Test and Commissioning Plan: MICE Demonstration of Ionisation Cooling

Introduction

MICE (the Muon Ionisation Cooling Experiment) aims to demonstrate that the emittance footprint of muon beams, formed from the decay of pions created by the interaction of high fluence, energetic, proton beams with targets may be reduced by ionisation cooling. Ionisation cooling is achieved by passing the Muon beam through dense, low atomic number absorbers. Suitable absorber materials include plastic, Lithium Hydride and Liq. Hydrogen. The muon beam will be controlled by a system of superconducting magnets to regulate the beam optics, since these (in particular the transverse β of the beam) strongly impact on the relative strength of the ionisation cooling and heating (multiple scattering) terms in the interaction of the particles with the material. Strong magnetic fields also allow the channel to transmit a beam with large emittance with relatively low particle losses. The beams to be investigated are representative of those proposed for neutrino factories and muon colliders.

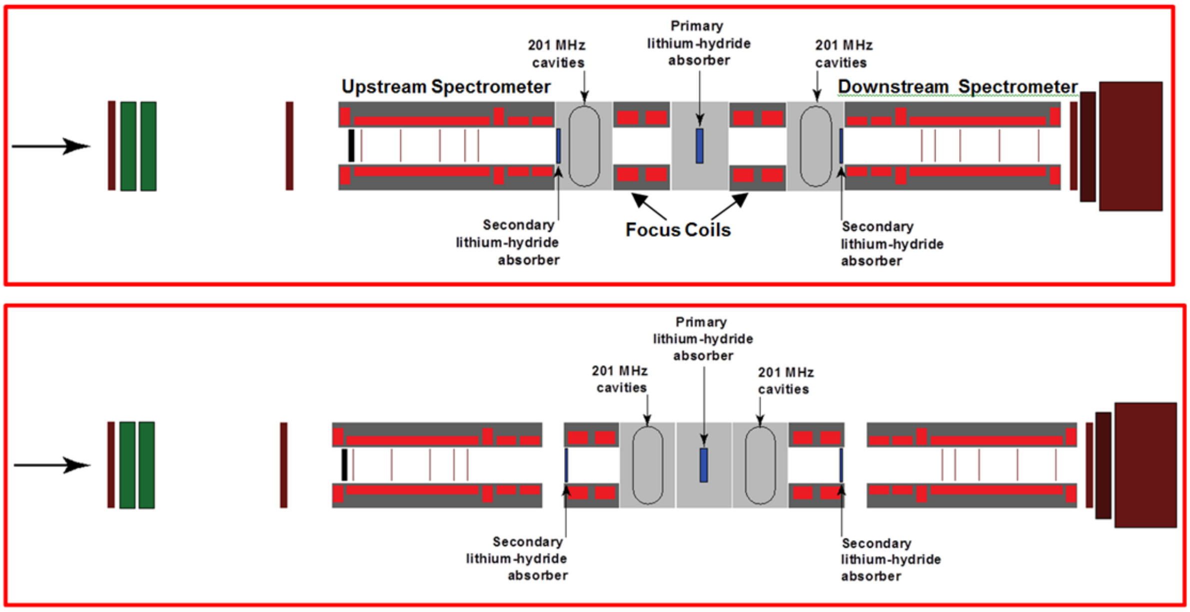

Figure 1: The main components of the MICE Ionisation Cooling (IC) apparatus, upper figure is the reference design, lower figure is an alternative lattice being considered at the time of writing. There are no substantive differences between these from an installation and commissioning perspective.

In addition to its sensitivity to the β_T of the muon beam, the ionisation cooling process is also sensitive to the muon energy/axial momentum. The process of ionisation cooling reduces all components of momentum equally. In order to repeat the process to achieve the emittance reduction demanded by realistic accelerator complexes, one must also show that the absorbers can be integrated with accelerators to maintain the energy in the correct range. The MICE demonstration of ionisation cooling (IC), illustrated in *Figure 1*, will verify that this can be achieved. Key challenges include the development of strong RF accelerating fields in the presence of strong magnetic fields, including special VHF cavities to reaccelerate the rather large emittance beams, the amplifier chains required to energise these cavities, the absorber cells themselves and timing diagnostics for determining the RF phase in the cavities during the muon transit and the necessary magneto-optical system to guide the muons through the cooling channel. All the required magnet systems have already been developed and tested in advance of MICE Step IV. The ionisation cooling experiments will require a relatively straightforward extension of the return yoke (the sole function of the yoke is to limit the magnetic fields interfering with apparatus outside the cooling channel).

To facilitate the operation of MICE in the IC configuration several development and test programmes are underway. These are described below along with a discussion of the installation and commissioning plan for the equipment in the MICE Hall. The test and commissioning programme is focussed on RF systems and is likely to involve simultaneous testing of various elements of the RF system at Daresbury Laboratory, RAL, FNAL, Berkeley and will draw on RF, electrical and mechanical engineering expertise from these labs and support from scientists at Strathclyde University, Imperial College & IIT. Mechanical, vacuum and cyrogenic expertise will be required in particular in installing the system at RAL. During commissioning, DAQ and physics expertise will also be required. Planning for 24 hours-per-day operational running, proposed in the experimental and operational Plan, will be informed by Step IV experience.

<u>Test & Development of RF systems and Auxiliary Hardware</u>

<u>RF Amplifiers</u>

The first RF amplifier has been tested at its nominal 2 MW peak output power level in pulses 1ms in duration and at a PRF of 1Hz at the test stand at Daresbury Laboratory, as illustrated in *Figure 2*. The first triode (output stage) amplifier is already installed in the MICE hall having been tested there in late 2013, shown in *Figure 3*. Details of the amplifier system, its power supplies and the tests are presented in the report by the MICE RF group to the EU TIARA project[i].The first triode amplifier remains installed at RAL. The other components of the 1st amplifier have been transported back to Daresbury where they will be used to commission the key subsystems of the second amplifier sequentially.

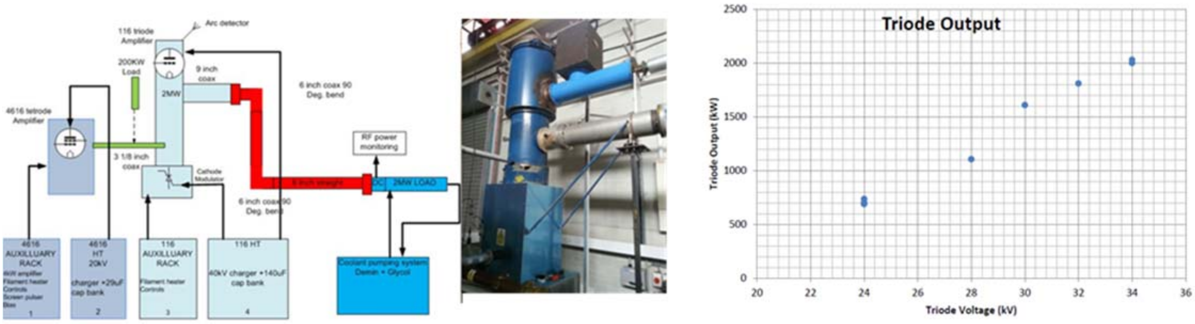

Figure 2: Showing the layout of the test station at Daresbury, an image of the final stage amplifier and the variation of amplifier chain output power with triode valve bias voltage

Figure 3: First triode amplifier installed in the MICE hall

The philosophy, for build-up of the second amplifier chain, is to make sequential single-changes, to the rack/cabinet line-up, in order to minimise potential complications from simultaneous technical risks. Hence the 2 MW end-stage of the second RF amplifier chain is being prepared at Daresbury, for running with the drive amplifier chain and power supplies, including the first 4616 valve stage, already proved at Daresbury and RAL. Electrical and RF testing will be undertaken as each new rack is introduced to the test-bed.

It is intended that the RF control system be incorporated, and tested as far as possible, at Daresbury. The software and hardware design will be undertaken by Daresbury experts, and will be largely generic, based on previous systems implemented by Daresbury on their accelerator projects and already utilised on MICE. Definition of the control requirements is in hand to ensure correct interface with the MICE EPICS control system. High-priority control interlocks and trips will be provided by local PLCs within the PSU racks for highest reliability and speed of response, e.g. any loss of supply of cooling water requires rapid muting of the tube amplifiers and run-down of the heating filaments.

The Power Supply system is being upgraded to incorporate higher-voltage crow-bar protection devices. The gas-discharge devices, used in the first system, were close to their limiting voltage and exhibited instances of false-firing. Two solid-state devices have been procured and bench-tested at Daresbury, demonstrating good reliability, and are the preferred solution. The necessary mechanical modifications to the power supply racks are in-hand.

Electrical engineering resources for 14/15 have been focused on completing Step IV. It is anticipated that the resources required for Step IV will be significantly reduced by April 2015, enabling the RF system assembly and test to progress. The experience of developing the first amplifier gives confidence in the assessment of the technical, timescale and cost risks. The resources available mean that in the timeframe of operation in 2017, it will be possible to complete two amplifier systems the first in 2015 and the second system in 2016.

<u>RF Distribution Network</u>

The RF distribution network will be largely built using components procured by Mississippi and already available at RAL and Daresbury. These components significantly exceed the component count required. It will be necessary to procure or modify certain lengths of line to accommodate the different physical location of the cavities from that for which the lines were originally cut (as a result of the switch from Step V to the IC configurations). There will now only need to be four 4” co-axial lines serving the cavities, fed by two 6” lines from the RF amplifiers. The transition between the 6” and 4” lines will be performed at the output of a pair of 6” quadrature hybrid couplers, sending half of the output of each amplifier chain to the two opposite couplers on a single cavity. The length of these coupled pairs of 4” lines will need to be correctly tuned in electrical length. The IC design demands that we deliver ~1MW along each of the 4” lines and 2MW in each 6” line. The peak power rating of these lines is 710kW and 1.5MW respectively. Given the risk of the E-field amplitude doubling due to the strong reflections expected during cavity fill, the collaboration feels that this redesign now merits the inclusion of SF_6 as the line insulation gas. Use of this gas at 1 psi positive relative (to atmospheric pressure) affords an increase in peak power handling of over a factor of 4, whilst 10 psi affords an increase of an order of magnitude in peak power. This represents a relatively minor modification since the lines were designed to be pressurised at 1.5-2 bar in nitrogen whilst the key areas of the hall are already equipped with oxygen depletion monitors. A health and safety analysis will need to be completed but as similar systems are regularly used at most major laboratories (including Fermilab and Daresbury) no particular difficulty is anticipated. The mechanical layout of the distribution network poses no significant difficulties (being simpler than the STEP V/VI layouts already completed, details may be found in the publications of the EU TIARA project[ii]).

<u>RF Cavities</u>

A key technical challenge of the cooling channel is the requirement for reasonably high gradient accelerators operating in a relatively strong magnetic field and with a large (and initially high emittance) muon beam. To address these requirements the Lawrence Berkeley National Laboratory (LBNL) has developed special cavity and coupler designs. The RF cavities for MICE are designed to resonate at 201.25MHz and take the form of discrete TM_{010} resonators with a Q of around 50,000. Each resonator is fed on two 4” diameter EM wave input ports and each feature two large, on axis, and very thin (0.38mm) beryllium windows to minimise impact on the passage of the muon beam. These designs have already been subject of significant de-risking in the ‘prototype’ cavity tested at the MuCool Test Area (MTA) at Fermi National Accelerator Laboratory (FNAL/FermiLab) in the presence of a fringe magnetic field up to a gradient of around 12MV/m (16MV/m in the absence of the magnetic field) with a drive power of up to 5MW. In this configuration the cavity showed little spark damage on axis, although evidence of sparking was seen inside the couplers. As a result the couplers for the MICE experiment have been redesigned. Manufacturing risk has also been addressed since 10 'production' cavities have now been fabricated by LBNL, along with two revised couplers and sufficient beryllium windows to fabricate 2 sets of four cavities (with spares). The vast majority of the required materials for the Ionisation Cooling (IC) cavities therefore either exists in fact, or has been prototyped.

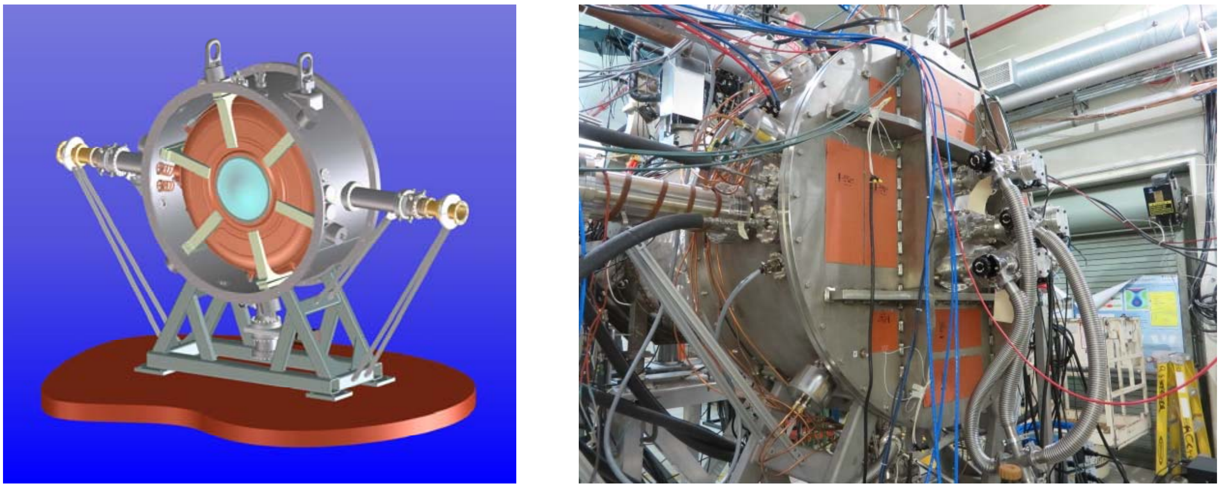

Figure 4: 3D model showing main features of the cavity and SCTS, this will also be the model for the cavity sections of the IC experiment. Photograph of the instrumented cavity in the MTA

The first production cavity and the first two production couplers have been assembled in a single cavity test cell at the MTA, see *Figure 4*. It is relevant to note that due to the thin Be windows, the cavity is not intended to form a vacuum tight envelope, but will sit within a larger evacuated volume. The prototype outer vacuum vessel and support structure for the cavity and couplers is known as the Single Cavity Test System (SCTS) and is nearly identical to the structure of the cavity sections envisioned for the IC apparatus. Construction of the SCTS allowed the collaboration to understand fully the assembly process and has led to some minor redesign of the suspension system which locates the cavity in the support vessel. It has also allowed the collaboration to fully understand the vacuum system and pump down requirements. The cavity (which was electropolished at LBNL and handled throughout assembly at FNAL in cleanroom facilities) pumped down with a light bake using bake-out heaters attached to the outer chamber, shown in *Figure 4* to a temperature of around 100^{o}C and has reached a pressure in the inner of the cavity of $4x10^{-8}$Torr and in the outer vessel of $9x10^{-8}$Torr. It is required that the interior of the cavity be held at a pressure below $1x10^{-7}$Torr whilst the pressure on the outside may be significantly higher (since only on the inside of the cavity is the E-field high). Given the revised configuration of the outer vacuum vessel for the IC experiment, which has rather larger volume and will contain more materials then the STEP V design, and in light of the experience gained from the tests of the SCTS, the size of the getter pump will be increased to 3800l/s whilst the differential pumping speeds between the cavity and the chamber will be modified (to reduce the pump rate on the outer chamber).

At the time of writing the RF cavity is under test at the MTA. The cavity was tested for Q and the couplers were adjusted for critical coupling at low power prior to vacuum pumping and bake-out. The performance was verified after evacuation. The cavity is presently heavily instrumented to detect breakdown events, and is equipped with copper beam windows (not yet Beryllium). The cavity is fitted with its tuner system, however the tuner control is not currently being used (instead the driver is tracking the cavity frequency drifts). At present the cavity is being tested in for operation in the absence of a magnetic field.

The cavity is estimated to be operating at a gradient of 14MV/m with 3.5MW of drive power (at 4th November 2014), having achieved the original MICE specification of 8MV/m without sparking. It has achieved ~2.5M pulses at 13MV/m and is continuing to accumulate pulses at 14MV/m with spark events occurring very infrequently and only at the higher gradients. This shows that the electro-polished cavity and revised couplers have performed very well with no significant conditioning required.

The future test plan looking towards the end of the year is to explore the maximum gradient in the absence of the magnetic field and within the limits of the available RF power amplifiers prior to shutdown. The shutdown will afford the opportunity to inspect the inner surface of the cavity for evidence of spark events, during the changeover to beryllium particle windows, and will also permit revisions to the vacuum system to be tested as outlined above. After the cavity is re-evacuated, with the upgraded vacuum pump systems, it will be possible to test the cavity behaviour with the beryllium windows and then in the presence of the fringe magnetic. Unlike the STEP V plan, these tests at the MTA more closely resemble the MICE IC apparatus's magnetic field and hence provide excellent de-risking for the final experimental configuration. It is anticipated that these tests will commence early in 2015 and run until late October 2015.

Given the successful test of the cavities at FNAL, the collaboration is in a strong position to commission the two MICE cavities and four couplers. It is planned that after low power testing, LBNL will select two cavities from the available nine and select the best combination of beryllium windows and cavities to achieve a matched frequency pair (within the tuning range) that is also well within the amplifier bandwidth. One, or two, spare cavities with beryllium windows will be selected as well. These cavities will then be electro-polished. Four new couplers will be fabricated with a slightly modified design along with a modified clamp to enhance the ability to tune the mutual coupling between the coupler loop and the cavity fields. This improvement will addresses a difficulty encountered in tuning the SCTS system for critical coupling. The vacuum chambers and supports for the Ionisation Cooling experiment will be derived directly from the SCTS with nearly identical outer vacuum vessel details. The experience of fabricating the SCTS provides a reliable basis for minimising the technical, schedule and cost risks. The final design of the RF cavity vacuum vessel is expected to be completed and reviewed by April 2015 with fabrication and leak checking to be finished by October 2015. Fit check of the entire RF module assemblies will be carried out at LBNL prior to disassembly and packing for shipping to RAL (arrival by April 2016)

<u>Low Level RF</u>

The MICE Low Level RF system (LLRF) is required to keep the voltage of the accelerating field constant over the 1ms RF pulse and to maintain a fixed phase difference between the two cavities in the system commensurate with the travel time for muons of the selected axial momentum range between the two resonator locations.

The system will use LLRF4 electronic boards that have been purchased for MICE, these have been developed by Larry Doolittle of LBNL. The boards digitise the RF signals (both cavity pickup, forward drive and reflection) from each of the cavities. The resulting signals will be compared with control setpoints and provide feedback via the drive signal to the amplifier system and also by driving the pressure controllers on the cavity tuners, maintaining the correct voltage and phase relationship inside the cavity whilst holding the cavities at a single frequency, compensating for any thermal drift and/or mechanical differences.

At Daresbury Laboratory a number of similar systems have been developed using in house designed software and commercial firmware communicating through an EPICS interface, these systems are providing regulation to 0.1 % amplitude and 0.3^{o} in 1.3 and 3 GHz accelerating cavities. This exceeds the required performance for MICE (1% amplitude and 0.5^{o} phase) at significantly more demanding frequencies. A MICE LLRF4 board has been tested using software developed from other LLRF4 implementations at Daresbury and was operated at 201MHz in August 2014.

The electronic cards are built into rack mount chassis with an Ethernet port to provide communication with the control system via an EPICS front end. This is well aligned with the control and monitoring architecture for the overall MICE project

A collaboration is currently being formed between the Daresbury RF group and the ISIS linac group which will see the LLRF software developed at Daresbury Laboratory being tested on the ISIS Linac test amplifier system. The requirements of the ISIS test system is a virtual copy of the system requirements for the MICE project and so will provide an ideal test bed for development of the software and hardware needed. It is expected that tests at RAL could be started during late 2014.

The build-up of the MICE LLRF chassis for the first MICE amplifier system will be undertaken during 2015 and can be tested on the test amplifier system at Daresbury Laboratory when it becomes operational.

RF diagnostics

The experiment will require a system to collate the particles by their RF transit phase. It is desired that the phase be known to <0.5% of the RF cycle, ~20ps. The most accurate time stamp for the muons will come from the ToF 1 detector, immediately upstream from the diffuser and the upstream spectrometer. The time stamp from this detector, combined with the trajectories reconstructed from the tracker hits, will allow the reconstruction software to project the particles through to the RF cavities, defining the transit time in each cavity (to within a systematic offset). The experiment will measure the RF phase by recording the signal from the pick up probes in the cavity using digitisers to record the signal amplitude as a function of time. The signal will be subsampled (that is to say it will be sampled at a rate significantly exceeding the Nyquist limit on the linewidth of the signal but well below the RF frequency), this mitigates the amount of data that needs to be recorded and allows the entire pulse to be recorded readily, reconstructed in the spectral domain and reverse Fourier transformed to give the phase at an arbitrary time during the pulse when a muon has transited the cavity.

A second technique is also being pursued based on the use of TDC technology driven by discriminators (in fact exactly the same instruments, co-located, as are used to record the ToF events). This will mitigate uncertainty associated with electronic delays. In this case a signal from the LLRF Master Oscillator (the LLRF system will be able to hold the cavity phase to the MO within 0.5^{o}) will be passed to the discriminators and every tenth zero crossing will be recorded.

The object of these two systems is primarily to bundle the particles by their entrance phase into the RF cavities. Providing the particles can be collected together with a random uncertainty of less that ~20ps, the systematic offset mentioned above can be determined by comparing the energy change measured by the trackers as the particle traverses the system with the predictions from software.

The use of two techniques is mutually supportive and mitigates risk. The overall scheme for the IC experiment is shown in *Figure 5*. The MO signal and the signals from the cavity pick up probes will be led to ToF 1 in high performance, stable microwave/RF cable and then returned to the datarecorders along RG213, from the same batch as the cables used for the ToF signals, length matched and laid along the same path.

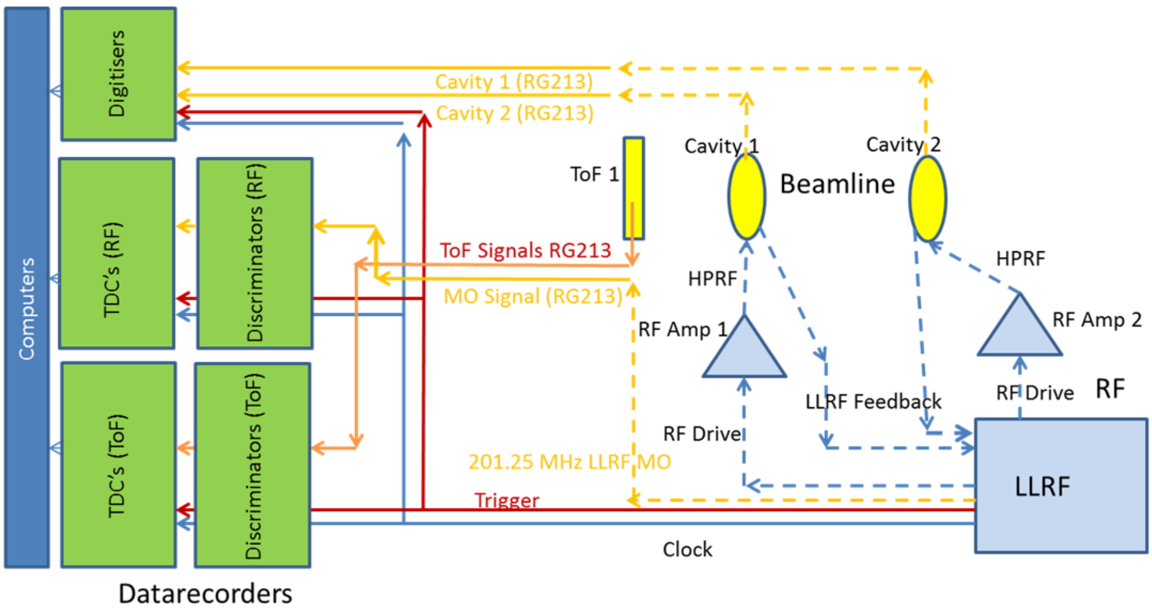

Figure 5: Overview of RF and ToF signal routes for determination of muon transit phase. Dashed lines correspond to high performance microwave cable.

The LLRF system, or a similar system, will provide a clock to the datarecorders to synchronise them. The LLRF will start the data recorders when the cavities reach nominal amplitude and phase synchronisation using the trigger signal. The TDC's are CAEN V1290 systems (only one channel will be required), 25ps, 21 bit units with 5ns double hit capability, driven by LeCroy 4415A discriminators. For reasons of interface compatibility with the rest of the DAQ system, the favoured digitiser is presently the CAEN V1761, 1GHz, 4G.Sa/sec, 10 bit, 2 Channel instrument with a VME bus interface and capable of 57.6MS/Ch. Discriminators and TDC hardware will be available at Strathclyde in November 2014 for RF environment tests. Digitiser tests are presently being undertaken using 8 bit, deep memory, oscilloscopes and tests on computer generated signals. The tests with the computer based signals have shown that the frequency domain signal reconstruction technique is effective, and tests with realistic data from an oscilloscope have shown that the system is resilient to noise and digitiser horizontal and vertical accuracy and resolution. Actual cavity signals have been produced by the tests at the MTA and will be used to further prove this technique. It is anticipated that the MTA tests will provide an opportunity to test any hardware developed and to provide additional signals to test the signal processing algorithms.

Absorbers

The principle absorber material planned for the IC apparatus is Lithium Hydride in the form of discs. One of these discs is already available and will be used in the STEP IV experiment, it is 45cm in diameter and 6.5cm thick. The IC configuration requires at least two additional disks that will be thinner, to shield the trackers. The appropriate thickness and material of the three absorber discs is presently being reviewed. As soon as the final sizes are optimised in simulation it will be possible to procure the discs from the US specialist manufacture Y12 who can fabricate to a maximum diameter of 65cm. The lead time for fabrication is 12 months. The collaboration plans to mount the absorbers in large vacuum chambers with a diameter close to the diameter of the main solenoids, which also corresponds closely to the outside diameter of the cavity vessels. This allows for ready take up of the magnetic forces. The absorber chambers will also form part of the outer vacuum jacket of the RF cavities. This brings the added benefit of reducing the muon retardation which would arise from passing the beam through multiple vacuum windows which must of necessity be of strong, thick material.

The two thinner absorber elements will be placed between the cavity beryllium windows and the spectrometers, with the thicker absorber placed between the two cavities, as shown in *Figure 1*.

Return Yoke

The return yoke for the IC experiments is a relatively straightforward extension of the yoke designed for the STEP IV experiment. Once final placement of the apparatus is finalised, drawings can be produced to define the additional plates of high performance magnetic steel to be procured and the fixing points in the trench to which they should be anchored. Lead time for the magnetic steel plates is estimated to be 6 months. With the elimination of the large coupling coil no significant new engineering challenges are anticipated. The components for the return yoke are expected to be delivered in March 2016.

Installation and Commissioning Plans

Installation of the IC beamline apparatus can commence only once STEP IV data taking is complete, currently projected to be July 2017, however off beamline apparatus can be installed when the STEP IV experiment is offline (e.g. for ISIS downtime). The IC apparatus will require some re-arrangement of the magnets, and it will be impossible to power the cavities until they are in situ in the beam line with the yoke installed.

Installation

Amplifiers

The installation process for the amplifiers is well understood having been explored as part of the EU TIARA project, with the first amplifier tested in the MICE hall in late 2013. Details of the installation and tests are documented in the previously referenced EU TIARA publication[i].

This test allowed the collaboration to understand the services requirements in the MICE Hall for the RF drive system and allows confidence in assessing the resources, technical, schedule and cost risks associated with the process. These will be refined and augmented in advance of the re-installation of the first RF drive system starting in August 2015 The MICE Hall Manager, having previously been a manager in ISIS, has a particularly strong understanding of the provision of services at RAL.

To optimise the installation of the RF system in the MICE Hall the individual components of the 1st Amplifier will be transported to RAL as they are systematically replaced during the testing at DL. The delivery sequence will be 4616 amplifier, 4616 power supply and instrumentation racks, TH116 power supply and instrumentation racks. The components of the 2nd amplifier will be delivered all together, along with the RF control system. The cables and cable management for the 2 RF systems will be installed before the components are delivered to the MICE Hall to optimise installation time. As the 2 RF systems will have been fully tested at DL, commissioning at RAL into dummy loads will be efficient, although commissioning with the cavities will require significant RF expertise.

Sequential install and testing of racks, as described above, is planned for RF drive system #1, in the second half of 2015, with the installation schedule flexibly adapted to work around the operation of STEP IV. Testing up to half-power (1MW) is possible by temporarily using a set of reject loads coupled with a quadrature hybrid coupler.

A similar four-month window is planned for installation and test of the second amplifier chain, finishing in November 2016.

Re-Arrangement of Magnets and Cooling Channel

The IC experiment requires that the magnets be reconfigured, and an additional focus coil added to the system, compared to STEP IV. All the magnets have been tested separately and have made currents in excess of that required for the IC. The final configuration of the magnets is affected by the final configuration of the cooling channel- see *Figure 1*. The foundations for the IC absorber/cavity system will be baseplates for the cavity modules and the AFC's. These will be installed in the period July 2016 through December 2016.

Transmission Lines

During assembly of the RF distribution and cavity systems it will be important to understand the characteristics of the RF parameters, including the measurement of RF path length and loss for each installed RF distribution line. The installation of the coax is scheduled between August 2016 and February 2017, and the measurement of the installed systems can be undertaken as soon as the lines are complete.

To perform these measurements, the RF coax will be terminated using special reducing coax couplers and two port vector network analysis performed. It will also be important to measure and adjust the RF coax network that is feeding each cavity, since the system needs to drive the correct phase angle in the cavity simultaneously on two couplers with different line lengths (and through quadrature couplers). A small range of adjustment is provided in one coupler arm to remove installation errors (with line trimmers). These measurements will be done at low power, with RF personnel in the hall directly operating the equipment.

Cavities and cavity chambers

The cavities will be assembled, starting from April 2016, in a clean room at RAL. The assembly process is likely to be a 6 to 8 week effort for a two to three person crew. After the assembly process, RF based measurements using network analysis will need to be performed to ensure that the cavities are set up in the correct manner. For each of the cavities, the matching for each input coupler, the coupling factor for the cavity probes, the cavity Q, the resonant frequency and the tuning range will be measured. The couplers will be adjusted as necessary by rotating them during the installation process. This will be done by the RF team in conjunction with the mechanical assembly team. Based on the low power tests of the cavities at FermiLab, this can be a somewhat time consuming process; however, the modifications by LBNL to the coupler clamp design are expected to significantly mitigate this issue. We anticipate about two weeks will be required for RF setup and tuning of each cavity.

Absorbers

The new LiH absorbers will be installed in the RF module when the RF power couplers are installed. The thin LiH disks will be mounted in a Delrin sleeve with tabs that will then be mounted on the stiffening ring of the RF cavity using spacers to put it at the proper position (just adjacent to the Be window). The thick main absorber will be mounted in a carrier between the two RF cavities. The detailed arrangement of these mountings is currently being reviewed. Absorber changeover is anticipated to be relatively infrequent (2 changes are envisioned in the experimental plan over 7 months).

Assembly of RF and Absorber Vessel

Once the RF cavities are assembled and tuned as outlined above, and integrated with the absorbers, each of the two cavity chambers will be completed with flanges supporting beam pipes that extend into the bore of the spectrometer solenoids and through the focus coils. These units, integrated with the focus coils will be secured to (and bracketing as a mirrored pair- see *Figure 1*) the central absorber section closing the vacuum envelope. 2 Weeks are allowed for this operation starting from mid January 2017.

Return Yoke

The return yoke will be an extension of that used for the STEP IV experiment. Installation is from mid December 2016 until early February 2017.

Commissioning

Amplifiers, Transmission Lines and Cavities

The cavities and chamber will be initially evacuated using a set of turbo-molecular pumps. It is important, especially when at high pressure, that a reasonable conductance path is allowed between the cavity vessel and the cavities to prevent any differential pressure being developed across the thin beryllium windows. It is planned that 2 weeks be allowed for evacuation of the vessel. Due to the relatively inaccessible nature of the cavity vessel in the IC apparatus, combined with the close proximity of components of large thermal mass, many of which may not respond well to high temperatures, the baking routine used at the MTA (which used heater elements secured to the air side of the vacuum vessel) is not appropriate. Fortunately the MTA test revealed that the cavity did not require aggressive baking and therefore it will be possible to provide gentle baking by heating the cavities with hot water in the cooling pipes. This takes advantage of the relatively limited thermal connection between the cavities and the jacket. This seems likely to achieve temperatures in the inner cavity only slightly less than those achieved at the MTA ~80^{o}C. Baking is expected to require 2 weeks. Once an acceptable, vacuum condition is attained, very high speed Getter pumps will be started with high speed pumping paths to the inner cavity vessel, ensuring the inner vacuum exceeds that required for RF operation.

The cavities will require low level retesting once under vacuum and baked- however this is simply to verify that nothing significant has changed and is a relatively quick operation. Once the transmission lines and the first amplifier are installed and tested (described above) it will be possible to begin HPRF tests of the system, operating the amplifiers into the relatively narrow band partially reactive load presented by the cavities. This will allow testing of the LLRF control system. It is expected that the prerequisites for this will be realised during February 2017. This stage has been largely derisked by the tests currently underway at FNAL. Tests will initially be without magnetic field and are expected to take about one month, and may be undertaken prior to completion of the return yoke (the yoke is scheduled for completion by February). One month is allowed for these tests, completion late March 2017. Once it is possible to complete the return yoke, the magnets may be re-commissioned (see below) and the HPRF tests should be completed to confirm operation in the strong magnetic field, planned for 4 weeks ending early May 2017. Although operation of the cavity in the magnetic field is an unusual feature of the MICE experiment, the MTA tests very significantly de-risk this operation.

Magnets

The magnets will need to be run up in their new locations before they are needed to shake down the RF system, this can of course only be undertaken when the return yoke is complete, and is planned for April 2017. The operation of the magnets has been described previously in section 4 of the Magnet and Beam Commissioning at Step IV document[iii]. The anticipated magnet currents for the IC are moderate compared to those required at STEP IV and within the range to which all magnets have already been individually commissioned.

Beamline

The beamline will require pre-commissioning as outlined in section 5.1 and 5.2 of the Magnet and Beam Commissioning at Step IV document[iii]. In this STEP IV preparation document the shift number was estimated at 23, corresponding to 8 days at 24/7 operation. These stages do not require the RF system and may therefore be taken at high data rates. The equivalent of the calibration runs defined in section 5.3 of the STEP IV magnet commissioning document are described in the IC Experimental and Operation proposal.

Summary

The plans outlined in this document show that the IC apparatus can be prepared, and either has been comprehensively derisked, or is currently being derisked, for installation commencing in Sept 2016. This includes the RF cavities and amplifiers, cavity and absorber vessels and support systems, LLRF and diagnostics. Installation can be achieved by the end of March 2017. Commissioning can be complete to allow experiments to commence in the ionisation cooling demonstration by September 2017 with some margin. The experimental plan assumes the start of measurements from September 2017, and includes the calibration experiments. There is some scope to be ready ahead of this timetable.

i Moss A., White C., Grant A., Stanley T., Alsari S., Long K., Whyte C.G. & Ronald K., 'Demonstration of the RF Power System for the ICTF', TIARA WP 7.2 Report, January 2014, http://cds.cern.ch/record/1647349/files/TIARA-REP-WP7-2014-002.pdf

ii Moss A., 'Report on the design and specification of ICTF RF power distribution system for MICE Step V', TIARA WP 7.1 Report, April 2012, http://cds.cern.ch/record/1439963/files/TIARA-REP-WP7-2012-005.pdf

iii Pasternak J. 'Magnet and Beam Commissioning at Step IV', August 2014, http://micewww.pp.rl.ac.uk/documents/96