OPTIMUM OPERATION OF SPLIT RF PHOTOINJECTORS

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Abstract

We· describe how to achieve minimum transverse emittance in RF photoinjectors by applying theoretical predictions from a fully analytical model of beam dynamics in a split injector. This device consists of a short two cell (full+partial) RF gun followed by a drift and a booster RF linac. Matching the beam in the booster to the invariant envelope, an equilibrium mode of laminar beam flow, is shown to be the basis of emittance correction. Analytical predictions are compared to numerical simulations, finding excellent agreement. We also show how a further improvement of the beam quality can be obtained by matching the beam out of the booster into a Brillouin flow with proper control of the envelope oscillations. If these are actually coherent plasma oscillations in the laminar regime, then the normalized rms transverse emittance can be even further reduced.

I. THE INVARIANT ENVELOPE EQUILIBRIUM OF RELATIVISTIC LAMINAR BEAMS

The beam dynamics in RF photoinjectors is mainly characterized by an rms beam envelope behavior which is almost insensitive to the initial temperature emittance ε_{nth} - this is set up by the photoemission processes at the photo-cathode surface - but is mostly affected by the equilibrium set up by the space charge outward pressure on the beam and the counteracting combined focusing effects of the ponderomotive RF focusing, the external solenoid and the adiabatic damping caused by strong acceleration in the device.

The resulting equilibrium represents a laminar beam flow described by an exact analytical solution of the rms envelope equation $\sigma'' + \sigma'\frac{\gamma'}{\gamma} + K_r\sigma - \frac{\kappa_s(\zeta)}{\sigma\gamma^3} - \frac{\varepsilon_{nth}^2}{\sigma^3\gamma^2} = 0$ which has been recently derived - under the laminarity approximation $\varepsilon_{nth} \cong 0$ - and called invariant envelope[1]:

$$\hat{\sigma} = \frac{2}{\gamma'}\sqrt{\langle I\rangle / \left[2I_0\gamma\left(1+4\Omega^2\right)\right]} \qquad (1)$$

where γ' is the accelerating gradient ($\gamma = \gamma_i + \gamma' z$), $\langle I\rangle$ is the rms beam current ($I_0 = 17$ kA for electrons), and Ω is the dimensionless focusing frequency. This is related to the average focusing gradient K_r by $K_r = \left(\Omega\gamma'/\gamma\right)^2$, implying a second order focusing channel made up by the combination of solenoid focusing and ponderomotive RF focusing, and is given by $\Omega^2 = \eta/8 + b^2$, where $b = cB_0/E_0$ is the ratio between solenoid field and peak RF field, and η depends on the space harmonics of the RF field - it is close to 1 for standing wave structures in use for photoinjectors, while is almost vanishing in case of travelling wave structures[2].

The reason for the term invariant envelope (IE) is that this particular beam mode performs correction of the emittance growth[3] caused by linear space charge correlations. These are related to the dependence of space charge field on the longitudinal coordinate - the slice position ζ - in the electron bunch, as shown by the beam perveance term $\kappa_s(\zeta) = Ig(\zeta)/2I_0$ in the envelope equation - here I is the peak current in the bunch and $g(\zeta)$ is a geometrical factor describing the field distribution, which for a Gaussian bunch in the central region ($|\zeta| \le \sigma_z$) is well described by $g(\zeta) = e^{-\zeta^2/2\sigma_z^2}\left\{1 + A_r^2\left[\left(1-\zeta^2/\sigma_z^2\right)\left(1/2 + \ln A_r\right) - 1\right]\right\}$, while for a uniform bunch of length L is $g_{un}(\zeta) = 1 - 2A_r^2\left[1 + 12\left(\zeta/L\right)^2 + 80\left(\zeta/L\right)^4\right]$. ($A_r \equiv \sigma/\gamma\sigma_z$ is the bunch aspect ratio in its rest reference frame - for the uniform $A_r \equiv R/L\gamma$).

The emittance correction process is effective as long as the beam is in the laminar regime, so that it behaves like a cold plasma undergoing surface plasma oscillations. The validity of the laminarity assumption holds whenever the dimensionless parameter $\rho = \left[\langle I\rangle g(\zeta) / \gamma\varepsilon_{nth} I_0 \gamma' \sqrt{1+4\Omega^2}\right]^2$ is much larger than 1, which is usually the case even up to 40 MeV for a typical photoinjector beam[4]. In this regime, since the incoherent betatron motion associated to the temperature emittance is negligible (by definition of laminarity), the emittance blow-up turns out to be a reversible effect which can be corrected by a proper control of the plasma oscillations.

II. OPTIMUM RF GUN OPERATION

The optimum operation of a split photoinjector is achieved when the RF gun setting is such as to match the beam onto the IE at injection into the booster linac. This requires not only that the beam rms size σ at the booster entrance should be as specified by Eq.1, but also that the beam must go through a waist with $\sigma' = 0$ at the same location, because the entrance focusing kick imposed by the conservation of canonical momentum when the particles enter the RF field is exactly equal to the negative beam divergence of the IE, which is $\hat{\sigma}' = -\gamma'\hat{\sigma}/2\gamma$.

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In order to find the optimum setting for the six free parameters specifying the RF gun working condition, namely the bunch charge Q, the laser cathode spot size σ_r and length σ_z, the cathode peak field E_0, the solenoid field amplitude B_0 and the accelerating phase φ, we have to trace back the beam through the drift down to the gun exit by means of the rms envelope equation for laminar beams in drifts, which reads

$$\nu'' - 1/\nu = 0 \qquad (2)$$

where $\nu \equiv \sigma/P$ and $P = I/2I_0\gamma_c^3$ is the beam perveance (γ_c is the beam energy at the gun exit, typically $\gamma_c \geq 6$). The general solution of Eq.2 is $\int_1^{\nu/\nu_c} dx \Big/ \sqrt{\nu_c'^2 + 2\ln x} = \Delta z/\nu_c$, which allows to express the beam spot ν_w at the waist and its position Δz_w as functions of rms size ν_c and divergence ν_c' at the gun exit:

$$\Delta z_w = \nu_c f(\nu_c') \;\; ; \;\; \nu_w = \nu_c e^{-\nu_c'^2/2} \qquad (3)$$

where the function $f(\nu_c') \equiv \int_{e^{-\nu_c'^2/2}}^{1} dx \Big/ \sqrt{\nu_c'^2 + 2\ln x}$ can be very well approximated in the range $|\nu_c'| \leq 6$ by the simple expression:
$g(\nu_c') = 1.09\nu_c'/1.69 + \nu_c'^2 + 0.423\nu_c' e^{-0.296\nu_c'^2}$. Since Eqs.3 are valid for any laminar space charge dominated beam they actually represent the generalization of a previous result derived by Reiser[5].

In order to finally link the beam conditions at the waist, which must be matched to the IE, with the beam conditions at the cathode we have to perform two transformations:

1) from the 6D physical parameter space (Q, σ_r, σ_z, E_0, B_0 and φ) to a 4D parameter space described by $A \equiv \gamma A_r$, $\alpha \equiv eE_0/2m\omega_{RF}c$, b and the Cauchy current $\Lambda \equiv I/\gamma'^2\sigma_r^2$.

2) from the physical beam rms size σ_c at the gun exit, as given in Ref.6, to the dimensionless $\tau_c \equiv \sigma_c\gamma'\sqrt{\gamma_c/\kappa_s(\zeta)}$.

As a final result of imposing two conditions (beam size and divergence) on the set of four free parameters, we may specify what are the optimum values for Λ and b in order to achieve emittance correction, once the aspect ratio A and the dimensionless field amplitude α are fixed. We find

$$\Lambda^{opt}\ [kA] = 57.3 - 12.4\alpha + 2.63\alpha^2 + 26.2A - 1.78\alpha A + 1.86A^2 \qquad (4)$$

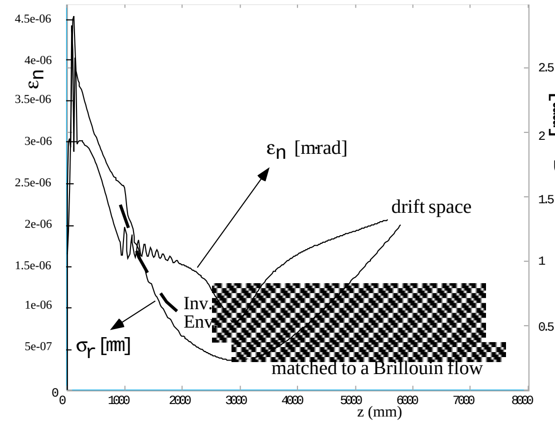

Figure 1: Beam envelope σ and associated normalized rms transverse emittance ε_n in a typical L-band split Photoinjector, showing control of the emittance oscillations by matching to a Brillouin flow

for the Cauchy current, while for the solenoid field amplitude $b^{opt} = 1.49 + 1.67/\sqrt{\alpha} - 2.07/\alpha^{1/4}$.

We test these analytical predictions versus a CIC simulation performed with ITACA[7] of a typical L-band split photoinjector (1+1/2 cell) whose booster linac is a 9-cell superconducting TESLA cavity placed 1 m far from the photo-cathode plane and operated at 25 MV/m peak accelerating field. Choosing $\alpha = 1.8$ and $A = 1/2$ we have $E_0 = 50$ MV/m (at 1.3 GHz, $\gamma' = 49$ m^{-1}) and we find $\Lambda^{opt} = 56$ kA from Eq.4. From the definition of Λ and the peak current in a gaussian bunch $I = Qc/\sqrt{2\pi}\sigma_z$ we find the cathode spot size as a function of Λ, Q, A and γ', *i.e.* $\sigma_r = \sqrt[3]{QcA/\sqrt{2\pi}\Lambda\gamma'^2}$.

Choosing for the bunch charge $Q = 1$ nC, we find for the cathode spot size $\sigma_r = 0.76$ mm, so the laser pulse length should be (from $A = 1/2$) $\sigma_z = 1.5$ mm. The predicted optimum value for the solenoid field amplitude is, from $b^{opt} = 0.94$, $B_0 = 1.6$ kG.

The simulation result is presented in Fig.1, where the norm. rms emittance, $\varepsilon_n \equiv \gamma\sqrt{<r^2><r'^2> - <rr'>^2}/2$, and the envelope are plotted: the actual laser intensity distribution has been taken uniform in time and radius with rms sizes equal to the ones listed above.

As clearly visible, the beam follows closely the IE along the booster, achieving an effective emittance damping down to 0.8 mm·mrad at the minimum ($z = 3$ m), with an emittance behavior reproducing quite well the prediction from the model based on weak stable oscillations around the IE: this gives

$$\varepsilon_n \cong \sqrt{\frac{\langle I\rangle}{3I_0\gamma}}\left|\left(\delta\sigma_i + 2\delta\sigma_i'\frac{\gamma_c}{\gamma'}\right)\cos(\psi) + \left(\delta\sigma_i'\frac{\gamma_c}{\gamma'} - \delta\sigma_i\right)\sqrt{2}\sin(\psi)\right|$$

where $\delta\sigma_i$ and $\delta\sigma_i'$ are the rms mismatches w.r.t. the IE at injection into the booster and $\psi = \ln(\gamma/\gamma_c)/2$ is the phase advance. The emittance is therefore expected to be damped as $1/\sqrt{\gamma}$, on average over a plasma wavelength $\lambda_p = \sqrt{8/3}\,\pi\gamma/\gamma'$, with anharmonic oscillations whose periodicity is two times shorter than the period of the perturbations about the IE.

III. EMITTANCE CONTROL IN LAMINAR BEAMS

The property of the IE to make the beam exit the booster as a parallel beam ($\sigma' = 0$) makes possible to match the IE to a Brillouin flow in order to avoid a further emittance growth, as shown in Fig.1, after the laminar waist where the minimum emittance occurs. Since the equilibrium rms beam size σ_{eq} in a Brillouin flow has the same scaling *vs* the current of the IE, $\sigma_{eq} = \sqrt{I/2I_0\gamma_f^3 K_r}$ (γ_f being the exit energy), a uniform focusing channel of gradient $K_r = \left(\sqrt{3/8}\,\gamma'/\gamma_f\right)^2$ can perform such a matching. In Fig.1 a solenoid of field amplitude $B_0 = \sqrt{3/2}\,mc\gamma'/e$ has been used to keep the beam close to a Brillouin flow equilibrium: the weak envelope oscillations are clearly associated with emittance oscillations of twice the frequency. This somewhat unusual behavior of emittance scaling with the rms size is typical of a beam in the laminar space charge dominated regime: indeed, this 65 A beam, accelerated up to 19.8 MeV, still retains a large value for the parameter ρ , namely $\rho = 80$.

This implies that the emittance can be even further reduced: indeed, the particle distribution plotted in Fig.2a (configuration space) and 2b (trace space), shows that the bunch tail and head behave like bifurcated parts, *i.e.* independent beams which have been overfocused since they were subject to a local space charge field weaker than in the bunch core (see previous expression for $g(\zeta)$). These bifurcated tails usually go through a crossover thus producing a halo in trace space (see Fig.2b) which clearly contaminates the emittance correction process. By filtering the bifurcated tails only 10% of the bunch charge is lost but the emittance is reduced down to 0.5 mm·mrad.

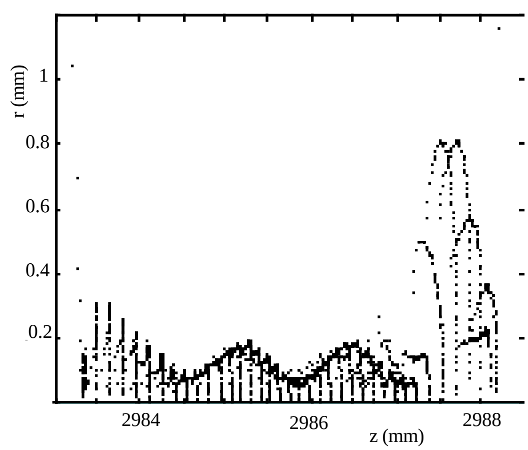

Figure 2a: Particle distribution in the configuration space (r,z) at the location of minimum emittance

We found that these bifurcated tails can be locally corrected by properly adjusting the matching from the IE to Brillouin flow into the solenoid field. With respect to the setting shown in Fig.1, we moved the solenoid further ahead and increased the solenoid field up to 1.9 kG. This makes the beam perform more gentle envelope oscillations: during the first one the bifurcated tails are overlapped in phase space to the beam core, producing a local minimum in the normalized rms emittance (calculated over all the particles) at an unprecedented ultra-low value of 0.3 mm·mrad .

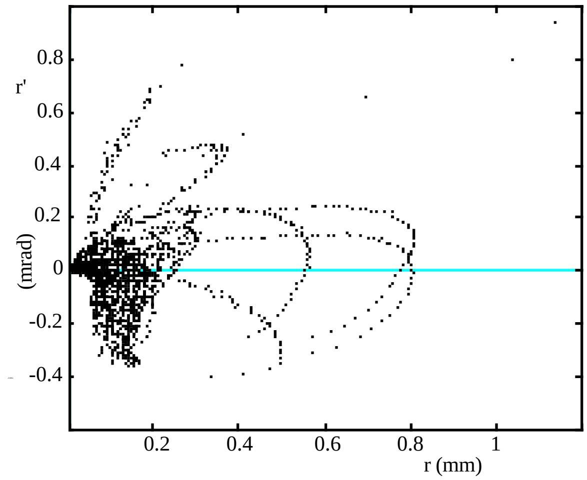

Figure 2b: Particle distribution in transverse trace space (r,r') at the location of minimum emittance

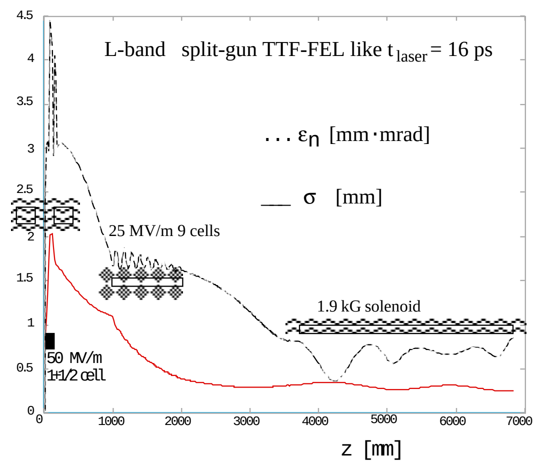

Figure 3: Envelope and emittance behavior of a beam matched from the IE to Brillouin flow with local correction of bifurcated tails

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