STATUS OF THE ALICE IR-FEL: FROM ERL DEMONSTRATOR TO USER FACILITY

N.R. Thompson[1], J.A. Clarke[1], T. Craig[2], D.J. Dunning[1], O.V. Kolosov[3], A. Moss[1], Y.M. Saveliev[1], M.R.F. Siggel-King[1,2], M. Surman[1], P.D. Tovee[3], P. Weightman[2]

[1]Accelerator Science and Technology Centre (ASTeC), STFC Daresbury Laboratory, UK
[2]Department of Physics, The University of Liverpool, L69 3BX, UK
[3]Department of Physics, Lancaster University, LA1 4YB, UK

Abstract

The ALICE (Accelerators and Lasers In Combined Experiments) accelerator at STFC Daresbury Laboratory in the UK was conceived in 2003. It was constructed as a short-term Energy Recovery Linac (ERL) demonstrator to develop the underpinning technology and expertise required for a proposed 600MeV ERL-based FEL facility. In this paper we present an update on the performance and status of ALICE which now operates as a funded IR-FEL user facility. We discuss the technological challenges of evolving a short-term demonstrator into a stable, reliable user facility and present a summary of the current scientific programme.

BRIEF HISTORY OF ALICE

In 2000 a proposal was developed at Daresbury Laboratory for 4GLS, a combined XUV/VUV/IR FEL facility driven by a 600MeV ERL [1]. This was to be a complementary photon source to the hard and soft X-ray sources of the ESRF and Diamond Light Source respectively. In 2003 funding was obtained to build a lower energy prototype, ERLP, to enable development of the underpinning technologies and expertise: assembling and operating TESLA cavities and cryomodules; operation of an ERL and associated RF, synchronisation and optics; photoinjector technologies; FEL techniques and operation; longitudinal beam dynamics and simulation; and diagnostic techniques and instrumentation. ERLP was sited in reused experimental areas, leading to some layout restrictions. The project benefitted greatly from collaboration with Jefferson Laboratory. In particular, the 350kV DC photocathode gun was based on the JLab design and a number of quadrupole magnets and chicane assemblies were provided on loan. The FEL wiggler had previously been used on the JLab IR-Demo FEL [2] and was re-engineered for variable gap operation. The FEL mirror cavities were loaned by LURE where they had previously been used on the CLIO FEL. The intention was to run ERLP for two years as an accelerator test facility before decommissioning.

Procurement and construction began through 2004/5. First beam from the gun was in August 2006 followed by a period of commissioning using a dedicated gun diagnostic beamline. 2007 was a challenging year: the gun suffered from strong field emission, rapidly deteriorating QE, mechanical failure inside the cathode ball, conditioning resistor failure and vacuum leaks. Nevertheless, by the end of 2007 100pC was achieved at 350keV with QE>3%. Unfortunately,

the linac suffered field emission which limited the gradient to 27 MeV rather than the design value of 35 MeV.

In 2008 the 4GLS project was cancelled and ERLP was renamed ALICE. By October, after repairs to the booster linac cryomodule at ACCEL and the installation of a smaller ceramic in the gun (generously loaned by Stanford University) the milestone of energy recovery was achieved.

As suggested by the new name, the purpose of the facility shifted in 2009 towards laser-related experiments and user exploitation. Coherently enhanced broadband THz was extracted from the final dipole of the bunch compression chicane, Compton back-scattering off a TW laser in a head-on geometry was successfully demonstrated [3] and electro-optic sampling was implemented as an electron bunch length diagnostic.

By 2010 the FEL undulator was installed and lasing was achieved in October that year. Details of the commissioning process up to first lasing, including a summary of the beam optics design, can be found elsewhere [4].

Larger scale user programmes commenced in 2011 after commissioning of the THz and FEL beamlines. The THz beam was transported to a tissue culture laboratory for biological experiments to determine safe limits of exposure of human cells to THz and the effect of THz on the differentiation of stem cells [5]. A Scanning Near-Field Optical Microscope (SNOM) was installed and integrated with the IR beamline—further details are given later in this paper.

In 2012, while the user programmes progressed, time was also spent studying the transverse and longitudinal beam dynamics [6] and the effect of chicane R_{51} and R_{52} on the THz emission.

ALICE is now funded via a three-year EPSRC grant [7] to provide three months of user IR-FEL/THz beamtime per year. A number of technology upgrades and operational improvements have been implemented to transition ALICE from a test facility to a stable, reliable user facility. These are described in subsequent sections. The layout of ALICE is shown in Figure 1.

RECENT UPGRADES

Digital Low-Level RF (DLLRF) Work had been started at Daresbury in 2009 to develop DLLRF systems to replace the existing analog systems. The motivations were: to have the ability to modify loop parameters during operations; to allow complicated control algorithms such as adaptive feed forward to overcome beam loading; to en-
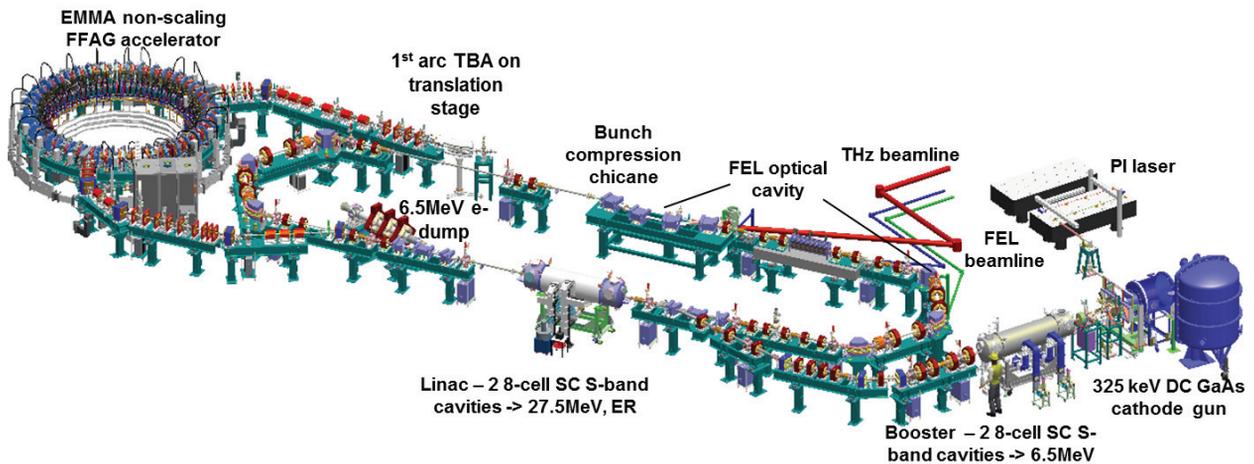
Figure 1: ALICE layout.

able controlled cavity filling to limit the RF power reflection in the waveguide and Lorentz force induced detuning control; and to introduce more extensive diagnostics. DLLRF has now been in operation for the ALICE buncher cavity for three years where *rms* phase and amplitude stability of 0.024° and 0.05% has been measured. Similarly, a 1.3GHz DLLRF system was successfully tested on the superconducting booster cavity demonstrating *rms* phase and amplitude stability of 0.028° and 0.04%.

The DLLRF system for the main linac was installed in 2014 and successfully commissioned at the start of 2015, immediately before user operations commenced. The improved reliabilty, stability and control of the new system soon became apparent and allowed introduction of a new system to stabilise drift in the photoinjector laser which markedly improved the stability of the FEL, as described in the next section.

Photoinjector Laser Synchronisation   In 2012 correlations had been observed between the FEL output power and the relative phase between the photo-injector laser and the RF. This year, to provide a more stable FEL beam for the user programme, more investigations were carried out. A LLRF4 digital card (designed by Larry Doolittle (LBNL) and produced by Dimtel) was clocked from the ALICE master oscillator at 1.3 GHz. Two 81 MHz signals connected to the ADC inputs of the LLRF4 were processed to provide I and Q measurements of the RF laser drive signal and a signal from the laser output cavity, both CW signals at 81 MHz. It was then observed that the FEL power variation was correlated with drift and step changes in I and Q of the laser cavity signal which indicated the signal had changed phase with respect to the 81 MHz drive signal. The correlation between laser phase and FEL power is shown clearly in Figure 2.

To compensate, a phase shifter was introduced in the laser drive signal and a PID control in EPICS was used to monitor and control the position of the phase shifter. This greatly improved the performance of ALICE—the short term stability
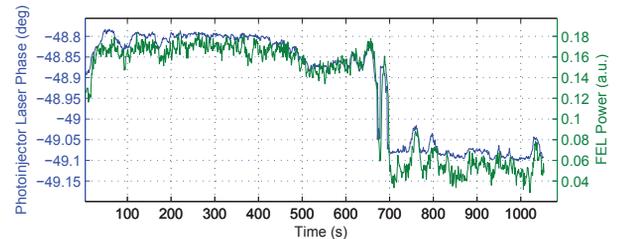

Figure 2: Observed correlation between photoinjector laser phase and FEL output power, prior to introduction of feedback.

of the FEL average power (measured on a macropulse basis) was improved from typically 5-10% to 1-2% and longer term drift was much reduced, greatly improving the utility of the beam for SNOM imaging which requires good stability over a one-hour timescale.

Diagnostic and Operational Improvements   A current monitor and BPM were installed in the main beam dump which proved useful for optimising the energy recovery efficiency. By minor 'missteering' in the dispersive dump beamline the change in beam energy at the onset of lasing could be resolved. This provided a useful online diagnostic for FEL optimisation and monitoring. The BPM system around the rest of the accelerator was upgraded to allow all BPMs to be monitored simultaneously (rather than in 4 switchable banks as previously) and an orbit correction algorithm was implemented and commissioned. This will be invaluable in maintaining the trajectory within the FEL undulator while the gap is rapidly scanned over its full range.

The ALICE hall has poor temperature stability - variations of several degrees over the course of 24 hours are typical. This can lead to local phase changes due to cable temperature variation, drifts in the FEL cavity length (see next section) and changes in the position of the PI laser spot on the cathode. To reduce the temperature variation for the last user run,

the magnets were left on overnight when the machine was operating on a 16 hour cycle. This was found to markedly reduce setup time the following morning, primarily due to better RF phase reproducibility. It then typically took one hour to achieve stable lasing from powering up. Later, operations commenced on a 24 hour/5 day cycle. In this regime lasing was maintained stably and continuously with the only interruptions due to cathode recaesiations which took about half an hour and were required every 2-3 days.

IR-FEL Feedback One of the main uses of the ALICE FEL light is SNOM imaging which requires stable wavelength, bandwidth, and power over scans lasting approximately one hour. Past FEL operation experience indicated cavity length variation over 16-hour runs with the rate of change initially linear at up to 5 μm/hr then slowing and reversing later in the day. This was consistent with a sinusoidal variation on a 24-hour timescale. Laser tracker measurements were used to confirm the 24-hour cavity length variation and correlate it to temperature. Tracker points mounted on the exterior of the FEL cavity showed cavity length variations of ± 10 μm strongly correlated to $\pm 0.5°$C air temperature variation. The width of the FEL detuning curve is ~ 20 μm, and variation of more than $1 - 2$ μm is sufficient to cause an unacceptable variation in FEL power and wavelength. Therefore, to meet the stability requirements action was required to maintain the cavity length to this level.

Several options that have been successfully used at other FELs were discounted, such as temperature stabilisation of the hall (due to cost) and interferometric measurement and correction of the cavity length (due to space restrictions in the cavity). An initial solution was a feedback system based on the measured spectrum of the FEL light. Different options were trialled, including feedback on cavity length based on the measured wavelength, and the use of response matrices to feed back on undulator gap based on measurements of measured wavelength, linewidth and FEL power. While these approaches were suitable under certain conditions they were unusable during extended sequences of rapid wavelength scans which were often required by users. Consequently, a second feedback technique was implemented in which temperature sensors were mounted on the girders around the FEL. The system was commissioned by recording temperature against cavity length for the peak of the detuning curve over an extended period of several days. A linear response was found, and a simple open loop control system implemented to vary the cavity length over the course of a scan to maintain constant wavelength. For SNOM scans this was used in tandem with a more rapid feedback on the undulator gap to compensate for any other parameter variation that directly or indirectly affected the FEL wavelength. Using these two systems together it was possible to achieve *rms* wavelength stability of $\sigma_\lambda/\lambda_0 \leq 0.1\%$ (approximately 10% of the relative bandwidth) over periods of several hours.

IR-FEL Beamline and End-station The beamline and end-station have been recently upgraded. The beamline was originally designed for 4 μm radiation but because ALICE operates at a lower energy than the original design energy of 35 MeV the output is at longer wavelengths. The beamline toroidal mirror has therefore been replaced with a larger mirror to avoid over-filling at these longer wavelengths. Computer controlled in-vacuum movement was added to enable better control and alignment. This upgrade contributed to a five-fold increase in FEL-IR power at the end of the beamline. A second exit port, and retractable mirror, were added to the end of the beamline to enable rapid switching between experiments.

SCIENTIFIC PROGRAMME

The scientific programme on ALICE is aimed at developing more accurate and sensitive diagnostic techniques to improve oesophageal, prostate and cervical cancer survival rates. The capabilities of the IR-FEL and broad-band THz sources make the ALICE accelerator ideally suited to the programme [7].

IR radiation is routinely used for the identification of molecules and materials. It can be used to create a chemical image of a sample, however, the spatial resolution with usual imaging techniques is limited by diffraction to half of the wavelength of the radiation. At this resolution one may resolve cells but not sub-cellular features. The ability to achieve nanoscale spatial resolution in biomedical research can help provide new medicines and treatments. Two complementary techniques, IR Scanning Near-field Optical Microscopy (IR-SNOM) and Atomic Force Microscopy in the IR (AFM-IR), have been developed and used to obtain spectrally selective IR images at complementary sub-micron spatial resolutions.

Infrared Studies

The accelerator and FEL are now optimised to cover the range of wavelengths 5.7-8.3 μm, which includes many of the characteristic absorption lines found in cells, tissue and cancerous materials. For both IR-SNOM and AFM-IR techniques, a fixed wavelength of the 10 Hz pulsed IR-FEL light is focussed onto the sample. A tip is positioned at the intersection of the light and sample at a fraction of a micron above the surface of the sample. The sample is then scanned relative to the tip whilst the sample-to-tip distance is kept constant. The tip is used to measure both the topography and the sensitivity of the sample to the absorption of IR light.

IR-SNOM IR-SNOM is being developed and used to obtain images with spatial resolutions down to 0.1 μm (Figure 3). At this level sub-cellular structures can be imaged and identified. A specially prepared tapered fibre tip is used to collect the light. The spatial resolution is determined by the diameter of the tip. The amount of light collected by the tip depends on the type of molecule or tissue directly under the tip. Reflection IR-SNOM is a well-developed tech-

nique where the IR radiation is focussed onto the sample at a grazing angle and the non-diffracting evanescent wave is collected by the fibre [8]. In this work, IR-SNOM has been extended to include transmission SNOM, where the IR radiation is focussed onto the underside of the sample and the fibre collects radiation transmitted through the sample. Both SNOM techniques have benefitted from a new SNOM instrument, which is mounted onto an inverted microscope.
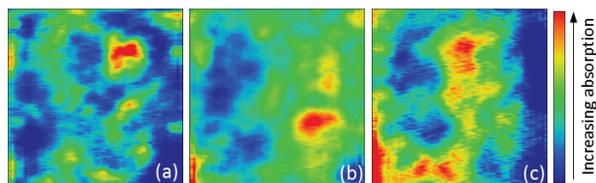

Figure 3: Images of oesophageal tissue recorded with IR-SNOM showing the relative amount of light collected by the fibre tip in reflection mode. (a) 8.05 μm, (b) 7.3 μm, (c) 6.5 μm. Image size is 250×250 μm..
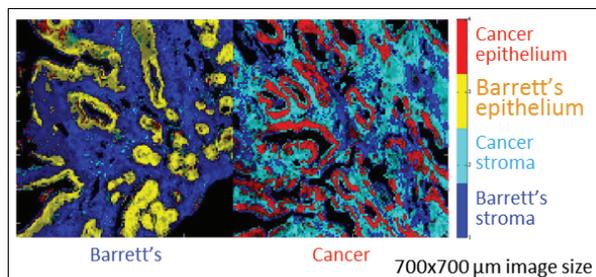

Figure 4: Results of image analysis development on FTIR hyper-spectral images of oesophageal tissue.

Images from biopsies of benign and cancerous tissue have been obtained using both SNOM techniques. The wavelengths were chosen to differentiate different types of tissue. Computerised algorithms, that have the potential to contribute to rapid analysis of biopsies, are being developed. These are initially based on analysis of IR hyperspectral images (HSI) [9]. The potential of IR imaging for cancer identification is illustrated in Figure 4, where cancerous and benign tissues are readily differentiated.

AFM-IR A recently developed atomic force microscopy technique, AFM-IR, which enables images with spatial resolutions of tens of nm to be obtained [10], was deployed. When the frequency of the radiation is tuned to a molecular absorption, the molecule becomes vibrationally excited. This excitation is converted to heat, which in turn causes the sample material to expand to release thermal stress. The reliable detection of this tiny expansion by the sharp (few nm in size) AFM tip has been demonstrated. The deflection of the tip is proportional to the amount of IR absorption. Therefore, by tuning the wavelength chemical analysis can be achieved. Successful AFM-IR imaging was demonstrated on breast cancer cell cultures and Aβ amyloid fibres [10]. Figure 5(b) shows fixed wavelength line scans

across one line of a topographic image. Each profile is an average of 128 intensity normalised line scans. Using this set-up, the difference between peptide fibres folded in β-sheets (which are indicators of the Alzheimer disease) and normally folded α-helix protein was observed.
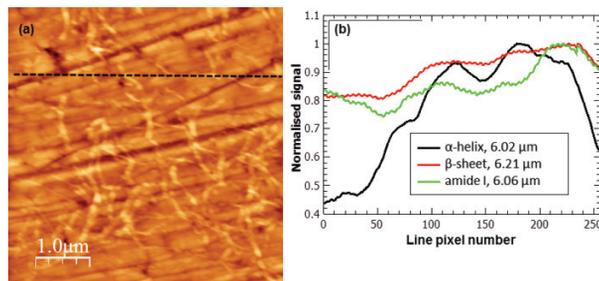

Figure 5: (a) Topographic image of Aβ amyloid fibres on CaF$_2$ with a dotted line showing the line from where the profiles were taken and (b) normalised line profiles for fixed wavelength line scans: α-helix (6.02μm), β-sheet (6.21μm) and amide I (6.06μm).

THz Studies

The high-intensity broadband THz radiation from ALICE is ideally suited to two projects aimed at advancing the development of cheap portable THz instruments for the diagnosis of cancer. The first project is extending compressive THz spectroscopic imaging to three dimensions [11, 12]. The second project is developing an ultra-sensitive Imaging Fourier Transform Spectrometer, which is an alternative to the traditional THz-TDS (Time-Domain Spectroscopy) imaging technique [13].

ACKNOWLEDGEMENTS

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