High-Quality electron bunch production for high-brilliance Thomson Scattering sources

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Abstract

Laser Wake Field accelerated electrons need to exhibit a good beam-quality to comply with requirements of FEL or high brilliance Thomson Scattering sources, or to be post-accelerated in a further LWFA stage towards TeV energy scale. Controlling electron injection, plasma density profile and laser pulse evolution are therefore crucial tasks for high-quality e-bunch production. A new bunch injection scheme, the Resonant Multi-Pulse Ionization Injection (RMPII), is based on a single, ultrashort Ti:Sa laser system. In the RMPII the main portion of the 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 energies in the range $265MeV - 1.15GeV$, normalized emittance as low as 0.08 mm·mrad and 0.65% energy spread can be obtained with a single $250\,TW$ Ti:Sa laser system. Applications of the e-beam in high-brilliance Thomson Scattering source, including $1.5 - 26.4\,MeV$ γ sources with peak brilliance up to $1 \cdot 10^{28} ph/(s \cdot mm^2 \cdot mrad^2 \cdot 0.1\,\%\,bw)$, are reported.

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I. INTRODUCTION

Ultra-high brilliance $UV/X/\gamma$ ray sources including Free Electron Lasers [1–3] and Thomson/Compton scattering sources [4, 5, 7–9], as well as multi-stage schemes in LWFA acceleration [10–12] require high-quality electron bunches. Controlled self-injection schemes as density downramp injection [15–19], colliding pulses injection [20–22] and ionization injection [23–28], are therefore under active theoretical and experimental investigation.

In the two-colour ionization injection [29–31] two laser systems are needed. The main pulse that drives the plasma wave has a long wavelength, five or ten micrometers, and a large amplitude $a_0 = eA/mc^2 = 8.5 \cdot 10^{-10}\sqrt{I\lambda^2} > 1$, being I and λ pulse intensity in W/cm^2 and wavelength in μm. The second pulse (the "ionization pulse") is constituted by a frequency doubled Ti:Sa pulse. While the main pulse cannot further ionize the electrons in the external shells of the of the large Z contaminant species due to its large wavelength, the electric field of the ioniziation 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 ($\approx 10\mu m$) 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.

A new injection scheme, the Resonant Multi-Pulse Ionization Injection [32], is derived from two-colour ionization and it has the possibility to be operative with present-day single Ti:Sa laser systems. Simulations show that such a scheme is capable of generating ultra-low emittance GeV-scale bunches that can be employed in High-Brilliance Thomson Scattering sources.

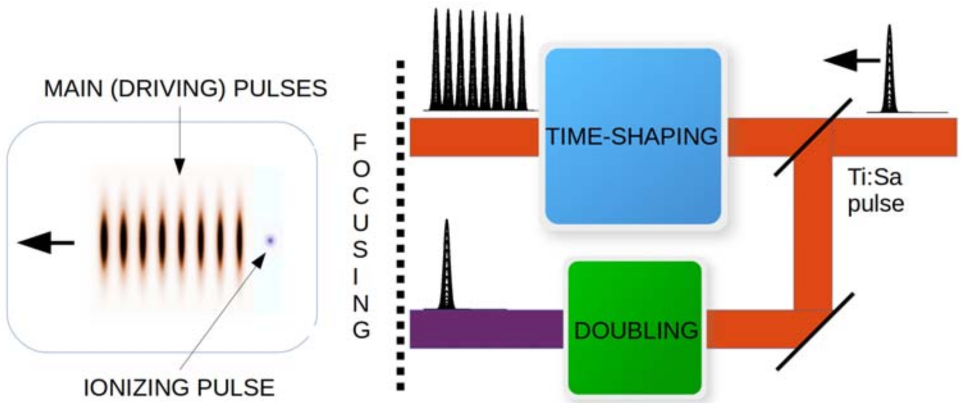

Figure 1. Multi-Pulse ionization injection scheme. A small fraction of a single Ti:Sa laser pulse is frequency doubled and will constitute the ionizing pulse. The main portion of the pulse is temporally shaped as a train of resonant pulses that will drive a large amplitude plasma wave.

II. THE RESONANT MULTI-PULSE IONIZATION INJECTION

A new ionization injection scheme, the Resonant Multi-Pulse ionization injection [32], has been recently proposed to overcome the (current) limitation of two-colour ionization injection. In the Resonant Multi-Pulse scheme only one short-wavelength laser system (e.g a Ti:Sa) is needed. The long wavelength driving pulse of the two-colour scheme is replaced by a short wavelength, resonant multi-pulse laser driver. Such a driver can be obtained via temporal shaping techniques from the *single*, linearly polarized, standard CPA laser pulse. A minor fraction of the same pulse is frequency doubled 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 [33, 34]. Noticeably, since the peak intensity of the driver is reduced by a factor equal to the number of train pulses, it is also possible to match the conditions of *both* particle trapping and unsaturated ionization of the active atoms level. Recently [35] new experimental results on the generation of such a time shaped pulses demonstrate that a multi pulse scheme is obtainable with present day technology.

Trapping analysis with a standard *single* pulse shows [32] that Nitrogen could be used in

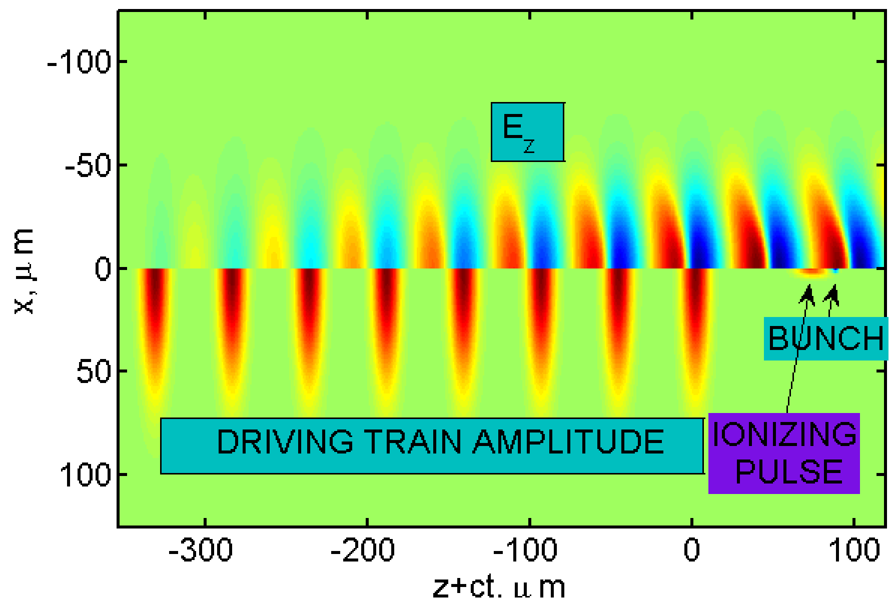

Figure 2. Pulse amplitude , bunch density and accelerating gradient after 100 μm of propagation.

a simplified ionization injection (as suggested in [29]). Since efficient ionization threshold for N^{6+} is $a_0 \approx 1.7$ for $\lambda = 0.8\,\mu m$, a two-pulses driver is an optimal choice since pulse amplitude in the range $1.1 < a_0 < 1.3$ allows us to strongly inhibite driver pulses ionization. Using Argon ($Ar^{8+} \rightarrow Ar^{9+}$) as a contaminant instead of Nitrogen gives us a drastic reduction of t http://spie.org/x14105.xml ransverse 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 $\lambda = 0.8\,\mu m$.

A. Flat background density simulation

The following QFluid [40] simulation of our Resonant Multi-Pulse Ionization Injection is based upon a Ti:Sa laser pulse that is initially split into the ionizing pulse and the eight-pulses driver train, each sub-pulse being 30 fs FWHM in duration and delivering 895 mJ of energy, with a maximum pulse amplitude $a_0 = 0.64$ and minimum waist size $w_0 = 45\,\mu$m. Plasma electron density is set to $n_e = 5 \cdot 10^{17}\mathrm{cm}^{-3}$ (plasma wavelength is $\lambda_p = 46.9\,\mu$m),

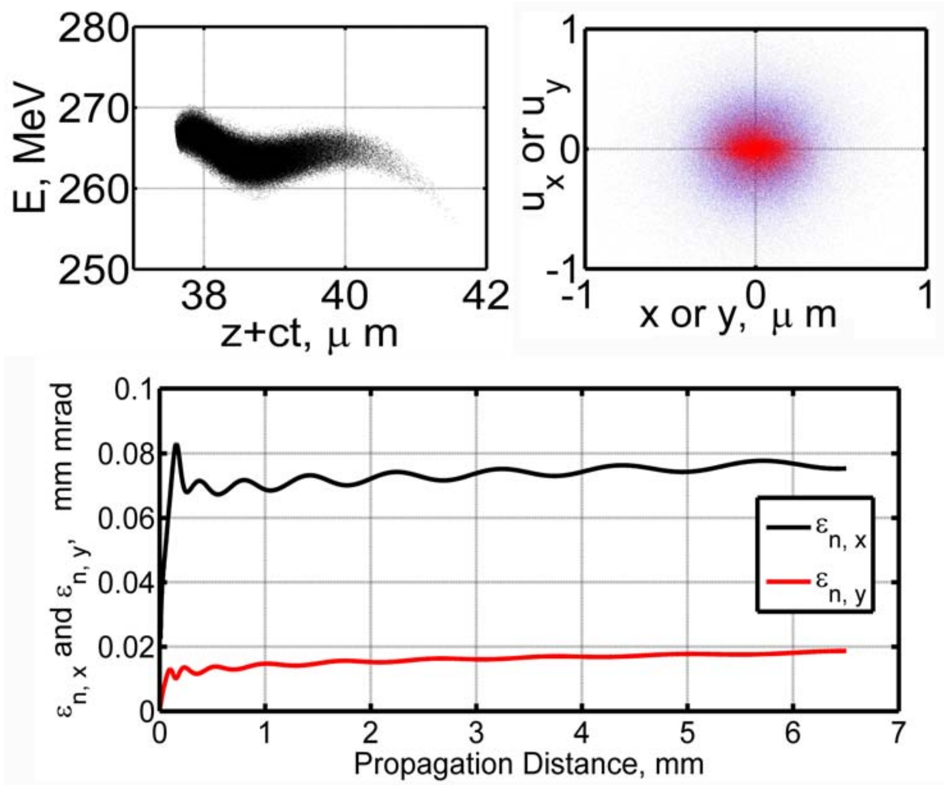

Figure 3. 265MeV simulation. Bunch quality as simulation ends. Top left: Longitudinal position-energy distribution. Top left: Transverse distribution (blue dots for x component and red dots for y component). Bottom: normalized emittance as the bunch propagates into the plasma.

obtained with a pure Argon pre-ionized up to level 8^{th}. The frequency doubled component ($\lambda_{ion} = 0.4\,\mu$m) with amplitude $a_{0,ion} = 0.41$ and duration $T_{ion} = 38\,$fs is focused with a waist $w_{0,ion} = 3.5\,\mu$m. The simulation (see Figs. 2 and 3) has been performed in a moving cylinder having a radius $4 \cdot w_0$ with a resolution of $\lambda_p/100$ and $\lambda_p/200$ in the radial and longitudinal coordinates, respectively.

Electrons extracted in the bulk of the ionizing pulse move suddenly backwards in the wake reaching the peak of the accelerating gradient. The short Rayleigh length $Z_R = \pi w_{0,ion}^2/\lambda_{ion} \approx 100\,\mu$m ensures a sudden truncation of beam charging that turns into a small rms absolute energy spread $\Delta E \approx E_{norm} \cdot E_0 \cdot Z_R \approx 5\,$MeV and extracted charge $Q = 3.8\,$pC .

At the end of beam charging, i.e after about $200\,\mu$m of propagation, the *rms* bunch length is $\sigma_l = 0.56\,\mu$m and the transverse normalized emittance is $\epsilon_{n,x} = 0.070$ mm·mrad in the polarization direction x and $\epsilon_{n,y} = 0.016$ mm·mrad along the y direction. Afterwards, the *quasi-matched* beam experiences dumped betatron oscillations with converging beam radius of $\sigma_t = 0.3\,\mu$m that generate an emittance growth of about 10% as simulation ends (see Fig. 3). 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 exceeding $2\,KA$. 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.

B. Preformed plasma-channel simulation

To extend the acceleration length a pulse guiding technique is necessary since low-density plasmas don't allow for pulse self-guiding at those pulse powers. A possible setup consists of a gas-jet containing pure Argon (for bunch injection) and a 5 cm long capillary waveguide filled with Helium (for energy boosting). The driver pulses are focused close to the entrance of the capillary and enter into the guide with a matched radius $w_m = w_0$ and radial density profile

$$n_e(r) = n_{axis}\left[1 + \eta\frac{1.1\cdot 10^{20}}{n_{axis}w_0^2}\left(\frac{r}{w_0}\right)^2\right], \tag{1}$$

being n_{axis} the on-axis plasma density. The η factor accounts for weakly nonlinear corrections and in the case of short pulses ($T << 2\pi/\omega_p$ can be evaluated as [43] $\eta \cong 1 - \frac{1}{16}(a_0\omega_p T)^2 \cdot (1 + 4.6\cdot 10^{-21} n_e w_0^2)$, which is very close to unity in our simulations.

Plasma background density is flat in the injector stage with nominal density of $3.5\cdot 10^{17}\,cm^{-3}$. At the end of the 4 mm long gas-jet, a contiguous capillary with preformed plasma having a channel with center density of $3.3\cdot 10^{17}\,cm^{-3}$ is placed. Transition scale to the first to the second stage has been set to $L_{trans} = 2\,mm$. The driver pulse train

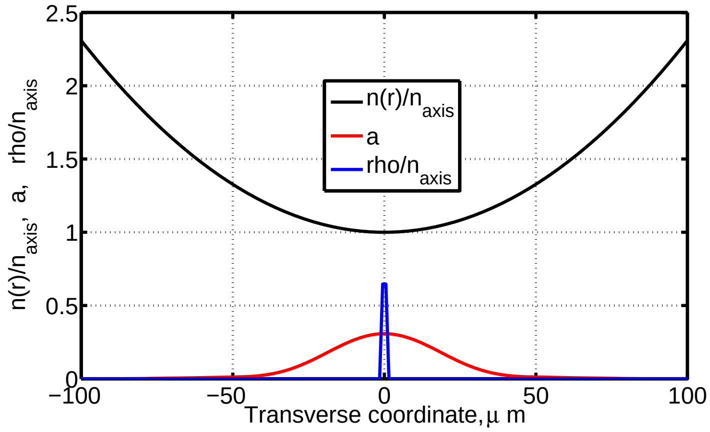

Figure 4. 1GeV simulation. Plasma radial density (back), pulse amplitude (red) and bunch density (blue) inside the plasma channel.

enters the gas jet with a waist $w = 45\,\mu m$ with minimum waist $w_0 = 40\,\mu m$ placed 3.2 mm after plasma entrance. At the end of the gas jet the driver pulses train has waist close the minimum value and enters into the channel with a matched size. The ionizing pulse has minimum waist $w_0 = 4\,\mu m$, a bit higher than the pulse of the 265 MeV case to compensate for the lower atomic density so as to extract 4.6 pC of charge. Due to the defocusing effect of the wake, at the end of the 3.5 cm of propagation the rear part of the train is partially disrupted (See Fig. 5).

The final electron bunch has energy 1.15 GeV and energy spread 0.81 % *rms*. While normalized emittance is the same of the lower energy bunch ($0.08\,mm \cdot mrad$ and $0.02\,mm \cdot mrad$ in x and y directions, respectively), the present bunch is spatially more compact than the 265 MeV one. Transverse size has been reduced down $0.2\,\mu m$ by transverse wakefield forces while longitudinal size has been strongly reduced down $0.25\,\mu m$ by having selected an injection phase closer to the maximum of the accelerating force (see Table 1).

III. POSSIBILE APPLICATION IN ULTRA HIGH BRILLIANCE SOURCES

The ultra-low emittance bunches reported above have ideal application in either X/γ Thomson/Compton scattering sources or FEL sources. The Thomson Scattering process is

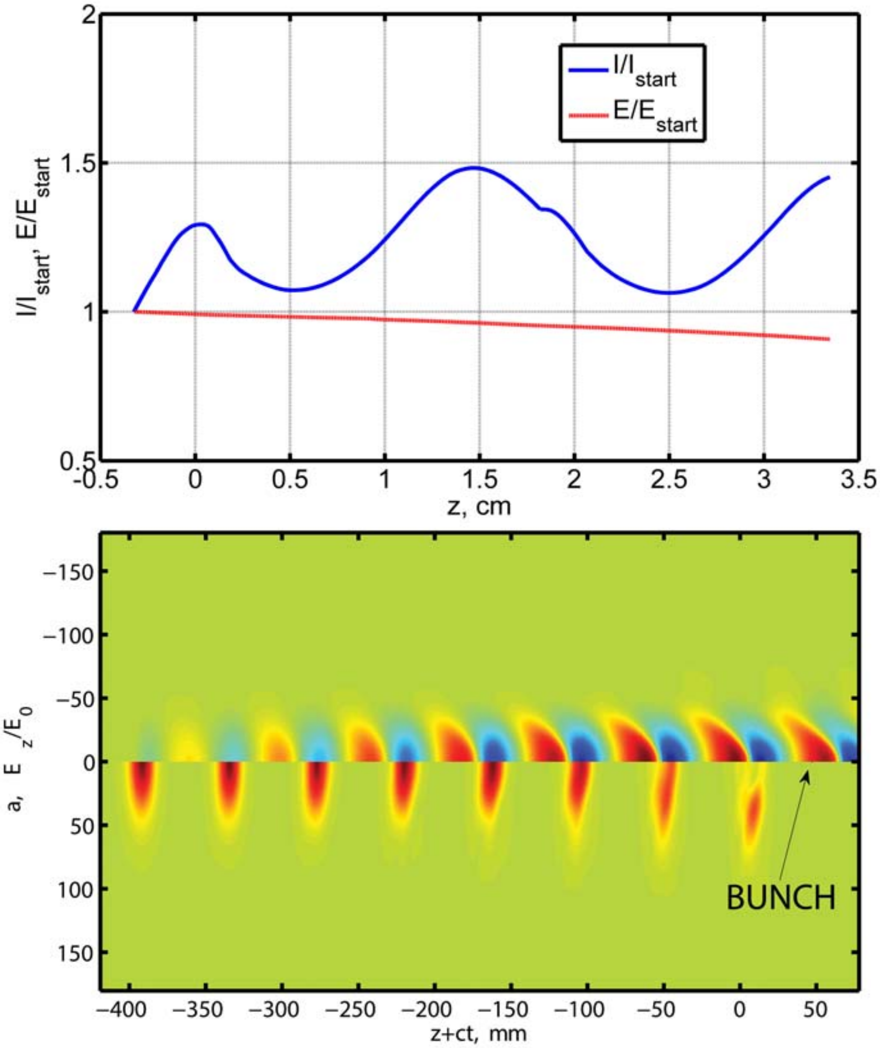

Figure 5. 1GeV simulation. Top: Pulses peak amplitude and total delivered energy as the train propagates into the plasma. Bottom: final snapshot of the longitudinal electric field and pulse(s) amplitude.

the classical limit of Compton Scattering, i.e. the limit of negligible quantum recoil of the electron when it absorbs one (or more) photons. This is the case when a Ti:Sa laser pulse impinges onto a bunch with energy below tens of GeV's [4, 5]. Relativistic effects generate a blue-shift of the scattered radiation

Bunch	E, GeV	σ_E/E	Q, pC	$\sigma_l,\ \mu m$	$\sigma_t,\ \mu m$	$\epsilon_{nx},\ \mu m \cdot rad$
A	0.265	0.65 %	3.8	0.56	0.30	0.078
B	1.15	0.81%	4.6	0.25	0.22	0.080

Table I. Bunches A and B quality

$$\lambda_{rad} = \lambda_0(1 + \tilde{\theta}^2 + a_0^2/2)/(4\gamma^2) \tag{2}$$

and its collimation into a cone of aperture $\theta \approx 1/\gamma$, being λ_0 the wavelength if the counterpropagating laser pulse and $\tilde{\theta}$ the angle from the scattered photon and the incoming electron [5, 6]. Nonlinear Thomson Scattering occurs when quivering velocity approaches c so as magnetic field induces non harmonic components in electrons trajectories, i.e. when more than one photon is absorbed. Main signatures of nonlinear features are harmonic generation and redshift associated to spectral broadening [4, 5]. In quasi-monocromatic X/γ sources, therefore, a linear or weakly-nonlinear regime is preferrable.

A possible sub-micromer γ source is obtained either with a single laser-system setup or with a two-laser systems setup. In the former case the counterpropagating pulse is a portion of the Ti:Sa pulse that generates the electron beam, while in the latter the pulse is generated by a dedicated laser system. In both cases the counterpropagating pulse should have a significantly larger duration than the beam driver pulse in order to reduce unwanted nonlinear effects.

In the following simulations a single laser system setup is assumed. The counterpropagating pulse has length $T = 1ps$ and delivers 1 J of energy in a spot of waist $w_0 = 15\,\mu m$. Since pulse amplitude is well below unity ($a_0 = 0.23$) a weakly-nonlinear regime is reached so the energy spread of the collected radiation mainly depends upon electron beam quality and acceptance angle. Following [5, 6] we can write an expression for the expected energy spread once the normalized acceptance $\Psi = \theta_{max} \cdot \gamma$ has been fixed

$$(\delta E/E)_{|FWHM} \approx \Psi^2 + 2(\delta\gamma/\gamma)_{|rms} + \delta u_\perp^2, \tag{3}$$

Peak Energy	Energy spread	Collected Photons per Shot	Duration
$1.5\,MeV$	4.8 % rms	$1.3 \cdot 10^6\,ph$	1.9 fs
Acceptance Angle	Source Surface	Spectral Density	Brilliance
0.65 mrad	$0.4\ \mu m^2$	$12\frac{ph}{eV\,bw}$	$9 \cdot 10^{26}\frac{ph}{s \cdot mm^2 \cdot mrad^2 \cdot 0.1\,\%\,bw}$

Table II. Thomson Scattering Source parameters list (bunch A)

it is therefore commonplace to set the normalized acceptance to a value close to $\Psi \approx [2(\delta\gamma/\gamma)_{|rms} + \delta u_\perp^2]^{1/2}$, value that can be adjusted after source optimization.

A. TS source from the 265 MeV bunch A

The low-energy bunch A energy spread and transverse momentum are $(\delta\gamma/\gamma)_{|rms} = 6.5 \cdot 10^{-3}$ and $\delta u_\perp = 0.32$, respectively, so from Eq. 3 we get $\Psi \approx 0.25$. We expect that the energy spread of the γ source will not decrease by reducing the accepted normalized below $\Psi \approx 0.25$. To collect the maximum number of photons still mantaining the energy spread as low as possible we perform parameters optimization in the range $0.2 < \Psi < 0.5$. The number of scattered photons roughly scales as Ψ^2 for $\Psi \ll 1$, therefore an optimization of the source leads to the best compromise between the flux and the energy spread on the basis of the application of the generated radiation. Here we suppose that the enphasis is on a limit energy spread of 10% FWHM. Simulations of the Thomson Scattering process were performed with the Thomson Scattering Simulation Tool (TSST) [6] with a sample of 1000 bunch macroparticles. In Figure 6a a scan of the energy spread and the number of collected photons as a function of the acceptance is reported. From Figure 6a we infer that, having selected a goal energy spread of 10%, the optimal normalized acceptance is $\Psi = 0.28$, that corresponds to an acceptance of $\theta_{max} = 0.56$ mrad and a flux of $N_{ph} = 1.3 \cdot 10^6$ collected photons per shot.

The angular/spectral distribution of the γ radiation exhibits strong anisothropy due to the different *rms* transverse momenta along x and y directions ($0.31\,mc$ and $0.14\,mc$, respectively. Finally, the integrated spectrum (Fig. 6 c) has peak energy of $1.5\,MeV$, *rms*

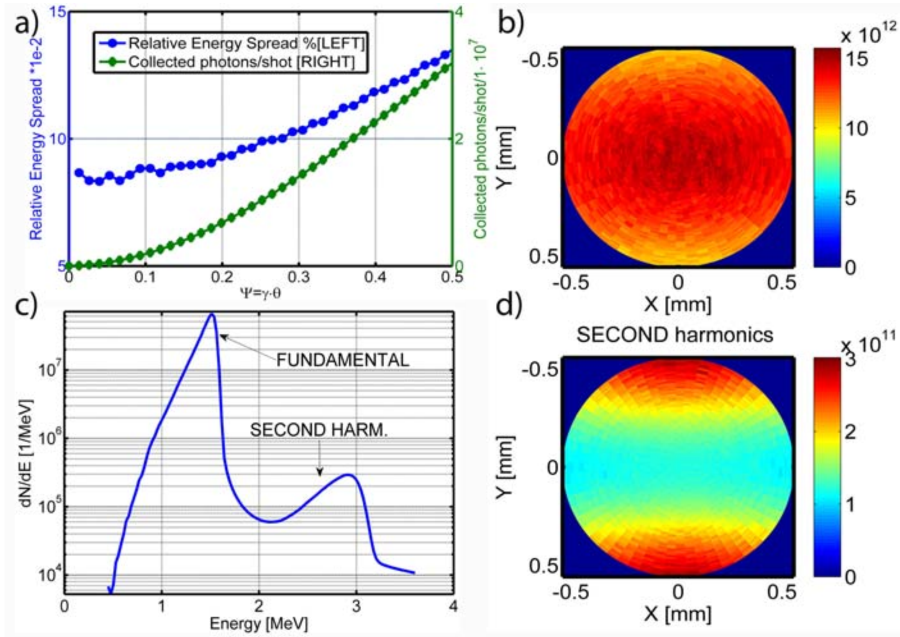

Figure 6. Thomson Source optimization and output from the 265 MeV bunch. a) Scan of the radiation energy spread (blue dots) and number of collected photons (green diamonds) vs acceptance angle. b) and d) Yield on a screen 1m downstream of the fundamental and second harmonics. c) Integrated spectrum (log scale).

energy spread of 4.8 % and FWHM energy spread 10%. The source emits ultrashort bursts of γ radiation, with *rms* duration $\delta t_\gamma \approx \sigma_l/c = 1.9\, fs$ within a spot of size $S = \pi\, \sigma_t^2 = 0.4\, \mu m^2$.

To compute peak brilliance of the source, we evaluated the number of photons emitted close to the peak with energy spread within 0.1 %, resulting in $N_{ph}/(0.1\%bw) = 2.9 \cdot 10^4$. Peak brilliance is

$$B = \frac{N_{ph}/0.1\,\%\,bw}{\delta t_\gamma(s)\, S(mm^2)\, \theta_{max}^2(mrad^2)} = 9 \cdot 10^{26} ph/(s \cdot mm^2 \cdot mrad^2 \cdot 0.1\,\%\,bw) \qquad (4)$$

which is orders of magnitude more than brilliance reported in Thomson scattering experiments with LWFA generated electrons [44, 45].

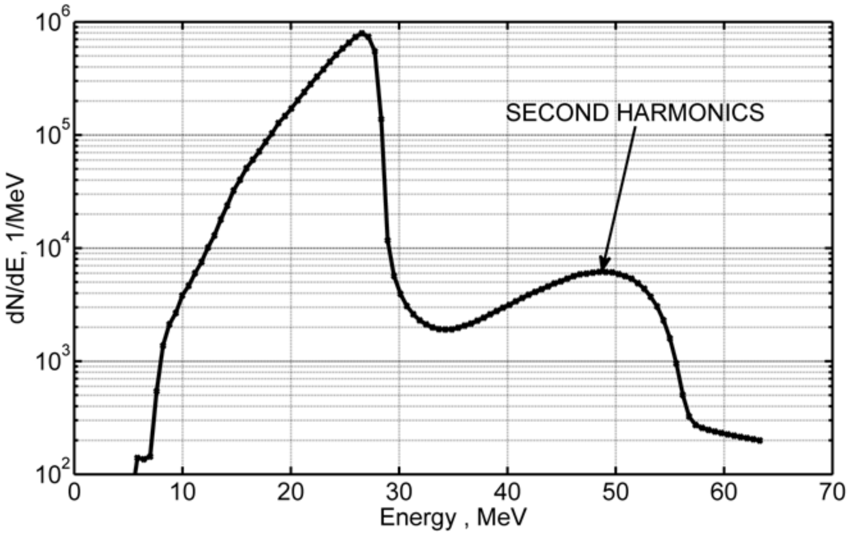

Figure 7. Integrated spectrum of the γ rays emitted by the TS source driven by bunch B within an acceptance angle of $0.21\,mrad$.

B. TS source from the 1GeV bunch B

Though the 1GeV bunch possesses the same emittance as the 265MeV one, we expect that the minimum energy spread of the TS source obtainable with the bunch B is higher than the previuous case. This is because during the post-acceleration phase focusing forces reduced the transverse size roughly by a factor 1.5. The transverse momentum spread along x and y directions are now $0.37\,mc$ and $0.21\,mc$, respectively. From Eq. 3 we can estimate the minum energy spread as $(\delta E/E)_{min} \approx 2(\delta\gamma/\gamma)_{|rms} + \delta u_\perp^2 \approx 0.2$. After source optimization with goal energy spread of 20% FWFM, the selected normalized acceptance is $\Psi = \gamma \cdot \theta_{max} = 0.45$, corresponding to a geometrical acceptance of $0.21\,mrad$. The TSST simulation, obtained with the same laser parameters of the previous case, results in a sub-fs bursts of γ radiation with rms duration $\delta t_\gamma = 0.8\,fs$ within a spot of size $S = 0.14\,\mu m^2$, with peak energy 26.4 MeV (see Fig. 7) and and a flux of $N_{ph} = 4.6 \cdot 10^6$ collected photons per shot.

As expected, the energy spread of this source is roughy as double as that of the 1.5 MeV source, with the peak of $N_{ph}/(0.1\%bw) = 4.9 \cdot 10^4$ photons emitted within 0.1 % spread.

Peak Energy	Energy spread	Collected Photons per Shot	Duration
$26.4\,MeV$	9.8 % rms	$4.6 \cdot 10^6\,ph$	0.8 fs
Acceptance Angle	Source Surface	Spectral Density	Brilliance
0.21 mrad	$0.14\ \mu m^2$	$1.6\frac{ph}{eV\,bw}$	$1 \cdot 10^{28}\frac{ph}{s \cdot mm^2 \cdot mrad^2 \cdot 0.1\,\%\,bw}$

Table III. Thomson Scattering Source parameters list (bunch B)

Nevertheless, since source size is considerably smaller than the case A, peak brilliance is one order of magnitude higher $B = 1 \cdot 10^{28} ph/(s \cdot mm^2 \cdot mrad^2 \cdot 0.1\,\%\,bw)$.

IV. CONCLUSIONS

We employed the new RMPII injection scheme to (numerically) generate two electron bunches with outstanding quality and compactness. Bunch A has been obtained with a flat density profile and reaches the energy of $265\,MeV$ prior laser pulse(s) defocusing. Bunch B has been generated with the REMPII scheme and further accelerated into a plasma channel for pulse guiding, obtaining a final energy of 1.15GeV with a similar beam quality. High-brilliance Thomson Scattering sources have been investigated with the classical nonlinear TSST code, showing that a sub-fs γ ray source with brilliance $B = 1 \cdot 10^{28}\frac{ph}{s \cdot mm^2 \cdot mrad^2 \cdot 0.1\,\%\,bw}$ can be obtained with this setup. A future work will be focused on the another natural application of those high-quality bunches, i.e. Free Electron Laser drivers.

V. ACKNOWLEDGMENTS

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[1] K. Nakajima, "Few femtosecond, few kiloampere electron bunch produced by a laser–plasma accelerator"; Nature Physics 4, 92 - 93 (2008).

[2] V. Petrillo, M. P. Anania, M. Artioli, A. Bacci, M. Bellaveglia, E. Chiadroni, A. Cianchi, F. Ciocci, G. Dattoli, D. Di Giovenale, G. Di Pirro, M. Ferrario, G. Gatti, L. Giannessi, A. Mostacci, P. Musumeci, A. Petralia, R. Pompili, M. Quattromini, J. V. Rau, C. Ronsivalle, A. R. Rossi, E. Sabia, C. Vaccarezza, and F. Villa, "Observation of Time-Domain Modulation of Free-Electron-Laser Pulses by Multipeaked Electron-Energy Spectrum"; Phys. Rev. Lett. 111, 114802 (2013).

[3] A Loulergue, M Labat, C Evain, C Benabderrahmane, V Malka and M E Couprie, "Beam manipulation for compact laser wakefield accelerator based free-electron lasers", New J. Phys. 17, 023028 (2015).

[4] E. Esarey, S. K. Ride, and P. Sprangle, "Nonlinear Thomson scattering of intense laser pulses from beams and plasmas", Phys. Rev. E 48, 3003 (1993).

[5] P. Tomassini, A. Giulietti D. Giulietti and L. A. Gizzi, "Thomson backscattering X-rays from ultra-relativistic electron bunches and temporally shaped laser pulses", Appl Phys. B 80, 4, pp 419–436 (2005).

[6] P. Tomassini, A. Bacci, J. CAry, M. FErrario, A. Giulietti, D. Giulietti, L.A. Gizzi, L. Labate, L. Serafini, V. Petrillo, C. Vaccarezza, "Linear and Nonlinear Thonson Scattering for Advanced X-ray Sources in PLASMONX", IEEE-Trans. Plasma Sci. 36, 4, 1782 (2008)

[7] S. Corde, K. Ta Phuoc, G. Lambert, R. Fitour, V. Malka, A. Rousse, A. Beck, and E. Lefebvre, "Femtosecond x rays from laser-plasma accelerators", Rev. Mod. Phys. 85, 1 (2013);

[8] V. Petrillo, A. Bacci, C. Curatolo, I. Drebot, A. Giribono, C. Maroli, A. R. Rossi, L. Serafini, P. Tomassini, C. Vaccarezza, and A. Variola, "Polarization of x-gamma radiation produced by a Thomson and Compton inverse scattering", Phys. Rev. ST-AB 18, 110701 (2015);

[9] D. Micieli, I. Drebot, A. Bacci, E. Milotti, V. Petrillo, M. Rossetti Conti, A. R. Rossi, E. Tassi, and L. Serafini, "Compton sources for the observation of elastic photon-photon scattering events", Phys. Rev. ST-AB 19, 093401 (2016).

[10] A. Döpp, E. Guillaume, C. Thaurya), A. Lifschitz, K. Ta Phuoc, and V. Malka, "Energy boost in laser wakefield accelerators using sharp density transitions", Phys. Plasmas 23 (5), 056702 (2015).

[11] T.L. Audet, F.G. Desforges, A. Maitrallain, S. Dobosz Dufrénoy, M. Bougeard, G. Maynard, P. Lee, M. Hansson, B. Aurand, A. Persson, I. Gallardo González, P. Monot, C.-G. Wahlström, O. Lundh, B. Cros, "Electron injector for compact staged high energy accelerator", NIM A 829, 304-308 (2016).

[12] G. Golovin, S. Banerjee, S. Chen, N. Powers , C. Liu, W. Yan, J. Zhang, P. Zhang, B. Zhao, D. Umstadter, "Control and optimization of a staged laser-wake field accelerator", NIM A 830, 375-380 (2016).

[13] J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J.-P. Rousseau, F. Burgy, V. Malka, "A laser plasma accelerator producing monoenergetic electron beams", Nature 541, 431(2004).

[14] G. R. Plateau, C. G. R. Geddes, D. B. Thorn, M. Chen, C. Benedetti, E. Esarey, A. J. Gonsalves, N. H. Matlis, K. Nakamura, C. B. Schroeder, S. Shiraishi, T. Sokollik, J. van Tilborg, Cs. Toth, S. Trotsenko, T. S. Kim, M. Battaglia, Th. Stöhlker, and W. P. Leemans, "Low-Emittance Electron Bunches from a Laser-Plasma Accelerator Measured using Single-Shot X-Ray Spectroscopy", Phys. Rev. Lett. 109, 064802 (2012).

[15] S. Bulanov, N. Naumova, F. Pegoraro, and J. Sakai, "Particle injection into the wave acceleration phase due to nonlinear wake wave breaking", Phys. Rev. E 58 , R5257 (1998).

[16] H. Suk, N. Barov, J.B. Rosenzweig and E. Esarey, "Plasma Electron Trapping and Acceleration in a Plasma Wake Field Using a Density Transition", Phys. Rev. Lett. 86, 1011-1014 (2001).

[17] P. Tomassini, M. Galimberti, A. Giulietti, D. Giulietti, L. A. Gizzi, L. Labate, and F. Pegoraro, "Production of high-quality electron beams in numerical experiments of laser wakefield acceleration with longitudinal wave breaking", Phys. Rev. ST Accel. Beams 6 , 121301 (2003).

[18] C. G. R. Geddes, E. Cormier-Michel, E. Esarey, K. Nakamura, G. R. Plateau, C. B. Schroeder, Cs. Toth, D. L. Bruhwiler, J. R. Cary, and W. P. Leemans, "Plasma gradient controlled injection and postacceleration of high quality electron bunches", Proceedings of the Thirteenth Advanced Accelerator Concepts Workshop, 1086 (2008).

[19] A. Buck, J. Wenz, J. Xu, K. Khrennikov, K. Schmid, M. Heigoldt, J. M. Mikhailova, M. Geissler, B. Shen, F. Krausz, S. Karsch, and L. Veisz, "Shock-Front Injector for High-Quality Laser-Plasma Acceleration", Phys. Rev. Lett. 110, 185006 (2013).

[20] E. Esarey, R. F. Hubbard, W. P. Leemans, A. Ting, and P. Sprangle, "Electron Injection into Plasma Wakefields by Colliding Laser Pulses", Phys. Rev. Lett. 79, 2682 (1997).

[21] H. Kotaki, *et al.* , "Electron Optical Injection with Head-On and Countercrossing Colliding Laser Pulses", Phys. Rev. Lett. 103, 194803 (2009).

[22] M. Chen, E. Esarey, C. G. R. Geddes, E. Cormier-Michel, C. B. Schroeder, S. S. Bulanov, C. Benedetti, L. L. Yu, S. Rykovanov, D. L. Bruhwiler, and W. P. Leemans, "Electron injection and emittance control by transverse colliding pulses in a laser-plasma accelerator", Phys. Rev. ST Accel. Beams 17, 051303 (2014).

[23] Min Chen, Zheng-Ming Sheng, Yan-Yun Ma, and Jie Zhang, "Electron injection and trapping in a laser wakefield by field ionization to high-charge states of gases", Jour. Appl. Phys. 99, 056109 (2006).

[24] A. Pak, K. A. Marsh, S. F. Martins, W. Lu, W. B. Mori, and C. Joshi, "Injection and Trapping of Tunnel-Ionized Electrons into Laser-Produced Wakes", PRL 104, 025003 (2010).

[25] C. E. Clayton, J. E. Ralph, F. Albert, R. A. Fonseca, S. H. Glenzer, C. Joshi, W. Lu, K. A. Marsh, S. F. Martins, W. B. Mori, A. Pak, F. S. Tsung, B. B. Pollock, J. S. Ross, L. O. Silva, and D. H. Froula, "Self-Guided Laser Wakefield Acceleration beyond 1 GeV Using Ionization-Induced Injection", Phys. Rev. Lett. 105, 105003 (2010).

[26] M. Chen, E. Esarey, C. B. Schroeder, C. G. R. Geddes, and W. P. Leemans, "Theory of ionization-induced trapping in laser-plasma accelerators", Phys. Plasmas 19 , 033101 (2012).

[27] M. Zeng, M. Chen, L. L. Yu, W. B. Mori, Z. M. Sheng, B. Hidding, D. A. Jaroszynski, and J. Zhang, "Multichromatic Narrow-Energy-Spread Electron Bunches from Laser-Wakefield

Acceleration with Dual-Color Lasers", Phys. Rev. Lett. 114, 084801 (2015).

[28] T. L. Audet, M. Hansson, P. Lee, F. G. Desforges, G. Maynard, S. Dobosz Dufrénoy, R. Lehe, J.-L. Vay, B. Aurand, A. Persson, I. Gallardo González, A. Maitrallain, P. Monot, C.-G. Wahlström, O. Lundh, and B. Cros, "Investigation of ionization-induced electron injection in a wakefield driven by laser inside a gas cell", Phys. Plasmas 23 023110 (2016).

[29] L.-L. Yu, E. Esarey, C. B. Schroeder, J.-L. Vay, C. Benedetti, C. G. R. Geddes, M. Chen, and W. P. Leemans, Two-Color Laser-Ionization Injection, Phys. Rev. Lett. 112, 125001 (2014).

[30] L.-L. Yu , E. Esarey , C. B. Schroeder , J.-L. Vay , C. Benedetti , C. G. R. Geddes , M. Chen , and W. P. Leemans, "Ultra-low emittance electron beams from two-color laser-ionization injection", Advanced Accelerator Concepts 2014 AIP Conf. Proc. 1777, 040019-1–040019-5; doi: 10.1063/1.4965621.

[31] X.L. Xu et al, "Low emittance electron beam generation from a laser wakefield accelerator using two laser pulses with different wavelengths", Phys.Rev.ST Accel.Beams 17 061301 (2014)

[32] P. Tomassini, L. Labate, P. Londrillo, R. Fedele, D. Terzani and L. A. Gizzi, "Resonant Multi Pulse Ionization Injection", submitted (2017)

[33] D. Umstadter, E. Esarey, and J. Kim, "Nonlinear Plasma Waves Resonantly Driven by Optimized Laser Pulse Trains", Phys. Rev. Lett. 72, 1224 (1994).

[34] S M Hooker , R Bartolini, S P D Mangles , A Tunnermann , L Corner , J Limpert, A Seryi and R Walczak, "Multi-pulse laser wakefield acceleration: a new route to efficient, high-repetition-rate plasma accelerators and high flux radiation sources", J. Phys. B 47, 234003 (2014).

[35] R.J. Shalloo, L. Corner, C. Arran, J. Cowley, G. Cheung, C. Thornton, R. Walczak, S.M. Hooker, "Generation of laser pulse trains for tests of multi-pulse laser wakefield acceleration", NIM A 829, 1, 383-385 (2016).

[36] E. Esarey and M. Pilloff, "Trapping and acceleration in nonlinear plasma waves", Phys. Plasmas 2, 1432 (1995).

[37] V.P. Krainov, W. Xiong, S.L. Chin, "An introductory overview of tunnel ionization of atoms by intense lasers", Laser Physics 2, 4 (1992).

[38] C. B. Schroeder, J.-L. Vay, E. Esarey, S. Bulanov, C. Benedetti, L.-L. Yu, M. Chen, C. G. R. Geddes, and W. P. Leemans, "Thermal emittance from ionization-induced trapping in plasma accelerators", Phys. Rev. ST AB 17, 101301 (2014).

[39] C. Benedetti, A. Sgattoni, G. Turchetti and P. Londrillo, "ALaDyn: A High-Accuracy PIC Code for the Maxwell-Vlasov Equations", IEEE Trans. On Pl. Science 36, 4 (2008).

[40] P. Tomassini and A.R. Rossi, "Matching strategies for a plasma booster", Plasma Phys. Control. Fusion 58 034001 (2016).

[41] P. Sprangle, E. Esarey and A. Ting, "Nonlinear Theory of Intense Laser-Plasma Interaction", Phys. Rev. Lett 64, 2011-2014 (1990).

[42] P. Sprangle, E. Esarey, and J. Krall, "Self-guiding and stability of intense optical beams in gases undergoing ionization", Phys. Rev. E 54, 4211 (1996).

[43] W. Lu, M. Tzoufras, C. Joshi, F. S. Tsung, W.B. Mori, J. Vieira, R.A. Fonseca, L.O. Silva, Phys. Rev. ST Accel. Beams **10**, 061301 (2007)

[44] G. Sarri, D. J. Corvan, W. Schumaker, J. M. Cole, A. Di Piazza, H. Ahmed, C. Harvey, C. H. Keitel, K. Krushelnick, S. P. D. Mangles, Z. Najmudin, D. Symes, A. G. R. Thomas, M. Yeung, Z. Zhao, and M. Zepf, "Ultrahigh Brilliance Multi-MeV γ-Ray Beams from Nonlinear Relativistic Thomson Scattering", Phys. Rev. Lett. 113, 224801 (2014).

[45] Changhai Yu et al, "Ultrahigh brilliance quasi- monochromatic MeV γ-rays based on self-synchronized all-optical Compton scattering", Sci Rep. 6 29518 (2016).