Science & Technology Facilities Council

Low Level RF Control on ISIS Andy Seville

National Instruments Big Physics Summit, February 12th 2016

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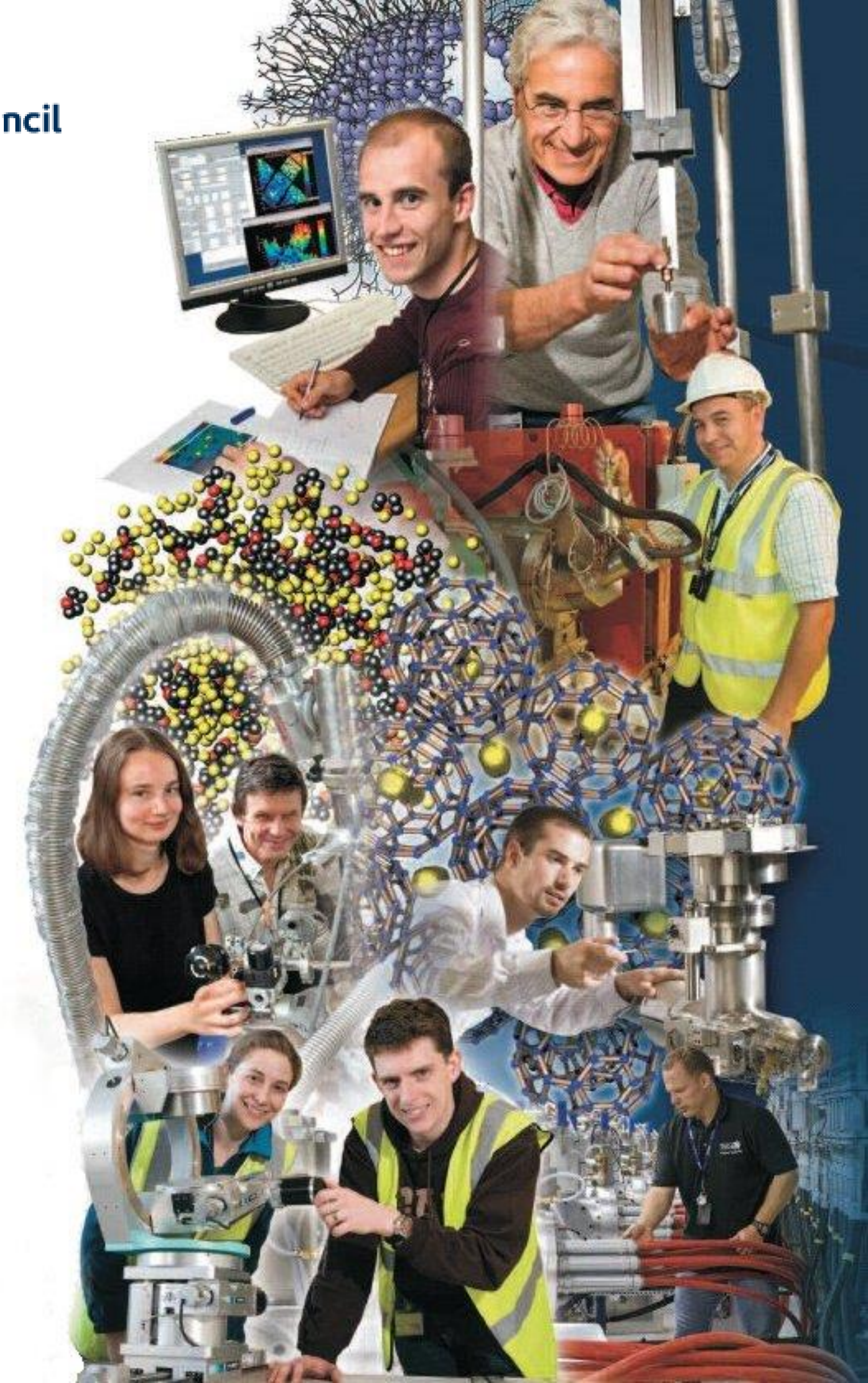
ISIS

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

31 years!

(as of 16th December 2015)



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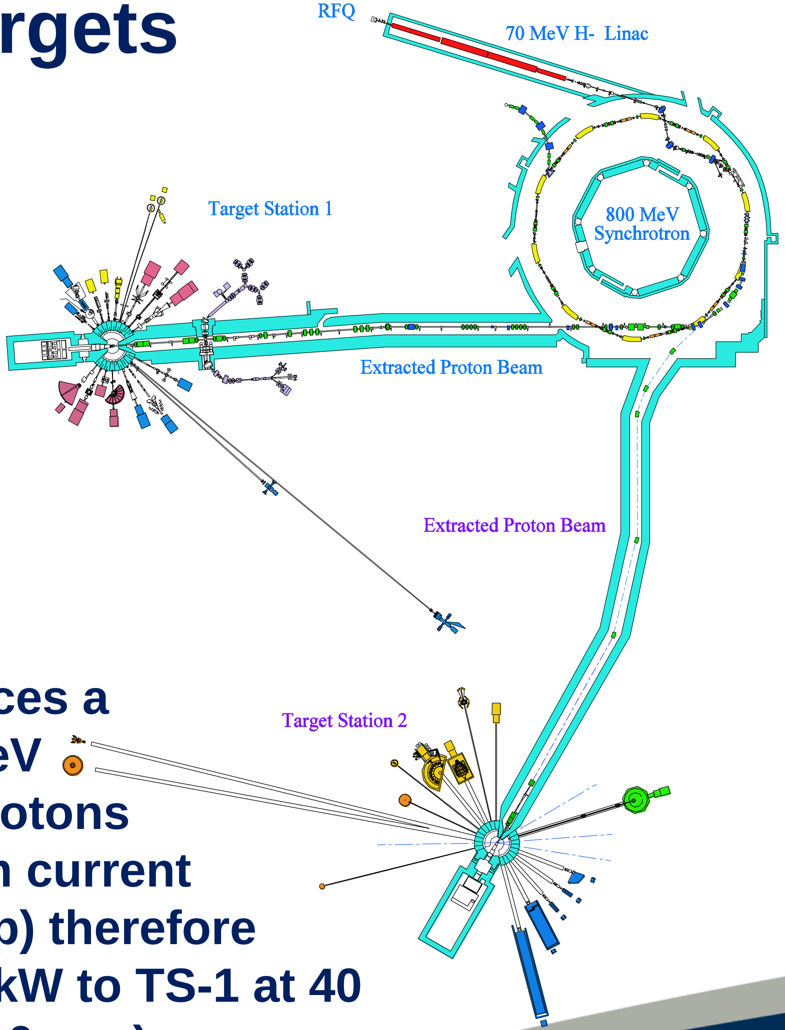
ISIS Neutron Source

ISIS Accelerators and Targets

- H^- ion source (17 kV)
- 665 kV H^- RFQ
- 70 MeV H^- 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 μA (2.9× 10^{13} ppp) therefore 184 kW on target (148 kW to TS-1 at 40 pps, 36 kW to TS-2 at 10 pps).

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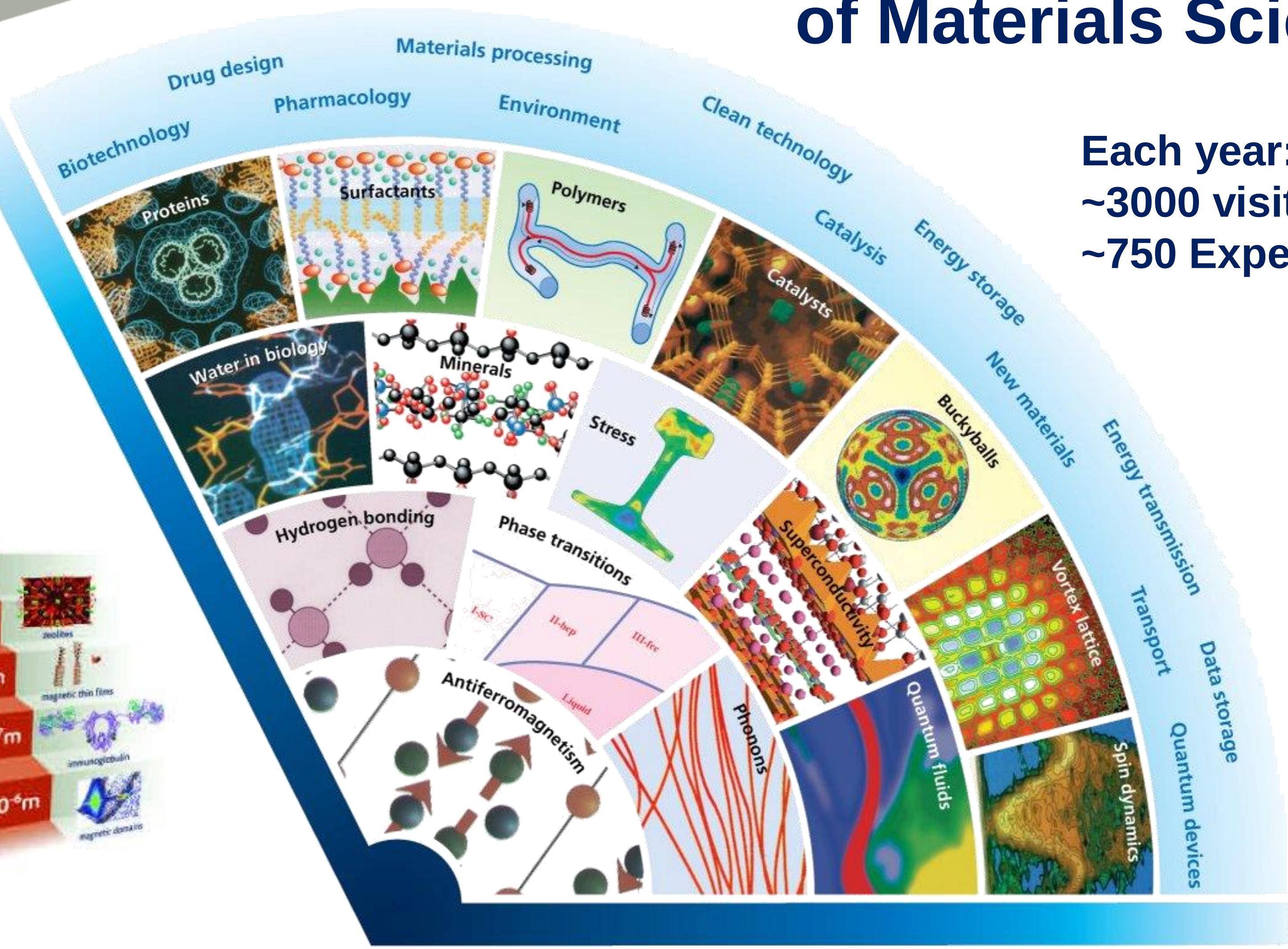
TS1
23 Instruments
+ 5 Muons!

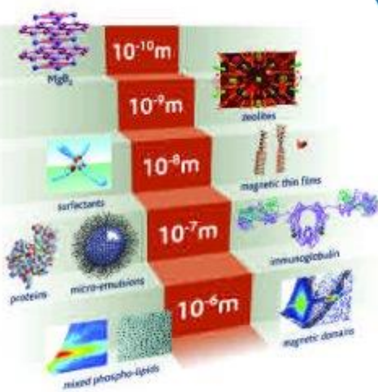
ISIS Target Halls

TS2
13 instruments

ISIS enables a huge breadth of Materials Science

Each year:
~3000 visitors
~750 Experiments





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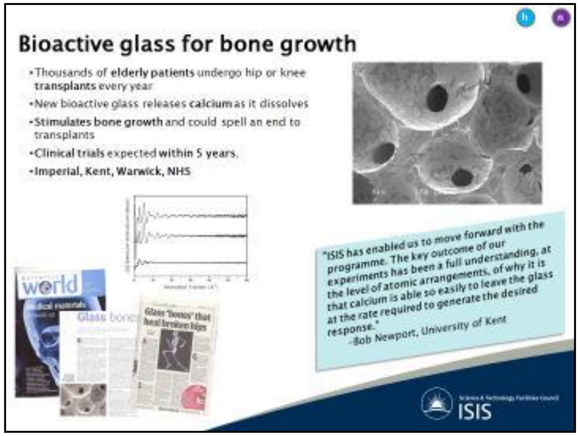
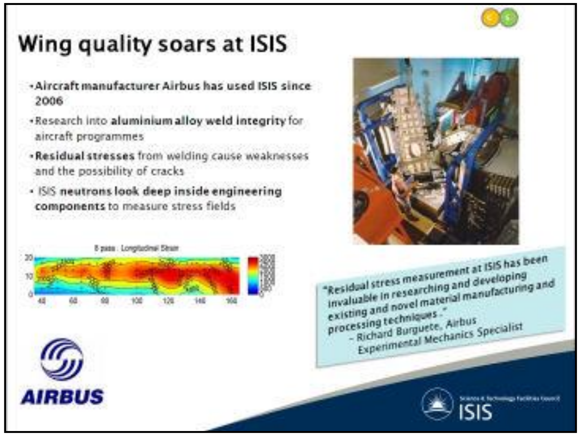
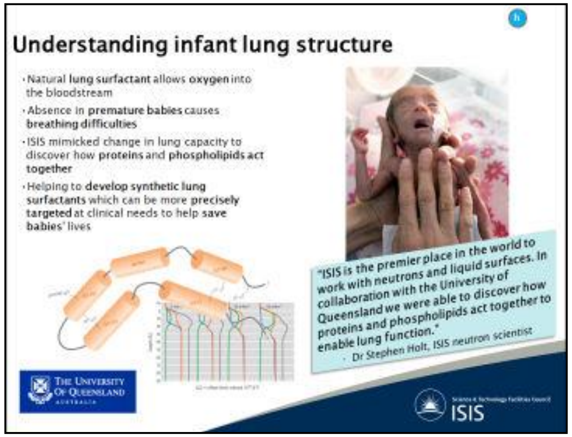
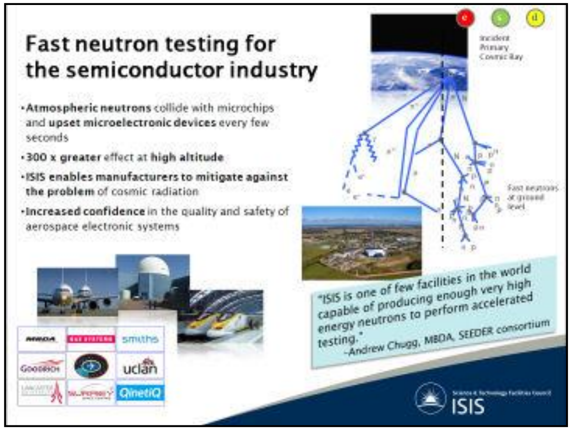
Results:

- ➢ 400 papers each year
- ➢ See www.isis.stfc.ac.uk for more



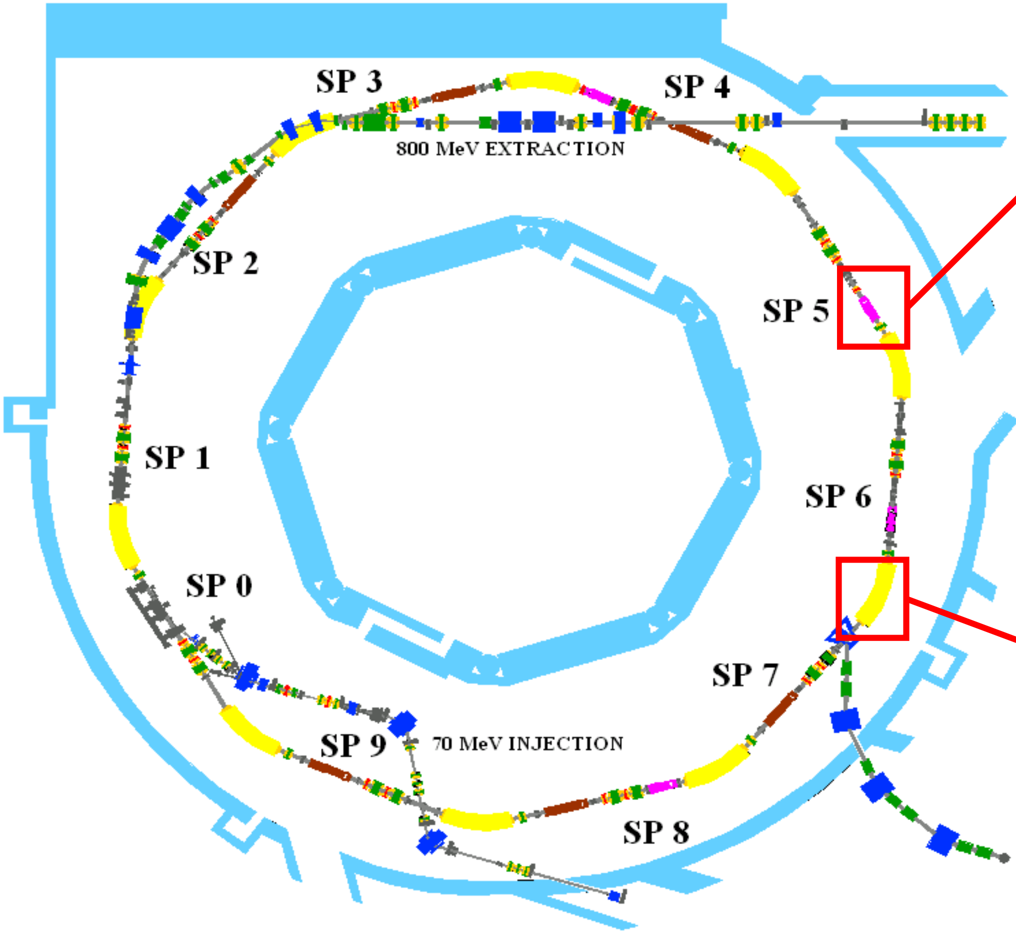






ISIS Synchrotron

- **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

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

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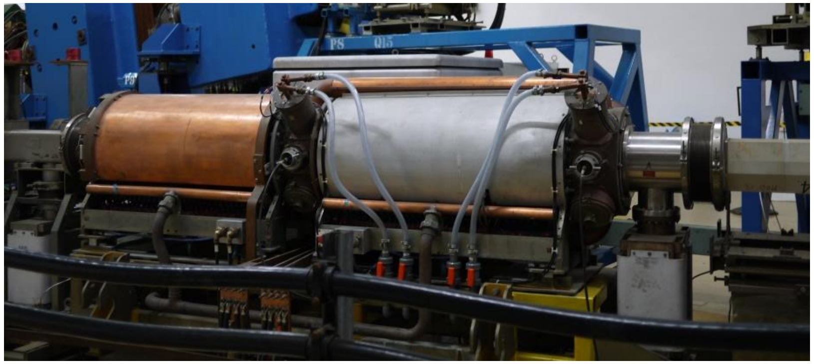
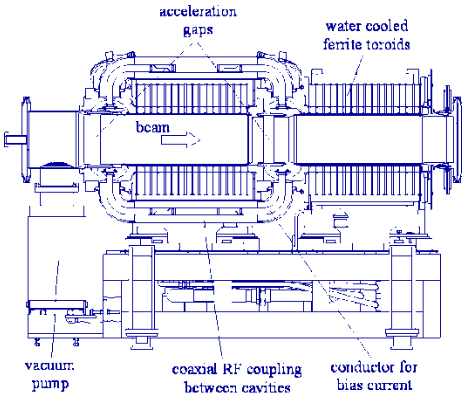
ISIS Synchrotron RF

1RF cavity



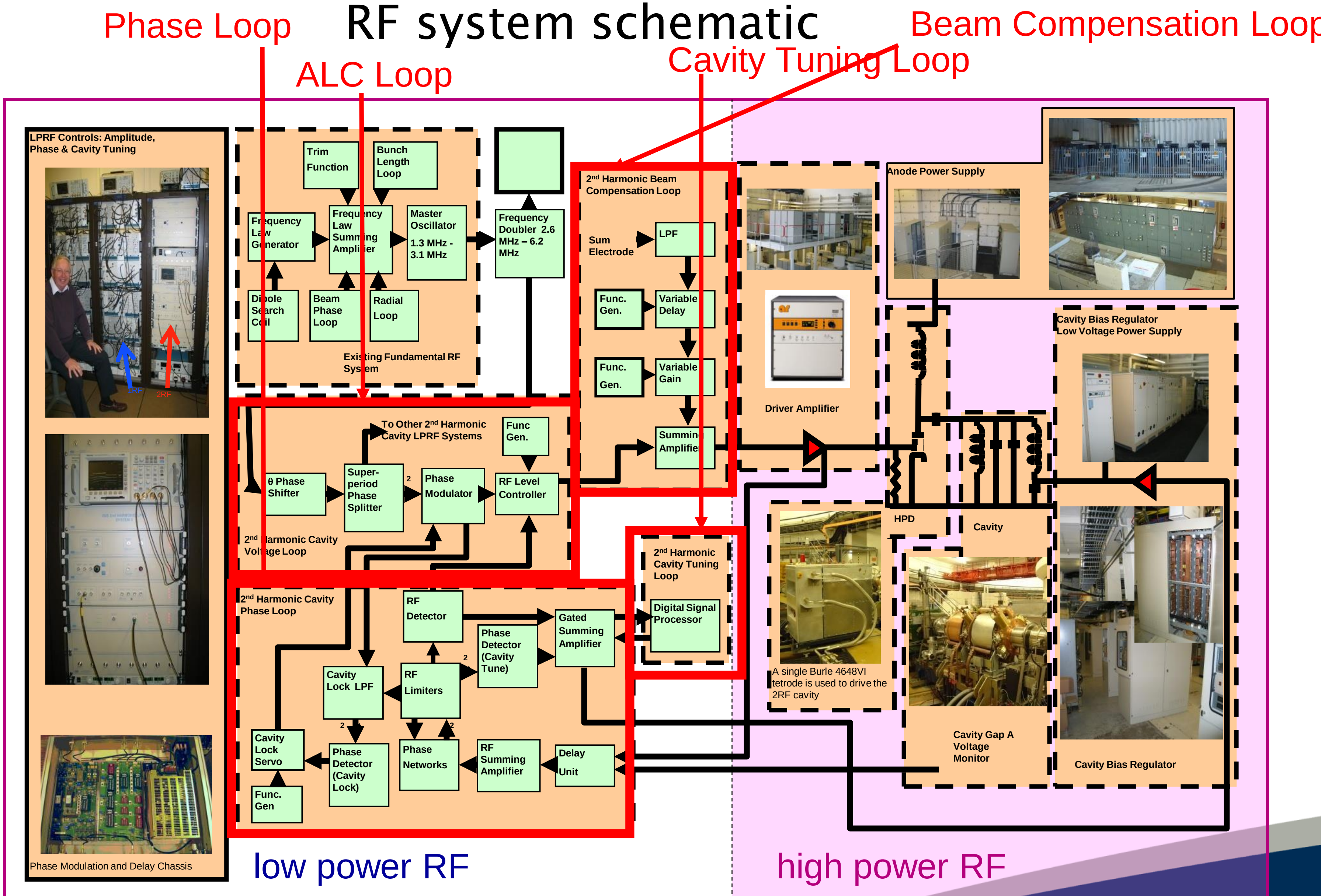
In each 10ms accelerating period,

- 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

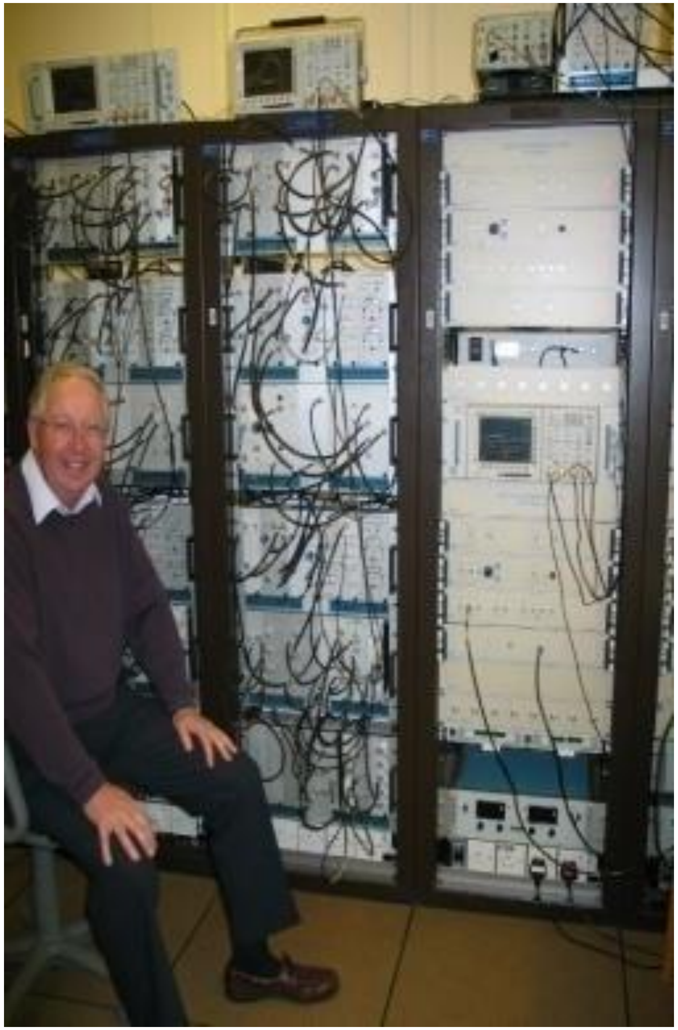


2RF cavity

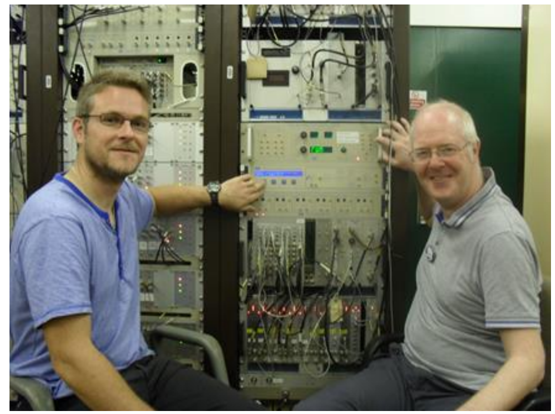
RF system schematic

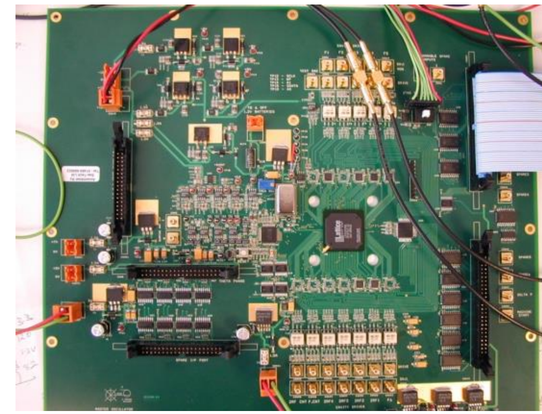


ISIS Low Power RF Upgrade



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

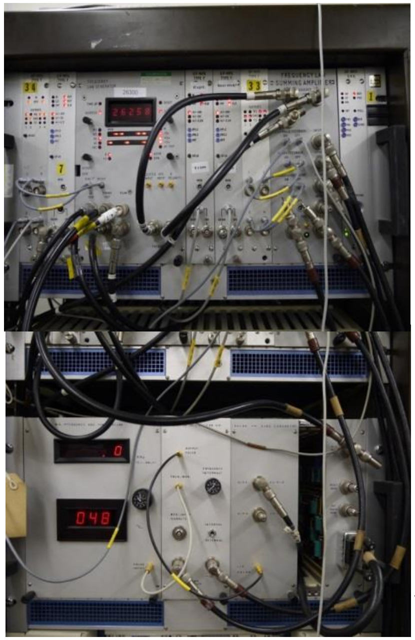




- Lattice ECP DSP series FPGA based (132MHz)
- Voltage-to-Frequency Converter
- Follows Magnet Field strength (16MHz ADC)
- Provides RF signal to10 Cavities : 6 x Fundamental, 4 x 2nd Harmonic
- Produce swept RF waveforms to accelerating cavities
- Applies θ phase delay to 2RF cavities
- Synchronised to ISIS Machine timing system

ISIS Dual Harmonic RF Upgrade

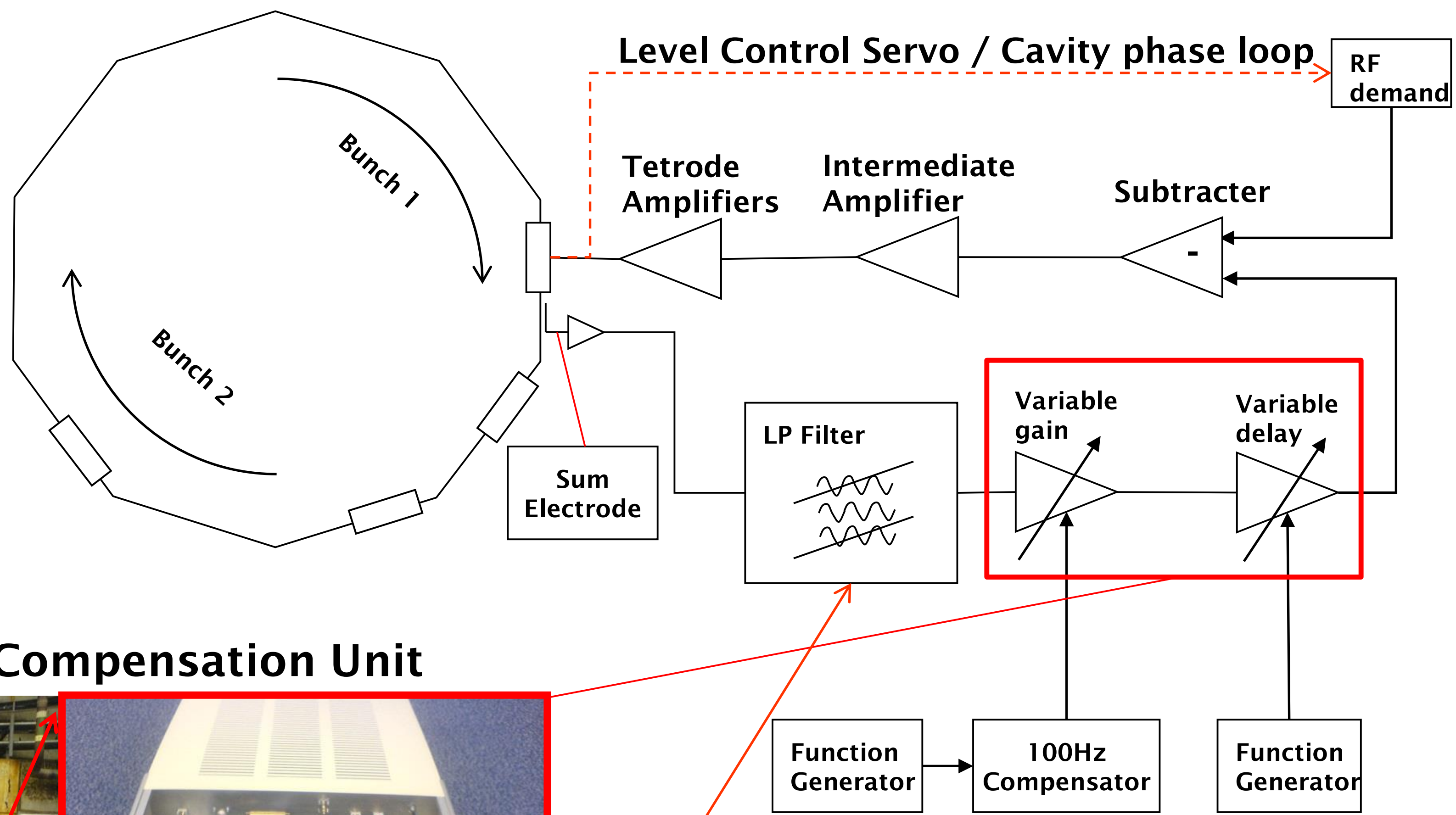
2RF LPRF Hardware issues: Modifications to LPRF units



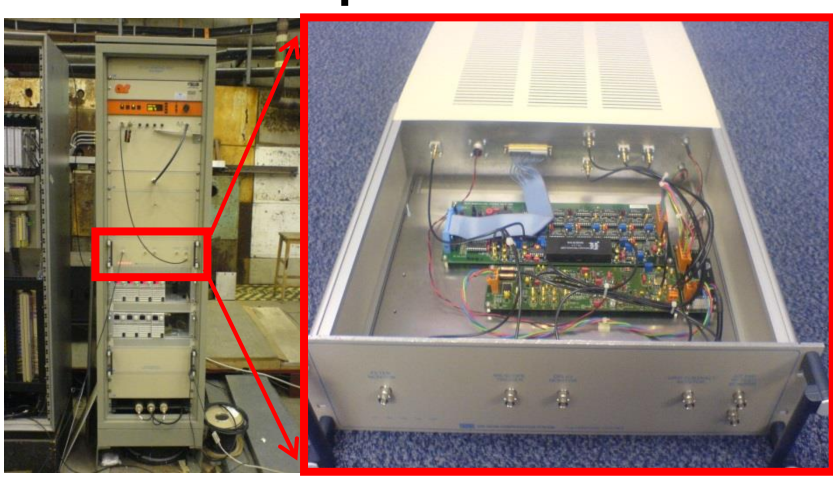
Initial plan to use new 2RF units as template for 1RF upgrade.

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

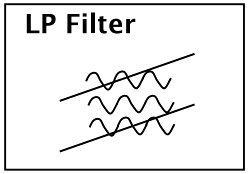


Beam Compensation Unit



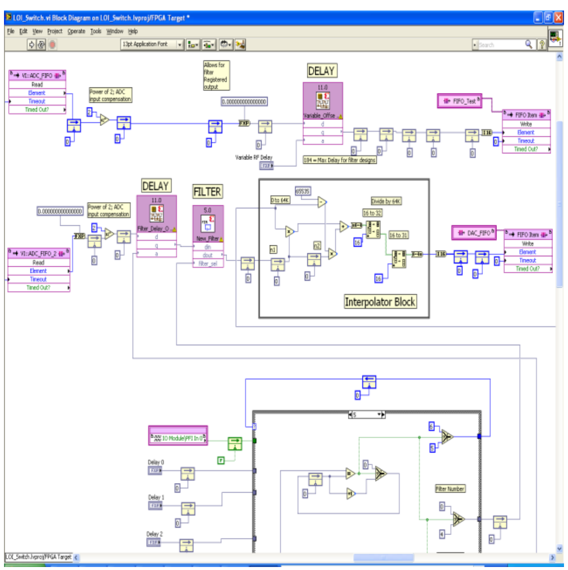
Fixed frequency – only usable over first 3ms or so

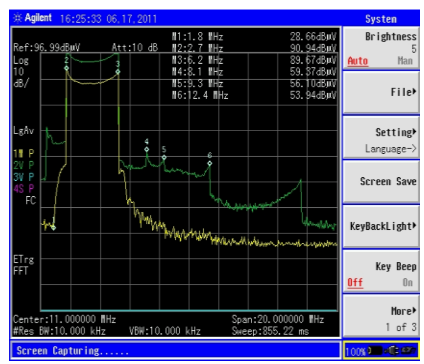
RF – Feed forward Beam Compensation



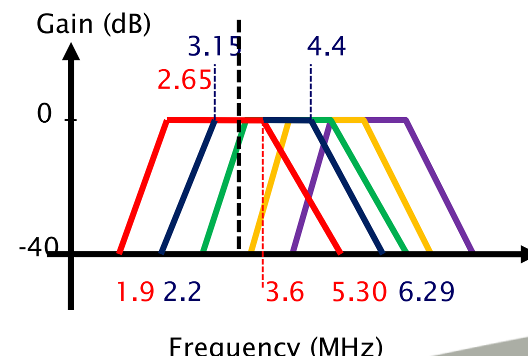
Swept digital filter implemented on NI 5641R PCI transceiver card
FPGA based
However latencies just too big.

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)



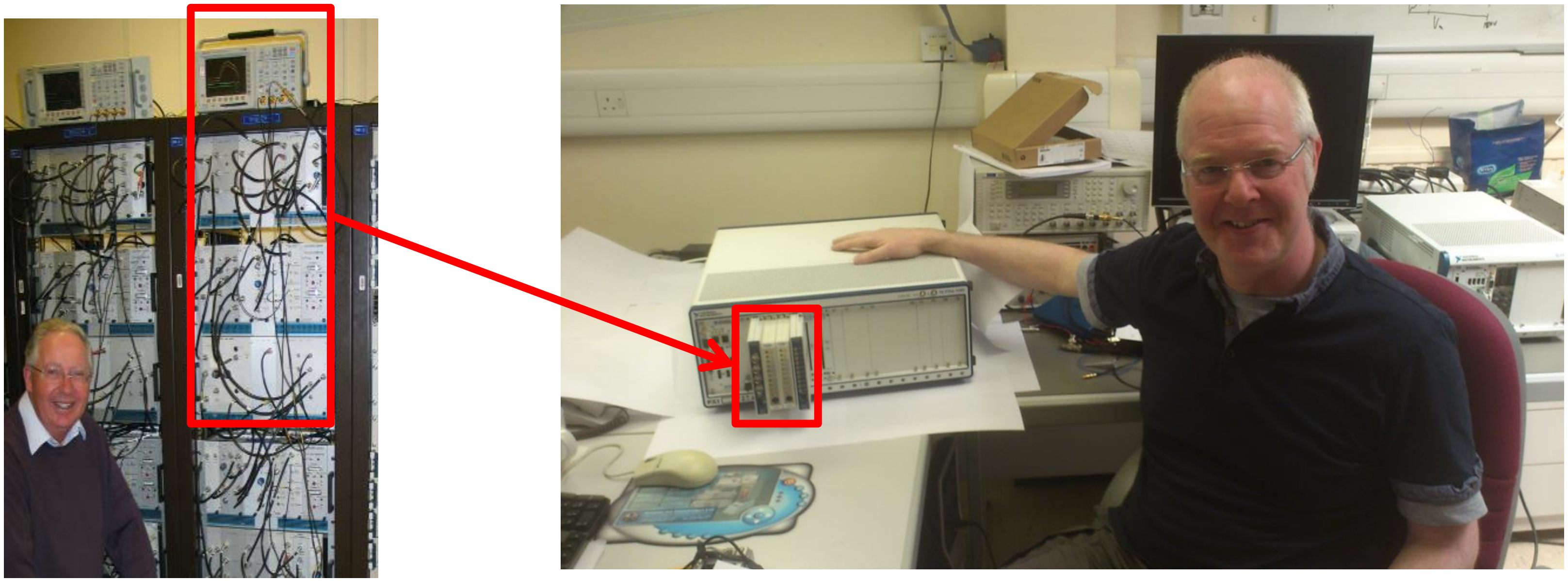


Spectrum of switched filter compared with unfiltered ISIS frequency sweep



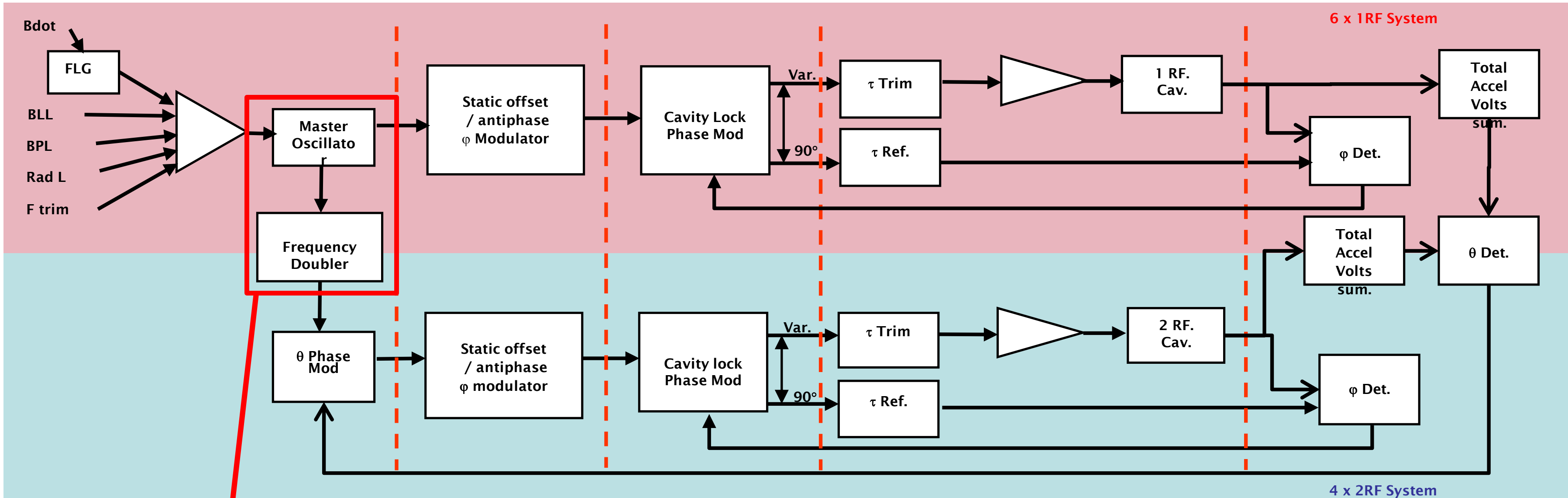
Why not use FlexRIO based system to replace all LPRF controls?

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

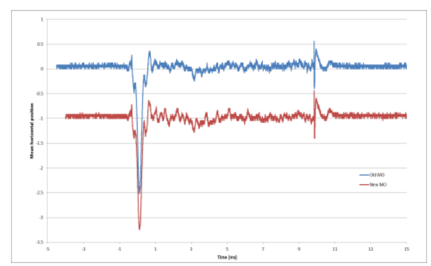
Initial tests – Digital Master Oscillator to replace VCO



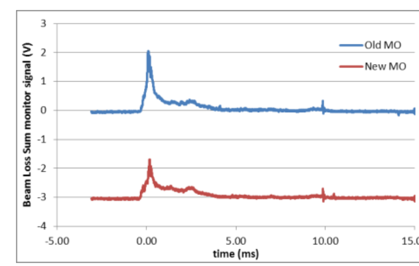
7966R FPGA module + 5781transceiver front end

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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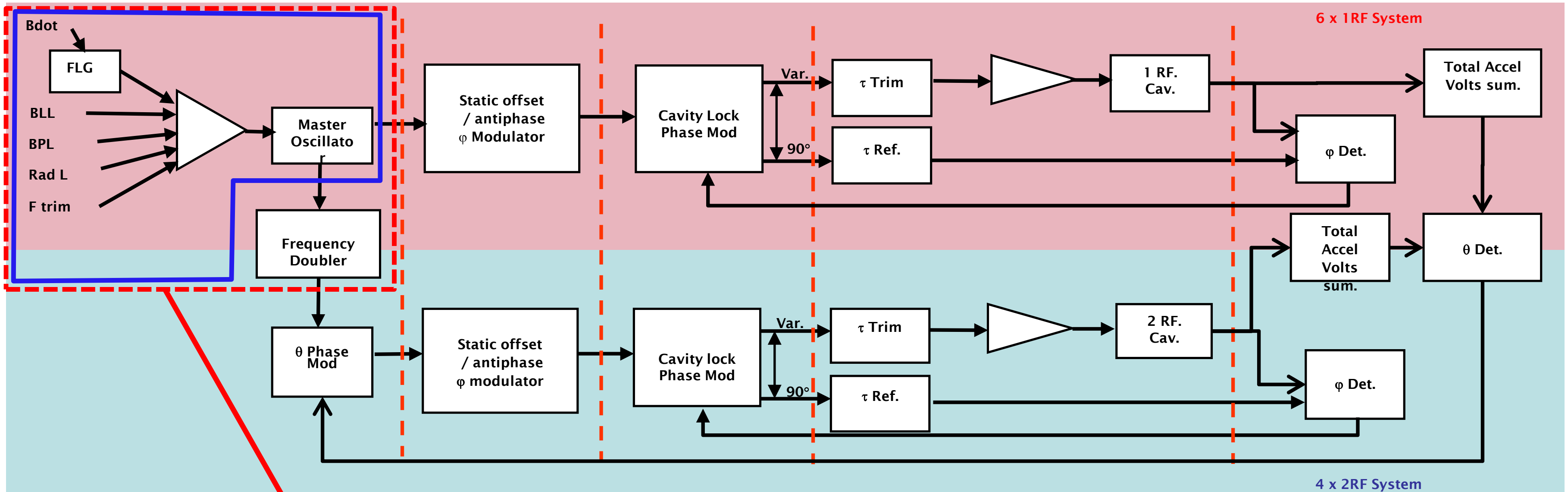
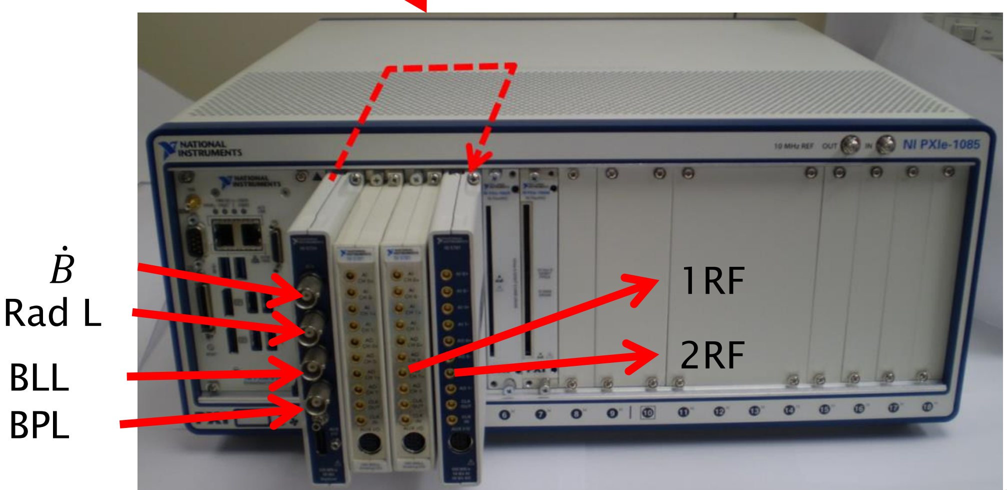
Initial tests – Combined Frequency Law Generator / Digital Master Oscillator



7966R FPGA module + 5734 digitiser

7966R FPGA module + 5781transceiver front end

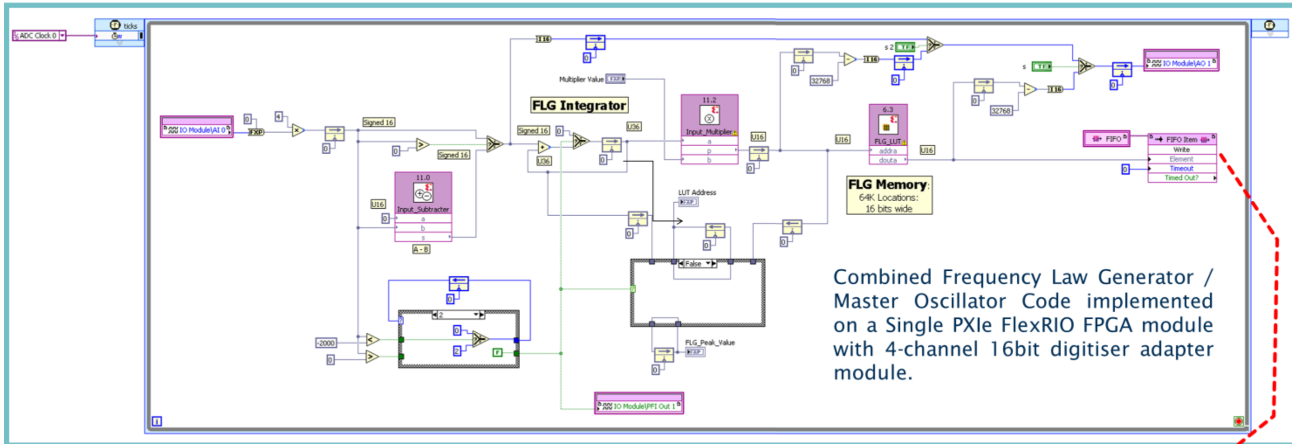


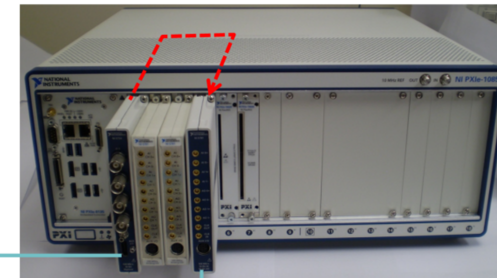
Machine Physics testing 4th and 6th April, 2014:

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

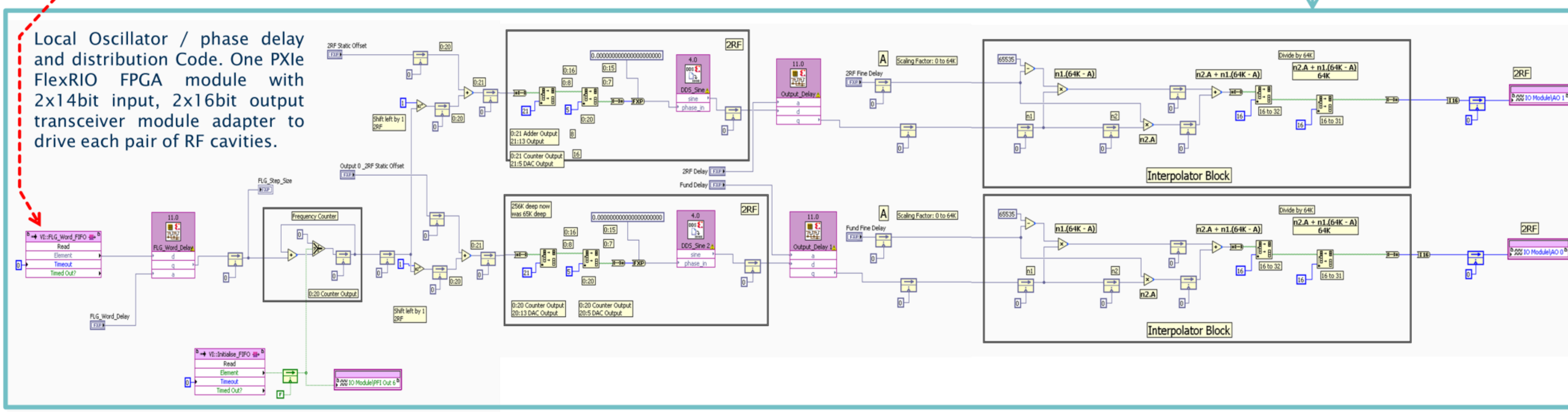
Initial tests – Combined Frequency Law Generator / Digital Master Oscillator

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 dive signal to each of the six fundamental frequency and four second harmonic RF cavities.

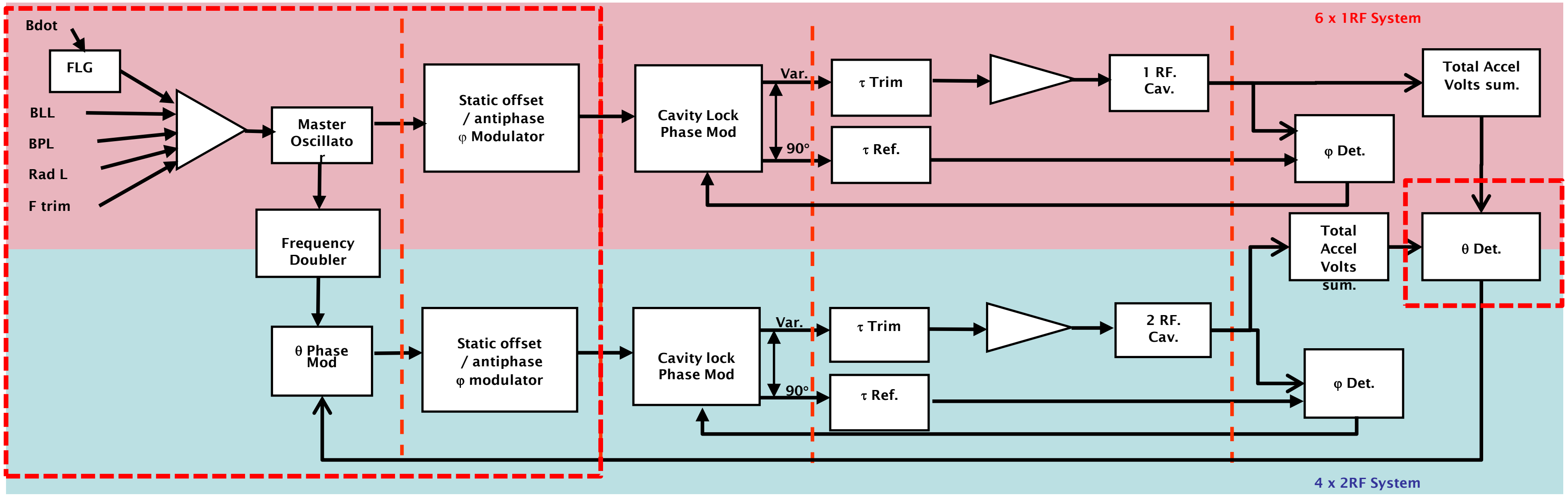




3 GB/s peer to peer data stream

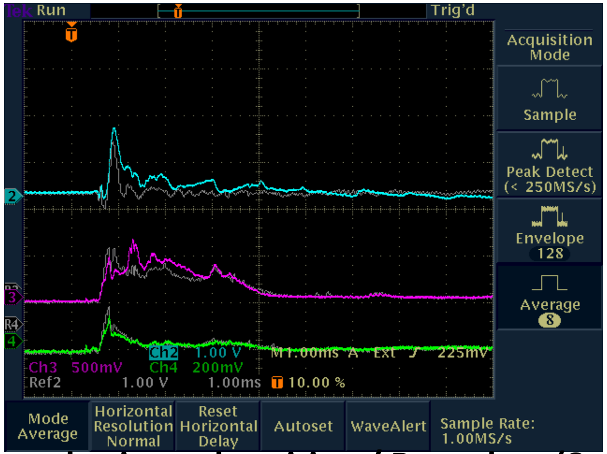


Initial tests – Combined Frequency Law Generator / Digital Master Oscillator / Phase Distribution / Theta Loop



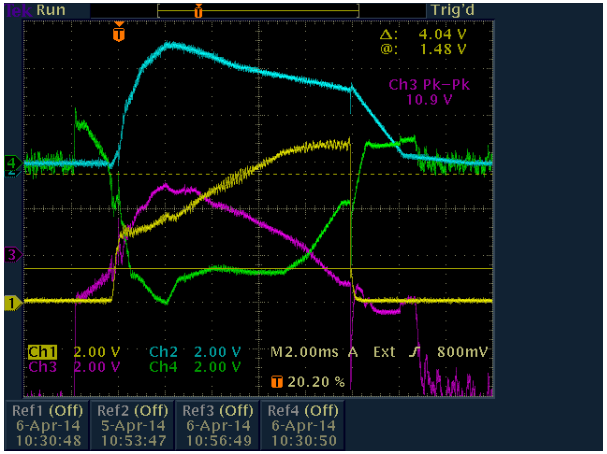
- Successfully tested in June / August 2014 machine physics
- Initial tests of IQ demodulator

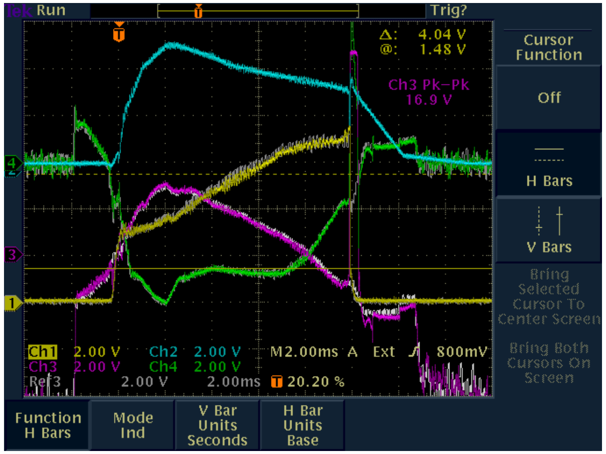
Digital 1RF only



Digital 1RF and 2RF

Mean horizontal position / Beam loss (8-averaged) base rate beam with 1RF from new MO only, 2.5e13 inj, 2.32e13 acc.





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

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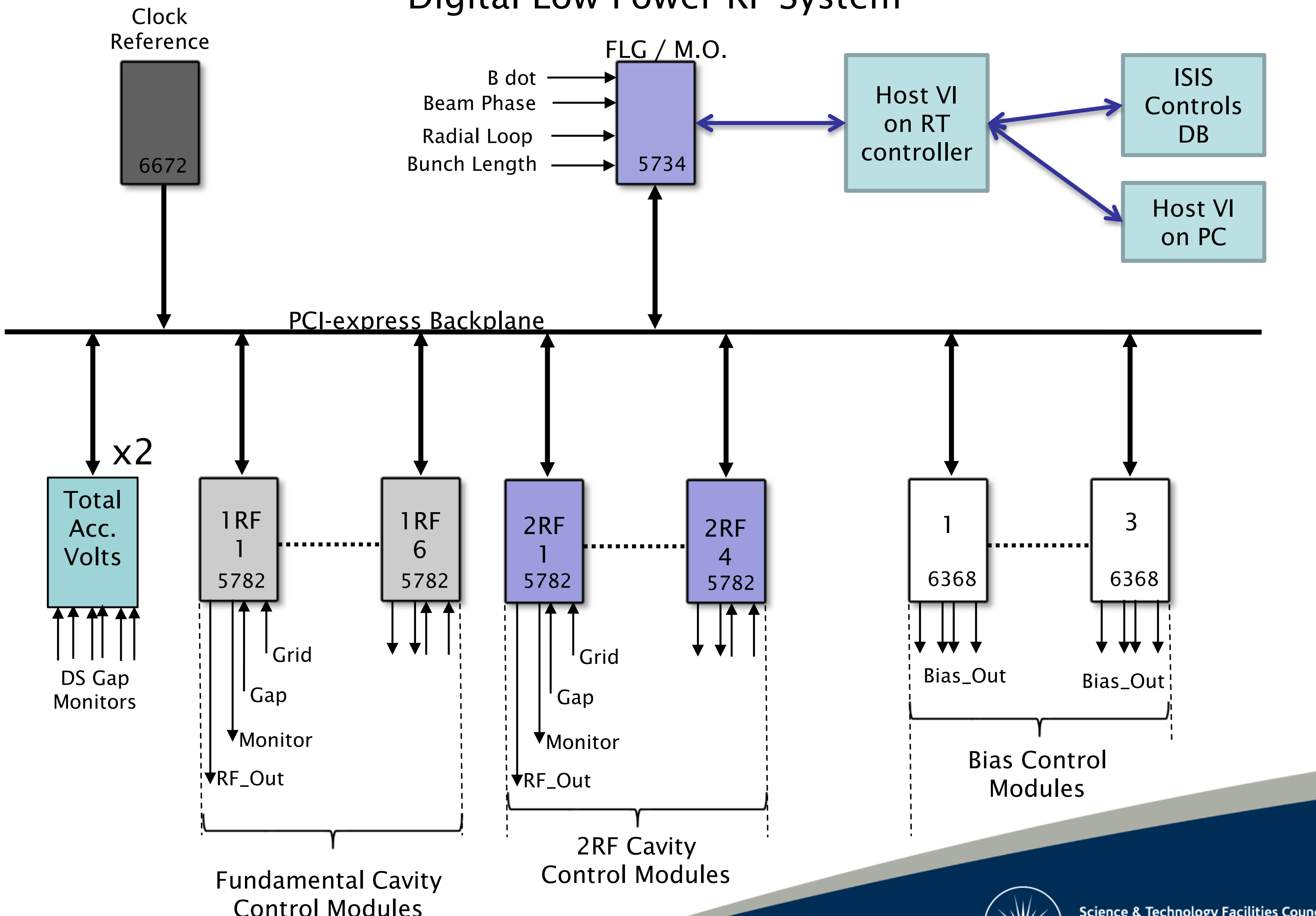
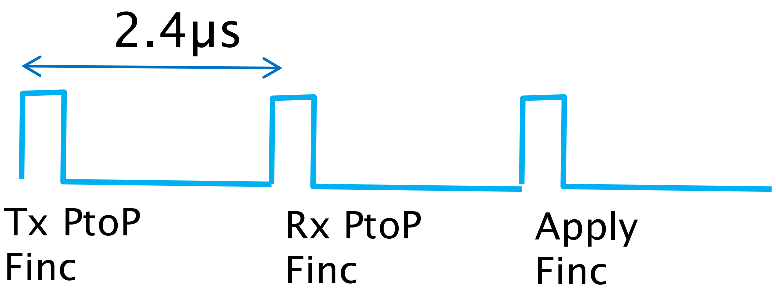
Digital Low Power RF System



Backplane latency

- Tests up to early 2015 were made on trial system consisting only 2 or 3 FPGA modules

- ~2.4μs clock pulse synchronising implementation of next Frequency increment word across the LOs.

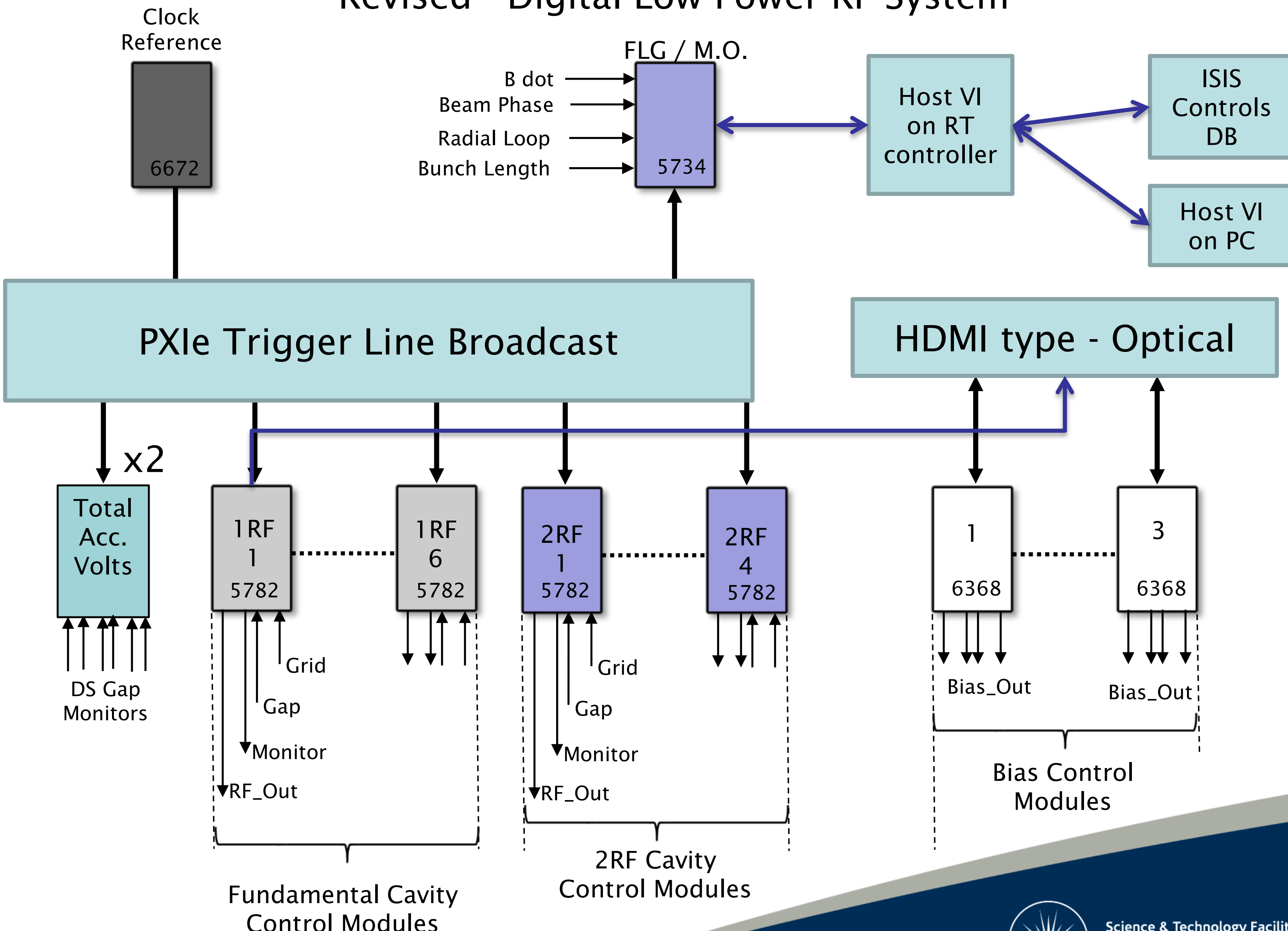


- With newer architecture, moved to various FPGA clock domains => 5.1μs synch pulse.
- When scaling up to the full 11 module system, require 2 x clock "pulses" to allow for longer PtoP latencies across the switch fabric of the PXI express backplane.

- However, trials on the longer latency system showed large instability in the beam phase loop, leading to high beam losses.

- 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 >7μs.

Revised - Digital Low Power RF System



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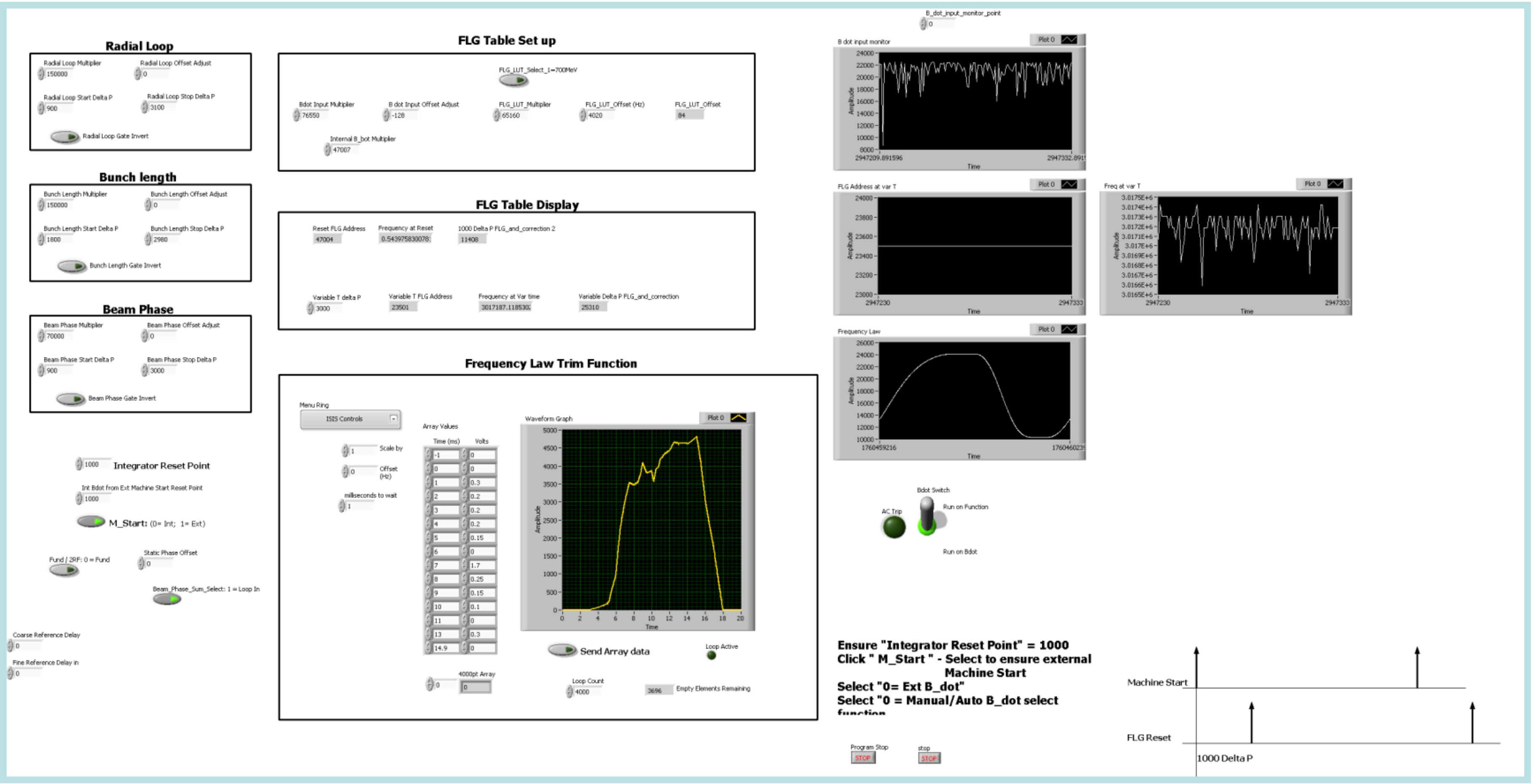
Revised Frequency word broadcast

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



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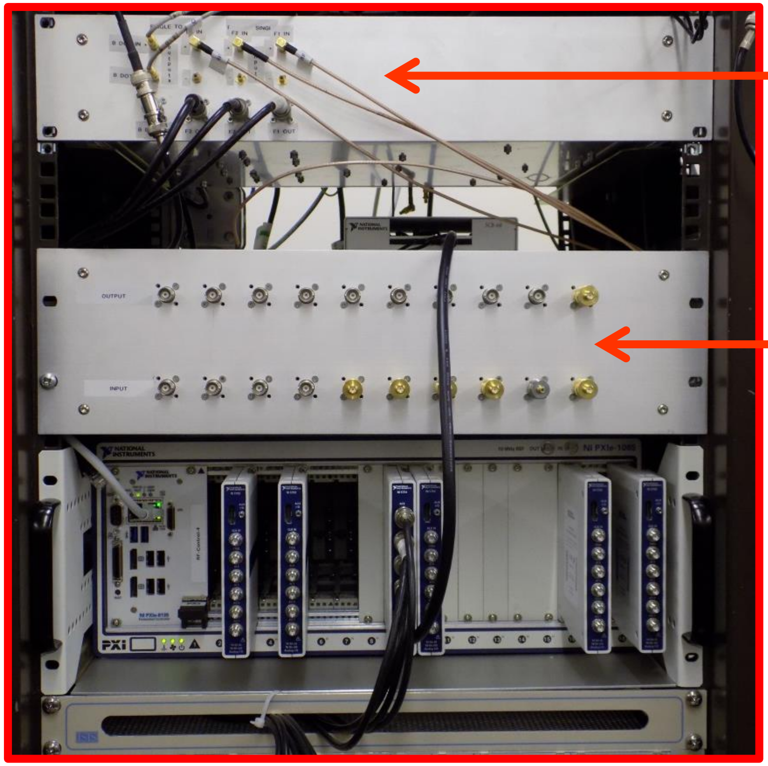
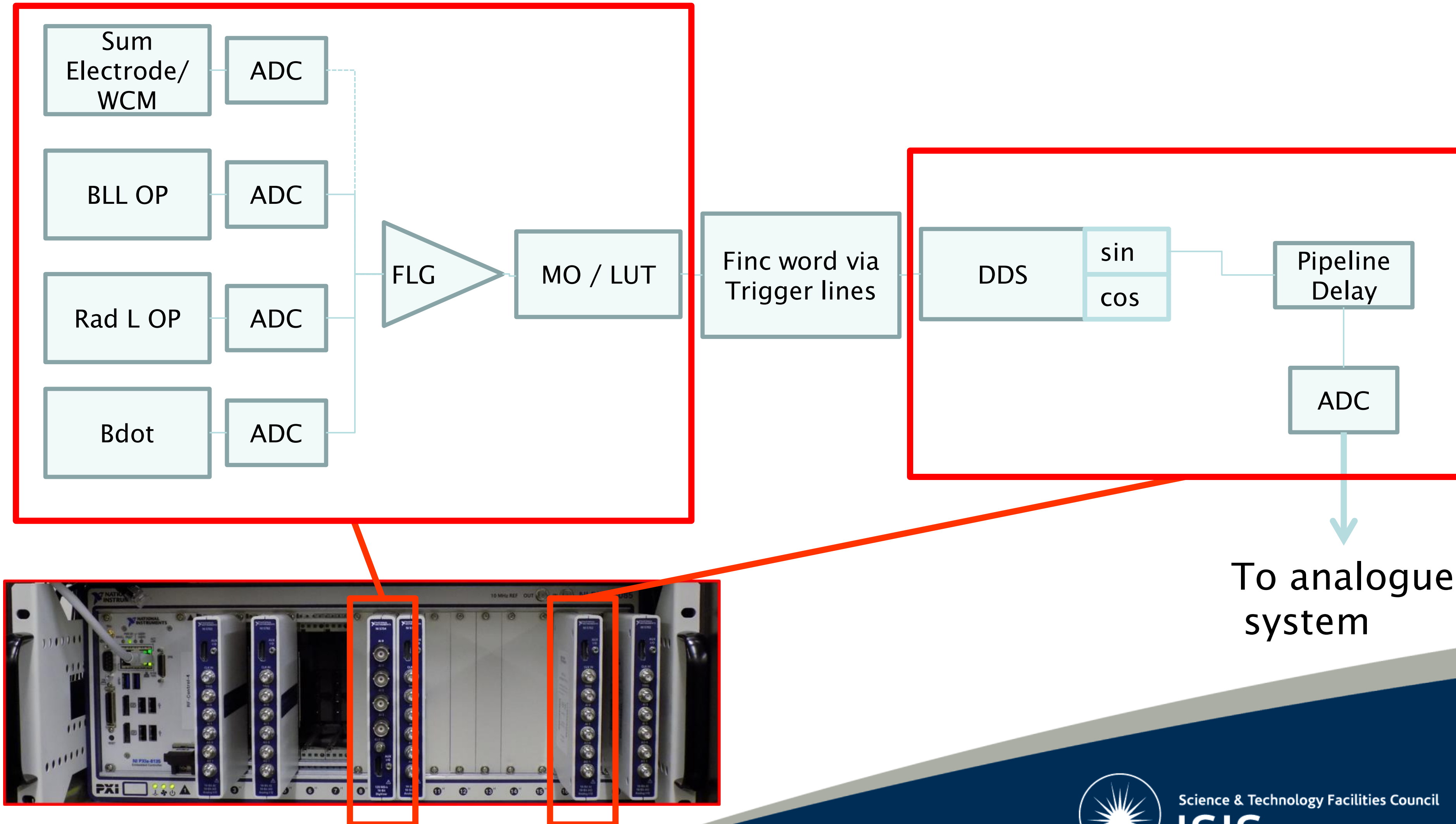
Current System – PXIe crate and Buffer Crates



Beam loop inputs

Input / output buffers

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



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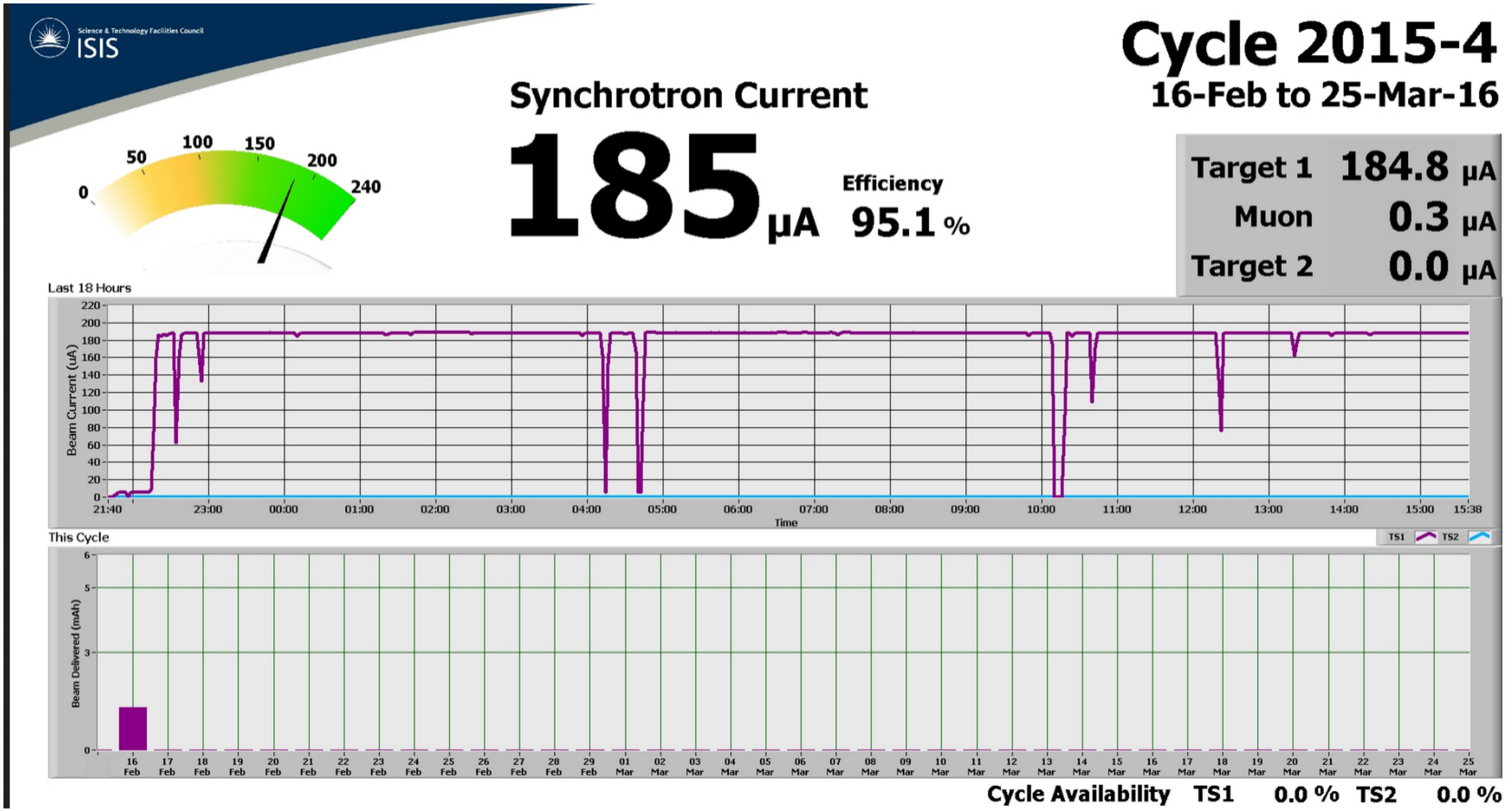
Digital FLG / MO installed 4/2/16 and in use during run-up for next user cycle



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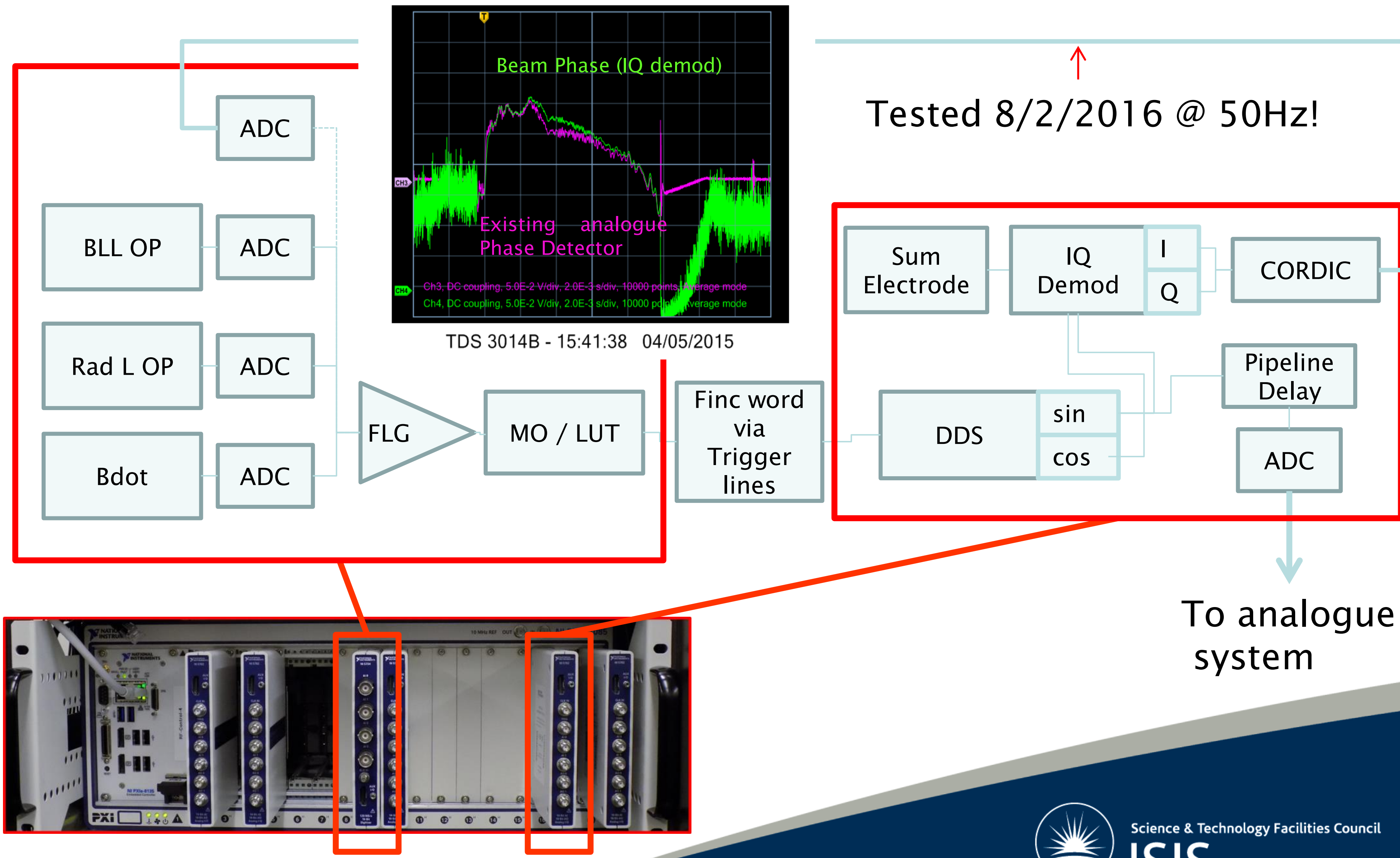
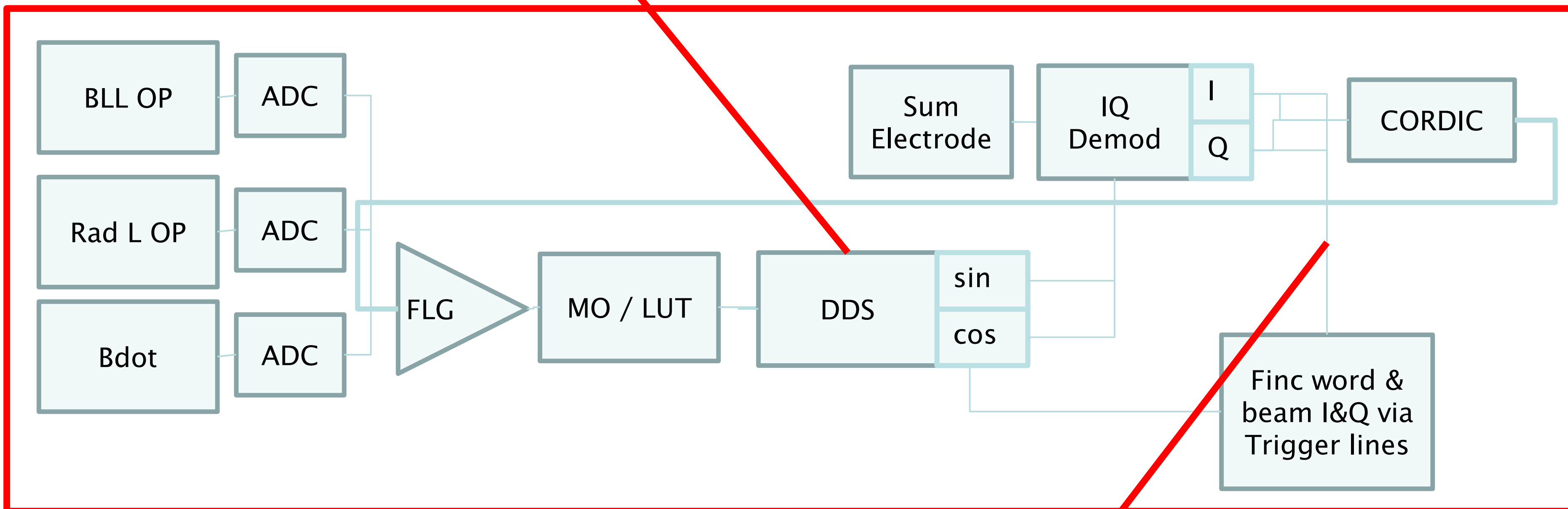
Current System – FLG / MO FPGA with digital beam phase loop + 1LO



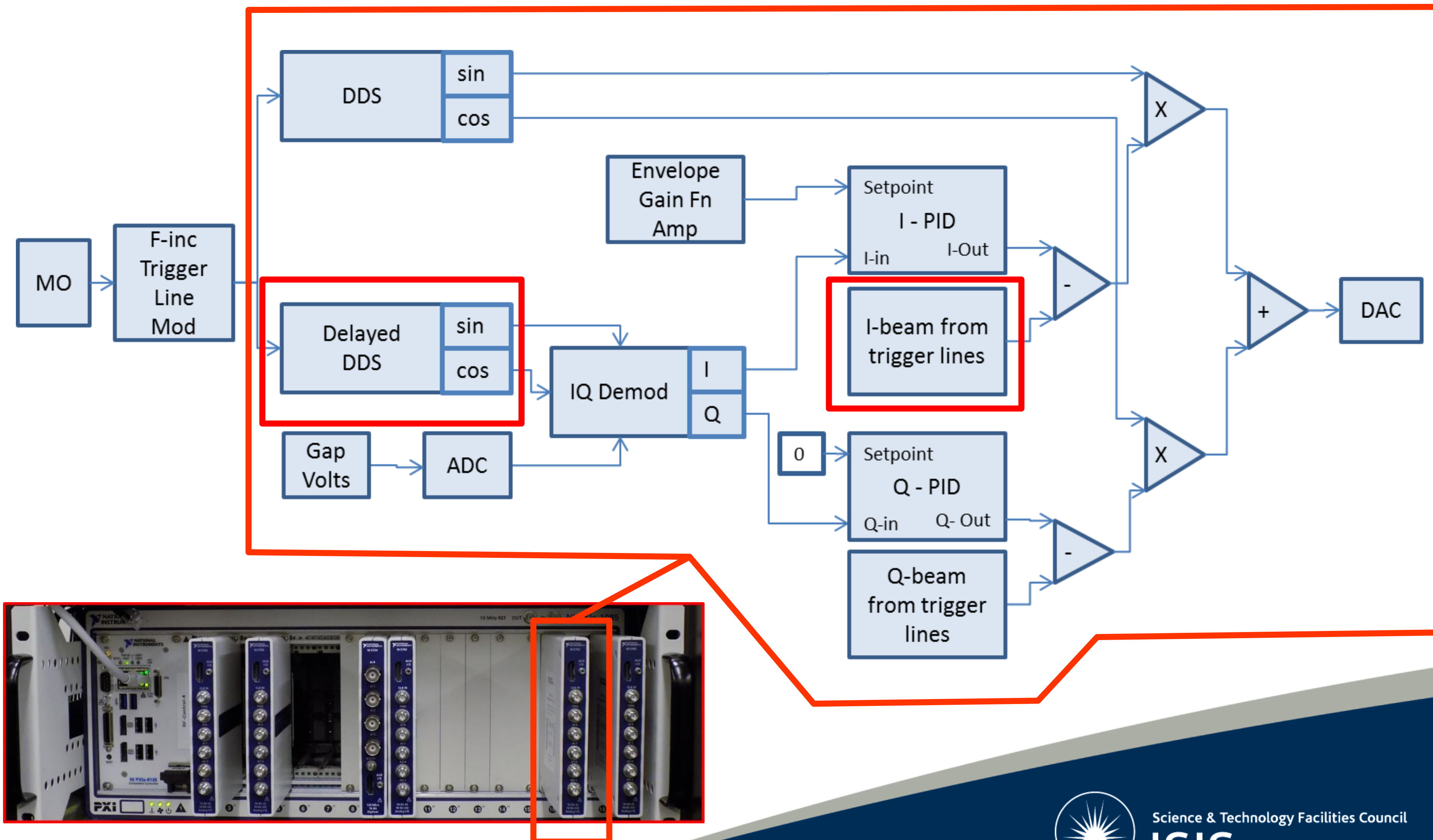
Next steps - Master Oscillator System Architecture

include digital beam phase loop in FLG / MO FPGA module

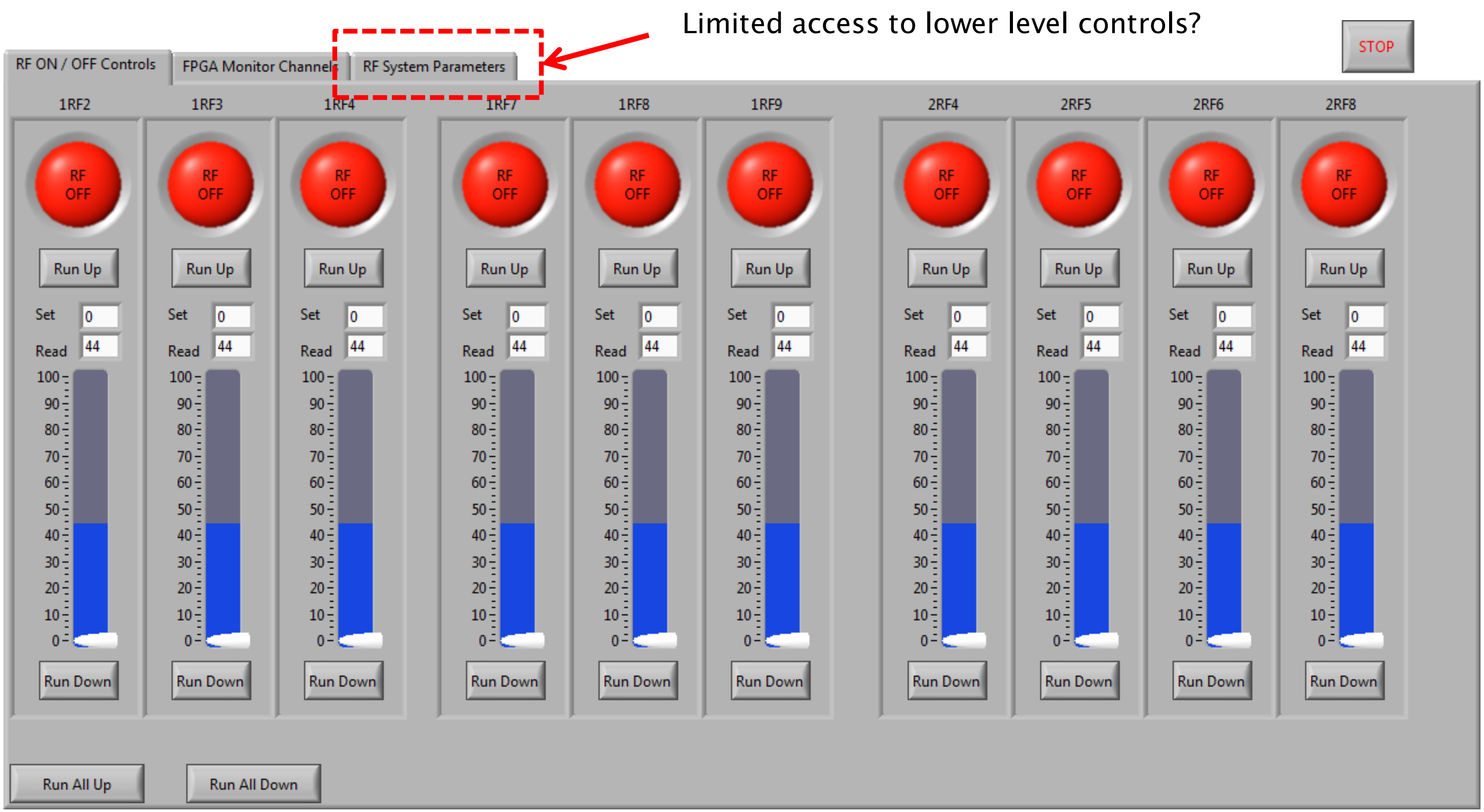


FFBC from Beam IQ

Next steps - Local Oscillator IQ loop System Architecture



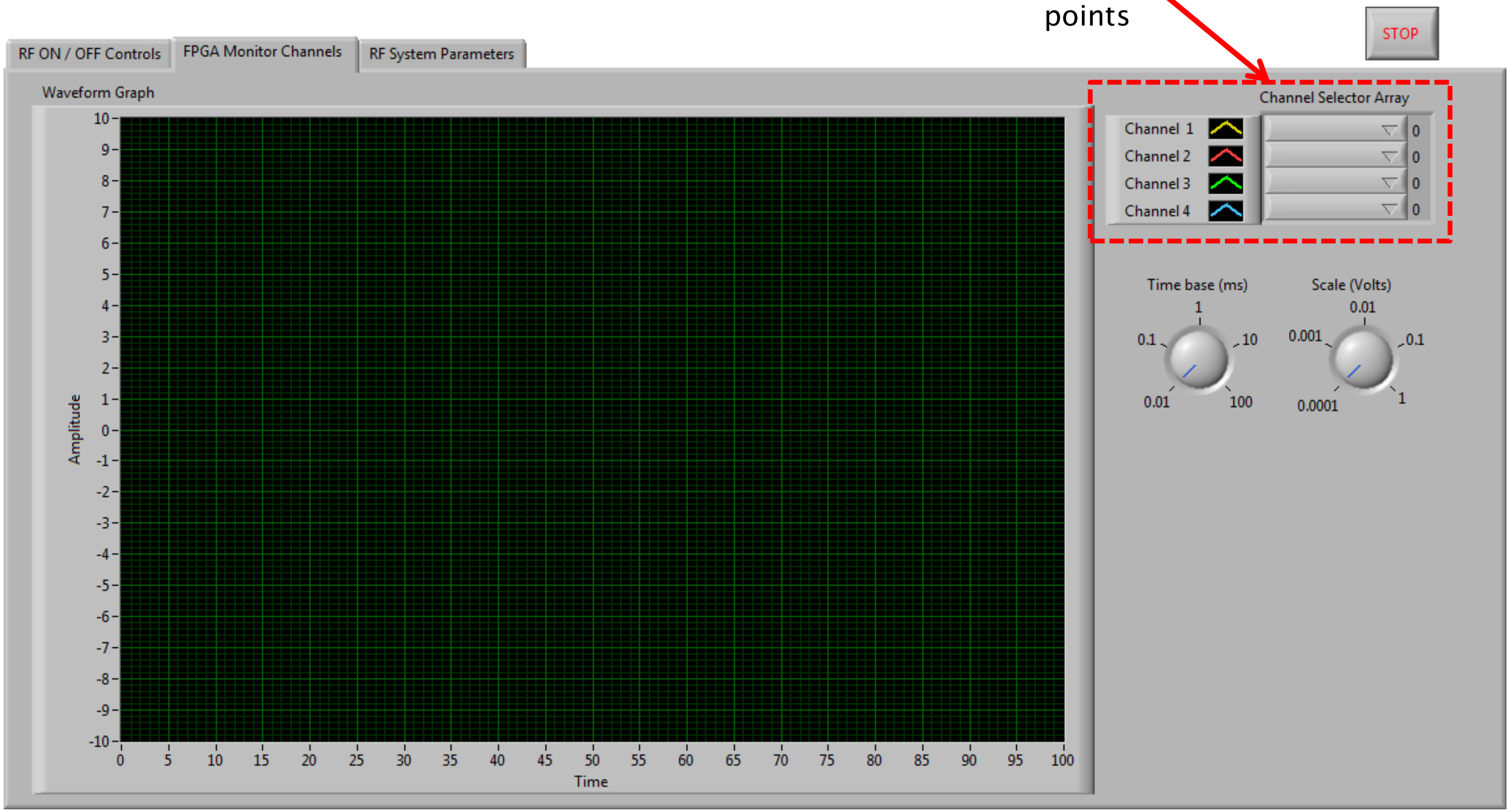
Next steps – Update Host VI Controls



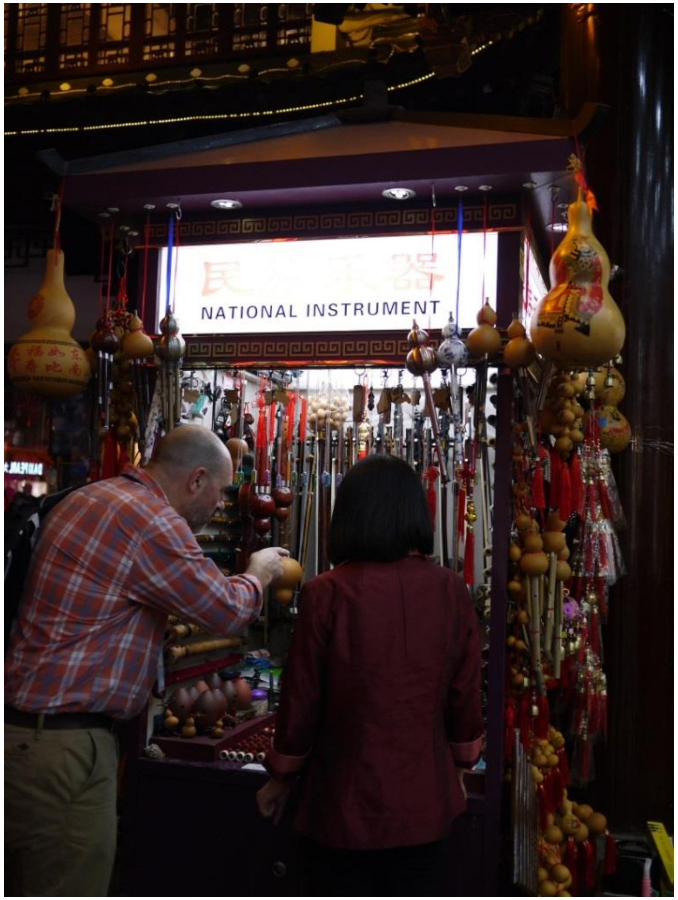
Slider controls / ON/OFF controls to be set / read from ISIS Controls pages

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 feasability 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!