# Status of the MICE RF System

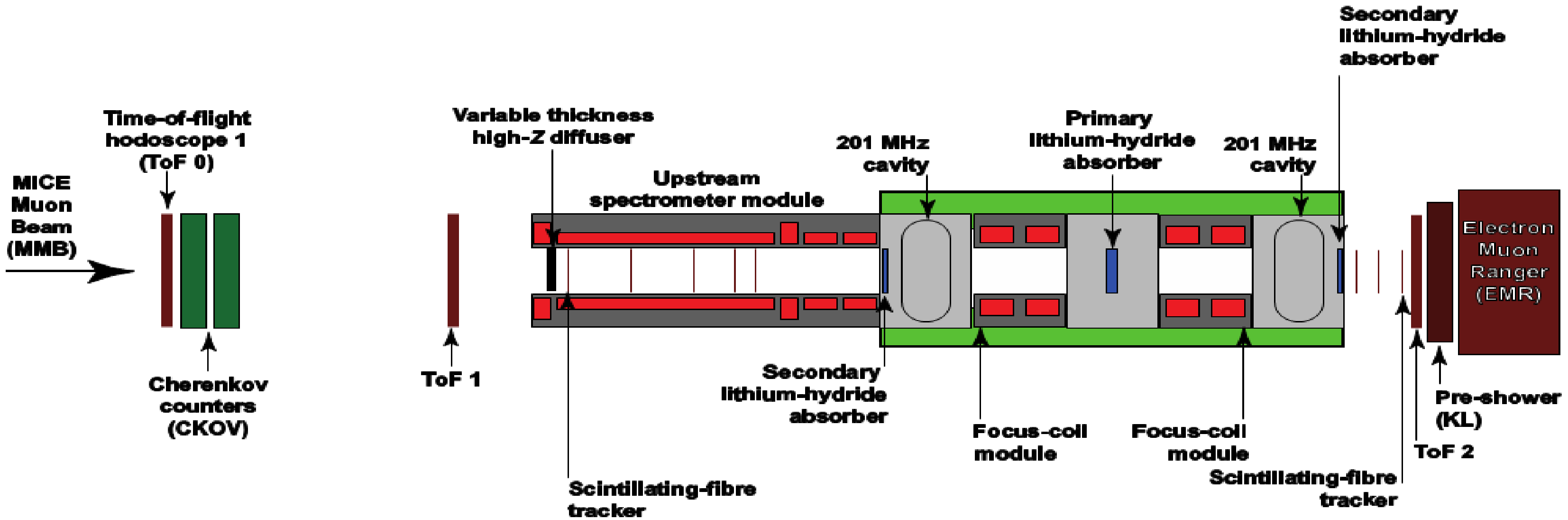
The MICE RF team

# Headline update

- Distribution network
  - Adapted from components procured under NSF-MRI for earlier configuration
  - Contractor identified, trial section modified
    - Modified component returned- quality of work high
    - Workshop viewed as qualified
    - Less expensive and faster than further procurement
- Status of RF drive system
  - Upgraded triode modulator No.1 operational at Daresbury
  - Triode No. 2 under test, started mid March
    - Exploiting 1$^{st}$ tetrode, and upgraded No. 1 modulator racks
    - Triode achieved 1MW using ex-ISIS valve (close to limit of valve)
  - Interface channels for RF controls defined
- Muon-RF phase determination
  - Subsample method with Fourier domain signal reconstruction
  - Accurately rebuilding signals from MTA experiments
  - Digitisation hardware is on order
  - RF discriminator delivered, currently under test at Strathclyde

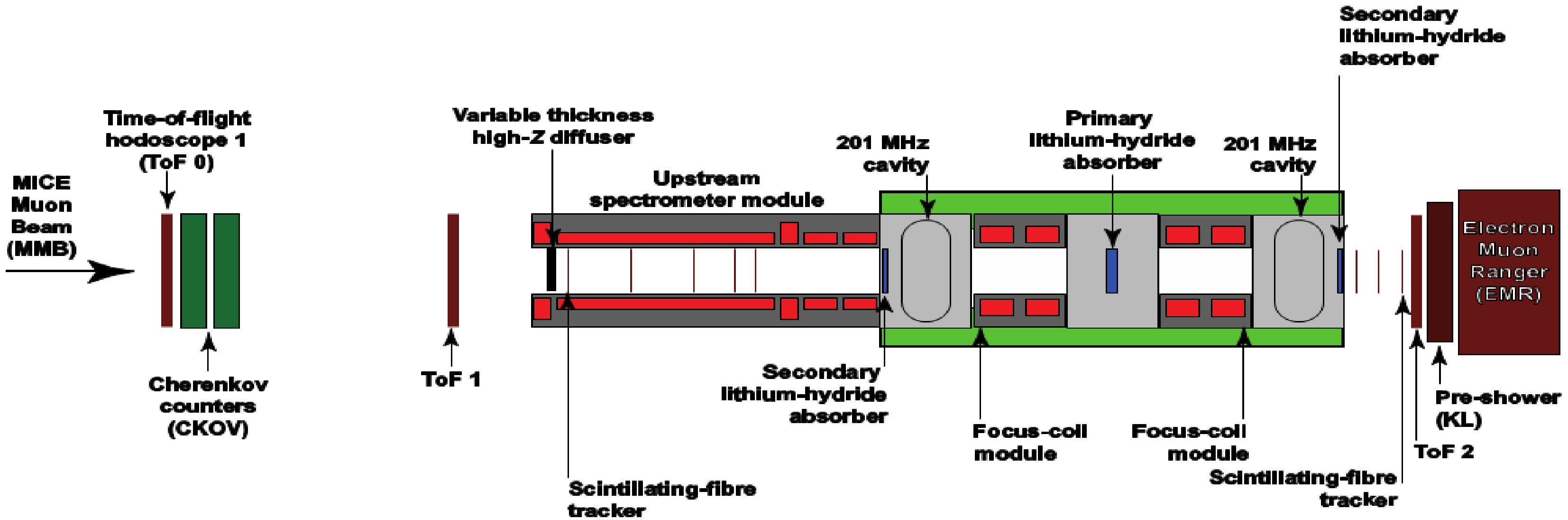
# MICE High Power RF system: Requirements

- MICE High Power RF system – Likely requirements have evolved
  - Two cavities, driven by ONE RF power amplifier- 2MW output
  - In place of two separate 2MW RF systems
    - Estimated gradient decreases from 10.3 MV/m to 7.2 MV/m
      - Allowing for realistic LLRF overhead and losses
  - 1st Amplifier proven and installed @ RAL(triode stage remains installed)
  - Cavity proving complete @ MTA
    - At much higher gradients
    - Cavity performance risk enormously mitigated
  - Cavity construction in hand @ LBNL



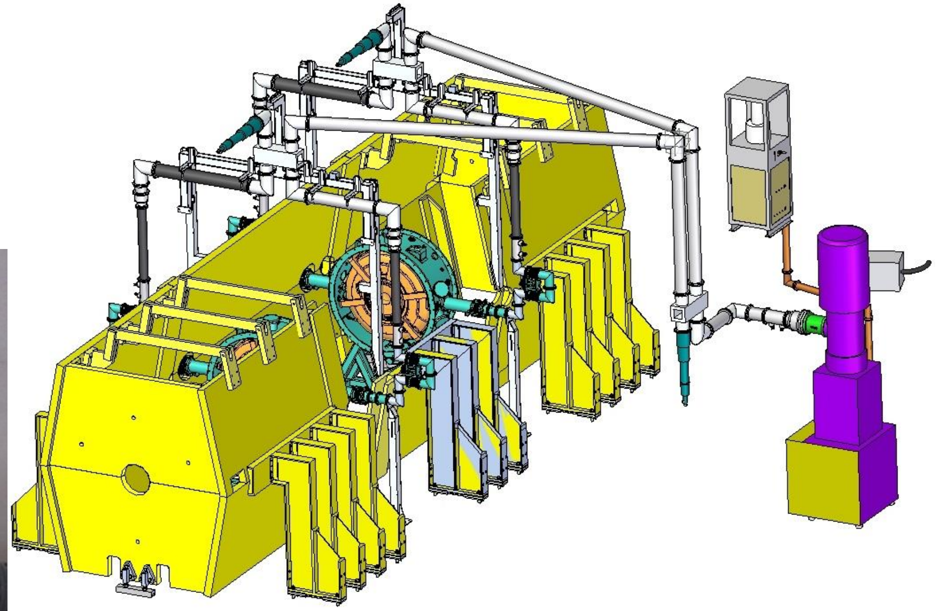
# MICE High Power RF system: Requirements

- MICE High Power RF system – Likely requirements have evolved
  - Two cavities, driven by ONE RF power amplifier- 2MW output
  - In place of two separate 2MW RF systems
  - Lower gradient means less risk/lower cost at cost of reduced $p_z$ uplift
    - Not without its own issues
    - No longer have electronic control of relative phase
    - Either predefined fixed phase setting or increments by mechanical adjustment of the transmission lines
    - Alternative: Quote received $25k US for 1.5m trombone phase shifter
  - Note: Means we lose control of the impedance presented at the amplifier



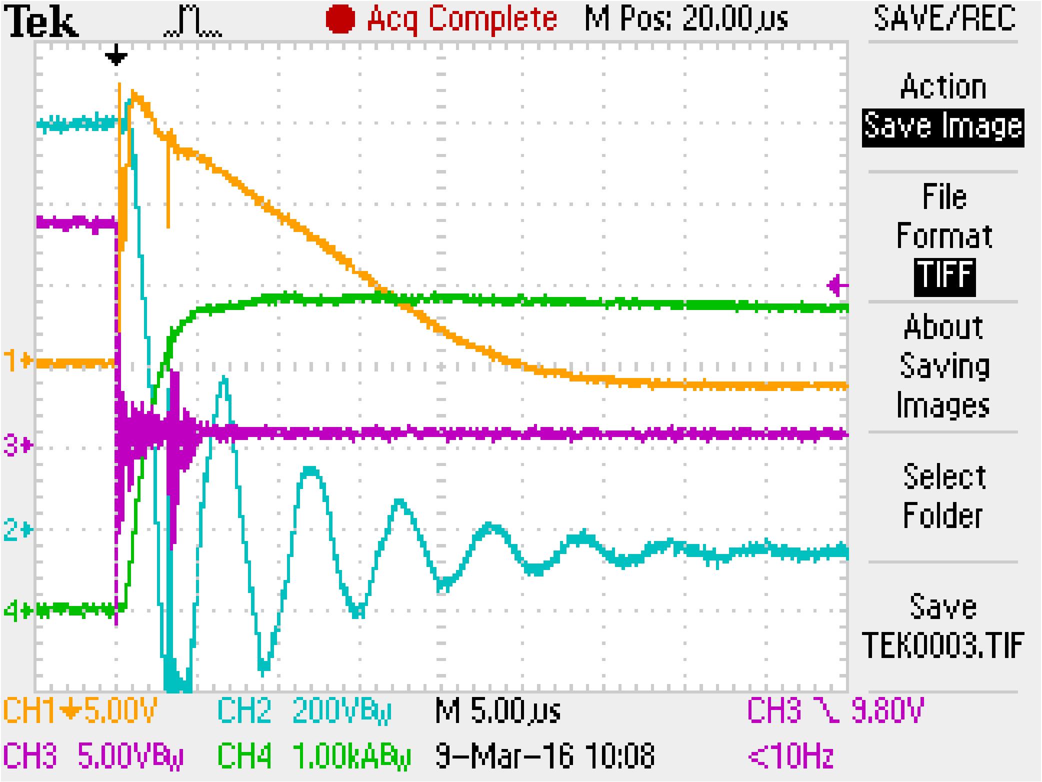
# RF Distribution Network

- Must Support 2MW in 6” line and 500 kW in 4” line with full reflect
  - 4” lines rated to 1.12MW at 1 atmosphere in dry air
  - Therefore will be pressurised by $N_2$ (with slow ramp) or $SF_6$ or gas
    - Will be treated as pressure vessels
  - Some of the 6” and 4” line from the NSF MRI procurement will be modified
  - All components/devices will be drawn from the NSF procured stock
  - Calibration components procured
  - Distribution network assembly at Daresbury advanced
  - A Grant, A Muir, N Rimmer

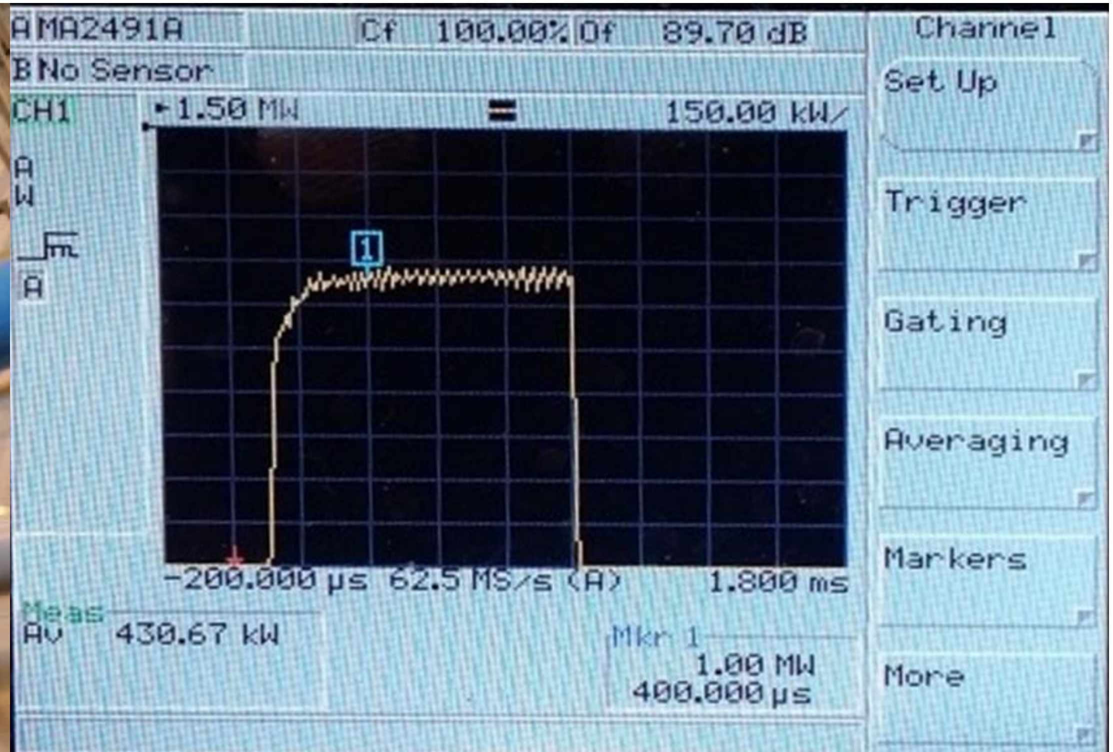


# RF Drive System

- $1^{st}$ triode modulator upgraded with solid state crowbar
- Crowbar bench test previously reported
- Now tested up to 35kV (maximum intended operating voltage) in triode modulator
  - Coupled to the triode amplifier
- C White, S Griffiths & Daresbury Team




# RF Drive Systems




- 1st Modulator set and Tetrode recommissioned at Darebury
- 2nd Triode now under proving tests
  - 1MW achieved using ex ISIS triode valve at 25kV
  - η: 57%, Gain: 8.6 dB, Tetrode: 136kW, η: 52%, Gain: 19 dB
  - Triode input return loss 11.5 d**B**
  - At MICE duty and pulse duration
- A Moss, T Stanley, C White, S Alsari, K Ronald, M Popovic, N Rimmer

# RF Drive System

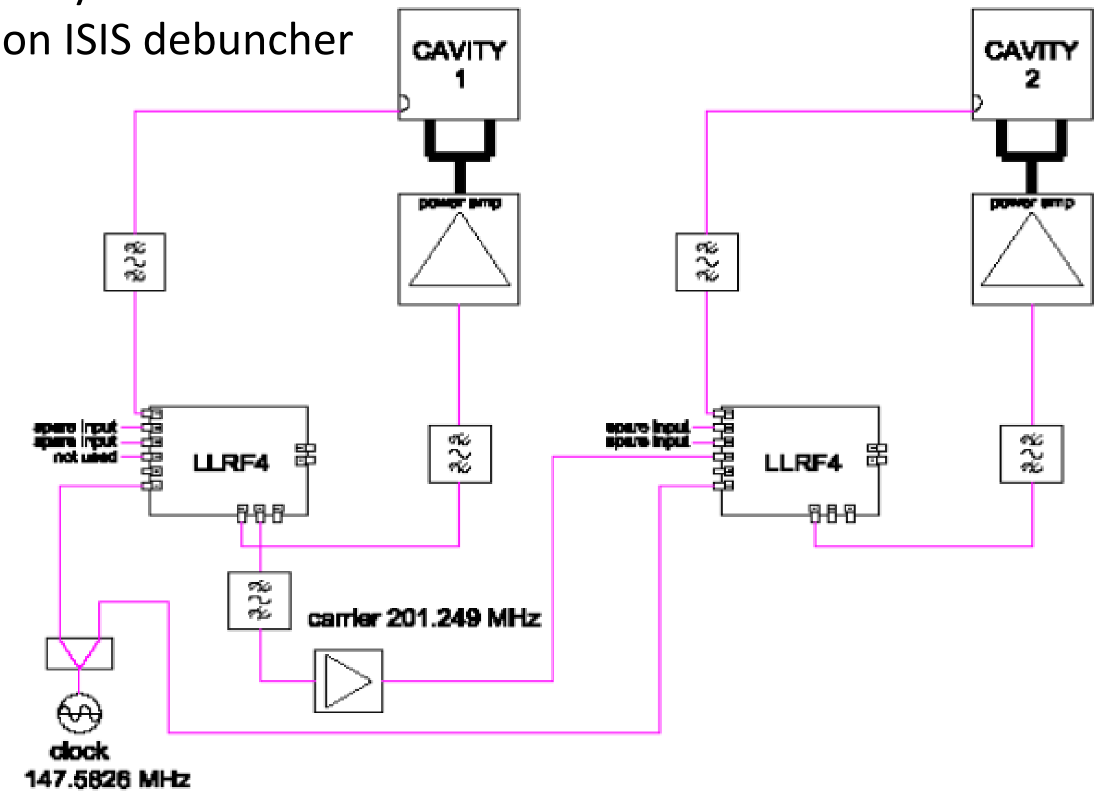

- Glitches observed in modulator current traces when Tetrode operates above 50 kW output
- Completely independent of RF output tuning of tetrode, triode, bias voltages on triode
- Maps to modulation of output signal of both triode and tetrode
- Does not happen when tetrode drives resistive load at MUCH higher power
    - Structure is very regular- suggested possible switching power supplies
    - Further tests with Daresbury EE eliminated this possibility- to be resumed

# RF Drive System

- First Amplifier Chain
  - Has delivered required 2MW at Daresbury test stand
  - Installed and commissioned at RAL autumn 2013- delivered 500kW
  - Output (triode) stage remains installed at RAL
  - Modulators and preamplifiers returned to Daresbury
    - Crowbar upgraded
  - Preamplifier recommissioned at Daresbury
    - Includes modification to the input circuit- improves reliability
    - Delivered 220kW
- Second amplifier chain
  - Output stage complete and under test
  - Second tetrode amplifier mechanically complete
  - Solid state power amplifier tested
  - Components for second modulator under construction
  - C White et al, Daresbury
  - ISIS Injector team working on upgrade to tetrode screen grid modulator

# LLRF Control System

- LLRF hardware development with effort from ISIS Injector RF team
  - Bob Anderson, ISIS Linac RF Team
- Selection of clock and operation frequency refined
  - Hardware under test- prototype batch of filters delivered
  - Next batch of filters will be slightly refined, leading to order for production filters
  - Required for both MICE and ISIS LLRF future requirements
  - Block diagram of system shown
  - Imminent test on ISIS debuncher

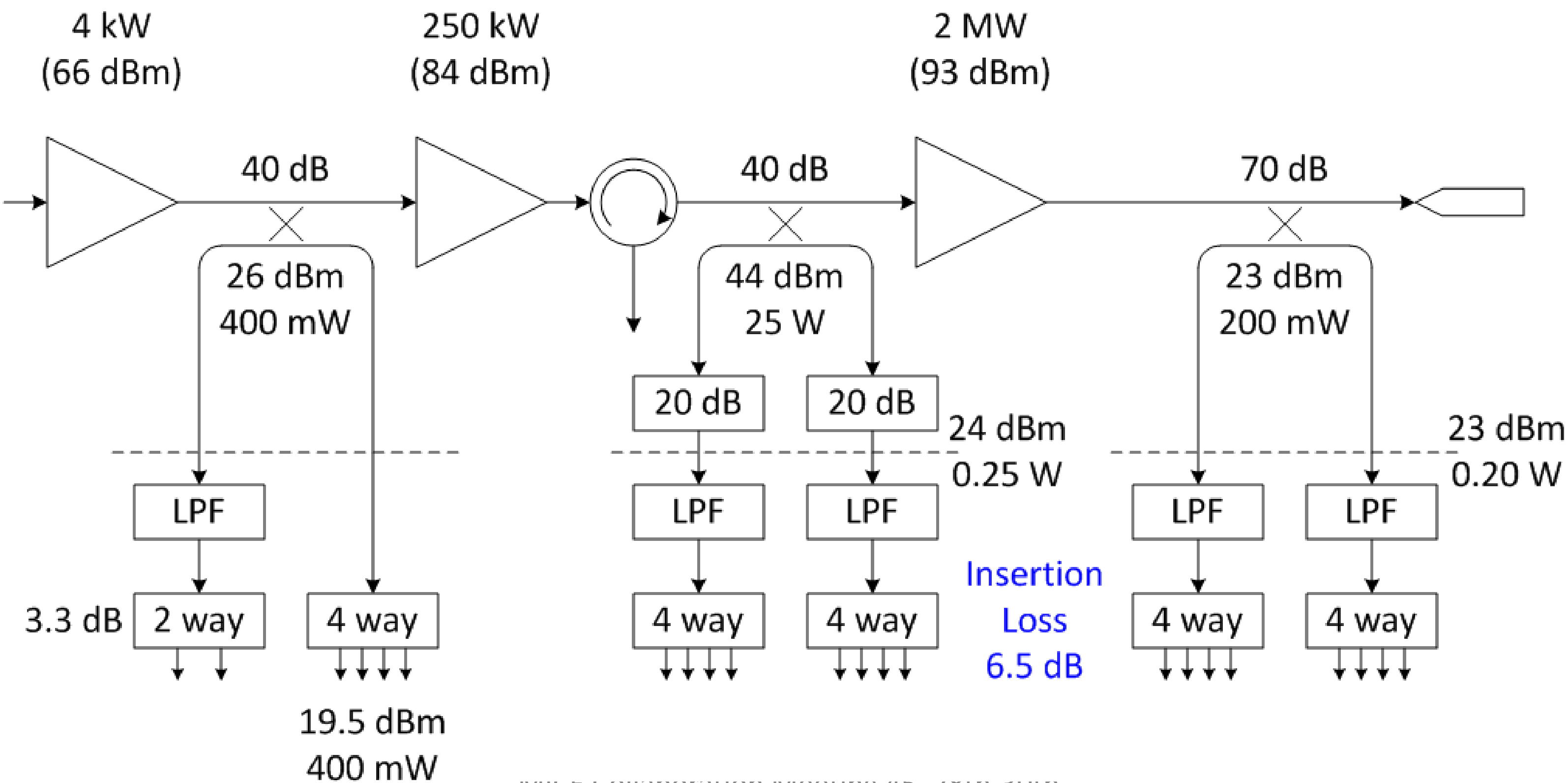


# RF Controls and Monitoring Systems

- A channel list and state machine has been defined for the RF amplifier controls
- T Stanley, A Kurup, S Alsari, K Ronald
  - Enable the build of the controls hardware at Daresbury- Underway by Daresbury Electrical Engineering (Chris White)
  - Also defines the logical interaction with the system states
  - Software development now underway: associating channels with variables for EPICS control
- Considering RF feedback model to keep cavities on tune:
  - Estimate correct gain for feedback loop to tuners to hold cavity on frequency
  - Plan to use measurement of reflection amplitude after several hundred microseconds
  - Arrange feedback loop to minimise this indicator
  - Dynamics: Cavity is 227 kg copper thermal mass,
    - Dissipated energy is < 2kJ/pulse,
    - Tuning rate vs cavity body temperature = about -6 kHz/C,
    - Water must be supplied at precisely regulated temperature,
- Note: At the MTA it has been shown the cavity can be held on resonance with feedback
  - Even in the face of a substantial thermal walk in the coolant system
  - ~1kHz in ~150s compensated by variation in pressure in tuners

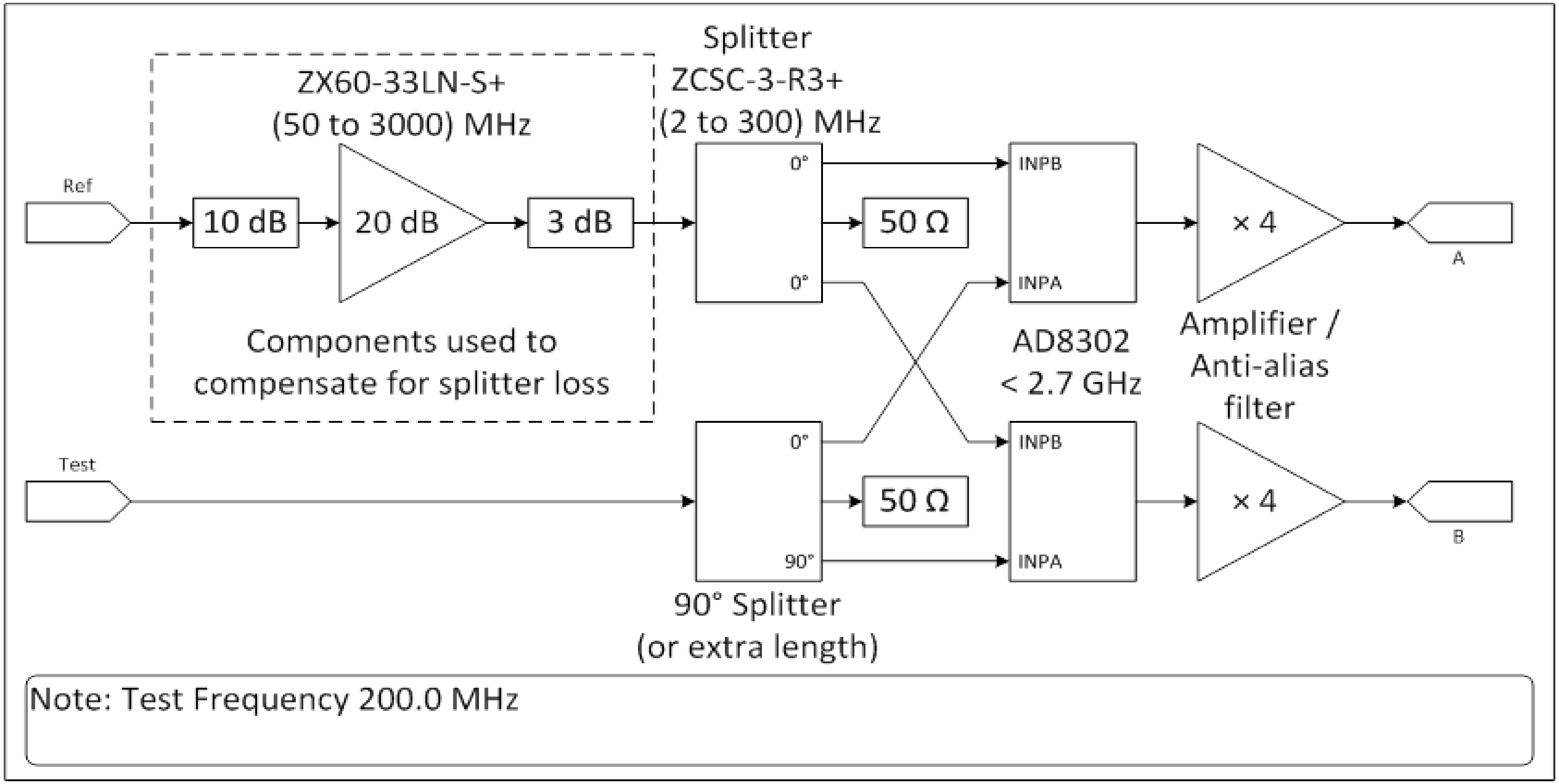
# RF Controls and Monitoring Systems

- Overview of RF monitoring parameters
  - NI hardware being developed at Daresbury to implement monitoring
  - For reasons of speed and cost will use relatively simple but well characterised rectifiers rather than power meters for most measurements
  - Envelope detectors and wide dynamic range log detectors on each measurement port
  - K Dumbell & A Moss



# RF Controls and Monitoring Systems

- Relative RF phase set by LLRF feedback- helpful to have independent analogue validation
  - Special quadrature phase detector being developed
  - Ensure accurate measurement over entire RF relative phase range
  - NI subsystem will communicate to EPICS via well known routines



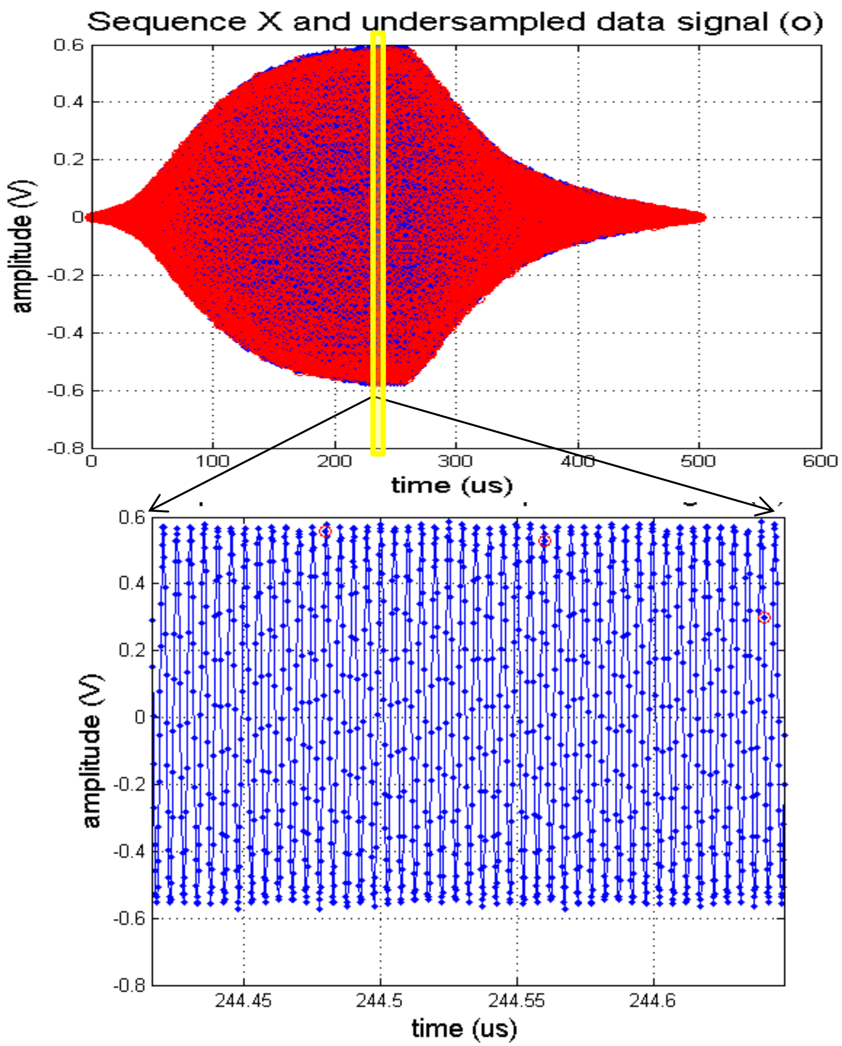
# Muon Transit Phase Detection

- Need to be able to select particles for analysis by their RF transit phase
  - Allows the ‘bundling’ of particles for coherent analysis
  - i.e. As if we are considering the interactions of a real particle ‘bunch’

- Cavity transit time inferred by the ToF transit time and the tracker measurement of momentum
  - Combining ToF resolution and Momentum projection resolution ~ +/- 51.5ps
  - Desire to know RF phase to better than 0.3 of this ~ 17ps

- Two Approaches
  - Digitisation (subsampled) of the RF waveform on the pickup probes
  - Direct recording of the wave inside the cavity
  - TDC recording of the RF waveform
  - Records zero crossings of a reference oscillator/Cavity waveform - provides RF phase reference for TDC particle events
  - Alex Dick has been working on this

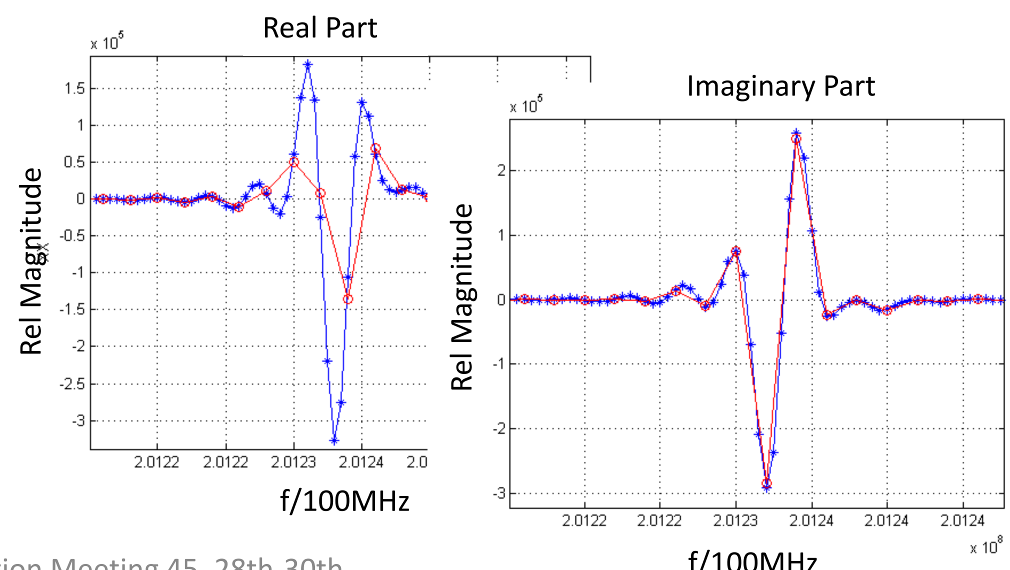
# Muon Transit Phase Detection




- Time domain: signal (blue) from FNAL cavity tests - 500μs window sampled at 5G.Sa/sec
- Subsample (red) at 12.5M.Sa/sec, reduce data by x400, and 48x < Nyquist @ 200MHz

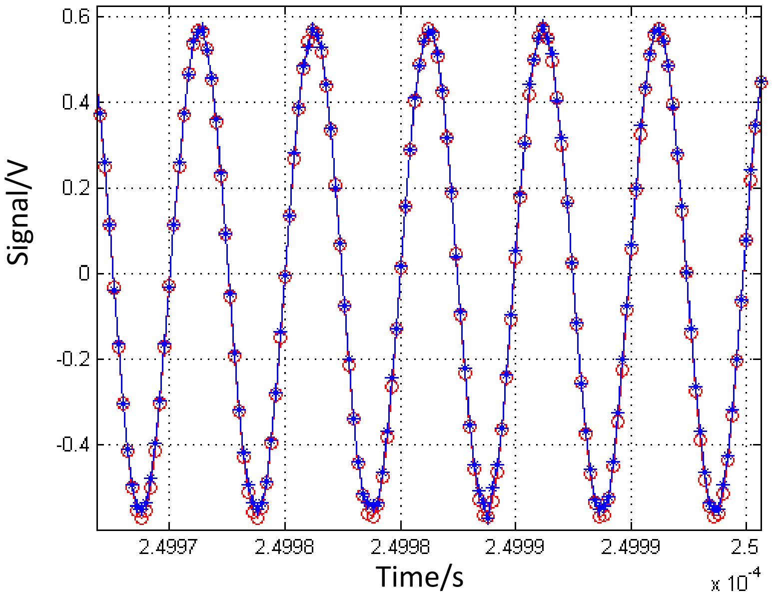
- Note time domain signal 'windowed': New data from MTA will remove this process

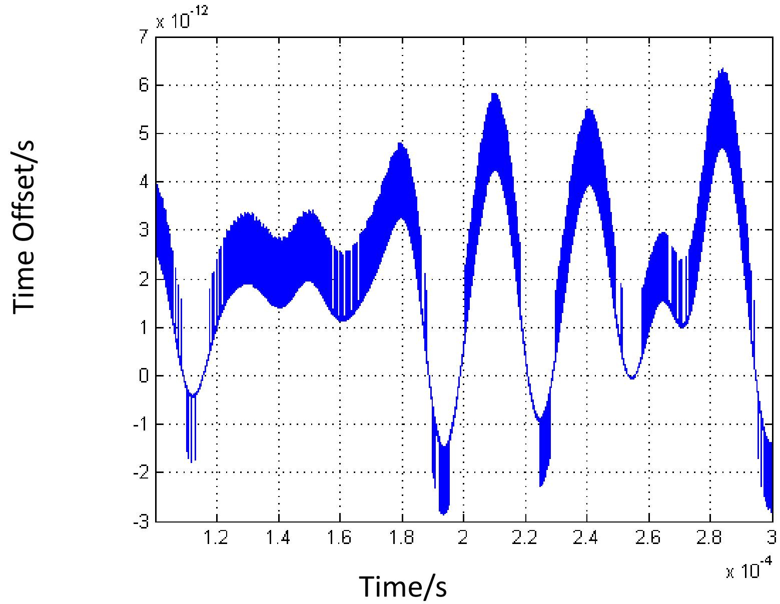
- Freq. domain: Red fft of entire recorded data, Blue enhanced dft of subsampled data



# Muon Transit Phase Detection

- Freq. domain reconstructions: high fidelity to raw signal over entire pulse duration (no spark)
- Blue is original data through 1MHz Butterworth filter, Red is reconstructed subsample data
- Note dft is effectively a (hard edged) 100kHz filter
- 10ps precision achieved on arbitrary pulses from MTA test- various dft widths analysed
- Further test on additional MTA data in different conditions also look promising

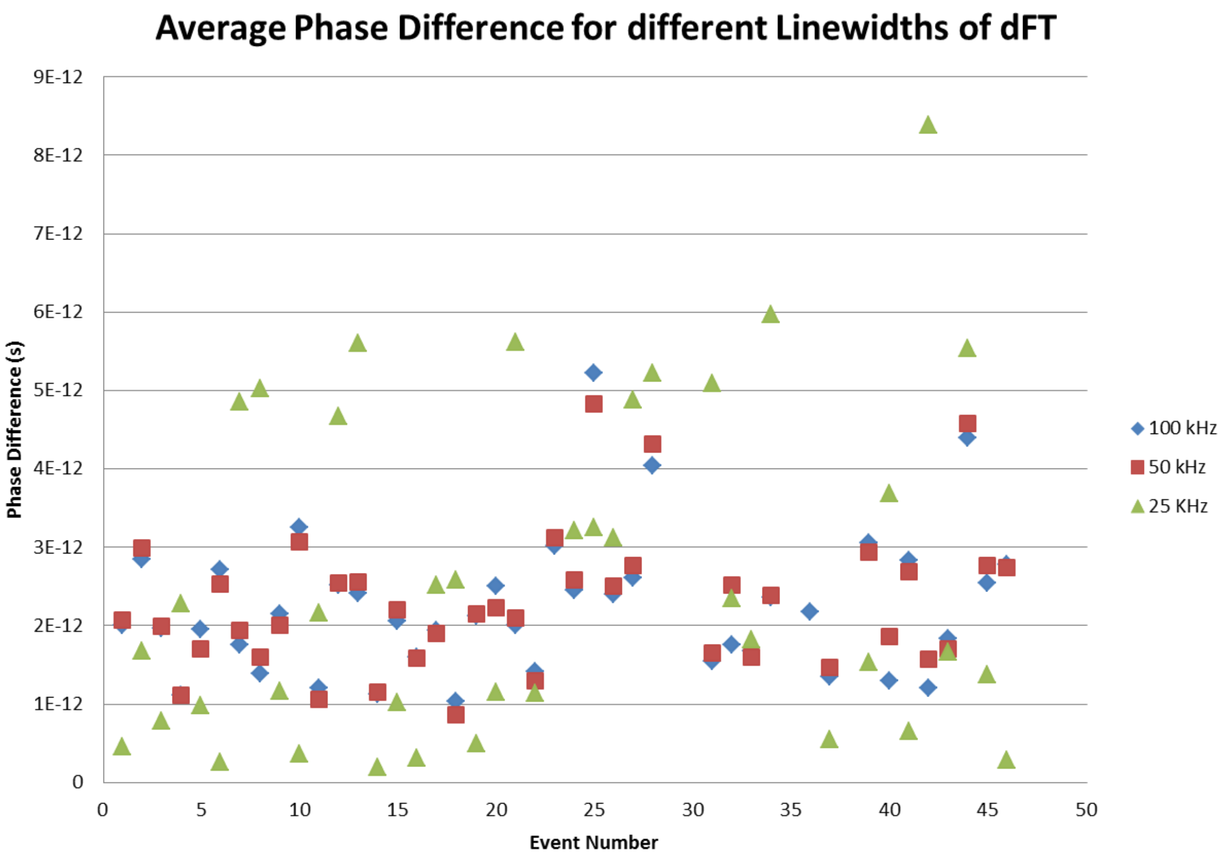



- Digitiser is in hand: CAEN V1760 VME unit
- Will need to synchronise digitiser trigger with TDC's TRST signal- discussion with CAEN suggests several routes

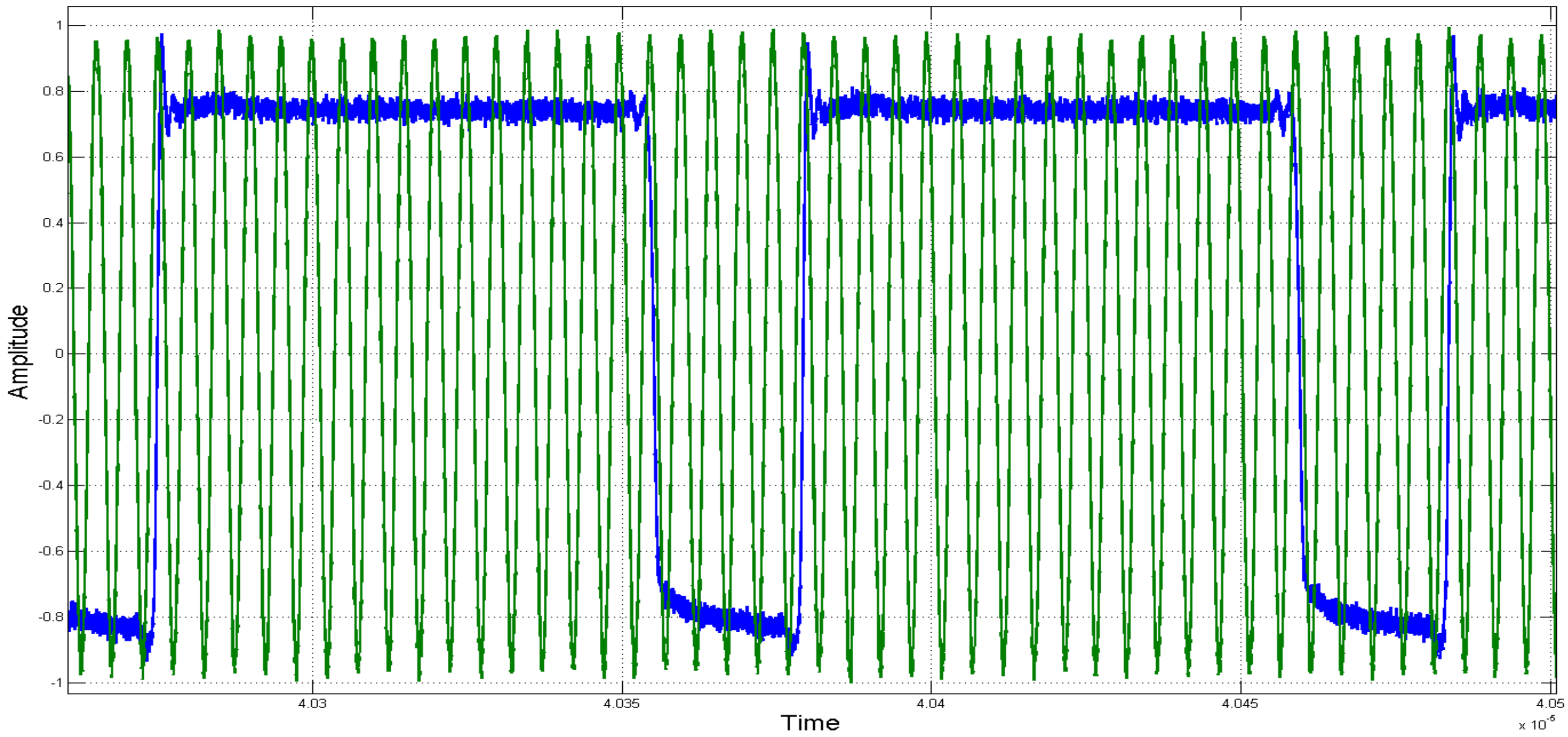
# Muon Transit Phase Detection

- Studied variation in mean offset phase delay as a function of dFT linewidth
- Note- in spite of 'enhancements' in the dFT resolution we only analyse a tiny fraction of the spectrum
- Likewise iFT back only needs to be a few RF cycles



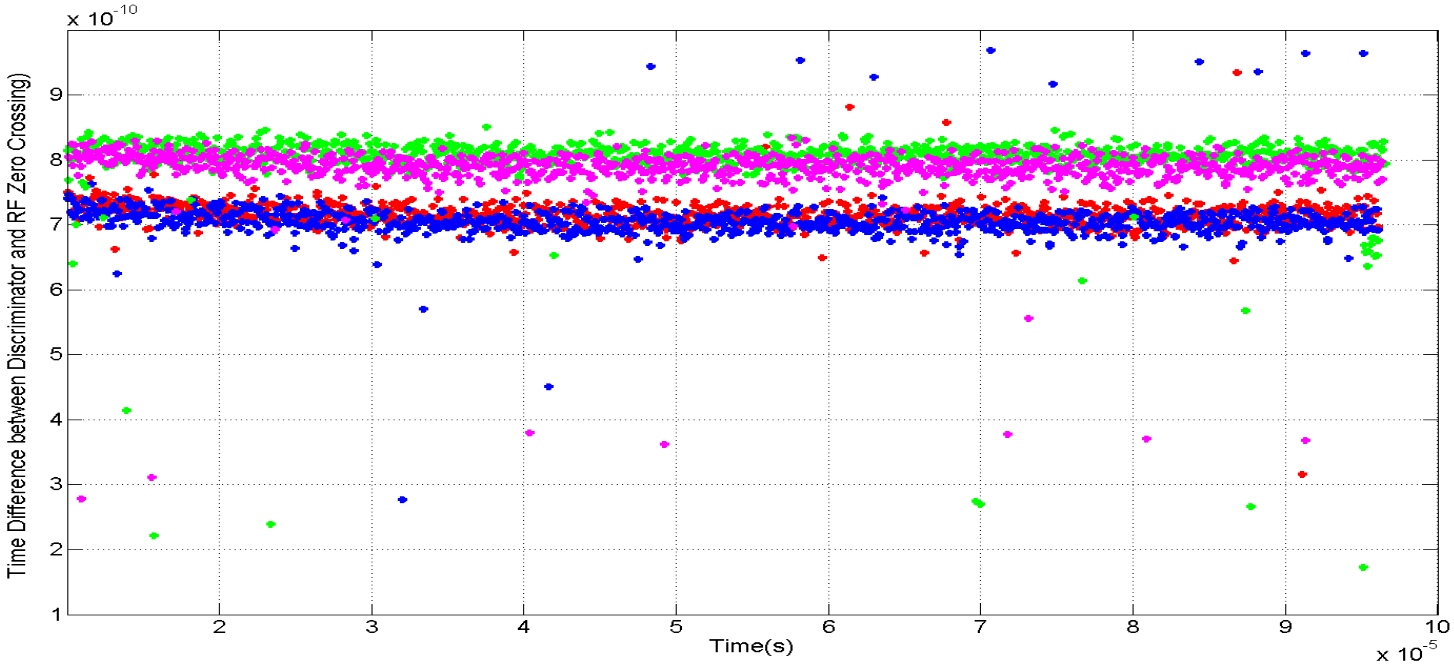
# Muon Transit Phase Detection

- Hardware for TDC method now available
- 4 Ch. 300 MHz leading edge discriminator (Philips 704D) on test at Strathclyde
- Non-updating, gate on a single period on RF wave, use output to trigger second discriminator channel and use that to veto the discriminator- select 1 in 17 or so events
- Detail setting of trigger levels critical to edge stability



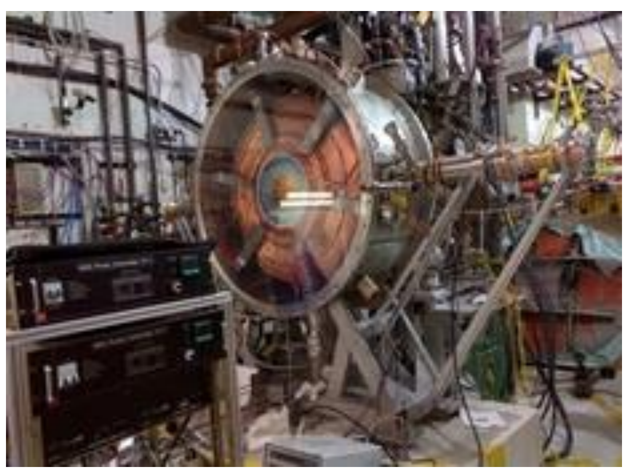
# Muon Transit Phase Detection

- Hardware for TDC method now available
- 4 Ch. 300 MHz leading edge discriminator (Philips 704D) on test at Strathclyde
- Some variation in edge alignment to understand- filtration may help detail jitter
  - Oscillocope is 20 GHz!
  - Big offsets may be related to jitter in veto'ing
- Offset variation on different records (see different colours being investigated- perhaps thermal)



# RF Cavities: Proving Tests

- MICE production cavity: Tests underway at MTA
  - Using production couplers, spring – summer 2016
  - Installation verifies much easier tuning expected for revised design
    - Tuned to 2% of critical coupling, arms balanced to 1%
    - Opportunity taken to inspect cavity
    - No evidence of sparks
  - Couplers and cavity continue to behave as expected under high power
    - MTA tests continue to provide critical data to Strathclyde for Muon timing diagnostics
  - Cavity room frequency centre frequency adjusted by Al spacing rings
    - Brings $f_0$ 201.3MHz (from 200.8MHz). Tuning range +300/-400kHz
  - MICE RF hugely derisked- Excellent work of Y Torun and team at MTA



# Summary

- Distribution Network
  - Capacity for modification of line lengths validated
  - Ready to modify other lengths of co-axial line as required
  - Calibration components ordered
  - Primary distribution network elements assembled and on hangers
- Power Amplifier tests Ongoing
  - Input structure of first tetrode improved, tetrode proven at 220kW
  - $2^{nd}$ Triode completed trials underway (> 1MW achieved)
  - Second SSPA proven at MICE duty
- LLRF
  - Frequencies for the clock and RF refined
  - Filters designed- $2^{nd}$ refined batch built
  - ISIS variation of the prototype is to be tested imminently
- Diagnostics, controls, monitoring and feedback
  - Channel list defined- allows hardware fabrication and software development
  - Hardware for monitoring system outlines, procurement underway, will interface to EPICS
  - Subsample diagnostic has required performance and minimises mathematics,
  - Hardware for TDC diagnostic under test
  - Hardware for Digitser approach delivered
- Major capital expenditure realised (esp if we stop at one amplifier), remaining are:
  - Completion of control hardware and software/diagnostics
  - Installation