Seeded Self-Modulation along a Proton Bunch at AWAKE

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Abstract
The AWAKE experiment uses the seeded self-modulation (SSM) to drive large amplitude wakefields in a plasma. The seed for the wakefields is a sharp ionizing front located near the middle of the proton bunch. It is created by an intense laser pulse ionizing Rubidium (Rb). For electron acceleration, the electron bunch must be injected into the accelerating and focusing phase of the wakefields, approximately 100 plasma periods behind the seed laser position. Here, we show that by using a replica of the intense laser pulse we can determine precisely the position (timings) of the proton micro-bunches with respect to the ionizing laser pulse. Since the relative phase of the wakefields is tied to the proton micro-bunches, this method can be used to determine experimentally the delay between the ionizing laser pulse and the electron bunch so that the electrons can be injected into the accelerating and focusing phase of the wakefields. The results presented also show that the timing of the micro-bunches is stable against variations of the proton input parameters. They show as well the difference between seeded and unseeded self-modulation.

The AWAKE Project

- **Goal:** Accelerate e− on short lengths to high energies (GeV-TeV) for HEP applications
- **The world’s first proton-driven plasma wakefield acceleration experiment**
- **Intense laser + Rb vapor for plasma, CERN SPS proton beam (400 GeV, σz = 12 cm) as a driver**
- **Match proton bunch length to plasma wavelength (~1mm), using self-modulation instability**
- **Seed self-modulation process using a sharp ionising front → Phase stability**

Seeded Self-Modulation

- **Density gradient:** + 6.7 %
- **Ionizing laser pulse too intense to observe on streak camera (SC)**
- **Ionization trigger jitter w.r.t. proton bunch of ~ 20 ps**
- **Guided a bleed-through of the ionizing laser dispersion-free and matched in time to the streak camera**
- **Seeding point in proton bunches marked on SC images**
- **Scan along p− bunch by moving marker and SC Window in parallel**

Laser Timing Reference Marker

- **Reference marker path:** 45.1 m + 15.1 m delay line
- **Seeding point in proton bunches marked on SC images**
- **Scan along p− bunch by moving marker and SC Window in parallel**

Same Seeding Point for Different SC Windows

- **Seeding self-modulation forms a train of micro-bunches on the size of the plasma wavelength recorded at Rb density 2.13×10^13 cm^−3, 0.0 % gradient**

Seeding: Phase Instability

- **Seed point 125 ps ahead the p− bunch center**
- **For 120 events, micro-bunches occur at the same phase**
- **Summing the image profiles shows modulation**
- **High phase stability for beamers + injection**

Analysis tools

- **Sum images along time axis, fit profile for marker position**
- **A FFT shows a clear peak around 120 GHz by A. Kaper**

Conclusion

- **The reference marker indicates precisely the seed point**
- **Shifting the marker gives precise timing / phase of micro-bunches**
- **Clear difference in phase stability between seeding and no seeding**
- **Seed self-modulation shows stable phases along the p− bunch for e− injection in the wakefields in AWAKE**