MICE High Power RF Distribution Design

Andrew Moss April 2011

Background

This document sets out to discuss key design areas of the high power RF system for the MICE experiment at RAL. A design review needs to take place of the actual RF transmission components between the amplifiers and the MICE cavities. Coax components at 200MHz are large, space in the MICE hall is at a premium and so careful consideration needs to be made as to what is needed for the experiment to run reliably and efficiently while still providing the required flexibility.

Amplifier systems

The amplifier system for MICE consists of a 4kW solid state amplifier, a Burle 4616 tetrode amplifier capable of delivering 250kW and TH116 amplifier system capable of delivering 2MW at 201 MHz. The first sets of amplifiers are currently on test at Daresbury Laboratory.

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, the hybrid will split the reflected power equally to both the incoming port and the load port. This means that half the driven power will be reflected back to the driving tube, and half will be absorbed in the hybrid load. See Fig 1.

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.

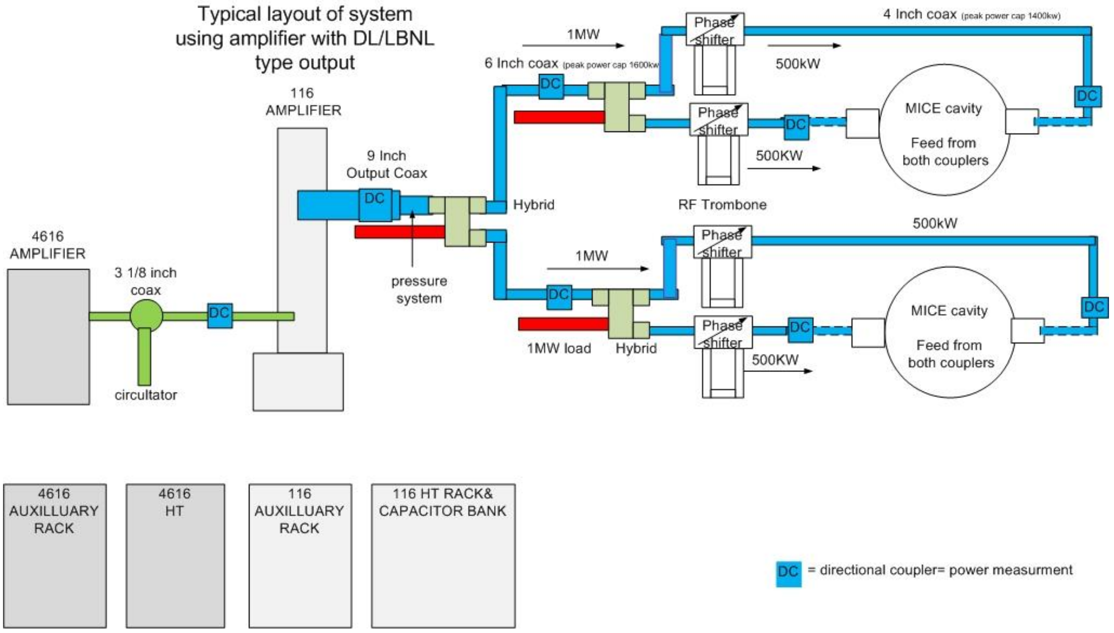

Fig 1: Berkeley amplifier general arrangement

Components in the coax lines, bends, 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 and in the 6 inch output coax. See CERN report **CERN-AB-2006-025.**

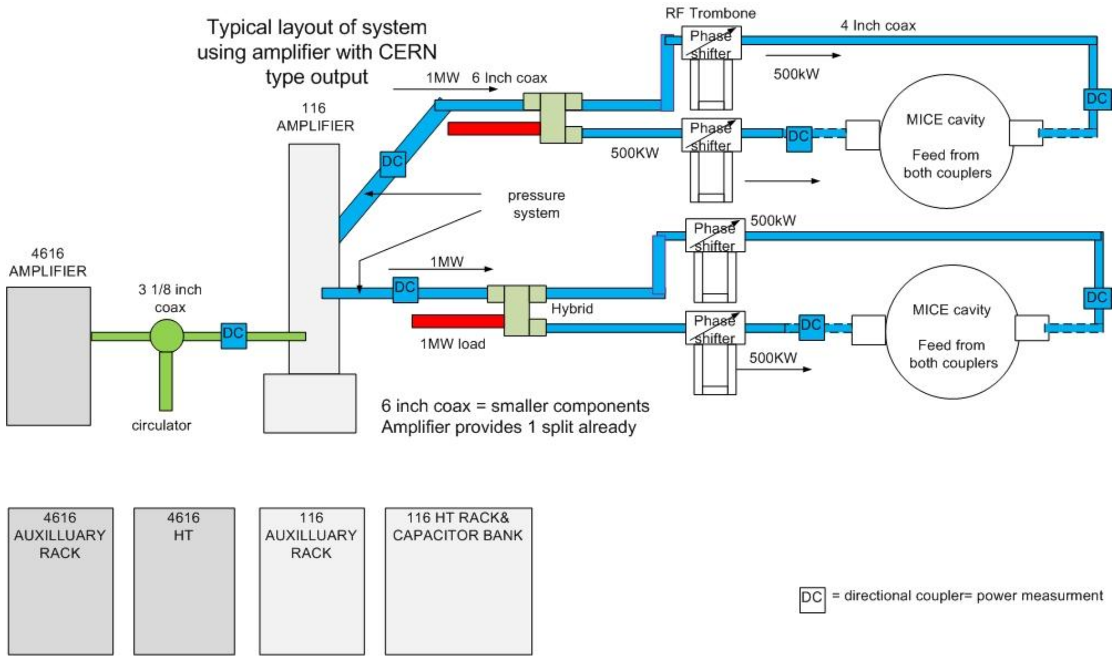

Fig 2: CERN amplifier general arrangement

Cavity Phasing

The RF power transmitted to the cavity must be fed via the two cavity couplers mounted on opposing sides of the cavity. To ensure that power adds inside the cavity optimally, the coax system must be designed so the path length as seen by the RF is appropriately phased. To allow for compensation, a small range phase shifter or line stretcher should be included in every cavity coupler arm.

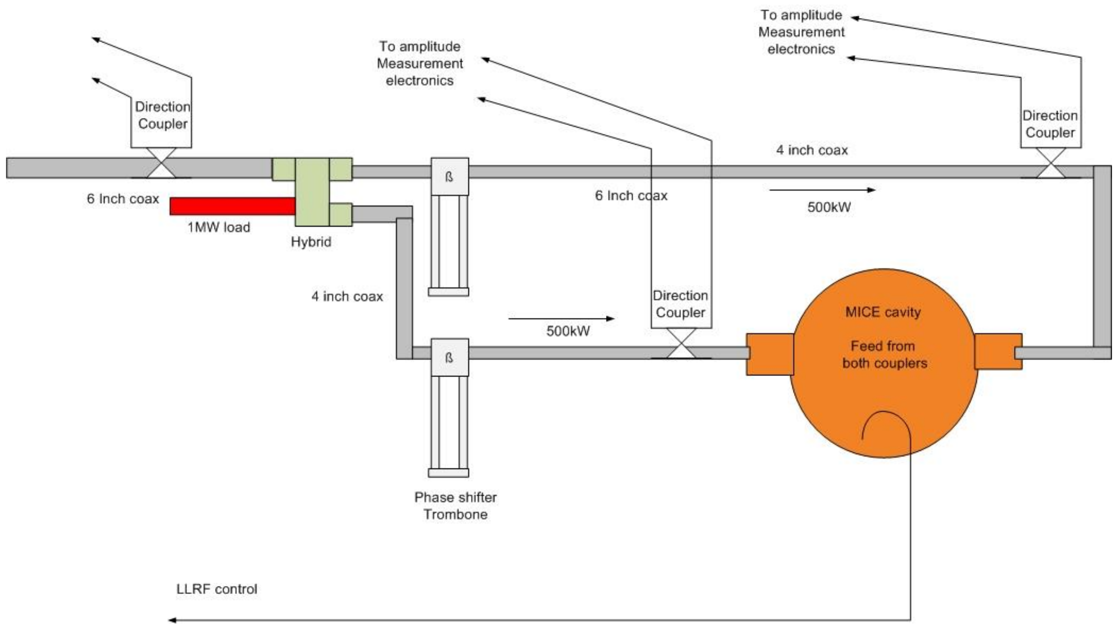

Fig 3: Coax distribution around the MICE cavity

It is intended that the high power phase shifters will be remotely controlled from the MICE control room. although it is not expected they will be moved once the RF system is set up.

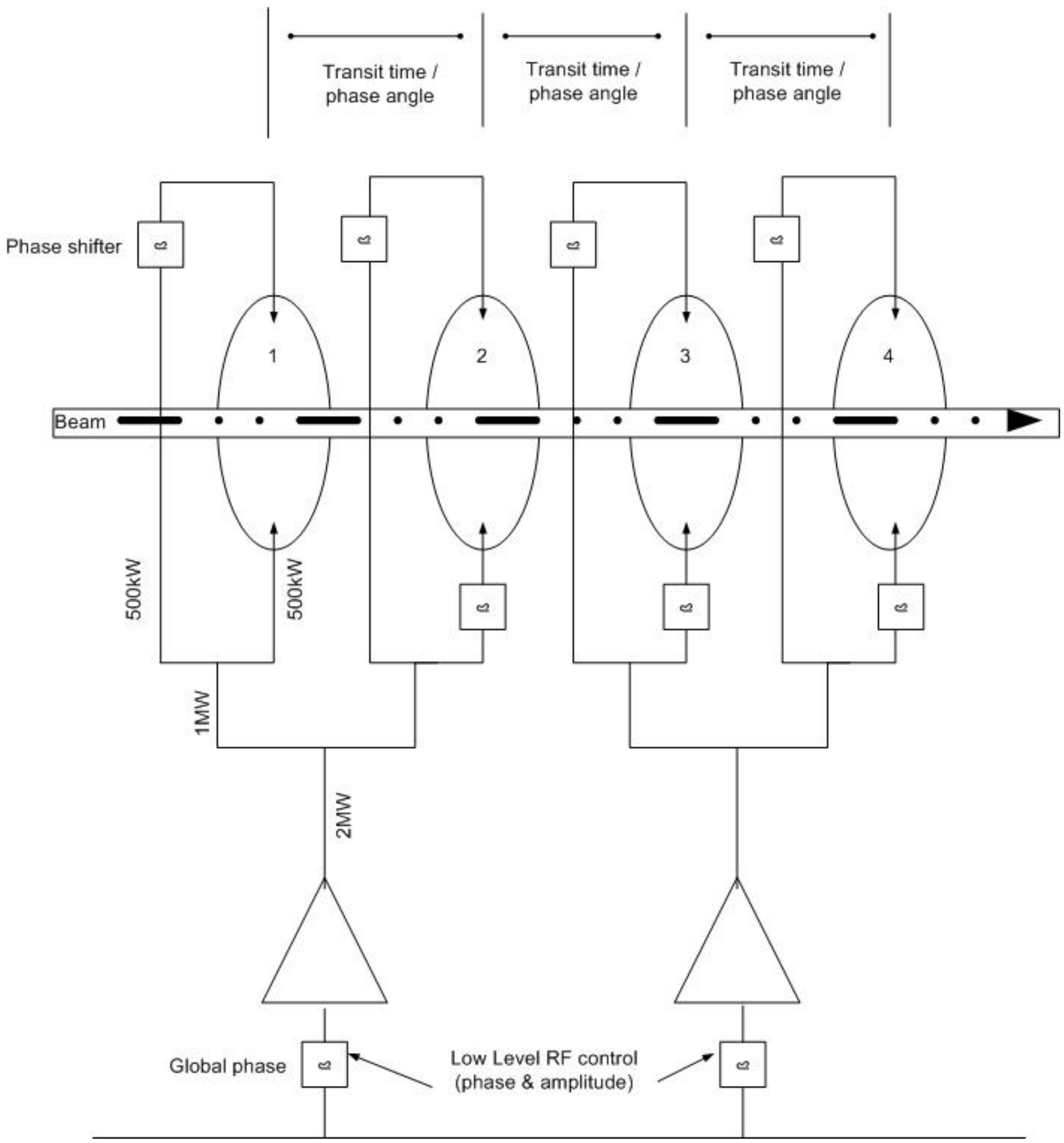

Fig 4: RF cavity phasing with Muon beam

We need to understand the relationship between the MICE cavities and the muon beam so that acceleration can be preserved inside the cooling channel.

Coax on cavity 1 will be constructed to present an equal phase angle so that power entering the cavity from the two coupler arms will add; small errors can be removed using the phase shifter in one coupler arm
The global phase angle of cavity 1 can be set via the LLRF. This will also move the global phase angle of cavity 2 and set the gradient of both RF cavities.

Coax on cavity 2 will once again be set so that RF power adds inside the cavity, small errors can be removed using either of the phase shifters in the coupler arms
The phase angle of cavity 2 needs to be set by understanding the transit time of the muon bean from cavity 1 (hence the phase angle at 201MHz) and then moving both phase shifters in the coupler arms by an equal amount to set the required phase angle of cavity 2.Cavities 3 &4 can be set in the same way.

The phase shifters in the coupler arms will be of limited travel ~ 60 degrees; this is due to these devices becoming excessively large if large phase changes are needed. So the transit time must be understood before the coax system is finalised. It is intended that all the phase shifters will have the same limited range, therefore additional fixed pieces of coax will be added to the coax system of cavity 2,3 and 4 to offset their phase angle as required.

There will be no beam loading effect to compensate for in the MICE cavities, however phase an amplitude control of 0.1 degrees and 1% are aimed for.

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: 5

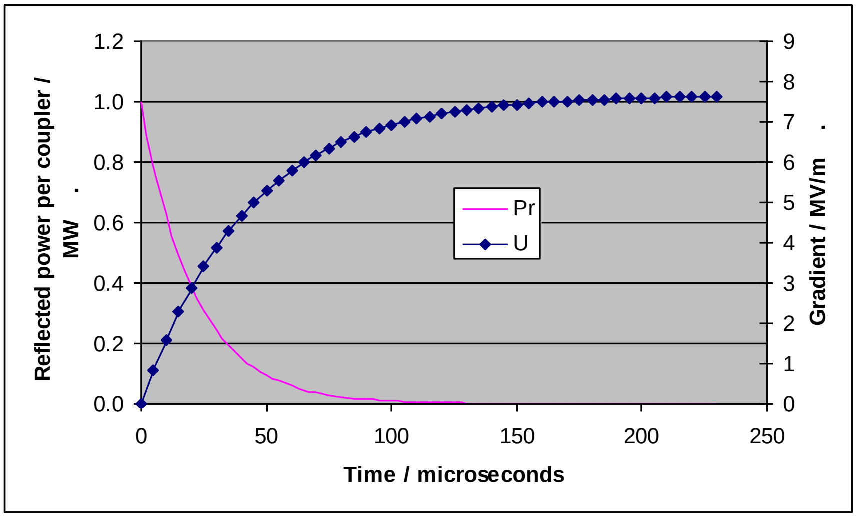

Fig 5: MICE cavity fill, blue = gradient, pink = reflected power

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 6 and 7 for peak and average power handling capabilities

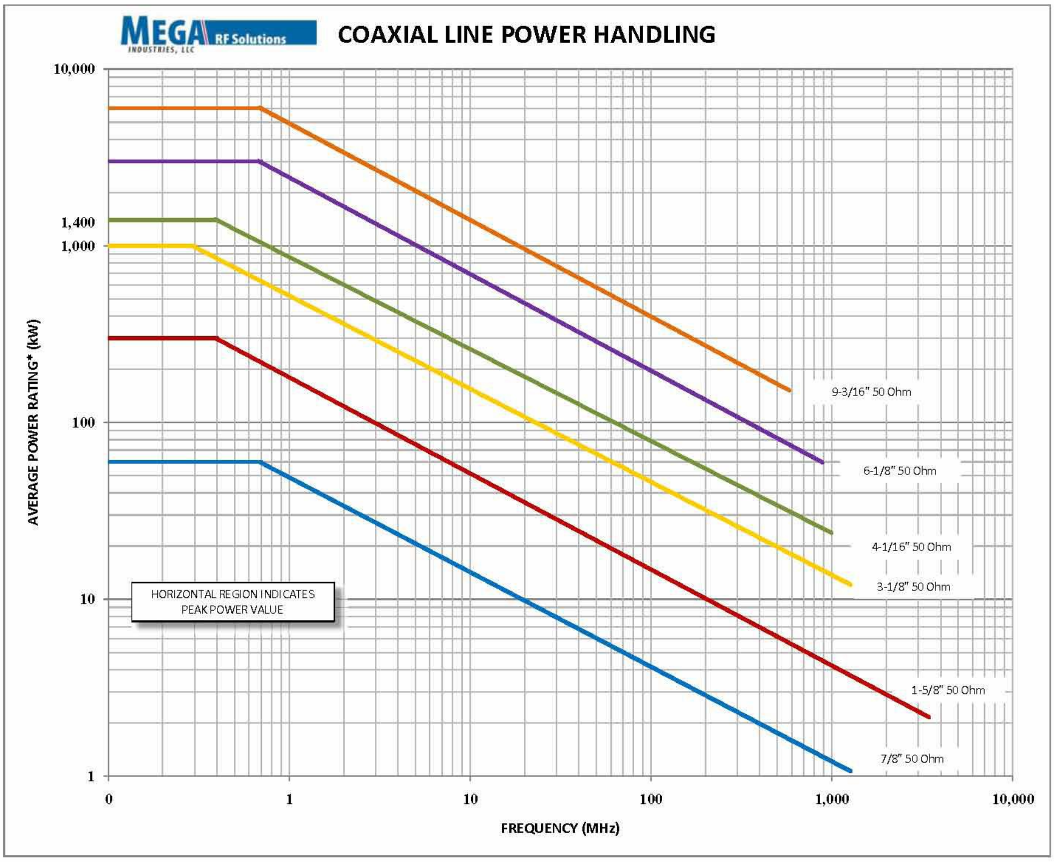

Fig 6: Mega Industries coax

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

Fig7: 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	1400?	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 with be sparking within the coax guide, this is unacceptable for the reliability of the system. .

The benefit of using SF6 insulating gas on the coax guide is shown in Fig8 where it is shown that an SF6 pressure of 1 PSI would improve the peak power rating by 3 times.

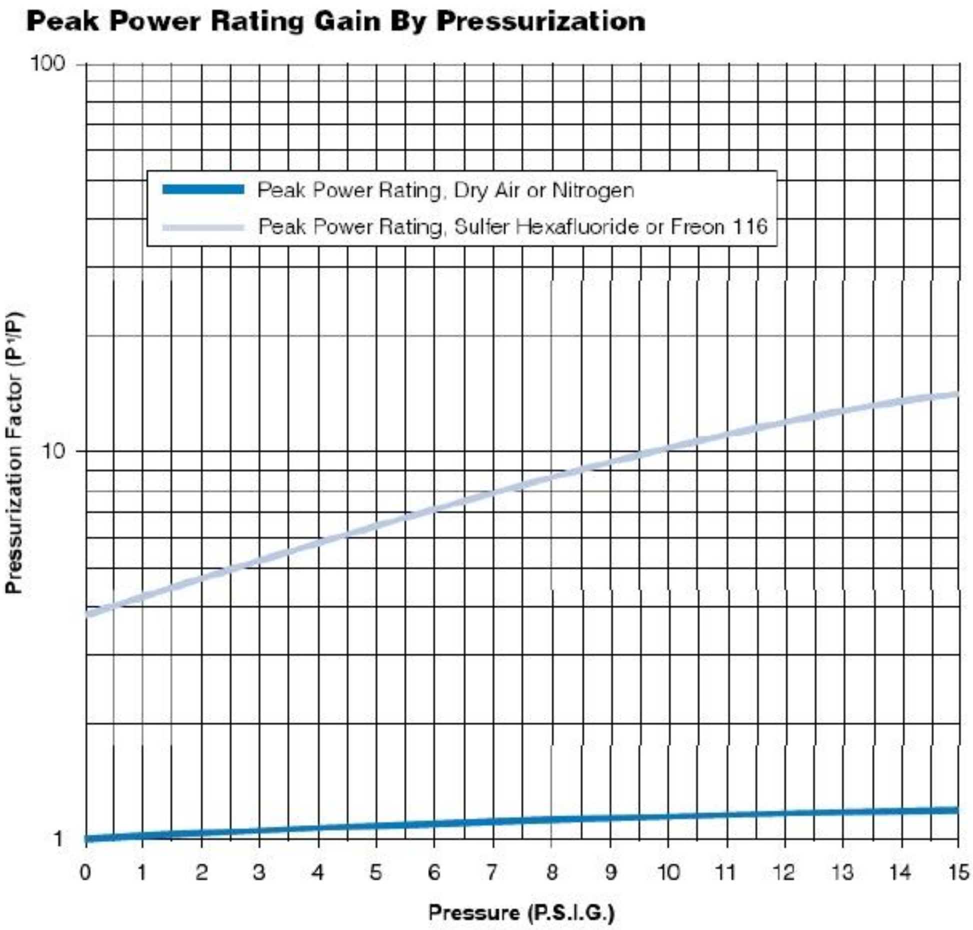

Fig 8: SF6 effect on peak power ratings

For the coax system to use SF6 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 SF6 filling and removal of gas safely. The pressure of Sf6 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.

An SF6 recovery system and control measures for personnel safety would be needed inside the MICE hall.

A possible way to avoid using SF6 is to use the LLRF system and RF pulse shaping to slow fill and slow empty 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. A similar possibility can be at the end of the RF pulse, rather than simply switching off; a ramp down of the RF power could avoid high peak reflected powers. Whether this is approach is satisfactory in operation will need to be determined. See paper TUP5A16 EPAC200 Vienna 2000

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 has real merit then the use of SF6 would seem to be unavoidable so my proposal is that we design the system to use SF6 in the coax guides.

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