RECENT DEVELOPMENTS ON ALICE (ACCELERATORS AND LASERS IN COMBINED EXPERIMENTS) AT DARESBURY LABORATORY

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Abstract

Progress made in ALICE (Accelerators and Lasers In Combined Experiments) commissioning and a summary of the latest experimental results are presented in this paper. After an extensive work on beam loading effects in SC RF booster and linac cavities' conditioning, ALICE can now operate in full energy recovery mode at a bunch charge of 40pC, a beam energy of 27.5MeV and train lengths of up to 100μs. This improved operation of the machine has resulted in generation of coherently-enhanced broadband terahertz radiation with an energy of several tens of microjoules per pulse and in successful demonstration of the Compton Back-Scattering x-ray source experiment. Experiments on the exposure of living cells to terahertz radiation have been started. These and other developments on ALICE are reported.

MACHINE STATUS

ALICE, an energy-recovery superconducting linac [1,2], operates currently at the electron energy of 27.5MeV, bunch charge of 40pC and bunch repetition frequency of 81.25MHz. The machine operates in a pulsed regime with the train lengths from ~10ns (single bunch) to 100μs. The pulse repetition frequency is also variable from 1 to 20Hz.

The electron energy is lower than the design value of 35MeV mostly due to the intense field emission in the main linac. The DC photoelectron gun is also operated at 230kV as opposed to the 350kV nominal gun voltage and this limits the bunch charge to ~40pC in order to avoid significant deterioration of the beam quality.

GaAs photocathode lifetime is now sufficiently long for routine ALICE operation at 40pC. Normally cathode re-caesiation is performed once a month, when the quantum efficiency decreases from initial ~3% to below ~0.5%.

Over the past year, a number of changes in gradient settings of SC cavities (booster and main linac) were made with the aim of optimising the RF set up and to accommodate limitations presented by the RF system. Each of these variations required significant changes in the overall machine set up. It can now be routinely operated at 27.5MeV with the total beam losses not exceeding 5 to 7%.

The energy spectrum of the beam exiting the first cavity of the booster (BC1) with the second cavity (BC2) switched off (resulting in a beam energy of 3.9MeV, compared to the nominal injector energy of 6.5MeV) is shown in Fig.1. The energy spread here is 150keV FWHM, attributed mostly to the correlated energy chirp and is compensated by the appropriate choice of the BC2 off-crest phase. Note a long low-energy tail that could be the property of the GaAs photocathode, which may emit a low-intensity electron beam over 100s of picoseconds after being illuminated by a short laser pulse [3] (~28ps FWHM in our case).

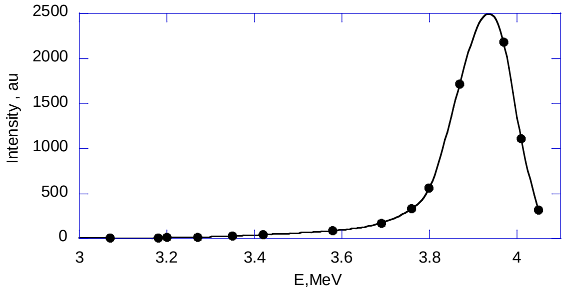

Figure 1: Energy spectrum of the beam after the first booster cavity.

The bunch length in injector and after the main linac (i.e. before the compression chicane) was measured using an RF zero-phasing method described in detail in [4] and found to be 4mm FWHM. This is acceptable for terahertz generation (see below) but introduces an energy spread after the main linac that is too large for IR FEL operation. The set up is currently being optimised to achieve ~1.5mm FWHM bunch length, with the final aim of reducing the bunch length to below 1ps after the compression chicane, where the bunch length will be measured using the electro-optic technique that is being currently commissioned.

Digital LLRF System Development

A digital Low-Level RF (LLRF) system is under development for use with the ALICE superconducting cavities. The system is based around the LLRF4 evaluation board, which was developed by L.Doolittle of LBNL.

A Lantronix networked serial port has been integrated with the system to allow remote communication with a host PC. The host PC runs a Labview user interface and also implements an EPICS PV server.

The FPGA code implements simple fast-feedback based on Proportional/Integral (PI) loops, with the host computer implementing a feed-forward algorithm to compensate for beam loading effects.

The system has been bench-tested extensively in the laboratory, achieving short-term phase stability of 0.03° RMS and amplitude 0.05% RMS when set up on the ALICE buncher cavity without beam (as measured by the LLRF system itself – not yet independently verified).

The system has also been tested with beam on the ALICE buncher cavity. At this point, unacceptable levels of phase and amplitude noise were observed. On investigation, large amounts of power supply noise and EMI pickup from other sources was measured on the LLRF4 board

Work is underway to provide effective EMI shielding and power supply regulation to try to minimise noise generated by the LLRF system.

Helium Processing of the SC Linac Module

The performance of both the cavities within the linac superconducting RF module have been limited by the level of field emission at accelerating gradients much less than that required for full-energy operation of ALICE at 35 MeV [5], and have caused additional heat loading to the cryogenic system. Additionally it is believed that the level of x-rays produced have contributed to the failure of a number of pieces of electronic equipment in the vicinity of the module. Thus it was decided to undertake helium processing, which is a process by which the cavity surface is cleaned by exciting the cavities with a high RF field in the presence of a small amount of helium gas. During the process electrons from field-emitter sites ionise the helium gas, the ions then stream back towards the field-emitter, bombarding it and causing the surface to heat up, thus generating more desorbed gas. The plasma thus generated extends around the field-emitter site thereby cleaning the surface of contamination.

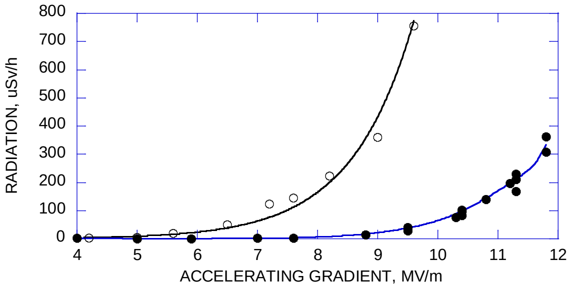

Figure 2: Linac cavity radiation levels pre- (open circles) and post- (full circles) helium processing.

Both linac cavities were conditioned separately with a helium pressure of around 5.0 x 10^{-4} torr, under both pulsed and CW conditions using a LLRF system incorporating a Voltage-Controlled Oscillator (VCO) configured into a Phased-Locked Loop (VCO-PLL). Improvements were seen in both the gradient at which radiation is first seen and the level of radiation in the first linac cavity (LC1), Fig.2, but no improvement was seen on the second linac cavity (LC2). This has significantly improved the operation of the linac module for 20 MeV gain, with a much reduced cryogenic heat load, though further improvements will be required for higher gradients.

Terahertz Studies

A beamline has been constructed to transport coherently-enhanced terahertz radiation generated in the compression chicane to a diagnostics room equipped with a Martin-Puplett interferometer for spectral measurements and on to a dedicated tissue culture laboratory. We are currently investigating the characteristics of the radiation emerging from the diamond window of the accelerator, in particular to ensure we maximise the coupling of the high-intensity source to the optical transport system rather than the scattered radiation which will not transport efficiently. Fig. 3 shows the horizontal terahertz beam profile at 1.1m from the diamond exit window. Fig. 4 shows the intensity of the terahertz beam on its axis as a function of the linac phase.

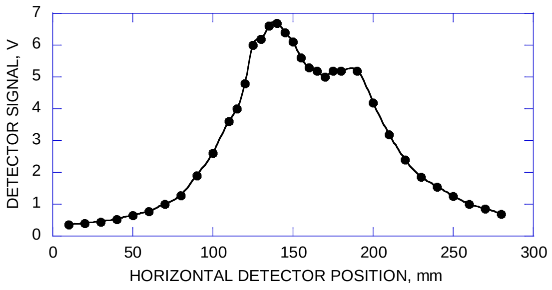

Figure 3: Horizontal terahertz beam profile at 1.1m from the exit window.

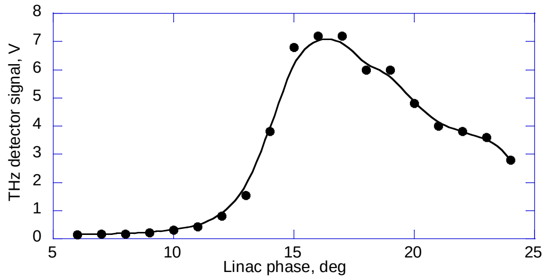

Figure 4: Intensity of the terahertz beam on its axis as a function of the linac off-crest phase.

We are also investigating terahertz intensity along the bunch train using a fast Schottky detector developed by STFC Space Science Department giving nanosecond resolution.

TERAHERTZ AND CELL CULTURE EXPERIMENTS

The terahertz radiation from ALICE accelerator is being used in two research programmes. The first is designed to determine the safe limits of human exposure to terahertz radiation and the effects of repeated low-level exposure to terahertz radiation on human tissue. The second research programme aims to explore the influence of terahertz radiation on mechanisms of biological organisation. The ALICE source is ideally suited to both these research programmes because it is a broadband source of high peak power and low average power and this combination makes it possible to separate the effects of terahertz radiation from thermal effects.

First experiments were conducted in a small hutch close to the source in the accelerator hall shielded with nine inches of lead. The terahertz radiation was transported over about four metres via a metal pipe with a reflective inner surface. Experiments on living cells contained in a CO_2 incubator in this hutch have begun with retinal epithelial cells. These anchorage-dependent cells are grown in polystyrene flasks and become attached to the flask surface via an adsorbed protein layer. Cell behaviour was evaluated initially in terms of degree of cell attachment and spreading, and increase or decrease in proliferation.

Several batches of retinal epithelial and embryonic stem cells were irradiated with terahertz beam with three and six hour exposures. The first results are being analysed and the overall programme investigating the effect of terahertz radiation on cell culture is continuing.

COMPTON BACK-SCATTERING EXPERIMENT

Short x-ray pulses from a Compton Back-Scattering (CBS) experiment were successfully demonstrated on ALICE in November 2009, Fig.5. The experiment was conducted with a "head-on" geometry, colliding the 70fs, 800nm, 500mJ Ti:sapphire laser beam with an electron beam of 29.6MeV energy and 40pC bunch charge. Full account of this experiment can be found elsewhere in these proceedings [7].

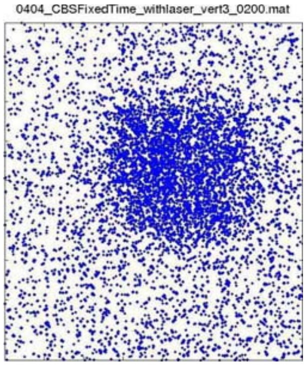

Figure 5: The CBS x-ray image

OTHER DEVELOPMENTS

NS-FFAG EMMA

EMMA is the first Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) accelerator that is in the final stages of construction at Daresbury Laboratory [6].

ALICE is also used as the injector for EMMA, and the first electron beam has been sent down the EMMA injection line to a temporary Faraday cup at its end. This was done to allow the injection line to be commissioned before EMMA is ready to accept beam. A 40 pC bunch charge 15 MeV beam was successfully transported to the end of the line. As well as confirming that all the magnet systems are working it was possible to capture images from all the YAG screens (for provisional phase space tomography analysis) and undertake some very preliminary measurements of energy spread.

IR FEL

The narrow-gap undulator vacuum vessel and the undulator itself have been installed and aligned. The FEL optical cavity was also pre-aligned using a laser tracker network and external HeNe lasers. Full energy recovery was achieved with the undulator vacuum vessel in place. The optical diagnostics, comprising of a liquid nitrogen-cooled MCT detector and spectrometer have been installed and commissioned.

With beam energy of 27.5 MeV, undulator period of 27mm and undulator parameter $K_{rms}=0.9$, the resonant wavelength is approximately 8.5μm, with the predicted cavity mode radius on the downstream mirror approximately 7.5mm. The calculated outcoupling fraction through the 1.5mm hole is thus found to be 7.5%. For comparison the calculated single pass gain for the nominal parameters is approximately 25%. Spontaneous emission was detected successfully on MCT detector. The fraction of intracavity power extracted through the outcoupling was measured to be 7.1%, in good agreement with the expected figure of 7.5%.

IR FEL lasing is expected to be demonstrated as soon as a new ALICE set up with a shorter (~1.5mm FWHM) bunch length prior the linac is established, thus ensuring a post-linac energy spread ~100keV and as a consequence, sufficient FEL gain for lasing.

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