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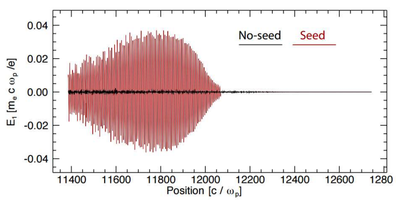
Investigation of the Self-Modulation Seeding by a Short Electron Bunch Within a Short Proton Bunch

Abstract

We present a concept for a different seeding mechanism of the self-modulation based on electron injection. The timing between laser and protons is shifted, so that the whole proton bunch propagates through a preformed plasma. The effective beam current is modulated by the external injection of a short electron bunch in the center of the proton beam. The resulting sharp edge in the effective current in the rear part of the proton bunch drives large wakefields that lead to a growth of the seeded self-modulation (SSM). Furthermore, we show first experimental results of the feasibility of this approach.

Theoretical Prediction of the SMI Growth Rate



According to OSIRIS simulations [1] the growth rate of the self-modulation instability by noise in the proton bunch is almost negligible on the scale of several meters. Only by seeding (e.g. with a co-propagating high-power laser pulse, with a sharp ionization front) the self-modulation can grow significantly and a train of proton micro-bunches with reproducible phase stability can be obtained. Such a bunch modulation is referred to as seeded self-modulation (SSM).

Fig. 1: Comparison between unseeded and seeded SMI growth of a proton beam after beam propagation of ~ 6.5 m in a plasma with $N_b = 11.5 * 10^{10}$ cm^{-3} (figure from [1])

Seeding Concepts

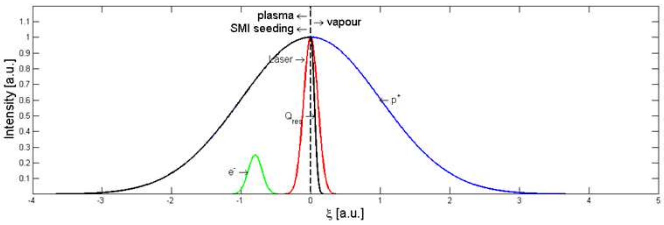


Fig. 2: Schematic of the seeding concept of AWAKE Run 1 – figure not to scale

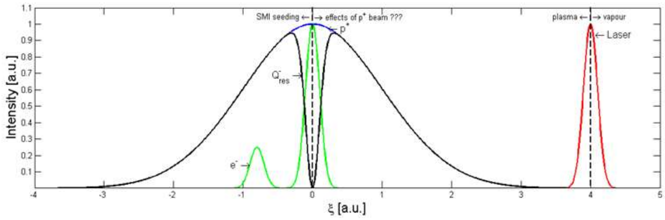


Fig. 3: Schematic of an alternative seeding concept for AWAKE Run 2 – figure not to scale

The approach would have several advantages for a possible accelerator design as it is planned for AWAKE Run 2; two independent plasma cells, split into a SM-seeding and an accelerating stage [2]. This design would go without a high-power laser and a Rb source, as the plasma could be created inside e.g. a discharge or helicon source operated with Argon.

Predictions from Linear Theory

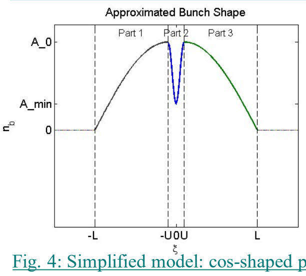


Fig. 4: Simplified model: cos-shaped proton bunch

The resulting wakefields are calculated for a simplified model (cos-shaped proton bunch) in an AWAKE-like case, with bunch density

$$n_{b||}(\xi') = \begin{cases} A_0 \cdot \sin\left(\frac{\pi\cdot(\xi'+L)}{2(L-U)}\right) & \xi \in [-L,-U] \\ \frac{A_{min}-A_0}{2} \cdot \cos\left(\frac{\pi\xi'}{U}\right) + \frac{A_{min}+A_0}{2} & \xi \in [-U,U] \\ A_0 \cdot \cos\left(\frac{\pi\cdot(\xi'-U)}{2(L-U)}\right) & \xi \in [U,L] \\ 0 & \text{else} \end{cases}$$

The rear part of the proton beam drives larges wakefields, in parallel and perpendicular direction.

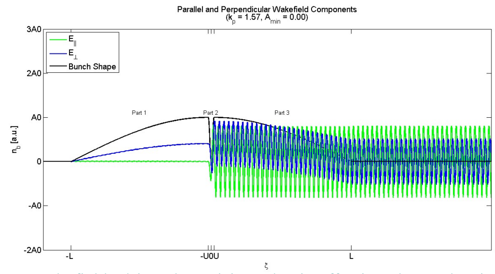


Fig. 5: Wakefields driven by a rising edge in effective charge density

First preliminary results from the last SSM Physics Runs show that the SMI growth rate of an unseeded proton bunch in a pre-formed plasma (laser pulse way ahead of the proton bunch) is much higher than predicted by simulations shown in Fig. 1. Even for a laser pulse which is about 10 µs ahead of the proton bunch (in space this would correspond to 3 km), there is still distinct micro-bunching of the proton bunch. Also hosing effects can be observed in this regime.

Results from first SSM Physics Runs

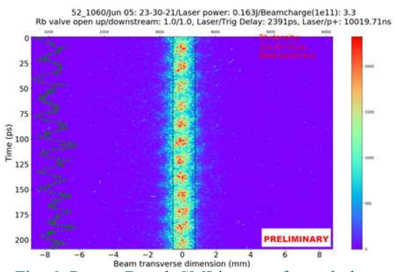


Fig. 6: Proton Bunch SMI in a pre-formed plasma – see Fig. 9b

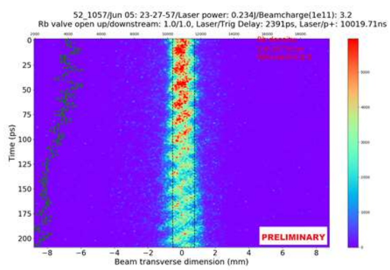


Fig. 7: Proton Bunch SMI in a pre-formed plasma (hosing beam)

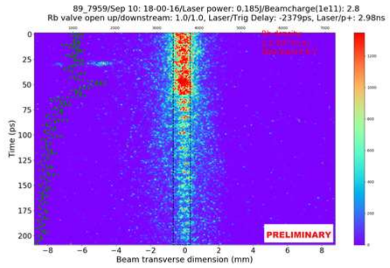


Fig. 8: Comparison: SSM in a laser-induced plasma (marker shows position of the laser) – see Fig. 9a

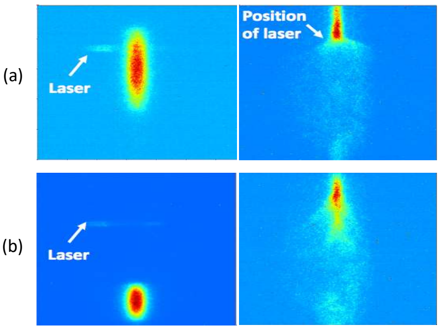


Fig. 9: Effects of laser position on p+ bunch modulation

Conclusion

Although the approach is theoretically very promising and the experimental test could be done within the electron phase of AWAKE Run 1, first experimental results show that the major requirement for feasibility – no significant growth of the SMI for an unseeded proton beam – is not initially given. The random modulation in the trailing part of the proton beam, will make it very hard to achieve the necessary phase stability for micro-bunching in the rear part of the proton bunch.

References

[1] Muggli, Patric, et al. "Physics of the AWAKE Project." (2013): TUPEA008.
[2] AWAKE Collaboration, "AWAKE Status Report 2016" (2016): SPSC-SR-194