FIRST RESULTS FROM THE ERL PROTOTYPE (ALICE) AT DARESBURY

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Abstract

The energy recovery linac prototype at Daresbury is now called ALICE (Accelerators and Lasers In Combined Experiments). This paper presents the results obtained in the past year, including the fourth period of gun commissioning. Following the completion of gun commissioning in November 2007, the dedicated gun diagnostic line was removed and the electron gun attached to the booster cavity and hence the rest of the machine.

The paper outlines some of the challenges experienced during the commissioning of both the photoinjector system and the superconducting cavities and presents the current status of the project as well as the very latest results from commissioning during the summer of 2008.

INTRODUCTION

Following the outcome of a review of synchrotron light sources in the UK, the proposed 4th Generation Light Source (4GLS) project was cancelled. The Energy Recovery Linac Prototype (ERLP), which was originally conceived as a prototype test-bed for the key concepts and technologies expected to feature in 4GLS, now has a broader role as an accelerator physics and technology test facility and for developing fourth generation light source science. Renamed ALICE (Accelerators and Lasers In Combined Experiments), the facility is being commissioned at present. The past year has been a frustrating combination of both progress and setbacks. A short productive period of gun commissioning has been book-ended with several vacuum problems with the gun. However in parallel to the commissioning work with beam, progress has also been made with the cryogenic and RF systems.

ALICE is based on a combination of a DC photocathode electron gun, a superconducting injector linac and a main linac intended to operate in energy recovery mode. These drive an IR-FEL, an inverse Compton Back-Scattering (CBS) x-ray source [1] and a terahertz beamline.

In addition, next year sees the start of construction the world's first non-scaling, Fixed-Field Alternating Gradient (FFAG) accelerator called EMMA, for which ALICE will act as an injector [2]. Fig. 1 shows the layout of both ALICE and EMMA.

PROGRAMME

At the end of 2007, the dedicated gun diagnostic beamline, with which the gun was commissioned and characterised, was removed as the rest of the machine was ready to accept its first beam. It was expected that operation in energy-recovery mode (initially without the beam-disrupting effects of the FEL) would have been achieved, followed by installation of the FEL components and progress with the CBS source and terahertz beamline made. Unfortunately at the time of writing ALICE is still on the brink of this step. This paper will record both the successes and the lessons learnt during this sometimes painful period.

OVERVIEW OF GUN COMMISSIONING

The first electron beam was obtained from the gun at 250 keV into a dedicated gun diagnostic beamline [3] in August 2006. Further operation of the electron gun was disrupted by various issues before the final (successful) period of operation at 350 keV towards the end of 2007.

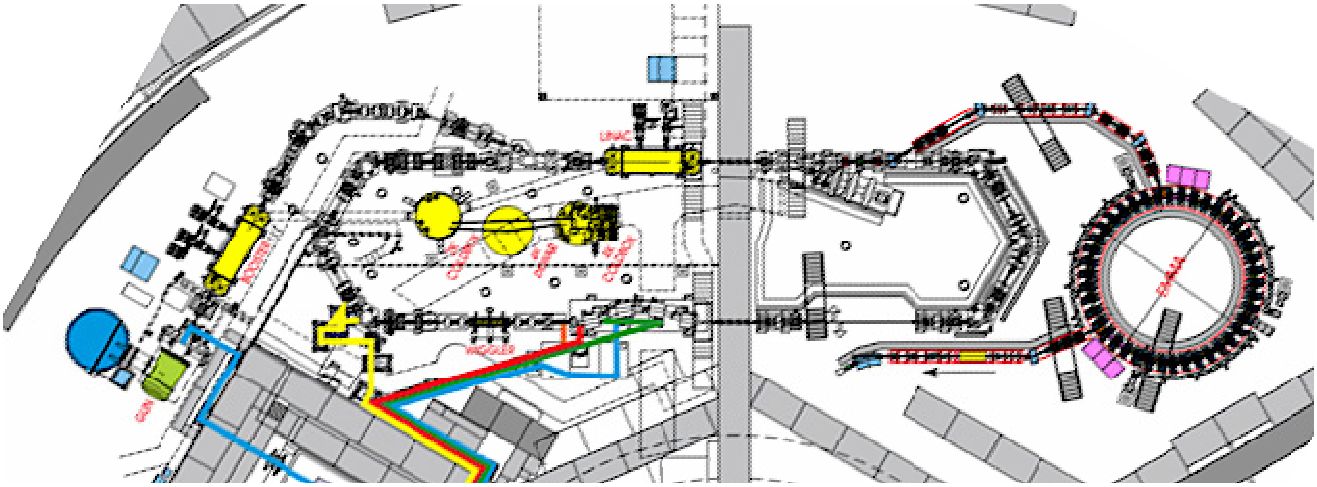

Figure 1: Layout of ALICE and EMMA.

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These problems can be summarised as either:

- Physical problems, such as vacuum leaks at brazed joints, valves or vacuum flanges, and current leakage along the ceramic surface due to contamination from braze particles;
- Procedural problems, such as over-caesiation of the cathode leading to contamination of the gun, particulate contamination leading to Field Emission (FE) from the wafer and wafer overheating during heat cleaning leading to halo generation.

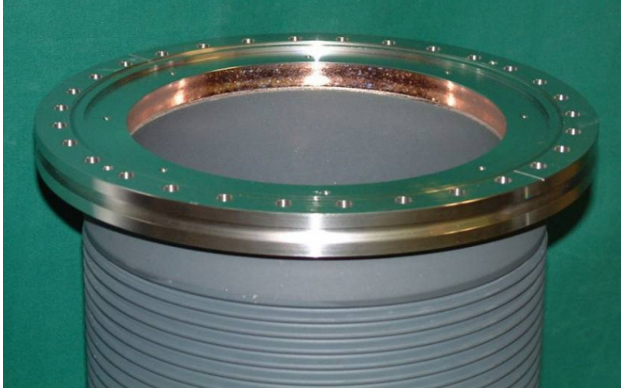

Figure 2: Gun ceramic showing problematic copper braze.

Vacuum Issues

One end of the gun ceramic can be seen in Fig. 2. This ceramic is different to that used at TJNAF, to whose design the gun was produced. A single piece of ceramic with a bulk resistivity was employed, rather than two smaller sections with a conductive coating. Although there are advantages to this method (particularly with respect to producing a constant voltage gradient along the ceramic), there were also problems with its production. Producing a vacuum-tight braze of the metal flange to each end of a large ceramic caused major delays in its procurement, and would cause further problems after installation in the gun. There have been a number of failures in the vacuum integrity of this joint during the cool down from the 250 celsius bake of the gun required to achieve the desired gun vacuum. In addition failures of both 12 and 14 inch Conflat flanges have also occurred at this point in the bake cycle. In order to minimise future occurrences of this problem, the following steps were taken:

- Removal of conflat joints where possible by in-situ welding of the flanges;
- Replacement of all 14 inch flange seals with high-temperature gaskets seals (from silver-plated copper to silver-plated silver alloy);
- Replacement of all bolts on large flanges with high tensile steel, silver coated bolts;
- Tightening of bolts on large flanges to known torque and post-bake testing;
- Reduction of the maximum gun bake temperature to 220 celsius.

In addition to the vacuum problems associated with the large-diameter seals and the ceramic braze, the failure of a feedthrough for a vacuum gauge and of a valve in the gas line used during cathode caesiation have disrupted progress. It seems that repeated baking (to >200 celsius) of these gun components will always be a potential problem. Thus a load-lock system for cathode exchange is currently being designed which will significantly reduce the number of gun bake cycles required.

Ceramic Contamination Issues

HV conditioning has also had to be aborted when the ceramic failed to hold off the voltage required for injector commissioning. The system was stripped down and an inspection of the ceramic indicated that the problem was due to contamination by particles of braze material on the ceramic surface.

Other Contamination Problems

The second and third periods of gun commissioning ended when the problem of field emission (limiting high voltage operation to 250 kV rather than the nominal 350 kV) and beam halo became insurmountable. Fig. 3 illustrates the typical level of halo seen. The relatively poor vacuum environment thus generated also led to a poor cathode lifetime.

It was believed that contamination of the gun with excess caesium released during cathode activation was the cause of the field emission. Thus it was decided to strip down and clean the gun. Prior to this, a new cathode activation process was devised, using a pulsed light source and lock-in amplifier, which allowed the caesium ion current to be measured, thus minimising excess caesium generation.

A further strip-down, clean and rebuild of the gun was necessary following the detection of hydrocarbon contamination in the residual gas analysis of the gun vacuum. The source of the contamination was traced quickly to the vacuum cleaning/bake process and the assessment criteria used to accept the components for installation. This resulted in further delays.

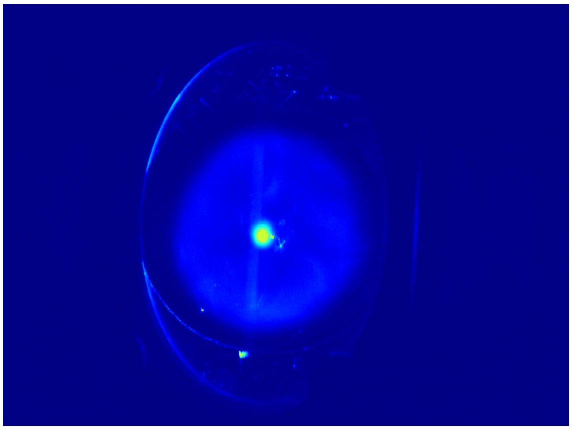

Figure 3. Screen image of the cathode showing laser-generated emission and the surrounding halo.

Commissioning Results

With these problems overcome, and the new cathode activation process producing a quantum efficiency (QE) of 3.5%, a charge per bunch of over 100 pC was achieved. This allowed the performance of the injector to be measured at high bunch charge during the first few shifts with beam. Several weeks of productive measurements of the properties of the gun were made [4] until field emission from the cathode became a problem again. This had been managed up to that point by setting the solenoid parameters to less than optimum values. Table 1 lists the results obtained compared to their specification.

Table 1: Gun Commissioning Results

Parameter	**Specification**	**Measured**	**Units**
Beam Energy	350	350	keV
Bunch Charge	80	>100	pC
Train Length	100	100	µs
Train Repetition Rate	20	20	Hz
Quantum Efficiency	~1	3.5	%
RF-laser timing jitter	<1000	650	fs

In summary:

- The gun can now be routinely conditioned up to 450kV;
- The beam was fully characterised (emittance, bunch length and energy spectra) in a wide range of bunch charges from 1 to 80pC;
- A good agreement between the ASTRA simulations and experimental data was found for the energy spread (Fig. 4) and bunch length (Fig. 5);

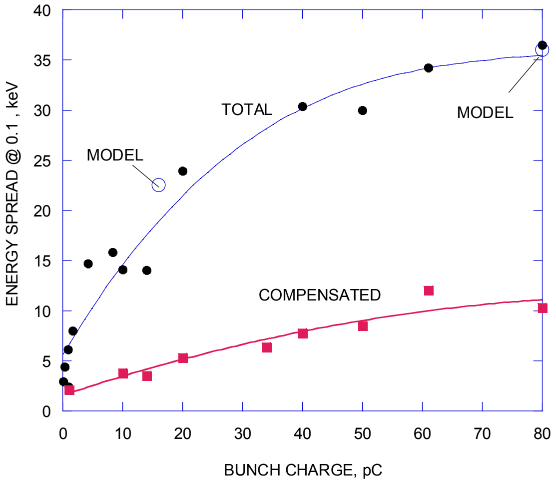

Figure 4: Comparison of the results from the ASTRA model with experimental measurements of the total and tilt-compensated energy spread as a function of the bunch charge, from [4].

- The emittance is however much larger than in simulations. This may be explained by the model lacking some factors and that the experimental conditions were not ideal (because of FE from the cathode, non-optimum setting of the solenoid fields, and macroscopically non-uniform QE on the cathode);
- A comparison of the bunch characteristics obtained with two different laser pulse lengths (7ps and 28ps), made at the modest bunch charge of 16pC. This indicates that there is little difference in bunch quality. The model indicates that there will be appreciable improvement in emittance with longer laser pulses at higher bunch charges, in the ideal case of a near flat-top laser pulse [5].

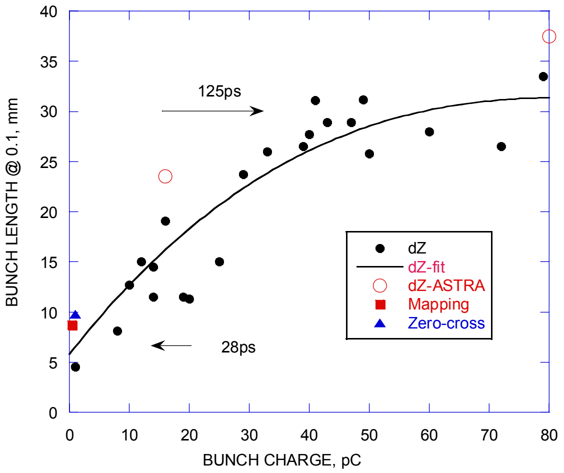

Figure 5: Bunch length at 10% of the peak value as a function of bunch charge from [4], comparing the results from the ASTRA model with three different measurement methods.

Fig. 6 shows the good agreement between the field in the first solenoid giving the minimum beamsize and the ASTRA model; Fig. 7 shows the slightly poorer results for the second solenoid.

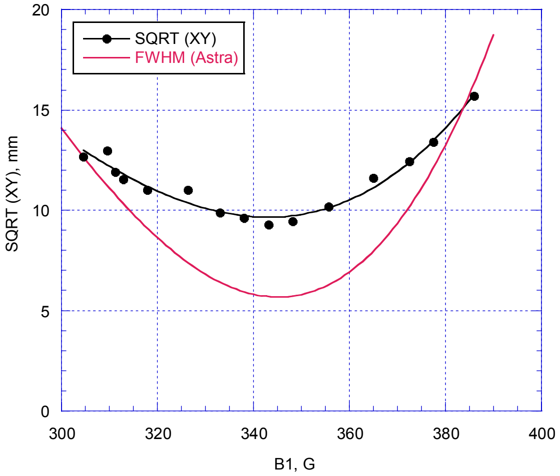

Figure 6: FWHM beam size at a bunch charge of 54 pC as a function of the first solenoid field compared to the results from the ASTRA model.

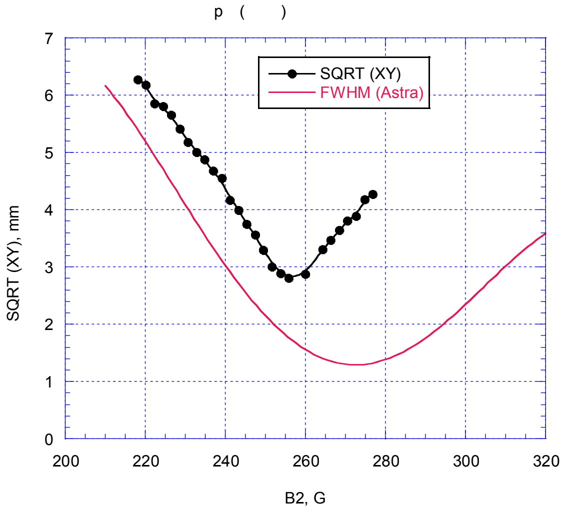

Figure 7: FWHM beam size at a bunch charge of 54 pC as a function of the second solenoid field compared to the results from the ASTRA model.

This is probably the first comprehensive investigation of the bunch parameters from this type of HV DC photogun.

CRYOSYSTEM COMMISSIONING

As expected with such a complex system, a number of problems with the cryogenic system had to be overcome before it met its operational specification [6]. These included repeated failures of the heater used to warm up the returning helium gas flow, suspected heat leaks and a lack of capacity in the 2K stage. As well as now having ample cooling capacity to sustain ALICE operation, the system has been pushed beyond its specified operational temperature to 1.8K, as part of a series of cryogenic tests aimed towards developing a thorough practical understanding of the change in superconducting cavity performance at lower operating temperatures.

SUPERCONDUCTING MODULES & RF SYSTEM

ALICE has two nominally identical superconducting modules, the first such devices to be obtained complete as commercial item, and manufactured by ACCEL. They consist of two 9-cell TESLA cavities in a cryomodule design from Stanford University and FZ Dresden. The two main issues with these modules have been:

- The reduction in performance between the vertical tests and when they are installed in ALICE;
- The very high levels of field emission (and therefore radiation) now being seen when operated at or below their intended gradient.

The test results from the cavities are summarised in Table 2, while the radiation measurements from the linac module can be seen in Fig. 8.

Table 2: Cavity Test Results

	Booster		**Linac**	
	Cavity 1	Cavity 2	Cavity 1	Cavity 2
Vertical Tests at DESY				
Eacc (MV/m)	18.9	20.8	17.1	20.4
Qo	5 x 10^9	5 x 10^9	5 x 10^9	5 x 10^9
Module Acceptance Tests at Daresbury				
Eacc (MV/m)	10.8	13.5	16.4	12.8
Qo	3.5 x 10^9 @ 8.2 MV/m	1.3 x 10^9 @ 11 MV/m	1.9 x 10^9 @ 14.8 MV/m	7 x 10^9 @ 9.8 MV/m
Limit-ation	FE Quench	FE Quench	RF Power	FE Quench

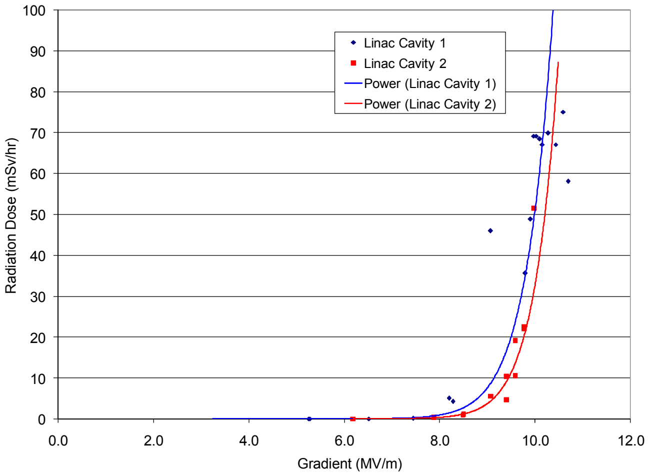

Figure 8: Radiation dose measured a short distance from the linac module.

The second issue has been mitigated by two strategies. The high radiation levels produced by operation of the booster (which requires a smaller gradient compared to the main linac) can be tolerated if some of the more sensitive equipment nearby is re-located. This module is planned to be replaced by the new module design currently being collaboratively developed [7] Secondly it was decided to surround the linac module with lead shielding to allow commissioning to continue in the short term. Further aggressive processing is now planned:

- Over longer conditioning periods;
- Varying frequency, pulse width and pulse repetition rate;
- CW conditioning (only possible at lower power levels);
- Possibly condition the cavity when warm;
- Introduce helium into the vacuum (this is risky as it is not always successful and would only be a last ditch attempt to improve the situation).

NEXT STEPS

Installation of photon beam transport systems required for the FEL output, Compton backscattering & electro-optic longitudinal diagnostic laser and terahertz beamlines are continuing in parallel to all the other activities where possible.

As the electron beam transport system and the RF system are now ready for beam, the gun diagnostic beamline has been removed and the gun connected to the completed accelerator. Unfortunately, there is not a working ceramic at present, except for two on loan from Stanford University, which had already been prepared for use. Because these ceramics are smaller in diameter they cannot be operated at the nominal gun voltage of 350 kV, they will be adequate for achieving the significant next step of energy recovery. They have already been conditioned to more than 270 kV.

Work is also underway with the supplier to resolve the brazing issues with the gun ceramic; a tapered joint is being developed along with material changes to some of the components.

First beam into the circulating part of the accelerator is expected in October 2008. This will be followed by:

- Fine tuning of the machine (injector tuning for minimum emittance, optimisation of energy recovery at nominal beam parameters, extensive beam measurements);
- Short pulse commissioning stage (longitudinal dynamics, electro-optical diagnostics);
- Energy recovery with FEL (after installation of the FEL and getting the first IR light from FEL).

Simultaneously with ALICE commissioning, the terahertz and infrared FEL research programmes will start, as well as CBS, using head-on electron-photon collisions.

Looking further ahead, in addition to the gun upgrade (the installation of a the load-lock system for cathode activation and exchange [8]) the improved high-current cryomodule will be installed.

SCIENCE PROGRAMME

In addition to the light derived directly from ALICE (mid-infrared FEL, CBS x-rays and terahertz radiation) an exciting research programme will also use combinations of these with a free-standing femtosecond tunable laser and the terawatt laser that is the photon source for the CBS, mostly for pump-probe experiments that will use one or another combination of light sources.

The ALICE capabilities will be extended into bioscience after completion of the Tissue Culture Laboratory.

CONCLUSIONS

The prime motivation for the construction and operation of ALICE is to gain experience in designing and operating the technologies which are critical to the success of future UK light sources. In the short period since the start of this project, a huge amount has been learnt, with more still to come. This has now been extended to include an exciting science programme.

Once fully operational, ALICE will be one of the few true electron beam test facilities available in the world. It will be used for development of photoinjector guns, diagnostics, superconducting linacs, synchronisation and for benchmarking codes.

In addition to the IR radiation generated by the FEL and the x-rays produced by the Compton backscattering source, a third beamline to utilise terahertz radiation from a dipole magnet in the bunch compressor is being built.

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