The ALICE Energy Recovery Linac – Project overview and injector performance

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Abstract. The ALICE accelerator (Accelerators and Lasers In Combined Experiments) at Daresbury Laboratory is a 35 MeV ERL. The electron beam drives an infra-red free-electron laser (FEL) and THz light sources, but can also be used to generate X–rays through Compton back–scattering (CBS). ALICE also acts as the injector for the EMMA NS–FFAG machine.

This paper will outline the project status and milestones achieved thus far, focussing on the status and performance of the photoinjector gun and the injection line.

1. Introduction
The ALICE ERL has a broad role as an accelerator physics and technology test facility, leading to the development of a full–scale ERL–based light source in the United Kingdom. Since the status of this project was last reported to this workshop [1], a number of significant milestones have been achieved such as the first beam acceleration in an SRF linac (23\textsuperscript{rd} October 2008), followed quickly by full energy recovery (12\textsuperscript{th} December 2008), generation and exploitation of THz radiation, and the generation of CBS X–rays [2].

2. ALICE Accelerator systems overview
ALICE uses a DC photoinjector gun which is a variant of the gun developed for the IR–FEL at the TJNAF [3]. It is designed to operate at 350 kV with a reflection–mode GaAs photocathode, activated in–situ by means of a caesium–oxidant ‘Yo–Yo’ procedure. However, due to repeated vacuum failures of the single–piece bulk–doped ceramic with which the gun was designed, the use of slightly smaller 2–piece ceramic currently limits the operating voltage to 230 kV.

The photoinjector drive laser beam is provided by a HighQ IC10000 Picotrain system, which uses diode-pumped neodymium yttrium vanadate (Nd:YVO\textsubscript{4}) to deliver > 10 W at 1064 nm wavelength, which is later frequency–doubled to 532 nm. The laser is passively mode-locked to generate 7 ps FWHM pulses at a repetition rate of 81.25 MHz, this being the 16\textsuperscript{th} sub-harmonic of the main linac frequency. The drive laser optical system [4] defines and delivers macropulses to the cathode at a repetition rate up to 20 Hz. The macropulse length can vary from a single laser pulse up to a 100 \(\mu\)s pulse train. This constitutes a maximum duty cycle of 0.2\% and represents an average electron beam current of 13 \(\mu\)A at an electron bunch charge of 80 pC.

\textsuperscript{1} Electron Model of Many Applications non–scaling Fixed–Field Alternating Gradient accelerator
Figure 1. Schematic layout of the ALICE ERL.

The booster linac uses $2 \times 9$–cell 1.3 GHz TESLA cavities to accelerate the beam to 8.35 MeV, with the main linac using a further 2 cavities to accelerate the beam to 35 MeV. The beam is passed through a compression chicane, and the compressed beam is used to drive the FEL.

3. ALICE Exploitation

The ALICE electron beam is intended primarily to drive an Infra–Red FEL, but in generating the high peak current needed to drive the FEL, the electron beam becomes a source of THz radiation due to coherent enhancement at these wavelengths as it passes through the dipole compression chicane. The intensity of the THz radiation is closely linked to the energy chirp applied by the linac phase, as shown in figure 2. ALICE constitutes the most intense pulsed THz source in Europe, and this radiation is supporting an experimental programme run by the University of Liverpool to investigate the effect of high–power THz radiation on living cells.

Ultra–short X–ray pulses have been generated with the ALICE electron beam through Compton back–scattering\(^2\) where the electron beam was collided head–on with a Ti:sapphire laser pulse (800 nm, 70 fs, 0.5 J) \([2]\), as shown in figure 3. The head–on geometry produces X–

\(^2\) Strictly known as Thompson scattering in this low–energy regime

Figure 2. Intensity of the THz emission from the dipole compression chicane as a function of linac RF phase.

Figure 3. CBS X–ray pulse.
Figure 4. Predicted output characteristics for the ALICE IR–FEL.

rays up to 30 keV with the pulse length limited by the electron bunch length. There remains an intention to re–visit this scheme using a more–challenging side–on collision geometry to generate X–rays pulses up to 15 keV whose pulse length is limited only by the laser pulse length.

The FEL output will be tunable between 4 and 12 µm by varying the electron beam energy between 24 and 35 MeV, and the wiggler gap between 12 and 20 mm. The predicted characteristics are shown in figure 4 where \( G_{\text{max}} \) is the single–pass gain. Achieving first lasing of the FEL is the highest priority for the commissioning team³.

ALICE also serves as the injector for the EMMA accelerator. EMMA is the world’s first non–scaling fixed–field alternating gradient electron accelerator, a machine which combines the best features of synchrotrons and cyclotrons [5]. ALICE provides electron bunches to EMMA via an injection line which contains a suite of diagnostics to fully–characterise the incoming beam. The electrons undergo rapid acceleration in EMMA, after which they will be extracted into a diagnostic line with a second suite of diagnostics to characterise the accelerated beam. The NS–FFAG technology has potential applications in the fields of hadron therapy and electricity generation under the accelerator–driven sub–critical reactor scheme. Currently, coasting beams have been circulated, but the beam has not yet been accelerated.

4. Photocathode performance

The GaAs wafer is indium–soldered to the end of a support tube located inside the cathode assembly support stem (shown in figure 5). During activation, the wafer is retracted inside the cathode ball such that it can be exposed to caesium from SAES sources. The oxidant is introduced via a fine leak valve, effectively back–filling the gun chamber. This in–situ process also exposes the high voltage surfaces to caesium, a situation which is not ideal and has prompted the development of an external Photocathode Preparation Facility (PPF) [6], as described in section 6. The lack of fine control through the in–situ activation limits the maximum achievable QE, the best performance so far seen with this system being a QE of 3.7% with a 900 hour dark lifetime. This lifetime was achieved despite suffering from a leak into the gun chamber which elevated the base pressure from the mid 10^{-12} mbar regime to the low 10^{-11} regime. The performance of the photoinjector gun was described in detail at the last PESP workshop [1].

5. Injector performance

There have been several recent performance measurements of the ALICE injector line. As a prelude to EMMA beam commissioning, using the EMMA setup, the emittance in the ALICE

³ Following the PESP workshop in September, first lasing of the ALICE FEL was achieved on 23\textsuperscript{rd} October 2010
injector was measured using a number of techniques [7]. At the time of these measurements, the drive laser beam footprint on the photocathode was sub–optimal, and rather than being circular with a 4 mm diameter, it was elliptical with semi–major and –minor axes of 8 and 4 mm respectively. This served to inflate the emittance significantly.

Working at a beam energy of 6.5 MeV, the emittance was determined using a single stationary slit. The beam size after the booster linac was determined from a YAG screen image, then the YAG screen was replaced with a 10 µm slit centred on the beam. Another image was taken from a YAG screen located a distance $d$ further downstream. These measurements showed that:

$$\epsilon_{n,x} = \frac{\sigma_1 \cdot \sigma_2}{d} \cdot \gamma = 11.0 \text{ mm mrad}$$  \hspace{1cm} (1)

When the slit was scanned to provide a better measurement of emittance, it was found that:

$$\epsilon_{n,x} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \cdot \gamma = 9.1 \text{ mm mrad}$$  \hspace{1cm} (2)

Quadrupole scans were also carried out. The measured beam size $\langle x \rangle$ at a distance $d$ from each quadrupole was related to normalised emittance as shown in equation (3), where $kL$ is the integrated quadrupole field strength and $A$, $B$ & $C$ are polynomial curve–fitting constants.

$$\langle x^2 \rangle = A(kL)^2 - 2AB(kL) + (C + AB^2)$$

$$\epsilon_n = \frac{\sqrt{A \cdot C}}{d^2} \cdot \gamma$$  \hspace{1cm} (3)

$$\epsilon_{n,x} = 15.1 \text{ mm mrad} \quad \text{and} \quad \epsilon_{n,y} = 4.0 \text{ mm mrad}$$

These measured values were compared to the values extracted from a GPT [10] simulation. GPT predicted $\epsilon_{n,x} = 9.5 \text{ mm mrad}$ and $\epsilon_{n,y} = 1.9 \text{ mm mrad}$ for the electron beam with a ‘perfect’ elliptical drive laser beam spot, though this is not in good agreement with the measured values. However, when the GPT simulation was modified such that the initial particle distribution was based on the actual non–uniform intensity distribution extracted from an image of the drive laser spot on the cathode, the values returned were $\epsilon_{n,x} = 17.7 \text{ mm mrad}$ and $\epsilon_{n,y} = 3.8 \text{ mm mrad}$. These values are in good agreement with the measured values, but fall significantly short of the design specification for ALICE.
The injector beam energy spread with the FEL setup has been measured using a magnetic spectrometer [8]. With booster cavity 1 operated on-crest to deliver beam at 3.9 MeV, and booster cavity 2 un-powered, the energy spectrum shown in figure 6 was obtained. This corresponds to a total energy spread of 150 keV FWHM. Booster cavity 2 was then powered to accelerate the beam to a final energy of 6.5 MeV, and its phase swept to find the minimum energy spread whilst the gradient was continually adjusted to maintain the beam at 6.5 MeV. This resulted in an un-correlated energy spread of 17 keV at 6.5 MeV, as shown in figure 7.

The ‘zero-cross’ method [9] has been applied to bunch length measurement in the injector. Operating ALICE with the FEL setup, it has been found that the bunch length in the injector beamline is 4 mm FWHM, corresponding to a bunch duration of 13.5 ps [8]. The ALICE injector can be configured with shorter bunch lengths, but this is at the expense of the energy spread.

The electro-optic technique has been applied in a separate bunch length measurement after the dipole compression chicane. Operating ALICE in the FEL setup, it has been found that the bunch length is less than 1 ps.

6. Photocathode Preparation Facility (PPF)

The ALICE photoinjector will be upgraded during Summer 2011 with the addition of an external three-chamber PPF [6], as shown in figure 8. This upgrade will also require modification of the gun vacuum chamber and the cathode assembly to facilitate the transfer in and out, loading and removal of photocathodes.

A transport vessel detaches from the PPF and is placed inside a nitrogen-purged glovebox for loading with up to 4 photocathodes. Photocathodes made at the Novosibirsk Institute of Semiconductor Physics are un-packed inside the glovebox, etched in HCl, rinsed in iso-propanol, then loaded into the transport vessel. The transport vessel is then sealed, removed from the glovebox and bolted to the PPF loading chamber. The loading chamber is pumped-down, then the gate valve isolating the cleaning chamber is opened. The middle chamber allows cathodes to be heat-cleaned, or previously-operated cathodes to be rejuvenated through exposure to atomic hydrogen (AHC). The preparation chamber is located beyond the cleaning chamber, and isolated by another gate valve. It contains a carousel capable of holding up to 6 photocathodes, a further 2 heat-cleaning stations, and an activation station with access to laser light at a number of different wavelengths. Two magnetic linear transfer arms facilitate movement of cathodes between the 3 PPF chambers, and between the PPF storage carousel and the photoinjector gun.

Attention has been paid to the preparation chamber vacuum environment, and pressures in the mid 10^{-12} mbar regime are normal. Operation of this PPF as a stand-alone facility has
become routine since its commissioning in March 2009, and QEs of 15% at 635 nm are common.

Figure 8. Engineering model of the 3–chamber PPF upgrade for the ALICE photoinjector. Left–to–right: Loading chamber; AHC and thermal cleaning chamber; preparation chamber.

7. Summary and future plans
Commissioning of the ALICE ERL has progressed significantly since the last PESP workshop. Operation with energy recovery has become routine, and the machine is supporting a number of scientific programmes, with more to follow. FEL Commissioning is the highest priority, and this will be the focus for the remainder of the final operational period of 2010. Beamlines for extraction of the FEL radiation are currently being installed to support the exploitation programme. Major upgrades planned for the next year include the installation of an up–graded linac cryomodule to support high–current operation at 35 MeV, addition of the PPF, and a gun diagnostic beamline. There is also a plan to replace the current analogue low–level RF system with a digital system for improved cavity phase stability and reduced beam loading.

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