Status of the MICE RF System

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For the MICE RF team

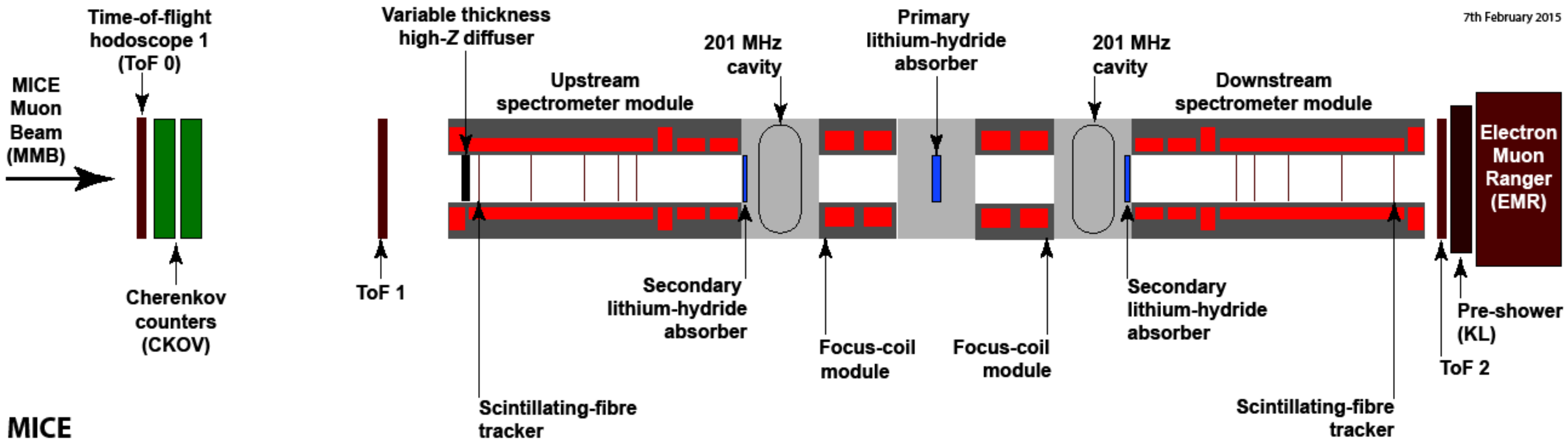
Content

- Redesigned distribution network
  - The demonstration experiment has simpler distribution requirements
    - Now makes sense to use ‘over air-gap’ network
    - Replaces STEP V under floor scheme
- Muon-RF phase determination
  - Initial tests with waveforms from MTA tests
  - Hardware now at Strathclyde for RF tests
- Status of RF drive system
  - Plans for test, delivery and installation of amplifiers
    - Proposal for a full system test at RAL
    - Requires appropriate EE and RF resources
  - Development of RF Controls & Monitoring systems
  - Development of LLRF
    - Resource Issues

MICE High Power RF systems

- MICE HPRF system requirements have changed
  - Fewer cavities, no coupling coil
  - Required operational date on the beamline is Summer 2017
    - Requires early commissioning of the hardware: Starting Aug 2016
  - Enables demonstration of ionisation cooling with re-acceleration
  - First results complete before end US fiscal year 2017

- The MICE Demonstration of Ionisation Cooling requires
  - Two cavities bracketed by two thin LiH absorbers, sandwiching main absorber

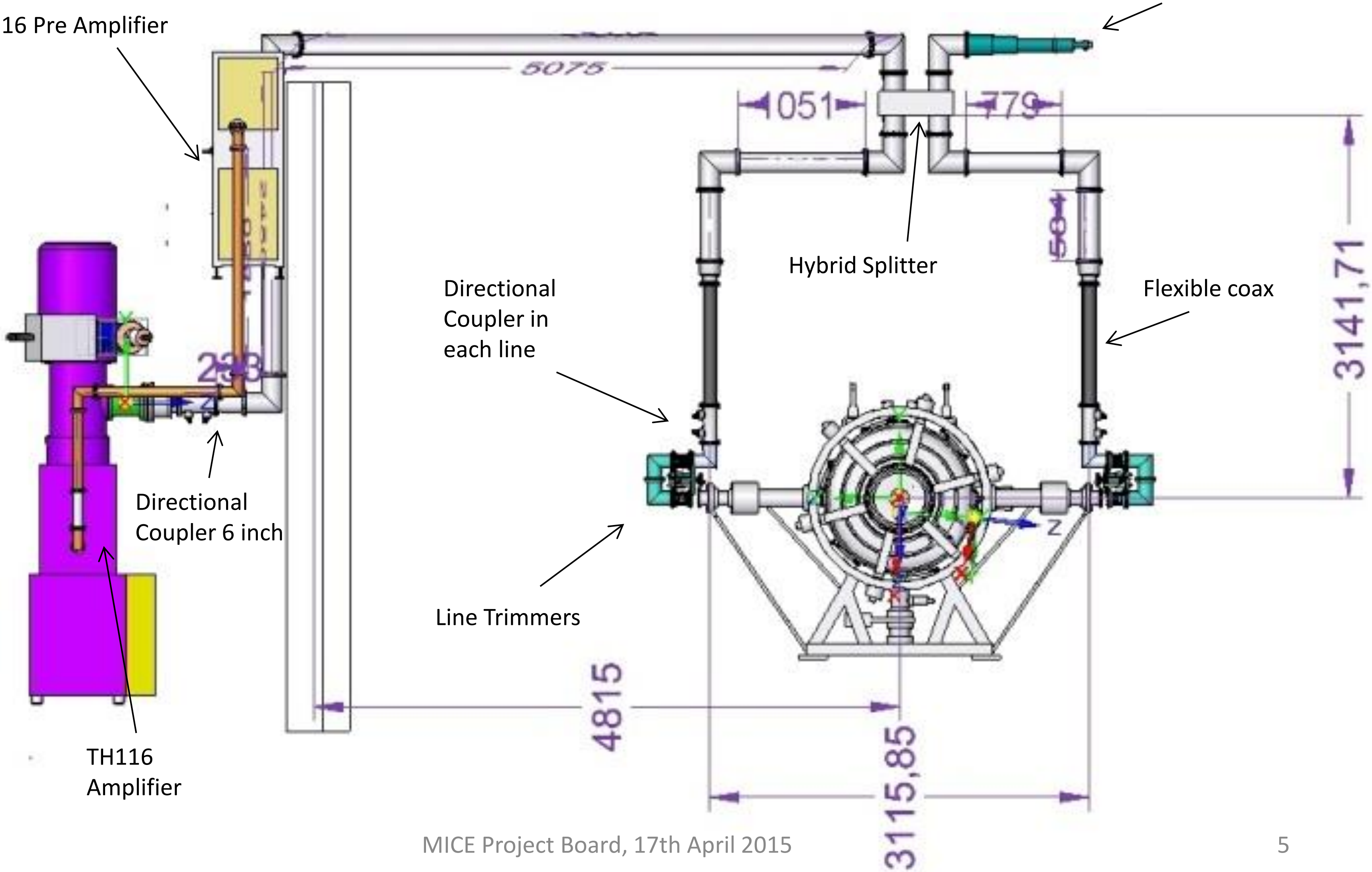


MICE High Power RF systems

- 2MW peak output from RF drive amplifiers, are unchanged
  - LLRF ~10 % overhead to achieve regulation
  - Estimated <10 % loss in transmission line
  - Power delivered to each cavity 1.62 MW,
  - Anticipated gradient in each cavity 10.3 MV/m
    - Slight uplift in gradient from 7.2 MV/m in each ‘STEP V’ cavity

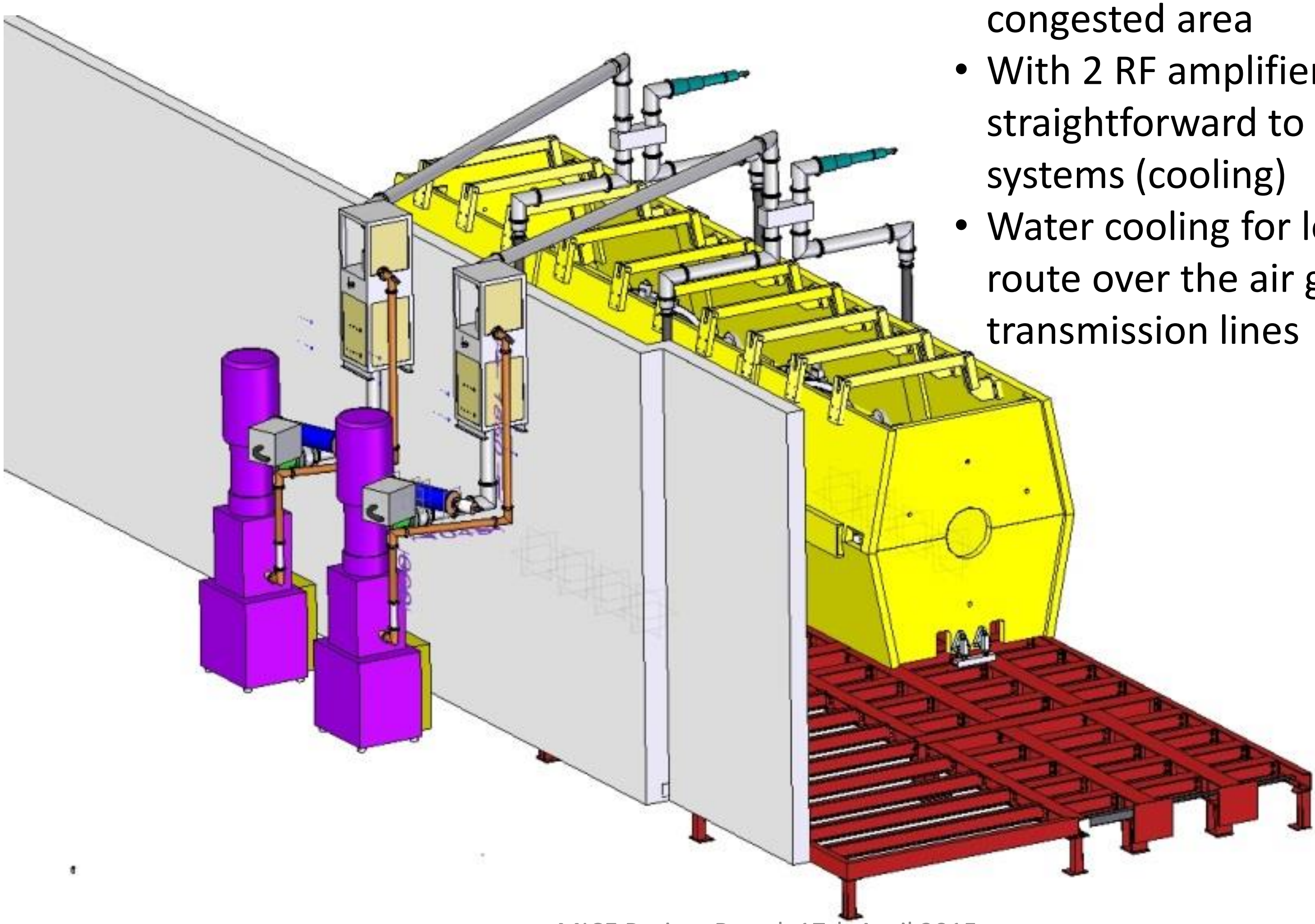
RF network

- Simplified distribution network- feasible to route overhead
- Off-centre mounting of hybrid takes up phase shift
- Orientation of load arbitrary- align with the 6” distribution line and share mountings
- Minimised length of 4” line- minimises losses



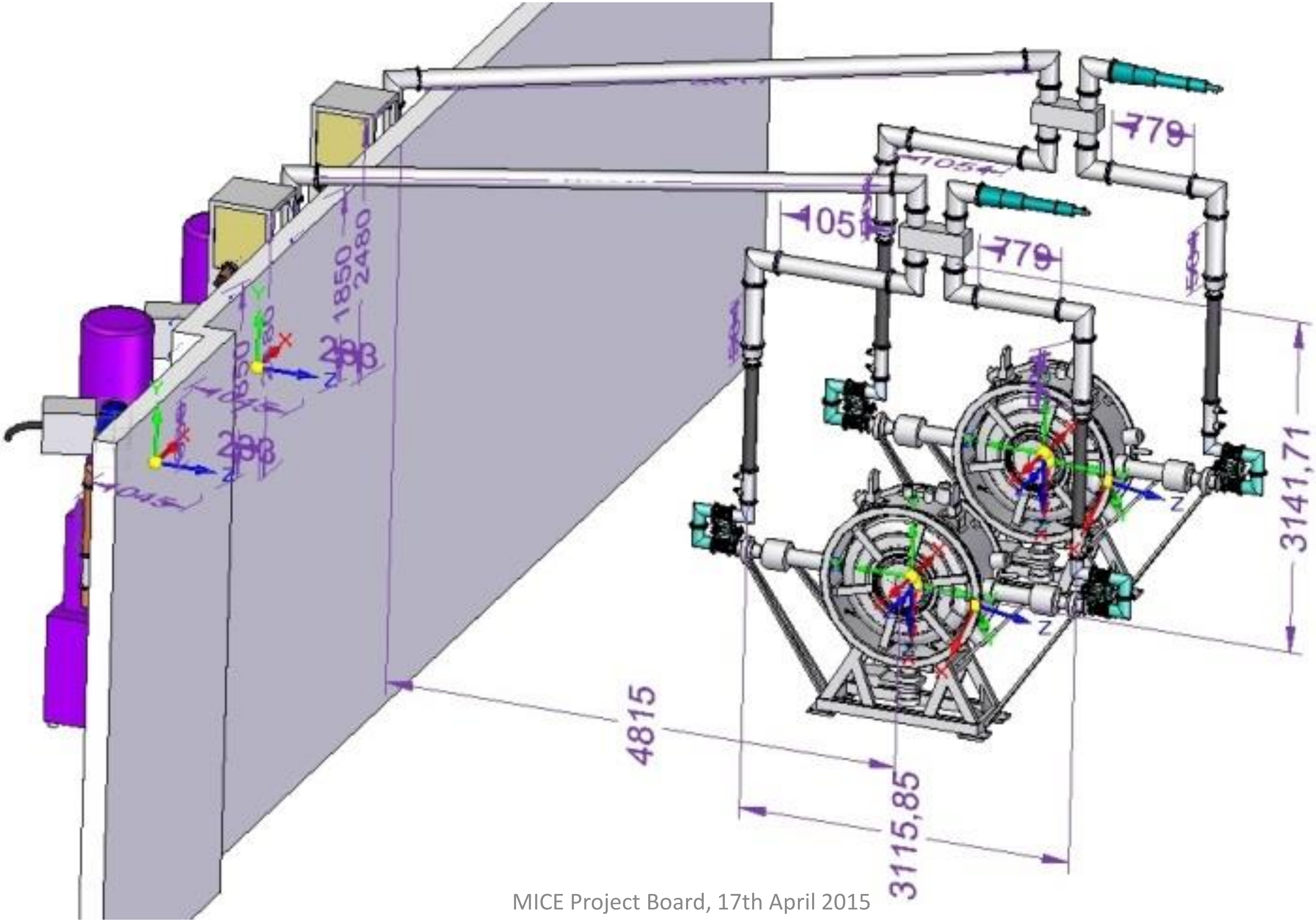
RF network

- Load on each splitter to absorb unbalanced reflections
- Retracted crane hook clears coax over the wall.
- Support from present 'shield wall' and yoke



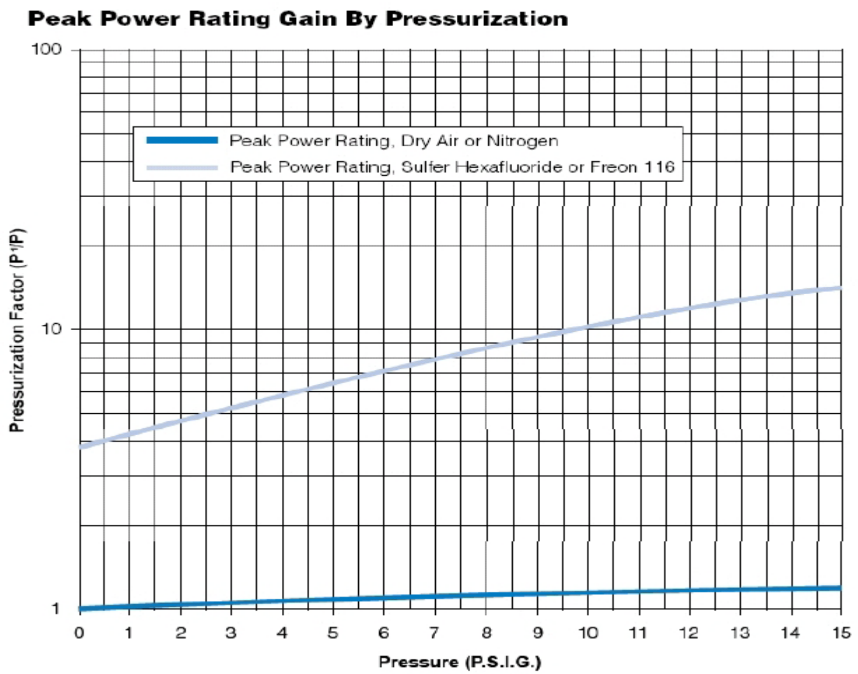
- 2nd amplifier moved to 3rd position behind wall to ease installation in congested area
- With 2 RF amplifiers now relatively straightforward to place auxiliary systems (cooling)
- Water cooling for load will need to route over the air gap on the transmission lines

RF network



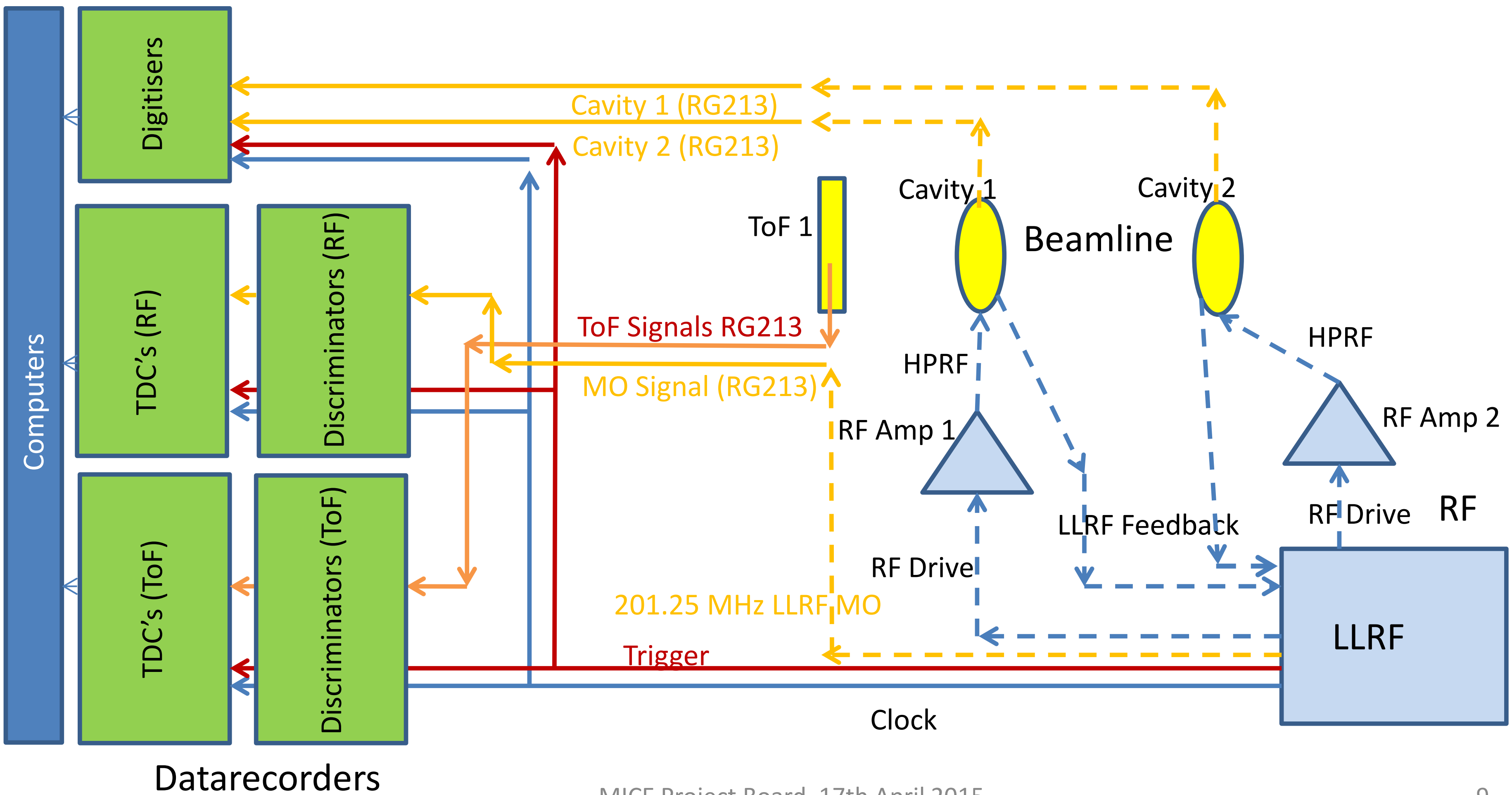
Power Distribution Network

- New experiment will demand higher power (1MW peak, 1kW average) in 4” lines
- 4” components rated to 1.12MW peak in air at 1 bar
- A full reflect (during cavity fill or spark) will double line voltage (eq. to 4MW)
- Mitigate by slow fill
- Mitigate with insulating gas



Timing System, Desired Specification

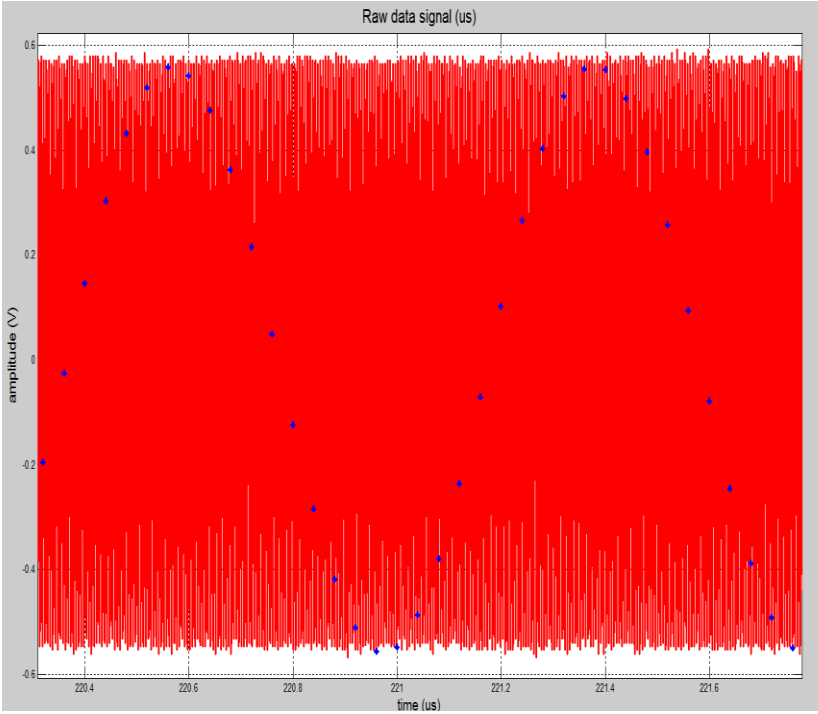
- We wish to know the difference between
  - Transit time of any of our muons (in essence through ToF1)
  - A zero crossing of the RF system in any cavity- choose the first cavity
- Specification for RF timing is ~3x stricter than ToF resolution 50ps

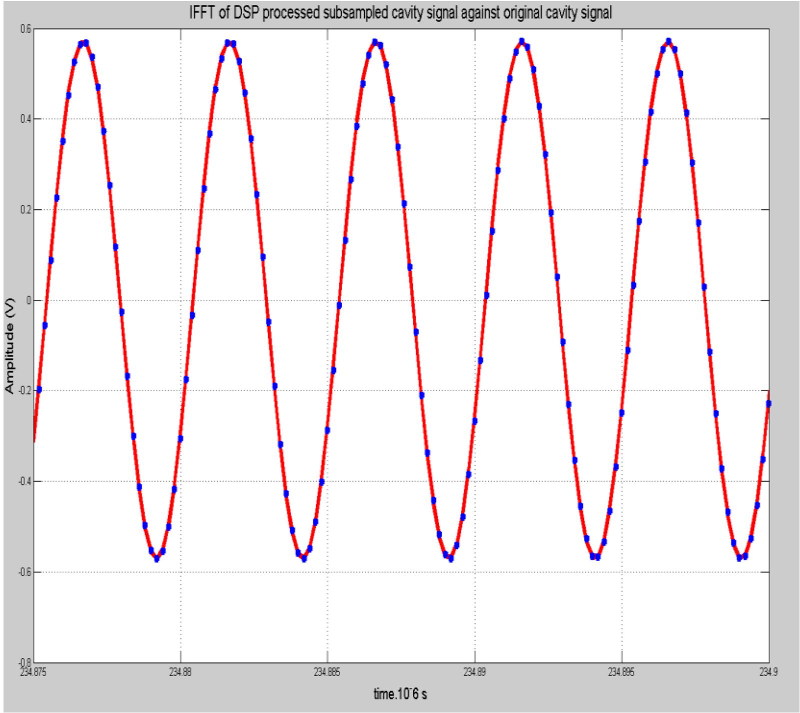


MICE Project Board, 17th April 2015

Fourier domain reprocessed signal

- Data from FNAL tests
  - Processed using subsample Fourier domain reconstruction
  - Compared to original high data rate recording





High Power RF Drive: System Status

- MICE RF systems demonstrated
  - 2MW, at 201.25MHz, for 1ms @ 1Hz
  - First amplifier tested in MICE hall
  - Triode amplifier (output stage) remains installed
    - Tetrode and all modulator racks shipped to Daresbury

- New higher voltage solid state crowbar tested
- Triode 2 will be tested using No. 1 tetrode and modulators
  - Use upgraded Triode No.1 modulator
  - Each major No. 1 subsystem will be swapped for No. 2 sequentially
  - Remote control system being developed
    - Test during commissioning of No. 2 valve systems

- Dependent on electrical engineering resource availability
  - No 1 tetrode ready for re-commissioning at DL
  - Triode No 2 testing with No 1 racks and tetrode, July 2015
  - No 2 amplifiers tested with No 1 racks & controls, Nov 2015

Cooling Demonstration: Preparation Programme

- From STEP IV the project becomes increasingly focussed on RF systems
  - First cavity expected May 2016
  - Opportunity to perform system shakedown
    - Address MPB Nov 14 recommendation on coupler conditioning

- Cavity can be installed parallel to upstream spectrometer solenoid
  - Installation between ISIS run cycles
  - Opportunity to test vacuum pump down and prepare cavity
  - Transmission lines can be run from amplifier station no 1
  - Shielding (if reqd.) can be provided across hall near upstream SS

- Triode amplifier No 1 already installed
  - Require re-installation of entire RF amplifier system No 1
    - Aux racks, Modulator racks, SSPA, Tetrode amplifier
  - Require automation and control logic
  - Require LLRF system

Amplifier No 1 Programme: Timeframes

- April 2015
  - Definition of controls and automation system/interfaces/interlocks
  - Draft documents under review

- Nov 2015
  - Amplifier no 1 PSU automation system completion
  - Commission and test amplifier No. 2 with No. 1 racks
    - Test automatic/remote control systems

- Aug 2016
  - Re-Installation and test into loads at RAL

- Key resources,
  - Engineering effort : 3.5 FTE EE, ED, M&ET, CE; 2015-16
  - Control and monitoring: RAL/FNAL + DL CE
  - RF & EE system specification/RF & EE system testing
  - 1-2 months of test operation through 2015
  - Requiring:
    - MICE RF engineer, DL RF engineer,
    - Imperial and Strathclyde (4 RF scientists/engineers)

Cavity No 1 Programme: Timeframes

- May 2016: Module delivered assembled, baked, LLRF tested from LBNL
  - Re-test tuning
    - Exercise Tuners
    - Acceptance Criteria
  - Prepare for evacuation: pump, gauge installation:
  - Prepare cavity diagnostic systems, control systems, cooling,
    - 4 weeks
  - Install in upstream space against shield wall (parallel to upstream solenoid)- See R. Preece talk
    - May require X-ray shield (est ~80 microSv/hr at 3m)
    - 2 weeks
  - Evacuation, 2 weeks
  - Install & tune overhead RF lines, 2 weeks concurrent with evacuation
  - Retest of cavity tune after evacuation, 1 week
- Can complete around July 2016

Proposal for Full RF System Tests

- Justification
  - Tight time schedule for demonstration experiment
  - Require rapid commissioning of whole system
  - Provides opportunity for full shakedown of RF system
  - Delivers pre-prepped cavities by end 2016

- Opportunity
  - HPRF Tests, start late August 2016, base est. 8 weeks for first cavity
    - As soon as amplifier no. 1 is available

  - Need to build discrete control racks for each system
    - Change from single integrated control system
    - Feasible given sufficient EE Resource through 2015 & 16
    - Requires LLRF control
    - Requires UK/US RF experts

  - Second cavity commissioned partially in parallel, ready for test as soon as 1st cavity completed
    - Test of second cavity (shorter timeframe)
    - Subsequent test of Amplifier 2 with cavity 2

RF System Controls

- Plans drafted (in review) for the controls and monitoring interfaces required for the RF system and interfacing to other vital subsystems
  - Will allow expedited build of remote control system and data logging system as soon as effort is available
  - Needs of each cavity and RF system have been analysed
  - The system will include a range of
    - analogue monitoring inputs, (both slow and fast ~MHz rate)
    - digital inputs (binary, 3 state, 8 state)
    - analogue control inputs
    - analogue outputs
  - Large number of individual variables
  - Reviewing which need individual interfaces

RF Control System

- RF systems will require remote, automated control system
- 'State Machine' description
- Headline list of primary states and conditions below

- OFF

No conditions

- ENABLED

Hardware keys inserted

- STANDBY

Heaters Nominal
Hardware keys
RF load coolant
RF tube coolant
Compressed Air
PSU coolant

- READY

PPS RF Permit
HT enclosures shut
Heaters Nominal
Cavity and Vessel pressure Nominal
Cavity coolant Nominal
Cavity tuner pressures
SF_6 pressure
Hardware keys
RF load coolant
RF tube coolant
Compressed Air
PSU coolant

- ON

Nominal RF waveforms
Radiation & Arc sensors
PPS RF Permit
HT enclosures shut
Heaters Nominal
Cavity and Vessel pressure Nominal
Cavity coolant Nominal
Cavity tuner pressures
SF_6 pressure
Hardware keys
RF load coolant
RF tube coolant
Compressed Air
PSU coolant

LLRF systems

- MICE LLRF: provide 1% amplitude, 0.5° phase regulation, power ramp-up
  - Will control tuner system
  - System is closely related to existing Daresbury accelerators

- Boards will be tested during the amplifier commissioning programme

- LLRF system, timeframe and resources
  - Crate build up, A Moss and DL Electronics staff
    - Includes all analogue aspects and hardware
  - Software Development
    - Requires FPGA software: 2 LLRF programmers recently left ASTeC
    - Specific requirement is VHDL - XILINX (Spartan) programmer
    - Principle code already exists
      - In use at DL (ALICE) and development at RAL (ISIS)
      - Requires modification
    - MICE requirement: synergy with ASTeC requirement to recruit
      - Combination LLRF and XILINX is rare, but VHDL software expertise is widely required- but also in demand
      - Meet ISIS RF group to review options

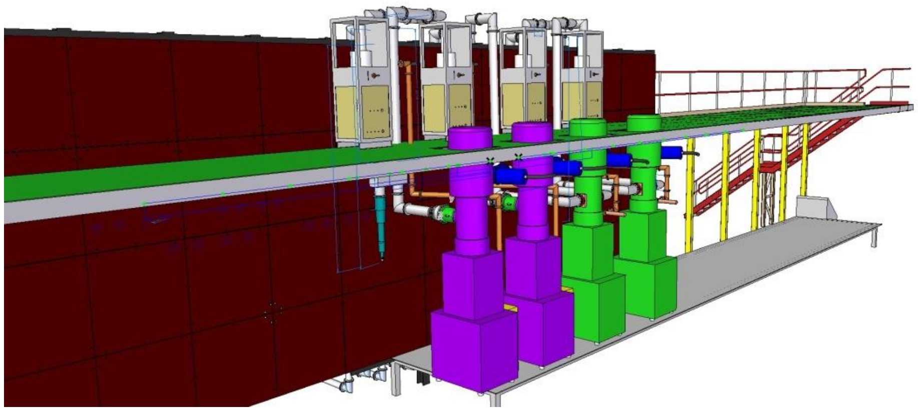
Summary

- Substantial redesign of distribution network
  - Mitigates installation conflicts (both schedule and potential physical)
  - Eliminates most of the 4” line
- Fourier domain reconstruction progressing with REAL pick off data from MTA
  - Some variation in time offset to understand
- Proposal for full system tests in mid-late 2016
  - Will debug system ahead of operation in summer 2017
- Control/Automation requirements drafted & under review
  - Needed to expedite control rack construction
  - Remote control essential for 2016 full system tests
- LLRF software staffing issue has emerged
  - Key software expertise has left Daresbury (hardware expertise in place)
  - Require to address urgently as required to allow system test in late 2016
  - Exploring solutions to problem

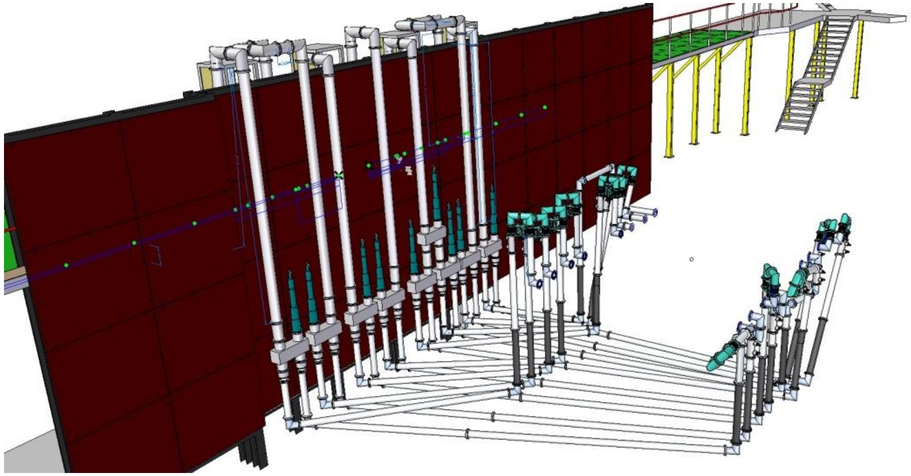
Additional Slides

RF network: STEP V/VI

Amplifiers behind Shield Wall



Distribution Network to MICE



- 4 off 6 inch coax lines over wall
  - Pressurised to increase power handling
- Manually adjustable line trimmers installed at cavity to take up assembly errors in coax length
- Flexible coax final feeds
  - Allows for small misalignments
- 10 hybrid splitters Split power for the opposed couplers of each cavity
- Lines pressurised with 2Bar Nitrogen

Preparation Programme: Timeframes

- Cavity No 1 programme:
  - May 2016: Module delivered assembled, baked, LLRF tested from LBNL
    - Re-test tuning, exercising of the tuners
      - Acceptance Criteria
    - Require
      - RF specialists: UK + US

    - Prepare for evacuation: pump, gauge installation: Vacuum engineer and mechanical technicians
    - Prepare cavity diagnostic systems, control systems, cooling, RF Engineering, Controls and Monitoring, Mechanical Technicians
      - 4 weeks

    - Install in upstream space against shield wall (parallel to Up Stream Solenoid)- See R. Preece talk
      - May require installing X-ray shield (est ~80 microSv/hr at 3m)
      - 2 weeks, mostly mechanical effort, plus Engineering/Health Physics for design

    - Evacuation, estimate 2 weeks (RF and Vacuum Engineering)
    - Install, tune overhead RF lines, 2 weeks concurrent with evacuation (RF, Mech. Technicians)
    - Retest of cavity tune after evacuation, 1 week

  - Potential to be ready around July 2016

RF System Controls

- Plans drafted (in discussion and review) for the controls and monitoring interfaces required for the RF system and interfacing to other vital subsystems
  - Will allow expedited build of remote control system and data logging system as soon as effort is available
  - Each Cavity: 17 analogue inputs, 1 analogue output, 4 digital inputs (2 logic states)
  - Each RF system: 24 digital inputs (2 logic states), 4 digital inputs (3 states), 1 digital input (8+ logic states), 22 analogue signal inputs (13 are high, ~MHz, speed), 3 analogue control inputs
  - Some of these may be logically 'AND-ed' outside the control logic

Timing System, Detailed Specification

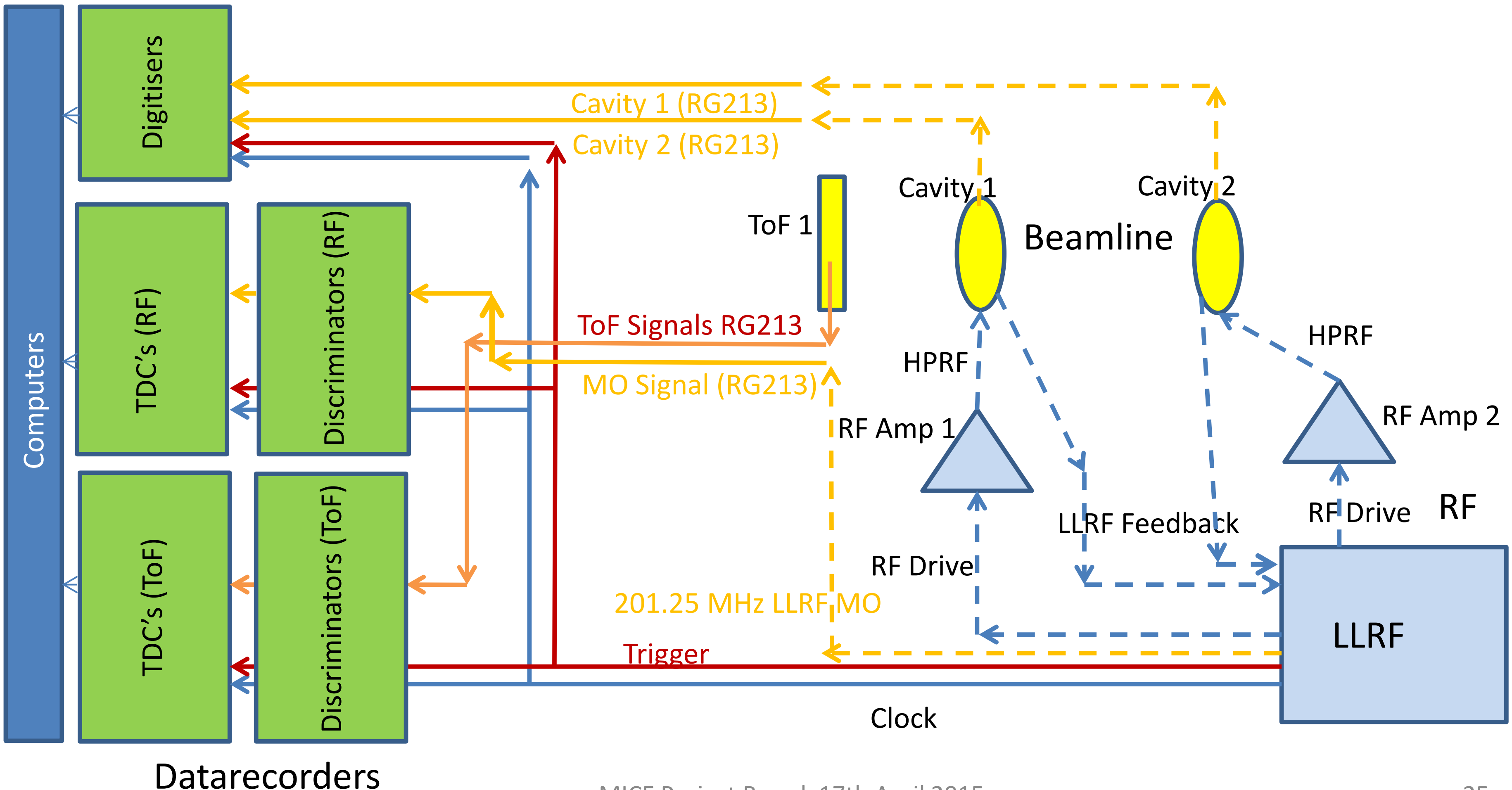
- We wish to know the difference between
  - Transit time of any of our muons (in essence through ToF1)
  - A zero crossing of the RF system in any cavity- choose the first cavity
  - Use tracker measurement of trajectories to project forward to each cavity in turn
- LLRF phase (0.5^{o}) stability specification is ~3x stricter than the resolution desired for the RF timing system <20ps or <0.4% 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% of RF cycle, 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 of signal reconstruction with lab generated and MTA cavity waveforms

  - Test sensitivity to vertical resolution, temporal sample rate, noise, bandwidth
- Work to be undertaken: Test TDC/Discriminators in 201.25 MHz environment



‘Sub’ Nyquist digitisation

- To acquire at Nyquist on 200 MHz would demand a sampling rate of ~1-2 G.Sa/sec, for 1ms
  - Demands ~1 to 2 MB per acquired channel, > 7.2 GB/hr (assuming an 8 bit digitiser)
  - 400μs window presently being acquired at MTA- requires minutes to record traces
- Fourier domain signal reconstruction
  - The Fourier transform of the undersampled data maps the signal into its ‘unaliased’, relatively low frequency range
- 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 ~5 kHz, effective linewidth is ~10 kHz, so sampling rate ~few hundred k.Sa/sec should be sufficient
- We assume 20 M.Sa/sec, with 1ms we now have about 20 kB per 8 bit recorded channel, data rate of ~72 MB/hr per channel

Timing hardware and Tests

- Use TDC and discriminators used in ToF system
  - TDC's CAEN V1290 25 ps multi-hit
    - 25ps bin size maps to 7ps uncertainty (assuming Uniform PDF)
  - LeCroy 4415A discriminators
    - Need to be tested in RF environment (alternatives available)
  - Use of same electronics as ToF mitigates systematic uncertainty & drift
- TDC hardware, discriminators and crates now assembled at Strathclyde.
- RF connection boards being fabricated to allow tests at RF frequencies
- To make efficient integration into DAQ ideally use VME digitisers for the sub-sample reconstruction
  - At present continue to use fast, 8 bit, DSO's to capture signal
  - Plan to use CAEN V1761 digitisers
  - 1GHz, 4G.Sa/sec, 10 bit, 2 Channel instrument
  - Capable of 57.6MS/Ch