RF System- Demonstration of Ionisation Cooling

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RF System Status

- 2MW demonstrated from prototype amplifier
  - System demonstrated at 500kW in MICE Hall
  - Triode amplifier still installed (valve removed)
  - Tetrode amplifier and all PSU's returned to Daresbury
  - Will be used to commission triode amplifier no. 2
  - Further progress limited by available electrical engineering effort (focussed on Step IV at this time)

- Development of RF timing diagnostic
  - Subsampled digitisation has been shown to allow accurate reconstruction of 'mathematical waveforms'
  - Also appears to allow reconstruction of real waveforms recorded on oscilloscopes
    - With slightly reduced accuracy

- First cavity under test at MTA
  - David Speirs will update on this in the next talk

RF Power System Plans

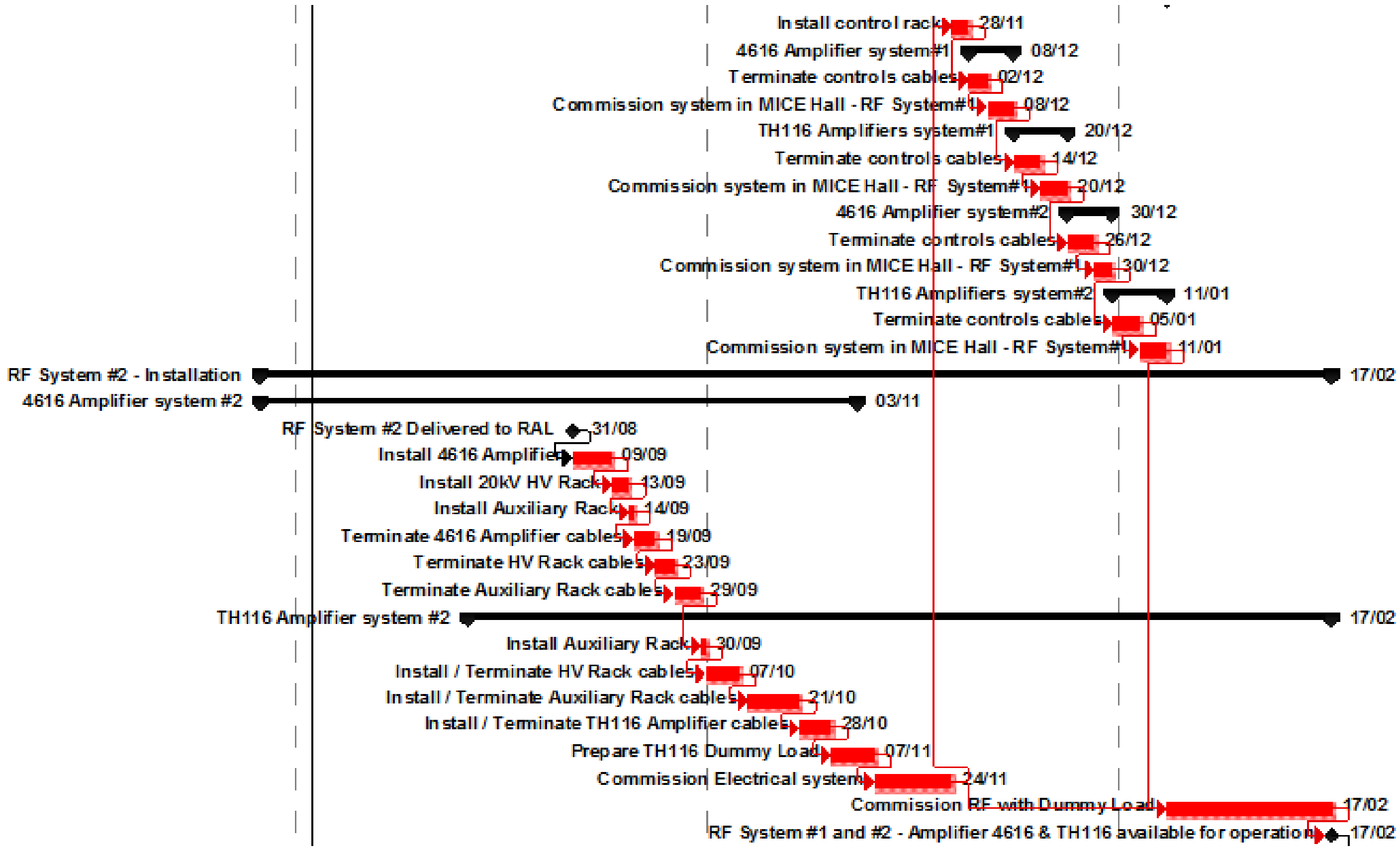
- Amplifier system No.2
  - Will be commissioned in stages
    - Tetrode No. 1 and existing PSU's will be used to commission triode no. 2
    - Each other major sub-component (tetrode, triode PSU, triode Aux PSU, tetrode PSU, SSPA) will be swapped out in sequence for its nominal 'twin'
    - Localises 'snagging' allowing more efficient commissioning
    - New crowbar switches will be used with higher peak voltage rating
  - Will start to provide 'remote' and semi-automatic control

- Control System
  - Meeting has been held at Daresbury to define the RF control system
  - This has led to the definition of some aspects of a state machine for the system
    - More work to be done
  - Understanding the states of the system allows the control interface and automation system to be designed
  - Also important in defining appropriate variables for the monitoring system

- Transition from STEP V to Demonstration of Ionisation Cooling
  - Has moved the RF drive system back to critical path
    - Will therefore become a key activity as soon as STEP IV is operational
  - STEP V timetable had assumed two amplifier systems installed by 2017 in any event
  - Timetable of operation by Sept 2017 means there is no longer an opportunity to 'shakedown' with a single cavity test at Daresbury

RF Power System Plans

- Timetable (from R. Preece Project Plan)
  - Envisions both amplifiers commissioned in the MICE hall in period Jan 2016-Feb 2017



  - About 1 month for baking, pumping and LLRF tests of cavities
  - Envisions a period of 1 month to commission the amplifiers into the RF cavities
  - This will be the first time the MICE RF amplifiers have driven a partially reactive load.

RF Power System Constraints

- Resources not available to bring Amplifiers 3 and 4 to operation ahead of 2017 deadline
- Only 2 amplifiers available to drive two cavities in schemes outlined at this meeting
- Nominally each amplifier should provide 2MW of RF drive power
  - Anticipate losing 10% in transmission lines
  - LLRF requires 10% overhead to regulate amplitude
  - Drive into cavities hence expected to be ~1.6MW
  - Using 8MV/m as reference for 1MW drive power
  - Implies at 1.6MW one should attain a gradient of just over 10MV/m
  - System has resilience as we have spare valves for the triodes
- Aspirational: should it be possible to commission amplifiers no. 3 and 4 later- ~3.2MW would be available per cavity
  - This could give a gradient in the range 14MV/m- comparable to the energy gain one might have expected from STEP V
  - Many components exist to enable this- would require additional crowbars and capacitors, and effort to build and commission
  - Could be an additional technical demonstration of high RF E-fields in strong B-fields

RF Distribution Network

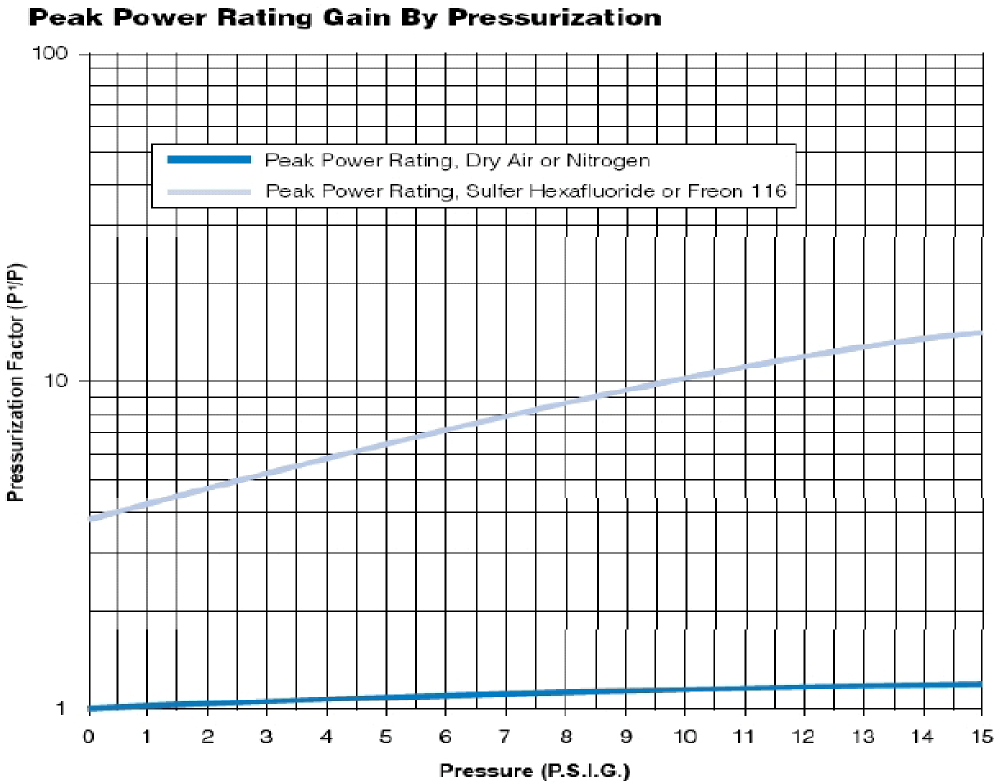
- The Demonstration of ionisation cooling has two cavities, each with two couplers

- This simplifies the installation
  - Only four 4” co-axial lines need go under the floor
  - Two 6” Quadrature hybrids will be used to split the signal, mounted on the present shield wall
  - 6” lines will come over the top of the wall to reach the hybrid couplers from the triode amplifiers
  - Line length matching is eased since only pairs of lines are now directly driven by a single amplifier
  - However recent discussions with FNAL indicate that there is advantage to ensure the valve never sees a large amplitude standing wave
  - Can be achieved by making lines integer half wavelengths long

- However the peak power in the lines has gone up to 1.6MW in the 6” lines and 800kW in the 4” lines (this will also result in standing waves in the 6” lines)
  - This latter number corresponds to 9kV across the line
  - In a full reflection the voltage would double across the line at antinodes of the Standing Wave reaching ~18kV
  - Even in STEP V configuration this was going to be an issue- but it is now more severe
  - 4” line is rated to peak power and voltage of 710kW or 6kV
  - 6” line is rated to peak power of 1.5MW or ~8.5kV

RF Line Protection

- To prevent overvolting the lines in STEP V we planned to combine a slow ramp in drive power with pressurisation of the co-axial line to (max) 2 bar N_2
- Now concerned that this will not be sufficient- given power in lines (of any size) has now doubled it seems likely that the system will need SF_6
- This brings some additional H&S to address
- However SF_6 regularly used at DL and FNAL (and probably at RAL)



The RF Drive System- time structure of the RF signal

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

- These amplifiers run on a pulsed duty cycle:
  - Nominally 1ms with 1Hz repetition
  - High Q cavities and couplers will reflect all power when empty, charge time ~1/Δf
    - With a Q of 44,000 on a 200MHz centre freq, bandwidth Δf~5kHz
    - Significant fraction of the pulse will be required to 'fill' the cavities

Timing System, Desired Specification

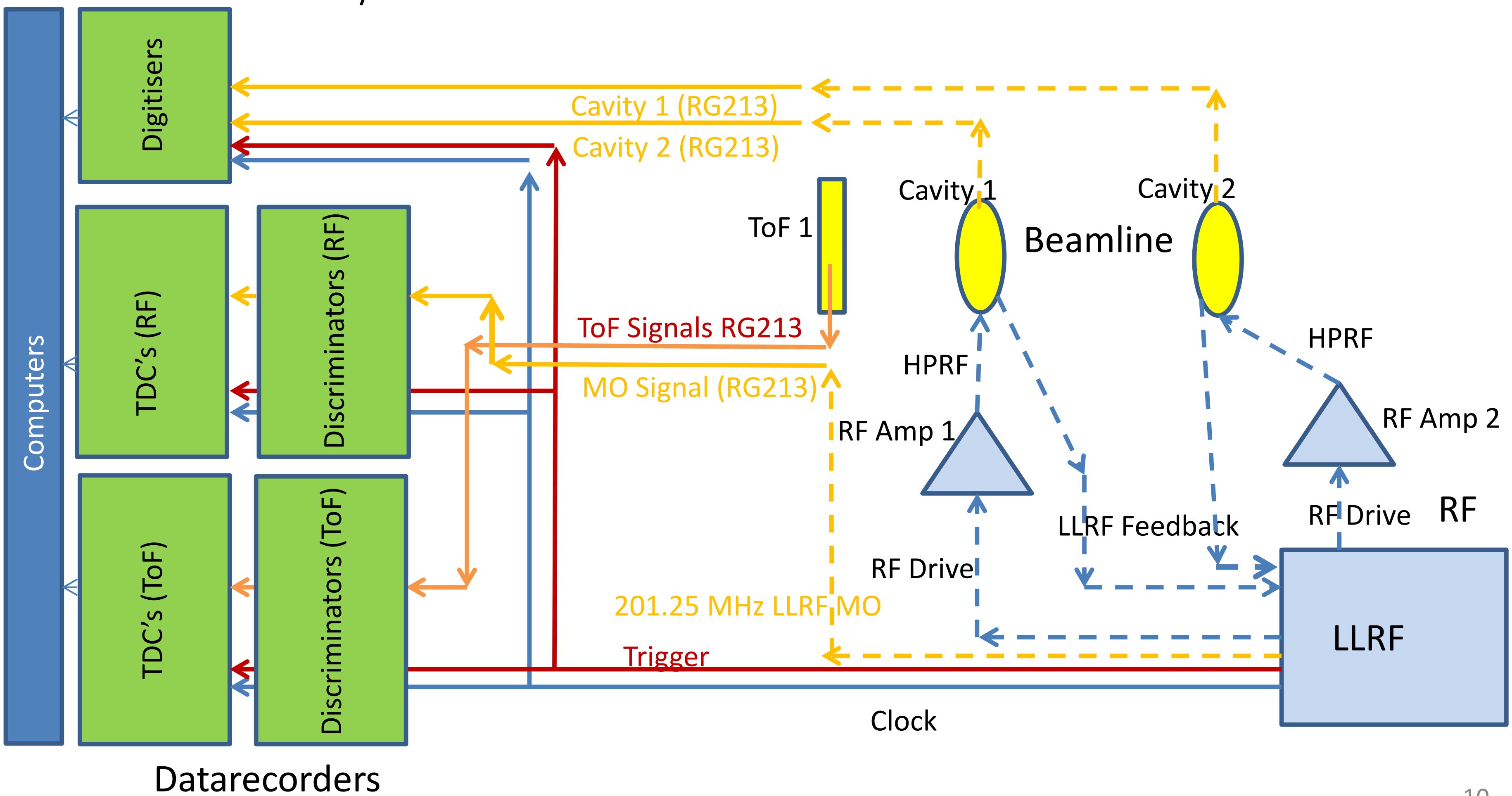
- We wish to know the difference between
  - Transit time of any of our muons (in essence through ToF1)
  - A zero crossing of the RF system in any cavity- choose the first cavity
    - The phase difference between the two cavities will be known to within the regulation of the LLRF system IF
    - Can we deal with all systematics in the system to this accuracy
      - λ=1.5m, so 0.5^{o} in phase implies <2mm, <0.13%
  - Use tracker measurement of trajectories to project forward to each cavity in turn

- Phase (0.5^{o} in phase) stability is x3 stricter than the resolution desired for the RF timing system ~1ps or 0.34% of the RF cycle
- In turn specification for RF timing is ~3x stricter than ToF resolution 50ps ~1%
- Should mean the timing accuracy is ~1%, defined by ToFs resolution

- Stability, and/or accurate knowledge, of all parameters in the system will be important
  - Long cable runs, with dielectric insulated coaxial lines?
  - Phase relationship between the cavity fields and the signals on the test ports
  - Relationship between ToF signals and actual Muon transit

Overview of Timing Critical Elements

- Sketch illustrates relationships of key components in the Demonstration experiment
- 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



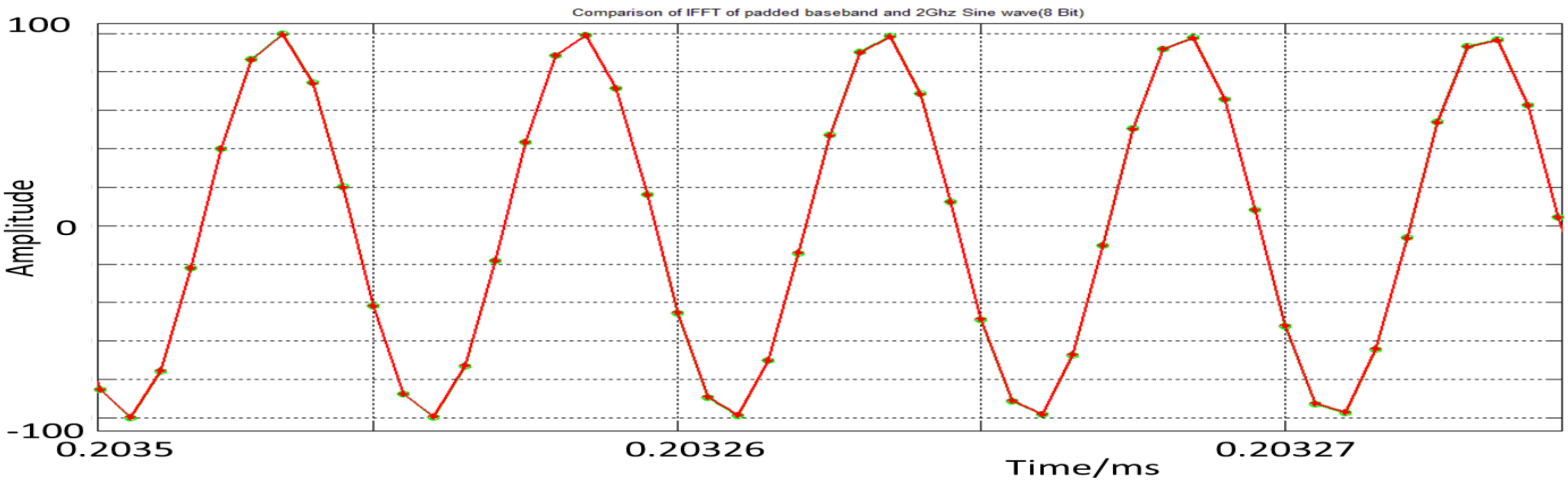
‘Sub’ Nyquist digitisation

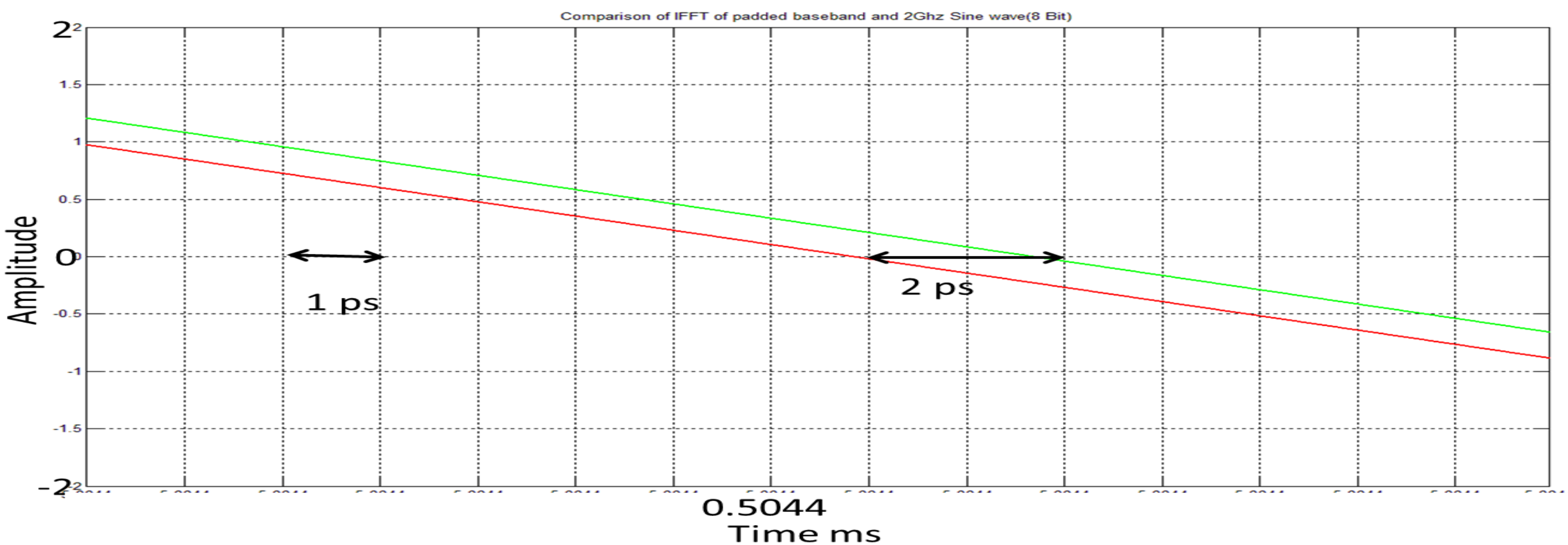
- To acquire at Nyquist on 200MHz would demand a sampling rate of ~1-2G.Sa/sec, for 1ms, possibly on 3 different signals at 1Hz repetition
- Demands ~1 to 2MB per acquired channel, > 7.2GB/hr (assuming an 8 bit digitiser)
- Subsampling
  - Is an option in signal processing for signals with a relatively well known narrowband spectrum
  - The Fourier Transform of the undersampled data maps the signal into its ‘unaliased’, relatively low frequency range
  - Providing this is sufficient to contain all the signal energy associated with the data one may re-map the signal in a simple systematic manner to the correct frequency
  - Since we know that elsewhere the signal is zero
- We may then retransform to the time domain to determine the time evolution of the signal at some arbitrary point in time
- Must satisfy Nyquist on the linewidth- for our cavity natural linewidth is ~5kHz, effective linewidth is ~10kHz, so sampling rate ~few hundred k.Sa/sec should be sufficient
- Suppose we take 20M.Sa/sec, with 1ms we now have about 20kB per 8 bit recorded channel, data rate of 72MB/hr per channel

Testing of Spectral Domain Remapping

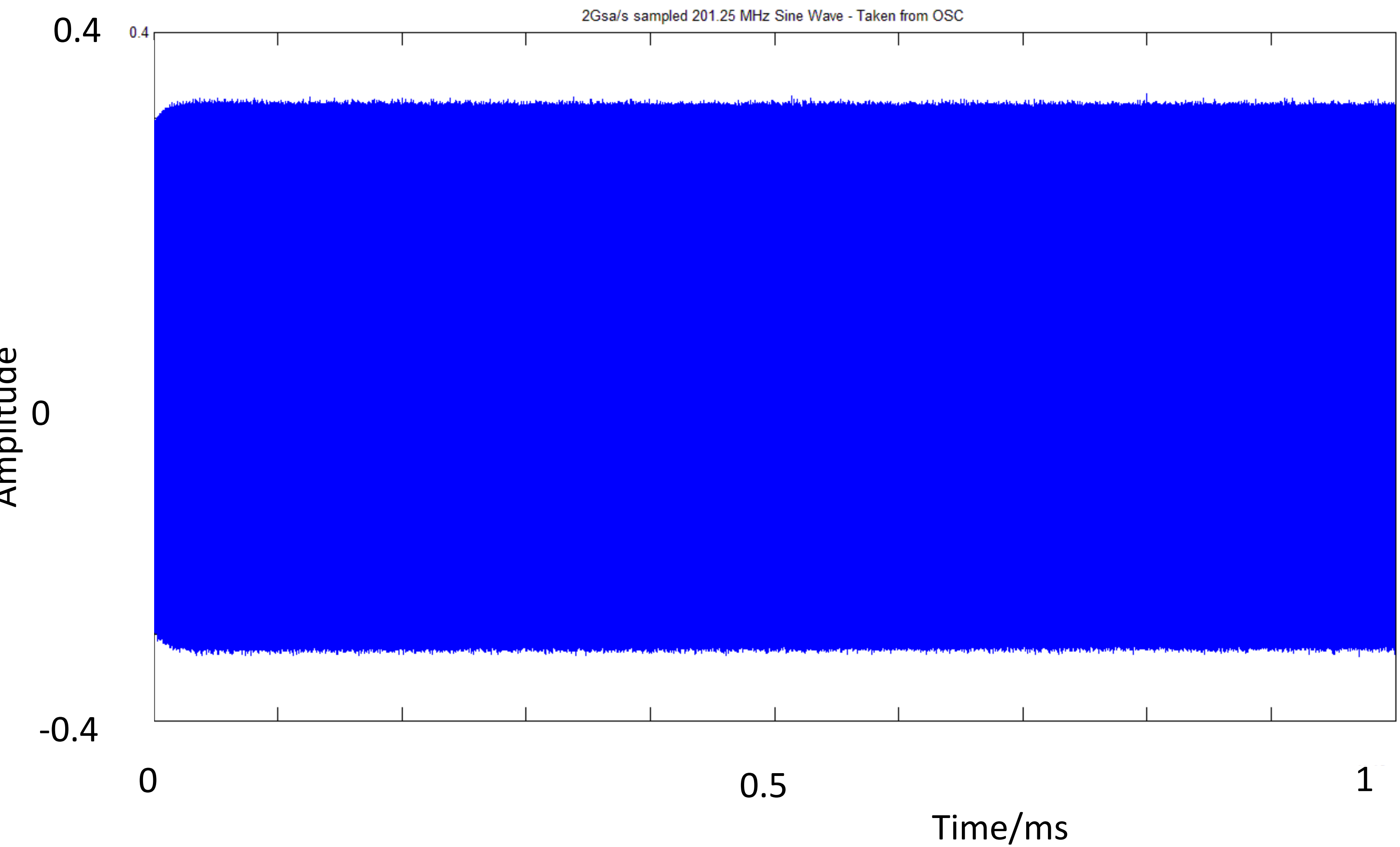
- 201.25MHz signals computed (with ramp envelopes) and recorded at both 2G.Sa/sec and 20M.Sa/sec effective digitisation rates
- Signals compared after FFT and spectral region remapping, and again after iFFT, to compare the time domain of source signal
  - Good agreement obtained
- Computer used to simulate vertical digitisation error (i.e. 8 bit resolution of digitising typical oscilloscope)
  - Again signals compared and reasonable agreement obtained
- Realistic data obtained by high speed oscilloscope
  - Process repeated

Comparison of synthesised 8-Bit digitised 201.25MHz wave recorded at 2G.Sa/sec with IFT of padded 20M.Sa/sec data

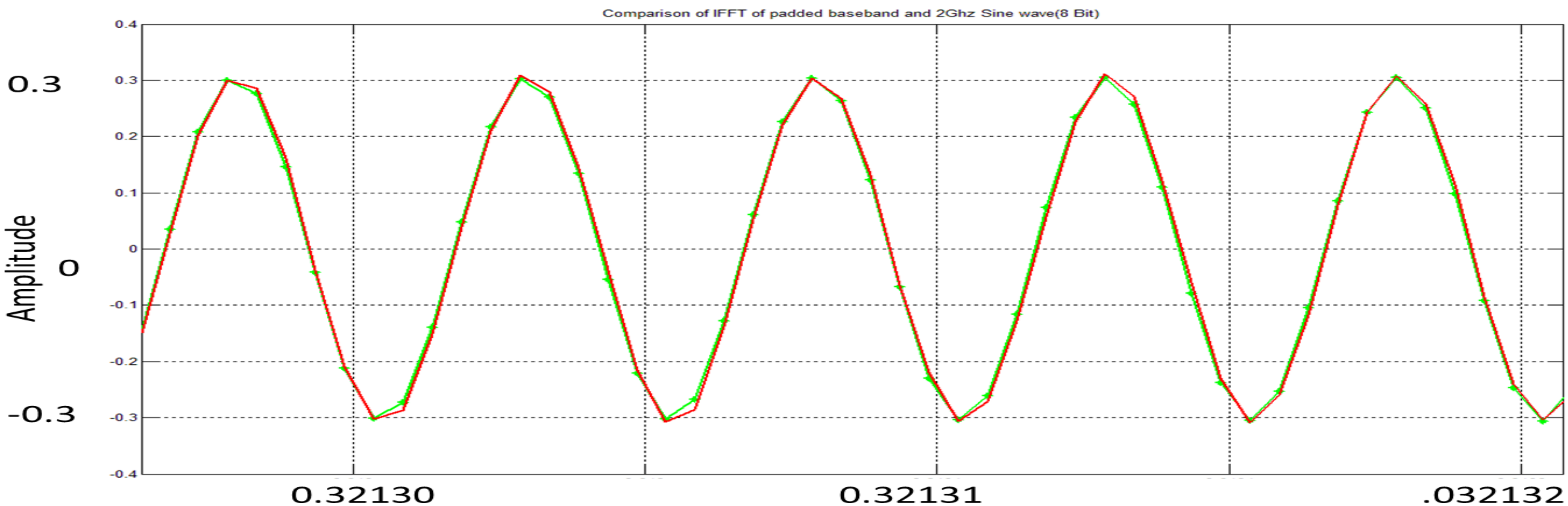


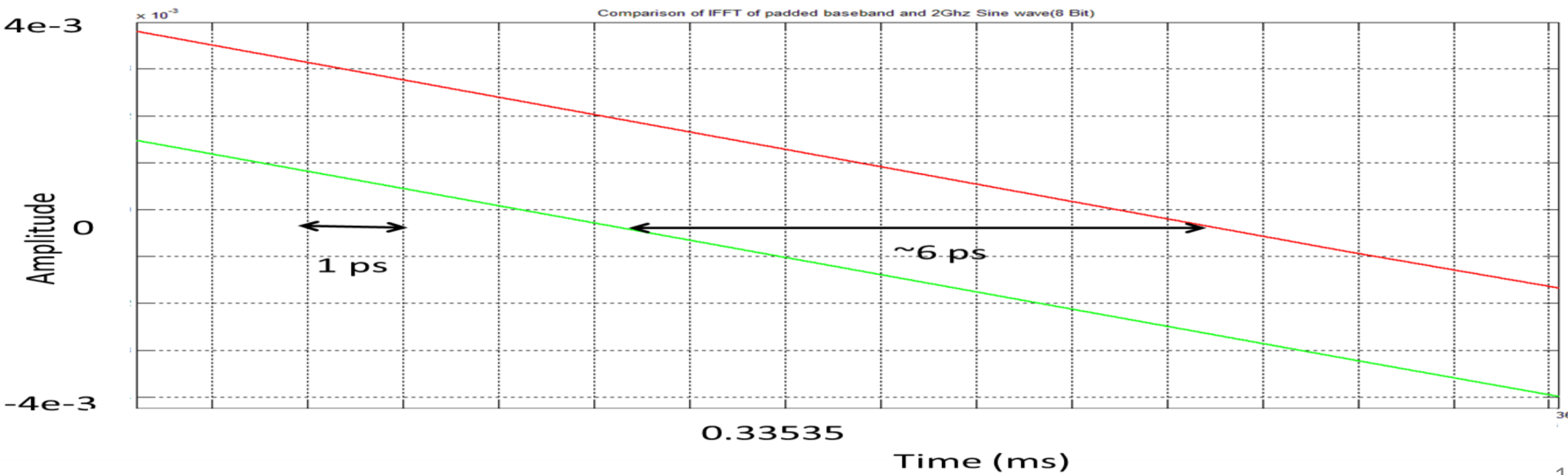


Real data taken from Agilent DSO-X G2004A



Comparison of 20M.Sa/sec subsampled captured oscilloscope signal with generated signal





Summary

- Changing from STEP V to the Demonstration experiment has limited impact on the RF drive aspects of MICE
  - Regrettably there will be no full system shakedown at Daresbury
- There are of course limitations in the voltage uplift available
- It should be possible to source transmission lines from the supply procured by Mississippi
  - May require a few modifications or new purchases, but very small compared to the previous commitment
  - The layout will need to be redesigned once the final experimental configuration is defined
  - We may need to address the issue of SF_6 in the lines
- The RF subsampling technique appears to work- must be tried on actual cavity signals
  - Must check relative horizontal performance of digitisers (the one used on this test is known to be unusually good- jitter in the timebase on slow sampling digitisers could compromise the technique)
  - Define instrument for procurement (currently CAEN unit is favoured but others are available)
- Alternative technique derived from ToF datarecorders
  - Needs to be tested in RF signal environment
  - Y. Karadzhov has identified two potential candidate TDC's and brought discriminators from Geneva which can support these tests
- Understand the relationships between the RF phase and the ToF timestamp on the particle