2nd European Advanced Accelerator Concepts Workshop

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Electron acceleration behind self-modulating proton beam in plasma with a density gradient

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Outline

- AWAKE experiment
- Motivation
- Baseline parameters
- Longitudinal motion of electrons
- Effect of plasma density gradient
- Summary

What is the AWAKE experiment?

- AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - Use SPS proton beam as drive beam (Single bunch 3e11 protons at 400 GeV)
  - Inject electron beam as witness beam
- Proof-of-Principle Accelerator R&D experiment at CERN
  - First proton driven plasma wakefield experiment worldwide
  - First beam expected in 2016
- AWAKE Collaboration: 14 Institutes world-wide:

Motivation

- Accelerating field of today's RF cavities is **limited to <100 MV/m**
  - Several tens of kilometers for future linear colliders

- Plasma can sustain up to **three orders of magnitude higher gradient**
  - SLAC (2007): electron energy doubled from 42GeV to 85 GeV over 0.8 m → 52GV/m gradient
  - However to reach 1 TeV energy with 50 GeV drive beam will require 20 stages. Similar staging problem exists for laser-driven plasma wakefield accelerators.

Why protons?

- There are proton beams available at CERN with TeV scale energy per particle and huge total stored energy. For example:

LHC nominal beam parameters:
(2808 bunches)*(1.15e11 protons)*(7 TeV) = 360 MJ

Fully loaded A320 (80 t) at take-off speed (300 km/h) carries similar amount of kinetic energy (280 MJ).
(However the momentum of the airplane is ~ c/v ~ 10^6 times larger than the LHC beam momentum)

Single LHC proton bunch **(7 TeV, 1.2e11 protons)** carries **130 kJ**
Single SPS proton bunch **(0.4 TeV, 3e11 protons)** carries **19 kJ**
Single ILC electron bunch **(0.5 TeV, 2e10 e+/e-)** carries **1.6 kJ**

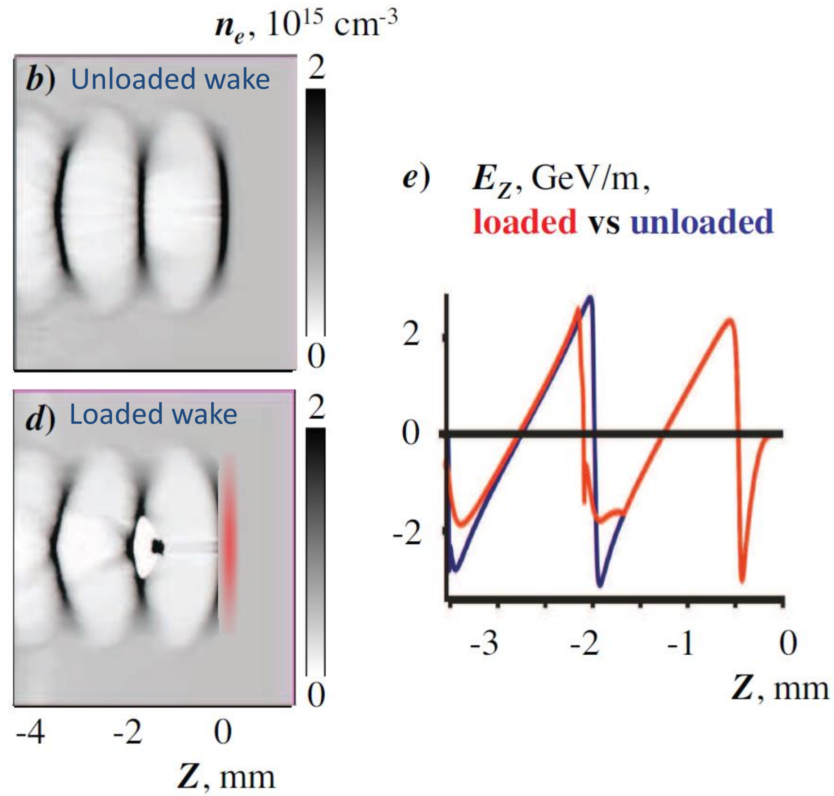
Using LHC beam as a driver it's possible to obtain TeV-level (e-/e+/muons) in a single stage!

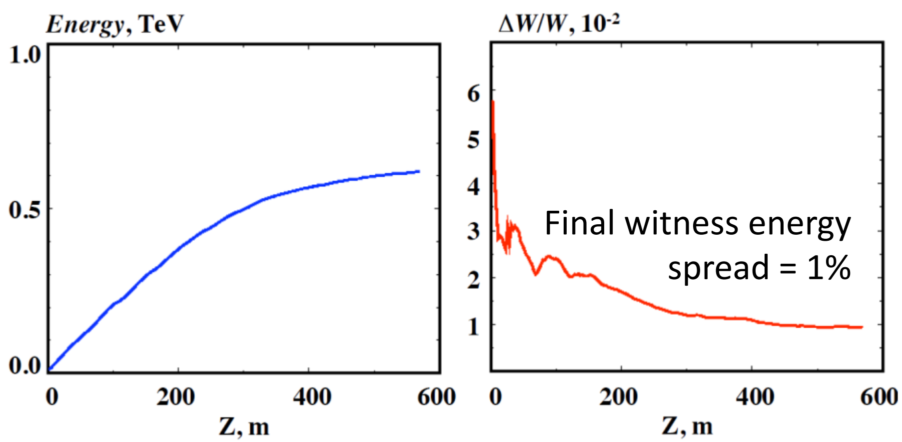
Motivation

A. Caldwell, K. Lotov, A. Pukhov, F. Simon, Nature Physics (2009):

Proton bunch driver: 1 TeV, σ_z **= 0.1 mm**

Witness bunch of $1.5 \cdot 10^{10}$ electrons

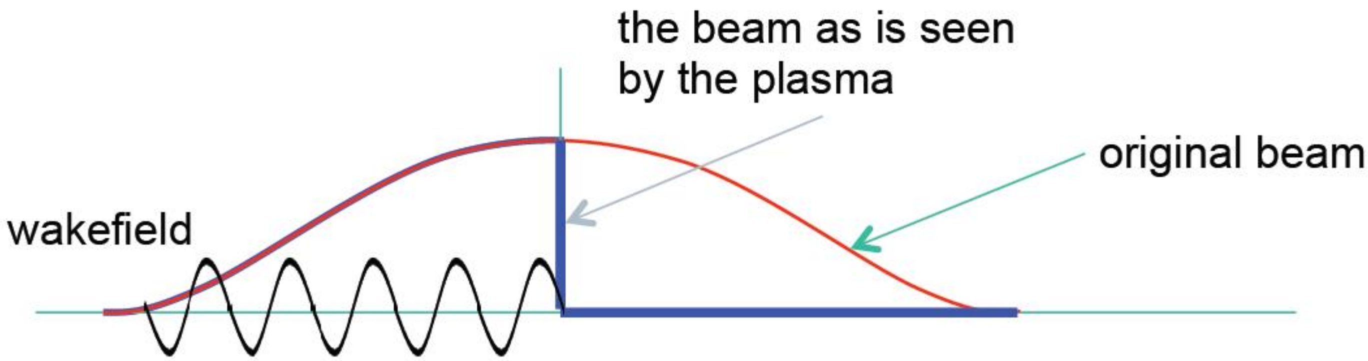


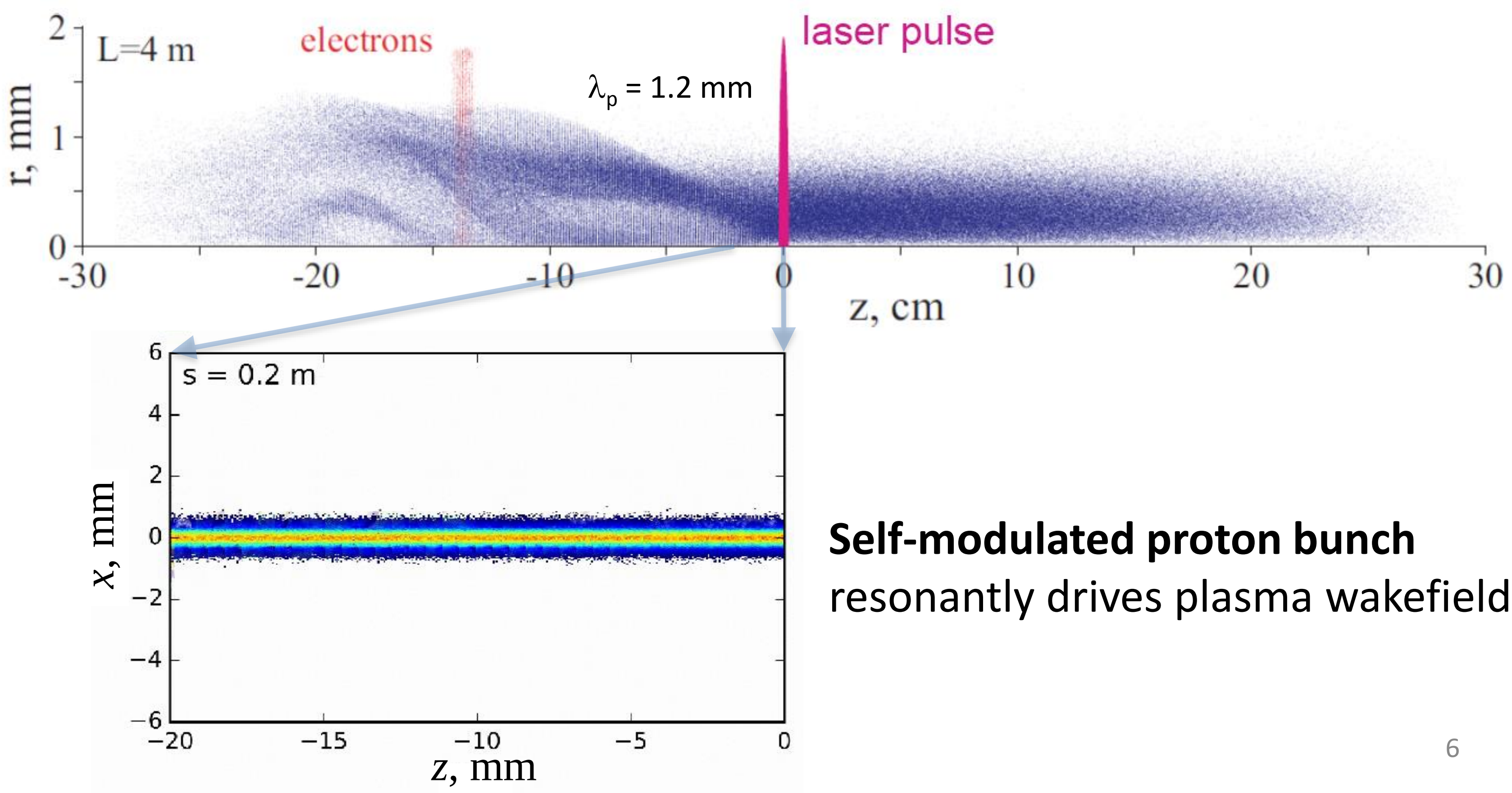


Unfortunately compressing **10 cm** long LHC bunch down to σ_z **= 0.1 mm** is very challenging and expensive (although technically possible).

Self-modulation of long proton bunch in plasma

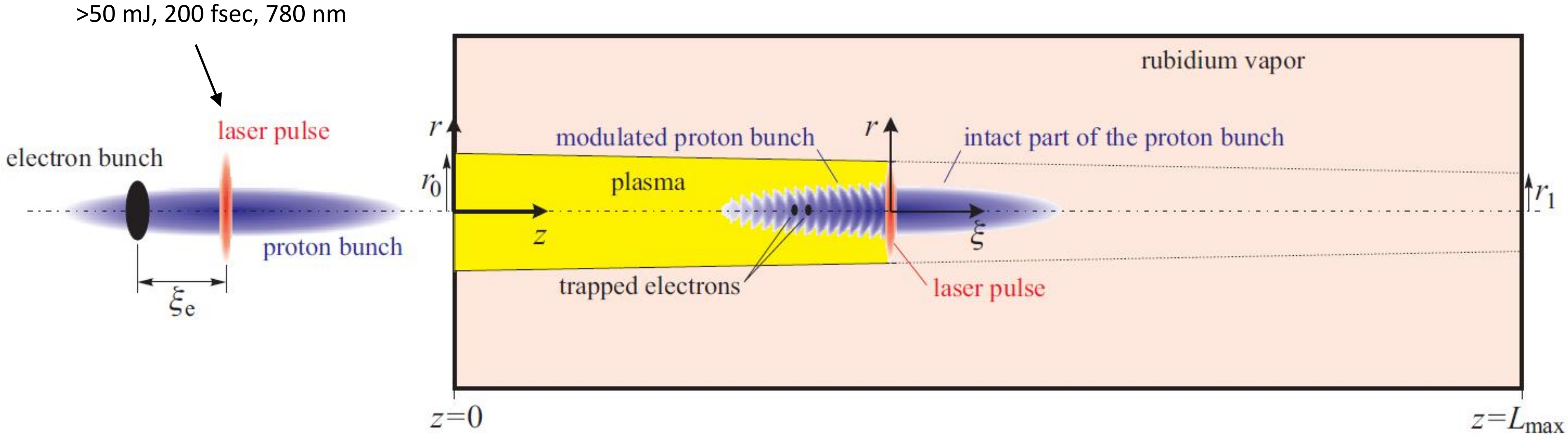
N. Kumar, A. Pukhov, K. Lotov, Phys. Rev. Letters (2010):





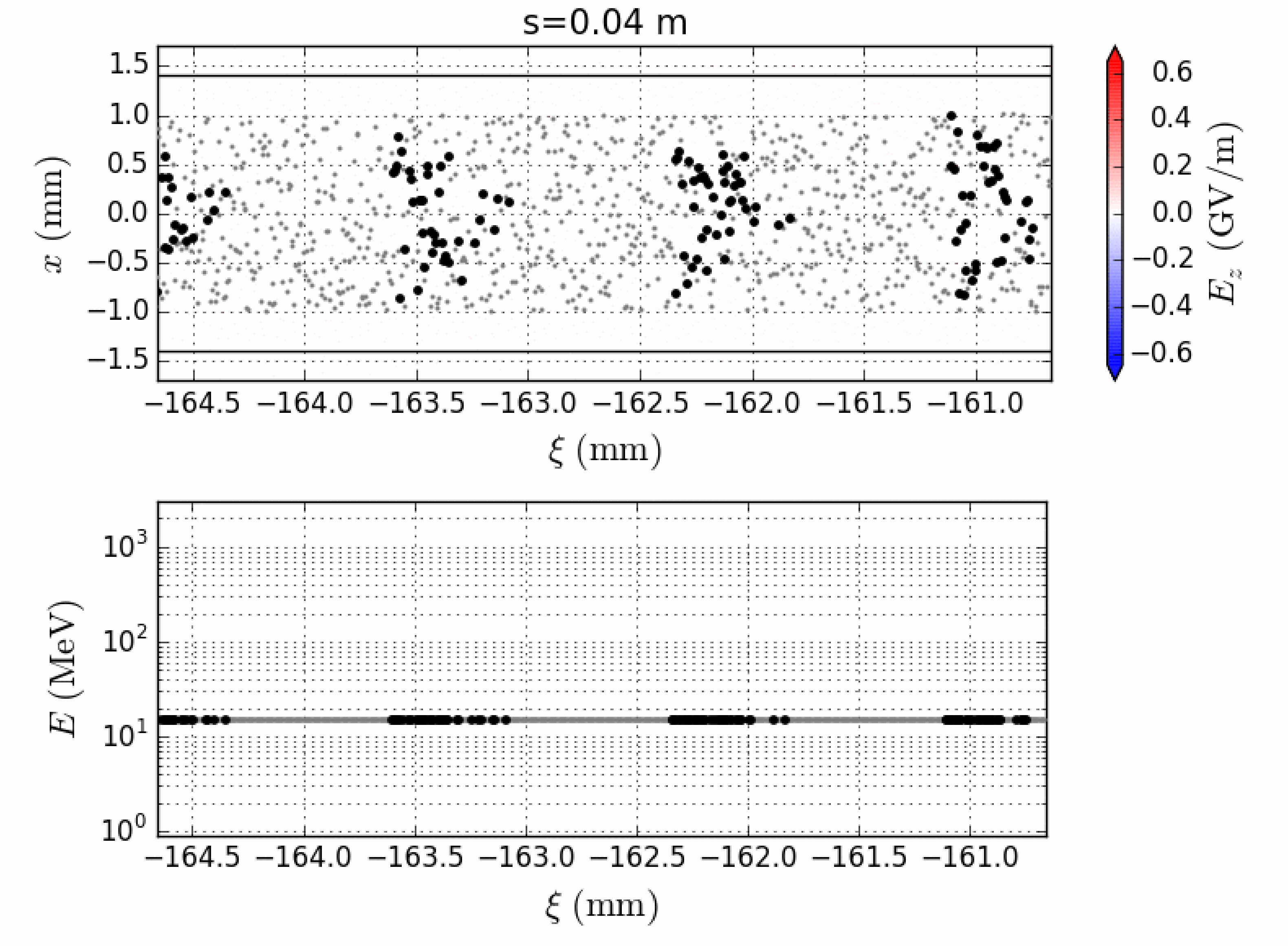
Self-modulated proton bunch resonantly drives plasma wakefields.

The AWAKE experiment configuration & baseline parameters:



Plasma density, n_0	$7 \times 10^{14}\,\text{cm}^{-3}$
Plasma length, $L_{\max}$	10 m
Atomic weight of plasma ions, M_i	85.5
Plasma skin depth, $c/\omega_p \equiv k_p^{-1}$,	0.2 mm
Initial plasma radius, r_0,	1.5 mm
Final plasma radius, r_1,	1 mm
Wavebreaking field, $E_0 = mc\omega_p/e$,	2.54 GV/m
Proton bunch population, N_b	3×10^{11}
Proton bunch length, σ_{zb}	12 cm
Proton bunch radius, σ_{rb}	0.2 mm
Proton bunch energy, W_b	400 GeV
Proton bunch energy spread, δW_b	0.35%
Proton bunch normalized emittance, ϵ_{nb}	3.6 mm mrad
Proton bunch maximum density, n_{b0}	$4 \times 10^{12}\,\text{cm}^{-3}$
Electron bunch population, N_e	1.25×10^9
Electron bunch length, σ_{ze}	1.2 mm
Electron bunch radius, σ_{re}	0.25 mm
Electron bunch energy, W_e	16 MeV
Electron bunch energy spread, δW_e	0.5%
Electron bunch normalized emittance, ϵ_{ne}	2 mm mrad
Electron bunch delay, ξ_e	16.4 cm

On-axis injection: LCODE simulation of electron trapping and acceleration



- Electrons are trapped from the very beginning by the wakefield of seed perturbation
- Trapped electrons make several synchrotron oscillations in their potential wells
- After z=4 m the wakefield moves forward faster than the speed of light

Electron trajectory in the longitudinal electric field (uniform plasma density):

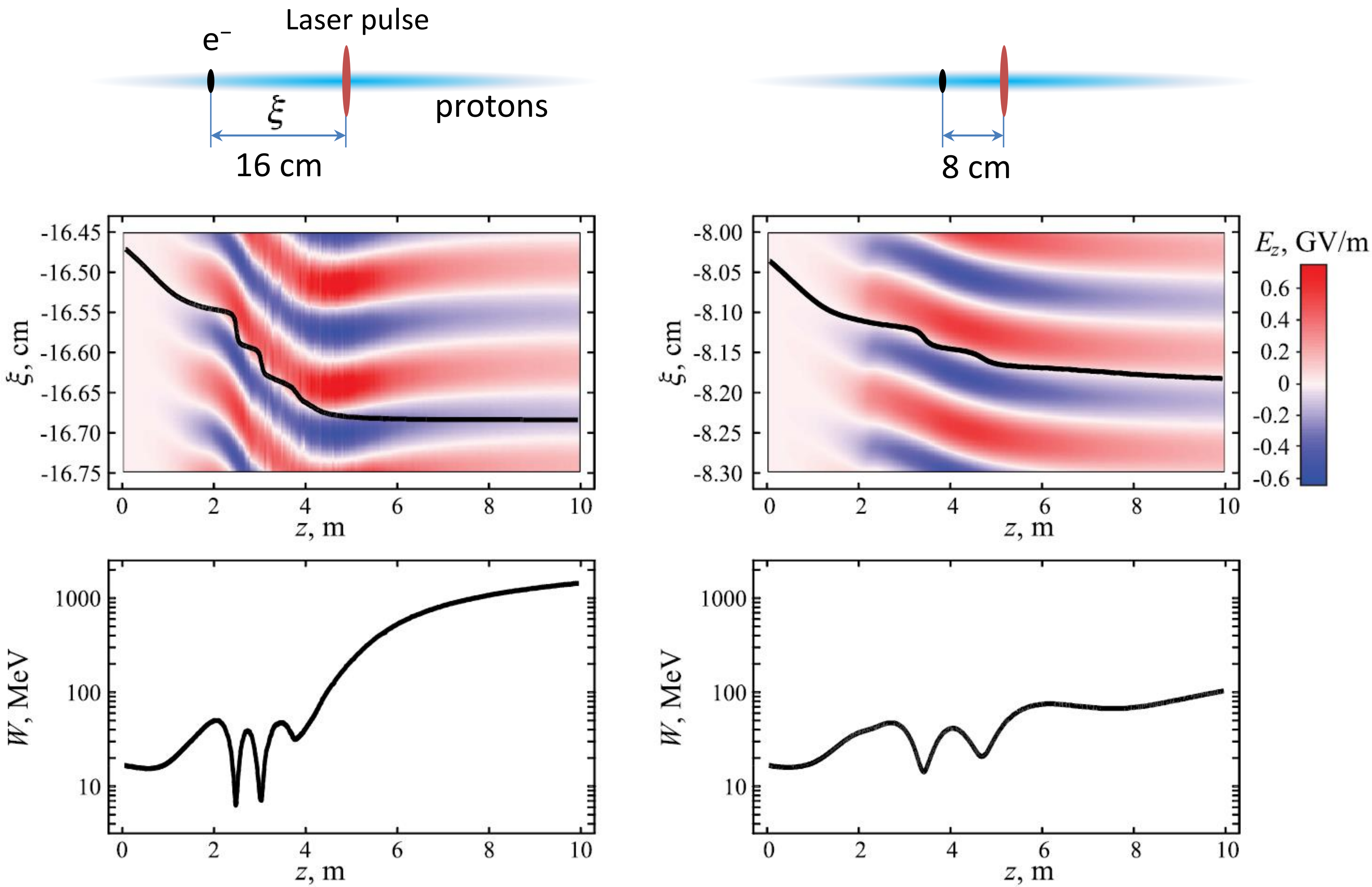
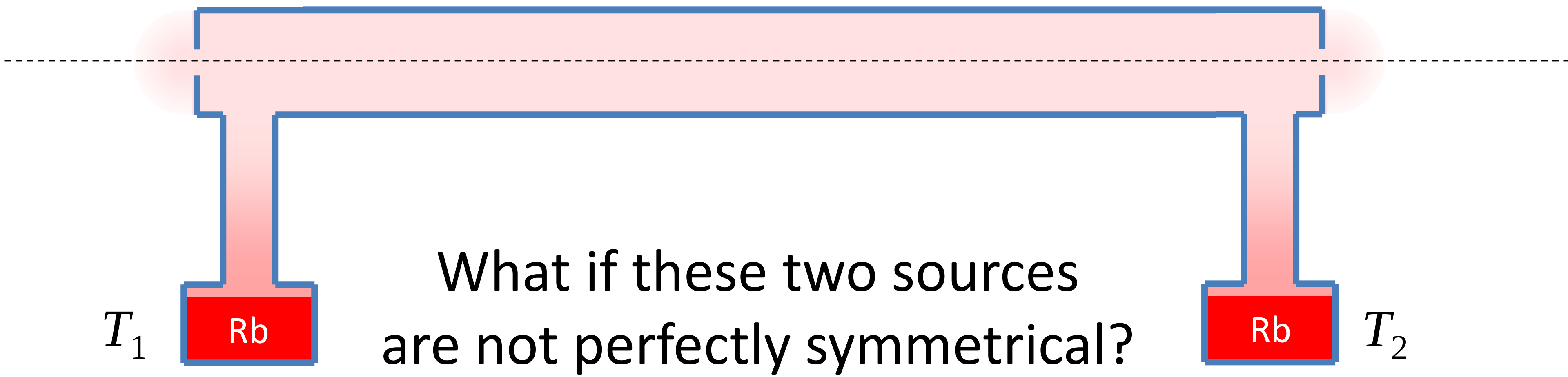


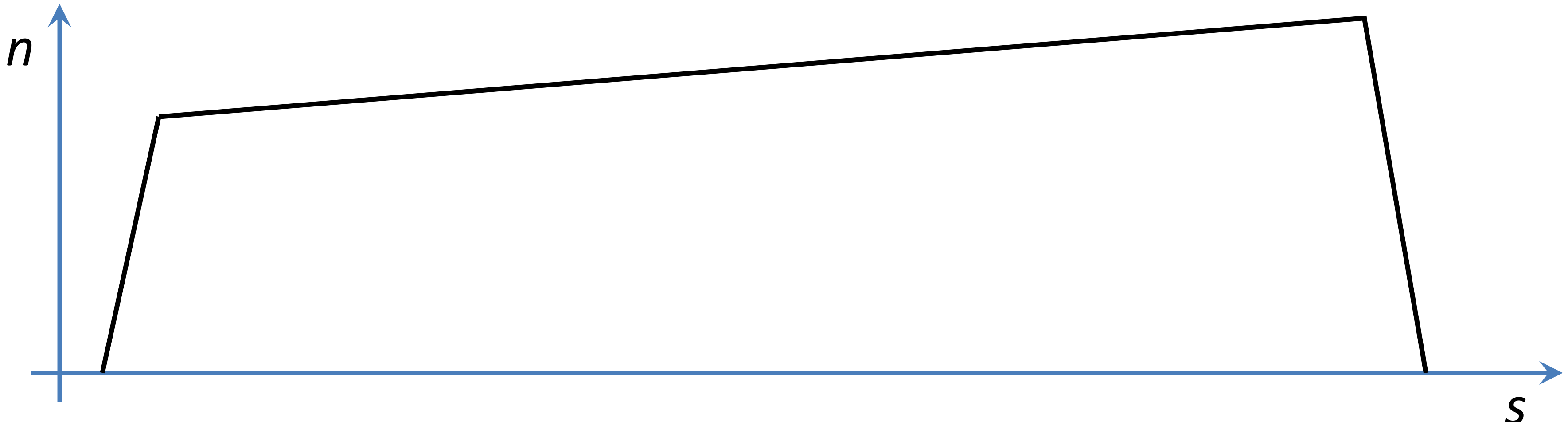
FIG. 3. The co-moving coordinate ξ (top) and the energy (bottom) versus the propagation distance for two typical test electrons injected with different delays with respect to the laser pulse. The top plots also show the color map of the on-axis electric field E_z in the vicinity of the electron.

See [K. V. Lotov et al. Phys. Plasmas 21, 123116 (2014)]

Rubidium vapor source with continuous flow:

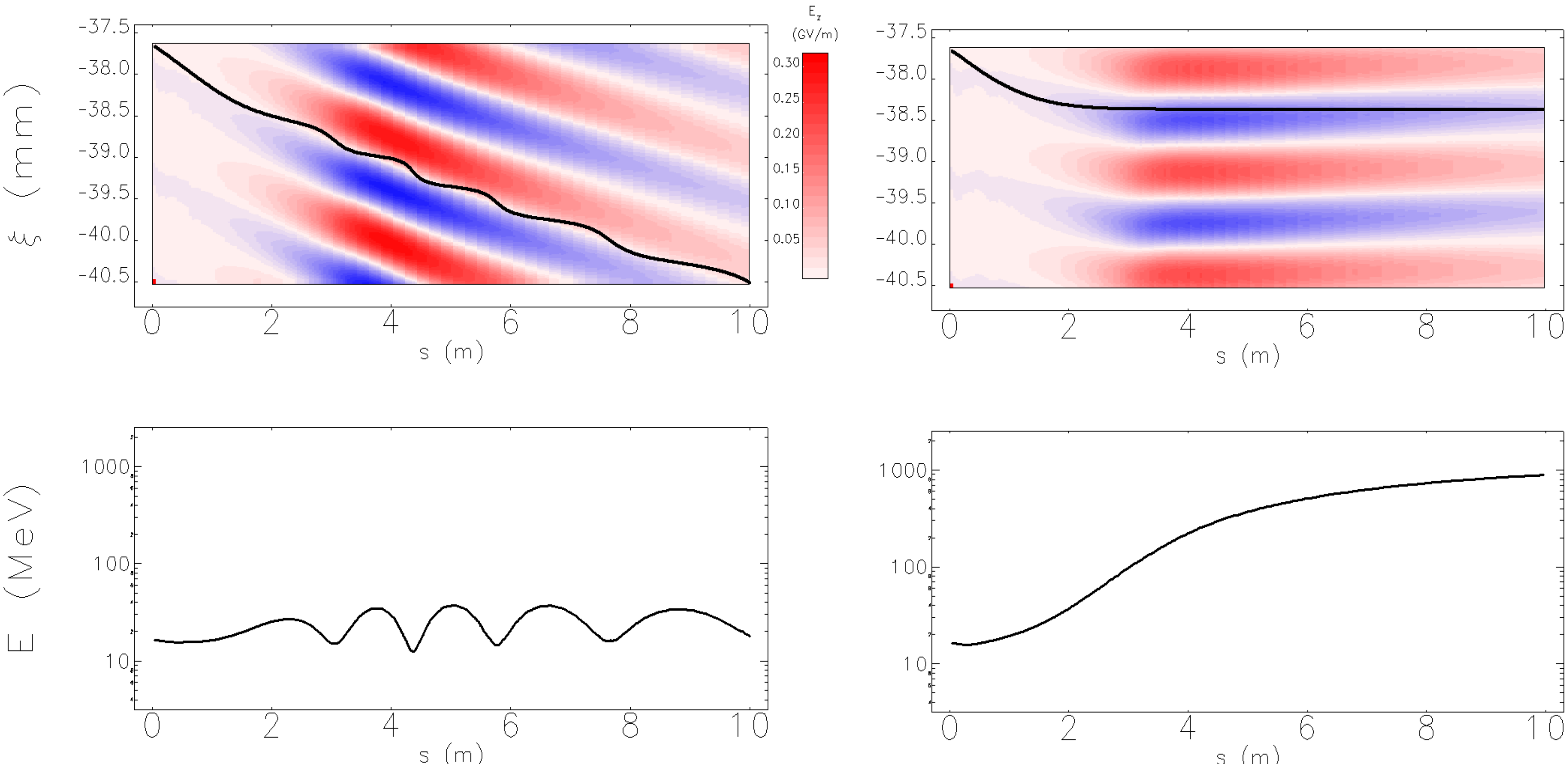


What if these two sources
are not perfectly symmetrical?

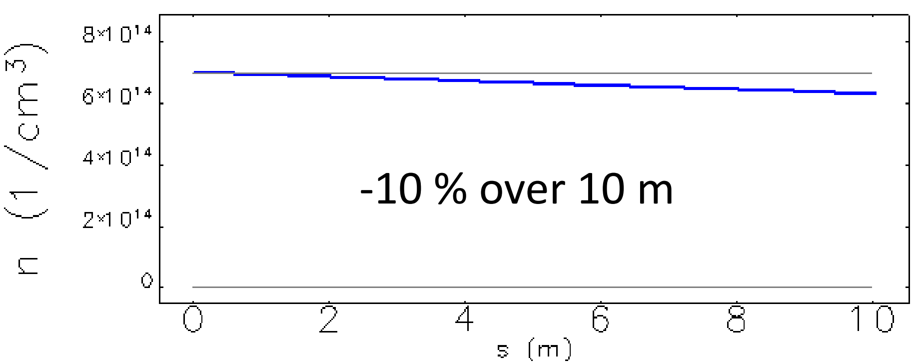


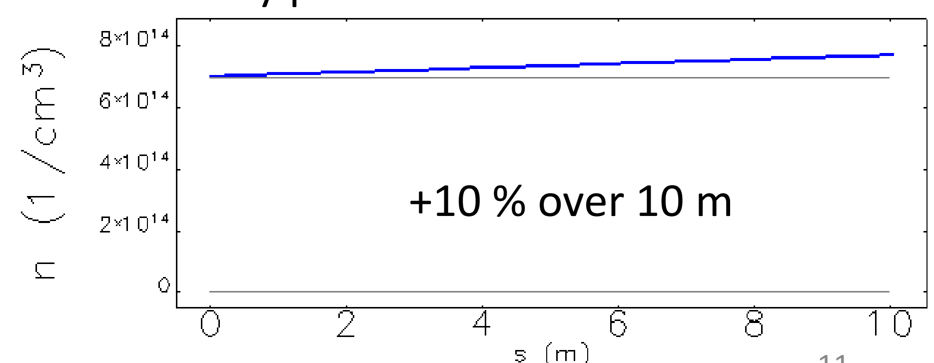
How sensitive is the acceleration to such plasma
density gradient over the whole system?

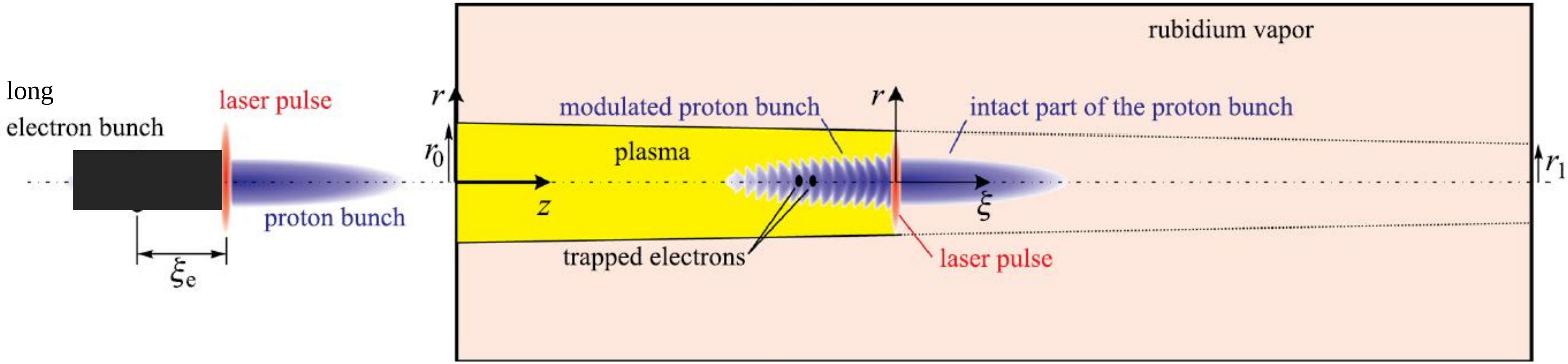
Electron trajectory in the longitudinal electric field (10% gradient case):

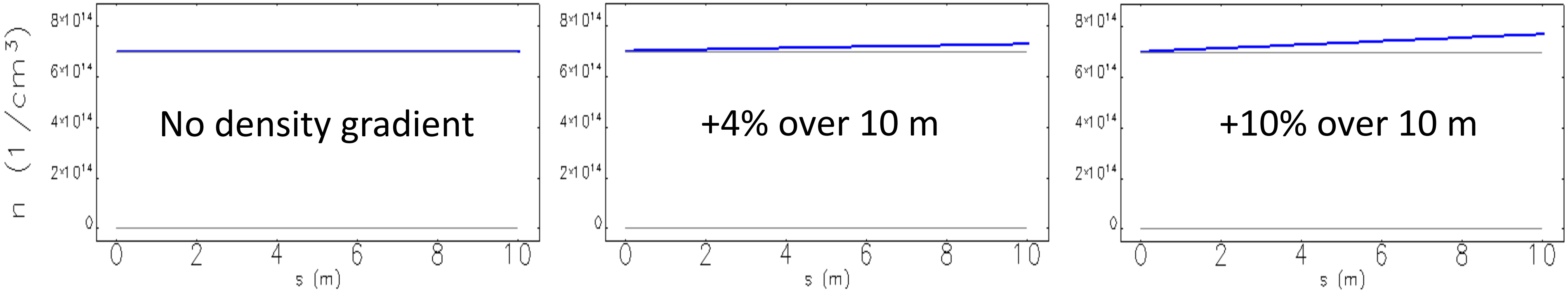


Longitudinal plasma density profile:

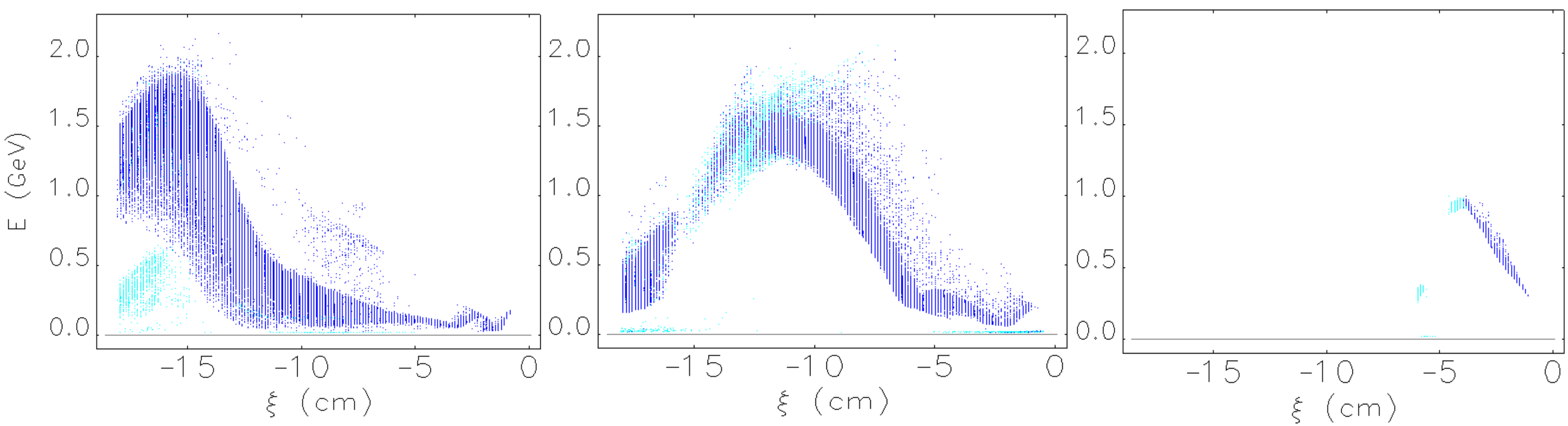


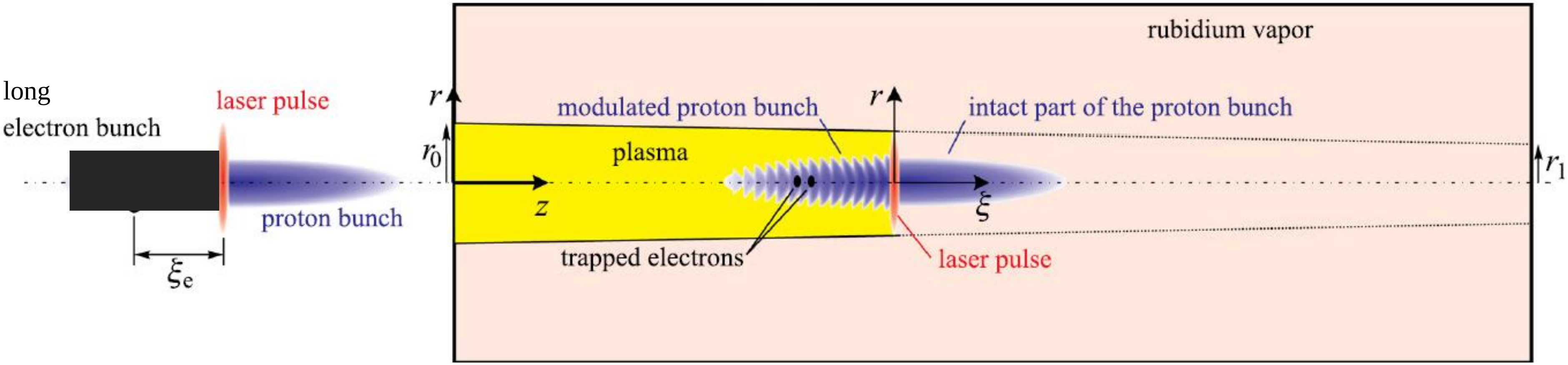


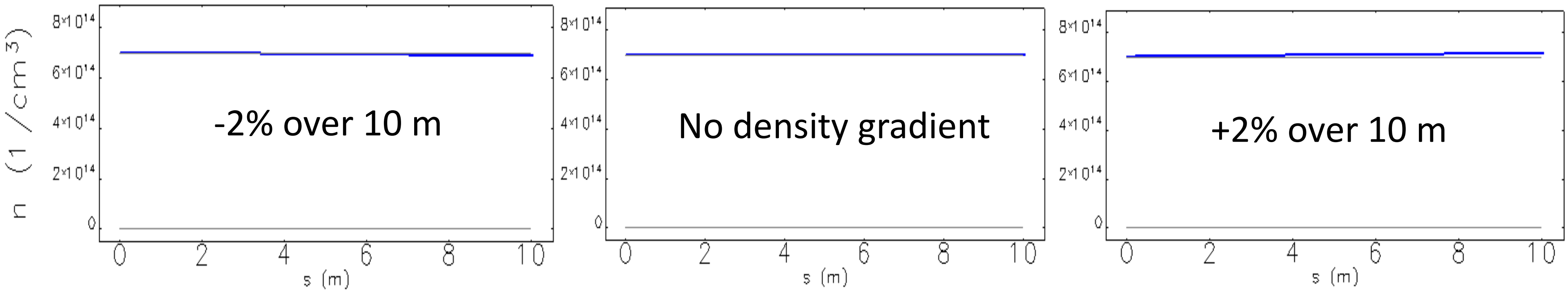




Final electron energy distribution as a function of ξ:







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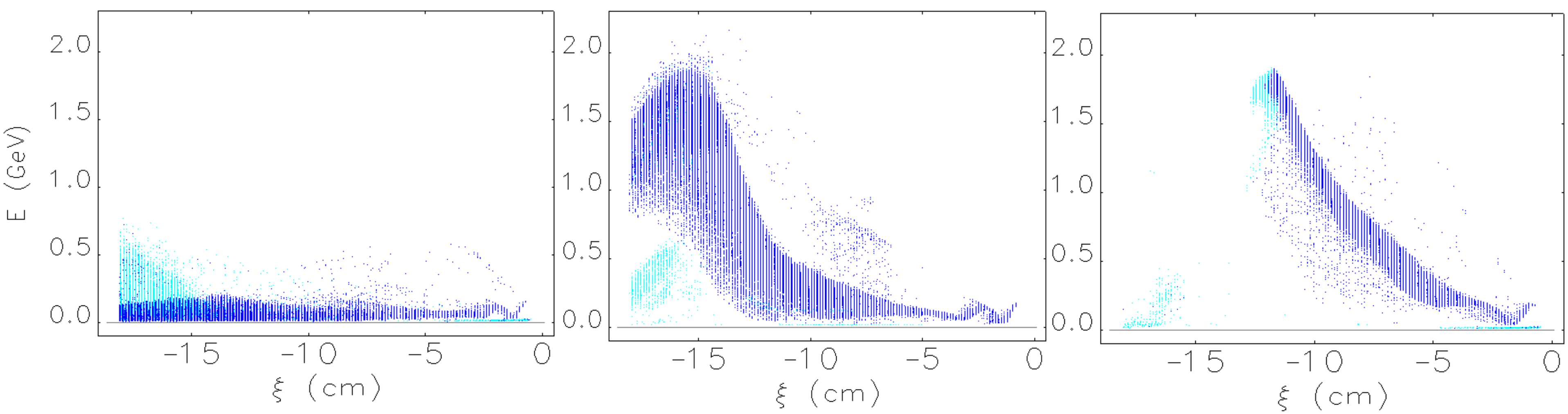
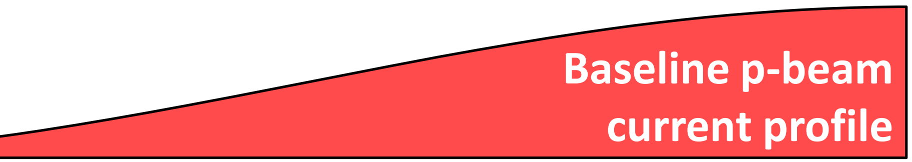
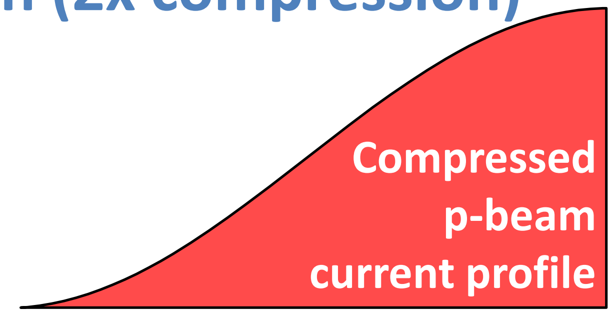
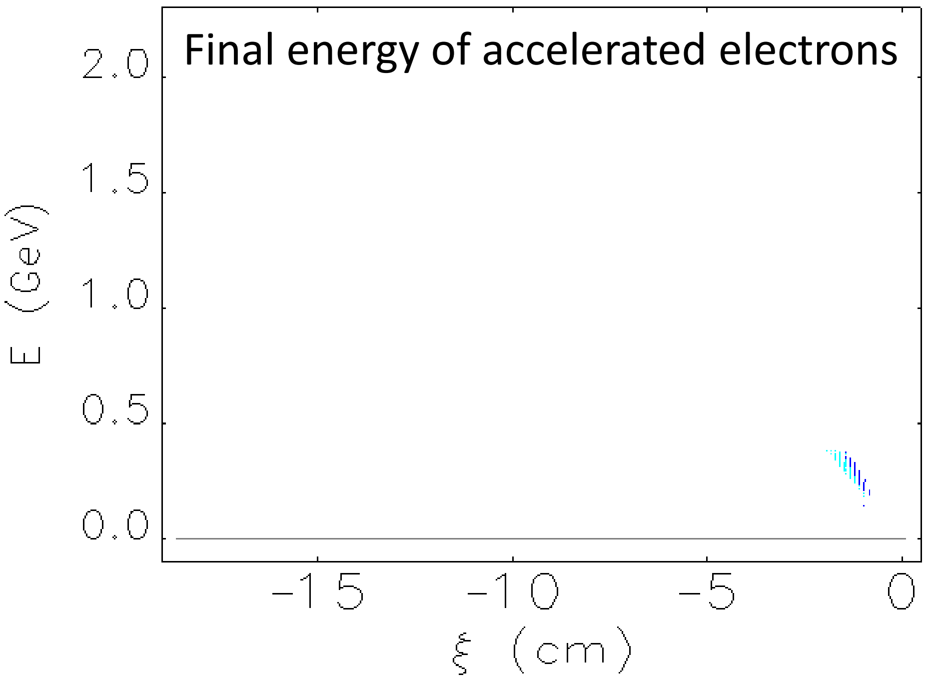
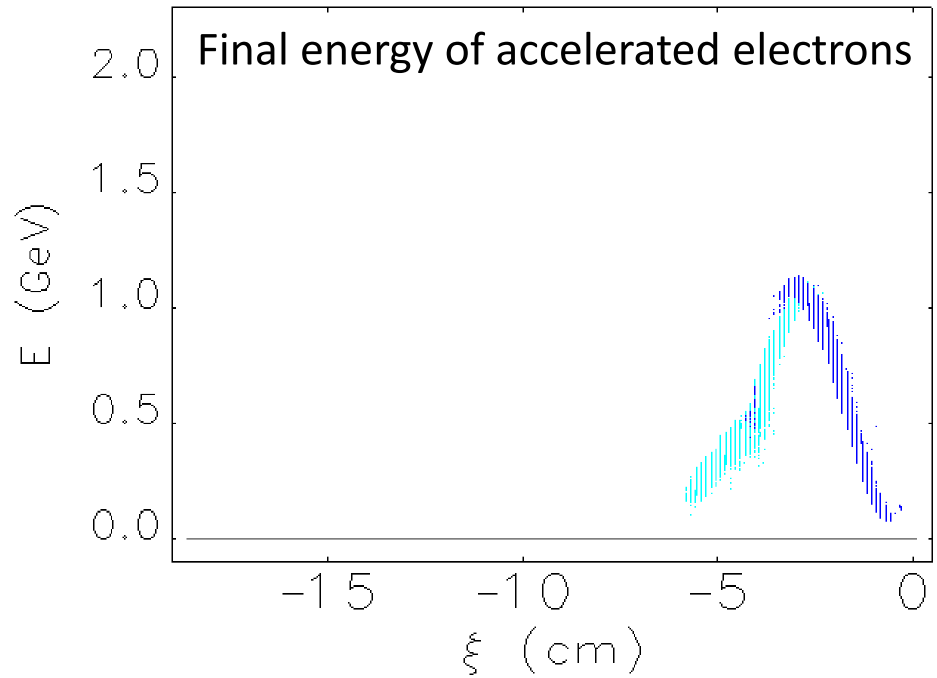


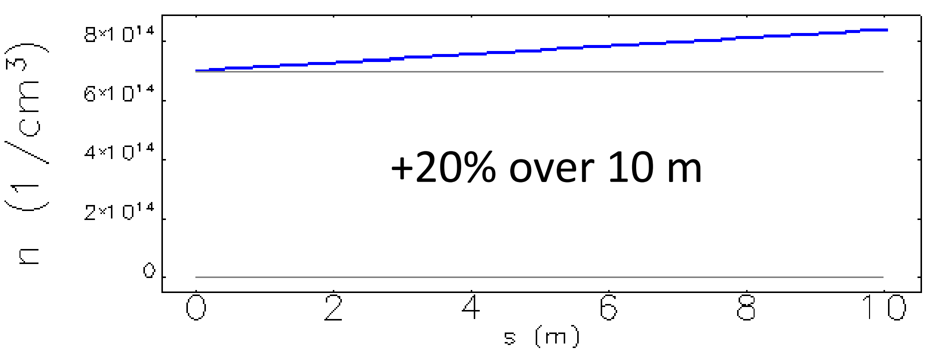
With longitudinally compressed proton bunch (2x compression) even higher density gradients are allowed:

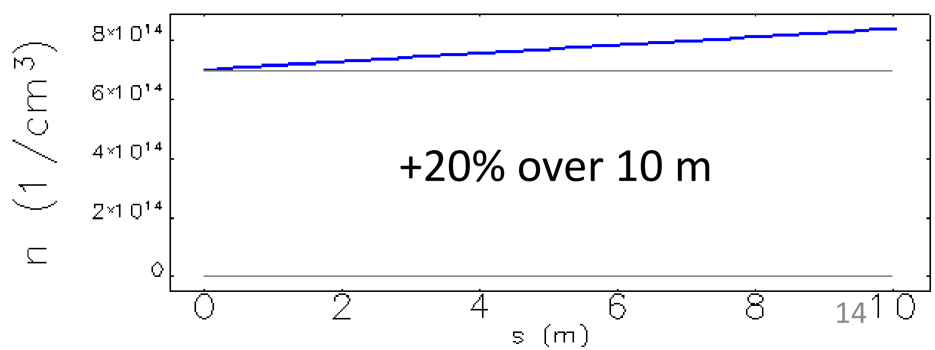












Conclusions

- Plasma density gradients offer a simple way to control the development of the proton beam self-modulation instability and acceleration of particles in it.
- In the AWAKE experiment it is possible to accelerate electrons injected on-axis to high energy (~1 GeV) in a plasma section with density gradient of up to 10% along 10 m.
- Using small positive gradients (below 10 % over 10 m) should simplify the electron injection and improve the overall stability of acceleration because we will rely on significantly less micro-bunches to drive the plasma wake-field (optimum electron injection position shifts towards the laser pulse).
- Even small negative plasma density gradient (-2% over 10 m for example) significantly reduces the achievable electron energy.
- With longitudinally compressed proton bunches it is possible to operate at higher density gradients (20% with 2x compression) – this will improve the acceleration stability further.