THE MICE RF SYSTEM

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Abstract

The Muon Ionisation Cooling Experiment (MICE) at the Rutherford Appleton Laboratory uses normal conducting copper cavities to re-accelerate a muon beam after it has been retarded by liquid hydrogen absorbers. Each cavity operates at 200MHz and requires 1MW of RF power in a 1ms pulse at a repetition rate of 1Hz. In order to provide this power, a Thales TH116 triode, driven by a Burle 4616 tetrode is used, with each amplifier chain providing ~2.5MW. This power is then split between 2 cavities. The complete MICE RF system is described, including details of the low level RF, the power amplifiers and the coaxial power distribution system. Testing of the amplifier chain, power supplies and low level RF is described

INTRODUCTION

Ionisation cooling is the process by which a particle beam is passed through a material medium (absorber) and individual particles lose energy (momentum) through ionisation interactions. The particle beam is then accelerated longitudinally using RF cavities. The particles are losing both transverse and longitudinal momentum, but the RF cavities are only replacing the longitudinal momentum, resulting in an overall reduction in the particle beam emittance.

The MICE experiment consists of three liquid hydrogen absorbers and eight RF accelerating cavities. Detectors and tracking devices before and after the cooling channel are used to measure the effectiveness of the ionisation cooling process (see Figure 1).

MICE RF REQUIREMENTS

MICE will operate at 201 MHz, with a 1ms pulse width at 1 Hz and require RF power levels of ~ 1 MW per cavity to produce a measurable amount of cooling. Peak power levels of this magnitude, in this frequency band require conventional high power vacuum tube technology, triodes and tetrodes. Four chains of three amplifiers will each produce a final stage RF pulse power level of ~ 2.5 MW. This will be split using 3 dB hybrids and coaxial matched Tees to deliver ~1 MW of RF power to each cavity. The following RF amplifier stages will be used;

- Pre amp: A Dressler 4 kW, solid state amplifier will be operated at ~ 2.5 kW nominal output power,
- Drive amp: A Burle 4616 tetrode, will be operated at ~ 250 kW nominal output power.
- Main amp: A Thales TH116 triode, will be operated at ~ 2.5 MW nominal output power

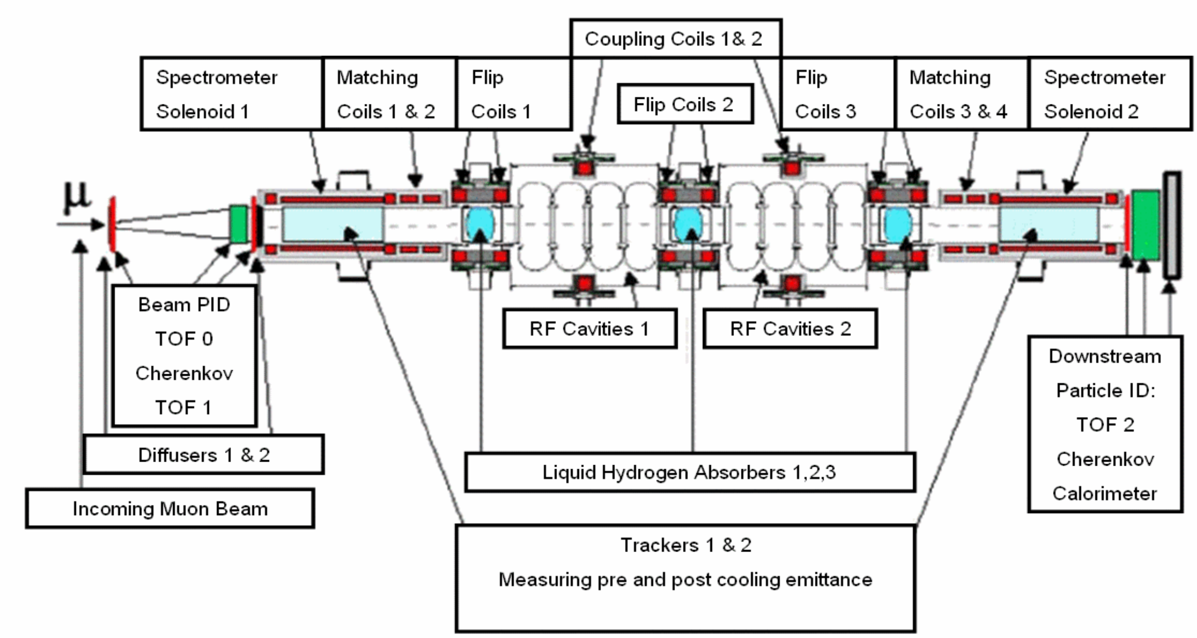

Figure 1: MICE cooling channel.

Burle 4616 Circuit

The Burle 4616 is a high power vacuum tube which operates in pulse mode at frequencies of 195-600 MHz. The 4616 RF circuit comprises tuneable input and output RF cavities and is operated at 20 kV anode voltage, 201 MHz, 1 ms pulse width at 1 Hz pulse repetition frequency (PRF). To operate this tube in pulse mode the grid is held at a DC voltage of 250 V negative with respect to (wrt) the cathode. This, in effect, biases off the tube. Pulsing the screen grid 2 kV positive wrt the cathode brings the tube into conduction for the duration of the pulse.

The first 4616 circuit has now been refurbished at DL and a high voltage power supply (HVPS) has been built by the DL Power Supplies Group. The HVPS consists of a 20 kV charging power supply feeding a 29 μF capacitor. Due to the relatively low duty factor a modest charging power 500 Js^{-1} can be used. However a considerable amount of capacitance is required (29 μF) to reduce HT droop across the pulse. This capacitance has a stored energy of 5.8 kJ and to protect the tube an ignitron based Crowbar has been incorporated into the HVPS. A 2 kV pulsed power supply has also been built to pulse the tube using the screen grid and a -300V supply to bias the control grid.

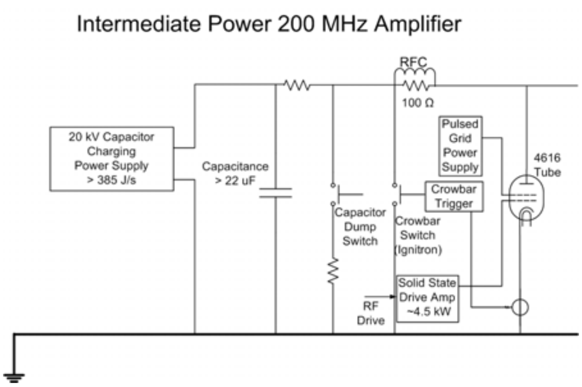

Figure 2: Intermediate amplifier.

Thales TH116 Circuit

The TH116 is a high power triode which operates in pulse mode with 5 MW peak power at up to 200 MHz. The operation of the tube for MICE will be similar to the 4616 tube. A 9 kJs^{-1} power supply will charge a 140 μF capacitor bank which supplies the ~ 40 kV HT to the tube. Pulsing will differ from the 4616, the TH116 is a triode and so screen grid pulsing is not an option. When last operated at LBNL on the Bevatron, the control grid was pulsed to bring the tube into conduction. However when the TH116 circuits are refurbished at Daresbury, it is planned to replace the grid pulsing system with a simpler and more efficient cathode switch. The cathode switch is in essence a high value (15kΩ) resistor in parallel with an Insulated Grid Bipolar Transistor (IGBT) based switch. When the IGBT is open any anode current will give a volts drop across the cathode resistor and this will self bias the tube off. During the pulse the IGBT will close, giving a low resistance path and allowing the tube to fully conduct. A thyristor based Crowbar will be used to protect the tube from the capacitor bank high stored energy (112kJ).

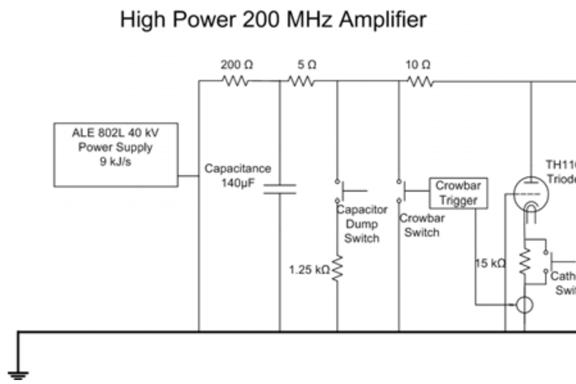

Figure 3: High power amplifier.

Low Level RF

The purpose of any Low Level Radio Frequency (LLRF) system is to maintain the desired accelerating structure phase and gradient regardless of external influences. This is achieved by monitoring the accelerating structure RF using a monitor coupler and comparing the signal with the required phase and amplitude. From this comparison the RF drive to the amplifier chain is modified to restore optimum operating conditions. This can be achieved using analogue techniques with phase detectors, RF detectors, comparators etc. However in recent years there has been a move to digital LLRF control. For digital LLRF control, the probe signal is (usually) frequency translated to an intermediate frequency (IF) or baseband. This IF signal is then sampled using an analogue to digital converter (ADC). Phase and amplitude information can be extracted from the sampled signal using digital signal processing (DSP) techniques. From this information a modified IF signal is produced using direct digital synthesis (DDS). This can then be frequency translated to RF and used to drive the amplifier chain. RF control with an accuracy of < 1% in amplitude and < 0.1^{o} in phase can be achieved using digital LLRF techniques.

For MICE it is proposed to evaluate a digital LLRF system based on the LLRF4 card designed by Larry Doolittle at LBNL. Initially this evaluation will be carried out at Daresbury Laboratory RF Test Stand to assess its suitability for the MICE system.

The LLRF4 card has four RF input channels which can be used to measure RF forward power, RF reflected power and cavity monitoring. In MICE each amplifier chain powers two cavities and so two channels can be used for cavity monitoring and the vector sum output computed to drive the amplifier chain. Figure 4, below shows the LLRF4 evaluation board.

Figure 4: LLRF4 evaluation board.

MICE Power Distribution

Figure 5 shows the proposed MICE RF power distribution system for the two LBNL supplied 116 amplifiers. Two more 116 amplifiers have been supplied by CERN; these have a number of differences, including an alternative configuration for output power coupling. The LBNL amplifiers have a single, large capacitive coupler (see Figure 6 below), whereas the CERN amplifiers have twin direct coupling connections which feed 6 inch coaxial transmission lines. The CERN amplifiers do not require the initial 2 way split to 6 inch coax shown in Figure 5. Due to the high peak powers, the coaxial line will experience, the line will be filled with N_2 to prevent voltage breakdown. The pressurised N_2 will also provide a useful interlock to indicate line disconnection.

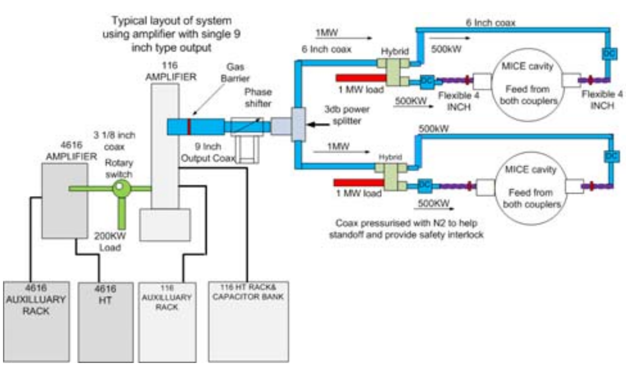

Figure 5: RF power distribution.

MICE RF STATUS

The 4616 circuits required relatively little refurbishment, apart from replacement of ageing hoses and electrical cabling. The refurbishment of the first 4616 circuit has now been completed and its HVPS, Grid Power Supply, Screen Pulser, Crowbar and all other necessary ancillary equipment has been fabricated or procured.

The TH116 circuits were in a far more dilapidated condition; RF surfaces were pitted, fingerstock was damaged and the cavity tuning mechanisms were seized. The first circuit has been completely stripped down and cleaned, damaged components replaced and all RF surfaces have been silver plated. The hand wheel operated tuning mechanisms have all been replaced with motors to enable remote tuning capability. This circuit is now in the final stages of its rebuild. The HVPS, Crowbar and other ancillary equipment for this tube are also almost ready for service. High power testing of the first TH116 amplifier will hopefully take place in the next couple of months. Figures 6 and 7 show the LBNL style output power coupler before and after refurbishment.

Figure 6: LBNL TH116 output power coupler.

Figure 7: Power coupler after refurbishment.

Testing

The first 4616 circuit has been successfully tested; this was carried out using the old 4616 tube which was in circuit when the equipment arrived from LBNL. This had not been in service for many years and little or no output power was expected. However, a power output of 170 kW was achieved; this proved the serviceability of the equipment. The TH116 circuit will be high power tested soon, using a surplus to requirement ISIS TH116 triode.

REFERENCES

[1] Doolittle L., "Digital Low-Level Control Using Non-IQ Sampling. Linac 2006.