

Probing strong-field QED in beam-plasma collisions



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Reviewers' comments:

Reviewer #1 (Remarks to the Author):

The manuscript by Matheron et al proposes a new scheme for achieving conditions of relevance to Strong Field Quantum Electro Dynamics. While the approach being investigated most commonly is that of using counterpropagating relativistic electron beam and intense laser pulses, this paper proposes a very interesting alternative, in which a beam of relativistic electrons is directed into a dense plasma and interacts with the reflection of its self-consistent fields. The manuscript explores in detail this experimental situation by means of high quality Particle in Cell simulations and analytical calculations, and presents a convincing case for this novel configuration, which would be potentially easier to implement than counter-colliding schemes and immune from temporal/spatial misalignment issues which are critical for the above mentioned schemes.

The case of the electron beam interacting with an ultrathin gold foil is specifically addressed as an experimentally achievable configuration, where free electrons in the conduction band, complemented by field-ionized electrons creates the necessary high density plasma. Using an ultrathin foil prevents significant signal resulting from the electron interaction with the foil so that the signatures of the SF QED interaction remain dominant.

Overall this is a very promising scenario, which is well documented in this manuscript and calls for an experimental demonstration. The idea proposed is original and is explained and supported well by the simulations. I believe this paper would be of significant interest for the broad readership of Communication Physics. The manuscript is written well and presented clearly, and I support its publication in its present form.

Reviewer #2 (Remarks to the Author):

I have read carefully the article "Probing strong-field QED in beam-plasma collisions" by A. Matheron et al., which explores the possibility of probing strong-field QED leveraging the interaction between a dense ultra-relativistic electron beam and a solid target. During the interaction the beam self fields are reflected at the plasma boundary and can exceed (in rest frame of the beam) the Schwinger field, which then leads to strong-field QED processes such as quantum nonlinear inverse Compton scattering and nonlinear Breit-Wheeler electron-positron pair creation. The major claim of the authors is that this setup mimic beam-beam collisions with the advantage of an automatic overlap between the beam and the reflected fields. By appropriately tailoring the beam energy, density profile and the choice of the target composition, the setup could offer a new experimental paradigm to probe strong-field QED in the deep quantum regime.

I would like to stress that the paper is very well written. The structure of the paper is laid out in such a way that the reader learn step by step all the necessary information that leads to the final conclusion. In particular, the authors took great care of showing that they clearly thought of most of the finest details of the beam-target interaction. Nonetheless I remain perplex that the paper in the present state deserves publication in Physics Communication for the following reasons:

1) The claims are actually not that novel. The setup is a sort of follow-up of the previous letter from the same collaboration (Ref 38: A. Sampath et al. Phys. Rev. Lett. 126, 064801 2021) where the authors already showed that the quantum regime ($\chi \sim 1$) could be reached with an almost identical setup. Obviously the parameters are not identical since the first paper aimed at optimising the gamma-ray beam with a sequence of thin aluminium foils. Though, the principle remains the same, this time a gold solid target is being used to ensure the best plasma screening and ionisation to obtain the highest value of the quantum parameter χ .

2) The impression that the results are not appropriately discussed in the context of previous literature.

(i) The authors did a great job at studying how the reflected and evanescent field could change as the beam profile was varied. I am however surprised that this part of the article is presented without almost no references to the work of several authors of the 80's who were studying the self-focusing of ultra-relativistic electron beams with plasmas. If I am not mistaken this is the regime where $\beta < 1$ (cigar beams) with $\alpha < 1$. In this regime, the plasma is very effective at shielding E but not B and the beam experiences the full effect of its azimuthal B field. I guess that the maximum χ should be less than a factor of two compared to the $\beta > 1$ regime. I am listing below some references of interest:

- P. Chen, Part. Accel. 20, 171 (1987).
- J.J Su et al. Phys. Rev. A 41, 3321 (1990)
- J. B. Rosenzweig and Pisin Chen, Phys. Rev. D 39, 2039 (1989)

(ii) the article contains 43 references, among which 37 are grouped in the first page (38, 39, 40, 42 are self-reference to). The references [1-3] to beam-beam collision that involve Beamstrahlung and pair production are only mentioned in the introduction, and since the authors states that the current beam-target interaction reproduces beam-beam setup, it would be interesting and enriching for the article to present a bit of comparison in the SF-QED effects, namely QED observables and not only in the field strength.

3) Dwelling of the same topic, the authors write in the introduction that "the gamma-ray photon and positron spectra generated in that configuration can provide unambiguous experimental signatures of strong-field QED." The main purpose of this setup is to probe SF-QED in a precise manner and a reader would perhaps expect more information regarding what are exactly these experimental signatures (I fully agree that NLCS and BW will dominate over the Bremstrahlung and Bethe-Heitler in this regime). As an example, the authors spent almost 5 pages on the beam-target interaction and regrettably one column on the QED observables, whose results are summarised on Fig.6. What are actually the units in Fig 6d ? The authors mention gamma and positron spectrum. Are they particle spectrum or energy spectrum or energy spectrum with some normalized bandwidth (0.1%BW). They appear to me as a kind of spectral brightness.

Another point that should be clarified to me "the beam electrons experience a high χ value over a very short duration, of the order of σ_z/c , which is beneficial for precision studies of strong-field QED". What are the number of photons emitted per particle. We know from Ref [1-3] that this number is critical as it affects the final shape of the photon spectrum (for instance the peak that appears for $\chi > 16$ and is begin washed out when many photons are emitted). How is it that this setup with allow to probe better the SF-QED theoretical predictions than others as beam-beam collision or electron beam - laser scattering. Answering this issue could definitively influence thinking in the field.

The conclusions seem to define quite a narrow range of parameters to probe SF-QED regime: $\alpha = [0.2-0.7]$ and $\beta = [0.2-1]$. If the energy of the electron beam could be increased, would it help in relaxing these constraints?

Reviewer #3 (Remarks to the Author):

Review Report: COMMSPHYS-22-1007-T: "Probing strong-field QED in beam-plasma collisions", by A. Matheron, et al.

The Authors show a high-field generation toward QED effects by a mirror field between an incoming electron beam and a target solid target (Au) by PIC simulations. A similar idea on the high field generation by electron beams was published in Ref.1, based on two counter electron beams. The difference between this manuscript and Ref. 1 is the high-field generation scheme. In this manuscript the mirror field is employed between an incoming electron beam and a target solid target. The proposal would be interested in this high-field physics or in QED.

In order to enhance the proposal viability and also to convince Readers that the proposal is realistic, the Authors are recommended to clarify the following points:

1) Validity of n_b : The electron number density of n_b used is very high: $n_b \sim 10^{23}/\text{cc}$. This number is almost a solid density or even higher than the solid density. The Authors should present how to prepare the high-density beam. This point is the key issue of the work in the manuscript. In addition, before reaching the solid target surface, the electron beam may be expanded or elongated in a short distance. The Authors are recommended to show a viable scenario to obtain the solid-density (or high-density) electron beam at the target surface.

2) Evaluation of collective effect on the proposal: For the high-density target, collective behavior would be important, as mentioned in the manuscript in p. 4. For example, $\Omega_{pe} \sim 5.6 \times 10^{16}/\text{s}$ for $n_e \sim 10^{24}/\text{cc}$. Or $\tau \sim 1/\Omega_{pe} \sim 1.7 \times 10^{-17}\text{s}$. The time scale T in the manuscript may be $T \sim 50\text{nm}/c \sim 1.7 \times 10^{-16}\text{s}$, which is much larger than the electron plasma oscillation time. During the time scale of T , the target electrons may oscillate many times, and may show the collective behavior in the parameters employed in the manuscript. The collective mode effect on the proposal should be clarified to make the phenomenon focused. The electron beam density is so high and it may also show strong field to deform the beam profile or shape.

3) It would be welcome that the Authors demonstrate the proposal is remarkable and innovative, compared with the idea in Ref. 1.

Some minor points:

/ What is the electron beam temperature or emittance?

/ In "Methods" for PIC simulations, we find a sentence of "The time step of this simulation is 0.36 nm". Do you describe the time by the unit of ct ? Please check the unit.

/ In PIC simulations, for example, we find "For the simulations of Figs. 2, 4 and 5, each simulation cell is initially filled with 2 macroparticles of ions, 10 macroparticles of plasma electrons and 5 macroparticles of beam electrons. ... ". In 3D PIC simulations, usually more super particles would be needed to reduce numerical noises. Have you checked numerical noises by the superparticle number / cell in your cases?

Dear all,

First, we wish to thank the three reviewers for their careful reading of our manuscript and comments. In particular, we thank Reviewer 1 for his very positive appraisal of our work and, more generally, Reviewers 2 and 3 for acknowledging the interest of our research and our effort to present it as clearly as possible.

In the following, we answer every point raised by the reviewers and explain how we have revised our manuscript accordingly. The major changes made to the manuscript are indicated in red in a separate “diff.pdf” file. The main manuscript file incorporates those modifications but without the color change.

Best regards,
The authors

Reviewer #1

The manuscript by Matheron et al proposes a new scheme for achieving conditions of relevance to Strong Field Quantum Electro Dynamics. While the approach being investigated most commonly is that of using counterpropagating relativistic electron beam and intense laser pulses, this paper proposes a very interesting alternative, in which a beam of relativistic electrons is directed into a dense plasma and interacts with the reflection of its self-consistent fields. The manuscript explores in detail this experimental situation by means of high quality Particle in Cell simulations and analytical calculations, and presents a convincing case for this novel configuration, which would be potentially easier to implement than counter-colliding schemes and immune from temporal/spatial misalignment issues which are critical for the above mentioned schemes.

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Overall this is a very promising scenario, which is well documented in this manuscript and calls for an experimental demonstration. The idea proposed is original and is explained and supported well by the simulations. I believe this paper would be of significant interest for the broad readership of Communication Physics. The manuscript is written well and presented clearly, and I support its publication in its present form.

We thank Reviewer 1 for his very appreciative comments, stressing the originality and potential impact of our work as well as its clear presentation.

Reviewer #2

I have read carefully the article "Probing strong-field QED in beam-plasma collisions" by A. Matheron et al., which explores the possibility of probing strong-field QED leveraging the interaction between a dense ultra-relativistic electron beam and a solid target. During the

interaction the beam self fields are reflected at the plasma boundary and can exceed (in rest frame of the beam) the Schwinger field, which then leads to strong-field QED processes such as quantum nonlinear inverse Compton scattering and nonlinear Breit-Wheeler electron-positron pair creation. The major claim of the authors is that this setup mimics beam-beam collisions with the advantage of an automatic overlap between the beam and the reflected fields. By appropriately tailoring the beam energy, density profile and the choice of the target composition, the setup could offer a new experimental paradigm to probe strong-field QED in the deep quantum regime.

I would like to stress that the paper is very well written. The structure of the paper is laid out in such a way that the reader learns step by step all the necessary information that leads to the final conclusion. In particular, the authors took great care of showing that they clearly thought of most of the finest details of the beam-target interaction. Nonetheless I remain perplex that the paper in the present state deserves publication in *Physics Communication* for the following reasons:

1) The claims are actually not that novel. The setup is a sort of follow-up of the previous letter from the same collaboration (Ref 38: A. Sampath *et al.* *Phys. Rev. Lett.* 126, 064801 (2021)) where the authors already showed that the quantum regime ($\chi \sim 1$) could be reached with an almost identical setup. Obviously, the parameters are not identical since the first paper aimed at optimising the gamma-ray beam with a sequence of thin aluminium foils. Though, the principle remains the same, this time a gold solid target is being used to ensure the best plasma screening and ionisation to obtain the highest value of the quantum parameter χ .

Those two papers differ in their goals, the conceptual ideas they demonstrate and, to some degree, the physics that they study. Although the setups considered are indeed similar, Sampath *et al.* (now Ref. [47]) mainly addressed the beam's self-focusing across a stack of foils, with the goal of optimizing the gamma-ray generation. By contrast, our objective here is to design a setup giving rise to well-controlled interaction conditions, allowing SFQED models to be benchmarked against experimental data.

Now, it turns out that the parameters used by Sampath *et al.* are not at all optimal in this respect. The interaction indeed enters the SFQED regime in the 7th foil only, when the beam density exceeds the plasma density ($\alpha \gtrsim 1$): the reflection (in a broad sense) of the beam self-field is then strongly suppressed and a strongly nonlinear, blowout wakefield is generated *inside* the plasma, which is precisely the process that we wish to prevent (see Sec. S1 of the Supplementary Material). Indeed, compared with the ultrashort surface interaction of the beam with its reflected self-fields, the blowout mechanism generally occurs over longer timescales (set by the foil's thickness), during which both the fields acting upon the beam and its phase space may vary significantly and not in a well-controlled way, thus hampering precision investigations of SFQED.

Our concept is optimized to achieve intense and highly localized plasma-induced fields, leading to transient interaction conditions akin to those characterizing the beam-beam setup proposed by Yakimenko *et al.* [1] to probe SFQED in a clean way, because secondary processes are then strongly suppressed. This is also similar to the laser-beam setup [Vranic PRL 2014, Lobet PRAB 2017], except that the driving (laser) field is then oscillatory rather than half-cycle, and with an actual profile highly sensitive to its carrier-envelope phase.

Compared to these setups, however, our concept has the prime advantage of ensuring perfect overlap of the beam with the driving fields. Therefore, provided the beam parameters are well monitored on each shot, one can accurately predict, via numerical simulations, the time evolution of the fields experienced by each beam element, a major plus for high-precision SFQED measurements.

We have added a discussion on page 5 (top of left column) to stress the differences between our work and Ref. [47].

2) The impression that the results are not appropriately discussed in the context of previous literature.

(i) The authors did a great job at studying how the reflected and evanescent field could change as the beam profile was varied. I am however surprised that this part of the article is presented without almost no references to the work of several authors of the 80's who were studying the self-focusing of ultra-relativistic electron beams with plasmas. If I am not mistaken this is the regime where $\beta < 1$ (cigar beams) with $\alpha < 1$. In this regime, the plasma is very effective at shielding E but not B and the beam experiences the full effect of its azimuthal B field. I guess that the maximum chi should be less than a factor of two compared to the $\beta > 1$ regime. I am listing below some references of interest:

We now cite the references mentioned by the Reviewer in the Introduction where we discuss the potential use of plasma lenses to achieve very small beam sizes in beam-beam or beam-plasma schemes. Yet it should be noted that such plasma lenses involve the wakefield driven by the beam *inside* the plasma, when the beam density is comparable with the plasma density. As already emphasized, this mechanism starkly differs from that studied in our paper, where the process is dominated by the interaction around the plasma-vacuum interface rather than in the plasma bulk. In fact, such a surface interaction with conducting foils was also considered in the 80s for beam-focusing purposes [Adler 1982, Humphries 1988, Fernsler 1990], though only in the case of very elongated beams ($\beta \ll 1$), entailing evanescent plasma-induced fields. These previous works are now also cited in our manuscript. Note that the analytical treatment of the conductor-induced fields (also called near-field coherent transition radiation) carried out by our team in [Sampath et al. 2021, ref. 47] and exploited in the present paper is, to our knowledge, the first to be valid whatever the aspect ratio of the (cigar- or pancake-shaped) beam.

(ii) the article contains 43 references, among which 37 are grouped in the first page (38, 39, 40, 42 are self-reference to). The references [1-3] to beam-beam collision that involve Beamstrahlung and pair production are only mentioned in the introduction, and since the authors states that the current beam-target interaction reproduces beam-beam setup, it would be interesting and enriching for the article to present a bit of comparison in the SF-QED effects, namely QED observables and not only in the field strength.

While, under certain conditions which we identify, the beam-plasma and beam-beam schemes lead to similar driving fields, our purpose is not to further elaborate on the

similarity or differences of the two configurations. A detailed comparison of the two schemes is therefore outside the scope of our paper.

Rather, our key objective is to design beam-plasma interactions suited to precision investigations of SFQED. Besides having a strong control over the interaction conditions, as is guaranteed by the beam-plasma setup, the requirement is to reach χ values well above unity, and over time scales brief enough that each beam electron emits on average less than one gamma-ray photon (see below). This ensures that the time history of the SFQED χ parameter (as seen by a given beam electron) is essentially determined by the initial beam parameters and not by the beam evolution during the interaction, which would otherwise greatly complicate the benchmarking of SFQED models.

This key objective is now clearly stated in the Introduction (p.2, right column).

3) Dwelling of the same topic, the authors write in the introduction that “the gamma-ray photon and positron spectra generated in that configuration can provide unambiguous experimental signatures of strong-field QED.” The main purpose of this setup is to probe SFQED in a precise manner and a reader would perhaps expect more information regarding what are exactly these experimental signatures (I fully agree that NICS and BW will dominate over the Bremsstrahlung and Bethe-Heitler in this regime). As an example, the authors spent almost 5 pages on the beam-target interaction and regrettably one column on the QED observables, whose results are summarised on Fig. 6.

We reiterate that our goal is to propose a beam-based setup that could serve as a testbed of SFQED, allowing the gamma-ray and positron energy-angle distributions (i.e., the main observables) to be characterized under accurately controlled interaction conditions, and hence to be directly confronted to numerical predictions of SFQED. Our beam-plasma setup happens to produce interaction conditions akin to those achieved in beam-beam collisions but in a much more straightforward and controlled way. The latter configuration is indeed susceptible to alignment errors and shot-to-shot jittering, forcing one to rely on the measured gamma-ray and positron spectra to infer, via a model-dependent deconvolution, the actual interaction conditions. This shortcoming will certainly be a hurdle in the way of developing a benchmarking platform for SFQED models. By contrast, as already stressed, the beam-plasma setup allows automatic overlap of the beam and the intense plasma-induced fields, the properties of which depend mainly on the beam parameters (assumed to be well-known), provided the target is sufficiently dense. The time evolution of the χ parameter as seen by each beam electron can therefore be predicted with good accuracy via PIC simulations.

The main challenge of the beam-plasma scheme is to reach, over extremely short time scales, χ values as high as possible by increasing the beam density (and, accordingly, the target density by a proper choice of its material) and thus the self-fields, while achieving good “reflection” (in a broad sense) of these to avoid the blowout regime encountered in

[Sampath et al. 2021, ref. 47]. Our paper focuses on how to fulfill such conditions, and hence does aim to conduct a full study of the generated photon and positron spectra. Note that this was also the case in Ref. [1] where the beam-beam setup was proposed and examined. We have clarified what are the key advantages of our scheme for precision studies of SFQED in p. 2 of the manuscript.

What are actually the units in Fig. 6d? The authors mention gamma and positron spectrum. Are they particle spectrum or energy spectrum or energy spectrum with some normalized bandwidth (0.1%BW). They appear to me as a kind of spectral brightness.

Figure 6d plots the number of electrons and positrons per 0.1% energy bandwidth, as is now clearly written. These quantities are commonly used in the physics of light sources.

Another point that should be clarified to me “the beam electrons experience a high χ value over a very short duration, of the order of σ_z/c , which is beneficial for precision studies of strong-field QED”. What are the number of photons emitted per particle. We know from Ref [1-3] that this number is critical as it affects the final shape of the photon spectrum (for instance the peak that appears for $\chi > 16$ and is begin washed out when many photons are emitted).

We agree with the Referee. As previously stated, we are interested in ultrashort interaction conditions such that the average number of gamma-ray photons emitted per beam particle remains less than unity, so that the photon spectrum can be predicted from merely convolving the NICS cross section with the temporal profile of the χ parameter (as seen by each beam electron), itself determined by the initial beam parameters.

In the case of the integrated PIC-QED simulation shown in Fig. 6, we have found that each beam electron emits an average of ~ 0.46 photon above 0.5 GeV, i.e., 5% of the initial energy of the beam electrons. Moreover, the beam energy drops only by $\sim 15\%$ during the interaction, essentially due to photon emission (the energy loss induced by the plasma-induced fields remains negligible). Such a weak variation in beam energy can further simplify the modeling of the interaction.

This important information and the associated discussion on the short interaction time and number of emitted photons per beam electron have been added in p. 7 of the manuscript.

How is it that this setup will allow to probe better the SF-QED theoretical predictions than others as beam-beam collision or electron beam-laser scattering. Answering this issue could definitively influence thinking in the field.

As already stressed, the beam-beam and laser-beam setups will be liable to uncontrolled overlap between the beam and the driving fields due to shot-to-shot jittering, which will cast uncertainty on the actual interaction conditions undergone by the beam electrons. Further, the laser-beam scenario is characterized by an oscillatory (multi-cycle) driving field, extending over tens of femtosecond time scales, and probably even longer given the finite intensity contrast of multi-PW laser pulses. These features will contribute to blurring the SFQED observables, and so, we believe, are not optimal towards precision studies. By contrast, our beam-plasma setup, thanks to progress in accelerator technology [Yakimenko PRAB 2019], will involve half-cycle, sub-fs driving fields. This will enable ultrafast SFQED processes to be triggered, under conditions only determined by the initial beam parameters as the beam hardly evolves during the interaction (constant beam profile, less than one photon per beam electron, weak energy decrease, no QED cascade). The latter characteristics are, in principle, shared by the beam-beam setup, yet experimental difficulties (beam-beam alignment) are bound to greatly complicate their realization. In comparison, the beam-plasma setup offers the prime advantage of allowing similar interaction conditions (in terms of field strength and time scales) to be accessed but in a perfectly controlled way, provided the beam parameters are accurately monitored. Evidently, it is also much easier to implement as it only makes use of a single accelerator beam.

Those points are now fully addressed on p. 2 and 7 of our manuscript.

The conclusions seem to define quite a narrow range of parameters to probe SF-QED regime: $\alpha = [0.2-0.7]$ and $\beta = [0.2-1]$. If the energy of the electron beam could be increased, would it help in relaxing these constraints?

This parameter range is optimal in the sense that it gives rise to ultraintense and ultrashort plasma-induced fields, well suited to clean SFQED measurements at high χ values. Again, we stress that “ultraintense” should be here understood as “comparable in strength with the beam self field” while “ultrashort” means “such that NICS is dominated by single-photon emissions”.

In our study, the beam energy was set to 10 GeV, a value accessible to SLAC-class high-energy accelerators. The important point here is that the strength of the beam self-field and the quality of its “reflection” by the plasma does not depend on the beam’s Lorentz factor γ so that χ is simply proportional to it. Therefore, increasing the beam energy would allow one either to reach a higher χ with the same beam parameters (e.g. $\chi \sim 100$ at 40 GeV), or to achieve the same χ value but relaxing the constraints on α and β . Indeed, given the $\alpha^{2/3}\beta^{1/3}$ scaling of the beam self field (at fixed beam charge Q), going from 10 GeV to 40 GeV would enable one to reach the same χ value as in Fig. 6 while lowering α by a factor of $(40/10)^{3/2} = 8$ (keeping β constant).

We have clarified the meaning of the optimal parameter range in the “Target ionization and parametric study” section (p. 6). The interest in increasing the beam energy is also discussed in the Conclusions (p. 8).

Reviewer #3

The Authors show a high-field generation toward QED effects by a mirror field between an incoming electron beam and a target solid target (Au) by PIC simulations. A similar idea on

the high field generation by electron beams was published in Ref.1, based on two counter electron beams. The difference between this manuscript and Ref. 1 is the high-field generation scheme. In this manuscript the mirror field is employed between an incoming electron beam and a target solid target. The proposal would be interested in this high-field physics or in QED.

In order to enhance the proposal viability and also to convince Readers that the proposal is realistic, the Authors are recommended to clarify the following points:

1) Validity of n_b : The electron number density of n_b used is very high: $n_b \sim 10^{23}/\text{cc}$. This number is almost a solid density or even higher than the solid density. The Authors should present how to prepare the high-density beam. This point is the key issue of the work in the manuscript. In addition, before reaching the solid target surface, the electron beam may be expanded or elongated in a short distance. The Authors are recommended to show a viable scenario to obtain the solid-density (or high-density) electron beam at the target surface.

First, it should be noted that even more challenging beam parameters ($5 \times 10^{25} \text{ cm}^{-3}$, $\sigma_{r,z} \sim 10 \text{ nm}$, 125 GeV) were considered in [Yakimenko 2019], as is standard in experimental designs for exploring SFQED. That said, we agree that the $10^{23-24} \text{ cm}^{-3}$ beam densities used in our study have not been achieved yet at high-energy accelerators. Though, the realization of such dense beams seems feasible in the foreseeable future using a combination of beam (transverse) focusing and (longitudinal) compression techniques. The former can be based on wakefield-mediated plasma lenses [Chen 1986, Rosenzweig & Chen 1989, Su et al. 1990] while the latter can leverage the energy chirp possibly imparted to the beam, as is envisioned to obtain sub-100-as beam durations in the PAX experiment at SLAC [C. Emma et al., *PAX: A plasma-driven attosecond X-ray source*, IPAC2021; APL Photonics **6**, 076107 (2021)]. [We now refer to these techniques on p. 2.](#)

As pointed out in the conclusion, the requirements on the beam density can be strongly relaxed by increasing the beam's Lorentz factor, since what ultimately matters for SFQED studies is the value of the quantum parameter χ rather than the strength of the driving fields. Indeed, for a given value of χ , boosting the beam energy would permit the electron density to be lowered by the same factor. Going from 10 GeV to 40 GeV while reducing the beam density by a factor of 8 would then lead to the same χ .

[The latter benefit of operating at high beam energy is now mentioned in the conclusion.](#)

2) Evaluation of collective effect on the proposal: For the high-density target, collective behavior would be important, as mentioned in the manuscript in p. 4. For example, $\Omega_{pe} \sim 5.6 \times 10^{16}/\text{s}$ for $n_e \sim 10^{24}/\text{cc}$. Or $\tau \sim 1/\Omega_{pe} \sim 1.7 \times 10^{-17}\text{s}$. The time scale T in the manuscript may be $T \sim 50 \text{ nm}/c \sim 1.7 \times 10^{-16}\text{s}$, which is much larger than the electron plasma oscillation time. During the time scale of T , the target electrons may oscillate many times, and may show the collective behavior in the parameters employed in the manuscript. The collective mode effect on the proposal should be clarified to make the phenomenon focused.

The key mechanism in our study, i.e., plasma shielding of the beam self-fields, is precisely a collective effect, fully taken into account in our multidimensional PIC simulations. In the

perfect conductor limit ($n_p \rightarrow +\infty$), this phenomenon is also well captured by the pseudo-photon method developed in [Sampath et al. 2021, ref. 47].

Deviations from this ideal limit are addressed in the “Plasma screening and transparency” section, where the effect of finite beam-to-plasma density ratio is treated in detail. In addition, for completeness, we discuss the case of a beam shorter than the plasma skin depth ($\sigma_z c / \omega_p < 1$). Then, the plasma electrons have insufficient time to induce the (reflected) field compensating the incident beam self-field, causing the peak in E^* / γ observed in Fig. 2(e) to be strongly suppressed. Such a situation, however, will be hard to reach experimentally given the nanometer-scale skin depth of solid-density plasmas; hence, we refer the reader to Sect. 2 of the Supplementary Information for a PIC simulation of this configuration.

We updated the discussion on time scale of plasma electron response on p.5 (top of right column).

The electron beam density is so high and it may also show strong field to deform the beam profile or shape.

Actually, the interaction is so short and the beam energy so large that the beam profile undergoes negligible change (at least during the interaction). This result, demonstrated by our PIC simulations (the parameters of which are detailed in the Methods section), can be readily understood by estimating the angular kick imparted to the beam by the plasma-reflected fields. Following [Corde et al., [Beam focusing by near-field transition radiation, Research Report hal-02937777v2 \(2020\)](#)] an electron located at radius $r = \sigma_r / 2$ in a beam of size $\sigma_r = \sigma_z$, energy ε_b and charge Q , would be deflected by an approximate angle:

$$\theta \simeq \frac{eQ}{16\pi\epsilon_0\sigma_r\varepsilon_b}$$

For $Q = 1$ nC, $\sigma_r = 5$ nm and $\varepsilon_b = 10$ GeV, we find $\theta \simeq 4$ mrad. For an interaction time $\sim \sigma_z / c$, the electron would then be displaced transversely by $\sigma_z \times \theta \simeq 0.2$ nm, which is negligible compared to the beam width σ_r .

3) It would be welcome that the Authors demonstrate the proposal is remarkable and innovative, compared with the idea in Ref. 1.

Similarly to the beam-beam collisions examined in Ref. [1], the beam-plasma scheme leverages the self-fields of very compact, ultra-relativistic particle beams to produce ultrashort interactions suited to precision SFQED studies. Compared to Ref. [1], however, it affords the following two major advantages:

- It allows automatic overlap of the beam and the plasma-induced driving fields, the spatiotemporal profile of which is determined by the *initial* beam and target parameters. If these are well-monitored (which is expected) so will be the interaction conditions. The time evolution of the driving field experienced by each beam electron, and hence of the χ parameter governing the gamma-ray emission, can therefore be predicted with good accuracy via PIC simulations. In turn, direct comparison can be made between the measured and simulated SFQED observables (i.e., the gamma-ray and positron distributions) under *perfectly controlled* conditions. By contrast, beam-beam collisions will be susceptible to alignment uncertainties and

shot-to-shot jittering, forcing one to rely on the measured gamma-ray (and positron) spectra to infer, via a model-dependent deconvolution, the actual interaction parameters.

- It is way easier to implement experimentally because it involves a single high-energy accelerator beam. Provided, as is expected, progress is made in a short-term period on beam compressing/focusing and/or energy boost, this scheme could be accessible to existing SLAC-class facilities in the not-too-distant future while the particle colliders required for the configuration of Ref. [1] have still to be built.

For these reasons, [now discussed in the Introduction \(p. 2\), the Proof-of-concept section \(p. 3\) and the Conclusions \(p. 8\)](#), the beam-plasma scheme offers a much easier and robust avenue to “clean” experiments on SFQED than the existing beam- or laser-based designs. As such, it represents a significant innovative advance in this fast-developing research field.

Some minor points:

/ What is the electron beam temperature or emittance?

Emittance effects can be safely neglected here as the beam profile hardly evolves during the interaction. We have therefore considered a cold electron beam in our simulations.

To clarify this point, let us estimate the minimum emittance that is needed to have a visible effect on the electron beam. Again considering the $\sigma_r = \sigma_z = 55$ nm electron beam of Fig. 6, we should observe an effect of the emittance when the β function is on the order of the full propagation distance, namely ~ 550 nm. This gives a minimum normalized emittance of $\epsilon_N \sim \gamma \frac{\sigma_r^2}{\beta} \simeq 100$ mm.mrad, which is very large compared to emittances achieved today in state-of-the-art accelerator facilities. Said in other words, a sub- μm β function is certainly not the most realistic path to reach small beam size, instead low-emittance beams are strongly desirable for this purpose.

[The negligible effect of emittance and the use of a cold electron beam in the simulations is now mentioned in the “Methods” section.](#)

/ In "Methods" for PIC simulations, we find a sentence of "The time step of this simulation is 0.36 nm". Do you describe the time by the unit of ct? Please check the unit.

[We have corrected this in the “Methods” section: the time step is now given in attoseconds \(as\).](#)

/ In PIC simulations, for example, we find "For the simulations of Figs. 2, 4 and 5, each simulation cell is initially filled with 2 macroparticles of ions, 10 macroparticles of plasma electrons and 5 macroparticles of beam electrons. ... ". In 3D PIC simulations, usually more super particles would be needed to reduce numerical noises. Have you checked numerical noises by the superparticle number / cell in your cases?

Simulations for parametric scans have been run using the quasi-3D CALDER-Circ code, which allows us to use a lot of macro-particles at a reduced computational cost. We performed convergence tests and checked that similar results were obtained in CALDER-Circ and CALDER 3D simulations. Checks on the absolute values and spatial distributions of the fields and particle densities confirmed that the lower number of macro-particles used in the CALDER 3D simulation was sufficient to provide sound and accurate results. Indeed, the

lower number of macro-particles was needed for the final 3D simulation of Fig. 6 that includes all the QED modules, ionization and Bremsstrahlung and Bethe-Heitler/Coulomb Trident processes, and that was very heavy to run (around 1 million CPU hours needed).

REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

I am generally satisfied with the responses and the revised manuscript. After a final check of the recent literature on possible setups to probe SFQED, I recommend the authors include the following articles in the final section

- Di Piazza et al., Phys. Rev. Lett. 124, 044801, 2020
- Baumann et al., Sci Rep 9, 9407, 2019
- W. L. Zhang et al., arXiv:2302.01321, 2023

They discuss QED observables for high values of χ , and in particular the presence of a peak in the photon spectrum. Once the bibliography complemented, the article can be published as is.

Reviewer #3 (Remarks to the Author):

Review Report: Manuscript#: COMMSPHYS-22-1007A: "Probing strong-field QED in beam-plasma collisions", by A. Matheron, et al.

The Authors have responded well to the last review report. Almost all the points raised in the last review report would be now well amended in the revised paper, except the key subtle issues of the very-high density (higher than solid density) employed and the beam self-field effect on the beam during the beam loading.

It would be better to discuss openly on the issues with Readers.

The paper structure and the presentation style are also well organized. Now the paper is recommended to be published in Communications Physics in its present form.

Dear Editor,

We wish to thank the three reviewers for their interesting comments and remarks on the paper which led to important changes in the main text.

We added the references proposed by Reviewer 2 as we found them relevant to the discussion about the already existing setups to probe SFQED and the associated observables.

We now believe that the paper is ready to be published in its revised form and wish to thank reviewers for their careful reading and relevant comments.

Best regards, The authors