Theoretical developments for the AWAKE experiment

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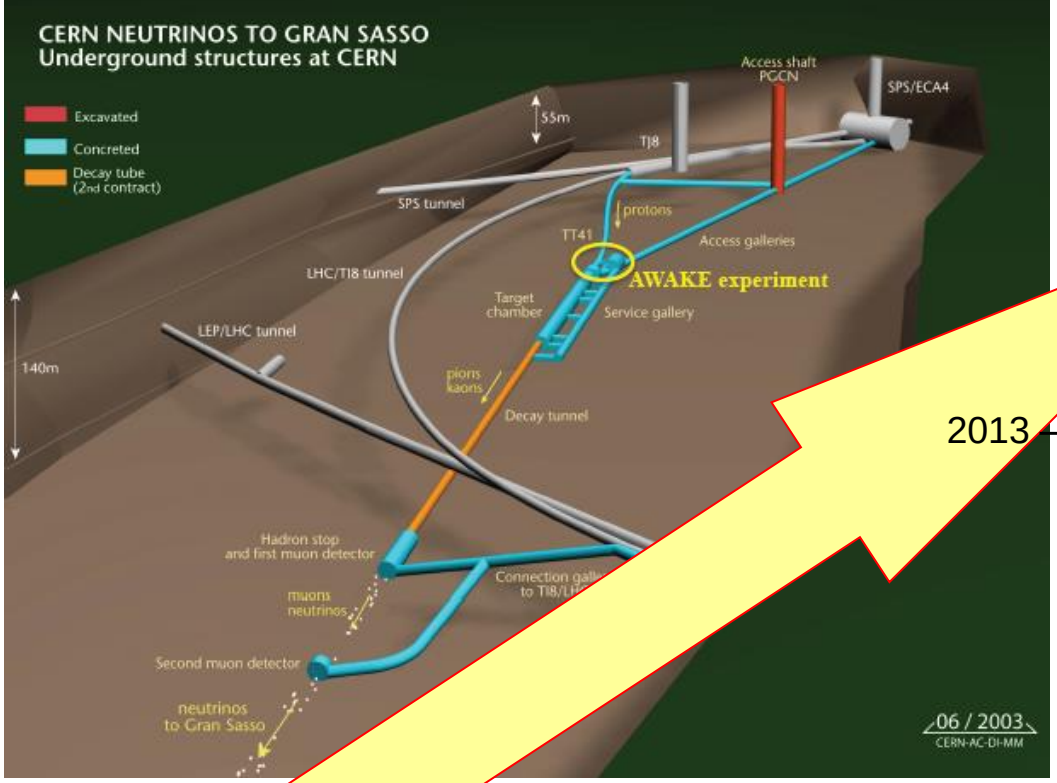
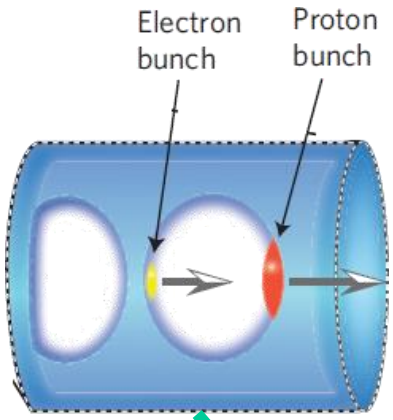
EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

Short story of



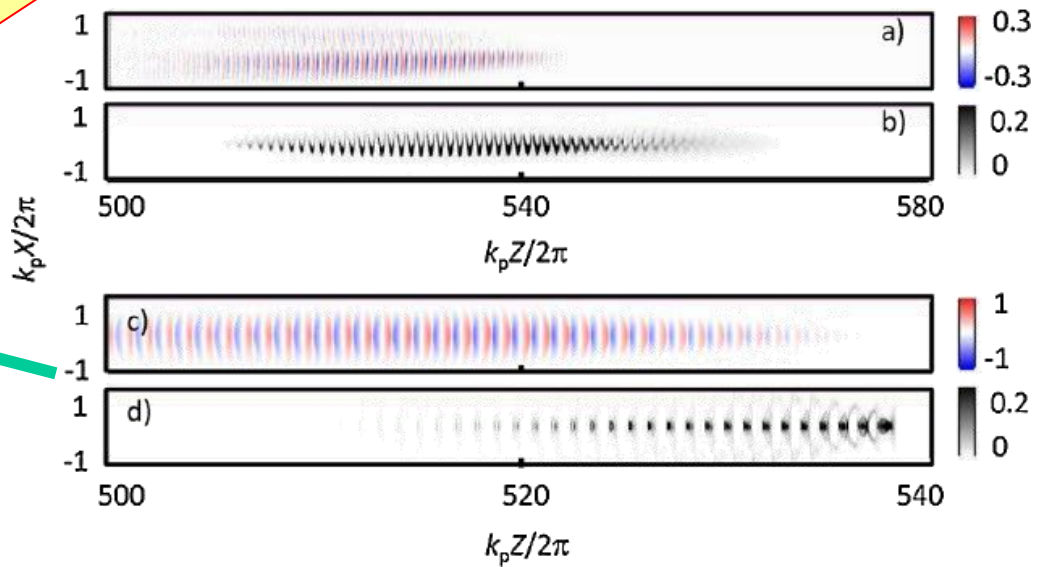
2017
first experiments

2013 – TDR, CNGS site,
AWAKE approval



2011 – Letter of Intent,

2010 – idea
of self-modulation

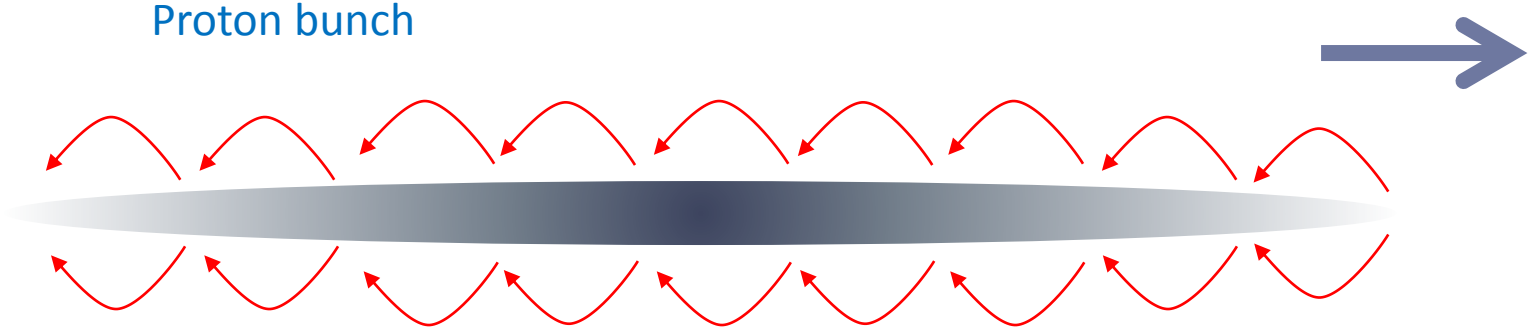


2009 – first idea of PDPWFA
(100 mm proton bunch,
1 TeV p^+ –> 600 GeV e^-)

Self-modulation idea

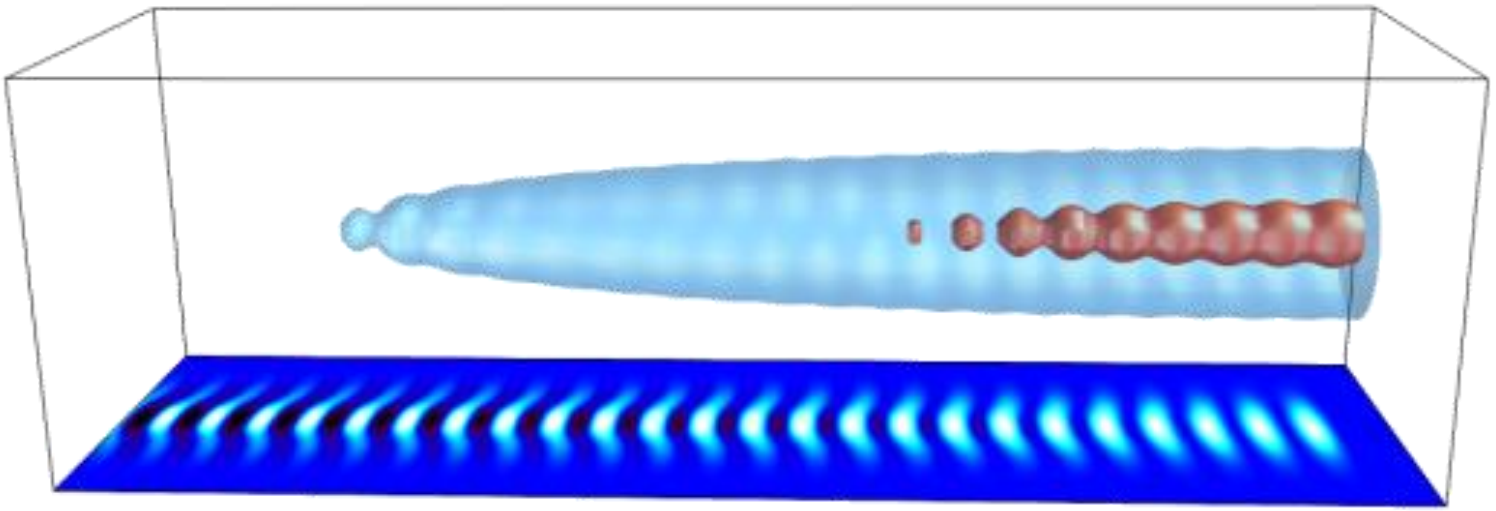
Kumar, Pukhov, Lotov PRL 104, 25503 (2010)

Proton bunch

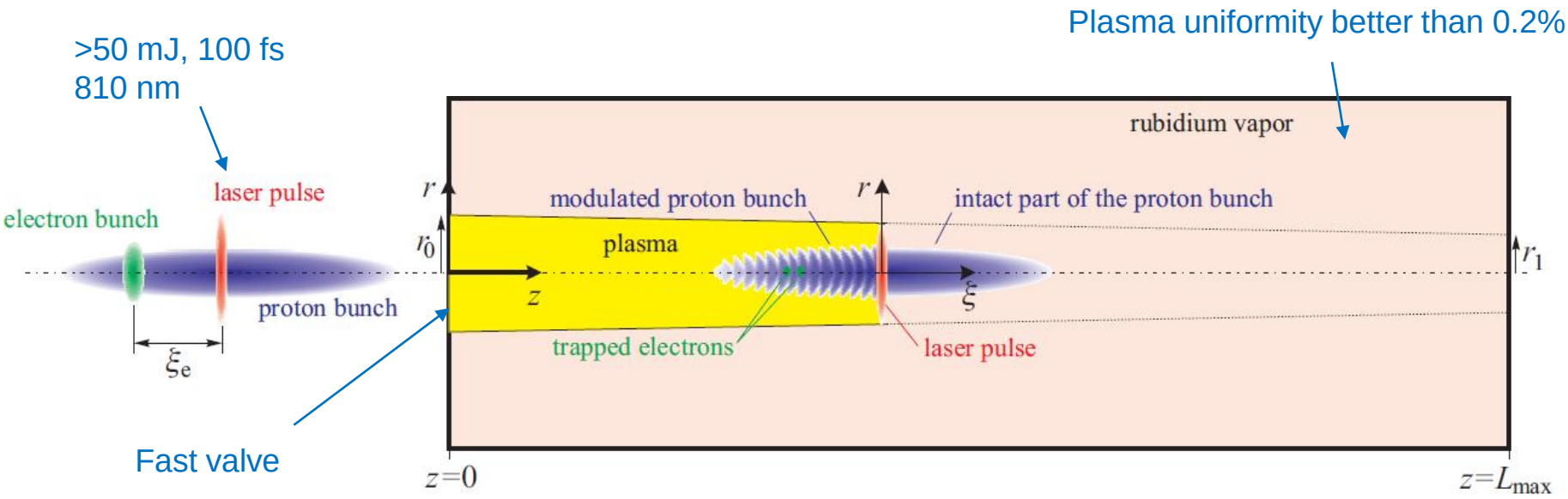


The bunch self-modulates at plasma wavelength…

…and excites resonant wake field

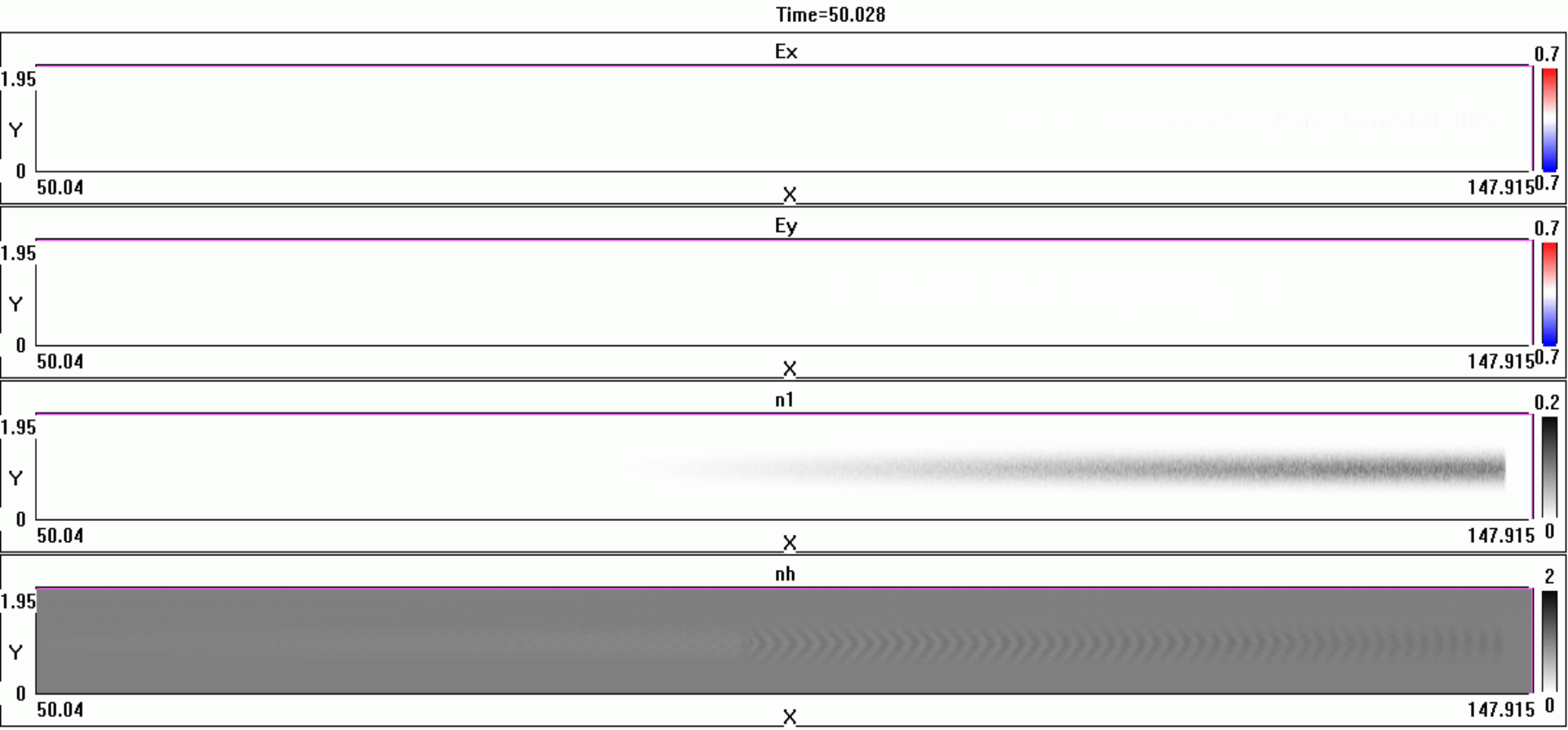


AWAKE baseline

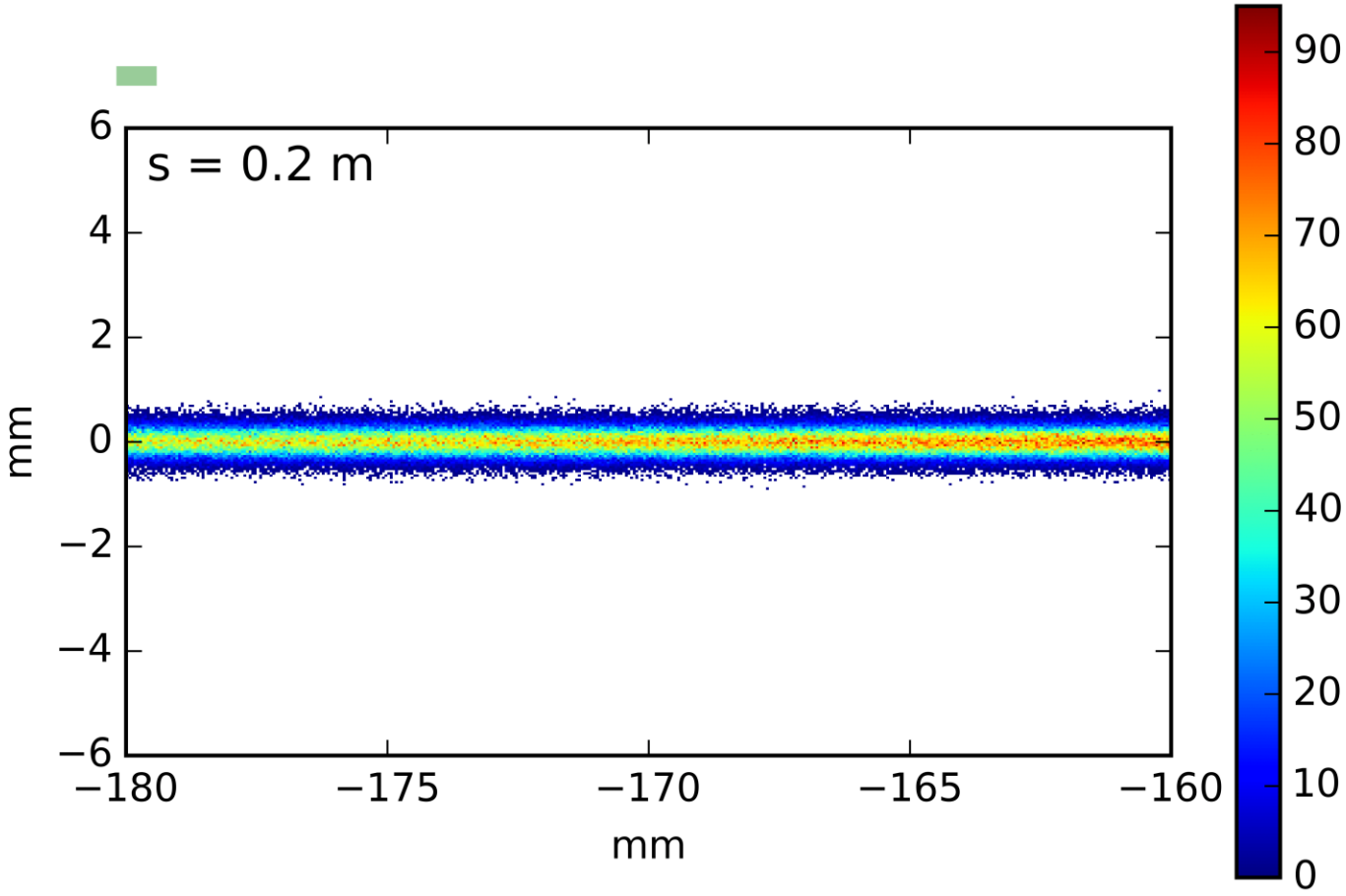


Plasma density	7×10^{14} cm^{-3}	Electron bunch population	1.25×10^{9}
Plasma column radius	1-1.5 mm	Electron bunch energy	16 GeV
Limiting field	2.54 GV/m	Electron bunch radius	0.25 mm
Proton bunch population	3×10^{11}	Electron bunch length	1.2 mm
Proton bunch length	12 cm	Electron bunch delay	16.4 cm
Proton bunch radius	0.2 mm	Acceleration distance	100 cm
Proton bunch energy	400 GeV		

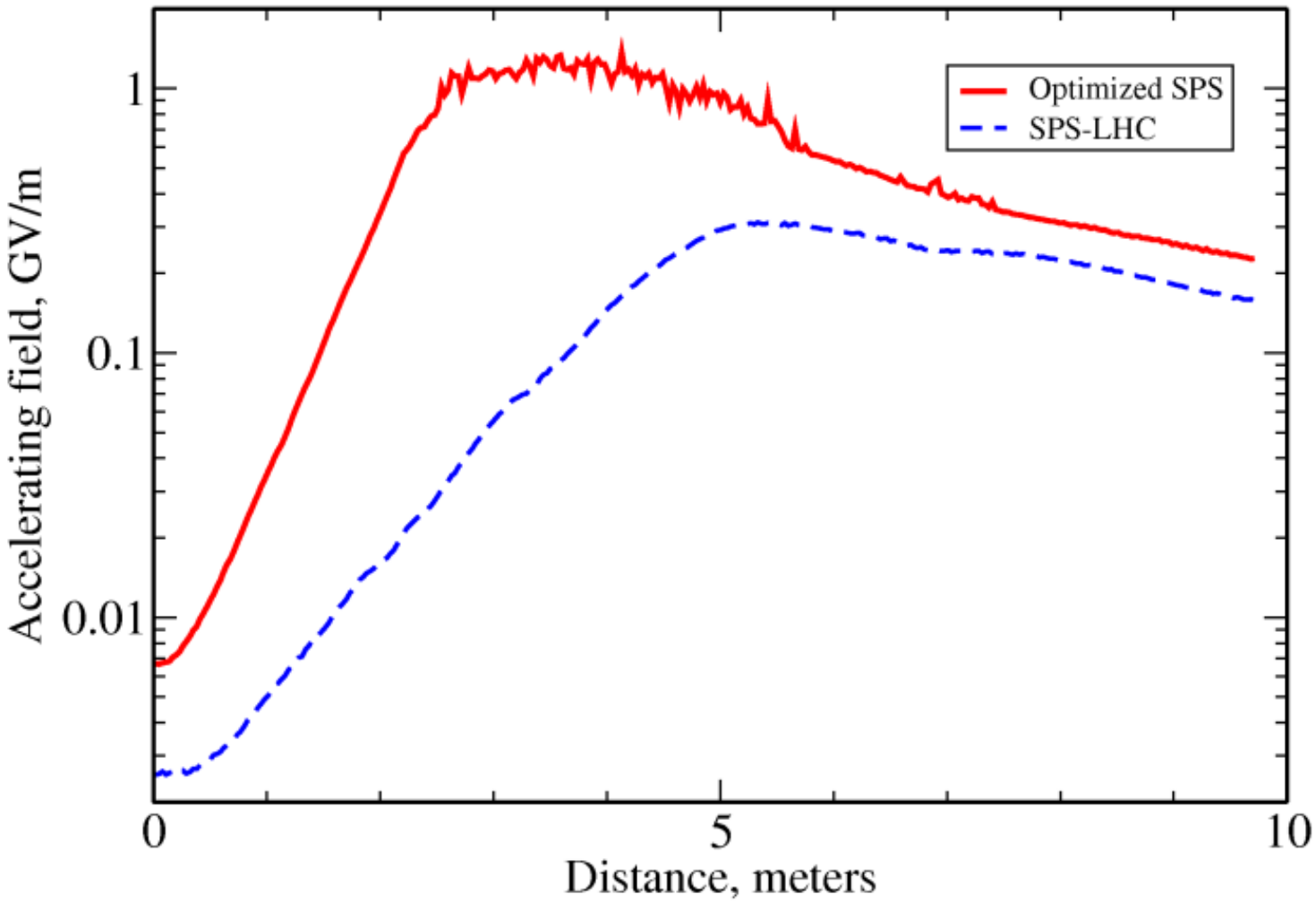
Self-modulation of the proton bunch



Self-modulation at the injection



Accelerating electric field



Phase velocity of the plasma wave

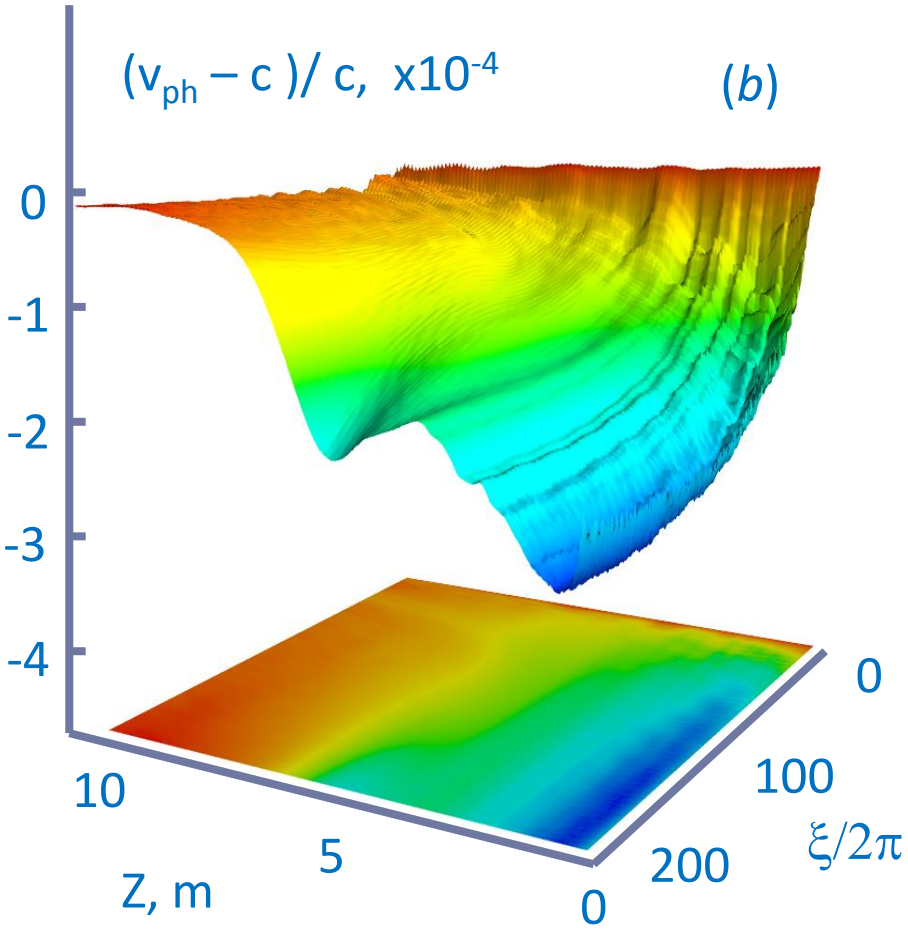
Pukhov et al., Phys Rev Lett (2011)

The wake is slowed down.
Its minimum gamma-factor is

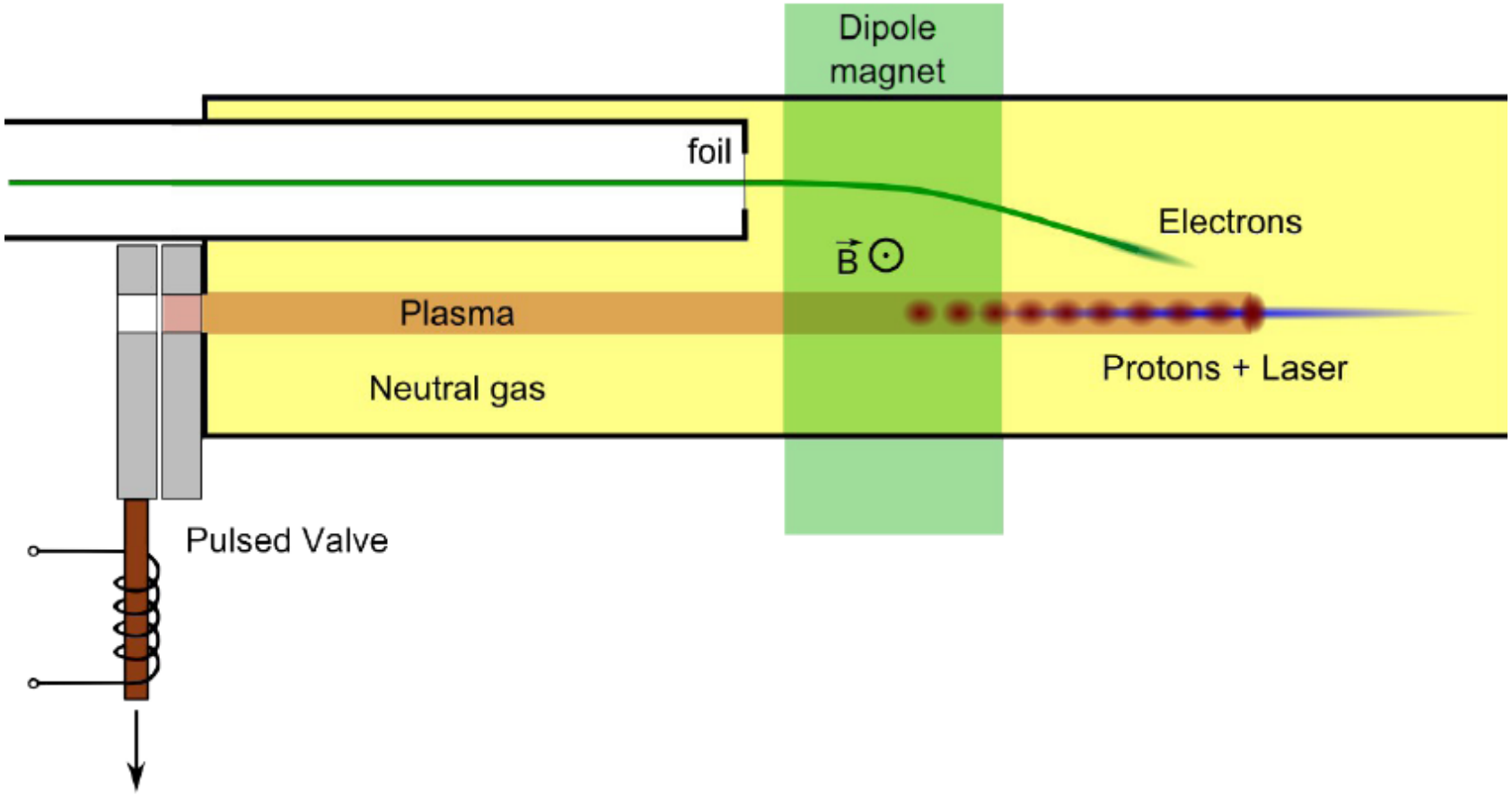
$\gamma_{min} \sim 40$

This is order of magnitude below that of the proton bunch

Electron injection sensitive to the phase velocity

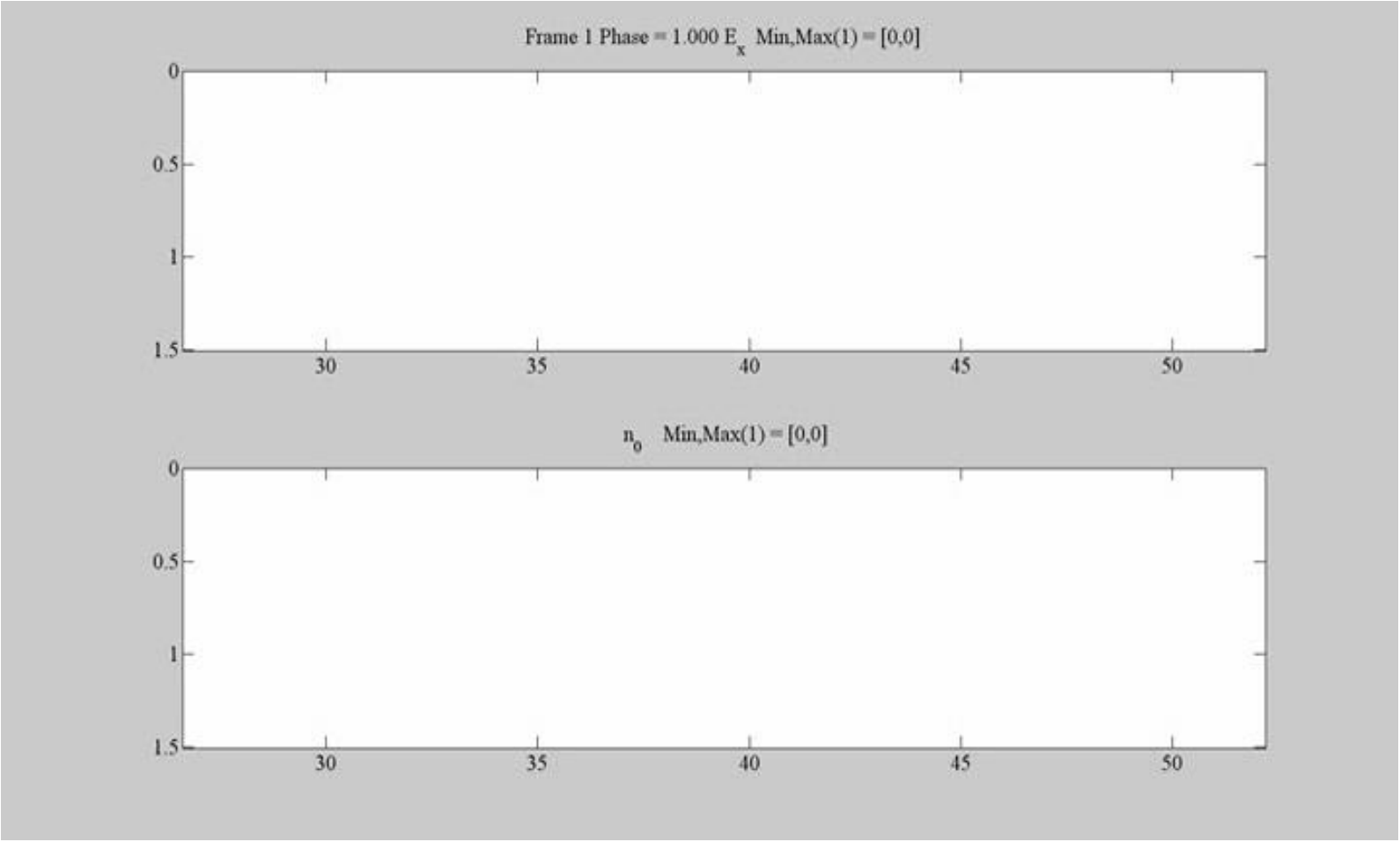


Side injection option



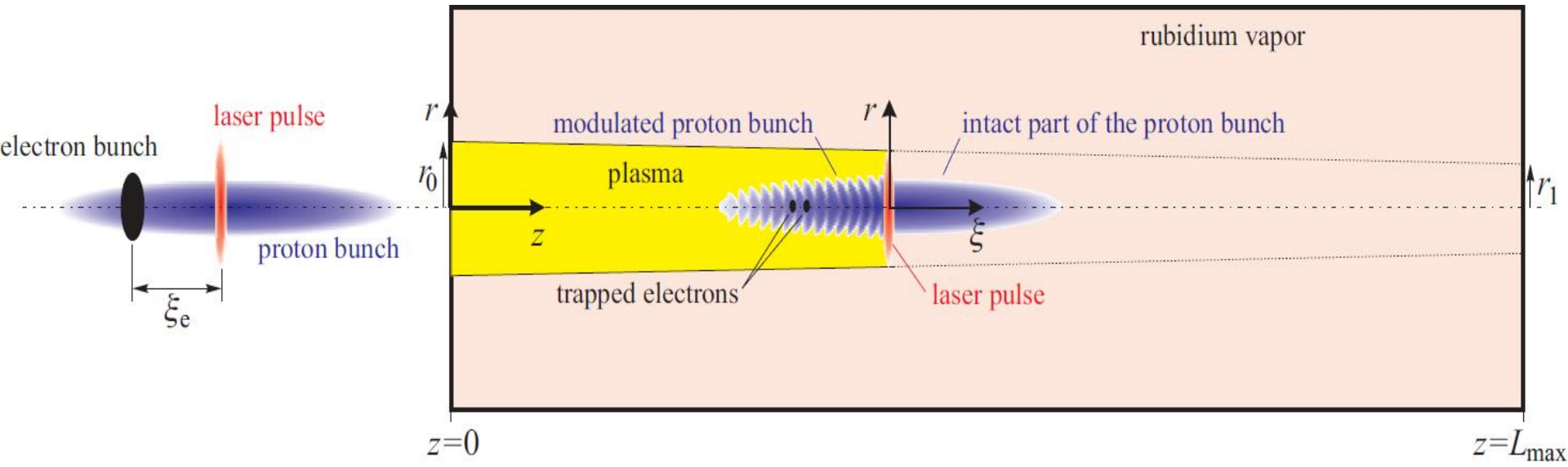
Side injection option

Side injection after 6 meters, at 0.005 rad angle



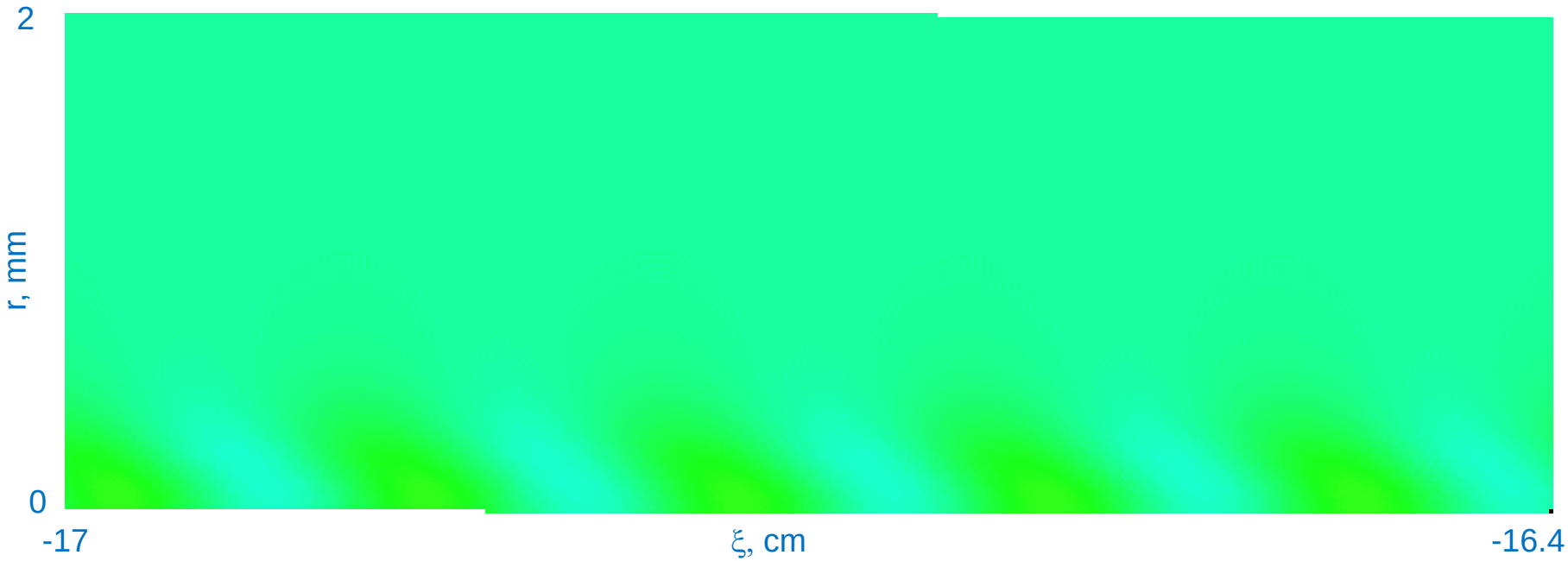
On-axis injection

On-axis injection in now viewed as the easiest and straightforward path to demonstration of electron acceleration



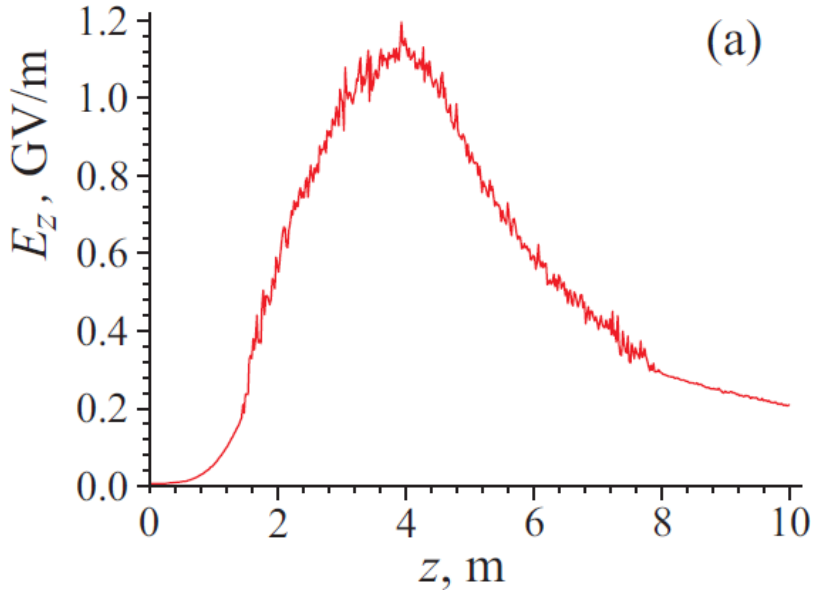
On-axis injection: animation

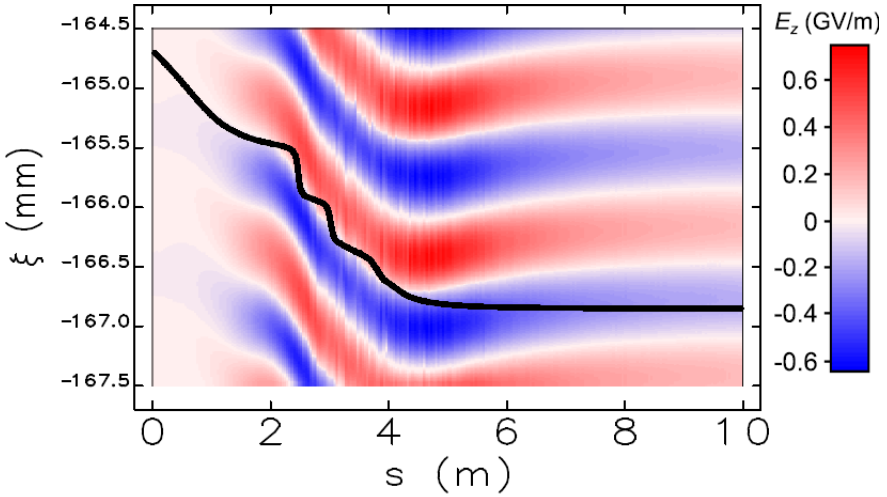
black points – injected electrons, color map – wakefield potential

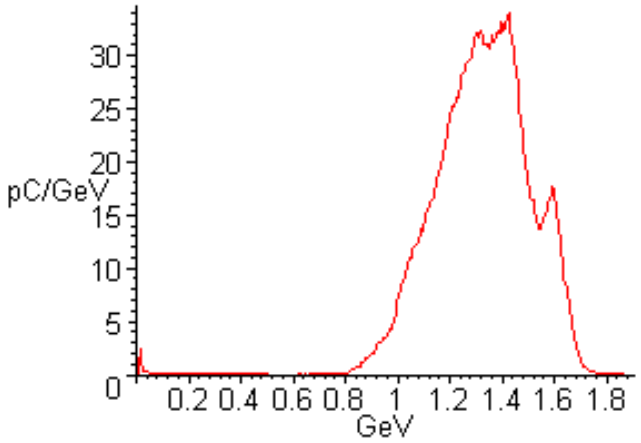


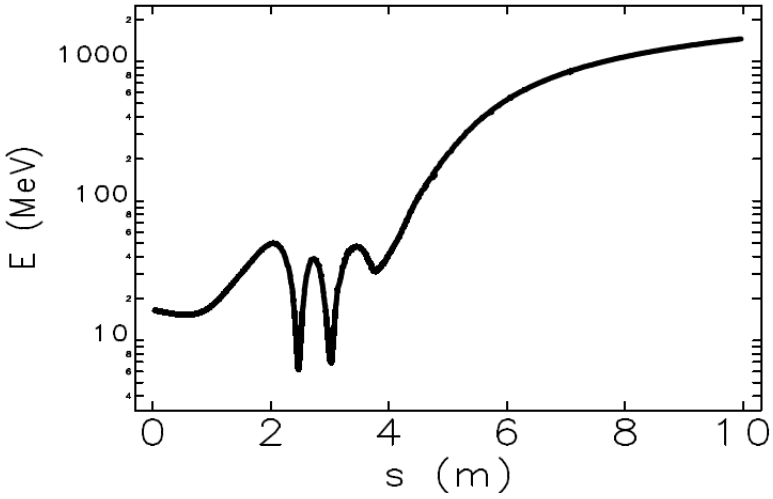
- Electrons are trapped from the very beginning by the wakefield of seed perturbation
- At r~3 c/ω_p there is a defocusing region for any ξ. Reason – incomplete neutralization of the beam current -> plasma lens effect for protons, defocusing lens for electrons
- Trapped electrons make several synchrotron oscillations in their potential wells

On-axis injection option

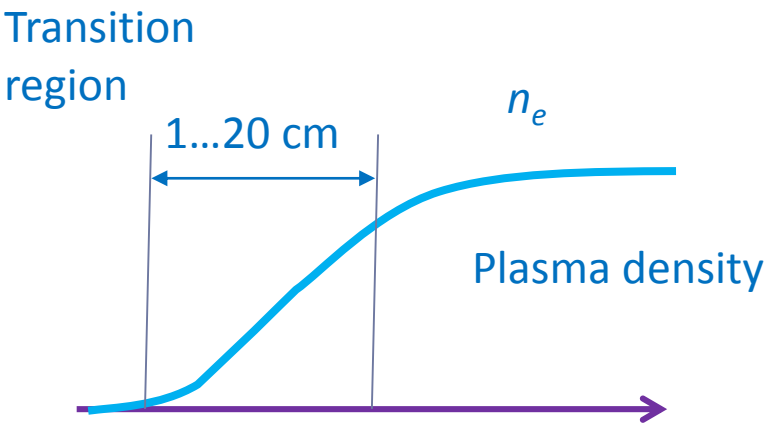




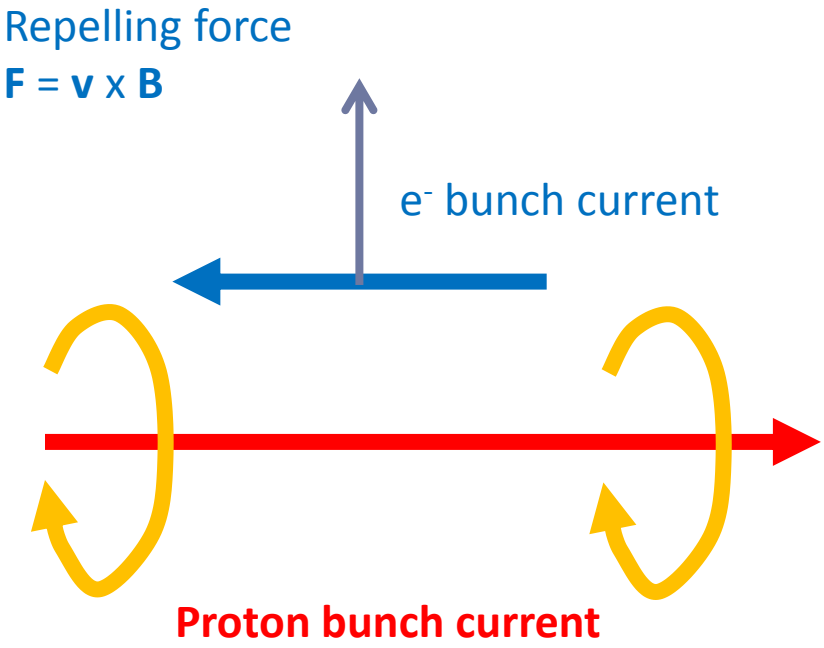




Entry into plasma issue



Electrons are scattered by magnetic field of the proton bunch before the self-modulation instability can develop



Entry into plasma issue

Possible solutions how to overcome the scattering:

1. Shorten the transition region

2. Use high current electron bunch

3. Use a transversely shaped proton bunch that has a minimum current density on-axis:
   donut shape proton bunch

3D PIC simulations

High current witness bunch on-axis: **trapping**

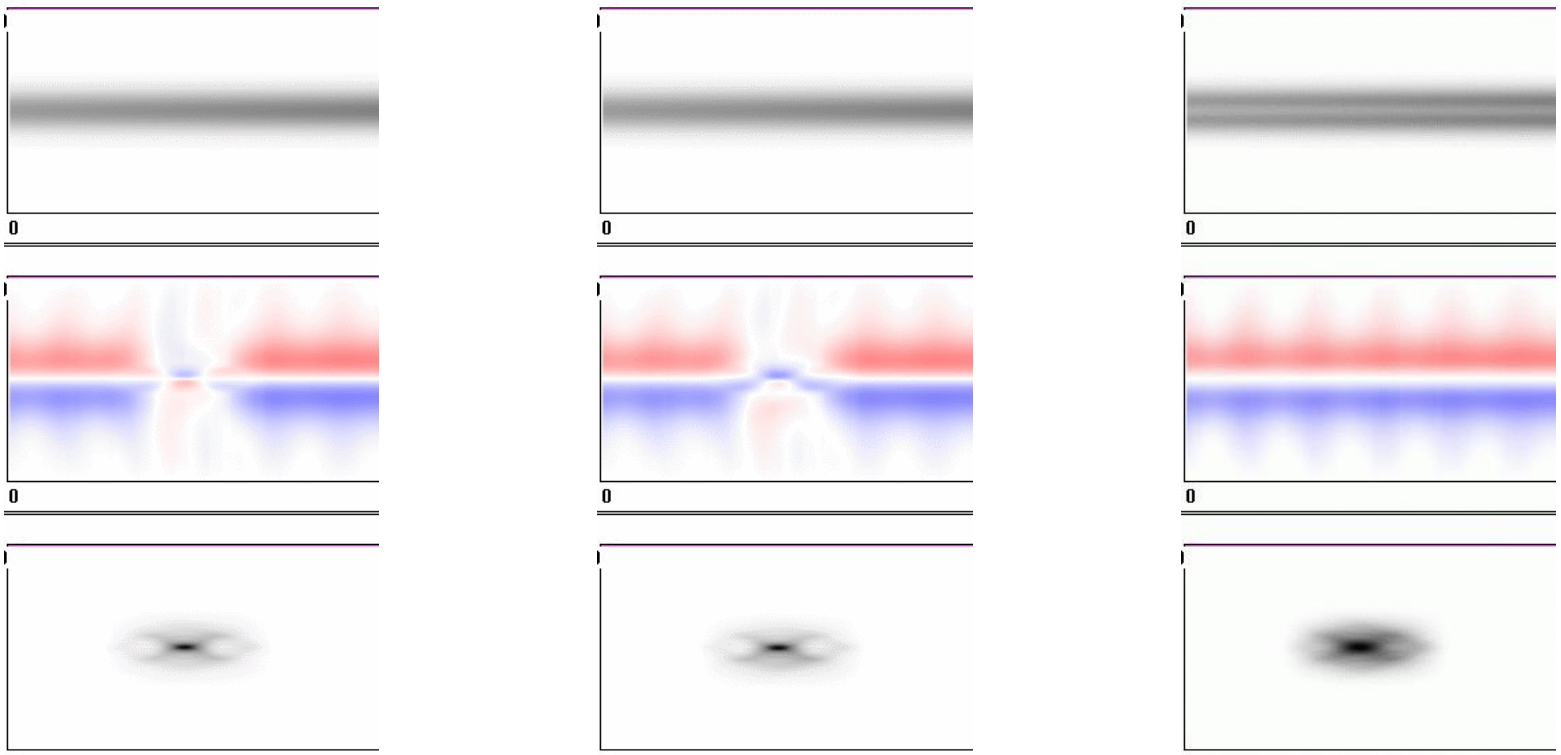
High current witness bunch off-axis: **bunch lost**

Donut-shaped proton bunch: **trapping**

Protons

B-field

witness bunch



Summary

- Theory and simulations support the experimental developments
- Transition from side injection to on-axis injection: simulated and theoretically explained
- Plasma density non-uniformity effects being studied
- The issue of vacuum-plasma transition region has been identified and solutions proposed

Publications

- Assmann, R. et al. *Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics*
  PLASMA PHYSICS AND CONTROLLED FUSION **56,** 084013 (2014)
- Tueckmantel, T.; Pukhov, A *H-VLPL: A three-dimensional relativistic PIC/fluid hybrid code*
  JOURNAL OF COMPUTATIONAL PHYSICS **269** , Pages: 168-180 (2014)
- Lotov, K. V et al. Electron trapping and acceleration by the plasma wakefield of a self-modulating proton beam
  PHYSICS OF PLASMAS **21**, 123116 (2014)
- Lotov, K. V.; Pukhov, A.; Caldwell, A. Effect of plasma inhomogeneity on plasma wakefield acceleration driven by long bunches
  PHYSICS OF PLASMAS **20,** 013102 (2013)