The REsonant Multi-Pulse Ionization injection

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The production of high-quality electron bunches in Laser Wake Field Acceleration relies on the possibility to inject ultra-low emittance bunches in the plasma wave. In this paper we present a new bunch injection scheme in which electrons extracted by ionization are trapped by a large-amplitude plasma wave driven by a train of resonant ultrashort pulses. In the REsonant Multi-Pulse Ionization (REMPI) injection scheme, the main portion of a single ultrashort (e.g. Ti:Sa) laser system pulse is temporally shaped as a sequence of resonant sub-pulses, while a minor portion acts as an ionizing pulse. Simulations show that high-quality electron bunches with normalized emittance as low as 0.08 mm×mrad and 0.65% energy spread can be obtained with a single present-day 100TW-class Ti:Sa laser system.

I. INTRODUCTION

High-quality Laser Wake Field Accelerated (LWFA) electron bunches are nowadays requested for several applications including Free Electron Lasers [1–5], X/γ radiation sources [6–8] and staged acceleration [9–13]. While performances of self-injected bunches generated in the so-called bubble-regime [14–15] continue to improve, other promising injection schemes, including injection via density downramp [16–20], colliding pulses injection [21–23] and ionization injection [24–32], are under active theoretical and experimental investigation.

Evolution of the ionization injection, based on the use of two laser pulses (either with the same or different wavelengths), were proposed in [33–36]. In the two-colour ionization injection [34] the main pulse that drives the plasma wave has a long wavelength, five or ten micrometers, and a large amplitude \( a_0 = \varepsilon A/\varepsilon mc^2 = 8.5 \cdot 10^{-19} \sqrt{I \lambda^2} > 1 \), being \( I \) and \( \lambda \) pulse intensity in \( W/cm^2 \) and wavelength in \( \mu m \). The second pulse (the “ionization pulse”) possesses a large electric field though its amplitude is low. This is achieved by doubling the fundamental frequency of a Ti:Sa pulse. While the main pulse cannot ionize the electrons in the external shells of the contaminant species due to its large wavelength, the electric field of the ionization pulse is large enough to generate newborn electrons that will be trapped in the bucket. This opens the possibility of using gas species with relatively low ionization potentials, thus enabling separation of wake excitation from particle extraction and trapping.

Two colour ionization injection is therefore a flexible and efficient scheme for high-quality electron bunch production. The main drawbacks of the two colour ionization injection are the current lack of availability of short (T<100 fs) 100TW-class laser systems operating at large (≈ 10μm) wavelength and lasers synchronization jitter issues. These limitation make the two-colour scheme currently unpractical for application to LWFA-based devices requiring high quality beams.

In this paper we propose a new injection configuration (we will refer to it as REsonant Multi-Pulse Ionization injection, REMPI) that overcomes these limitations and opens the way to a reliable generation of high quality Laser Wakefield accelerators. The breakthrough of our REMPI scheme is to replace the long wavelength driving pulse of the two-colour scheme with a short wavelength, resonant multi-pulse laser driver. Such a driver can be obtained via temporal shaping techniques from a single, linearly polarized, standard CPA laser pulse. A minor fraction of the same pulse is frequency doubled (or tripled) and used as ionizing pulse. Due to the resonant enhancement of the ponderomotive force, a properly tuned train of pulses is capable of driving amplitude waves larger than a single pulse with the same energy [37–38] (see Fig. 2 where a comparison between a single-pulse and an eight-pulses train is shown). Noticeably, since the peak intensity of the driver is reduced by a fac-
Figure 2. Single-pulse vs eight-pulses train comparison. Pulses (moving through the left) with duration of 10fs and waist size of 25 µm are focused in a $n_e = 5 \times 10^{18}$ cm$^{-3}$ plasma. The single-pulse (red thick line) with peak intensity of $5.9 \times 10^{18}$W/cm$^2$ drives a plasma wave whose maximum accelerating gradient is 20% less than that of the wave excited by the eight-pulses train having the same delivered energy and intensity $7.4 \times 10^{17}$W/cm$^2$. QFluid and PIC (ALaDyn 2D) simulation are in excellent agreement.

Figure 3. Trapping conditions. Blue lines: weak trapping condition; red lines: strong trapping condition. Top: trapping conditions in a 1D nonlinear limit vs plasma density from 1D analytical expression Eqqs. 2 and 3. RUN 1,2 refer to the working points of the state-of-the-art simulation (Sec. IV) and the simulation in Appendix II, respectively. Bottom: scan of maximum accelerating normalized fields as in the RUN 1 setup ($T = 30$ fs, $n_e = 5 \times 10^{17}$cm$^{-3}$, $w_0 = 45$ µm) as a function of pulse amplitude and the number of pulses in the train. The cases of a single pulse and two, four and eight-pulses trains with three different delivered energies of 2.5J, 5.0 J and 7.5 J have been considered.

II. TRAPPING CONDITIONS IN REMPI

To set conditions of particles trapping in the plasma wave we will set focus on a laser pulse configuration with a beam waist $w_0$ exceeding the plasma wavelength $\lambda_p$, where the longitudinal ponderomotive force dominates over radial wakefield force. In the 1D limit, the Hamiltonian of a passive particle in the plasma wave is [41]

$$H = (1 + u_z^2)^{1/2} - \beta_{ph} u_z - \phi$$

where $\beta_{ph}$ is wave phase velocity (transverse contribution to the Lorentz factor has been neglected since relatively low values of the pulse amplitudes will be considered here). The separatrix Hamiltonian $H_s$ decomposes the phase space in a sequence of periodic buckets, so trapping of newborn electrons occurs if the particle Hamiltonian satisfies $H \leq H_s$, i.e if

$$\phi_e \geq 1 - 1/\gamma_{ph} + \phi_{min} \tag{1}$$

being $\phi_e$ the normalized electrostatic potential at particle extraction and $\phi_{min}$ the minimum potential. Eq. 1 clearly states that trapping condition relies on wave phase velocity and on wake electrostatic potential, i.e. on plasma density and normalized electric field $E_{norm} = E_z/E_0$ solely, being $E_0 = m c^2 \omega_p / e$. Exact solution of the fully nonlinear wave equation in the 1D limit gives us a relationship between the normalized electric field and maximum/minimum potential $\phi_{max,min} = E_{norm}^2/2 \pm \beta_{ph} \sqrt{(1 + E_{norm}^2/2)^2 - 1}$.
Trapping starts when Eq. 1 holds, i.e. when electrons reach the end of the bucket with the same speed as the wake phase speed \((v = \beta_{ph}c)\). Since these electrons will not be accelerated further, we will refer to this condition as a “weak trapping condition”

\[
2\beta_{ph}\sqrt{(1 + E_{\text{norm}}^2/2)^2 - 1} \geq 1 - 1/\gamma_{ph}.
\]

Moreover, electrons that reach the speed of the wake before they experience the maximum accelerating field will dephase in the early stage of acceleration. As a consequence, a “strong trapping condition” can be introduced in such a way that electrons move with \(v = \beta_{ph}c\) when they are in phase with the maximum longitudinal accelerating field. In this case the potential at \(E_z = E_{\text{max}}\) is null, so we get

\[
E_{\text{norm}}^2/2 + \beta_{ph}\sqrt{(1 + E_{\text{norm}}^2/2)^2 - 1} \geq 1 - 1/\gamma_{ph}.
\]

Trapping analysis (see Fig. 3) reveals that efficient trapping occurs in a nonlinear wave regime since \(E_{\text{norm}} > 0.5\), but well below longitudinal wavebreaking for a cold nonrelativistic plasma \((E_{\text{norm}} < 1)\). Such an analysis is confirmed by our simulations and it is useful to set trapping threshold values for peak pulse amplitude \(a_0\) in single or multi-pulse schemes.

If a plasma density of \(n_e = 5 \times 10^{17}\text{cm}^{-3}\) is selected, a matched set of parameters gives a pulse duration of \(T = 30\) fs FWHM, with a minimum waist \(w_0 = 45\) \(\mu\)m (the same parameters set will be used in the 250 TW state-of-the-art simulation, see below). A scan of the maximum accelerating field versus pulse amplitude and the number of pulses in the train is reported in Fig. 3. Three delivered energies of 2.5 J, 5.0 J and 7.5 J have been considered and, for any of them, a single-pulse, two, four and eight-pulses trains have been simulated. As shown in Fig. 3 (bottom), for a fixed total delivered laser energy, as the number of pulses in the train increases the maximum accelerating gradient of the wake increases due to a resonance enhancement of the wave. Moreover, from Fig. 3 (top and bottom) we can infer that the weak-trapping threshold Eq.2 is reached with a single-pulse of amplitude exceeding \(a_0 = 1.6\), while in the case of a eight-pulses train, weak-trapping threshold amplitude is reduced to \(a_0 = 0.5\).

III. IONIZATION DYNAMICS IN LINEAR POLARIZATION

Ultraintense laser pulses possess electric fields large enough to make tunneling as the dominant ionization mechanism (i.e. Keldysh parameter \(\gamma_K = \sqrt{2U_f/mc^2/a_0} << 1\)) so as the Ammosov-Delone-Krainov (ADK) ionization rate [42] can be assumed to evaluate electron extraction from the initial level (see Appendix). Ionization potential of 6th electron from Nitrogen is \(U_{\text{th}}^{6}\) = 552 eV and efficient extraction of 6th electron of Nitrogen requires \(a_0 \approx 1.7\) for a few tens of femtoseconds long pulses at \(\lambda = 0.8 \mu\)m. On the other hand, Argon can be ionized from level 8th to level 9th \(U_{\text{th}}^{8} = 422.5\) eV at a much lower intensity, being \(a_0 \approx 0.8\) and \(a_0 \approx 0.4\) with \(\lambda = 0.8 \mu\)m and \(\lambda = 0.4 \mu\)m, respectively.

We point out that a detailed description of ionization dynamics is crucial not only to correctly estimate the number of bunch electrons but (more importantly) to get a precise measure of the transverse phase space covered by newborn electrons. In the linear polarization case most of the electrons are ejected when the local electric field is maximum, i.e. when the pulse potential \(a_c\) is null. These electrons will leave the pulse with a negligible quivering mean momentum along the polarization axis \(x\). If newborn electrons leave the atom when electric field is not exactly at its maximum, a non null transverse momentum \(u_x = p_x/mc = -a_{\text{ex}}\) is acquired, being \(a_{\text{ex}}\) the local pulse potential at the extraction time. Moreover, ponderomotive forces introduce an axisymmetrical contribution to particles transverse momentum. Following [43] we can write an expression for the rms momentum along the \(x\) direction as a function of the pulse amplitude envelope at the extraction time \(\sigma_{u_x} \approx \Delta \cdot a_{\text{ex}} = \sqrt{a_0^3/a_c}\)

where \(a_c = 0.107(U_f/U_H)^{3/2}\) \(\lambda\) is a critical pulse amplitude and \(\Delta = \sqrt{a_0^3/a_c}\) (see Eq. 7 and 10 in [43]). Eq. 4 gives us an accurate estimate of the minimum transverse momentum obtainable by the ionization process.

Trapping analysis with a standard single pulse shows that Nitrogen could be used in a simplified ionization injection (as suggested in [34]). Since efficient ionization threshold for \(N^{6+}\) is \(a_0 \approx 1.7\) for \(\lambda = 0.8 \mu\)m, a small interval of \(1.6 < a_0 < 1.3\) for the pulse amplitude is suitable for both trapping and ionization purposes. Such a simplified scheme could be useful either for demonstration purposes or to obtain a controlled injection for good-quality bunches without ultra-low emittance requirements. A two-pulses driver is a far better choice since an optimal pulse amplitude \(1.1 < a_0 < 1.3\) allows us to strongly inhibit driver pulses ionization. Using Argon \((Ar^{8+} \rightarrow Ar^{9+})\) as a contaminant instead of Nitrogen gives us a drastic reduction of transverse particle momentum. Multi-pulse ionization injection with Argon requires trains with at least four pulses since ionization level is saturated with amplitude above \(a_0 = 0.8\) at \(\lambda = 0.8 \mu\)m.
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At the end of the 6.5 mm long extraction/acceleration phase the bunch has mean energy 265 MeV, with final normalized emittances of 0.076 mm×mrad (x axis) and 0.018 mm×mrad (y axis), with an rms energy spread 0.65% and peak current of about 1 kA. These extremely low values of emittance and energy spread show that the proposed RESonant Multi-Pulse Ionization injection scheme is ideal for the generation of very high quality accelerated bunches.

V. CONCLUSIONS

We propose a new ultra-low emittance LWFA injector scheme that uses a Resonant train of pulses to drive plasma waves having amplitude large enough to trap and accelerate electrons extracted by ionization. The pulses train is obtained by temporal shaping of an ultrashort pulse. Unlike two-colour ionization injection, a single laser system (e.g Ti:Sa) can be therefore employed to both drive the plasma wave and extract newborn electrons by ionization. Simulations consistently show that the main processes, including extraction of electrons due to the ionizing pulse, their trapping in the bucket and subsequent acceleration can be controlled by tuning electron density and laser intensity. Simulations also show a negligible contribution of spurious electrons extracted directly by the driver pulses. Simulations carried out in different plasma conditions show feasibility of the scheme with state-of-the-art-lasers making REMPI suitable either for direct interaction (e.g Thomson Scattering or FEL) or as ultra-low emittance injector for GeV-scale energy boosting.

Very recently J. Cowley et al. [40] reported on very encouraging results about the feasibility of their time-shaping setup, with the demonstration of efficient excitation of the plasma wave via Multi-Pulse LWFA. The REMPI scheme could be tested with two pulses in the train at first, with Nitrogen as a contaminant species. In order to obtain very good-quality electron bunches, however, Argon should be preferred and in this case more than four pulses in the train are necessary as shown in Sec. II.

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VII. APPENDIX I. ADK IONIZATION RATE

In this paper we use the following formulation of the instantaneous ADK ionization rate in the tunnelling regime [42]

$$w_{ADK}(|m|) = C \times \rho_{ADK} \times \exp\left(-1/\rho_{ADK}\right),$$  

(5)

where $n(|m|) = -2n^* + |m| + 1$, $C$ is a coefficient depending on the atomic numbers and ionization energy $U_I$ ($U_H = 13.6 eV$)

$$C = \frac{1}{4\pi} \left(\frac{U_I}{U_H}\right)^{3/2} \times \begin{bmatrix} 4e^2 \left[n^* - l^* \right] \begin{bmatrix} n^* - l^* \\ n^* + l^* \end{bmatrix}^{l+\frac{3}{2}} \end{bmatrix},$$

(6)

and $\rho_{ADK} = 3/2(E/E_{at})^{1/2}$, being $E_{at} = 0.514 TV/m$ and $E$ the atomic and the local electric fields, respectively. The effective quantum numbers are $n^* = Z\sqrt{U_H/U_I}$ and $l^* = n_0^* - 1$, being $n_0^*$ referred to the lower state with the same $l$. A critical electric field $E_c = 2/3E_{at}(U_I/U_H)^{3/2}$, giving a scale of a short-time scale ionization, can be introduced. By expressing $E/E_c$ using vector potentials we get $a/a_c = \rho_{ADK} = 9.37(U_H/U_I)^{3/2}a/\lambda$ which is nothing but the square of the $\Delta$ parameter in [43].

In the circularly polarized pulse case the electric field rotates within each cycle still retaining the same intensity, so in the tunnelling regime the mean-cycled ionization rate coincides with the instantaneous rate of Eq. 5

$$<w_c> = w_{ADK}.$$

(7)

In the linearly polarized pulse case the mean over a cycle can be performed analytically after a taylor expansion
of the leading exponential term. The well known result (rewritten in our notation) is

\[ < w_L > = w_{ADK}(\rho_{ADK,0}) \times (\frac{2}{\pi} \rho_{ADK,0})^{1/2}, \]  

(8)

where \( \rho_{ADK,0} \) is the peak value of \( \rho_{ADK} = a/a_c \) within the cycle. A numerical estimation of the mean-cycled rate confirms the validity of Eq. 8 with errors below 4% in the ionization rates, for \( \rho_{ADK} \) parameters in the range of interest for ionization injection techniques (see Fig. 7).

VIII. APPENDIX II QFLUID CODE

QFluid is a cold-fluid/kinetic code in 2D cylindrical coordinates, employing plasma dynamics in a Quasi Static Approximation [46]. Electrons macroparticles move kinetically in a full 3D dynamics depicted by the longitudinal \( E_z \) and radial \( E_r \) electric field, the azimuthal magnetic field \( B_\phi \) and ponderomotive forces due to laser pulses. The main laser pulse train propagates following the envelope evolution equation with the second time derivative included [47], while the evolution of the ionization pulse follows the Gaussian pulse evolution prescription. For our purposes, in the absence of non-fluid plasma behavior, strong longitudinal background gradients and radial anisotropies, QFluid returns the same results of a 3D PIC code with much less demanding computation time/resources. Particle extraction from atoms/ions is simulated with an ADK rate including the mean over a pulse cycle, while newborn particles are finally ejected with a random transverse momentum \( u_\perp \), whose rms value depends on the polarization of the pulses. For a linear polarization (as for the ionizing pulse) we assigned \( \sigma_{u_\perp} \equiv \Delta \cdot a_{0e}/a_c \) (see Eq. 4), while for the circular polarization each extracted particle is associated to a random extraction phase \( \phi_e \) so as \( u_x = a_{0e} \cdot \cos(\phi_e), \ u_y = a_{0e} \cdot \sin(\phi_e) \). Benchmark of QFluid with a multipulse setup has been obtained in a nonlinear regime with an ADK rate including the mean over a 3D PIC code with much less demanding computation time/resources.

FB-PIC simulations were performed with two azimuthal modes, i.e. possible deviation from perfect azimuthal symmetry were included.

The comparison between FB-PIC and QFluid simulation (see Fig. 8) shows a perfect superposition between the codes output, notwithstanding the nontrivial evolution of the pulses due to both nonlinear effects and the variation of the susceptivity due to the wake.

The first QFluid and ALaDyn comparison shown here, has been focused on an eight-pulses drivers train with Argon as atomic species, with selected working point as the same as the state-of-the-art setup. To fasten the 3D PIC simulation, ALaDyn has been equipped with an envelope pulse solver. The Aladyn/envelope code implements a fully 3D PIC scheme for particle motion whereas the laser pulses are represented by the envelope model proposed in [50].

Once again (see Fig. 9), QFluid outcomes deviate at most of a few percent from those of a 3D PIC (full 3D in this case).

Finally, a full-PIC (not in envelope approximation) in 2D slice geometry vs QFluid comparison, including the bunch extraction and trapping, will be presented (RUN 2). To save computational time an high-density setup has been simulated. A train of eight 10 fs linearly po-

![Figure 7. Comparison between the numerical estimation of the mean-cycled ADK rate and the widely used analytical result of Eq. 9 for Ar$^{3+}$ and N$^{6+}$ final states.](image)

![Figure 8. FB-PIC vs QFluid in a two-pulses driver configuration with Nitrogen. Snapshot after 700 μm of propagation into a plasma with background density of \( n_e = 1.5 \times 10^{16} \text{cm}^{-3} \). Left: longitudinal electric field on axis. Right: pulse electric field (FB-PIC) and its amplitude (QFluid). The injected pulse amplitude (blue dotted line) has been shown for reference.](image)
larized Ti:Sa pulses impinge onto a preformed plasma of $\text{Ar}^{8+}$ with density $5 \times 10^{18} \text{cm}^{-3}$. The driver pulse train has a waist size $w_0 = 25 \mu \text{m}$ and an amplitude $a_0 = 0.589$, having a pulse delay of a single plasma period $T_p = 2\pi/\omega_p$. We use a relatively large focal spot with $w_0 > \lambda_p = 14.8 \mu \text{m}$, so as to reduce the effects of the missing third dimension in the PIC simulations. The frequency doubled ionizing pulse is injected with a delay of $1.5 \times T_p$ in the vicinity of its focus with a waist $w_{0,\text{inj}} = 3.5 \mu \text{m}$ and possesses a peak pulse amplitude of $a_{0,\text{inj}} = 0.41$. PIC simulations were performed with a $170 \times 150 \mu \text{m}^2$ box in the longitudinal and transverse directions with a resolution of $\lambda/40$ and $\lambda/10$, respectively. QFluid simulations were carried out in the same (cylindrical) box size with resolution $\lambda_p/70$ and $\lambda_p/35$ in the longitudinal and radial coordinates, respectively.

The final snapshot of both simulation, after 300 $\mu$m propagation in the plasma is shown in Fig. 10, where the injected electron bunch just at the end of the charging phase is visible (black and blue dots). Due to the large ponderomotive forces (that scale as $a^2_{0,\text{inj}}/w_{0,\text{inj}}$, see Eq. 23 in [43]), bunch transverse rms momentum ($0.26 \text{mc}$ for QFluid and $0.27 \text{mc}$ for ALaDyn, respectively) shows an increase of about a factor of 2 from the value expected by Eq. 4.

We finally stress that QFluid cannot face with the plasma exit of the generated bunch since the Quasi Static Approximation requires a steady plasma density within the box. A PIC code will be used in a future work to simulate the plasma exit, too.

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Figure 9. ALaDyn vs QFluid in a eight-pulses setup with Ar- gon (state-of-the-art run parameters). Top: Snapshot of the on-axis longitudinal electric field after 1 mm of propagation. Bottom: radial maps of $E_{\text{norm}} = E_z/E_0$ for QFluid (upper side) vs ALaDyn (lower side).

Figure 10. 2D-slice ALaDyn and QFluid in RUN 2 setup. QFluid and ALaDyn PIC results after 300 $\mu$m of propagation. Top: (on-axis) ALaDyn phase space of particles (black dots), QFluid phase space of particles (blue dots), ALaDyn accelerating field (blue line, a.u.) and QFluid accelerating field (red line, a.u.). The green line represents fluid momentum of QFluid output. Bottom: Longitudinal electric field $E_{\text{norm}} = E_z/E_0$ from QFluid (upper) and ALaDyn (lower).
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