BEAM BREAK-UP INSTABILITY IN THE FERMI @ ELETTRA LINAC

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Abstract

The beam break-up instability is studied for the 1.2 GeV linac of FERMI@ELETTRA FEL [1]. This instability is driven by transverse wake fields acting on an electron beam travelling off-axis in the accelerating structures due to the launching errors in positions, angles, energy and misalignment of various lattice elements. Two operational scenarios are considered: one with a relatively long electron bunch of 1.5 ps and a moderate peak current of 500 A and one with a shorter bunch of 0.7 ps and a higher peak current of 800 A. Attention is given to the correction of the "banana" shape of the electron bunch caused by the instability. The simulation results are compared with the analytical predictions.

INTRODUCTION

This paper is focused on the simulation of the BBU instability in the Fermi linac affecting the beam transport in presence of lattice errors. In addition to the usual trajectory correction, local trajectory bumps have been used in order to reduce the emittance dilution. The sensitivity of such technique to trajectory jitters has been evaluated. This study applies to two different bunches that will be used for the Fermi FEL operation [1]; their features are listed in Table 1.

Simulations have been performed through the Elegant tracking code [2]. A theoretical description of the BBU in the Fermi linac and a comparison between results from beam dynamics simulations and from the analytical model are in [3].

Figure 1 shows the transverse wake functions [4, 5] for all the accelerating structures involved in the Fermi linac. We can see that the S-sections (or BTWs, Backward Travelling Wave structures), located in the last part of the Fermi linac [1], are characterized by really strong wake functions w.r.t the others.

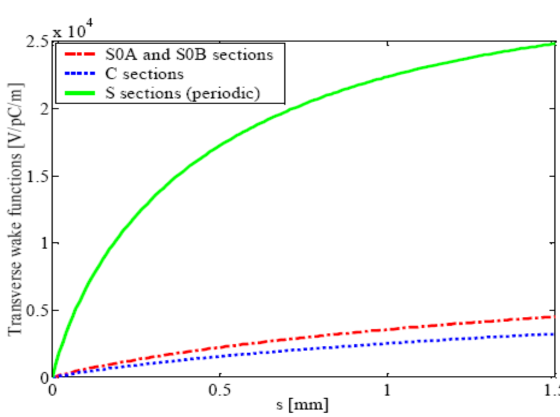

Figure 1: Transverse wake functions for the accelerating structures in the FERMI linac [4, 5].

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Table 1: Nominal parameters for the Fermi bunches.

Bunch type	Charge [nC]	Comp. Factor	$\Delta t_{i,FW}$ [ps]	$\Delta t_{f,FW}$ [ps]	I_f [A]
Medium	0.8	10	9	0.7	850
Long	1.0	7.5	11	1.5	500

TRAJECTORY DISTORTION

A satisfactory trajectory correction has been obtained by placing one Beam Position Monitor (BPM) and one steerer, separated by a quadrupole magnet, in each drift between two consecutive accelerating structures This scheme allows for providing two different methods of correction: (i) one-to-one trajectory correction that is each steerer corrects the beam position at the BPM located at the end of the downstream accelerating structure; (ii) global trajectory correction that is all the steerers and BPMs are involved in the minimization of the off-axis motion of the bunch centroid along the Linac.

Figure 2 shows an ensemble of 120 trajectories for the Medium bunch after the beam steering; the budget of lattice errors that has been considered is reported in Tables 2. A launching error of 100 μm and 100 μrad in both planes is included. Set up in Table 2 forces the steerers to a maximum kick of 3 mrad; the RMS off axis-trajectory is about 350 μm. Very similar results have been obtained as for the Long bunch. The BBU instability has been included in the trajectory correction because it modifies the transverse distribution of the particles position and finally the computation of the centroid position at the BPMs.

Table 2: Elements misalignment and field quality (RMS values) used for the simulation of the BBU instability. Multipolar components of the dipoles field are evaluated at a radius r=20mm. $b_{n,0}$ is the main field component according to the magnet index [6].

	Δx, Δy [μm]	Δz [μm]	Δθ [μrad]
DIPOLE	-	-	300
QUADRUPOLE	150	200	300
BPM (30μm res.)	150	200	-
ACCEL. STRUCT.	300	-	-
	$\lvert\Delta b_0/ b_{n,0}\rvert$	$\lvert\Delta b_1/ b_{n,0}\rvert$	$\lvert\Delta b_2/ b_{n,0}\rvert$
DIPOLE BC1	1×10^{-4}	0.5×10^{-4}	4.0×10^{-4}
DIPOLE BC2	1×10^{-4}	1.0×10^{-4}	4.0×10^{-4}
QUADRUPOLE	-	1.0×10^{-3}	-

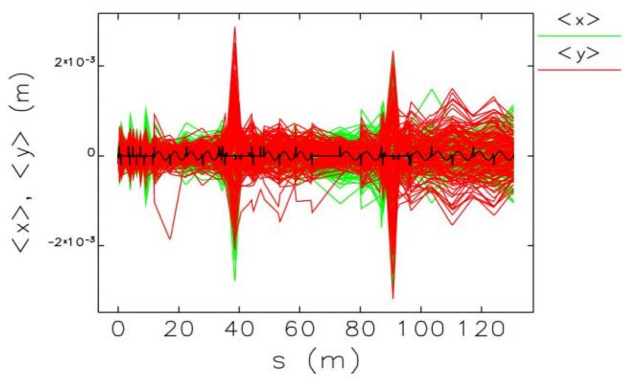

Figure 2: Ensemble of 120 corrected trajectories along the Fermi linac (Elegant tracking result), including errors listed in Tables 2 (excursion in the chicanes is shown w.r.t the straight path).

BBU INSTABILITY

Beam Break-Up instability (BBU) has been recognized as the main source of emittance dilution in the Fermi Linac. An electron beam travelling off-axis in an accelerating structure excites the short-range transverse wake field which in turn gives a kick distributed along the bunch length. The bunch tail starts oscillating w.r.t. to the head axis, so forming in the t-x and t-y plane the so-called "banana" shape (Figure 3).

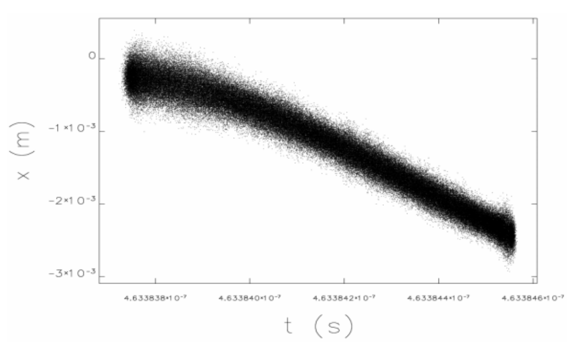

Figure 3: Banana shape over 600 fs at the Linac end. for the Medium bunch (Elegant tracking result). Bunch head is on the left.

Lasting of such oscillations along the linac and their amplification may cause the beam break up that is the total conversion of the bunch time duration into the transverse dimension. Thus, the projected geometrical emittance results largely increased and the time structure of the beam is lost.

Figure 4 shows typical banana shapes (Medium bunch) at the linac end, without any particular approach to preserve the emittance. The emittance dilution has been quantified by mean of the transverse deviation of the bunch tail w.r.t. the head, in units of unperturbed RMS beam size (which is 120 μm at the linac end): *Ratio* = x/σ_x. In Fig.4, RMS value *Ratio* is about 6.5 times in both planes (over 600 fs bunch duration); the maximum tail deviation is 2 mm with respect the bunch head axis.

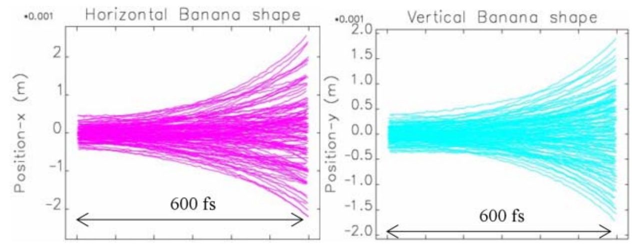

Figure 4: Banana shape of the Medium bunch in the horizontal (left) and vertical (right) plane at the linac end. Head of the bunch is on the left.

Effect of the Trajectory Correction

Table 3 reports the effect of the BBU instability after the trajectory correction for the Medium and Long bunches, in terms of the parameter R*atio*, of the emittance blow up and of the dimensionless coupling strength between the beam and the transverse wake field defined in [3, 8] in absence of correction.

Table 3: Coupling strength ε_r [5, 8], banana shape and emittance dilution for Medium and Long bunches.

	MEDIUM bunch (0.7 ps)	**LONG bunch (1.5 ps)**
ε_r	8.6	22.0
RatioX (RMS)	3.5	4.0
RatioX (MAX)	8.1	10.8
$\varepsilon_x/\varepsilon_{x,0}$ **(MAX)**	15	30

In absence of trajectory correction ε_r predicts a larger emittance dilution for the Long bunch w.r.t. the Medium. Trajectory correction (showed in Fig. 2) reduces the difference between the two cases allowing to provide a similar RMS head-tail deviation over the whole bunch lengths (3.5 vs. 4.0). Nevertheless, the emittance dilution can be really large. According to some considerations in [7], numbers in Table 3 would compromise the FEL process.

Control of the BBU Induced Banana Shape

A particles distribution like that shown in Figure 3 would diminish the efficiency of the FEL process. In fact, after the steering of the bunch centroid at the entrance of the undulators, the bunch head and tail would result being far from the magnetic axis of the device of an amount determined by the amplitude of the banana shape. Thus, the electron beam and the laser seed would fail to overlap each other in the first undulator (the minimum spot size of the laser seed is taken to be roughly 200 μm). When the electron beam is displaced by more than the spot size within the modulator, the energy modulation and thus the final output power is severely reduced [7]. Results in Table 3 demonstrate that the trajectory correction in the Fermi linac is not sufficient to avoid a large degradation of the projected emittance. For this reason, a local bump has been applied at the beginning of the linac region where the transverse wake fields are strongest that is at the entrance of the first BTW structure [1].

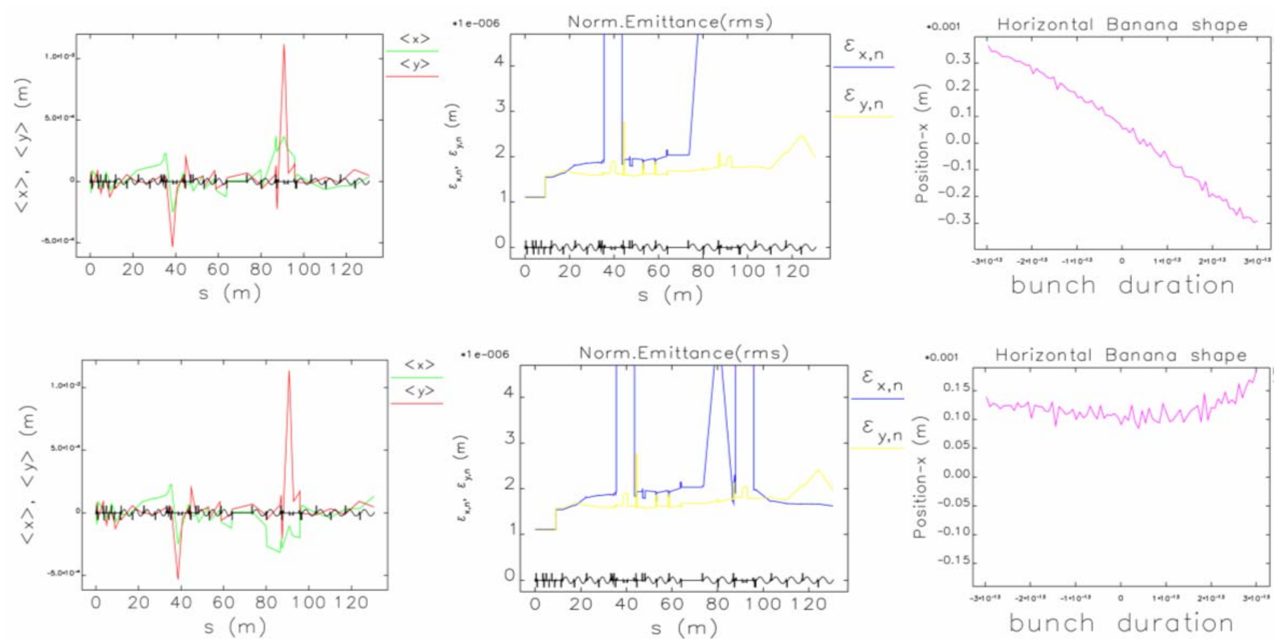

Figure 5: BBU instability of the Medium bunch in the horizontal plane, before (top) and after (bottom) the local trajectory bump. From left to right: trajectory, normalized emittance evolution and final banana shape. Before the bump, the emittance exploits as the bunch enters the first BTW (top centre); the final banana shape covers 600 µm in the transverse plane (top right). After the bump, the horizontal trajectory changes its sign (green line, bottom left) allowing for the emittance preservation (bottom centre); the final banana shape is compensated to the level of 1-σ_x (bottom right).

Figure 5 shows that the local bump allows for compensating the emittance dilution and for reducing the final banana shape to the level of 1-σ_x. This means that a trajectory has been found in which all the wake field kicks compensate each other.

Effect of Trajectory Jitter on the Banana Shape

Since local methods of correction depend on the conditions of operation at their specific location, jitters may be a source of error of the local correction. A study of the effect of the trajectory jitter on the final banana shape has been performed.

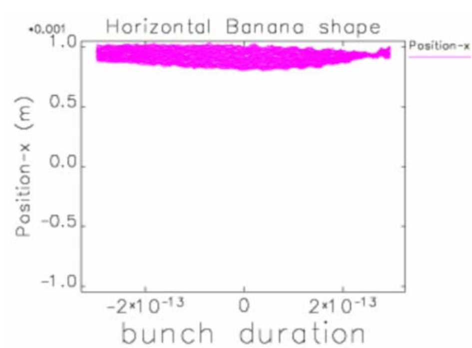

Figure 6: Initially the BBU instability is suppressed (*Ratio* < 0.1, not shown). After adding the jitter, the trajectory bump is perturbed, but the banana shape still remains below the 1-σ_x level (RMS *Ratio* = 0.4).

Figure 6 demonstrates that 100 µm jitter (absolute value) of the launching error does not affect a properly corrected banana shape. Simulations also suggest that a non-local trajectory correction (distributed along the Linac) results being equally efficient and allows for reducing the maximum strength required by the steerers for the emittance preservation.

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[6] $|\Delta b_k / b_{n,0}| = \{[\Delta\int_L(\partial^k B_y/\partial x^k)dl] \cdot [\int_L(\partial^n B_y/\partial x^n)\, dl]^{-1}\} \cdot (R^k / R^n)$ with n=0,1,2,etc…

[7] G. De Ninno, B. Fawley and G. Penn, "Effect of Off-Axis Displacement Errors on FEL-1", ST/F-TN-06/01 (CBP Tech Note-356).

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ACKNOWLEDGEMENTS

The authors are grateful to P. Emma, A. Zholents and M. Cornacchia for many useful discussions.