PROGRESS OF THE RF SYSTEM FOR EMMA AT DARESBURY LABORATORY*

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Abstract

The RF system on EMMA (Electron Model for Many Applications), the world's first Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) accelerator is presently being installed and commissioned at Daresbury Laboratory. The RF system is required to provide precise amplitude and phase control to each of the 19 identical normal conducting, 1.3 GHz RF cavities which provide the acceleration of the electron beam from 10 MeV to 20 MeV. The system incorporates a high power RF system, which includes a single 90 kW Inductive Output Tube (IOT), a unique RF distribution system and a low level RF (LLRF) control system. The design of the RF system and the commissioning progress to date is presented.

INTRODUCTION

EMMA (Electron Model for Many Applications) is a proof of concept accelerator presently under construction at Daresbury Laboratory, which aims to prove that NS-FFAG (Non-Scaling Fixed Field Alternating Gradient) accelerators can successfully accelerate particles and to study the electron dynamics of the machine. The ring is 5.3 m in diameter and is designed to accelerate a single electron bunch of up to 40 pC injected from ALICE (Accelerators and Lasers in Combined Experiments) from 10 MeV up to 20 MeV. It consists of 21 straights with 19 evenly distributed RF cavities, apart from two cavities being omitted for the injection and extraction lines, and is designed to operate between 1.2960 and 1.3015 GHz. Each of the RF cavities are required to provide an acceleration of up to 180 keV, although for the first phase of commissioning the level required is only 120 keV. The main parameter requirements are shown in Table 1.

Table 1: EMMA Parameters

Machine Parameters	Values	Units
Frequency	1.2960 – 1.3015	GHz
Number of straights	21	
Number of cavities	19	
Total acceleration	2.3 (3.4)	MeV/turn
Acceleration	120 (180)	kV/cavity
Beam aperture	40	mm
RF pulse length	1.6	mS
RF repetition rate	1 to 20	Hz
Amplitude control	0.3	%
Phase control	0.3	°

The RF system for EMMA is required to provide precise amplitude and phase control to each of the 19 RF cavities and consists of 4 main sections:- 19 x 1.3 GHz normal conducting RF cavities, a high power RF system comprising of a single 90 kW IOT, a waveguide RF distribution system, and a single LLRF (low level RF) control system. Design details have previously been discussed [1], and we present here a more detailed progress to date on the first 3 topics whereas a separate paper will detail more specifically the EMMA LLRF system [2].

RF CAVITY

The RF cavity is a torus shaped normal conducting design consisting of an input coupler tuner, and a pick-up probe for feedback to the LLRF system with a Q_0 of 20,000 and an R/Q of 100 Ω, so that 3.6 kW of dissipated RF power is required to generate the required 120 kV accelerating voltage. The design study for the cavity and its specific requirements has previously been discussed [3], since then 20 cavities have been manufactured and delivered by Niowave Inc, USA. Measurements performed on the fabricated cavities show an average $Q_0 = 18{,}000$ is achieved and each loop input coupler has been optimised in terms of its coupling to achieve a nominal $Q_L = 9000$ (for $\beta = 1$) for each installed cavity. Four cavities have been successfully conditioned, without any vacuum event issues, one to 10 kW, and three to 5 kW. The majority of the cavities have now been installed on their respective girders, and a number are already located in their final positions on the ring.

HIGH POWER RF SYSTEM

For the first stage of commissioning on EMMA a single high power RF system has been designed, built, and installed by CPI Inc USA, to provide the necessary RF power for all 19 EMMA cavities. CPI's VIL409 Heatwave™ IOT-based RF high power amplifier (RF HPA) [4] shown in Figure 1, consists of a CPI IOT (VKL9130B), a 1.5 kW solid state amplifier produced by Bruker, (BLA1500 RF SSPA), a 50 kV high voltage capacitive charger power supply, ancillary power supplies and an embedded processor that controls the system as well as interfacing with the EMMA EPICS control system. The beam voltage to the IOT can be adjusted between -38 and -45 kV, which enables the system to be run efficiently dependent upon the RF output power required. The RF HPA incorporates a proprietary grid circuit developed by CPI, which reduces the quiescent beam (typically 240 mA down to 15 mA) during the off

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*Work supported by the UK Basic Technology Fund grant number EPSRC EP/E032869

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period of the RF pulse by raising the grid voltage from the nominal operating voltage to -120 V, thus also improving the operational efficiency of the system. Additionally it is possible to operate the system locally or remotely. The IOT has been optimised from CPI's 30 kW CW IOT for pulsed operation and has been tested to power levels greater than 100 kW, whilst operating with a beam voltage of -45 kV.

Figure 1: CPI's VIL409 High Power RF Amplifier.

Results from the acceptance tests performed with the RF HPA providing a peak RF power of 90 kW at the output of the circulator (up to 96 kW from the IOT) at top, middle and bottom frequencies are shown in Table 2. This was performed with the IOT tuned to the centre frequency, so as to provide optimum performance across the whole frequency range. Measurements were performed on the power supply systems, which showed that the voltage droop across the pulse was 1.25 kV, the peak to peak ripple on the beam voltage was 150 V at -44 kV and the peak to peak ripple on the grid supply was 0.4 V at -95 V. During the initial tests an issue was discovered with the RF trip response time and its repeatability. Improvements were made to the trip circuit board, which reduced the trip response time from around 240 µs to 80 µs (repeatable). A crowbar wire test was successfully performed a number of times with 6 inches of AWG32 enamelled wire, showing that the stored energy within the system under a fault condition was less than 15 J. Additionally at the cubicle external panel, the ionising radiation level measured was 0.3 µSv/h.

Table 2: High Power RF System Performance

Frequency (GHz)	**IOT Harmonics**		**Waveguide Harmonics**		**Noise (dB)**
	2nd (dB)	**3rd (dB)**	**2nd (dB)**	**3rd (dB)**	
1.29600	-43	-54	-60	-71	-70
1.29875	-36	-48	-54	-65	-76
1.30150	-25	-44	-42	-62	-69

WAVEGUIDE DISTRIBUTION SYSTEM

The RF waveguide system (Figure 2) for EMMA has been designed by Q-Par Angus Ltd UK and consists of 17 hybrids and 19 phase shifter modules. The system distributes the RF power to the cavities evenly through a cascade arrangement, which goes clockwise (10 cavities) and anti-clockwise (9 cavities) around the outside of the EMMA ring. The 7/8 EIA cables to each of the cavities were cut to length with the phase shifters as appropriately set to enable maximum range for maintaining the phase in each of the cavities. A hybrid splitter is used to split the RF power from the high power RF amplifier system in the ratio of 10/19 and 9/19.

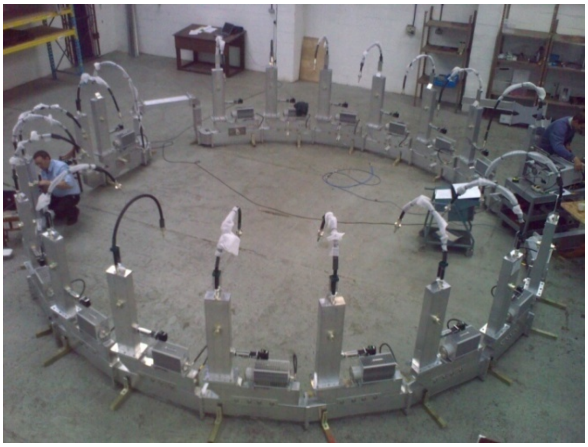

Figure 2: EMMA Waveguide Distribution System.

Results obtained during the acceptance test showed that the full range of the phase shifter was 196 ° and that a resolution of 0.1° could be obtained for 0.01mm movement in the tuner motor, which is sufficient to meet the phase needs for EMMA. The input return loss to each half of the ring was measured to better than -30 dB over the operational frequency range, with each of the cavities terminated with 50 Ω loads. A single input test, which used a 3 dB hybrid to split the power between the clockwise and anti-clockwise sections demonstrated that the full phase shift control could be achieved. The entire output responses for amplitude (see Figure 3) and phase (see Figure 4) are shown with all the cables and their phase shifters set to produce a co-phased output at the lowest operating frequency for 0 ° and 180 °.

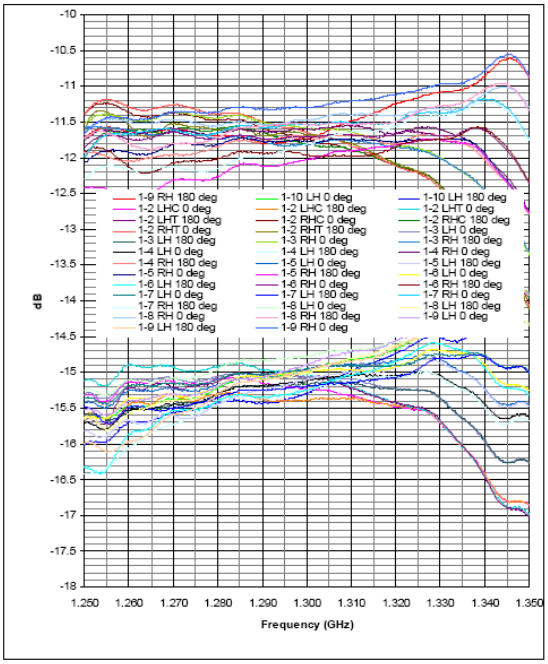

Figure 3: Amplitude Output Response for Single Input Tests.

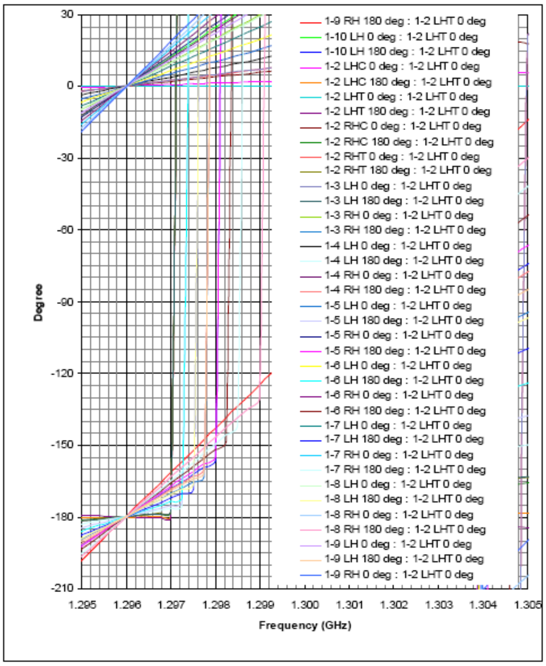

Figure 4: Phase Output Response for Single Input Tests.

Sample testing of the isolation between ports was performed and results showed this to be better than 42 dB (typically 50 dB). Additionally measurements performed on the forward and reverse directional couplers showed that directional coupler directivity was greater than 41 dB (specification >40 dB). However, it was noted that the coupling and directivity varied depending on the position of the phase shifter, believed to be due to parasitic interaction with the phase shifter short circuit. Thus, the phase shifters had to be positioned further away from the directional couplers to minimise this effect. The waveguide distribution system is presently being installed (see Figure 5), and full system commissioning of the complete high power system is expected in June/July 2010.

Figure 5: RF Waveguide Distribution System Installation.

OPERATION

During operation of the EMMA ring the RF system must be capable of being tuned and operated at different frequencies and at different power levels on a daily basis. Thus the system has been designed, so that the system is course tuned initially by tuning all the cavities to the resonant frequency of the operating frequency and locking all the phases, without any electron beam using Instrumentation Technologies' Libera LLRF system. Fine tuning is then achieved by driving the cavity with the lowest Q_0 to the required gradient and detuning all the other cavities to achieve the same accelerating gradient. The phases are once again locked. As EMMA is only being operated with a single electron bunch of up to 40 pC the beam loading effects are negligible.

SUMMARY

Presently all the major RF systems have been procured and individually tested. Installation of the individual sub-systems, so that commissioning tests can commence in June 2010.

REFERENCES

[1] A. Wheelhouse et al, "Design Progress of the RF System for EMMA at Daresbury Laboratory", PAC'09, Vancouver, May 2009, TU5PFP097, pp. 249 (2009).

[2] A. Moss et al, "The EMMA LLRF System and its Synchronisation with ALICE", IPAC'10, Kyoto, May 2010, TUPEA058.

[3] C.D. Beard et al, "EMMA RF Cavity Design and Prototype Testing at Daresbury", EPAC 2008, Genoa, pp.3374-3376.

[4] M. Marks et al, "CPI's 1.3 GHz, 90 kW Pulsed IOT Transmitter for the EMMA Accelerator", IPAC'10, Kyoto, May 2010, THPEB061.