The AWAKE Experiment and Simulations of Self-Modulation

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  - e- bunches expelled
  - transverse momentum of p+
  - effect of e- charge on seeding
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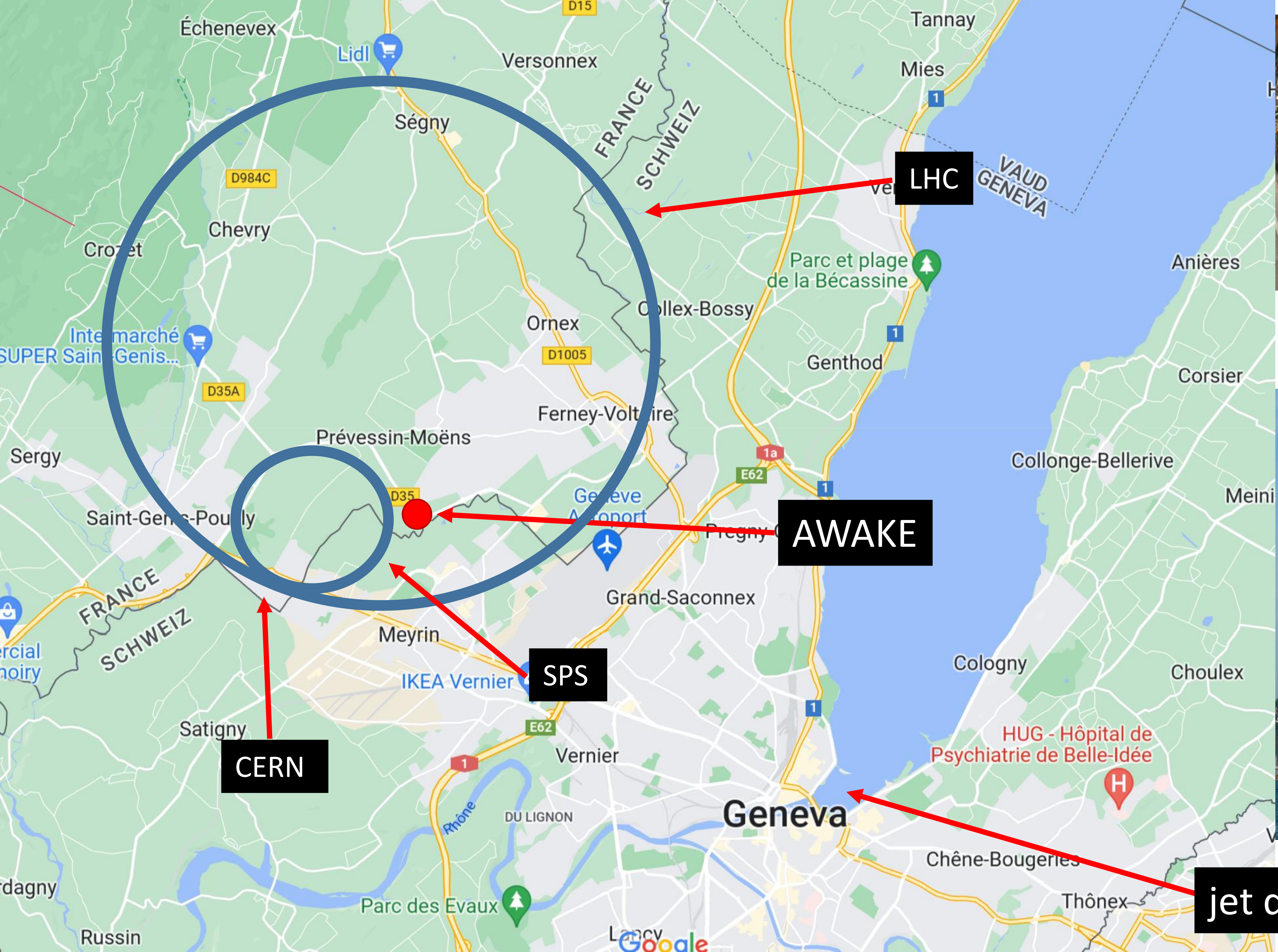
- Virtual visit


LHC
AWAKE
SPS
CERN
jet d'eau
Échenevex
Versonnex
Tannay
Mies
Ségny
Chevry
FRANCE
SCHWEIZ
VAUD
GENEVA
Parc et plage de la Bécassine
Anières
Ornex
Genthod
Corsier
Ferney-Voltaire
Prévessin-Moëns
Sergy
Collonge-Bellerive
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Geneva
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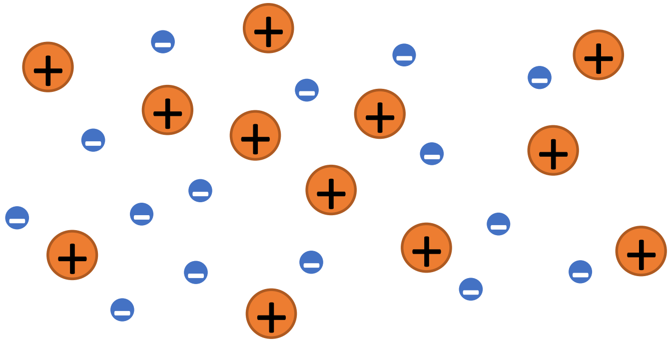
Thônex
Parc des Evaux
Russin
Lidl
D984C
D35A
D1005
D35
E62

Plasma

- Fourth state of matter: free e- and ions
- AWAKE case → cold neutral plasma, e- and ions at rest
- Ions are heavy → ignore their motion

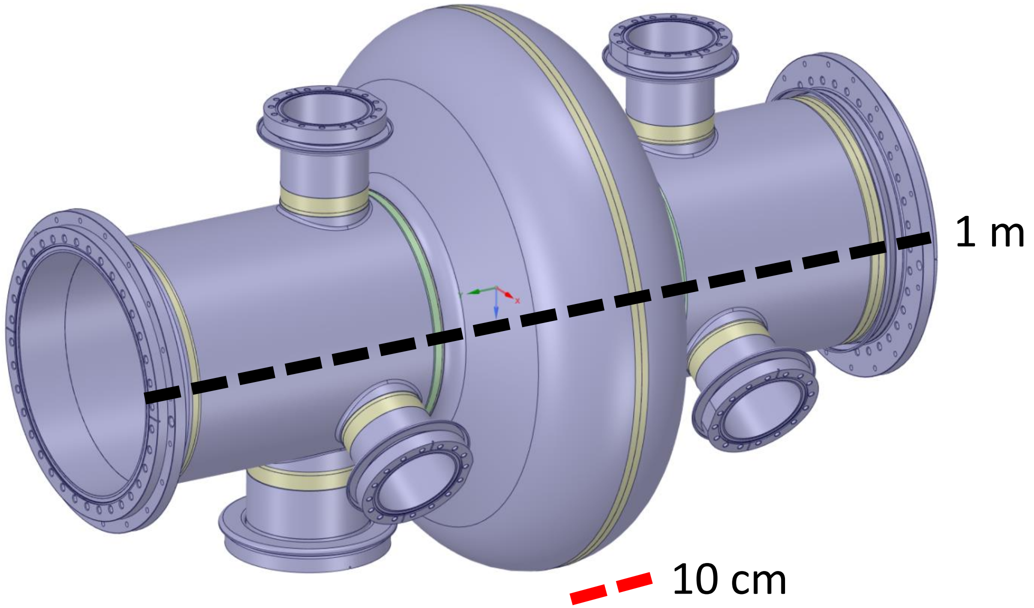
AWAKE helicon plasma cell R&D lab, cern.ch



Why plasma?

Conventional acceleration cavities

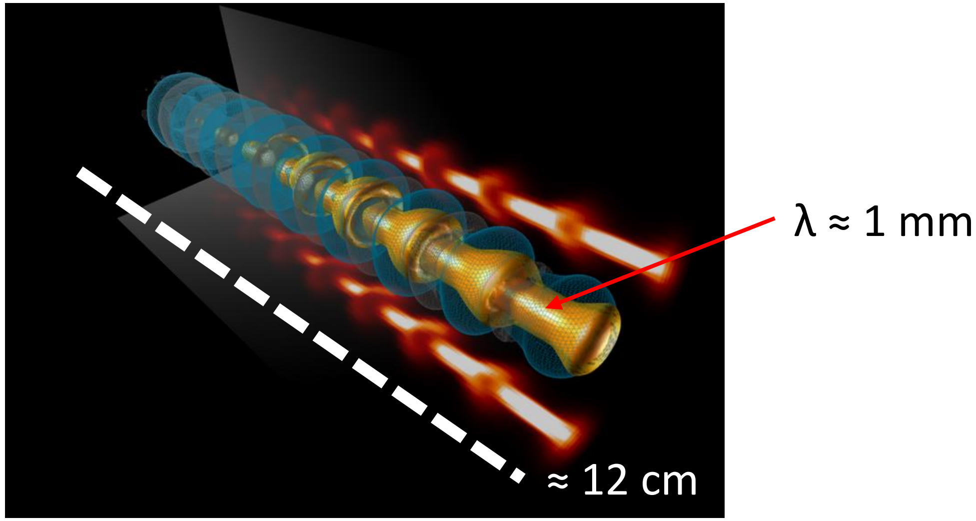
- At the material limit → accelerating gradient = 100 **MV/m**



Broeck (2019), Robotic solutions – RF cavities visual inspection system

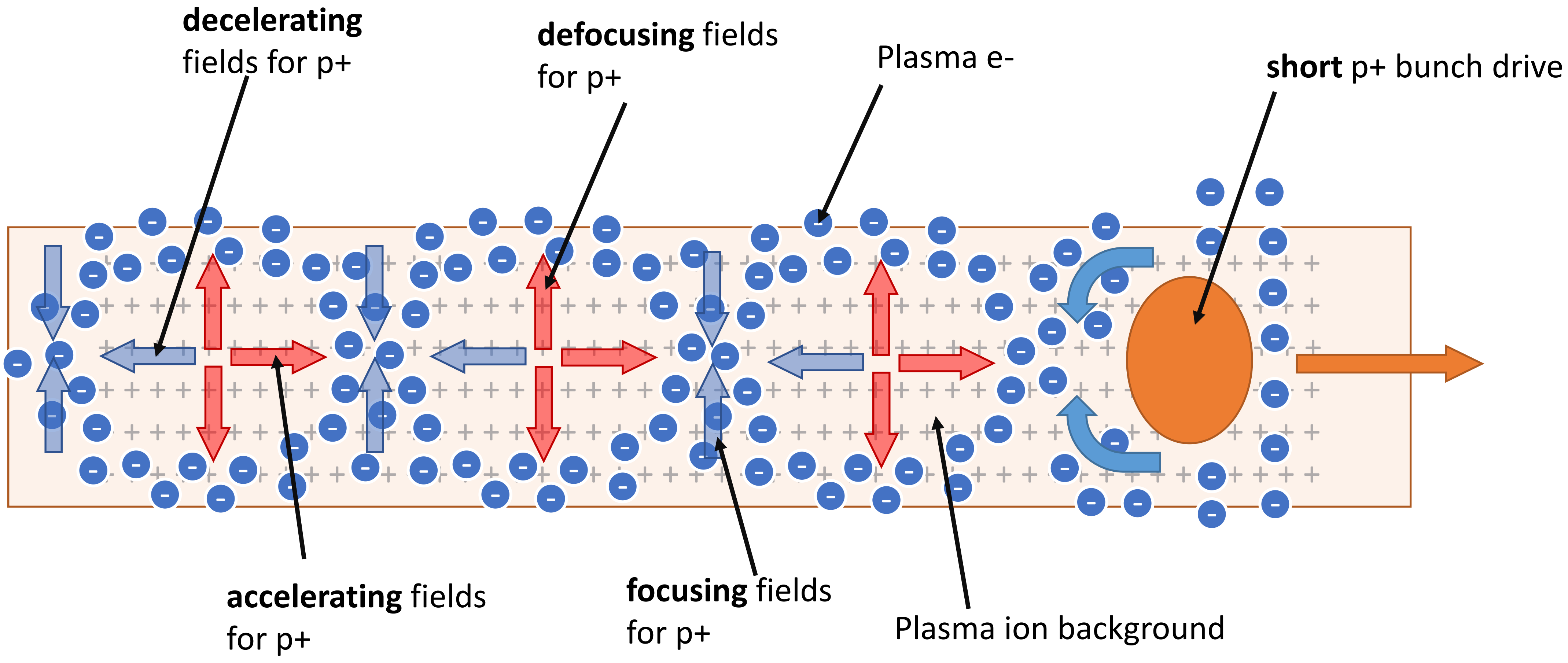
Plasma wakefield acceleration

- Acceleration gradient = 100 **GV/m**
- Three orders of magnitude increase



Simulation picture of the p+ beam (yellow) forming bunches under the action of the plasma field. e- can be accelerated on these "waves" (Image: J. Vieira)

Wakefields driven by a proton bunch



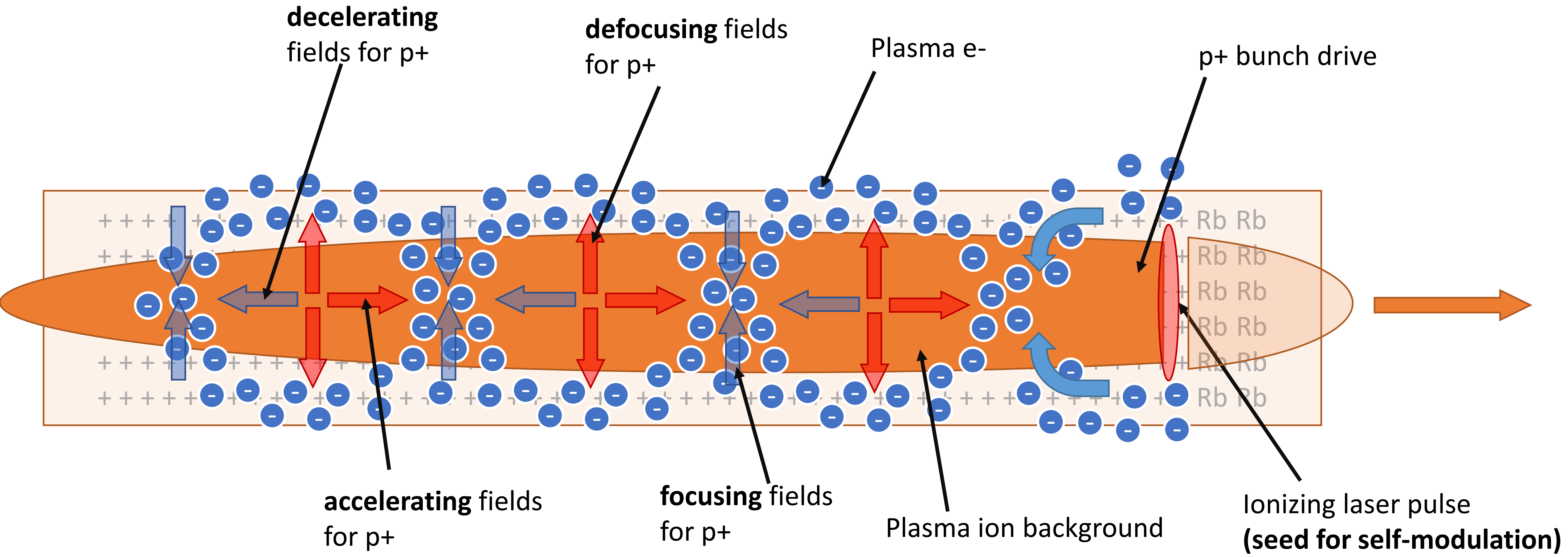
- p+ bunch attracts plasma e- transversely
- Plasma e- concentrate on axis and repel each other
- Then they are pulled back to axis by the ion background

Self-modulation

The idea behind AWAKE

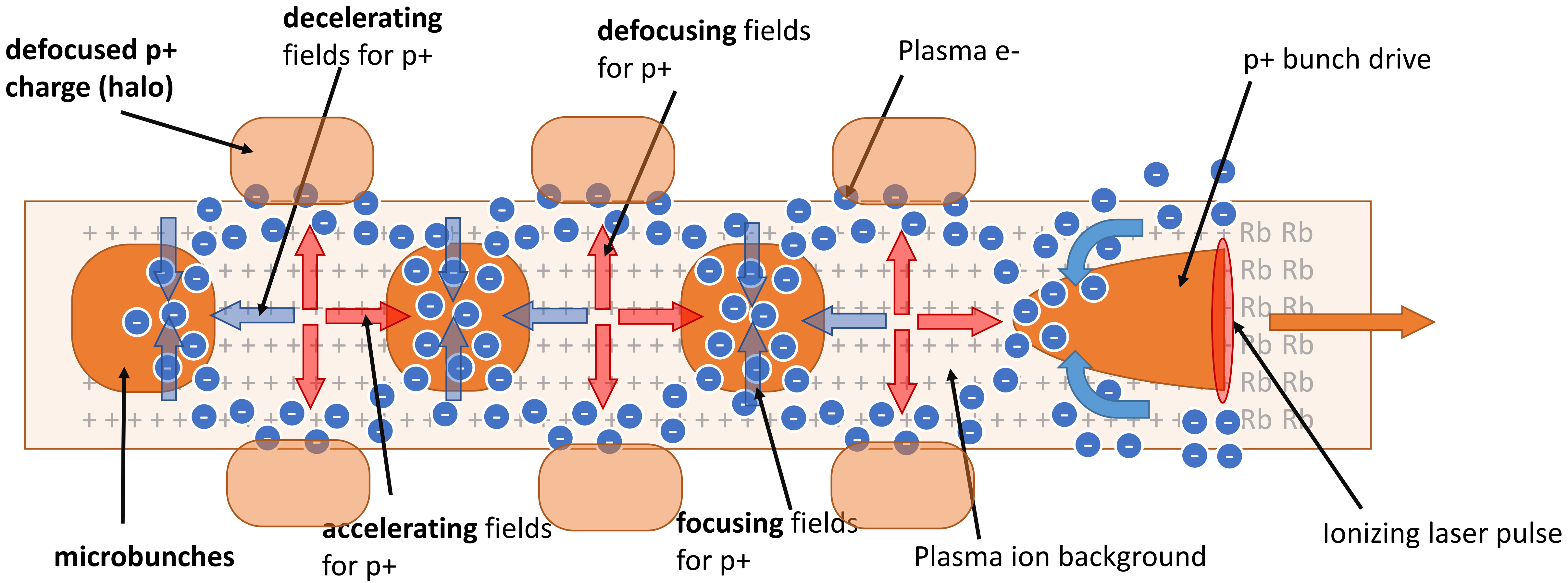
N.Kumar et al (2010) Phys. Rev. Lett. 104, 255003

Self-modulation (SM) process



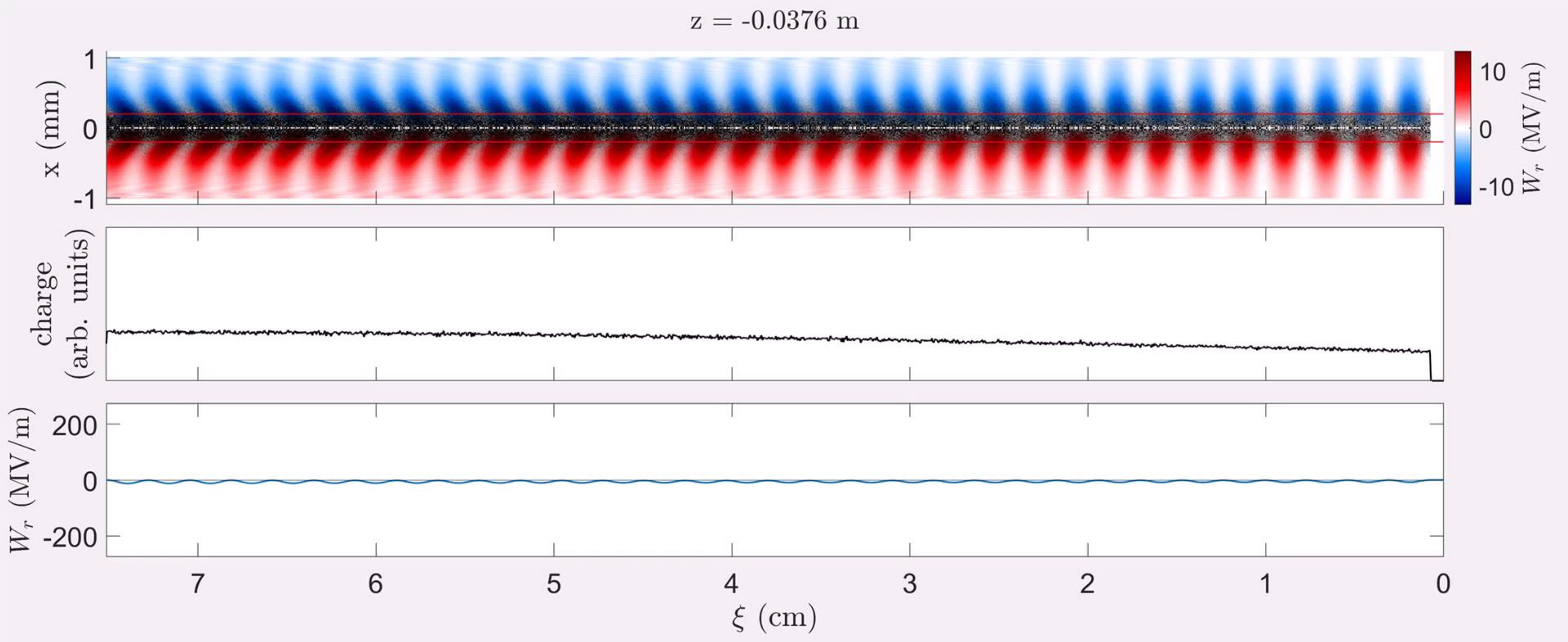
- Bunch with a steep cut in the density profile drives seed wakefields
- p+ are repelled or attracted to the axis due to the focusing and defocusing fields

Self-modulation (SM) process



- The modulation of the p+ bunch makes the plasma e- more attracted to the axis
  → feedback loop: p+ completely expelled from or focused to the axis.
  → train of microbunches separated by $\sim\lambda_p$,
  - coherently drives wakefields

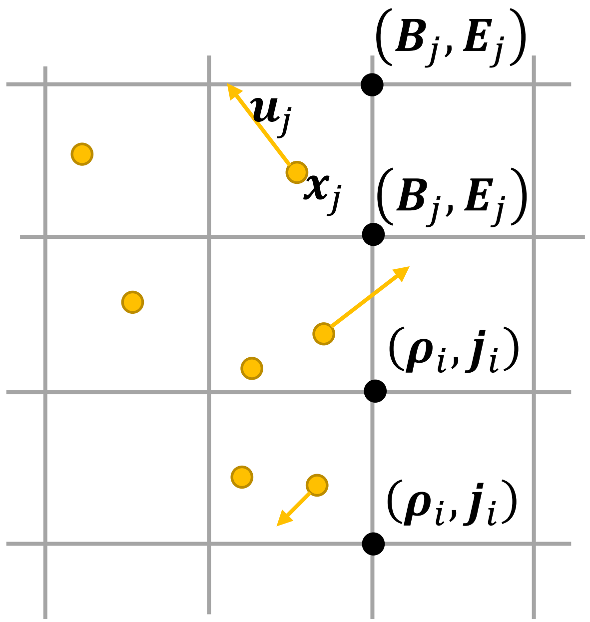
SM in simulations



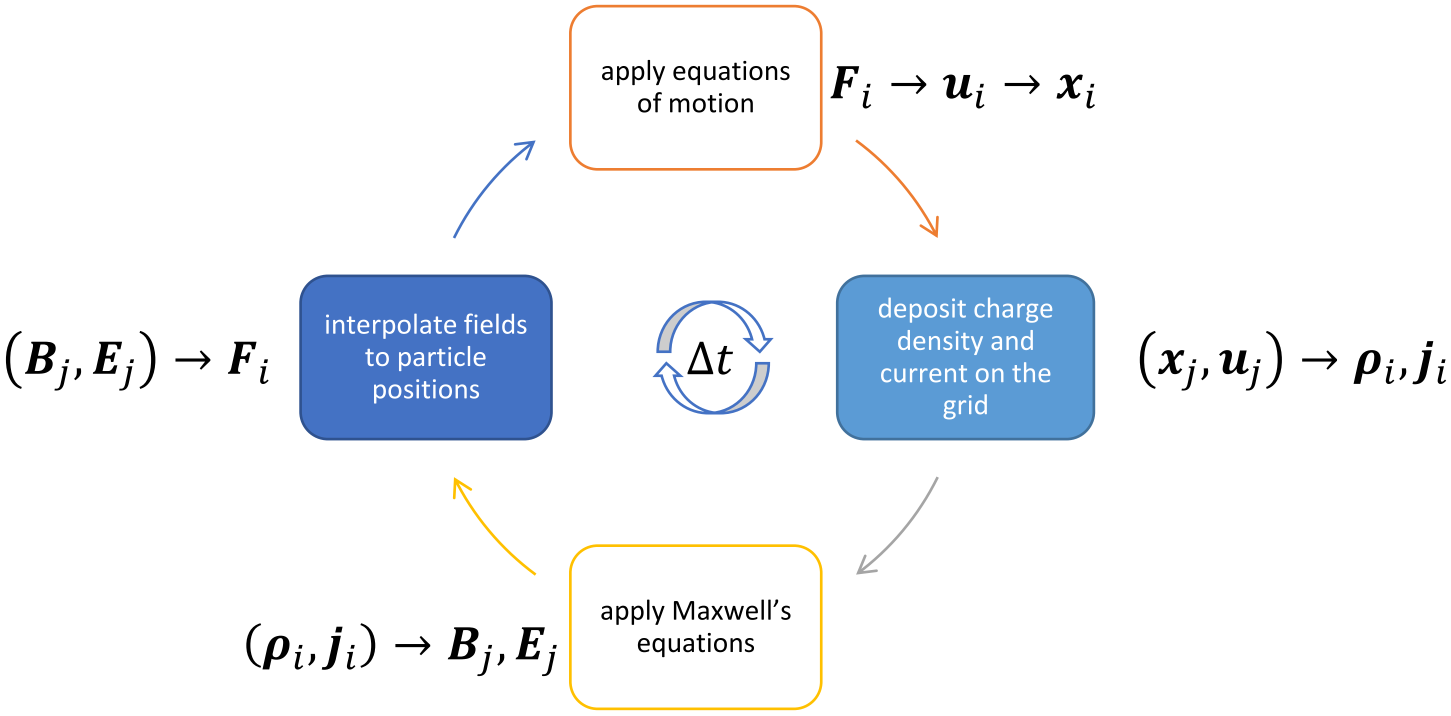
Simulations and my work

Solve numerically Newton equations of motion and Maxwell equations to describe the plasma processes.

Particle-in-cell (PIC) simulations



$$\frac{d\boldsymbol{u}}{dt} = \frac{q}{m}\left(E + \frac{1}{\gamma c}\boldsymbol{u} \times \boldsymbol{B}\right)$$



$$\frac{\partial \boldsymbol{E}}{\partial t} = c^2 \vec{\nabla} \times \boldsymbol{B} - \frac{\mu_0}{\epsilon_0}\boldsymbol{j}$$

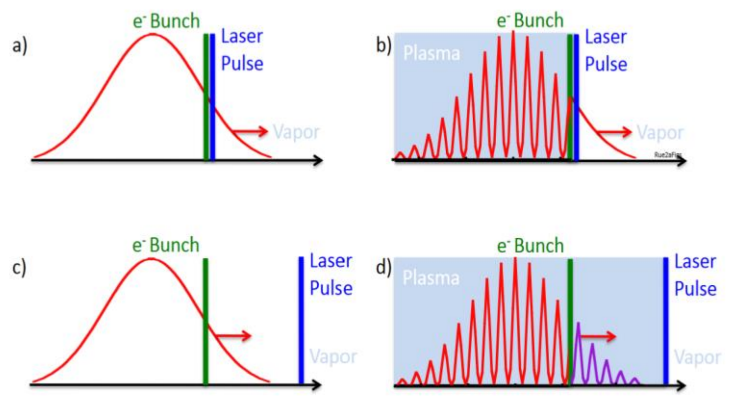
$$\frac{\partial \boldsymbol{B}}{\partial t} = -\vec{\nabla} \times \boldsymbol{E} \qquad \frac{\rho}{\epsilon_0} = \vec{\nabla} \cdot \boldsymbol{E}$$

- Particles placed inside cells
- Density, current, and fields calculated on the grid
- Particles pushed

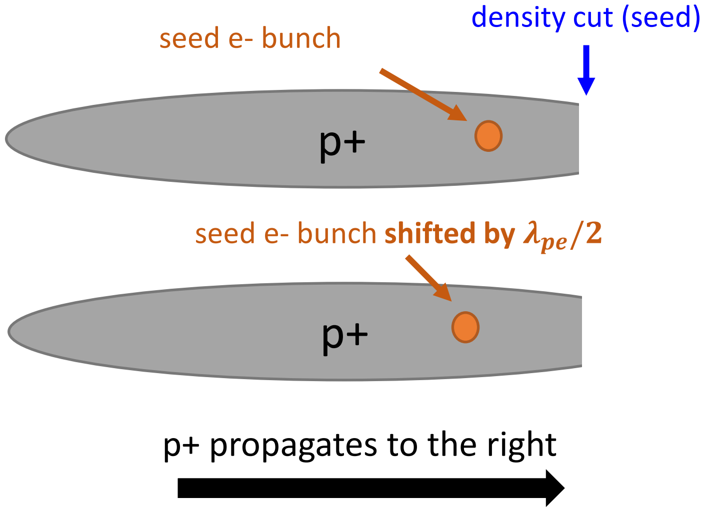
My work in run 2a

Experiment

© P. Muggli



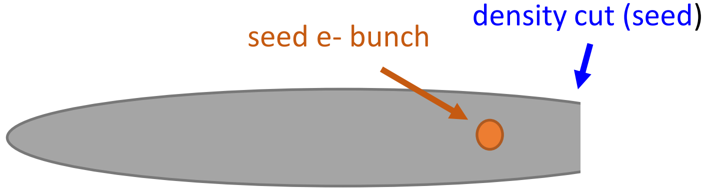
Simulations (LCODE 2D axisymmetric)

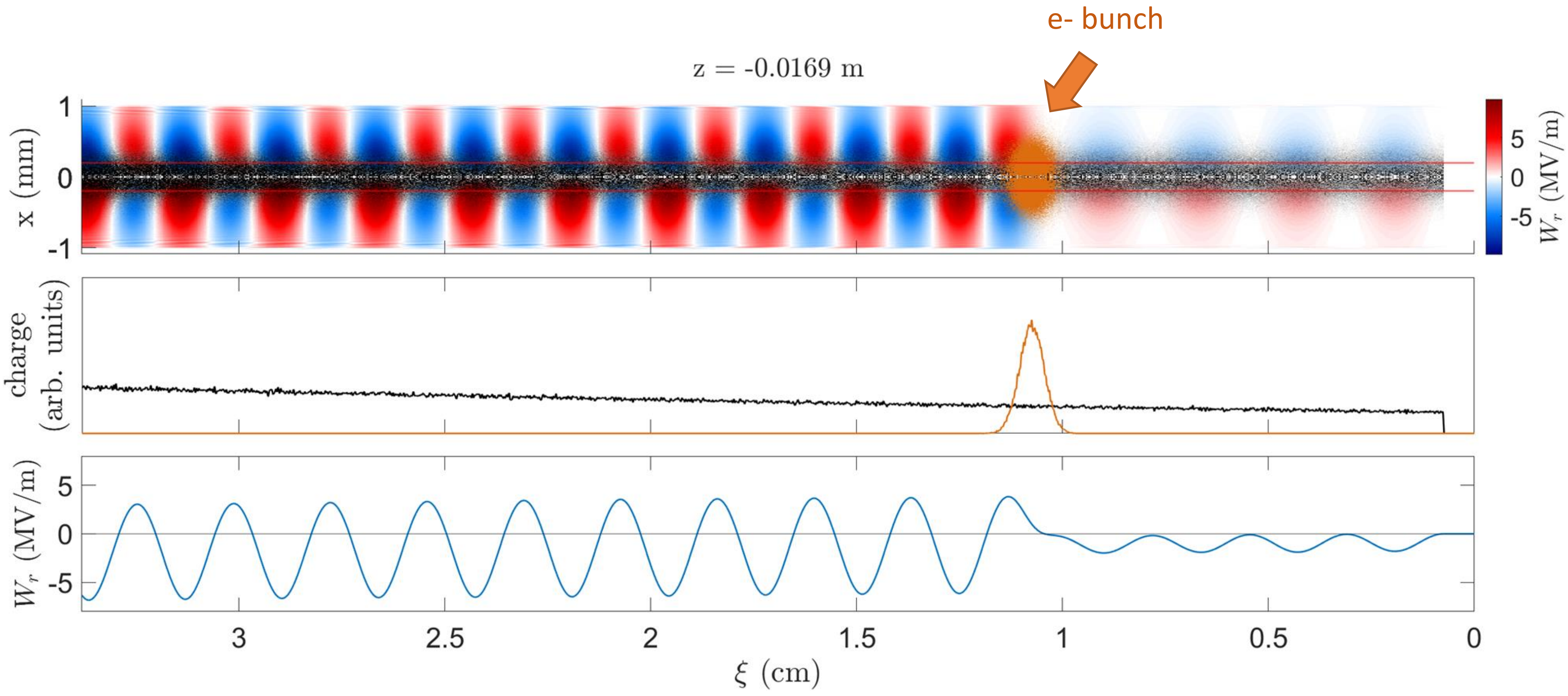


- Simulations and experiment
  - e- bunch seed inside the p+ bunch
  - Laser pulse (density cut) propagating ahead of the e- bunch
- Simulations
  - Measure the e- bunch seeding by sending two simulations, one of them with a shift of $\lambda_{pe}/2$ and measuring the dephasing of the wakefields and microbunches in $z = 10\ \mathrm{m}$
- Understand the conditions under which the e- bunch seeds
- Understand the interaction of two self-modulating parts coming from different seeds

Run 2a

Simulations
Beginning of the plasma





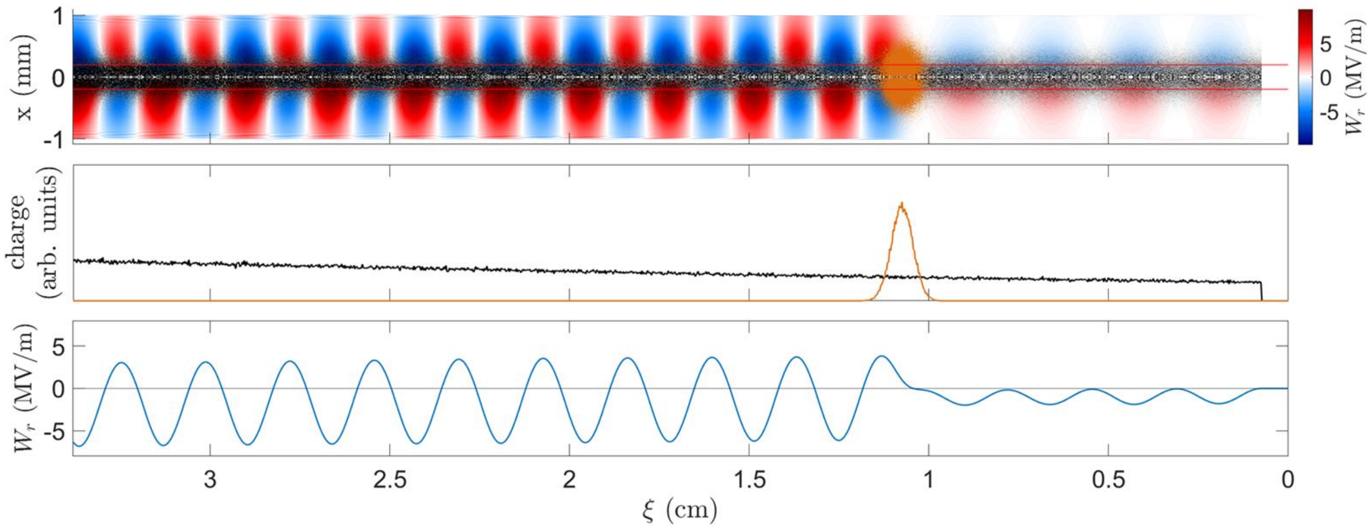
transverse fields and p+ and e- bunch densities

charge profiles within $|x| < 200\mu m$

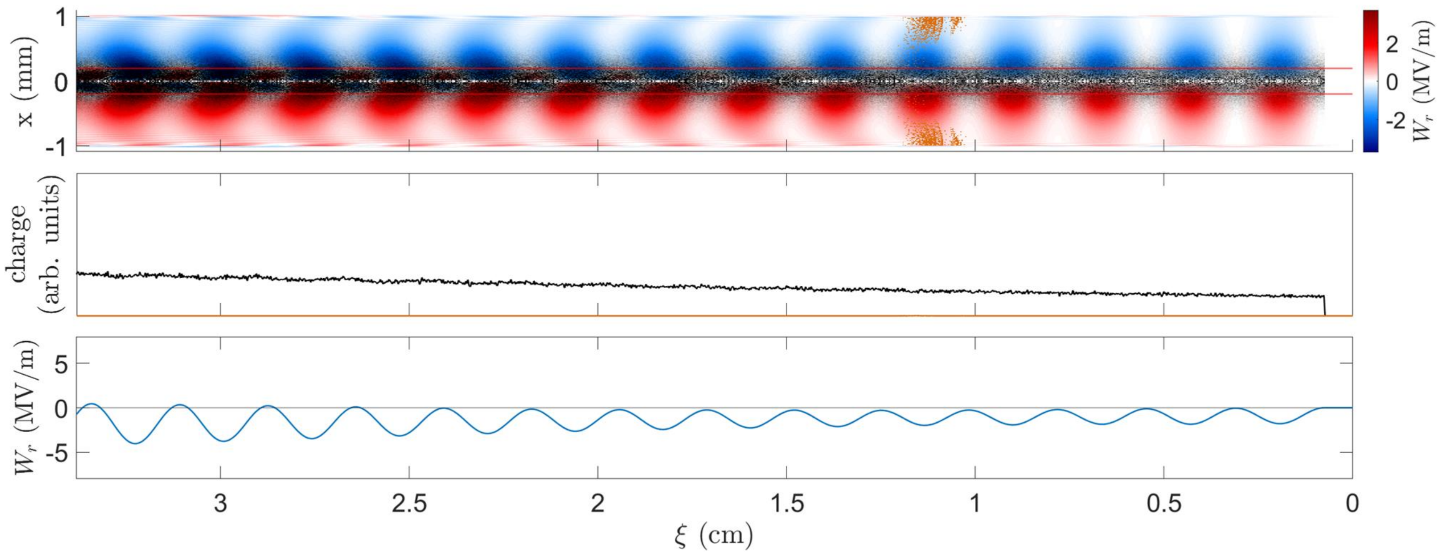
lineout of transverse fields at $x = 200\mu m$

Electron bunch is expelled from axis early in the plasma

beginning of plasma



$z = 0.484$ m



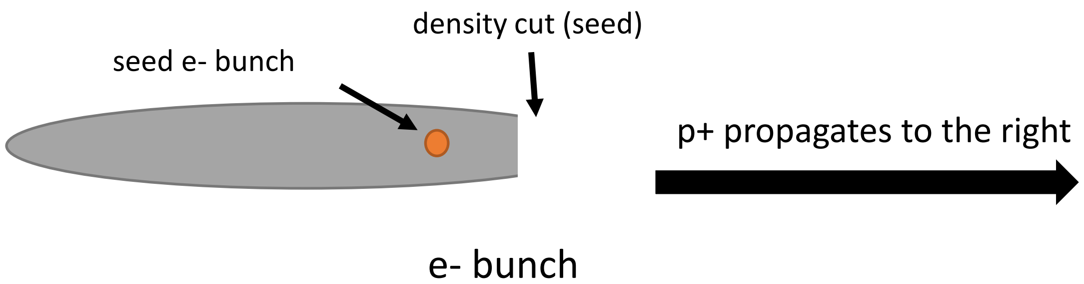
- e- bunch is subject to the defocusing seed wakefields of the p+ bunch (density cut + adiabatic response)
- In this case, it was expelled at $z \approx 60$ cm
  - density cut $2\sigma_z$ ahead of bunch center
  - e- bunch 1cm behind density cut
- No radial modulation
- No wakefields from e- bunch

→ Does it seed?

Transverse momentum

Simulations

Beginning of the plasma

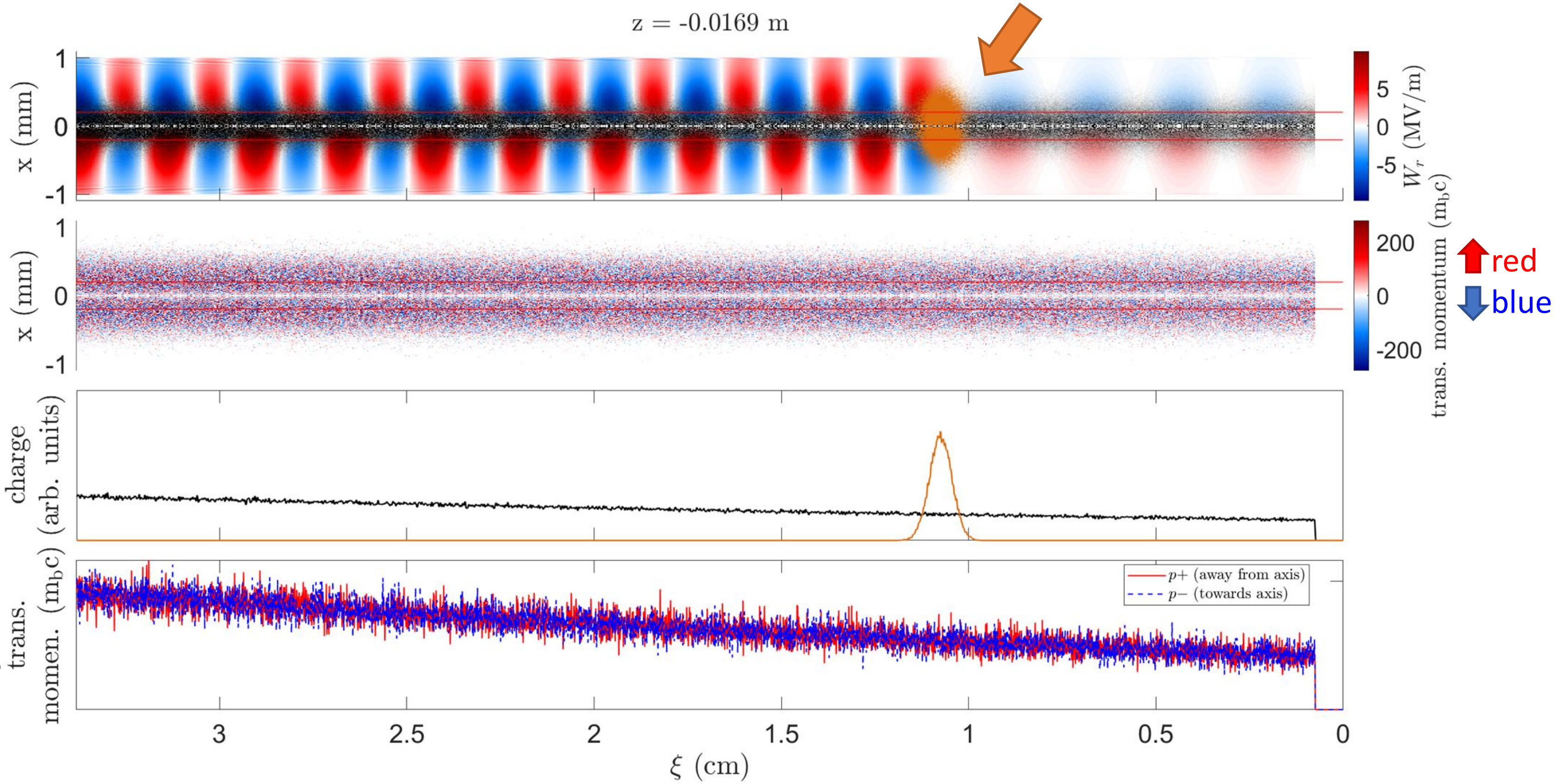


transverse fields and densities

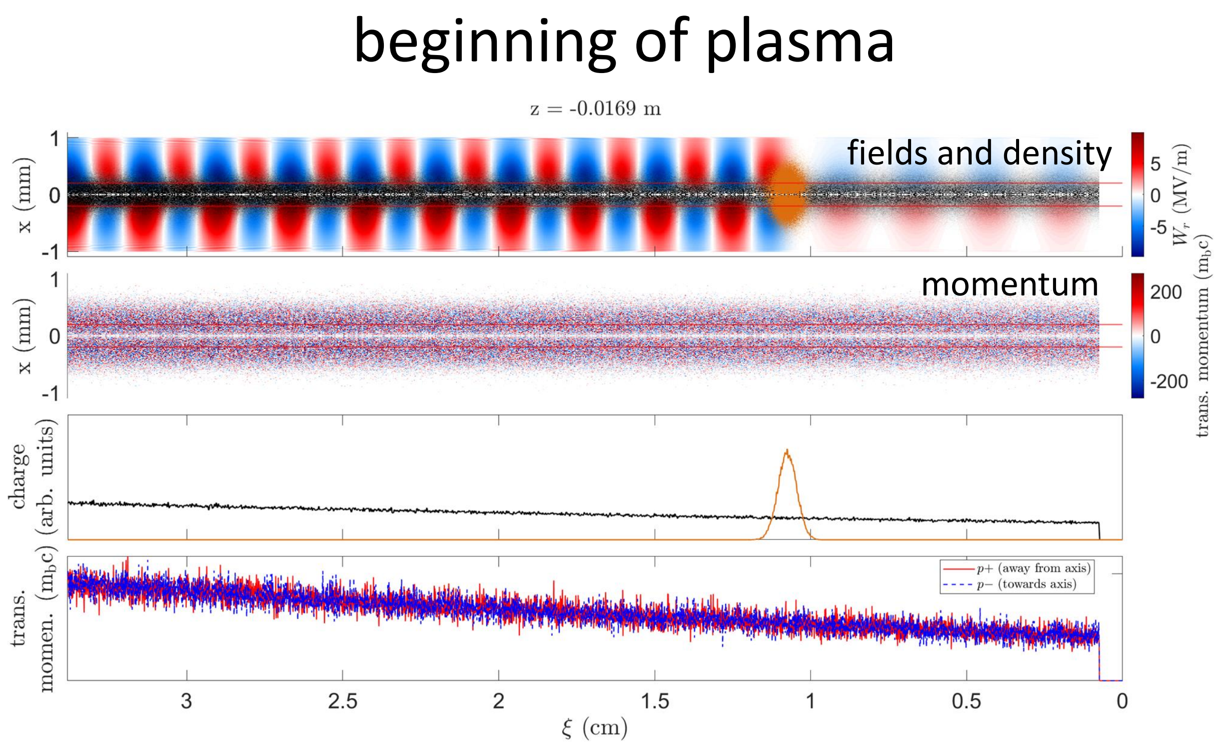
p+ transverse momentum

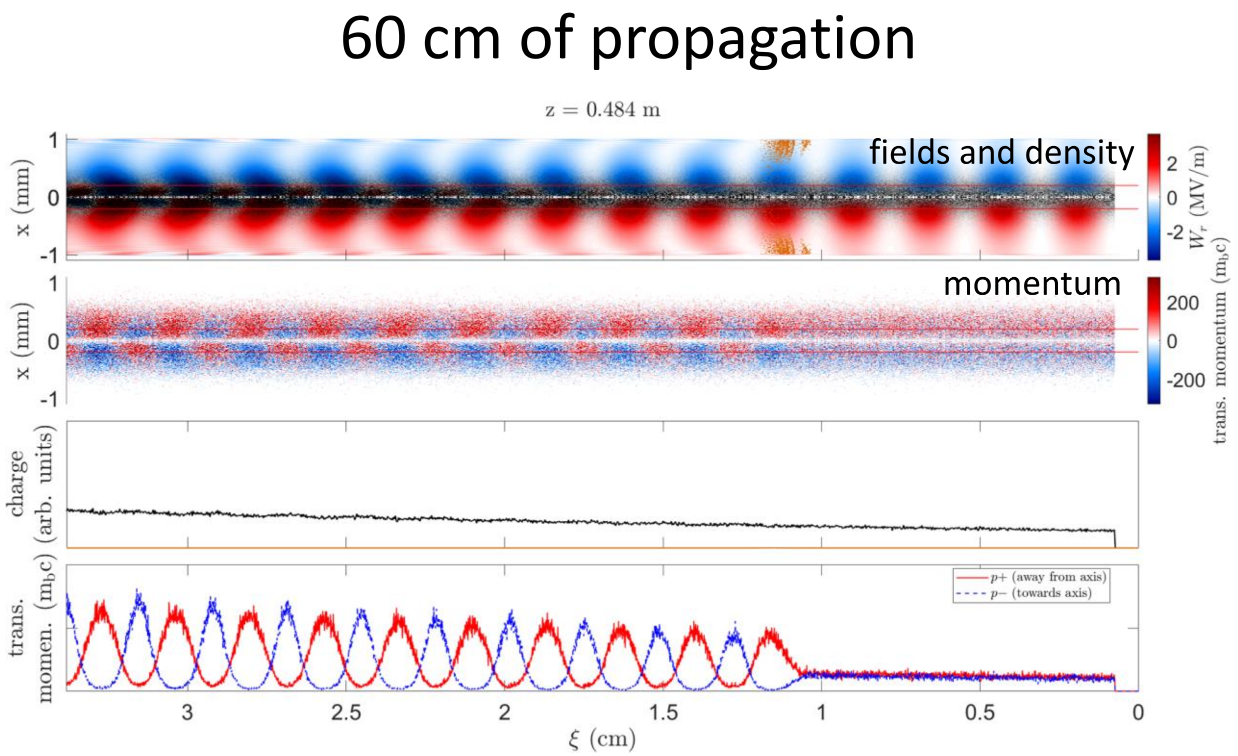
density profiles within $|x| < 200\mu m$

sum of transverse momentum per slice



Electron bunch leaves momentum imprint

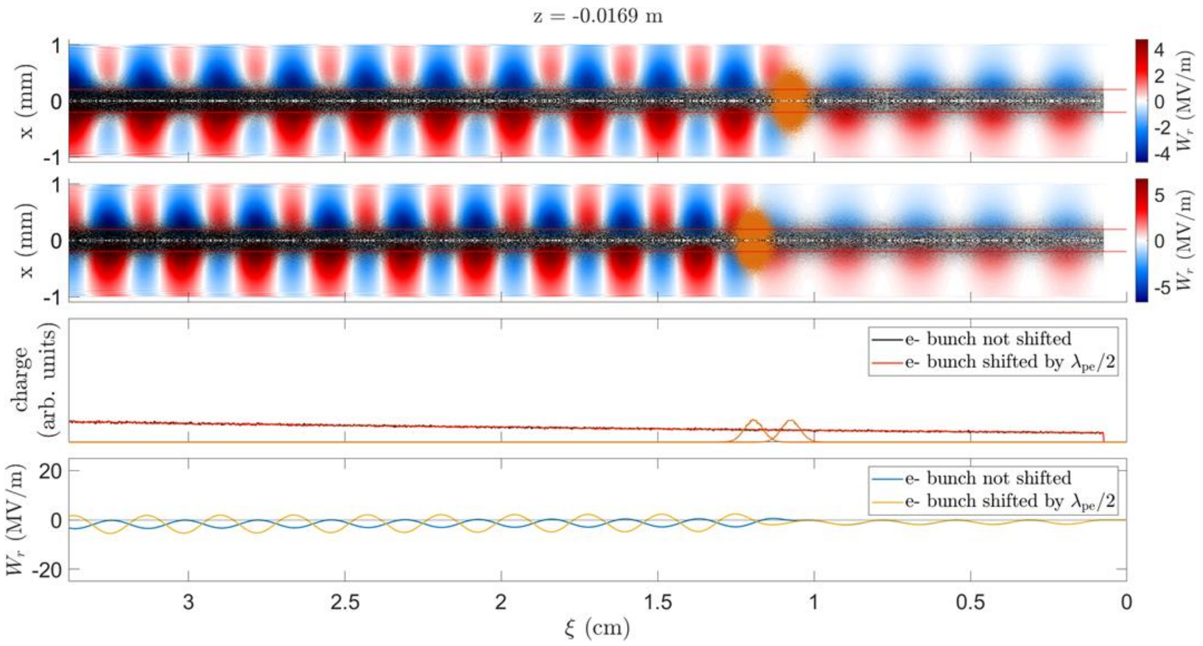




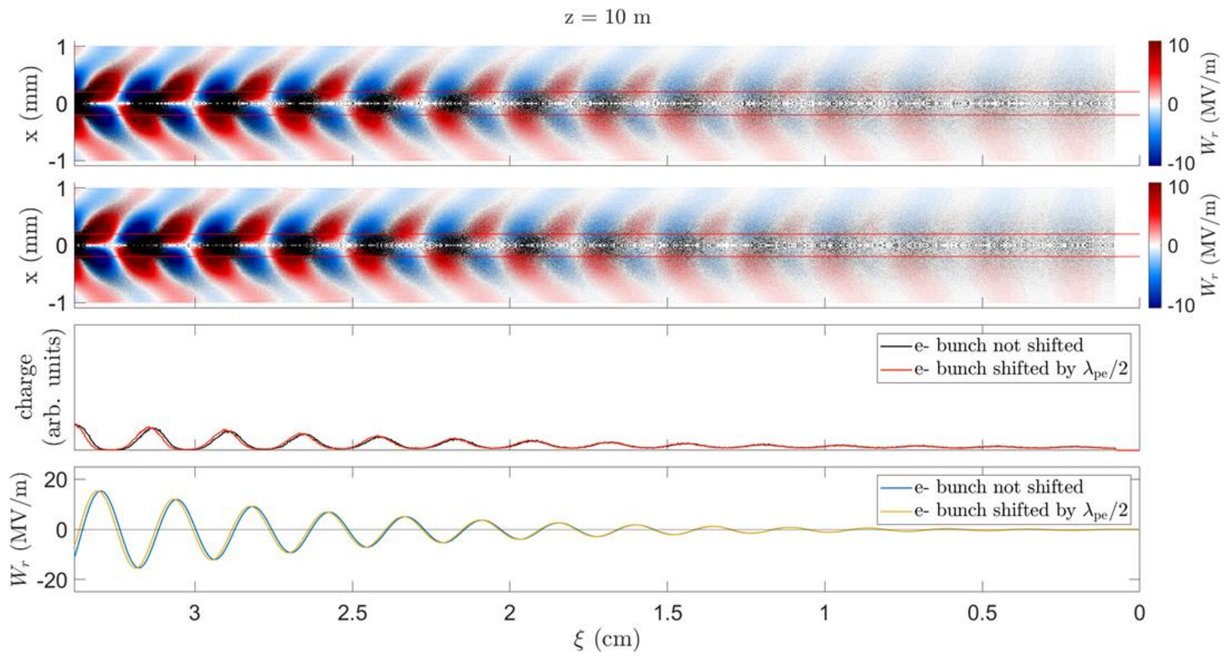
- e- bunch leaves a transverse momentum imprint on the p+ bunch
- If the momentum imprint is high enough, the radial modulation will follow it, despite the seed wakefields from the density cut

Phase by the end of the plasma low charge (100 pC)

beginning of plasma



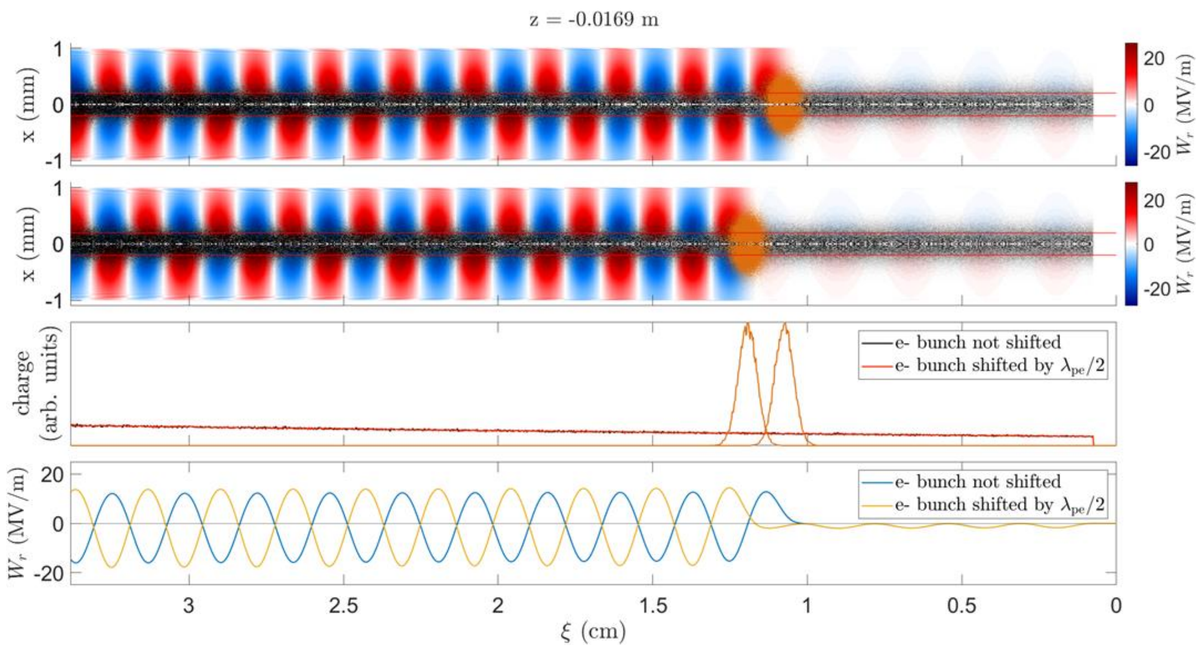
end of plasma



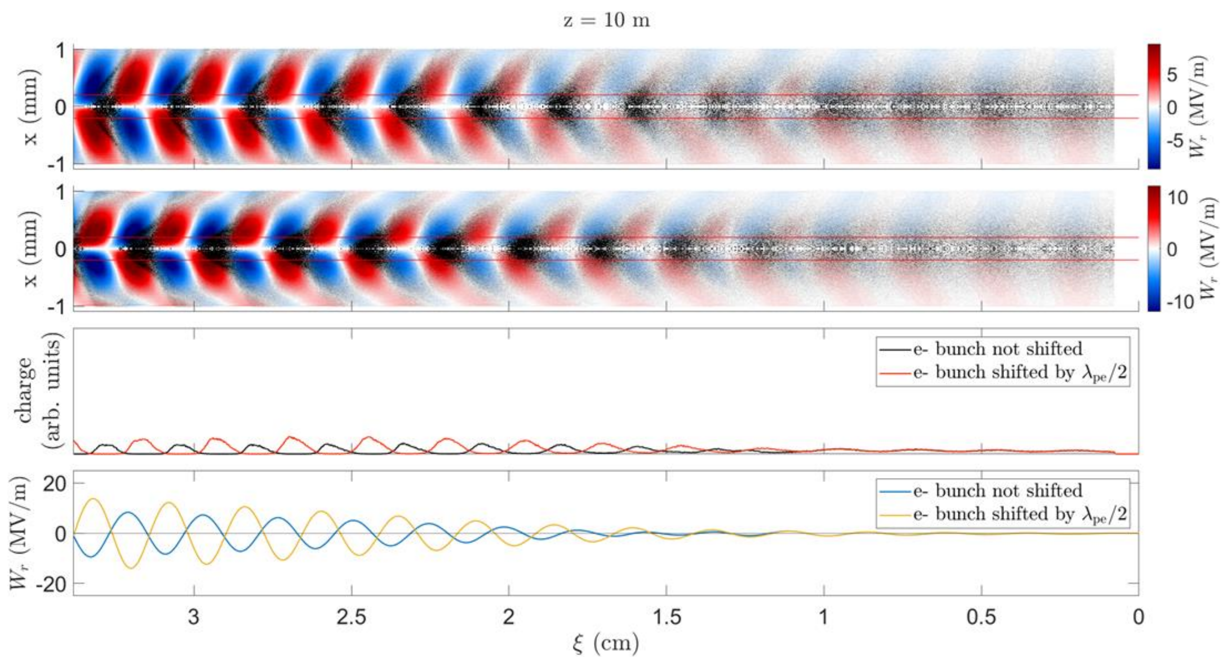
- Low e- bunch charge → low amplitude wakefields
  - → not enough momentum is transferred to p+
  - → no seeding: phase along the bunch is independent of the e- bunch

Phase by the end of the plasma high charge (550 pC)

beginning of plasma



end of plasma



- High e- bunch charge → high amplitude wakefields
  - → momentum is transferred to p+, even though e- bunch is quickly expelled from axis ($z \approx 80\text{cm}$)
  - → seeding: phase of microbunches and wakefields depend on e- bunch

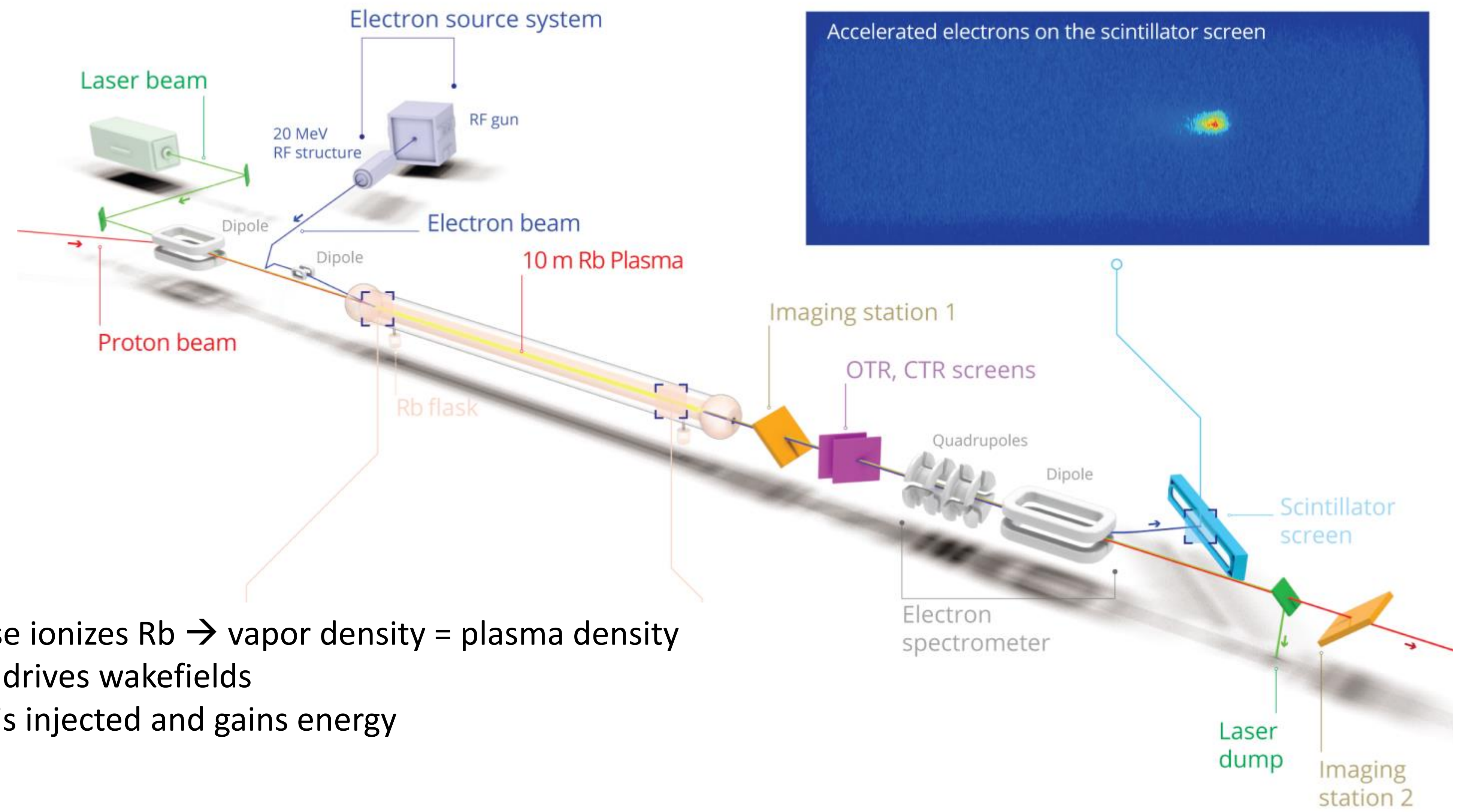
Conclusions

- AWAKE: experiment that uses wakefields driven by a p+ bunch to accelerate e- bunches
- Simulations can …
  - support and explain experimental results, by showing parts of the process not accessible in the experiment
  - make predictions when theoretical solutions have no analytical form
- My current project explores the conditions in which there is seeding or not, and predicts what could be observed in the experiment
  - The e- bunch is expelled from the axis early in the plasma when propagating inside the p+ bunch.
  - e- bunches seed by modulating the transverse momentum of the p+ bunch.
  - e- bunches seed when they have **sufficient charge**

Virtual visit

https://my.matterport.com/show/?m=21e5ne2M9TV

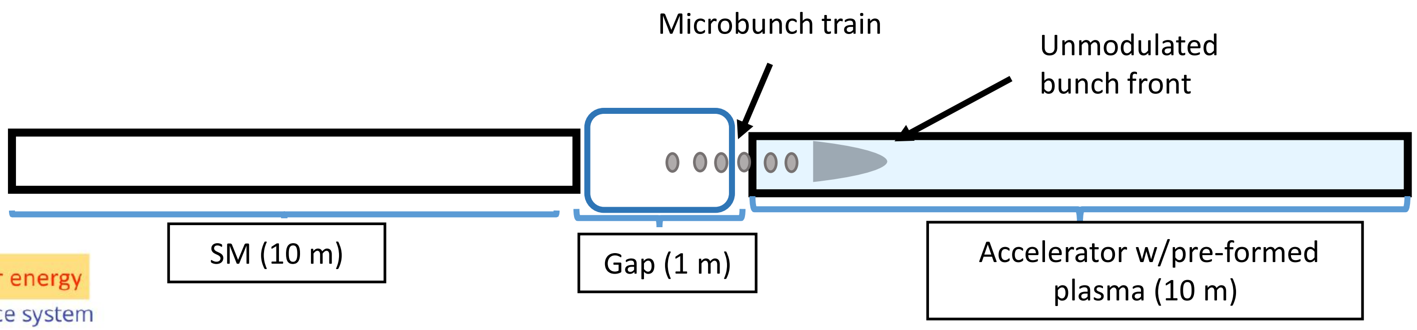
AWAKE - facility

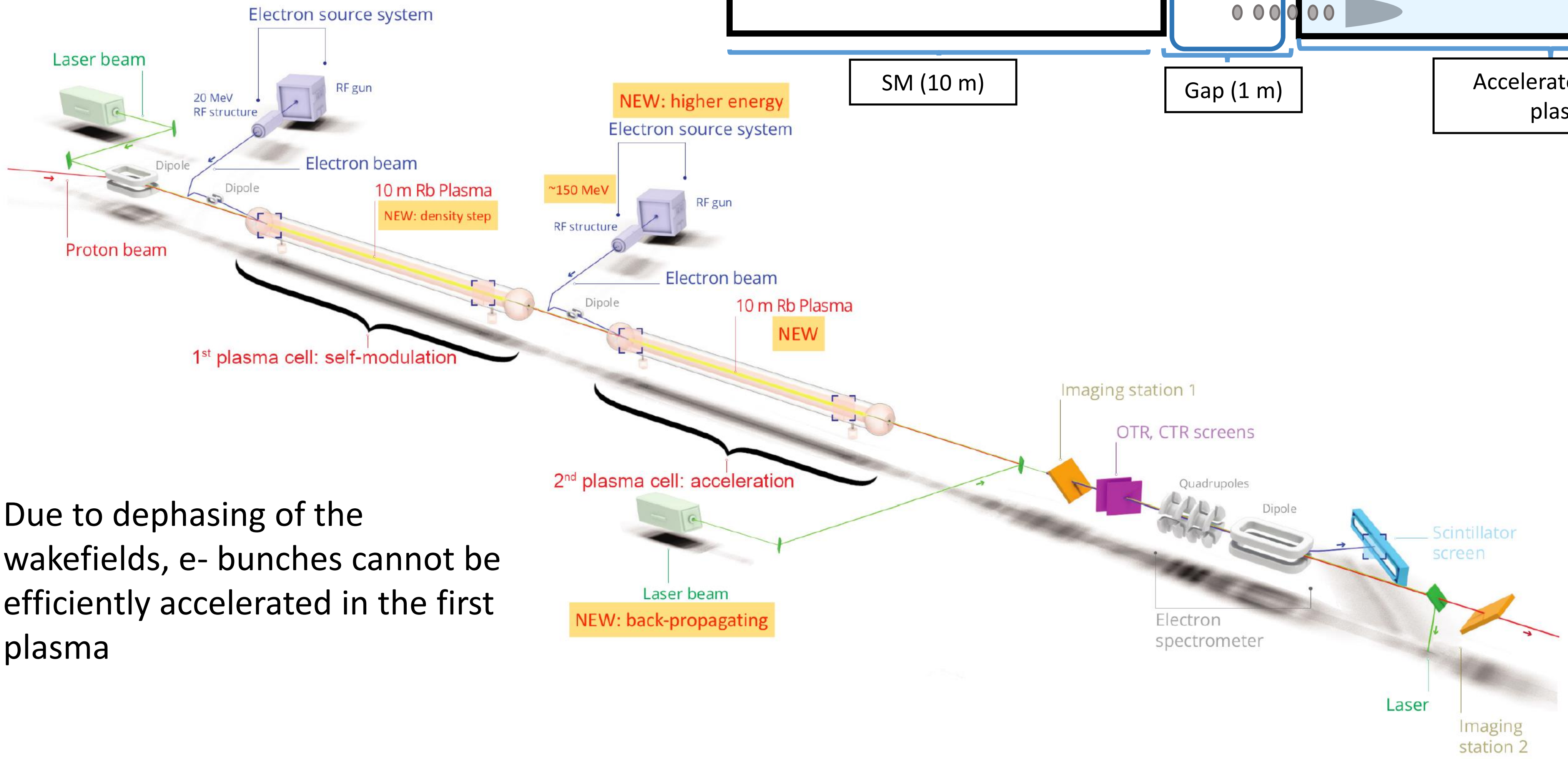


AWAKE Collaboration, Nature **561**, (2018)

- Laser pulse ionizes Rb → vapor density = plasma density
- p+ bunch drives wakefields
- e- bunch is injected and gains energy

Future runs (run 2c)





- Due to dephasing of the wakefields, e- bunches cannot be efficiently accelerated in the first plasma

AWAKE Collaboration, unpublished

Driving wakefields

- Effectively?

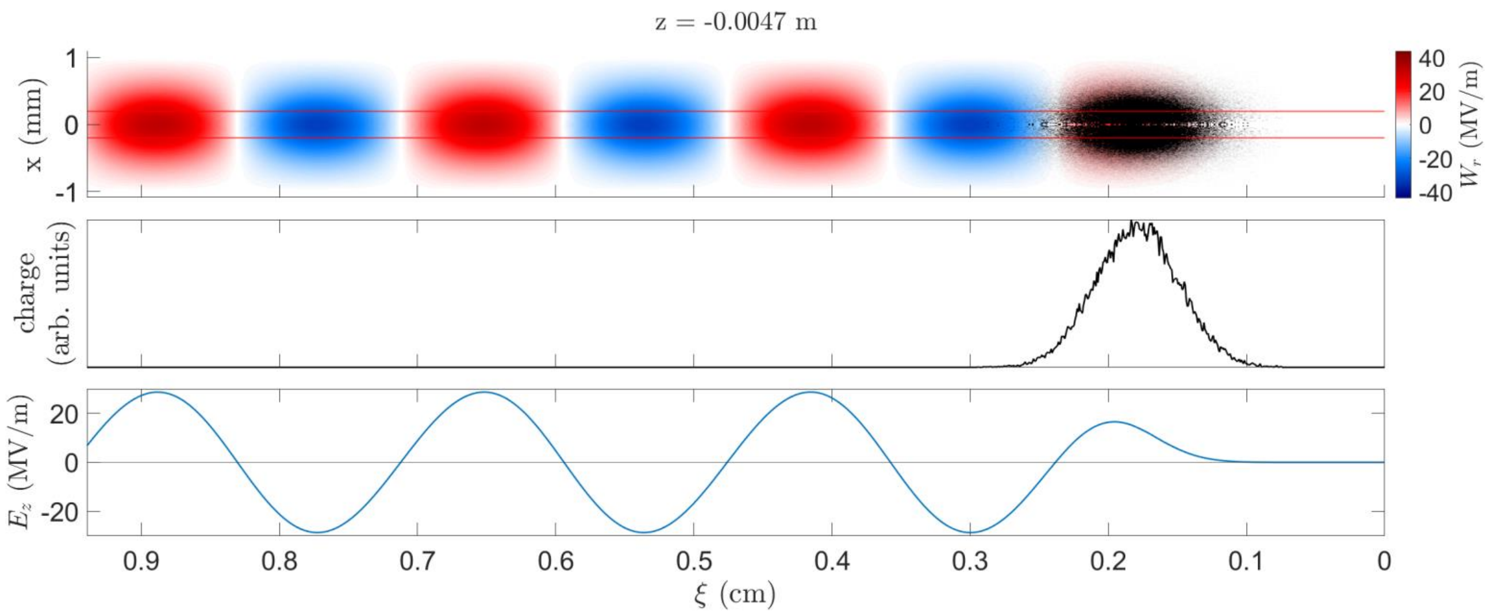
$$W_z(\xi) = K \int_{-\infty}^{\xi} n_b \cos[k_{pe}(\xi - \xi')]\, d\xi'$$

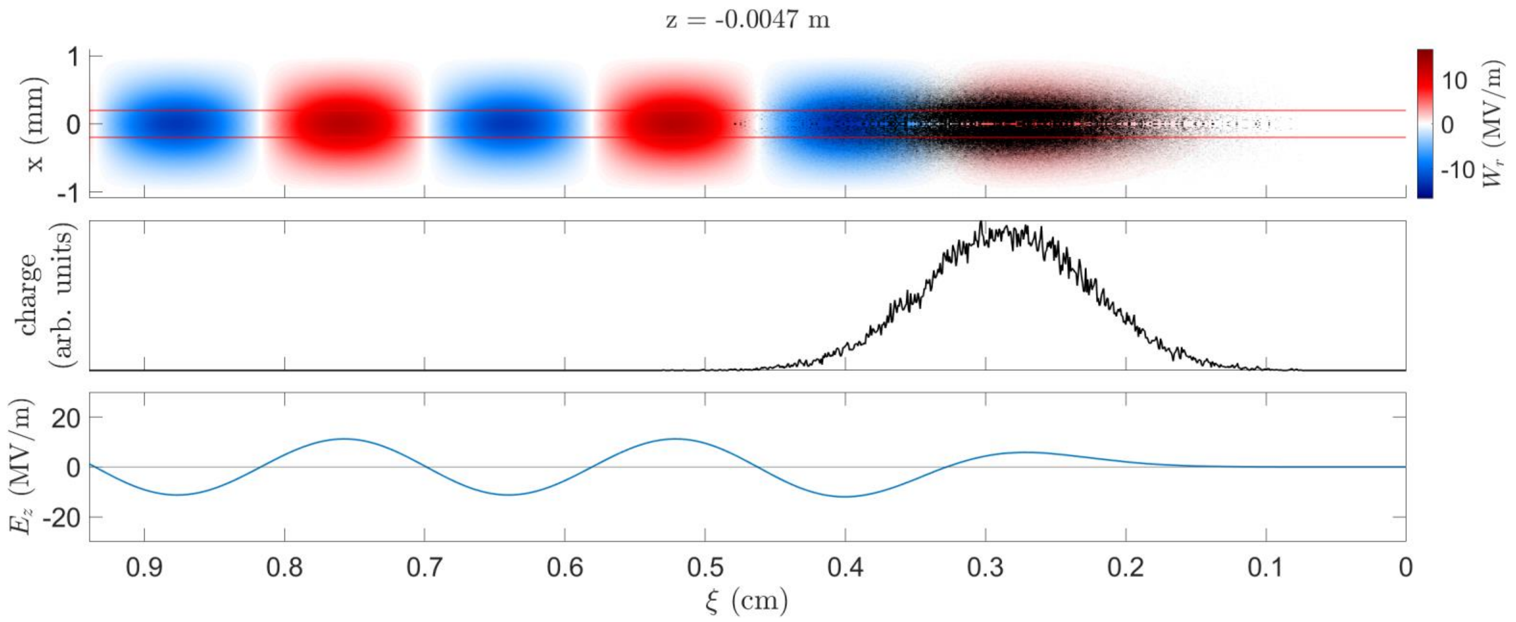
All particles must be in the decelerating phase → bunch must be ~ ½ λ_{pe} long.

High energy p+ bunch are much larger than λ_{pe}!

$$\sim 7.5 \text{ cm} \gg \sim 1 \text{ mm}$$

What to do?





Driving wakefields

- To highest energies in one stage
- **Energy gained by witness bunch ≤ energy lost by driver bunch**

Energy carried by:

Laser pulse	≈ 10s J, < 100 fs
e- bunch	≈ 10s J, < 1 ps
p+ bunch	**≈ 10s kJ, ≈ 1 ns**

Short plasma stage with high gradient

Very long plasma stage, but small gradient

How to use large energy from a long p+ bunch?

Maximum fields amplitude is on the order of the wave-breaking fields, which scales with the inverse of the length of the beam

$$E_{wb} = \frac{m_e c \omega_{pe}}{e} = \frac{2\pi m_e c^2}{e\lambda_{pe}} \approx \frac{1}{\sigma_z}$$