SRF SYSTEM OPERATION ON THE ALICE ERL FACILITY AT DARESBURY

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Abstract

ALICE (Accelerators and Lasers in Combined Experiments) is a 35 MeV energy recovery linac based light source. ALICE is being developed as an experimental test-bed for a broad suite of science and technology activities that make use of electron acceleration and ultra-short pulse laser techniques. ALICE utilises two super-conducting radio frequency (SRF) cryomodules, each with two identical 9-cell, 1.3 GHz cavities that are powered by 5 inductive output tubes (IOTs) from 3 different commercial suppliers. The experience gained in both commissioning these systems and ultimately operating for energy recovery is presented. Developments for a new ERL cryomodule upgrade for ALICE are also described.

INTRODUCTION

ALICE, formerly known as ERLP [1], is a new R&D facility currently being commissioned at Daresbury Laboratory. The accelerator is an energy recovery SRF linac operating at the nominal beam energy of 35 MeV. A high voltage DC photoelectron gun operates at a nominal voltage of 350 kV and bunch charge of 80 pC. The bunch trains can be of variable length from a single bunch regime to 100 μs with a bunch repetition frequency of 81.25 MHz within the train. The train repetition frequency can also be varied from 1 - 20 Hz.

In addition to the accelerator, several light sources will be available for conducting a variety of R&D research, including pump-probe experiments. These are (i) an IR FEL with wavelength of ~4 μm; (ii) a THz source with coherent enhancement of the radiation intensity due to sub-picosecond bunch lengths generated by ALICE; (iii) a Compton Backscattering (CBS) X-ray source with photon energy of 15 or 30 keV depending on the collision angle between the photons and electrons. The CBS source is powered by a terawatt IR femtosecond laser that can also be used as a stand-alone light source for a variety of experiments.

PRESENT ALICE STATUS

Full energy recovery and demonstration of the coherently enhanced THz radiation were successfully achieved on ALICE by the beginning of 2009. The injector can now reliably deliver beams with bunch charges well in excess of 80 pC and with the design bunch structure, i.e. 81.25 MHz bunches in trains up to 100 μs, repeating at 1 - 20 Hz. However, due to a number of mostly technical problems, some of the other ALICE design parameters have not been achieved at present (see Table 1).

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

The gun operating voltage of 350 kV was initially used for gun commissioning [2] but, after several failures of the high voltage insulating ceramics [3], it was necessary to install a more robust but smaller inner diameter ceramic, which was kindly provided by Todd Smith (Stanford University), which reduced the maximum gun operating voltage to ~250 kV. Furthermore, a field emitter on the GaAs cathode wafer located close to its centre necessitated a reduction of the gun voltage down to 230 kV. This field emitter is likely to be responsible for a hole in the quantum efficiency map of the cathode. This hole becomes more pronounced towards the end of the cathode activation cycle but virtually disappears after the cathode re-caesiation (Figure 1). An improved 500 kV ceramic insulator is currently being developed and manufactured in collaboration with Jefferson Laboratory and Cornell University that will restore the ALICE gun nominal voltage to 350 kV.

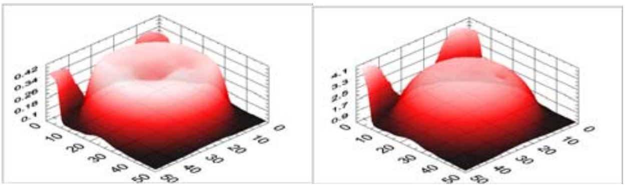

Figure 1: QE maps at end of the activation cycle before re-caesiation (left) and after full cathode activation including wafer heat cleaning treatment (right).

Due to excessive field emission from the main linac module, designed to bring the beam energy to 35 MeV, the beam energy was initially reduced to 21 MeV for the machine commissioning conducted for first energy recovery demonstration. The corresponding beam energy after the injector was 4.8 MeV to allow injection and extraction chicanes to operate correctly. Recent work on extensive SRF linac cavity conditioning, improvements in the cryogenic system and optimisation of the linac operating parameters has allowed ALICE to operate at a

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higher beam energy of up to ~30 MeV with 40 pC bunch charge in a non-energy recovery mode (the latter will be used for the CBS experiments).

ENERGY RECOVERY AND BEAM CHARACTERISATION

The gun was commissioned and the 350 keV electron beam fully characterised at a range of different bunch charges of up to 80 pC [4]. Initially, full energy recovery was established at 21 MeV beam energy and several bunch charges up to 20 pC. This is illustrated by the RF power demand signals from the two superconductive cavities of the main linac (Figure 2). Higher bunch charges were not not attainable at this time, due to beam loading effects in the injector SRF booster cavities.

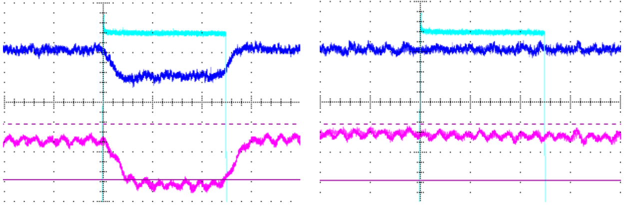
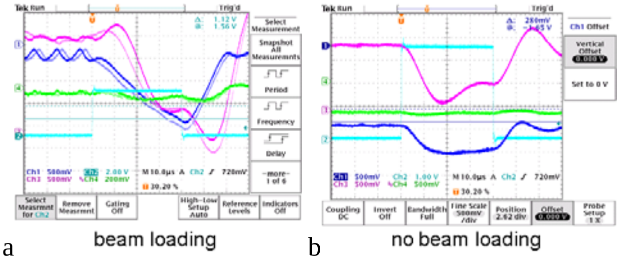


Figure 2: Main linac RF power demand signals: without (left) and with (right) energy recovery.

Beam loading in the booster cavities was clearly visible on the LLRF signals at train lengths of a few tens of microseconds and bunch charges above 10 pC (see Figure 3a). The major impact of this on the beam was that the beam energy towards the end of the macropulse was lower than at the beginning by a few percent. The effect of beam loading was also observed on the Faraday cup located in a dispersive section of the injector beam line. In the presence of the beam loading, the current measured by the Faraday cup is not constant because the beam sweeps across the cup aperture due to such change in the mean energy during the train length.



a beam loading b no beam loading

Figure 3: ALICE SRF cavity LLRF gradient (dark blue) and Phase (purple) compensation signals a) WITH beamloading evident and b) WITHOUT, to keep beam energy (green) stable.

Extensive work on optimisation of the LLRF system response and external quality factors of the booster cavities has allowed extended operation of the machine to ~40 pC bunch charge and up to 100 µs train lengths in an energy recovery regime (see Figure 3b).

Towards the end of the latest commissioning period, after elimination of a minute vacuum leak detected in the gun vacuum vessel followed by a full cathode activation, the achieved cathode quantum efficiency was reliably ~4%, and the cathode dark 1/e lifetime exceeded 800 hours. This will ensure ALICE operation at nominal bunch charges of 80 pC for prolonged periods of time, expected to be 2-4 weeks, between cathode re-caesiations.

ALICE SRF SYSTEMS

For ALICE design parameters, Booster SRF injector cryomodule, with accelerating gradients of 4.8 and 2.9 MV/m for the 1st and 2nd cavities, (cavity active length of 1.036m), gives a total module energy gain of 8 MeV. 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 linac cavities, highlighting also the different types of RF power sources utilised.

Table 2: ALICE RF system requirements

	Booster		ERL Linac	
Cavity	BC1	BC2	BC3	BC4
Eacc (MV/m)	4.8	2.9	12.9	12.9
Qo	$5x10^9$	$5x10^9$	$5x10^9$	$5x10^9$
Qe	$7.4x10^5$	$4.5x10^5$	$7x10^6$	$7x10^6$
Power (kW)	32	20	6.2	6.2
Power Source	2 x e2v IOTs	CPI IOT	e2v IOT	Thales IOT

0.1ms bunch trains @ 20 Hz repetition rate

Both cryomodules were fabricated in industry by ACCEL Instruments, GmbH (now Research Instruments, GmbH), under commercial licence from FZD Rossendorf [5]. From the outset, ALICE has been developed as an accelerator R&D facility, whereby modified sub-systems can be implemented and thoroughly evaluated with beam. 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.

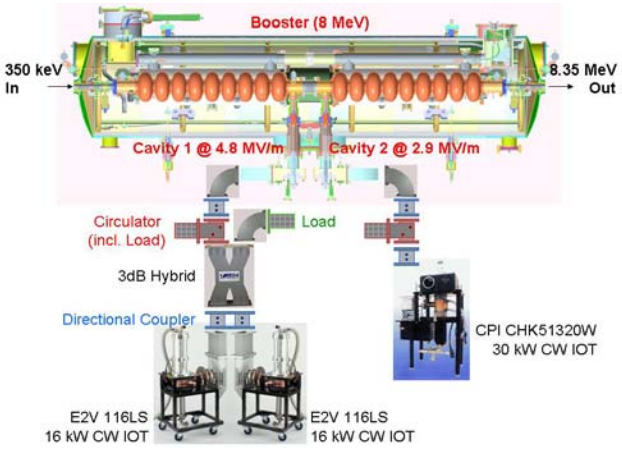


Figure 4: Booster RF configuration.

The high power RF configuration for the Booster module is shown in Figure 4, which in order to provide the necessary power of 30 kW (BC1) and 20 kW (for BC2); two e2v 116LS, 16 kW CW, IOT's are combined and a single CPI CHK51320W, 30 kW CW, IOT is 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.

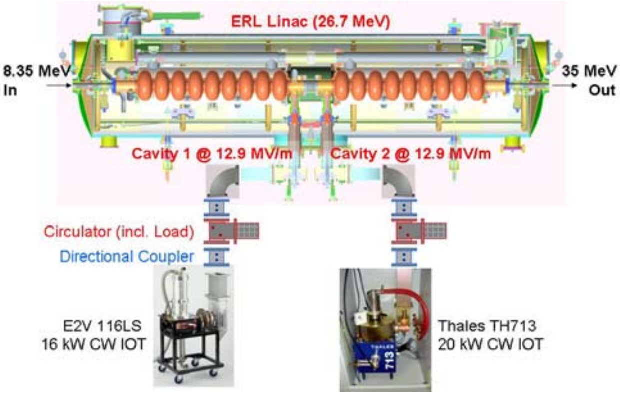


Figure 5: ERL module RF configuration.

For the ERL module, the high power RF system comprises a single e2v 116LS IOT for LC1 and a single Thales TH713, 20 kW CW, IOT for LC2 (see Figure 5). 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 it 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.

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

FIELD EMISSION LIMITATIONS

All of the ALICE SRF cavities have been vertically tested at DESY under contract from ACCEL, between July-Dec 2005 in CW-mode and showed excellent performance, with acceptable levels of field emission (FE) observed (see Table 3). The integrated cryomodule performance however, have not matched this level, with each cavity showing a relatively early onset for FE (from ~7 MV/m onwards), limiting by FE induced quench at comparatively low gradients, even at a 10% duty factor.

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 cryomodule assembly at ACCEL. Attempts have been made to quantify the magnitude of the FE problem, particularly for the higher gradient ERL module linac cavities. A major concern being, that local electronics in the vicinity of the module will require substantial shielding to prevent radiation damage with prolonged use.

Table 3: SRF cavity vertical test results

Vertical tests at DESY (July – Dec 2005)				
	Booster		Linac	
Cavity	BC1	BC2	LC1	LC2
Eacc (MV/m)	18.9	20.8	17.1	20.4
FE Onset	15	13.4	9.8	14
Qo	5×10^9	5×10^9	5×10^9	5×10^9
Module acceptance testing (May – Sept 2007)				
Eacc (MV/m)	10.8	13.5	16.4	12.8
Qo	3.5×10^9@ 8.2MV/m	1.3×10^9@ 11MV/m	1.9×10^9@ 14.8MV/m	7.0×10^9@ 9.8MV/m
Qe	2.5×10^6	2.6×10^6	6.4×10^6	4.7×10^6
FE Onset	8	8	9	7
Limitation	Quench	Quench	RF Power	Quench

Figure 6 shows measurements from an ionisation chamber radiation monitor, positioned 7 m away from LC1 in the ERL module, as gradient is increased. At 7 MV/m, the peak radiation jumps to 9.2 mSv/hr, which then quickly saturates the radiation monitor at 13 mSv/hr when the gradient reaches 9 MV/m. 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 the ERL linac cryomodule 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 7). It must be noted however, that the expected lifetime will actually be much shorter at the required operating gradient of 12.9 MV/m per cavity.

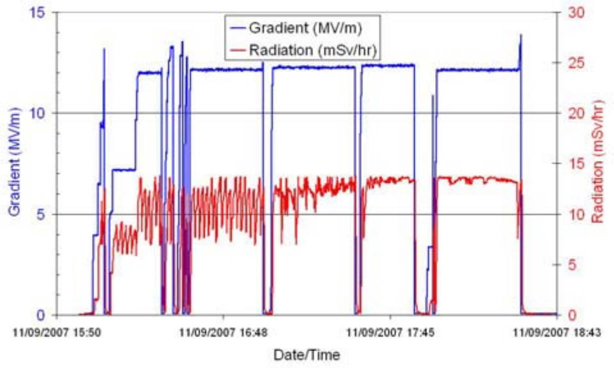


Figure 6: Field emission induced radiation.

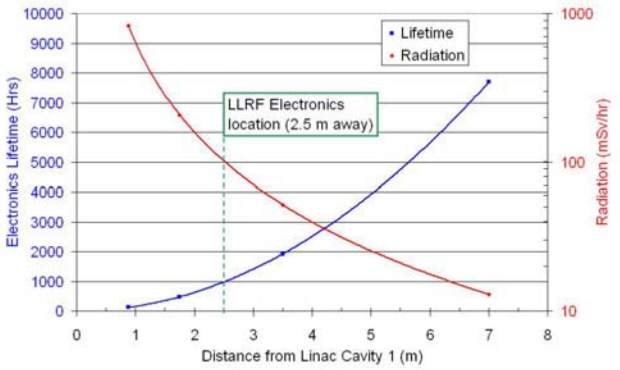


Figure 7: LLRF electronics lifetime at 9 MV/m.

A long-term solution to this FE problem is being investigated, such as helium-processing or repeated cavity high pressure rinsing, however in the short-term, lead shielding of the module itself has been implemented.

CRYOMODULE COMMISSIONING

The ALICE cryogenic system commissioning was completed in May 2007 and has been reported elsewhere [6]. SRF module commissioning and formal acceptance testing started with the ERL module on 22/5/2007.

Booster Module Testing

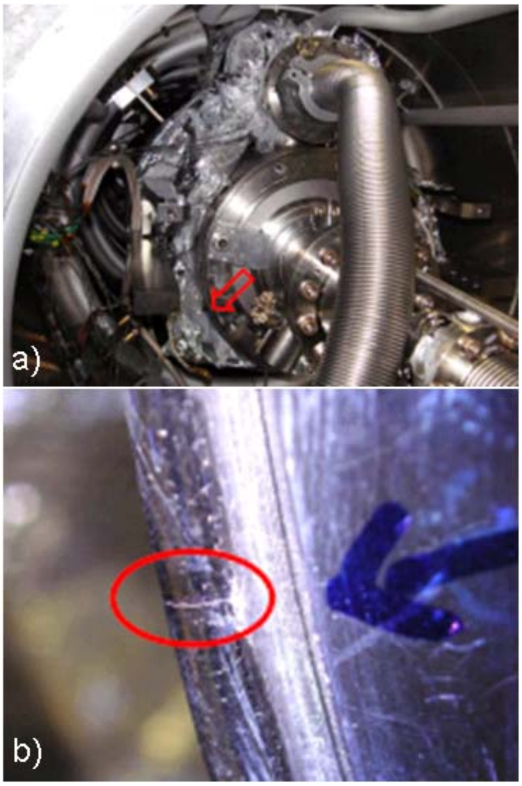


Figure 8: a) Booster cryomodule cavity inspection and b) localised Helium vessel leak location.

Owing to the lower Qe for the Booster module cavities, RF testing was initiated in pulsed-mode for cavity BC2 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. BC1 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.

In October 2007, it was observed during a cooldown, sequence that the booster module isolation vacuum remained at a very high pressure and once at 80 K was in fact four decades higher in pressure compared to the main linac module. The cooldown was subsequently aborted and the module warmed up to facilitate fault diagnosis. It was identified that a leak was evident between the LHe and isolation vacuum circuits. The module was then returned to ACCEL for repair. With the module end-cap removed, subsequent inspection revealed a fracture in the helium can electron beam weld on cavity 2 (BC2) as shown in Figure 8a) and b). A repair weld was performed in-situ and the module returned for re-installation on ALICE in early 2008. Once installed, the module was cooled down and leak checks revealed a successful repair. Normal operation of the module was then resumed.

A year later in October 2008, extensive commissioning of the ALICE high power IOTs and high voltage power supply (HVPS) unit was taking place. During which time, a fault occurred resulting in overheating of cavity BC2's warm window (see Figure 9). On investigation, it was revealed that RF power at the time of the failure was very low at ~ 300 W, however all of the module protection systems were inactive, following an inadvertent change in the system configuration. Consequently, the isolation vacuum, warm window temperature and arc detector protection signals did not initiate a system shut-off.

Figure 9: Booster cavity 2 (BC2) warm window failure.

It is still however not understood how such low level RF power could have caused such a failure under these conditions. Suspicion of an IOT instability, generating higher power outside of the 1.3 GHz detected power, or otherwise some form of foreign substance becoming attached to the Rexolite window resulting in localised heating and thermal runaway, are our only possible explainations. As a consequence of this event, the ALICE machine protection implementation and procedures have been substantially improved so as to prevent this type of failure occurring in the future.

ERL Module Testing

From 22/5/2007, cavity LC1 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 (see Figure 10). Although this did not prevent continuation of RF conditioning, it did require a warm up of the cryomodule to affect a repair.

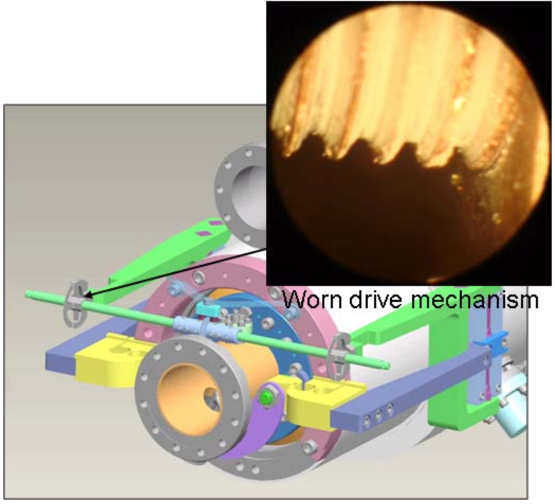


Figure 10: LC1 worn tuner drive mechanism.

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. Limitations with the ALICE 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 easily attainable.

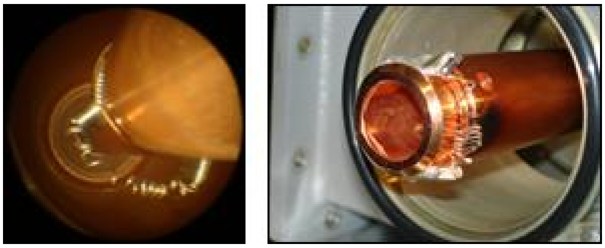


Figure 11: ERL linac LC2 coupler spring inspection.

The ERL module cavity LC2 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 11). 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.

INTERNATIONAL CRYOMODULE DEVELOPMENT

The collaborative development of an optimised cavity/cryomodule solution for application on ERL accelerators has now progressed to final assembly and testing of the cavity string components and their subsequent cryomodule integration [7]. To date, the international partners who have participated in this collaborative development; Daresbury Laboratory, Cornell and Stanford Universities, Lawrence Berkeley Laboratory, FZD Rossendorf, DESY and more recently TRIUMF, have identified appropriate sub-system solutions to achieve the fundamental requirements for this new cryomodule design (see Figure 12), which will be installed on the ALICE ERL accelerator at Daresbury Laboratory and validated with beam in 2010.

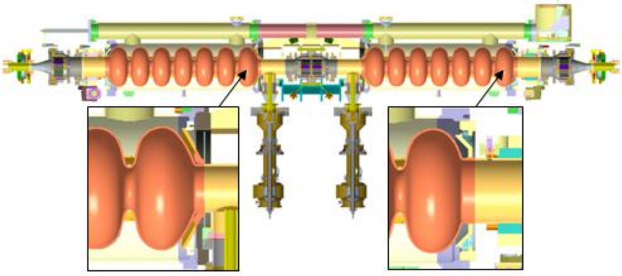


Figure 12: New cryomodule configuration.

Cavity Fabrication Status

Two 7-cell niobium (Nb) cavities have been provided by DESY. These cavities were originally fabricated and tested together in TTF-I as a superstructure. Subsequently the cavities have been sent to Cornell for modification. LBNL, Daresbury and Cornell have developed a new design for the cavity end-groups and associated beam-pipes, in order to propagate higher order mode power to ferrite-lined beam-pipe loads, similar to the HOM absorbers used for the Cornell Injector Cryomodule.

Figure 13: 7-cell cavity after final electron-beam welding.

Buffered Chemical Polishing (BCP) final treatment, since the operating gradient is of the order of 20 MV/m, has been performed for the first modified cavity (see Figure 13). All flange designs were changed to knife-edge conflat interconnections, with brazing to Nb beam tubes similar to that used for the Cornell Injector cryomodule. The Titanium-Helium vessel and gas return pipe designs were modified to conform to the FZD Rossendorf ELBE cryomodule configuration [8].

So far one of the two cavities has been tested twice in a vertical cryostat (see Figure 14). The first test was performed after light BCP (10 to 15 microns of surface material removal) and HPR. A low field Q of the π-mode was measured to be 2.2×10^9 at 1.8 K. In this test we were not able to couple to all modes of the fundamental pass-band, hence we could not localize the cells responsible for the low Q. Also, the coupling was too weak to perform reliable RF field calibration and Q vs E measurement. After an additional light BCP (about 20 microns) and HPR, the cavity was re-tested. Again, a low Q (1.5×10^9 at 2 K) was measured for the π-mode. This time however, we were able to measure low field Q's of all seven fundamental pass-band modes. These measurements indicated that excessive losses in the end cell(s) are responsible for the low quality factor of modes with high fields in those regions. The $\pi/7$ mode, which has very low fields in the end cells, has a rather decent Q of 1.1×10^{10}.

The second cavity is in the final stage of preparation for a vertical test. The results of which, along with close examination of the first cavity's end groups will guide further decisions for repeated tests.

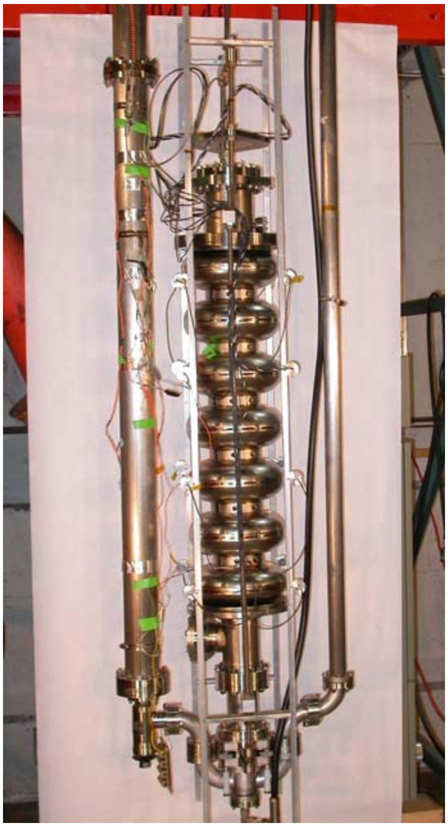


Figure 14: First cavity prepared for vertical test at Cornell.

Ancillary Components Status

The blade tuner used for the TTF superstructure test has been changed to a modified Saclay II tuner design so that it would fit in the chosen cryomodule envelope. The input couplers and HOM loads are chosen to be identical to the proven devices used in the Cornell Injector module (see Figure 15). The design of the cavity string is carefully laid out to fit inside the cryomodule.

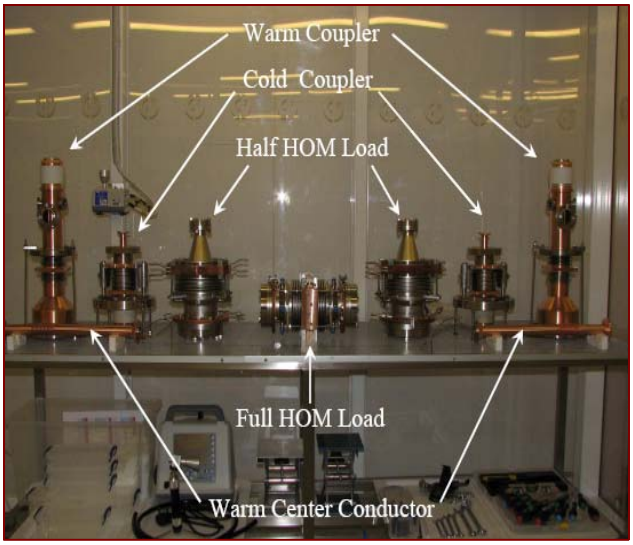


Figure 15: HOM absorber and input coupler components in the Daresbury cleanroom.

Both input couplers have now been baked and assembled in a back-to-back configuration, onto a high power coupling box to allow for high power conditioning (see Figure 16).

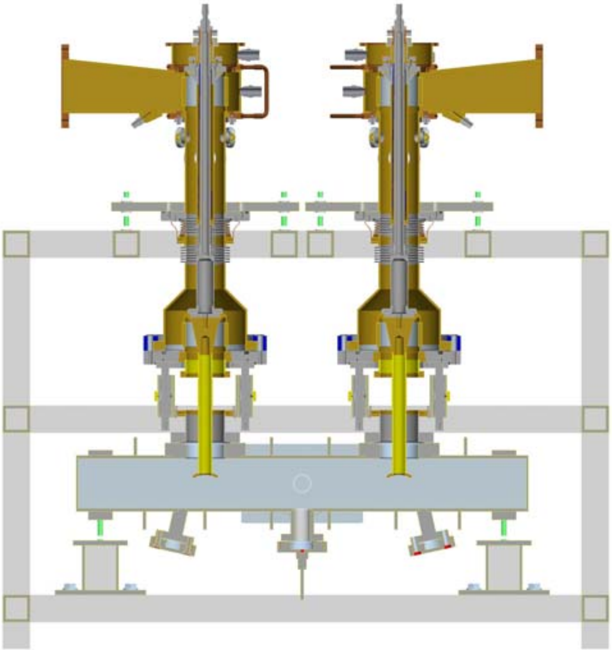


Figure 16: Input coupler RF conditioning assembly.

RF power will be limited to ~10 kW CW during conditioning, as gaseous helium (GHe) cooling will not be available. Pulsed conditioning will then be performed up to the 30 kW limit of the test IOT at Daresbury (see Figure 17).

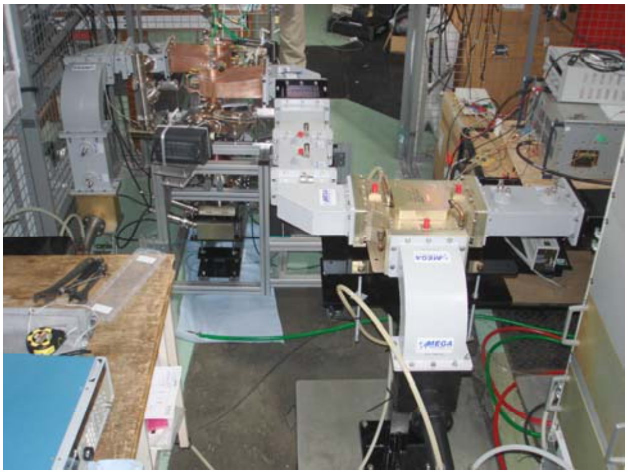


Figure 17: High power coupler test stand.

By utilisation of a cantilevered rail system, the sealed cavity string assembly can be rolled into the outer cryomodule vessel (see Figure 18). Once positioned, the cavity string is then locked in by a single titanium locking fixture, which then provides a longitudinal constraint on the mechanical component contraction when the cryomodule is cooled to cryogenic temperatures. In this way, the contraction occurs from both ends of the cryomodule towards this central, locked position. This ensures that the input couplers (which are positioned very close to the central locked reference position) do not get exposed to excessive lateral stresses during cool-down.

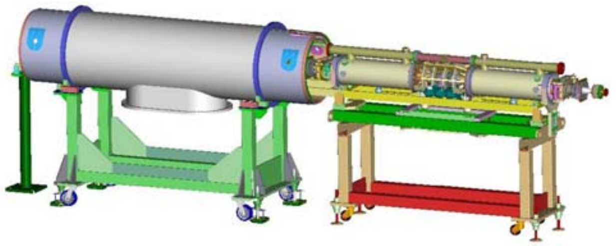


Figure 18: Cavity string assembly rail system.

The vast majority of the cryomodule hardware is now either available or under fabrication. It is anticipated that both couplers will be RF conditioned and cavities available at Daresbury by later this year. All tooling and fixtures required for the cryomodule assembly are complete and therefore cleanroom assembly of the cavity string is expected to start immediately afterwards. Final installation of the new cryomodule is scheduled for summer 2010, with a thorough beam validation period envisaged thereafter.

FUTURE ALICE DEVELOPMENTS

The ALICE R&D facility faces several exciting challenges in the years 2009-10. First, the Compton Backscattering experiment will be conducted with a head-on geometry that is less demanding in terms of laser/electron beam synchronisation compared to a side-on 90^o geometry. ALICE will be able to deliver electron bunch charges in excess of 80 pC to the laser-electron beam interaction point tightly focussed to a less than 100 μm spot and with the beam energy close to 30 MeV. At the same time, an extensive programme of THz studies is planned including the first experiments at the TCF to determine the safe limits of human exposure to THz radiation. This will be followed by installation and commissioning of the IR FEL. Towards the end of 2009 experiments with EMMA, the first non-scaling FFAG [9], will commence and continue throughout 2010. Three major upgrades are also expected including installation of the load-lock system on the photogun, extension of the gun beamline to include diagnostics for full beam characterisation before the booster. Many SRF related problems have had to be addressed and it is intended that the identified ongoing improvements, by optimisation of the SRF system operating parameters and verification of a new ERL cryomodule, will ensure successful demonstration of ALICE operating at its design specification of 80 pC acceleration upto 35 MeV in energy recovery mode.

In conclusion, ALICE commissioning has reached the point when it is now becoming a true R&D facility capable of accommodating and testing novel ideas, and conducting proof-of-principle experiments.

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