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Beam dynamics in a high brightness linac for short wavelength SASE-FEL experiments

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Abstract. Short wavelength SASE-FEL requires generation and transport up to the undulator entrance of low emittance (∼1–2 mm mrad) high peak current (∼1–3 kA) electron beams with energy higher than 1 GeV. The propagation of such a high brightness beam takes place in a transition regime from space charge to emittance dominated dynamics, as the beam energy increases. In addition, in downstream magnetic compressor devices where the peak current increases up to kA range, the transition may occur again. Under these conditions, the electron beam has to be properly matched to the linac accelerating sections in order to keep under control emittance oscillations driven by residual space charge effects. Generalized invariant envelope matching conditions are discussed in this paper, showing that an equilibrium between RF focusing forces and space charge/emittance defocusing forces can be attained without any additional external focusing along the linac (no quadrupoles), thus reducing alignment problems and mitigating emittance dilutions due to misalignments and beam parameter jitters.

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1. Introduction

VUV and x-ray FEL linac drivers must produce high brightness electron beams with energy in excess of 1 GeV. A beam of such kind behaves, up to this energy, as a cold relativistic non-neutral plasma subject to collective plasma behaviour more than thermal gas-like behaviour in the transverse plane dynamics. The theoretical understanding of this dynamics has become quite mature after many photo-injectors have been commissioned and characterized. What is surprising is the extension of such a plasma regime up to GeV energies: in this paper, we discuss the impact of the plasma behaviour in the design of a x-ray FEL linac driver. The traditional formalism based on a rms description of the beam distribution, via the envelope equation, fails to explain the coherent collective plasma motion which dominates the behaviour of these beams: in the next section a complete description based on a generalized model is presented, able to describe both the collective (laminar) regime, which dominates the first part of the injector, and the transition into the thermal regime, which dominates the dynamics into the downstream part of the linac. We present an analytical expression for the envelope which is able to model the transition from the laminar regime into the emittane regime: it represents an enhancement of the invariant envelope concept, which is applicable only in the pure laminar regime, though it is an exact analytical solution in this regime of the envelope equation. The impact of such a model on the performances in the generation of high brightness electron beams is finally discussed in section 3 with some numerical example performed with the code HOMDYN.

2. Beam dynamics around the transition from space charge to emittance dominated regimes

The theoretical understanding of transverse beam dynamics in RF photo-injectors [1], which basically deals with relativistic quasi-laminar beams, has brought to light the more general problem of describing intense accelerated beams undergoing the transition from the laminar flow regime into the thermal flow domain by means of acceleration: this fact normally happens in any accelerator which starts from a source and takes the beam up to relativistic energies. The peculiarity of linacs for high brightness electron beams, such as those needed by x-ray FELs, is that the energy where this transition takes place can be as high as 1 GeV.

The concept of invariant envelope is restricted to the pure laminar regime, where the emittance correction process [2] mainly takes place: in this regime the single particle motion is dominated by cold plasma-like envelope oscillations, while the incoherent betatron motion is almost absent, causing the particle trajectories in the beam not to cross each other. In the presence of bunched beams, where correlated effects are relevant, the emittance dilution process can be a reversible one [3], making the projected emittance blow-up correctable: this is accomplished by properly focusing and accelerating the beam close to an equilibrium condition named invariant envelope [1], which is a generalization of the concept of Brillouin flow for accelerated beams.

The success of the concept of invariant envelope is reported in various references [1, 4] where the predictions of optimum injector operating conditions to achieve maximum beam brightness are compared to simulation results. In those references, it was pointed out that the laminar flow description fails at some energy along the linac which follows the injector and boosts up the beam energy: at such an energy cross-overs start to occur, i.e. the thermal motion takes off, and the emittance correction mechanism is stopped. A generalization of the invariant envelope treatment is therefore necessary to extend the analysis further to describe the transition between the two regimes.

For this purpose we have to get back to the general discussion on the envelope equation treatment as originally due to Lapostolle [5], and try to compare two different approaches, one based on coasting beams subject to tune depression effects due to space charge, and the other based on the invariant envelope concept. The first one is performed via a perturbative treatment of acceleration (leading to adiabatic damping) that takes into account exactly the superposition of emittance and space charge effects, while the second one neglects the emittance effects (laminar flow) but it describes exactly the acceleration process. For the sake of brevity, we will use the notation LS for the first treatment and SR for the second one.

We start by writing the rms transverse envelope equation for a bunched beam in a linac

$$\sigma'' + \frac{\gamma'}{\gamma}\sigma' + K\sigma = \frac{k_s}{\gamma^3\sigma} + \frac{\varepsilon_{th}^2}{\gamma^2\sigma^3}. \tag{1}$$

Here, the beam spot size σ is assumed to be a function of axial position z along the linac, while $\gamma' \equiv d\gamma/dz$ is the acceleration gradient, and $k_s \equiv I/2I_0$ the beam perveance, $I_0 = 17\,\text{kA}$ being the Alfven current. The quantity K in equation (1) is the focusing gradient (which is given by $K = (eB_0/2mc\gamma)^2$ for the case of a solenoid of field B_0), while ε_{th} is the thermal normalized emittance, which is mainly due to the photo-emission process characteristics at the cathode surface and is a Liouvillian invariant throughout acceleration.

The usual approach followed to derive an equilibrium solution of equation (1) (as described in [6]) consists of neglecting acceleration (i.e. $\gamma' = 0$) so to find a steady state solution given by

$$\sigma_R = \sigma_{0R}\left\{\frac{1}{2}\frac{k_s}{\varepsilon_{th}\gamma^2\sqrt{K}} + \sqrt{1 + \left[\frac{1}{2}\frac{k_s}{\varepsilon_{th}\gamma^2\sqrt{K}}\right]^2}\right\}^{1/2}. \tag{2a}$$

This represents a constant spot size σ_R for the beam, assumed to be propagating through a uniform focusing channel of gradient K under the defocusing effect of its space charge field, combined with the outward pressure of its thermal emittance. At zero space charge (negligible beam current), the equilibrium beam spot size is σ_{0R} : it is customary to introduce the tune depression factor Δ_K, defined as the ratio between the applied focusing gradient K and the effective reduced gradient seen by the beam K_{SC}, i.e.

$$\Delta_K \equiv \sqrt{\frac{K_{SC}}{K}} = \frac{\sigma_{0R}^2}{\sigma_R^2} = 1\Bigg/\left[\frac{\nu}{2} + \sqrt{1 + \left(\frac{\nu}{2}\right)^2}\right],$$

given $\nu \equiv (k_s/\varepsilon_{th}\gamma^2\sqrt{K})$.

Invoking the usual adiabatic damping assumption, i.e. $\gamma'/\gamma \ll \sqrt{K} = 2\pi/\lambda_\beta$ (meaning that the acceleration scaling length γ'/γ is much longer than the betatron wavelength λ_β), one can see [6] that the equilibrium beam spot size will scale (for a constant gradient K) like $1/\sqrt{\gamma}$ when acceleration is taken into account, i.e.

$$\sigma_{0R} = \sqrt{\frac{\varepsilon_{th}}{\gamma\sqrt{K}}} = \sqrt{\frac{\varepsilon}{\sqrt{K}}} = \sqrt{\varepsilon\beta^*}, \tag{2b}$$

according to the usual definitions of the geometric emittance ε and the betatron function β^*. This leads to a general expression for the equilibrium beam spot size given by

$$\sigma_R = \sigma_{0R}\Big/\sqrt{\Delta_K} = \sigma_{0R}\left[\frac{\nu}{2} + \sqrt{1 + \left(\frac{\nu}{2}\right)^2}\right]^{1/2}, \tag{2c}$$

that will be referenced in the following as the LS model (tune depression formalism based on adiabatic damping assumption). The merit of this description is clearly the capability to describe an equilibrium state for the beam which is a mixing of space charge and emittance effects (defocusing), balanced by focusing external forces: in this way it is possible to describe the transition from a pure laminar flow (at $\Delta_K \to 0$, e.g. the Brillouin flow in a solenoid field) into a thermal flow ($\Delta_K = 1$, negligible space charge effects) which is usually achieved just by varying the applied focusing gradient K or simply by accelerating the beam (see above the scaling of the parameter ν as $1/\gamma^2$). On the other hand, a clear limit of this treatment is the need for external focusing in order to set up an equilibrium state for the beam (no equilibrium solution is possible for $K = 0$): this model is indeed not able to describe the particular equilibrium state that can be achieved with the equivalent focusing effect produced by acceleration.

In order to study this new kind of equilibrium we must assume a pure laminar flow condition: in this way it is possible to find an exact solution of equation (1) when the focusing is of second order, i.e. when the focusing gradient can be written as $K = (\Omega\gamma'/\gamma)^2$. Secular envelopes of beams in linacs and/or in FODO lattices are actually subject to this kind of focusing [7]: the normalized focusing frequency Ω takes the form $\Omega^2 = \eta/8 + (cB_{SOL}/2E_{acc})^2$, where the factor $\eta/8$ represents the RF ponderomotive focusing ($\eta \cong 0$ for TW linacs, while $\eta \cong 1$ for SW linacs [7]), while the second term gives the focusing effect of an external solenoid (recalling that $\gamma' = eE_{acc}/mc^2$). This means considering equation (1) without the emittance term, i.e.

$$\sigma'' + \frac{\gamma'}{\gamma}\sigma' + K\sigma = \frac{k_s}{\gamma^3\sigma}, \tag{3}$$

under the assumption of constant accelerating gradient $\gamma'' = 0$ and $K = (\Omega\gamma'/\gamma)^2$. An exact particular solution is:

$$\hat{\sigma} = \frac{1}{\gamma'}\sqrt{\frac{k_s}{\gamma(1/4+\Omega^2)}}, \tag{4}$$

the so-called invariant envelope. This is also an approximate solution for equation (1) as far as the laminarity parameter

$$\rho \equiv \left\{\frac{k_s}{\varepsilon_{th}\gamma\gamma'\sqrt{1/4+\Omega^2}}\right\}^2,$$

is very large ($\rho \gg 1$), which means a quasi-laminar flow dominated by space charge with negligible betatron motion. Note that the laminarity parameter represents the ratio between the space charge term in equation (1) and the emittance term, when the beam size σ is assumed to follow the invariant envelope solution $\hat{\sigma}$ of equation (4).

The relevant property of the beam equilibrium state corresponding to such a solution is as follows: an optimal design for a photo-injector should be the one able to produce a beam envelope gently oscillating around the invariant envelope, as shown for example in [4]. It is worth noticing that, in analogy to what happens with the Brillouin flow, current replaces here the role of emittance: indeed, comparing equation (4) with equation (2*b*) we find that the analogies are

$$\varepsilon \equiv \frac{\varepsilon_{th}}{\gamma} \Leftrightarrow \frac{k_s}{\gamma'\gamma} \qquad \text{and} \qquad \beta^* \Leftrightarrow \frac{1}{\gamma'(1/4+\Omega^2)}. \tag{5}$$

A clear merit of this model (referenced in the following as the SR approach) is the capability to describe exactly the acceleration process: in fact, equilibrium exists even at zero focusing, $\Omega = 0$, because of the acceleration. The main drawback consists of the fact that the transition from laminar into thermal flow cannot be described, since the validity of $\hat{\sigma}$ as a solution for equation (1) is limited to $\rho \gg 1$, while the transition occurs at $\rho = 1$ and the thermal flow corresponds to $\rho \ll 1$. For a typical electron linac driven by a photo-injector, the energy at which the transition occurs can be nevertheless quite high. This is defined by

$$\gamma_l = \sqrt{\frac{2}{3}\frac{2k_s}{\varepsilon_{th}\gamma'}},$$

for the case of $\Omega^2 = 1/8$, which corresponds to a standing wave linac with no external solenoid focusing. For a high current cold beam $I = 1$ kA, $\varepsilon_{n,th} = 0.6$ mm mrad, accelerated by a 25 MV m^{-1} linac, equivalent to $\gamma' = 50$, the transition energy comes out to be $\gamma_l = 2000$, i.e. 1 GeV, see figure 1.

In order to find out a complete solution of equation (1) able to model exactly acceleration and the transition as well, we start by noticing the following: substituting the expression of the laminarity parameter ρ, which has an expression very similar to the square of the parameter υ defined above ($\nu \equiv (k_s/\varepsilon_{th}\gamma^2\sqrt{K}) = (k_s/\varepsilon_{th}\gamma'\gamma\Omega)$), into the equilibrium state defined by the LS approach (equation (2*c*)), we find

$$\bar{\sigma} = \sqrt{\frac{\varepsilon_{th}}{\gamma\sqrt{K}}}\left\{\frac{1}{2}\left[\rho\sqrt{\frac{(1/4+\Omega^2)}{\Omega^2}}\right]^{1/2} + \sqrt{1+\left[\frac{1}{4}\rho\sqrt{\frac{(1/4+\Omega^2)}{\Omega^2}}\right]}\right\}^{1/2},$$

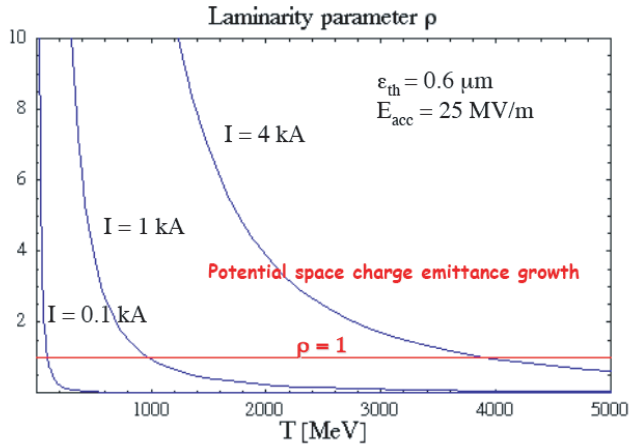

Figure 1. Laminarity parameter ρ versus beam energy T for different beam currents. Notice that a 1 kA beam is space charge dominated up to 1 GeV energy.

which clearly reveals a mismatch by a factor $(1/4+\Omega^2)/\Omega^2$ in the expression for the normalized focusing frequency. We interpret this mismatch as due to the error made by the tune depression formalism (LS approach) in treating the effective focusing produced by acceleration. We therefore make an ansatz [8] (see also [9] for an more rigorous derivation), which consists of plugging in a different expression for the normalized focusing frequency taking the same value as that predicted by the invariant envelope expression in equation (4) (SR model):

$$\bar{\sigma} \equiv \sqrt{\frac{\varepsilon_{\mathrm{th}}}{\gamma\sqrt{K_{\mathrm{eff}}}}}\left\{\frac{1}{2}\sqrt{\rho}+\sqrt{1+\frac{\rho}{4}}\right\}^{1/2} = \sqrt{\frac{\varepsilon_{\mathrm{th}}}{\gamma'\sqrt{1/4+\Omega^2}}}\left\{\frac{1}{2}\sqrt{\rho}+\sqrt{1+\frac{\rho}{4}}\right\}^{1/2}. \tag{6}$$

This clearly shows that the quantity $\sqrt{\rho}=k_{\mathrm{s}}/\varepsilon_{\mathrm{th}}\gamma\gamma'\sqrt{1/4+\Omega^2}$ actually substitutes the quantity ν in equation (2a) (for the case of $K=(\Omega\gamma'/\gamma)^2$). Equation (6) represents therefore an enhancement of the LS model obtained by adjusting the correct expression for the normalized focusing frequency ($K_{\mathrm{eff}}\equiv(1/4+\Omega^2)(\gamma'/\gamma)^2$): it can be further manipulated into an expanded form showing clearly the three different types of focusing which are involved. This is done just by considering that the normalized focusing frequency is given by $\Omega^2=1/8+(\Omega_{\mathrm{L}}/c\gamma')^2$, where Ω_{L} is the Larmor frequency in the solenoid field (a similar expression can be found for a FODO lattice, in which case Ω_{L} is substituted by the average normalized focusing gradient of the FODO channel, see [10]), and substituting into equation (6) to get

$$\bar{\sigma} = \sqrt{\frac{\varepsilon_{\mathrm{th}}}{\sqrt{\frac{\gamma'^2}{4}+\frac{\gamma'^2}{8}+\left(\frac{\Omega_{\mathrm{L}}}{c}\right)^2}}}\left\{\frac{1}{2}\sqrt{\rho}+\sqrt{1+\frac{\rho}{4}}\right\}^{1/2}. \tag{7}$$

The first term, $\gamma'^2/4$, is a pure acceleration equivalent focusing gradient which was missing before in the LS model (because of the adiabatic damping treatment), the second term, $\gamma'^2/8$, is the focusing gradient due to RF ponderomotive potential, while the third one, $(\Omega_{\mathrm{L}}/c)^2$, is the

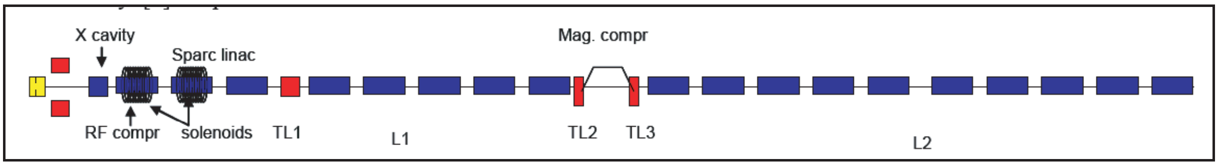

Figure 2. High brightness S-band linac model.

external gradient provided by the restoring force applied by the solenoid (or by an equivalent FODO channel).

Equation (7) actually provides a general expression for both the laminar regime, which is asymptotically found for very large values of the laminarity parameter ρ, and for the pure thermal flow, which is found at the limit of very small values of ρ. Indeed, the invariant envelope solution $\hat{\sigma}$ is a particular expression of equation (7), obtained by $\rho \to \infty$

$$\hat{\sigma} = \frac{2}{\gamma'}\sqrt{\frac{k_s}{\gamma(1/4+\Omega^2)}} = 2\sqrt{\frac{k_s}{\gamma(\gamma'^2/4+\gamma'^2/8+(\Omega_L/c)^2)}},$$

and the same is true for equation (2*b*), which is found by taking the limit $\rho \to 0$

$$\sigma_{0R} = \sqrt{\frac{\varepsilon_{th}}{\gamma\sqrt{K_{eff}}}} = \sqrt{\frac{\varepsilon_{th}}{\gamma'\sqrt{1/4+\Omega^2}}}.$$

3. Matching on to the generalized invariant envelope (GIE) in a high brightness linac

As discussed in the previous section, when $\rho \gg 1$ the transverse beam dynamics is dominated by space charge effects, the typical injector regime. Correlated emittance oscillations are observed in this regime [1, 4], caused by the different local current along the bunch and by finite bunch length effects. In this case, special matching conditions should be adopted to properly damp the residual correlated emittance oscillations. By accelerating the beam, a transition occurs to the so-called emittance dominated regime, when $\rho \ll 1$, in this case the transverse beam dynamics is dominated by the emittance and correlated effects are no longer observed. In the case where bunch compressor systems are present along the linac, space charge effects might become important again downstream of such compressors, and the transition from space charge to emittance dominated regimes shifts at higher energy, see figure 1. In addition, most of the time the beam propagates close to the transition regime, with $\rho \approx 1$. In this case, the whole linac behaves like a long injector [11] and the GIE matching solution, equation (6), should be adopted at higher energy. Equation (6) describes conveniently the condition for a proper matching and damping of residual emittance oscillations. In this section, we will discuss the concepts presented above by means of a specific example.

In figure 2, the layout of our high brightness S-band travelling wave linac model is shown, designed to produce a 1.2 GeV, 1.2 kA beam with 1 μm normalized emittance. It consists of a high brightness photoinjector with velocity bunching [12], able to provide a 450 A peak current beam at 184 MeV that is matched throught a transfer line TL1 to a first linac section (L1) where

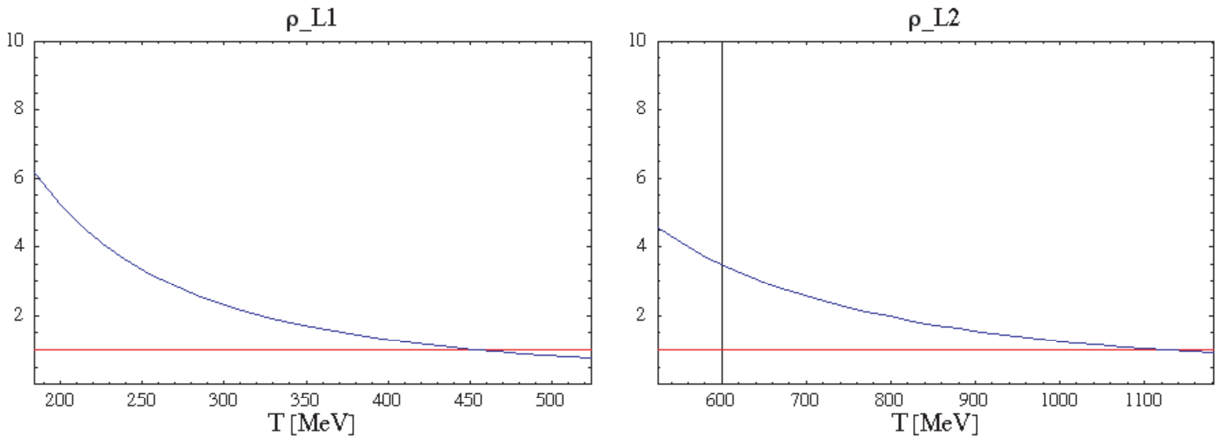

Figure 3. Laminarity parameter ρ versus beam energy T along the L1 (left plot) and L2 linac sections (right plot).

Table 1. Electron beam parameters at different positions along the linac.

	L1 input	L1 output	L2 input	L2 output
γ'	45	45	50	50
T (MeV)	184	524	524	1182
I_{peak} (A)	450	450	1228	1228
ε_{th} (μm)	0.6	0.6	0.6	0.6
η	0.3	0.3	0.3	0.3
ρ	6	0.7	4.5	1
$\bar{\sigma}$ (mm)	0.27	0.2	0.24	0.19

it is accelerated up to 524 MeV. The beam is then injected in a magnetic compressor via a second tranfer line TL2 in order to achieve a 1.2 kA current and then matched (TL3) to a second linac section (L2) and accelerated up to 1.2 GeV, the energy required to drive a typical VUV-SASE-FEL source.

As one can see from figure 3, where the laminarity parameter evolution is shown along the L1 and L2 linac sections, the beam dynamics evolve close to the transition regime $\rho \geqslant 1$ along the whole linac. In L1 section, the beam is accelerated 26° off crest in order to provide the required energy spread for the subsequent magnetic compression. The accelerating gradient $\gamma' = 45$ drives the beam from 184 up to 534 MeV where the threshold condition $\rho = 1$ is achieved. After the compression stage the peak current increases from 450 up to 1228 A, and the laminarity parameter increases consequently to $\rho > 1$. In L2 section, the beam is accelerated on a crest with $\gamma' = 50$ up to 1.2 GeV where the beam is extracted and injected in the undulator. See also table 1 for a parameter summary. In figure 4, the solution of equation (6) is shown with the parameters of our test case.

We have reproduced the envelope behaviour shown in figure 4, with a computer simulation performed with HOMDYN [4], taking into account all the relevant beam dynamics effects along the linac, including longitudinal wake fields [11]. As shown in the figures the beam envelope is matched to the first linac section L1 close to the theoretical predictions (that do not include wake fields and energy spread effects), thus leaving the corresponding emittance to gently oscillate

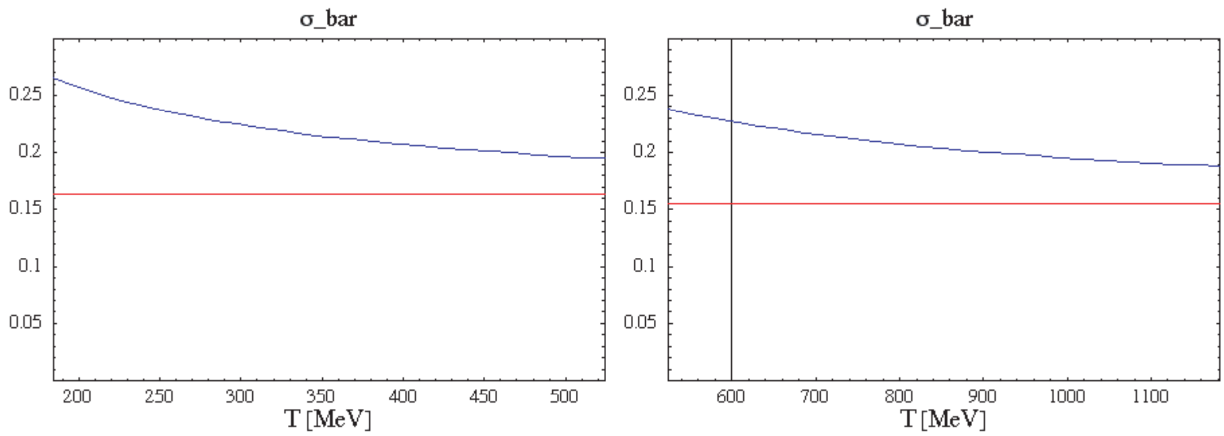

Figure 4. Rms beam envelope $\bar{\sigma}$ as computed by equation (6), blue lines, versus beam energy T along the L1 (left plot) and L2 linac sections (right plot). Red lines correspond to the asymptotic solution $\rho \rightarrow 0$.

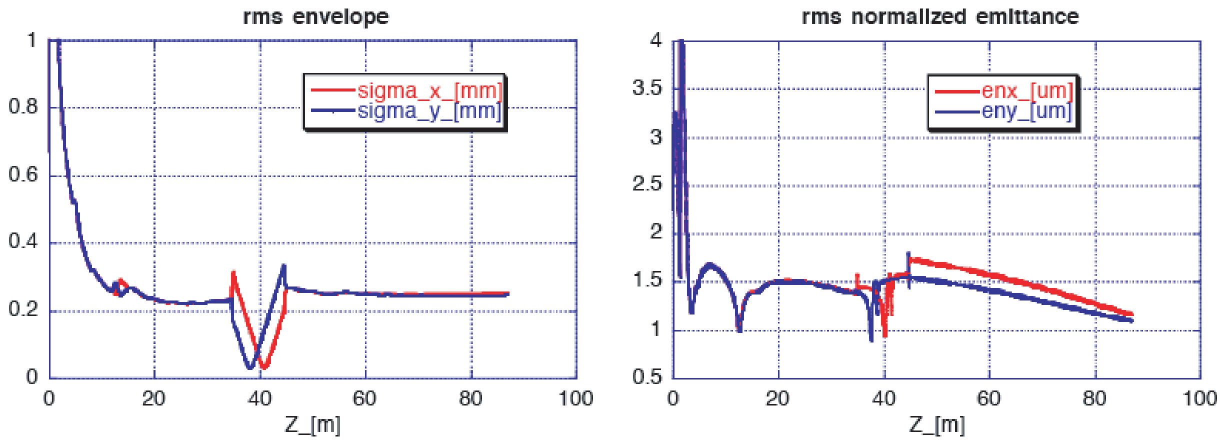

Figure 5. Rms beam envelopes (left plot) and rms normalized emittances (right plot) as computed by HOMDYN along the linac without any FODO lattice.

until the L1 exit. Space charge effects should not be any more important at this stage for a constant peak current. In our linac model the beam is now injected in a magnetic chicane that increases by a factor 3 the peak current thus exciting again space charge forces. A triplet at the exit of the magnetic compressor is used to match the beam envelope to the second linac section (another possibility could have been to change the gradient in L2 in order to satisfy equation (6)). An additional emittance oscillation is cleary visible in figure 5, with a minimum at the exit of the linac as desired. Notice that if we exclude the three sets of quadrupoles required in the matching sections, no additional FODO lattice has been used along the linac. Acceleration focusing is enough to transport the beam until the exit of the linac with a gentle envelope evolution, thus keeping under control the emittance oscillations. Figure 6 is shown for comparison an HOMDYN simulation of the same linac with a FODO lattice as in a standard linac design. It clearly shows that there is no clear advantage to keeping the beam envelope under control with an external focusing. In contrast, the final emittance results to be even higher than the previous case: furthermore,

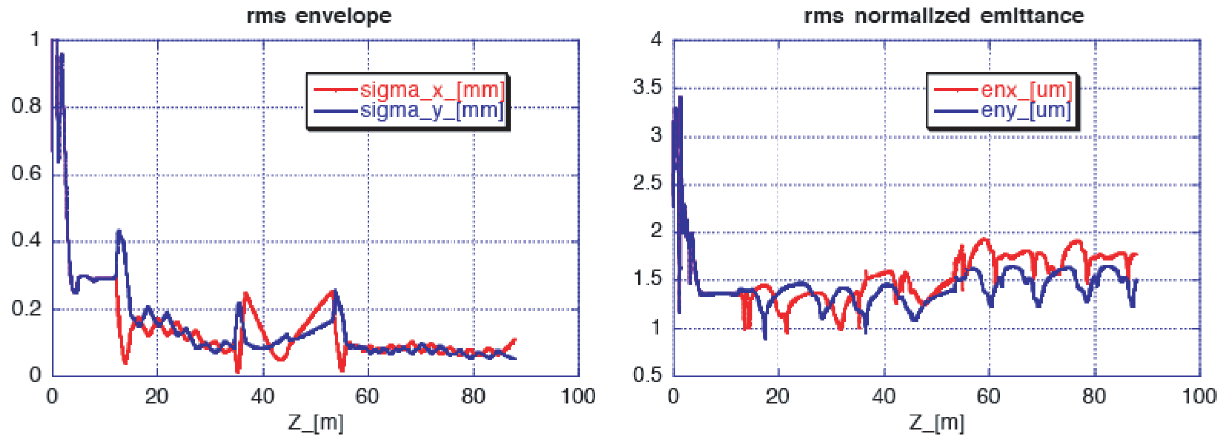

Figure 6. Rms beam envelopes (left plot) and rms normalized emittances (right plot) as computed by HOMDYN along the linac with a FODO lattice.

Table 2. Sensitivity to parameter fluctuations.

	$\Delta\varepsilon/\varepsilon$ FODO	$\Delta\varepsilon/\varepsilon$ GIE
Linac phase $\pm 1^\circ$	14%	1%
Beam charge $\pm 5\%$	12%	7%
Beam offset 100 μm	14%	8%

without external focusing, the alignment procedure is simplified and any transverse beam offset can be simply corrected with steering magnets.

In terms of stability, propagation on the GIE results to be less sensitive to phase and charge stability, as shown in table 2, being almost free from chromatic effects along the linac. We have reported also a case with a 100 μm transverse beam injection error, without correction, for comparison.

4. Conclusions

Beam dynamics along a high brightness linac show sensitivity to space charge forces causing emittance oscillations until the exit of the linac. In order to keep under control and properly damp such emittance oscillations, a careful matching of the beam envelope has been theoretically predicted and supported by numerical simulations. It implies a new concept of transport along the linac that does not require external focusing, as does the one provided by a FODO lattice, but relies on the natural focusing effect of the RF field and the effective focusing resulting from acceleration. The example discussed shows a better performance in terms of final achievable emittance and less sensitivity to parameter fluctuations. In addition, alignment procedures are expected to be much simplified without quadrupoles, since any beam offset can be taken under control as usual with steering magnets, but no undesired effects originated from quadrupole misalignments.

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