COMMISSIONING OF THE ERLP SRF SYSTEMS AT DARESBURY LABORATORY

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Abstract

The Energy Recovery Linac Prototype (ERLP) has been installed at Daresbury Laboratory and its baseline commissioning completed. The SRF systems for ERLP comprise two 9-cell, 1.3 GHz accelerating cavities in the injector (or Booster) cryomodule, which provide a nominal energy gain of 8 MeV for the injected 350 keV beam from the photo-injector. The beam is then accelerated in an identical two cavity cryomodule in the energy recovery main Linac, giving a final ERLP energy of 35 MeV. Each SRF accelerating cavity is powered by commercially available Inductive Output Tubes (IOTs) and the analogue LLRF control system is identical to that employed on the ELBE facility at FZD Rossendorf. This paper details the commissioning experience gained for these systems and highlights the ultimate performance achieved.

INTRODUCTION

The ERLP facility has recently been renamed to Accelerators and Lasers in Combined Experiments (ALICE) and will be referred to as such from here on in. The remit of the ALICE facility is to provide a R&D facility for the development of advanced accelerator systems; from high-intensity electron sources, CW SRF linac cryomodules, short pulse FEL undulators and associated optical diagnostics [1].

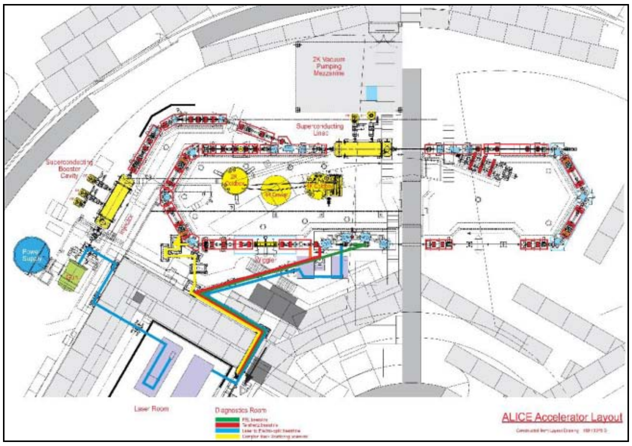

Figure 1: ALICE Machine Layout.

Figure 1 shows a schematic layout of the ALICE facility, identifying the main accelerator components and Table 1 details some of the nominal machine parameters. The electron gun adopted is a copy of the JLab IR-FEL 350 keV DC photo-injector, utilising GaAs wafer cathodes, which on ALICE is excited by an 81.25 MHz mode locked drive laser. In combination, a chopper and shutter ensure that the drive system is capable of delivering three basic photoinjector operating modes:

- single bunches at 20 Hz;
- short (20 μs) or
- long (100 μs) pulse trains.

Table 1: ALICE Machine Parameters

Parameter		**Units**
Nominal Gun Energy	350	keV
Injector Energy	8.35	MeV
Circulating Beam Energy	35	MeV
RF Frequency	1.3	GHz
Bunch Repetition Rate	81.25	MHz
Nominal Bunch Charge	80	pC
Maximum Train Length	100	μs
Maximum Train Repetition Rate	20	Hz
Maximum Average Current	13	μA

In each case the bunch charge available is up to 80 pC, equivalent to a CW average current of 6.5 mA although the actual average current is limited to about 13 μA due to the 0.2 % duty factor employed. Beam commissioning of the photo-injector has been completed and is reported elsewhere at this conference [2].

ALICE SRF SYSTEM

Table 2: ALICE RF System Requirements

	Booster		ERL Linac	
	Cav1	Cav2	Cav1	Cav2
Eacc (MV/m)	4.8	2.9	12.9	12.9
Qo	$5x10^9$	$5x10^9$	$5x10^9$	$5x10^9$
Qe	$3x10^6$	$3x10^6$	$7x10^6$	$7x10^6$
Power (kW)	32	20	6.2	6.2
Power Source	2 x e2v	CPI	e2v	Thales

0.1ms bunch trains @ 20 Hz repetition rate

In the Booster SRF injector cryomodule, accelerating gradients of 4.8 and 2.9 MV/m for the 1st and 2nd cavities, (which for an active cavity length of 1.036m), give a total module energy gain of 8 MeV. The beam is then fed to the Energy Recovery Linac (ERL), where its energy is increased up to 35 MeV by an identical 2-cavity cryomodule, providing gradients of 12.9 MV/m per cavity. Table 2 shows the individual cavity operating parameters for both the Booster and ERL cryomodules,

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highlighting also the different types of RF power sources utilised. Both cryomodules were fabricated in industry by ACCEL Instruments, GmbH, under commercial licence from FZD Rossendorf. From the outset, ALICE has been developed as an R&D facility, whereby modified sub-systems can be implemented and thoroughly evaluated with beam; an example of which is detailed here [3]. As part of this remit, it was decided that a variety of IOT solutions would be adopted, to allow Daresbury staff to gain valuable operational experience with a variety of different configuration power sources.

The high power RF configuration for the Booster module is shown in Figure 2, which in order to provide the necessary power of 30 kW (for cavity 1) and 20 kW (for cavity 2); two 116LS, 16 kW CW, e2v IOT's are combined and a single CHK51320W, 30 kW CW, CPI IOT utilised, for each cavity respectively. The low duty factor employed ensures that each IOT, has enough RF power overhead to comfortably achieve what is needed for the ALICE injector cryomodule.

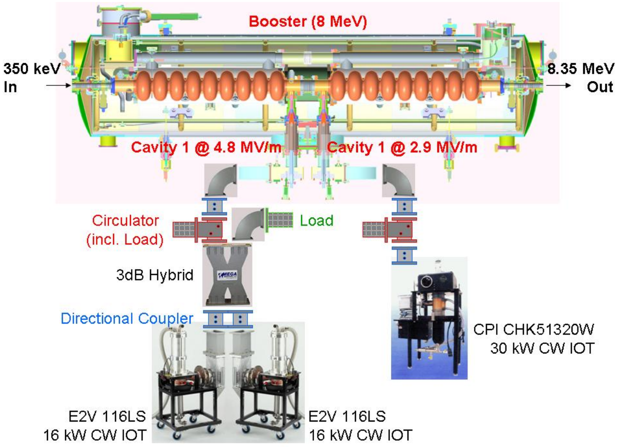

Figure 2: Booster RF Configuration.

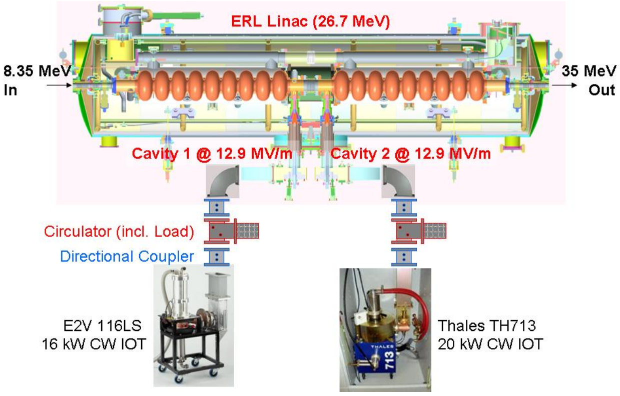

Figure 3: ERL Module RF Configuration.

For the ERL module, the high power RF system comprises a single 116LS e2v IOT for cavity 1 and a single TH713, 20 kW CW, Thales IOT for cavity 2 (see Figure 3). Although for optimised ERL operation, the RF power requirement for each cavity is relatively low at ~6.2 kW, each IOT should provide sufficient overhead to compensate for excessive microphonics and also sustain circulating beam (to some degree) when the beam is not precisely phase synchronised in the ERL ring. The stipulated RF power for this module, assumes a 25 Hz peak microphics susceptibility, however provisional measurements have indicated a much better performance, of < 10 Hz. If the Qe can be increased to 1e7 for these cavities, a further RF power reduction can be anticipated, down to ~4.4 kW, based on Equation 1.

$$P_g = \frac{V_{acc}^2}{4\frac{R}{Q}Q_e}\left\{1+\left(\frac{2\Delta\varpi Q_e}{\varpi_c}\right)^2\right\} \qquad (1)$$

For an optimum cavity external Q_e for ERL accelerators - as the effects of beam loading cancel in the accelerating and decelerating phases, the chosen gradient and peak microphonics cavity detuning ($\Delta\varpi$) become the driving mechanisms for defining the optimum cavity coupling and corresponding generator power (P_g). An optimum cavity Qe for the above parameters is 6.5e7, requiring an RF power of only ~1.3 kW. Once beam commissioning through the ERL module is initiated on ALICE, it is anticipated that a full Qe characterisation will be performed to verify these predictions.

CRYOMODULE COMMISSIONING

The ALICE cryogenic system commissioning was completed by May 2007 and has been reported elsewhere [4]. SRF module commissioning and formal acceptance testing started with the ERL module on 22/5/2007.

ERL Module Testing

Cavity 1 conditioned very quickly (within 2 days) upto 12 MV/m in CW-mode, until problems were observed with the cavity tuner mechanism. On inspection, it was found that the tuner drive rod mechanism had worn and subsequently stuck. Although this did not prevent continuation of RF conditioning, it did require a warm up of the cryomodule to affect a repair later.

This was performed at Daresbury by ACCEL personnel, requiring the removal of the module end-cap to access the failed motor actuator. Once repaired, a maximum peak gradient of 12.8 MV/m at 10% duty factor was achieved on 23/8/2007, limited by a field emission (FE) induced quench. Problems with the cryogenic-plant mass flow diagnostic, in terms of its resolution at such low duty factors, has prevented accurate load measurements from being performed (for all cavities) and so conventional Q_o vs E_{acc} characterisation plots are not yet available.

The ERL module cavity 2 started testing on 24/5/2007 however at 9 MV/m in CW-mode, excessive heating was observed on the input coupler cold and warm windows. With the input waveguide disconnected, it was found that a co-axial spring was dislodged, reducing the RF contact in the coupler coax (see Figure 4). Once replaced, commissioning resumed without further incidents and on 24/8/2007, a peak gradient of 16.4 MV/m was achieved with 10% duty factor, limited by available RF power.

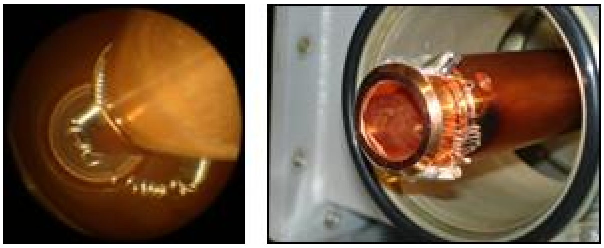

Figure 4: ERL Linac Coupler Spring Inspection.

Booster Module Testing

Owing to the lower Qe for the Booster module cavities, RF testing was initiated in pulsed-mode for cavity 2 on 15/8/2007 and within the first 24 hours reached 10 MV/m and on 22/8/2007 reached its maximum gradient of 13.5 MV/m at 10% duty factor, limited by FE induced quench.

Cavity 1 also conditioned very quickly from 16/8/2007, reaching a maximum peak gradient of 10.8 MV/m at 10% duty factor on 17/8/2007, limited by FE induced quench.

FIELD EMISSION LIMITATIONS

Each ACCEL SRF cavity has been vertically tested at DESY under contract from ACCEL, between July-Dec 2005 in CW-mode and showed excellent performance, without onset of FE (see Table 3). The integrated cavity performance however, has not matched this level, with each cavity showing a relatively early onset for FE (at ~5-7 MV/m), limiting by FE induced quench at comparatively low gradients, even at a 10% duty factor.

Table 3: SRF Cavity Vertical Test Results

Vertical tests at DESY (July – Dec 2005)				
	Booster		Linac	
	Cavity 1	Cavity 2	Cavity 1	Cavity 2
Eacc (MV/m)	18.9	20.8	17.1	20.4
Qo	$5x10^9$	$5x10^9$	$5x10^9$	5×10^9
Module acceptance testing (May – Sept 2007)				
Eacc (MV/m)	10.8	13.5	16.4	12.8
Qo	$3.5x10^9$@ 8.2MV/m	$1.3x10^9$@ 11MV/m	$1.9x10^9$@ 14.8MV/m	$7.0x10^9$@ 9.8MV/m
Qe	$2.5x10^6$	$2.6x10^6$	$6.4x10^6$	$4.7x10^6$
Limitation	Quench	Quench	RF Power	Quench

Table 3 also shows a summary of the high power testing performed from May–Sept 2007. It is not fully understood as to why the cavities show a limitation due to FE, however the fact that all four cavities behave similarly with regards to onset of FE activity, indicates a potential systematic problem during the processing and/or assembly at ACCEL. Attempts have been made to quantify the magnitude of the FE problem, particularly for the higher gradient ERL module cavities. A concern being, that local electronics in the vicinity of the module will require substantial shielding to prevent radiation damage with prolonged use. Figure 5 shows measurements from an ionisation chamber radiation monitor, positioned 7 m away from cavity 1 in the ERL module, as gradient is increased. At 7 MV/m, the peak radiation reaches 9.2 mSv/hr, which then starts to saturate at 13 mSv/hr when the gradient reaches 9 MV/m.

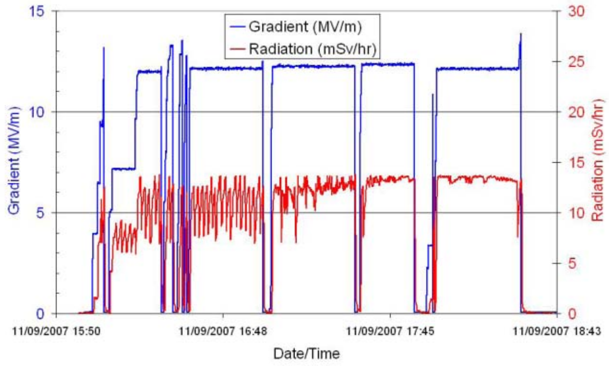

Figure 5: Field Emission Induced Radiation.

At 9 MV/m, electronics 7 m away will have an estimated lifetime of only 7,700 hrs (assuming a 100 Gy accumulated dose fatality limit). On ALICE, the LLRF electronics is positioned ~2.5 m away from cavity 1 and so scaling this measurement, using the inverse square power relationship vs distance, we can estimate a radiation level of ~100 mSv/hr, which corresponds to a LLRF electronics lifetime of ~1,000 hrs (see Figure 6). Lifetime will actually be much shorter at the required operating gradient of 12.9 MV/m per cavity.

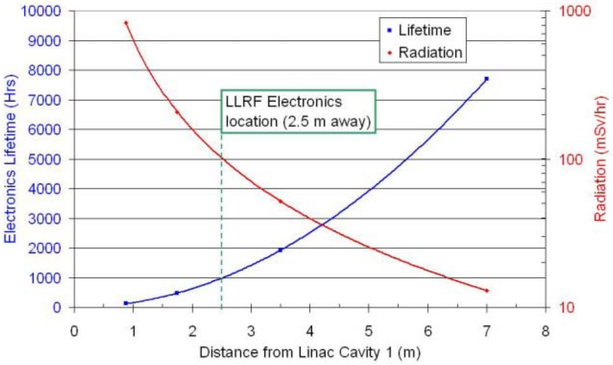

Figure 6: LLRF Electronics Lifetime at 9 MV/m.

A long-term solution to this FE problem is being investigated, however in the short-term lead shielding of the module itself has been implemented to allow for energy recovery demonstration of ALICE later this year.

REFERENCES

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