LONGITUDINAL BEAM DYNAMICS STUDIES FOR THE FERMI@ELETTRA LINAC

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Abstract

The stringent constraints on the electron beam parameters required by FERMI, such as emittance, pulse to pulse energy and current stability, as well as arrival time of the bunch at the input of the undulator chain, impose very stringent requirements on the parameters and operating conditions of the Linac accelerating sections. To address the problem, i.e. evaluating the operating conditions of the machine and the flexibility of the adopted layout, beam dynamics studies with the LiTrack code [1] have been performed. Here the results of different Linac settings as well as the allowed variations of the phase and amplitude of the accelerating RF field are presented and discussed.

INTRODUCTION

The machine [2] consists of an RF gun followed by two accelerating sections, four Linac stations L1 to L4, two bunch compressors BC1 and BC2, a laser heater and a spreader (Fig.1).

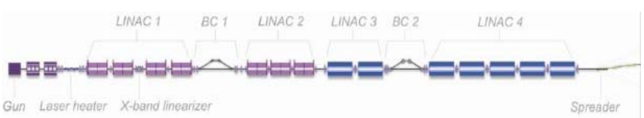

Figure 1: Linac layout

The energy of the electron beam at the L1 entrance is ~ 100 MeV with a peak current of 60-70 A. At the end of the acceleration chain the final energy is approximately 1.2 GeV and the electron peak current is 500 A or 800 A, depending on the bunch length needed for the FEL operating modes.

Table 1: Linac Section Parameters

Linacs	Quantity	ΔE(MeV)	Operaiting Margin %	Energy on crest (MeV)
L1, L2	7	55	15	329
L3, L4	7	140	14	840
X Band	1	0	0	-20

Table 2: Bunch compressors parameters

	Number of dipoles	Bending angle (rad)	Dipole Length (m)	Energy (MeV)	R56 (mm)
BC1	4	0.07	0.5	230	-2.87
BC2	4	0.05347	0.5	584	-1.67

The basic parameters for the Linac sections and bunch compressors BC1 and BC2 are given in Table 1 and Table 2. Nominal operating voltages and phases of the Linac stations are summarized in Table 3.

Table 3 : Nominal operating voltages and phase

Linacs	Voltages (MV)	Phase (deg)
Linac 1	47 x 4	-36
X Band	18	180
Linac 2	47 x 3	-20
Linac 3	120 x 2	-20
Linac 4	120 x 5	19

The beam parameters presented in this paper have been calculated with the LiTrack code for the Medium Length Bunch mode (MLB) with a bunch duration of 700 fs (rms), a peak current of 800 A (0.8 nC) and a final mean energy between 1.14 GeV and 1.2 GeV. At the Linac entrance a particle file with a ramped charge distribution is used to simulate the beam coming out of the photoinjector [3]. Table 4 summarizes the beam parameters at different locations along the Linac, and Figure 2 shows the nominal structure of the beam at the Linac exit.

Table 4 : Beam parameters

	σE/E	Emean (MeV)	σz (mm)	Peak current (KA)
L1 Entrance	0.6%	97	1.039	0.08
BC1 Entrance	2.67%	230	1.039	0.08
BC1 Exit	2.67%	230	0.270	0.3
BC2 Entrance	1.13%	584	0.270	0.29
BC2 Exit	1.13%	584	82	0.8
L4 Exit	0.1	1141	82	0.8

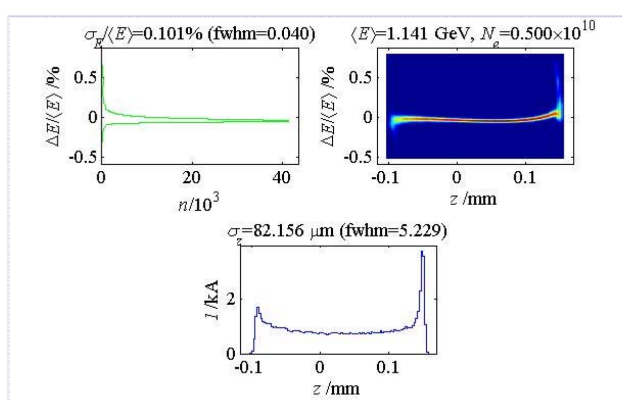

Figure 2: Nominal beam parameters at Linac exit

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Table 5: Simulated failures or power losses in the Linac sections

	C1	C2	XBand	C3	C4	C5	C6	C7	S1	S2	Linac 4 (S3 to S7)
Case 1	fault	fault	ok	ok	ok	ok	ok	ok	ok	ok	ok
Case 2	ok	ok	ok	fault	fault	ok	ok	ok	ok	ok	ok
Case 3	ok	ok	ok	ok	ok	fault	ok	ok	ok	ok	ok
Case 4	ok	ok	ok	ok	ok	ok	fault	fault	ok	ok	ok
Case 5	ok	ok	ok	ok	ok	ok	ok	ok	fault	ok	ok
Case 6	ok	ok	ok	ok	ok	ok	ok	ok	ok	fault	ok
Case 7	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	one section in fault
Case 8	-30%	-30%	ok	ok	ok	ok	ok	ok	ok	ok	ok
Case 9	ok	ok	ok	-30%	-30%	ok	ok	ok	ok	ok	ok
Case 10	ok	ok	ok	ok	ok	-30%	ok	ok	ok	ok	ok
Case 11	ok	ok	ok	ok	ok	ok	-30%	30%	ok	ok	ok
Case 12	ok	ok	ok	ok	ok	ok	ok	ok	-30%	ok	ok
Case 13	ok	ok	ok	ok	ok	ok	ok	ok	ok	-30%	ok
Case 14	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	-30% on one section

OPERATIONAL MACHINE SETTINGS

The FEL operation requires stringent specifications for the stability of the Linac output parameters such as mean energy, peak current and electron bunch arrival time. The Linac sensitivity and tolerance budget were studied and presented in a previous paper [4]; we refer to that work for details on these parameters.

To investigate the flexibility of the Linac layout, different operating cases have been analyzed and they are presented in Table 5. Each case takes into account the complete failure of one or more klystrons (case 1 to case 7) or a partial power loss (-30%) in one or more accelerating sections (case 8 to case 14).

For each situation we have defined a new machine setting (Table 6) in terms of voltages, phases and bunch compressor magnetic field. Each settings is optimized to obtain, at the Linac output, the nominal electron bunch parameters (in terms of bunch length, peak current, mean energy and energy spread) required for FEL operation, and reported in Table 4.

Table 6: Machine settings for the cases in Table 5

	L1		XBand		L2		L3		L4		BC1		BC2	
	V (MV)	Φ (deg)	V (MV)	Φ (deg)	V (MV)	Φ (deg)	V (MV)	Φ (deg)	V (MV)	Φ (deg)	R56 (mm)	E (MeV)	R56 (mm)	E (MeV)
Case 1	55x2	-46.5	10.4	180	53x3	-45.6	138x2	-27	139x5	22	-2.87	161	-1.67	515
Case 2	55x2	-46.5	10.4	180	53x3	-45.6	138x2	-27	139x5	22	-2.87	161	-1.67	515
Case 3	47x2	-36	18	180	50x2	-20	138x2	-20	130x5	19	-2.87	230	-1.67	565
Case 4	47x2	-36	18	180	47	-20	138x2	-18	135x5	15	-2.87	230	-1.67	518
Case 5	47x2	-36	18	180	50x3	-20	135	-10	135x5	8	-2.87	230	-1.67	500
Case 6	47x2	-36	18	180	50x3	-20	135	-10	135x5	8	-2.87	230	-1.67	500
Case 7	47x2	-36	18	180	50x3	-20	135	-22	135x5	16	-2.87	230	-1.67	618
Case 8	158	-39.5	13.4	180	50x3	-20	130x2	-25	120x5	16	-2.87	230	-1.67	577
Case 9	158	-39.5	13.4	180	50x3	-20	130x2	-25	120x5	16	-2.87	230	-1.67	577
Case 10	47x2	-36	18	180	126	-20	120x2	-20	120x5	19	-2.87	230	-1.67	570
Case 11	47x2	-36	18	180	111	-20	120x2	-20	120x5	19	-2.87	230	-1.67	556
Case 12	47x2	-36	18	180	47x3	-20	204	-20	120x5	16	-2.87	230	-1.67	551
Case 13	47x2	-36	18	180	47x3	-20	204	-20	120x5	16	-2.87	230	-1.67	551
Case 14	47x2	-36	18	180	47x3	-20	120x2	-20	564	16	-2.87	230	-1.67	551

The Linac is composed of 14 accelerating sections and an X-Band cavity. Each section is connected to a klystron as follows: in L1 the sections C1 and C2 are connected to klystron K3, C3 and C4 to klystron K4 and the X-Band is connected to Kx; in L2 the section C5 is driven by K5 and the sections C6, C7 by K6; in L3 section S1 and S2 are driven by K7 and K8, in L4 each section is connected to a klystron from K9 to K14. Matlab code has been developed to calculate the voltage and phase selections for each setting in Table 5. This code takes into account the failure or the power loss of a specified klystron, increases the voltage of the remaining working sections and varies their phases step by step as long as the nominal bunch parameters at the Linac exit are recovered.

Table 7: Main beam parameters for the machine settings in Table 6

	BC1 ENTRANCE			BC1 EXIT			BC2 ENTRANCE			BC2 EXIT			LINAC EXIT		
	σE/E %	σz (μm)	Peak current (kA)	σE/E %	σz (μm)	Peak current (kA)	σE/E %	σz (μm)	Peak current (kA)	σE/E %	σz (μm)	Peak current (kA)	σE/E %	σz (μm)	Peak current (kA)
Nominal	2.67	1039	0.08	2.67	270	0.3	1.13	270	0.3	1.13	82	3.8	0.1	82	3.8
Case 1	2.67	1039	0.08	2.57	298	0.26	1.36	298	0.26	1.36	73	3.9	0.1	73	3.9
Case 2	2.67	1039	0.08	2.67	298	0.26	1.36	298	0.26	1.36	73	3.9	0.1	73	3.9
Case 3	2.67	1039	0.08	2.67	270	0.3	1.15	270	0.3	1.15	80	3.8	0.1	80	3.8
Case 4	2.67	1039	0.08	2.67	270	0.3	1.17	270	0.3	1.17	77	4.1	0.1	77	4.1
Case 5	2.67	1039	0.08	2.67	270	0.3	1.17	270	0.3	1.17	82	3.8	0.1	82	3.8
Case 6	2.67	1039	0.08	2.67	270	0.3	1.17	270	0.3	1.17	82	3.8	0.1	82	3.8
Case 7	2.67	1039	0.08	2.69	270	0.29	1.17	270	0.29	1.17	82	3.8	0.1	82	3.8
Case 8	2.67	1039	0.08	2.69	264	0.29	1.12	2.64	0.29	1.12	78	3.96	0.1	78	3.96
Case 9	2.67	1039	0.08	2.67	264	0.3	1.12	2.64	0.3	1.12	78	3.96	0.1	78	3.96
Case 10	2.67	1039	0.08	2.67	270	0.3	1.14	270	0.3	1.14	80	3.8	0.1	80	3.8
Case 11	2.67	1039	0.08	2.67	270	0.3	1.16	270	0.3	1.16	78	3.96	0.1	78	3.96
Case 12	2.67	1039	0.08	2.67	270	0.3	1.16	270	0.3	1.16	77	3.99	0.1	77	3.99
Case 13	2.67	1039	0.08	2.67	270	0.3	1.16	270	0.3	1.16	77	3.99	0.1	77	3.99
Case 14	2.67	1039	0.08	2.67	270	0.3	1.13	270	0.3	1.13	82	3.8	0.1	82	3.8

Settings

The voltage and phase settings calculated for the cases presented in Table 5 are listed in Table 6. The beam parameters at the BC1 and BC2 locations and at Linac exit are reported in Table 7. In these calculations the specified klystron is assumed to be broken and the related sections are inoperative. To recover the final mean energy and bunch parameters required for FEL operation, we increase the voltage and optimize the phase of the remaining working Linac sections. The bunch compressor magnetic field is adjusted according to the electron energy at the entrance of the chicanes BC1 and BC2. In these simulations we keep the momentum compaction factor R56 of the bunch compressors at the nominal value given in Table 1. Since R56 is related to the magnet bending angle θ, the magnet length L_B and the projected distance ΔL between the first two magnets of the chicane, by the relation: $R56 = -2\theta^2(\Delta L + 2/3\ L_B)$, we adjust the magnetic field of the magnets composing the chicane and keep the bending angle θ at the nominal value given in Table 2. The quadratic energy time bunch correlation is corrected tuning the X-Band voltage. Cases 1 and 2 are the most critical since the energy of the electrons reaching the BC1 chicane (160 MeV) is much lower than the nominal value (230 MeV). At this low energy, space charge and coherent synchrotron radiation (CSR) could cause a beam emittance and energy spread blow up. Since the LiTrack code does not take into consideration these physical effects, further studies have to be performed with other tracking codes to evaluate CSR and space charge in the BC1 chicane at 160 MeV. Case 8 and 9, where section L1 works with less than 30% of the nominal power, are not so critical since the beam parameters at the BC1 entrance are comparable with the nominal values and no space charge or destructive CSR effects on the beam emittance and energy spread are expected. Failures in sections L2, L3 or L4 can be easily recovered by varying phase of the remaining operating sections and keeping L1 at the nominal values.

CONCLUSION

The FERMI@ELETTRA FEL project has been conceived as an user facility. For this reason the beam reliability is one of the most important requirement on the machine. Linac flexibility has been investigated in situations where klystrons do not operate in nominal conditions. Different cases have been studied assuming a full klystron drop-out or a 30% power deficiency. Simulations demonstrate in almost all cases that, there is the possibility to adapt the Linac settings in order to obtain final beam parameters appropriate to FEL operations. The most critical klystron failures are those related to section C1/C2 or C3/C4 (case 1 and case 2) in L1. In these cases, if one wishes to obtain the nominal beam parameter at the Linac exit, the voltage and phase in the remaining working sections must be varied significantly with respect to the nominal conditions. Since the attainable beam energy at BC1 is limited to 160 MeV, space charge or CSR effects must be studied in more detail in order to evaluate emittance blow up and energy spread increase.

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