HIGH POWER RF TESTING OF THE EMMA RF SYSTEM*

C. Beard[#], P. McIntosh, A. Moss, J. Orrett, A. Wheelhouse
ASTeC, STFC, Daresbury Laboratory, Warrington, UK

Abstract

EMMA is a prototype non-scaling FFAG that requires a demanding RF system. Production for the final RF system is due for completion in Summer 09 and high power testing of initial hardware has taken place. This paper describes the high power verification tests using a similar IOT transmitter, a prototype waveguide section coupling to two RF cavities. In order to understand potential levels of control a digital phase control system was used to determine feasible values of control.

INTRODUCTION

FFAGs provide a means of rapid acceleration through numerous accelerating structures located around the ring. EMMA [1] is a demonstrator non-scaling FFAG, in construction at Daresbury Laboratory in the UK. In order to investigate a large parameter space operationally, the RF system has to be broad in its operating specification. The EMMA RF system has to provide sufficient acceleration, synchronously for each of the machine operating conditions. The final energy gain for the accelerator is 10 MeV, taking the injected beam from ALICE from 10 MeV up to 20 MeV.

Table 1: EMMA Machine Parameters

Machine Parameters	Values	Units
Frequency	1.3	GHz
Frequency range	-4.0 to 1.5	MHz
Number of straights	21	
Number of cavities	19	
Total acceleration per turn	2.3	MeV
Upgrade acceleration per turn	3.4	MeV
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	Degrees

To achieve this, each of the RF cavities has to be able to provide an acceleration of up to 180 kV, and have the ability to operate over a wide frequency range of up to 5.5 MHz under the conditions defined in Table 1.

EMMA is currently under construction with numerous parts of the RF system either delivered or in manufacturing. System tests comprising two EMMA cavities, a section of RF waveguide distribution, a high power IOT and a commercially available LLRF system have been performed at Daresbury in an attempt to qualify appropriate RF system performance for EMMA.

RF CAVITY

It is proposed that EMMA will not have a vacuum isolation from ALICE [2], therefore handling of the cavities has taken place in ISO 4 class clean room conditions. To minimise the conditioning time and provide the highest achievable efficiency, the cavities were also chemically etched in a bath of phosphoric acid, nitric acid, and hydrofluoric acid, at a ratio of 2:1:1, respectively, prior to final bakeout.

20 RF cavities have been procured from Niowave Inc. Low power testing of each cavity on delivery gave a range of Qs from 19000 as high as 22500, each cavity achieving far higher than the specified 18500.

For the high power tests, the two cavities were connected via a 2 ¾“ T-piece section with a turbo pump on the interconnecting port. The set-up is shown in Figure 1 below.

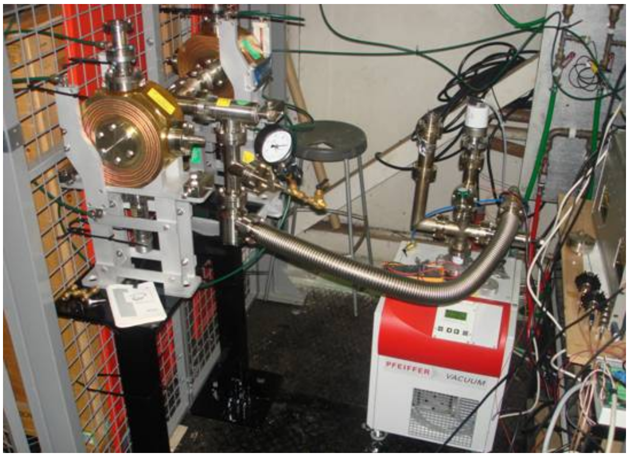

Figure 1: Two cavities prepared for high power testing.

High power conditioning of four of the 19 cavities has now taken place, up to a value of 10.8 kW, with little vacuum activity, suggesting the cleaning and handling of the cavities has been a great success.

Prior to high power testing, a comparison of two cavities simultaneously highlighted a slight difference in the transmission response for each cavity. One cavity response suggested either over-moding of the cavity, transmission line, or coupler, or potentially cross-talk between the coupler and the RF pick-up.

To investigate, the cavities were taken back into the clean room and the orientation of the input coupling loop adjusted.

As can be seen for the left hand graph on Figure 2, an unphysical response in the S2,1 was observed. In its original orientation, the coupling was adjusted for critical coupling. Rotating the coupler 180° provided high coupling, without the initial drop in power.

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[#]carl.beard@stfc.ac.uk

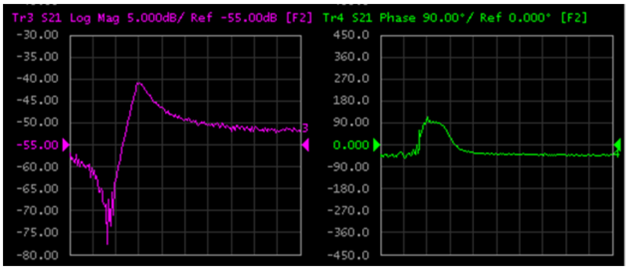

Figure 2: S-parameter response prior to coupler rotation.

Each cavity went through final tuning to ensure optimum operating conditions had been achieved. Figure 3 shows the final S-parameter response of the same cavity in Figure 2 following tuning. This shows an external Q of 10645, and the required transmission loss of -40 dB.

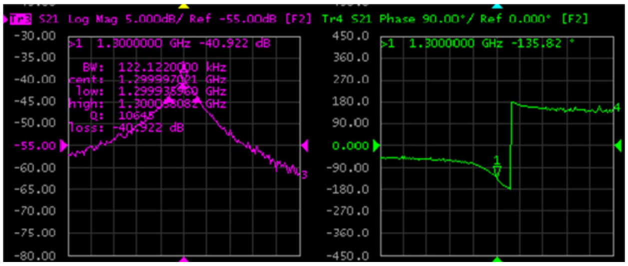

Figure 3: S-parameter response following tuning.

RF DISTRIBUTION PROTOTYPE

The RF distribution could be considered to be the most demanding part of the EMMA RF system. Its purpose is to equally distribute RF power to each of the 19 RF cavities located around the ring. A more detailed explanation of the final waveguide design can be seen in [3]. The RF distribution system was procured with Q-Par Angus, who are based in the UK. To minimise the physical size of the system, the hybrids include both a directional coupler and phase shifter in a single unit. A minimum of 40 dB isolation between the RF cavities was required to reduce cross talk and potential limitations to the LLRF control system.

The prototype waveguide section provided by Q-Par was a 3 dB hybrid, this gave equal power levels distributed to each cavity under test, as would be required for the high power validation. Calibration of the waveguide system demonstrated isolation between the two output ports of better than 40 dB and phase adjustment greater than 180°, which. is within the desired specification. The peak power transmitted through the hybrid section was 11 kW from the CPI IOT, splitting then approximately 5 kW of RF power per cavity, which was sufficient for the minimum cavity operating voltage of 120 kV to be achieved.

Figure 4: Waveguide hybrid and power source.

Initial measurements showed high levels of RF power being reflected back towards the IOT. Without protection on the IOT, there appeared to be a double resonance measured on the pick-up of one of the cavities, suggesting some cross-talk between the distribution. This is displayed in Figure 5 by the pink trace.

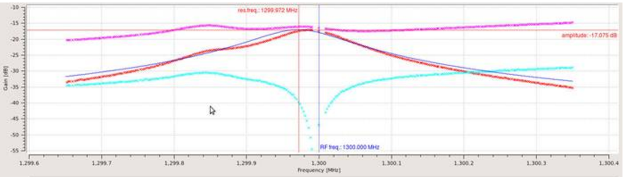

Figure 5: Cavity response without circulator.

A circulator was then placed immediately at the output of the IOT to provide protection, in order to operate at higher powers. In doing so, the double peak measured on the cavity disappeared. This suggested that there was interaction between the RF cavities and the IOT output cavity.

RF POWER SOURCE

The factory acceptance tests of the CPI High peak power IOT amplifier for EMMA has yet to be finalised due to delays in the manufacturing. This integrated amplifier system includes a 1 kW Bruker solid state amplifier to drive the CPI IOT (CHK51320W), plus all ancillary IOT and vacuum PSU’s and the main high voltage power supply itself. The system also includes all local protection and diagnostics controls and interfaces. High peak power test results of the IOT are displayed in Table 2.

The final design of the EMMA distribution system includes a circulator for protection of the IOT. This would remove any cross-talk between the cavities and the EMMA cavities through the distribution.

Table 2: CPI IOT Characteristics

Beam Voltage (kV)	Beam Current (A)	Output Power (kW)	Efficiency (%)	Gain (dB)
40	3.42	82.0	59.9	20.9
41	3.48	86.1	60.3	21.1
42	3.52	90.0	60.9	21.3
43	3.60	93.6	60.5	21.5
44	3.64	98.6	61.6	21.7
45	3.70	103.8	62.3	21.9

In line with the drive requirements for the IOT, CPI has tested the Bruker solid state RF amplifier (BLA1500 RF SSPA) under pulsed conditions up to 1.8 kW, without significant levels of gain compression.

LLRF CONTROL SYSTEM

The Low Level RF (LLRF) system is the only part of the EMMA RF system that has yet been procured. In order to assess the capability of commercially available LLRF systems, an evaluation of the phase and amplitude control capability of the Libera LLRF System, developed by Instrumentation Technologies, has been performed.

The process of achieving the desired 10 kW of RF drive split to the two cavities, required a gradual increase in forward power, whilst the LLRF system had to be configured to achieve stable operation. The final phase and amplitude levels achieved are displayed in Table 3.

Table 3: Phase and Amplitude Control Levels

IOT Output Power (kW)	Cavity 1		Cavity 2	
	Amp Stability (%)	Phase Stability (°)	Amp Stability (%)	Phase Stability (°)
3.3	-	-	0.008	0.008
5.0	-	-	0.007	0.0078
6.0	-	-	0.006	0.0082
7.2	0.006	0.0082	0.006	0.0083
10.0	0.007	0.003	0.006	0.0093

This required a continual adjustment of the attenuation into the Libra system, to ensure optimum reflected power signal was measured.

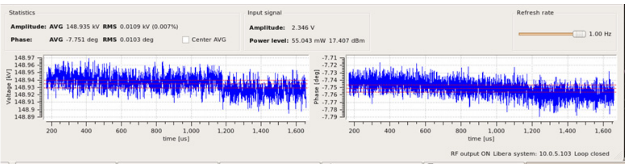
Statistics
Amplitude: AVG 148.935 kV RMS 0.0109 kV (0.007%)
Phase: AVG -7.751 deg RMS 0.0103 deg ☐ Center AVG
Input signal
Amplitude: 2.346 V
Power level: 55.043 mW 17.407 dBm
Refresh rate
1.00 Hz
RF output ON Libera system: 10.0.5.103 Loop closed

Figure 6: Libera control system output at 10 kW.

At the maximum specified power of 10 kW of RF power, with 5 kW split equally to 2 cavities, the phase and amplitude of each cavity was measured and controlled to within 0.0093° degree phase and 0.006% amplitude. Figure 6 shows the RF system response from the Libera LLRF system, displaying the achieved amplitude and phase measurements. Clearly as the system becomes more complex with additional cavities and weaker coupling hybrids, the RF control stability will be substantially harder to maintain, and therefore the final operational performance of the RF system, will not be known until the hardware is fully integrated and commissioned.

ACKNOWLEDGEMENTS

The authors would like to thank the Instrumentation Technologies team working on the Libera system for the opportunity to evaluate the potential LLRF control parameters, desired by the EMMA accelerator.

SUMMARY

Initial high power testing of the EMMA RF system, suggests an extremely stable system in terms of RF breakdown and power handling, to very tight stability, albeit for only a small part of the full system.

The RF cavities have performed much better than originally specified, with a much wider tuning range than was anticipated. Potential issues with cross talk between the power coupler and RF probe was observed and quickly rectified. High power tests of the cavities showed excellent care had been taken during the cavity manufacture and handling stages, resulting in rapid cavity conditioning.

First high power testing of the waveguide model, demonstrated excellent performance in distribution, phase control and isolation between each output port. Once additional waveguide sections are manufactured, the full system performance will be further evaluated and understood.

With the inclusion of a circulator after the IOT, the test results of the complete RF control system suggest no anticipated problems from the RF source.

Control of the RF system to within 0.01° phase and 0.01% amplitude with an off the shelf commercial item, suggest the desired tolerances for the complete EMMA RF system is both realistic and achievable.

REFERENCES

[1] S.L.Smith et al, "EMMA, the World's First Non-Scaling FFAG Accelerator", PAC 2009, Vancouver, 2009.

[2] S.L. Smith et al, "Progress on the Commissioning of ALICE, the Energy Recovery Linac Based Light Source at Daresbury Laboratory", TU5RFP083, PAC 2009, Vancouver, 2009.

[3] A.E.Wheelhouse et al, "Design Progress for the RF System for EMMA at Daresbury Laboratory", TU5PFP097, PAC 2009, Vancouver, 2009.