Status of the ALICE Energy Recovery Linac

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Abstract. The ERLP energy recovery linac prototype at Daresbury Laboratory has been re-branded, and is now called *ALICE* (**A**ccelerators and **L**asers **I**n **C**ombined **E**xperiments). This paper gives an overview of the project and its status, outlines some of the challenges experienced during the commissioning of the photoinjector and superconducting accelerating systems, and presents our photoinjector gun commissioning results. An outline is given of the planned photon science program for ALICE, and its under-pinning role in the EMMA NS–FFAG[1] project.

Keywords: superconducting, linac, photoinjector, GaAs, electron, FEL, CBS, THz
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INTRODUCTION

The ALICE ERL prototype was conceived as a test–bed for the key concepts and technologies expected to feature in the 4$^{\text{th}}$ Generation Light Source (4GLS). Despite the cancellation of 4GLS, it now has a broader role as an accelerator physics and technology test facility, and for developing fourth generation light source science. The facility is undergoing commissioning at present, and the past year has been a frustrating combination of progress and setbacks. A short productive period of gun commissioning has been book–ended with several gun vacuum problems. However in parallel to the beam commissioning work, progress has been made with the cryogenic and RF systems.

ALICE ACCELERATOR SYSTEMS OVERVIEW

The photoinjector is a DC photocathode gun operating at 350 kV, based on the Jefferson Laboratory IR-FEL gun [1]. It combines a caesiated gallium arsenide (Cs:GaAs) reflection–mode cathode (activated in–situ) with a laser system specified to deliver 80 pC per electron bunch. The gun uses a one–piece bulk–doped ceramic insulator, which has demonstrated extremely good high voltage performance during conditioning to 450 kV.

The drive laser is a *High Q* IC10000 Picotrain model, delivering $>$10 W at 1064 nm wavelength. The lasing medium is diode–pumped neodymium yttrium vanadate (Nd:YVO_4), mode–locked to generate 7 ps FWHM pulses at a repetition rate of 81.25 MHz, this being the 16^{th} sub–harmonic of the 1.3 GHz RF frequency. The drive laser optical system [2] defines and delivers *macrobunches* to the cathode at a repetition rate up to 20 Hz, the length of which can vary from a single laser pulse up to a 100 μs

[1] Electron Model of Many Applications non–scaling Fixed–Field Alternating Gradient accelerator

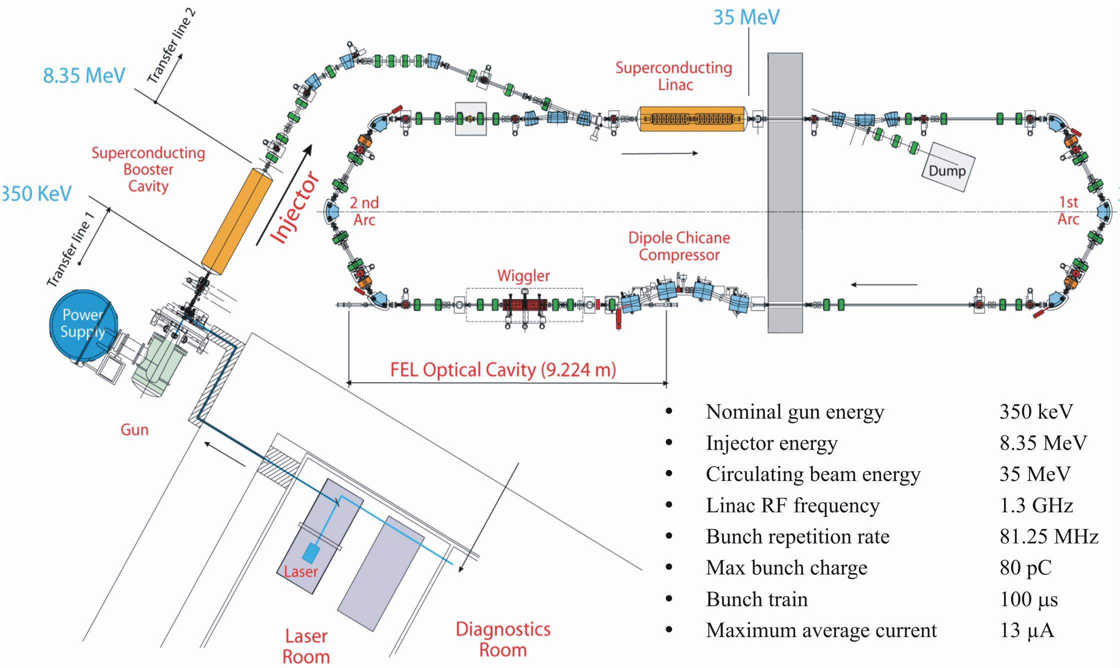

FIGURE 1. Schematic showing the layout of the ALICE machine and its main parameters.

pulse train. This constitutes a maximum duty cycle of 0.2% and represents a maximum average electron beam current of 13 μA.

Cryogenic system and accelerating modules

The cryogenic system [3] was installed during 2006 as a collaborative effort between Daresbury Laboratory, Linde, ACCEL and DeMaco, with both accelerating modules delivered in the first half of that year. Both modules were cooled to 2 K in December of 2006, and were tested with a simulated dynamic heat load of 112 W. Pressure stability of $\pm$0.03 mbar at 2 K and $\pm$0.10 mbar at 1.8 K has also been demonstrated, and the cryogenic system is now performing beyond its design specification.

ALICE uses two Stanford/Rossendorf cryomodules assembled by ACCEL, each containing 2 $\times$ 9-cell TESLA cavities with a total cryogenic load of $\sim$ 180 W at 2 K. One module is configured as the *booster* and the other as the *main linac*, both using a JLab HOM coupler. The booster has up to 52 kW of RF power to provide a 4 MV/m gradient to accelerate the beam by 8 MeV. Due to energy recovery, the linac has only 16 kW of RF power to provide a 13.5 MV/m gradient accelerating the beam to 35 MeV.

Extreme levels of field emission were observed during RF commissioning at Daresbury, cavity performance being significantly worse than during vertical tests at DESY, as shown in table 1. This necessitated the re–location of sensitive equipment close to the booster linac, and installation of a lead shield around the main linac, with a long–term plan of aggressive cavity conditioning fitted around the beam commissioning program.

TABLE 1. Booster & main linac gradient test results.

	Booster		Linac	
	Cavity 1	Cavity 2	Cavity 1	Cavity 2
	Vertical tests at DESY, July – December 2005			
E_{acc} (MV/m)	18.9	20.8	17.1	20.4
Q_o	5×10^9	5×10^9	5×10^9	5×10^9
	Acceptance tests at Daresbury, May – September 2007			
Max E_{acc} (MV/m)	10.8	13.5	16.4	12.8
Measured Q_o	3.5×10^9 @ 8.2 MV/m	1.3×10^9 @ 11 MV/m	1.9×10^9 @ 14.8 MV/m	7.0×10^9 @ 9.8 MV/m
Limitation	FE Quench	FE Quench	RF Power	FE Quench

COMMISSIONING STATUS

The gun delivered first beam at 01:08 on Wednesday 16th August 2006, has been operated since then for several commissioning periods into a dedicated diagnostics beamline [4]. Problems were experienced with poor quantum efficiency (*Q.E.*) and cathode lifetime, but steady improvements have been achieved through better cathode handling and activation procedures, and improved vacuum. Additionally, beam halo, field emission and high voltage breakdown have been encountered during gun commissioning to–date, giving the ALICE team useful experience in dealing with these challenges. We have also suffered repeated failure of the one–piece ceramic at its flange welds, and are now using a smaller spare loaned to us by Stanford which limits our operating voltage to ~ 250 kV.

Commissioning goals achieved so far include: beam energy of 350 keV; bunch charge of > 80 pC; *Q.E.* of 3.7% with a $\frac{1}{e}$ lifetime of $\sim$100 hours; macrobunch length from a single 7 ps pulse to 100 μs train and train repetition rate up to 20 Hz.

ALICE EXPLOITATION AND UPGRADE PROGRAM

ALICE will drive a mid–IR FEL using a wiggler device loaned from Jefferson Laboratory. The gap will be tuneable (12 – 20 mm), which combined with a variable electron beam energy (24 – 35 MeV), will yield radiation tuneable over a range of $\lambda = 4 - 12\,\mu$m. Additionally, a multi–10 TW laser system will provide beams to generate X–rays through Compton backscattering (CBS), and for a longitudinal electro–optic (EO) electron bunch length diagnostic [5] which will be critical to optimise FEL performance. The CBS source will use head–on and side–on geometries in collisions with the electron beam, yielding $h\nu$ to 30 keV [6]. The bunch compressor will be an *intense* pulsed THz source, and will be used to study exposure in live biological cells [7].

In addition to the light derived directly from ALICE (mid–IR FEL, CBS X–rays & THz), an exciting research programme will also use *combinations* of these with a free–standing tunable femtosecond laser and the multi–10 TW laser, mainly for pump–probe experiments that will use a combination of light sources. ALICE exploitation capabilities will be extended into bioscience after completion of a tissue culture laboratory.

The photoinjector will be up–graded by adding a load–lock chamber and re–designed cathode ball, permitting external activation of photocathodes, so improving its HV performance and reducing cathode–change downtime from several weeks to hours [8]. There are also plans to re–install a gun diagnostic beamline as a permanent feature. The ultimate upgrade comes in the form of EMMA: a prototype non–scaling FFAG electron accelerator which will use ALICE as its injector. It is hoped that NS–FFAG technology will provide a cost–effective means to build hadron therapy centres in the UK [9].

PHOTOINJECTOR GUN COMMISSIONING RESULTS

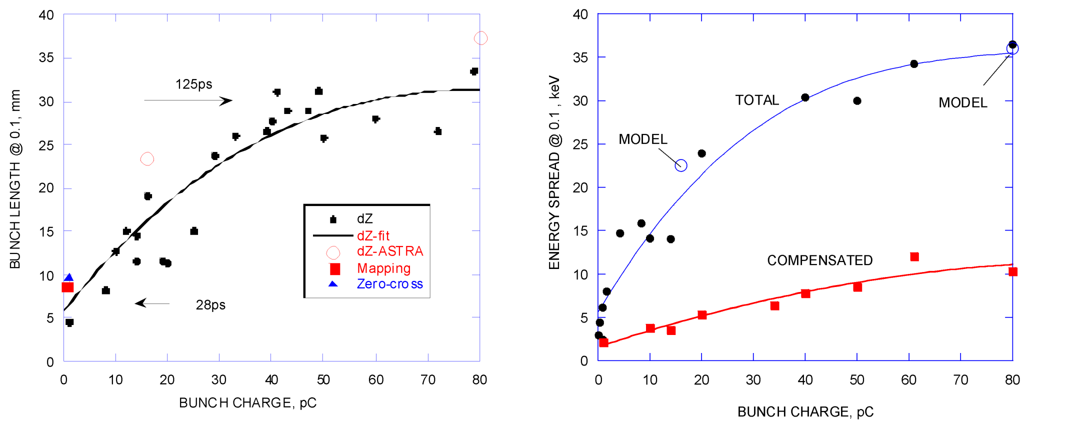

FIGURE 2. **(Left)** Bunch length at 10% of peak **(Right)** Total and tilt–compensated energy spread

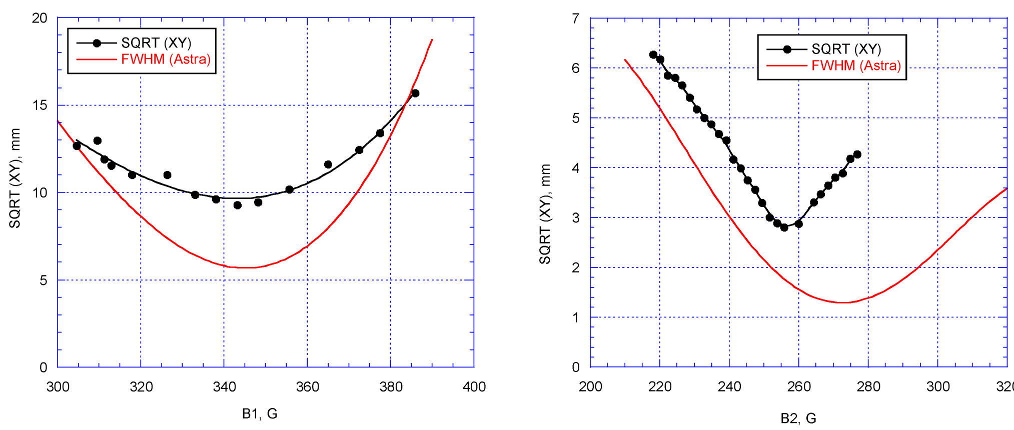

FIGURE 3. **(Left)** Beam size at the 1st solenoid **(Right)** Beam size at the 2nd solenoid

Having overcome the problems described earlier, an improved cathode activation process produced a *QE* of 3.5%, and a bunch charge of $> 100\,\text{pC}$ was achieved. This allowed injector performance to be measured at high bunch charge, and several highly–productive weeks of measurements were made to characterise the gun until field emission from the cathode again became a problem [10]. This had been managed to that point by setting the solenoid parameters to sub–optimum values. In summary:

- The gun has been repeatedly HV conditioned to 450 kV;

- The beam was fully–characterised operating at 350 keV (emittance, bunch length and energy spectra) in a wide range of bunch charges from 1 to 80 pC [10];
- Despite sub–optimal experimental conditions (e.g., field emission and non–uniform cathode *QE*), good agreement between ASTRA simulations and experimental data was found for the bunch length and energy spread (figure 2) and beam size (figure 3);
- Figure 4 compares some of the bunch characteristics measured using 7 ps and 28 ps drive laser pulses, at a bunch charge of 16 pC. This indicated little difference in bunch quality, though appreciable improvement in emittance is expected with longer laser pulses at higher bunch charges, in the ideal case of a near flat–top laser pulse [11];
- A complete review of the commissioning results is contained in references [10, 11].

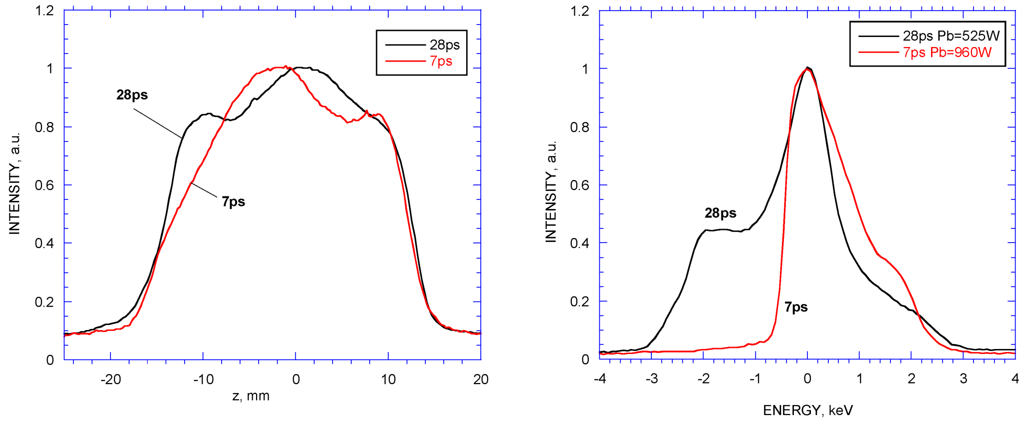

FIGURE 4. **(Left)** Bunch length with 7 and 28 ps laser pulses **(Right)** Compensated energy spread

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