Study of The Electron Seeded Proton Self-modulation Using FBPIC

Presented by Linbo Liang

On behalf of

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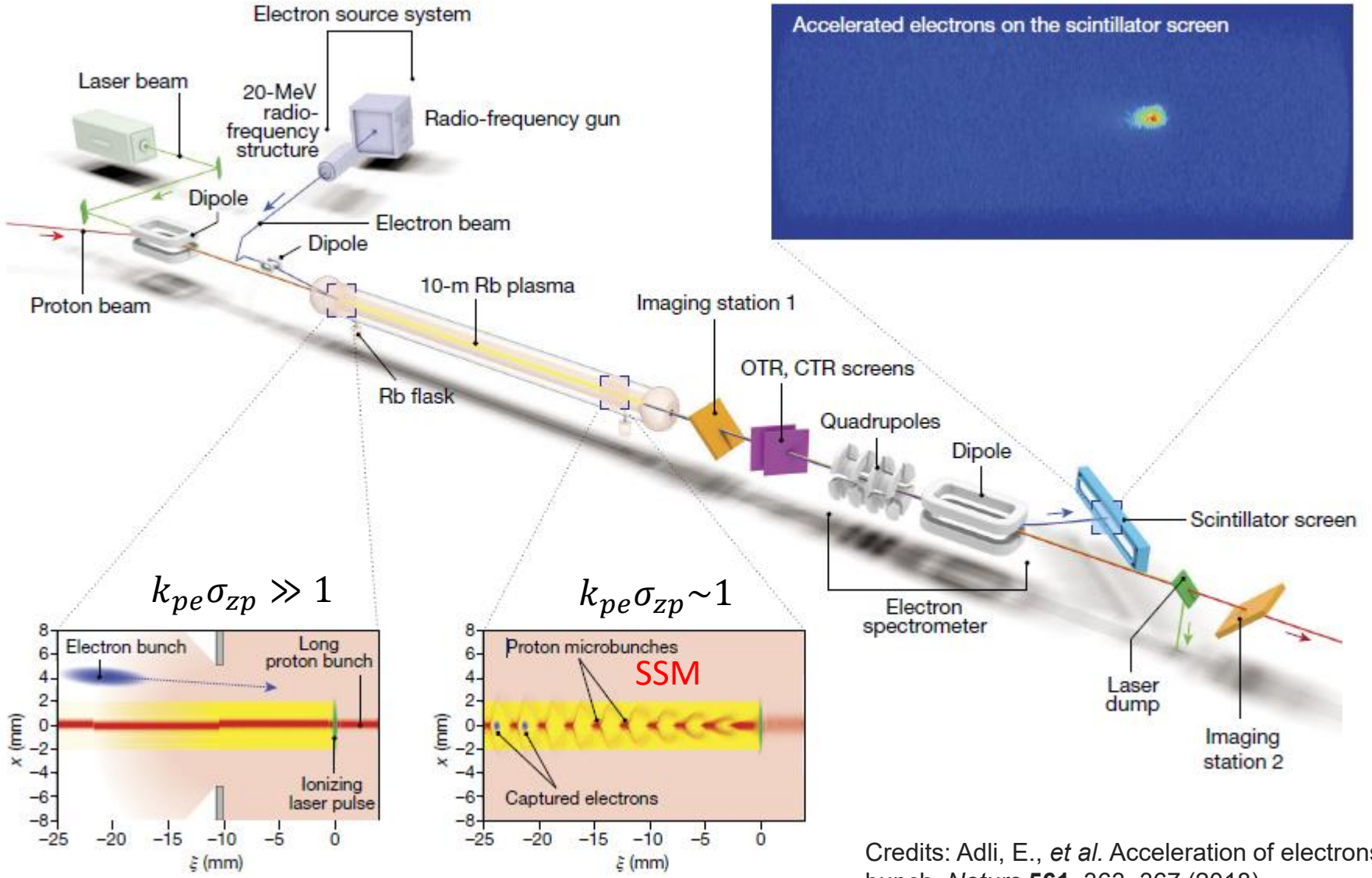
CERN Advanced Wakefield experiment (AWAKE)



Achievements:

- Self-modulation of the SPS proton bunch;
- Acceleration of externally injected, 18 MeV electrons to the 2 GeV→ ~200 MV/m

Problems:

- Only use half of the proton beam->weak wakefields;

➢ **Layout of the Run 1 experiment setup**

Credits: Adli, E., *et al.* Acceleration of electrons in the plasma wakefield of a proton bunch. *Nature* **561,** 363–367 (2018).

Proton density self-modulation

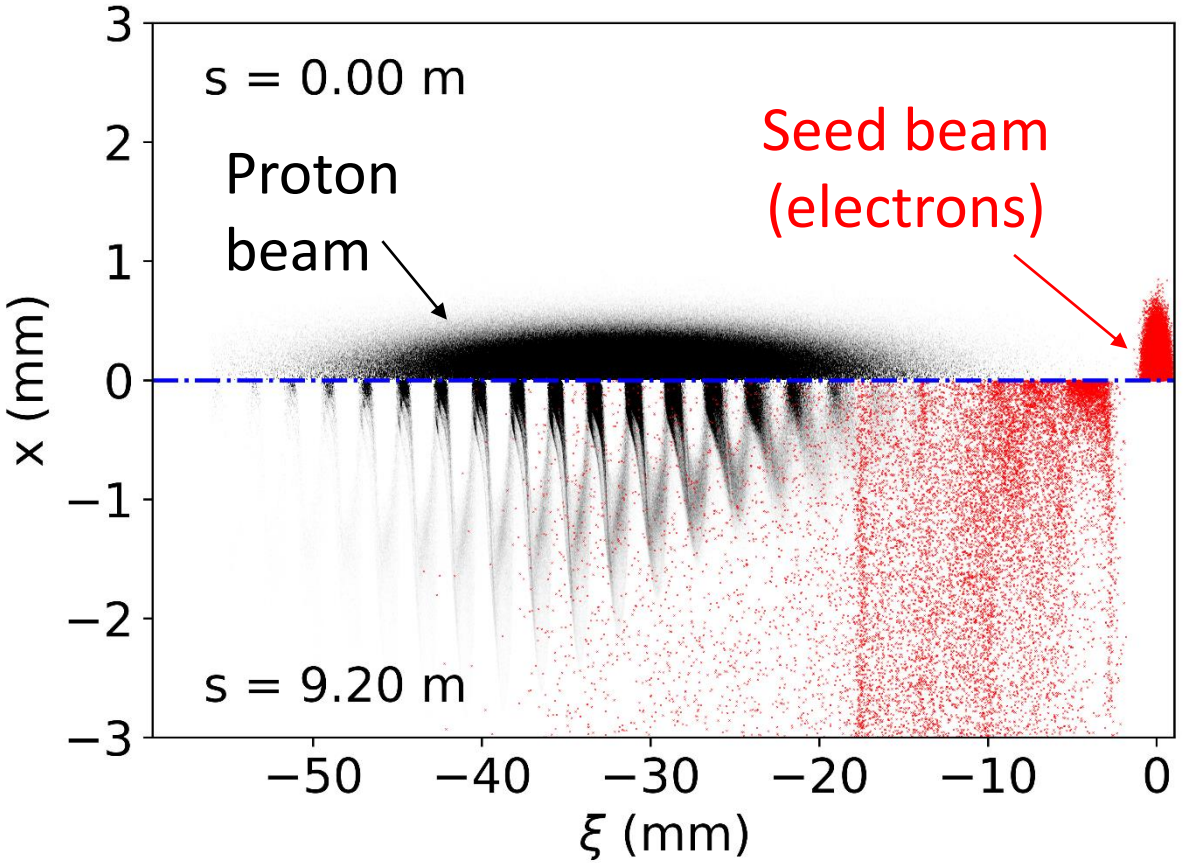


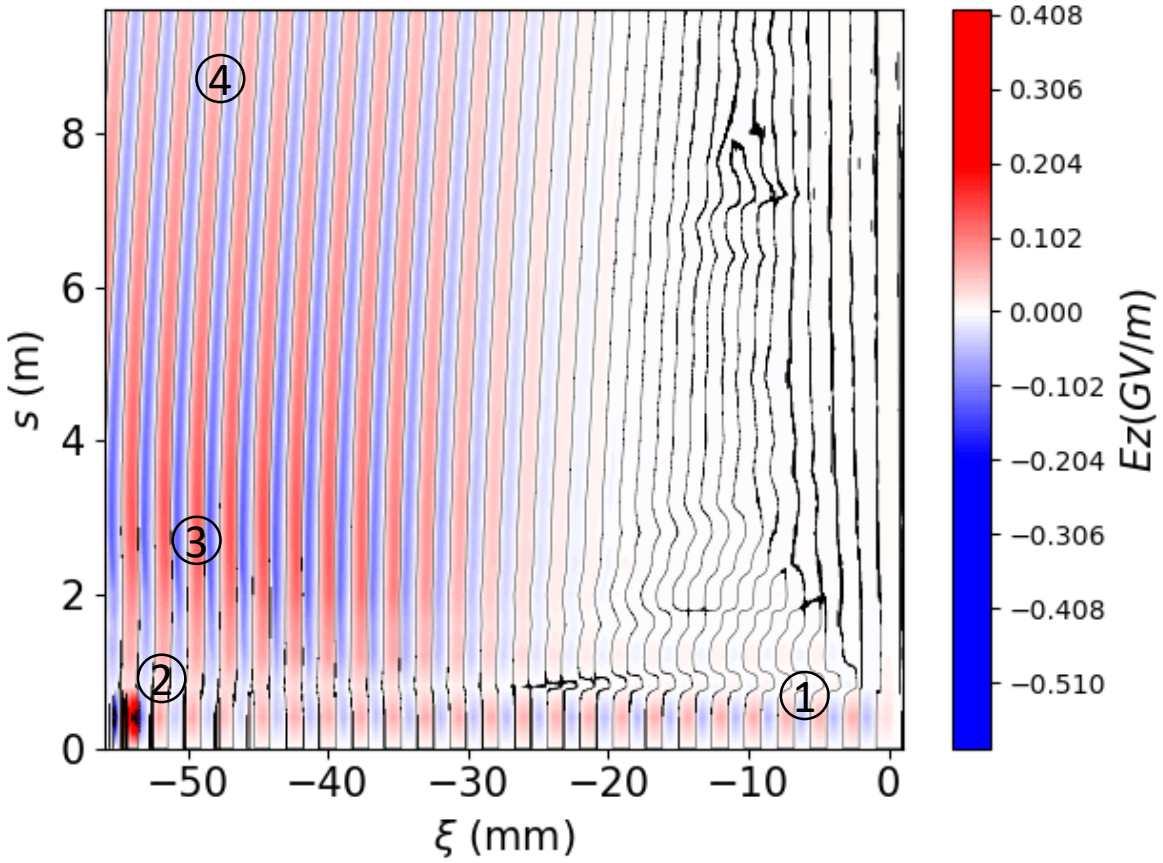
Figure 1: Simulation-obtained proton density (black) and electron macroparticle (red) distribution plot at the beginning (up-half, s = 0 m) and after self-modulation (down-half, s = 9.2 m). Longitudinal plasma profile: Uniform.

Initial Beam/Plasma parameters

- Proton beam: $Q_p = 4.8$ nC, $\sigma_{zp} = 7$ mm, $\sigma_{rp} = 0.2$ mm, $E_{p0} = 400$ GeV, $\Delta E_{p0}/E_{p0} = 0.035\%$,
- Seed beam: $Q_e = 0.5$ nC, $\sigma_{ze} = 0.3$ mm, $\sigma_{re} = 0.2$ mm, $E_{e0} = 18$ MeV, $\Delta E_{p0}/E_{p0} = 0.1\%$
- Plasma: $n_0 = 2 \times 10^{14}$ cm^{-3}, Rubidium

*Co-moving coordinate $\xi = z - ct$, z–longitudinal coordinate, c—the speed of light
*Propagation distance s=ct

Longitudinal plasma wakefield Ez



1. Seed beam depleted -> damping of the seed wakefield
2. Plasma electron trajectory crossing -> Wave-breaking
3. Proton self-modulation reaches saturation -> the maximum longitudinal wakefield
4. Phase shift of the wakefield w.r.t micro proton bunches -> wakefield amplitude decay

Figure 2: Evolution map of the on-axis longitudinal plasma wakefield Ez for the uniform plasma profile case.

Trajectory crossing and wave-breaking

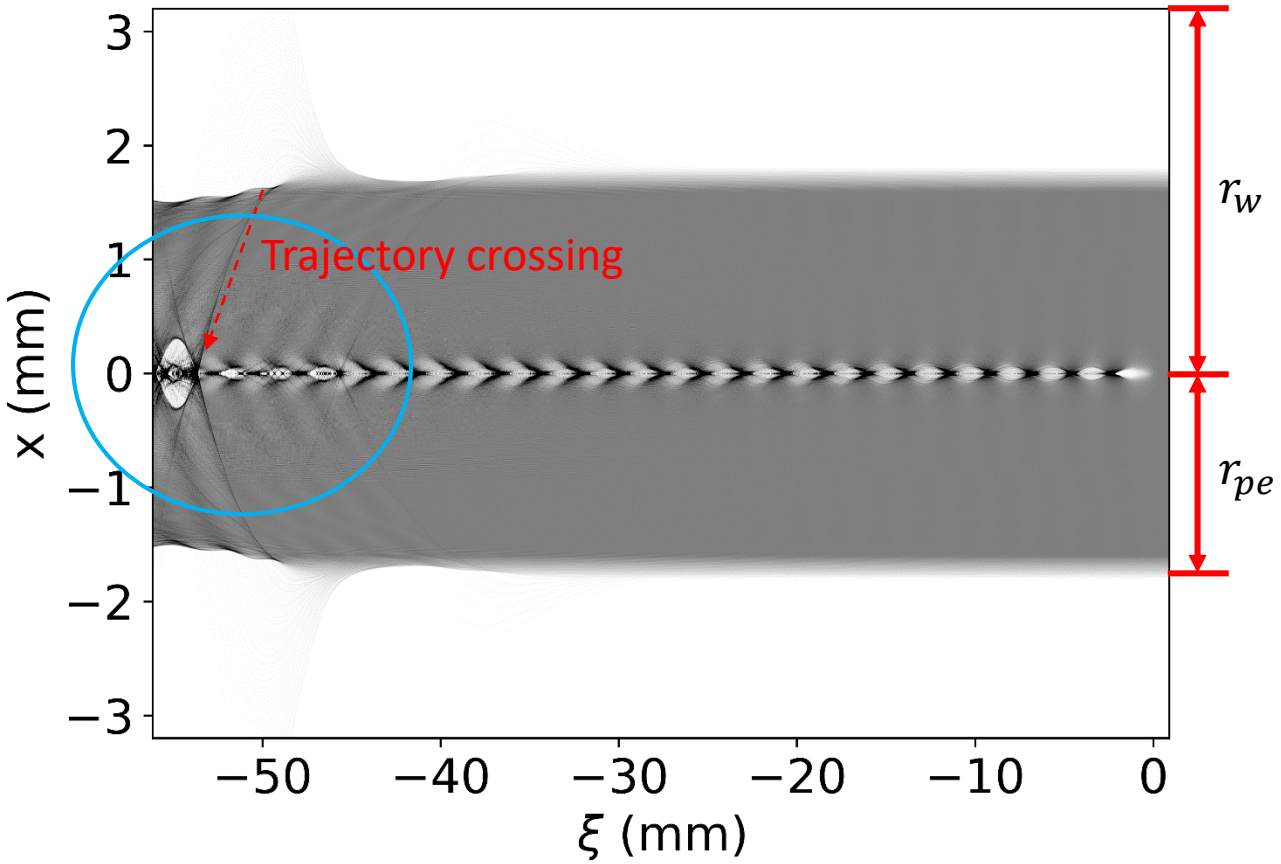


Figure 3: Plasma electron density distribution at s = 0.4 m.

- Some plasma electrons are pushed out of the plasma column by seed wakefield.
- Re-entry of kicked-out plasma electrons due to charge separation force.
- Plasma wave-breaking as a result of trajectory crossing of re-entry plasma electrons.

r_w: simulation window width, $r_w = 3.2$ mm
r_{pe}: plasma column radius, $r_{pe} = 1.6$ mm

Effect of plasma density step

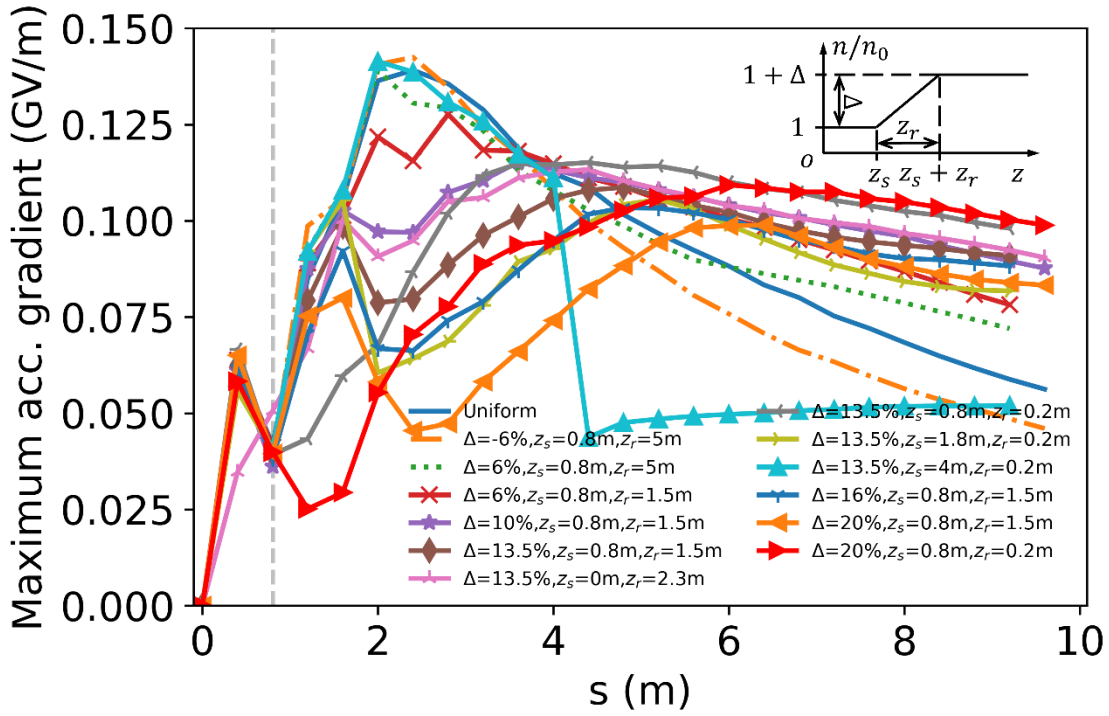


Figure 4: The maximum accelerating gradient for distinct plasma density profiles. The vertical dashed line marks s = 0.8 m. The insert at the upper-right conner shows the schematic layout of the plasma density step.

- Proper plasma density step can make the self-modulation slow down and maintain the wakefield amplitude for longer distance.
- The final maximum accelerating gradient of the case with proper plasma density step is about 75% higher than that of a uniform plasma profile.
- Plasma density step should be implemented before reaching the saturation point.

Conclusion

- The electron seeded self-modulation is observed in the simulation by the quasi-3D full PIC code FBPIC.
- By using a proper plasma density profile, one can effectively maintain the final accelerating gradient at a significantly higher level.
- The results generally agree with those from other codes.
- The study of the full scale problem using FBPIC is still very difficult due to the ultra-high computing cost.

Thanks for your attention!