

Seeding of self-modulation using truncated seed bunches as a path to high gradient acceleration

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This manuscript proposes a method to enable controlled high gradient particle acceleration when requiring self-modulation (SM) of the drive bunch. While electron bunch seeding of self-modulation has been realized at a plasma electron density [L. Verra *et al.*, (AWAKE Collaboration), Controlled growth of

the self-modulation of a relativistic proton bunch in plasma, *Phys. Rev. Lett.* **129**, 024802 (2022)], it has not been demonstrated at higher plasma densities due to limitations of available seed bunch properties. As experimentally shown in this manuscript, truncating available seed bunches with a relativistic ionization front allows these limitations to be overcome. This seeding method is called truncated electron bunch seeding of self-modulation (teSSM), and experiments confirm that—when using teSSM—self-modulation becomes reproducible. Additionally, the seed wakefield amplitude is also increased, which is known to be advantageous because it shortens the length needed to reach self-modulation saturation. The presented results establish teSSM as a method for achieving controlled, high gradient particle acceleration with long drivers and available seed bunches.

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Plasma wakefields offer a promising route for high gradient acceleration of charged particles. When using plasma electron densities $n_{pe} \gtrsim 10^{14} \text{ cm}^{-3}$, accelerating fields $\gtrsim \text{GV/m}$ can be reached [1,2]. Together with energetic ($\gtrsim 10 \text{ kJ}$) relativistic drivers, energy gains $\gtrsim 100 \text{ GeV}$ can be achieved in a single plasma stage [3,4].

However, a challenge remains: at present, such available energetic drivers are relatively long and, therefore, of relatively low density, $n_b < n_{pe}$. This is because their duration ($\sigma_{t,d}$) exceeds the characteristic timescale of the wakefields given by τ_{pe} , where $\tau_{pe} = 2\pi/\omega_{pe}$. Here, $\omega_{pe} = \sqrt{n_{pe}e^2/m_e\epsilon_0}$ is the plasma electron angular frequency, where m_e and e are the electron mass and charge, respectively, and ϵ_0 is the vacuum permittivity.

Generally, long and low-density bunches cannot effectively drive high amplitude wakefields. Even when the bunch has a sharp onset, the low n_b always results in low field amplitude E_z , which can be estimated by

$$E_z \sim \frac{n_b}{n_{pe}} E_{wb}, \quad (1)$$

where $E_{wb} = m_e c \omega_{pe} / e$ is the cold plasma wave breaking field and c is the vacuum speed of light. For example, for typical experimental values of $n_b = 8 \times 10^{12} \text{ cm}^{-3}$ and $n_{pe} = 7 \times 10^{14} \text{ cm}^{-3}$ [5], $E_z \sim 30 \text{ MV/m}$, far below the possible GV/m when $n_b \sim n_{pe}$.

To drive $\gtrsim \text{GV/m}$ wakefields, initially long and low-density drivers must be transformed into trains of microbunches with microbunches of periodicity τ_{pe} . Such microbunch trains can resonantly drive wakefields, in which case

$$E_z \sim N_{mb} \frac{n_b}{n_{pe}} E_{wb}, \quad (2)$$

where N_{mb} is the number of microbunches. For example, using the same n_b and n_{pe} as above and assuming $N_{mb} = 50$, $E_z \sim 1.5 \text{ GV/m}$.

One way of transforming initially long drivers into trains of microbunches is the self-modulation (SM) process [6–8]: drivers entering plasma excite transverse and

longitudinal wakefields with amplitudes equal or lower than those given by Eq. (1). When $\sigma_{t,d} \gg \tau_{pe}$, the transverse wakefields act periodically, focusing and defocusing the initially long drivers, longitudinally modulating their $n_b(t)$. Here the time coordinate t corresponds to the longitudinal position along the driver in the comoving frame (moving at c). The effect is self-reinforcing, whereby the increasingly modulated drivers excite higher amplitude wakefields, which in turn increase their density modulation until the microbunch trains are fully formed [7,9]. SM can grow from noise [10], e.g., from random perturbations in the density profiles of the drivers. In this case, the process is called the self-modulation instability (SMI), and the phase and amplitude of the wakefields are inherently random. This poses a challenge when accelerating charged particles (i.e., witness bunches), which must always be injected at a precise wakefield phase (time).

It has been demonstrated experimentally [11,12] that phase reproducibility can be achieved by seeding SM, i.e., when providing the same initial perturbation (seed) from which SM grows. When seeded, SM is referred to as seeded self-modulation (SSM). There are three requirements on the seed for SSM to occur: (1) *Dephasing*: The relativistic gamma factor of the seed (γ_{seed}) should be approximately equal to that of the self-modulating driver γ_{SM} . When they differ, the seed and the driver dephase by a distance

$$\Delta L \simeq \frac{1}{2} \left(\frac{1}{\gamma_{SM}^2} - \frac{1}{\gamma_{seed}^2} \right) L_{seed}, \quad (3)$$

where L_{seed} is the seeding distance, i.e., the distance over which the seed must interact with the driver to initiate SSM [10]. Both γ_{SM} and γ_{seed} vary along the plasma [9,13,14]. Successful seeding requires $\Delta L \ll c\tau_{pe}$.

Previous experimental results [11] show SSM for $\Delta L/L_{seed} \lesssim c\tau_{pe}/8$ (with estimated $L_{seed} \sim 2 \text{ m}$ [15]) or when expressed as duration $\Delta\tau/\tau_{pe} \lesssim \tau_{pe}/8$, where $\Delta\tau$ is the accumulated time difference between the seed and driver over L_{seed} . (2) *Amplitude*: The amplitude of the wakefields driven by the seed E_{seed} must exceed the

amplitude of the noise E_{noise} [10]:

$$E_{\text{seed}} > E_{\text{noise}}. \quad (4)$$

Greater E_{seed} shortens the length of plasma required to complete SM, also called saturation [16]. (3) *Reproducibility*: As illustrated in Fig. 1(a) using linear wakefield theory calculations [17], variations ($\Delta\tau_{\text{seed}}$) in seed arrival time τ_{seed} or onset translate into identical variations of wakefield phase $\Delta\phi_{\text{wake}}$ [14], therefore requiring:

$$(\Delta\tau_{\text{seed}} \simeq \Delta\phi_{\text{wake}}) \ll \tau_{\text{pe}}. \quad (5)$$

One method of seeding SM is with a relativistic ionization front (RIF) [12], which creates plasma from gas. For RIF seeding, each short laser pulse propagates through gas, colinearly and temporally overlapped with the driver. The transition to plasma from gas occurs sharply at the leading edge of the laser pulse [12,18,19]. The plasma experiences a sudden onset in drive bunch density at the RIF, which determines the phase and amplitude of the wakefields [12].

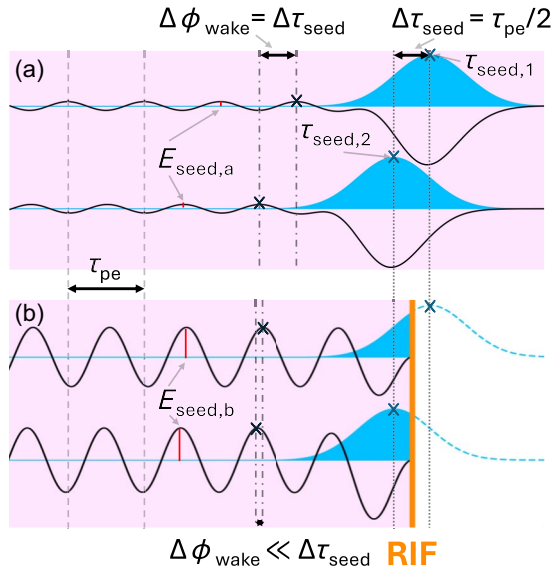


FIG. 1. Transverse wakefields (black solid lines) in plasma (pink shaded areas), driven by Gaussian seed pulses (blue shaded areas). Two vertical gray dashed lines mark the wakefield period τ_{pe} . Figures (a), (b): Wakefield phase difference $\Delta\phi_{\text{wake}}$ (difference between wakefield peak locations, marked by the black crosses and the two vertical gray dotted-dashed lines) from seed arrival time jitter $\Delta\tau_{\text{seed}}$ (difference between $\tau_{\text{seed},1}$ and $\tau_{\text{seed},2}$, marked by the blue crosses and the two vertical gray dotted lines) for the (a) electron bunch seeding of self-modulation (eSSM) and (b) truncated electron bunch seeding of self-modulation (teSSM). Field amplitudes E_{seed} (vertical red solid lines) on the same vertical scale. Figure (b): Solid vertical orange line is the RIF position. Bunches and wakefields propagate to the right.

RIF seeding was experimentally demonstrated using 400 GeV proton drivers ($\gamma_{\text{SM}} = 427$) in plasma with $n_{\text{pe}} \approx 1\text{--}10 \times 10^{14} \text{ cm}^{-3}$ and laser pulses of central wavelength $\lambda_l = 780 \text{ nm}$ ($\gamma_{\text{seed}} \approx 1600$) (meeting condition 1. Dephasing), with seed amplitude $\geq 4 \text{ MV/m}$ (meeting condition 2. Amplitude) [12] and $\Delta\tau_{\text{seed}} \approx 0.1 \text{ ps} \ll \tau_{\text{pe}} \sim 11\text{--}3.5 \text{ ps}$ (meeting condition 3. Reproducibility) [18,19].

RIF seeding has several limitations: the part of the drivers located ahead of the RIF remains in gas and therefore does not contribute to the wakefields; this part could undergo SMI when entering a subsequent preionised plasma (e.g., second plasma stage), potentially disrupting the wakefields [13,20]. Furthermore, the seed wakefield amplitude cannot be adjusted independently of the driver parameters and of the RIF position.

Alternatively, wakefields from preceding bunches can seed SM, enabling modulation of the entire driver and independent adjustment of the seed wakefield amplitude [11]. This was experimentally demonstrated using $\sim 20 \text{ MeV}$ electron bunches ($\gamma_{\text{seed}} \sim 40$) in plasma (eSSM) with $n_{\text{pe}} \approx 1 \times 10^{14} \text{ cm}^{-3}$ [11].

Meeting all three SSM conditions becomes increasingly difficult at higher n_{pe} , because τ_{pe} decreases, and conditions 1. Dephasing and 3. Reproducibility become more difficult to meet. An example of typically available bunch and plasma parameters that are not compatible can be found in the Appendix. A higher n_{pe} is generally preferred (e.g., $n_{\text{pe}} = 7 \times 10^{14} \text{ cm}^{-3}$ for Advanced WAKEfield Experiment [AWAKE]), since it enables higher accelerating fields with appropriate drivers [Eqs. (1) and (2) with $E_{\text{wb}} \sim 2.6 \text{ GV/m}$]. At such n_{pe} , eSSM does not work with available seed bunches (e.g., see the Appendix). However, there is a solution: truncating electron seed bunches with an RIF. This can be realized by overlapping every seed bunch with an RIF [as illustrated in Fig. 1(b)], creating a sharp plasma onset within the seed. The SSM conditions are then as follows: (1) *Dephasing*: γ_{seed} is now defined by the RIF and becomes γ_{RIF} , provided the RIF is inside the seed bunch. The optimal initial placement of the RIF within the seed ($t_{\text{RIF}}^{\text{opt}}$) was found by maximizing the average energy loss of the electron beam in plasma in the absence of protons. In practice, it can be estimated as:

$$t_{\text{RIF}}^{\text{opt}} = 2\sigma_{\text{t,s}} + \frac{L_{\text{seed}}}{2c} \left(\frac{1}{\gamma_{\text{RIF}}^2} - \frac{1}{\gamma_{\text{bunch}}^2} \right), \quad (6)$$

where γ_{bunch} is the relativistic gamma factor of the seed bunch and $\sigma_{\text{t,s}}$ is its duration. Since $\gamma_{\text{RIF}} > \gamma_{\text{bunch}}$, an increasing fraction of the seed bunch charge is in plasma and experiences focusing as the bunches propagate [22]. This is illustrated by linear theory calculations in Fig. 1(b), where the seed bunch moves later by $\tau_{\text{pe}}/2$ with respect to the RIF and the additional seed charge that enters the plasma [23] induces only a small wakefield phase

difference $\Delta\phi_{\text{wake}} \sim \tau_{\text{pe}}/8 \ll \Delta\tau_{\text{seed}}$. (2) *Amplitude*: When seed bunches are longer than optimal ($\sigma_{t,s} > \tau_{\text{pe}}/(\sqrt{2}\pi)$), they can be shortened by the RIF to increase E_{seed} [17], as illustrated in Figs. 1(a) and 1(b) by comparing the field amplitudes behind the seeds (red vertical lines), which show $E_{\text{seed},b} \simeq 6 \times E_{\text{seed},a}$. (3) *Reproducibility*: Differences in the seed arrival time ($\Delta\tau_{\text{seed}}$) are also illustrated by Fig. 1(b). The benefit is that, instead of variations in $\Delta\tau_{\text{seed}}$ directly translating into variations in the wakefield phase, $\Delta\phi_{\text{wake}}$ is reduced. In the example of Fig. 1(b), $\Delta\phi_{\text{wake}}$ is $\approx \Delta\tau_{\text{seed}}/8$ with teSSM instead of $\approx \Delta\tau_{\text{seed}}$ with eSSM [Fig. 1(a)].

Experiments are conducted in AWAKE [5] at CERN. A schematic of the experimental setup is shown in Fig. 2, at the center of which a 10.3 m long rubidium vapor source (gray) provides vapor densities $n_{\text{vapor}} = 1\text{--}10 \times 10^{14} \text{ cm}^{-3}$ [24]. The rubidium atoms are singly ionized by a $(100 \pm 5) \text{ mJ}$, 120 fs laser pulse, creating a plasma column (pink) with density equal to that of the rubidium vapor [25]. In this manuscript, measurements are performed with $n_{\text{pe}} = (7.01 \pm 0.05) \times 10^{14} \text{ cm}^{-3}$ (AWAKE density baseline for acceleration).

The drivers are 400 GeV proton bunches provided by the CERN SPS of charge $(46000 \pm 2000) \text{ pC}$. They are

longitudinally approximately Gaussian with an rms duration of $\sigma_{t,p} = (170 \pm 8) \text{ ps} \gg \tau_{\text{pe}}$ and rms transverse sizes at the entrance of the plasma of $(200 \pm 15) \mu\text{m}$. Their rms arrival time jitter is $\sim 6 \text{ ps}$.

Electron seed bunches (with an energy per particle of 17.8 MeV) are produced by an S-band rf photo-injector [26] and transported to the entrance of the vapor source by a 15-m-long transfer line [27,28]. The last quadrupole triplet in the transfer line focuses the seed bunches and places the waist (rms transverse sizes $\sigma_{r,s} = (200 \pm 40) \mu\text{m}$) at the entrance of the vapor source [29]. The rms longitudinal duration of the seed bunches is $\sigma_{t,s} = (2.1 \pm 0.5) \text{ ps}$ for a charge per bunch of $(200 \pm 20) \text{ pC}$. Due to diagnostics limitations, the arrival time jitter cannot be quantified.

Each ionizing laser pulse in vapor creates an RIF. For each event and measurement configuration [Figs. 2(a)–2(c)], the RIF is positioned $\sim 650 \text{ ps}$ ahead of the driver center, which is defined as $t = 0$. However, the seeding method differs in each configuration. For SMI [Fig. 2(a)], there is no seed bunch, the RIF arrives much before the driver and SM starts from driver noise. For eSSM [Fig. 2(b)], the electron bunch seed arrives $\approx 60 \text{ ps}$ after the RIF and is therefore entirely in plasma. For teSSM [Fig. 2(c)], the electron bunch

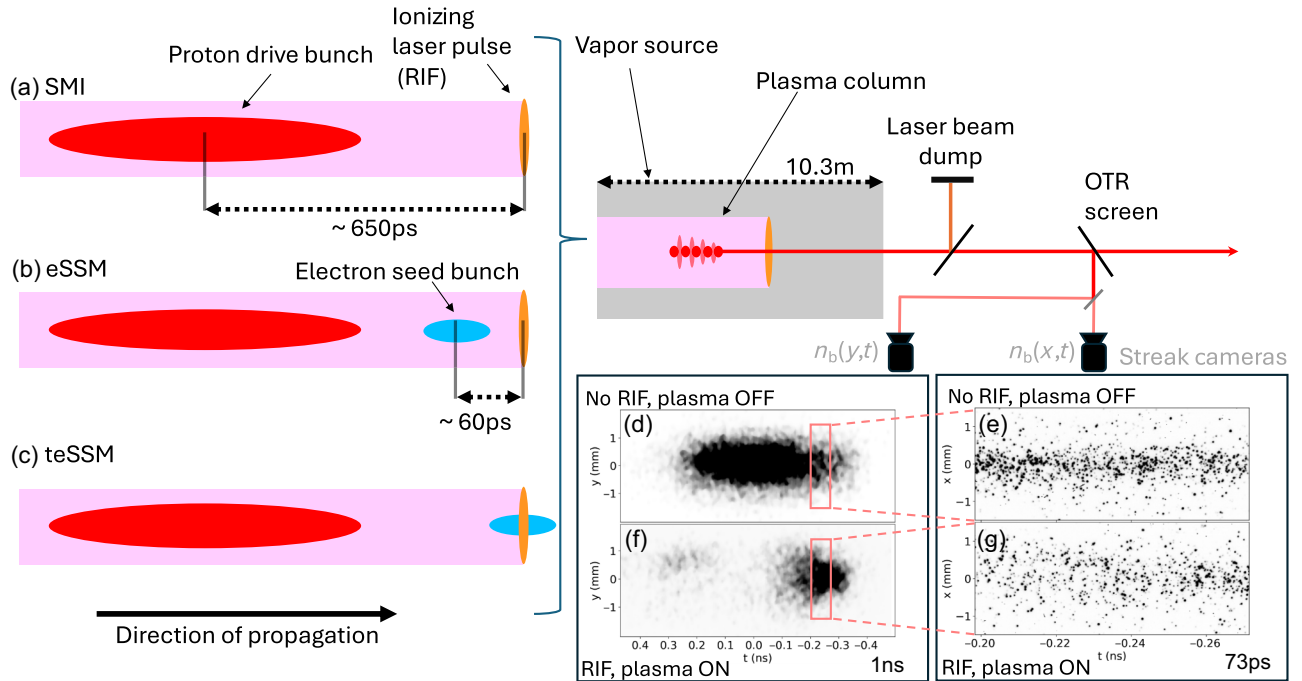


FIG. 2. Schematic of the experimental setup. Proton drivers (red) propagate through plasma (pink) in the vapor source (gray). Rubidium vapor is ionized by the RIF (orange). There are three configurations: SMI (a): drivers preceded by an RIF; eSSM (b): drivers preceded by seed bunches, both preceded by an RIF; teSSM (c): drivers preceded by seed bunches, which are overlapped in space and time with the RIF. Downstream of the plasma and the laser beam dump, longitudinal proton bunch densities are measured using an optical transition radiation (OTR) screen and two streak cameras [21]. One streak camera measures the time-resolved drive bunch density with a time window of 1 ns ($n_b(y, t)$) and the second one with a time window of 73 ps [$n_b(x, t)$], where x and y are perpendicular transverse dimensions and t is the axis along the bunch. Subfigures (d) and (e): Measurements without plasma, in a vacuum; (f) and (g): Measurements with plasma [in configuration (a)]. Bunches and pulses propagate to the right.

is positioned such that it overlaps with the RIF at $t_{\text{RIF}}^{\text{opt}} \sim +\sigma_{t,s}$ (optimum from Eq. (6) with $\gamma_s \sim 40$, $\gamma_{\text{RIF}} \sim 1600$, and an estimated $L_{\text{seed}} = 2$ m [15]).

Downstream of the plasma, proton drivers traverse an aluminum-coated metallic screen, where they emit OTR. The backward OTR is split by a 45:55 beamsplitter, filtered with a bandpass filter transmitting only wavelengths within a range of (450 ± 25) nm, and imaged onto the entrance slits of two streak cameras. Each slit selects a $\Delta x, \Delta y \sim 80$ μm -wide region around the bunch axis, with the two slits oriented orthogonally in the x and y planes [30]. Time-resolved driver bunch densities, $n_b(x, t)$ and $n_b(y, t)$, are thus measured simultaneously over time windows of 73 ps and 1 ns, respectively. Typical measurements of the bunch after propagation in vacuum (no plasma) are shown in Figs. 2(d) and 2(e). In this case, the bunch structure is approximately Gaussian on the 1 ns timescale and approximately uniform on the 73 ps timescale, as expected when the driver duration ($\sigma_{t,p} \approx 170$ ps) is much longer than the measurement time window (73 ps).

Measurements of $n_b(x, t)$ and $n_b(y, t)$ are then also performed in the presence of plasma [Figs. 2(f) and 2(g)]. In this case, the measured $n_b(y, t)$ [Fig. 2(f)] differs significantly from those obtained without plasma, as expected when SM develops [8,25]. Similarly, $n_b(x, t)$ measurements with plasma [Fig. 2(g)] show subtle differences, particularly a lower bunch density due to proton defocusing by the wakefields. Due to measurement noise and the limited temporal resolution of the streak camera, microbunches at this n_{pe} are not well defined for all three scenarios. The measurement quality is insufficient to determine the microbunch timing and frequency from all individual measurements and therefore to distinguish between SSM and SMI.

However, the key feature of SSM is that the microbunch timing is reproducible from event to event, which can still be assessed by summing multiple measurements of $n_b(x, t)$, as shown in Fig. 3. Summing is made possible by using an absolute time reference with respect to the RIF, as described in Ref. [12]. When the microbunch timing is different from event to event, the periodic longitudinal modulation averages out in the sum. This means that although SM occurs, it is not reproducible. This was observed when using either no seed [SMI, Fig. 3(a)] or the entire electron bunch as a seed [eSSM, Fig. 3(b)], in which case the vertical projections [blue dotted and orange dashed lines in Fig. 3(d)] do not show any periodic structure at this n_{pe} .

Conversely, when the microbunch timing is reproducible—meaning that the microbunch positions along t are consistent from event to event—the signal-to-noise ratio and therefore modulation depth increases when multiple measurements are summed, making the longitudinal structure observable. This was the case with teSSM, where a periodic modulation (microbunch

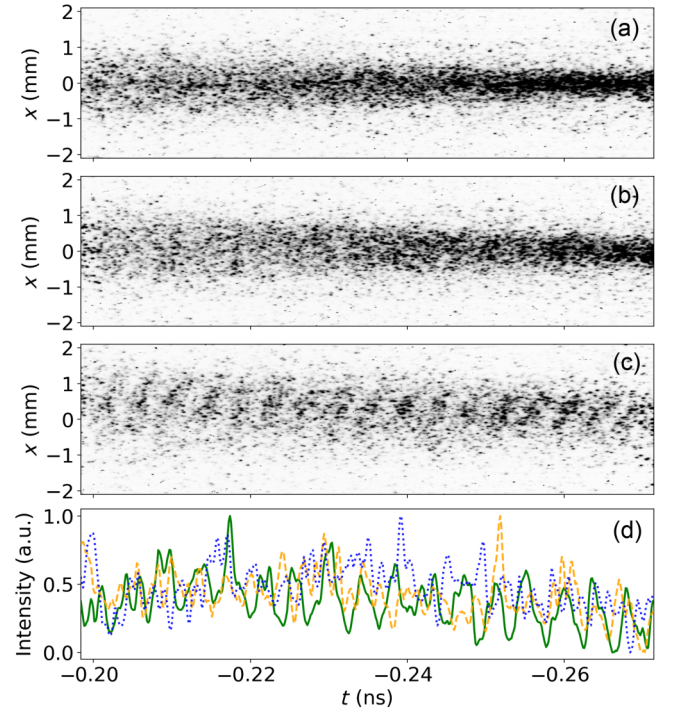


FIG. 3. Measurements of 12 summed proton bunch density profiles $n_b(x, t)$, aligned in time following the same procedure as in Ref. [12], when using (a) SMI, (b) eSSM, and (c) teSSM. Figures (a)–(c): On the same color scale and identical streak camera settings. Figure (d): Vertical projections for SMI [(a), blue dotted line]; eSSM [(b), orange dashed line]; and teSSM [(c), green solid line]. Intensity normalized to the peak value. Bunches propagate to the right.

structure) becomes visible in the summed measurement [Fig. 3(c)] as well as its vertical projection [green solid line in Fig. 3(d)]. The teSSM measurements in Figs. 3(c) and 3(d) show approximately 17 microbunches within the 73 ps time window. This indicates that the observed periodic structure results from the driver undergoing SM, because the measured modulation period, $\tau = 73 \text{ ps}/17 \approx 4.3 \text{ ps}$, is close to the plasma period predicted by wakefield theory for this n_{pe} , $\tau_{pe} = 2\pi/\omega_{pe} = (4.21 \pm 0.2) \text{ ps}$.

To obtain a more accurate measurement of the wakefield period and to also test for the presence of periodic modulation in the SMI [Fig. 3(a)] and eSSM [Fig. 3(b)] measurements, a FFT analysis is performed on all the lineouts shown in Fig. 3(d). Results are shown in Fig. 4, where for SMI (blue dotted line) and eSSM (orange dashed line), the FFT frequency spectrum shows no prominent peak [max. peak amplitude: 0.0042 (SMI), 0.0048 (eSSM), $\ll 0.014$ (teSSM)], indicating that no dominant frequency is present. This is as expected when the longitudinal microbunch structure is not reproducible and is thus averaged out by the summation. However, for teSSM (green solid line), the FFT frequency spectrum shows a prominent peak at the expected period, $\tau/\tau_{pe} = 1$

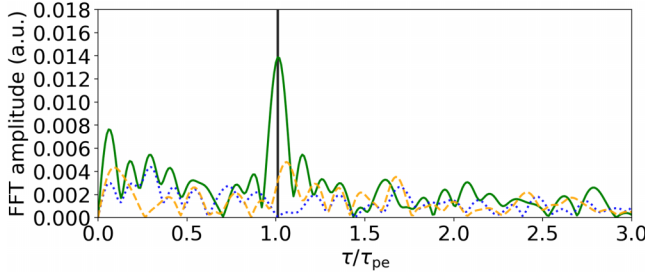


FIG. 4. Normalized amplitude resulting from the fast Fourier transform (FFT) analysis as a function of the normalized period τ/τ_{pe} on the projections in Fig. 3(d), for SMI (blue dotted line), eSSM (orange dashed line), and teSSM (green solid line). Black vertical line centers around the FFT peak, and its width indicates the FFT bin width.

(indicated by the vertical black solid line). This is only possible when SM is seeded and implies that all conditions discussed above are fulfilled.

Simultaneously with the measurements shown in Fig. 3, measurements on the nanosecond timescale in the perpendicular plane ($n_b(y, t)$) are also performed. Representative single-event measurements are shown in Fig. 5: for SMI (a), for eSSM (b), and for teSSM (c).

First, the clear difference between these measurements and the no-plasma case shown in Fig. 2(d) indicates that SM develops for all configurations and events. The indication that SM developed is the charge disappearance ($t > -0.2$ ns) along the bunch. Particles that are focused and defocused by the wakefields during SM diverge downstream of the plasma, and their density within the streak camera slit decreases. This implies that individual measurements contributing to Figs. 3(a) and 3(b) are from self-modulated drivers. Therefore, SM must start from noise for SMI and from either noise or the electron seed bunch for eSSM.

However, Figs. 5(a) (SMI) and 5(b) (eSSM) also differ. This is clear when, e.g., comparing the vertical projections and their uncertainties, shown in Fig. 5(e): for eSSM (orange dashed line), the projection peaks at slightly earlier t and at lower amplitudes (0.90 ± 0.05) than for SMI (blue dotted line) at 1.00 ± 0.03 . Because SM develops in the eSSM configuration and differs from SMI for the given bunch and plasma parameters [Fig. 5(e)], the conditions for 1. Dephasing and 2. Amplitude must have been satisfied; otherwise, SM could not have developed. However, the lack of reproducibility in microbunch timing (Fig. 3) shows that the 3. Reproducibility condition was not met.

In addition to the measured $n_b(y, t)$, Figs. 5(a)–5(c) (colored lines) show the transverse sizes of each pixel line of the bunch $n_b(y)$, obtained as in Ref. [11]. All of these sizes, along with their uncertainties (given by the standard deviation over 12 measurements), are summarized in Fig. 5(d). Both the projections [Fig. 5(e)]

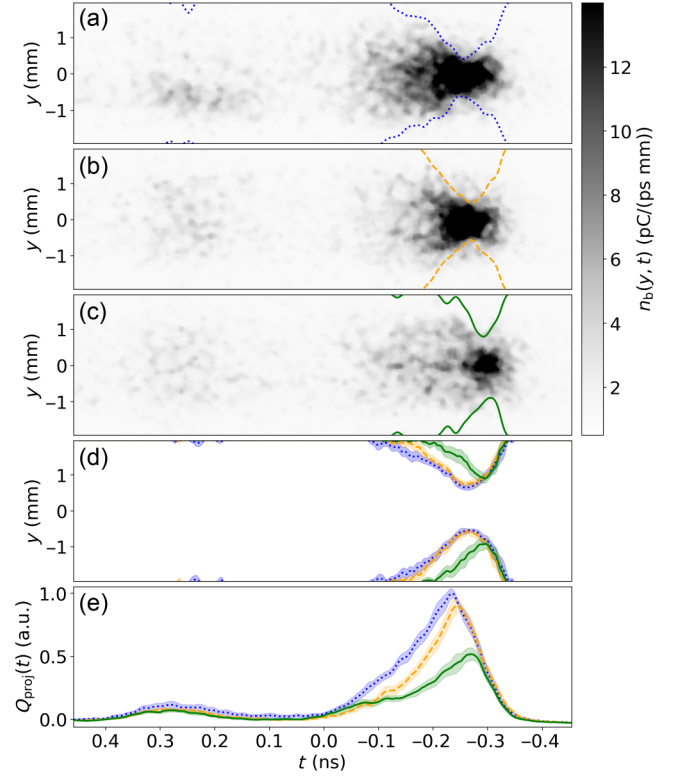


FIG. 5. Single measurements of $n_b(y, t)$ for (a) SMI, (b) eSSM, and (c) teSSM. Figures (a)–(c): On the same color scale and identical streak camera settings. Median filter [31] with size = 3 applied to reduce measurement noise. Where $< \pm 2$ mm, colored lines in (a)–(c) mark where $n_b(y)$ profiles reach 20% of their peak value, as in Ref. [11]. Figure d: Same quantity, but displays the mean (line) and standard deviation (colorband) of the 12 measurements of Figs. 3(a)–3(c) for SMI (blue dotted line), eSSM (orange dashed line), and teSSM (green solid line). Figure (e) shows the mean (line) and standard deviations (colorband) of the vertical projections of $n_b(y)$ for the 12 measurements. Bunches propagating to the right.

and the transverse bunch sizes along t [Fig. 5(d)] exhibit faster variations for teSSM than for eSSM, and both vary faster than for SMI. This indirectly gives information about the seed field amplitude E_{seed} because higher E_{seed} results in faster SM growth along both the plasma and the bunch. Along the bunch, this appears as a more rapid rise and fall in the vertical projections and a faster evolution of the transverse size, as discussed in Refs. [30,32].

One can also compare, e.g., at which t transverse sizes reach a value of ± 2 mm in Fig. 5(d): before the charge peak ($t < -0.25$ ps), this size is reached around $t = (-0.35 \pm 0.05)$ ps for all configurations, showing that SM starts at the same t . After the peak ($t > -0.25$ ps), this size is reached first with teSSM at $t = (-0.2 \pm 0.05)$ ps, followed by eSSM at $t = (-0.15 \pm 0.05)$ ps, and last with SMI at $t = (-0.1 \pm 0.06)$ ps. This means that E_{seed} is higher for teSSM than for eSSM and lowest for SMI,

as expected. As mentioned above, a higher E_{seed} offers several advantages: for example, it reduces the seeding distance L_{seed} and allows SM to dominate over other instabilities, such as the beam hose instability [33,34].

For the bunch and plasma parameters used in the presented measurements, the teSSM configuration increases E_{seed} , with respect to eSSM since the available seed bunches are initially longer than optimal ($\sigma_{t,s} \approx 2$ ps compared to $\sigma_{t,s,\text{opt}} = \tau_{\text{pe}}/(\sqrt{2}\pi) \sim 1$ ps). The teSSM configuration then effectively shortens the seed initially, removing front-to-back energy transfer in the wakefield and therefore increasing E_{seed} as illustrated in Fig. 1 when comparing $E_{\text{seed,a}}$ [Fig. 1(a)] and $E_{\text{seed,b}}$ [Fig. 1(b)].

The results in this manuscript experimentally show that truncating seed bunches with an RIF (teSSM) overcomes limitations encountered with established seeding methods [11,12]. For RIF seeding, the head of the driver may self-modulate when entering a pre-ionized plasma and seeding with available bunches [Fig. 2(b)] was previously only demonstrated at low plasma density (n_{pe}) [11]. These limitations are overcome by using teSSM, where seeds are shaped by truncation at the overlap with the RIF. In this way, there are no driver particles ahead of the RIF, and the relativistic gamma factor of the seed wakefields is close to that of the drivers, despite evolution. This enables seeding of SM of entire drivers at high n_{pe} . When using available seed bunches in AWAKE, the timing of microbunches is reproducible at the baseline plasma density of $n_{\text{pe}} = 7 \times 10^{14} \text{ cm}^{-3}$, only when using teSSM. Additionally, by measuring the time-resolved proton bunch charge density, it can be inferred that teSSM increases the seed wakefield amplitude, which is advantageous since it shortens the length needed until SM saturates and helps SM dominate over other instabilities [33,34]. These results are important because they provide a method to seed reproducible SM at any plasma density with available seed bunches. Therefore, the method of teSSM enables controlled high gradient particle acceleration when requiring SM, e.g., for a preionized plasma.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX

For example, for 400 GeV/c proton drivers undergoing SM in a plasma of $n_{\text{pe}} = 7 \times 10^{14} \text{ cm}^{-3}$ ($\tau_{\text{pe}} \approx 4$ ps) and seeding using 20 MeV electron bunches ($\sigma_{t,s} \approx 2$ ps, $n_b \approx 1.7 \times 10^{13} \text{ cm}^{-3}$) with an estimated arrival time jitter of $\Delta\tau_{\text{seed}} \sim 2$ ps: (1) *Dephasing*: Using $\gamma_{\text{SM}} = 427$ and $\gamma_{\text{seed}} = 40$ results in $\Delta\tau/\tau_{\text{pe}} \sim 1.3$ ps/m. Requirement may be violated, depending on L_{seed} . (2) *Amplitude*: $E_{\text{seed}} \sim 10$ MV/m [11] and $E_{\text{noise}} \sim 3$ MV/m [12]. However, the electron bunches exceed the optimal duration ($\sigma_{t,s,\text{opt}} = \tau_{\text{pe}}/(\sqrt{2}\pi) \sim 1$ ps) at this n_{pe} , reducing E_{seed} through front-to-back energy transfer within the seed. (3) *Reproducibility*: Requirement violated since $\Delta\tau_{\text{seed}} \sim 2$ ps and $\tau_{\text{pe}} \approx 4$ ps.

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- [1] E. Esarey, C. B. Schroeder, and W. P. Leemans, Physics of laser-driven plasma-based electron accelerators, *Rev. Mod. Phys.* **81**, 1229 (2009).
 - [2] T. Tajima and J. M. Dawson, Laser electron accelerator, *Phys. Rev. Lett.* **43**, 267 (1979).
 - [3] A. Caldwell, K. Lotov, A. Pukhov, and F. Simon, Plasma wakefield acceleration with a proton beam, *Nat. Phys.* **5**, 363 (2009).
 - [4] AWAKE Collaboration, Acceleration of electrons in the plasma wakefield of a proton bunch, *Nature (London)* **561**, 363 (2018).
 - [5] E. Gschwendtner *et al.* (AWAKE Collaboration), The awake run 2 programme and beyond, *Symmetry* **14**, 1680 (2022).
 - [6] M. Turner *et al.* (AWAKE Collaboration), Experimental study of wakefields driven by a self-modulating proton bunch in plasma, *Phys. Rev. Accel. Beams* **23**, 081302 (2020).
 - [7] N. Kumar, A. Pukhov, and K. Lotov, Self-modulation instability of a long proton bunch in plasmas, *Phys. Rev. Lett.* **104**, 255003 (2010).
 - [8] M. Turner *et al.* (AWAKE Collaboration), Experimental observation of plasma wakefield growth driven by the seeded self-modulation of a proton bunch, *Phys. Rev. Lett.* **122**, 054801 (2019).
 - [9] C. B. Schroeder, C. Benedetti, E. Esarey, F. J. Gr ner, and W. P. Leemans, Growth and phase velocity of self-modulated beam-driven plasma waves, *Phys. Rev. Lett.* **107**, 145002 (2011).
 - [10] K. V. Lotov, G. Z. Lotova, V. I. Lotov, A. Upadhyay, T. T ckmantel, A. Pukhov, and A. Caldwell, Natural noise and external wakefield seeding in a proton-driven plasma accelerator, *Phys. Rev. ST Accel. Beams* **16**, 041301 (2013).

- [11] L. Verra *et al.* (AWAKE Collaboration), Controlled growth of the self-modulation of a relativistic proton bunch in plasma, *Phys. Rev. Lett.* **129**, 024802 (2022).
- [12] F. Batsch *et al.* (AWAKE Collaboration), Transition between instability and seeded self-modulation of a relativistic particle bunch in plasma, *Phys. Rev. Lett.* **126**, 164802 (2021).
- [13] K. V. Lotov, Physics of beam self-modulation in plasma wakefield accelerators, *Phys. Plasmas* **22**, 103110 (2015).
- [14] A. Pukhov, N. Kumar, T. Tückmantel, A. Upadhyay, K. Lotov, P. Muggli, V. Khudik, C. Siemon, and G. Shvets, Phase velocity and particle injection in a self-modulated proton-driven plasma wakefield accelerator, *Phys. Rev. Lett.* **107**, 145003 (2011).
- [15] With an electron beam energy of ≈ 20 MeV and $E_{\text{seed}} \approx 10$ MV/m, $L_{\text{seed}} \sim 2$ m.
- [16] A. Clairembaud *et al.* (AWAKE Collaboration), Measurement of the saturation length of the self-modulation instability, [arXiv:2602.16624](https://arxiv.org/abs/2602.16624).
- [17] R. Keinigs and M. E. Jones, Two-dimensional dynamics of the plasma wakefield accelerator, *Phys. Fluids* **30**, 252 (1987).
- [18] G. Demeter, J. T. Moody, M. Á. Kedves, F. Batsch, M. Bergamaschi, V. Fedosseev, E. Granados, P. Muggli, H. Panuganti, and G. Zevi Della Porta, Generation of 10-m-lengthscale plasma columns by resonant and off-resonant laser pulses, *Opt. Laser Technol.* **168**, 109921 (2024).
- [19] V. Fedosseev *et al.*, Proc. int. part. acc. conf. (IPAC'16), in *Proc. Int. Part. Acc. Conf.* (2016).
- [20] L. Verra *et al.* (AWAKE Collaboration), Filamentation of a relativistic proton bunch in plasma, *Phys. Rev. Lett.* **109**, 055203 (2024).
- [21] K. Rieger, A. C. Caldwell, P. Muggli, and O. Reimann. Streak Cameras and Optical Transition Radiation as a Diagnostic for Self-Modulation of Charged Particle Beams in Plasmas, Master's Thesis, Technical University, Munich, 2014.
- [22] With an initial timing of $t_{\text{RIF}}^{\text{opt}}$, the laser pulse reaches $2\sigma_{t,s}$ ahead of the electron beam centre after propagating over L_{seed} . This setting resulted in the fastest defocusing along the proton bunch [Fig. 5(c)] from all tried settings.
- [23] It is noted that the self-field of the electron bunch is not sufficient to ionise rubidium vapour or further ionise rubidium ions.
- [24] P. Muggli, M. Bergamaschi, J. Pucek, D. Easton, J. Pisani, and J. Uncles, Plasma light as diagnostic for wakefields driven by developing self-modulation of a long particle bunch, in *Proc. Adv. Acc. Conf. (AAC2022)* (2022).
- [25] AWAKE Collaboration, Experimental observation of proton bunch modulation in a plasma at varying plasma densities, *Phys. Rev. Lett.* **122**, 054802 (2019).
- [26] Y. Kim *et al.*, Commissioning of the electron injector for the awake experiment, *Nucl. Instrum. Methods Phys. Res., Sect. A* **953**, 163194 (2020).
- [27] K. Pepitone *et al.*, The electron accelerators for the awake experiment at CERN—baseline and future developments, *Nucl. Instrum. Methods Phys. Res., Sect. A* **909**, 102 (2018).
- [28] J. S. Schmidt *et al.*, Status of the proton and electron transfer lines for the awake experiment at CERN, *Nucl. Instrum. Methods Phys. Res., Sect. A* **829**, 58 (2016).
- [29] N. Z. van Gils, M. Turner, G. Z. Della Porta, V. Bencini, E. Gschwendtner, L. Ranc, F. Pannell, and A. Gerbershagen, Preparation for realisation of external electron injection for awake run 2b, in *Proceedings of the International Particle Accelerator Conference (IPAC'24)* (JACoW Publishing, Geneva, Switzerland, 2024), pp. 549–552.
- [30] M. Turner and P. Muggli, Understanding time-resolved images of awake proton bunches, *J. Phys.:Conf. Ser.* **3124**, 012007 (2024).
- [31] C. R. Harris *et al.*, Array programming with NumPy, *Nature (London)* **585**, 357 (2020).
- [32] M. Turner *et al.* (AWAKE Collaboration), Experimental observation of the motion of ions in a resonantly driven plasma wakefield accelerator, *Phys. Rev. Lett.* **134**, 155001 (2025).
- [33] J. Vieira, W. B. Mori, and P. Muggli, Hosing instability suppression in self-modulated plasma wakefields, *Phys. Rev. Lett.* **112**, 205001 (2014).
- [34] M. Moreira, P. Muggli, and J. Vieira, Mitigation of the onset of hosing in the linear regime through plasma frequency detuning, *Phys. Rev. Lett.* **130**, 115001 (2023).