STATUS OF THE ALICE IR-FEL

J.A. Clarke, D.J. Dunning, S. Leonard†, A.D. Smith, M. Surman, and N.R. Thompson, ASTeC,
STFC Daresbury Laboratory & The Cockcroft Institute, UK.
† also at University of Manchester, UK.

Abstract

An infra-red (IR) oscillator FEL was installed into the accelerator test facility, ALICE, at Daresbury Laboratory at the end of 2009. The FEL will be used to study energy recovery performance with a disrupted, large energy spread, beam and also to test novel FEL concepts. This paper will describe the installed hardware, the pre-alignment techniques that have been employed, the diagnostics that are being used to detect the IR output, and the progress with commissioning of the FEL itself.

INTRODUCTION

An IR oscillator FEL has recently been installed into ALICE, the superconducting energy recovery linac accelerator test facility at Daresbury Laboratory. The key purpose of the FEL is to induce large energy spread (several %) into the electron beam in order to confirm that the transport optics design of the ALICE return arc is robust with very low particle loss, as required by a high beam power energy recovery facility. A secondary function of the FEL has been to strengthen the direct experimental skills of UK scientists in this research area, both in terms of commissioning an FEL and in using the generated output for a select experimental programme.

ALICE itself has been developed over a number of years, with the latest status being reported in [1]. Whilst the majority of the ALICE design parameters have been demonstrated, the standard energy recovery operating mode typically runs with parameters somewhat relaxed from these. This naturally has implications for the FEL performance [2]. A summary of the parameters relevant to the FEL are given in Table 1.

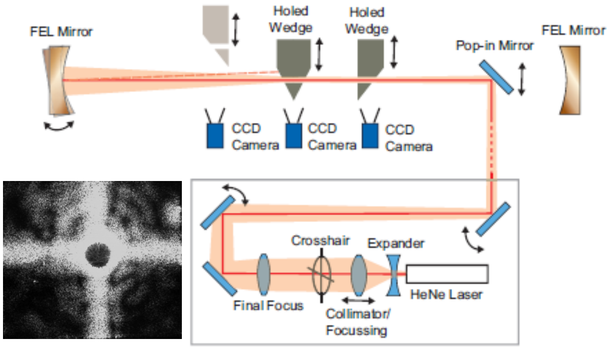

Figure 1: Schematic of the systems used for alignment of the FEL optical cavity. The inset picture shows the actual laser image with cross hair on one of the wedges.

Table 1: Comparison of the ALICE FEL design parameters with those used during recent commissioning.

Parameter	Design Value	Operational Value
Energy (MeV)	35.0	27.5
Bunch Charge (pC)	80	40
Normalised Emittance (mm-mrad)	10	~12
Bunch Length, FWHM (ps)	1.4	<2
Energy Spread, FWHM (%)	0.25	~0.7
Max. Train Length (μs)	100	100
Bunch Repetition Rate (MHz)	81.25	81.25
Max Number of Bunches per Train	8125	8125
Cavity Length (m)	9.224	9.224
Cavity Mirror ROC (m)	4.75	5.01±0.25
Single Pass Gain (%)	86	18

FEL HARDWARE

The FEL equipment was assembled offline prior to installation during December 2009. The undulator, which is on loan from Jefferson Laboratory where it was previously used for the IR-DEMO FEL project, has been converted from a fixed-gap to a variable gap device to allow an increased wavelength tuning range, with a full range of ~4 – 12 μm achievable through gap tuning (with undulator parameter, $K = 0.7 - 1.0$) and electron beam energy tuning (24 – 35 MeV). Magnet measurements of the undulator before and after conversion have confirmed that the magnetic field strength and quality is essentially unchanged. The undulator vessel, also on loan from Jefferson Laboratory, incorporates three beryllium wedges (see Figure 1) that are integral to our alignment strategy. Each wedge has a 1 mm diameter hole which is used to define the FEL axis. A HeNe laser and photodiode combined with a laser tracker were used to align the three wedges to the magnetic axis of the undulator.

The cavity mirror vacuum vessels and motion systems were supplied on loan by LURE where they were used successfully for a number of years on the CLIO FEL. Both the upstream and downstream vessels provide pitch and yaw motion of the mirror and the downstream one additionally provides cavity length adjustment. The mirrors themselves have a diameter of 38 mm and are made from a copper substrate with a gold coating. The installed upstream mirror has no outcoupling hole and the downstream mirror has a 3 mm diameter outcoupling hole on axis.

To detect the spontaneous IR radiation generated by the undulator a Mercury Cadmium Telluride (MCT) detector operated at liquid nitrogen temperatures was installed beyond the downstream cavity mirror. A pair of 45° mirrors allow the detector to be mounted below beam height. A flip mirror allows this light to be diverted to an IR spectrometer instead so that the undulator spectrum can be determined to ensure it has the expected narrow width. The spectrometer is based upon a Czerny Turner monochromator and a second MCT detector.

COMMISSIONING OF THE FEL

Pre-alignment

Once the hardware systems were installed (except for the upstream mirror) a theodolite was temporarily aligned using an accurate crosshair target mounted on the upstream exit flange of the cavity such that a line of sight was visible through the entire FEL cavity vacuum system. This technique confirmed that the downstream mirror exit hole was on the FEL axis, as were the three alignment wedges within the undulator vessel.

To pre-align the resonator mirrors in terms of pitch and yaw a permanently installed HeNe laser alignment module has been developed, as illustrated in Figure 1. The HeNe is injected into the cavity via a 45° pop-in mirror and aligned with the holes in the wedges by use of remotely steerable mirrors on the alignment module. The HeNe beam can be brought to a 1 mm focal spot at the wedges with the moveable focussing lens, and the diffraction pattern from a cross-hair target inserted into the HeNe beam provides a useful aid for more precise centering of the HeNe beam on the holes in the wedges. The HeNe beam image as focussed to one of the wedges within the undulator is also shown in Figure 1. Once the HeNe beam is correctly aligned with the two relevant wedges, the resonator mirror is adjusted until the reflected HeNe beam is centred on the back face of the central wedge. An identical system is provided at the other end of the cavity for alignment of the other resonator mirror. This system has proven to be extremely effective (and repeatable) for the angular alignment of the cavity mirrors.

The cavity length was set to the reference value by a laser tracker system using external targets on the cavity mirror vessels. These targets were previously set with respect to the cavity mirror faces before final assembly.

Electron Beam Set-up

The FEL undulator vessel has a full horizontal internal aperture of only 9.2 mm, making it the narrowest aperture within the ALICE facility and so a likely source of electron beam loss. Following installation of the FEL the electron beam was carefully steered and focussed through this vessel to minimise the losses. It has been found to be possible to transport the full 100 µs, 40 pC per bunch, electron beam macropulse around ALICE without loss and to operate with full energy recovery. The beryllium wedges are used routinely (with short bunch trains) to ensure that the electron beam is correctly focussed and steered onto the FEL axis. When the wedges intercept the electron beam the local radiation level in the vicinity of the undulator rises significantly. Similarly, a poor electron beam steering setup generates significant radiation levels at the undulator. It is potentially possible for this radiation to damage the NdFeB permanent magnet blocks of the undulator. For this reason the radiation levels are carefully monitored and recorded in the vicinity of the undulator. Initially TLD monitors were attached to different parts of the undulator as a cross-calibration for the permanently installed monitors. These confirmed that the greatest radiation dose is received at the undulator entrance where the vessel first narrows, as expected. It is reassuring that the magnetic measurements of the undulator made at Daresbury on receipt from Jefferson Lab showed that there was no measureable change in the magnetic field following its successful use on the IR-DEMO FEL.

IR Output Measurements

Once the electron beam steering was established the undulator gap was closed to 13.1 mm and the MCT detector was used to observe the IR output. Following remote optimisation of the beamline mirror and lens steering a clear signal was detected from the MCT (see Figure 2). The signal reduced by an order of magnitude when the circulation of the photons within the optical cavity was deliberately prevented. This clearly demonstrated that the initial cavity mirror alignment was excellent as the photon beam had been stored within the cavity without any need for further adjustments.

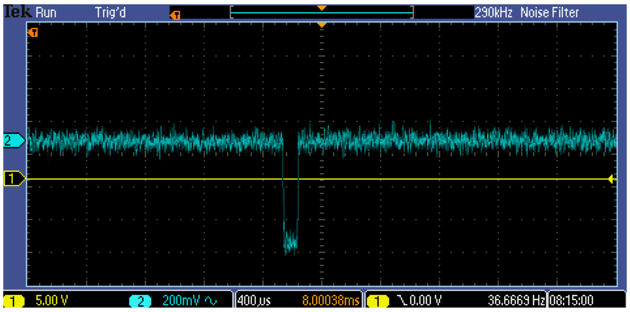

Figure 2: Early oscilloscope trace from the MCT. The negative going pulse is due to the MCT responding to the spontaneous IR radiation stored within the cavity. The pulse length of 100 µs corresponds to the train length.

At this point efforts were made to set the correct cavity length for the FEL by looking for enhancement of the MCT signal as the downstream cavity mirror position was altered longitudinally. No enhancement was observed at this stage and so efforts were made to examine the spectrum of the spontaneous output to ensure it was as predicted.

The flip mirror was used to divert the IR light to the spectrometer. A signal was detected at the exit of the spectrometer and this was optimised by careful steering and focussing of the light onto the entrance slit. The spectral width for the ALICE FEL is dominated by the number of undulator periods (40), the energy spread of the beam, and the field errors in the undulator magnetic field. The minimum FWHM width of the undulator spectrum at 8 µm wavelength was anticipated to be 3.0%. The first spectra recorded are shown in Figure 3. These show how the spectral width and the peak wavelength is minimised when the electron beam is steered to the FEL axis (x = 0), as expected. In this case the FWHM of the spectrum was 3.7%.

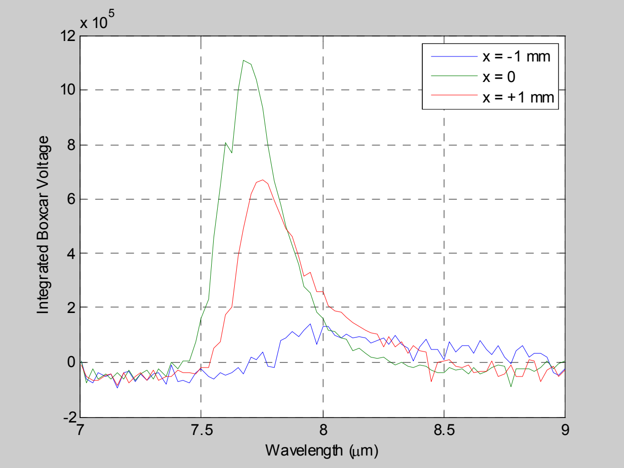

Figure 3: Spectrum of spontaneous undulator radiation as a function of different horizontal steering through the undulator. The beam is steered to the FEL axis at x = 0.

The spectrum as a function of linac phase is shown in Figure 4. This illustrates how the spectral width increases as the electron beam is accelerated further off crest due to the subsequent increase in electron bunch energy spread.

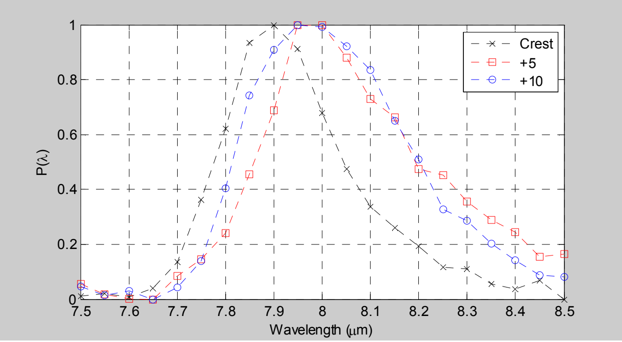

Figure 4: Spectrum of spontaneous undulator radiation as a function of linac phase (in degrees). The energy spread is minimised when the linac is on crest and so the spectrum is narrowest (FWHM = 3.4%).

During the commissioning of the FEL the width of the spectrum has been observed to be significantly less than the anticipated minimum value of 3.0%. In addition, side-band structure has also been observed occasionally. Two examples are given in Figure 5. An unequivocal explanation of these results is not yet forthcoming but it would appear to be correlated with the longitudinal phase space of the electron bunch and so it is thought that these effects are due to coherent behaviour within the optical cavity.

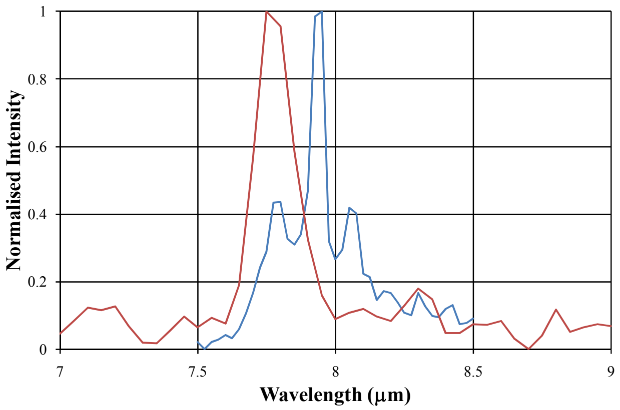

Figure 5: Two example spectra obtained during the commissioning that have very narrow bandwidth compared with the expected FWHM value of 3% (0.24 µm).

Further evidence of coherent effects within the cavity have been observed when scanning the cavity length to find the correct value for lasing. With the spectrometer set at a fixed wavelength (on the falling edge of the spectrum at a wavelength longer than the peak output value) the cavity length has been scanned on several occasions. Periodic oscillations in the output intensity are observed which are thought to be due to successive photon bunches interfering within the cavity, demonstrating good pulse to pulse phase coherence. Similar results have been observed elsewhere [3]. Since the wavelength is 8 µm it would be expected that the period observed should be 4 µm as the round trip length of the cavity is double the mirror movement. Strong oscillations with this period have indeed been observed (Figure 6). Interestingly, a number of other features are apparent when the cavity length is changed with very fine resolution. Every 4 µm there appears to be a few strong peaks and within these peaks there are number of fine oscillations which are separated by ~0.05 µm. The source of this fine structure is not clear.

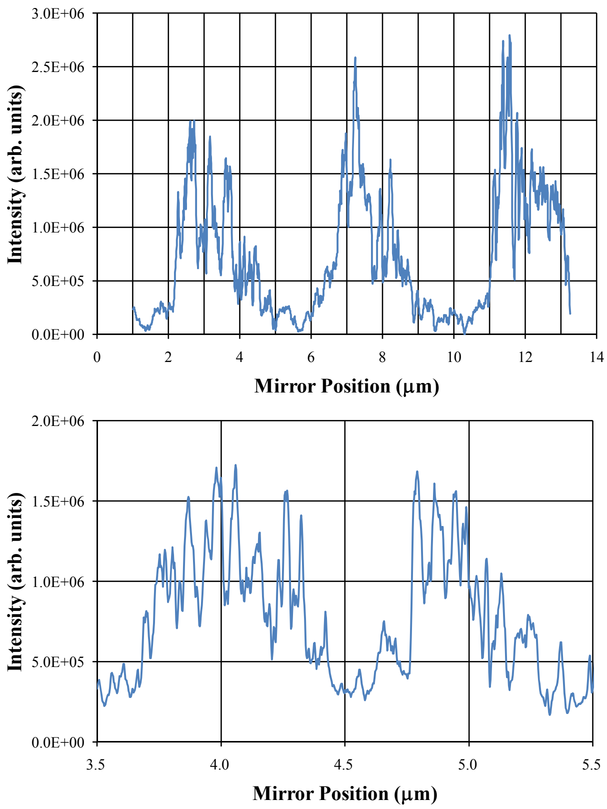

Figure 6: Output at a fixed wavelength as a function of the cavity length. The top figure shows the main peaks are separated by half the wavelength and the bottom figure, taken with finer resolution, shows the many oscillations within the main peaks.

CONCLUSIONS AND FUTURE WORK

The ALICE FEL has been successfully assembled and installed into the energy recovery test accelerator. The pre-alignment strategies employed have been extremely helpful in ensuring that the electron, optical, and magnetic axes are all overlapping prior to full beam commissioning. Although lasing has yet to be achieved a tremendous amount of progress has been made in the short time since installation. The electron beam can be transported through the narrow undulator vessel without any impact on the 100% energy recovery of the accelerator. Spontaneous radiation from the undulator has been detected and the IR was in fact immediately stored within the optical cavity. The spectrum of the radiation from the undulator has the expected profile, in general, and the collection of spectral data has provided valuable information about the electron beam alignment and energy spread. Interesting longitudinal effects have been observed both in the output spectrum and the intensity as a function of cavity length. These suggest that interference effects between photon bunches within the cavity are taking place which provides encouragement regarding the setting of the exact cavity length.

Since the predicted gain with the present ALICE setup is lower than originally anticipated the downstream mirror has recently been changed for one with a smaller outcoupling hole (1.5 mm diameter instead of 3 mm) to reduce the cavity losses. In addition, a number of hardware changes will be implemented which will allow the bunch charge to be increased. The beam loading within the booster cavity is thought to be the main limitation to the bunch charge and so a digital low level RF system will be installed which incorporates adaptive feed forward to compensate for this effect. Initial trials of the system have already been carried out with very encouraging results. Additionally, a new photoinjector laser pulse chopper system has been procured which will allow the bunch repetition rate within the macropulse to be reduced by a factor of five. This will again combat the effect of beam loading allowing higher bunch charge but will not affect the FEL performance since the bunches within the cavity only overlap every fifth bunch.

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