Linear and Nonlinear Thomson Scattering for Advanced X-ray Sources in PLASMONX

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***Abstract*—Thomson scattering of laser pulses onto ultrarelativistic e-bunches is becoming an advanced source of tunable, quasi-monochromatic, and ultrashort X/gamma radiation. Sources aimed at reaching a high flux of scattered photons need to be driven by high-brightness e-beams, whereas extremely short (femtosecond scale or less) sources need to make femtosecond-long e-beams that collide with the laser pulses. In this paper, we explore the performance of the PLASMONX TS source in several operating regimes, including preliminary results on a source based on e-bunches produced by laser wakefield acceleration and controlled injection via density downramp.**

***Index Terms*—Compton scattering, Thomson scattering (TS), X-ray sources.**

I. Introduction

FUNDED by the Istituto Nazionale di Fisica Nucleare (INFN), the PLasma Acceleration at Sparc and MONOchromatic X-ray generation project (PLASMONX) will operate at the National Laboratories in Frascati, close to Rome. One of the main goals of the project is the development of a multipurpose tunable X-ray source, with emphasis on either monochromaticity or shortness of the radiation pulse. In the SPARC-LAB, PLASMONX is one of the most relevant activities; a Ti:Sa laser system (6 J in 20-fs 10-Hz of repetition rate) will be installed close to the advanced RF photoinjector under commissioning, as a part of the SPARC Project which is mainly devoted to the generation of visible FEL radiation. The possibility to obtain an overlapping between high-quality electron beams and ultraintense/highly energetic laser pulses can thus be employed to explore either laser wake field acceleration (LWFA) with internal/external injection or Thomson scattering (TS) physics and applications. TS X-ray sources are attracting strong attention because of their flexibility and potential compactness with respect to conventional synchrotron sources. A TS source driven by high-quality e-beams can be switched on in several operating modes, namely, the high-flux-moderate-monochromaticity mode (HFM2), the moderate-flux-monochromatic mode (MFM), and the short-and-monochromatic mode (SM). The HFM2 mode is suitable, e.g., for medical imaging, when high-flux sources are needed and a moderate monochromaticity is useful to improve the detection/dose performance. The MFM mode is useful for static probing when high monochromaticity and, possibly, tunability are needed (e.g., imaging with subtraction of images taken with different energies). The SM mode is finally useful for pump-and-probe experiments, e.g., in physical chemistry and nanobiology when tens of femtosecond-long monochromatic pulses are needed.

LWFA can be a valid alternative to conventional RF photoinjectors [1], provided that the beam quality is good enough. Among the possible methods to self-inject particles in the accelerating region of the plasma wave, controlled injection via sharp density downramp looks like one of the most promising in terms of both longitudinal and transverse emittances of the ec-beam [2], [3], which are critical issues for the final TS outcome [4]. Advantages of LWFA accelerators rely essentially in the compactness of source and in a higher flexibility on the energy of the e-beam (that can presently be accelerated in the energy range from few megaelectronvolts up to 1 GeV in the bubble regime). Moreover, the e-beams produced by LWFA accelerators can be extremely short (less than 1 fs), thus opening new horizons in the development of ultrashort (US) X-ray sources.

In this paper, we will sketch the expected performances of the PLASMONX TS source driven by the conventional RF photogun, with emphasis on the flux/monochromaticity/shortness of the source. We will also show preliminary results of numerical simulations of the TS source driven by an LWFA with a density downramp injection which is capable of producing extremely short (1 fs) X-ray pulses with moderate monochromaticity.

II. Basics of TS Physics and Simulation Code $(TS)^2$

TS [4]–[6] is the electromagnetic process in which each electron absorbs one (linear TS) or more (nonlinear TS) photons from (typically) a laser pulse, emitting one scattered photon without a sizable recoil (i.e., the so-called Thomson limit of

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the Compton process). If the electrons are ultrarelativistic, the scattered radiation looks frequency-upshifted and is mostly emitted forward with respect to the motion of particles in a small cone of aperture roughly given by the inverse of their Lorentz gamma.

The physics of TS is quite complex in the nonlinear regime, i.e., when the laser pulse strength $a0 = 8.5 \cdot 10^{-10}(I\lambda^2)^{1/2}$ approaches or exceeds unity. At intensities above the so-called "relativistic intensity" $I\lambda^2 = 10^{18}\ \mu\text{m}^2 \cdot \text{W/cm}^2$, the extremely intense electric field makes the electrons' quivering speed approach the light speed, making the magnetic field relevant for dynamics, thus generating a complex particle motion.

The computation in the far field of the scattered photons' distribution N_λ of pulsation ω can be performed in the classical regime provided that the energy of the electrons is far below tens of gigaelectronvolts, as it is the case for this paper, by using

$$\frac{d^2N_\gamma}{d\omega d\Omega} = \frac{\alpha}{4\pi^2}\omega\left|\vec{J}(\vec{n},\omega)\right|^2$$
$$\vec{J}(\vec{n},\omega) = \vec{n}\times\left(\vec{n}\times\int dt\vec{\beta}(t)e^{i\omega\left(t-\frac{\vec{n}\cdot\vec{r}(t)}{c}\right)}\right) \qquad (1)$$

where r and β represent the particle position and speed, respectively, and $\vec{n}$ is the emitted photon unit versor. By taking the retarded effects into account, which are the nonlinear quivering and secular motion of each electron in the bunch due to pulse longitudinal ponderomotive forces, an analytical computation of the scattered radiation distribution valid in the case of a planar flattop pulse (see [4]) shows that the spectral distribution of the photons emitted by a single particle is almost completely correlated with the scattering angle and is composed of a sum of harmonics

$$\frac{d^2N_\gamma}{d\omega d\Omega} \cong \sum_{n=1}^{\infty} V(n,\vartheta,\varphi)\delta(\omega - n\omega_{\text{F}}). \qquad (2)$$

In (2), n represents the harmonics order, $(\theta\phi)$ denotes the scattering angles in cylindrical coordinates (see Fig. 1), and ω_{F} is the fundamental pulsation

$$\omega_{\text{F}} \cong \omega_{\text{L}} \cdot 4\gamma^2/(1+\gamma^2\tilde{\vartheta}^2 + a_0^2/2) \qquad (3)$$

where ω_{L} is the laser pulsation and $\tilde{\vartheta}^2 = \vartheta^2 + \vartheta_{\text{e}}^2 - 2\vartheta\vartheta_{\text{e}}\cos(\phi - \phi_{\text{e}})$. The structure functions, represented by $V(\theta\phi)$, have a complex dependence upon the particle energy, incidence angles $(\theta_{\text{e}}\phi_{\text{e}})$, and scattering angles, and their detailed description can be found in [4]. We stress here that in the linear regime $a_0 \ll 1$, only one harmonic is produced, whereas in the case of weak nonlinearity (a_0 approximately unity), only a few harmonics are generated.

The properties of the photons emitted by the whole electron bunch can be simulated by summing up the contributions in intensity of each electron (i.e., in the incoherent regime). To do that, we have employed the "TS Simulation Tool" $(\mathbf{TS})^2$ code developed by one of the authors (PT). The code works as follows. The secular trajectory of each particle of the bunch is first computed by neglecting transverse ponderomotive effects (this approximation is fully consistent with the laser pulse and

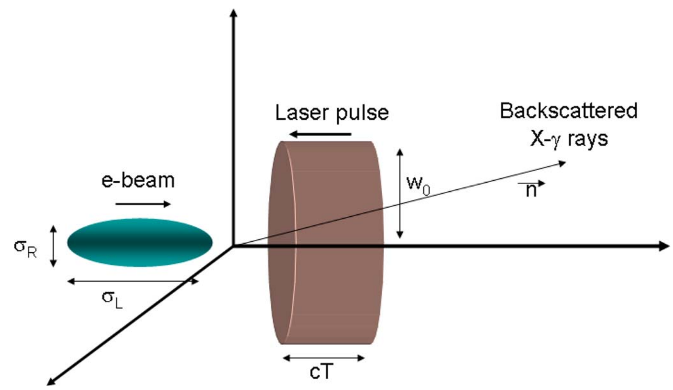

Fig. 1. Thomson backscattering geometry. The electron beam of longitudinal and transverse sizes σ_{L} and σ_{R}, respectively, is moving at a relativistic speed from left to right, colliding with a photon beam of waist size w_0 and duration T, thus emitting scattered radiation mainly in the direction of motion of the electron beam.

electron bunch parameters considered in this paper; see [4]). Considering that the analytical outcome sketched in (2) and (3) are valid only for the case of planar long flattop laser pulse, the code decomposes the pulse in a sequence of single cycles, with each cycle having its own phase shift and intensity. While the particle is moving along its secular path, it interacts with different cycles of the pulse, and the coherent summation of the radiation emitted in each cycle gives rise to the radiation emitted during the entire interaction.

III. HFM2 Operating Mode

In this operating mode the source is required to deliver high-flux X-ray beams having some degree of monochromaticity. We have optimized the PLASMONX source for applications in medical imaging, with emphasis on mammography. The goal of the TS optimization step is that of generating the highest X-ray flux of energy, which is about 20 KeV, while keeping the relative energy spread of the radiation below 20% FWHM for the fundamental. An additional requirement was the recommendation that high-order harmonics should be as low a possible in order to prevent their unacceptable enhancement after filtration.

The final goal of the whole e-beam generation system is that of producing and transporting bunches of energy E_{beam} of about 30 MeV (corresponding to $\gamma = 60$), which reach the focal spot with a transversal size comparable to the laser focal spot size ($\sigma_{\text{T}} \approx 8\text{–}10\ \mu$m) and with a longitudinal length σ_{L} comparable to the minimum of the β function (β^*), in order to permit the optimization of the geometrical overlapping with the laser pulse on the whole interaction duration. These considerations impose severe constraints on the longitudinal energy spread and on the transversal emittance of the beam. The longitudinal energy spread causes chromatic aberration with a consequent degradation of the focusing of the system. The correction of the longitudinal phase space is obtained by using a traveling wave S-band acceleration structure (3-m-long SLAC type) in addition to a short nine-cell X-band acceleration structure [7], [8]. Moreover, a low transversal emittance value is obtained by following the prescriptions proposed in the

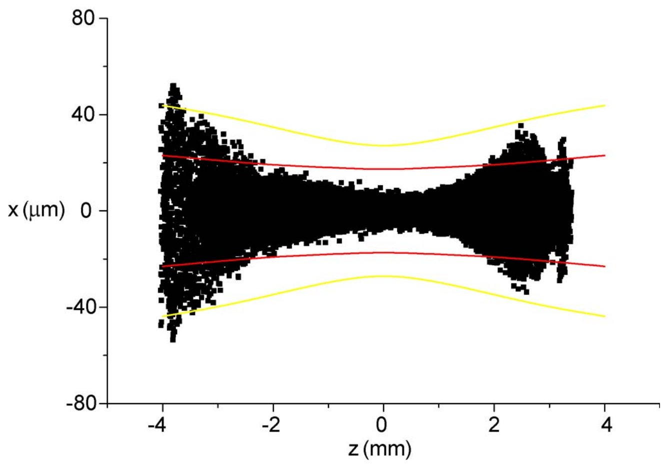

Fig. 2. Snapshot of the beam in the plane (x, z) at the instant of the maximum superposition with the laser. Here, the coordinate z is shown with respect to the baricentrum of the beam. (Red line) Field level curve of 50%. (Yellow line) Field level curve of 20%.

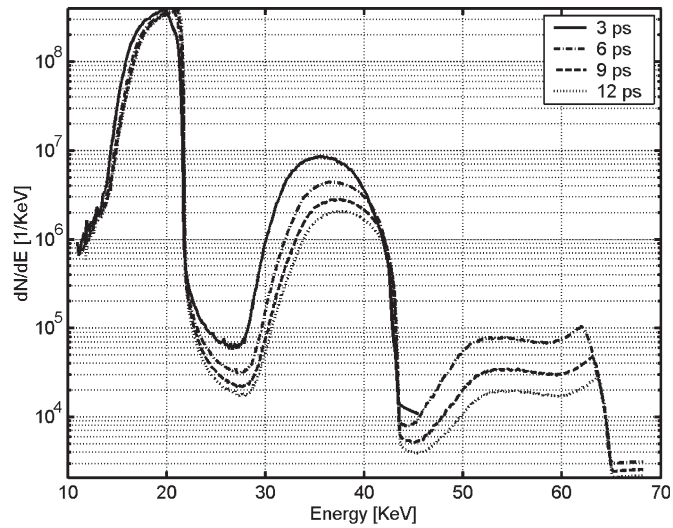

Fig. 3. Spectra of the collected radiation for pulses of duration 3, 6, 9, and 12 ps.

theoretical study of the emittance compensation process in the photoinjectors [9], which show how the emittance can be controlled by accelerating the beam as closely as possible to the relevant beam equilibrium corresponding to a laminar Brillouin flow in the drifts and to an invariant envelope in the accelerating sections.

The e-bunch is generated by an advanced high-gradient 1.6-cell RF photocathode gun that accelerates the beam up to 5–6 MeV. The photocathode is driven by a 15-ps flattop laser pulse (Ti:Sa 266-nm laser) able to extract a charge of 1 nC. The RF gun is followed by a first solenoid necessary for the emittance compensation, with a maximum field intensity of 0.27 T.

At the focus, the e-beam is expected to be 8 mm long (full width), with a minimum waist $\sigma_{\rm T} = 13\ \mu$m, whereas the energy spread and normalized emittance should be $\Delta E/E = 0.1\%$ rms and $\varepsilon_{\perp} = 1.5$ mm $\cdot$ mrad, respectively (Fig. 2).

On the laser-pulse side, the free parameters are the following: 1) pulse focusing size (waist size w_0); 2) pulse duration T; and 3) acceptance angle $\theta_{\rm M}$ of the scattered radiation. The choice of the optimal laser pulse focusing size is determined by two competitive phenomena. At a very small focusing size, diffraction enables the laser pulse to spread transversally in a longitudinal size $2Z_{\rm R} = 2\pi w_0^2/\lambda$ smaller than the electron bunch length $\sigma_{\rm L}$, making the queues of the bunch interact with a poorly intense laser pulse. On the opposite side, a too large focusing size reduces the pulse intensity and, thus, the scattered radiation yield. The determination of the best time duration T is deeply linked to the nonlinear phenomena that appear at high pulse intensities. In particular, the intensity of higher harmonics must be minimized in most applications of radiological imaging in order to avoid radiation deposition in tissues without information carried to the detector. However, while the pulse duration should be set as long as possible so as to reduce nonlinearities, the diffraction effect imposes an upper limit to T. Considering that the pulse spreads out while it propagates the focus out, the maximum pulselength above that the pulse cannot be considered as fully focused is roughly given by $cT_{\max} \approx 2Z_{\rm R}$.

Moreover, the requirements for the maximum energy spread and high-order harmonics maximum intensity impose strong constraints on the maximum collecting (or acceptance) angle $\theta_{\rm M}$. Considering that the energy of a scattered photon is almost completely correlated with the scattering angle (3) in linear or weakly nonlinear regimes, it comes out that by collecting the radiation within a cone of half aperture $\theta_{\rm M} = 1/\gamma$, an overall energy spread exceeding 50% is obtained.

In the case of electron beam with negligible emittances, an analytic formula can be employed to relate the radiation yield and energy spread to the acceptance (see [4])

$$N_\gamma \propto \Psi^2 \frac{(1+\Psi^2+2\Psi^4/3)}{(1+\Psi^2)^3}$$
$$\Delta\omega_{\rm F}/\omega_{\rm F} \cong \Psi^2/(1+\Psi^2/2) \qquad (4)$$

with $\Psi \equiv \gamma\vartheta_{\rm M}$ being the normalized acceptance angle. Note that for $\Psi \ll 1$, the radiation energy spread can be considerably reduced up to a minimum value depending on the electron beam and laser pulse qualities; however, the collected yield is reduced accordingly because $N_\gamma \approx \Psi^2$ and $\Delta\omega_{\rm F}/\omega_{\rm F} \approx \Psi^2$. By solving (4) for the normalized acceptance by assuming an energy spread of 20%, a normalized acceptance $\Psi \cong 0.5$, with a collection of 17% of the total scattered yield, is found.

Once the acceptance angle has been fixed to $\vartheta_{\rm M} = \Psi/\gamma = 8$ mrad, a sequence of runs of the $(\mathbf{TS})^2$ code with a scan of the focusing size and pulse duration has started, leading to the choice of 15 μm for the focusing size, with a Rayleigh length $Z_{\rm R} = \pi w_0^2/\lambda 885\ \mu$m. The dependence of the number of collected photons upon the pulse duration is weak, and this enables the optimization for taking care of the unwanted nonlinear effects. In Fig. 3, some of the spectra of the collected radiation (in the case of pulses of duration 3, 6, 9, and 12 ps) are shown.

As it is apparent in Fig. 3, the time duration affects mainly the intensity ratio between harmonics, whereas the fundamental is

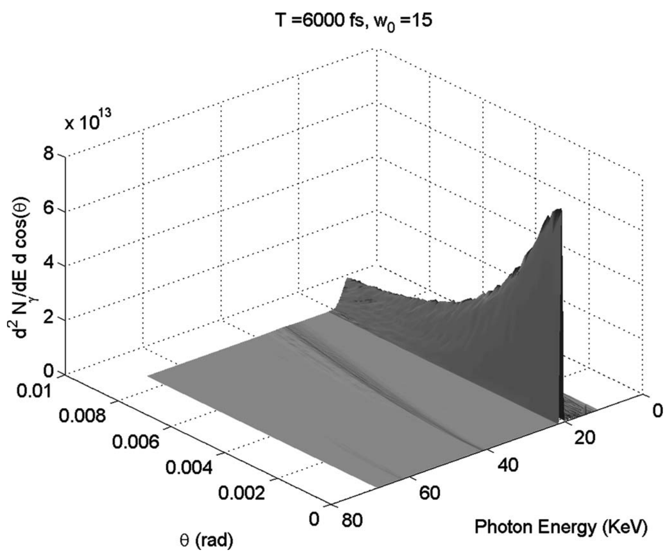

Fig. 4. Spectral–angular (integrated in the azimuthal angle ϕ) distribution of the collected radiation for the optimized parameters $w = 15$ μm and duration $T = 6$ ps, where $\vartheta_{\mathrm{M}} = 8$ mrad.

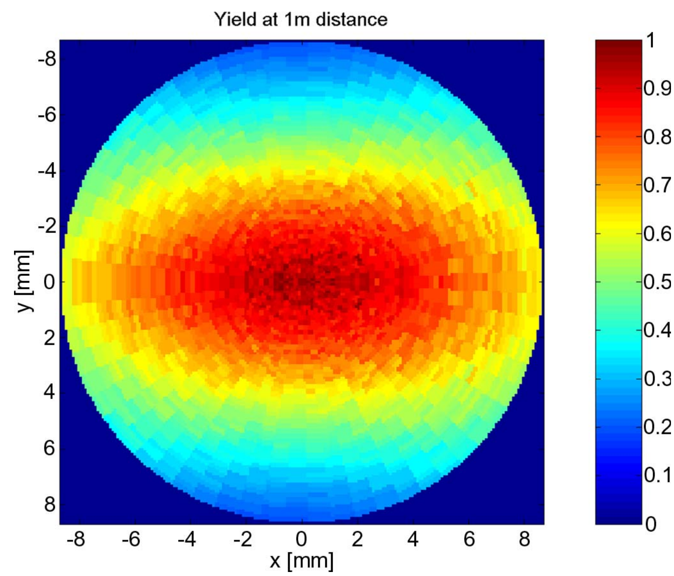

Fig. 5. Relative irradiation on a screen placed 1 m away from the collision point.

marginally modified by a moderate nonlinearity. The best duration has been fixed to $T = 6$ ps, a value that maximized the photon yield up to $2 \cdot 10^9$ for the shot, yet preserving a relatively low value of the second-to-first harmonic yield $N(2)/N(1) = 2 \cdot 10^{-2}$ and third-to-first $N(3)/N(1) = 8 \cdot 10^{-4}$ ratios. By looking at the spectra in Fig. 3, a computation of the bandwidth FWHM of the fundamental can be shortly obtained, confirming the analytical estimation of 20% limited by the acceptance angle of 8 mrad. In Fig. 4, the spectral–angular (integrated in the azimuthal angle ϕ) distribution of the collected radiation is shown. The fundamental at energy of about 20 KeV and the second harmonic are clearly visible, whereas the third harmonic is much less intense. Note the dependence of the energy on the scattering angle.

Finally, Fig. 5 shows a simulation of the relative intensity of the radiation impinging on a screen located 1 m away from the collision point. We note that the intensity profile is not flat inside the illuminated area and this nonuniformity should be taken into account in the X-ray imaging simulation.

In conclusion, as a result of the optimization process, a pulse of waist size $w_0 = 15$ μm, duration $T = 6$ ps, intensity $I = 2.3 \cdot 10^{17}$ W/cm^2, and amplitude $a_0 = 0.33$ is made to collide with the electron bunch. The backscattered radiation is collected within a cone of aperture $\vartheta_{\mathrm{M}} = 8$ mrad, yielding a flux of $2 \cdot 10^9$ photons/shot ($2 \cdot 10^{10}$ photons/s 10 Hz of the laser pulse repetition rate) with an energy spread of 20% FWHM.

IV. MFM

To switch from the HFM2 to the MFM mode, only a reduction of the acceptance angle ϑ_{M} is needed. For an ideal e-beam (i.e., having null emittances), (4) would be the basic relation stating the link between yield, acceptance, and monochromaticity so that for a required $\Delta\omega_{\mathrm{F}}/\omega_{\mathrm{F}} \ll 1$, the corresponding normalized acceptance should be $\Psi \cong \sqrt{\Delta\omega_{\mathrm{F}}/\omega_{\mathrm{F}}}$, corresponding to a geometric acceptance $\vartheta_{\mathrm{M}} \cong (1/\gamma)\sqrt{\Delta\omega_{\mathrm{F}}/\omega_{\mathrm{F}}}$. In a real e-beam, both the longitudinal and transverse emittances induce a noncorrelated energy spread of the scattered radiation $\Delta\omega_{\mathrm{F}}/\omega_{\mathrm{F}} \approx \psi^2 + 2\Delta\gamma/\gamma + 2(p_\perp/mc)^2$ that limits the possibility of producing monochromatic beams. In other words, a reduction of the acceptance down to $\psi_{\min} \approx \sqrt{\Delta\gamma/\gamma + (\varepsilon_\perp^2/\sigma_{\mathrm{T}}^2)}$ no longer corresponds to a reduction of the energy spread in the X-ray outcome but solely in a reduction of its flux. The energy spread of the e-beam is about 0.1%, whereas its normalized transverse emittance and focusing size are 1.5 mm $\cdot$ mrad and 13 μm, respectively, corresponding to an rms transverse momentum $\varepsilon_\perp/\sigma_{\mathrm{T}} \approx 0.1$ in mc units. Considering that $\Delta\gamma/\gamma \ll (\varepsilon_\perp^2/\sigma_{\mathrm{T}}^2)$, the minimum acceptance and the corresponding minimum energy spread of the source are $\psi_{\min} \approx (\varepsilon_\perp/\sigma_{\mathrm{T}}) \approx 0.1$ and $(\Delta\omega_{\mathrm{F}}/\omega_{\mathrm{F}})_{\min} \cong \psi_{\min}^2 \approx 1\%$, respectively. We observe that the expected number of collected photons can be estimated by scaling the yield of the HFQM2 operating mode by using (4), obtaining $N_{\gamma\mathrm{MFM}} \cong 0.06 \cdot N_{\gamma\mathrm{HFQM2}} \cong 1.2 \cdot 10^8$ photons/shot. A more accurate estimation can be easily performed by simply reducing the acceptance angle of the previous simulation $(\mathbf{TS})^2$ down to $\psi_{\min} = 0.1$ in the postprocessing of the same simulation reported in Section III, confirming the validity of the scaling in (4) and giving a yield of $N_{\gamma\mathrm{MFM}} = 1.3 \cdot 10^8$ photons/shot (i.e., $1.3 \cdot 10^9$ photons/s 10 Hz), with an energy spread of 2% FWHM (roughly 1% rms).

V. SM Operating Mode

The time duration of the X-ray bursts produced by the backscattering of pulsed laser beams and ultrarelativistic e-beams is given by the maximum value among the e-beam duration σ_{L}/c and the double-Lorentz compressed duration of the laser pulse $T/4\gamma^2$ for $\gamma \gg 1$ (see [4] for details). Considering that the Lorentz compression greatly helps in reaching US X-ray pulses (for example, a laser pulse that is 1 ps long colliding with a single 30-MeV electron produces X-ray radiation that is

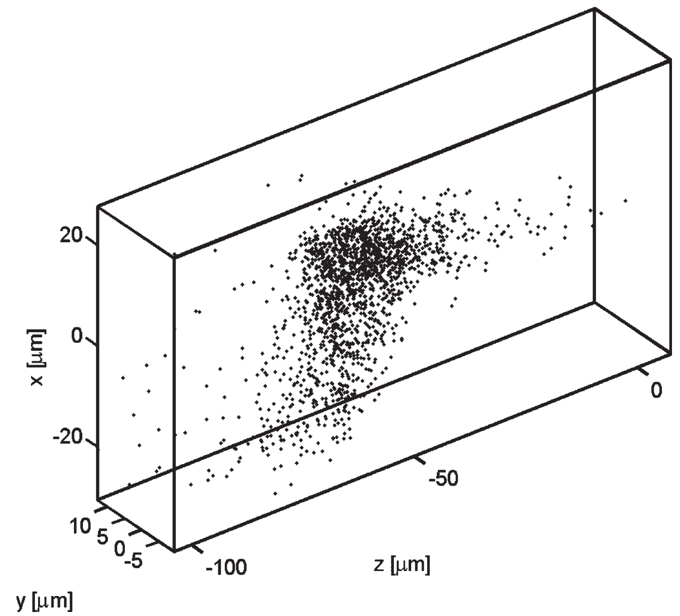

Fig. 6. Spatial distribution of the US beam on focus.

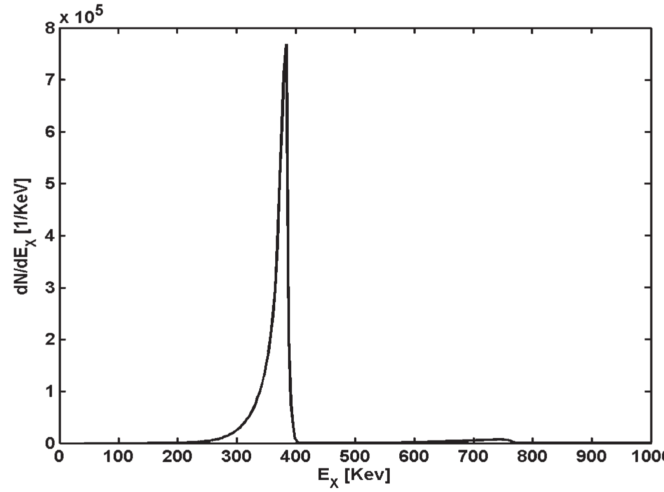

Fig. 7. Spectrum of the collected radiation of the SM operating mode. The energy spread in the fundamental is about 4% FWHM with a total flux of $N_{\gamma \mathrm{SM}} = 2 \cdot 10^7$ photons/shot.

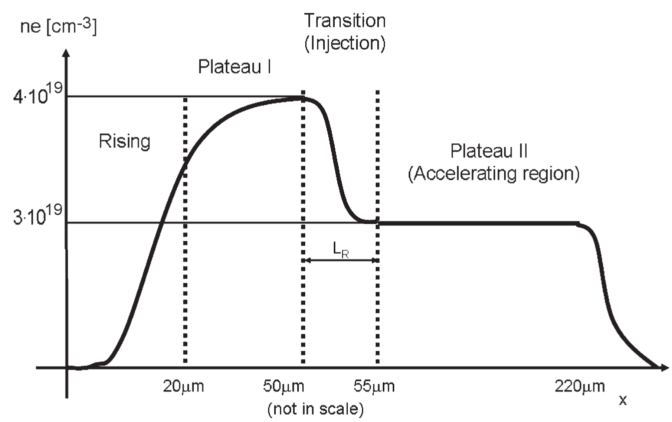

Fig. 8. Background plasma density useful for e-beam injection and acceleration.

TABLE I

LASER			PLASMA			
Energy (J)	Waist (μm)	Intensity (W/cm²)	n_{01} (1/cm³)	L_R (μm)	n_{02} (1/cm³)	λp (μm)
0.8	12	$7 \cdot 10^{18}$	$4 \cdot 10^{19}$	5	$3 \cdot 10^{19}$	5

70 ps long), the main requirements for an SM source are on the bunch length.

The e-beams suitable for the production of US X-rays must be as short as possible. In PLASMONX, two beamlines will be installed after the photogun, i.e., one devoted to the production of high-charge e-beams and one for the generation of US e-bunches that can be employed either for LWFA or TS experiments. While the beam for the Thomson source is transported unchanged through the dog-leg, the US bunch is produced by properly selecting a thin slice (25 μm) having a charge of 20 pC of the e-beam produced at 134 MeV by the SPARC photoinjector. The slice selection is accomplished as follows. The first RF deflector induces a correlation between the vertical position of each bunch slice at the slit position (located at the symmetric plane of the double dog-leg) and its longitudinal coordinate within the bunch. The slit then clips a specific slice. Finally, the second RF deflector removes the time-longitudinal correlation imparted by the first deflector. It should be noticed that this technique is somewhat similar to the one proposed [10] for LCLS with the aim of generating femtosecond-long electron bunches, but it differs from that in the use of RF deflectors, which removes the need of correlated energy spread (energy versus slice position within the bunch). At the focus, the spatial distribution of the US e-beam looks nonaxisymmetric (see Fig. 6), with a longitudinal size $\sigma_{\mathrm{L}} = 13$ μm rms and a mean transverse size $\sigma_{\mathrm{T}} = 6$ μm rms. The energy spread and transverse normalized emittance are $\Delta E/E = 0.1\%$ rms and $\varepsilon_{\perp} = 1.2$ mm · mrad, respectively.

Considering that the aim of the operating mode is the generation of a radiation having both a short length and good monochromaticity, the choice of the best acceptance angle must operate as in the case of the MFM mode. Here, the minimum normalized acceptance angle is $\psi_{\min} \approx (\varepsilon_{\perp}/\sigma_{\mathrm{T}}) \approx 0.2$ so that an energy spread $(\Delta\omega_{\mathrm{F}}/\omega_{\mathrm{F}})_{\min} \cong \psi_{\min}^2 \approx 4\%$ FWHM is expected. Moreover, considering that nonlinearities in the TS usually increase the energy spread of the scattered radiation, we optimized the working point so as to keep the pulse intensity as low as possible while maintaining the X-ray flux as large as possible. As a result of the optimization step, the laser pulse is 5 ps long and is focused down to a waist $w_0 = 15$ μm to keep nonlinearities as low as possible.

Simulations performed with the $(\mathbf{TS})^2$ code confirm once more the correctness of the simple scalings of (4) (see Fig. 7) and indicate the yield of $N_{\gamma \mathrm{SM}} = 2 \cdot 10^7$ photons/shot (i.e., $2 \cdot 10^8$ photons/s 10 Hz) with a mean energy of 380 KeV and an energy spread of 4% FWHM (roughly 2% rms) of 45-fs rms duration.

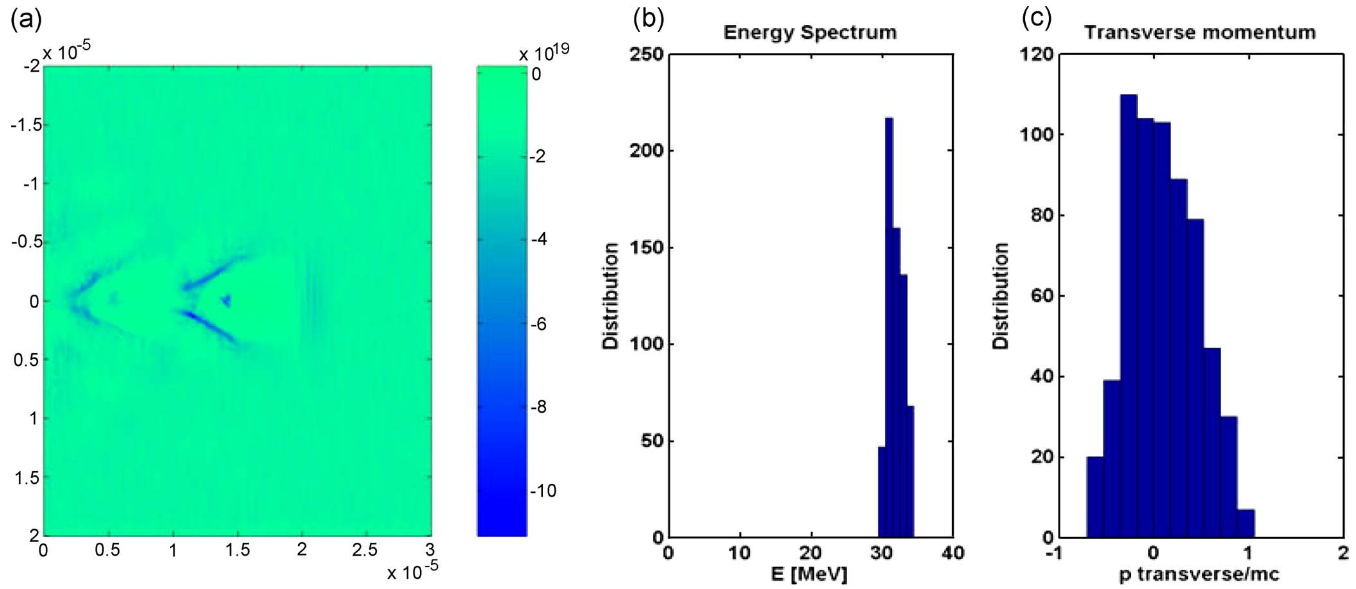

Fig. 9. (a) Snapshot of the electron density after 200 μm of propagation of the laser pulse in the plasma. (b) Distribution of the longitudinal momentum of the e-beam. (c) Distribution of the transverse momentum.

VI. TS Source Driven by LWFA-Produced e-Beams. The US Operating Mode

Laser wakefield acceleration with controlled injection can be a valid alternative to conventional RF photoinjectors for TS sources, provided that the beam quality is good enough. Considering that the energy spread of the scattered radiation cannot be reduced to $(\Delta\omega_{\rm F}/\omega_{\rm F})_{\min} \approx 2\Delta\gamma/\gamma + 2(p_\perp/mc)^2$, both the longitudinal and transverse sizes of the momentum distribution play a relevant role. Among the several schemes that have been proposed and investigated so far to obtain a controlled injection of electrons in the plasma wave, the injection by longitudinal nonlinear breaking of the wave at a density downramp looks like one of the most promising because it can produce e-beams having *both* a low energy spread and low transverse emittance [3]. *However, we stress that the transverse emittance is not directly linked to the monochromaticity but that the ratio* $(p_\perp/mc) \cong \varepsilon_\perp/\sigma_{\rm T}$ *should be used instead.*

Simulations of the LWFA process were performed with the fully self-consistent particle-in-cell code VORPAL [11] in the 2.5-D (3-D in the fields and 2-D in the coordinates) configuration. The initial plasma density profile (see Fig. 8) is composed of a smooth rising edge (laser coming from the left) and a first plateau of density n_{01}, where a high-amplitude plasma wave is excited. Next, a density downramp with a scale length $L_{\rm R}$ makes a transition to a second plateau of density n_{02}.

A partial break of the wave crests at the transition occurring when $L_{\rm R} \approx \lambda_{\rm p}$ injects the electrons in the appropriate phase of the plasma wave excited in the second plateau (accelerating region).

The optimization of the parameters was performed according to the PLASMONX 300-TW laser system performance. Here, we used only a portion of the laser energy, giving rise to a first set of plasma and laser pulse parameters shown in Table I.

Simulations of the injection–acceleration process were performed in a moving window of longitudinal and transverse sizes of 30 and 40 μm, respectively, sampled in a box with

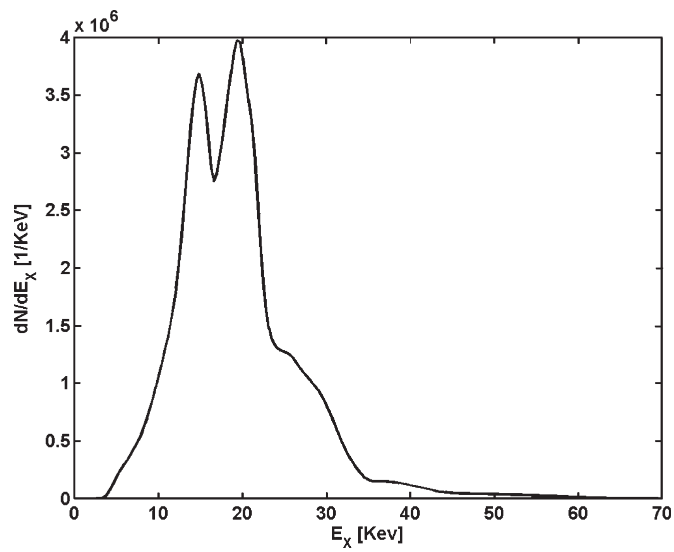

Fig. 10. Spectrum of the TS radiation of the US source in the case of normalized acceptance $\Psi = 0.5$.

20 macroparticles/cell corresponding to a longitudinal and transverse resolution of $\lambda_0/15$ and $\lambda_0/4$, respectively. In Fig. 2(a), the electron density after an acceleration length of about 200 μm is reported. The electron beam of charge $Q \cong$ 20 pC gets a mean energy of about 32 MeV with an energy spread of 10% (rms), longitudinal rms size $\sigma_{\rm L} = 0.27$ μm, transverse rms size $\sigma_{\rm T} = 0.47$ μm, and transverse normalized emittance $\varepsilon_\perp = 0.23$ mm $\cdot$ mrad (see Fig. 9).

We note that even if the emittance appears very low, the rms value of the transverse momentum $(p_\perp/mc) \cong \varepsilon_\perp/\sigma_{\rm T} \cong 0.5$ is quite large, thus limiting (along with the energy spread) the possibility of producing really monochromatic e-beams below $(\Delta\omega_{\rm F}/\omega_{\rm F})_{\min} \approx 2\Delta\gamma/\gamma + 2(p_\perp/mc)^2 \approx 0.7$ FWHM. Simulations with the TS code show that the energy spread of the scattered X-rays can be reduced to $(\Delta\omega_{\rm F}/\omega_{\rm F})_{\min} \approx$ 0.5 (25% rms) instead, as it is shown in Fig. 10, where the

TABLE II

Operating Mode	Spot size [μm]	Ang. div. [mrad]	Flux @10Hz [phot/sec]	Mean energy [keV]	Energy spread (rms)	Rms Duration [fs]
HFM2	13	8	$2 \cdot 10^{10}$	20	10%	6000
MFM	13	1.7	$1.3 \cdot 10^{9}$	20	1%	6000
SM	6	0.7	$2 \cdot 10^{8}$	380	2%	45
US	0.5	8	$4 \cdot 10^{8}$	20	25%	< 1

spectrum of the scattered radiation collected within a normalized acceptance of $\psi_{\min} \approx (\varepsilon_\perp/\sigma_T) \approx 0.5$ is reported. Simulations were performed by supposing a splitting of the 6-J laser pulse in two counterpropagating pulses, namely, the 0.8-J pulse driving the e-beam and a 5-J-producing TS. The 5-J pulse must not be compressed down to 20 fs in order to limit nonlinearities in the TS process; however, its duration should be roughly the same as the pulses in the other operating modes (5–6 ps). The duration of the scattered radiation, however, looks remarkably low, being less than 1 fs, and this seems to be the most intriguing feature of the source. As a result, the head-on collision of the 20-pC e-bunch and the 5 J in 5-ps laser pulse focused in 15 μm of waist can produce a 1-fs-long X-ray pulse of mean energy 20 KeV in the fundamental and energy spread of 25% rms with a total flux $N_{\gamma \mathrm{US}} = 4 \cdot 10^7$ photons/shot (i.e., $4 \cdot 10^8$ photons/s 10 Hz). We stress here that the results on the source driven by the LWFA-produced e-beams should be considered as preliminary results. Critical issues in this scheme are the Coulomb explosion of the e-bunch if the collision with the laser pulse is tuned to occur just after the plasma and the possible laser–plasma instabilities of the "wiggler" laser pulse if the interaction occurs inside the high-density plasma. Moreover, the tailoring of the background plasma profile so as to generate a sharp (5 μm) density transition is a challenging task. Full 3-D simulations are in progress, and the optimization of the working point is toward the production of e-beams with a lower transverse temperature.

VII. Conclusion

We have shown the results of start-to-end simulations of the PLASMONX TS source in several operating regimes, revealing the flexibility of the source and the capability of switching between requirements on the monchromaticity, flux, tunability, and shortness of the X-ray source. In Table II, the main parameters in the different operating modes are reported.

We mention here that the "Spot size" column can give a relevant information not only for the choice of the laser pulse transverse size but also for estimations of the transverse coherence of the X-ray pulse. The Thomson source produces radiation which is completely longitudinally incoherent because of the lack of phase links among each particle trajectory; however, the transverse coherence of the pointlike source can be employed in several applications, including contrast-phase mammography.

The proposed source should be compared with the other tabletop US X-ray sources based upon ultraintense laser–plasma interactions, namely, $\mathrm{K}\alpha$ and betatron sources. For the sake of comparison with the case reported here (see, in particular, Sections IV and V), we can say that a total number of 10^6 $\mathrm{K}\alpha$ ph/shot can be collected in a cone subtended by a 10-mrad angle in the case of laser–plasma $\mathrm{K}\alpha$ sources [12]. The X-ray bunch duration, mainly due to the transport time of the hot electrons inside the solid target, is, in this case, on the order of 100 fs.

In the last few years, a new mechanism of X-ray production in ultraintense laser–plasma interactions has been reported to be effective [13] based upon the betatron oscillations of the relativistic electrons produced during the interaction. In contrast with the $\mathrm{K}\alpha$ case, the spectrum of the emitted radiation, to some extent resembling the one from a synchrotron source, extends, in this case, over a broad range (from some kiloelectronvolts to hundreds of kiloelectronvolts) depending on the energy of the electrons undergoing the oscillations. This kind of sources thus needs to be monochromatized for a practical use. Although the X-ray flux integrated over the whole solid angle is some orders of magnitude smaller with respect to the $\mathrm{K}\alpha$ sources, the X-ray emission has, in this case, a much smaller divergence, which is on the order of millirads; recent simulations reported in the literature [14] show that the average brightness of such a source can be expected, with 100-TW laser pulses, to be three orders of magnitude higher than in the case of the $\mathrm{K}\alpha$ sources, with typical durations that are, in this case, of a few tens of femtoseconds.

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