COMMISSIONING OF THE MICE RF SYSTEM*

A. Moss, A. Wheelhouse, T. Stanley, C. White, STFC, Daresbury Laboratory, Warrington, UK
K. Ronald, C.G. Whyte, A.J. Dick, D.C. Speirs, SUPA, Dept.of Physics, University of Strathclyde, UK S. Alsari, Imperial College of Science and Technology, London UK
on behalf of the MICE Collaboration

Abstract

The Muon Ionisation Cooling Experiment (MICE) is being constructed at Rutherford Appleton Laboratory in the UK. The muon beam will be cooled using multiple hydrogen absorbers then reaccelerated using an RF cavity system operating at 201MHz. This paper describes recent progress in commissioning the amplifier systems at their design operation conditions, installation and operation as part of the MICE project.

INTRODUCTION

The muon ionisation cooling experiment is a demonstration of practical cooling for future muon acceleration schemes. Liquid hydrogen absorbers followed by RF cavities to reaccelerate the muon beam will provide a reduction of emittance in the momentum range of 140-240MeV/c. For the MICE experiment muons are produced from decaying pions formed by plunging a target into the proton beam of the ISIS synchrotron [1]. The muons produced arrive randomly spread in time and hence RF phase so only partial cooling and reacceleration within the cooling channel is possible. The RF system consists of a chain of amplifiers operating in pulse mode at 1mSec 1Hz timed to coincide with the target application. Recent trials with the amplifier have succeeded in operating at the design requirements of 2MW RF output power at the desired frequency of 201MHz at the RF test area at Daresbury laboratory. The amplifier system was then dismantled and reassembled in the MICE experimental hall to demonstrate operation of the amplifier system within the tight confines of its eventual location.

AMPLIFIER SYSTEM

The amplifier system consists of a number of elements starting with a solid state power amplifier (SSPA) 4kW Dressler amplifier. This is fed by an RF signal of up to 10dBm and a trigger pulse set for the MICE operation at 1mSec 1Hz. The output is transmitted through a RG223 cable and a reflectometer directional coupler with coupling factors of 30dB to provide an indication of matching at the input port of the 4616 tetrode amplifier.

4616 tetrode amplifier

The Tetrode amplifier is a Super Power Beam Tetrode manufactured by Photonis USA. It is housed in a concentric amplifier cavity; the input cavity is equipped with a variable capacitor that tunes the resonant frequency, whilst the 'N' type connections to the cavity feature adjustable sections to change the response of the cavity to both input line and resistive load. On the output of the amplifier, the cavity length and hence its resonant frequency can be adjusted, whilst a stub tuner is located in the output coax section to alter the coupling factor into the output coax so that the amplifier may be used to drive a range of different load conditions. For use in the MICE system the 4616 operates in long pulse mode using grid pulsed operation and can provide up to 250kW RF output power.

4616 power supply

The power supply for the tetrode amplifier consists of a TDK-Lambda 500A capacitor charger power supply connected to a 29uF capacitor bank. Grid one is connected to a Sorensen xfr 300V 10A power supply, during operation this is set at 180 V which biases the tube off. Grid two (screen grid) is connected to a pulse transformer and IGBT driver unit with a bulk power supply consisting of a second Sorensen xfr power supply. The screen grid is pulsed to ~2kV during the RF pulse to control the amplifier operation.

116 Triode amplifier

The triode amplifier is a modernised unit [2] (fig 1), a coaxial structure with movable motor driven grid and anode taps, output load coupling can be changed using the output capacitor. The output of the 116 amplifier is an 8 1/3 inch rigid coax that is reduced to 6 inches before transmission though rigid coax and connected to a 2MW glycol water load built by MEGA Industries to allow high power testing of the amplifiers and power supplies at the Daresbury laboratory MICE RF test area. The HT input for the amplifier includes the water cooling for the triode and a ¼ wavelength tuning stub to reduce RF propagating back to the power supply.

Figure 1: TH116 Triode installed in HT tank

The system is blown with air through the centre of the amplifier structure to cool the heat load from the tube filament operating at 500A 20V.

116 power supply

The power supply consists of a TDK-Lambda ALE 802 8kJ/S constant current power supply with a high voltage capacitor bank of 140uF. Generally the HT for this amplifier will be 35kV during operation although for testing purposes it can operate from 10kV. An in house designed bias supply holds the earth, in the base of the amplifier at +450V to maintain the system in an off state and a cathode modulator switches out the bias voltage pulsing the amplifier into conduction [3].

During 2012 this amplifier had operated at 1.2MW RF output; however damage to the power supply had occurred and prevented further operation. This was traced to the crowbar protection device which would not reliably hold off voltages above 20kV. With such a large stored energy (101kJ) any sparking inside the electron tube could destroy it, so the crowbar has to act reliably and very quickly (<5uS) to remove voltage from the tube. A replacement crowbar was loaned to the project from e2v Technologies and was proved be reliable up to 38kV, this allowed testing to resume.

4616 testing

The output of the tetrode amplifier is 3 1/8th inch rigid coax. For initial tests this was connected via a reflectometer directional coupler to a test water load on loan from CERN. This provided the ideal setup to explore the amplifiers tuning characteristics with a known 50 ohm matched load. Initially the amplifier was configured using an old tube to limit any possible damage to the valuable new tube required for the experiment. This allowed an RF output power of 170kW to be achieved relatively easily. On changing to a new 4616 tube, a period of conditioning was needed where the amplifier system settings needed to be changed radically to get operation from the system without tube oscillation. Careful setting of the output loading was critical to reach a condition whereby the amplifier was stable enough to allow the gradual increase of power level. It was found that RF input matching of the system was crucial. A match of 30dB was possible during cold conditions, but in operation such a setting is too narrow band and in the hot condition the frequency of optimum match moves away from the operating frequency resulting in a poor hot match. To obtain an acceptable hot match, initially a poorer but more broadband cold match must be chosen which can be optimised during operation with RF drive present. This period took several days to complete, however once the tube was conditioned and optimised for our desired frequency an output power level of 246kW was achieved into the dummy load.

Optimisation of the amplifier system

The dummy load was removed from the output of the tetrode amplifier and connected to the input of the 116 triode amplifier; no other adjustments were made to the tetrode amplifier set up. Generally with triode amplifier systems of this type it is important to ensure that the RF drive to the system is present before application of the HT as the system is vulnerable to oscillation, so 10kW forward power from the tetrode was applied to the input of the triode amplifier, then HT volts of 10kV. At these initial settings it was immediately possible to develop 30kW output from the triode amplifier and this was optimised by moving the grid and anode taps of the triode amplifier to give an indicated 90kW.

With the HT at 15kV, gain of the triode system was 11dB with an electrical to RF conversion efficiency of 41%. To ensure the optimum tuning point, a scan was performed of the adjustable taps (grid and anode) of the triode amplifier to see if there were multiple operating points in the tuning range of the triode system, however it appeared that for the desired frequency the grid tap has to be fully retracted for the system to operate with good gain.

While operating at 30kV ~1.2MW the crowbar system repeatedly tripped the system. Using a high voltage divider probe on the anode of the crowbar, 201MHz RF signals could be seen on the HT circuit within the power supply unit. There are two stages of capacitive filter installed in the power supply that should filter RF from the system; one of these was an adjustable ¼ wavelength HT tuning stub in the high voltage line of the triode amplifier. While monitoring the induced RF on the crowbar the HT stub was moved to a point which minimised the RF seen on the crowbar anode. This was an important development as immediately it was possible to go to higher HT voltage of 34kV and therefore greater RF output power. Measurements performed around the amplifier at very high powers revealed that there was no significant ionizing or non-ionizing radiation produced by the systems during operation (fig 2).

Figure 2: measurement of ionizing and non-ionizing radiation during operation at 1.2MW power output

The system could now be optimised further towards higher power level with the correct pulse conditions of 1Hz 1mSec. As the working point for the amplifier will be at very nearly its maximum power it was important to optimise the system to give high gain and conversion efficiency at a very high output power. The amplifier operating conditions at the end of this extensive optimisation were Dressler SSPA at 2.3kW, the 4616 tetrode operating with 18kV HT producing 203kW with 19dB of gain and a power reflection coefficient of 8%. The 116 triode system was producing 2MW (fig 3) with 35kV HT and 130A per pulse (4.5 MW electric power in the tube), with a gain 10.3dB and electrical conversion efficiency of 46%.

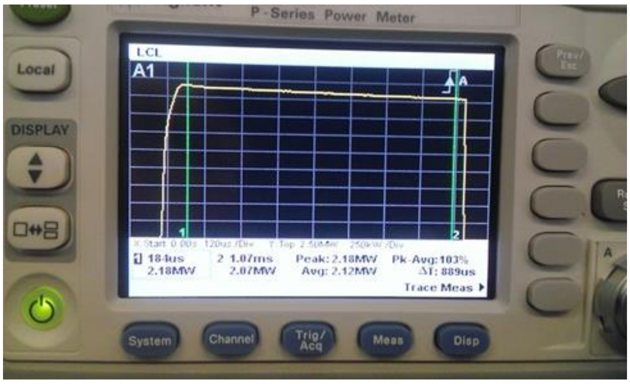

Figure 3: RF power meter showing 2MW RF output

Installation in the experimental hall

The amplifier and its distribution system are large pieces of engineering that are required to perform in a very confined space, the installation of system took place during 2013 with the high power coax lines and ancillary equipment needed to operate the system. Testing to re-establish operation was performed over several periods and the system successfully operated producing high power RF for the first time for the MICE project in the experimental hall.

FUTURE WORK

For reliability during the MICE experiment a crowbar device with greater high voltage standoff capability will be required. Investigations using a hybrid solid state crowbar switch which is rated at 48kV with a 15kA peak current from APP are being performed. Tests at 38kV with the 140uF capacitor bank (stored energy of 101kJ) and a 5 Ohm discharge resistor are being performed (fig 4) and are proving successful; the device will be installed into the amplifier power supply for the next set of tests with the amplifier running.

While some of the adjustments on the amplifier systems are under remote motor driven control, it may be desirable to automate more of the critical tuning mechanisms before the amplifiers are locked in the experimental area. This will maximise the ability of the RF system to be tuned by the experimental controllers from outside the experimental area, this remote control is essential since the RF power stations are close to the high gradient accelerator cavities. This work will be assessed during the build-up of the next set of amplifiers and power supplies for the MICE experiment.

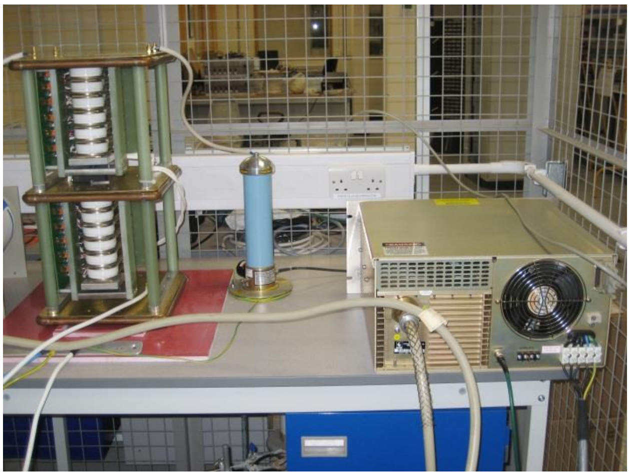

Figure 4: solid state crowbar under test at 38kV

CONCLUSION

The amplifier system for MICE has now operated at the design RF parameters for the experiment. Many technical issues have been resolved in the operation of the amplifier at 2MW and improvements to the system will be made in the next amplifier systems and their power supplies. Improvements will be retro fitted to the existing systems to ensure conformity of operation during the experiment.

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REFERENCES

[1] K. Ronald, “The RF System for the MICE Experiment”, IPAC’13, Shanghai, May 2013, http://www.JACoW.org

[2] J. Orrett, “The MICE RF System”, PAC’09, Vancouver, May 2009, p. 1057 (2009); http://www.JACoW.org

[3] B. Brady, “Cathode Modulation of High Power RF output Triodes of the ISIS Linac”, EPAC’98, Stockholm, June 1998, p. 1909 (1998); http://www.JACoW.org