STFC Daresbury Laboratory

High Power RF system for MICE

RF Design review December 2011

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Contents

Introduction

This aim of this report is to discuss the philosophy of the high power RF system for MICE.
The primary objective is to discuss in particular whether the high power coax system design can be recommended to go ahead to procurement for the components and coax sections to be made prior to installation in the hall.
A second objective is the question of cavity phasing and the use of coax phase shifters in the system, their effect on the flexibility of the RF system in the experiment, and the suitability of such devices.
Thirdly the use of gas pressurisation in the coax line to aid in increased level of peak voltage standoff due to reflected power in the coax guide system. In addition the implications for high reflected power for the triode and its associated power supply should be addressed.

Amplifier systems

The amplifier system for MICE consists of a 4kW solid state amplifier, a Burle 4616 tetrode amplifier capable of delivering 250kW with a gain of 20dB and TH116 amplifier system capable of delivering in excess of 2MW (gain 9dB) at 201 MHz, at 1Hz with 1mSec pulse width.
The amplifiers have been completely refurbished in all cases, the first set of completed amplifiers and power supplies are currently on test at Daresbury Laboratory and a power level of 1MW has been reached using old tubes.
The plan is to refurbish each amplifier, test it in the system at DL, build up more power supplies and prove them in the test system, before they are transferred to the MICE hall at Rutherford Appleton Laboratory and installed in the MICE hall.

Fig 1: 116 amplifier operating at 1MW, no x-rays or microwave radiation detected

Amplifier Isolation

Amplifier systems feeding RF cavities typically use isolators or circulators to prevent reflected power affecting the driving system; however at 200MHz these devices become very large, in the case of the MICE hall, too large.
Having sought the advice of experts who use this type of triode amplifier, two differing views on how it can and should be connected to accelerating structures are found. Laboratories that use triodes to power linac structures, generally mount the tube amplifier close to the linac structure. Significantly, no attempt is made to limit the reflected power back to the tube; the coax section simply terminates at the input to the linac tank. It is generally accepted that the triode amplifier is very tolerant of reflected power and no additional methods are used to remove or protect the tube from this effect.

Experience at the Muon Test Accelerator (MTA) at FNAL, where the prototype MICE cavity has already been tested, is that a hybrid should be used to split the power to the two arms of the MICE cavity. Also a high power phase shifter is put in the incoming line before the hybrid, to move the loading of the amplifier with respect to the reflected power from the cavity. This configuration is confirmed by experience at Brookhaven, whereby they also suggest this approach for MICE.

The question of reflected power affecting the driving tube plate currents and tube voltages needs to be understood. During the amplifier testing being carried out at DL we should experiment with the power distribution and understand how the power supplies can combat this loading effect.

RF coax distribution system

In order for the amplifier to supply 2 x MICE cavities with 1MW of RF power, the amplifier output must be split in two. This power splitting will be done using a hybrid. A 3 db Tee splitter could be used here; however the greater isolation of the hybrid means it is better suited to the task, also experience at the MTA would suggest the T splitter is far from ideal in this position. Using the hybrid will provide an isolation of 30dB between the two cavity systems.

Hybrids are used to split the power again before the MICE cavity, as the cavity has two input couplers. The hybrid will provide a 30dB isolation between the outgoing ports of the device and hence the input couplers to the cavity. However when reflected power is sent back in phase, during the cavity filling for example, all the reflected power will be passed back towards the driving amplifier. The general layout of the Berkeley amplifier coax distribution system is shown in Fig 2.

Directional couplers will be used to measure forward and reflected power around the coax installation. Controls will ensure that unsafe levels of RF power are monitored, flagged and will trip the system off if excessive levels are measured.

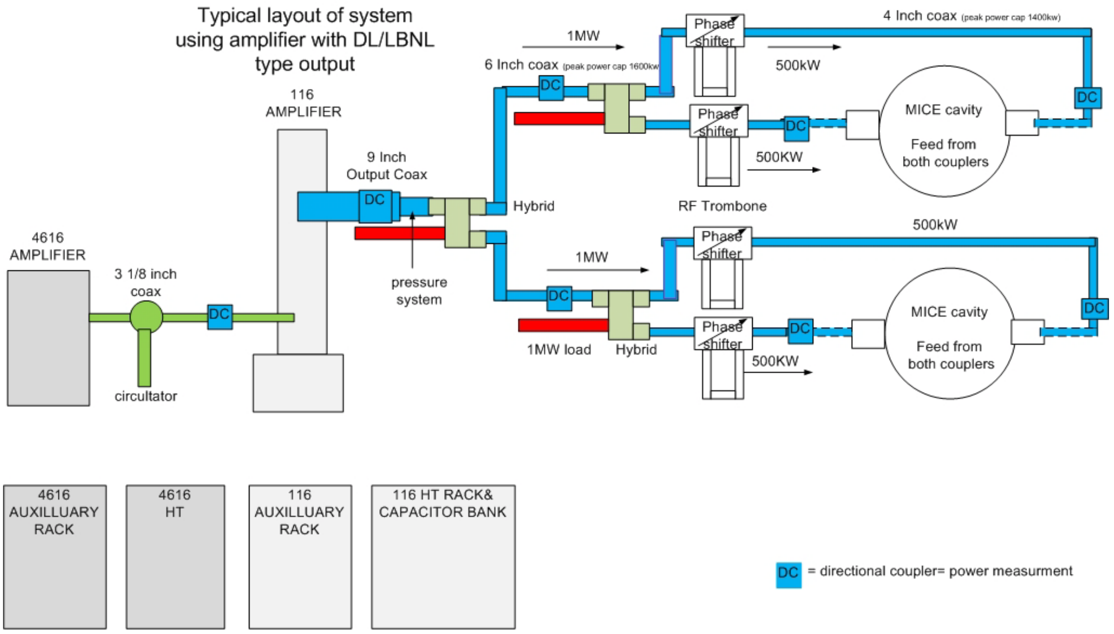

Fig 2: Berkeley amplifier general arrangement

Components in the coax lines, bends, and changes in diameter, phase shifters and 'flexible' coax may add small reflections to the system. These effects need to be understood. Carful design to minimise the number of 90 degree bends in the coax and the removal of 'flexible' from the coax system should produce a well matched system.

It should be noted that the CERN has two outputs; in effect the power is already split inside the amplifier. The coax design then follows the same ideas as in the Berkeley system. The CERN amplifier has been tested at 88MHz and has shown that the amplifier is capable of up to 2.6MW of output power; however this is limited by arcing in the tank circuit and in the 6 inch output coax. See CERN report **CERN-AB-2006-025.**

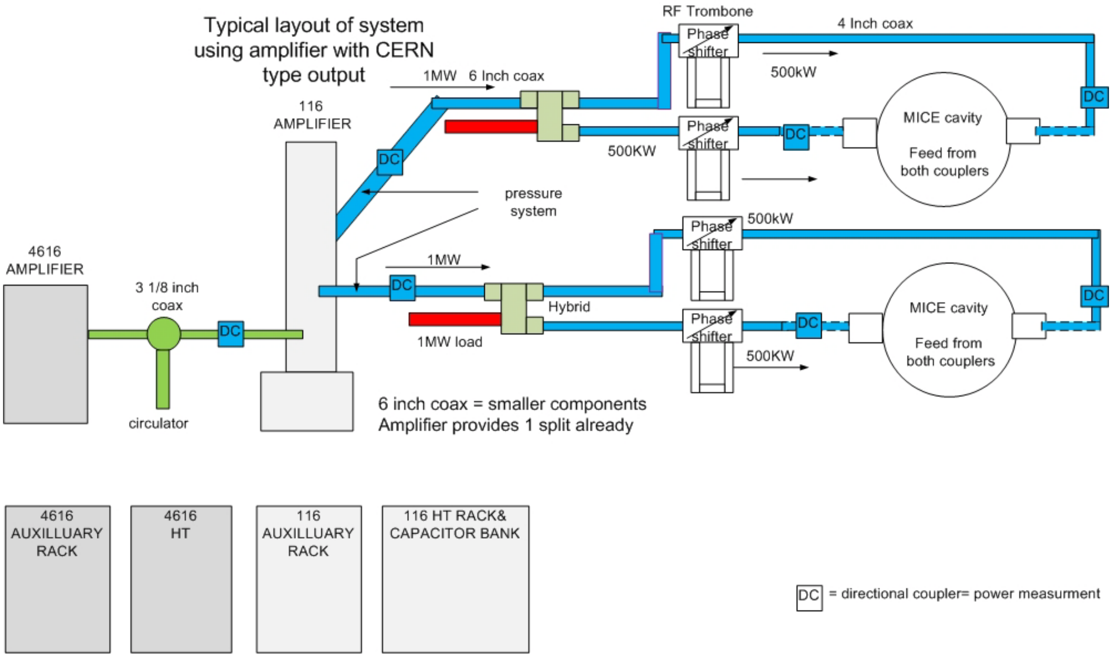

Fig 3: CERN amplifier general arrangement

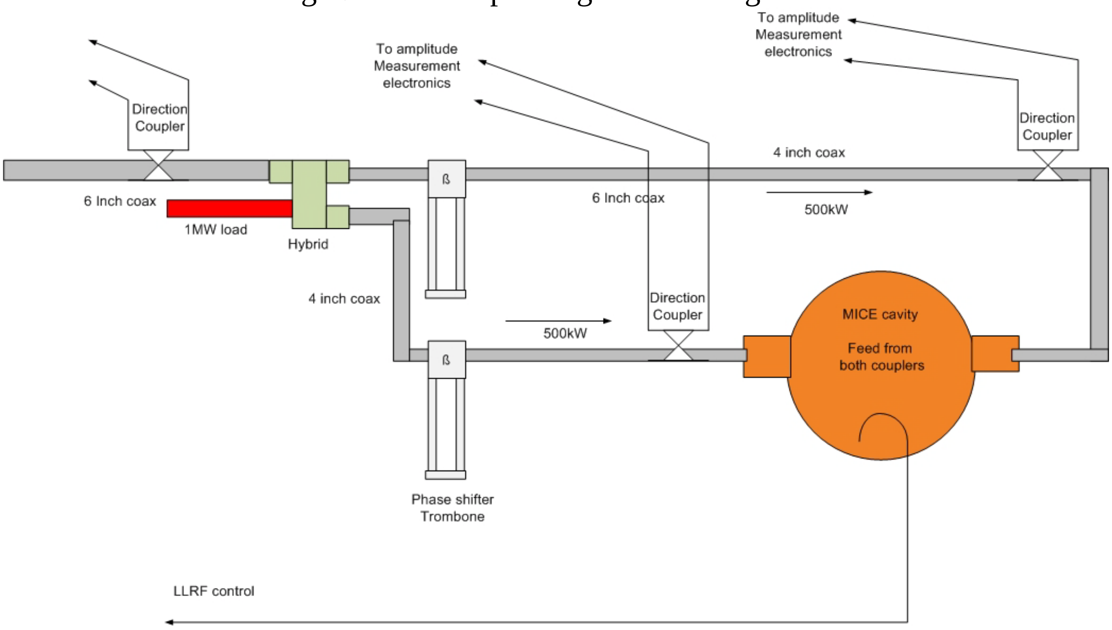

Fig 4: Coax distribution around the MICE cavity

CAD drawings have been produced; see Figures 5, 6, 7 to optimise the layout within the MICE hall. During this process, the phase length of each of the coax run from the amplifier has been measured and matched to the coax for the opposing cavity coupler; this means that incoming power to the cavity couplers will add in voltage inside the cavity. A small phase optimisation will be possible to take up any installation errors using coax phase shifters (see next section).

Fig 5: layout of amplifiers and coax system behind shield wall

The layout of the 6 inch coax from the amplifier outputs to the hybrid splitters is shown in figure 6. The phase length of each RF path has been measured and account taken of differing path lengths through the hybrids so that the correct phase relationship can be produced in the subsequent coax systems.

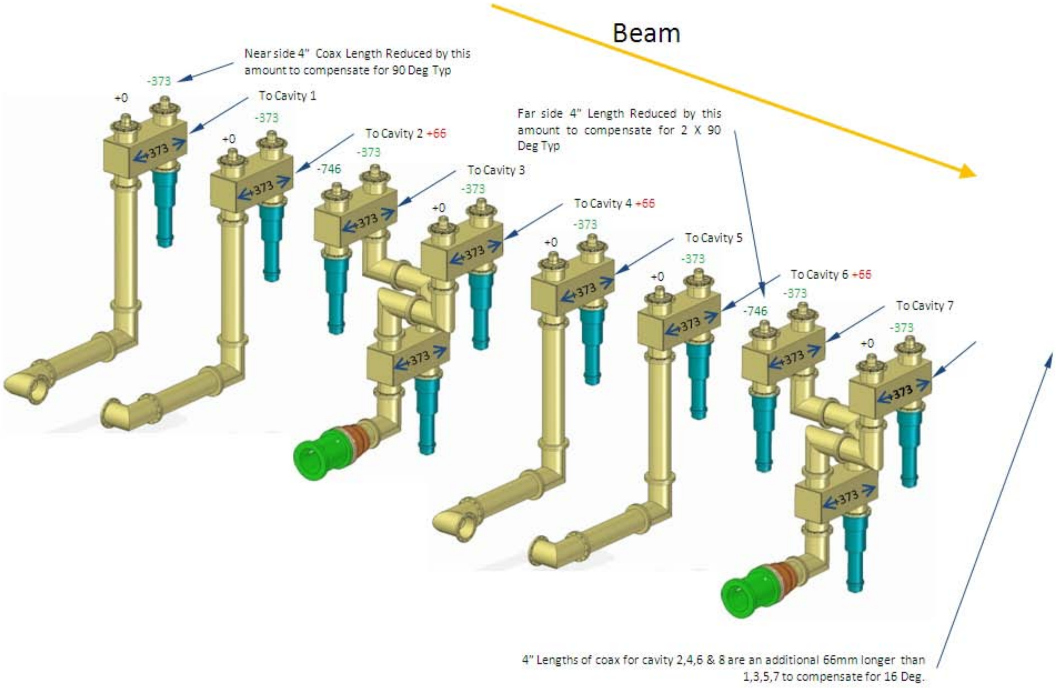

Fig 6: Coax distribution from amplifiers to hybrid power split

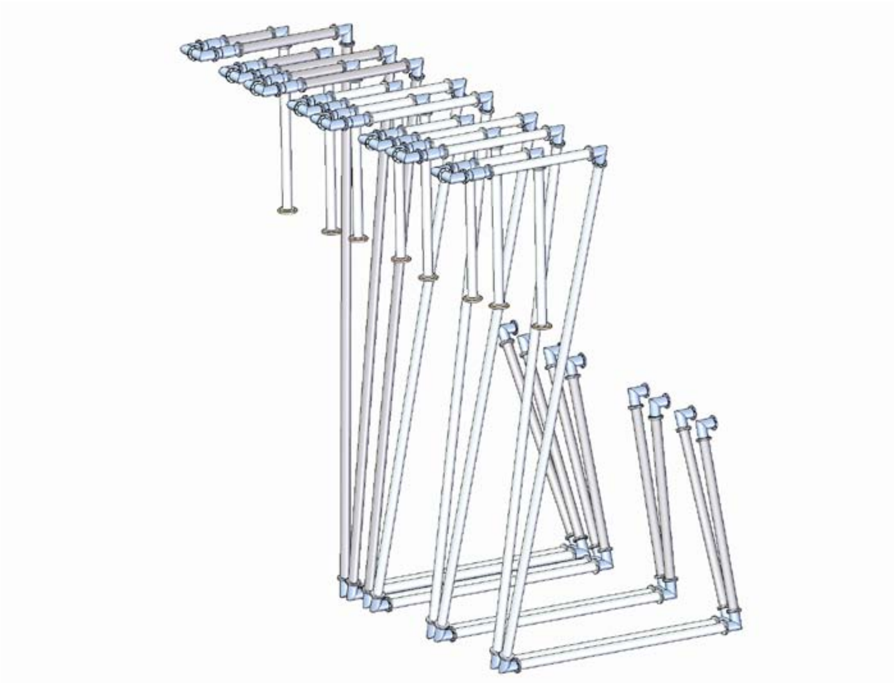

Fig 7: coax to cavity coupler distribution for north side of MICE hall

The 4 inch coax distribution shown in Figure 7, shows the output from the hybrid being bent 90 degrees and travelling through a coax line trimmer, before proceeding down the shield wall and underneath the false floor of the MICE hall.
The coax for the south side couplers (Fig 8) on the cavities, preservers the same number of 90 degree bends, and using the CAD system, the lengths of the coax lines have been matched to provide exactly the same phase length to both cavity couplers..

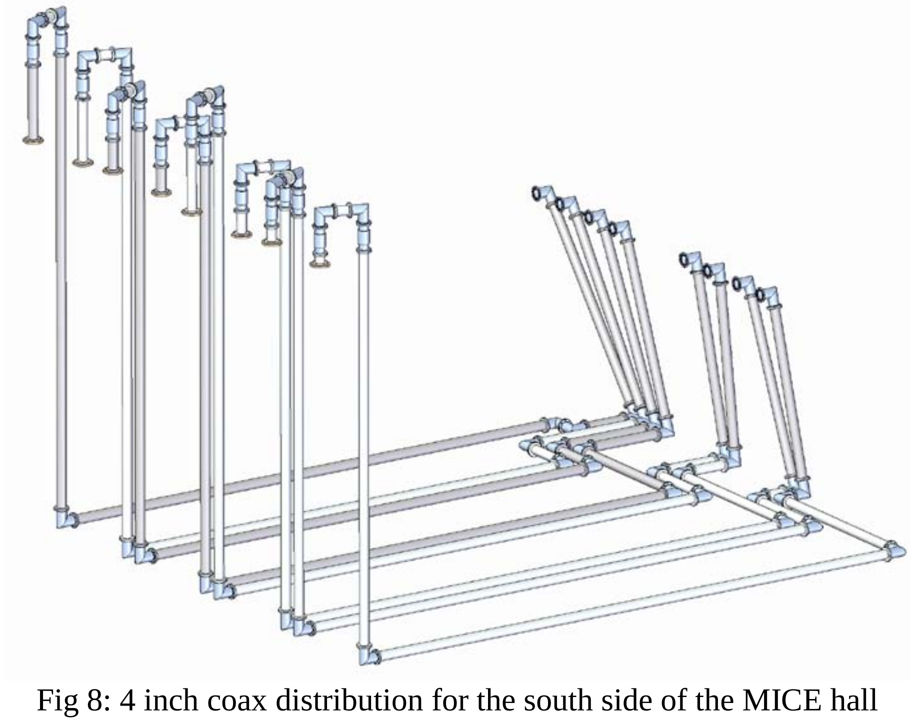

Fig 8: 4 inch coax distribution for the south side of the MICE hall

Again the coax connection from the hybrid is taken though a coax line trimmer, down the shield wall and under the false floor of the MICE hall.

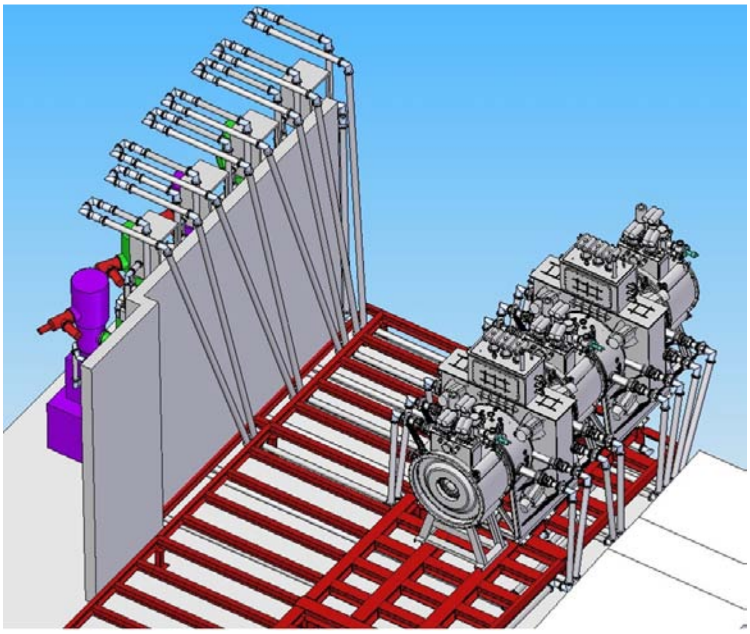

Fig 9: coax distribution to the MICE cavities

Cavity Phasing

Cavity phase relationship needs to change to maintain acceleration at differing energies. This will be achieved using combinations of the low level RF control (LLRF) which can adjust phase before each amplifier system, and for the second cavity on each amplifier (cavity 2, 4, 6 and 8) we need to move the phase in the high power coax.

Local motorised phase shifters will be used to meet this requirement.
The coax phase shifters can also be used to balance up any phase errors produce in the installed coax system so that power will add inside the cavity.
A possible solution is a coax line trimmer (Fig 10); this is made of stainless steel bellows with up to 60mm of travel and has been used in the RF transmitter domain as a line compensation device for many years. The trimmer will be fitted with a motor for remote operation, however these devices will have a finite lifetime and should only be used to adjust phase at modest regularity. Phase trombones could be used to provide greater range, however then quickly become physically large, which is a real issue in the hall.

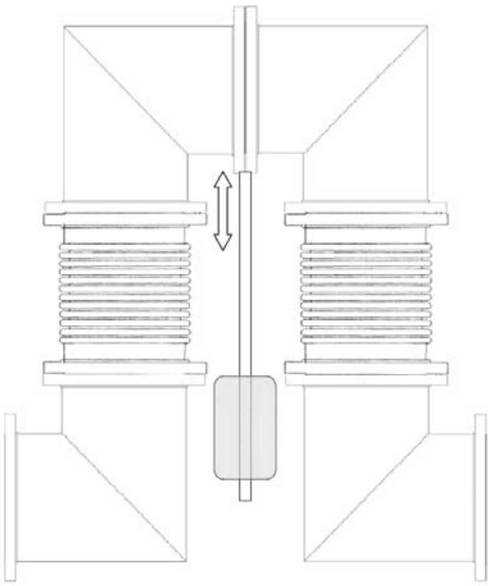

Fig 10: Coax line trimmer

Simulations of time of flight through MICE cavity system for 140-240 MeV/c have been calculated and checked by MICE physicists. Results can be seen in Figure 12. The change in phase angle equates to a phase change of 60 degrees between particles at 240MeV/C to140MeV/C which is within range of the coax line trimmers. An alternative approach that would give far great flexibility in terms of phase change and allow unlimited number of operations would be the use of ferrite loaded phase shifters. These devices are physically small but would significantly increase the cost as opposed to the coax trimmer shown.

The position of phase shifters and there action in the distribution chain can be seen in Figure 13.

Cavity	**z [mm]**	**t_0 [ns]**	**t_1 [ns]**	**Dt [mm]**	**Pphi [deg]**
1	0.0	0.0	0.0	0.0	0.0
2	430.0	1.57	1.8	0.23	16.62
3	860.0	3.13	3.59	0.46	33.23
4	1290.0	4.7	5.39	0.69	49.85
5	2750.0	10.02	11.48	1.47	106.27
6	3180.0	11.58	13.28	1.7	122.88
7	3610.0	13.15	15.08	1.93	139.5
8	4040.0	14.71	16.87	2.16	156.11

t-0 for particle with p=240 MeV/c
t-1 for particle with p=140 MeV/c

Fig 12: Calculations of time of flight and phase change through the RF cavities

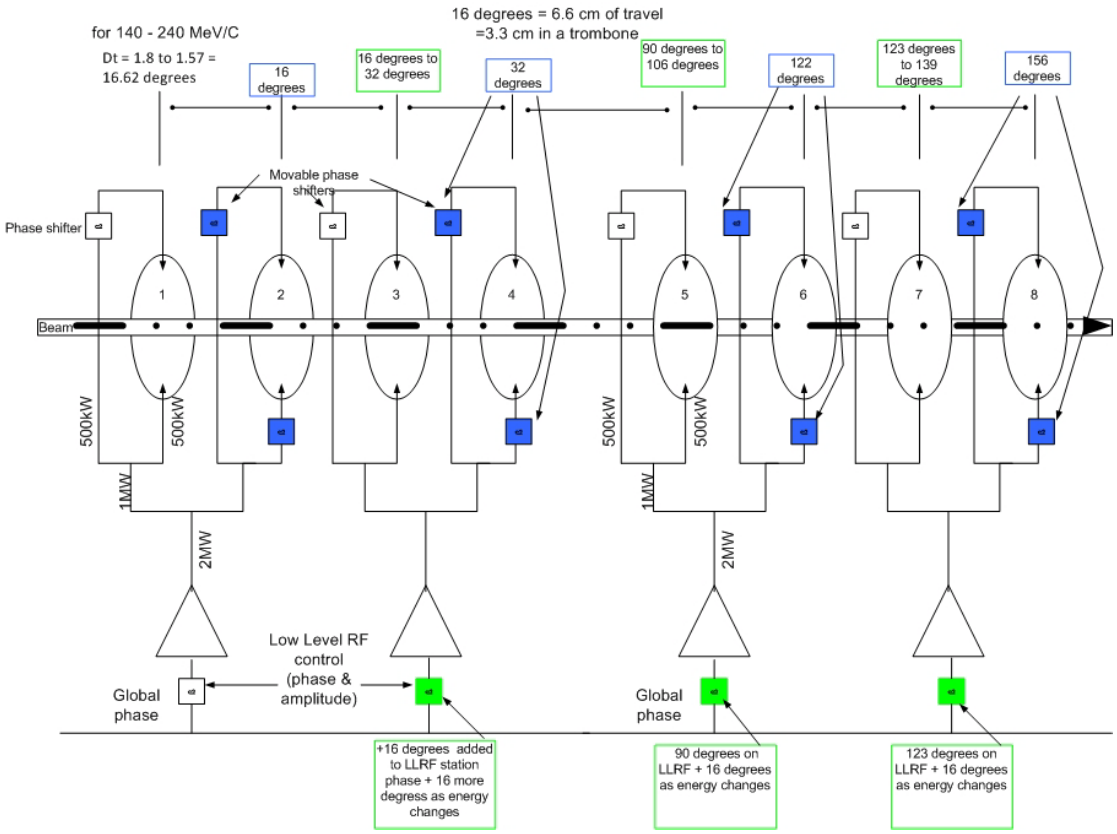

Fig 13: Phase adjustment of the amplifier and coax distribution system for different momentum of muon.

Coaxial Line Size/Pressurisation

The coax system is required to transmit RF power from the amplifiers to the MICE cavities in a reliable and predictable fashion. As space in the hall is so limited the drive to use smaller dimensions of coax becomes the best option. Also the MICE cavity input couplers are already designed at 4 1/8th inch, so any distribution coax would ultimately have to match to this flange.

During high power testing at the MTA, the incoming 9 3/16th inch coax from the 5MW triode amplifier is reduced to 6 1/8th inch and this is further reduced to 4 1/16th inch coax before connection to the cavity couplers, the entire coax guide is pressurized with SF6 insulating gas. High power tests at the MTA have been at significantly higher fields than will be possible in the MICE cooling channel. However the breakdown prosperities of the coax line need to be taken into account in the MICE experiment to ensure reliable operation.

As the RF is switched on to each MICE cavity, the cavity will begin to ‘fill’, however during the first 200 uSec there will be significant reflected power from the cavity back into the coax system. See Fig: 14

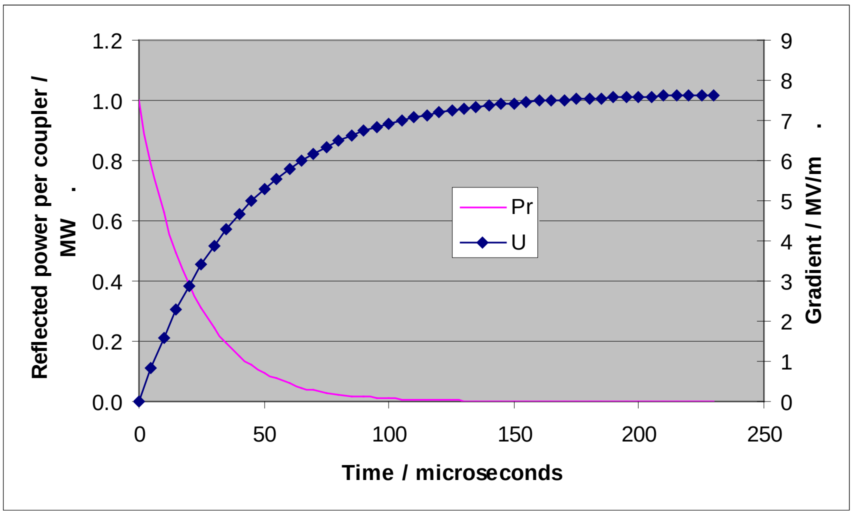

Fig 14: MICE cavity fill, blue = gradient, pink = reflected power

Inside the coax the power of the forward and reflected waves will add along the guide producing a total power that is double the incoming power, and more importantly, the effective voltage will then four times the input voltage. All coax manufactures produce data of peak power and average power handling for their coax guides, also peak voltage standoff is quoted as this is important if the coax is installed at high altitude, in warmer climates or if the guides are subjected to sunlight, all of these factors de-rate the maximum RF carrying capabilities of the coax guide. See Fig 15 and 16 for peak and average power handling capabilities

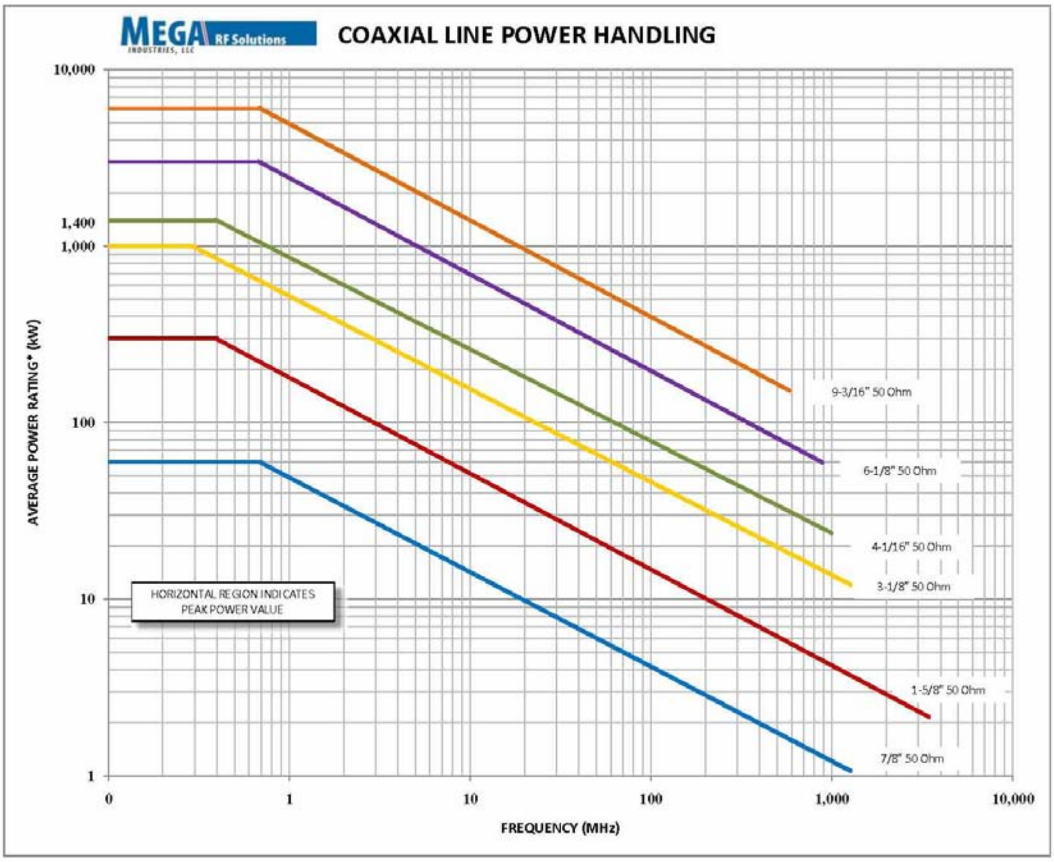

Fig 15: Mega Industries coax

LINE SIZE	Zo	Production test voltage @ 20°C	RF Voltage Limit	Peak Power (watts)
7/8'	50	5825	1442	41600
1 5/8"	50	10409	2576	132700
3 1/8"	50	18971	4695	440900
4 1/16"	50	24076	5959	710100
6 1/8"	50	35411	8764	1536100
6 1/8"	75	36179	8954	1069000
7 3/16"	75	41788	10342	1426100
8 3/16"	75	47273	11699	1825000
8 3/16"	50	46460	11498	2644200
9 3/16"	50	51879	12839	3296900
9 3/16"	75	52730	13050	2270700
12'	50	68336	16912	5720500

Fig 16: Myatt data for coax guides

For the MICE cavity operating at 1MW at 1 pulse per second (PPS) and 1 mSec pulse width, the average power is a one thousandth of the peak power ~1kw which is clearly not an issue. However during the cavity filling process with the associated reflected power adding to the forward power, the peak power inside the 6 and 4 inch coax guides will be higher than the peak breakdown capabilities of the coax guide.

Guide size	Peak kW	Average kW at 200Mhz	Peak voltage capability kV
9 3/16th	3200	800	13050
6 1/8th	1550	100	8764
4 1/16th	700?	50	5959

Table 1: peak and average capabilities of coax guides

Although the over voltage effect will only be for a very short time each RF pulse, the effect will be sparking within the coax guide, this is unacceptable for the reliability of the system.

The benefit of using SF6 or Nitrogen insulating gas on the coax guide is shown in Fig 17 where it is shown that an SF6 pressure of 1 PSI would improve the peak power rating by 3 times; use of nitrogen while not offering such a profound effect could offer significant improvement in peak power handling while not producing the complex handling and storage requirements of SF6.

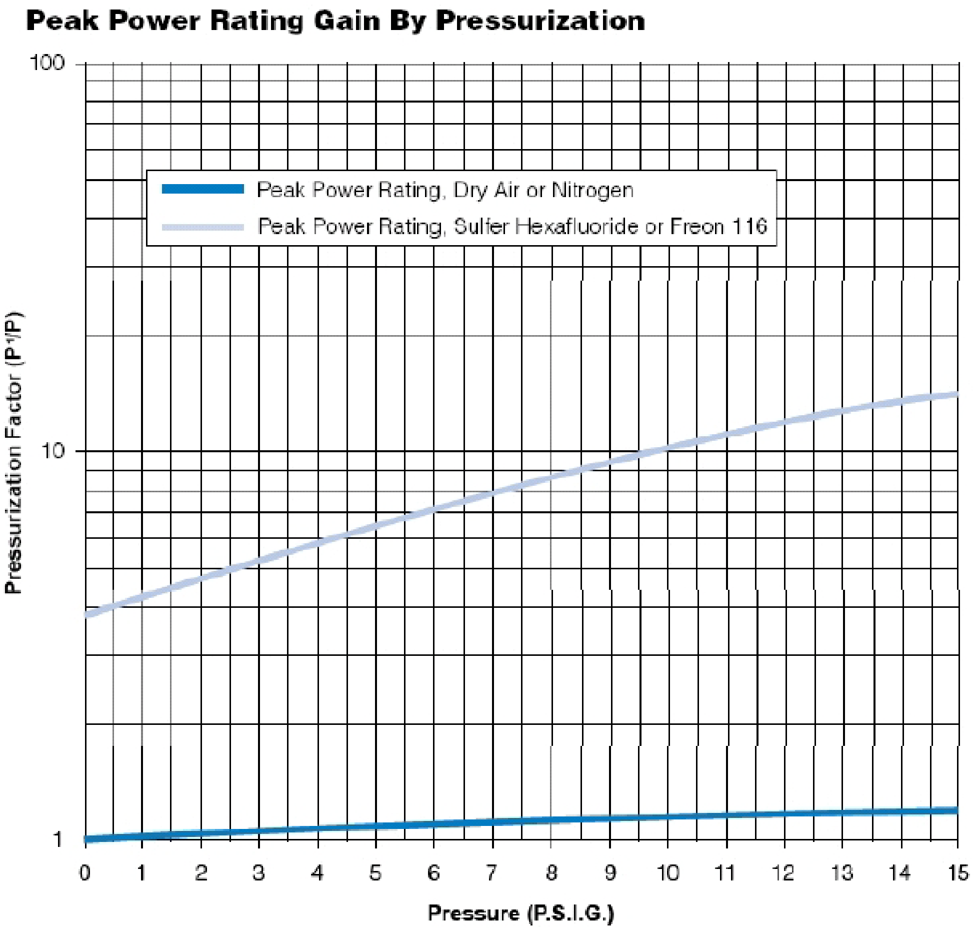

Fig 17: SF6 and Nitrogen effect on peak power ratings

For the coax system to use pressurisation there are a number of design issues to address. There will need to be pressure windows at various points along the coax guide, valves to allow gas filling and removal of gas safely. The pressure of the gas would then become a control interlock that would prevent operation of the amplifier. The coax system itself would need to be supplied with sealing flanges to limit leaks. For SF6, a recovery system and control measures for personnel safety would be needed inside the MICE hall, however for Nitrogen as the MICE hall already has an oxygen depletion system installed due to the use of cryogens and hydrogen, no other safety features would be needed.

A possible way to aid using pressurised gas is to use the LLRF system and RF pulse shaping to slow fill the cavity. Normally the RF is switched on very quickly to get the cavity up to the field required as quickly as possible. It is possible to provide a more gradual switch on to get the cavity to fill slowly and avoid very high peak reflected powers. See paper TUP5A16 EPAC200 Vienna 2000 for an explanation of this technique.

A second part of the MICE proposal is to run MICE Step V at higher RF powers, by supplying the 4 RF cavities with 2MW of RF power, if this proposal is carried forward, then the use of SF6 becomes unavoidable and we should design the system to make full use of the benefits it will bring in terms of RF power rating.

Conclusion

The report has show that extensive design work has taken place on the coax system to include all necessary items to provide a balanced well isolated system that will be flexible enough for the MICE experiment during its lifetime.
We are at the point where ordering the majority of the coax to be installed in the MICE hall could be made.

Several types of high power phase shifters have been identified that could be used in the system. Physically small, low phase shift devices are available at modest cost, however they have limited range and finite lifetimes for movement. Ferrite devices could be employed providing far greater range at increased cost if the experiment deems it necessary.

The coax system has been designed to fit inside a small area and as such has benefitted for reducing the coax system down to 4 inches. However the peak power will necessitate the use of pressurized gas as an insulator. Nitrogen s the preferred option due to the modest safety restrictions it posses on the MICE hall, however if the plan to get to higher powers for a reduced number of MICE cavities is taken, then SF6 will have to be installed to protect the coax system.
In addition the subject of reflected power and its effect on the triode and its associated power supplies should be discussed as this has not been tested within the current Daresbury tests.

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