JITTER STUDIES FOR THE FERMI@ELETTRA LINAC

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Abstract

The FEL project FERMI@ELETTRA [1] will use the existing linac upgraded to 1.2 GeV to produce photon pulses in the wavelength range between 100-10 nm by means of harmonic generation in a seeded scheme. FEL operations foresee stringent requirements for the stability of the global linac output parameters, such as the electron bunch arrival time, peak current, average energy and the slice electron bunch parameters, such as the slice peak current and slice average energy. In order to understand the sensitivity of these parameters to jitters of various error sources along the linac an elaborate study using tracking codes has been performed. As a result, we created a tolerance budget to be used as guidance in the design of the linac upgrade. In this paper we give a detailed description of the applied procedures and present the obtained results.

INTRODUCTION

This paper addresses questions on the sensitivity of the linac output parameters to the various jitters in the phase and amplitude of the accelerating fields, electron bunch charge and emission time. Figure 1 shows the linac layout used in sensitivity studies which is mainly composed by four linacs and two bunch compressors (BC1 and BC2). Layout also foresees a X-band cavity as a linearizer for longitudinal phase space and a laser heater to suppress microbunching instability [2].

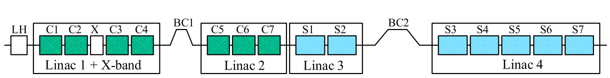

Figure 1: Layout of the FERMI@ELETTRA linac used in sensitivity studies.

FEL operations presume different options for the electron bunch length which foresee different configurations for parameters in the FERMI@ELETTRA. Here we present studies for medium (M) and long (L) bunch length. In addition, each option foresees a different particle distribution out of the photo-injector: with parabolic (M2 and L2) and ramped (M6 and L4) charge distributions [3]. Table 1 shows the nominal compression, R56 terms in bunch compressors (BC) and acceleration parameters, amplitude and phase of the accelerating fields in linacs used in longitudinal tracking simulations. For sensitivity studies LiTrack code [4], a macro-particle fast tracking program that follows longitudinal position and relative energy deviation of the particles, was used. Acceleration is applied as a sinusoidal variation and the bend systems are described simply by their 1st, 2nd, and 3rd order path length vs. energy coefficients (R56, T566, and U5666) and the nominal energy. Wakefields of accelerating structures are included by convolution of a point charge wake with the evolving temporal distribution.

Table 1: Nominal parameters, compression (BC1 and BC2) and acceleration, for different configurations of the FERMI@ELETTRA linac: medium bunch cases M2 and M6 and long bunch cases L2 and L4. Bunch charge is 800 pC and 1 nC respectively for long and medium bunch case. Phase reference is 0 deg for "on crest".

Parameters	M2	M6	L2	L4	Unit
L1 RF voltage	188				MV
L1 RF phase	-36	-36	-39	-25	deg
LX RF voltage	17	18	14	18	MV
LX RF phase	182	180	135	180	deg
L2 RF voltage	141				MV
L2 RF phase	-20	-20	-5	-18	deg
L3 RF voltage	240				MV
L3 RF phase	-20	-20	-15	-18	deg
L4 RF voltage	600				MV
L4 RF phase	-20	19	0	5	deg
BC1 R_{56}	-2.67	-2.87	-2.77	-2.95	cm
BC2 R_{56}	-1.65	-1.67	-3.70	-3.40	cm

We have used the sensitivities to form a tolerance budgets for each options presented in Table 1. The tolerance budget has been adopted as a collection of rms values for input parameters to perform global jitter analysis and the results between LiTrack and Elegant [5] are compared. Further analyses was done on various numbers of slices inside the bunch and new parameter for particle distribution, the "flatness" of the longitudinal phase space [6], was analyzed as well. It defines the value of the quadratic component of energy variation along the bunch.

JITTER SENSITIVITIES AND TOLERANCE BUDGET

Tables 2 and 3 list sensitivities for RF phase and voltage, chicane bend power supplies and electron bunch charge and emission time. Each sensitivity, independently, causes a 10% rms peak current increase, 0.1% rms relative mean energy increase and $150 fs$ rms final timing increase. In general the sensitivities are approximately linear except when a linac is operated on crest or in other particular cases. From the tables we can see that in general the emission time out of photo-injector is compressed and that RF phase and amplitude in linac 1 and linac 4 are critical for sensitivity.

The sensitivities reported in Tables 2 and 3 are used to generate a tolerance budget based on summing random, un-

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Table 2: Individual rms sensitivities p_{sen} for medium bunch case M2 and M6 (in parenthesis). Each causes a variation in electron beam energy, peak current and arrival time with rms value specified in the table.

	Unit	$\Delta I/I_0 = +10\%$	$\Delta E/E_0 = +0.1\%$	$\Delta t_f = +150fs$
ϕ_1	deg	-0.26 (-0.26)	-0.65 (0.27)	-0.19 (-0.18)
ϕ_x	deg	0.92 (0.85)	-3.99 (-3.35)	10.70 (9.81)
ϕ_2	deg	-4.09 (-4.24)	1.92 (0.96)	-1.89 (-1.87)
ϕ_3	deg	-2.39 (-2.48)	1.13 (0.56)	-1.11 (-1.10)
ϕ_4	deg	> 10	0.32 (-0.33)	> 10
V_1	%	-10.09 (13.42)	-0.53 (0.48)	0.25 (-0.24)
V_x	%	8.61 (11.05)	5.62 (-3.85)	2.28 (2.06)
V_2	%	-7.47 (-7.91)	1.30 (0.63)	-1.20 (-1.19)
V_3	%	-4.34 (-4.60)	0.76 (0.37)	-0.71 (-0.70)
V_4	%	> 20	0.20 (0.20)	> 20
Δt_0	ps	3.16 (3.31	0.47 (0.42)	-2.52 (-1.66)
Q	%	-13.98 (-35.73)	-14.50 (-8.31)	18.25 (18.67)
BC1	%	-1.07 (-1.56)	-0.25 (1.59)	-0.22 (-0.20)
BC2	%	-2.01 (-2.22)	-0.57 (-0.52)	-0.27 (-0.27)

Table 3: Individual rms sensitivities p_{sen} for long bunch case L2 and L4 (in parenthesis). Each causes a variation in electron beam energy, peak current and arrival time with rms value specified in the table.

	Unit	$\Delta I/I_0 = +10\%$	$\Delta E/E_0 = +0.1\%$	$\Delta t_f = +150fs$
ϕ_1	deg	-0.71 (-0.52)	0.81 (0.87)	-0.15 (-0.25)
ϕ_x	deg	2.93 (1.30)	-5.57 (-4.42)	1.73 (9.79)
ϕ_2	deg	-3.36 (-2.32)	3.58 (1.16)	-3.11 (-1.06)
ϕ_3	deg	-1.77 (-1.29)	0.94 (0.68)	-0.67 (-0.62)
ϕ_4	deg	> 10	3.03 (-1.36)	> 10
V_1	%	1.53 (1.32)	2.21 (1.59)	-0.21 (-0.21)
V_x	%	-4.76 (-25.15)	25.77 (13.90)	3.31 (2.04)
V_2	%	-7.66 (-7.25)	0.82 (0.74)	-0.52 (-0.60)
V_3	%	-6.63 (-7.25)	0.50 (0.43)	-0.31 (-0.35)
V_4	%	> 20	0.20 (0.43)	> 20
Δt_0	ps	-1.17 (8.70)	0.51 (0.20)	2.94 (-4.44)
Q	%	> 40 (-20.65)	10.56 (-9.75)	10.16 (11.69)
BC1	%	1.72 (1.17)	-0.85 (0.64)	-0.23 (-0.26)
BC2	%	-2.58 (-1.67)	2.22 (0.95)	-0.12 (-0.13)

correlated effects [7]:

$$\sqrt{\sum_{i=1}^{N}\left(\frac{p_{tol}}{p_{sen}}\right)_i^2} < 1 \qquad (1)$$

The sensitivities p_{sen} in the tables are weighting values for the summation in (1). If the tolerances are chosen such that, $p_{tol} < p_{sen}$ for all i, a budget is formed. Tables 4 and 5 list three possible tolerance budgets for medium case M2 and long case L2 respectively. The parenthesis denote the tolerance budgets for medium case M6 and long case L4. If the first budget (third column in tables) is used, the relative peak current fluctuations at the linac end will be held to $< 10\%$ rms. Analogous considerations can be done for the fourth and fifth columns in the tables. If the smaller tolerance from each column is applied (bold text), all three performance requirements ($|\Delta I/I_0| < 10\%$, $|\Delta E/E_0| < 0.1\%$ and $|\Delta t_f| < 150fs$) will simultaneously be met. From Table 4 we can observe that the relative mean energy jitter is the leading output parameter that establishes the value of the tolerances in the out of the photo-injector and on the linac parameters. In the M6 case, the relative mean energy is more sensitive than in the M2 case to RF phase and amplitude of the linac 1, 2 and 3 up to factor 2. This fact likely depends on the different current distribution out of the photo injector since nominal RF phase and amplitude in the linacs are the same in the two cases. We can conclude that the tolerance budget for the M6 case is slightly more stringent than the M2 case, and in particular the tolerance of the relative amplitude in linac 4 should be in the order of magnitude of $5 \cdot 10^{-4}$ with an emission time out of the photo-injector of $250fs$.

From the long bunch cases L2 and L4, in Tables 3 and 5, we see that the final timing jitter together with the relative mean energy jitter are the leading output parameter which establish the tolerance on the photo-injector and linacs in both cases.

In general, note that there is a compromise between the RF phase and voltage of the accelerating field and the photo-injector parameters. The photo-injector parameters could be loosened if the voltage is tightened and vice versa.

Table 4: Medium bunch case M2 and M6 (in parenthesis) tolerance budgets (p_{tol}) for $< 0.1\%$ rms final relative mean energy, $< 10\%$ rms peak current jitter or $< 150fs$ rms final timing jitter. The tighter tolerance is in BOLD text and all criteria are satisfied if the tighter tolerance is applied.

	Unit	$\lvert\Delta I/I_0\rvert = 10\%$	$\lvert\Delta E/E_0\rvert = 0.1\%$	$\lvert\Delta t_f\rvert = 150fs$
ϕ_1	deg	0.15 (0.20)	0.15 **(0.10)**	**0.10 (0.10)**
ϕ_x	deg	**0.50** (0.50)	0.60 **(0.30)**	0.70 (0.70)
ϕ_2	deg	0.50 (0.50)	**0.20 (0.10)**	0.40 (0.40)
ϕ_3	deg	0.20 (0.20)	**0.15 (0.10)**	0.20 (0.20)
ϕ_4	deg	0.70 (0.70)	**0.10 (0.10)**	1.00 (1.00)
V_1	%	0.70 (1.00)	**0.15 (0.10)**	**0.15** (0.15)
V_x	%	0.60 (0.80)	1.00 **(0.50)**	**0.50 (0.50)**
V_2	%	0.50 (0.80)	**0.15 (0.10)**	0.20 (0.20)
V_3	%	0.30 (0.50)	**0.10 (0.10)**	0.15 (0.15)
V_4	%	1.40 (1.50)	**0.08 (0.05)**	1.00 (1.00)
Δt_0	ps	0.35 (0.35)	**0.30 (0.25)**	0.50 (0.35)
Q	%	5.00 (5.00)	**4.00 (3.00)**	5.00 (4.00)
BC1	%	0.07 (0.15)	0.02 (0.10)	**0.02 (0.02)**
BC2	%	0.14 (0.25)	0.04 (0.03)	**0.02 (0.02)**

GLOBAL JITTER STUDIES

Previously obtained tolerance budgets have been adopted as rms values for the input parameters, such as RF phase and amplitude, R56 in chicanes and charge and emission of the electron beam, for a Latin Hypercube Sampling (LHS) [8]. In this way it was possible to get different error seeds for the linac and photo-injector to be used as random inputs for LiTrack runs. Statistical analysis of the global output parameters such as mean energy, peak current and final timing have confirmed that the adopted tolerance budgets are consistent. Table 6 shows statistical parameters of the electron beam at the end of the accelerator on 400 LiTrack runs. We can conclude that adopting

Table 5: Long bunch case L2 and L4 (in parenthesis) tolerance budgets (p_{tol}) for $< 0.1\%$ rms final relative mean energy, $< 10\%$ rms peak current jitter or $< 150fs$ rms final timing jitter. The tighter tolerance is in BOLD text and all criteria are satisfied if the tighter tolerance is applied.

	Unit	$\lvert\Delta I/I_0\rvert$ $= 10\%$	$\lvert\Delta E/E_0\rvert$ $= 0.1\%$	$\lvert\Delta t_f\rvert$ $= 150fs$
ϕ_1	deg	0.30 (0.30)	0.20 **(0.12)**	**0.09 (0.10)**
ϕ_x	deg	0.70 (0.70)	**0.50 (0.50)**	**0.50** (0.70)
ϕ_2	deg	0.50 (0.50)	0.40 **(0.15)**	**0.20** (0.25)
ϕ_3	deg	0.25 (0.25)	**0.10 (0.10)**	**0.10** (0.15)
ϕ_4	deg	1.50 (1.50)	**0.25 (0.15)**	0.60 (1.00)
V_1	%	0.30 (0.30)	0.25 (0.15)	**0.10 (0.10)**
V_x	%	0.60 (2.00)	1.90 (0.90)	**0.30 (0.60)**
V_2	%	1.00 (1.60)	**0.10 (0.15)**	**0.10 (0.15)**
V_3	%	0.90 (0.90)	**0.10 (0.10)**	**0.10 (0.10)**
V_4	%	2.50 (2.00)	**0.08 (0.08)**	1.20 (1.20)
Δt_0	ps	0.80 (1.00)	**0.35 (0.35)**	0.40 (0.60)
Q	%	10.00 (6.00)	4.00 **(4.00)**	**3.00** (5.00)
BC1	%	0.15 (0.08)	0.06	**0.02 (0.02)**
BC2	%	0.20 (0.10)	0.15	**0.01 (0.02)**

the above tolerance budget the performance requirements are simultaneously met. As previously mentioned, another

Table 6: Collection of the statistical parameters on 400 runs with LiTrack for case M1, M6, L2 and L4.

	$\sigma_{\Delta I/I}[\%]$	$\sigma_{\Delta E/E}[\%]$	$\sigma_{\Delta t}[fs]$
M2	9.7	0.101	136
M6	6.3	0.099	121
L2	5.1	0.089	155
L4	7.4	0.100	137

requirement for the electron beam is to have a flat distributions in the longitudinal phase space. To analysis the "flatness" parameters we performed slice jitter studies (400 runs for each case) and for each run the energy variation in the central part of the bunch was approximated, in a least squares sense, by second order polynomial. The flatness of the longitudinal phase space can be defined as the average quadratic component in the energy chirp (mean of the polynomial coefficient a_2). Table 7 shows the statistics of the a_2 coefficient together with its rms fluctuation (σ_{a_2}). For instance, figure 2 shows the slice mean energy and peak current as a function of absolute time defined by a master clock for 10 randomly chosen seeds. From the figures it is clear that jitters affect flatness of the electron bunches and peak current.

Table 7: Statistical parameters of the "flatness" of the longitudinal phase space for case M2, M6, L2 and L4.

	$\hat{a_2}$ $[MeV/ps^2]$	σ_{a_2} $[MeV/ps^2]$	$\sigma_{a_2}/\hat{a_2}$ $[\%]$
M2	6.5	2.2	34
M6	3.6	1.0	28
L2	2.5	0.3	12
L4	1.0	0.5	50

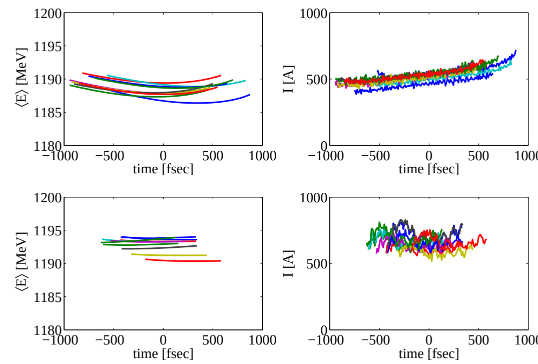

Figure 2: Slice mean energy (left plots) and peak current (right plots) versus absolute time defined by a master clock. Long case L2 (upper plots) and L4 (lower plots).

Preliminary results from Elegant tracking

Consistent s2e simulations from the RF gun to the photon beam taking in account errors along different parts of the injector, the linac and the undulator will be performed soon. Here are presented the preliminary results from Elegant tracking, with errors in the linac and in the photo-injector for medium case M2. Two codes were used: GPT [9] for photo-injector and Elegant for linac part. 84 different output particle distributions in the 6D phase space from GPT were randomly generated and converted to the Elegant input format. The particle distribution was tracked under the combinated influences of the linac errors with rms values taken from Table 4. As a results there are 84 output particle distributions at the linac end which were used as inputs in the FEL simulations. Statistical analysis on 84 different particle distributions obtained from Elegant are in good agreement with LiTrack results (i.e. $\Delta I/I < 9.2\%$ rms, $\Delta E/E < 0.092\%$ and $\Delta t_f < 93fs$). It is interesting to notice that in GPT and Elegant runs charge and bunch compression variations were not accounted for.

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