EMMA RF COMMISSIONING

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Abstract

EMMA (Electron Model for Many Applications), the world's first Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) accelerator is presently in operation at Daresbury Laboratory. The LLRF system is required to synchronize with ALICE (Accelerators and Lasers in Combined Experiments) its injector, which operates at 1.3GHz, and to produce an offset frequency of (+1.5 MHz to -4 MHz) to probe the longitudinal beam dynamics and to also maintain the phase and amplitude of the 19 copper RF cavities of the EMMA machine. The design, commissioning and results of the EMMA RF system is presented.

INTRODUCTION

EMMA [1] is a prototype non-scaling FFAG (Fixed Field Alternating Gradient) facility currently in operation at Daresbury Laboratories. The accelerator installation was completed by September 2010. Beam is injected from ALICE (Accelerators and Lasers in Combined Experiments) at between 10 and 18 MeV, the RF parameters for which are shown in Table 1. EMMA is a compact accelerator of 5.3 m diameter and the RF acceleration system consists of 19, 1.3 GHz identical normal conducting RF cavities, which are distributed evenly around the 42-cell machine, with two cavities removed to allow access for the beam injection and extraction lines (see Figure 1).

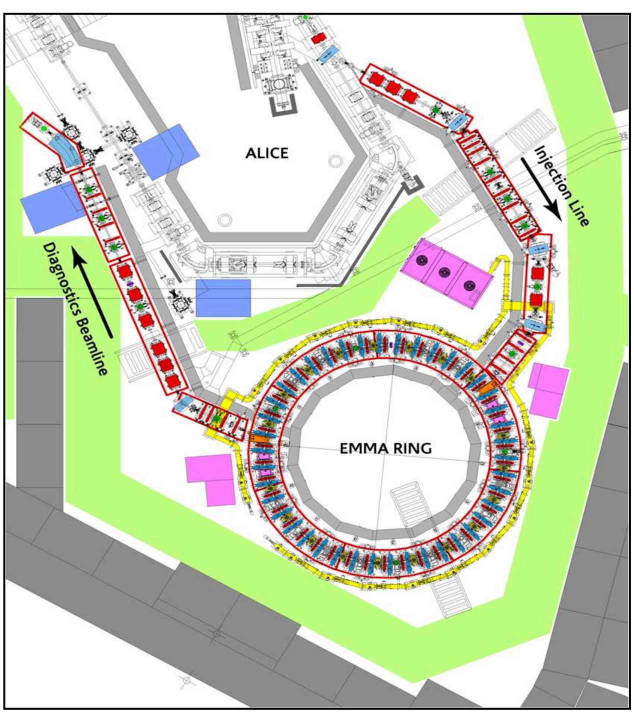

Figure 1: EMMA facility layout.

Since EMMA is a demonstrator machine, the RF system has been designed with flexibility as a core objective, which includes varying the RF frequency and the rate of acceleration. Initially an acceleration of 2.3 MeV per turn is required with the potential to upgrade to a maximum of 3.4 MeV.

Table 1: RF Design Parameters for EMMA

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	MV
Upgrade acceleration per turn	3.4	MV
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

EMMA RF STATUS

The EMMA RF system is explained in detail in [2], The EMMA RF system was commissioned in August 2010 in collaboration with Instrumentation Technologies (ITech) who provided the LLRF control system [3]. Previous to this, the amplifier system had already operated at full power for its site acceptance tests at Daresbury. Figure 2 shows the complete EMMA ring installed.

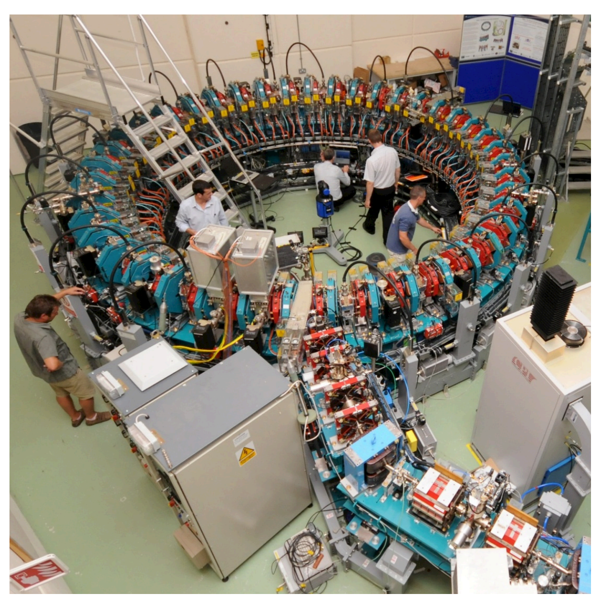

Figure 2: EMMA machine complete.

RF Amplifier

The power amplifier consists of a CPI IOT (CHK51320W) and a Bruker BLA1500 solid state amplifier (SSA). The amplifier can produce up to 90 kW of RF power over the required frequency range of -4MHz to +1.5MHz (f_c = 1.3GHz) at the stipulated 3.2 % duty factor.

RF Cavity and Waveguide Systems

The RF accelerating cavity in EMMA has been designed to provide an acceleration of 120 kV per cavity in the initial design for the machine. The waveguide system was designed and manufactured by Q-Par Angus and incorporates a reflected power rejection load for each cavity and a waveguide phase shifter.

During commissioning of the system all cavity Q's, probe signals and waveguide forward and reflected power coupling factors were measured for inclusion in the configuration file of the Libera LLRF. Whilst some effort had been made to match all the cavities, there are tolerable differences in the measured characteristics of the cavities, with loaded Q variations of between 7385 and 10686.

Also, from the waveguide (30 meters of UR67 RF cables have been installed) power readings are in some cases 10 dB lower in the central part of the distribution system due to the additional lengths of cable. This can be compensated for in the LLRF but does mean that some signals are not at an optimum level. Using the Libera network analysis mode (Figure 3), problems were identified in response of certain cavities; this is due to coupling between the input coupler and feedback probe.

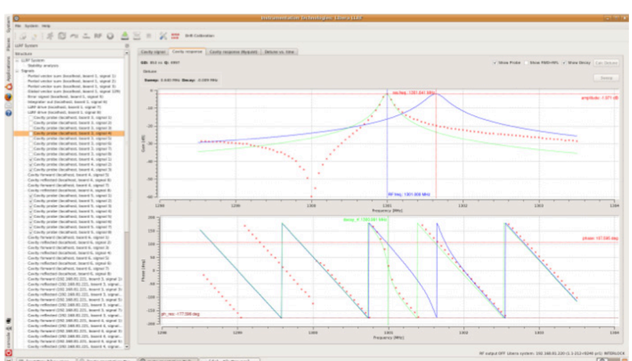

Figure 3: Libera LLRF in sweep mode showing a low frequency notch in response.

This was corroborated by the cavity data as shown in Figure 4 from localised network analyser characterisations. This notch in cavity response can affect the way the Libera views the system, a best fit response is obtained from the frequency sweep, however by tuning all the cavities to the correct frequency and reducing the sweep span to 1 MHz, the effect is removed and stable operation can be obtained.

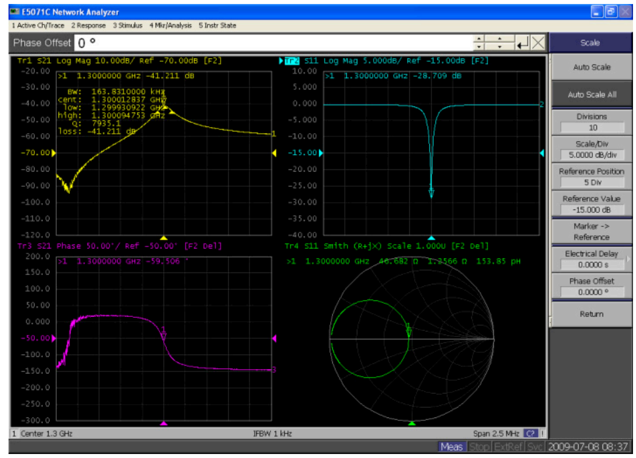

Figure 4: EMMA RF cavity response using VNA showing notch in response.

Cavity Tuning

Early in the commissioning, it became apparent that the automated control of the cavity tuning motors was problematic, both in terms of erratic communication and also inconsistent mechanical behaviour. Subsequent tests have revealed that mechanical aspects of some of the cavity tuners have sticking issues which prevent them from moving in a repeatable fashion. So far this is preventing fully automatic control of the cavity tuners and will require venting of 6 cavities to remedy the problems later this year.

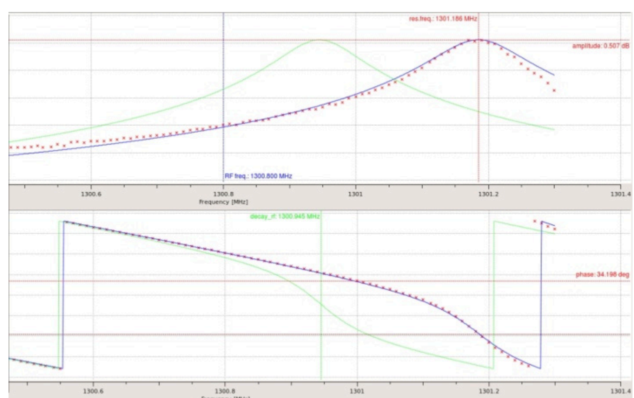

Figure 5: Red and Blue traces show the results of sweep analysis; Green is the current cavity frequency.

The cavities on EMMA can however be tuned from the nominal 1.3 GHz and using the diagnostics available on the Libera LLRF, the cavities can be powered in open loop mode, then as a cavity tuner motor is moved the cavity frequency response calibrations can be performed (Figure 5). Forward and reflected power signals are used to check and further optimise the tune of each cavity. Retuning of the all 19 cavities to a new frequency takes less than one hour to achieve. Over successive physics shifts only minor retuning of individual cavities is needed, this is due to cavity water temperature variations. The Libera control loop can then be closed around all cavities and the operators are able to select acceleration of between 100 kV and 2.4 MV per turn at any phase angle required.

LLRF Calibrations and Phasing

The Libera LLRF system supports calibration of the installed RF system by providing a configuration file where calibrations can be entered for subsequent parts of the system including:

- Cavity probe cable loss
- Cavity probe phase angle
- Internal Instrument phase measurements
- Internal instrument power measurements
- Drive system cable loss
- Forward and reflected cable loss

A network analyser was used to measure the loss of cables between the Libera LLRF and the EMMA machine some 30 meters away. Whilst this measurement is acceptable in power loss terms, the phase measurement results are prone to errors due to the long test cables. The calibrations allow the system to measure accurately the power conditions inside the machine, the drive applied by amplifier, and the total cavity voltage inside the RF system.

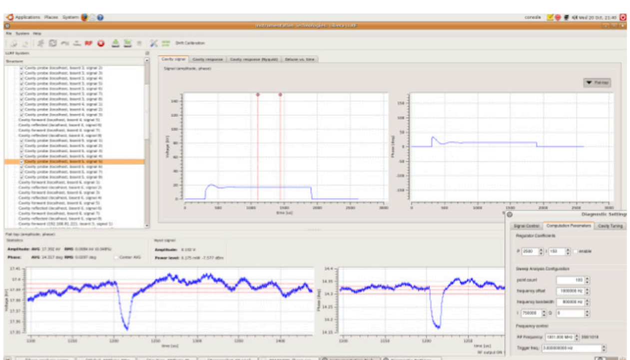

Figure 6: Beamloading signal showing power being drawn from a cavity.

Each cavity distribution arm is equipped with a high power waveguide phase shifter, so that each cavity phase angle can be moved. In practice the phase change is limited to around 220 degrees on some of the phase shifters, so a phase map of the machine has been produced to optimise the system performance. It was always intended that beam based techniques would be used to accurately set the zero crossing point each of each cavity and therefore define the phase angle for each of the respective EMMA cavities, however when using the Libera LLRF it was found that by reducing the proportional & integral loop constants, the LLRF system response could be made slow enough, so that cavity beam loading characteristics could be seen in the machine.

As only a single bunch is injected into EMMA, the beamloading observed is for multiple turns of the machine (Figure 6). Initial tests showed that the total beam energy gain measured was only equal to half of the global vector sum voltage being applied; however when the system was phased using the beamloading method, the measured and predicted results matched and beam energy gain became consistent with up to 2.0 MV per turn.

Operation and Acceleration

The EMMA machine has been operating now for over one year. Most of the physics runs have been with the frequency of the EMMA cavities at 1.301GHz, this mode of operation relies on the synchronisation [3] that the Libera LLRF system performs on every timing pulse. This allows the frequency variable EMMA machine to stay in relative phase lock to the fixed frequency 1.3 GHz of the ALICE RF system.

With all of the EMMA RF cavities tuned to the same frequency and the LLRF optimised, a global vector sum voltage of 2.4 MV has been achieved. In addition, the phase and amplitude control of the RF cavities is consistently <0.02 degrees and 0.007 % in amplitude.

Over the past year the RF system has progressed from needing extensive specialist RF support on each EMMA shift, to the position today whereby the physics team members operating the EMMA machine use the RF system routinely themselves. Typically when the RF system is switched on, a coarse phase scan of the global RF phase is performed to locate the phase angle at which the RF has the least effect on the circulating beam, this is then taken as the phase reference, or zero angle. Fine global vector phase scans are then performed whilst storing data from the BPM's and machine diagnostics; these are compared with simulations offline.

SUMMARY

Detailed physics simulations are in agreement with measured results from the machine commissioning [4], the global vector sum voltage of the RF cavities directly correlates with the simulated data and the energy gained by the electron beam, which can also be seen by the change in extraction kicker strength required.

REFERENCES

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