PRELIMINARY DESIGN OF A SYNCHRONIZED NARROW BANDWIDTH FEL FOR TAIWAN LIGHT SOURCE

W.K. Lau, J.R. Chen, T.C. Fan, F.Z. Hsiao, K.T. Hsu, C.S. Hwang, C.C. Kuo, G.H. Luo, D.J. Wang, J.P. Wang, M.H. Wang, NSRRC, Hsinchu, Taiwan
C.W. Chen, H.Y. Chen, NTHU, Hsinchu, Taiwan

Abstract

Design study for a narrow bandwidth, high power IR-FEL has been carried out at NSRRC. This device will be synchronized with the Taiwan Light Source (TLS) storage ring for two-colour experiments. Instead of using lower gradient super-conducting linacs at UHF frequency, it has been proposed to use a high gradient 1300 MHz TESLA super-conducting linac to accelerate a high average current electron beam up to 60 MeV to drive this FEL oscillator. To obtain narrow bandwidth, the beam is stretched in bunch length by using a chicane de-compressor before it passes through the U5 undulator of the FEL. Operating this linac in energy recovery mode is beneficial to improve system stability, wall-plug efficiency and to reduce neutron generation at beam dump. This device will be equipped with a low emittance injector for future upgrade towards shorter wavelengths. The ideas of the TESLA linac plus bunch stretcher scheme as well as a new type of low emittance high average current thermionic DC gun will be introduced in this report.

INTRODUCTION

Many high power THz and IR, FEL facilities that based on energy recovery linac (ERL) technology have been constructed [1-3]. Similar devices have been proposed and some are under construction [4-5]. Applications are mainly on photo-chemistry, isotope separation and material processing [6] etc.

TLS is a 1.5 GeV third generation storage ring synchrotron radiation source. It has been operating stably in the pass few years with high availability. The feasibility of building a high power IR FEL facility that will be synchronized with the synchrotron radiation from TLS beam-line is being discussed. It is believed that this facility will be a very valuable tool for local photo-chemistry and condensed matter research community. Some basic performance requirements as suggested by potential users are summarized as follows:

- Wavelength range: 2.5 ~ 10 μm
- Resolution: < 1 cm^{-1}
- Wavelength Stability: < 0.1 cm^{-1}
- High peak power
- Macro-pulse energy > 1 J/pulse
- Synchronize with TLS storage ring

Note that these requirements are actually quite similar to the FEL proposed for Chemical Dynamics Research Laboratory (CDRL) in 1992 at Berkeley [4]. However, as described in the later sections, we have a different approach. Figure 1 is a cartoon of the IR-FEL facility. Since the revolution frequency of the TLS storage ring is 2.4983 MHz, assuming that the storage ring is evenly filled with two electron bunches, the bunch crossing frequency is will be two times of the revolution frequency. Whereas the total number of rf buckets is 200. Continuous 4.9967 MHz IR pulses from the FEL oscillator will be synchronized with the synchrotron radiation from the U9 undulator in the TLS storage ring also at the same pulse repetition rate.

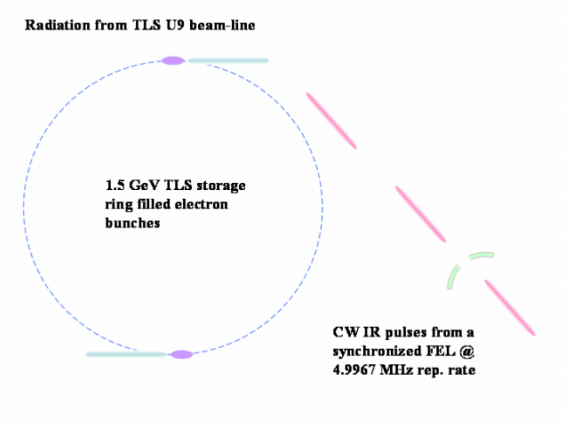

Figure 1: A cartoon showing the proposed IR-FEL in synchronization with the U9 radiation from the TLS storage ring

BASIC CONSIDERATIONS

Since the bandwidth of a linac-based FEL oscillator is just the Fourier transform of the electron bunch length [7], the choice of bunch length has to be consistent with the bandwidth requirement. To produce coherent infrared radiation at very narrow band-width, long bunch length is preferred. In our case, at 10 μm wavelength for example, the bandwidth according to users' wish list is better than 0.1%. Therefore, the required bunch length should be longer than 33 ps. Other means such as putting a grating in the optical cavity can be considered as further reduction in bandwidth. On the other hand, the injector should have significant peak beam current to get reasonable single pass gain to overcome total round trip loss in the optical cavity, but available bunch current is limited by total bunch charge provided the injector. For a fixed amount of bunch charge, as the bunch length become longer, the achievable peak current would be lowered. Therefore, an injector for high bunch charge is necessary. Although the emittance requirement of an IR-FEL is not too stringent, we would also like to have a lower emittance injector so that upgrade for shorter wavelengths will be possible.

For high power operation, the choice of using super-conducting is natural. Furthermore, it also provides good stability because of its slow response time to external perturbations. To avoid the effect of Lorentz detuning, it is advantageous to employ the energy recovery concept and operate the super-conducting linac at CW mode (i.e. Energy Recovery Linac, ERL). ERL also helps to improve wall-plug efficiency and reduce neutron production at the beam dump. Since we are pursuing a relatively long bunch, it seems straight forward to use lower frequency linac (e.g. 500 MHz) to accelerate the beam to nominal beam energy without much degradation in energy spread. However, the gradient for such linacs are much lower than that for higher frequency linacs. For example, the TESLA linac has a record gradient of 35 MV/m [8] whereas a typical gradient of a few hundreds MHz linac is ~5 MV/m. But to accelerate such a long bunch with higher frequency linac, larger beam energy spread is expected due to the rf curvature. An alternative solution is to accelerate a short bunch electron beam to nominal energy with higher frequency linac and followed by a bunch de-compressor to elongate the bunch to specified beam length. Such scheme is in principle feasible except the beam current in the linac will be much higher. Longitudinal phase space manipulation and beam instability that may be excited in the ERL has to be treated carefully.

THE FEL OSCILLATOR

As an initial study, a single undulator FEL oscillator configuration is considered. And the parameters of the U5 undulator as described in the Berkeley CDRL IR-FEL design report [4]. It is a 40-period undulator with period length of 5 cm. The peak magnetic field is 0.45 T. The gap is adjustable from 23 mm to 36.5 mm. It provides a deflection parameter setting ranging from 0.9 to 2.1. The electron beam energy is set at 60 MeV based on the FEL resonant condition for planar undulator. An undulator with shorter period length helps to reduce beam energy. However, a narrow undulator gap (e.g. 12 mm) is required for operation in wavelength range from 2.5 to 10 μm. In the U3 case, operation at wavelength longer than 10 μm will be limited by the interception between the optical beam and narrow vacuum chamber. The optical cavity is a 30 m confocal configuration with a hole on one mirror for outcoupling of laser power. The choice of cavity length is determined by the micropulse repetition rate. The Rayleigh length of this optical cavity is chosen at half of the undulator length and a total round trip loss of 10% is assumed.

To meet those performance requirements as stated in the last section, some basic design parameters for the IR-FEL are listed in the following table and the electron beam parameters are listed in next section:

Table 1: Basic Design Parameters for the NSRRC IR-FEL

Wavelength [μm]	2.5~10
Bandwidth	0.1 % @ 10 μm (transform limited)
Micro-pulse peak power [MW]	16
Micro-pulse duration [ps]	33
Micro-pulse rep. rate [MHz]	4.996
Minimum Macro-pulse [ms]	> 10
CW mode operation	yes

Tuning of the laser wavelength is of critical importance to users. Interruptions to the users during tuning should be minimized. As depicted in Figure 2, wavelength tuning from 2.5 to 10 μm is unavoidably required a change in driver accelerator operation state. However, change of accelerator system energy and optimize all parameters for FEL lasing without much disturbance to the users is not an easy task. This is especially true for ERL.

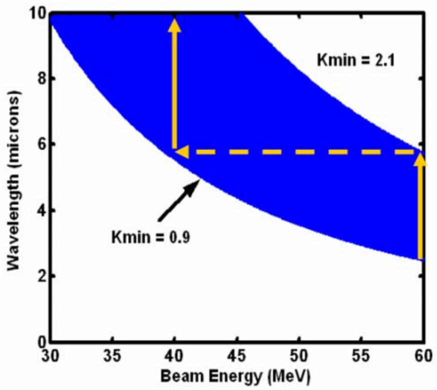

Figure 2: Wavelength tuning of the IR-FEL oscillator using U5 undulator

The use of a planar in-vacuo super-conducting elliptically polarized undulators with period length of 5 cm (SEPU5) is being study. At 100 MeV, the undulator is continuously tuneable from 1 to 10 μm without changing the electron beam energy. And the polarization of the laser field is also tuneable [9].

ACCELERATOR SYSTEM

In designing the accelerator system as a driver for the FEL, the 1300 MHz TTF SC linac is used as an example simply because it has a record high gradient of 35 MV/m. However, the linac is decided to operate at 15 MV/m for reasonably low cryo-load. Since the revolution frequency for TLS storage ring is 2.49833 MHz, the linac cavity frequency has to be multiples of the revolution frequency. The closest multiple to the TESLA linac cavity is 520. That is, the desired cavity frequency is 1299.13 MHz. The resonant frequencies of the cavities have to be adjusted to this value during fabrication [10]. The TESLA cryo-

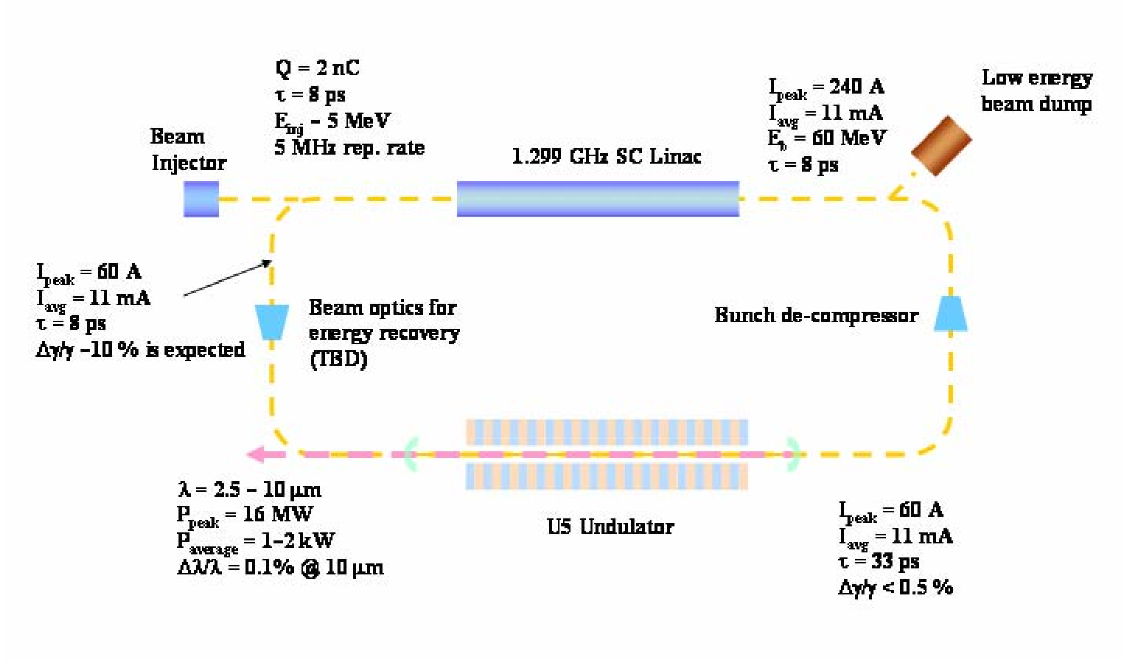

Figure 3: Layout of the ERL with bunch de-compressor before undulator

module consists of eight cavities and each cavity has 9 cells [11]. We hope we will have one such module in the system provide an energy gain of 120 MeV. The above FEL design parameters are based on a beam with following properties:

Table 2: Expected Electron Beam Parameters

Maximum beam energy [MeV]	60
Bunch current [A]	30-60
Beam average current [mA]	11
Bunch charge [nC]	> 2
Bunch length [ps]	> 33
Bunch rep. rate [MHz]	4.9967
FWHM energy spread	< 0.5%
RMS normalized emittance [mm-mrad]	< 25

A possible layout of the driver accelerator for the FEL oscillator is depicted in Figure 3. The beam injector provides a ~5 MeV beam with bunch charge of 2 nC. And bunch length is adjusted to about 8 ps before injection to the main linac. Since bunch repetition rate of the beam is about 5 MHz (two symmetrical filled bunches). Hence, the average current of the beam provided by the injector will be 11 mA. After the main linac, the beam is accelerated to 60 MeV. The expected energy spread induced by the linac is about 0.2 %. It is much lower than the allowable beam energy spread for the FEL interaction. The bunch de-compressor will be designed to expand the bunch by four times. In the first stage of the proposed project, the FEL will be operated at low macro-pulse repetition rate without energy recovery. Design of the return arc in the ERL that will remains as a challenge for future CW operation.

Two types of cathode technologies are being studied. That is, the photo-cathode DC gun and the CeB_6 cathode DC gun. For the photo-cathode dc gun which operates routinely at JLab's IR-FEL, the repetition rate is high but it provides only 135 pC bunch charge. Also, the GaAs cathode has to work in ultra-high vacuum environment of 10^{-12} torr. A high power mode-lock laser and special technique in treating the cathode are also required. The CeB_6 crystal cathode in the electron gun developed at Spring8 for the SCSS project is pulsed at -500 kV for 3 µs. And the repetition rate is at 60 Hz. In spite of its low duty factor, it has the advantages of low emittance, long lifetime and ultra-high vacuum is not essential. The measured normalized emittance of this gun is 1.1 π mm-mrad at 1 A beam current [12]. It has been discussed whether this type of electron gun can be built for high average current operation. Operation at lower cathode voltage for DC mode operation without causing breakdown is possible. For example, the cathode voltage can be set at -100 kV. A control grid can be added to pulse the beam at 5 MHz repetition rate (Figure 4). It allows an average beam current of 11 mA [13]. Preliminary EGUN simulation results showed that by changing the control grid voltage, emittance degradation due to space charge can be compensated by the focusing field near the grid.

It has been discussed in house that some users may find applications in the UV range with wavelength less than 200 nm. In such wavelength range, single pass high gain FEL can be used. The high gradient SC linac plus bunch de-compressor scheme allows easy beam energy upgrade just by adding more cryo-modules into the system. The de-compressor can be converted into compressor for single pass high gain FEL operation. At such beam energy, ERL is of essential importance in relaxing rf power requirement.

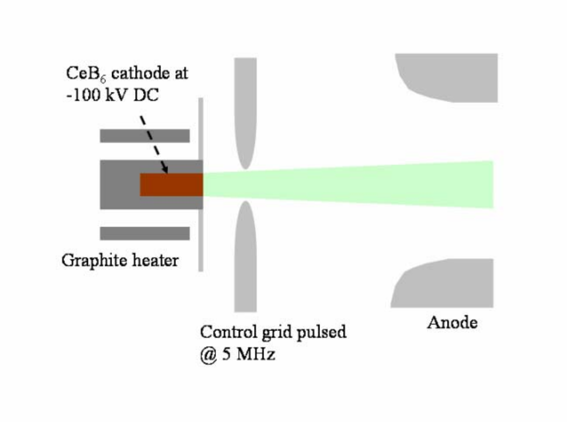

Figure 4: A CeB_6 cathode DC gun with control grid

SUMMARY

The feasibility of using the TESLA high gradient field super-conducting linac plus a bunch de-compressor to drive IR-FEL oscillator for a narrow bandwidth is being investigated. Further studies includes: the design of a low emittance high average current injector that based on CeB_6 cathode technology and beam transport system for energy recovery.

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