21st Real Time Conference, Williamsburg

Development of next generation LLRF control system for J-PARC rapid cycling synchrotron

Fumihiko Tamura [1]

Yasuyuki Sugiyama [1]   Masahito Yoshii [1]
Masatsugu Ryoshi [2]

[1] J-PARC Center

[2] Mitsubishi Electric TOKKI systems Corporation

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2. LLRF functions for RCS
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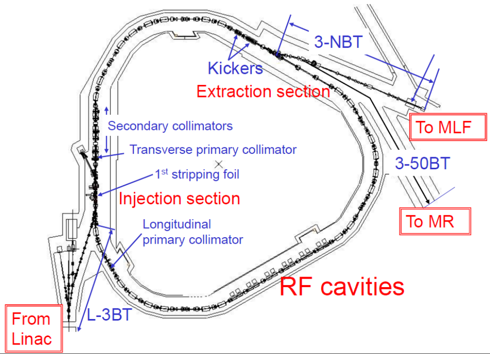
   - System overview
   - Key features and performance

4. Summary and outlook

J-PARC rapid cycling synchrotron (RCS)

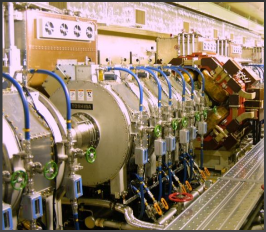
RCS is a very high intensity proton driver, which delivers beams to Material and Life Science Experimental Facility (MLF) and main ring synchrotron (MR).



parameter	
circumference	348.333 m
energy	0.400–3 GeV
beam intensity	8.3×10^{13} ppp
beam power	1 MW
repetition rate	25 Hz
accelerating freq	1.22–1.67 MHz
harmonic number	2
max rf voltage	440 kV
No. of cavities	12
Q of rf cavity	2

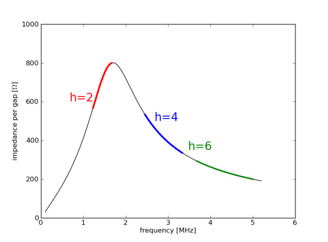
- Magnetic alloy (MA) cavities employed
  - high rf voltage, 440 kV by 12 cavities
  - driven by high power tetrode tube amp
  - Wideband, Q = 2

MA cavity and tube amplifier:

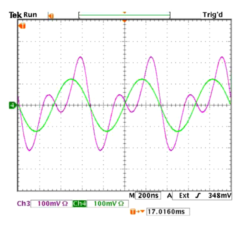


Wideband (Q = 2) MA cavity

Frequency response of Q = 2 cavity:



Dual harmonic voltage:

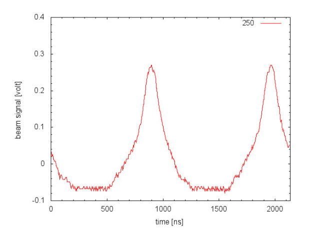


- No tuning bias loop necessary to follow accelerating frequency sweep (h = 2)
  - Ferrite cavity requires it
- Dual harmonic operation
  - A single cavity driven by superposition of accelerating and second harmonic rf (h = 2, 4)
  - Bunch shaping using second harmonic is indispensable for high intensity acceleration
- Wake voltage is multiharmonic; multiharmonic beam loading compensation is necessary

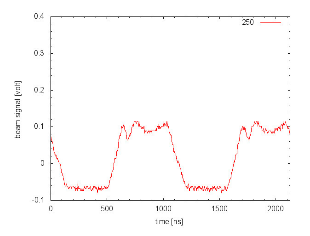
LLRF is responsible for driving MA cavity with these requirements.

Wideband (Q = 2) MA cavity

Fundamental accelerating rf only:



With second harmonic:



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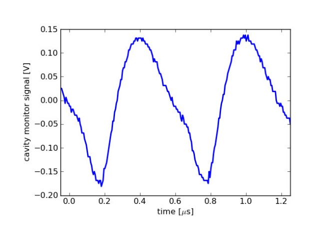
Measured wake voltage waveform:



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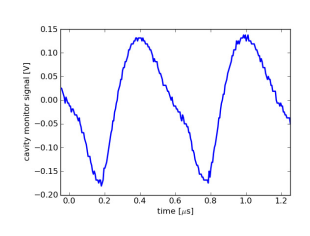

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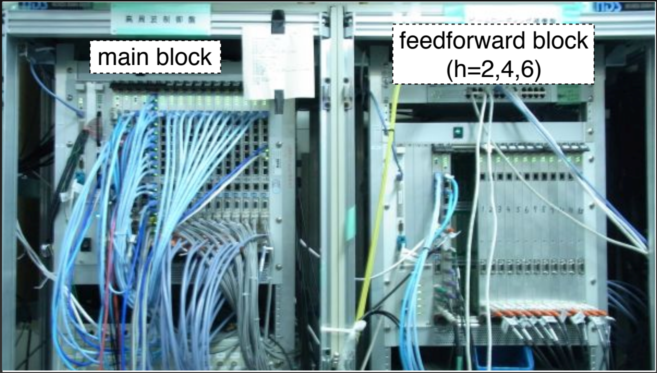
  - J-PARC RCS and its rf system

2. LLRF functions for RCS
  - Existing LLRF control system and functions
  - Why new system?

3. Next generation LLRF control system
  - System overview
  - Key features and performance

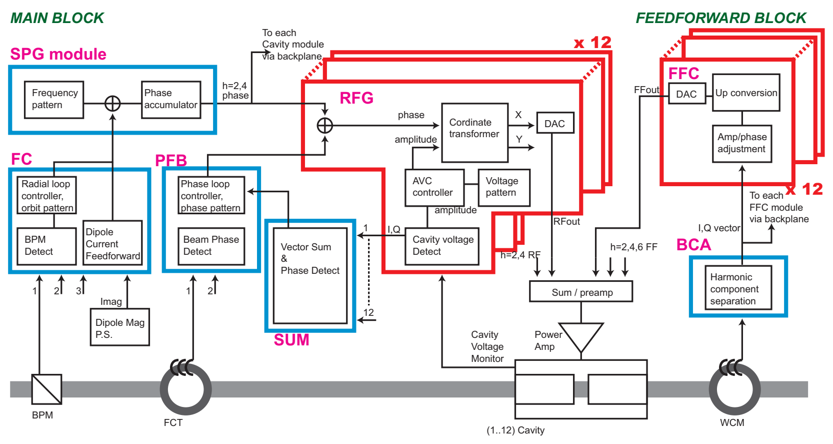
4. Summary and outlook

Existing LLRF control system



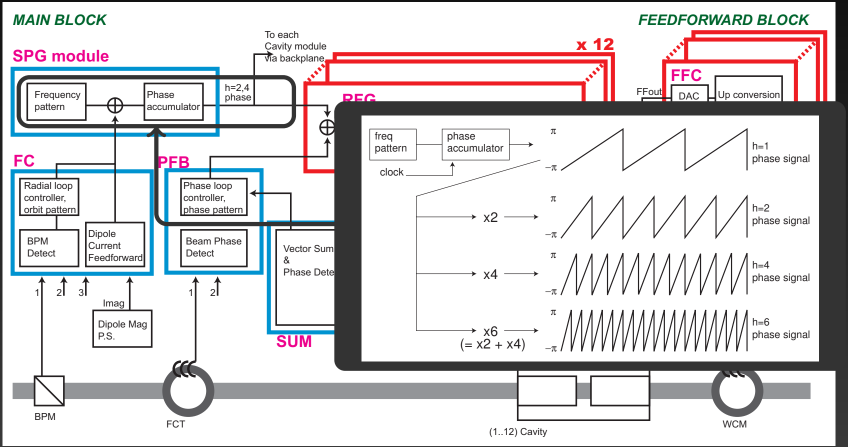
- Developed JFY 2003-2006, in operation since 2007
- Consists of specialized 9U height VME modules
  - P1: VME
  - P2, P3: specialized parallel bus for signal distribution
  - Virtex II pro and Spartan-II used
- System clock: 36 MHz

LLRF functions for RCS



- (Blue) common functions for whole system
- (Red) for each of 12 cavities

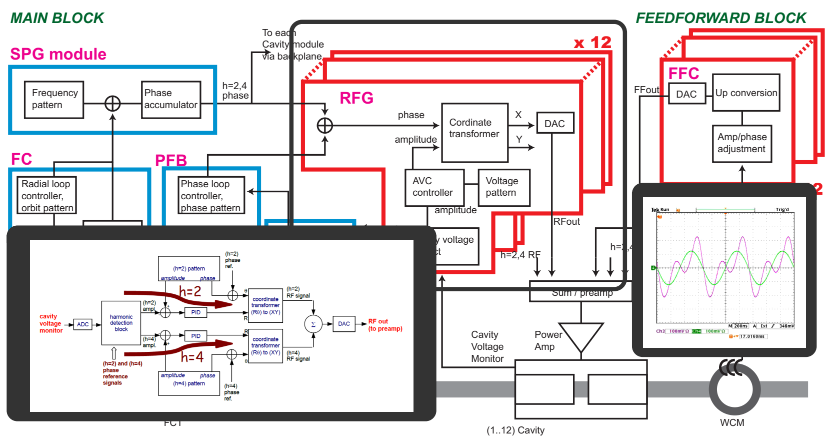
LLRF functions for RCS



For frequency sweep:

- Revolution frequency pattern
- Phase accumulator generates revolutional phase signal from −π to π. Multiplying h, higher harmonic phase signal generated
- h = 2, 4 phase signals distributed to modules

LLRF functions for RCS

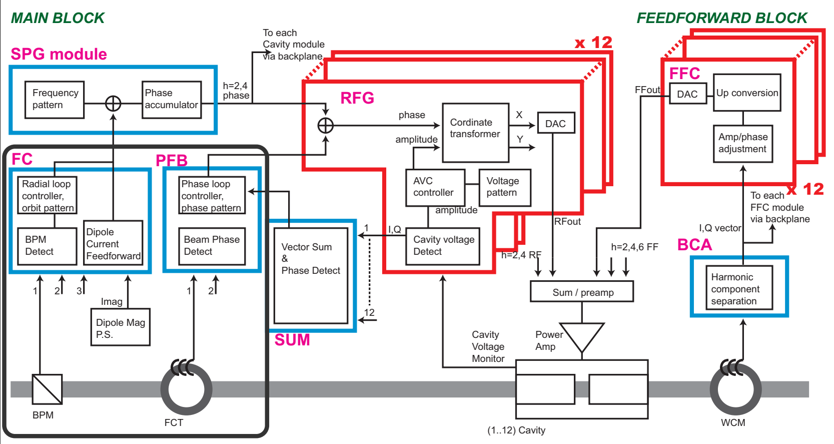


Dual harmonic cavity voltage control:

- for each of 12 cavities
- (Scalar) amplitudes of h = 2, 4 controlled by feedback loops

F. Tamura et al., Phys. Rev. ST Accel. Beams, vol. 11, 072001, 2008

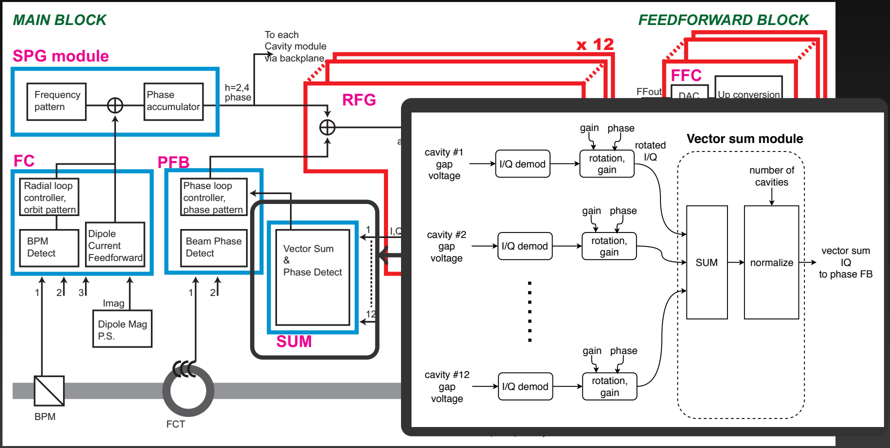
LLRF functions for RCS



Beam feedback loops:

- Radial loop for correction of frequency using BPM signal
  - Implemented but not used
- Phase loop for damp the longitudinal oscillations
  - Compares phases of beam and cavity vector sum

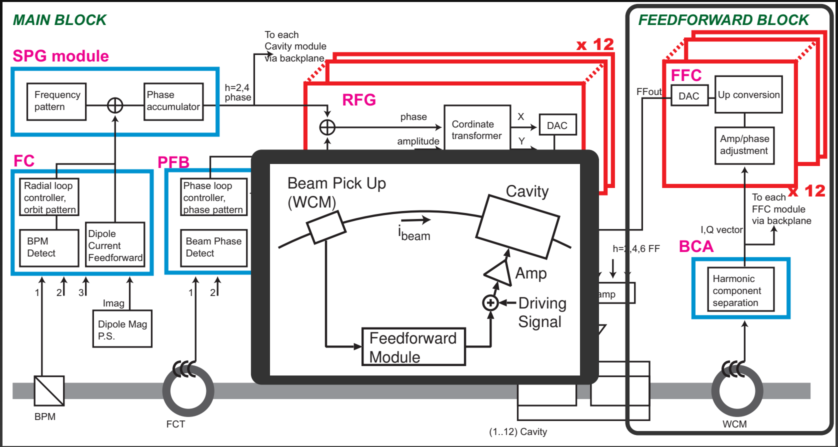
LLRF functions for RCS



Vector sum function:

- Detected I/Q cavity voltage of the harmonic is rotated and sent to the vector sum module
  - Rotation angle corresponds to the cavity position in RCS ring
- Summation signal is normalized by number of cavities

LLRF functions for RCS

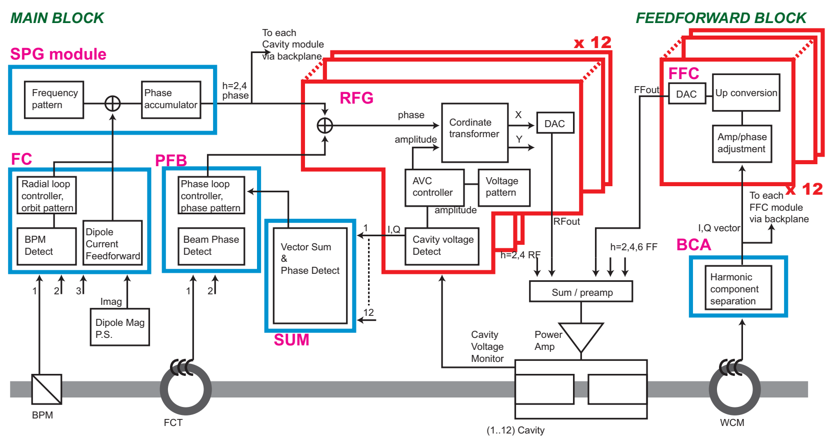


Multiharmonic feedforward for beam loading compensation:

- Pick up beam current signal by WCM
- FF compensation signal generated so that $-i_{beam}$ is fed to the cavity in addition to driving current, to cancel wake voltage. h = 1..6 are compensated

F. Tamura et al., Phys. Rev. ST Accel. Beams, vol. 14, 051004, 2011
F. Tamura et al., Phys. Rev. ST Accel. Beams, vol. 18, 091004, 2015

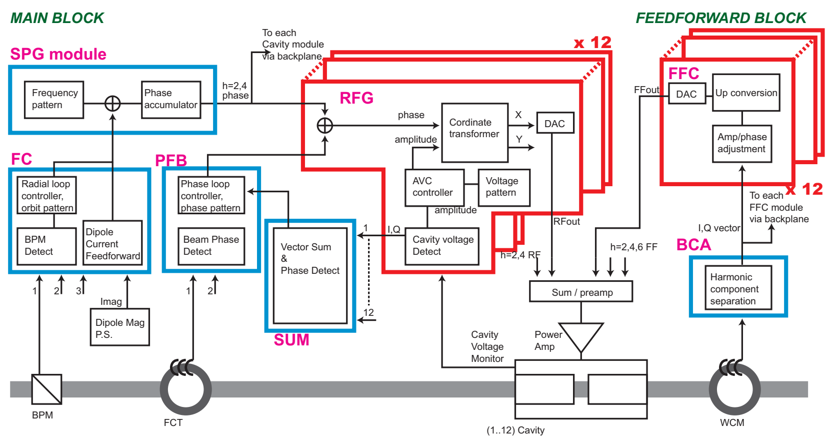
LLRF functions for RCS



Miscellaneous functions (not shown in diagram):

- Kicker trigger, linac chopper gate pulse generation
- Revolution clock for measurement

LLRF functions for RCS



The existing system has been working well without major problems for more than ten years.

Why new system?

Although the existing system working well…

- Old FPGAs (Xilinx Virtex-II pro and others) used in the modules are already discontinued and not supported by the current development environment
- We have spare modules, but it will be difficult to maintain the system in near future

Therefore, we decided to develop new system.

Considerations:

- All functions except radial loop to be implemented
- Generic FPGA module + I/O module for specific function preferred
  - Existing modules are different for functions
  - Easier management of spares expected

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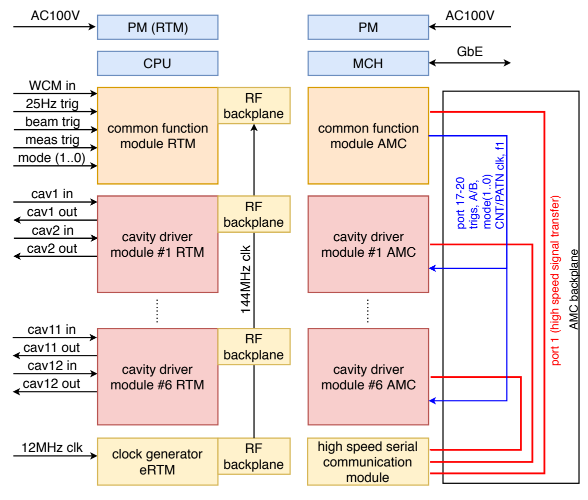
System overview

MicroTCA.4 is employed for next generation system.



System clk:

- 144 MHz (existing: 36 MHz)
- generated by clock gen eRTM, distributed via DESY-type rf backplane

Modules classified into two categories:

- Common function module: frequency pattern, phase FB, ...
- Cavity driver: rf gen for cavities, feedforward driver

A special module in MCH2 slot:

- High speed serial communication module, detail described later

System overview

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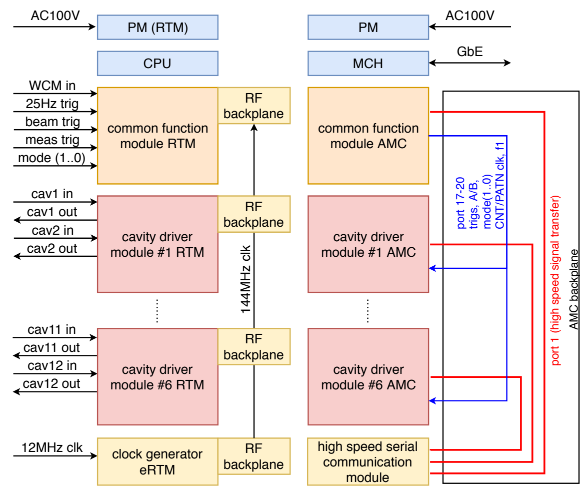

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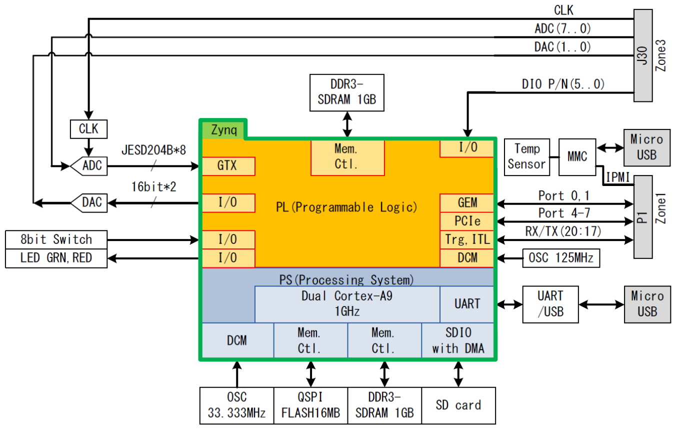
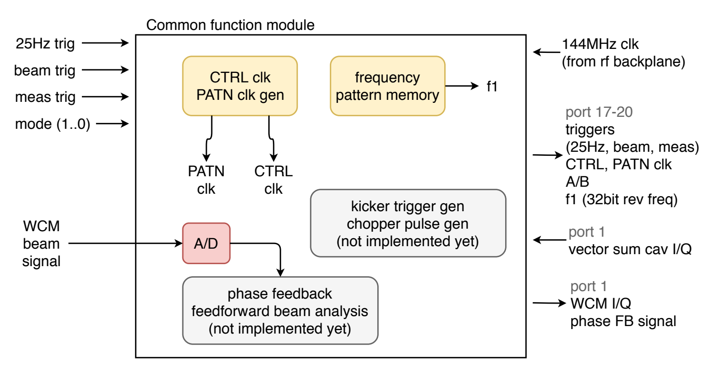
Multipurpose AMC by Mitsubishi Electric TOKKI systems



- Modern SoC FPGA, Xilinx Zynq XC7Z045
  - EPICS IOC with Linux embedded, setting / monitoring by CA
  - I/Q Waveform monitor is useful for commissioning
- 1 GB SDRAM used as pattern memory
- 8x ADC, 2xDAC
  - An AMC can handle two cavities

Common function module

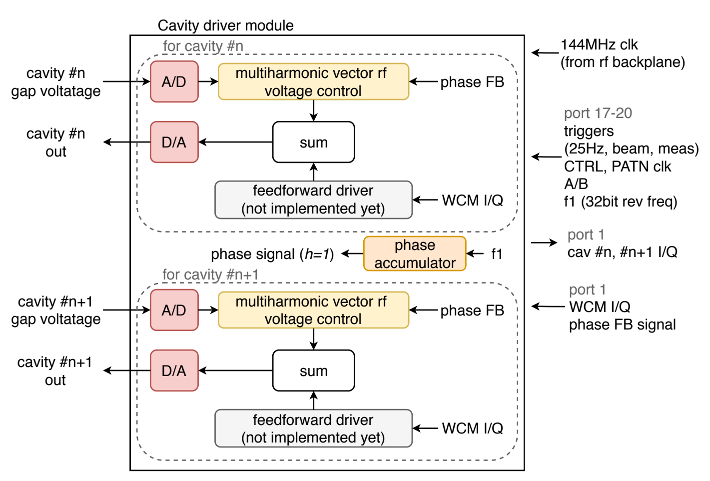


- Receives triggers/modes. Generates CTRL/PATN clocks. Distributed to modules via backplane
- Revolution frequency pattern memory, f_1 distributed to the modules
  - Existing system: phase signals (h = 2, 4)
  - More flexibility for multiharmonic rf generation in cavity drivers

Below are not implemented yet:

- Phase feedback, WCM beam signal analysis for rf feedforward
- Miscellaneous functions (kicker trigger / chopper pulse generation)

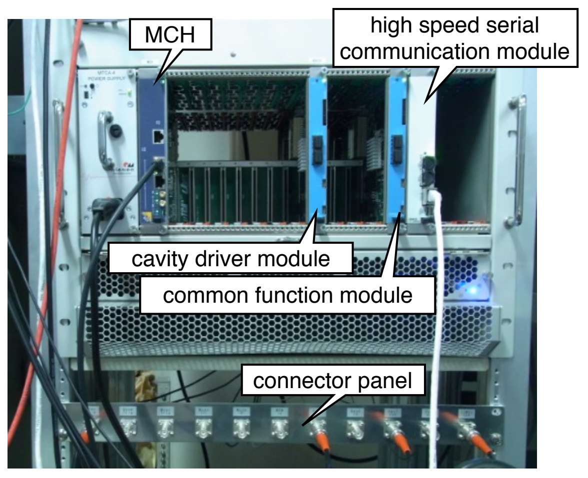
Cavity driver module



- Can control two cavities, thanks to logic capacity of modern FPGA
- Phase accumulator generates phase signal
- Multiharmonic vector rf voltage control and feedforward (not implemented yet)

Current status

The system was built in JFY 2017.



We have at present:

- Infrastructures (shelf, PM, CPU, MCH)
- 1x common function module
- 1x cavity driver module
- 1x high speed serial communication module

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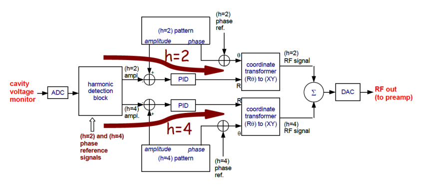
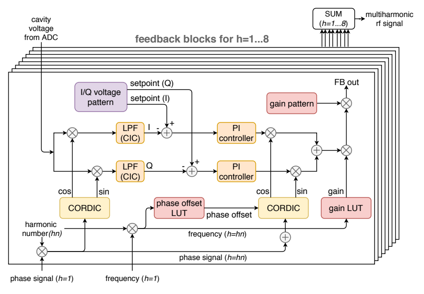
Key features (1): multiharmonic vector rf voltage control



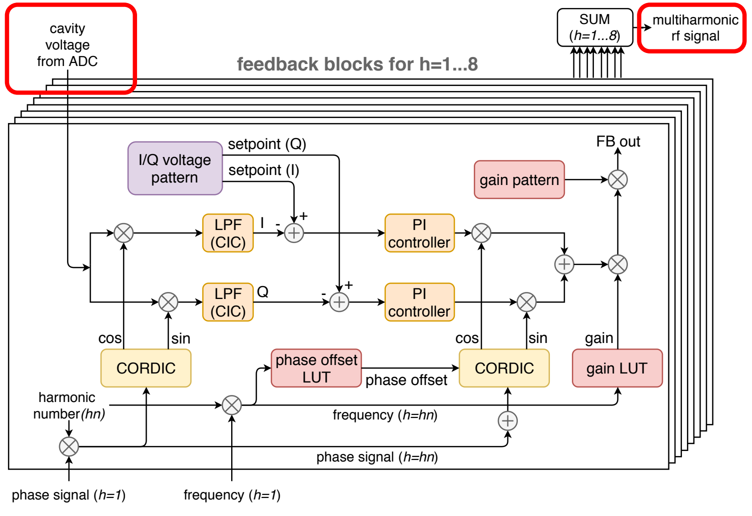


Existing system: dual harmonic, scalar amplitude control

→ New: multiharmonic vector rf voltage control

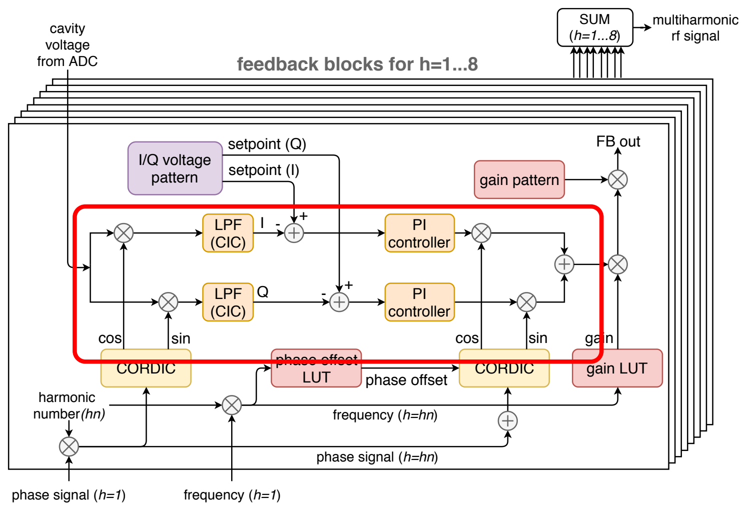
- Number of harmonics increased, thanks to capacity of Zynq
- Phase control possible
- can compensate beam loading

Key features (1): multiharmonic vector rf voltage control



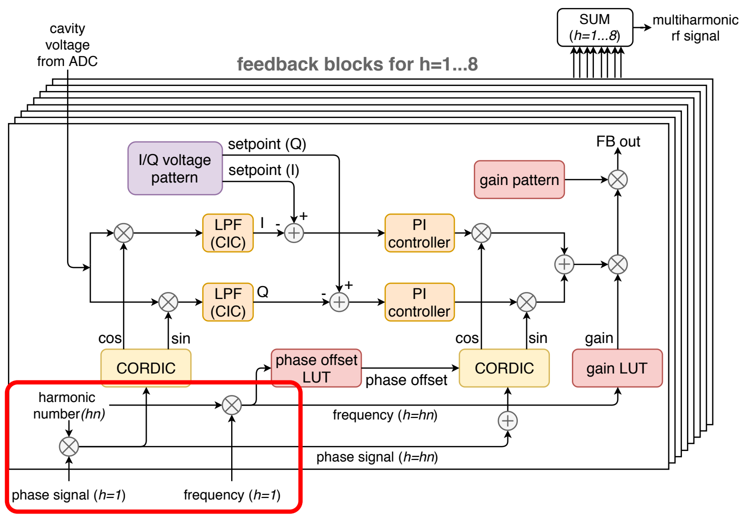
Input: cavity voltage, output: multiharmonic rf signal.
Eight FB blocks (h = 1..8).

Key features (1): multiharmonic vector rf voltage control



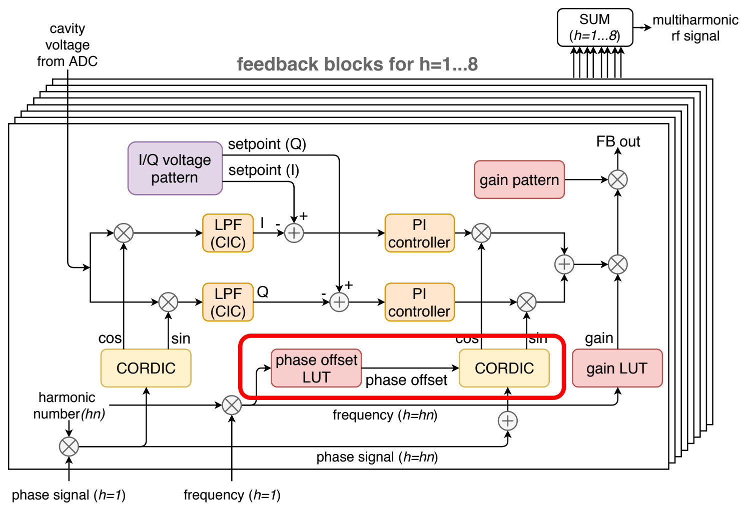
Well-known I/Q feedback structure:
I/Q demodulator, setpoint, PI control, and I/Q modulator.

Key features (1): multiharmonic vector rf voltage control



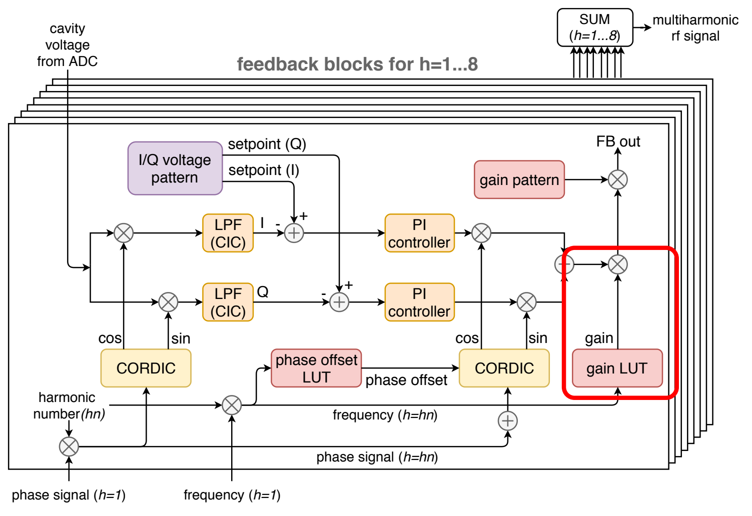
Phase signal and frequency of the selected harmonic obtained by multiplying revolution phase signal and f1 with harmonic number hn. Used for I/Q demod/mod and addressing of LUT. LUTs are necessary for frequency sweep.

Key features (1): multiharmonic vector rf voltage control



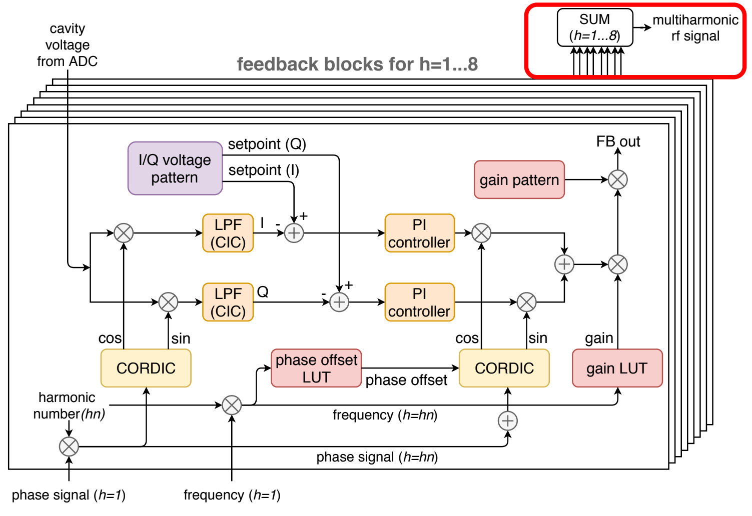
Phase offset LUT gives phase offset between I/Q demodulator and modulator, to control phase transfer function as well as to compensate frequency response of 1-turn transfer function.

Key features (1): multiharmonic vector rf voltage control



Gain LUT compensates cavity frequency response.

Key features (1): multiharmonic vector rf voltage control



Finally, multiharmonic rf signal obtained by summing up the signals from blocks.

Multiharmonic rf generation

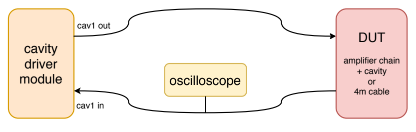
Demonstration of multiharmonic rf generation: Sawtooth wave

Fourier series of a sawtooth wave up to m-th harmonic:

$$f(t) = \frac{2}{\pi} \sum_{h=1}^{m} \frac{(-1)^{h+1}}{h} \sin h\omega_1 t$$

- ω_1: revolution angular freq
- Unity amplitude
- h: harmonic number

Test setup:



- DUT: amplifier chain + cavity

For m = 8,

$$f(t) = \frac{2}{\pi}\left(\sin \omega_1 t - \frac{1}{2}\sin 2\omega_1 t + \frac{1}{3}\sin 3\omega_1 t \cdots - \frac{1}{8}\sin 8\omega_1 t\right)$$

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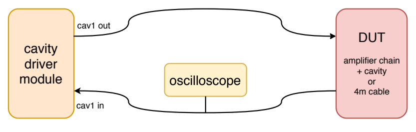

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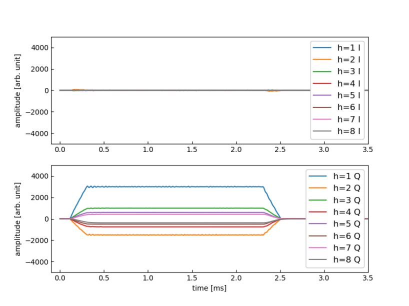
Multiharmonic rf generation

Measured I/Q amplitude:



Waveform comparison, calc/meas:

- $\omega_1 = 2\pi \cdot 1$ MHz
- $(I_1, Q_1) = (0, 3000)$ for $h = 1$, higher harmonics according to the equation
- Measured amplitudes close to the set points
- Calc and meas waveforms agree very well

Multiharmonic rf generation

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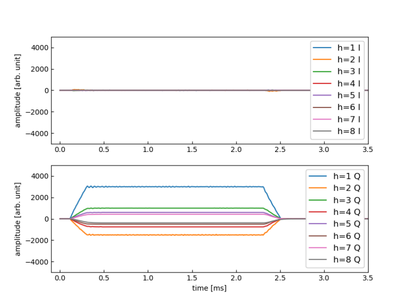

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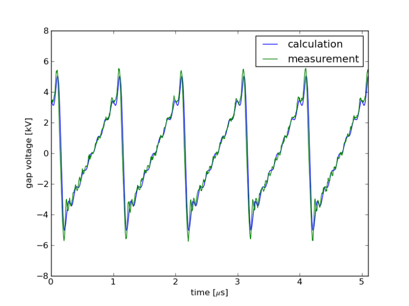

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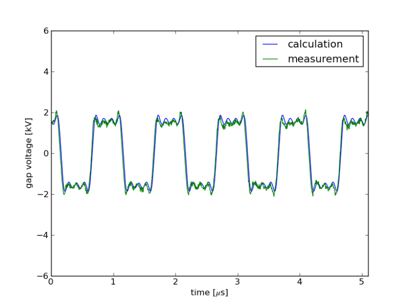
Multiharmonic rf generation

Fourier series of a square wave (h = 2n – 1):

$$f(t) = \frac{4}{\pi}\sum_{n=1}^{m}\frac{1}{2n-1}\sin(2n-1)\omega_1 t$$

$$= \frac{4}{\pi}\left(\sin\omega_1 t + \frac{1}{3}\sin 3\omega_1 t + \frac{1}{5}\sin 5\omega_1 t + \frac{1}{7}\sin 7\omega_1 t\right)$$

Waveform comparison, calc/meas:



Multiharmonic vector rf control works nicely:

- Existing system: dual harmonic (h = 2, 4), scalar amplitude control
- New system: eight harmonics, vector control
  - Bunch shaping using third/fourth (h = 6, 8) harmonics in addition to second (h = 4) harmonic is possible
  - Beam loading compensation done by voltage control (existing: FF only)

Multiharmonic rf generation

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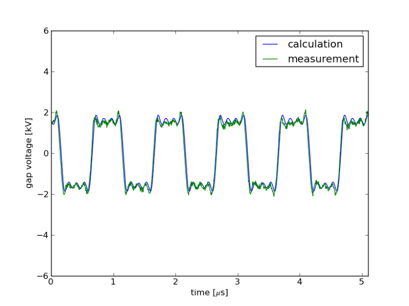

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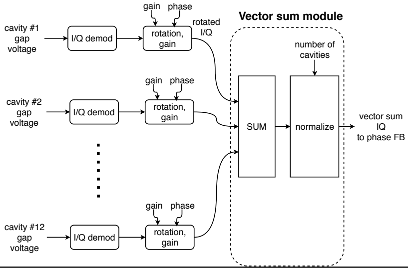
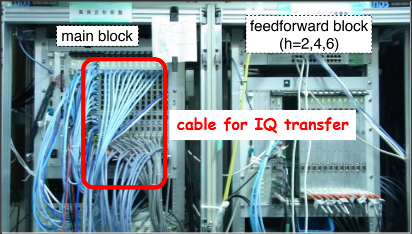
Key features (2): high speed serial communication

Vector sum:





Signal transfer is star topology.

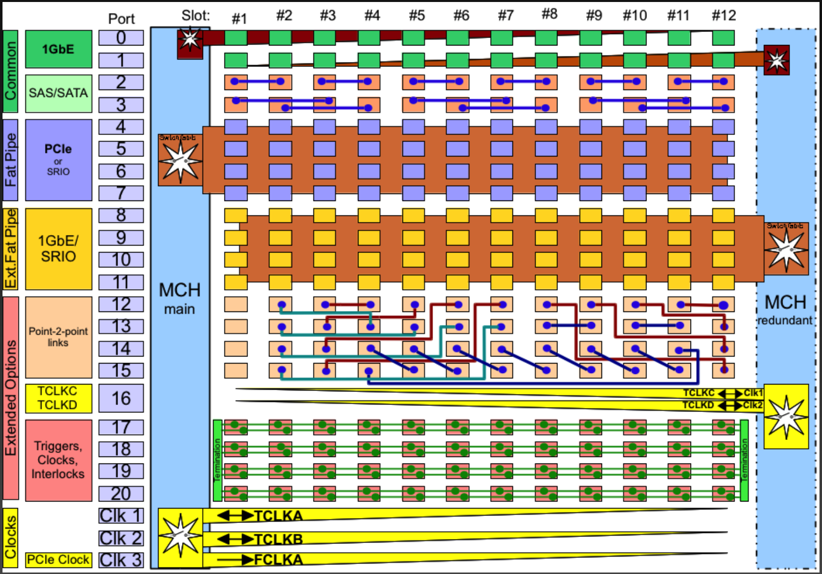
- Vector sum:
  Cavity IQs (drivers)
  → vector sum → phase FB
- Phase FB signal (common)
  → volt control (driver modules)

Existing system uses cables and parallel backplane.

- Not very sophisticated

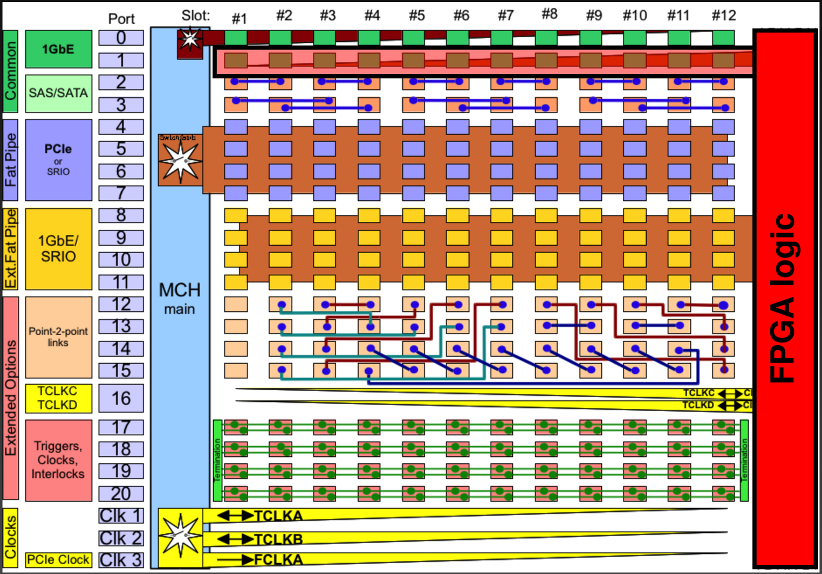
How can we realize star topology with MicroTCA.4?

Key features (2): high speed serial communication



- There are no trivial star-like connections among AMCs
- Idea: putting FPGA logic in MCH2 slot and using Port1, although it sacrifices redundancy of MCH

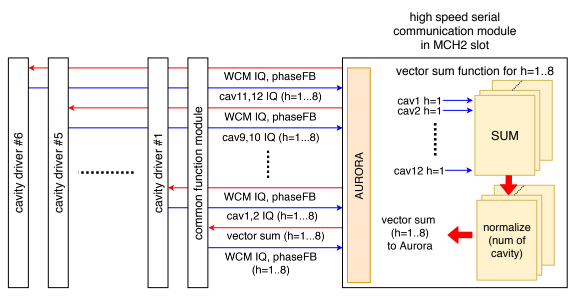
Key features (2): high speed serial communication



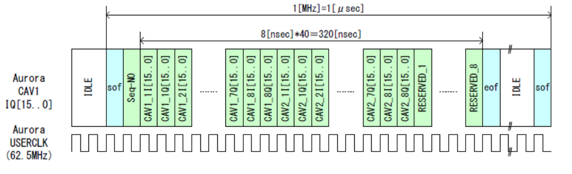
- There are no trivial star-like connections among AMCs
- Idea: putting FPGA logic in MCH2 slot and using Port1, although it sacrifices redundancy of MCH

Key features (2): high speed serial communication

Signal flow using Port1:



Aurora data format:



High speed serial communication module:

- Virtex-5 used
- Gathers and delivers signals from/to cavity driver modules and common function module
- Vector sum function implemented

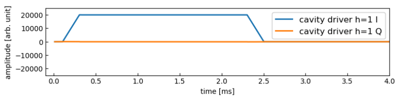
Xilinx Aurora used:

- 1 data frame contains 40 data blocks of 16-bits
- Enough for sending 2x cavities' I/Q signals of 8x harmonics
- Sent every control clock (1 MHz)

Vector sum function test with various setting

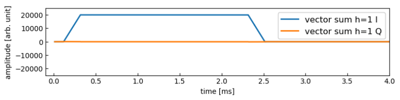
Cavity driver I/Q signal:

(I, Q) = (20000, 0)



Vector sum received by common module:

(1) no rotation, normalized by 1



→ Received I/Q signal identical to cavity driver

- DUT: 4 m cable
- Cav1 (I, Q) = (20000, 0), cav2 (I, Q) = (0, 0)
- Cavity driver
  → communication module (vector sum)
  → common module

This simple test proves that the vector sum function works as expected.

Vector sum function test with various setting

Cavity driver I/Q signal:

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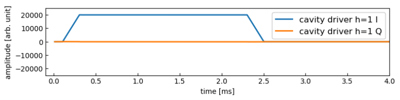

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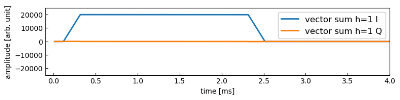
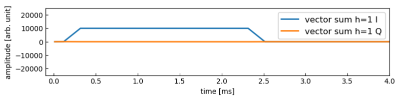


→ Received I/Q signal identical to cavity driver

(2) no rotation, normalized by 2



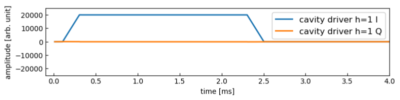
→ Received amplitude is half

This simple test proves that the vector sum function works as expected.

Vector sum function test with various setting

Cavity driver I/Q signal:

(I, Q) = (20000, 0)



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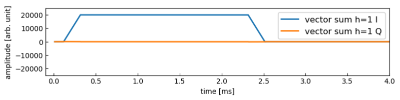

→ Received I/Q signal identical to cavity driver

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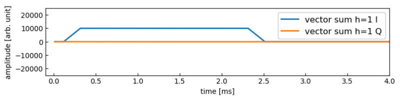
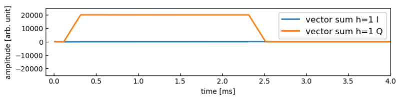


→ Received amplitude is half

(3) 90 deg rotation, normalized by 1



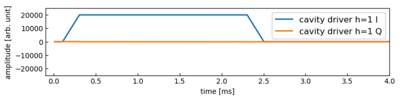
→ (0, 20000) received

This simple test proves that the vector sum function works as expected.

Vector sum function test with various setting

Cavity driver I/Q signal:

(I, Q) = (20000, 0)



- DUT: 4 m cable
- Cav1 (I, Q) = (20000, 0), cav2 (I, Q) = (0, 0)
- Cavity driver
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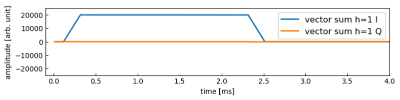
  → common module

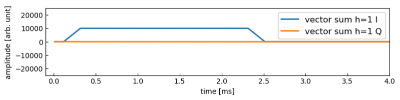
Vector sum received by common module:

(1) no rotation, normalized by 1



→ Received I/Q signal identical to cavity driver

(2) no rotation, normalized by 2



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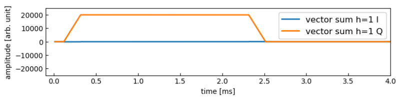
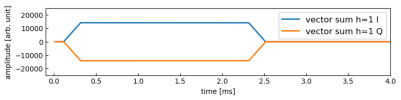


→ (0, 20000) received

(4) −45 deg rotation, normalized by 1



→ close to (14142, −14142), $20000 \times 1/\sqrt{2}$

This simple test proves that the vector sum function works as expected.

Vector sum function test with various setting

Cavity driver I/Q signal:

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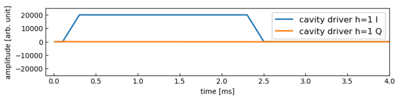
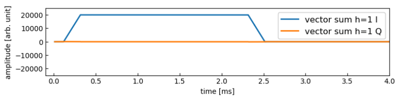


- DUT: 4 m cable
- Cav1 (I, Q) = (20000, 0), cav2 (I, Q) = (0, 0)
- Cavity driver
  → communication module (vector sum)
  → common module

Vector sum received by common module:

(1) no rotation, normalized by 1



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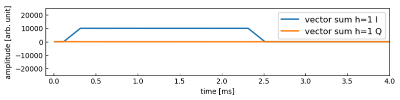
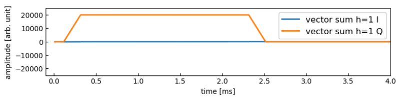


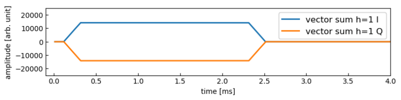
→ Received amplitude is half

(3) 90 deg rotation, normalized by 1



→ (0, 20000) received

(4) −45 deg rotation, normalized by 1



→ close to (14142, −14142), $20000 \times 1/\sqrt{2}$

This simple test proves that the vector sum function works as expected.

SUMMARY AND OUTLOOK

- NEW SYSTEM SEEMS PROMISING
- 5x CAVITY DRIVER WILL BE BUILT, REMAINING FUNCTIONS TO BE IMPLEMENTED
- HOPEFULLY NEW SYSTEM WILL SERVE 1MW OPERATION, AND OPERATION BEYOND THE DESIGN BEAM POWER