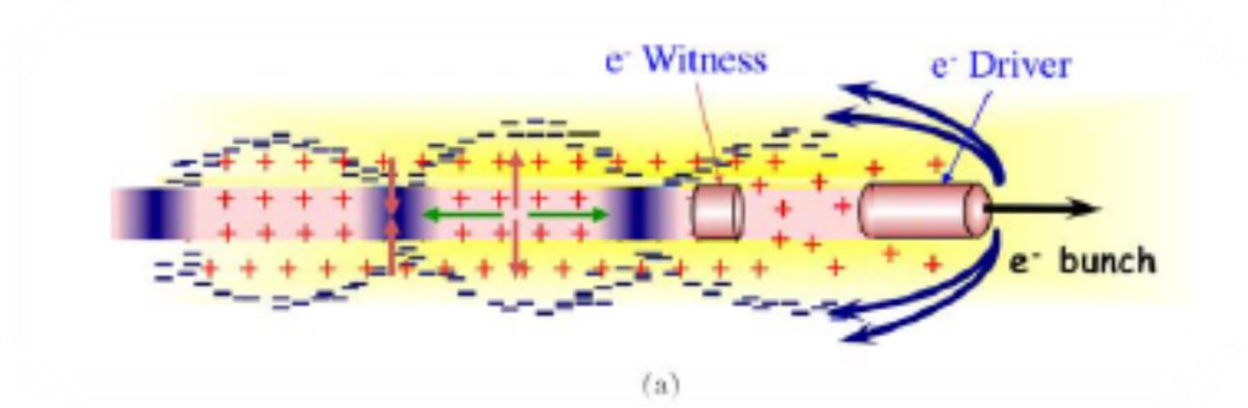
AWAKE Project

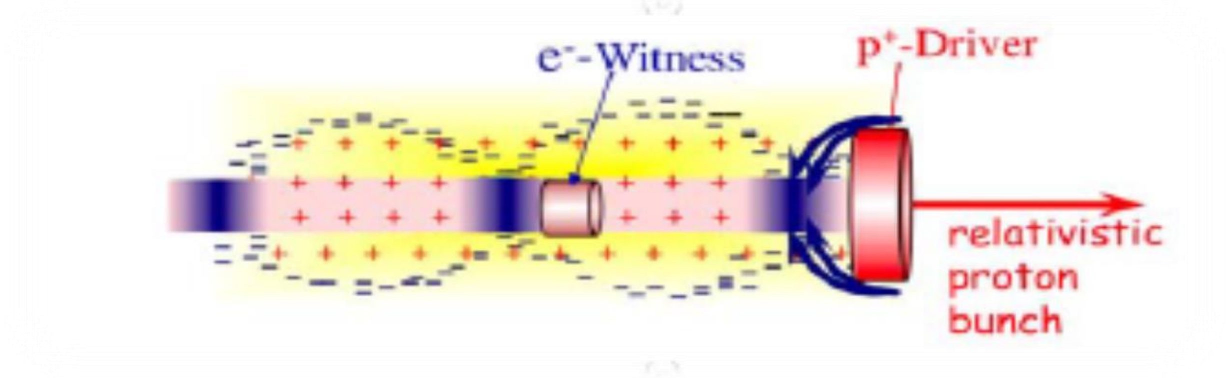
PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

Electron bunch driver

❖Particle driver



proton bunch driver

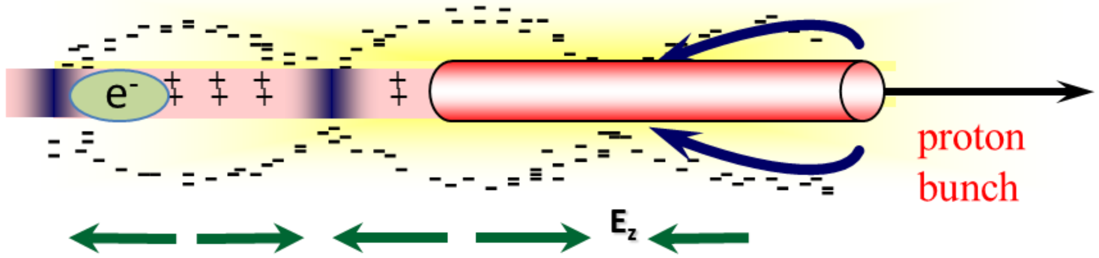


1- Adli, Erik, and Patric Muggli. "Proton-beam-driven plasma acceleration." *Reviews of Accelerator Science and Technology* 9 (2016): 85-104.

PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

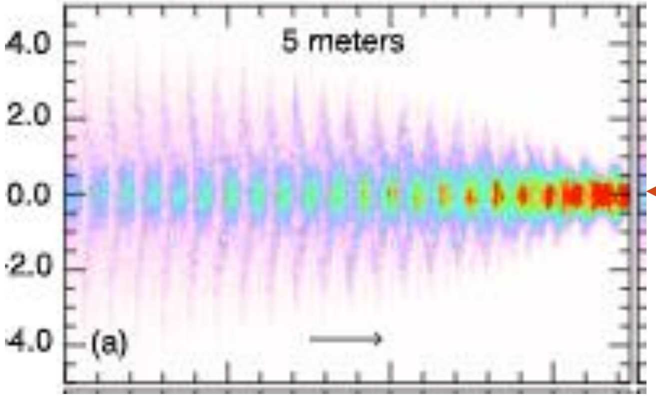
❖ Microbunching and self-modulation

Long proton bunch driver
SSM develops

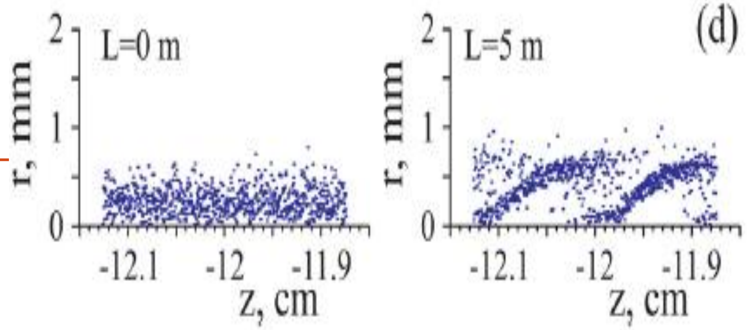


transverse focusing

1-synchronize the Wakefield with an injected witness bunch, seeding is important.
2-if the SMI is not seeded the competing transverse hosing instability may destroy the plasma wake-fields



seeding

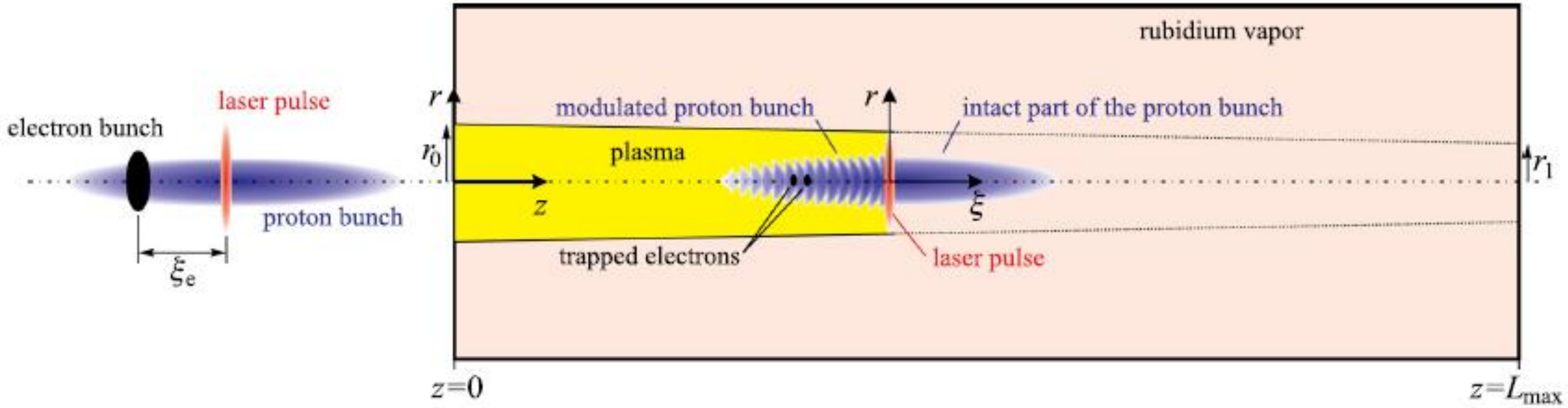


2-Lotov, K. V., A. P. Sosedkin, A. V. Petrenko, Lígia Diana Amorim, Jorge Vieira, R. A. Fonseca, L. O. Silva, E. Gschwendtner, and Patrick Muggli. "Electron trapping and acceleration by the plasma wakefield of a self-modulating proton beam." *Physics of Plasmas* 21, no. 12 (2014): 123116.

PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

✓ Electron injection → 1- On-axis 2- Oblique 3- side

1- On-axis electron injection



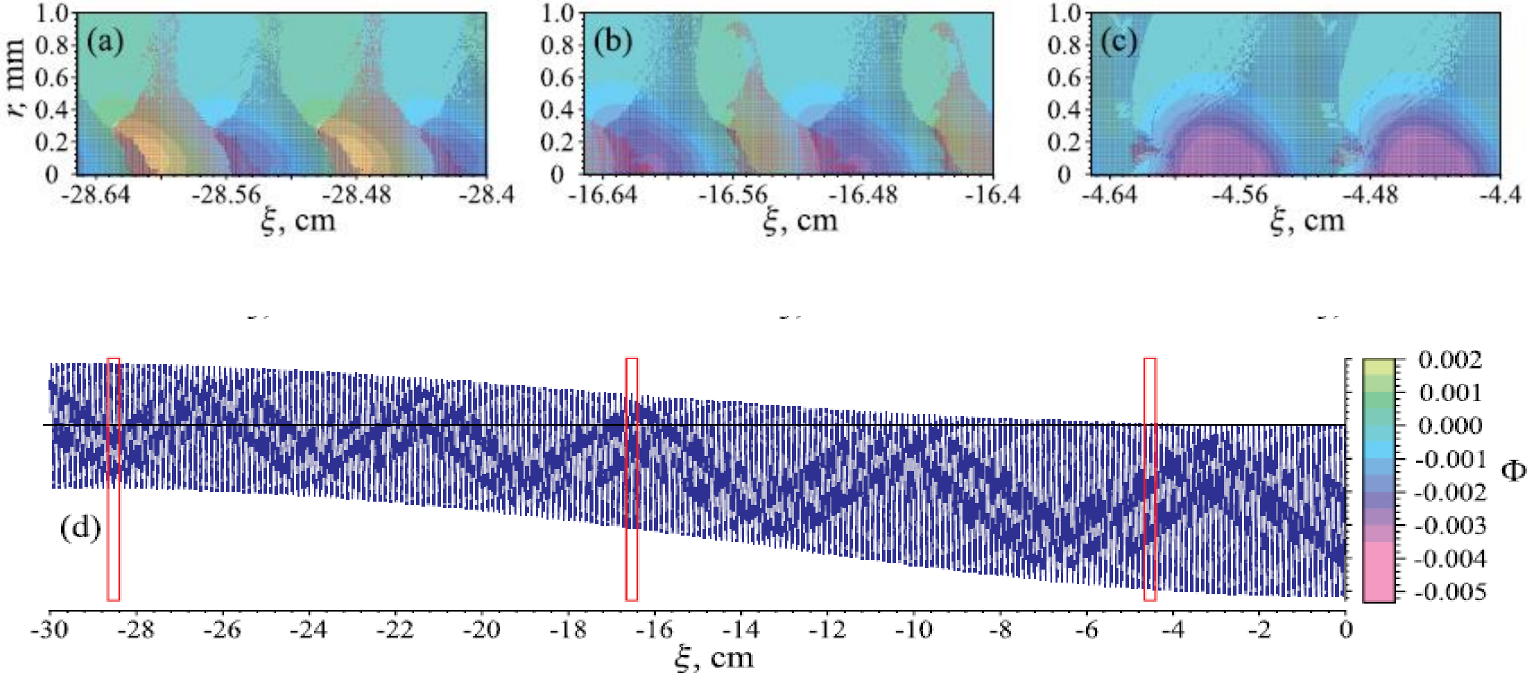
1- Adli, Erik, and Patric Muggli. "Proton-beam-driven plasma acceleration." *Reviews of Accelerator Science and Technology* 9 (2016): 85-104.

2-Lotov, K. V., A. P. Sosedkin, A. V. Petrenko, Lígia Diana Amorim, Jorge Vieira, R. A. Fonseca, L. O. Silva, E. Gschwendtner, and Patrick Muggli. "Electron trapping and acceleration by the plasma wakefield of a self-modulating proton beam." *Physics of Plasmas* 21, no. 12 (2014): 123116.

PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

1- On-axis electron injection

- (a)–(c)Acceptance of the plasma wave for positrons (blue dots) and electrons (red dots) plotted over the potential map at three locations along the proton bunch
- (d) the wake-field potential on the axis



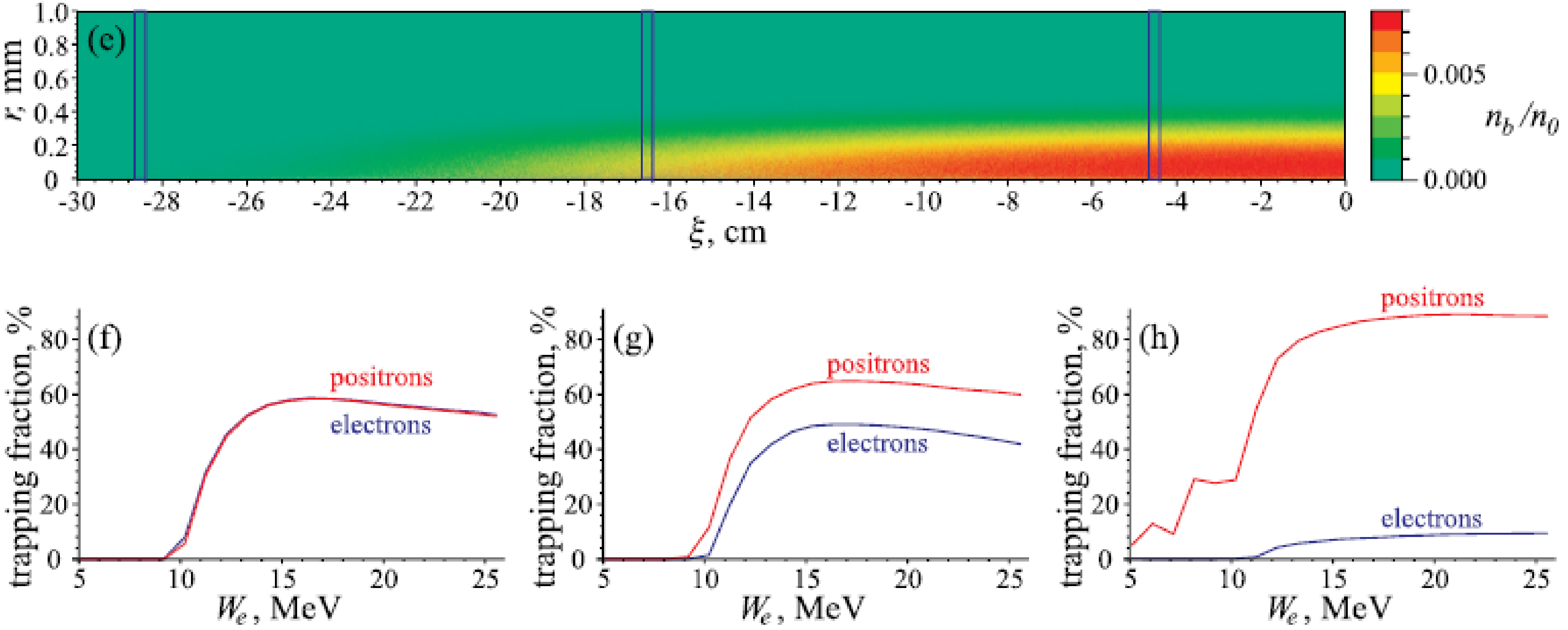
$$F_\perp(r,\xi) = 4\pi e^2 A_\perp n_{b0} r\left(e^{-\xi^2/(2\sigma_{zb}^2)} - \cos(k_p\xi)\right)$$

2-Lotov, K. V., A. P. Sosedkin, A. V. Petrenko, Lígia Diana Amorim, Jorge Vieira, R. A. Fonseca, L. O. Silva, E. Gschwendtner, and Patrick Muggli. "Electron trapping and acceleration by the plasma wakefield of a self-modulating proton beam." *Physics of Plasmas* 21, no. 12 (2014): 123116.

PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

1- On-axis electron injection

(e) the corresponding map of the proton beam density; (f)-(h) dependence of the trapping fraction on the electron or positron beam energy for the selected locations. The beams propagate to the right.



Simulations are made with the fluid code LCODE.

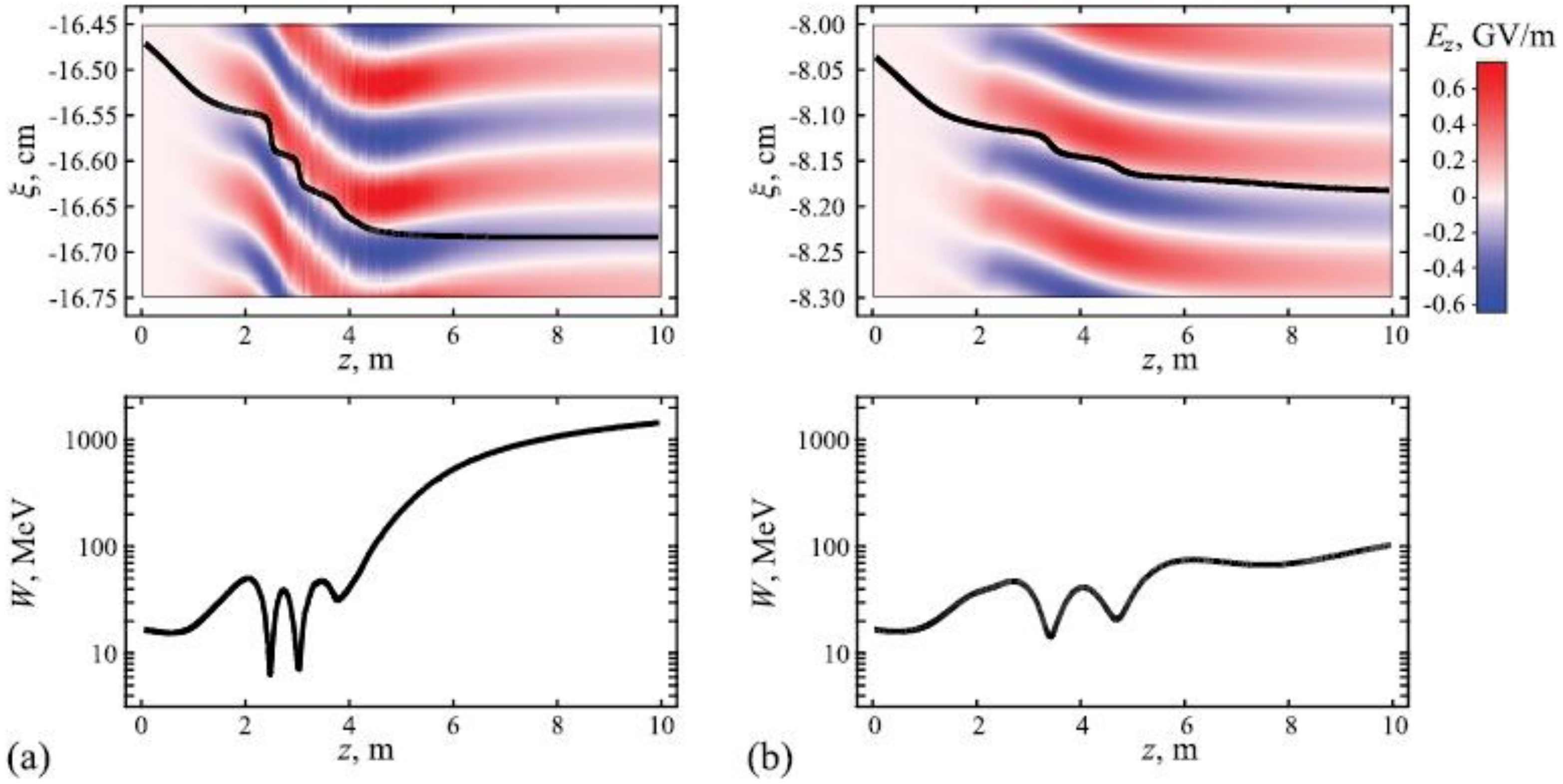
2-Lotov, K. V., A. P. Sosedkin, A. V. Petrenko, Lígia Diana Amorim, Jorge Vieira, R. A. Fonseca, L. O. Silva, E. Gschwendtner, and Patrick Muggli. "Electron trapping and acceleration by the plasma wakefield of a self-modulating proton beam." *Physics of Plasmas* 21, no. 12 (2014): 123116.

PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

1- On-axis electron injection

✓ acceleration

The co-moving coordinate n (top) and the energy (bottom) versus the propagation distance for two typical test electrons injected with different delays with respect to the laser pulse. The top plots also show the color map of the on-axis electric field E_z in the vicinity of the electron.



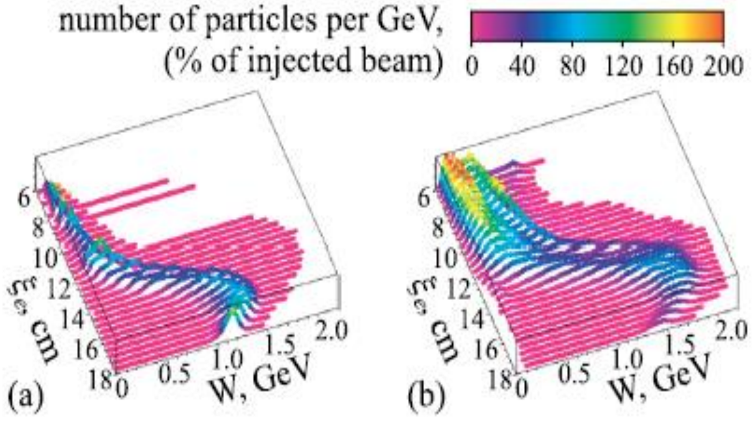
2-Lotov, K. V., A. P. Sosedkin, A. V. Petrenko, Lígia Diana Amorim, Jorge Vieira, R. A. Fonseca, L. O. Silva, E. Gschwendtner, and Patrick Muggli. "Electron trapping and acceleration by the plasma wakefield of a self-modulating proton beam." *Physics of Plasmas* 21, no. 12 (2014): 123116.

PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

1- On-axis electron injection

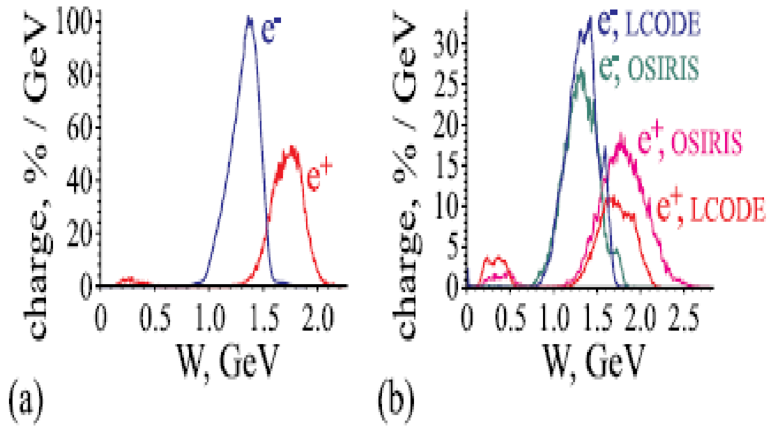
✓ acceleration

- Different εe



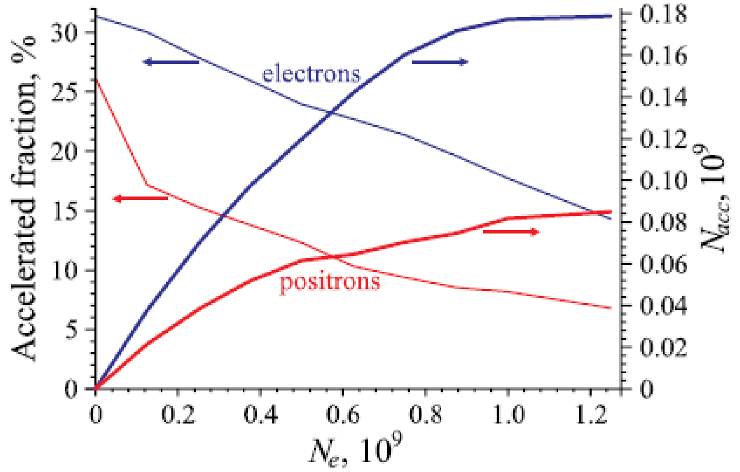
Final energy spectra for (a) electrons and (b) positrons as a function of injection delay ne with no beam loading effect taken into account

- εe= 16cm and beam loading effect



Final energy spectra of electron and positron bunches injected at the nominal delay Ɛe=16.4 cm without (a) and with (b) beam loading.

- Different number of injected particles



Fraction of accelerated and total number of accelerated particles N_{acc} (thick lines, right scale) versus the number of injected particles N_e for electron and positron beams.

2-Lotov, K. V., A. P. Sosedkin, A. V. Petrenko, Lígia Diana Amorim, Jorge Vieira, R. A. Fonseca, L. O. Silva, E. Gschwendtner, and Patrick Muggli. "Electron trapping and acceleration by the plasma wakefield of a self-modulating proton beam." *Physics of Plasmas* 21, no. 12 (2014): 123116.

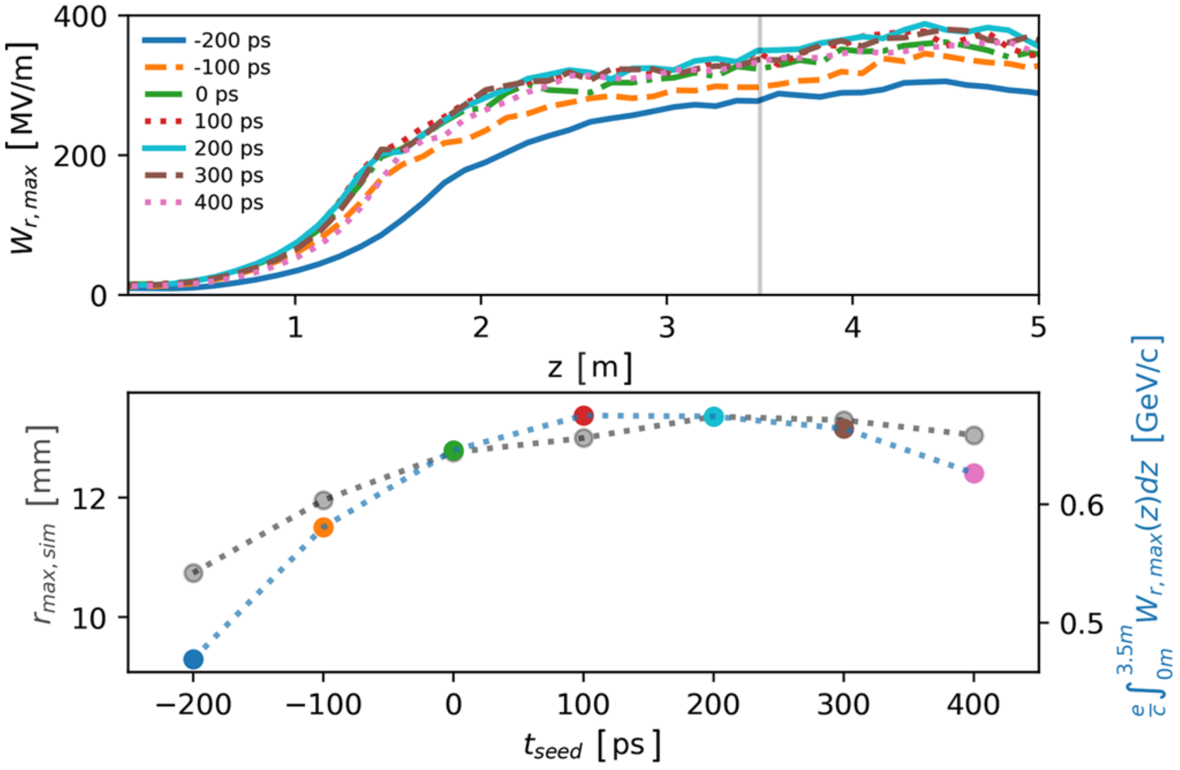
PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

1- On-axis electron injection

✓ Seeding time

- Top: maximum amplitude of the simulated transverse wake-fields W_r over the first 5 m of plasma for different seed timings t_{seed}.

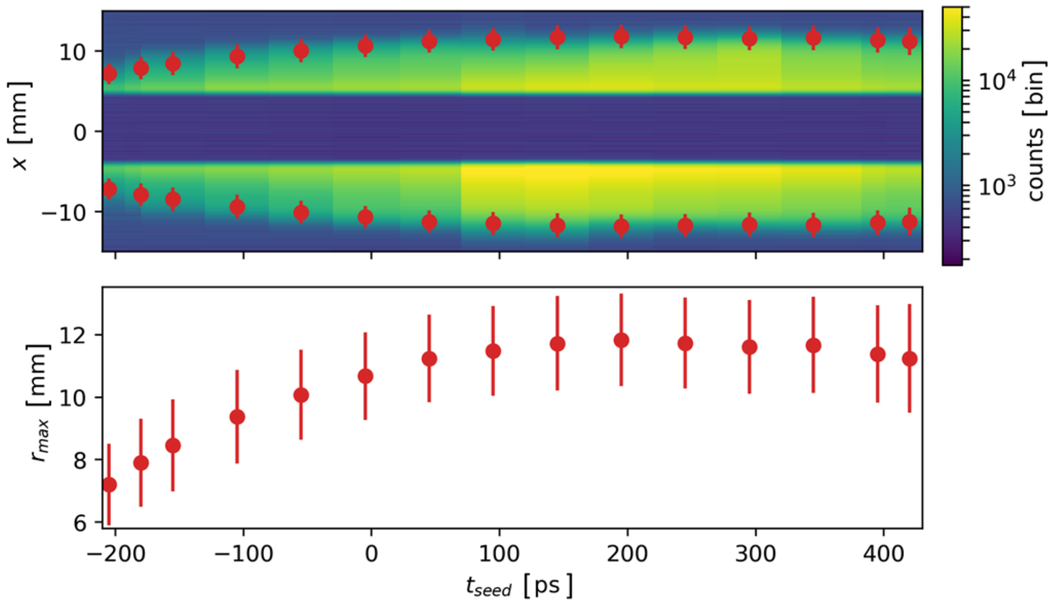
- Bottom: integral of the wake-fields over the first 3.5 m (symbols with same color as the corresponding line of the top graph, connected by the blue dotted line, right axis) and maximum radius of the simulated proton bunch transverse distribution $r_{max;sim}$



3-Turner, M., P. Muggli, E. Adli, R. Agnello, M. Aladi, Y. Andrebe, O. Apsimon et al. "Experimental study of wakefields driven by a self-modulating proton bunch in plasma." *Physical Review Accelerators and Beams* 23, no. 8 (2020): 081302.

PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

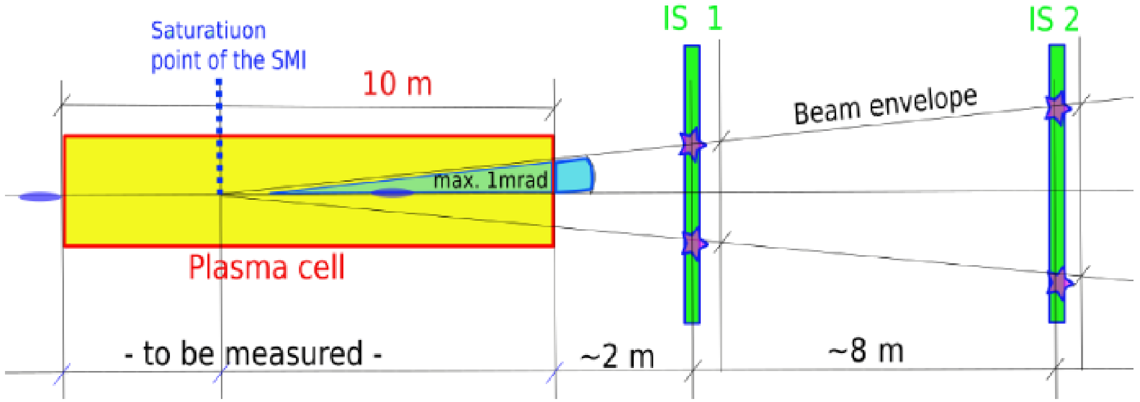
1- On-axis electron injection



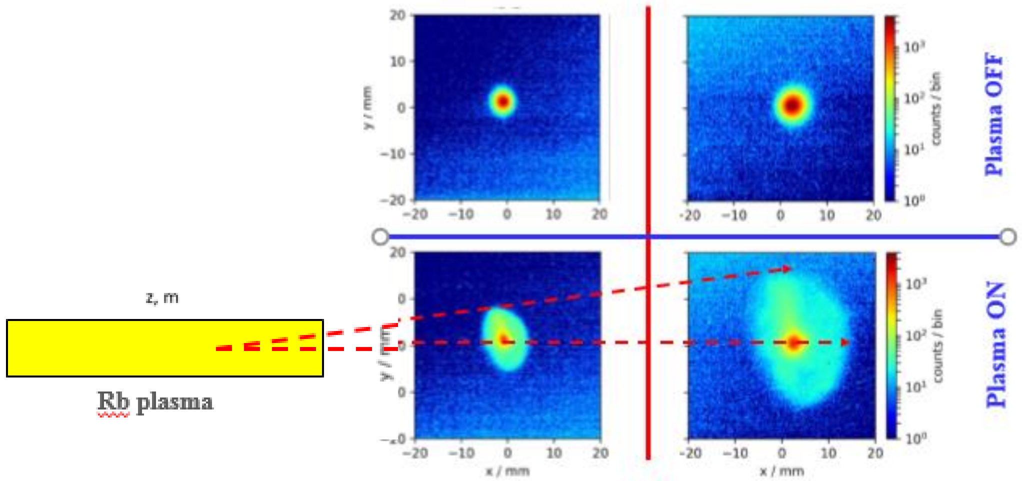
summed waterfall plot of the horizontal line-outs of the measured self-modulated proton bunch transverse distribution as a function of t_{seed}.

3-Turner, M., P. Muggli, E. Adli, R. Agnello, M. Aladi, Y. Andrebe, O. Apsimon et al. "Experimental study of wakefields driven by a self-modulating proton bunch in plasma." *Physical Review Accelerators and Beams* 23, no. 8 (2020): 081302.

- Two-screen diagnostic tool



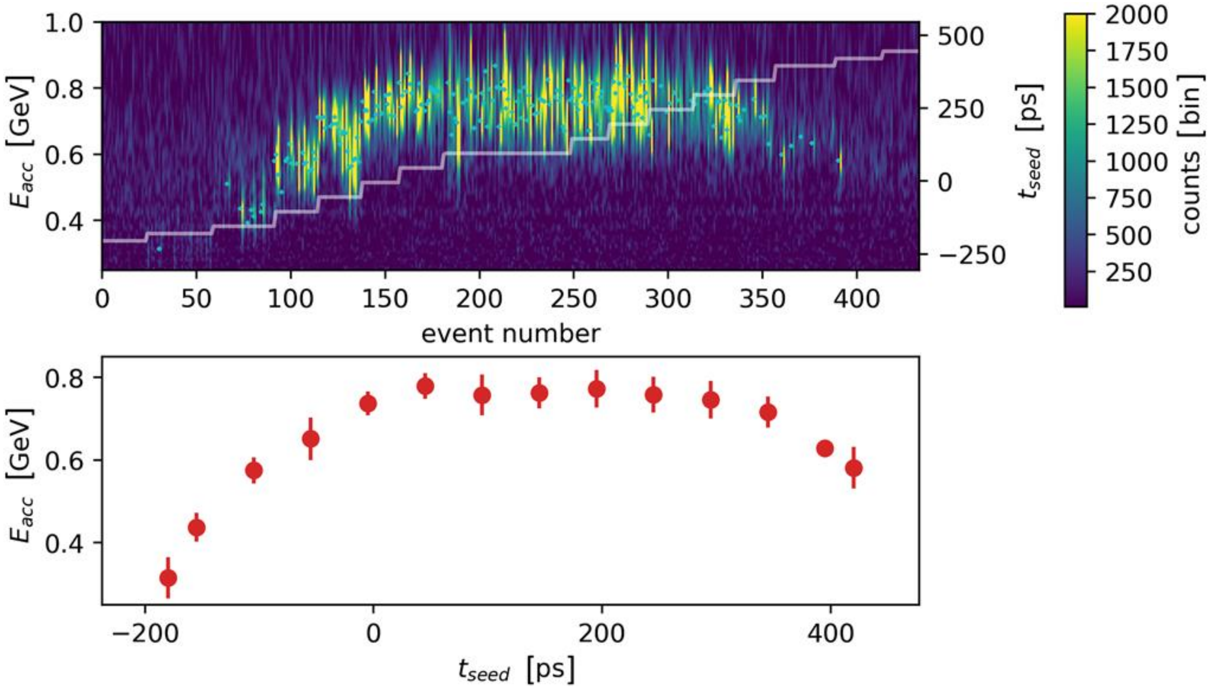
Schematic drawing of the principle behind the two screen measurement setup.



4-Turner, Marlene, Vincent Clerc, Ishkhan Gorgisyan, Edda Gschwendtner, Stefano Mazzoni, and Alexey Petrenko. "Upgrade of the two-screen measurement setup in the AWAKE experiment." In *Journal of Physics: Conference Series*, vol. 874, no. 1, p. 012031. IOP Publishing, 2017.

PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

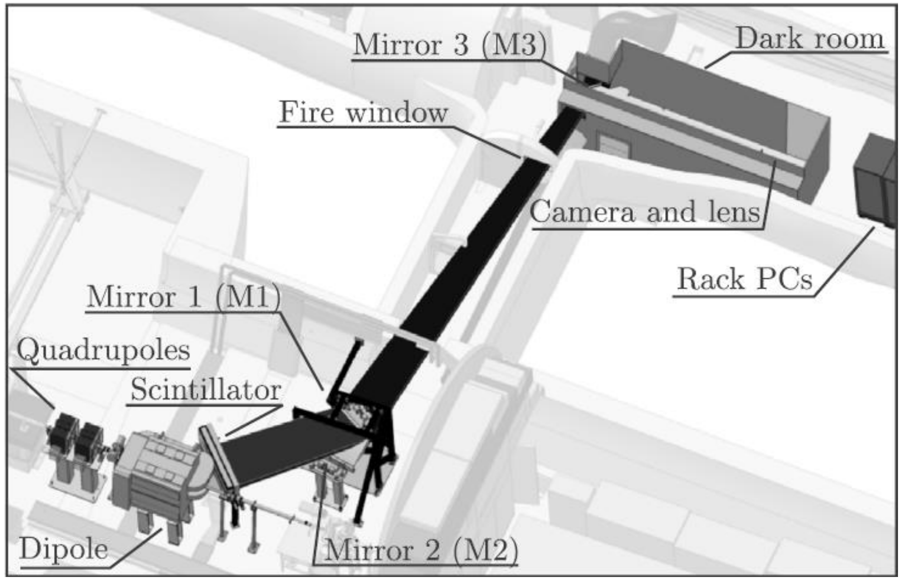
1- On-axis electron injection



Top: waterfall plot of the measured electron energy spectra (right axis) during the seed scan. The value of t_{seed} is shown by the white line and the vertical axis on the right. Bottom: energy of the charge peak of the accelerated electrons as a function of seed timing.

3-Turner, M., P. Muggli, E. Adli, R. Agnello, M. Aladi, Y. Andrebe, O. Apsimon et al. "Experimental study of wakefields driven by a self-modulating proton bunch in plasma." *Physical Review Accelerators and Beams* 23, no. 8 (2020): 081302.

- Imaging magnetic spectrometer

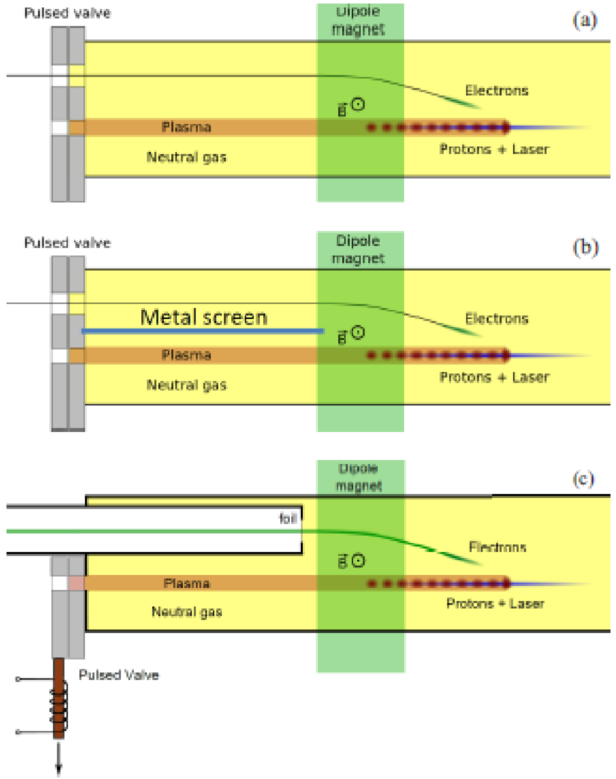


The electron spectrometer at AWAKE

4-Bauche, J., B. Biskup, M. Cascella, J. Chappell, N. Chritin, D. Cooke, L. Deacon et al. "A magnetic spectrometer to measure electron bunches accelerated at AWAKE." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 940 (2019): 103-108.

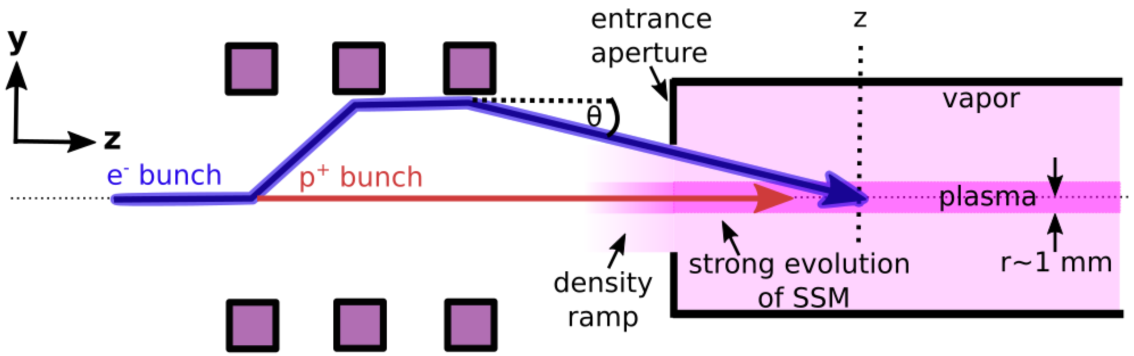
PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

✓ **Side electron injection**



Various designs of electron beam side injection

5- Caldwell, Allen, Erik Adli, L. Amorim, Robert Apsimon, Theodoros Argyropoulos, Ralph Assmann, A-M. Bachmann et al. "Path to AWAKE: Evolution of the concept." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 829 (2016): 3-16.

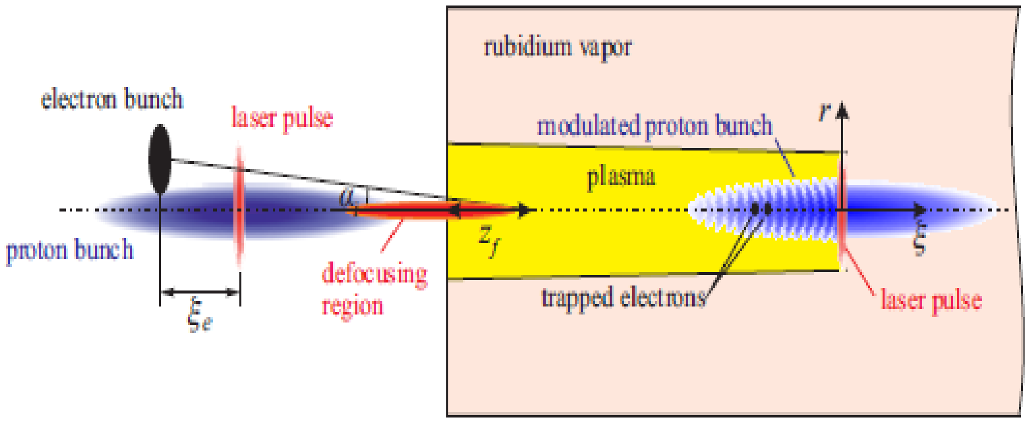


Schematic drawing of the electron injection scheme in the vertical plane (only corrector magnets are shown, see Fig. I). The proton bunch propagates along the horizontal axis (horizontal black dotted line).

6-Turner, Marlene, Chiara Bracco, Spencer Gessner, Brennan Goddard, Edda Gschwendtner, Patrie Muggli, Felipe Pefia Asmus, Francesco Velotti, and Livio Verra. "External electron injection for the AWAKE experiment." In *2018 IEEE Advanced Accelerator Concepts Workshop (AAC)*, pp. 1-4. IEEE, 2018.

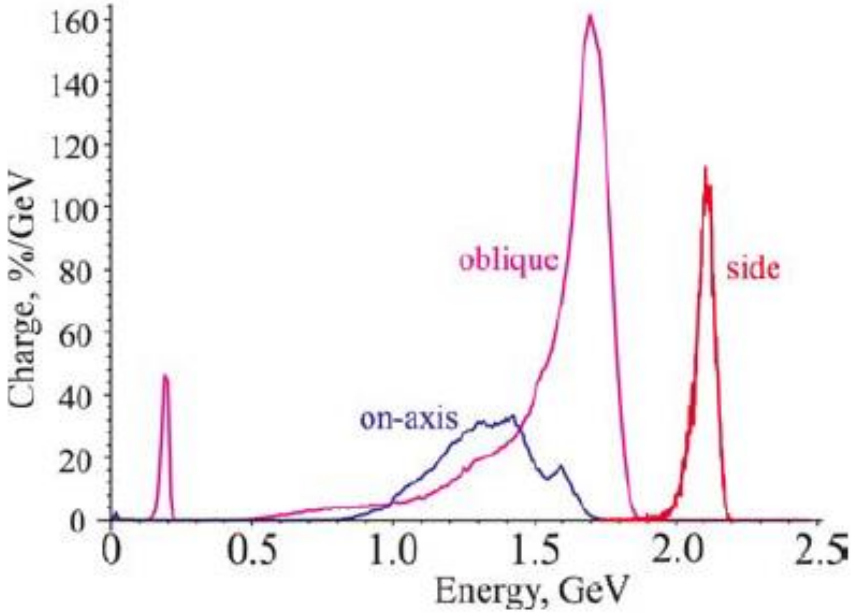
PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

✓ **Oblique electron injection**



The optimum values found in simulations are: electron delay ε_e = 11.5 cm, injection angle α = 2.8 mrad, and focusing point z_f = 140 cm.

5- Caldwell, Allen, Erik Adli, L. Amorim, Robert Apsimon, Theodoros Argyropoulos, Ralph Assmann, A-M. Bachmann et al. "Path to AWAKE: Evolution of the concept." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 829 (2016): 3-16.



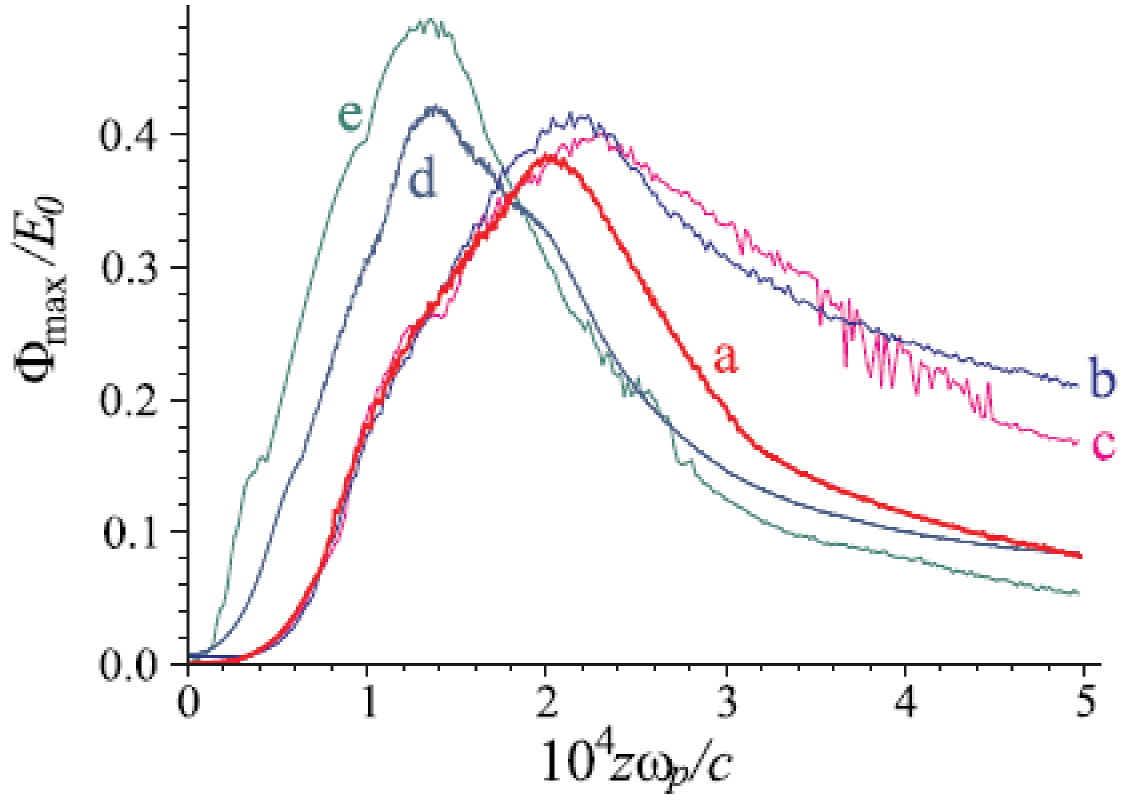
✓ The final simulated energy spectra of electrons in cases of the side, on-axis and oblique injection methods.

1- Adli, Erik, and Patric Muggli. "Proton-beam-driven plasma acceleration." *Reviews of Accelerator Science and Technology* 9 (2016): 85-104.

PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

✓ **Excitation of two-dimensional plasma wake-fields by trains of equidistant particle bunches**

a = corresponds to the baseline variant of AWAKE experiment at CERN
b = the opposite charge beam (antiprotons)
C = differs from the baseline case "a" by 10 times smaller beam emittance
d = corresponds to the longitudinally compressed beam with 4 times higher peak density.
e = compressed the baseline beam 4 times longitudinally and 4 times radially



7- Lotov, K. V. "Excitation of two-dimensional plasma wakefields by trains of equidistant particle bunches." *Physics of Plasmas* 20, no. 8 (2013): 083119.

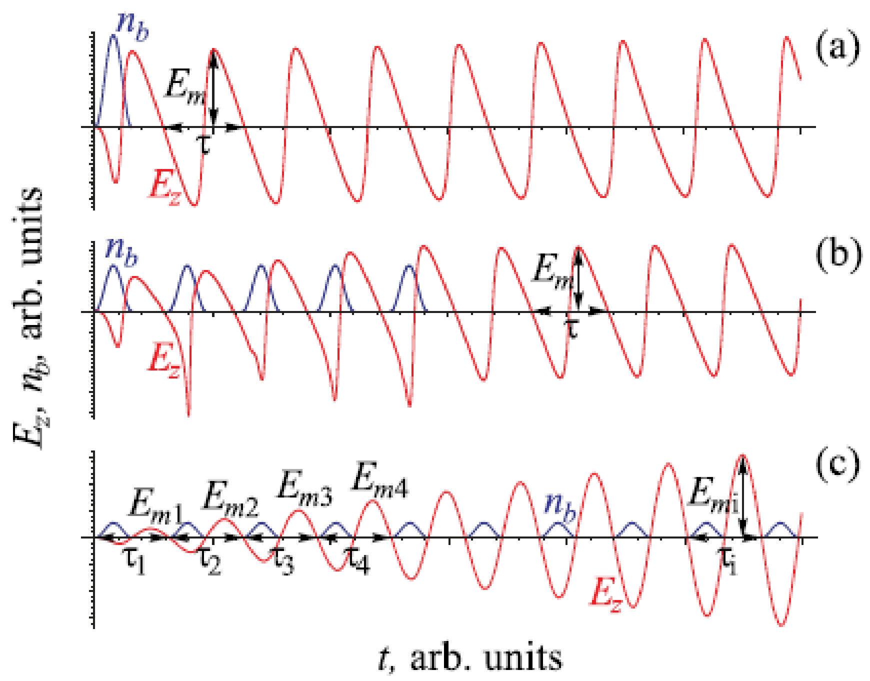
PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

✓ **Excitation of two-dimensional plasma wake-fields by trains of equidistant particle bunches**

TABLE I. Simulated modes of wakefield excitation.

No.	Driver
1	Single bunch, p^+, variable charge, $\sigma_r = 15\, c/\omega_p$
2	Single bunch, p^+, variable charge, $\sigma_r = 3\, c/\omega_p$
3	Single bunch, p^+, variable charge, $\sigma_r = c/\omega_p$
4	Train of 5 bunches, p^+, variable charge, $\sigma_r = c/\omega_p$
5	Train of 5 bunches, p^-, variable charge, $\sigma_r = c/\omega_p$
6	Train of 5 bunches, p^+, variable charge, $\sigma_r = 0.3\, c/\omega_p$
7	Train of 5 bunches, p^-, variable charge, $\sigma_r = 0.3\, c/\omega_p$
8	Infinite train, p^+, variable location, $\sigma_r = c/\omega_p$
9	Infinite train, p^-, variable location, $\sigma_r = c/\omega_p$
A	Theory of one-dimensional wave
B	Empirical approximation for the free wave
C	Empirical approximation for the driven wave

$$n_b(r,z,t) = 0.5\, n_{bm}\, e^{-r^2/2\sigma_r^2}[1 - \cos(2\omega_p(t - z/c))],$$
$$i\tau_0 < t - z/c < (i + 1/2)\tau_0, \quad i = 0, 1, \ldots;$$
$$n_b(r,z,t) = 0, \quad \text{otherwise},$$

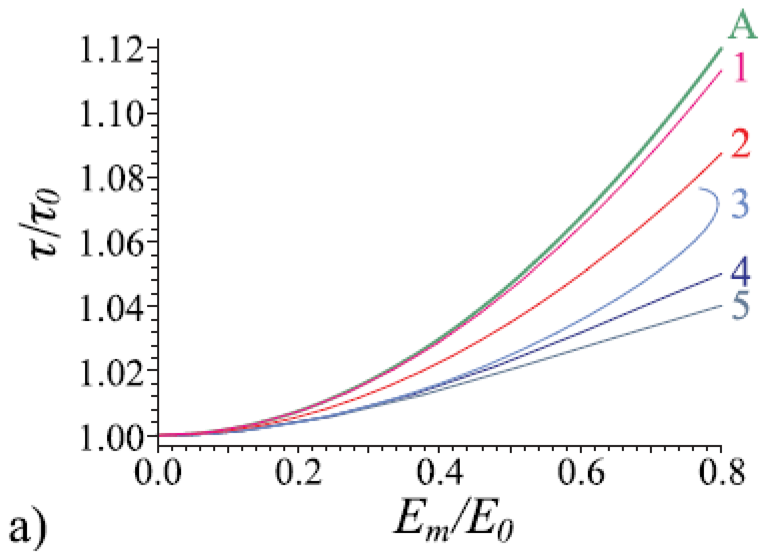


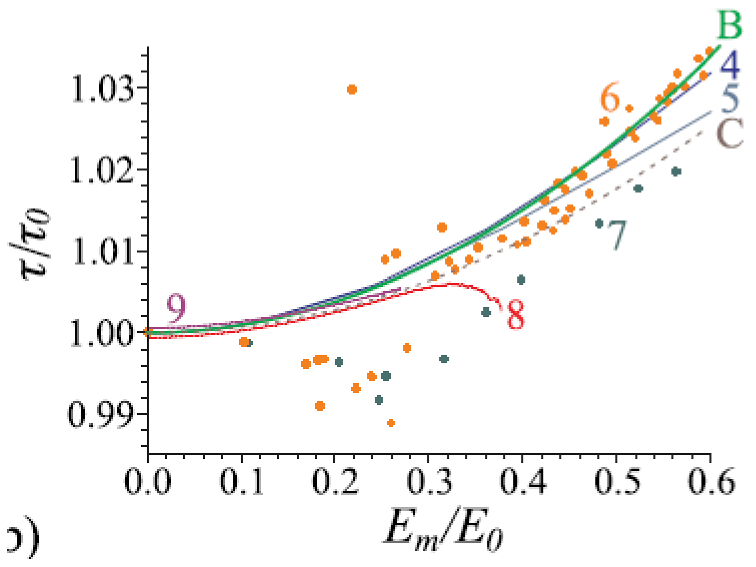
Location of the measured wave periods for the single bunch of variable charge (a), the train of 5 bunches (b), and the infinite bunch train (c).

7- Lotov, K. V. "Excitation of two-dimensional plasma wakefields by trains of equidistant particle bunches." *Physics of Plasmas* 20, no. 8 (2013): 083119.

PROTON-BEAM-DRIVEN-PLASMA ACCELERATOR

✓ **Excitation of two-dimensional plasma wake-fields by trains of equidistant particle bunches**





Dependence of the wake-field period on the wave amplitude for various drivers.

7- Lotov, K. V. "Excitation of two-dimensional plasma wakefields by trains of equidistant particle bunches." *Physics of Plasmas* 20, no. 8 (2013): 083119.