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TRANSVERSE TOLERANCES IN THE PLASMA-WAKEFIELD ACCELERATION BLOWOUT REGIME

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Abstract

We report on recent progress in transverse instabilities and transverse tolerances for plasma-wakefield accelerators in the blowout regime. This regime provides both strong focusing as well as strong deflection via transverse wakefields. Based on comprehensive particle-in-cell simulations, we summarize recent findings of the instability–efficiency relation for the blowout regime. The transverse instability and subsequent emittance growth may lead to very tight tolerances for the drive-beam jitter. Ion motion may mitigate the instability. Independent of wakefield effects, the strong focusing fields may also lead to tight jitter-tolerances. We quantify these tolerances using examples from HALHF start-to-end simulations, using the recently developed ABEL framework.

INTRODUCTION

Plasma wakefield accelerators have been suggested as main linacs for linear colliders in order to make these more compact. In many concepts [1–3] dense electron bunches are used to drive nonlinear plasma wakefields. In this nonlinear "blowout" regime [4], the drive bunch blows out the plasma electrons, generating a plasma cavity containing only ions. While GV/m gradients have been demonstrated in numerous experiments [5], there are open questions whether a high luminosity-per-power can be reached, especially when taking into account machine imperfections. We here report on two separate effects: the transverse beam-breakup instability (BBU), and main beam kicks due to strong focusing fields, both mentioned in earlier reviews of plasma-based accelerators [6]. Both effects may be detrimental to collider luminosity if not properly mitigated.

EFFICIENCY-INSTABILITY CONSIDERATIONS

While both simulation [7] and experiments [8] have indicated the possibility of 40+% power-transfer efficiency, η_p, from the wake to the trailing bunch in plasma acceleration, Ref. [9] proposes an inherent relation between this efficiency and the strength of the BBU, quantified using the ratio between the transverse deflecting force and the focusing force,

$$\eta_t = \frac{\eta_p^2}{4(1-\eta_p)}. \tag{1}$$

The relation assumes there is no ion motion or energy spread, and a uniform accelerating field experienced by the trailing bunch. In another recent work [10], the authors aim to validate Eq. 1 by performing an extensive multi-dimensional scan across the parameters that affect the BBU. It is concluded that the proposed instability–efficiency relation represents with good accuracy a lower limit on the strength of the BBU, at any given efficiency [10].

EFFICIENCY-INSTABILITY OPTIMAL WORKING POINT

For a given efficiency and blowout radius R_b, Ref. [10] shows that η_t and thus the BBU can be minimized, i.e. bringing η_t close to the value predicted by Eq. 1. This is done by choosing an optimized E_z (and wakefield phase) for the main beam. Ref. [10] suggests, based on fitting simulated data, that the normalized accelerating field

$$\frac{E_z}{E_0} \approx 0.23(1-0.78\eta_p^{1.86})(R_b k_p)^{1.5} \tag{2}$$

gives an η_t close to the prediction. To minimize the BBU in a high-efficiency plasma linac, it is thus recommended that the parameters adhere to this relation.

INSTABILITY MITIGATION BY ION-MOTION

For colliders, minimizing the BBU with the use of Eq. 2 may not mitigate the BBU sufficiently to preserve beam emittance. Ion motion in the blowout regime [11] can be exploited to mitigate the BBU further. How much the ions in a plasma stage move depends on the beam density and the ion mass. The choice of an appropriate gas species for the stage may lead to a detuning of the BBU resonance, and therefore decrease the oscillation-amplitude growth from BBU [10, 12–14].

EXAMPLE FROM HALHF: BBU

To quantify the BBU, we have performed start-to-end simulations for the 1.1 km long HALHF [3, 15, 16] plasma linac consisting of 48 plasma-acceleration stages and interstages using the ABEL framework [17]. In the linac, an electron beam with 1×10^{10} electrons, with a normalized vertical emittance of $\varepsilon_{ny} = 0.32$ mm mrad, is accelerated from 3 GeV to 375 GeV. The plasma density is 6×10^{14} cm^{-3}. The gas species is He. The drive-beam beta functions are 0.5 m at plasma stage up-ramp, while the main beam is matched to the ion channel. The linac wake-to-beam power-transfer efficiency (η_p) is 50%. This gives a driver-to-beam efficiency is 40%. Note that this is higher than that of CLIC, with a driver-to-beam efficiency of ~28% [18]. The linac

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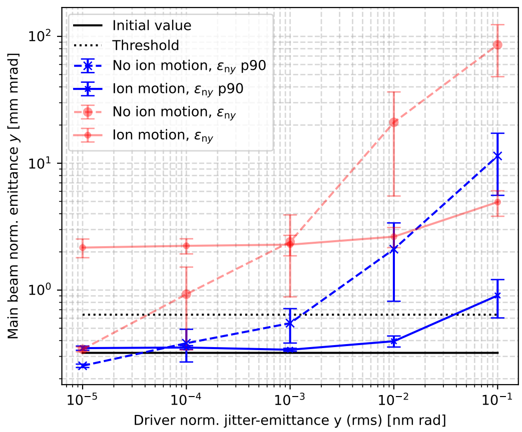

Figure 1: Main beam vertical emittance growth from transverse wakefields at the end of the plasma linac, as function of the drive-beam vertical jitter-emittance. Simulations are performed without ion motion (dotted lines) and with ion motion (solid lines). ε_{ny} is the rms emittance. "p90" is the rms emittance of the 90th lowest-percentile single-particle-emittance particles. A threshold line indicates a factor two in emittance growth. Figure 2 shows example beams for the jitter value of 10^{-2} nm rad.

parameters follow Eq. 2 closely as a first step to minimize the BBU.

The plasma stages are simulated using simplified, fast models for the transverse wake [19–21] and ion motion [12–14]—more details can be found in Ref. [17]. The interstage lattices, required for matching and injection between each plasma stage, are in these simulations represented by analytic phase-space rotations and compression, performing the HALHF longitudinal self-correction [22].

One approach to quantifying whether the BBU has been sufficiently mitigated, is to calculate the effect of transverse jitter on the linac emittance growth, drive-beam jitter in particular [6]. We have simulated this as follows: the machine starts perfectly aligned. The drive beam has a vertical jitter-emittance [23] (we here seed the instability only in the vertical plane). At the injection into each plasma cell, a random jitter-emittance value is converted into a drive-beam offset and angle. Ion motion can be turned off or on. The jitter-emittance level is increased until the emittance growth increases above a certain threshold—here taken to be a factor two—yielding a tolerance level for this type of jitter.

Figure 1 shows the results of the jitter-emittance scan. For the two cases of ion motion/no ion motion, both the full vertical rms emittance and the 90th percentile emittance (see figure), is calculated at the end of the linac. With no ion motion, the initial emittance rapidly grows more than the threshold. With ion motion, the emittance is well preserved across two more orders of magnitude of jitter. However, with ion motion, the full rms emittance increases about a factor ten regardless of jitter value. The reason is indicated by Fig. 2, showing example beams for a jitter-emittance of 10^{-2} nm rad. With no ion motion, the BBU is significant.

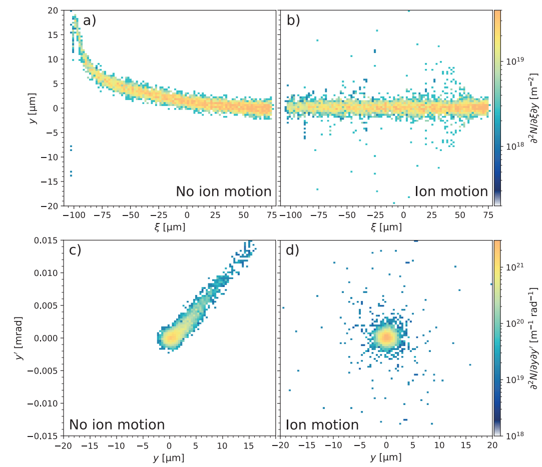

Figure 2: Phase-space views of the main beam at the end of the linac, for an example shot for a jitter of 10^{-2} nm rad. For no ion motion (a and c), the BBU is significant. For ion motion (b and d), the BBU is efficiently mitigated. For the latter case, a halo of large amplitude particles has formed, driving up the full rms emittance value. The beams in a) and b) are traveling to the right.

With ion motion, the BBU is efficiently mitigated. However, a halo of large-amplitude particles has formed, driving up the rms emittance. We note that even with ion motion, the emittance starts to increase at jitter values of 10^{-1} nm rad, which indicates that further mitigation strategies may be needed in order to bring the tolerances towards current state-of-art jitter levels [23].

KICKS DUE TO DRIVE-BEAM JITTER

The strong focusing fields of the blowout regime [24] help mitigate the BBU. However, as consequence, the main beam becomes more sensitive to kicks due transverse jitter of the drive beam. In the blowout regime, the drive beam defines the focusing axis; if the drive beam is injected offset with respect to the main beam, the main beam centroid will oscillate around the axis due to the ion-focusing force, as discussed in for example [6]. At the plasma-stage exit, the main beam will therefore generally pick up an offset and an angle: a "kick". Consequently, the main beam will move off-trajectory, possibly leading to emittance growth both in the plasma stages and in the interstage optics. Additional luminosity loss may happen due to centroid offsets at the interaction point.

KICK MITIGATION

These main-beam kicks may in principle be mitigated by adjusting the length of each plasma cell towards an integer number of betatron oscillations [6]. However, in general, a drive beam will jitter in both offset and angle. The main beam centroid will oscillate around the focus axis also for a drive beam injected at an angle. If not mitigated, angle-jitter can be much more severe than offset-jitter, and cannot be mitigated by an integer number of betatron oscillations.

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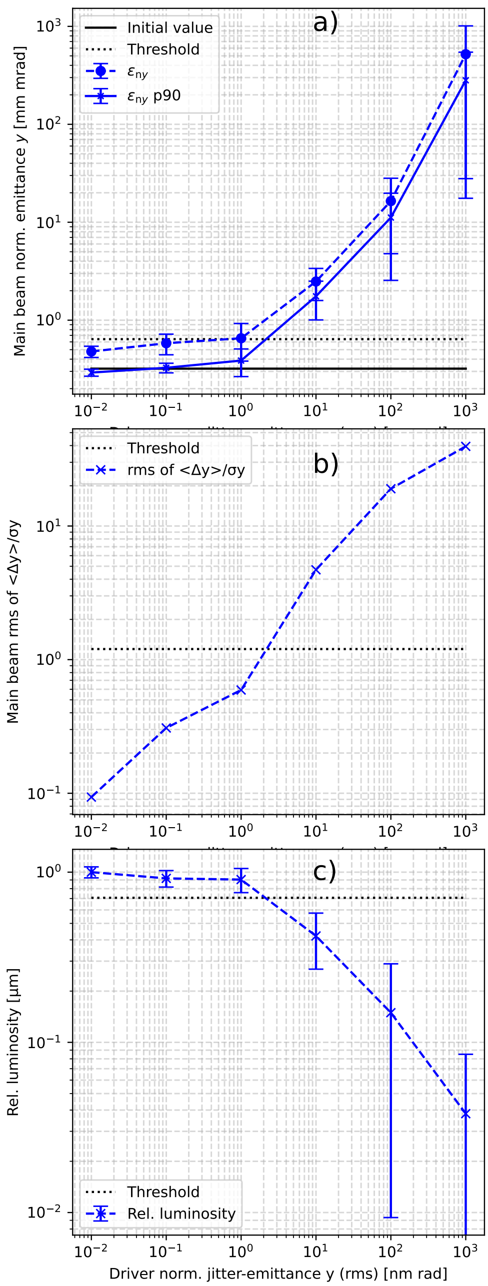

Figure 3: The effect of main beam kicks in the plasma stages as function of the drive-beam jitter-emittance. a) Main beam vertical emittance growth at the end of the plasmas linac. b) Vertical beam offset at the interaction point. c) Relative luminosity loss. The threshold value indicates a factor two in emittance growth (or a factor $1/\sqrt{2}$ for luminosity loss).

As a further mitigation strategy, we therefore propose to guide the drive beam with an external magnetic field from either a quadrupole channel or a plasma discharge current (i.e., active plasma lensing). The field will make the drive beam oscillate back towards the axis. The external focusing strength must be tuned to make the head of the driver (which remains at the initial energy) oscillate a half-integer number of betatron oscillations, in order to bring it back to the original axis. While the technical implementation of a guiding field surrounding a plasma source is yet to be studied, early simulation results indicate that by correctly tuning the magnetic field, the main-beam offset due to the initial driver angle may be fully mitigated.

EXAMPLE FROM HALHF: KICKS

We study the effect of kicks due to drive-beam jitter, using ABEL [17], for the HALHF plasma linac described above. The aim is to understand the effect of kicks separately from the effect of the wakefields. The plasma stages are now simulated with the code Wake-T [25], which calculates the plasma wakefield using a 2D wake calculation, with no transverse wakes. Transverse kicks and chromatic emittance growth are calculated in 3D. We assume that the drive beam is perfectly guided in a magnetic field, as explained above, by ignoring drive-beam angle-jitter in the simulation. We include the full HALHF interstage optics, implemented in ELEGANT [26]. This novel interstage lattice design [27] includes a non-linear plasma-lens and a sextupole, which may add additional emittance growth to an off-trajectory main beam.

To assess the transverse tolerances, we calculate the emittance growth, the main-beam offset at the interaction point and the luminosity loss, using GUINEA-PIG [28], as functions of the drive-beam jitter. The results are shown in Fig. 3. A threshold line indicates a factor of two in emittance growth, and a corresponding factor $1/\sqrt{2}$ for luminosity loss. The results show a drive-beam jitter-emittance tolerance of order 1 nm rad before the threshold is reached—an order of magnitude larger than that of the above BBU-study. Since the results are the first studies of its type for plasma colliders, they should be taken as preliminary, and we plan to refine them further within the HALHF study.

CONCLUSION

We have discussed two key effects that lead to emittance growth in a plasma-based collider: transverse wakefields and kicks. Using the ABEL framework, we have calculated tolerances originating from these two effects separately. Both tolerances are tighter than jitter levels in state-of-the-art RF linacs, implying that further work may be needed to improve the transverse tolerances. While these preliminary results indicate very tight tolerances on the drive-beam jitter, fully integrated studies with the combined effects of wakefields, interstage optics with possibly further mitigation techniques, and luminosity calculations based on actual beam distribution after simulation, remain to be performed.

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