The AWAKE collaboration achieves control over the instabilities of a proton bunch in plasma

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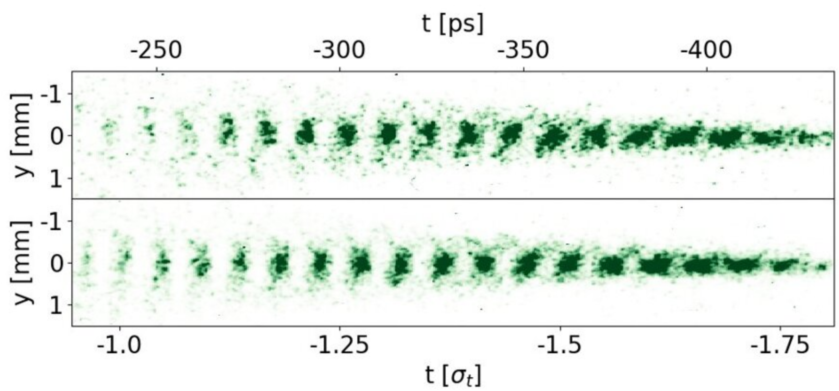

The image summarises one of the paper's important points: that the electron bunch seeds the proton bunch self-modulation (the timing of the micro-bunch train is reproducible from event to event) and that when delaying the timing of the electron bunch, the timing of the modulation is delayed by the same amount. In the bottom figure, the electron bunch is delayed by 7ps, and so is the timing of the micro-bunch train. Credit: AWAKE Collaboration.

The Advanced WAKEfield Experiment (AWAKE) is a large experiment carried out at CERN that investigates plasma wakefield acceleration. It is the first research effort in this field to use a relativistic proton bunch as a driver of plasma wakefields to accelerate witness electrons to high energies.

The use of a proton bunch has numerous advantages for plasma acceleration experiments. Most notably, it allows researchers to maintain a large accelerating gradient over long distances, without having to split the accelerator into several different sections.

The AWAKE collaboration, the group of researchers involved in the AWAKE experiment, includes more than 100 engineers and physicists from 23 different institutes worldwide. In a recent paper published in *Physical Review Letters*, this large team of scientists shows that the self-modulation of a proton bunch can be controlled by seeding the instability.

"Available proton bunches are much longer than the typical plasma wavelength," Livio Verra, one of the researchers who carried out the study, told Phys.org. "To drive large amplitude wakefields, we rely on the self-modulation instability of the bunch in plasma. This process transforms the long bunch into a train of micro-bunches, spaced by the period of the wakefields, that drive large amplitude wakefields."

To ensure that the proton bunch's self-modulation process is reproducible and can be controlled with high levels of precision, the instability of the bunch needs to be "seeded." In their previous studies, the researchers achieved this by turning on the plasma within the proton bunch using a laser pulse.

Despite their promising results, they found that this method had the significant limitation of modulating only a fraction of the proton bunch.

"In our new paper, we show that the self-modulation can be seeded using the wakefields driven by a preceding electron bunch," Verra explained. "In this case, the entire proton bunch self-modulates in a controlled and reproducible way, that is an important milestone for the future of the experiment."

In the context of proton-driven plasma wakefield accelerators, the self-modulation process is essentially an instability, where the amplitude of the wakefields in plasma grows along the proton bunch and along the plasma. The growth of this self-modulation is determined by two key parameters, namely the amplitude of the seed wakefields, which defines the starting value of the fields, and the growth rate, which defines how fast the instability grows.

"By seeding the self-modulation with the preceding electron bunch, we disentangle these two parameters, with which other seeding methods are always correlated," Verra said. "This means that the parameters of the seed electron bunch define the seed wakefields amplitude and the parameters of the proton bunch define the growth rate of the instability."

Using the approach presented in their paper, Verra and his colleagues were able to independently control the growth of the self-modulation of a proton bunch in CERN's plasma particle accelerator using two distinct "knobs." These are essentially the two key parameters that define the self-modulation's growth.

The recent work by this team of researchers shows that the entire proton bunch in their plasma particle accelerator self-modulates in a reproducible way. This crucial finding could pave the way for new experimental design in proton-driven plasma wakefield acceleration, which rely on two separate plasmas.

One of these plasmas would be specifically involved in the self-modulation process, while the other in electron acceleration. These two plasmas will be separated by a gap region, where the injection of the witness electron bunch occurs.

"Since the second plasma will be pre-formed, the entire proton bunch needs to be self-modulated," Verra said. "Moreover, showing the control of an instability is an important standalone physics result, that could be extended to other particular subjects in plasma physics."

Since the beginning of 2022, the AWAKE collaboration has been conducting several studies focusing on the seeding of the self-modulation instability in plasma using an electron bunch. Currently, they are specifically exploring their method's tolerances in terms of the spatial and timing alignment between beams.

"The questions we are trying to address are: how far from each another in transverse position can the electron and proton beams be injected, without destructive instabilities to occur?" Verra added. "And: how far ahead the electron bunch needs to be injected with respect to the proton bunch for seeding effectively? In 2023–2024, we are going to study the effect of a plasma density step on the self-modulation and on the amplitude of the wakefields, and afterwards we will modify the experiment to accommodate the second plasma for the acceleration experiment."

The team's ultimate goal will be that of delivering high-quality and high-energy electron bunches within particle physics experiments. Their next studies will take further steps in this direction.

More information: Controlled growth of the self-modulation of a relativistic proton bunch in plasma. *Physical Review Letters*(2022). DOI: 10.1103/PhysRevLett.129.024802.