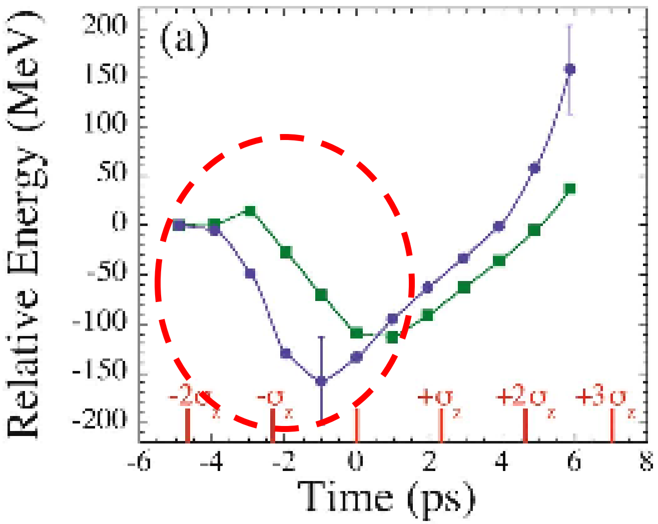
Meter-Scale Plasma-Wakefield Accelerator Driven by a Matched Electron Beam

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


VOLUME 90, NUMBER 21 PHYSICAL REVIEW LETTERS week ending 30 MAY 2003

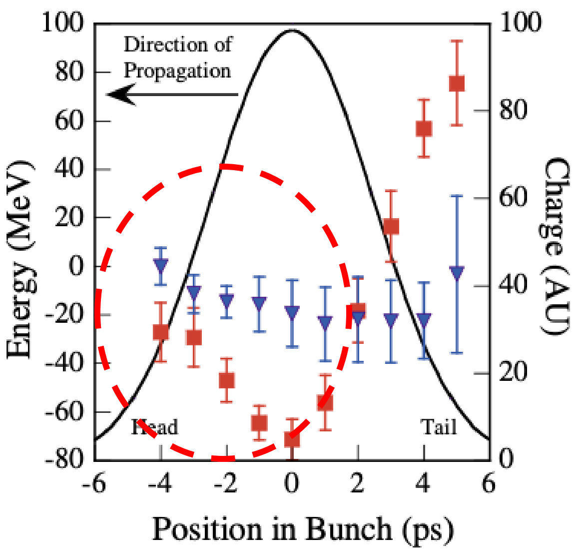
Plasma-Wakefield Acceleration of an Intense Positron Beam

B. E. Blue,[1] C. E. Clayton,[1] C. L. O'Connell,[2] F.-J. Decker,[2] M. J. Hogan,[2] C. Huang,[1] R. Iverson,[2] C. Joshi,[1] T. C. Katsouleas,[3] W. Lu,[1] K. A. Marsh,[1] W. B. Mori,[1] P. Muggli,[3] R. Siemann,[2] and D. Walz[2]



e^-

Long Bunches:
Head and center lose energy



e^+

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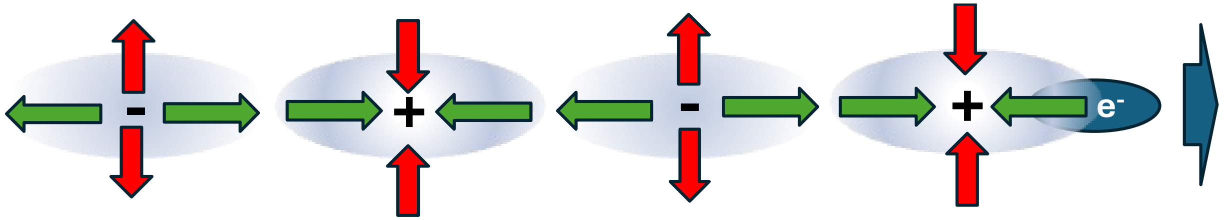
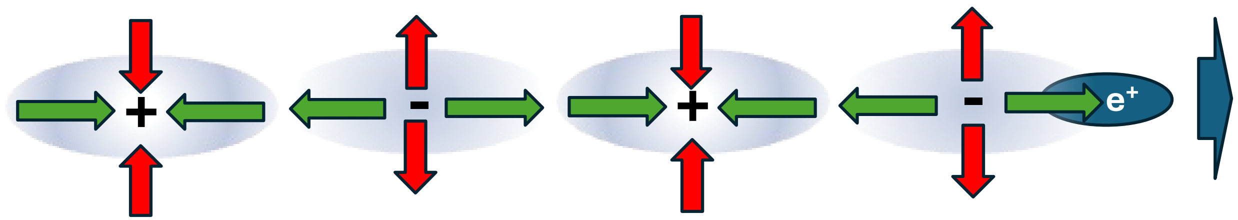
In principle, just a π phase difference in the wakefields





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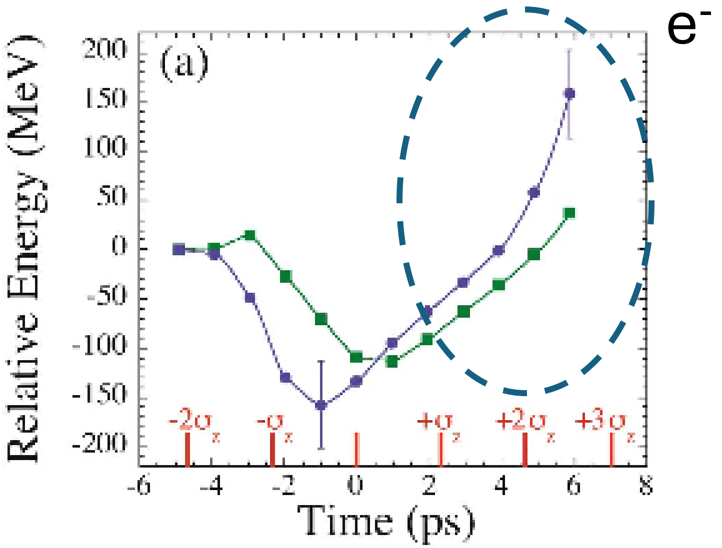
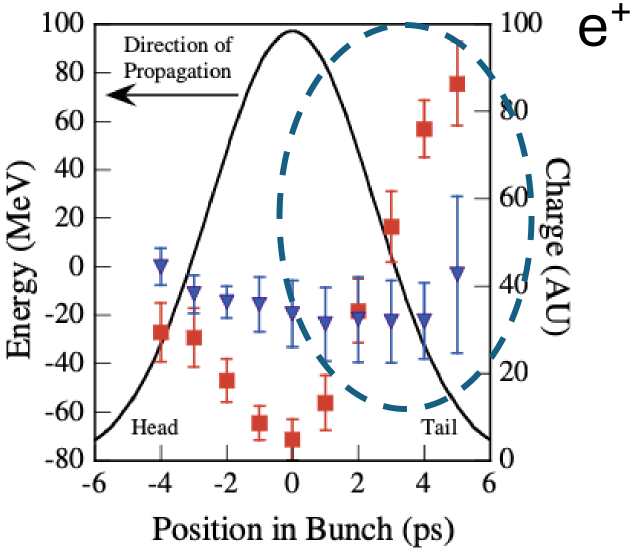
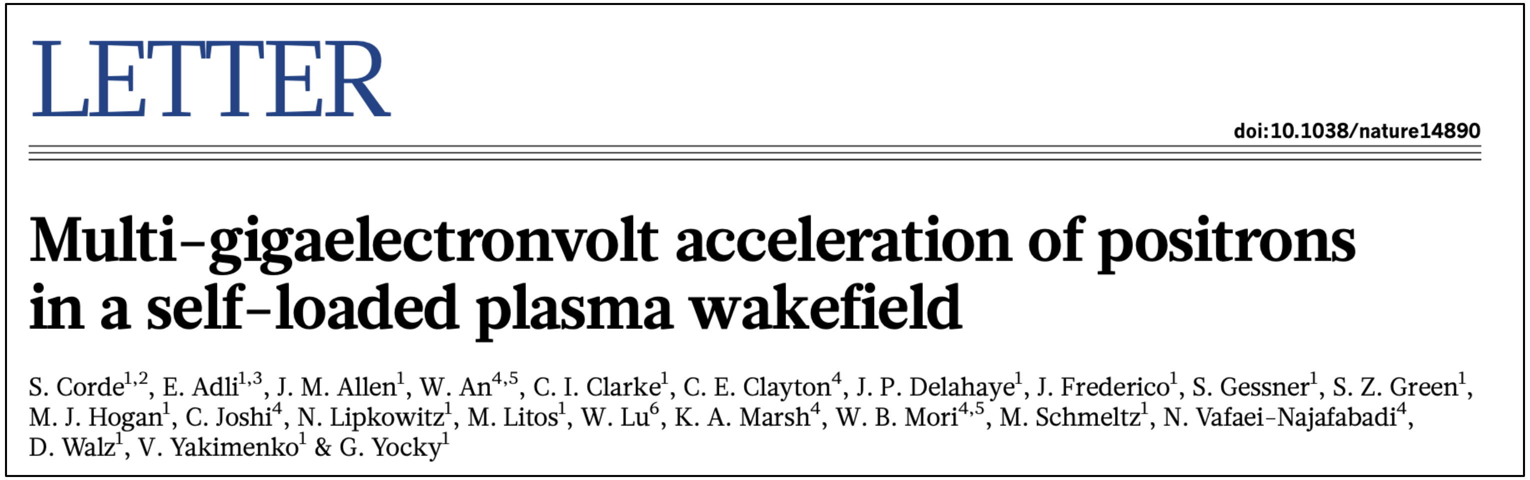


Long Bunches:
Head and center lose energy
Tail gains energy



PWFA — Positrons

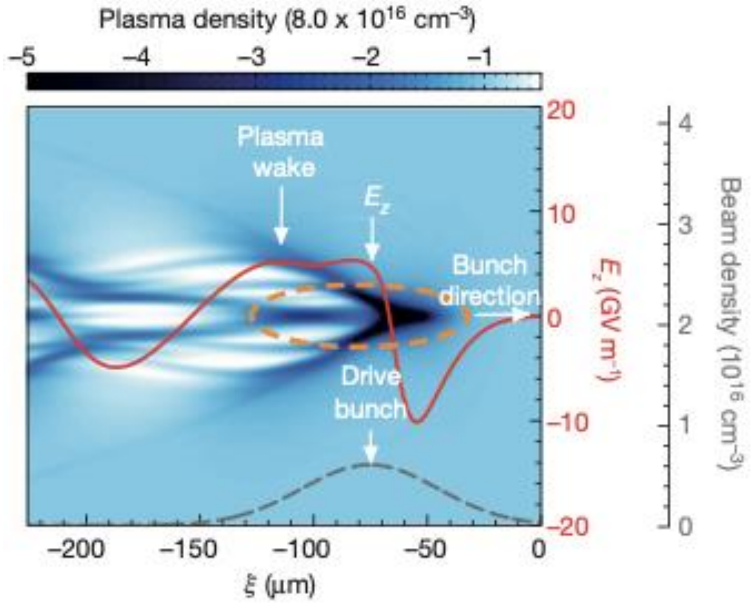
→ Positrons may be needed for future lepton colliders
In principle, just a π phase difference in the wakefields
→ Acceleration demonstrated also in the non-linear regime


LETTER

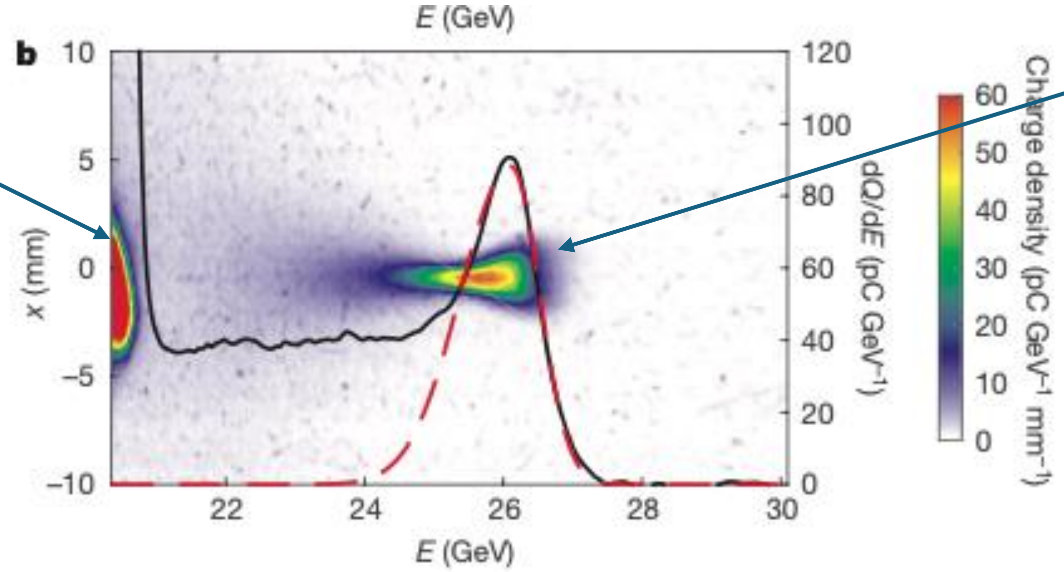
doi:10.1038/nature14890

Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield

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



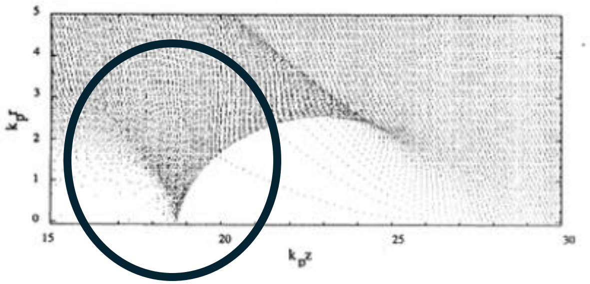
Initial energy

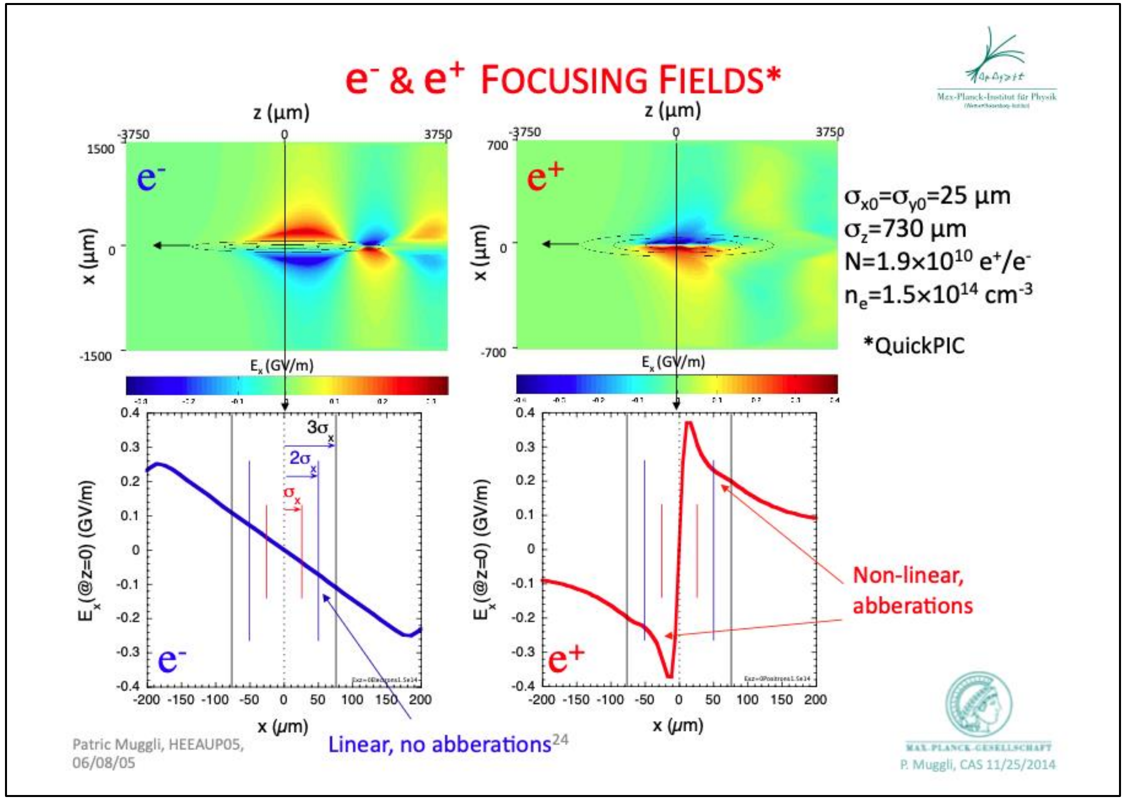


Maximum energy

PWFA — Positrons

→ BUT: In the blowout regime, e^+ witness bunches need to be placed very close to the singularity





(P. Muggli, CAS 2014)

PWFA — Positrons

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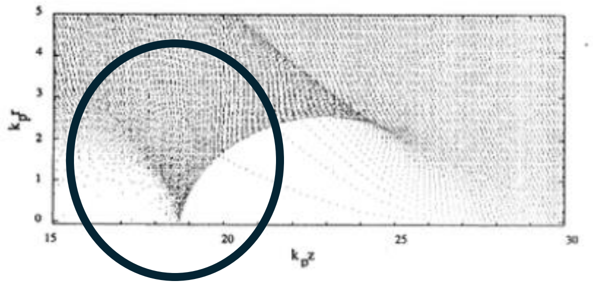
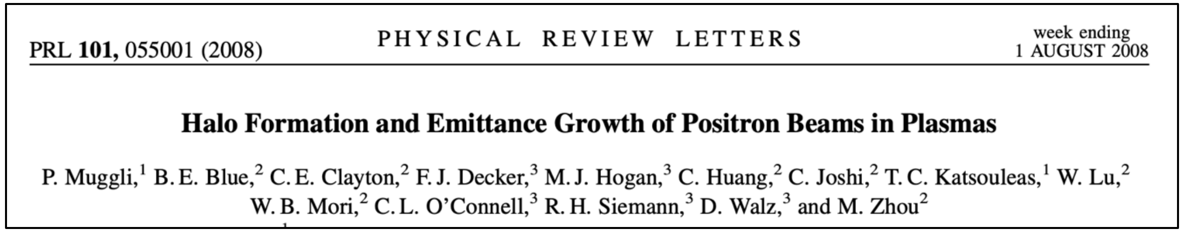
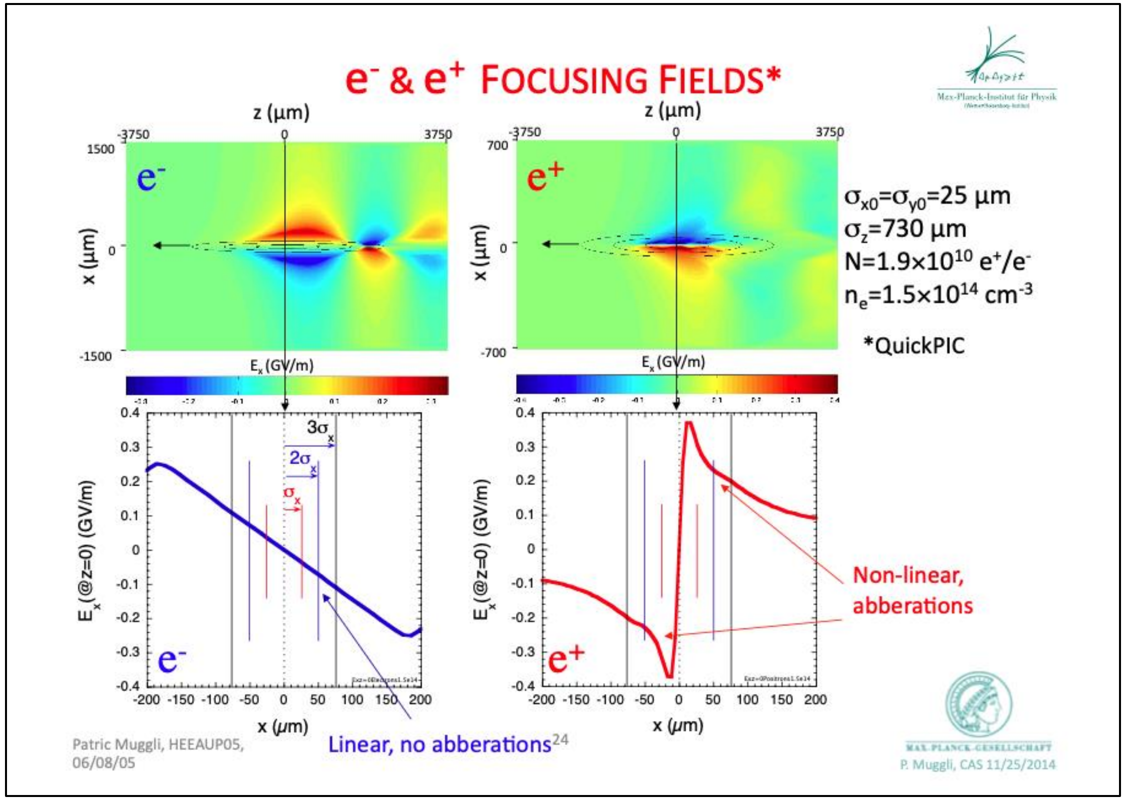
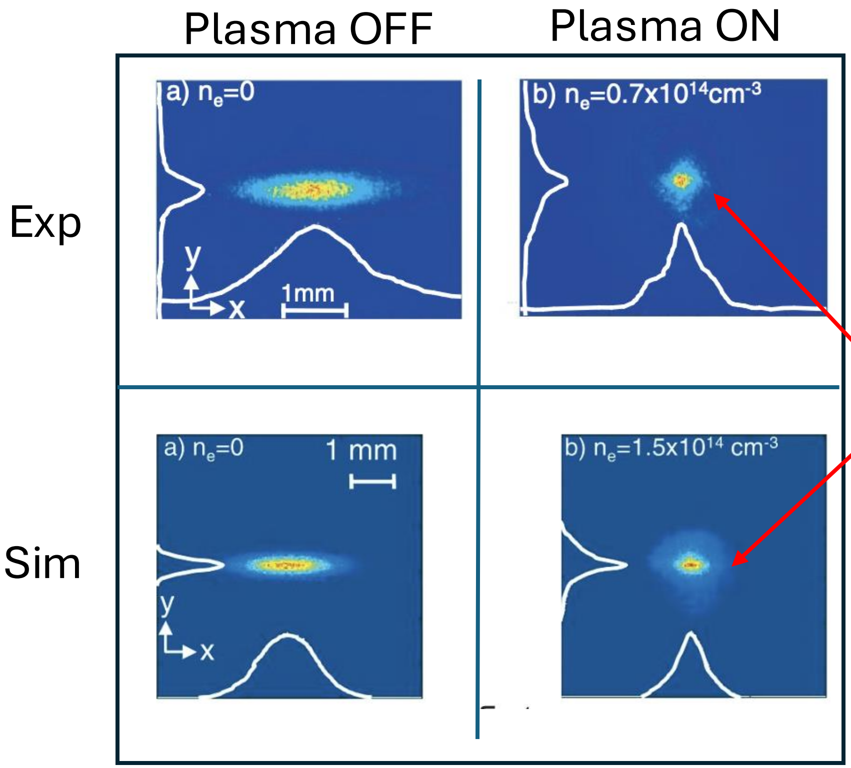






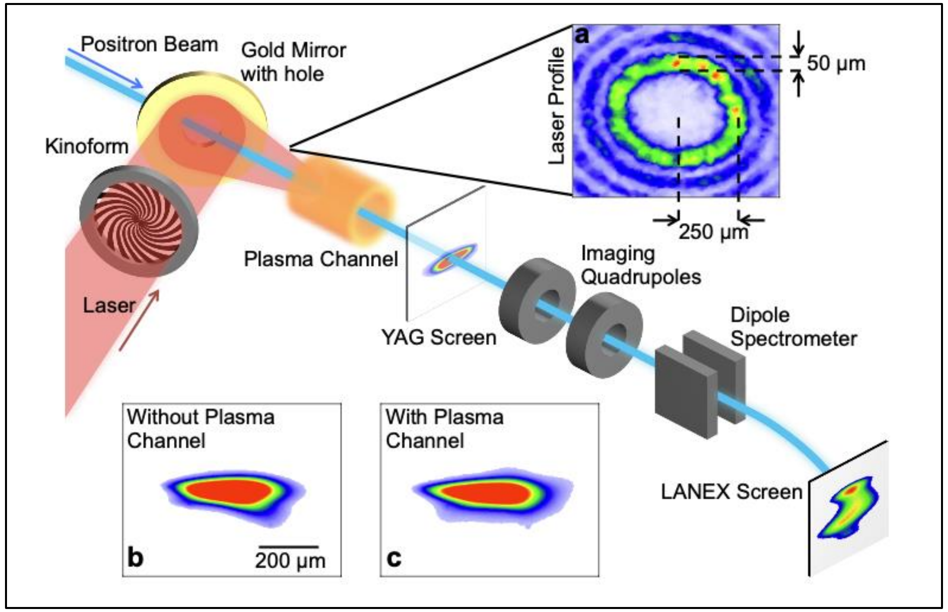


Halo due to aberrations
→ emittance growth

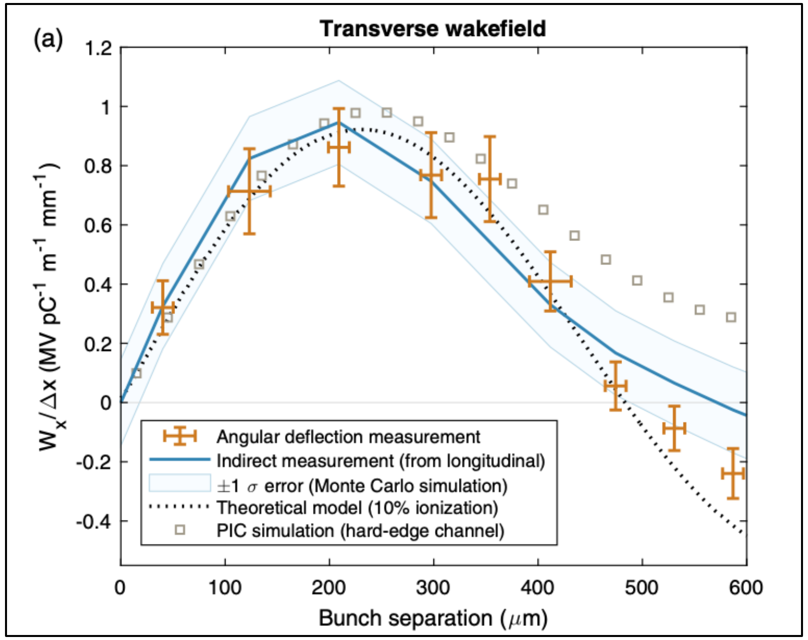
(P. Muggli, CAS 2014)

PWFA — Positrons

→ BUT: In the blowout regime, e^+ witness bunches need to be placed very close to the singularity
→ Some creative solutions were proposed:



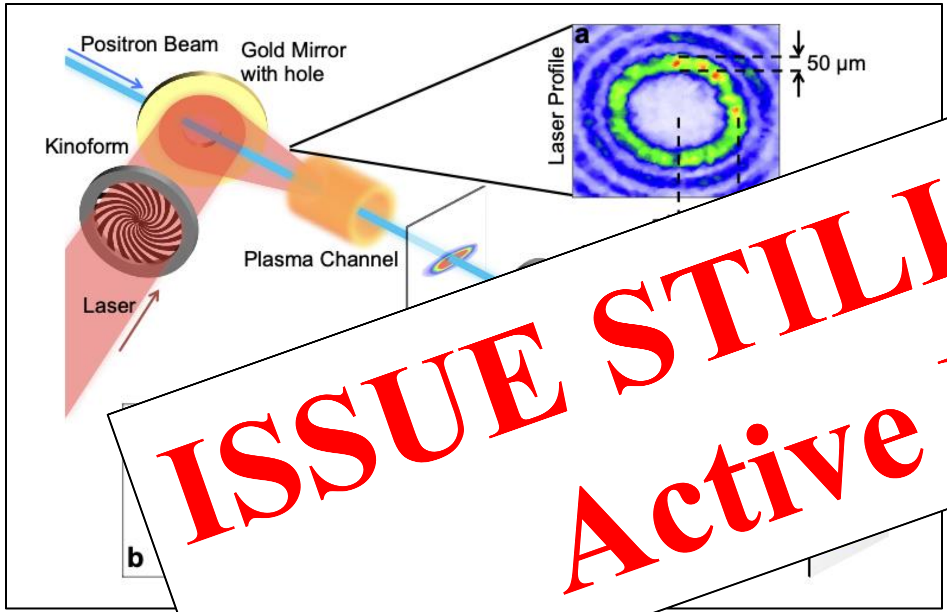
→ Acceleration in hollow plasma (avoiding focusing force on axis)
Gessner et al., Nat. Comm. 7, 11785 (2016)

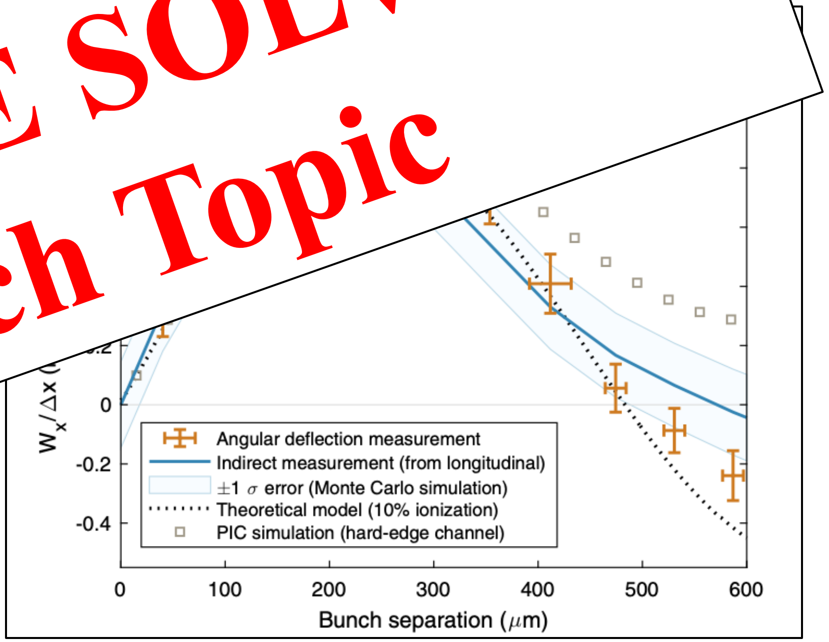


→ But tight alignment tolerance to avoid transverse instabilities
Lindstrøm et al., PRL 120, 124802 (2018)

PWFA — Positrons

→ BUT: In the blowout regime, e⁺ witness bunches need to be placed very close to the singularit
→ Some creative solutions were proposed:





ISSUE STILL TO BE SOLVED!!
Active Research Topic

→ Acceleration ... (avoiding focusing force on axis)
Gess..., Nat. Comm. 7, 11785 (2016)

→ But tight alignment tolerance to avoid transverse instabilities
Lindstrøm et al., PRL 120, 124802 (2018)

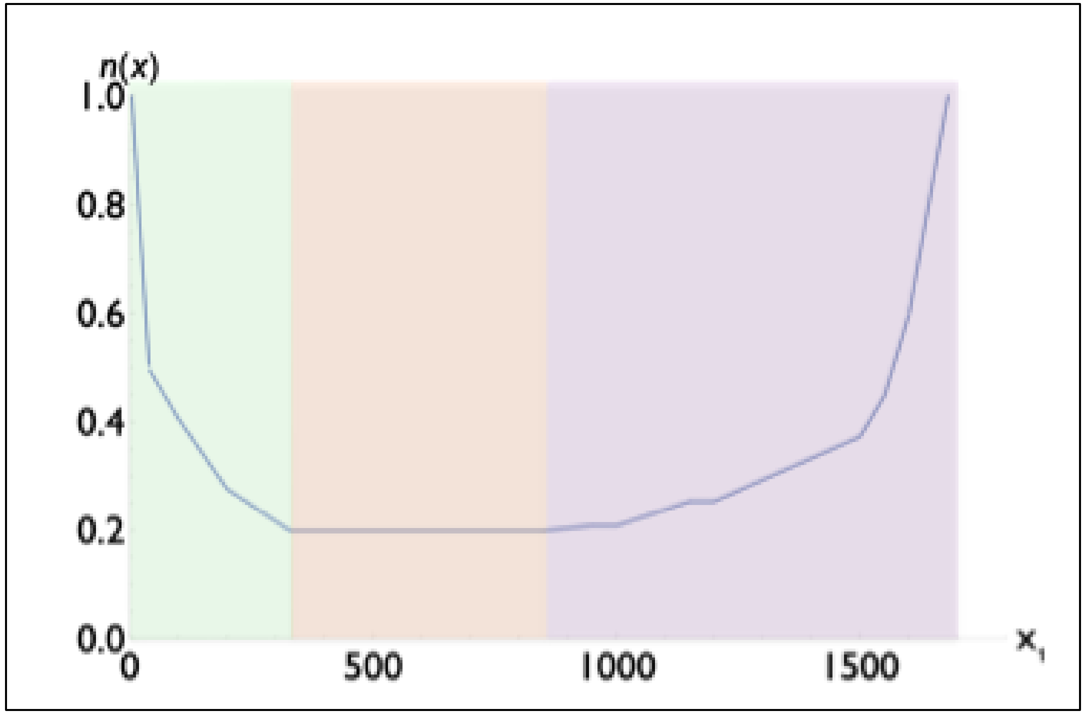
PWFA — Muons

Acceleration of muons is possible in principle, but:

- if injected with v<<c: need for a slow (non-relativistic) driver
  → dephasing upon acceleration (witness gets closer to the driver)

- Possible solution: tapered plasma density profile

  - Initial down ramp to slow down the wake
  - Constant density region after $v_{\mu} \sim v_d$
  - Up ramp region to mitigate dephasing



C. Badiali (IST), EAAC 2023

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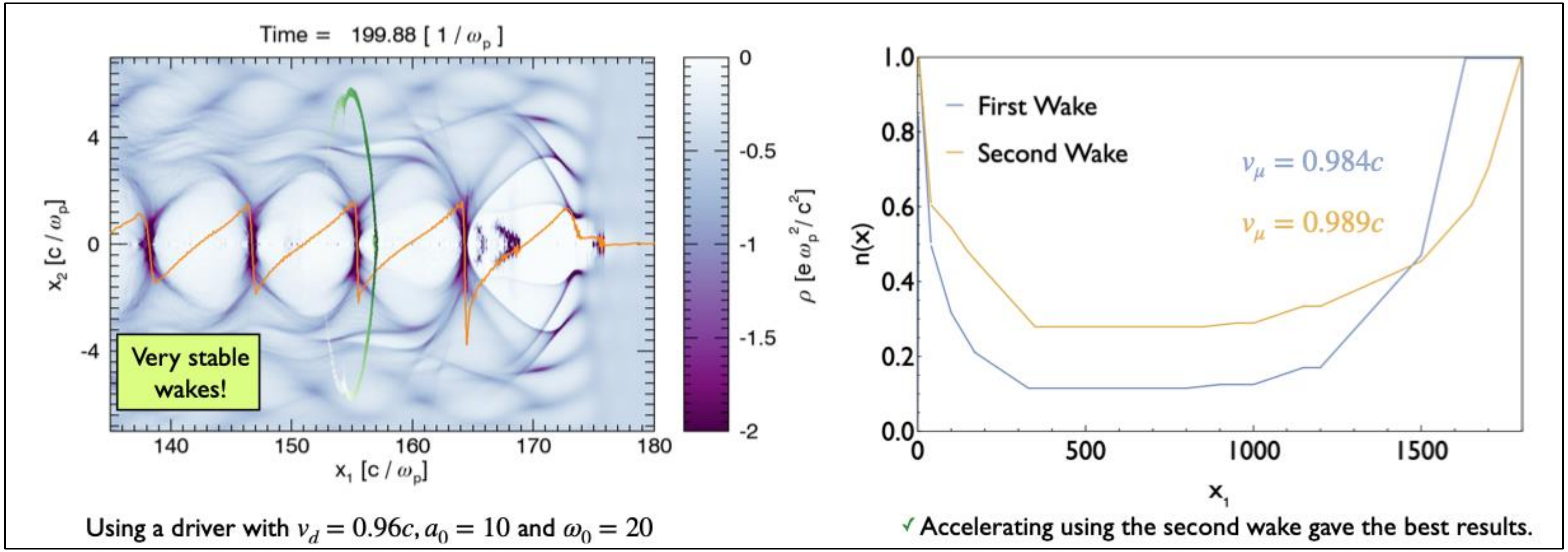

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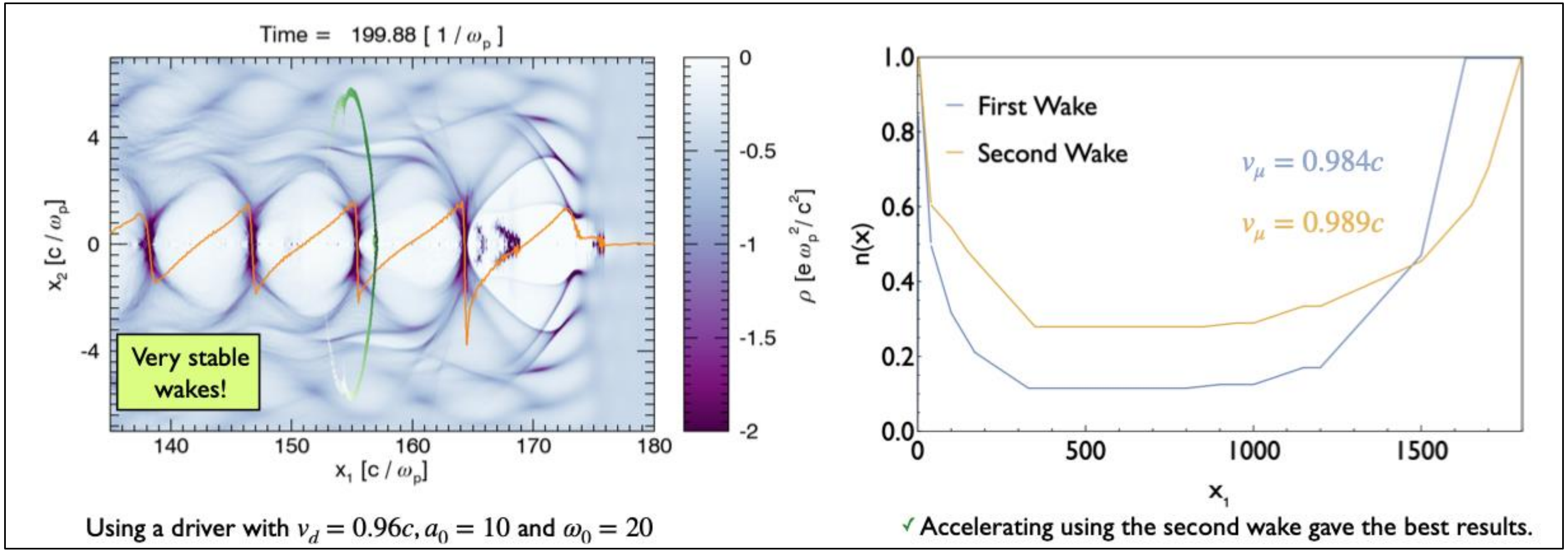


C. Badiali (IST), EAAC 2023

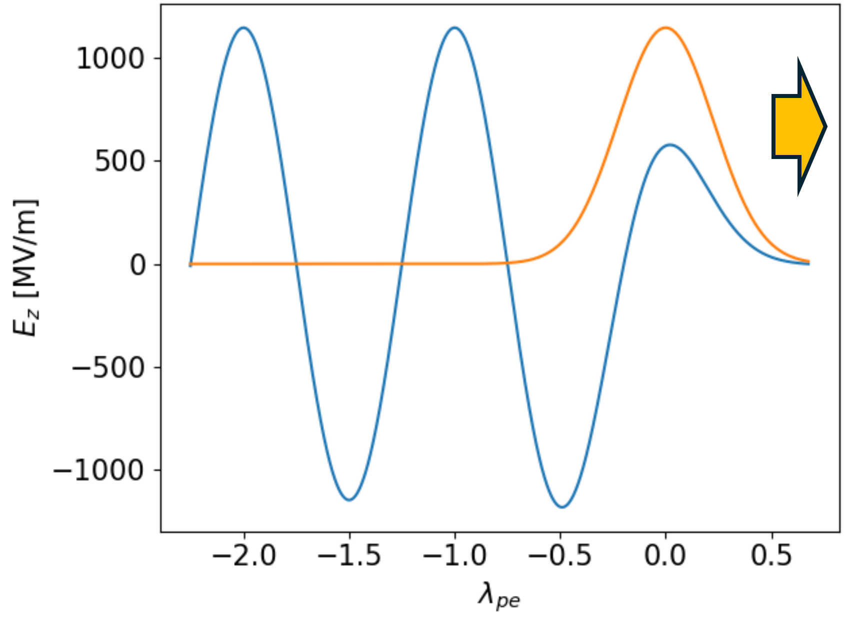
But: need a muon beam to test..

PWFA — Very high energy

- The maximum net energy gain of the witness bunch is in general limited to:

$$\Delta E \sim 2 \times E_d$$

(and for energy conservation $Q_W \Delta E_W \leq Q_D \Delta E_D$)



e.g: 1 GeV drive bunch drives 1 GV/m accelerating field

→ Depleted after 2m (500MV/m decelerating field)

→ Maximum energy gain of witness: 2GeV

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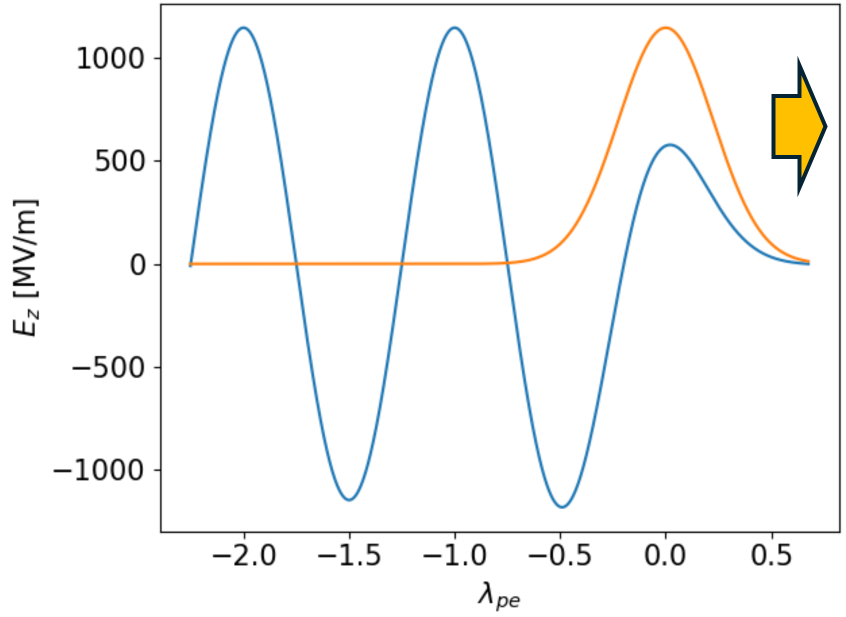

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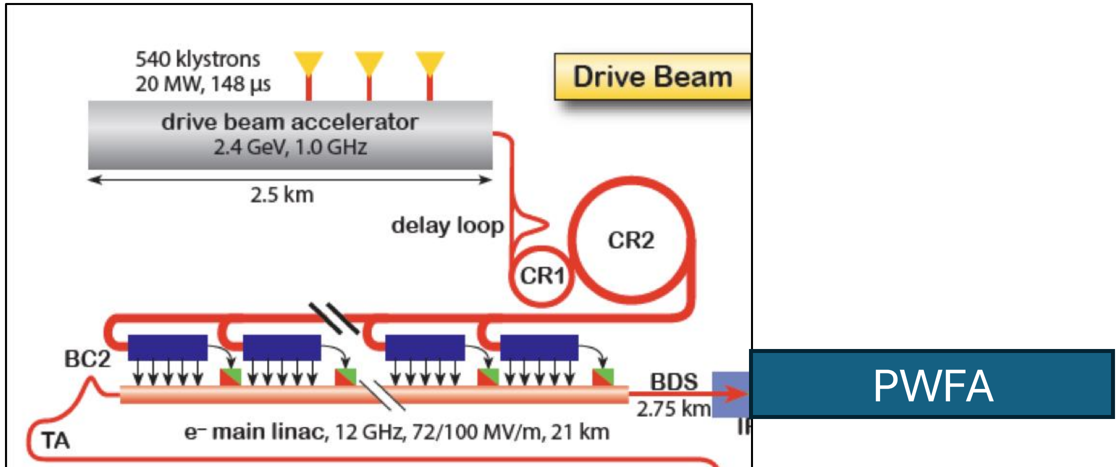
To reach VERY high energy (e.g. 5 TeV)

- **One highly energetic driver to accelerate witness in a single stage (afterburner):**

  Assuming energy tripling of witness bunch
  → need a 1.7 TeV driver and witness couple
  → CLIC-scale main linac



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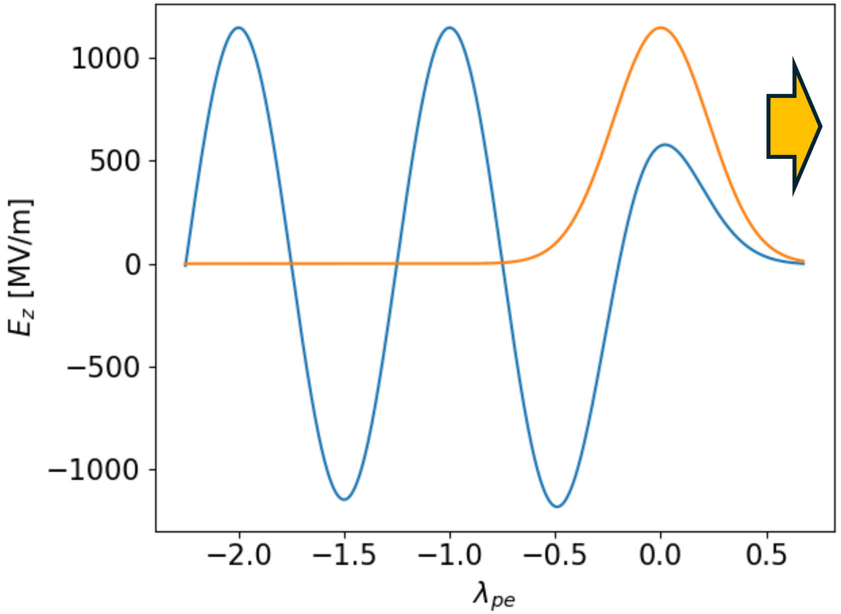

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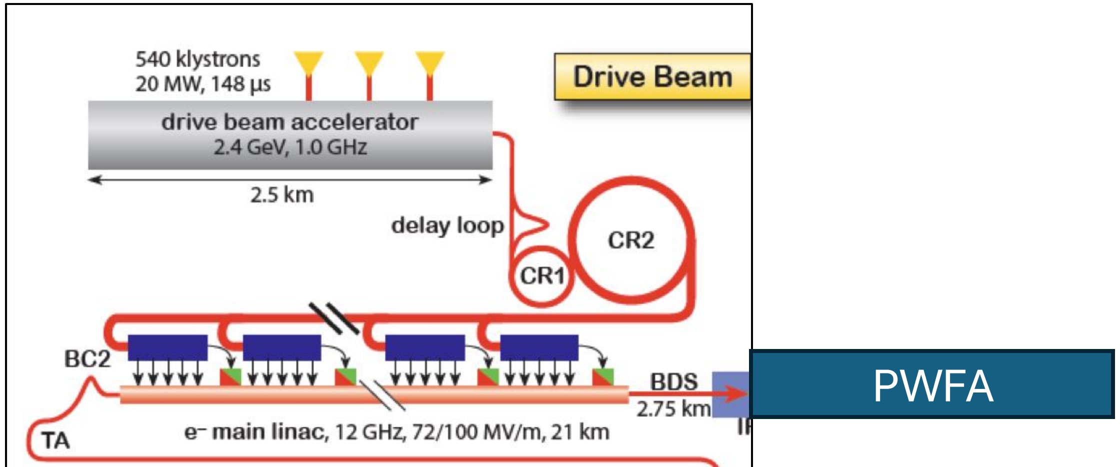
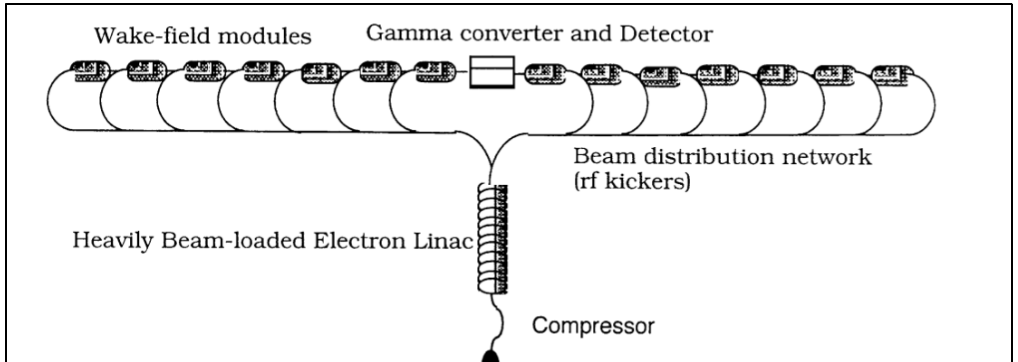


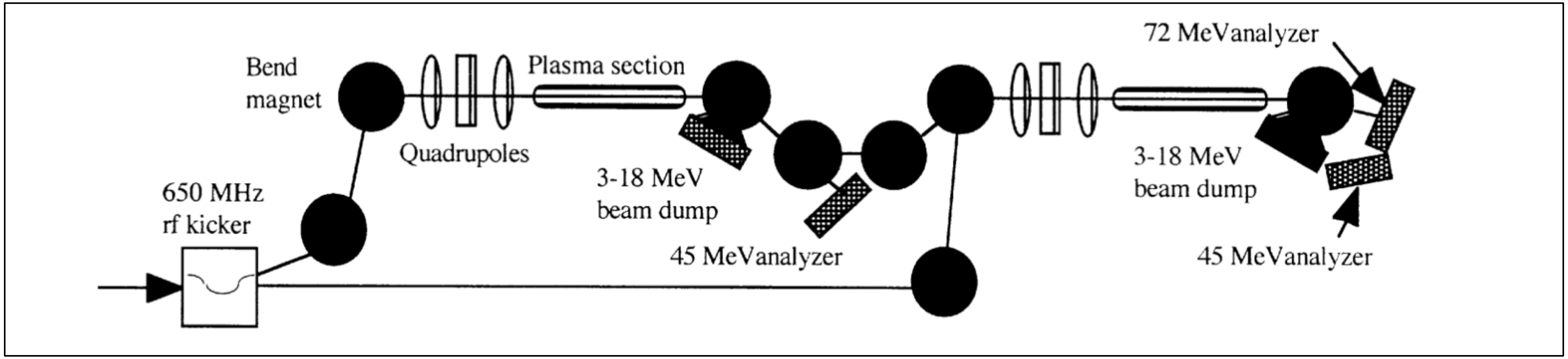
Many low-energy (cheaper) drivers in multiple stages
Using e.g. 30 GeV drive bunches (requiring a > 300 m-long linac)
→ ΔE < 60 GeV (R<2 for single symmetric driver)
→ Need > 83 stages



J. Rosenzweig et al., NIM A 410 (1998) 532—543

PWFA — Staging

- The most outstanding challenge in PWFA:



J. Rosenzweig et al., NIM A 410 (1998) 532—543

In each of them:

- Inject the driver bunch
- Inject and match the witness bunch with appropriate beam loading
- Accelerated with high gradient and high net energy gain
- Extract (i.e., reduce divergence)
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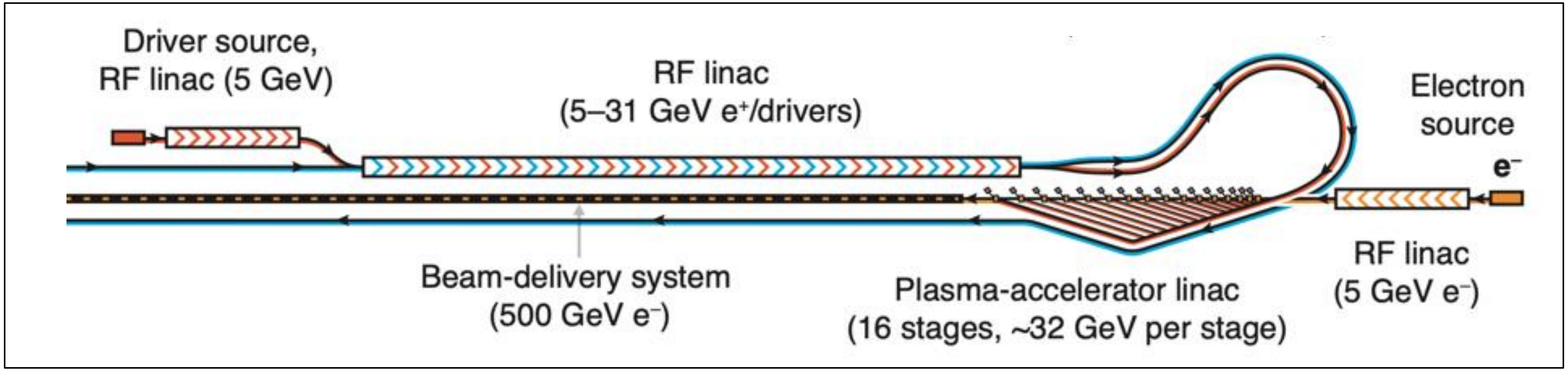

From HALHF design
Foster et al 2023 New J. Phys. **25** 093037

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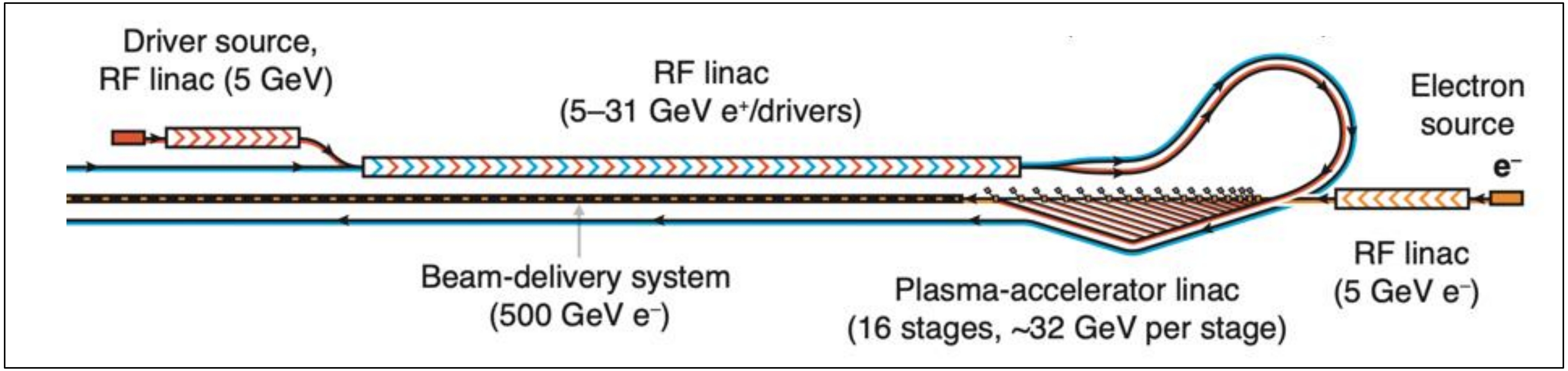

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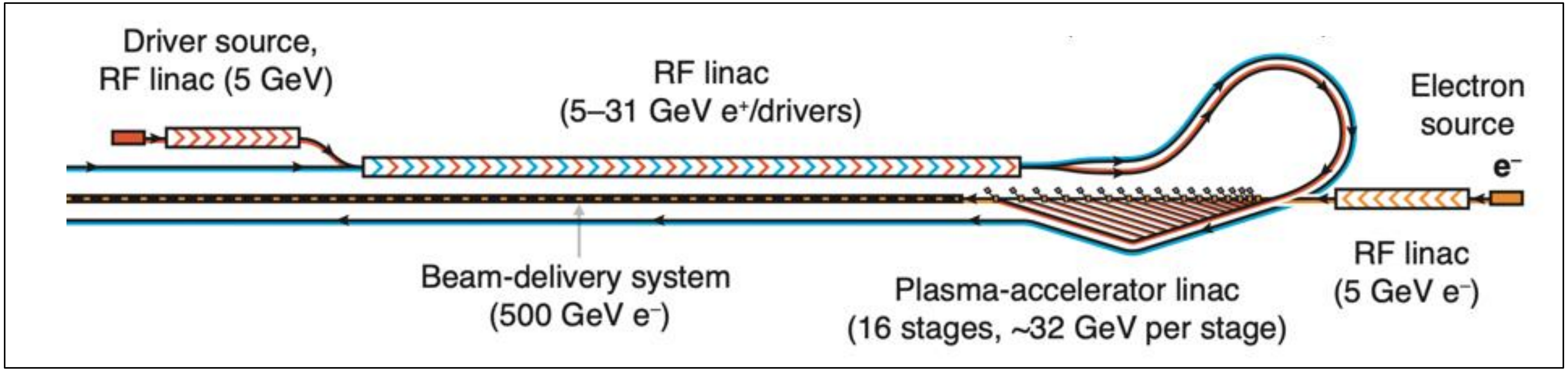

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Basically, repeating EuPRAXIA n times..

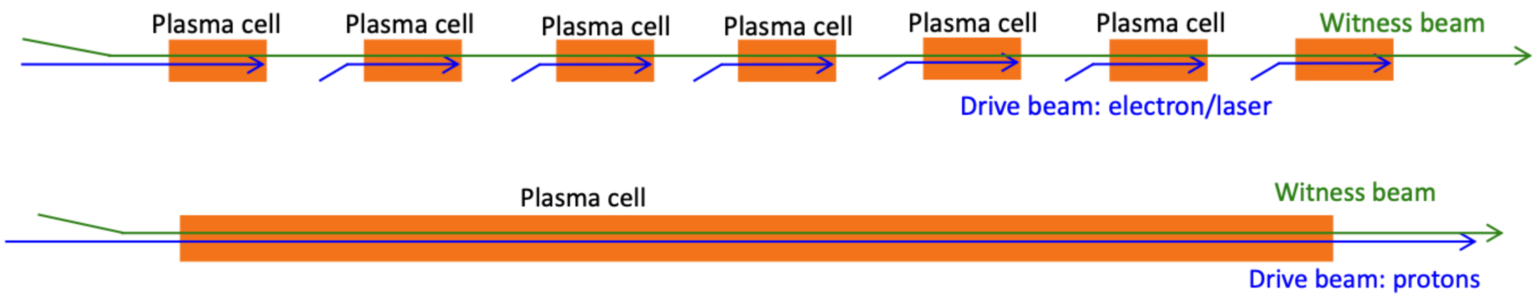
SPARC_LAB and EuPRAXIA could play a major role on this topic!

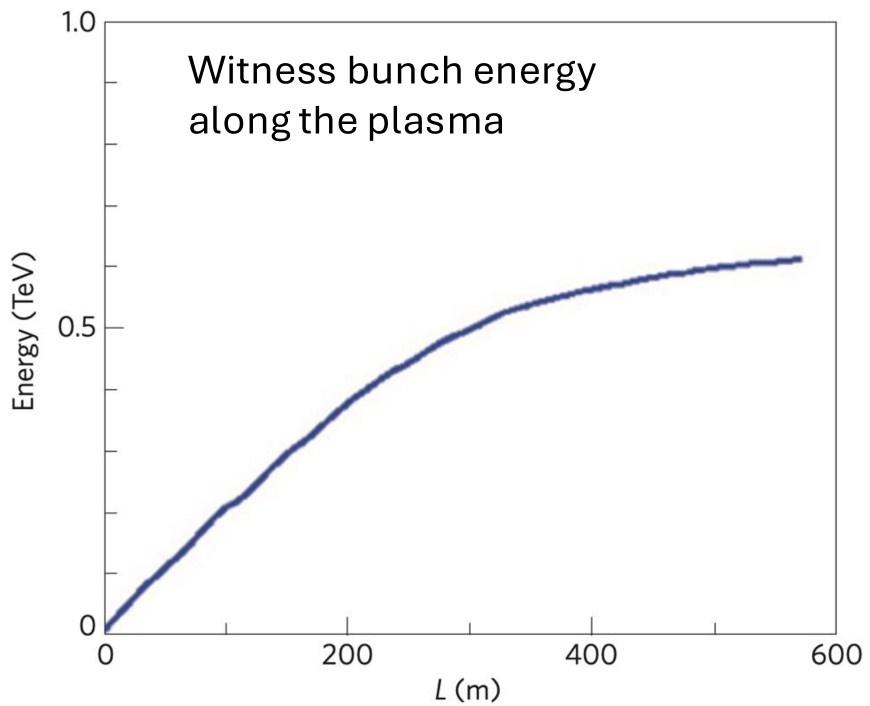
PWFA — Avoiding staging

- Alternative: single long stage with extremely energetic driver:
  → Proton bunches from synchrotrons

- Available proton bunches carry large amounts of energy:
  - CERN SPS proton bunch: $3 \cdot 10^{11}$ p^+ at 400 GeV/c → 19.2 kJ
  - CERN LHC proton bunch: $1 \cdot 10^{11}$ p^+ at 7 TeV/c → 112 kJ
  - SLAC FFTB electron bunch: $7 \cdot 10^{9}$ e^- at 40 GeV/c → 40 J

⇒ **Drive wakefields over very long distance!**
no need for staging





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

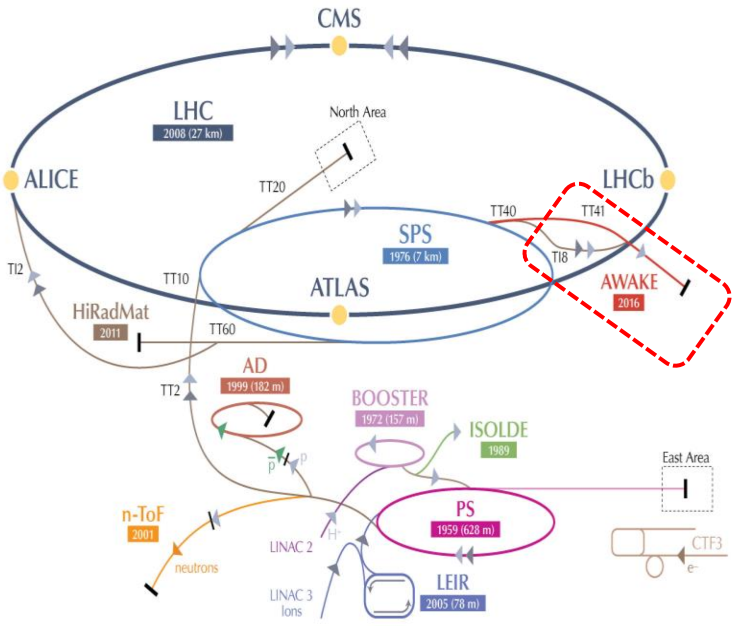
Parameters:
single proton bunch
σ_z = 100 μm,
E = 1 TeV,
population: $1 \cdot 10^{11}$ particles per bunch
(16nC)

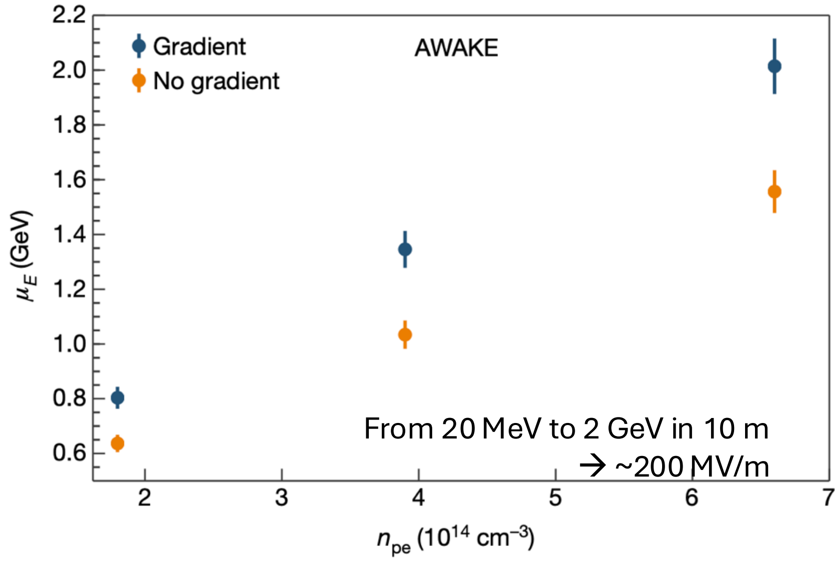
PWFA — Avoiding staging

- Alternative: single long stage with extremely energetic driver:
  → Proton bunches from synchrotrons

→ Acceleration of electrons demonstrated at AWAKE
(using 400 GeV p+ from SPS and 10-m-long plasma source)

→ But: rely on beam-plasma instability to drive large amplitude wakefields





AWAKE Coll., Nature **561**, 363–367 (2018)

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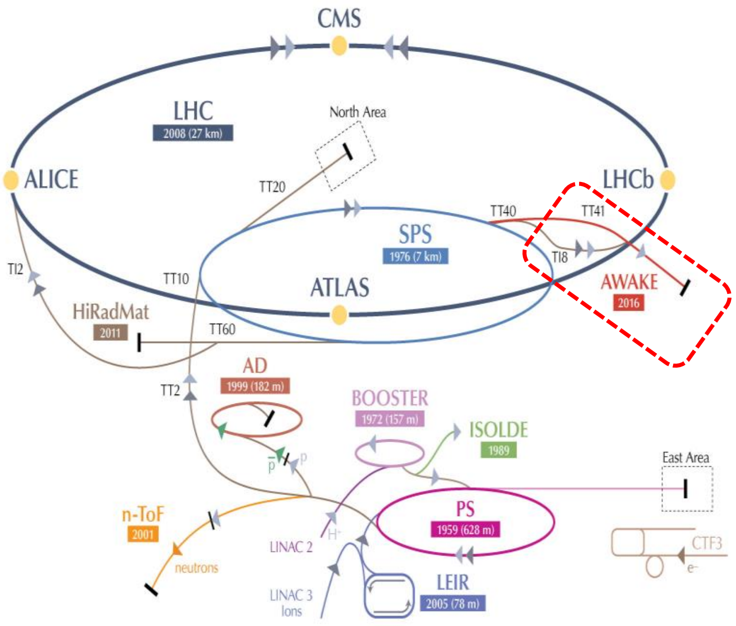

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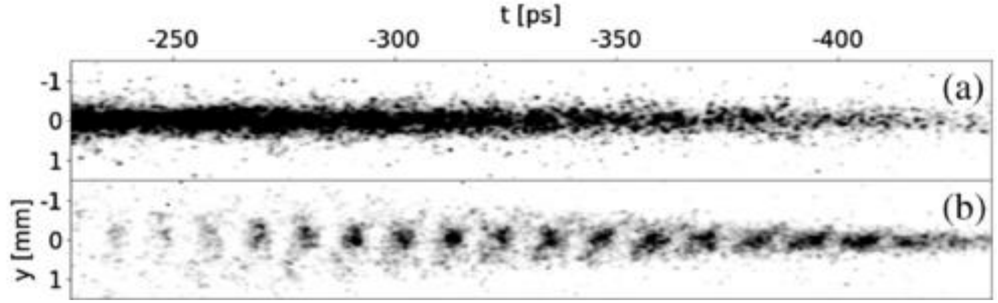
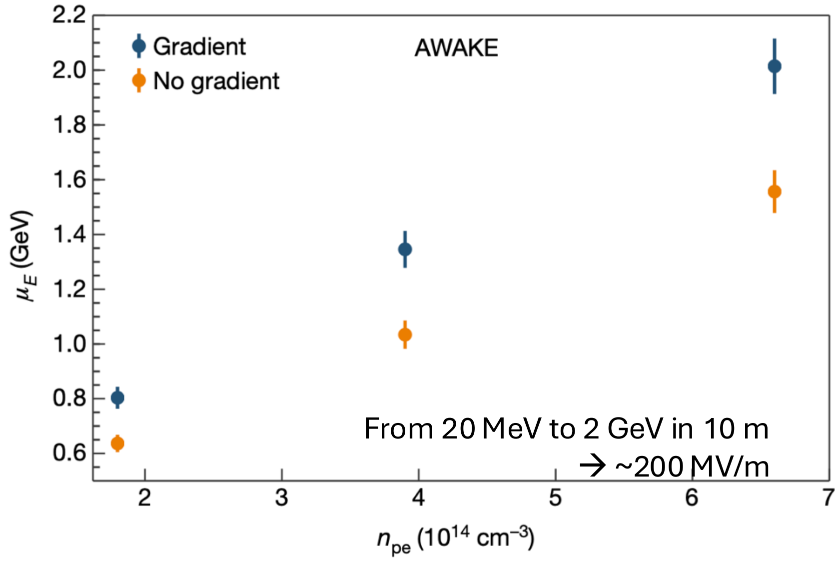


Bunch converted into train of microbunches

L. Verra et al. (AWAKE Collaboration) Phys. Rev. Lett. **129**, 024802 (2022)



→ Difficult to achieve collider-quality beams

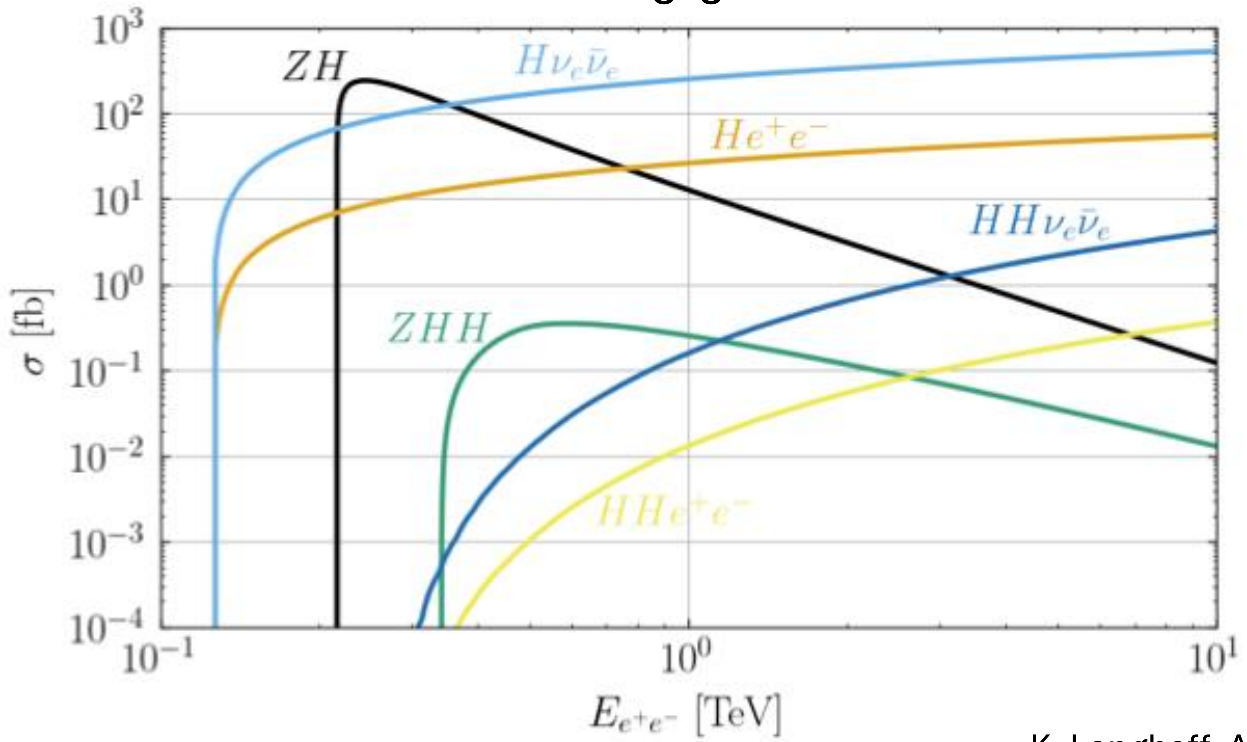
→ Applications for fixed target experiments

AWAKE Coll., Nature **561**, 363–367 (2018)

Applications to Particle Physics

- Need to reach high center-of-mass energy (100’s GeV or multi-TeV) (relevant for the target application/process to investigate)
  - Beam Species → impact on the physics and on the statistics

e^+e^-



K. Langhoff, ALEGRO Workshop 2025

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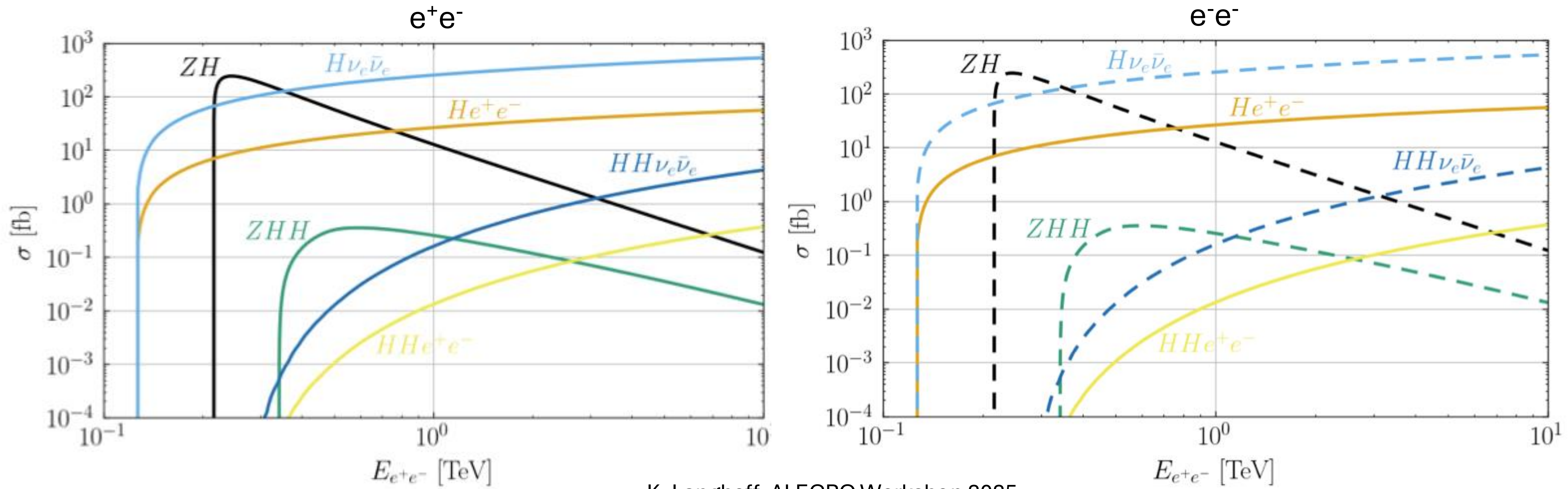

K. Langhoff, ALEGRO Workshop 2025

Applications to Particle Physics

- Center-of-mass energy
  (relevant for the target application/process to investigate)

  - Beam Species → impact on the physics and on the statistics

- Luminosity
  (gathering enough data in reasonable amount of time):

charge

Rep rate

$$\mathcal{L} = \frac{N^2 n_b f_{rep}}{4\pi\sigma_x\sigma_y} \cdot F$$

Transverse size

Which reads:
- **High charge (~nC)**
- **High rep rate (~kHz)**
- **Extremely high quality (~nm normalized emittance)**

Applications to Particle Physics

- Center-of-mass energy
  (relevant for the target application/process to investigate)

  - Beam Species → impact on the physics and on the statistics

- Luminosity
  (gathering enough data in reasonable amount of time):

- Luminosity per power
  - Better metrics to quantify the luminosity one can "buy"

Efficiency:

- Wall-plug → Drive beam (Klystrons, etc..)
  ~55% (CLIC)
  M. Aicheler et al., CLIC CDR (2012)

- Drive Beam → Plasma
  ~60% with Gaussian bunch
  F. Peña et al., Phys. Rev. Res. 6, 043090 (2024)

- Plasma → Witness
  ~22% preserving quality
  Lindstrøm et al., Nat. Comm. 15, 6097 (2024)

Which reads:

- **High quality**
- **High efficiency**

$$\frac{\mathcal{L}}{P_{tot}} = \frac{\eta N}{4\pi\sigma_x\sigma_y E_b}$$

Bunch energy

Applications to Particle Physics

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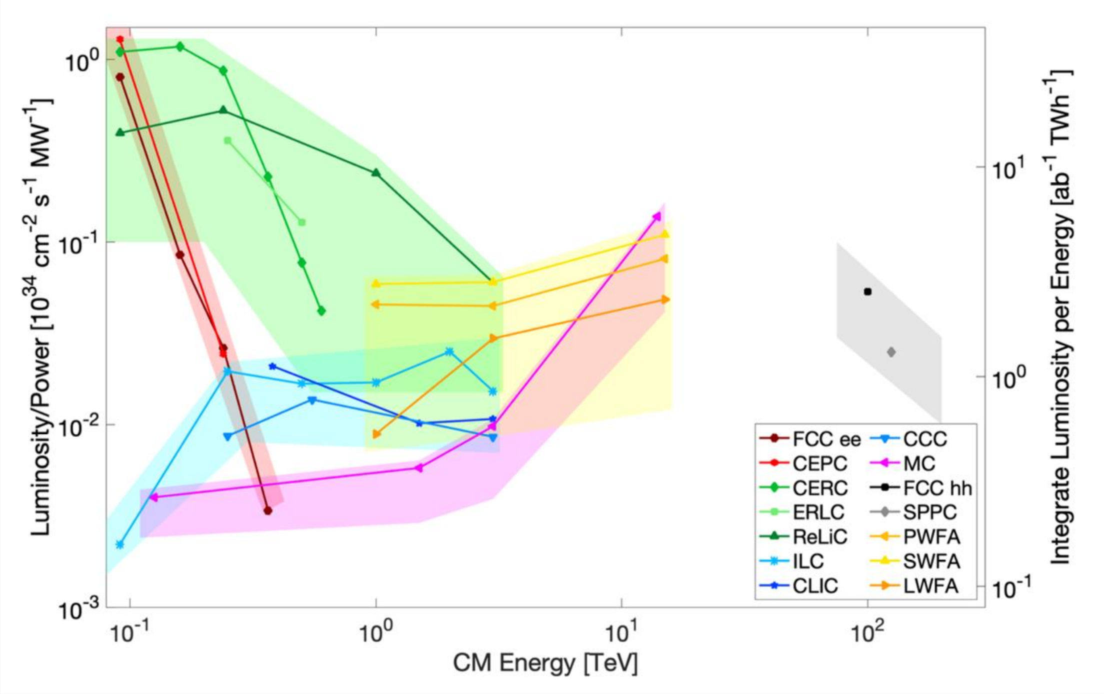

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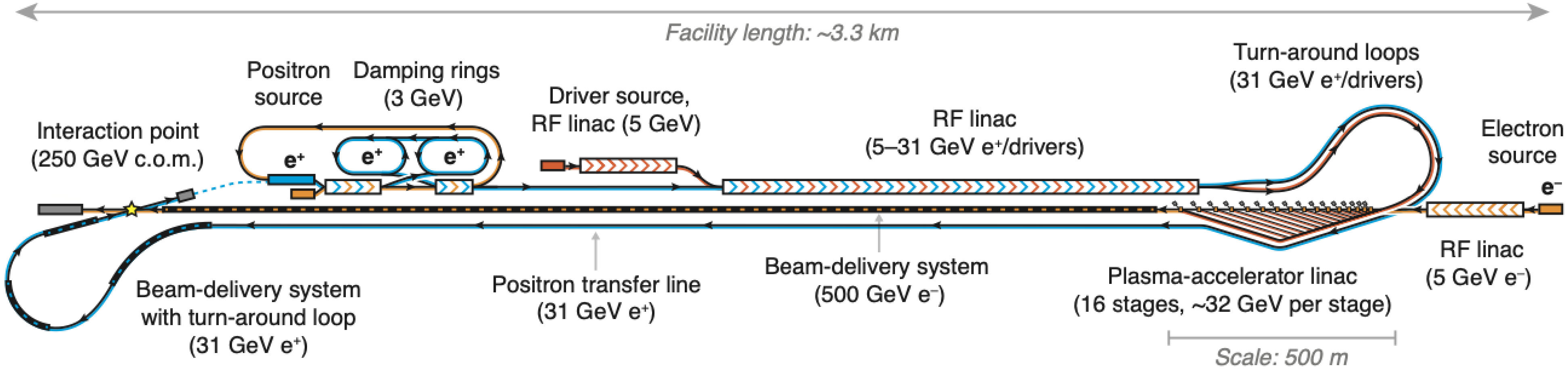
Recent Proposals – HALHF

HALHF: a hybrid, asymmetric collider concept

Plasma acceleration for electrons + RF acceleration for positrons

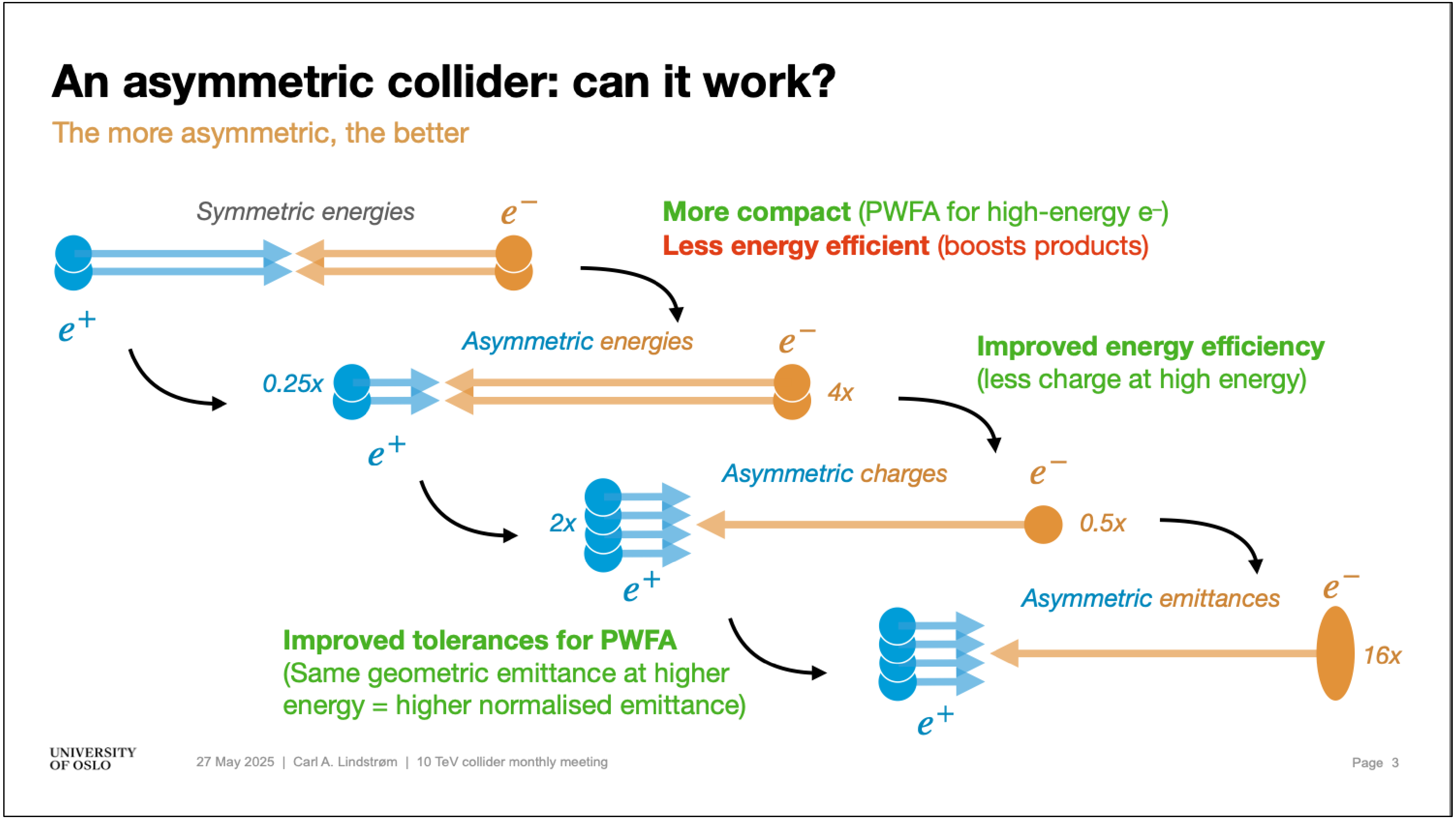
> Solving the plasma positron problem by accelerating positron with RF linacs.



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

> Length dominated by the beam-delivery system. Cost dominated by the RF linac.

Recent Proposals – HALHF



Recent Proposals – HALHF

Lessons learned from HALHF

Based on Bayesian optimisation of a detailed collider physics+cost model

- Cost of power dominates (not length)
  - *Must design the plasma accelerator for the driver, not vice versa*
- Lower density is greatly favoured
  - *Little need for gradients beyond 1 GV/m (for sub-TeV machines)*
  - *Suppresses further beam ionisation of plasma*
  - *Requires high-charge beams (multi-nC)*
- Maximise the *effective* transformer ratio (transformer ratio × number of stages)
- Ion motion is required for transverse stability
- HALHF bunch trains have the potential to heat plasma to *O*(100 keV) temps
  - **The next key R&D issue will be plasma heating, cooling, and confinement**

Recent Proposals – HALHF

Cost estimation, to be compared with:

- FCC-ee (~20B€)
- ILC-CLIC (~7-12B€)

arXiv:2503.19880

Domain	*Sub-domain*	*Cost [MILCU]* 250 GeV	380 GeV	550 GeV
Main-beam production	Electron source (photocathode, polarized)	82	82	82
	Electron injector linac	22	22	22
	Positron source (helical undulator, polarized)	178	178	178
	Positron injector linac	32	32	32
	Positron transport	55	74	96
	Positron damping rings (2x)	200	200	200
Drive-beam production	Electron source	10	10	10
	Driver linac modules	113	173	254
	Driver linac RF	325	501	731
	Frequency multiplication (combiner rings)	127	127	127
	Driver transport (surface-to-underground)	24	25	26
Electron linac (PWFA)	Plasma modules	17	26	38
	Interstage transport	30	37	44
	Driver delay chicanes	90	120	155
	Driver beam dumps	11	17	25
Positron linac (cool-copper RF)	Cool-copper linac modules	113	176	259
	Cool-copper linac RF	298	465	683
	LN_2 reliquification plants	34	53	78
Beam delivery and post collision lines (dual IPs)	Electron beam delivery systems (2x)	158	194	234
	Positron beam delivery systems (2x)	53	65	78
	Final focus, experimental area	20	20	20
	Post collision lines/dumps	45	64	88
Civil engineering	Surface driver and complex	63	92	130
	Surface-to-underground tunnel	31	31	31
	Electron arm tunnel	44	59	75
	Positron arm and damping ring tunnels	54	77	106
	Beam-delivery systems	164	201	243
	Interaction region	154	154	154
Infrastructure and services	Electrical distribution	104	125	150
	Survey and alignment	80	96	116
	Cooling and ventilation	302	439	622
	Transport / installation	24	29	35
Machine control, protection and safety systems	Safety systems	30	36	43
	Machine control infrastructure	60	72	87
	Machine protection	6	7	9
	Access safety & control system	9	11	14
Total (in 2012 MILCU)		**3162**	**4090**	**5275**
Total (in 2024 Swiss francs)		**3.8 BCHF**	**4.9 BCHF**	**6.3 BCHF**

Recent Proposals – 10 TeV Wakefield Design Study

- Response to 2023 Snowmass P5 Report (analogue to ESPP in USA)
-

Recommendation 4: Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

Investing in the future of the field to fulfill this vision requires the following:

a. Support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years (sections 3.2, 5.1, 6.5, and Recommendation 6).

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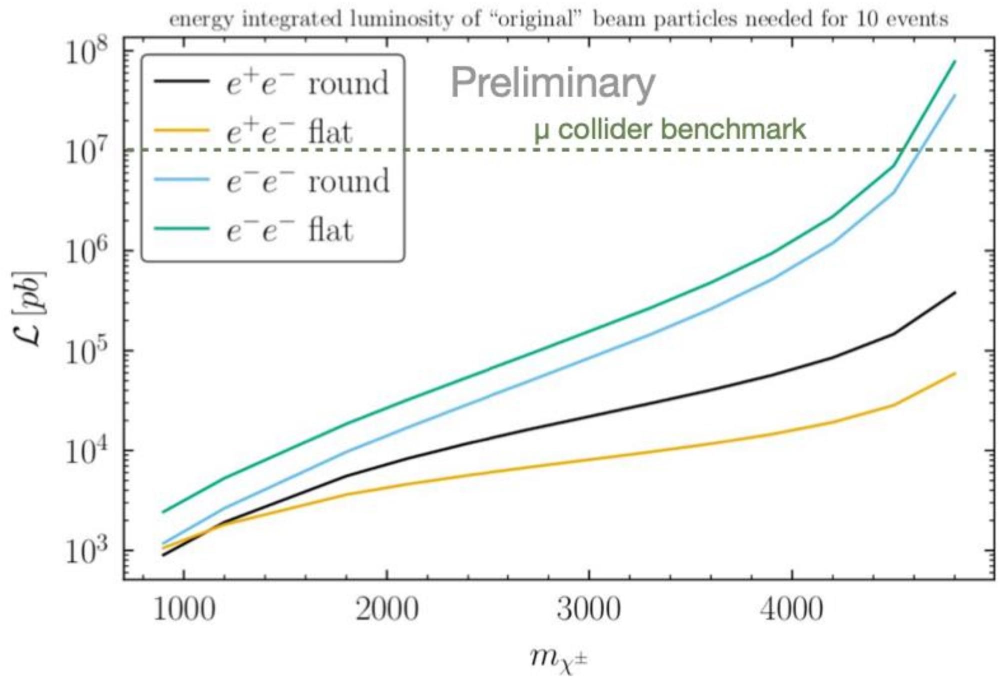

L. Xu, T. Opferkuch, I. Savoray, C. Scherb, S. Chigusa, SK in progress

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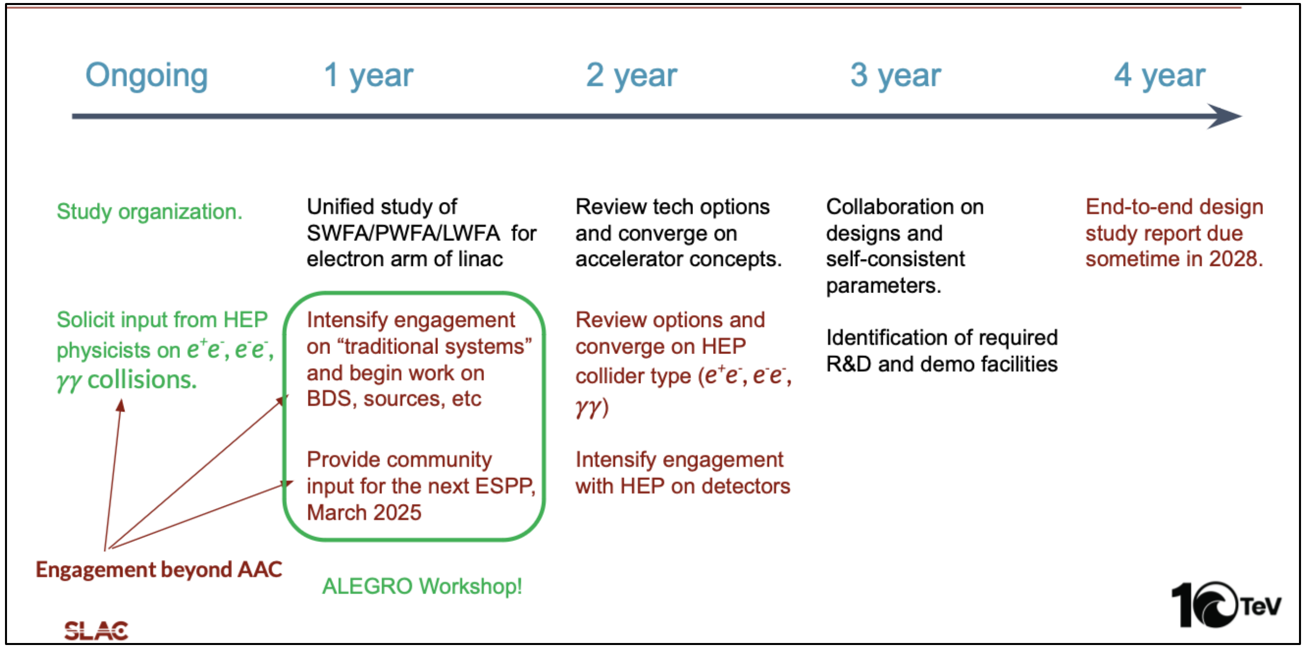

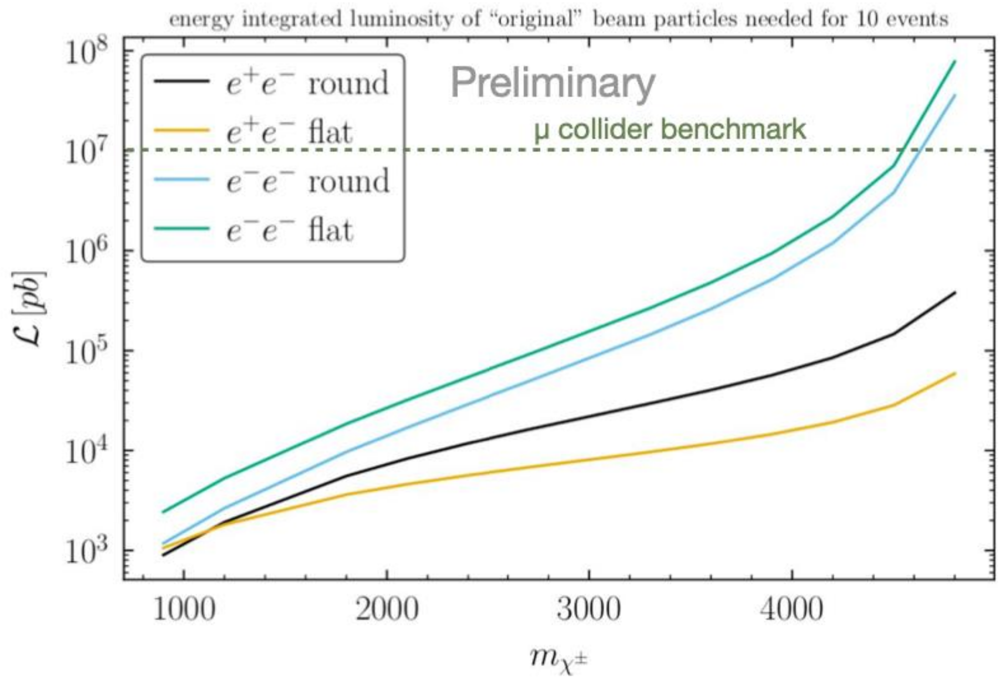

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- Response to 2023 Snowmass P5 Report (analogue to ESPP in USA)
- "Discovery machine" at 10 TeV c.o.m. competitive with other technologies
- Goal: present an end-to-end design concept with consistent parameters
- Evaluating the best acceleration technique and investigating new aspects as:
  - beam-beam interaction → e.g. flat or round beams?
  - environmental impact
  - Beam delivery system
  - **STAGING**
  - **Full-program cost → is it really competitive?**

- System integration and optimization
- Beam sources (incl. damping rings)
- Drivers
  - Laser
  - Beams - SWFA
  - Beams - PWFA
- Linacs
  - LWFA
  - SWFA
  - PWFA
- Beam delivery system
- Beam-beam interactions
- Beam diagnostics
- Machine-detector interface
- HEP detector
- HEP physics case
- Environmental impact
- Simulations/computing/AI

Contributions in any of these areas are welcome!

Recent Proposals – 10 TeV Wakefield Design Study

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  - **STAGING**
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- Submitted a contribution to ESPP Update

Design Initiative for a 10 TeV pCM Wakefield Collider

https://arxiv.org/abs/2503.20214

10TeV WFA indico page:
https://indico.slac.stanford.edu/category/138/

Advertised by Nature:
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NEWS | 14 April 2025

Radical approach to shrink particle colliders gains momentum

Plans are taking off to use an unconventional technique to accelerate particles in a future collider.

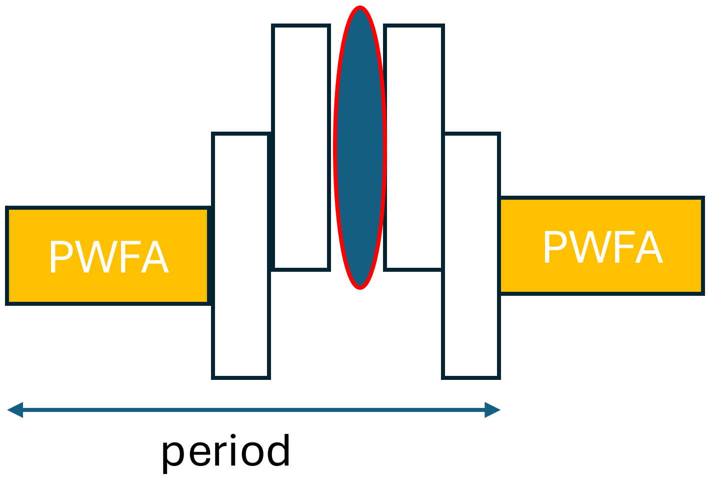
By Elizabeth Gibney

Recent Proposals – 10 TeV Wakefield Design Study

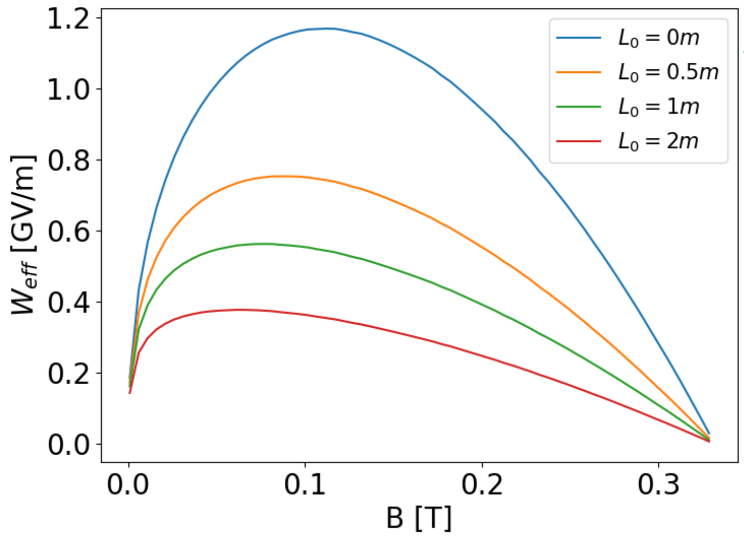
- Starting working on the "details" to design a real machine:

  e.g. energy loss due to synchrotron radiation in chicanes between each stage
  → Reducing the effective gradient (energy / full length of the linac)
  → Length of optics increases with energy

Optics: $L_O \propto \sqrt{\gamma}$



5 GV/m in plasma

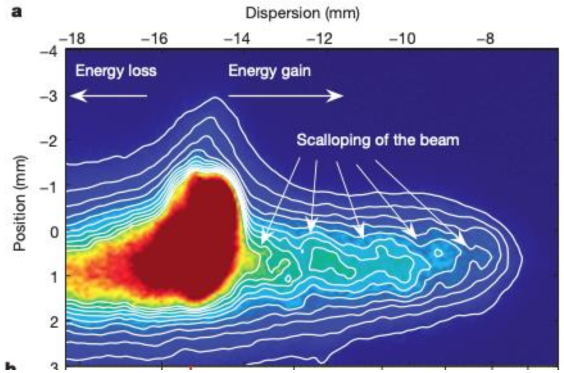


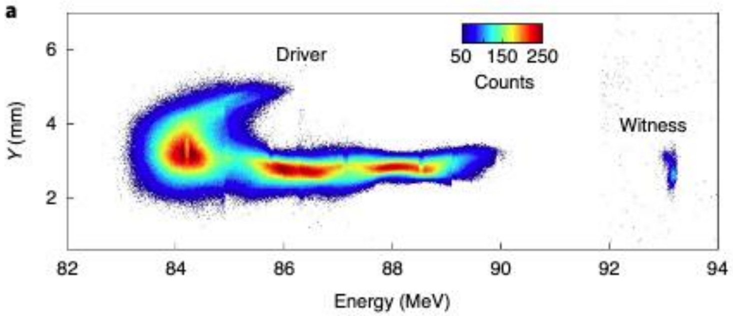
Length at first stage

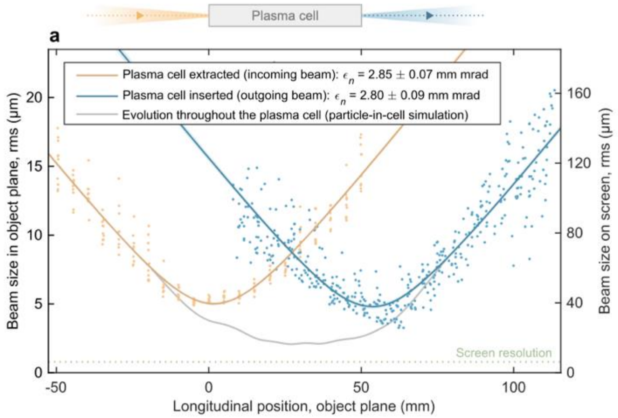
→ Lower B field for longer optics
→ W_{eff} quickly goes <0.5GV/m if length of optics is increased

Summary

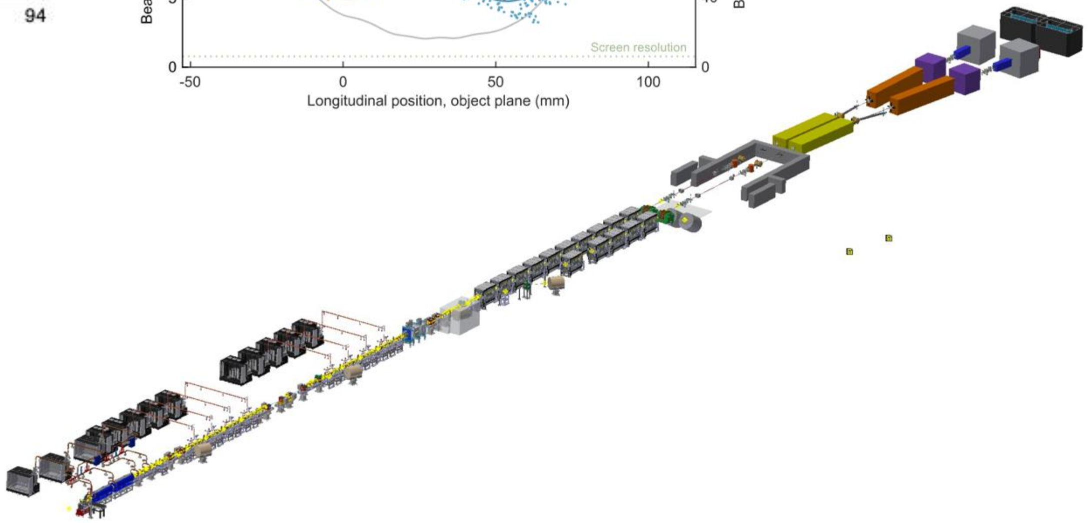
- Plasma Wakefield Acceleration is a vibrant research field



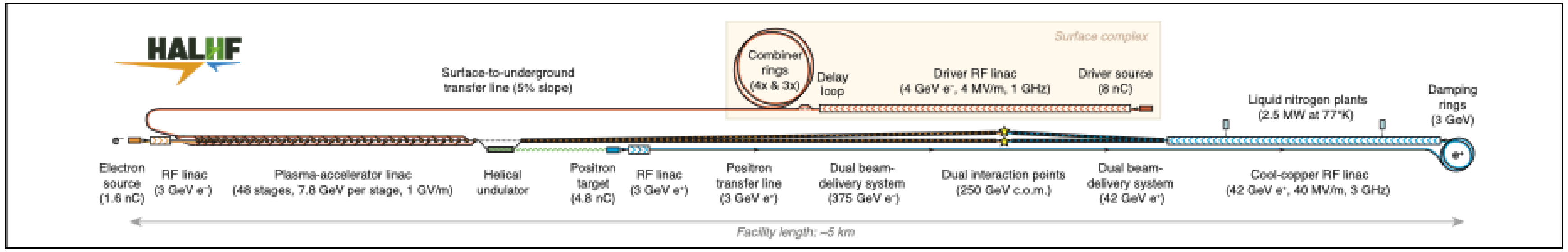




- Long promised revolutionary applications



- Time to deliver!
  - Single-stage: FEL (EuPRAXIA)
  - Multi-stage: fixed target, SFQED, colliders
  - Lots of physics to investigate along the way



ALEGRO Workshop 2026

- The **ALEGRO (Advanced LinEar collider study GROup) Workshop** gathers the advanced and novel accelerator community and reflects the global ambition towards ultra-high energy colliders driven by wakefield acceleration technology, while **also seeking engagement from HEP Theorists and Experimentalists.**

- We will host the next iteration at LNF in 2026!
  https://agenda.infn.it/event/47329/

- Presentations and discussions on:
  - Beam Physics
  - Collider Physics Case
  - Other applications
  - etc..

- You are all invited!

Thank you for listening!

Backup Slides

List of not mentioned issues

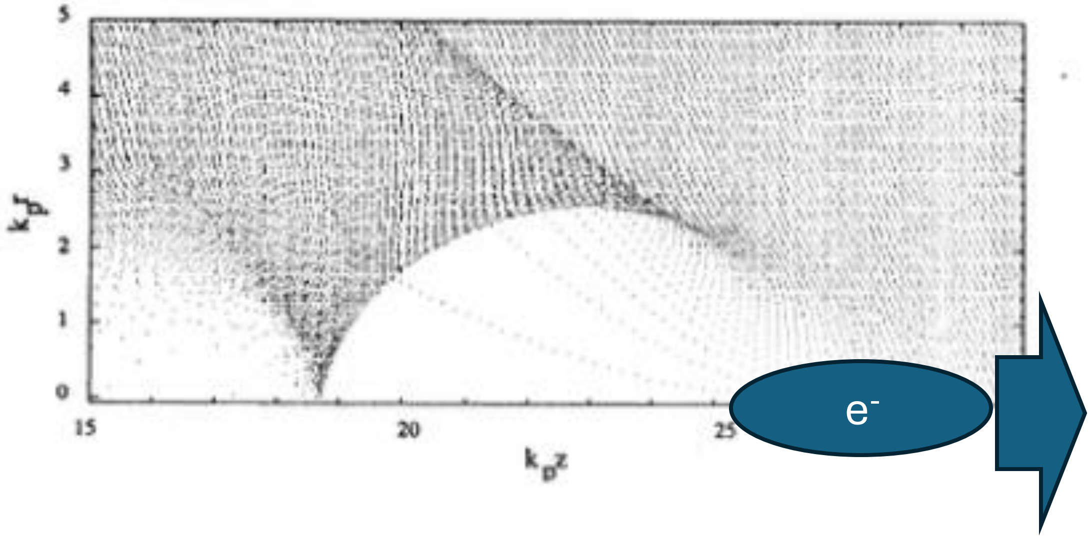
Instabilities
Jitter
Tolerances
Rep rate
Heat resistance plasma sources (plasma generation + beam power deposition)

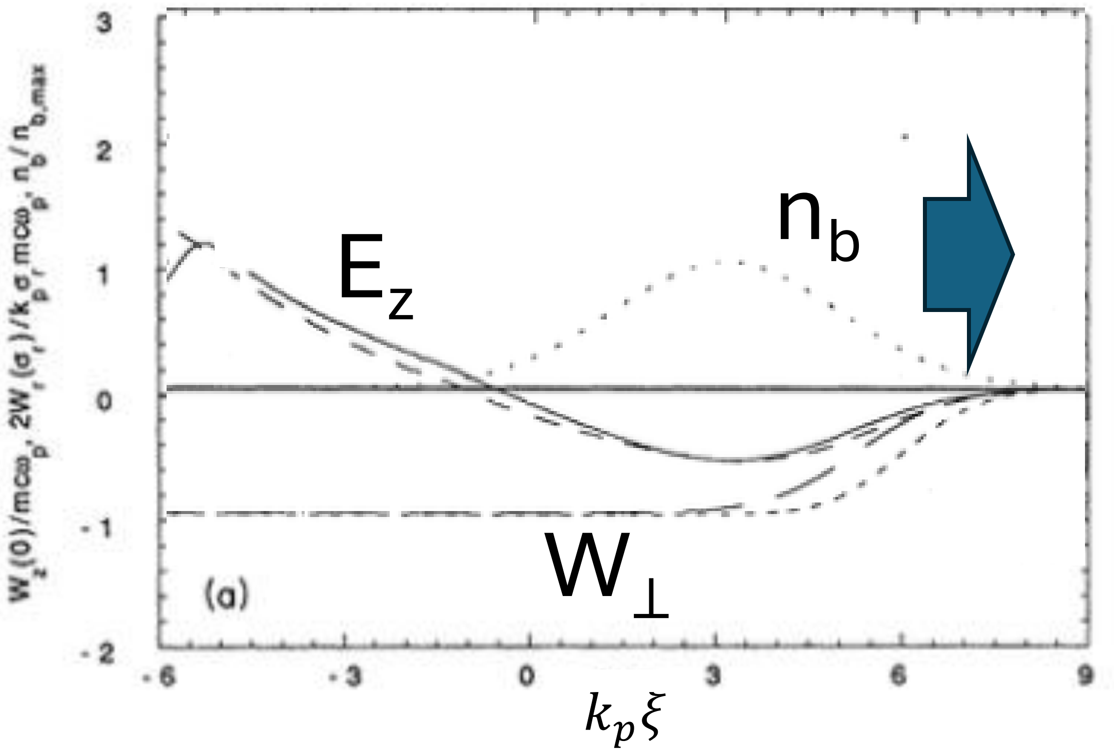
PWFA — Non-linear Regime

- When the electric field of the bunch is strong enough to expel ALL plasma electrons
  → BUBBLE of plasma electrons around a column of pure ions

Requirement:

$n_b \gg n_{pe}$





Along ξ:
- Periodic ''Steepened'' accelerating field
- Uniform focusing field

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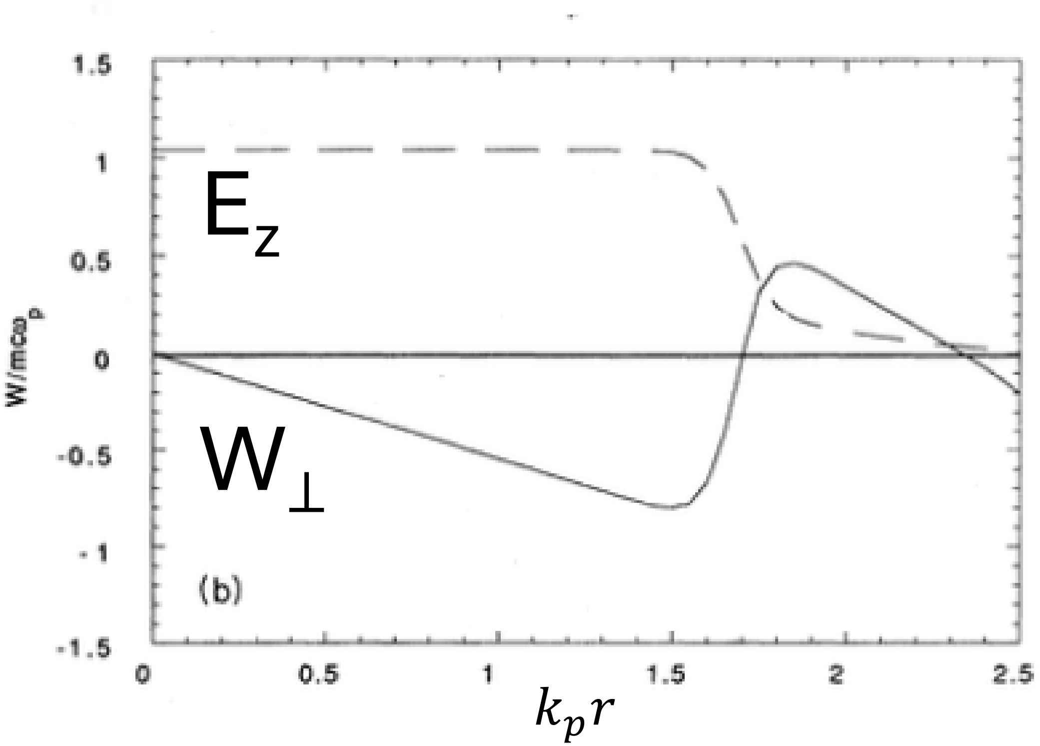
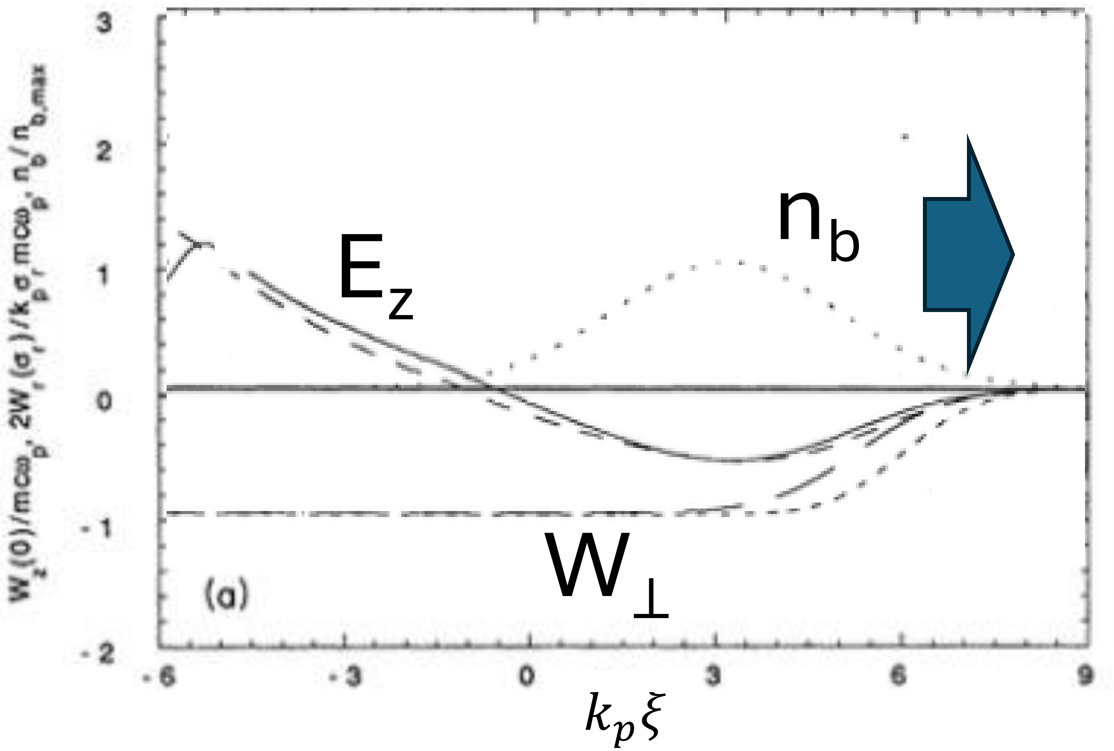




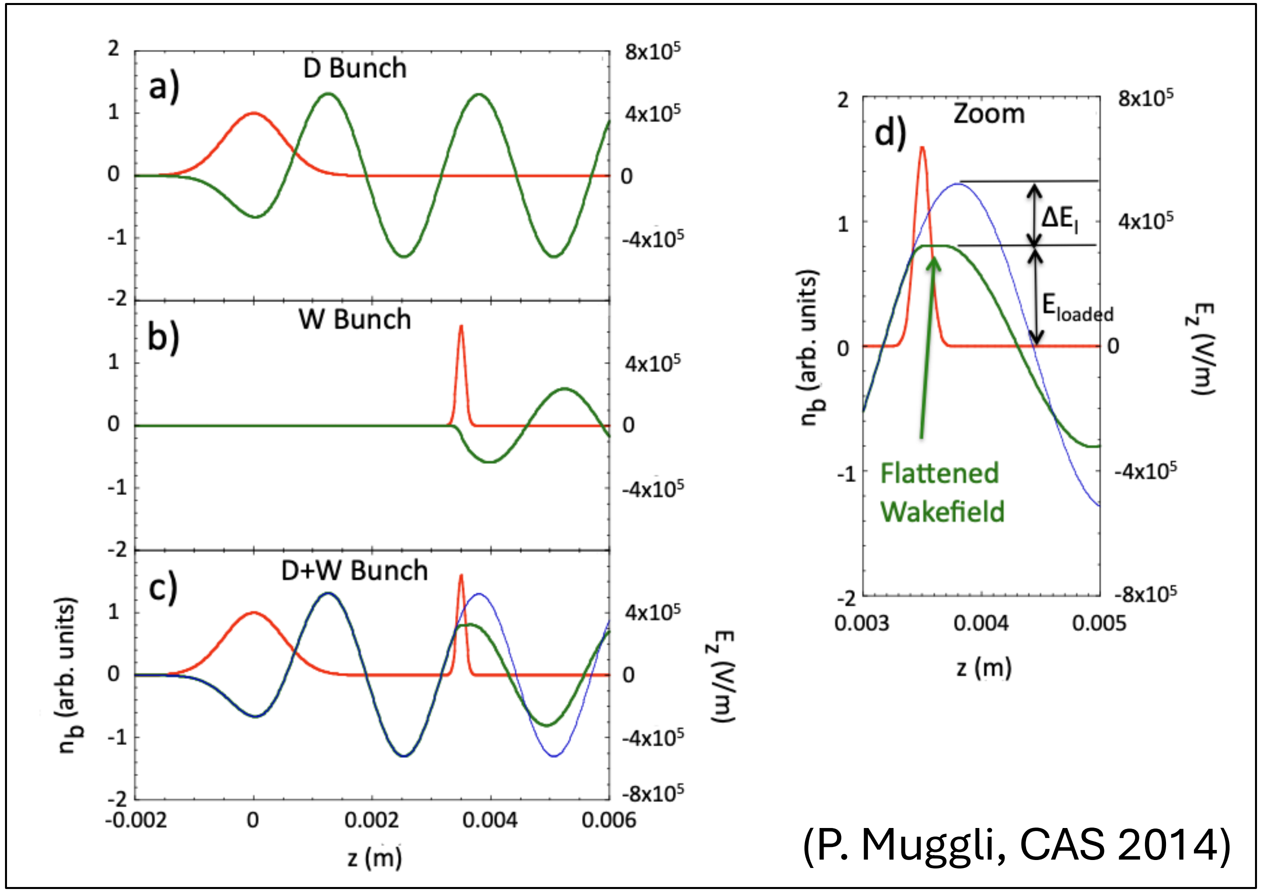
Along r (behind the bunch):
- Uniform accelerating field ➔ uniform acceleration
- Linear focusing force ➔ possible emittance preservation

Along ξ:
- Periodic ''Steepened'' accelerating field
- Uniform focusing field

PWFA — Beam Loading

➔ BEAM LOADING:
The presence of the witness bunch affects the wakefields

Linear regime



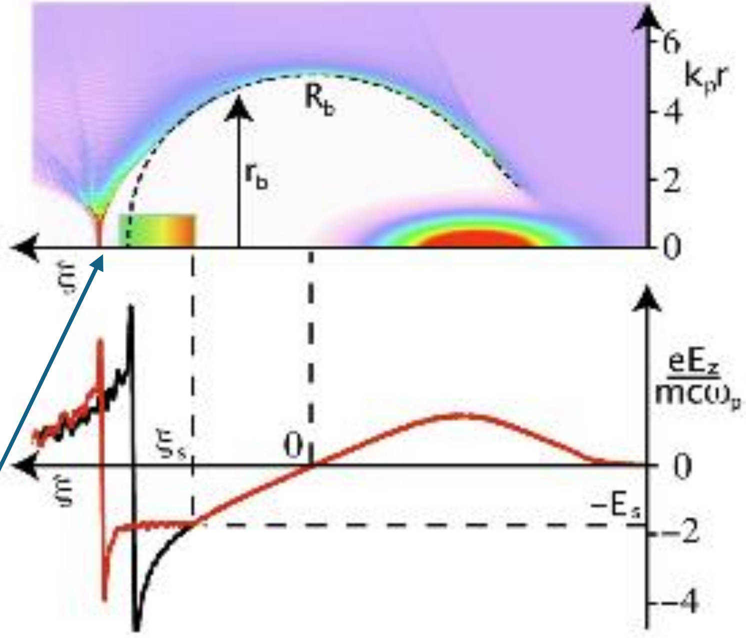
(P. Muggli, CAS 2014)

Non-linear regime

PRL 101, 145002 (2008) PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2008

Beam Loading in the Nonlinear Regime of Plasma-Based Acceleration

M. Tzoufras,[1] W. Lu,[1] F. S. Tsung,[2] C. Huang,[2] W. B. Mori,[1,2] T. Katsouleas,[3] J. Vieira,[4] R. A. Fonseca,[4] and L. O. Silva[4]



The bubble closes later

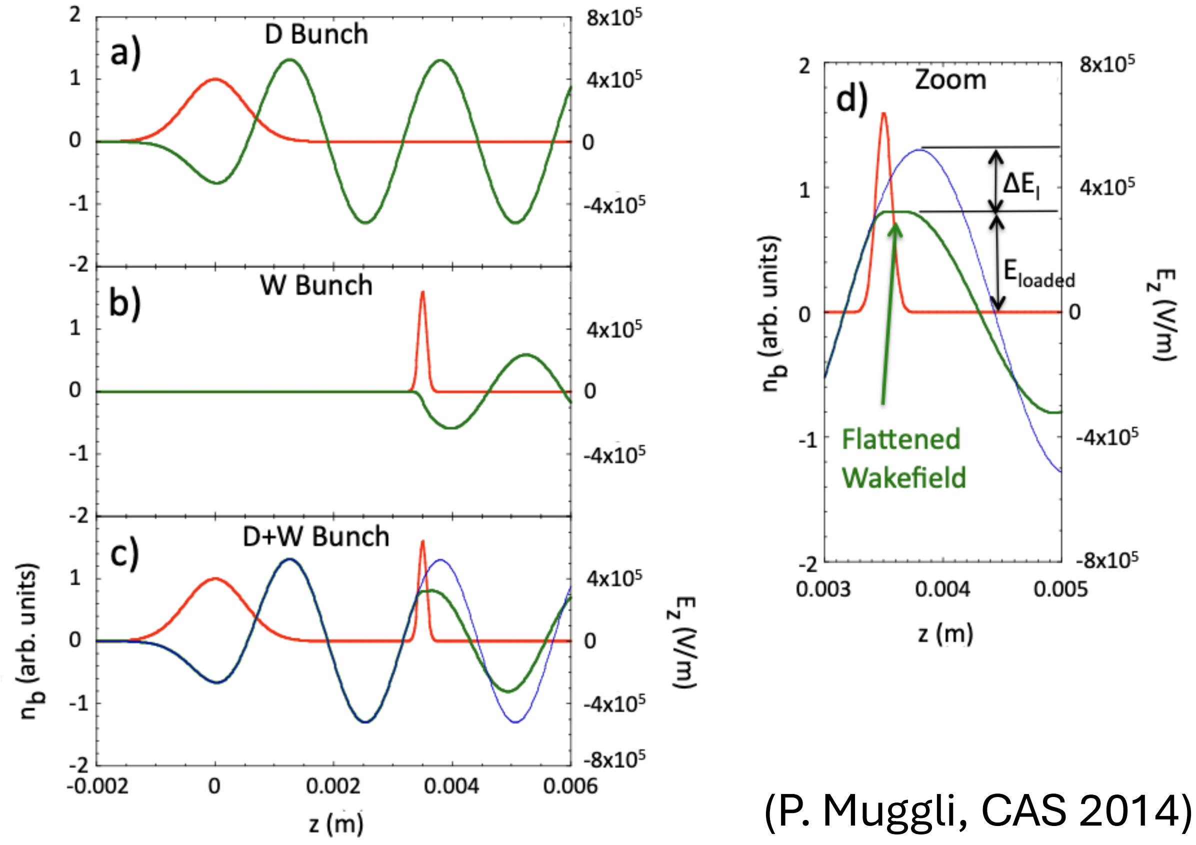
The point is: compromise on accelerating gradient ➔ smaller energy spread → beam quality

II. Non-linear Regime – Beam Loading

➔ BEAM LOADING:

The presence of the witness bunch affects the wakefields

Linear regime



(P. Muggli, CAS 2014)

Particle Accelerators, 1987, Vol. 22, pp. 81–99
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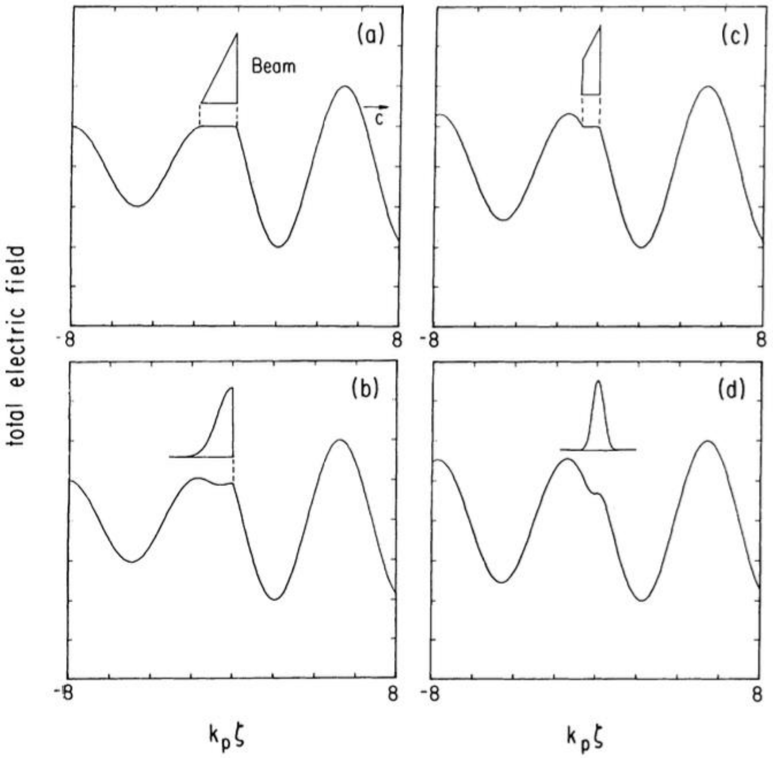
BEAM LOADING IN PLASMA ACCELERATORS

T. KATSOULEAS, S. WILKS, P. CHEN,† J. M. DAWSON and J. J. SU
Department of Physics, University of California, Los Angeles, CA 90024



- Triangular/trapezoidal shape gives constant field
- Short Gaussian placed at the right phase can work

0b. Beam Physics

- Relativistic particle bunches:
  - Propagate at $v_b \sim c$
  - Not affected by index of refraction
  - Large inertia (γm >> m)

https://arxiv.org/pdf/2007.04102.pdf

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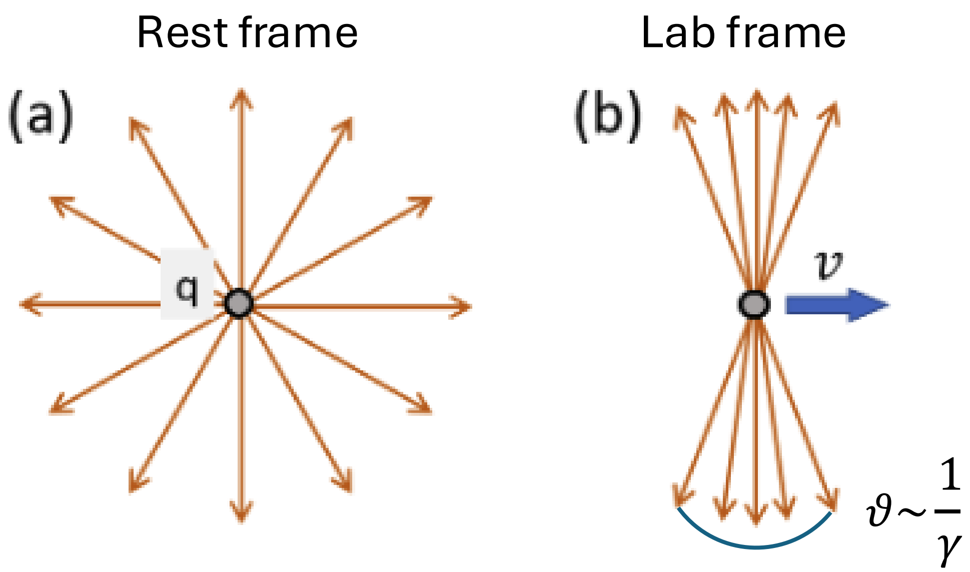
- In Lab frame, space-charge electric field is almost purely transverse:



$$\overrightarrow{E_0} = \frac{1}{4\pi\varepsilon_0} - \frac{e}{r^2}\frac{\vec{r}}{|r|}$$

$$E'_{\parallel} = E_0$$
$$E'_{\perp} = \gamma E_0$$

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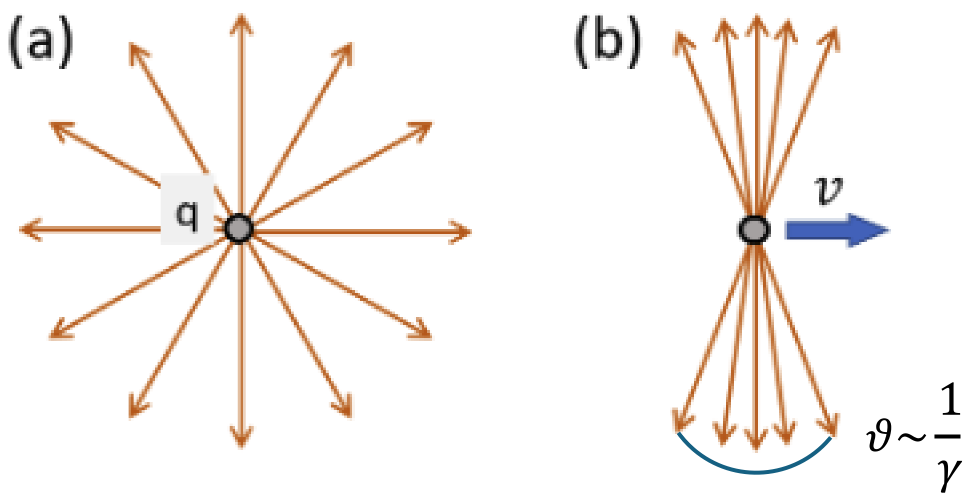
0b. Beam Physics

- Relativistic particle bunches:
  - Propagate at v_b~c
  - Not affected by index of refraction
  - Large inertia (γm >> m)
- In Lab frame, space-charge electric field is almost purely transverse:
  - **Effectively sets in motion the plasma electrons**
- Propagation of the beam distribution is dominated by the emittance (at high energies)

$$\sigma'' = \frac{\epsilon_{rms}^2}{\sigma^3}$$

$$\sigma(z) = \sqrt{\left(\sigma_0 + \sigma_0'(z - z_0)\right)^2 + \frac{\epsilon_{rms}^2}{\sigma_0^3}(z - z_0)^2}.$$

Rest frame Lab frame



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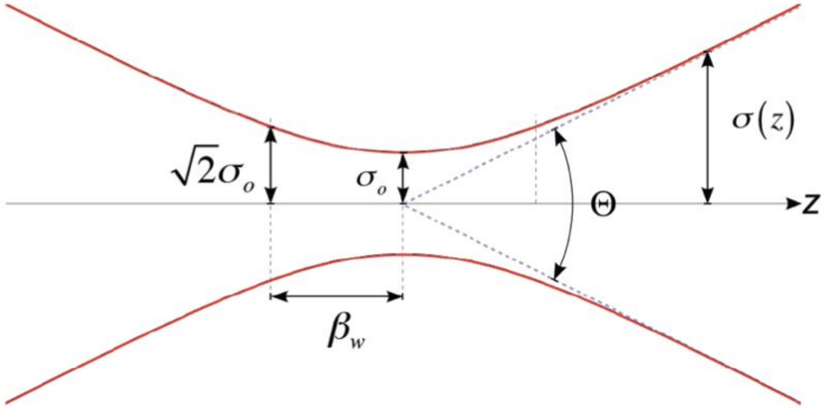


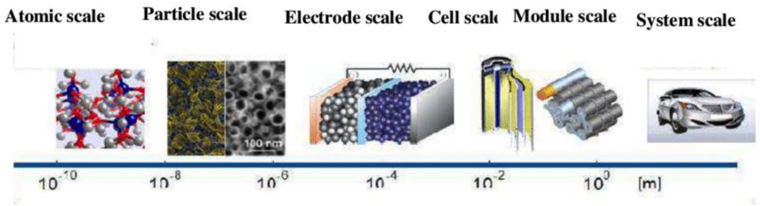
EuPRAXIA@SPARC_LAB

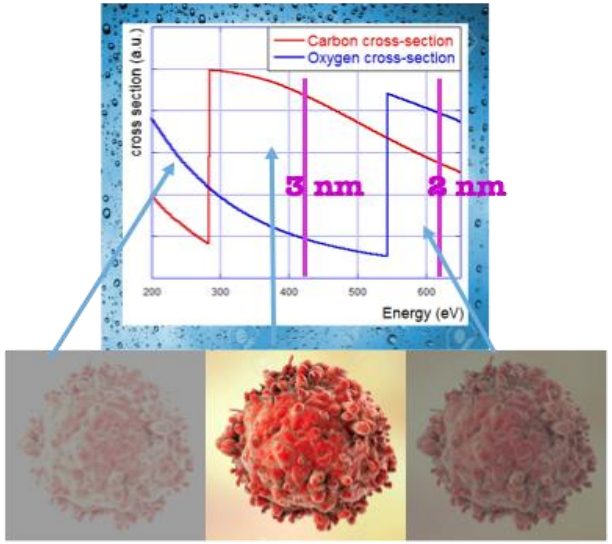
Radiation Parameter	Unit	PWFA	Full X-band
Wavelength	nm	**3-5**	4
Pulse length (fwhm)	fs	**10.0**	-
Photons per Pulse	$\times 10^{12}$	**0.1- 0.25**	1
Photon Bandwidth	%	**0.1**	0.5
Undulator Area Length	m	26	
ρ(1D/3D)	$\times 10^{-3}$	**1**	1
Photon Brilliance per shot	$\left(\frac{s\ mm^2 mrad^2}{bw(0.1\%)}\right)$	$\mathbf{1{-}2\ \times 10^{28}}$	$1\ \times 10^{27}$

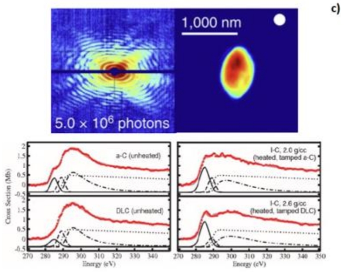
Electron Beam Parameter	Unit	PWFA	Full X-band
Electron Energy	GeV	**1-1.2**	1.2
Bunch Charge	pC	**30 - 50**	200-500
Peak Current	kA	**~ 2.2**	1-2
RMS Energy Spread	%	**< 1**	0.1
RMS Bunch Length	μm	**3-6**	24-20
RMS norm. Emittance	μm	**0.7 – 1.2**	1
Slice Energy Spread	%	**≤0.05**	≤0.05
Slice norm Emittance	mm-mrad	**0.5 – 0.8**	0.5
Energy jitter	%	**< 1**	0.1

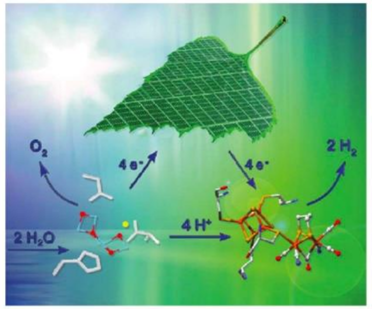
- **Bold values indicate the main working point**

Application Area	Scientific Focus	Techniques	Key Impact
Renewable Energy	• Charge transport in solar cells & catalysts • Photocatalytic H_2 production • PFAS/PClAS analysis	XAS, XES, PI-MS	• Efficient solar materials • Clean hydrogen production • Environmental remediation
Warm Dense Matter (WDM)	• Extreme temperature/density • Astrophysics & fusion	Time-resolved XAS, TR-XES	• Stellar/planetary modeling • Fusion research support
Battery Technology	• Ion migration & interfaces • Solid-state battery study	XAS, non-linear X-ray spectroscopy	• Safer, longer-life batteries • High energy density
Structural Biology	• Live-cell imaging • Cellular processes (stress, DNA damage)	CDI, XAS, CEI	• Real-time biomolecular studies • Disease mechanism insight
Health & Radiobiology	• DNA damage by radiation	X-ray pump–probe, photo-fragmentation	• Radioprotection • Cancer treatment improvement
Atmospheric Chemistry	• VOC/NOx oxidation • Aerosol dynamics	PI-MS, ion spectroscopy	• Pollution models • Climate studies
Astrochemistry	• Radiation chemistry in space • Organic molecule formation	XAS, photochemistry	• Space molecular evolution

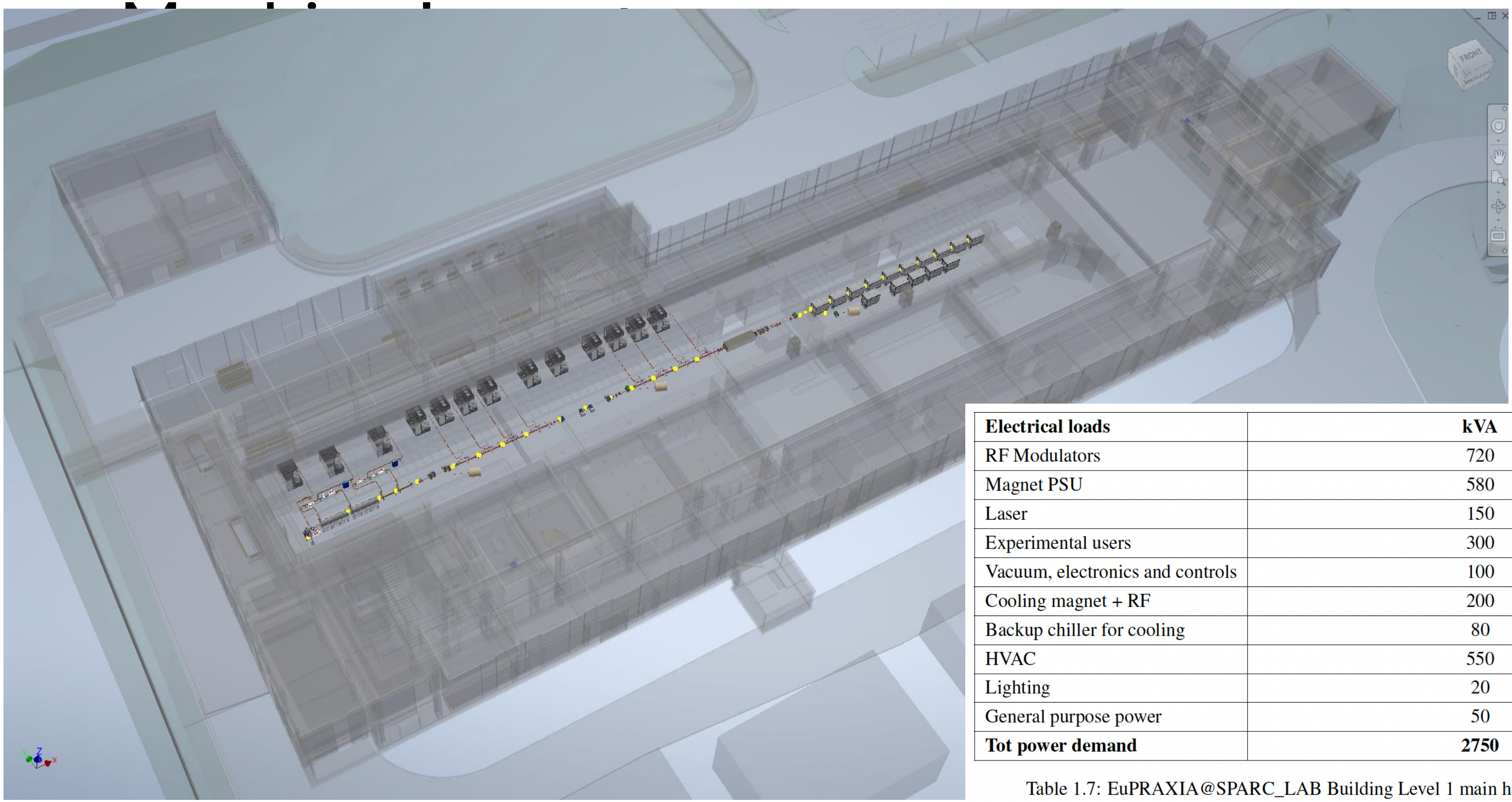








Courtesy F. Stellato



Electrical loads	kVA
RF Modulators	720
Magnet PSU	580
Laser	150
Experimental users	300
Vacuum, electronics and controls	100
Cooling magnet + RF	200
Backup chiller for cooling	80
HVAC	550
Lighting	20
General purpose power	50
Tot power demand	**2750**

Table 1.7: EuPRAXIA@SPARC_LAB Building Level 1 main halls interior finishes

Courtesy M. Del Franco