**Design Considerations for Muon transit RF phase determination**

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The ideal requirement for this diagnostic is to determine the RF phase to well within the uncertainty defined by the resolution of the ToF detectors (50ps). So that the overall measurement is not meaningfully compromised it would be ideal if the measurement of the RF phase were to within one third of that of the ToF detectors. This implies a resolution of ~15ps as an initial target. The period of a 200MHz signal is 5ns, so this corresponds to an accuracy of $1^{o}$. The accuracy may possibly be relaxed in future depending on feedback from the analysis group, but this is a specification to work towards for the present. A meeting was convened at RAL of interested parties (named above) on the 6th Aug 2013, and augmented by discussions at CM37 at RAL on the 6th November. This has informed the substance of this note.

**Absolute or Relative Calibration**

Although in principle it might be possible to use measurements of the Muon entrance and exit phase space positions from the trackers to determine an absolute calibration for the diagnostic (i.e. to define the systematic timebase discrepancies) providing the jitter in the two signals (RF and ToF diagnostics) could be reduced adequately, this appears to place an unnecessary expectation on and assumption in the validity of the physical understanding of the interactions between the absorbers and the Muons, which the experiment is intended to demonstrate. It is therefore desirable that at least the entrance phase of the Muons should be determined independently of the reconstruction of the trajectories through the cooling channel. The accuracy of the model of the cooling process can then be confirmed by analysing the experience of particles with varying entry phase.

**Source of Muon transit time data**

The most accurate timing information available for the transit of the Muons comes from two particle detectors, the ToF (Time of Flight) detectors and the momentum spectrometers. Only the former have high time resolution and can provide accurate timestamps on the particles entrance into the system. However as the particles trajectories through the solenoids will be affected by the fields and their momentum distribution, the actual entrance time will have to be projected (by software) from the second ToF detector (ToF 1) which will provide the accurate timestamp, using data on the particles location and momentum provided by the tracking spectrometers to compute the trajectories. The time provided by the software projection of these two data sources will be the time at which one wishes to determine the RF phase.

**Transit times**

The ToF signals are created by detection of photons excited by the transit of the Muons through two slabs of dielectric. Signals are measured at each end of each dielectric slab by PM tubes and an event is recorded if suitable coincidence is noted between these signals. In addition to the delays associated with the transit time through the di-electric slabs, there are the delays associated with the PM tubes and cables. The sensitivity to the transit location caused by delays through the dielectric slabs is eliminated by an averaging of the times sensed at each PM tube. The cables are RG-213. Ideally the RF diagnostic would exploit the same type of cable so that any thermal sensitivity effects would automatically compensate (if the cables are laid along the same paths and are the same length). It would be desirable to lay a ‘dummy’ cable, not in use for signals but laid along the same path, whose electrical length could be periodically checked. RG-213 is suitable for RF use with reasonably low loss out to 1GHz, however it is not specifically designed to be highly phase stable. Tests on these cables are currently underway to determine their response to mechanical distortion and thermal excursion. This may result in a requirement for thermal stability in the hall. These tests will ultimately inform the choice of cable for this application. Given that the LLRF will hold the phase of each cavity to a tightly defined differential from a reference signal, it would be possible, rather than running the cables back from one of the cavities, to instead take the RF oscillator signal out to ToF1 in extremely high performance and stable RF cable, and then return the signal in RG213 along exactly the same paths as the ToF detector cables.

Delays in the ToF detection system are currently eliminated mathematically by performing sophisticated differential measurements. This means that the actual times recorded by the ToF detectors have systematic offsets. Discussions with the detectors group suggest however that these systematic delays are well understood.  This will form an ongoing discussion linking the RF and ToF specialists.

The RF detection system will add new, specific, systematic delays that must be calibrated. In addition to the diagnostic cables alluded to above, we must consider the RF pickups, splitters and couplers used to separate the diagnostic signal from the feedback signals to be used in other detection and control systems, and indeed to allow use of more than one detector system on a single pickup in the RF cavities. Much of this can simply be measured by a VNA (accuracy of modern VNA’s in this spectral range ~$0.2^0$), and can be checked for thermal and as appropriate mechanical sensitivity. Long cable lengths however do pose problems due to their stability to changes in mechanical configuration. Calibration will need to take account of this issue. The response to thermal excursion (and in particular the stability of this response) will need to be measured and assessed against the required specification. Accurate computer models will be developed to relate the phase in the cavity centre to the diagnostic port on the cavity to which the cabling and couplers are attached.

**Approach: Triggering and Clocks**

It will be vital that all the fast diagnostics share the same timing reference points. At present the time critical systems are the Caen 25ps TDC’s on the ToF detectors. These have clocks running at 40MHz. At present these clocks are independent, though the time zero is set by the first trigger con-incidence on the ToF system. The trigger and T=0 is therefore defined by the transit of the first Muon in each experimental cycle. To implement the diagnostic for the RF phase (for STEP V and VI) it will be important to synchronise the RF detector clocks with those of the ToF detectors. The clock could readily be provided by the high performance 10MHz clock typically incorporated in the LLRF system. In Step V and VI useful data may only be logged once the RF has achieved the required gradient in the cavities, completing the feed-forward part of the RF cycle. It therefore seems reasonable to use an enable trigger issued from the LLRF when it has brought the system to the requested gradient to define T=0 for the experimental cycle.

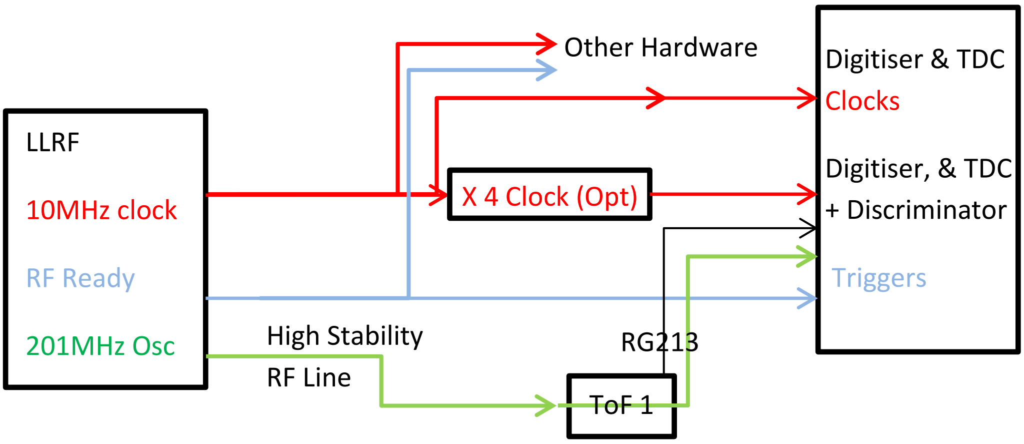


Figure 1: Illustration of proposed clock and time synchronisation scheme, showing RF phase return path parallel with the ToF1 signal path. This scheme shows the use of the LLRF master 201MHz oscillator as the point at which the RF phase should be measured. Implicit in this scheme is that the ToF and RF systematic delays are well understood.

**Measurement methods**

The software analysis will provide, in the course of a 1ms experimental cycle, various times $T_n$ after the trigger at T=0. These times will be assessments based on the timestamp reported by ToF 1 projected forward to the $1^{st}$ cavity using the phase space measurements obtained from the tracker detector. The RF diagnostic needs to be able to determine the RF phase at these times $T_n$ to within $1^o$.

One may take advantage of the fact that the RF signal may not change rapidly in time. The analogue bandwidth of the resonators is only a few 10's kHz which severely constrains the rate at which the cavity phase can evolve. Moreover the LLRF system will exploit a feedback loop which will enforce the phase relationship between the cavities to $<0.5^o$ with a loop bandwidth significantly less than the cavity linewidth. As the LLRF will regulate the cavity phase with respect to the reference signal (the monitor of the acceleration field in cavity 1), we need only compare one of these cavities (or indeed the reference oscillator) to know the status of all cavities. It may however be beneficial to have some measure of each cavity. Depending on the method adopted this may be possible (see discussion below). The limited bandwidth of the system, and the LLRF regulation, can hence be exploited to reduce the amount of data which needs to be recorded.

Two approaches have been outlined based on TDC techniques and two using Digitiser methods which can provide this information. It is proposed that all techniques be developed and assessed against each other for the present, as digitisation of the analogue waveforms can provide additional information on the amplitude stability.

In the following sections we discuss the approaches and work which should be undertaken to demonstrate their feasibility.

**TDC approach**

The output from the PM tubes on the ToF detectors is used to trigger a discriminator circuit (LeCroy 4415A) the transition of which is recorded by a Caen V1290 TDC. In principle it is possible that a similar system could be used to determine the RF phase crossings. This need only be done every 20 cycles (20 positive (or negative) slope zero crossings) since at a bandwidth of 50kHz on a centre frequency of 201MHz we can project about 10 cycles from a recorded data point with 1 degree accuracy. This means we would need a TDC measure of the RF signal zero crossing every 100ns, and corresponds to 10,000 events each 1ms experimental pulse. As the LLRF specification is developed it may be possible to reduce this in recognition of the feedback loop bandwidth. There is benefit in using the same TDC and discriminators for the ToF and phase measurement diagnostics since then at least the intrinsic delays and the thermal sensitivities of the detectors will be similar. However there may be advantages in using alternative hardware. Quotes have been obtained for the hardware for each of the following systems.

***TDC approach 1: Caen V1290***

As noted above this approach has the benefit that intrinsic delays and thermal responses will be more likely to track those of the ToF's to which we wish to compare the RF phase measurement. Although the instruments have a maximum delay of 52$\mu$s, this can be increased to over 100s by use of the 'extended trigger tagging mode' in its 'trigger matching' configuration, and is able to record multiple events. They have a 32,000 entry 32bit output buffer and should therefore be adequate for the 10,000 samples required to provide the basis for interpolation as indicated above. This would provide a dataset of ~320kb per channel, per experimental run. The devices are also able to seek events which precede the trigger by some 100ns. In principle one can therefore imagine an alternative mode of operation where the TDC is triggered 'in arrears' by the ToF system. This could be used to reduce the data recorded, but since the actual time of interest must be computed by the software from the inputs from two detectors, this is not seen as a primary route for development.

The LeCroy discriminators used to drive the Caen TDC's are known to have temporal tracking errors of less than <1ns (this gives reason to believe they can respond to the rising edge of a 201MHz AC signal, however this remains to be tested). The discriminators however can only, at maximum, respond at a repetition rate of 30MHz. It will therefore be necessary to ensure the discriminator is not forced to trigger repetitively from the 201MHz RF signal. As we actually only need the crossing point data every 20 cycles or so, it seems reasonable to use the veto input of the discriminators to ensure that there is no reacquisition for 100ns. This requires that the veto signal (and the recognition of the veto by the discriminator's internal electronics) can be enabled within 5ns of the trigger. It may potentially be possible to provide a regular acquisition window with a 10.05MHz pulse train synchronised to the RF, however it should be noted that there is a 10ns delay between the dropping of the veto and the first acquisition. As noted above it will be important to test the performance of these discriminators in a 201MHz signal environment. Alternative discriminators should be investigated as a backup for the use of the now rather elderly LeCroy technology.

The key limitation of the Caen V1290 TDC's is their minimum bin size of 25ps, which is rather larger than desired for a resolution of ~15ps for the RF phase. It may be possible to enhance the resolution of these instruments by setting staggered thresholds for the discriminators (each LeCroy 4415A has 16 independently set inputs) and triggering at different amplitude levels during the rise of the AC waveform from zero. Providing one knows the amplitude of the signal, and hence the signal slew rate, one may effectively interpolate the point where the time bin increments for enhanced precision. This is however dependent on the internal accuracy of the TDC system and must be tested. A device has been identified at RAL that can be used for such tests with no immediate cost implications. With 16 channels available from a discriminator and TDC pairing, one might hence divide two of the TDC's bins into 8 segments each in a form of analogue interpolation.

Additional benefits are associated with the known programming interface and physical hardware interface (VME) used throughout the rest of the MICE apparatus.

***TDC approach 2: Agilent U1050A TC842***

An alternative approach is offered by an Agilent device which has 5ps resolution but only on 12 channels, and is 'single stop' in that each channel can report only one event. Unlike the Caen V1290 device which is a digital TDC the Agilent U1050A exploits an analogue element to achieve this performance. Each channel is started in synchronism with a single start trigger. It is however possible to perform a multiple acquisition using repeated start commands. The dead time between a stop trigger and the availability of a restart is not yet clear, however there is a 10ns delay between the trigger and the start of the acquisitions. As each channel has sufficient resolution for the required measurement and includes the trigger system in its front end there is no requirement for external discriminators nor further interpolation. Unfortunately as there is only a common veto, the only sensible use for the multiple channels appears to be independent monitoring of each cavity.

A further concern is that these very fast digitisers can only record 128 events internally. Even assuming the circuits can be re-armed in a suitable timeframe to record all 128 event in a 1ms pulse, this implies the spacing of the measurements of the zero crossings of the RF phase some 10μs apart. This will become viable if the bandwidth of the system is reduced to 500Hz by the LLRF feedback system. If a higher rate is required then it would be necessary to use additional digitisers with delayed starts.

A final consideration is that the Agilent system will require additional measurement and calibration for the delay lengths of the circuits and the thermal stability of those delays compared to the Caen systems used in the rest of the hardware. Moreover the Agilent system requires the adoption of a new PCI type of bus and will add new hardware to be programmed. Nonetheless the 5ps resolution is attractive and the option should continue to be investigated, as part of a wider survey into suitable instruments, as insurance against a problem with the interpolation in the Caen TDC's.

**Digitiser approach**

Another approach, which offers the additional advantage of amplitude information from the same diagnostic, is the use of digitisers to perform ADC conversion of the signal returned from the cavities. The digitisers would be triggered by the same reset signal as the ToF TDC's to define T=0. For modern digitisers, the 201MHz signal is not particularly challenging, however to record the entire 1ms pulse whilst comfortably meeting the requirements of the Nyquist criterion with an 8 bit digitiser will require a sample rate of ~1GSa/sec or more, corresponding to > 1M Samples and > 1MB of data. However it should be possible to fit this data locally with a sinusoidal waveform wherever the phase data is required to locate a zero crossing of the RF acceleration gradient. This should be workable, and it is therefore proposed that digitisers should be placed to record every cavity, however it is interesting to consider whether we need to record at high speed throughout the 1ms pulse to provide adequate phase resolution. Quotes have been obtained for digitisers in either the

PCI or VME interface formats from Agilent and Caen. It may be possible to use a derivative of the LLRF boards to provide this functionality.

***Sub-Sample approach***

Here we exploit the fact that we know with accuracy the structure of the RF wave, and specifically that it is a bandpass signal, meaning that it contains all of its energy in a strictly limited spectral window. If we sub sample (we need to satisfy Nyquist on the cavity or loop bandwidth) then we could substantially reduce the data required, and might be able to increase the bit resolution of the digitisers. For example if we sample at some 10MSa/sec . This would imply no more than 10,000 points and some 80kB of data. The difficulty is that the waveform would appear to have the wrong frequency due to aliasing. If one performs a Fourier transform into both the Sinusoidal and Co-Sinusoidal parts, the signal will appear to be transformed into the window between 0 and 5MHz, repeating every 5MHz, and since our sampling bandwidth has been chosen to be such that it comfortably exceeds the bandwidth of the signal, these aliases do not overlap. As we know the correct frequency for the signal, we may eliminate the 'wrong' aliases and hence reconstruct the waveform. Tests of the effectiveness of this method are being undertaken (based on mathematically defined wavefunctions). If successful they will be extended to include sensitivity to noise, digitisation resolution and sample rate.

The key advantage of this method is that it reduces the fast memory requirement of the digitisers and the sampling rate required. It is important to note that the analogue bandwidth of the front end should remain significantly greater than 200MHz. It may be possible to implement this method using the same ADC's as will be used in the LLRF system, but with long term data recording.

***Burst Sampling approach***

This method involves using a trigger from the ToF's, or a periodic trigger, to record, at high speed, a segment of the RF waveform close to the transit time of the Muon rather than recording the entire waveform at low speed. This would exploit the capability in modern digitisers to acquire an oscillogram trace in discontinuous segments rather than the entire timebase. The periodic approach is preferred since, as outlined above, the transit time of the muon through the second ToF detector must be convolved in software with the muon's phase space location to define the time that is in fact of interest (entrance to the cooling channel). This periodic method would acquire regularly spaced segments (say spaced by about 100ns) of fixed duration (say 10ns). Again a sinusoidal waveform can be fitted to this data and interpolated to locate the zero crossings. This demands a high speed digitiser comfortably satisfying the Nyquist criterion on the centre frequency of the signal, but continues to mitigate the total number of samples required, in this illustration by a factor of 10.

**Test plans**

The performance of the RG213 cables must be tested (in progress)

The performance of the discriminators, the Caen TDC's and the schemes to manage the trigger rate must be subject to experimental test

The capability of the Agilent (and other alternative) TDC's must be more fully understood

The DSP process for undersampling needs to be tested (in progress)

The fitting process for the burst sample data needs to be tested (in progress)

*Both of these processes are currently being undertaken with artificial, mathematically created, data and will also be tested with real, experimental, oscillograms*

Cavity tests

*As part of the LLRF programme Daresbury have proposed to build a ‘cavity simulator’ to facilitate testing of the phase determination apparatus ahead of STEP V*

*A single cavity test stand would allow tests of the system in full ahead of STEP V*