DESIGN OPTIMIZATIONS OF X-RAY FEL FACILITY AT MIT

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Abstract

In recent years, a number of short wavelength FEL experiments have demonstrated key technologies and obtained good agreement between experiment and theory. The x-ray FEL at MIT[1] is one example of a design for a new generation linac-based light source. Such a new machine requires very high quality electron beams. Besides the usual requirements on beam quality such as emittance, energy spread, peak current, etc., there are new challenges emerging in the design studies, e.g., the precise arrival timing of electron beam at lower tens of femtoseconds level to ensure the laser seed overlap the desired sections of electron bunch in the multiple-stage HGHG process. In this paper we report the progress on design optimization towards high quality and low sensitivity beams.

INTRODUCTIONS

The proposed MIT x-ray laser incorporates design features that take advantage of many recent developments. It blends proven technologies into a powerful new instrument that combines the high power, coherence, and ultrashort timescale probe of a laser with the energy reach and spatial resolution of synchrotron x-rays. It is a primary goal to integrate the instruments and experimental methods from the laser and synchrotron radiation communities at the earliest stages of design. Integrated high-harmonic generation laser technology will seed the electron beam and generate photon beams with high longitudinal coherence and pulse lengths significantly below 100 femtoseconds, perhaps below 1 femtosecond. The FEL itself will use the high gain harmonic generation (HGHG) method to produce multiple harmonics of the tunable input seed. The output radiation has the full longitudinal and transverse coherence and stability of the seed laser, providing substantial improvement over performance based solely on SASE.

A sketch of linac layout is shown in Figure 1. The major components are the superconducting electron linac of length ~300 m, plus undulator tunnels and experimental halls. The production of x-ray laser pulse begins with generation of the electron beam in the RF photoinjector. The photoelectrons are produced by a conventional laser striking the photocathode contained in a high field RF cavity, producing 200 pC to 1 nC pulses that are about 10 to 25 picoseconds long. The superconducting linac will accelerate electron beam to up to 4 GeV energy. At about 200 MeV and 900 MeV, the beam enters the first and second magnetic chicane, which compress the pulse length to between 100 to 1000 femtoseconds and increase the bunch current from a few tens of amps to a few thousand amps.

Table 1: Parameters of electron beam

Final Beam energy	4 GeV
Bunch length	100 – 1000 fs
Normalized emit.	0.5-2 mm.mrad
Charge per bunch	200 – 1000 pc
Energy spread	0.01% (sliced)
Peak current	~ 1 - 2 kA

BEAM AND SEED LASER SYNCHRONIZATION REQUIREMENT

In FEL production with laser seeds, the arrival time of electron beam must be very precise to overlap the seed. The typical bunch length is between 100 and 1000 fs in new FEL facilities. The requirement of arrival timing of beam is even tougher in multi-stage HGHG process in which a single electron bunch may be used section by section in different stages. Figure 2 shows the time structure of an electron bunch in a typical multi-stage HGHG process.

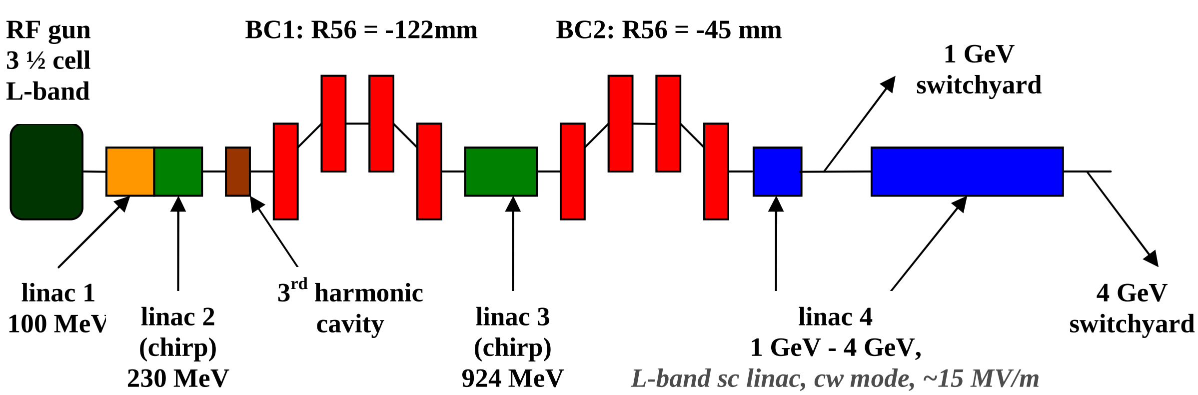


Figure 1: Layout of linac for the MIT x-ray FEL.

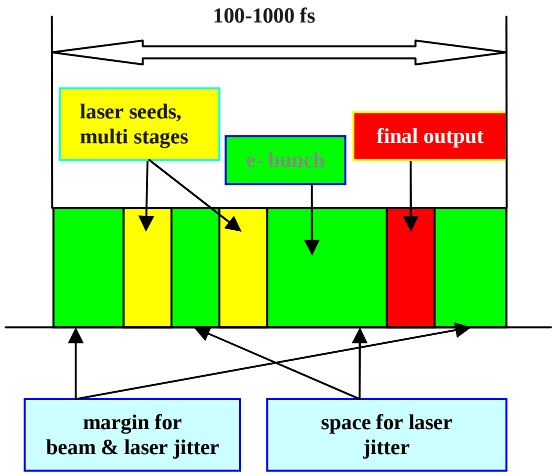


Figure 2: Arrival timing requirement of electron bunch and laser seed in the multi-stage HGHG process.

To ensure that the electron bunch and laser meet each other, the arrival times of both beams must be very precise, i.e., the arrival timing jitters are significantly shorter than the electron bunch length. When bunch length is between 100-200 femtoseconds, the arrival timing needs to be as precise as ~20 fs to efficiently utilize the full length of the electron bunch.

DESIGN OPTIMIZATIONS INCLUDING JITTER REQUIREMENTS

The unprecedented precision requirement for arrival time of electron bunches has become one of the most challenging issues in design studies of MIT x-ray FEL facility. For comparison two major ongoing x-ray FEL projects (LCLS and TESLA XFEL) [2] [3] have studied tolerance budgets for <12% rms peak-current jitter and 0.1% rms final electron energy jitter. By applying these tolerance budgets the resulting arrival time jitters of beam are at about 100 fs level. Our recent studies show that to limit arrival timing jitter to 20 fs level the requirements for RF phase and amplitude control can be quite strict. Hence in our recent design studies the arrival jitter issue is treated as an integral part of the optimization.

The arrival time jitter of electron bunch can be caused by various errors in accelerators. The analytical estimates work mainly for simple cases, for example, for a single bunch compressor or linac section.

$$\Delta t_i = \Delta t_{i-1} + \frac{1}{c}\left(\frac{\Delta E}{E}\right)_i R'_{56i} \qquad (1)$$

and

$$R'_{56i} = R_{56i} + 2T_{566i}\left(\frac{\Delta E}{E}\right)_i$$

$$\left(\frac{\Delta E}{E}\right)_i = \frac{E_{i-1}}{E_i}\left(\frac{\Delta E}{E}\right)_{i-1} - \frac{\Delta N}{N}\frac{\Delta E_{loadi}}{E_i} +$$

$$\left(1-\frac{E_{i-1}}{E_i}\right)\left[\frac{\cos(\varphi_i + \Delta\varphi + 2\pi c\Delta t_{i-1}/\lambda_i}{\cos(\varphi_i)} - 1\right]$$

$$\Delta E_{load_i} \approx \frac{1}{2}E_i \Delta z_i k_{w_i}$$

i denotes the current section of the linac, i-1 the previous section, Δt the timing error, $\Delta E/E$ the energy spread, ΔE_{load} the wake loading, φ the RF phase in linac, N the number of electrons.

In order to better understand the issue a fast optimization code [4] based on above simplified theoretical models is used. The sensitivities of arrival timing, as well as beam energy and peak current, to the major components in the linac are calculated in each iteration of the optimization. Figure 3 shows an example of the second chirp linac section. Figure 4 shows the typical beam characteristics at exit of the 4 GeV linac. The initial laser pulse length on the cathode is about 25 ps. The bunch charge is 1 nc. Table 2 and 3 show two sets of machine parameters that both fulfill the general beam quality requirements shown in Table 1 but have different sensitivities to the errors.

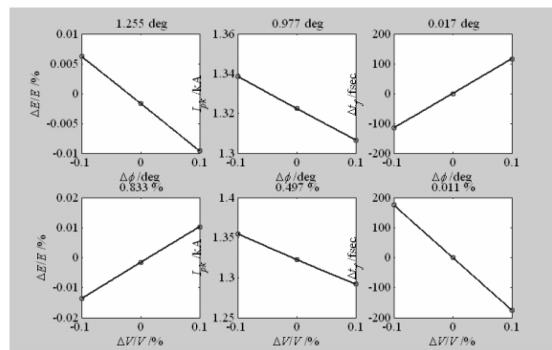


Figure 3: Sensitivities of beam quality to jitters in each section of linac (shown here is 2nd chirp linac section).

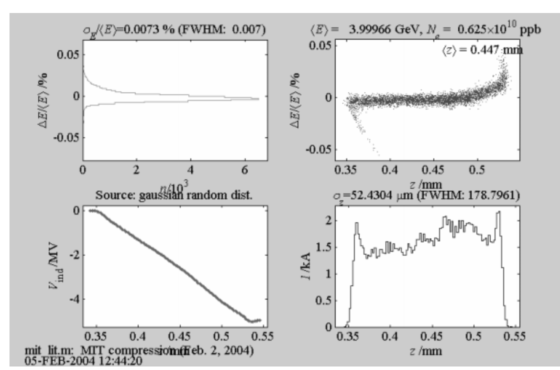


Figure 4: Typical beam characteristics from Litrack.

The sensitivities of beam quality to different parameters are calculated. See Table 4 and 5. Besides sensitivities to the change in energy (0.1%) and peak current(12%) the arrival timing requirement(20 fs) is also calculated and shown in the 5th column. The monitored parameters include initial charge variation, RF phase jitters in gun, four major linac sections and the 3rd harmonic cavity, Rf amplitude jitters in linac sections and the 3rd harmonic cavity. It is clear that the arrival timing jitter requirement has become the dominant factor. On the other hand one can see that the sensitivity can be significantly improved by optimizing the linac parameters. For example the requirement of RF phase control level in section 2 (the most sensitive one) is relaxed by a factor of two in the latter case.

Table 2 and 3: Two typical sets of parameters of linac

	E gain (MeV)	RF phase (deg)	R56 (mm)	Energy (MeV)
Linac 1	94.05	0.0		
Linac 2	138.414	-22.25		
3rd harm.	-27.913	-180		
BC 1			-129.6	194.423
Linac 3	814.47	13.18		
BC 2			-82.0	990.138
Linac 4	3012.3	-0.0005		

	E gain (MeV)	RF phase (deg)	R56 (mm)	Energy (MeV)
Linac 1	94.05	0.0		
Linac 2	128.46	-13.55		
3rd harm.	-24.8	-180		
BC 1			-223.9	200.1
Linac 3	741.25	-11.84		
BC 2			-47.5	924.57
Linac 4	3077.9	-0.0017		

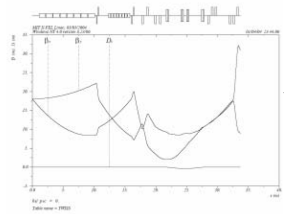
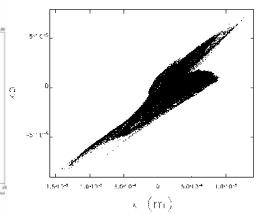
Table 4 and 5: Comparison of sensitivities of beam quality to various jitters in different sections of the linac

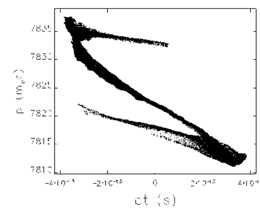
		dE/E	I_peak	dt/t
Gun	phase	17.7	1.2	1.2
	dQ/Q	107%	19%	3%
Linac 1	phase	2.8	0.062	0.499
	dV/V	0.7%	0.18%	0.006%
Linac 2	phase	0.66	0.034	0.006
	dV/V	0.55%	0.37%	0.005%
3rd har.	phase	3.9	0.071	0.842
	dV/V	2.5%	0.6%	0.02%
Linac 3	phase	1.1	1.4	0.02
	dV/V	0.47%	1.5%	0.009%
Linac 4	phase	2.8	-	-
	dV/V	0.13%	-	-

		dE/E	I_peak	dt/t
Gun	phase	12.6	1.3	1.9
	dQ/Q	161%	32%	3.5%
Linac 1	phase	3.7	0.068	0.518
	dV/V	1.1%	0.41%	0.007%
Linac 2	phase	1.67	0.046	0.012
	dV/V	0.79%	1.46%	0.005%
3rd har.	phase	4.1	0.087	1.0
	dV/V	3.9%	1.7%	0.025%
Linac 3	phase	1.5	1.7	0.045
	dV/V	0.54%	3.0%	0.016%
Linac 4	phase	2.5	-	-
	dV/V	0.13%	-	-

START-TO-END SIMULATION

To verify the results by the fast optimization code the start-to-end simulations have been conducted with more sophisticated simulation codes. The Parmela[5] is chosen for the photo-injector and low energy acceleration section where the space-charge effects play important role in the beam evolutions. For rest part of the linac the Elegant [6] is chosen as it includes some important effects like CSR (Coherent Synchrotron Radiation) and non-linearities, etc. The optics of chirp linac sections and bunch compressors are optimized to minimize the effects of CSR. Figure 6-8 show the beam distributions in transverse and longitudinal phase spaces at exit of the 4 GeV linac accelerator. Basically the start-to-end simulations confirm the results from fast optimization code. The evaluations of sensitivity to errors with start-to-end simulation are being conducted.



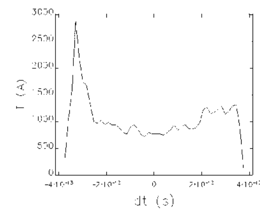


Figure 5 (top-left): Optics from linac2 to BC1.
Figure 6 (top-right): Transverse phase space at 4 GeV.
Figure 7 (bottom-left): Energy spread at 4 GeV.
Figure 8 (bottom-right): Beam current at 4 GeV.

SUMMARY

The requirements on electron quality become more demanding as the novel FEL schemes emerge. The accelerator design studies for the MIT x-ray FEL facility have been aiming at very high quality electron beams. Besides major important parameters common for most FEL facilities including emittance, energy spread, peak current and bunch structure, some new issues in seeding type x-ray FEL facilities are taken into account from the earliest stages of machine design. In jitter studies the very precise arrival timing requirement (~20 fs) for electron beam has become dominant factor. The optimizations have been conducted and preliminary results are very encouraging. More studies are underway.

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