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# Low Level RF Control on ISIS Andy Seville

National Instruments Big Physics Summit, February 12<sup>th</sup> 2016





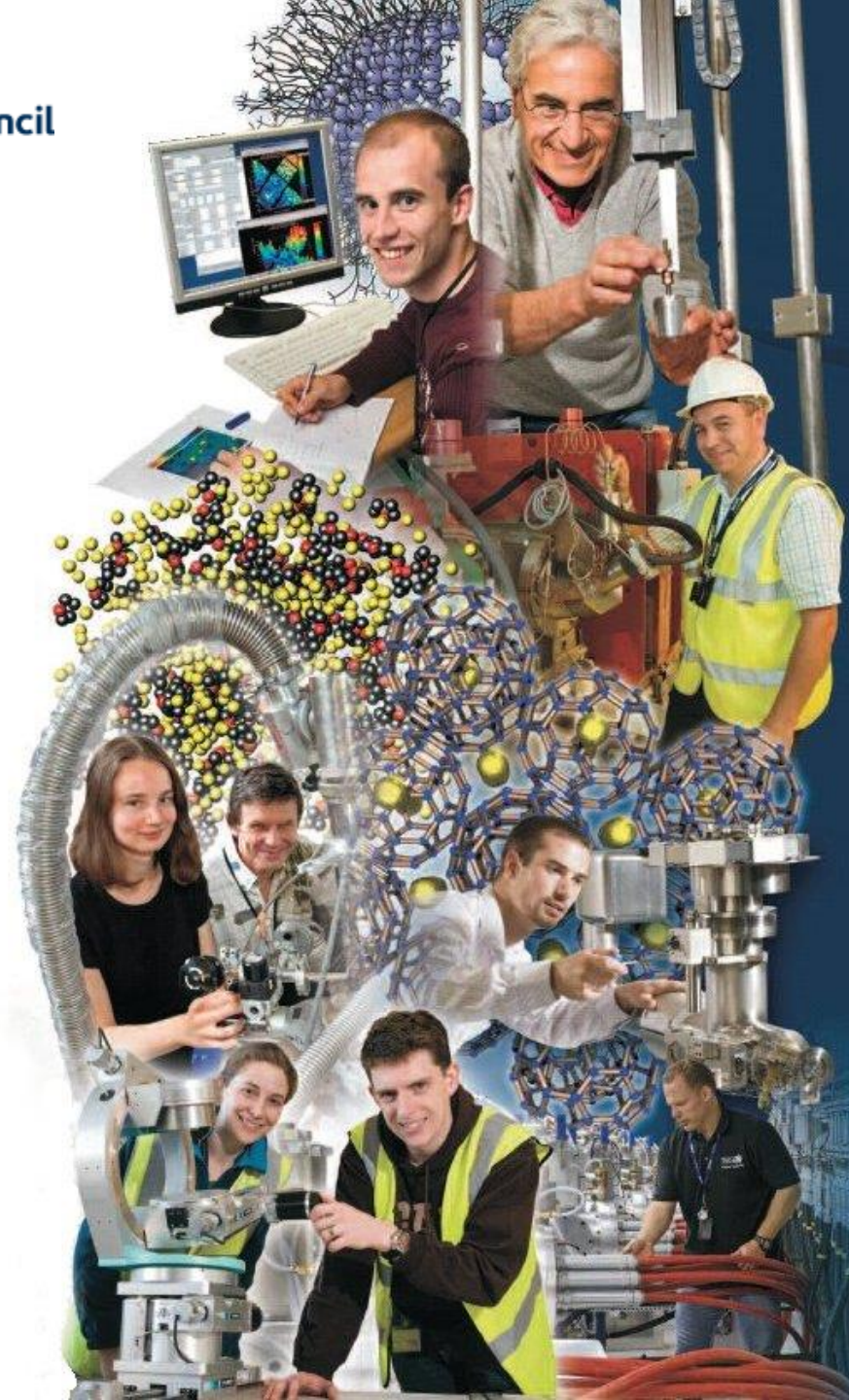
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# ISIS

is the  
world's  
leading  
pulsed  
neutron  
and muon  
research  
centre

## 31 years!

(as of 16<sup>th</sup> December 2015)





Science & Technology Facilities Council

ISIS

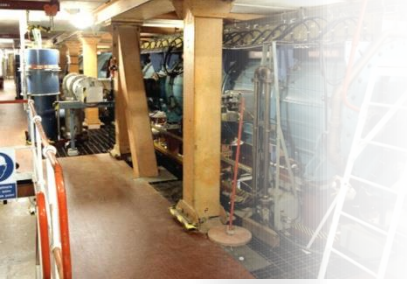
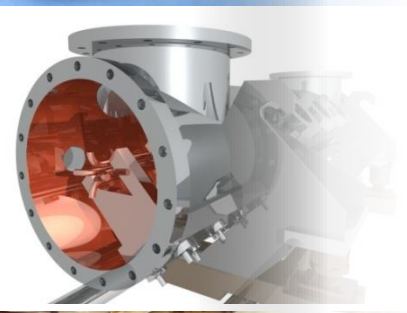
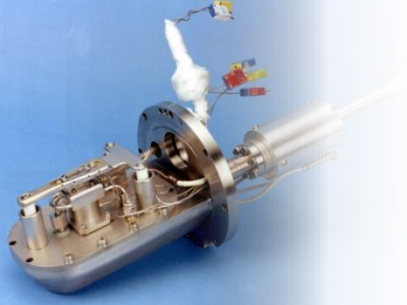
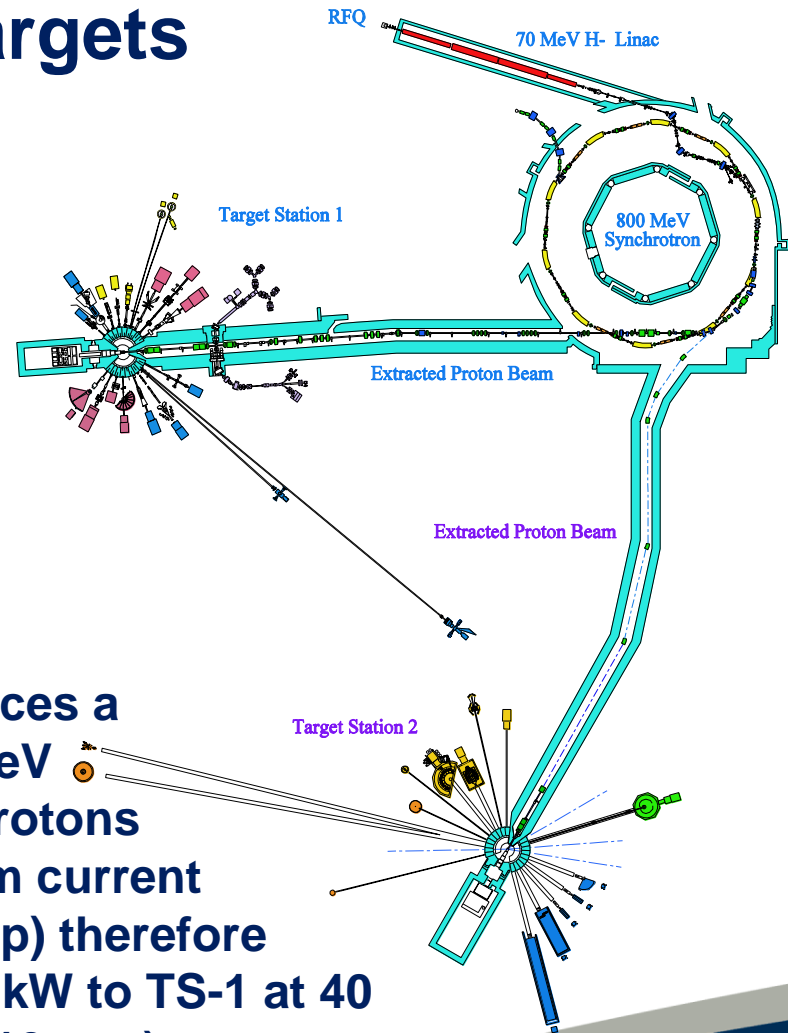
# ISIS Neutron Source



# ISIS Accelerators and Targets

- H<sup>-</sup> ion source (17 kV)
- 665 kV H<sup>-</sup> RFQ
- 70 MeV H<sup>-</sup> linac
- 800 MeV proton synchrotron
- Extracted proton beam lines
- Targets
- Moderators

The accelerator produces a pulsed beam of 800 MeV (84% speed of light) protons at 50 Hz, average beam current is 230  $\mu\text{A}$  ( $2.9 \times 10^{13}$  ppp) therefore 184 kW on target (148 kW to TS-1 at 40 pps, 36 kW to TS-2 at 10 pps).





TS1  
23 Instruments  
+ 5 Muons!

## ISIS Target Halls



TS2  
13 instruments



## ISIS enables a huge breadth of Materials Science

Each year:  
~3000 visitors  
~750 Experiments



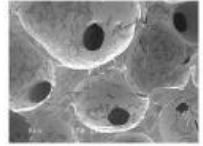


## Results:

- 400 papers each year
- See [www.isis.stfc.ac.uk](http://www.isis.stfc.ac.uk) for more



### Bioactive glass for bone growth

- Thousands of elderly patients undergo hip or knee transplants every year
- New bioactive glass releases calcium as it dissolves
- Stimulates bone growth and could spell an end to transplants
- Clinical trials expected within 5 years.
- Imperial, Kent, Warwick, NHS




"ISIS has enabled us to move forward with the programme. The key outcome of our experiments has been a full understanding, at the level of atomic arrangements, of why it is that calcium is able so easily to leave the glass at the rate required to generate the desired response."

- Bob Newport, University of Kent

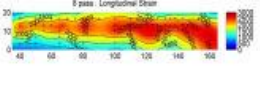


### Wing quality soars at ISIS

- Aircraft manufacturer Airbus has used ISIS since 2006
- Research into aluminium alloy weld integrity for aircraft programmes
- Residual stresses from welding cause weaknesses and the possibility of cracks
- ISIS neutrons look deep inside engineering components to measure stress fields




"Residual stress measurement at ISIS has been invaluable in researching and developing existing and novel material manufacturing and processing techniques."

- Richard Burgueze, Airbus Experimental Mechanics Specialist

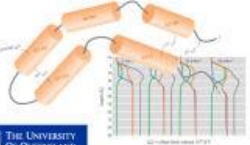


### Understanding infant lung structure

- Natural lung surfactant allows oxygen into the bloodstream
- Absence in premature babies causes breathing difficulties
- ISIS mimicked change in lung capacity to discover how proteins and phospholipids act together
- Helping to develop synthetic lung surfactants which can be more precisely targeted at clinical needs to help save babies' lives



"ISIS is the premier place in the world to work with neutrons and liquid surfaces. In collaboration with the University of Queensland we were able to discover how proteins and phospholipids act together to enable lung function."

- Dr Stephen Holt, ISIS neutron scientist

### Spintronics for IT, automotive and health sectors

- Spintronics underpins applications as diverse as biosensors for blood screening, computer memory and safety systems for cars
- Potential for smaller, faster devices with more capacity and lower power consumption
- Most promising materials for future devices only work at low temperatures and high magnetic field
- ISIS supporting global efforts through SpinART consortium of UK universities and industry



"Many of the most promising materials to deploy in future devices only work under extreme conditions. ISIS gives a unique nanoscale understanding of the materials in the quest to make them work at room temperature."

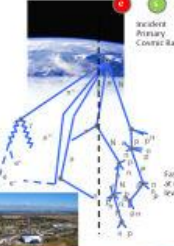
- Sean Langridge, ISIS Senior Fellow, Visiting Professor University of Leeds








### Fast neutron testing for the semiconductor industry

- Atmospheric neutrons collide with microchips and upset microelectronic devices every few seconds
- 300 x greater effect at high altitude
- ISIS enables manufacturers to mitigate against the problem of cosmic radiation
- Increased confidence in the quality and safety of aerospace electronic systems



"ISIS is one of few facilities in the world capable of producing enough very high energy neutrons to perform accelerated testing."

- Andrew Chugg, MBOA, SEFEDER consortium

### ISIS contributes to zero-emission vehicles

- Hydrogen-powered cars are feasible using today's technology
- Harmful emissions reduced to zero
- Method of safe, low-cost hydrogen storage on-board holding up deployment
- Hydrogen-rich solids safely releasing hydrogen developed using ISIS neutrons
- New materials hold upwards of 10 percent of their own weight in hydrogen



"We've discovered new sets of materials that can store hydrogen more efficiently than hydrogen itself. Neutrons are without doubt the best way to see hydrogen entering and leaving in real time."

- Professor Bill David, ISIS Senior Scientist





### ISIS helps mobile phone component manufacturers

- Mobile phones and base stations contain ceramic antennas called dielectric resonators
- ISIS recreated the firing stage of ceramic components at more than 1000 °C
- Testing at ISIS has aided manufacture of ceramic resonators to the correct specification.



"ISIS, in collaboration with Liverpool University, generated the intrinsic data necessary for the understanding of the structure of these complex materials"

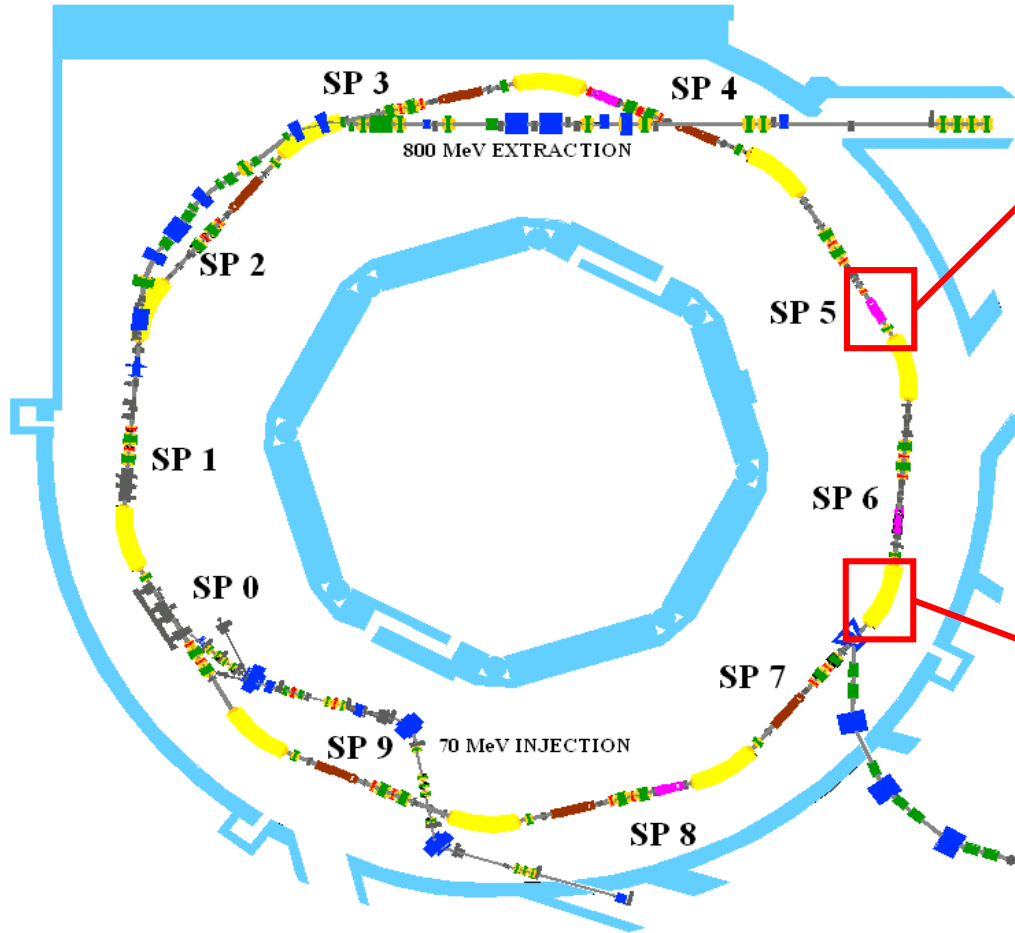
- David Idles, Powerwave UK, Ceramics Development manager





# ISIS Synchrotron

- Circular machine 70 – 800 MeV
- $H^-$  ions stripped to protons when injected
- Fifty 10 ms acceleration cycles per second



RF electric fields to accelerate particles



Magnets to bend particles round in a circle



**Synchrotron** because strength of magnetic field and frequency, amplitude and phase of RF all have to be *synchronised*.

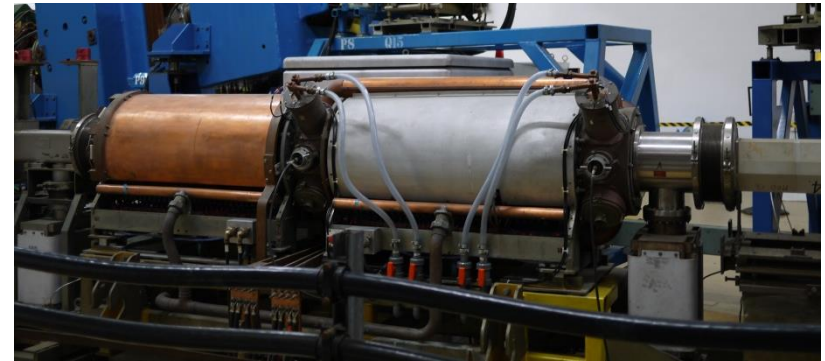




# ISIS Synchrotron RF

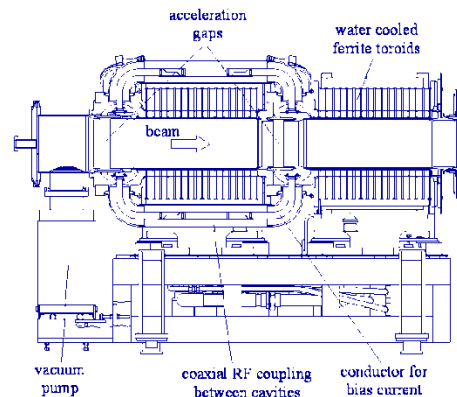


1RF cavity



In each 10ms accelerating period,

- voltage provided by: 6 x 1RF + 4 x 2RF Ferrite loaded cavities
- 1RF frequency sweeps: 1.3 - 3.1MHz to match 2xproton rotational frequency
- Ferrite biased by 200A - 2000A to increase resonant frequency
- Peak RF gap voltages ~13kV



2RF cavity



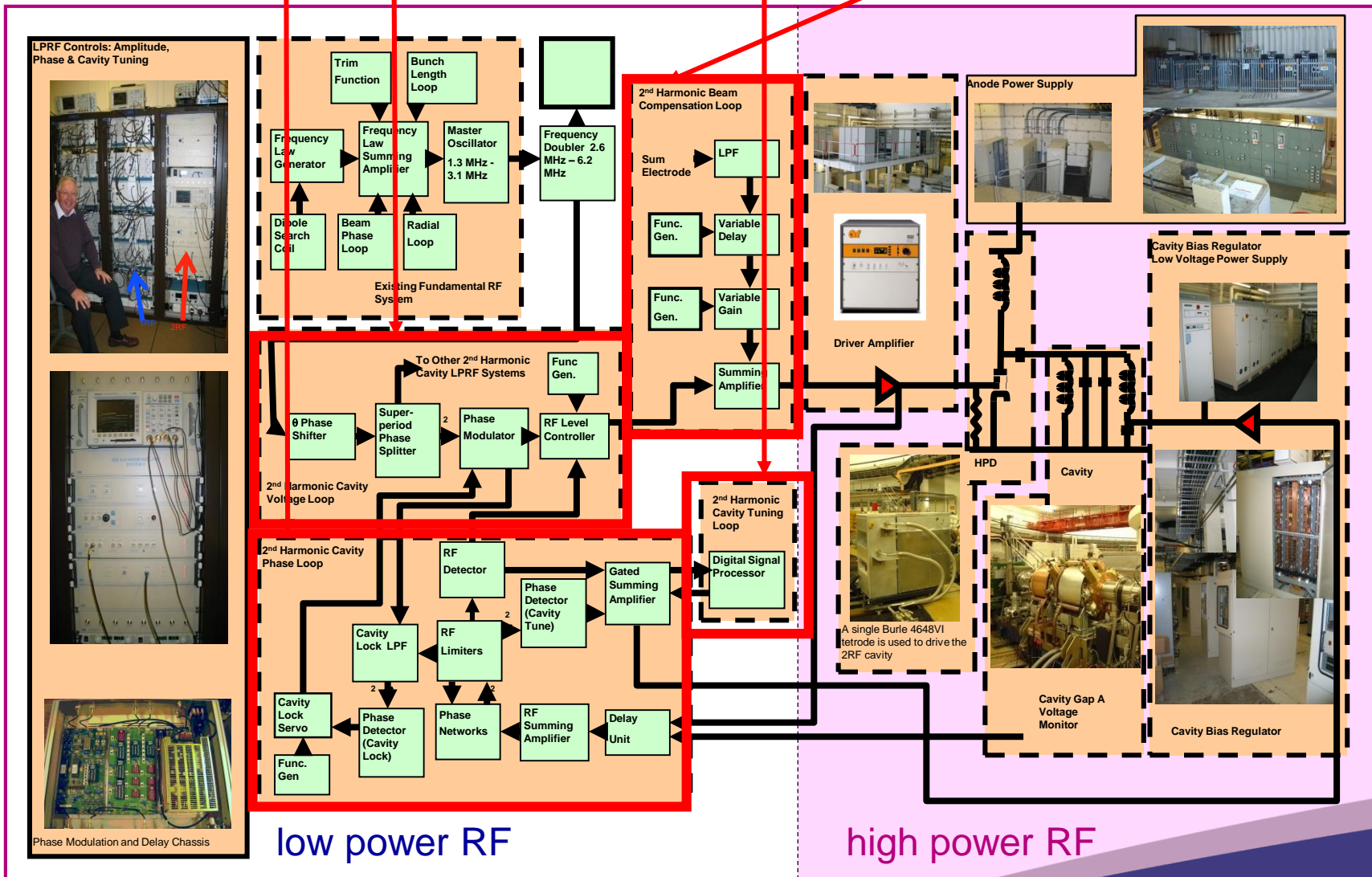
# Phase Loop

# RF system schematic

# Beam Compensation Loop

## ALC Loop

## Cavity Tuning Loop



low power RF

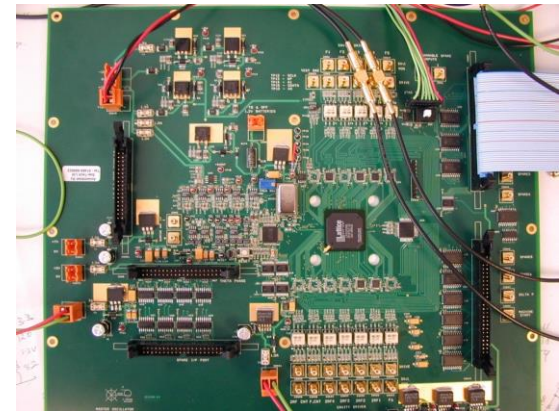
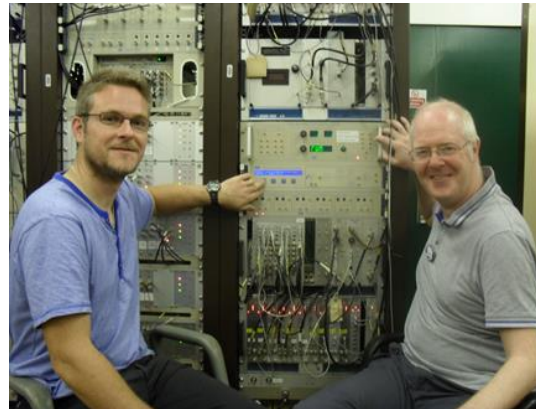
high power RF



# ISIS Low Power RF Upgrade



~2005, started to consider replacements for the ageing LPRF controls  
Digital Master Oscillator:

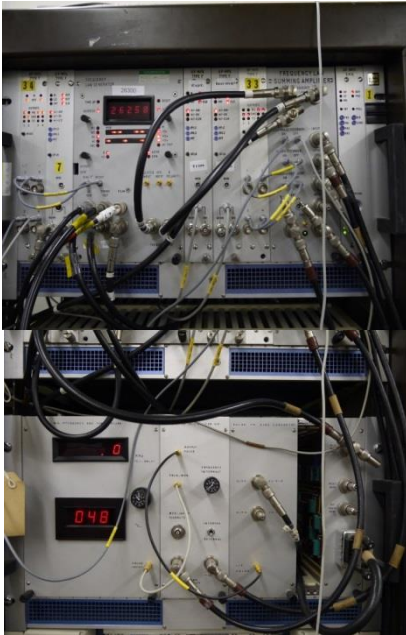


- Lattice ECP DSP series FPGA based (132MHz)
- Voltage-to-Frequency Converter
- Follows Magnet Field strength (16MHz ADC)
- Provides RF signal to 10 Cavities : 6 x Fundamental, 4 x 2<sup>nd</sup> Harmonic
- Produce swept RF waveforms to accelerating cavities
- Applies  $\theta$  phase delay to 2RF cavities
- Synchronised to ISIS Machine timing system



# ISIS Dual Harmonic RF Upgrade

2RF LPRF Hardware issues: Modifications to LPRF units

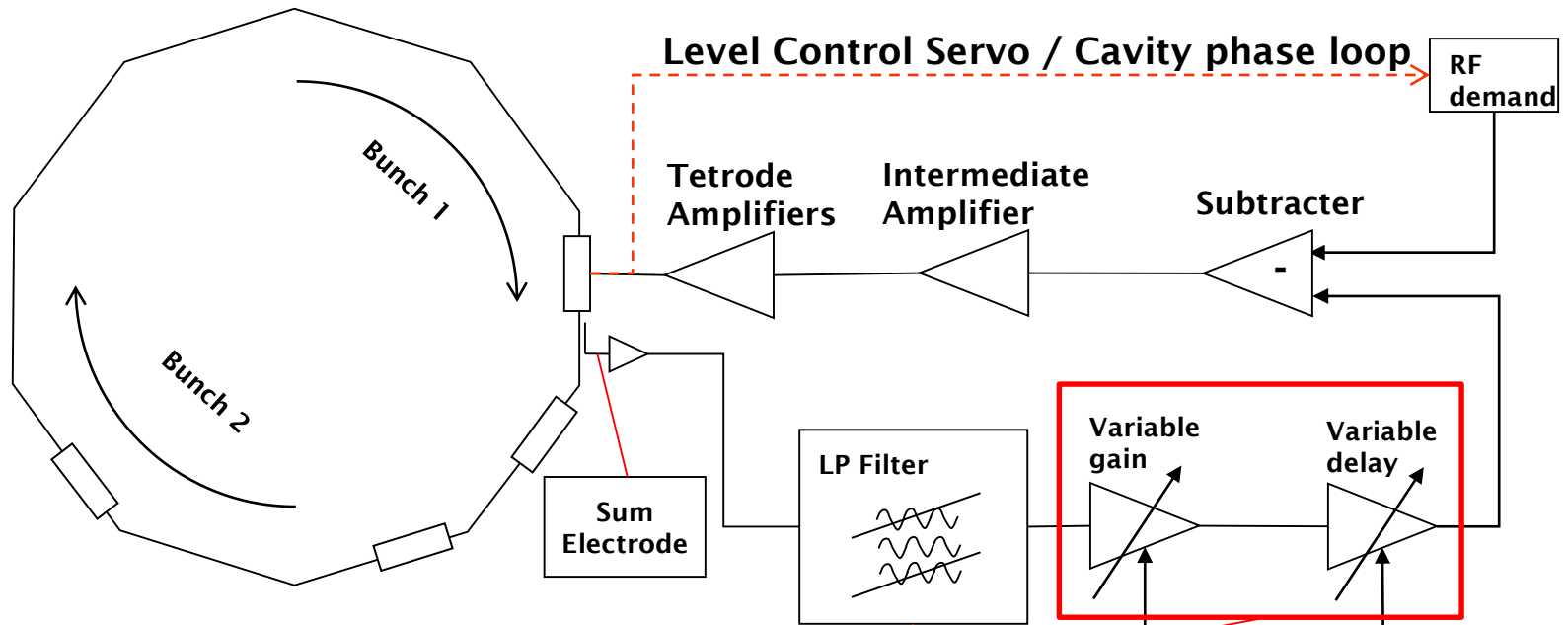


Initial plan to use new 2RF units as template for 1RF upgrade.

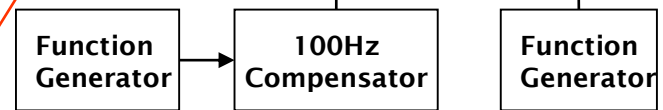
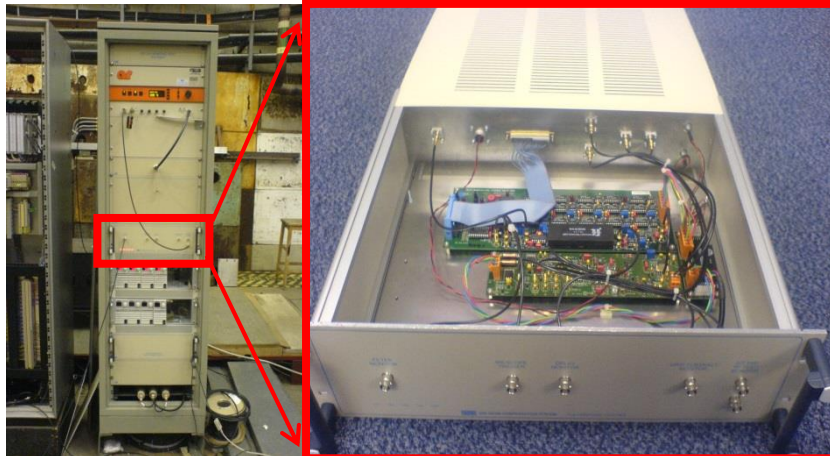
But after several faults on new 2RF units, due to overheating on large horizontal PCBs it worked out the other way around!



# RF – Feed forward Beam Compensation



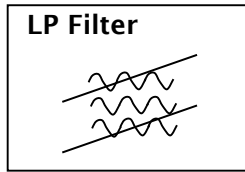
## Beam Compensation Unit



Fixed frequency – only usable over first 3ms or so



# RF – Feed forward Beam Compensation

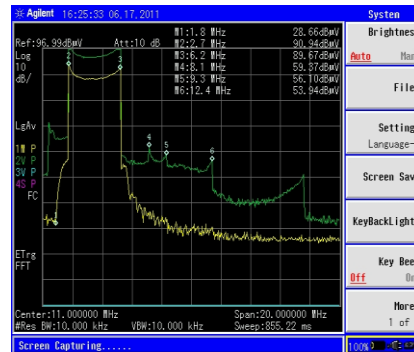
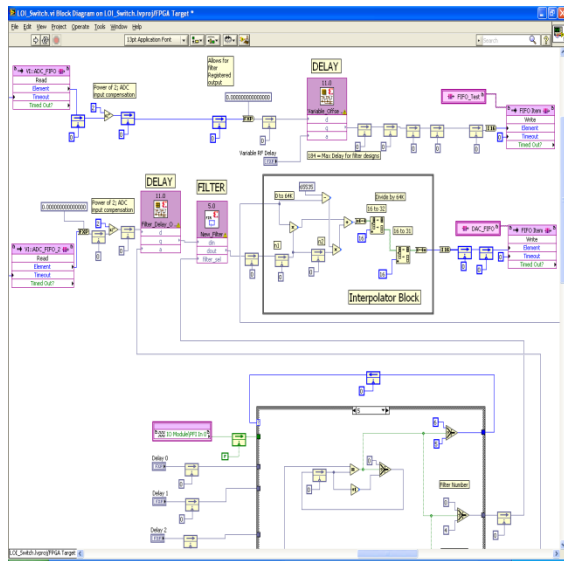


Swept digital filter implemented on NI 5641R PCI transceiver card  
 FPGA based  
 However latencies just too big.

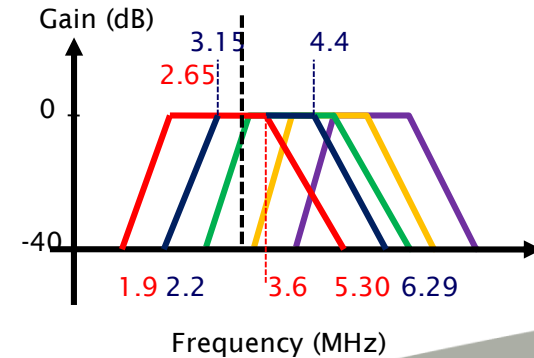


November 2008 - Joe Woodford visit to RAL

- New FlexRIO platform
- PXIe based FPGA modules with optional front end adapters
- implemented Switched Digital Filterbank -5 filters switched to match 10ms ISIS 2RF frequency sweep (2.6-6.3MHz)

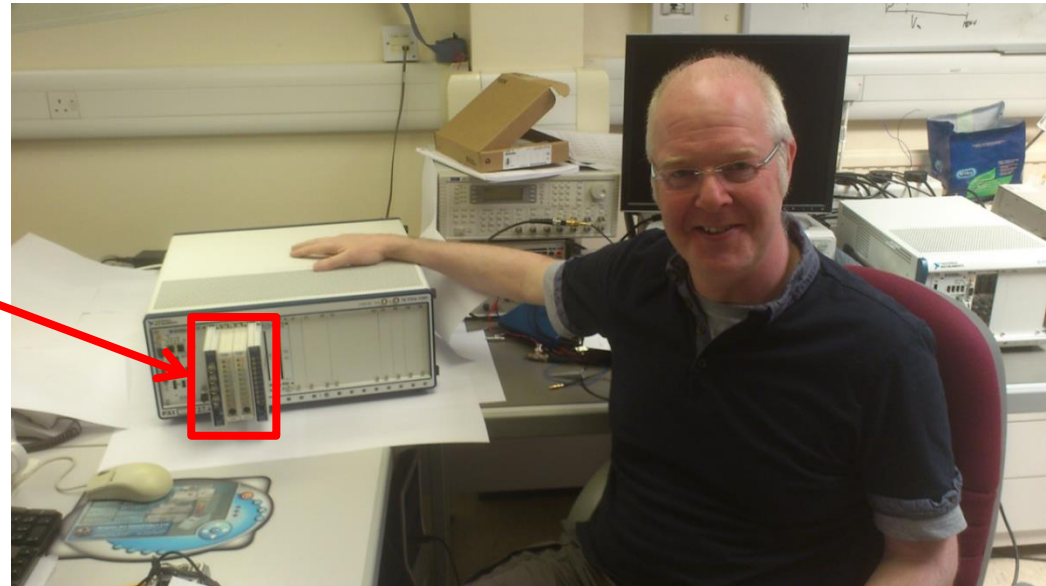
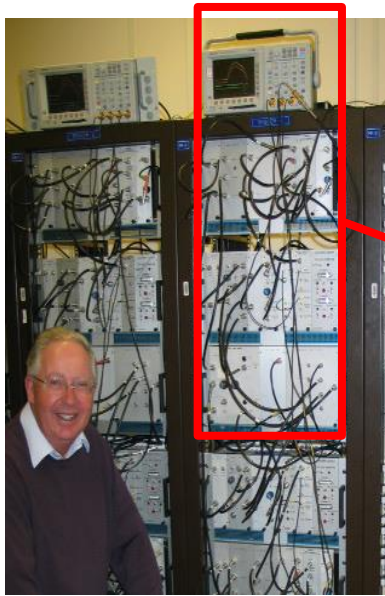


Spectrum of **switched filter** compared with **unfiltered** ISIS frequency sweep



## Why not use FlexRIO based system to replace all LPRF controls?

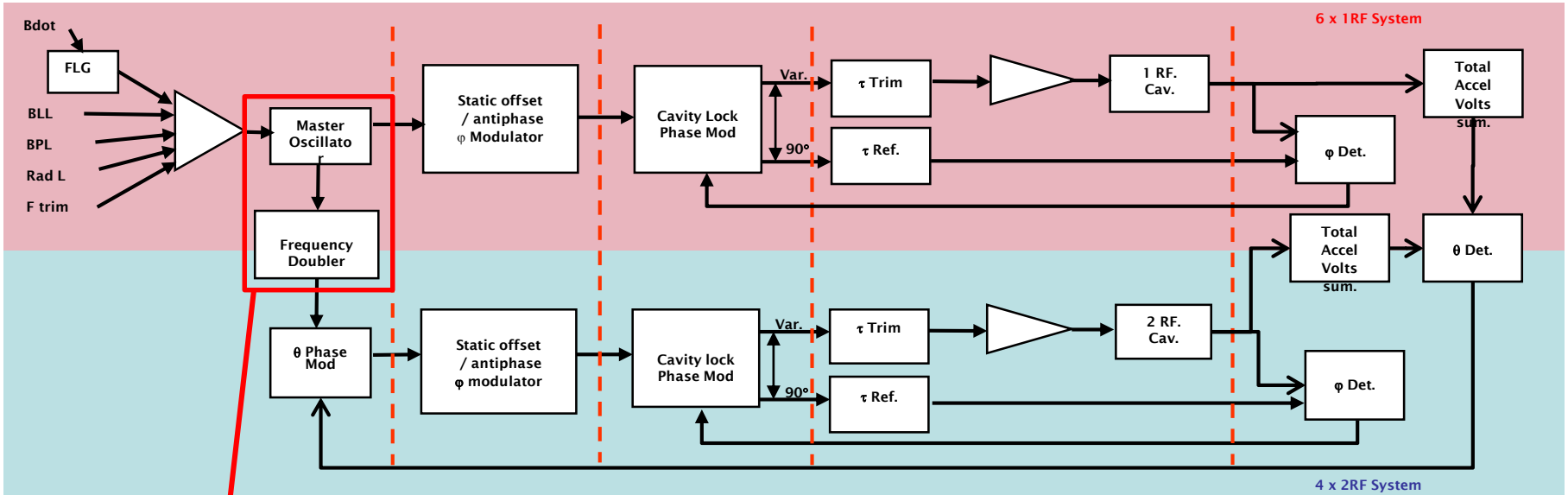
One FPGA module to replace Frequency Law Generator / Master Oscillator  
+ 10 slave FPGA module to act as a local oscillator / IQ loop for each RF system



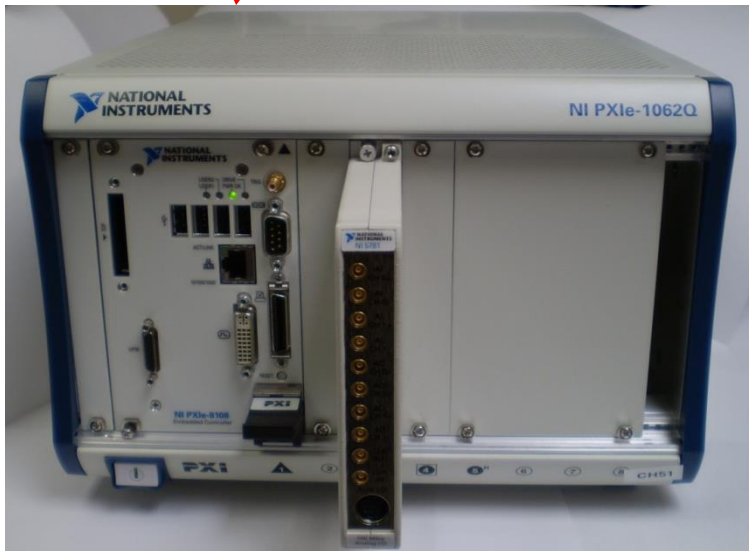
- Phase 1 - combined FLG / MO with RL/BLL/BPL corrections
- Phase 2 - PXI provides all RF feeds to each RF system
- Phase 3 - PXI closes local amplitude/phase (IQ loop)
- Phase 4 - Run tuning loops on each cavity



# Initial tests - Digital Master Oscillator to replace VCO



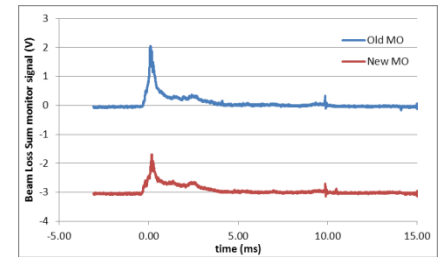
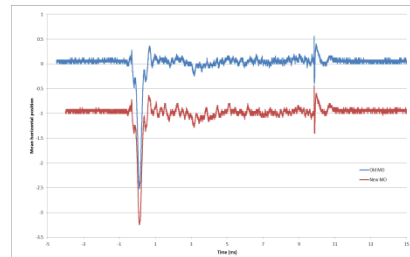
7966R FPGA module +  
5781 transceiver front end



## Initial Tests (November 2012):

Mean Horizontal position

Beam Loss Signal



2.5E13 proton beam accelerated  
but with slightly different loop  
responses

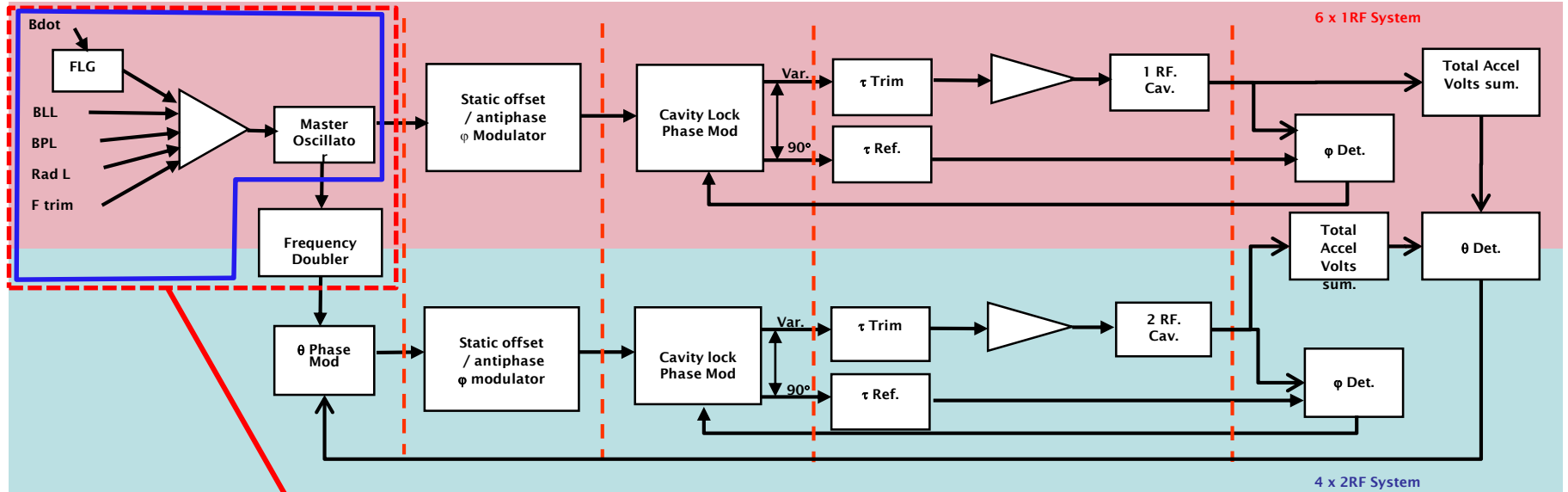


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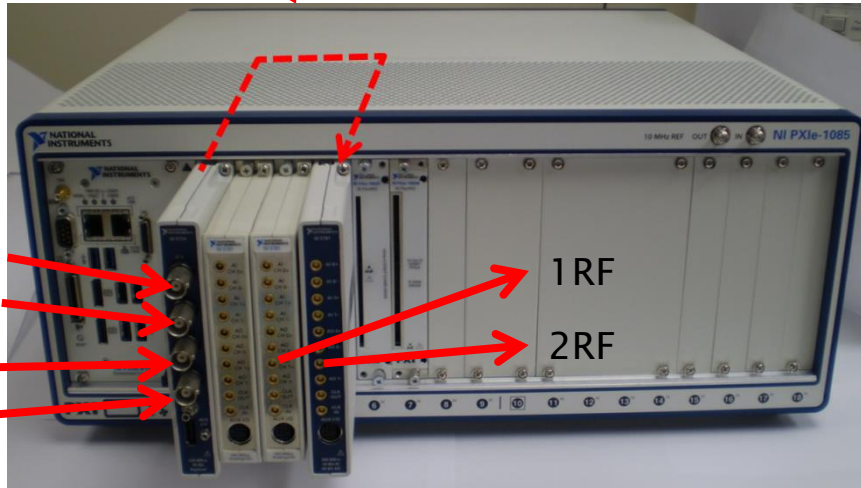


# Initial tests – Combined Frequency Law Generator / Digital Master Oscillator



7966R FPGA module + 5734 digitiser

7966R FPGA module + 5781 transceiver front end



## Machine Physics testing 4<sup>th</sup> and 6<sup>th</sup> April, 2014:

Ran base rate beam to set up loop multiplier gains: tuned radial loop gain to yield good beam losses.

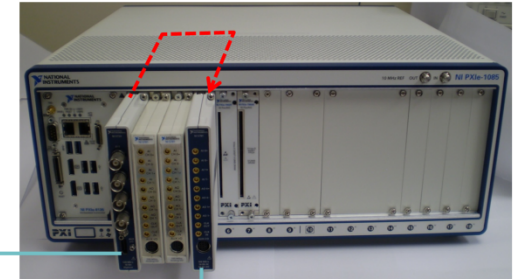
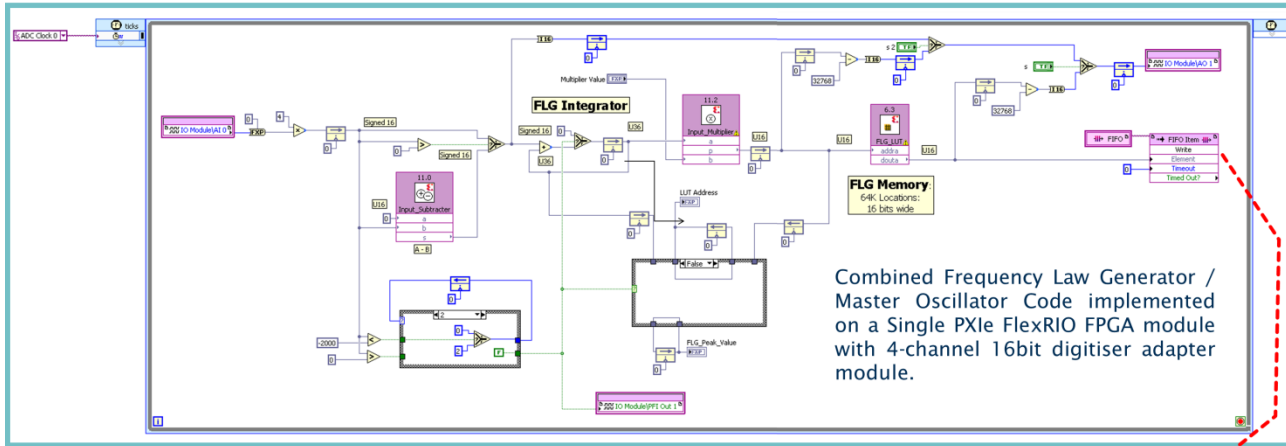


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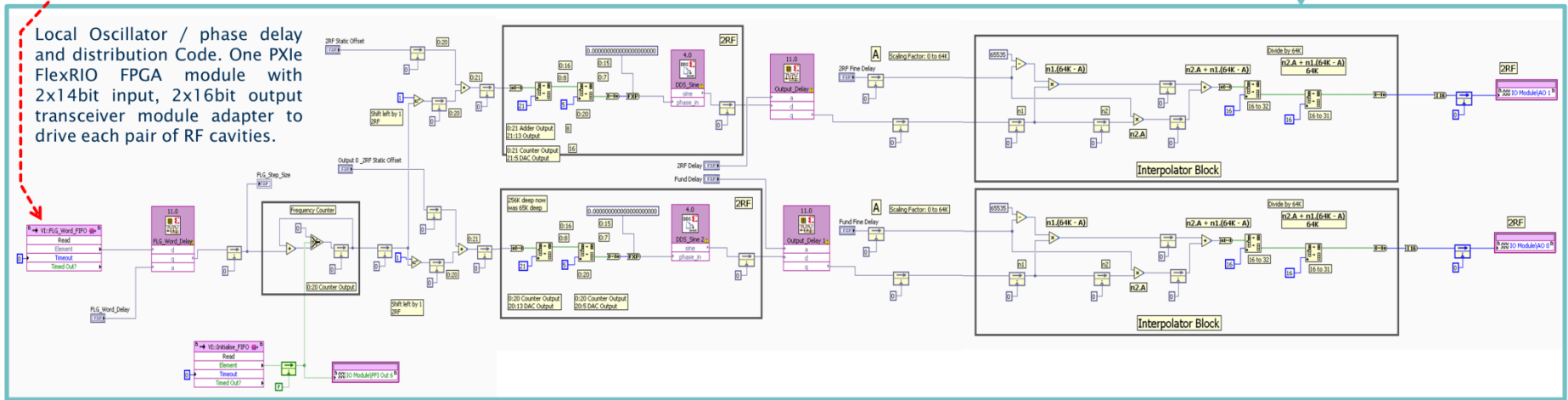
# Initial tests – Combined Frequency Law Generator / Digital Master Oscillator

Combined frequency law generator / master oscillator to sample  $\dot{B}$ , and map this to a frequency counter increment on one FPGA module. This is then broadcast to up to five local oscillator FPGA modules via the 3MB/s data stream available on the PXI express backplane, where trim delays and phase offsets are then applied to provide the RF drive signal to each of the six fundamental frequency and four second harmonic RF cavities.

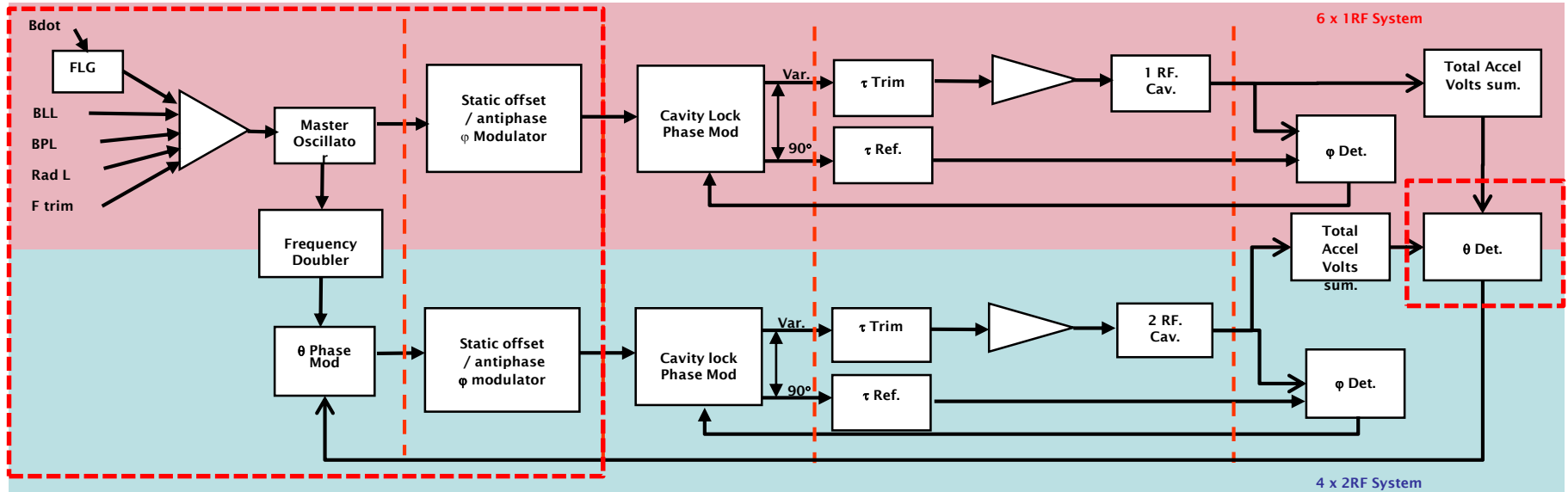


3 GB/s peer to peer data stream

Local Oscillator / phase delay and distribution Code. One PXIe FlexRIO FPGA module with 2x14bit input, 2x16bit output transceiver module adapter to drive each pair of RF cavities.



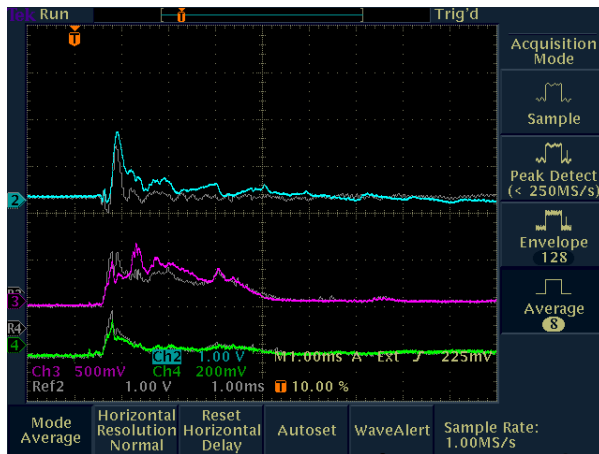
# Initial tests – Combined Frequency Law Generator / Digital Master Oscillator / Phase Distribution / Theta Loop



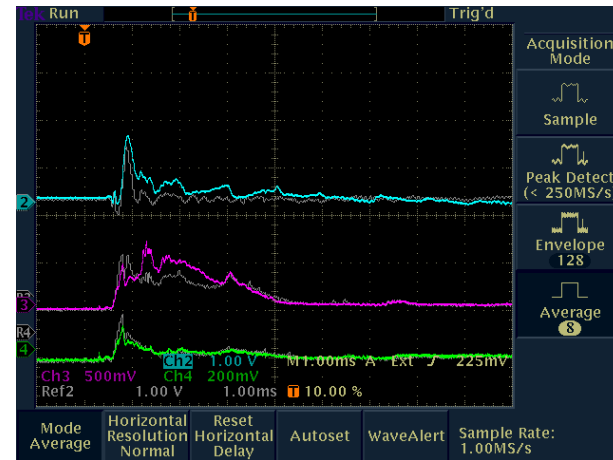
- Successfully tested in June / August 2014 machine physics
- Initial tests of IQ demodulator



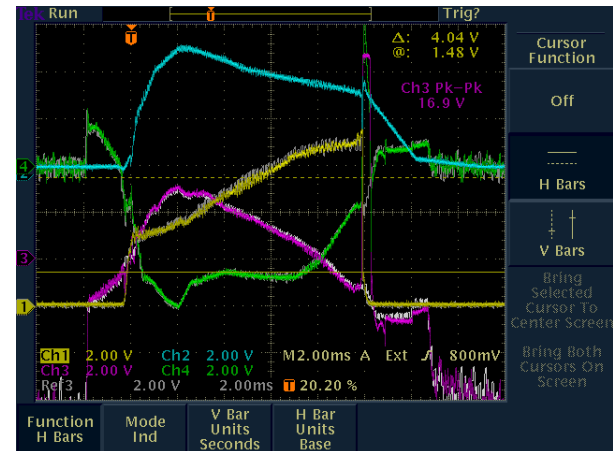
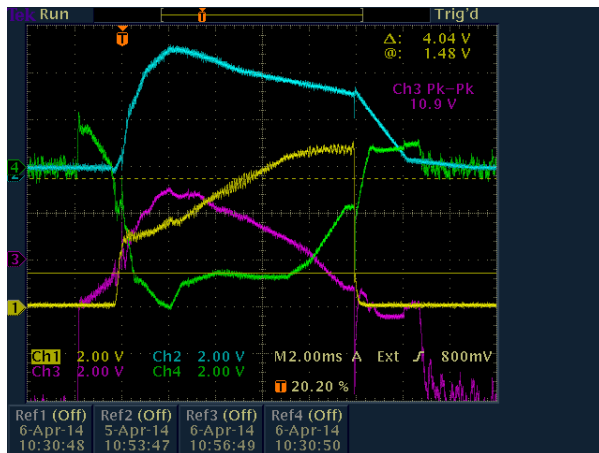
## Digital 1RF only



## Digital 1RF and 2RF



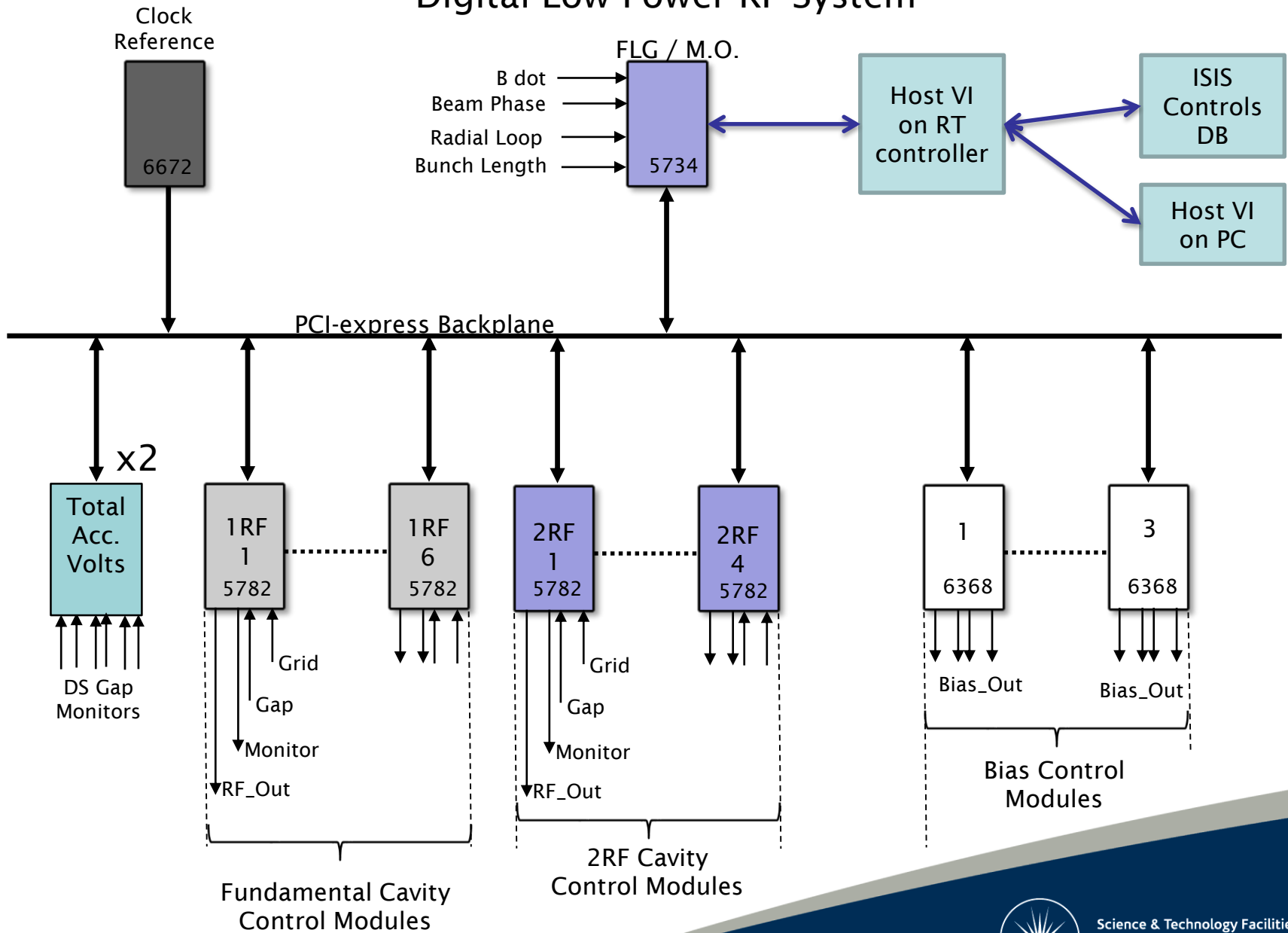
Mean horizontal position / Beam loss (8-averaged) base rate beam with 1RF from new MO only,  $2.5 \times 10^{13}$  inj,  $2.32 \times 10^{13}$  acc.



Ch1 = Bunch PtoP height signal, Ch2: 2RF5 Gapvolts envelope, Ch3: theta servo output, Ch4: theta PD monitor.

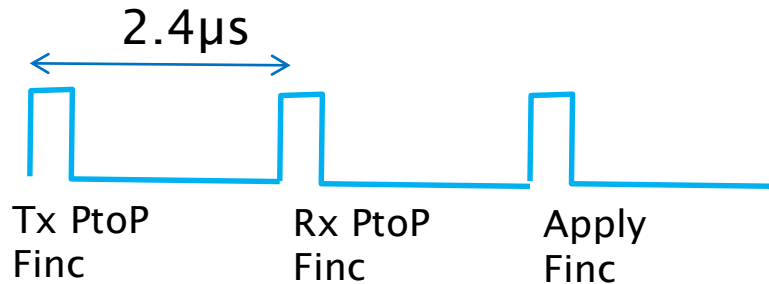


# Digital Low Power RF System



# Backplane latency

- Tests up to early 2015 were made on trial system consisting only 2 or 3 FPGA modules
- $\sim 2.4\mu\text{s}$  clock pulse synchronising implementation of next Frequency increment word across the LOs.



- With newer architecture, moved to various FPGA clock domains  $\Rightarrow 5.1\mu\text{s}$  synch pulse.
- When scaling up to the full 11 module system, require 2 x clock “pulses” to allow for longer PtoP latencies across the switch fabric of the PXI express backplane.
- However, trials on the longer latency system showed large instability in the beam phase loop, leading to high beam losses.

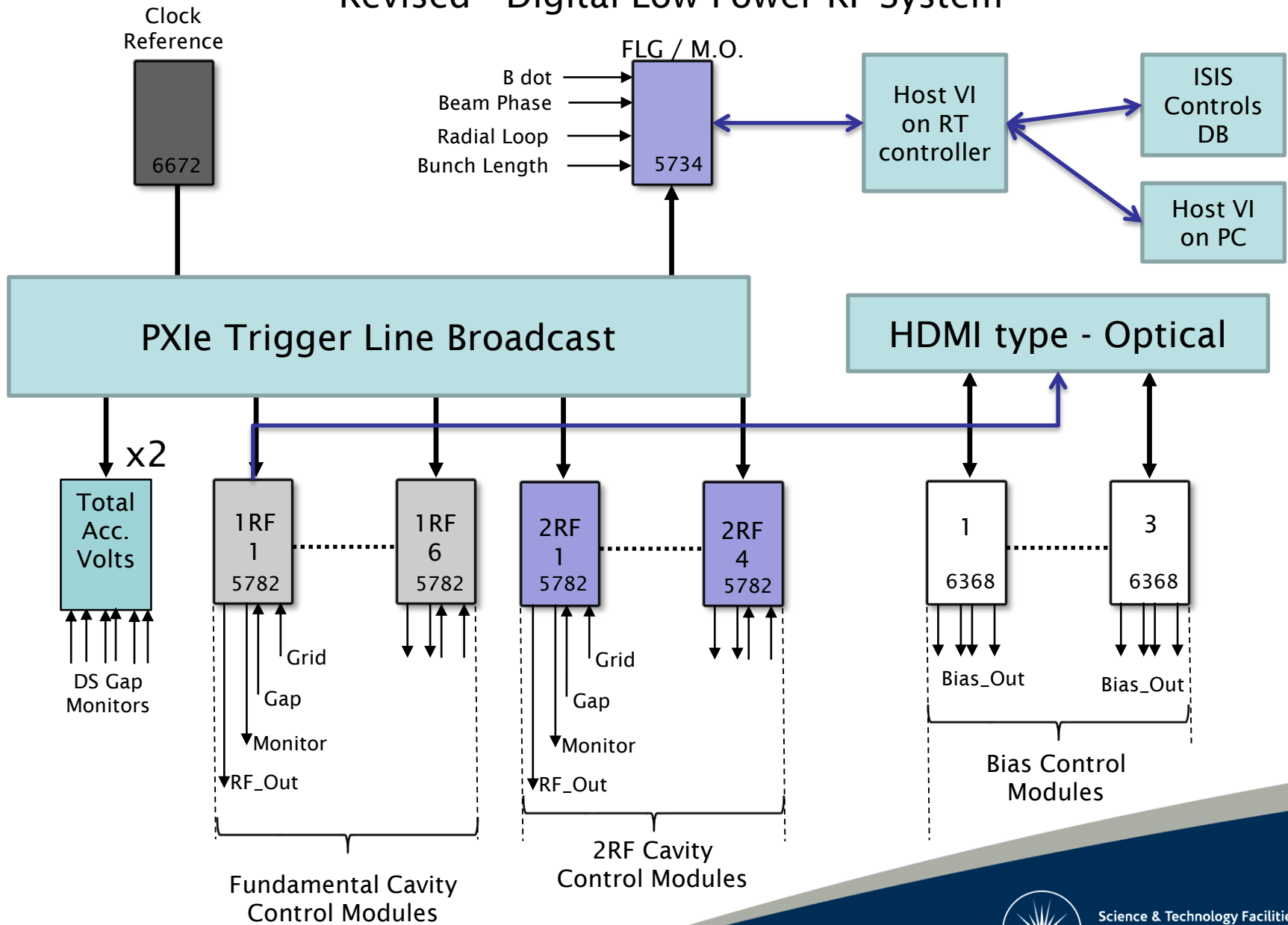


**DISASTER**

- This was verified by taking the two module system and adding a pipeline delay in to the Frequency word broadcast. Instability too great for a total delay  $>7\mu\text{s}$ .



# Revised - Digital Low Power RF System



# Revised Frequency word broadcast

## Revised FLG Backplane Communication over trigger lines:

- 600ns Synchronisation
- 1 FLG Inc word sent every 150ns -> 4 words sent within sync period.
- Latency ~ 800ns
- Uses TTL trigger lines for parallel broadcast to all System cards from central FLG Module.
- Uses crate wide 10MHz Clock distribution for timing reference
- Clock source currently from Desktop Rubidium standard
- Each FlexRIO card phase locked to 10MHz clock reference





# Current Implementation - Host VI on PC

### Radial Loop

Radial Loop Multiplier: 150000  
Radial Loop Offset Adjust: 0  
Radial Loop Start Delta P: 900  
Radial Loop Stop Delta P: 3100  
Radial Loop Gate Invert:

### Bunch length

Bunch Length Multiplier: 150000  
Bunch Length Offset Adjust: 0  
Bunch Length Start Delta P: 1800  
Bunch Length Stop Delta P: 2980  
Bunch Length Gate Invert:

### Beam Phase

Beam Phase Multiplier: 70000  
Beam Phase Offset Adjust: 0  
Beam Phase Start Delta P: 900  
Beam Phase Stop Delta P: 3000  
Beam Phase Gate Invert:

### Integrator Reset Point

Integrator Reset Point: 1000  
1st Bit from Ext Machine Start Reset Point: 1000  
M\_Start: (0 = Int; 1 = Ext)  
Fund / 20P: 0 = Fund  
Static Phase Offset: 0  
Beam\_Phase\_Sum\_Select: 1 = Loop In

Coarse Reference Delay: 0  
Fine Reference Delay In: 0

### FLG Table Set up

FLG\_LUT\_Select\_1 = 700MHz  
Bdot Input Multiplier: 78550  
B dot Input Offset Adjust: -128  
Internal\_B\_dot Multiplier: 47807  
FLG\_LUT\_Multiplier: 65160  
FLG\_LUT\_Offset (Hz): 4020  
FLG\_LUT\_Offset: 94

### FLG Table Display

Reset FLG Address	Frequency at Reset	1000 Delta P FLG_and_correction 2
47004	0.543975830078	11400
Variable T deka P	Variable T FLG Address	Frequency at Var time
3000	29601	301787.118532
Variable Delta P FLG_and_correction		25318

### Frequency Law Trim Function

Menu Ring: ISIS Controls

Scale by: 1  
Offset (Hz): 0  
milliseconds to wait: 1

Time (ms)	Volts
1	0
2	0
3	0.3
4	0.2
5	0.2
6	0.15
7	1.7
8	0.25
9	0.15
10	0.1
11	0
12	0.3
13	0
14.9	0

Waveform Graph:

Send Array data:  Loop Active:

Loop Count: 4000 / 3696 Empty Elements Remaining

### Bdot Input Monitor

### FLG Address at var T

### Freq at var T

### Frequency Law

AC Trip:  Bdot Switch:  Run on Function:  Run on Bdot:

**Ensure "Integrator Reset Point" = 1000**  
**Click "M\_Start" - Select to ensure external Machine Start**  
**Select "0 = Ext B\_dot"**  
**Select "0 = Manual/Auto B\_dot select function"**

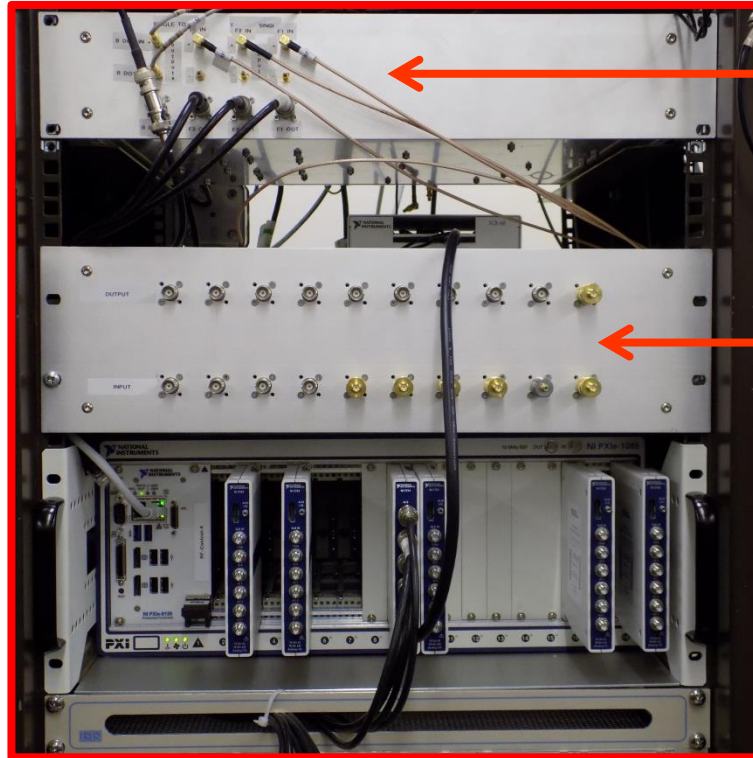
Program Stop:  stop

Machine Start:

FLG Reset:

1000 Delta P

## Current System – PXIe crate and Buffer Crates



Beam loop inputs

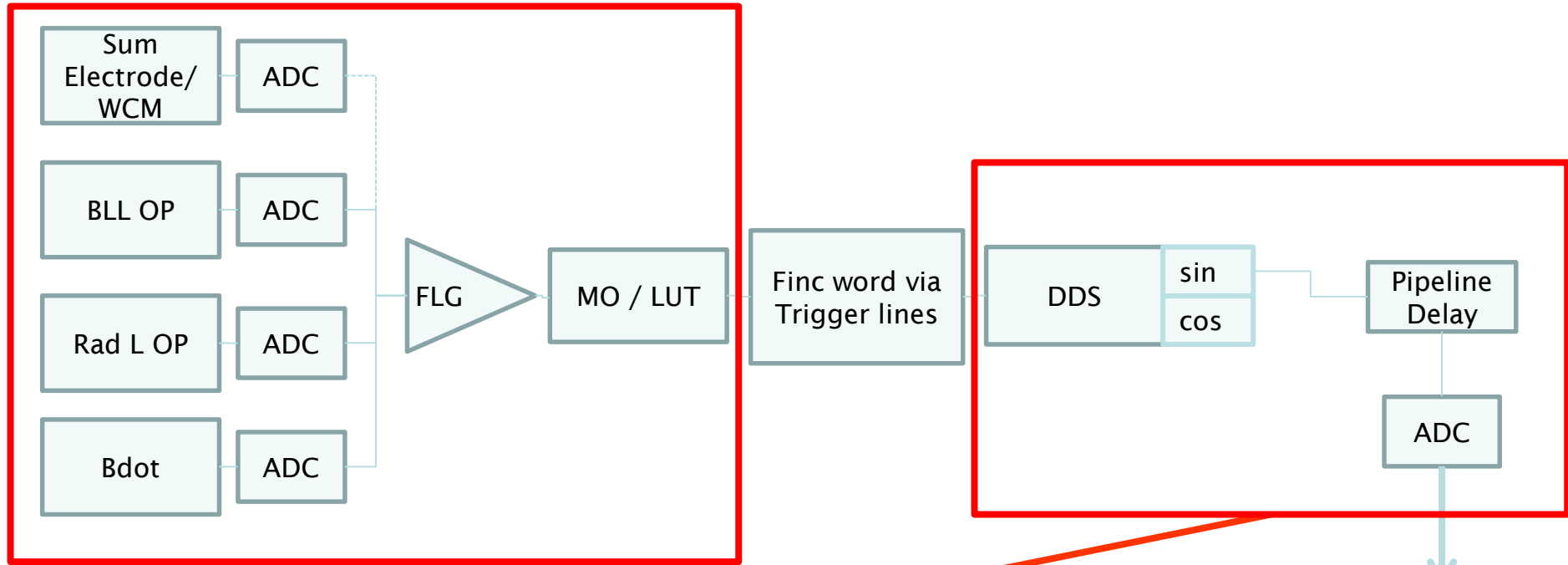
Input / output buffers



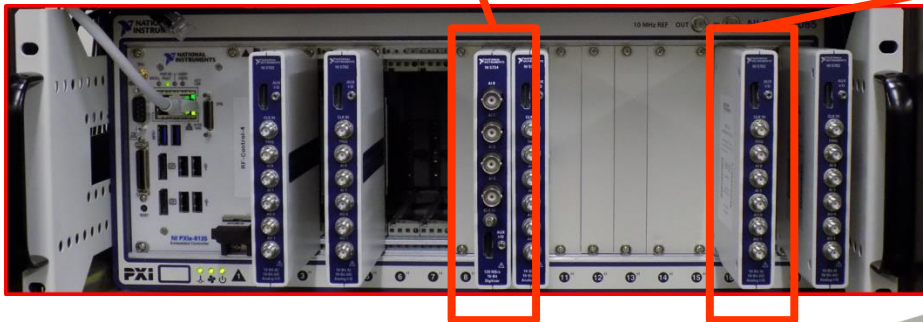
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# Current System - FLG / MO FPGA with analogue beam loop inputs + 1LO



To analogue system



Digital FLG / MO installed 4/2/16 and in use during run-up for next user cycle



# Cycle 2015-4

16-Feb to 25-Mar-16

## Synchrotron Current

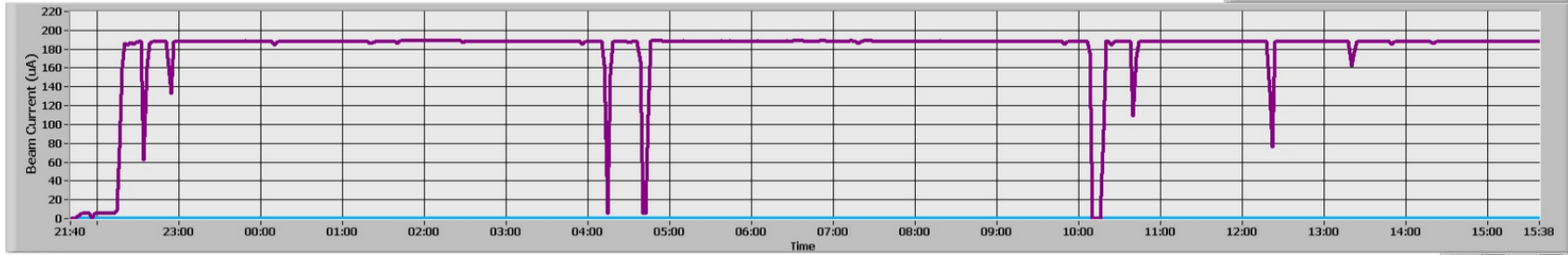


# 185 $\mu\text{A}$

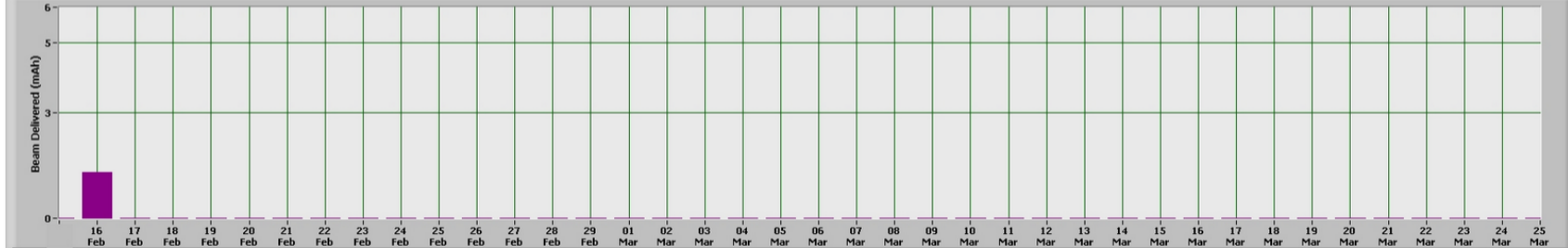
Efficiency **95.1 %**

Target 1	<b>184.8 <math>\mu\text{A}</math></b>
Muon	<b>0.3 <math>\mu\text{A}</math></b>
Target 2	<b>0.0 <math>\mu\text{A}</math></b>

Last 18 Hours



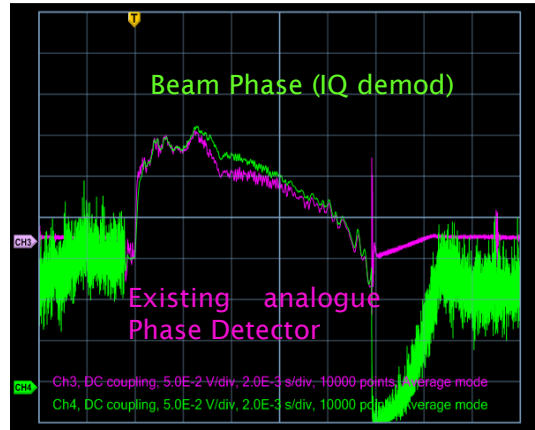
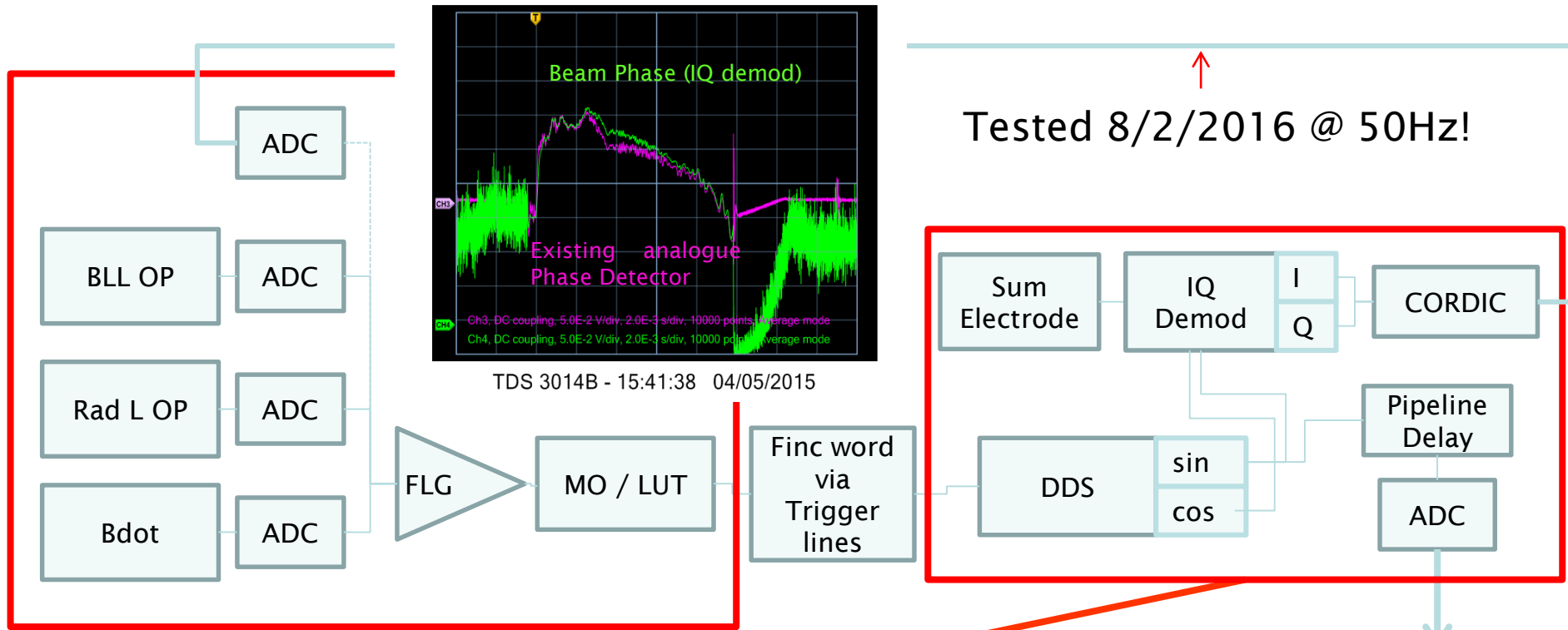
This Cycle



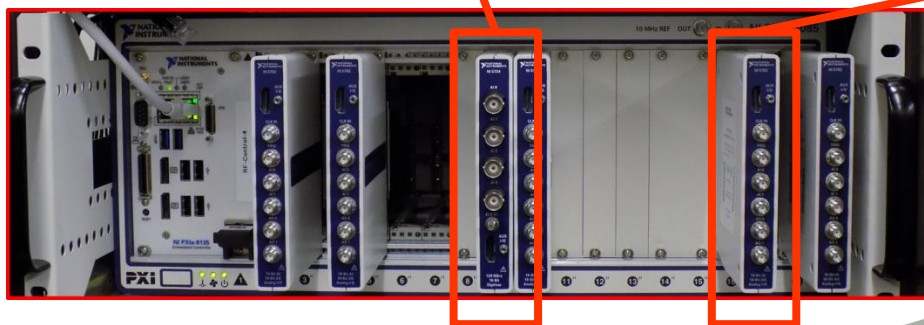
Cycle Availability TS1 **0.0 %** TS2 **0.0 %**



# Current System - FLG / MO FPGA with digital beam phase loop + 1LO

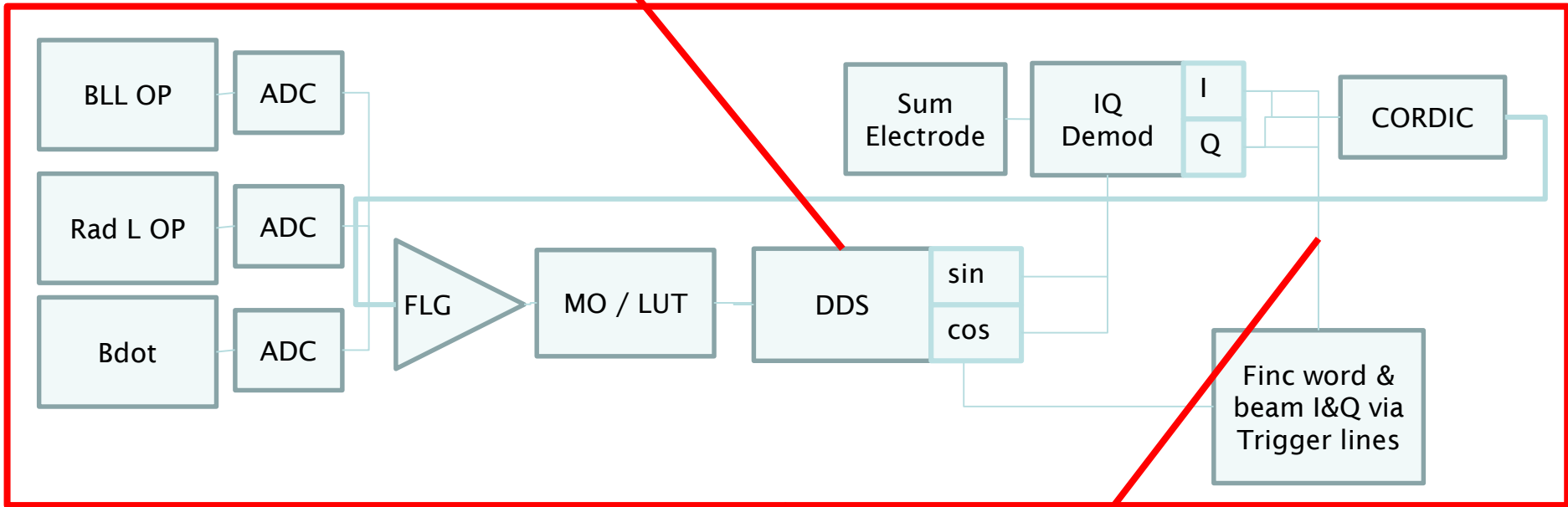


TDS 3014B - 15:41:38 04/05/2015

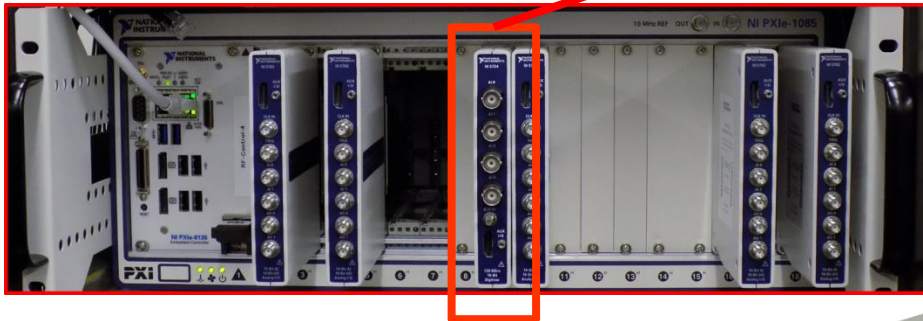


# Next steps - Master Oscillator System Architecture

include digital beam phase loop in FLG / MO FPGA module



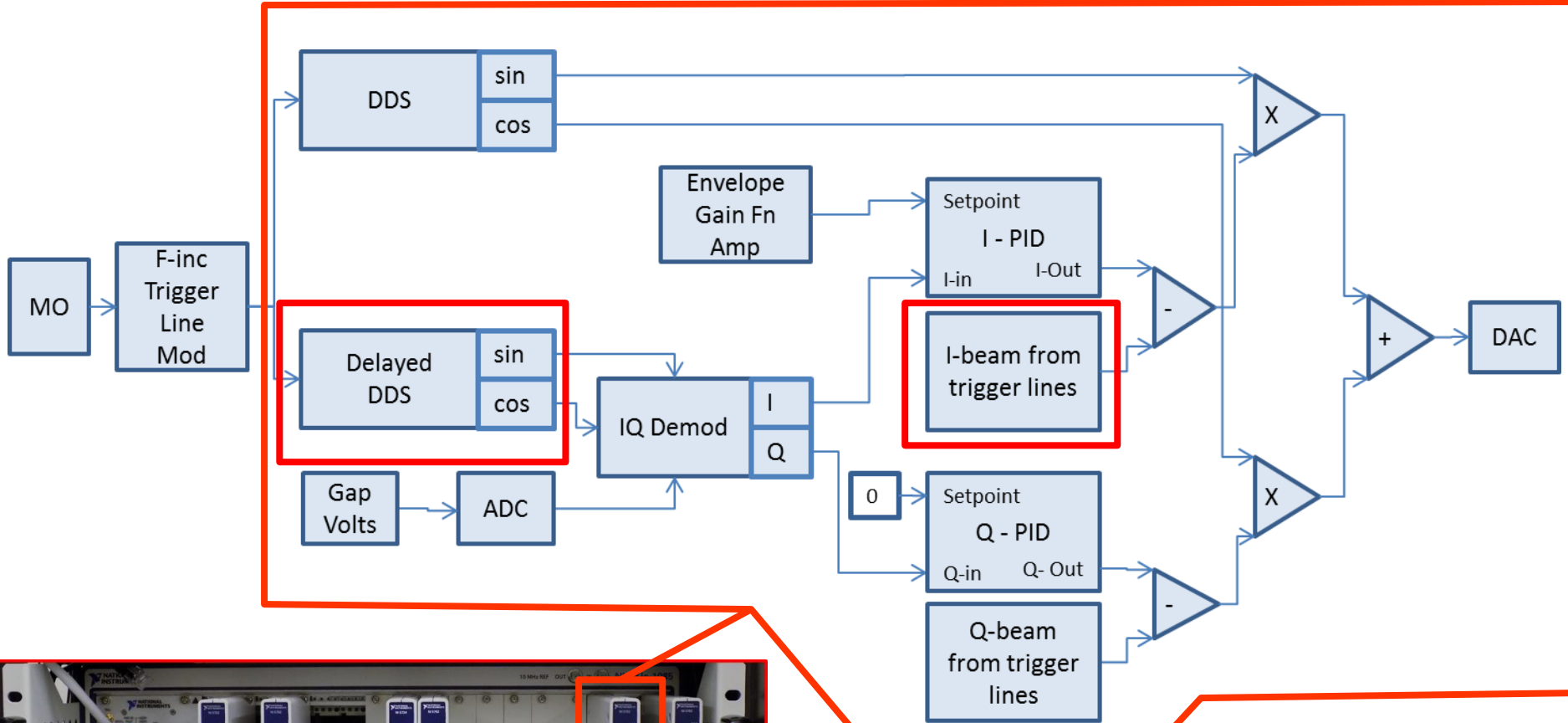
FFBC from Beam IQ



Science & Technology Facilities Council

ISIS

# Next steps - Local Oscillator IQ loop System Architecture



# Next steps - Update Host VI Controls

Limited access to lower level controls?

The screenshot displays a control panel for RF systems. At the top, there are tabs for 'RF ON / OFF Controls', 'FPGA Monitor Channel', and 'RF System Parameters'. The 'RF System Parameters' tab is highlighted with a red dashed box and an arrow pointing to it from the text 'Limited access to lower level controls?'. Below the tabs, there are ten channels labeled 1RF2, 1RF3, 1RF4, 1RF7, 1RF8, 1RF9, 2RF4, 2RF5, 2RF6, and 2RF8. Each channel has a red circular indicator with 'RF OFF' text, a 'Run Up' button, a 'Set' field with '0', a 'Read' field with '44', a vertical slider with a blue bar at 44, and a 'Run Down' button. At the bottom, there are 'Run All Up' and 'Run All Down' buttons. A 'STOP' button is located in the top right corner.

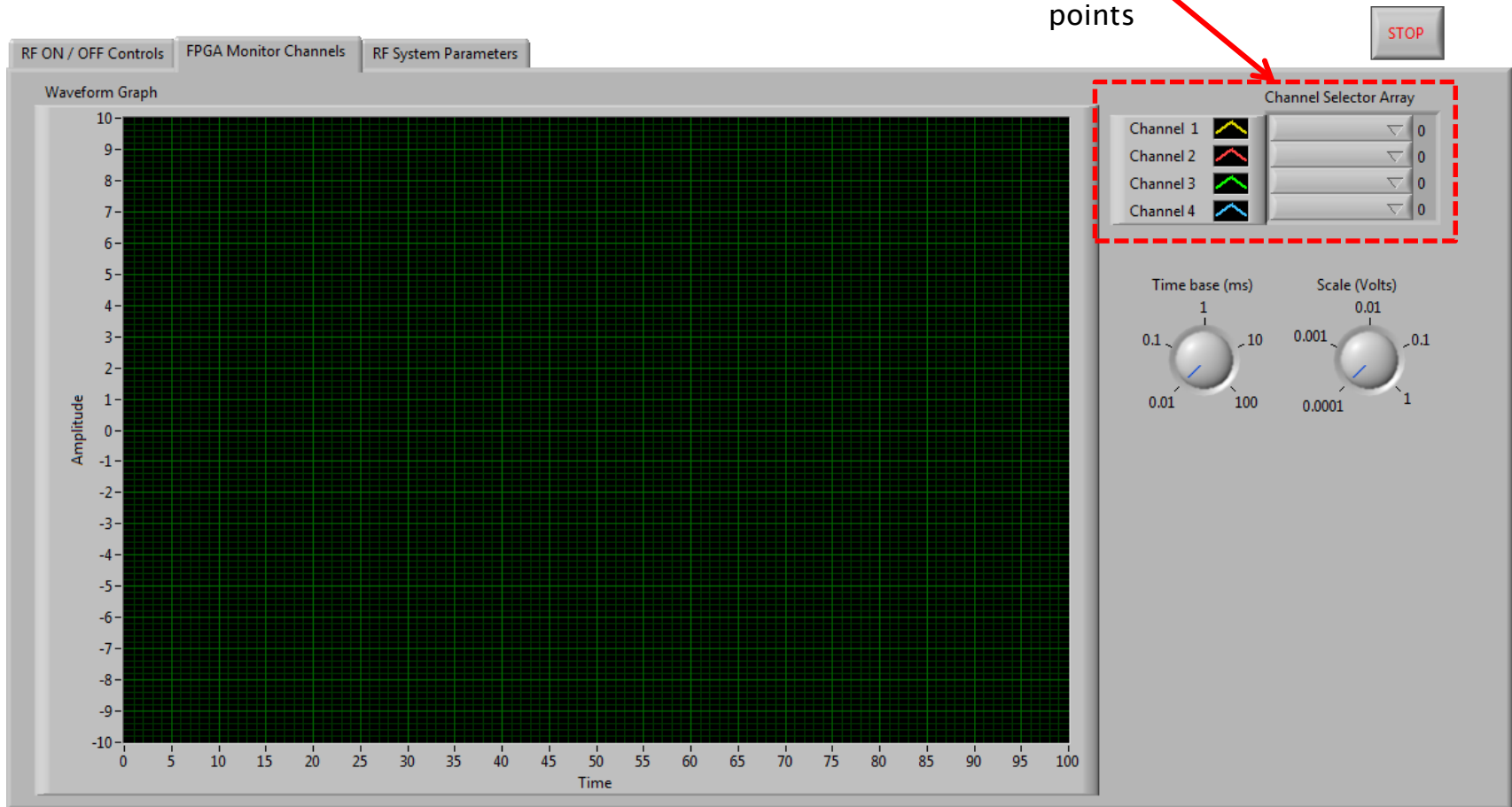
Slider controls / ON/OFF controls to be set / read from ISIS Controls pages



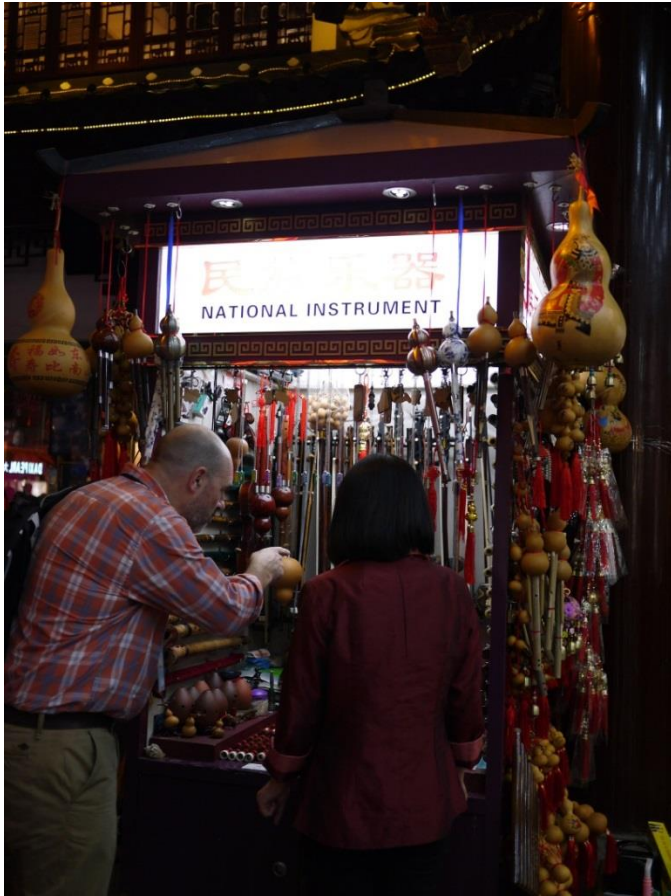


# Next steps – streaming diagnostic signals

Virtual scope channels linked to selectable code block diagram test-points



# Summary



- ISIS LPRF upgrade -very “ORGANIC” project.
  - Ran with feasibility study until hit obstacle
  - Haven’t hit anything major yet!
- Choice of FlexRIO platform (in hindsight good):
- Modular change suited to reconfigurable FPGA
- Large support network
- STFC has Labview Enterprise agreement
- ISIS has many Labview users/ few VHDL
- ISIS RF is a small team -buying “off the shelf” allows time for other work – coding and keeping a 30 year old machine running!
- Bespoke MO -3 years cf FlexRIO MO -6 months
- NI is a truly global company!

