Numerical Analysis of Space Charge Effects in Electron Bunches at Laser-Driven Plasma Accelerators

Anthony Ashmore¹, Riccardo Bartolini¹², Nicolas Delerue¹∗

¹ John Adams Institute for Accelerator Science, University of Oxford, Keble Road, OX1 3RH Oxford, United Kingdom
² Diamond Light Source, Harwell, OX11 0DE Didcot, United Kingdom

Abstract: Laser-driven Plasma Accelerators (LPA) have successfully generated high energy, high charge electron bunches which can reach many kA peak current, over short distances. Space charge issues, even in transport lines as simple as a drift section, have to be carefully taken into account since they can degrade the beam quality, preventing any further application of such electron beams. We analyse the space charge effects within an electron bunch with numerical simulations in order to assess their effect on the beam. We use LPA beam parameters published in previous experimental studies. These studies can give an indication of the working point where space charge can dominate the beam dynamics and has to be taken into account in the application of such beams.

PACS (2008): 41.75.Jv, 41.75.Ht, 29.27.Bd, 29.27.Eg
Keywords: Emittance • Space-charge • Laser-driven plasma acceleration.

© Versita Warsaw and Springer-Verlag Berlin Heidelberg.

1. Introduction

Laser-driven plasma wakefield accelerators have received much attention in the last years after the experimental demonstration of the possibility of plasma based acceleration [1], achieved at many different laboratories with the pioneering experiments in the early 2000s [2]. Most notably, high-quality GeV electron beams were generated using cm-scale plasmas at Lawrence Berkeley National Laboratory [3]. The ability to sustain extremely large acceleration gradients, enabling compact accelerating structures has opened the possibility of using such electron beams for a wide range of applications. Indeed, the low emittance and high peak current attainable has increased interest in laser-plasma acceleration as a driver for compact light sources [4] [5] and TeV-class linear colliders [6]. These applications, however, demand extremely good beam quality which has yet to be fully demonstrated

∗ E-mail: delerue@lal.in2p3.fr; Now at LAL, F-91898 Orsay, France
experimentally, although rapid progress is expected from the new laser generation with multiterawatt pulses of a few femtoseconds length. While the low emittance and high peak current achievable with LPAs are necessary to drive Free Electron Lasers (FELs) they might also amplify space charge effects within the bunch, causing emittance growth and debunching [7] [8] limiting the possibility of using such beams. Even the simple problem of transport of a high charge ultra short electron bunch requires careful analysis, since the bunch properties have to be maintained through the whole transfer line down to the final utilisation of the electron beam. In view of the future application of LPA beams as a driver for FELs, this study aims to quantify to what extent the Coulomb forces within a bunch will affect the quality of the beam travelling in a drift section and suggest a boundary on beam parameters for a space charge dominated beam. The analysis presented here relies on an extensive campaign of numerical simulations performed with the code CSR-Track using the LPA beam parameters drawn from a survey of the main experimental data available to date. The analysis has also been extended to study the effect of space charge on LPA electron beams which constitute a modest improvement over the beam quality presently achieved by LPA.

2. Numerical computation of space charge effects

Laser-plasma acceleration is realized by using a short-pulse, high-intensity laser to ponderomotively drive a large electron plasma wave (or wakefield) in an underdense plasma. The electron plasma wave has relativistic phase velocity, approximately the group velocity of the laser, and can support large electric fields in the direction of propagation of the laser. As a result of this type of interaction, high peak current bunches can be generated with different beam parameters depending on the specific parameters of the laser and of the plasma used in the experiment. To investigate the effect of space charge in the propagation of these electron bunches we have considered a simple drift space and followed the evolution of a macroparticle distribution along the drift as a function of the initial beam parameters such as charge, emittance and pulse length. The numerical analysis is based on the code CSR-track [9] which is capable of describing the physics of beam transport in presence of space charge and coherent synchrotron radiation. The particle distributions used in these studies represent the beam qualities shown in Table 1. Where more than one set of parameters were reported for a given experiment, those which would produce the greatest space charge effects were used.

CSR-track has several methods to compute the space charge effects. The method used in this report models the bunch as a collection of sub-bunches rather than point-like macroparticles and provides point to point calculations of Coulomb forces between sub-bunches. Shape and number of the sub-bunches were chosen as a compromise between speed and accuracy of the results. Clearly larger numbers of macro-particles will more accurately recreate the original bunch but lead to longer calculations: 3000 macro-particles were used in this study, however, simulations ran with up to 25000 macro-particles showed no significant change in results supporting this choice. In this study ellipsoidal self-scaling sub-bunches were used to cope with the significant expansion of the electron
bunches under consideration. Fig. 1 shows the behaviour of emittance with varying macro-particle number for two fixed R.M.S. sub-bunch sizes and the self-scaling sub-bunches. A 1 nC bunch charge was used. For smaller charges these results are more stable at lower macro-particle numbers suggesting this is a worst case scenario which is not reached in the simulations carried out in this paper. The ellipsoidal self-scaling sub-bunches show the greatest stability against macro-particle number change above $\sim 2000$ with a variation in emittance of $\sim 1.5\%$ between $3000$ and $25000$. The bunches considered in this paper were drifted over $2$ m in vacuum unless otherwise specified.

![Normalized transverse emittance vs. Macroparticle number](image)

**Figure 1.** Calculated emittance increase as a function of the macro-particle number.

### 3. Results

We report here the results of the numerical simulations performed with CSR-Track. We have used various initial beam distribution based on a number of examples of electron bunches produced in different experiments. In each case we have considered an electron bunch travelling in a drift section of $3$ m and we have computed the evolution of emittance, energy spread and bunch length with the aim of understanding whether the beam properties are degraded as a result of the space charge self forces in the bunch. The analysis concentrates first on beam parameters already demonstrated in series of experiments carried out at different laboratories. Then we consider an example of an electron beam with properties which constitute a moderate improvement over the results presently achieved. The whole set of results are summarised in table 1.
Kneip et al. [10] reported the generation of a 200 MeV beam with 10 kA peak current and a normalised emittance estimated to 31.3 mm-mrad. The CSR-Track numerical simulations showed that the horizontal emittance of the bunch remained constant to less than 0.2% suggesting the emittance growth due to Coulomb expansion is negligible compared to the initial emittance. The transverse size of the bunch increased according to the initial divergence of the beam with no apparent space charge effects. The large divergence caused the bunch to expand quickly in the transverse direction producing a corresponding decrease in the strength of the Coulomb forces thus accounting for the lack of significant space charge effects. Bunch lengthening in the longitudinal direction was negligibly small due to the relatively large initial bunch length which itself is Lorentz contracted. This also ensured a stable peak current for the duration of the drift space.

Ibbotson et al. [11] generated a 400 MeV beam with 0.875 kA peak current and a normalised emittance estimated to 34.4 mm-mrad. The CSR-Track numerical simulations showed that the horizontal emittance of the bunch remained constant to less than 0.1% which is within computational error. This suggests the bunch is completely divergence-dominated with the Coulomb forces being negligible. The transverse size increased exactly in line with that predicted by a divergent, space charge free bunch model. This suggests that space charge effects are negligible under these conditions. Bunch lengthening was again negligible and the peak current constant.

Leemans et al. [3] generated a 500 MeV beam with 12.5 kA peak current and a normalised emittance estimated to 24.5 mm-mrad. The CSR-Track numerical simulations showed that the horizontal emittance of the bunch remained constant to less than 0.5% which suggests the bunch is again divergence-dominated with the Coulomb forces being negligible. The transverse size increased in line with the divergence once again. The large initial emittance and high bunch energy reduced the impact of any space charge effects. This result is expected when the beam parameters, including an increased beam energy, are compared with those of Kneip et al.

In the case of Rowlands-Rees et al. [12] the parameters found in the paper would suggest a smaller emittance growth than those of Kneip et al. due to a smaller bunch charge. CSR-Track simulations with these parameters show no emittance growth with the transverse size being completely divergence dependent.

The beam parameters considered so far, although achieved experimentally, do not yet provide electron bunches with the quality necessary to drive compact light sources based on FELs. We considered therefore the beam characteristics required for the Oxford Plasma Accelerator Light Source (OPALS) [13] which is aimed at the production of FEL radiation in the VUV and Soft X-ray region. The predicted achievable emittance by the Laser Plasma Accelerator driving the OPALS FEL is much smaller than that examined in the other papers: the normalised emittance is 1 mm-mrad and the peak current 25 kA. The CSR-Track simulations show that for such small initial emittance the divergence driven expansion of the bunch is decreased. Due to this and the relatively large bunch charge we would expect significant space charge effects. Results for bunches of various energies with 25 kA peak current which evolve in a drift over 1.5 m are found in table 2.

As the parameters of operation for OPALS are not yet fixed, we have performed an extensive parametric study of the initial beam characteristics on the final one after a drift section of 3 m. Contours plots of parameter space
with varying bunch charge, energy and drift length were produced to investigate when space charge effects become important. The results can be seen in Fig. 2.

At 400 MeV a 10% increase in horizontal emittance is reached after a 1.5 m drift length. The same space charge effects have a much larger relative effect on the emittance compared with the other papers examined due to both a smaller initial emittance and the smaller divergence allowing the bunch to stay compact for longer. At energies lower than 200 MeV it is apparent that the emittance growth is very large even when drifted over relatively small distances. To remain within a 1% growth at 400 MeV the bunch can be drifted over approximately 0.6 m. It is also proposed to run OPALS in a more aggressive 1 GeV configuration; this would allow much more freedom in how far the electron bunch can be drifted without space charge adversely affecting its emittance.

To observe how the initial emittance of the electron bunch affected the relative emittance growth, bunches with various emittances were tracked over a 4 m drift length and the fractional change calculated. As the bunch had a
fixed initial size, varying the emittance is equivalent to changing the initial divergence of the beam. The results are plotted in Fig. 3.

The experimental studies examined all have emittances above 10 mm mrad and exhibit the same small emittance growth as plotted. OPALS, with its predicted 1 mm mrad, can be expected to have an emittance growth of more than 50% if drifted for 4 m at 400 MeV. Looking to the future, with emittances ~ 0.1 mm mrad we can expect a doubling over 1.5 m unless the bunch energy is increased.

The variation of space charge forces with the bunch charge was also examined and the effect on the emittance coupled with varying energy plotted for an electron bunch drifted over 1.5 m.

Fig. 4 shows the steep emittance growth with increasing charge for low energy bunches confirming the unsuitable nature of low energy, high charge bunches for applications requiring a small emittance. The effect of the space charge forces drops off rapidly with energy due to their $\gamma^{-2}$ dependence which originates from the Lorentz contraction of the bunch observed in the lab frame. At energies of 1 GeV, as proposed in OPALS, bunch charges of up to 0.5 nC could be drifted over 1.5 m with only a 1% increase in transverse emittance.

A shorter bunch length will cause increased space charge forces. To understand the magnitude of this effect, simulations were ran for various bunch charges and lengths and the bunch length and emittance increase calculated.
The results are shown in Fig.’s 5 and 6. At 10 fs and 250 pC the simulations showed less than a 1% increase in the bunch length suggesting debunching due to space charge is not of concern at OPALS. At smaller bunch lengths and higher bunch charges more significant effects are seen which may be of concern for future accelerators with larger peak currents.

Decreased bunch length at constant charge gives a larger peak current leading to more Coulomb repulsion. For long bunches (∼100 fs) less than a 1% increase in emittance would be seen at 250 pC; by 10 fs this is 10% and by 1 fs is 45%. The simulations outlined indicated how emittance growth will become a significant problem if bunches become shorter without a corresponding increase in energy.

4. Conclusion

We have considered a series of electron bunch data obtained from Laser Plasma Accelerators at a various major experiments. Given the high peak current of such bunches we have investigated their evolution in simple transfer lines with the aim of assessing the effect of space charge forces. The results obtained with CSR-Track show that the effect of space charge on the emittance and bunch length is generally negligible for the bunch data obtained...
Numerical Analysis of Space Charge Effects in Electron Bunches at Laser-Driven Plasma Accelerators

References

[1] T. Tajima, J.M. Dawson, Phys. Rev. Lett., 43, 267, (1979)

Figure 4. Contours of fractional emittance change as a function of beam energy and bunch charge.

Experimentally. Of the previously published papers that were considered in this investigation, those with relatively large normalised emittance were found to be least affected. This was due to the fact that the initial divergence and emittance of the beams was too large for the Coulomb repulsion to have a serious impact. However moving towards future generations of LPAs with smaller emittances and larger bunch charges as seen in the case of the OPALS, our investigations show that space charge will have a significant effect unless operational energies of the LPAs are increased.

5. Acknowledgments

The authors are grateful to the John Fell fund from the University of Oxford for the funding provided to support their work.

References

[1] T. Tajima, J.M. Dawson, Phys. Rev. Lett., 43, 267, (1979)
**Fractional bunch length change**

1.5 m drift length, 10 μm transverse size, 400 MeV with 1% spread,  
1 mm mrad normalised transverse emittance

**Figure 5.** Contours of fractional bunch length increase as a function of initial bunch length and bunch charge.

[2] Cover Issue of Nature titled "dream Beams", Nature, 431, (2004)
[3] W. Leemans et al., Nature Phys., 2, 696, (2006)
[4] H.P. Schlenvoigt et al., Nature Phys., 4, 130, (2007)
[5] M. Fuchs et al., Nature Phys., 5, 826, (2009)
[6] C. Schroeder et al., Phys. Rev. Special Topics AB, 13, 101301, (2010)
[7] F. J. Gruner, C. B. Schroader, A. R. Maier, S. Becker and J. M. Mikhailova, Phys. Rev. ST Accel. Beams 12 (2009) 020701.
[8] G. Geloni et al., nucl. Inst. and Meth., A578, 34, (2007)
[9] M. Dohlus and T. Limberg, http://www.desy.de/xfel-beam/csrtrack
[10] S. Kneip et al., Phys. Rev. Lett., 103, 035002, (2009)
[11] T. P. A. Ibbotson et al., Phys. Rev. ST Accel. Beams 13 (2010) 031301.
[12] Rowlands-Rees et al., Phys. Rev. Lett., 100, 105005, (2008)
[13] S. Bajlekov et al., Proceedings of FEL08, MOPPH081, 163, (2008)
Numerical Analysis of Space Charge Effects in Electron Bunches at Laser-Driven Plasma Accelerators

Fractional emittance change

Bunch length (fs)

Bunch charge (nC)

1.5 m drift length, 400 MeV with 1% energy spread, 10 μm transverse size, 1 mm mrad normalised transverse emittance

Figure 6. Contours of fractional emittance change as a function of bunch length and bunch charge.