# Progress on the MICE RF Systems

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For the MICE RF team

# Specifications for the MICE RF system

- To demonstrate sustained cooling (MICE Step VI) requires 8 cavities at 8MV/m
  - Two sets of four cavities bracketed by the absorber chambers
  - Each cavity is 430mm long with a Q of 44,000 and is resonant at 201.25MHz
  - The cavities must operate in a strong magnetic field environment
- Driver system must provide 1MW to each cavity (500kW on each coupler)
  - Provide required energy with four 2MW amplifier chains
  - Distribution network must not impede service access to cooling channel
  - LLRF phase control of $0.5^{o}$ and 1% in amplitude regulation
- Require a system to determine the RF phase in each cavity during the transit of each individual Muon
  - Required to allow the experiment to compare the impact of the cooling channel on each particle
  - Comparison of tracker measurements of phase space with predictions will test our understanding of the cooling process

# Contents

- To meet the above requirements, there have been four main activities in the MICE RF project in the last six months
- Each will be presented here
  - High power RF driver system tests to demonstrate require 2MW power
  - Demonstration of installation and operation in Hall constraints
    - i.e. behind the shield wall
    - TIARA deliverable
  - Preparations to test the first MICE cavity at the MTA (FNAL)
  - Outline design of a system to determine the RF phase at muon entry to channel

# High Power Driver System

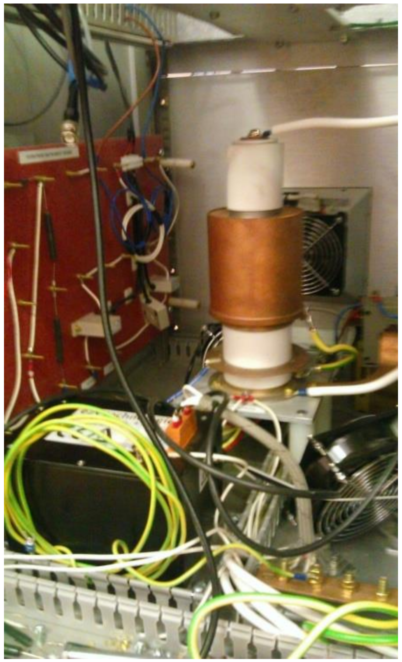
- The RF cavities are to be driven in adjacent, coupled pairs with a fixed phase angle between coupled pairs

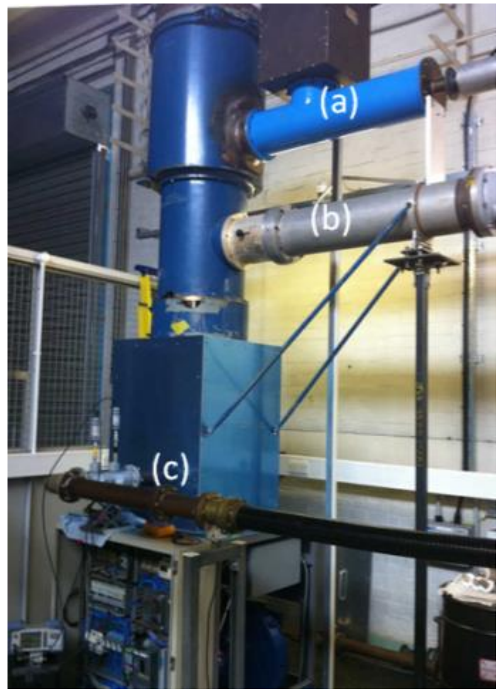
- Each coupled pair to be driven by a 2MW, 201.25MHz amplifier chain
  - Arbitrary phase control between separate coupled pairs of cavities
  - SSPA (~4kW) driving Tetrode (~250kW max) driving Triode (2MW max)

- Since last report all issues with the Power Supply and valve seating have been successfully resolved
  - Key difficulty was a faulty thyratron valve in the crowbar (protection) circuit
    - Temporary solutions with lower specification switch
    - Required reduced operating specification to protect TH116
  - e2v Technologies offered outstanding support
    - Three prototype thyratron valves made available to project
    - Stable operation at required bias voltage possible
    - Allowed correct tuning of amplifier to be realised

# Demonstration of required RF signal

- Once tuned the amplifier chain operated at the desired pulsed output level, 1Hz, 1ms, 2MW, 201.25MHz







a) HT feedline,
b) Output 9 inch coaxial line,
c) Input 3 inch line

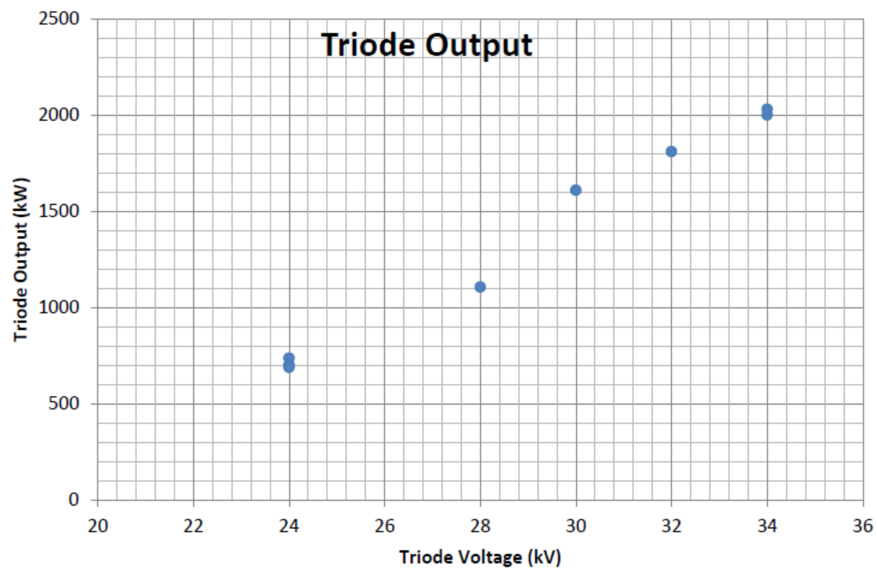
- Team developed for RF tests and installation at MICE
  - A. Moss and C. White (Daresbury) have worked with T. Stanley (RAL), K. Ronald, C. Whyte and A. Dick (Strathclyde) and S. Alsari (Imperial)
  - This provides the team required to operate the system at MICE

# High Power Driver System

- Triode DC bias and drive brought up together
  - Maintaining ~10dB gain

- Performance achieved:
  - 2.06MW output RF
  - 34kV bias voltage
  - 129A forward average current
  - η=46% (electronic)
  - Gain 10.8dB
  - Input port return loss -12.5dB
    - VSWR 1.6

- Drive from Tetrode
  - 170kW output RF
  - 18kV bias voltage
  - 15.5A forward average current
  - η=61% (electronic)
  - Gain 19dB




- Drive from SSPA
  - 2.27kW

- Drive from synthesised oscillator
  - 3.7dBm

# Distribution network and procurement

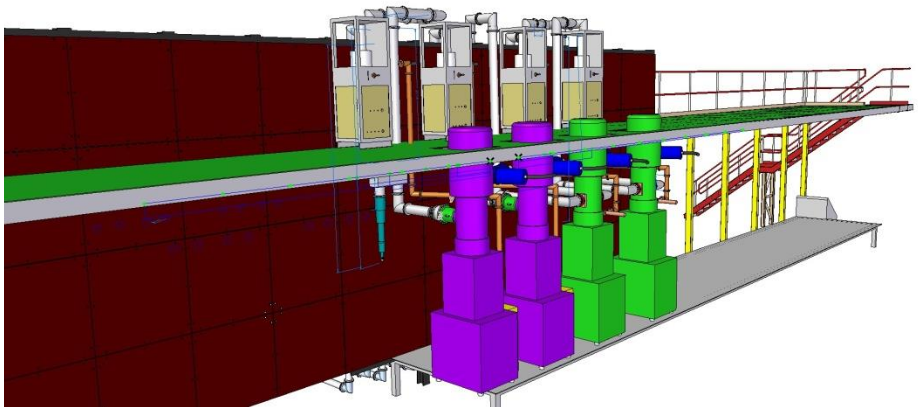
- Unchanged since last meeting
  - Vast majority of distribution network procured through Univ. of Mississippi
  - Encompasses Loads, Hybrid Couplers, Reducers, Gas Barriers, Directional Couplers, elbows, line trimmers, etc

- In addition Mississippi have procured key components to build further amplifiers chains and components for the RF cavities, including
  - Capacitors and Chargers
  - Tetrode valves and tetrode valve amplifier enclosures
  - LLRF boards
  - Tuner components for cavities

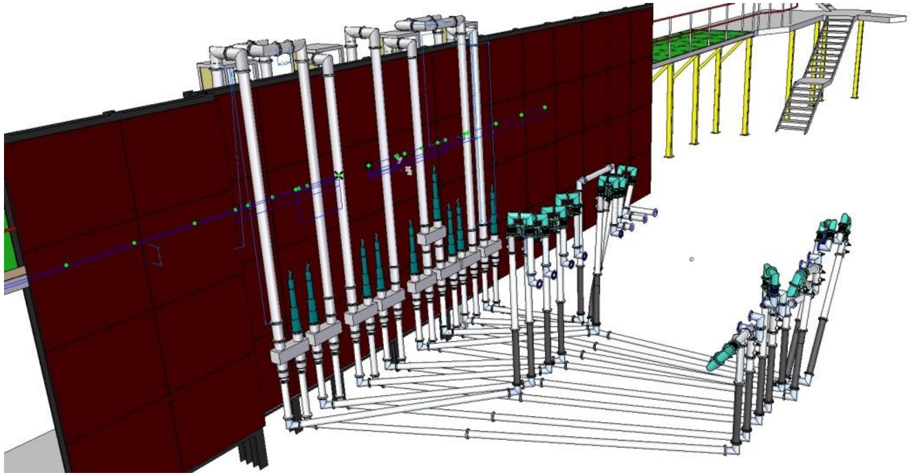
- Some $1M (US) delivered to RAL under MoU between STFC and Univ. of Mississippi
  - Total consignment > 6 tonnes

# Distribution network

*Amplifiers behind Shield Wall*



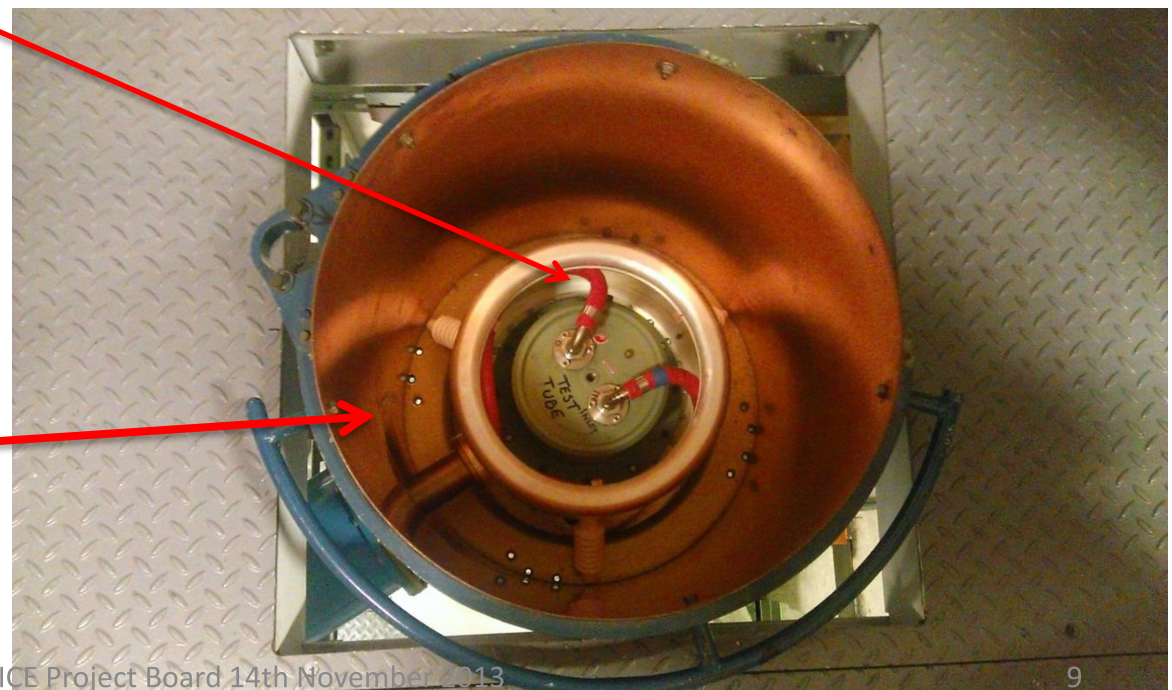
*Distribution Network to MICE*



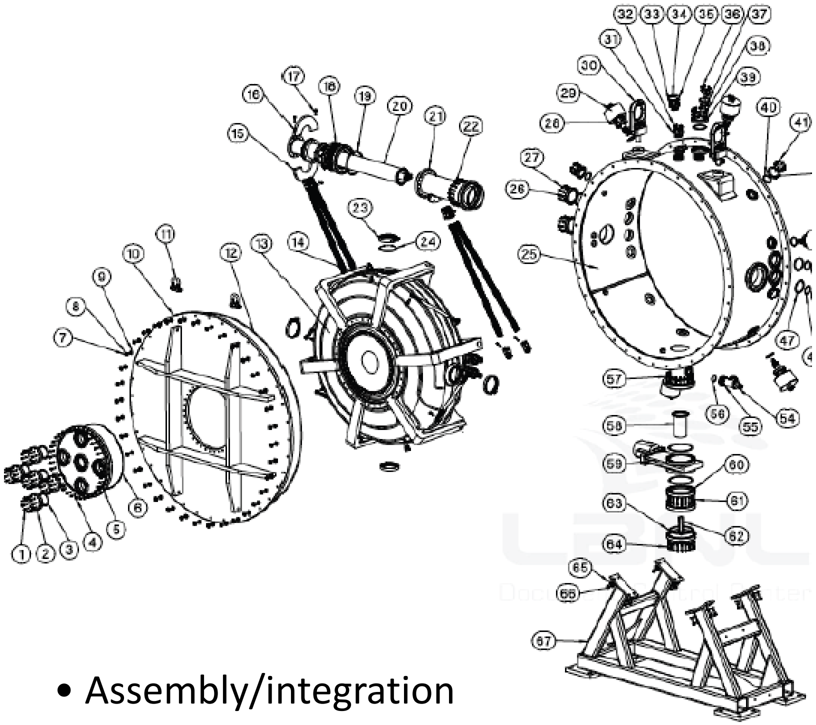
- Amplifiers installed behind shield wall
  - Triodes on main floor, Tetrodes on Mezzanine
  - Impact of B-fields negated by yoke
    - Line installation planed before yoke support risers
  - High power dynamic phase shifters removed
- 4 off 6 inch coax lines over wall
  - Pressurised to increase power handling
- Hybrid splitters moved - more accessible
  - Minimises clutter and increases service access to the amplifier stations
- Line lengths matched using 3D CAD
- Manually adjustable line trimmers installed at cavity to take up assembly errors in coax length
- Easier to assemble – introduced flexible coax
  - Allows for small misalignments
- 2 Hybrids split output from the Berkeley Amplifiers (one on amplifier side of wall)
- CERN amplifiers have two outputs
- 9 hybrids on MICE side of shield wall
  - Split power for the opposed couplers of each cavity
- Lines will be pressurised with 2Bar Nitrogen

# TIARA test preparations

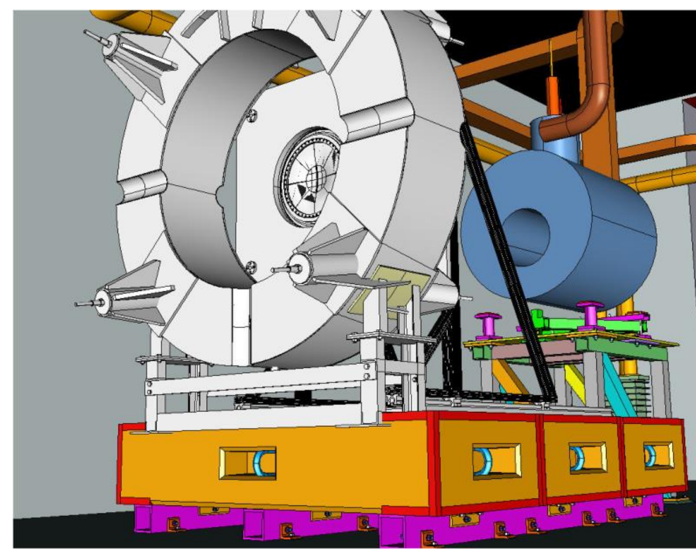
- Tiara final requirement is to demonstrate one of the amplifiers operating in the confines of the MICE Amplifier space
  - Amplifier No.1 dismantled at DL and Transported to RAL
  - Installation proceeding rapidly
  - Expect demonstration of entire chain in MICE hall by December 2013
  - 4616 tetrode system awaiting electrical connections
  - 116 triode valve fitted to final stage amplifier
  - Water and air distribution systems installed



# Cavity tests at the MTA

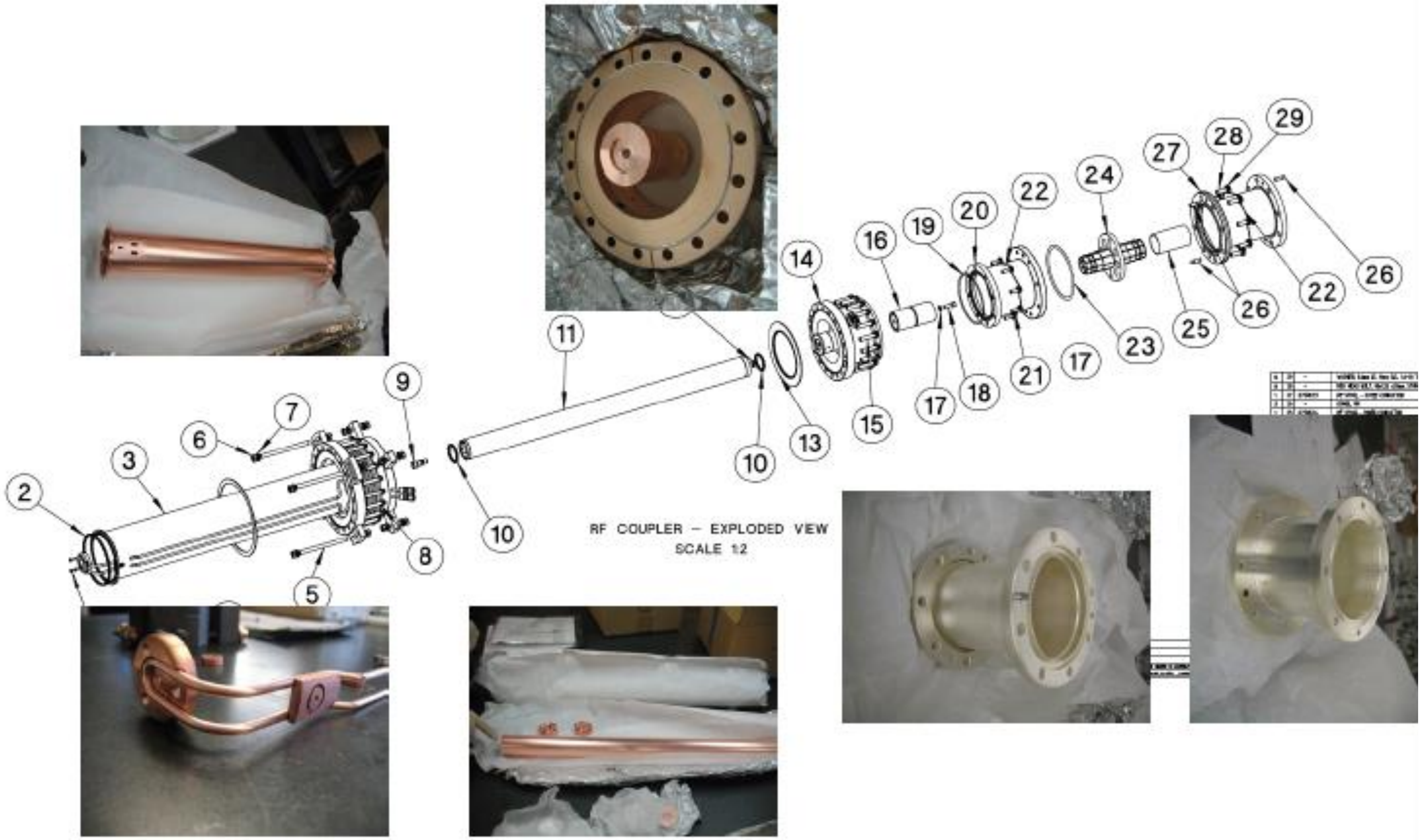


- The first MICE cavity will be tested at the MTA
- Tests will be done in a specially commissioned single cavity test stand
  - 1st MICE cavity EP'ed at LBNL
  - Vacuum vessel built at Keller
  - Be windows in hand
  - Actuators built at LBNL
  - Tuner forks built at FNAL
  - New coupler fabrication in progress at LBNL



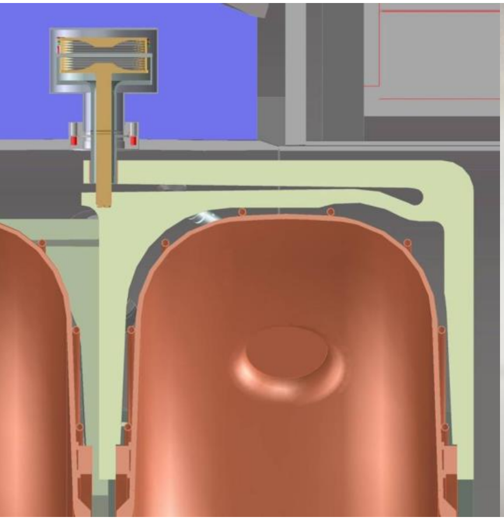
- Assembly/integration
  - Cavity and vessel at Lab-6
  - Clean room prepared, assembly in progress
  - Tuner control bench tested
  - Detailed installation and logistics plan developed
  - Expect operation early 2014
- Ultimately will be tested with the first Coupling Coil Magnet
  - Requires 6-month MTA shutdown (2015)

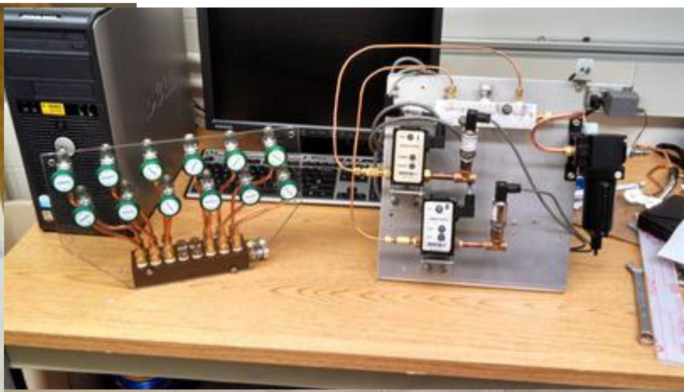
# Coupler fabrication at LBNL




- Fabrication nearing completion for the first two couplers
    - Coupler conditioning planned to be conducted in situ on cavity

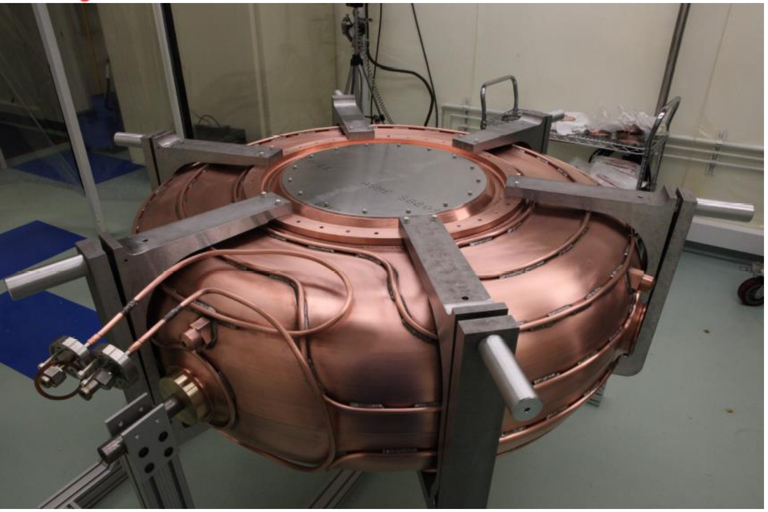
# Demonstration of tuner operation

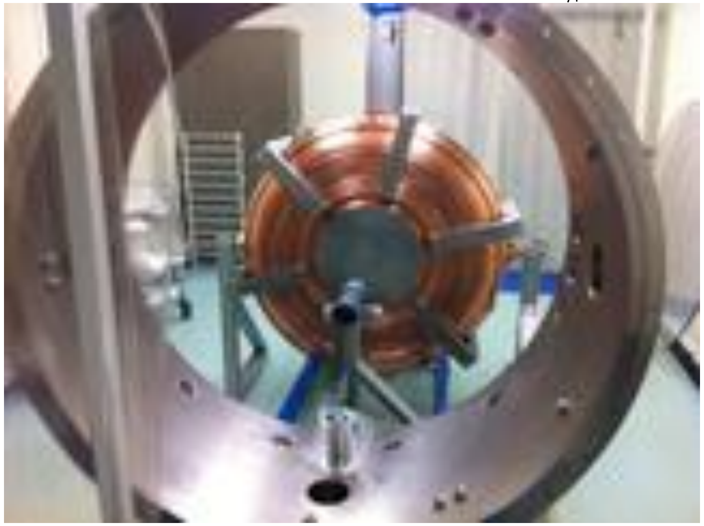


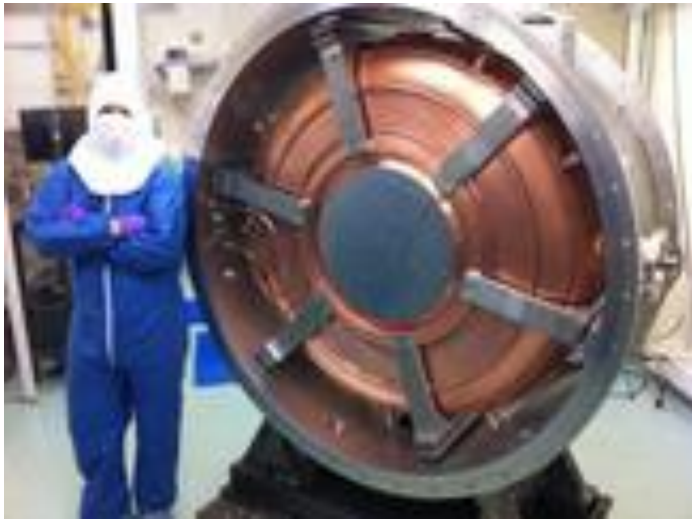

- Cavities will be tuned to and ultimately held on resonance by mechanical deformation by a set of six pneumatically driven tuner forks
- Fork test fit on cavity in Lab-6
- Stiffener rings and forks surveyed
- Fork contact pads overcut for shims
- Gas control system has been build
- Controls tested by deformation of a test ring (single tuner)
- After initial tests the RF control will be linked to the tuner control via RS-485 and pneumatic system

# Cleanroom assembly and test installation of cavity

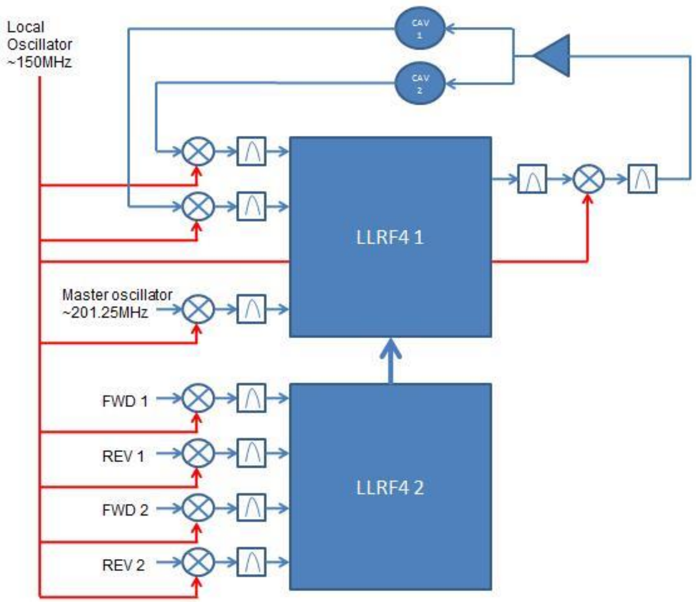


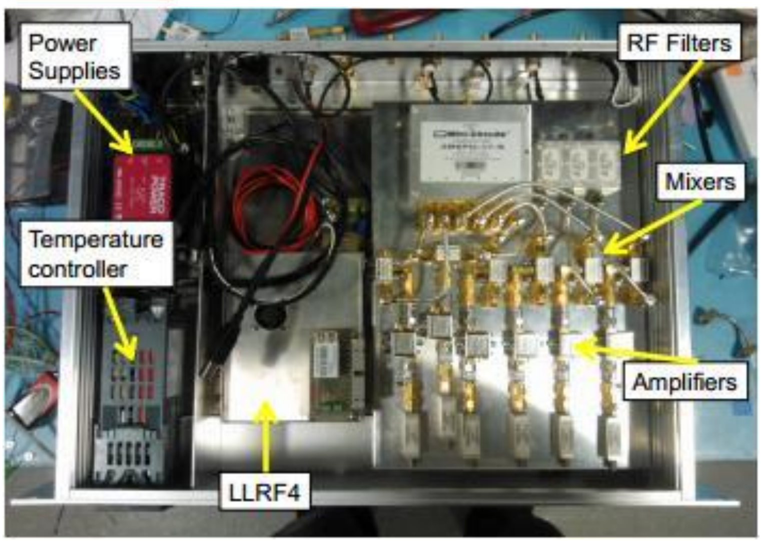


- Test stand vacuum envelope tested to ~$10^{-7}$mBar
- Cavity has been assembled with tuners
  - Six tuner tests in December
- Trial of cavity insertion allowed testing of
  - Simplified insertion fixture
  - New lift attachment
- Cavity successfully inserted and suspended with struts
  - Minor issue revealed with strut suspension system
  - Cavity temporarily removed
  - Replacement strut bodies from dissimilar material under fabrication
- Builds experience for assembly of first RFC Module



# LLRF development




- Exploits two LLRF4 boards from LBNL – now purchased
- Agreements with LBNL established to develop system
- Basic design of hardware and software is done
- Daresbury have tested all major features, including the feed-forward control system on a recent 1.3GHz system (separate project)
- Design remains fundamentally unchanged
    - Hardware and software can be applied to MICE 201.25MHz
    - Requires straightforward modification of the analogue system
    - Can be achieved in ~ 3 months
    - Systems in use already with EPICS control
    - Prior to cavities arriving, can build cavity simulator
        - Allows testing of the timing diagnostic

# Requirements for Muon-RF Phase Timing

- ToF detectors provide 50ps resolution time stamp for the particle
  - Systematic delays well understood
- Trackers define muon orbital trajectory
- Predict delay to first cavity- this is the time we want to 'perform' our RF phase measurement
  - It is likely that this time mark will not be available until significantly later than the transit time of the Muons
- In order to not compromise the current resolution
  - Ideally want accuracy to be 50ps/3, ~17ps, ~1$^{o}$.
  - May be relaxed subject to advice from analysis group
  - Vital to achieve stable synchronisation with ToF signals
- Can exploit known properties of RF signal to assist
- Worst case scenario- cavity linewidth is ~50kHz in 201.25MHz centre,
  - 2.5 parts in 10000
  - Max phase shift in 1 cycle is ~0.1$^{o}$.
  - Can therefore project about 10 cycles from measurement point
    - Adding only 1$^{o}$ to the error
  - Requires accurate measurement as baseline for projection
  - May be substantially eased by the LLRF feedback loop gain bandwidth

# Phase Detection Schemes

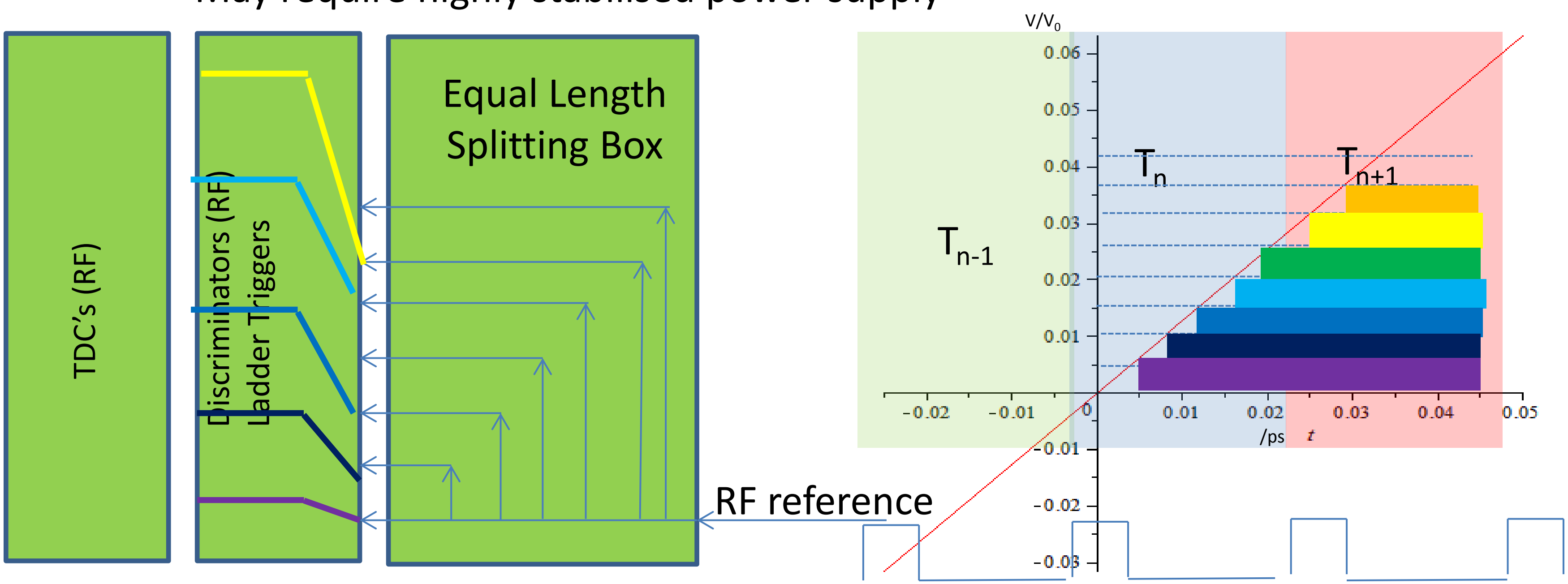
- RF zero crossing easiest to define and provides best trigger edge
- Detector clock should be synchronised with ToF
- Use external clock (from LLRF or alternative source) to sync clock cycles
- Use LLRF Feed-Forward complete trigger to sync all timebases
  - No interesting data till LLRF enters closed loop for phase
  - Confirms peak gradient achieved

# Phase Detection: TDC Approach

- Could use Caen V1290A TDC's and LeCroy 4415A Discriminators used for ToF
  - Known hardware and programming interface
  - Minimises electrical length uncertainty and thermal variability
  - Limited to 25ps resolution (though stnd deviation for uniform pdf $\sim\Delta t/2\sqrt{3}$)
    - Options for resolution enhancement
      - Analogue interpolator (requires knowledge of amplitude)
      - Enhanced digital Vernier needs high clock and comparator performance
    - Requires discriminators tested in 201MHz environment:
      - Alternate Phillips 704 rated to 300MHz
- Use alternative, faster TDC
  - Agilent/Acqiris semi analogue device
  - Is unproven, new programming and hardware interface
  - Has different hardware limitations to understand

# TDC Enhancement Scheme

- The resolution of the ToF detectors is ~50ps
  - In order not to compromise this when quadrature combining errors, ideally our error should be <1/3 the ToF uncertainty
- The Caen TDC's do not quite match this in terms of their resolution (25ps)
- It may be possible to enhance resolution with a form of analogue interpolation
  - Exploits knowledge of the signal amplitude and time evolution
  - Dependent on the performance of the discriminators and stability of the TDC
  - Either by delay lines to offset phase OR staggered triggers in discriminators
    - Thermal stability of LeCroy 4415A seems promising for staggered triggers
    - May require highly stabilised power supply




TDC 'Clock'

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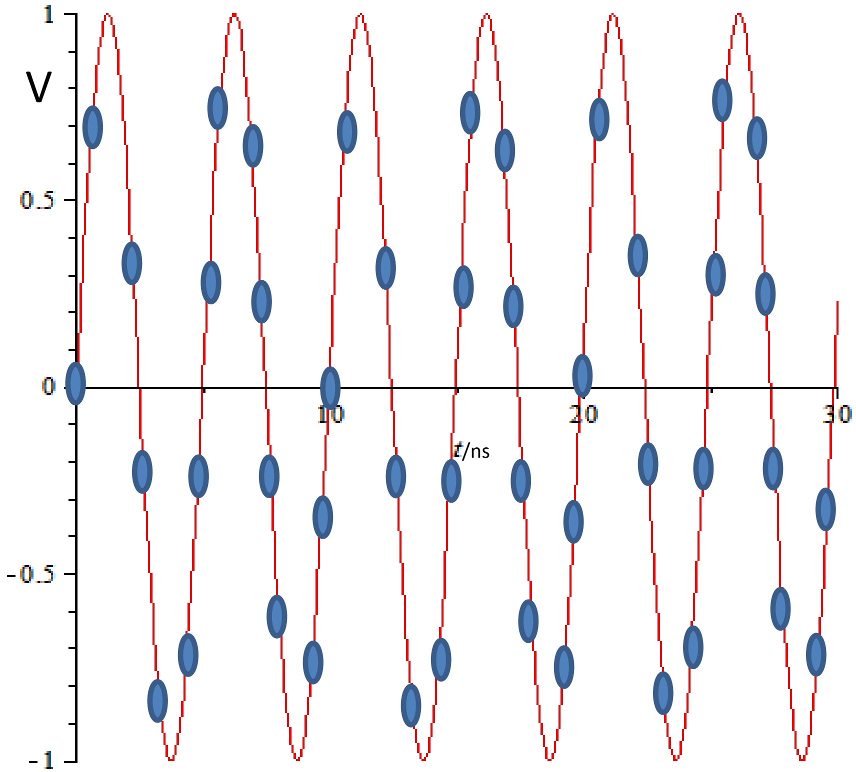
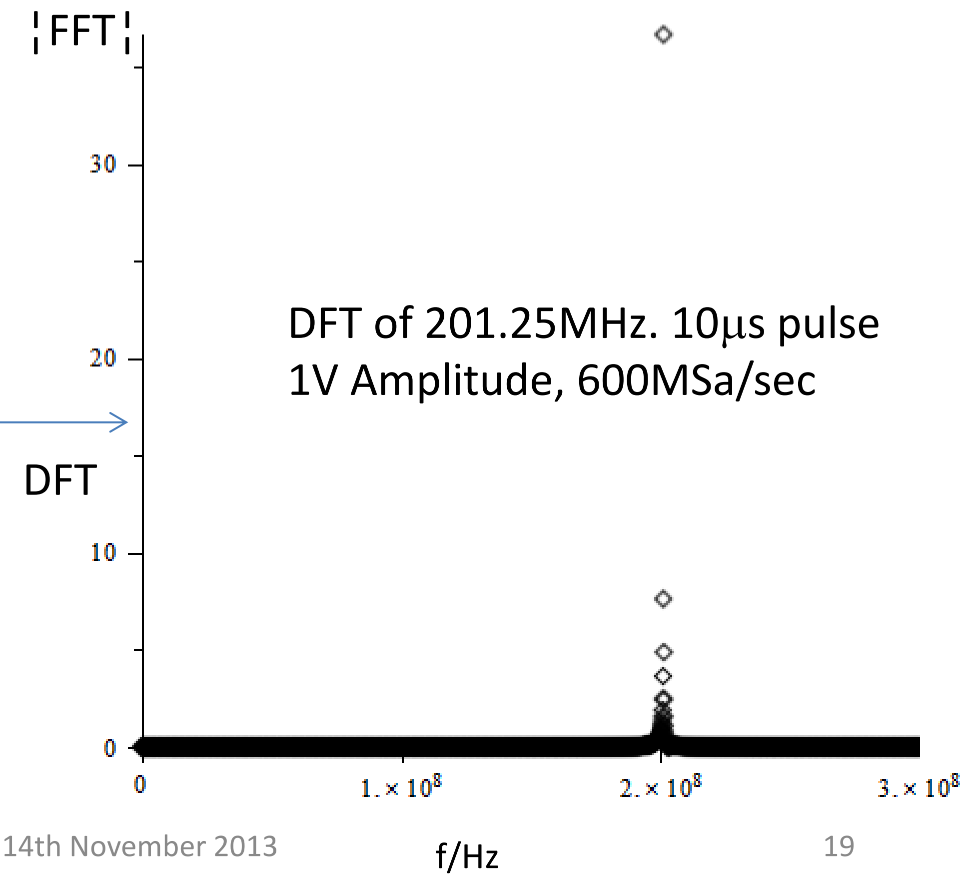
# Phase Detection: Digitiser Approaches

- Could use digitisers to record waveform
  - Would involve a lot of data if we require Nyquist on 201MHz
    - But since narrowband- have options
    - Sequential burst acquisitions on a regular periodicity
    - Undersampled waveforms and DSP signal reconstruction
    - Both techniques require proving
    - Give amplitude data- useful for TDC analogue interpolation
  - Suitable digitisers quoted by Agilent and Caen; Additional vendors possible

# Digitiser Sparse Data Approach 1: Subsampling

- We know with quite high precision the form of the accelerating field in time
  - 201.25MHz (50kHz width)
  - Do not need to satisfy Nyquist on the signal, only on the bandpass signal




DFT of 201.25MHz. 10μs pulse
1V Amplitude, 600MSa/sec

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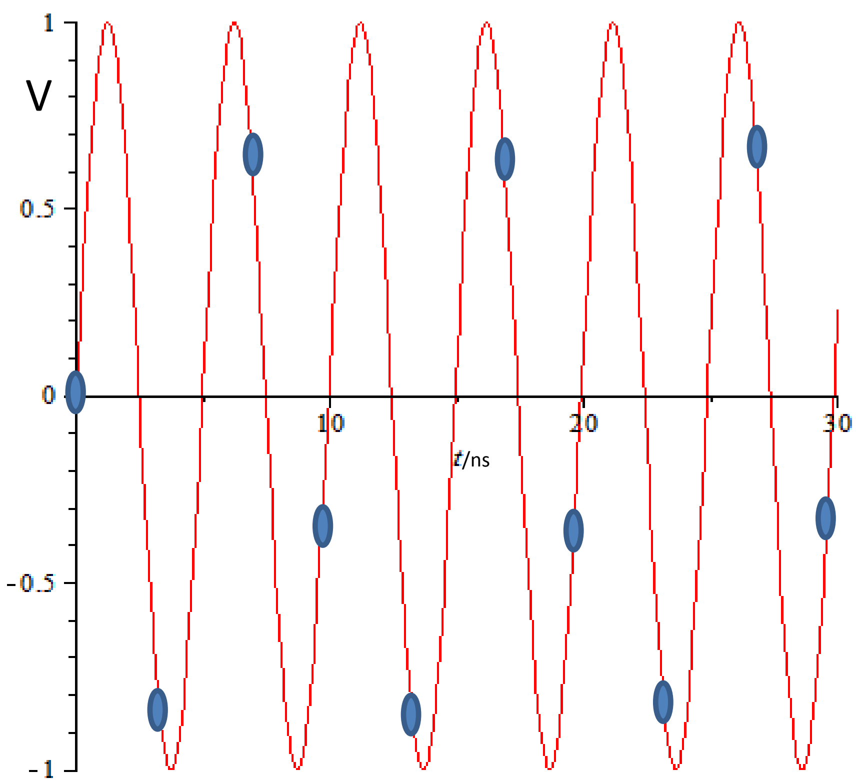
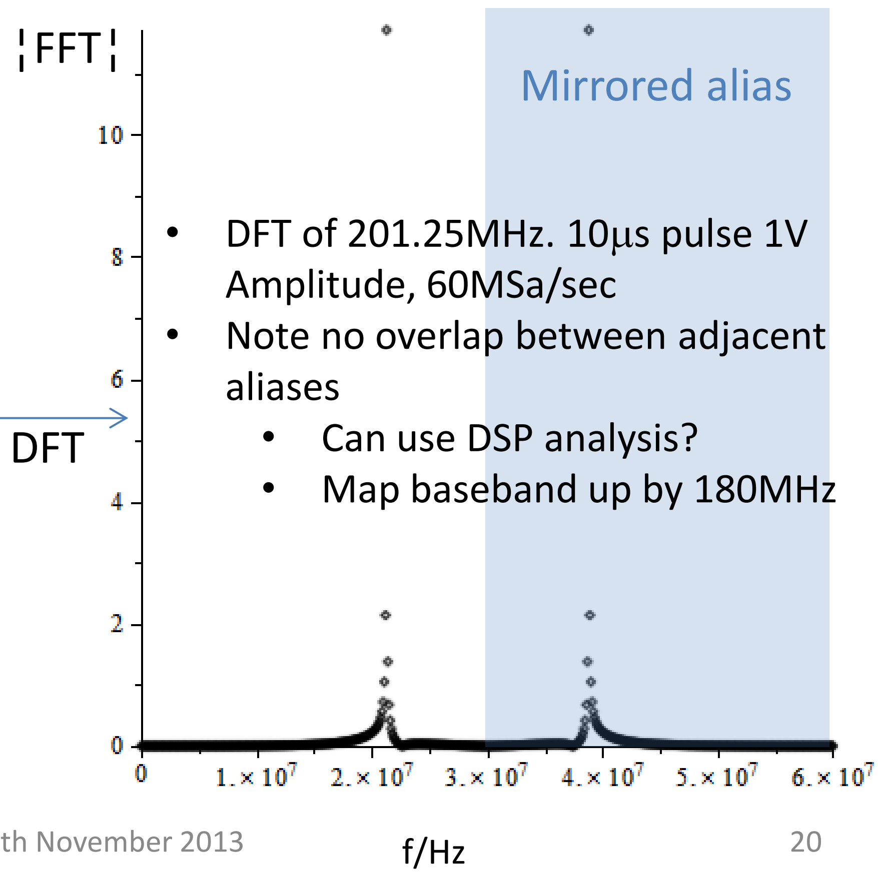


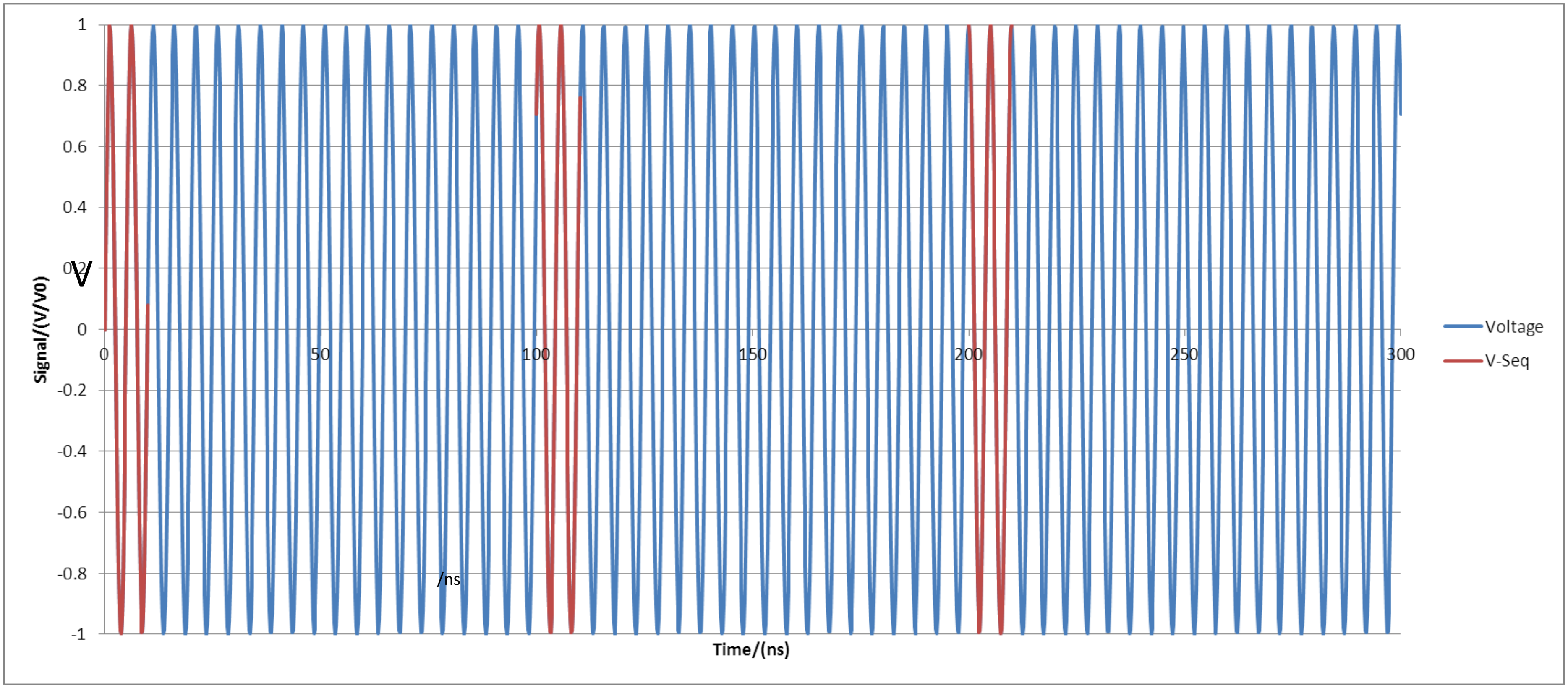

DFT




- DFT of 201.25MHz. 10μs pulse 1V Amplitude, 60MSa/sec
- Note no overlap between adjacent aliases
  - Can use DSP analysis?
  - Map baseband up by 180MHz

# Digitiser Sparse Data Approach 1: Sequential Sampling

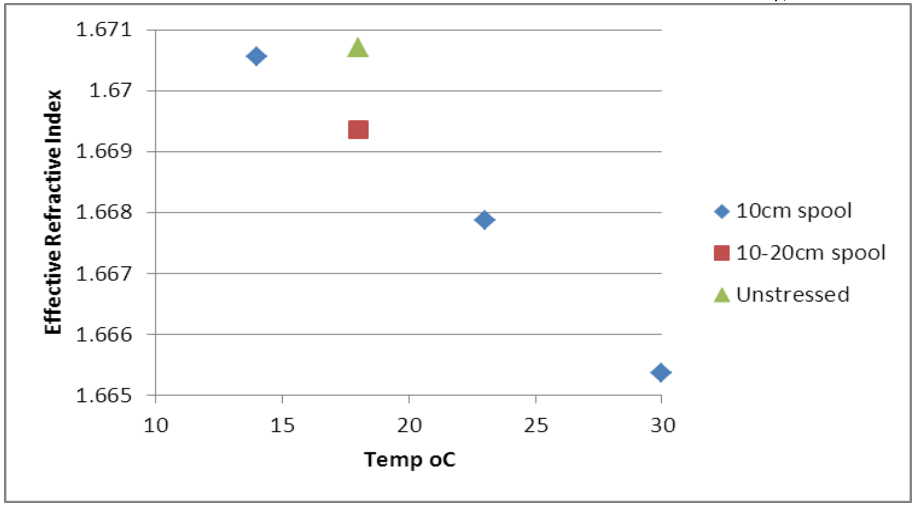
- We know with quite high precision the form of the accelerating field in time
  - Could sample short burst of the signal using high speed (> Nyquist on 201.25MHz) digitisers in sequential timebase mode




- Need to understand the accuracy of the fitting process and resulting projections
  - As a function of the sample rate and sequence spacing, duration
  - As a function of the noise in the system, tuning by the LLRF

# Time delays

- If we use new electronics, we will need to assess the delays and delay stability cf. the ToF electronics
- Network analysers/simulations to define the systematic delays in the RF system
- Cable used in the ToF system
  - RG213, 40m long
  - Has acceptable RF bandwidth
  - Not particularly mechanically nor thermally stable

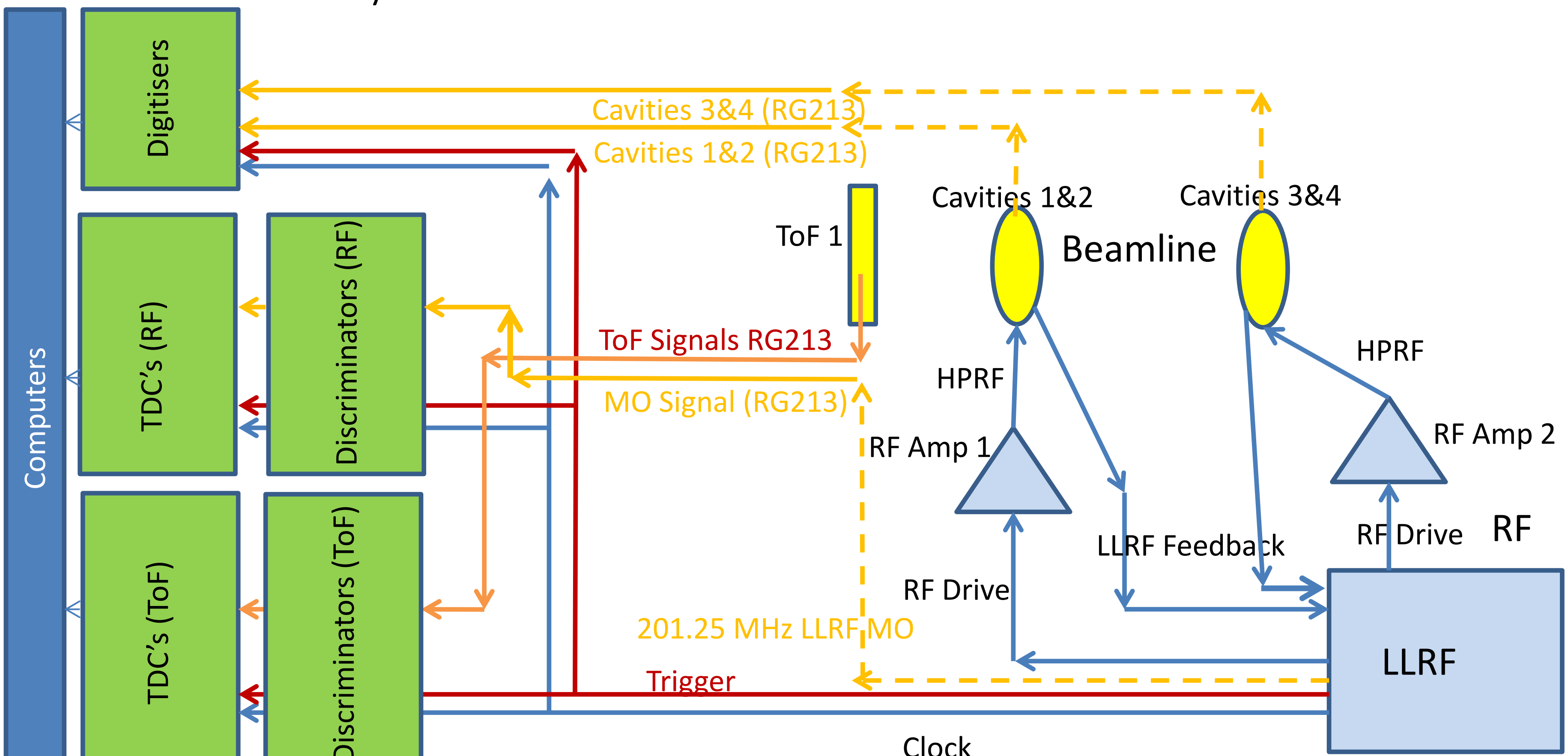



# Cable solutions

- Could take cavity signal to ToF, or LLRF reference oscillator signal to ToF on high performance cable
- Use RG213 laid in parallel with ToF cable to achieve maximum equalisation of the thermal response
- Measure to define electrical length after installation
- Provide redundant spare cables to test for variation in electrical length
- Check cable performance as we want a stability below the ToF detectors resolution

# Overview of Timing Critical Elements

- Sketch illustrates relationships of key components in STEP V configuration STEP VI similar
- Work in progress: Mathematical tests of digitiser interpolation
  - Test sensitivity to vertical resolution, temporal sample rate, noise
- Work in progress: Understand cable stability
- Work to be undertaken: Test TDC/Discriminators in 201.25 MHz environment
  - If necessary test alternative hardware



# Summary

- High Power Drivers
  - Have achieved specification on system No.1, 2MW for 1ms at 1Hz and 201.25MHz
  - Require commissioning of systems No.2-4
  - Installation of system No.1 at RAL underway
    - Tests will be undertaken in December
- Major procurement effort complete
  - Most components required for distribution network
  - Many components required for amplifiers and LLRF work
- Cavity Status
  - Cavity test assembly has been undertaken,
  - Tuner tests underway: completion December
  - Coupler fabrication in hand
  - High power tests expected in January, later tests in magnetic fields
- System has been defined to allow RF phase to be compared to Muon event times
  - Will exploit a combination of TDC and digitiser techniques
  - Interpolation methods for subsampled and sequential waveforms being tested now
  - Performance of TDC/Discriminators needs to be proven experimentally
  - Daresbury have offered to build a 'Cavity Simulator' using LLRF boards
    - Will allow tests of the timing system components
    - In a normal lab-benchtop environment