Muon-transit RF Phase Determination

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For the MICE RF group

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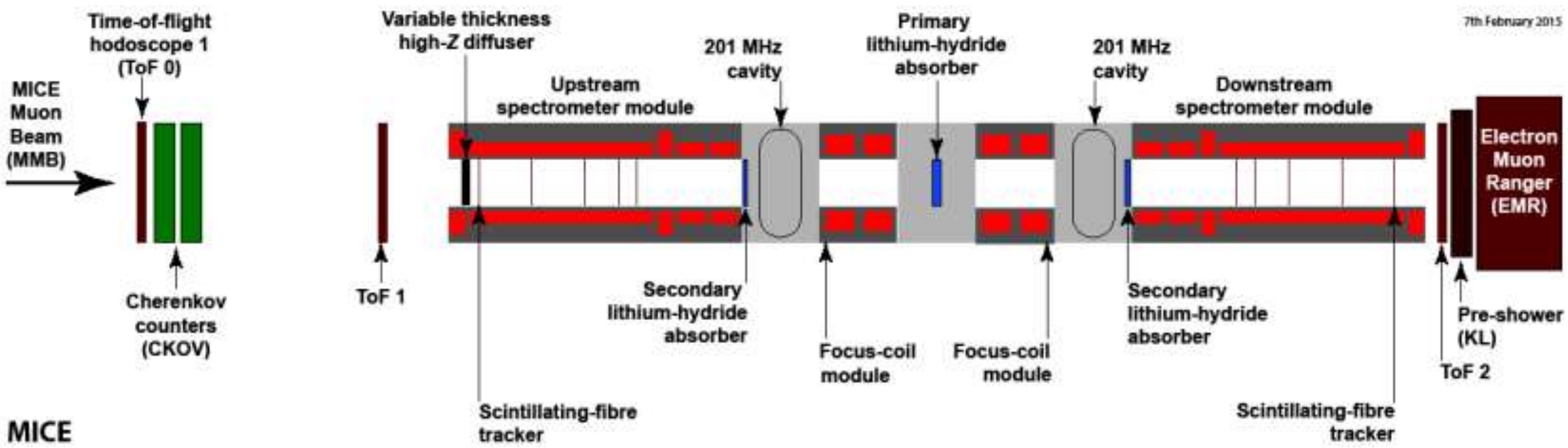
Muon RF Phase Determination: Requirement

- MICE is a physics experiment NOT an accelerator cooling channel
  - Muons are produced in spills, duration ~ms
  - There is no particle buncher
  - Muon arrival is completely asynchronous with the RF phase
- The MICE measurement approach
  - Muon 'beam' is tenuous
    - Particles are measured individually
  - Beam is selected 'after the fact'
    - Ensemble of particles satisfying a range of 'qualification' parameters
    - Representative of a beam in a real accelerator cooling channel
- Ionisation cooling is a function of the particle energy
  - Cooling is therefore a function of the acceleration each particle experiences
- 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'

Detector and Cavity Locations

- Three ToF hodoscopes- provide precise time stamps for particles
- Two momentum spectrometers- measure components of p, r upstream and downstream
- Two cavities, bracketed by two thin LiH absorbers, sandwich main absorber
  - Restore part of the momentum lost in transiting the absorbers
- Cavity Q of ~50,000, Resonant freq: 201.25MHz, (est. by simulation, verified by measurement with network analyser)
  - Simulation of shunt impedance implies 8MV/m for 1MW input power
  - Cannot be verified without passing a beam through an energised cavity with upstream and downstream diagnostics



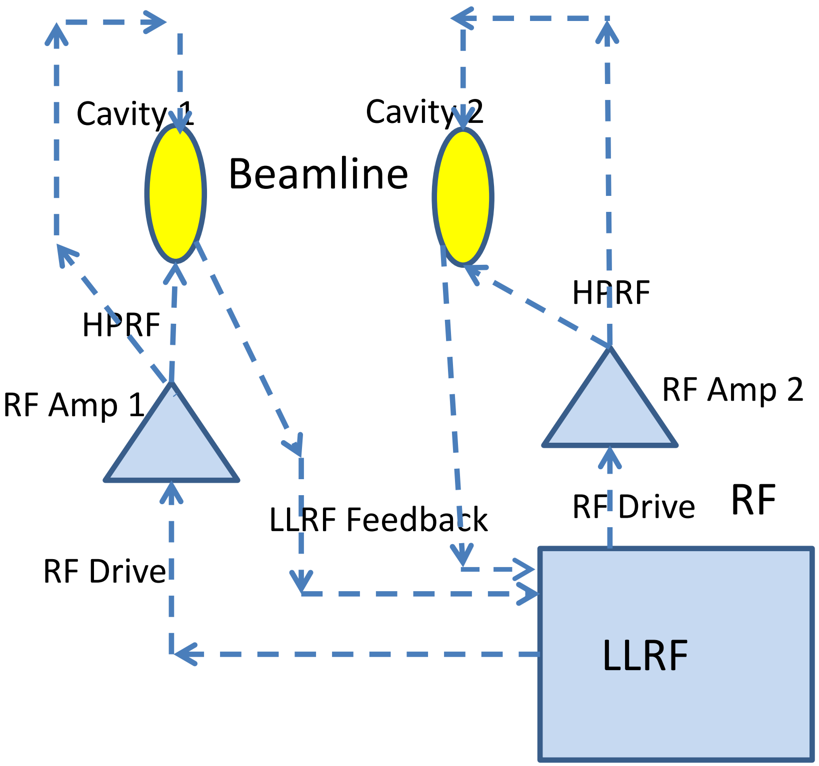
RF Phase precision requirement

- Particle transit time determined by ToF detectors- used in difference measurements
  - ToF resolution ~50ps, systematic delay not completely known
    - Not an issue for difference measurements between ToF detectors
  - Closest ToF's are ~2.5m upstream of 1st cavity/downstream of 2nd cavity

- Cavity transit time inferred by the ToF transit time and the tracker measurement of momentum
  - Tracker resolution, p_z ~ 200MeV/c is Δp_z ~2MeV/c
    - For particles with p_t > 50MeV/c
  - For 2.5m gap transit delay is ~10ns +/- 25ps
  - Combine ToF resolution and momentum projection resolution in quadrature
    - Cavity transit precision from particle diagnostics ~ 70ps
  - Desire to know RF phase to better than 0.3 of this ~ 20ps
    - i.e. 10% impact on error in quadrature
  - Key requirement is stability of measurement systematics
  - Absolute calibration will be done by particle measurement

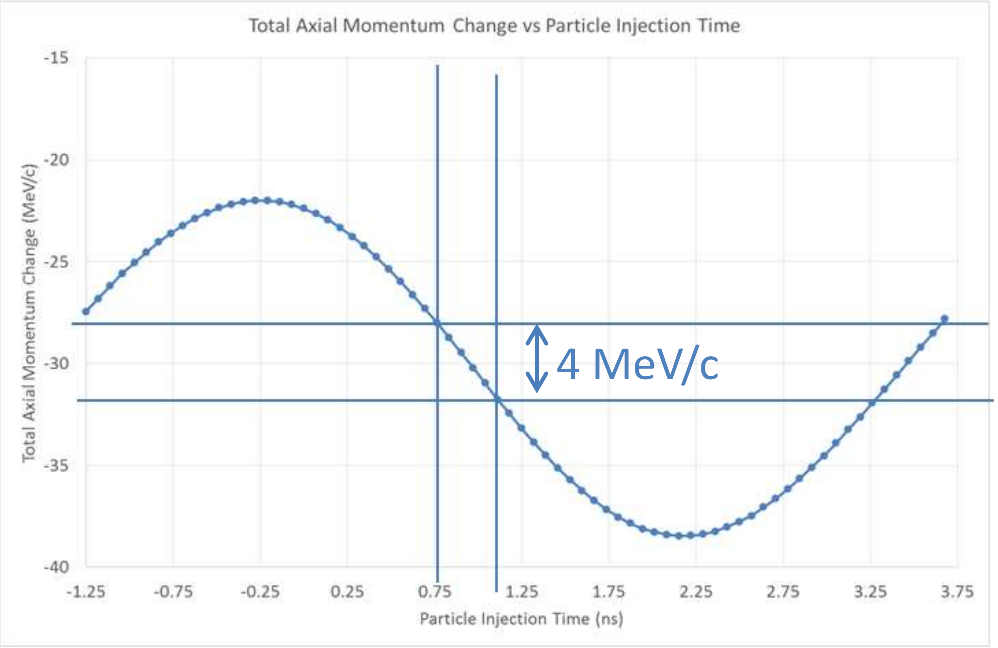
MICE RF system

- 2MW peak output from High Power RF (HPRF) drive amplifiers BUT
  - Low Level RF (LLRF) control system
    - Regulates RF amplitude and phase in each cavity
    - ~10 % overhead to achieve regulation
  - Operating into reactive load and transmission line
    - Estimate ~10 % reduction in power
  - Power delivered to each cavity 1.62 MW
  - Each cavity fed from two couplers
    - Output from each amplifier split in 90^{o} hybrids
    - Line lengths balance 90^{o} phase shifts
  - Anticipated gradient in each cavity ~10.3 MV/m



RF Phase absolute calibration

- ToF hodoscopes normally used in difference mode
  - Fixed systematic delays unimportant
- Now wish to compare to fundamentally different detector
  - Different systematic delays
- Need to align measurements
  - Use perturbation of particles by RF as fn of phase
  - e.g. Plot momentum change against RF phase with arbitrary offset
  - First measurement of cavity shunt impedance



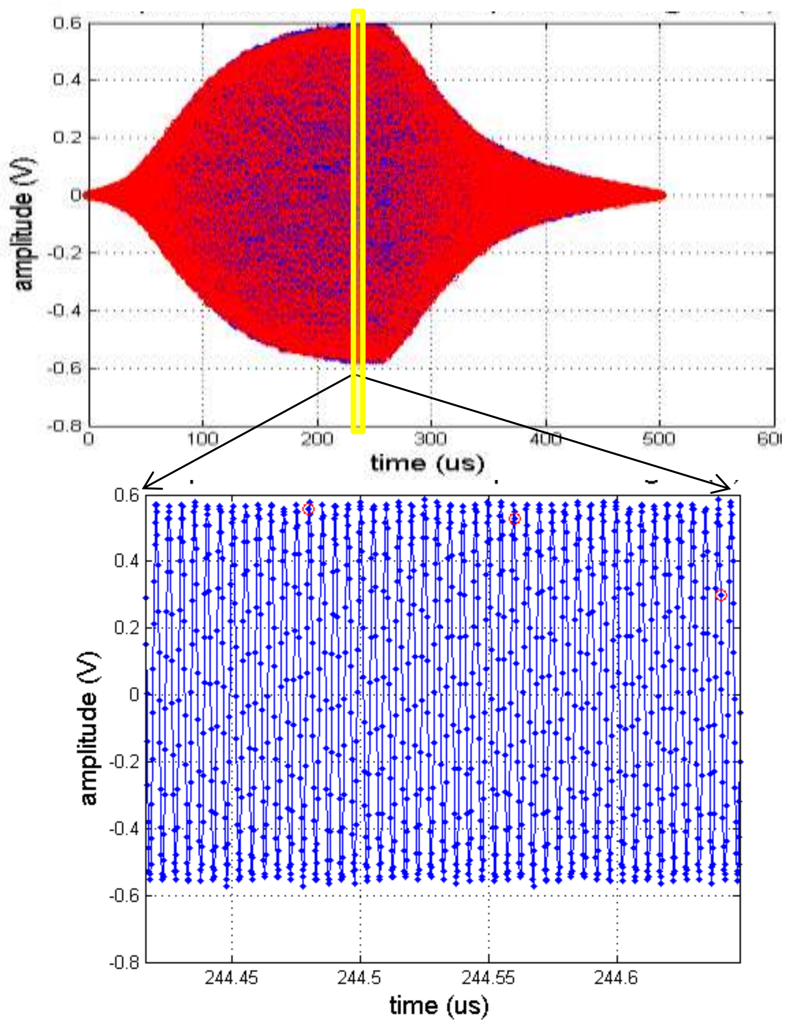
- Assume the trackers have a p_z resolution of about 2 MeV/c
  - For particles p_t > 50MeV/c
- Estimate ~ 170ps uncertainty in absolute phase (~3.5% of the cycle, ~ 12.5^o)
- Implies alignment at accelerator bunch significant level

Sub sample digitisation

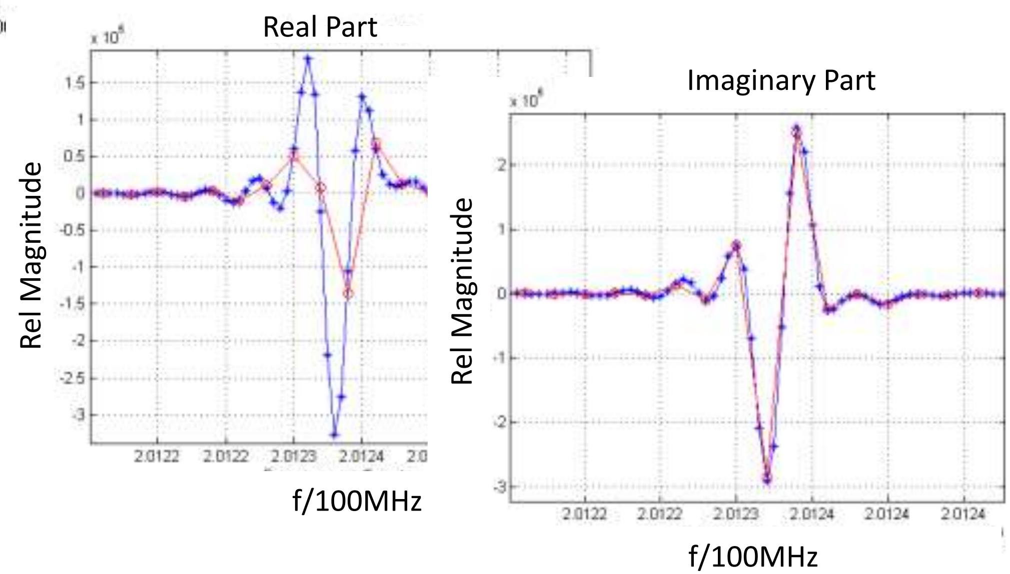
- RF cavities are high Q
  - f_0=201.25MHz, tuning range ~few hundred kHz
  - LLRF control will regulate frequency tightly
  - Q ~50,000 hence Δf~5kHz
    - Nyquist limit would normally suggest $f_s=3xf_0$ ~600 M.Sa/sec
      - i.e. 3 points per RF cycle
      - Realistically 2-5 G.Sa/sec for good fidelity
    - Our system is highly spectrally constrained,
      - We KNOW frequency, linewidth, repetition rate
      - Nyquist limit is really $f_s=3x\Delta f$, ~10's k.Sa/sec
    - No requirement to sample at high speed – mitigate recorded data depth
    - We can perform enhanced Fourier transform
      - Fourier domain resolution enhanced by knowledge of duty pattern
      - Fourier domain width reduced by knowledge of signal spectral structure
    - IFT back to time domain
      - Only over 'live' spectral domain and only to 'live' temporal domain

Sub sample digitisation

- Signal (Blue) from FNAL cavity tests- 500μs window sampled at 5G.Sa/sec- 2.5M.Sa
- Subsample (Red) at 12.5M.Sa/sec, reduce data by x400

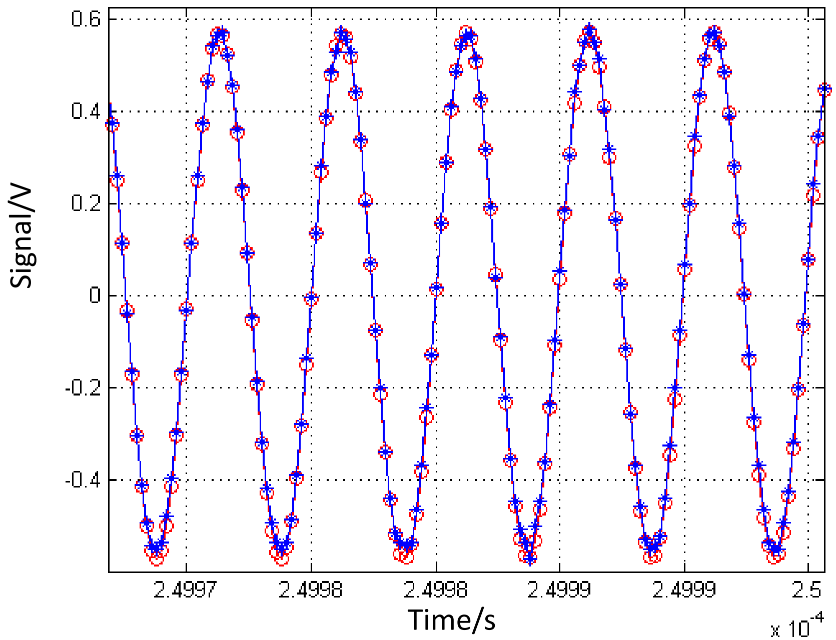


- dFT to spectral domain
- Focus on 100kHz linewidth about 201.25MHz
- Spectral resolution enhanced (x4)
- Red is fft of whole data set and Blue is dFT x 400 of subsampled data

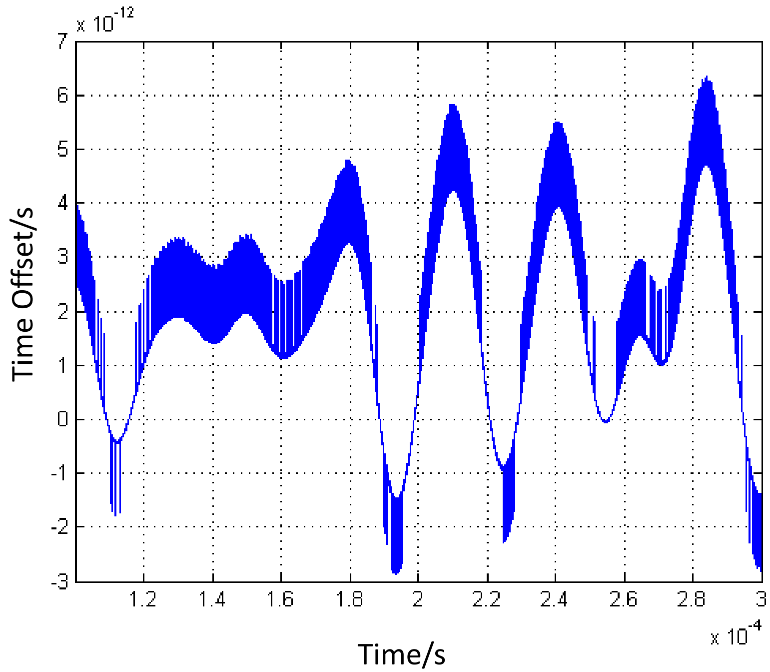


Sub sample digitisation

- Reconstructing by DSP gives high fidelity to raw signal (Blue is Raw, Red is DSP data) over entire pulse duration



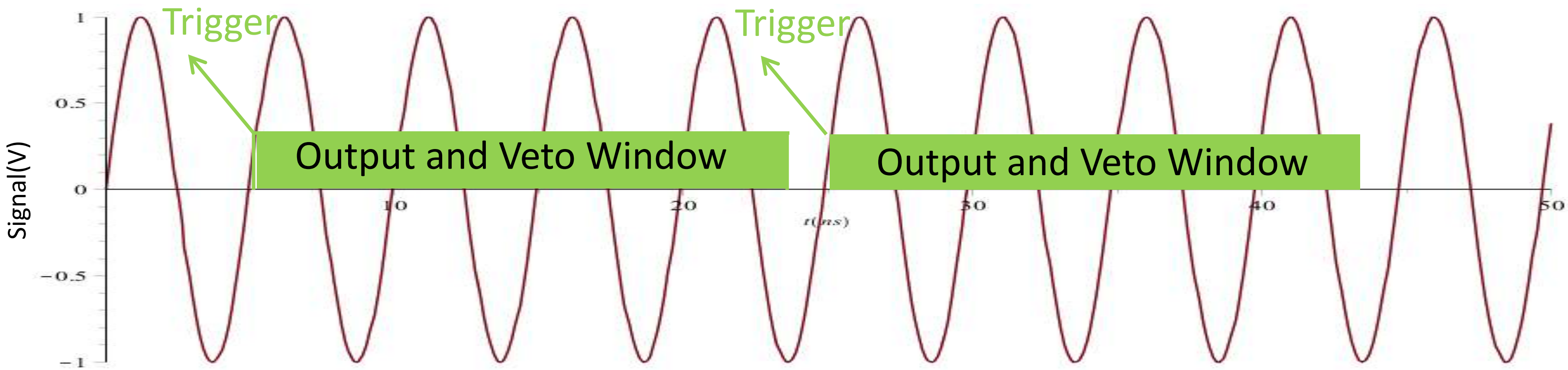
- Phase error ~10ps near flat part of pulse
- Systematic offset ~3ps
- DSP is effectively a 100kHz filter
- Raw data subject to 1MHz Butterworth Filter



- In MICE will not need to perform full pulse ift
- ToF will indicate when we wish to know relative phase
- dft & ift (computationally expensive) are efficiently applied
  - Narrow spectral range and narrow temporal range

TDC approach

- Time to Digital Convertors (TDC) timestamp particle hits in hodoscopes: ToF's 0,1,2
  - TDC's clock @ 40MHz (25ns): Vernier schemes to yield 25ps bin lengths
  - Sufficient for required accuracy based on UPDF statistics
- Need a device to turn RF signal into edges for TDC
- RF signal is relatively simple
  - Amplitude and frequency fixed by LLRF feedback
  - No need for CF, leading edge threshold discriminators are acceptable
  - Discriminator threshold above noise but in linear part of trig function
  - Interpolate from TDC readout using prior knowledge of wave amplitude and frequency- acquire every few (say 10) cycles

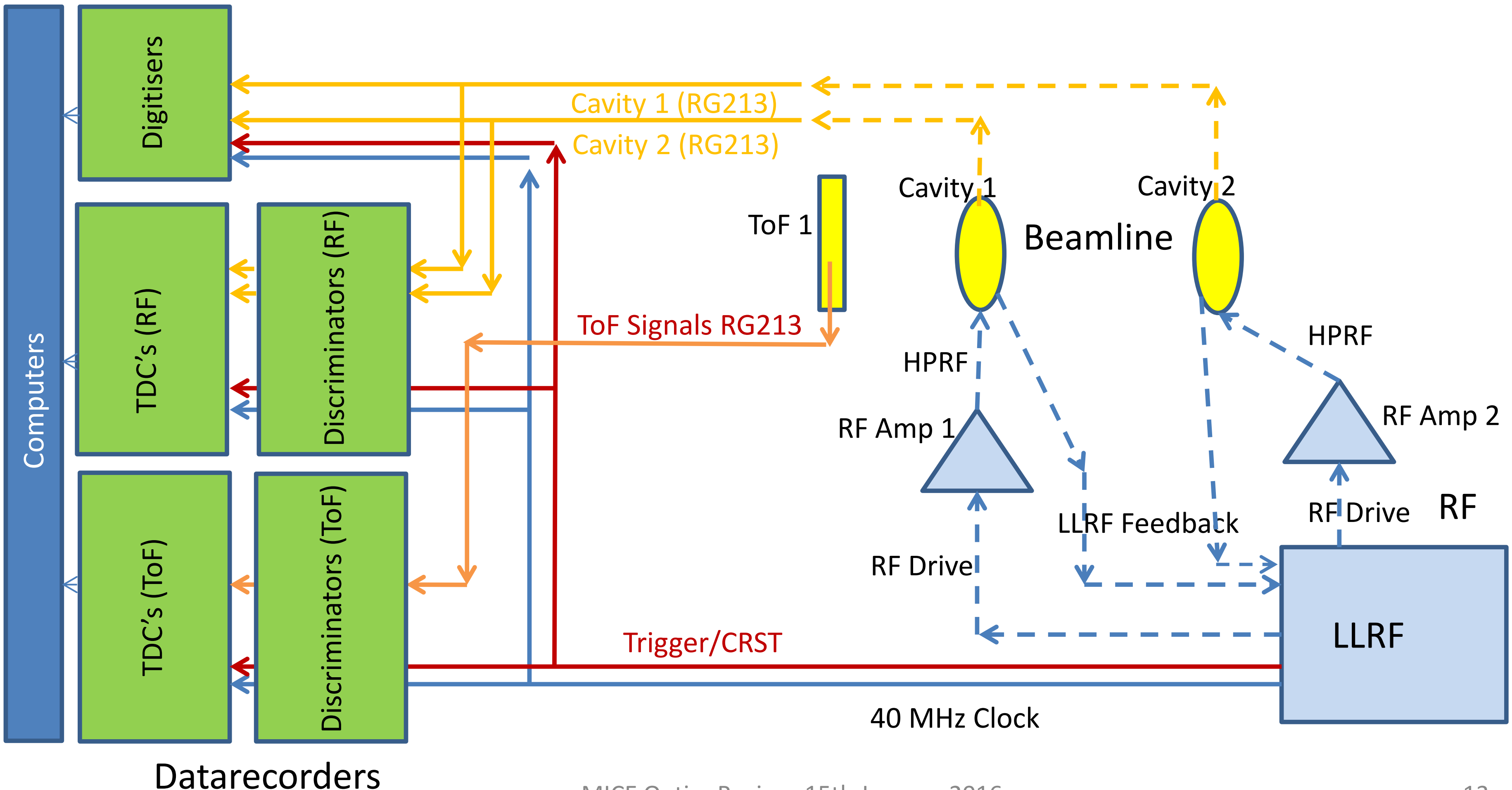


Timebase Synchronisation

- Need to consider mechanism to align timebase of diverse measurements
  - Provide TDC's and Digitisers for RF measurements
  - Align timebase with hodoscope TDC's
- CAEN V1290A TDC's are used to record the hodoscope events
  - Currently operating with asynchronous clocks
- Use identical TDC for RF
  - TDC's require a 40MHz clock for high resolution
  - Distribute 40MHz clock using LLRF technology
  - Discussion with Daresbury LLRF group
- Use digitiser which can also use 40MHz clock rate
- Trigger signal to digitiser needs to synchronise to TRST signal to TDC's

Timing System, General Layout

- TDC's and Digitisers in same environmentally regulated room
- Trigger for digitisers (TRST for TDC's) from RF diagnostics
- Clock from LLRF derived technology



Hardware

- TDC's presently used to record ToF: CAEN V1290A, VME instruments
    - 32k events: can record every tenth zero crossing
- RF frequency < 1 part in ~ 40,000
    - For a significant drift of ~ 25ps, requires 200 cycles
    - Propose to sample at every 50ns- every 10 cycles
    - Should enable accurate projection
- Discriminator: Phillips Scientific 704D Quad channel NIM discriminator
    - Non-updating variant of 300MHz leading edge discriminator
- Use external clock- 40MHz to sync all TDC's
- Digitiser: CAEN V1761,
    - 2 Ch, 10 bit, 4G.Sa/s, 7.2M.Sa VME digitiser
    - Can accept external clock at 40MHz i.e. same as TDC's
    - User programmable relationship sync clock to sample closk

Summary

- Nature of MICE requires measurement of RF phase for each particle
  - RF phase should ideally be known to a stability of 20ps
  - Does not compromise existing resolution limits imposed by precision and location of particle detectors
  - Absolute calibration by measurement of momentum change in transit of cooling channel
    - Calibration achieved by trackers
    - Possible early calibration measurements using ToF detectors

- Two techniques possible: TDC driven by Discriminators and Digitisation
  - Digitisation potential enhanced by sparse radio spectrum
    - Mitigate data by Fourier domain reconstruction methods
  - TDC gives required resolution and FSR
    - If it can be driven correctly by discriminators

- Hardware being procured to
  - Facilitate clock synchronisation
  - Provide fast discrimination of RF waveform
  - Appropriate digitisation

- Clock generation being discussed with LLRF team @ Daresbury