THE STATUS OF THE ALICE R&D FACILITY AT STFC DARESBURY LABORATORY

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Abstract

The ALICE accelerator, the first energy recovery machine in Europe, has recently demonstrated lasing of an infra-red free electron laser (IR-FEL). The current status of the machine and recent developments are described. These include: lasing of the IR-FEL, a programme of powerful coherent terahertz radiation research, electro-optic diagnostic techniques, development of high precision timing and distribution system, implementation of digital low level RF control. ALICE also serves as an injector for the EMMA non-scaling FFAG machine.

INTRODUCTION

The ALICE (Accelerators and Lasers In Combined Experiments) accelerator at Daresbury Laboratory is an energy recovery machine which has developed several different applications.

The ALICE machine consists of a DC electron gun, a superconducting booster module, and a main energy-recovery loop containing a superconducting linac, a bunch compressor and an undulator. The DC photoinjector gun produces electrons at 230keV which are bunched with a normal-conducting cavity, boosted to 7 MeV by the first superconducting module, and injected into the linac where they are accelerated up to 30 MeV. The ALICE layout is show in Figure 1.

ALICE applications include the IR-FEL, a THz radiation source, and the use as an injector for the EMMA non-scaling FFAG.. The machine parameters are optimised for each application. Bunches of up to 100 pC are used; bunch repetition rates (within a bunch train) can be varied up to 81.25 MHz; and train lengths up to 100 µs are used. The train repetition rate is 10 Hz and the fundamental RF frequency is 1.3 GHz.

In October 2010 the ALICE oscillator-type IR-FEL achieved first lasing, initially at 8 µm and 10-30 mW average power. This was the first demonstration of a FEL in the UK, and the first FEL driven by an energy recovery machine in Europe.

The ALICE bunch compressor chicane is a powerful THz source which is currently utilised in biological experiments and has a secondary use as a bunch length diagnostic. Recently transport of THz to a dedicated tissue culture laboratory has been achieved and the first live-cultured-cell experiments with THz radiation have been performed.

ALICE injects into the EMMA accelerator (Electron Machine with Many Applications) a novel non-scaling fixed field alternating gradient accelerator [1].

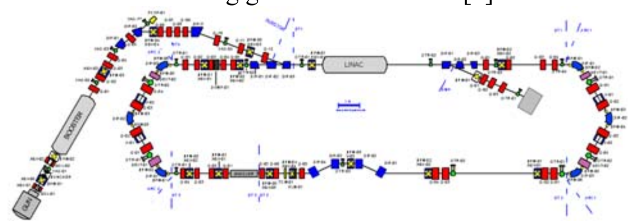

Figure 1: ALICE layout.

INFRA-RED FREE ELECTRON LASER

The ALICE machine was originally designed as a prototype for a next generation light source[2]. The purpose of the FEL was to demonstrate energy recovery with beam disrupted by the FEL interaction, and to develop experimental skills in this area. The variable gap undulator was installed in ALICE in December 2009. A more detailed account of recent progress can be found in [4].

FEL commissioning began in February 2010 with 40 pC bunch charge, 81.25 MHz bunch repetition frequency (within a train), and 100 µs bunch trains. Spontaneous radiation was detected quickly[5]. However no gain was observed and lasing continued to prove elusive in several attempts over the next few months, while the effort on the IR-FEL was balanced with pursuit of other ALICE projects.

First spectral measurements of the spontaneous radiation were performed in June 2010. Measurements of the spectral width were used to optimise the electron trajectory in the undulator - the narrowest linewidth and minimum peak wavelength correspond to the on-axis trajectory. Much effort was directed at attempting different injector set-ups to ensure both small bunch length and small energy spread, through different settings of the buncher and booster cavities. This included pragmatic scanning of parameters to increase the intensity

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of the spontaneous emission, corresponding to maximising bunch compression. More details on ALICE beam dynamics can be found in [6].

The spectrum and amplitude of the undulator radiation exhibited various features and behaviour in response to these machine parameter changes. It was possible to obtain a narrow measured spectra at approximately the theoretical natural line width of the undulator. Setups were developed in which enhancements in the signal were seen as the FEL cavity length was scanned about the expected length. This indicated strong coherent emission but not FEL gain.

Bunch profile measurements were made using an electro-optic bunch length diagnostic located at the undulator entrance, and these indicated sufficient bunch compression. It was strongly suspected that beam loading effects in the linac were leading to energy variation along the bunch train, limiting bunch charge to 40pC and resulting in insufficient gain. In order to reduce losses in the optical cavity the FEL outcoupling cavity mirror was replaced by one with a smaller outcoupling hole (0.75mm radius compared to 1.5mm) in July 2010. Several more attempts with the new mirror did not result in lasing, and it was thus decided to reduce the bunch repetition frequency to reduce the beam loading.

To enable flexible bunch repetition rate operation of ALICE required modification of the photoinjector (PI) laser. The bunch train duration is controlled by a Pockels cell, and an additional Pockels cell was installed to divide the frequency of the PI laser pulses within a bunch train, allowing bunch repetition rate to be reduced by a factor of 5.

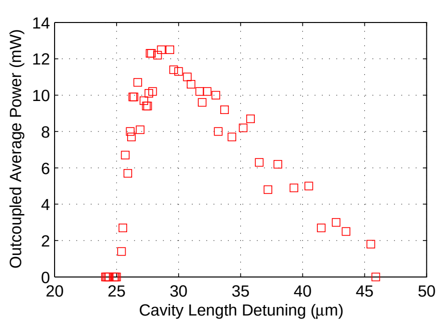

Figure 2: ALICE IR-FEL detuning curve. FEL average power as a function of FEL cavity length detuning.

With the lower bunch repetition rate, higher bunch charges of up to 100 pC at 16.25 MHz frequency within a train were used and only a few days later lasing was achieved on 23rd October 2010. Lasing was first indicated by complete saturation of the MCT detector over the duration of the bunch train, at the lowest pre-amplifier gain. The average FEL power was measured to be >10 mW. The characteristic detuning curve of the cavity length was then measured and is shown in Figure 2. The effect of lasing on the electron beam was to reduce the mean energy and increase energy spread. However these effects were sufficiently small that the beam transport did not need to be modified to maintain energy recovery during lasing.

Once lasing was achieved at higher charge, it could subsequently be maintained down to 40 pC. The difference compared to the earlier unsuccessful attempts at 40pC may be attributed to a combination two factors; energy variation due to beam loading, and that operating at a higher charge allows lasing over a larger parameter range, making it easier to establish, and subsequently optimise for lower charge operation.

The highest FEL average power measured so far is around 30 mW. This equates to a power within the bunch train of 30 W and a FEL pulse energy of around 3 µJ . The conversion efficiency of electron beam energy to FEL pulse energy is measured to be 0.15% which is smaller than the theoretical maximum due to the small outcoupling hole presently used. The FEL pulse length has been estimated from the spectral width to be 0.8-1.5 ps, assuming transform-limited pulses. The single-pass cavity gain has been calculated from MCT measurements of the cavity rise time and ringdown times. The maximum value measured is 22% in good agreement with expectations from the current set of beam parameters.

Continuous tunability of the FEL wavelength has been demonstrated with lasing maintained while tuning from 8.0-5.75µm through varying the undulator gap. Spectra at different wavelengths are shown in Figure 3.

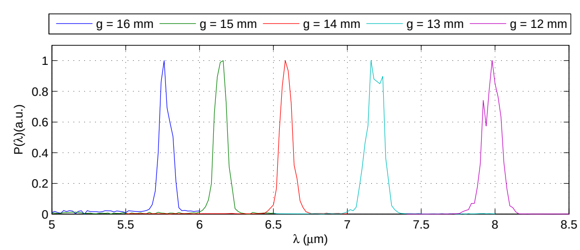

Figure 3: ALICE FEL spectra at different undulator gaps.

Preliminary ALICE IR-FEL radiation characteristics were measured with detector close to the beam transport system. In the machine shutdown in Nov-Jan 2010/2011 a FEL beamline was installed to transport FEL radiation to a dedicated diagnostics room, with ~35% transport efficiency achieved so far. Efforts have continued to optimise the machine set-up for increased output FEL power and stability.

ELECTRO-OPTIC BUNCH LENGTH DIAGNOSITC

An electro-optic (EO) diagnostic has been used in ALICE primarily for bunch length measurements for the IR-FEL[7]. The diagnostic uses the birefringence induced in a ZnTe crystal and probed by a fs-pulse Ti Sapphire Laser. The first results (see Figure 4) indicated an RMS bunch length of 1-2 ps.

This diagnostic provided crucial confirmation that the bunch compression scheme of ALICE provides sufficiently high peak charge for FEL operation.

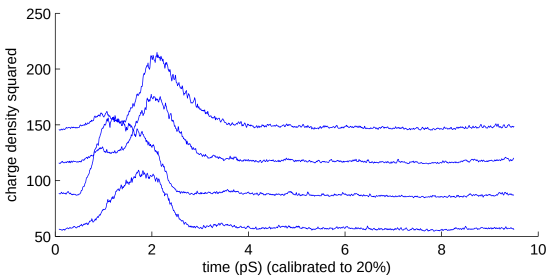

Figure 4: Examples of shot-to-shot bunch profile measurements at the ALICE IR-FEL location obtained with the electro-optic diagnostic.

TERAHERTZ SOURCE

The ALICE THz source is broadband and of much higher power than conventional lab-based sources. It continues to be used in biological experiments as reported previously [5]. The THz radiation energy in these experiments was measured to be 120 μJ per bunch train, this gives an estimate of over 10 kW peak power in a single THz pulse, assuming an electron bunch length/THz pulse length of around 1 ps.

Work continued on measuring the THz radiation characteristics using detectors close to the accelerators. These measurements were used to construct and optimise a beamline to transport THz to a dedicated tissue culture laboratory (TCL) situated 30 m away from the source. In June 2011 radiation was transported to the TCL at an estimated efficiency of 20% in good agreement with modelling. The capability of transmitting high peak power THz radiation directly into an incubator to allow exposure of growing human cells in culture is unique and experiments are currently underway to determine the safe limits of human exposure to THz radiation and the effects of THz on the differentiation of stem cells.

As with the IR-FEL, the THz set-up uses a lower than nominal bunch repetition rate of 40.125 MHz since machine operation is less challenging at this value.

With THz transport now established along the dedicated beamline, the use of a Martin Pupplett inteferometer-spectrometer is being investigated to measure the THz spectrum which may enable bunch profile information in the compression chicane to be deduced.

EMMA

ALICE serves as the injector for EMMA (Electron Machine with Many Applications), the world's first non-scaling FFAG (Fixed Field Alternating Gradient) machine. The role of ALICE role is to provide single bunches at ~10 MeV and 3-5 Hz with minimal energy spread. Historically this was achieved by running the main linac at lower gradient, but this lead to detuning of the cavities. An alternative set-up was established where the first and second linac cavities accelerates are set to accelerate and decelerate respectively, with fine adjustment of the phasing to minimise energy spread. In June 2010 EMMA achieved injection and circulation of beam[8]. In April 2011 acceleration was demonstrated[1]

OTHER DEVELOPMENTS

Recently a significant improvement has been made to the hour-to-hour phase stability of ALICE. Temperature dependent effects in the master oscillator were identified and corrected using a phase measurement and control feedback loop.

Several other R&D projects are currently being pursued on ALICE. A digital low level RF system is being developed [9], and a beam loss monitoring system has been installed and preliminary commissioning has been performed [10]. An optical timing distribution system with active stabilisation is under development, along with a high precision beam arrival monitoring system.

The installation of a new linac cryomodule, as part of the Daresbury International Cryomodule Collaboration Project[11] is planned in the coming year. In addition it is planned to install a new ceramic HV insulator in the DC gun which will enable 350 kV operation.

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