COMMISSIONING OF S-BAND RF GUN AND LINAC FOR THE MARK-III FEL FACILITY AT DUKE UNIVERSITY

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Abstract

At the Free Electron Laser (FEL) Laboratory of Duke University, there is an S-band linac based Mark III FEL facility which can supply coherent FEL photon in the infrared wavelength range. To supply high quality electron beams and to have excellent pulse structure, we installed an S-band RF gun with a Lanthanum Hexaboride (LaB_6) single crystal cathode for the Mark III FEL facility in 2005. Its longest macropulse length is about 6 μs, and maximum repetition rates of a macropulse and a micropulse are 15 Hz and 2856 MHz, respectively. Therefore we can generate about 17142 bunches within a bunch train and about 257142 bunches within one second by the S-band gun. In this paper, we describe recent commissioning experiences of our newly installed S-band RF gun and linac for the Mark III FEL facility.

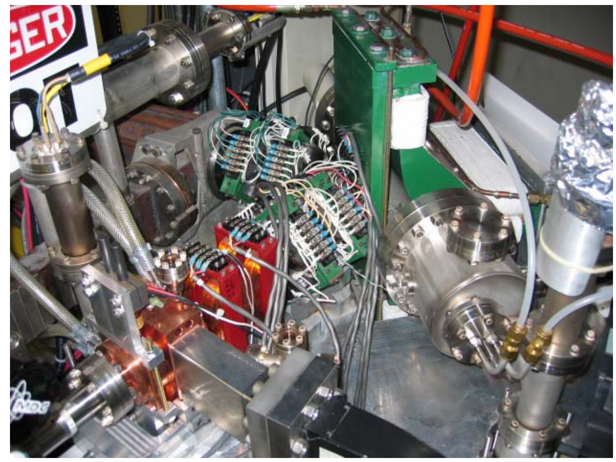

Figure 1: Photograph around the newly installed gun.

INTRODUCTION

The Mark III FEL is a wavelength-tunable light source facility which can generate coherent and ultra-bright FEL photon beams in the infrared wavelength range. Originally, the Mark III FEL facility was operated at Stanford University, then it was moved to Duke University in 1989 [1]. After relocating to Duke University, we had upgraded several machine components of the Mark III FEL facility [2], [3]. Recently, many FEL facilities started to use the laser driven RF photoinjector to generate high quality electron beams with a high peak current and a low transverse emittance. However, the laser driven RF photoinjector has a limitation to generate a good micropulse structure due to a low repetition rate of the gun driving laser. Since many users working for biophysical and biomedical science request high repetition rate of FEL photon beams, we have used an S-band thermionic RF gun with a LaB_6 cathode to supply excellent micropulse and macropulse structures [4]. After successful operation for several years, in 2003, we had met a strong back bombardment problem which caused malfunction of our gun [2], [5]. Therefore we re-installed a new S-band thermionic RF gun in 2005 to generate stable FEL photon beams continuously. In this paper, we describe our commissioning experiences of the new S-band RF gun and linac for the Mark III FEL facility.

LAYOUT OF GUN AND LINAC

The geometry and parameters of the newly installed gun are almost the same as those of our original gun. Its original shape and parameters can be found in reference [6] and [7]. In our new gun, we modified geometry of a deflection magnet and shifted its core position to backward by 3.175 mm for easy fabrication. Photograph around the new gun and layout of the Mark III FEL facility are shown in Figs. 1 and 2. And its main accelerator parameters are summarized in Table 1 where all emittances are estimated from ASTRA and ELEGANT simulations. As shown in Figs. 1 and 2, at the upstream of the gun cavity, there is the deflection magnet which bends electron beam orbit vertically to reduce the back bombardment on the LaB_6 cathode surface. At the downstream of the gun cavity, there are two vertical correctors to compensate vertically bended beam orbit which is intentionally generated by the deflection magnet. After those correctors, there is a quadrupole doublet (GQ1 and GQ2) and the first gun toroid (T1) to measure electron beam current in a macropulse or bunch train. Then electron beams are transferred to an α-magnet [8]. Since horizontal dispersion is not zero in the α-magnet, electron with a higher energy takes an outer or longer path, and electron with a lower energy takes an inner or shorter path in the α-magnet. In that manner, bunch length is compressed by the combined function of the nonzero momentum compaction factor R_{56} and nonzero energy spread in the α-magnet [6]. Since horizontal beam size becomes larger in the α-magnet due to nonzero dispersion as shown in Fig. 2, we chop tail or head part of electron beams by lower and higher energy filters to control beam energy spread, beam energy, and transverse emittance. Only electron beams which can go through two energy filters are transferred to linac [6]. Additionally, to supply macropulse with a frequency of 1 Hz,

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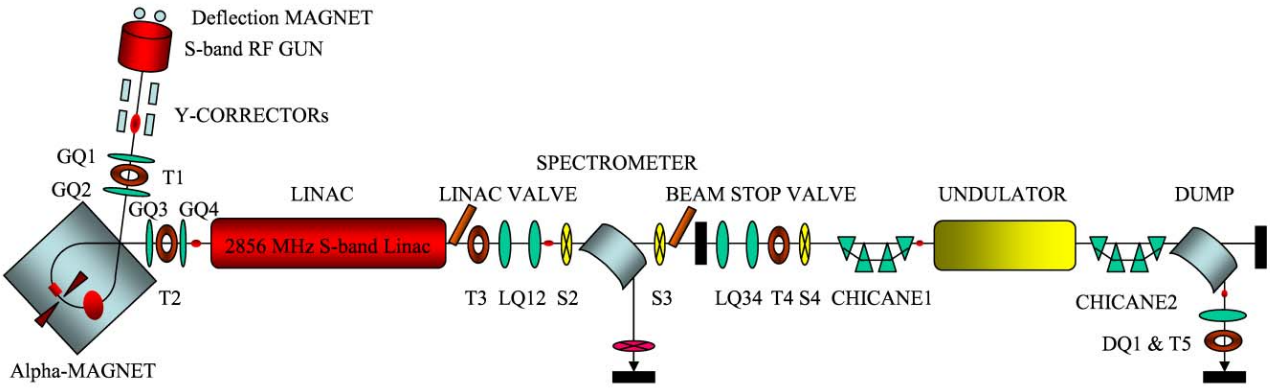

Figure 2: Layout of Mark III FEL Facility.

Table 1: Accelerator parameters of the Mark III FEL.

Parameter	Unit	Value
RF frequency of gun and linac	MHz	2856
number of gun cell	cell	1
cathode diameter	mm	1.75
cathode operation temperature	K	~ 1800
cathode energy spread	eV	~ 0.4
cathode work function	eV	2.69
cathode heater power	W	~ 11
operating vacuum in gun	Torr	$< 10^{-7}$
single bunch charge	nC	0.14
macropulse current at gun exit	mA	~ 400
macropulse current at α-magnet exit	mA	~ 180
klystron power	MW	30
gun forward RF power	MW	~ 1.8
max gradient on cathode	MV/m	~ 30
cavity cooling water temperature	deg	32.2
total beam energy at gun exit	MeV	~ 1.6
total beam energy at linac exit	MeV	$25 - 45$
beam energy spread at linac exit	%	0.3
peak current at linac exit	A	$15 - 45$
thermal emittance at cathode	μm	~ 0.35
projected emittance at linac exit	μm	~ 5
slice emittance at linac exit	μm	~ 1
macropulse length at linac exit	μs	$2 - 6$
max macropulse rate	Hz	15
micropulse length at linac exit	ps	$0.5 - 3$
micropulse rate	MHz	2856

there is a 11.5 kV kicker in the α-magnet. In this case, only one macropulse is transferred to linac in one second, and all other macropulses are dumped in the α-magnet by the kicker [6].

After the α-magnet, beams are focused by the second quadrupole doublet (GQ3 and GQ4). There are two toroids (T2 and T3) to measure beam current at the downstream of the α-magnet and linac. By accelerating electron beams with a 3 m long S-band accelerator, beam energy is increased up to about 45 MeV, and bunch length is more compressed to about 0.5 ps by the bunch compressor (CHICANE1). By optimizing two quadrupole doublets (LQ12 and LQ34) and steerers at the downstream of linac, we can get a beam waist in undulator which is helpful to increase interaction between electron beams and spontaneous emitted photon beams. After making the interaction to induce the microbunching in electron beams and lasing, electron beams are sent to the beam dump.

COMMISSIONING EXPERIENCES

To reduce space charge effects which increase transverse emittance and bunch length, we have to accelerate electron beams quickly in the gun cavity. By sending about 2 MW RF power to the gun cavity, electron beams can be accelerated to about 1.6 MeV in the gun. However, we could not send such a high power at the beginning stage of our commissioning due to too strong waveguide bangs, arcs, and poor vacuum at the gun region. Hence, first of all, we had to reduce gun reflected RF power by matching the resonance frequency of gun cavity with a driving RF frequency. By optimizing temperature of cavity cooling water, position of a gun cavity tuner, and position of the LaB_6 cathode, we could change volume of the gun cavity slightly, and we could get a best matched point which gives a minimum reflected RF power and the best beam emittance as shown in Fig. 3 [6]. Here the left means the head region of macropulse, and a large reflected RF power at the tail region was generated by a resonance frequency shift which was induced by the increased back bombardment and beam loading effect along the macropulse [5]. After reducing reflected power, by increasing gun forward power and macropulse length gently, we performed continuous gun cavity RF conditioning until we could get a stable vacuum status in gun region. Since gun reflected power is changed as forward RF power and macropulse length are increased, we had to re-optimize gun reflected RF power at a higher power and a longer macropulse. After performing continuous RF conditioning for three months, we could obtain required basic beam parameters for the Mark III FEL operation, and vacuum at gun region was also stabilized as shown in Fig. 5. Here macropulse length is about 6 μs, the maximum beam current in the macropulse is about 400 mA at T1, and its maximum beam current at T2 is about 180 mA as shown in Figs. 3 and 4.

Although we optimized the deflection magnet to reduce the back bombardment on the cathode surface, we could not avoid the problem completely when macropulse length was longer than about 2 μs and beam current at T1 was higher than about 200 mA. Therefore, as shown in Figs. 3 and 4, beam current at T1 was continuously increased along the macropulse, and a large spike was generated at the tail region of the reflected power due to the resonance frequency shift. Generally, electron emission rate from a thermionic cathode becomes higher as the gradient on the cathode surface is increased. This increased current density J_s can be described by the well-known Schottky equation which is given by

$$J_s = A \cdot T^2 \exp\left[-(\Phi - e\sqrt{eE_c/(4\pi\epsilon_0)}\,)/kT\right], \quad (1)$$

where $A = 120\ \mathrm{A}/(\mathrm{cm}^2 \cdot \mathrm{K}^2)$ is the Richardson constant, T is the cathode temperature, $\Phi = 2.69$ eV is the work function of the $\mathrm{LaB_6}$ cathode, $k = 8.62 \times 10^{-5}$ eV/K is the Boltzmann constant, and E_c is the external electric field on the cathode surface [6], [9]. Therefore there are two ways to obtain a higher beam current at T1. One way is increasing RF forward power while keeping cathode temperature at a low value. The other way is increasing cathode temperature while keeping RF forward power at a low value. According to our experience, the latter way was useful to reduce the back bombardment along the macropulse. Hence during commissioning, we operated our gun with a high cathode temperature of about 1800 K.

After considering beam loading effect and the higher beam current at the tail region, we had to send more higher RF forward power along the macropulse to get a uniform energy distribution. If gun reflected power is close to unbalanced shape as shown Fig. 3(top left), head and tail parts in the macropulse are chopped by two energy filters in the α-magnet, and pulse length after the magnet became shorter. Therefore we optimized reflected and forward power signals to have a good linearity along the macropulse as shown in Fig. 3(bottom left) and (bottom right). From the information on position of the lower energy filter and magnetic field of the α-magnet, we could estimate total electron beam energy E at the gun exit which is given by

$$E\,[\mathrm{MeV}] \simeq 0.511\sqrt{1 + (0.205 \cdot I_\alpha[\mathrm{A}])^2}\,, \quad (2)$$

where I_α is the current of a power supply for the α-magnet, and the lower energy filter is located at 16 mm. By scanning I_α and monitoring T2 signal, we could estimate the lowest and the highest beam energies as well as energy spread in the macropulse, which are useful for us to keep reproducibility of gun RF amplitude and phase. Since peak current and beam loss along linac were sensitive to I_α, a

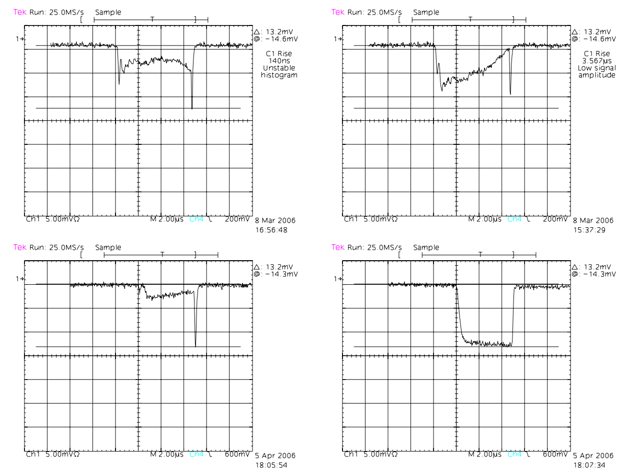

Figure 3: Signal of gun reflected RF power when reflected power are unbalanced at head and tail parts (top left), when head part has a high reflected power (top right), when reflected power is minimum and its slope along macropulse is optimized (bottom left), and signal of forward RF power when reflected power is optimized (bottom right).

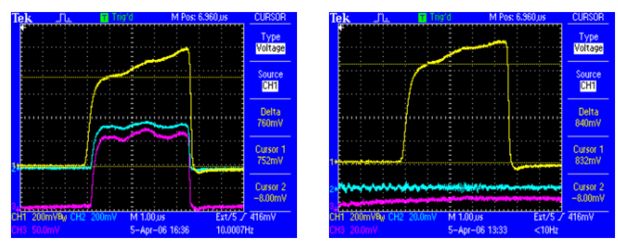

Figure 4: (left) signals of the first gun toroid (yellow), the second gun toroid (cyan), and linac toroid (magenta) when beam transmission from gun to linac and back bombardment along macropulse are optimized, (right) signal of the first gun toroid when there is no transmission in the α-magnet. Here calibration factors for T1, T2, and T3 are 0.4 A/V, 0.4 A/V, and 1.0 A/V, respectively.

fine tuning of I_α was also needed to get a lasing. After optimizing gun reflected power, quadrupoles, correctors, and the α-magnet properly, we could get about 45% transmission and a flat current distribution at the downstream of the α-magnet as shown in Fig. 4(left). If beam energy is too low or I_α is too high, we could not get any beam transmission at the α-magnet as shown in Fig. 4(right).

To optimize beam orbit and optics at gun and linac regions, we used signals from three radiation monitors which are distributed along linac. Although those signals were low during 1 Hz operation, they were significantly increased during 10 Hz operation as shown in Fig. 6. Due to the excellent pulse structures, those loss level were very high when beam orbit and optics at gun and linac region were slightly changed from a golden orbit and optics which give the minimum radiation loss and the best emittance for lasing. Therefore, we had to optimize all quadrupoles, steerers, and the α-magnet carefully to reduce those loss.

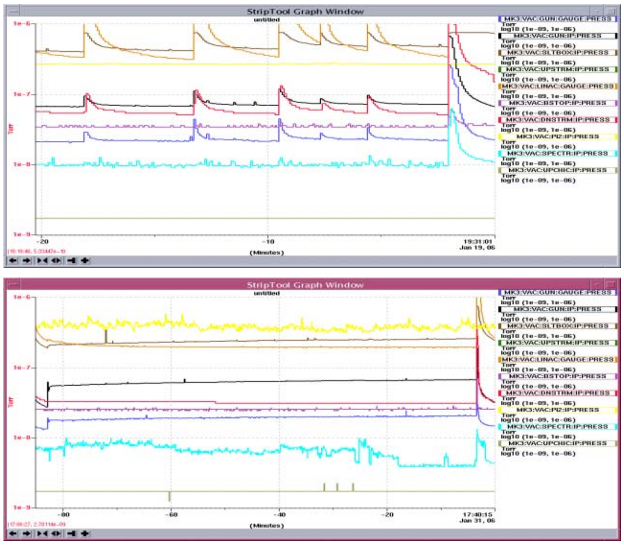

Figure 5: (top) spiky vacuum status on January 19, 2006 when gun generated 400 mA at T1 for the first time, (bottom) stabilized vacuum status on January 31, 2006 when gun generated 400 mA at T1 without any vacuum interlock for about 80 minutes.

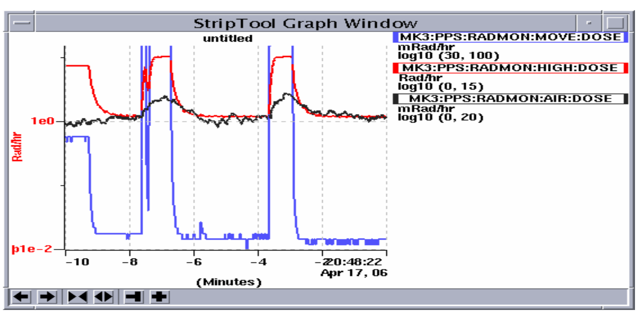

Figure 6: Signals of three radiation monitors along linac during 1 Hz and 10 Hz operations.

FUTURE UPGRADE PLANS

We are under developing and considering following upgrade plans to improve performance of the Mark III gun and linac. First of all, to keep electron beam current constant and to reduce the strong back bombardment problem, we need a real time cathode temperature monitoring system. By installing an infrared temperature detector and by giving a feedback to the power supply of a cathode heater, we can keep cathode temperature and beam current constant. And to remove the back bombardment problem completely, we are also under operating the other RF gun with the photoemission mode by shooting a Continuum Minilite-II Nd:YAG laser on the LaB_6 cathode surface [10]. Since the thermal emittance of the LaB_6 cathode is about 0.35 μm for a diameter of 1.75 mm, and quantum efficiency is about 0.05% at 266 nm, to improve transverse emittance, peak current, and energy spread more, we would like to use a high-class laser such an Nd:YLF laser whose the rms pulse length is about 4.4 ps, energy per a micropulse is about 1 μJ, and the maximum micropulse repetition rate is 9 MHz [11], [12]. This photoemission mode operation will be certainly helpful to increase the peak power of our Mark III FEL facility. Normally, electron beam quality and FEL performance are significantly changed even though RF amplitude and phase of gun and linac are slightly changed. Therefore we would like to develop a real time RF monitoring system to get a stable and reproducible FEL operation. And we want to develop an optical fiber based on-line beam loss monitor to stabilize beam orbit around undulator, which is certainly helpful to keep continuous and stable interaction between electron beams and spontaneous emitted photon beams in undulator. At the moment, we do not have a direct diagnostic tool to measure bunch length of about 0.5 ps long electron beam. To measure bunch length directly and to optimize FEL performance, we would like to install a small S-band deflection cavity in the near future. To control bunch length or peak current easily and to reduce geometrical wakefields and coherent synchrotron radiation, we are under developing a new bunch compressor with four electromagnetic dipoles. Now we are also under developing an emittance measurement system with a Flea digital camera of the Point Grey Research [13].

SUMMARY

By performing gun cavity RF conditioning for three months, we could get a stable vacuum status and required basic beam parameters. After optimizing reflected power, toroid signals, radiation loss along linac, and focusing around undulator, in January, 2006, we could send electron beams to the beam dump successfully. Since we could get a strong signal from a power meter in April, 2006, it is certain that our new gun and linac were optimized properly to generate FEL photon beams from our undulator. Authors thank to M. Pentico, O. Oakley, V. Rathbone, S. Huang, V. Popov, S. Mikhailov, and Y. Wu for their helpful comments and contributions for Mark III recommissioning project.

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