Plasma Wakefield Acceleration – Advantages and Challenges

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04.12.2024

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Istituto Nazionale di Fisica Nucleare
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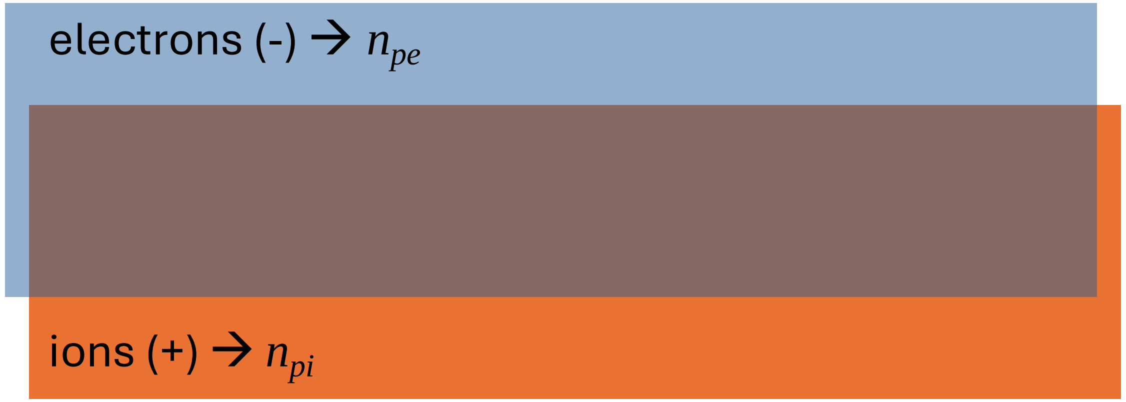
Plasma

Plasma:

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



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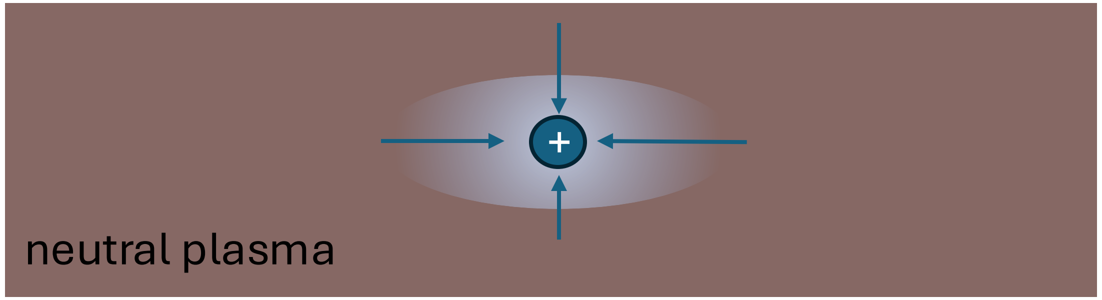
  → It tends to keep the charge and current neutrality:
  Plasma electrons ($m_{ip} >> m_{pe}$) move to compensate for the disturbance
  → Plasma screens electromagnetic fields



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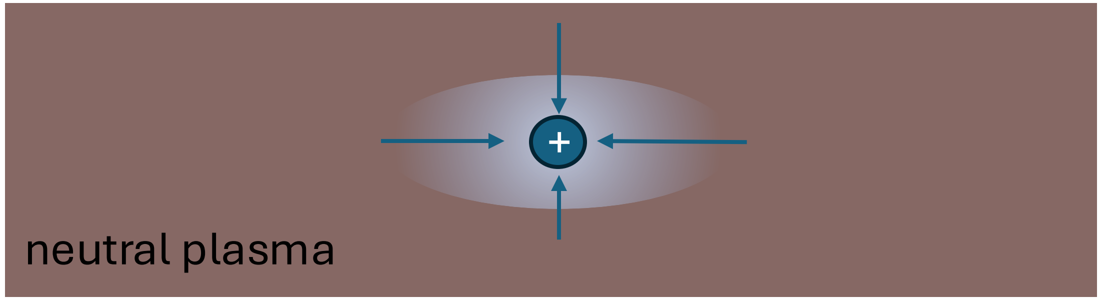

When the equilibrium is perturbed:

- 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 Wakefield Acceleration

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

(inspired by P. Muggli's CAS lecture)

1. Transverse E field expels plasma electrons

2. Positively charged region behind the bunch head
   → restoring force

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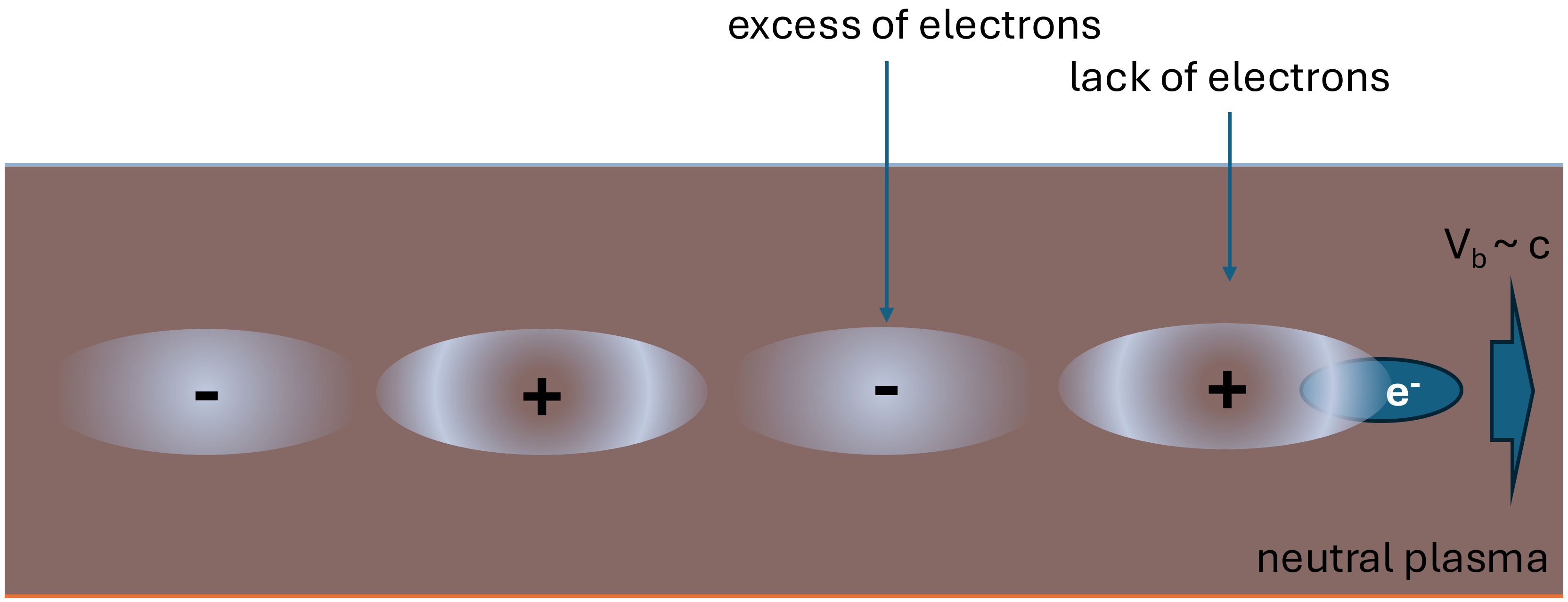

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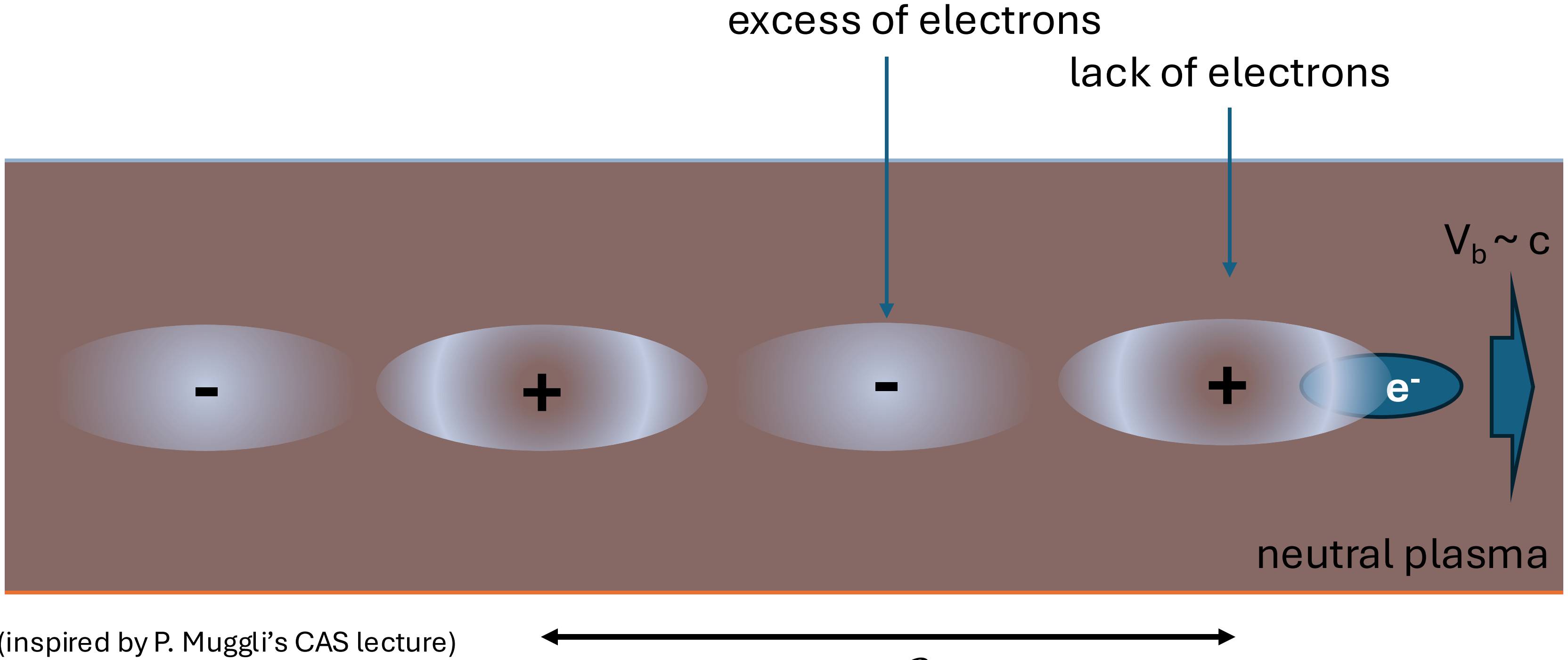

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$$\lambda_{pe} = \frac{2\pi c}{\omega_{pe}}$$

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3. Oscillation of plasma e^- with ω_{pe}
   → periodic density variation

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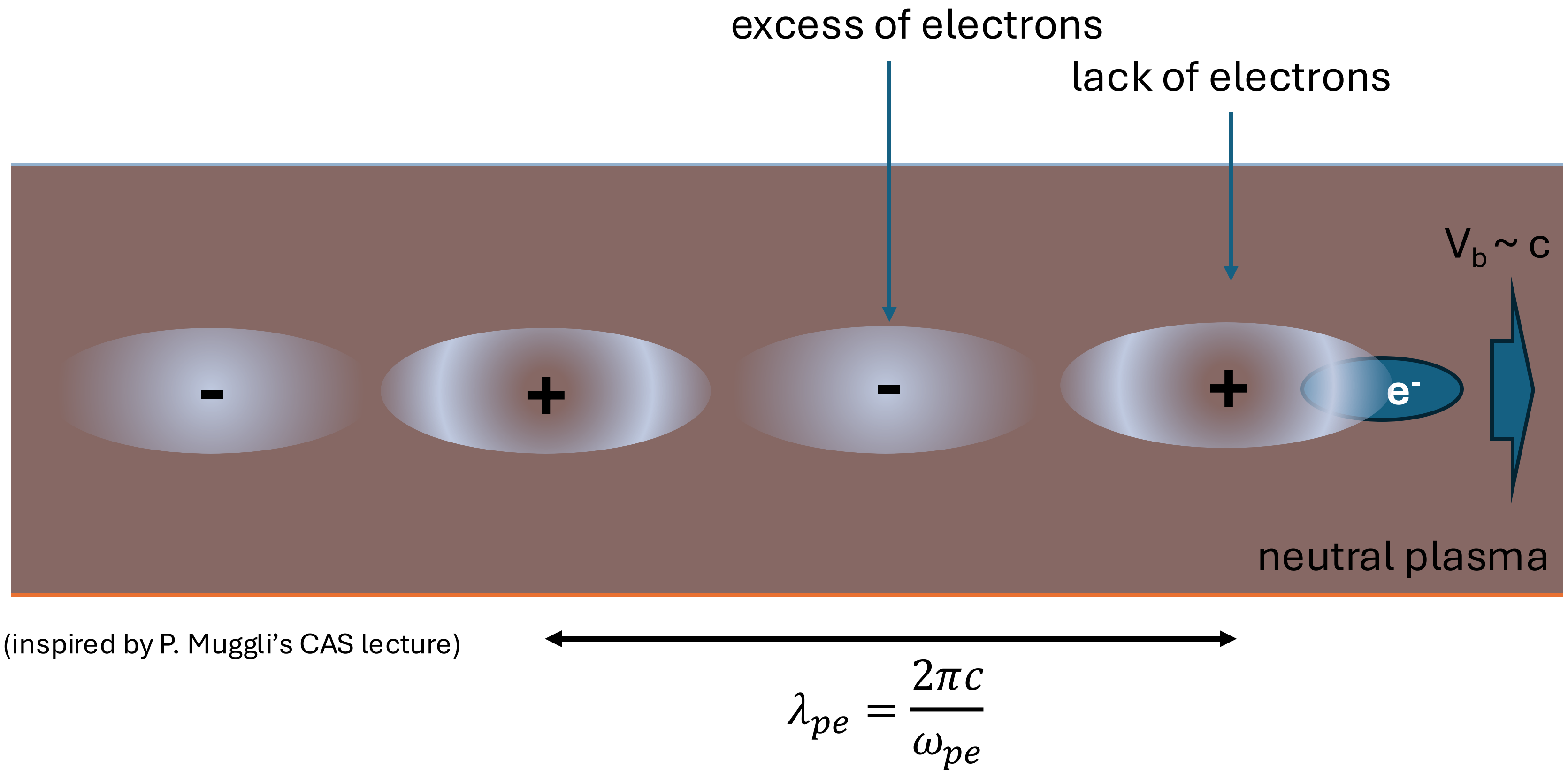

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$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

→ Wakefields ←

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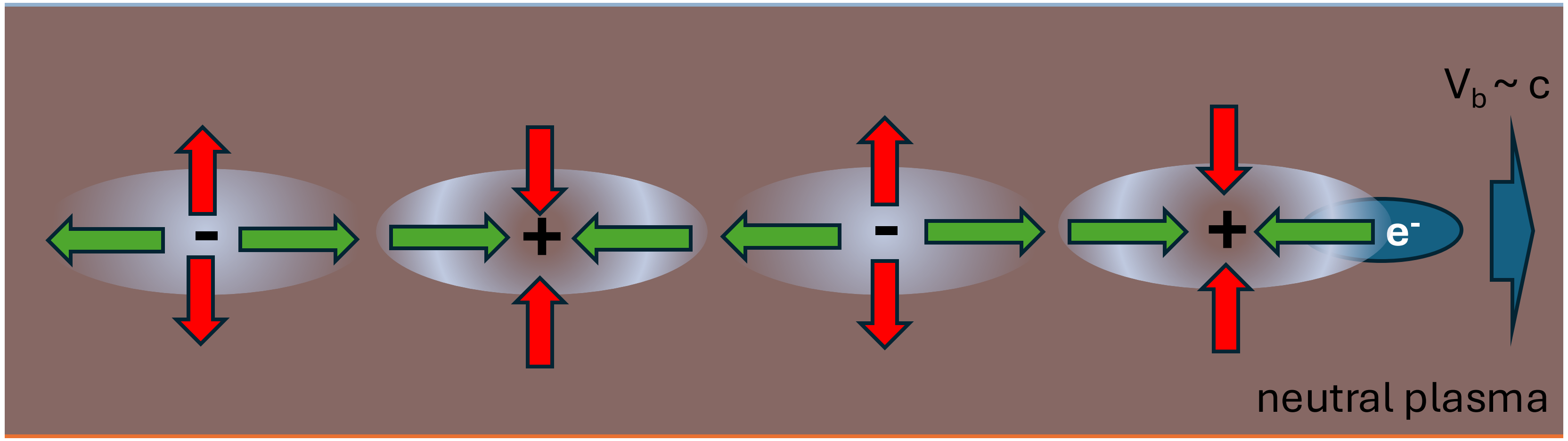

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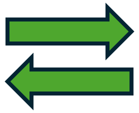
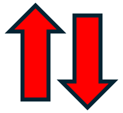
 Longitudinal (accelerating – decelerating) wakefields

 Transverse (focusing – defocusing) wakefields

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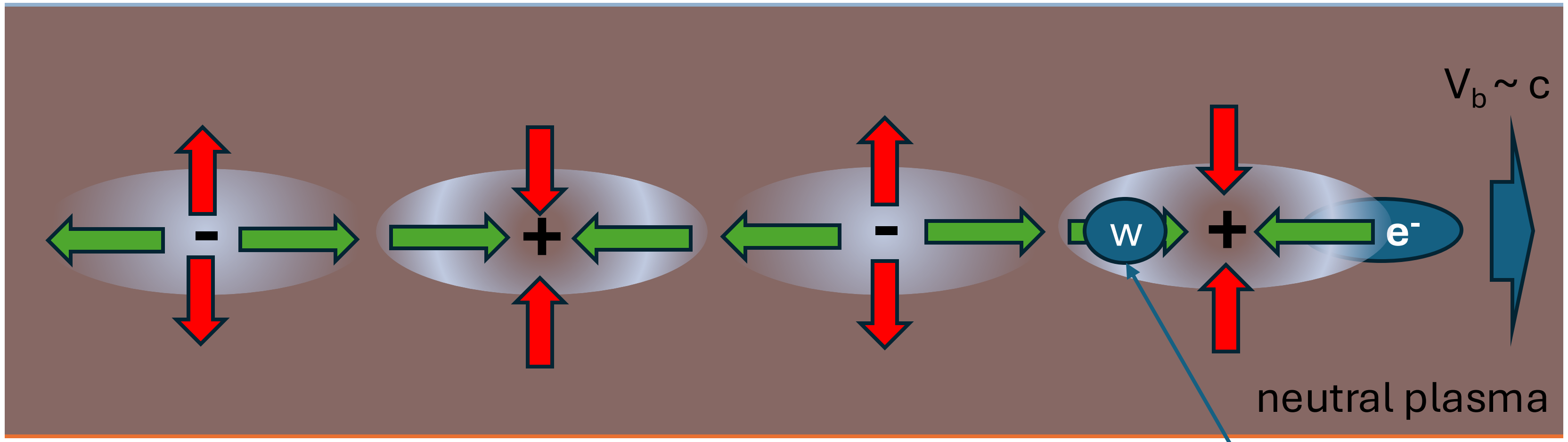

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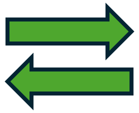

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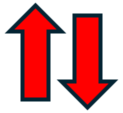

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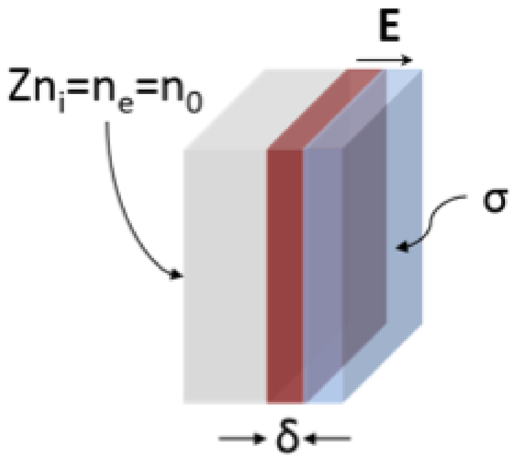
A witness bunch can be accelerated to high energies if injected in the right phase!

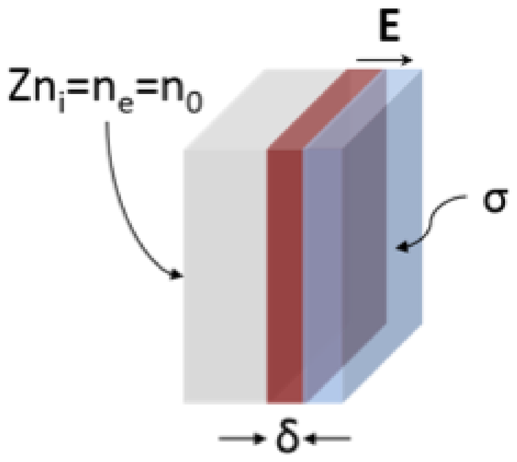
Accelerating Gradient

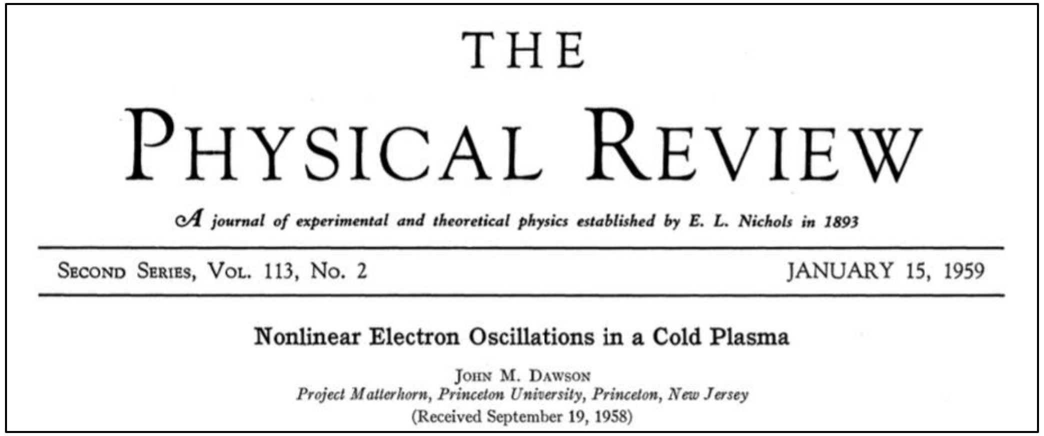
- Fields in plasmas are sustained by the charge separation



Accelerating Gradient

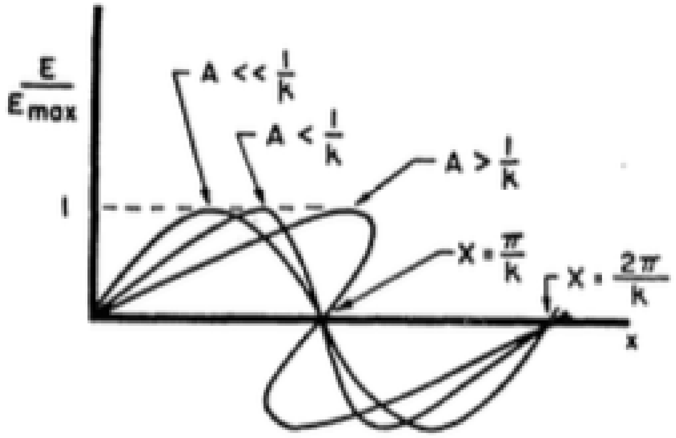
- Fields in plasmas are sustained by the charge separation
  - As high as the cold wave-breaking field: $E_{WB} = \frac{m_e\, c\, \omega_{pe}}{q}$ → oscillation length cannot exceed plasma wavelength
  - E.g. for n_{pe} = ($10^{14} - 10^{18}$) cm^{-3}, $E_{WB} \sim 100 \frac{V}{m} \sqrt{n_{pe}[\,cm^{-3}]}$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




THE
PHYSICAL REVIEW
A journal of experimental and theoretical physics established by E. L. Nichols in 1893
SECOND SERIES, VOL. 113, NO. 2 — JANUARY 15, 1959

Nonlinear Electron Oscillations in a Cold Plasma

JOHN M. DAWSON
Project Matterhorn, Princeton University, Princeton, New Jersey
(Received September 19, 1958)



Wave «breaks» when the maximum amplitude is reached

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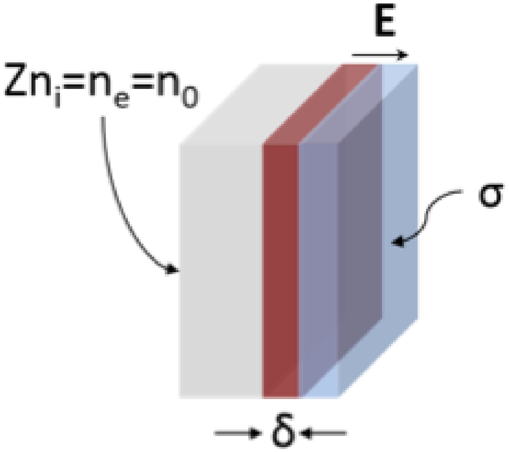

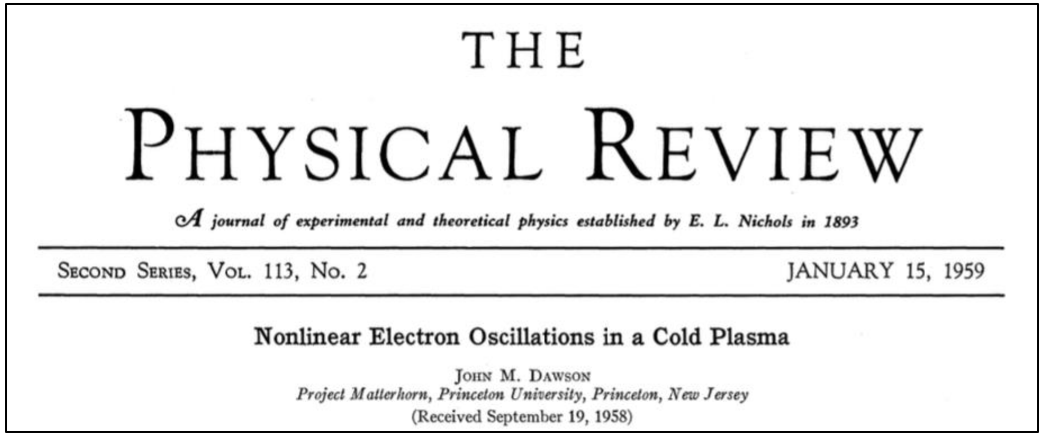
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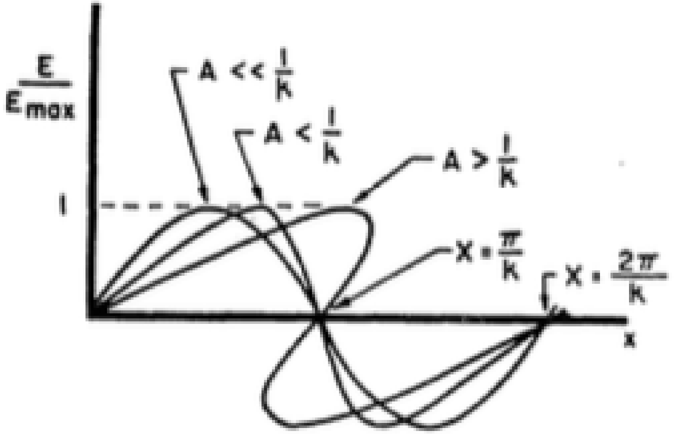
- RF cavities limited to 100MV/m by breakdown, caused e.g. by fatigue, pulse heating, etc..

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



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Accelerating Gradient – Experimental Results

Laser Wakefield Acceleration (LWFA)

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
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Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

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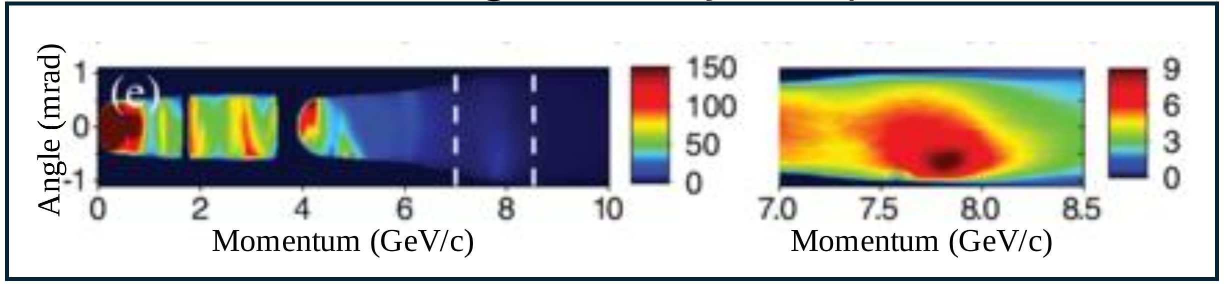
Driver: high-intensity laser pulse



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

A. J. Gonsalves et al., PRL 122, 084801 (2019)

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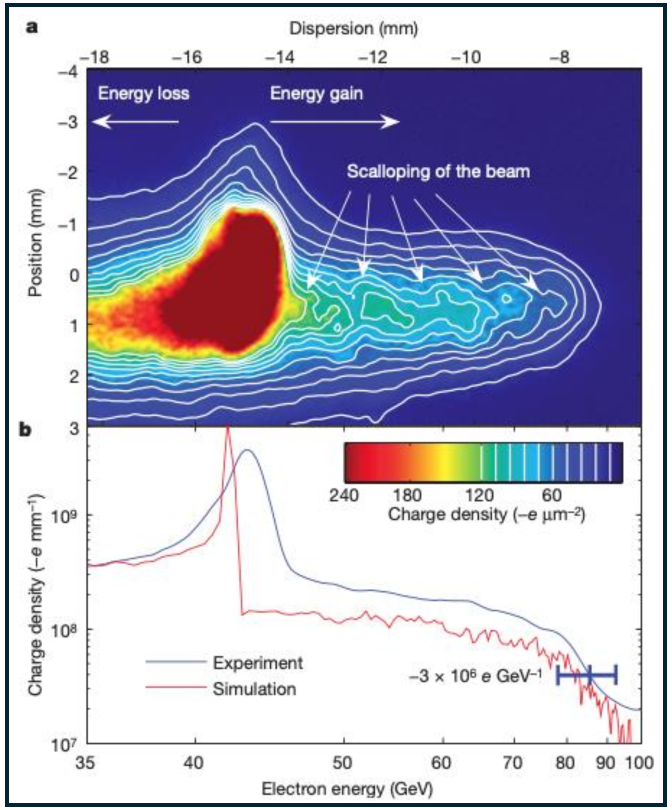
Driver: relativistic charged particle bunch



~ 42 GeV in 85 cm → ~50GV/m
n_{pe} = 2.8 x 10^{17} cm^{-3}

I. Blumenfeld et al.,
Nature 455, 741-744 (2007)

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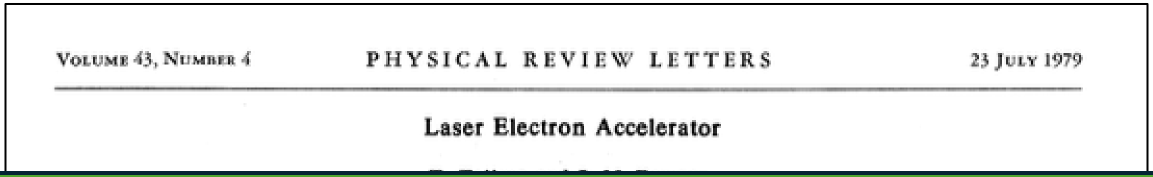
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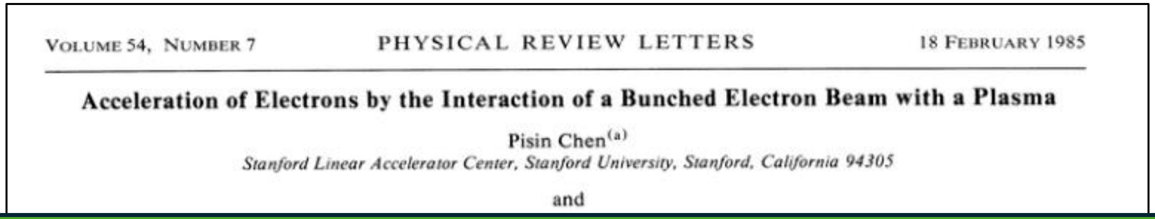
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Plasma's main advantage:

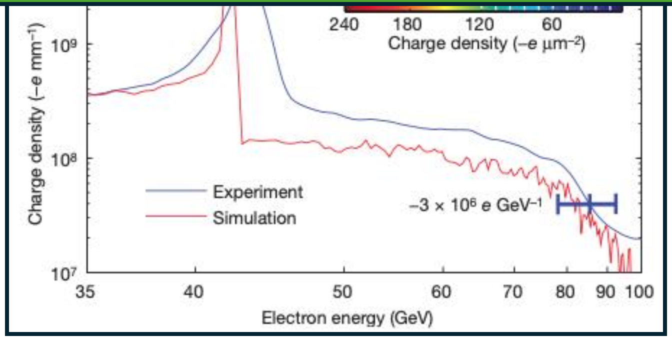
Same (or higher) beam energy in considerably smaller space

→ Cheaper accelerators

→Cheaper light sources, etc..

→More of them

A. J. Gonsalves et al., PRL 122, 084801 (2019)



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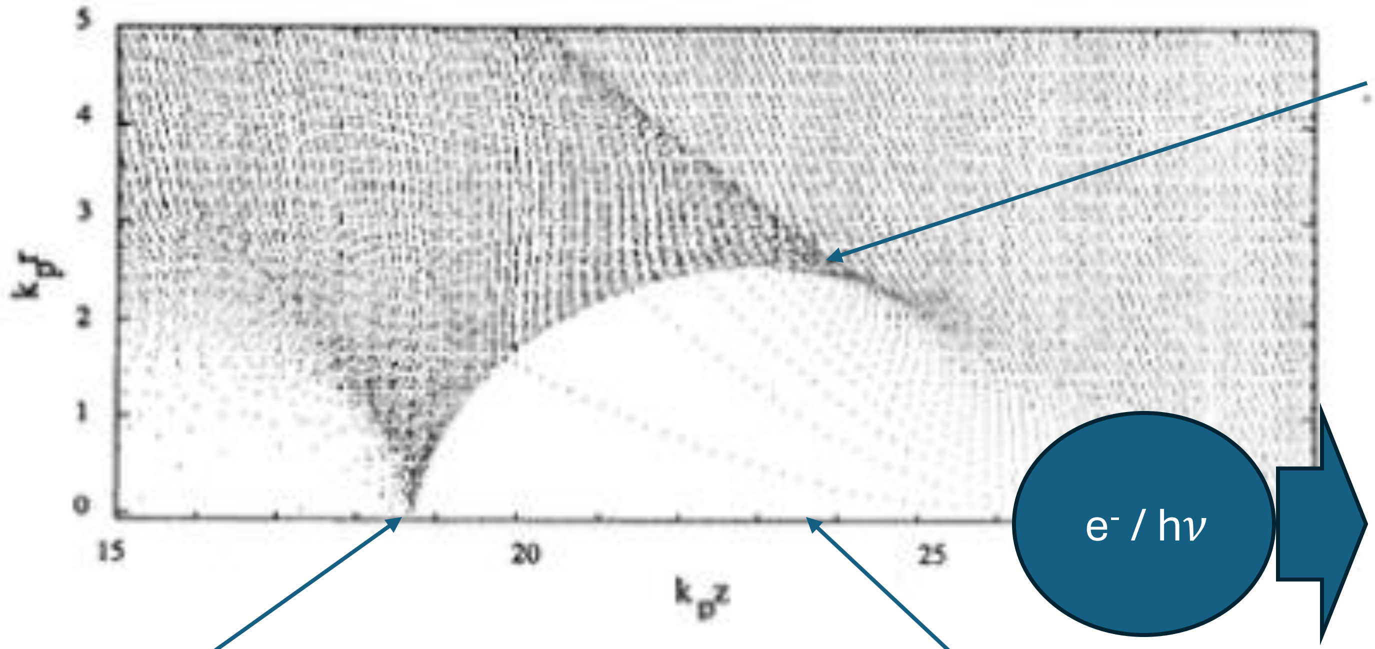
Main challenge – Beam Quality Preservation

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



Plasma electrons are expelled outwards forming a "bubble"

They cross the axis after $\sim\lambda_{pe}$
→ Singularity
→ Non-linearities

No electrons on axis (blowout)

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

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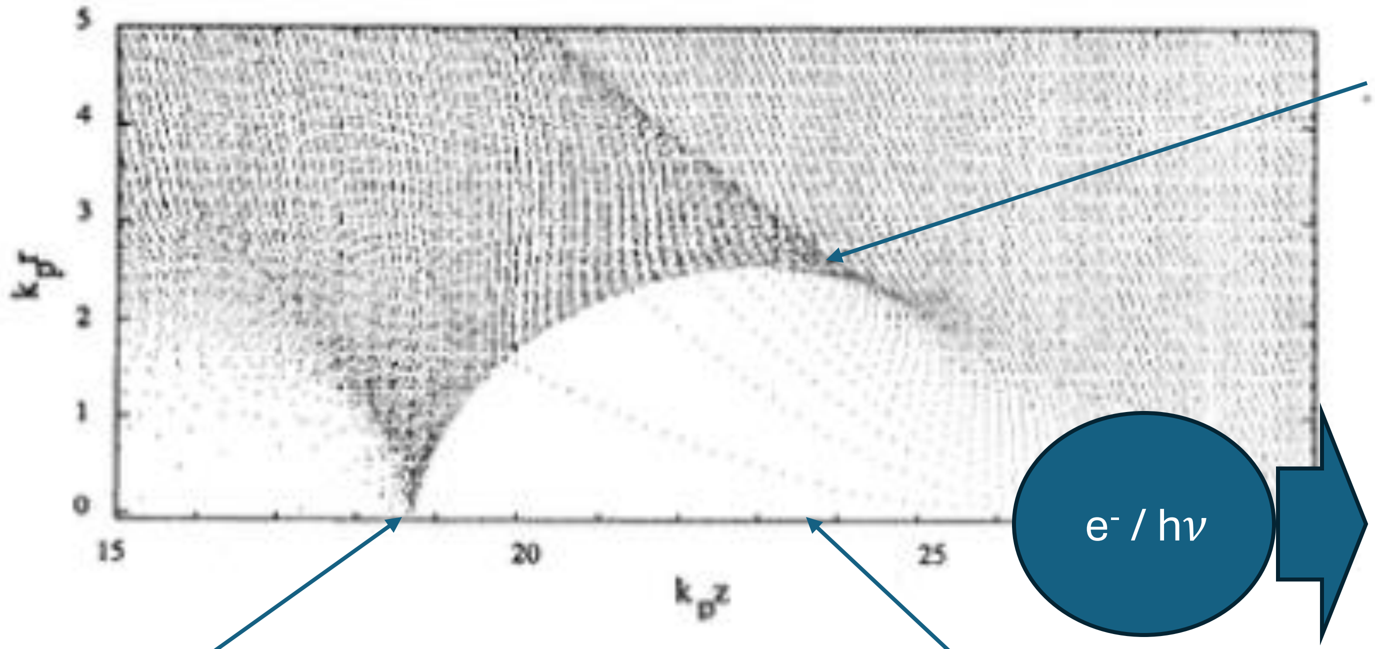
- High gradient
- Linear focusing force



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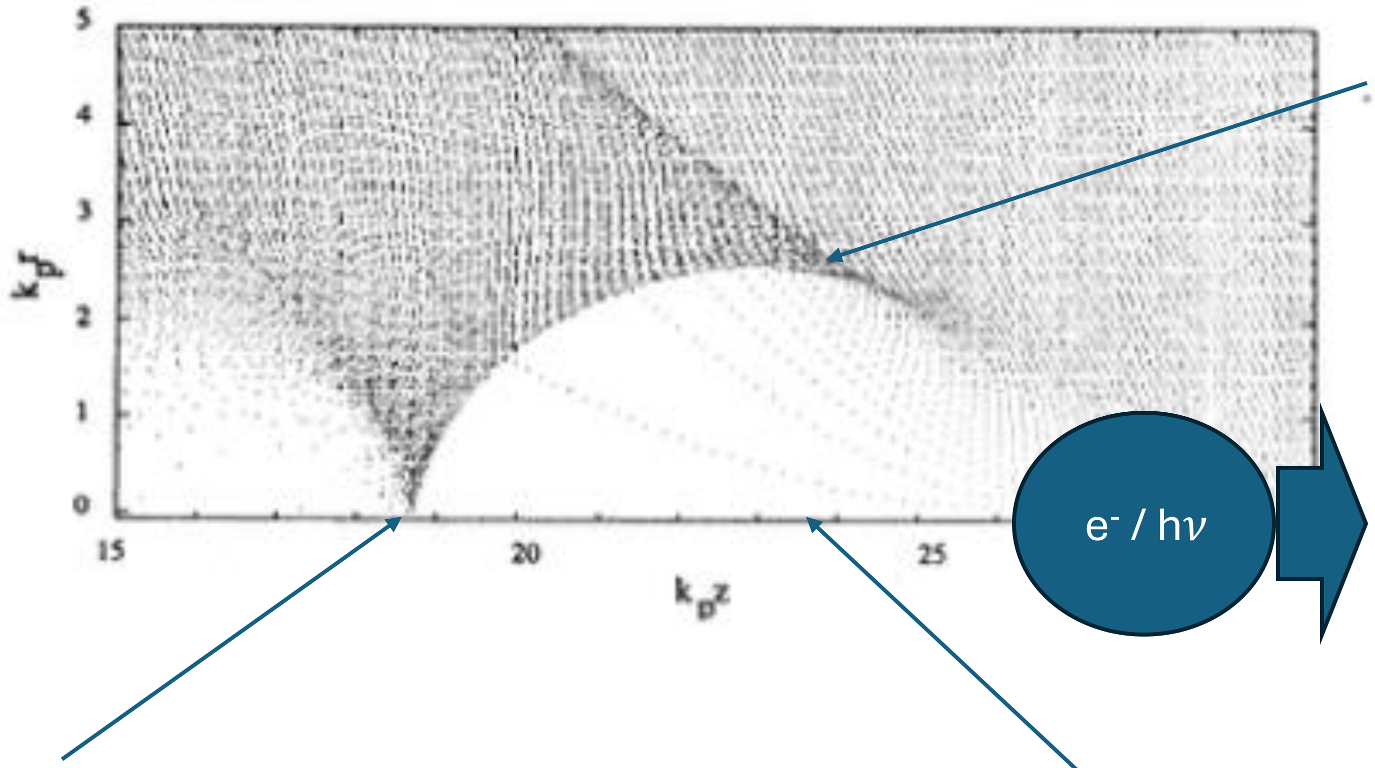
→ Causing the main challenge: beam quality preservation (vital for applications)



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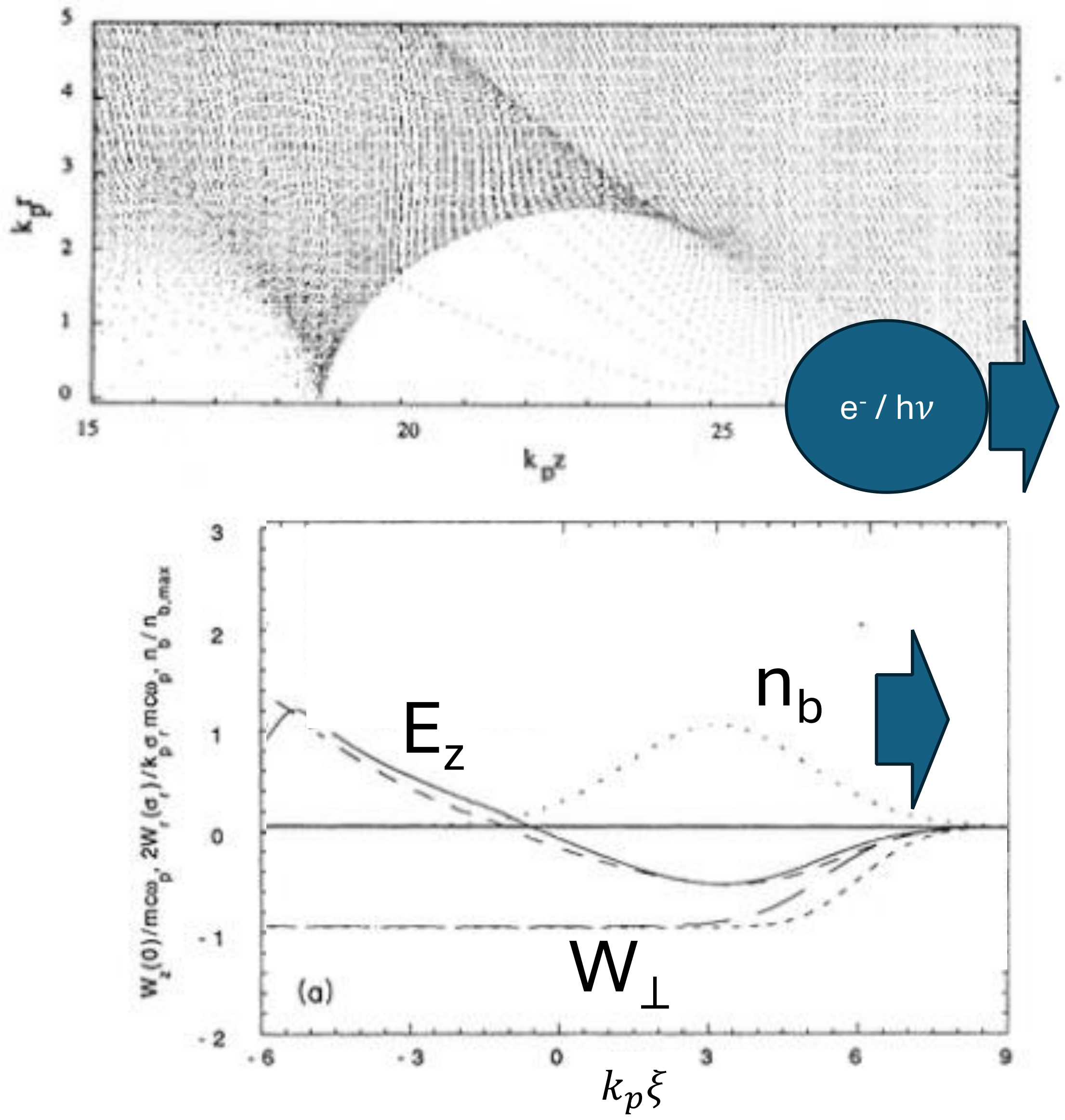
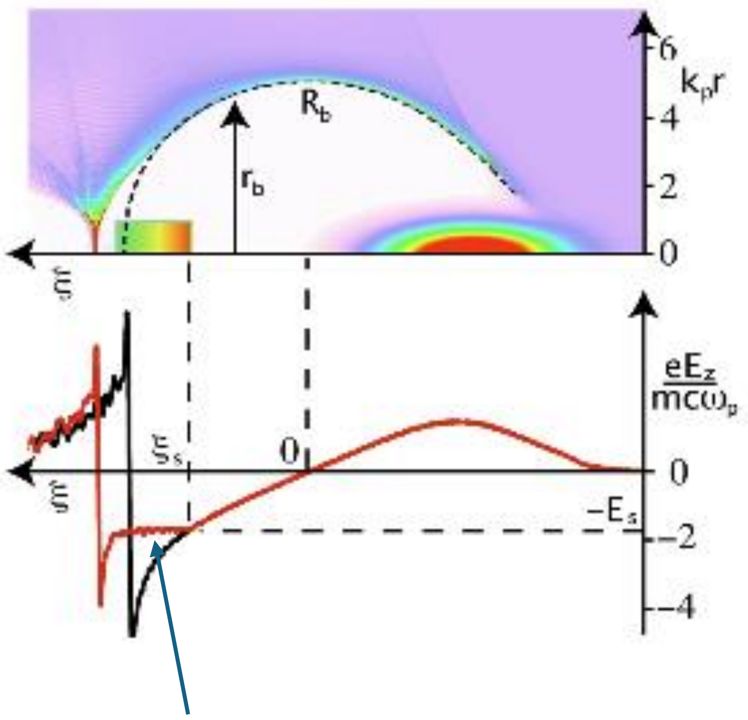


J. B. Rosenzweig et al., Phys. Rev. A 44, R6189(R) (1991)

- Accelerating field not uniform along the bubble
  → Energy spread increasing while acceleration happens
- Solution: "*loading*" the wake with the presence of the witness bunch itself



Costant accelerating field within the witness bunch

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

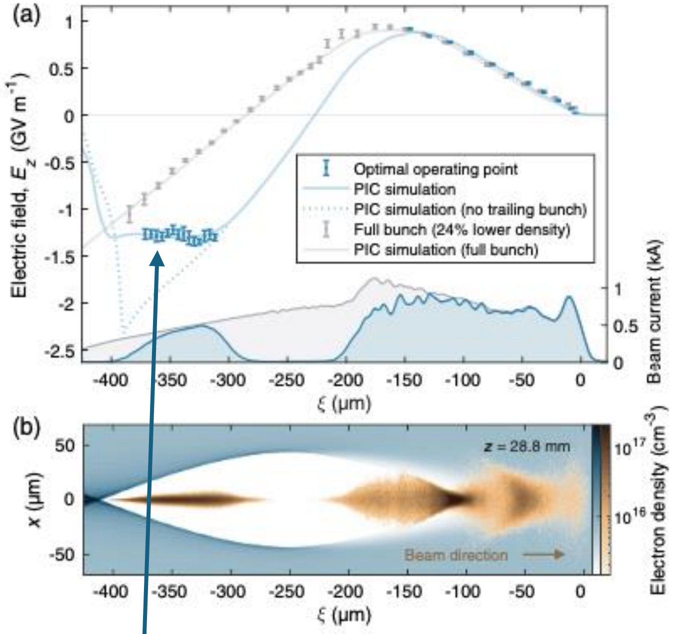
Main challenge – Energy spread (*longitudinal* quality)

➔Experimental Demonstrations:

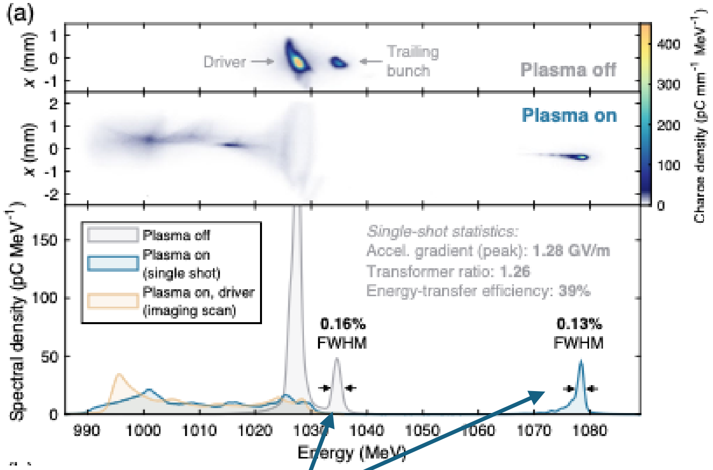
PHYSICAL REVIEW LETTERS **126,** 014801 (2021)

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

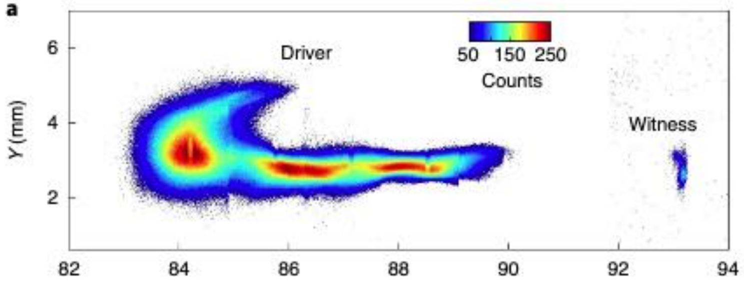


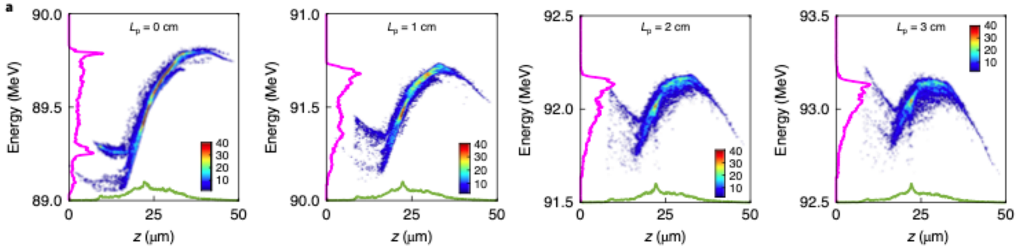
~GV/m acceleration
Preserved relative energy spread

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

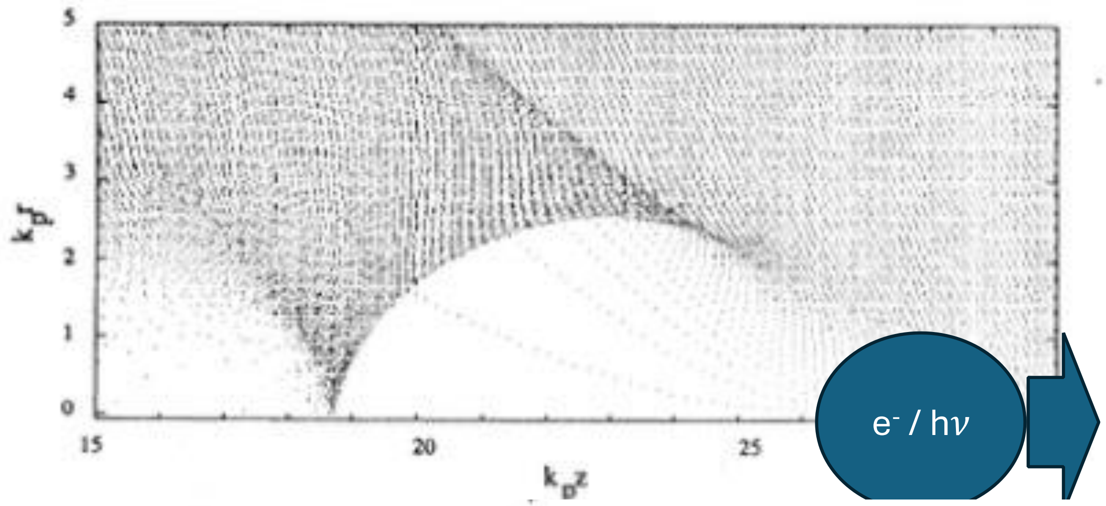
R. Pompili[1]✉, D. Alesini[1], M. P. Anania[1], M. Behtouei[1], M. Bellaveglia[1], A. Biagioni[1], F. G. Bisesto[1], M. Cesarini[1,2], E. Chiadroni[1], A. Cianchi[3], G. Costa[1], M. Croia[1], A. Del Dotto[1], D. Di Giovenale[1], M. Diomede[1], F. Dipace[1], M. Ferrario[1], A. Giribono[1], V. Lollo[1], 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]

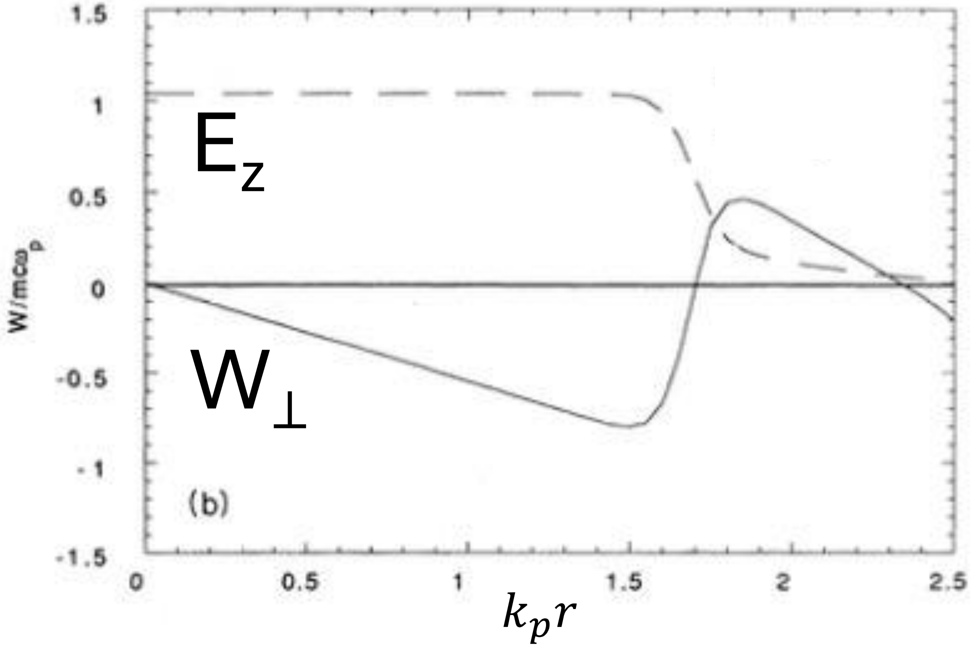




Combination of beam loading and initial chirp to obtain final small energy spread

Main challenge – Emittance Preservation (*transverse* quality)



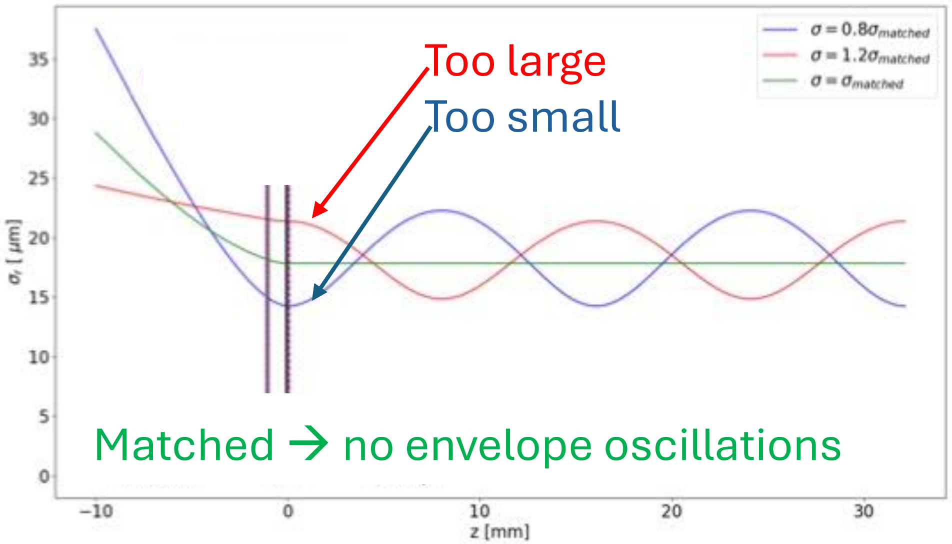


J. B. Rosenzweig et al., Phys. Rev. A 44, R6189(R) (1991)

- Focusing force is transversely linear

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

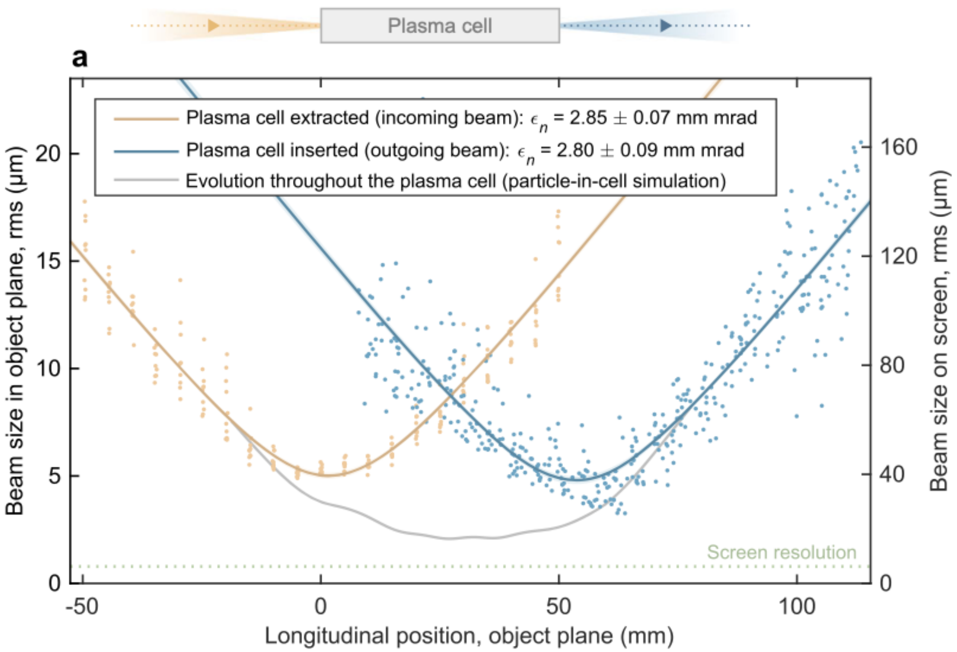
else: different energy slices rotate at different rates in transverse phase space
→ slice emittance preserved (linear focusing)
→ projected (i.e., overall) emittance grows!

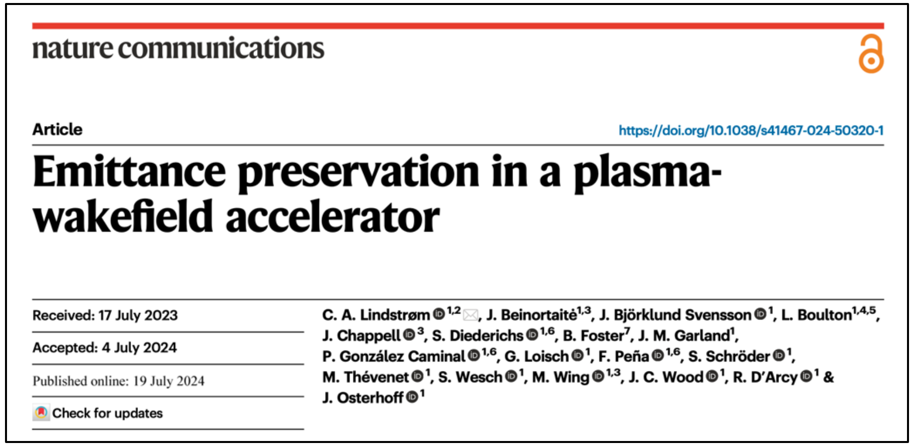


(L. Verra *et al* 2020 *J. Phys.: Conf. Ser.* **1596** 012007)

Main challenge – Emittance Preservation (*transverse* quality)

➔ Experimental Demonstration:





nature communications

Article

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Emittance preservation in a plasma-wakefield accelerator

Received: 17 July 2023

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Check for updates

C. A. Lindstrøm[1,2], J. Beinortaitė[1,3], J. Björklund Svensson[1], L. Boulton[1,4,5], J. Chappell[3], S. Diederichs[1,6], B. Foster[7], J. M. Garland[1], P. González Caminal[1,6], G. Loisch[1], F. Peña[1,6], S. Schröder[1], M. Thévenet[1], S. Wesch[1], M. Wing[1,3], J. C. Wood[1], R. D'Arcy[1] & J. Osterhoff[1]

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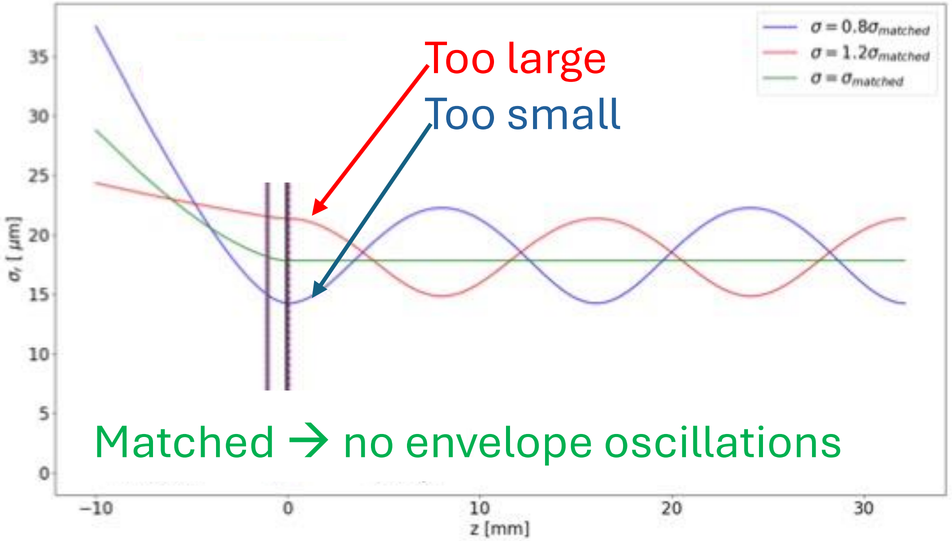
if: beam envelope is *matched* to the focusing force (which is extremely strong!)

→ 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!

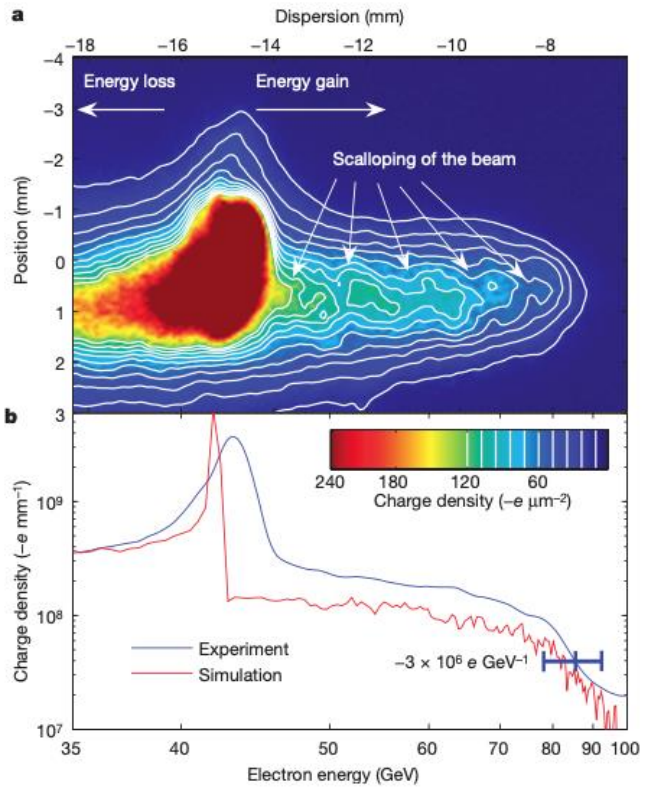


(L. Verra *et al* 2020 *J. Phys.: Conf. Ser.* **1596** 012007)

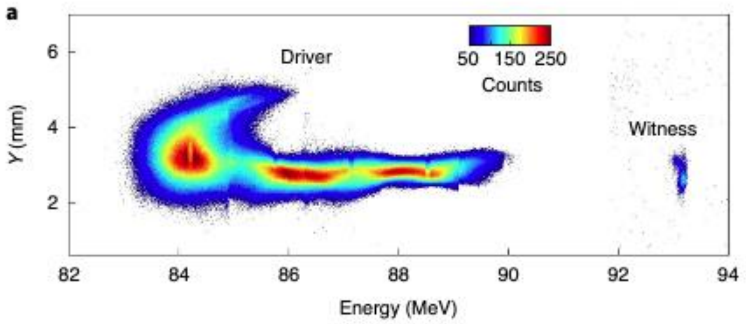
Main Challenges

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

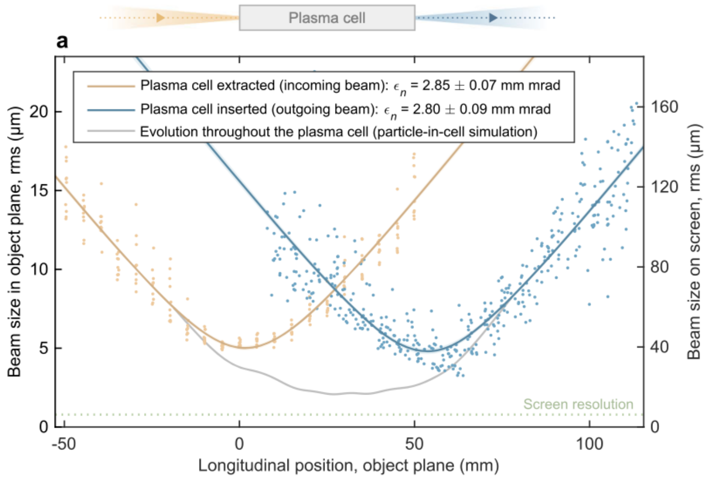
Extremely high gradient



Energy spread minimization



Emittance preservation



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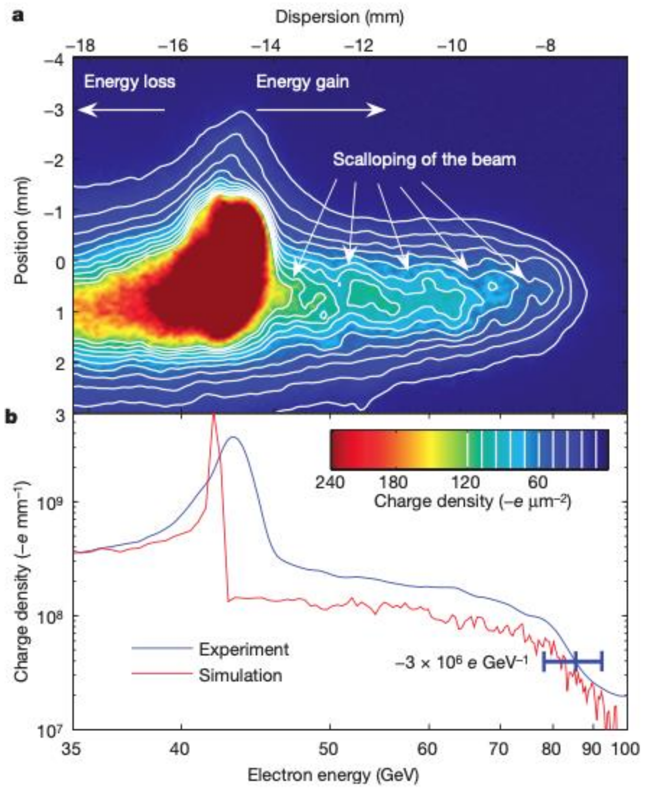

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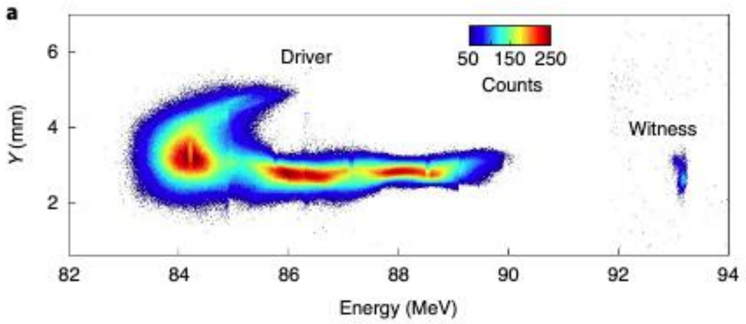

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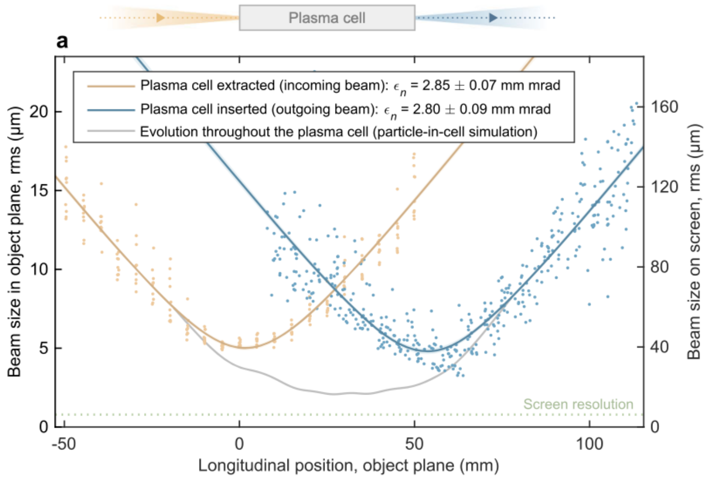
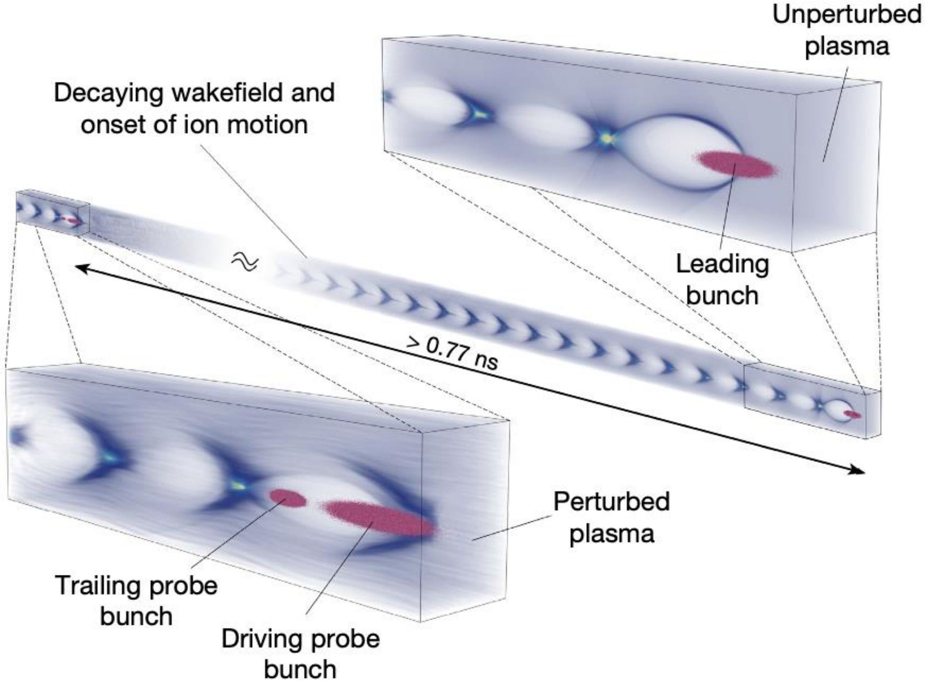


- Do it many times → high repetition rate



Plasma was shown to recover at ns time-scale

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

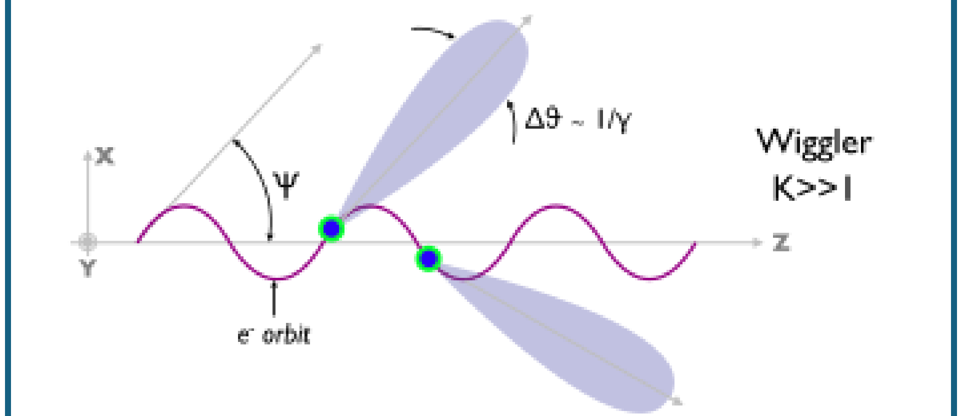
R. Pompili et al., Comm. Phys. 7, 241 (2024)

Still a technological challenge:

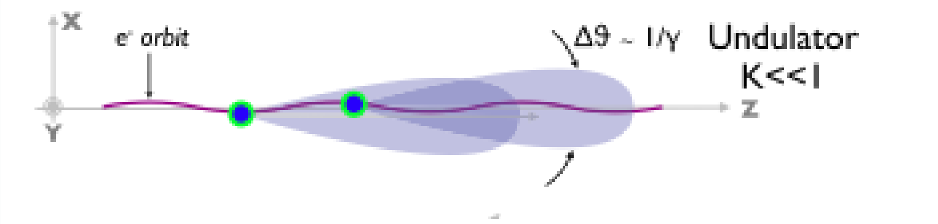
(Angelo Biagioni's talk)

Challenges → Opportunities

- Transverse (betatron) oscillation induces radiation emission in plasma (A. Frazzitta's talk)

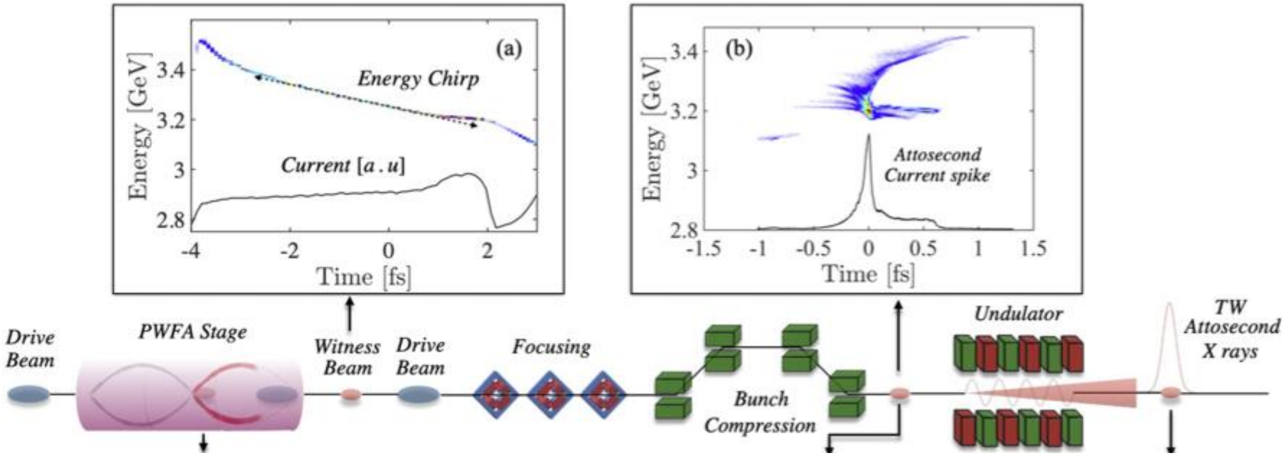


Betatron radiation source



Ion Channel Laser

- Large energy chirp may be used to compress the witness bunch

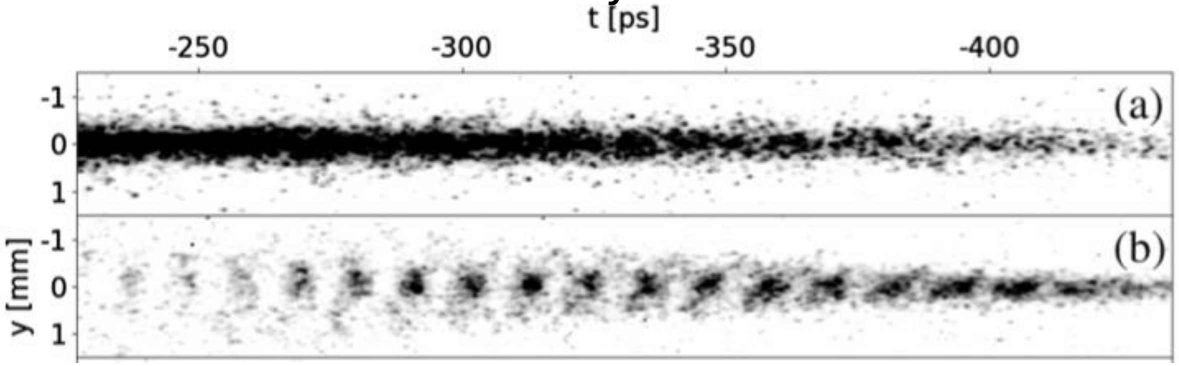


→ Extremely short bunches and light pulses (<fs)

Challenges → Opportunities

- Study of Beam-Plasma interactions and instabilities is an active field (e.g., laboratory astrophysics)

Self-Modulation Instability



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

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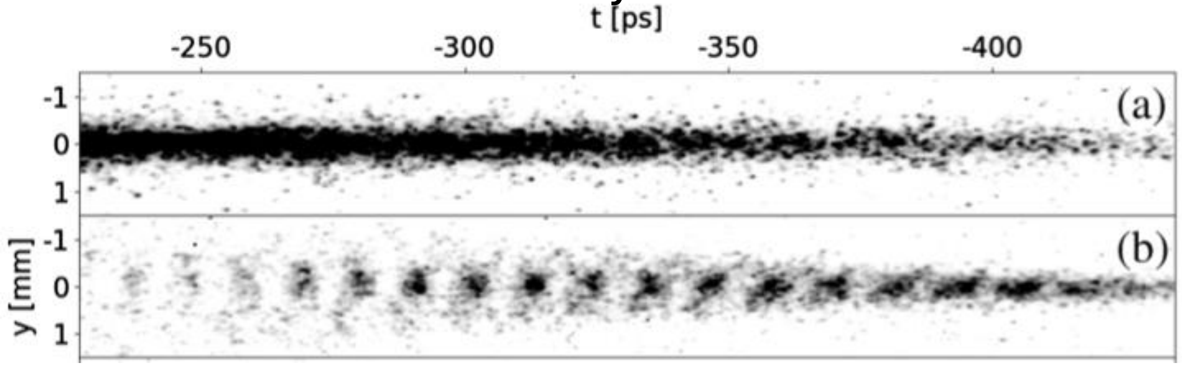
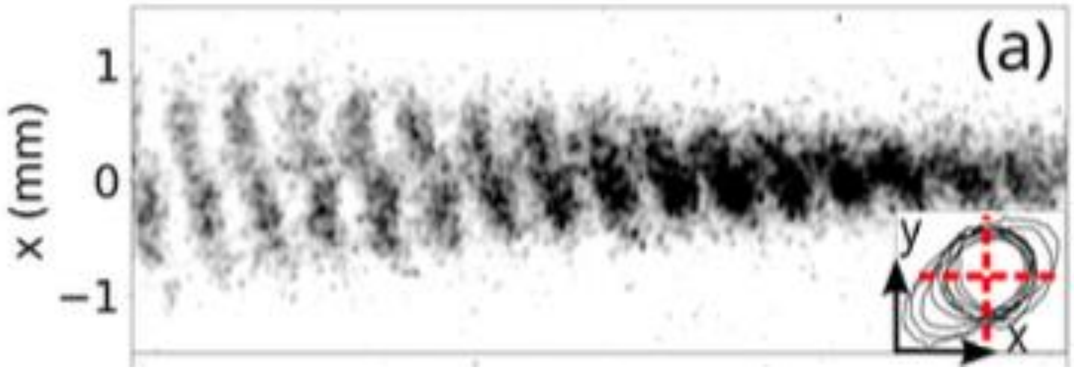


L. Verra et al. (AWAKE Collaboration) Phys. Rev. Lett. **129**, 024802 (2022)

Hosing Instability



T. Nechaeva, L. Verra et al. (AWAKE Coll.) Phys. Rev. Lett. **132**, 075001 (2024)

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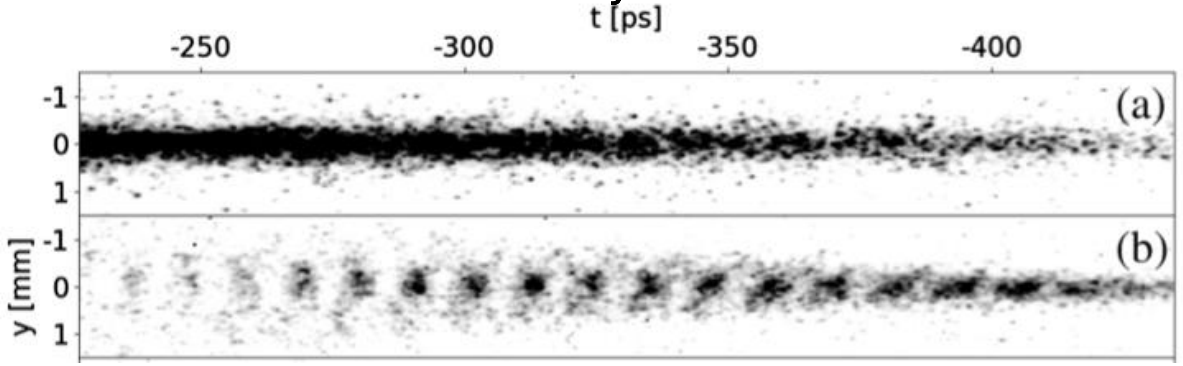
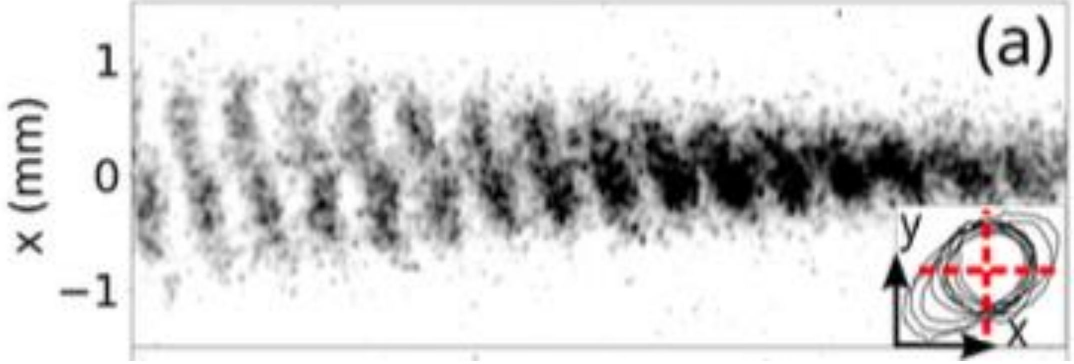


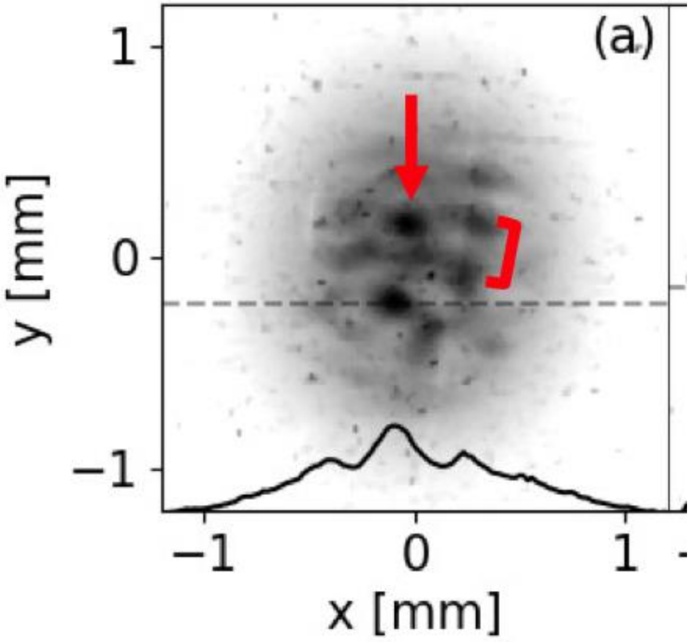
L. Verra et al. (AWAKE Collaboration) Phys. Rev. Lett. **129**, 024802 (2022)

Hosing Instability



T. Nechaeva, L. Verra et al. (AWAKE Coll.) Phys. Rev. Lett. **132**, 075001 (2024)

Filamentation Instability



L. Verra et al. (AWAKE Collaboration), Phys. Rev. E **109**, 055203

At EuPRAXIA

- We will exploit the advantages (large energy gain), while handling the challenges to deliver high-quality bunches
  → Compact Free Electron Laser

- Opportunities for “fun physics”, where the challenges are used
  → Radiation generation
  → Compression to ultra-short bunches
  → Beam-plasma instabilities
  → ....

Thank You For Listening!