Summary of Paper Studies on AWAKE and the Electron Injection Schemes

Hossein Saberi

General Points

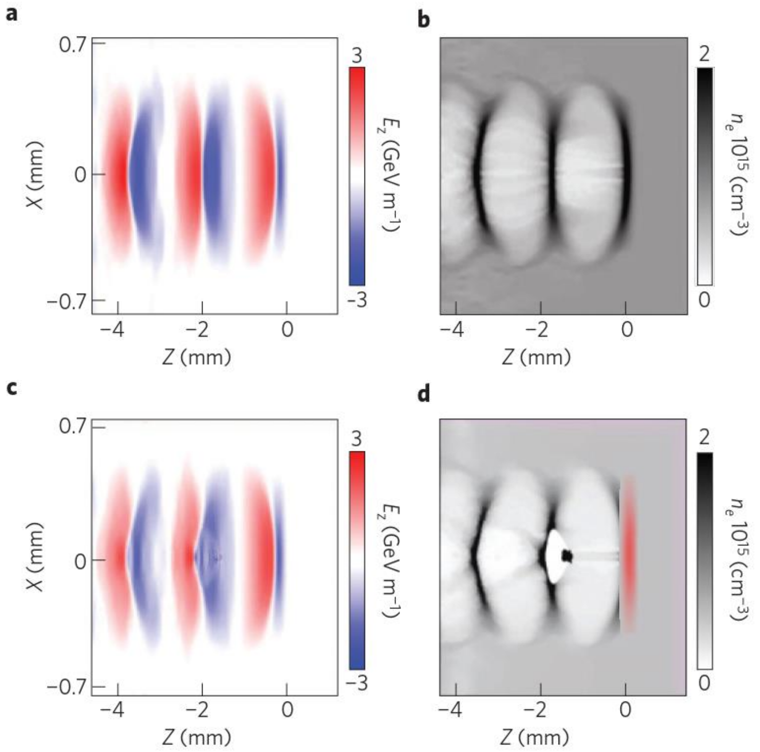
- Presentation is summary of published papers
- It might be repetitive for you!
- Your comments help to better involve the project

In Today's Lecture

- PDPWA and Electron Injection
- Electron On-axis Injection- [Plasma Density Gradient]
- Electron Side Injection
- Electron Self Injection
- RUN 2 Electron Injection
- Discussion

A. Caldwell et al, *Nat. Phys.* **5**, 363 (2009)

- Wakefield Generation:
  - Interaction of small, energetic proton bunch
  - Plasma electrons being ‘sucked in’ by the p-bunch.
  - The electrons move across the beam axis and create a depletion region
- Electron acceleration:
  - In simulation, electron witness bunch is placed on the left edge of the first bubble
  - They show a 10 GeV electron bunch accelerates to near 1 TeV.



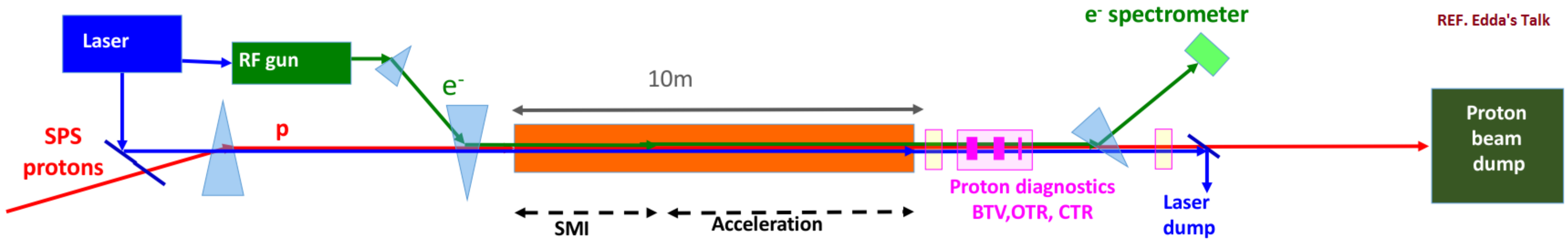
Self-Modulation Instability (SMI)

- N. Kumar et al, PRL **104** 255003 (2010)
  - A long proton bunch generates a wake inside its body which modulates the bunch itself.
  - The SMI of the proton beam can be used for TeV regime of electron acceleration.

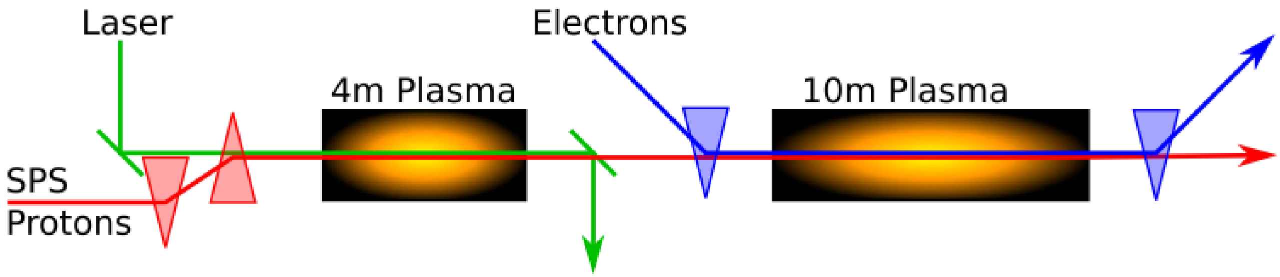
But how inject electrons to the Wakefield of modulated proton bunch?

AWAKE Experiment: Electron Injection

- **AWAKE RUN 1**



- **AWAKE RUN 2**



V. K. B. Olsen et al, PRAB 21, 011301 (2018)

Classification of Papers vs. Injection Schemes

On-axis Injection

- (2009) A. Caldwell et al, Nat. Phys. **5**, 363
- (2010) K. V. Lotov, PRSTAB, **13** 041301
- (2011) A. Caldwell and K. V. Lotov, PoP **18** 103101
- (2011) C. B. Schroeder et al, PRL, **107** 145002
- (2014) K. V. Lotov et al, PoP, **21** 123116
- (2014) A. Petrenko et al, IPAC2014
- (2016) A. Petrenko, Nucl. Inst. Meth. Phys. Res. A, **829** 63

Side Injection

- (2011) A. Pukhov et al, PRL, **107** 145003
- (2012) K. V. Lotov, JPP, **78** 455

Self-injection

- (2017) Z. Hu and Y. Yang, PoP, **20** 123109

RUN 2 Injection

- (2018) V. K. B. Olsen, PRAB, **21** 011301
- (2018) B. Williamson et al, "Simulation Study of an LWFA-based Electron Injector for AWAKE Run 2" arXiv:1712.00255v2

In Today's Lecture

- PDPWA and Electron Injection
- Electron On-axis Injection- [Plasma Density Gradient]
- Electron Side Injection
- Electron Self Injection
- RUN 2 Electron Injection
- Discussion

C. B. Schroeder et al, *PRL*, **107** 145002 (2011)

- The studied SMI and the electron acceleration:
  - The phase velocity of the wake is less than the beam velocity.
  - The energy gain of the electrons is limited by dephasing.

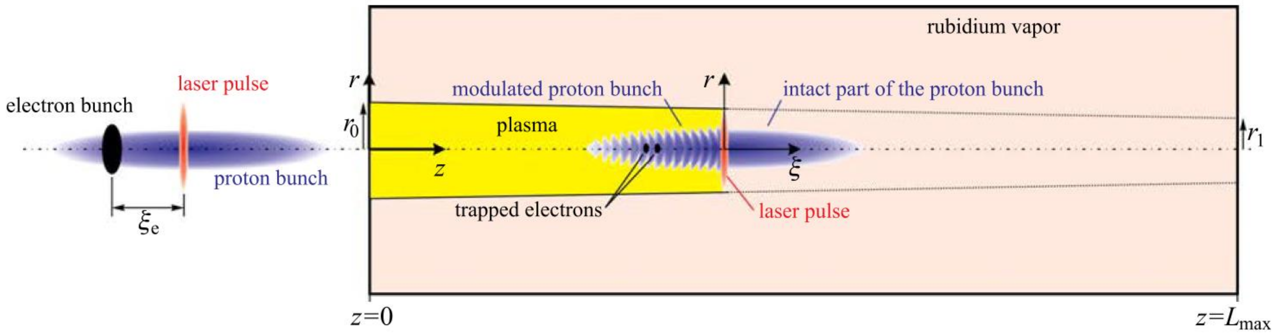
- Ideas to improve the efficiency of PDPWA
  - Tapering the plasma density:
    - Increase plasma density ➔ reduce plasma wavelength ➔ increase phase velocity
  - Use a staged approach:
    - Stage 1 for SMI ➔ Stage 2 for electron injection into the modulated drive beam

K. V. Lotov et al, *PoP*, **21** 123116 (2014)
A. Petrenko et al, IPAC2014 (2014)

- Simulation with LPIC and OSIRIS
  - On-axis injection of electrons
- Main Results:
  - The witness beam must co-propagate with the tail part of the driver
  - The trapped charge is limited by the beam loading effect

TABLE I. Baseline AWAKE parameters and notation.

Parameter, notation	Value
Plasma density, n_0	7×10^{14} 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}	4×10^{12} 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



A. Petrenko, *Nucl. Inst. Meth. Phys. Res. A*, **829** 63 (2016)

- Simulation with LPIC
  - On-axis injection of electrons
  - Consider constant plasma density gradient
- Main Results:
  - With a positive plasma density gradient up to 10% along 10 m plasma, electrons can be accelerated to high energies (> GeV)
  - The negative plasma density gradient will reduce the electrons energy gain.

In Today's Lecture

- PDPWA and Electron Injection
- Electron On-axis Injection- [Plasma Density Gradient]
- Electron Side Injection
- Electron Self Injection
- RUN 2 Electron Injection
- Discussion

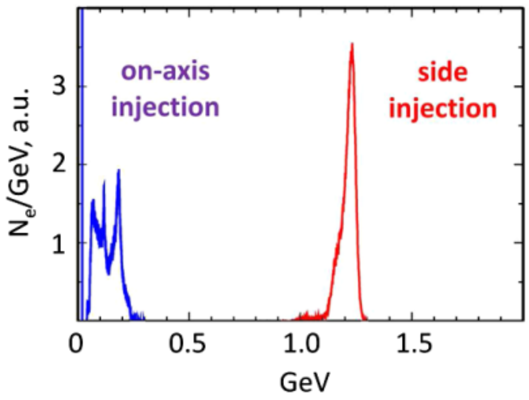
A. Pukhov et al, *PRL*, **107** 145003 (2011)

- The studied SMI and the electron acceleration
  - Phase velocity reduction is proportional to the growth rate: $v_{ph} = v_b[1 - \frac{2}{3\sqrt{3}}\frac{\Gamma}{\omega_p}]$
  - In the linear stage of SMI the reduction of phase velocity is largest.
  - As the instability non-linearly saturates, the phase velocity approaches that of the driver.

- How to overcome dephasing issue:
  - Side-injection of electrons to regions where the instability is saturated
  - Smooth plasma density gradient to control the wake's phase velocity

A. Pukhov et al, *PRL*, **107** 145003 (2011)

- Electron Side Injection
  - Electron bunch propagates at small angle with respect to the proton bunch
  - Electrons are gradually sucked-in at the right phase by the wake transverse field.
- Simulation result



K. V. Lotov, *JPP*, **78** 455 (2012)

- Theoretical study of electron injection to the linear plasma Wakefield
  - 2D theory for side injection
  - Optimum angle for side injection

- Consider side injection of electron to Wakefield potential
  - Co-moving frame

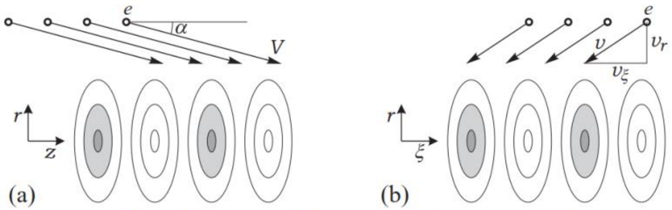


Figure 2. The geometry of the problem in (a) laboratory coordinates, and (b) co-moving coordinates.

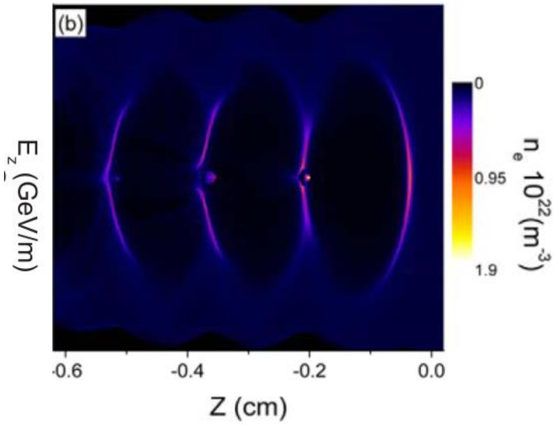
  - Wakefield potential at large radii ➔ electron's radial equation of motion
  - Radial motion can be investigated numerically to obtain the optimum angle

In Today's Lecture

- PDPWA and Electron Injection
- Electron On-axis Injection- [Plasma Density Gradient]
- Electron Side Injection
- Electron Self Injection
- RUN 2 Electron Injection
- Discussion

Z. Hu and Y. Yang, *PoP*, **20** 123109 (2017)

- Simulating self-injection by a 2D EM PIC Code
- Results
  - Electrons are self injected into the back of the first acceleration bucket
  - Self-injected electrons are initially located within a distance of the skin depth
  - When the wake's phase velocity increases the electron self injection terminates leading to a monoenergetic electron bunch.



In Today's Lecture

- Proton-driven Wakefield and Electron Injection
- Electron On-axis Injection- [Plasma Density Gradient]
- Electron Side Injection
- Electron Self Injection
- RUN 2 Electron Injection
- Discussion

V. K. B. Olsen, *PRAB*, **21** 011301 (2018)

- Beam loading in quasi linear plasma Wakefield for AWAKE RUN 2:
  - Simulation with QuickPIC
  - By properly choosing the electron beam parameters considering the beam loading effect, the electron gains large amount of energy without significant emittance growth.

B. Williamson et al, arXiv:1712.00255v2 (2018)

- Simulation Study of an LWFA-based Electron Injector for AWAKE Run 2
  - Simulation with EPOCH
  - A set of laser and plasma parameters for a shock-front injected LWFA have been investigated as a possible electron injector for Run 2 at the AWAKE experiment.

In Today's Lecture

- PDPWA and Electron Injection
- Electron On-axis Injection- [Plasma Density Gradient]
- Electron Side Injection
- Electron Self Injection
- RUN 2 Electron Injection
- Discussion

How to Proceed?

- Experiment
  - RUN 1
  - RUN 2
- Theoretical Model
  - As I understand, there is not a comprehensive model in the literature
  - Which model should choose?
- Numerical Simulation
  - In 3D, it can help to explore electron injection and acceleration.
  - Using simulation codes, NEXT slide

Simulation Codes

Name	About the Code
LPIC	❖ freely-distributed code for simulations of particle beam-driven plasma Wakefield acceleration, ❖ 2-dimensional (2d3v), with both plane and axisymmetric geometries
OSIRIS	❖ Fully explicit, multi-dimensional, parallelized, relativistic, PIC code ❖ Not free
QuickPIC	❖ open-source ❖ Fully relativistic 3D quasi-static PIC code
WARP	❖ open-source electrostatic and electromagnetic PIC Python package ❖ Self-consistent simulation of space-charge dominated beams, ❖ particle injection and electron-cloud effects in realistic geometries ❖ models ranging from full 3D, transverse slice x-y (including p_z), and axisymmetric r-z (including p_{theta}), as well as simple beam envelope models useful for problem setup
WARP-X	❖ U.S. DOE Exascale Computing Project for advanced accelerators ❖ Coupling of WARP+BoxLib/AMReX+PICSAR ❖ Ultimate goal: enable modelling of 100 stages of plasma accelerators by 2025 for 1 TeV collider design! ❖ will be open source and make available to the public toward the end of 2018.
EPOCH	❖ MPI parallelised, explicit, second-order, relativistic PIC code.

In the case of simulation, which code is better to use?


Thank you

C. B. Schroeder et al, *PRL*, **107** 145002 (2011)

- Theoretical study of SMI of a long relativistic particle beam in plasma
  - Cold plasma fluid + Maxwell's equations
  - Assumptions:
    - Linear wake regime
    - Highly relativistic drive beam
    - Quasi-static approximation
  - Obtain the envelope equation for the drive beam radius
  - Consider small perturbation ➔ equation for the evolution of the beam radius perturbation
    - instability growth rate
    - Phase velocity ➔ dephasing length

A. Pukhov et al, *PRL*, **107** 145003 (2011)

- Theory to study SMI
  - Envelope description of the driver
  - Long and thin proton bunch ➔ equation of bunch's radius
  - Linear perturbation theory ➔ dispersion relation
  - Obtain the instability growth rate
  - Phase velocity $v_{ph} = v_b[1 - \frac{2}{3\sqrt{3}}\frac{\Gamma}{\omega_p}]$
- 3D PIC Simulation
  - Hybrid code VLPL3D
    - Simulate background plasma hydrodynamically,
    - High energy bunches are fully kinetic