LLRF07, Knoxville, 2007/10/24

LLRF control systems for J-PARC synchrotrons

J-PARC Ring-RF Group

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Overview

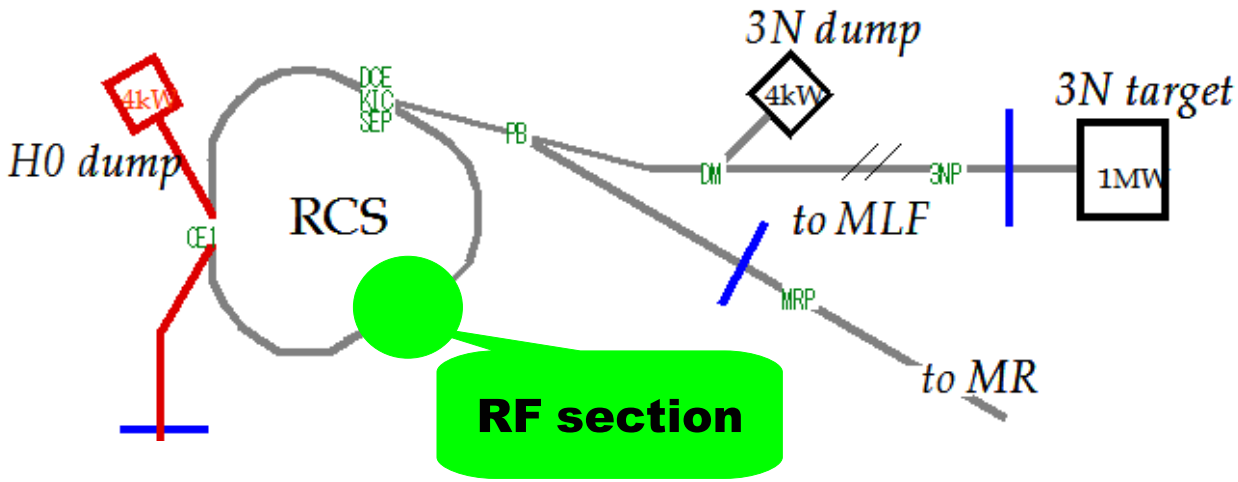
- Introduction
  - J-PARC accelerators, status
  - Synchrotron RF parameters and features
- The LLRF system, and selected features
  - RCS and MR LLRF system
  - Software
  - Dual-harmonic AVC for RCS, high-power test results
- Summary

J-PARC complex

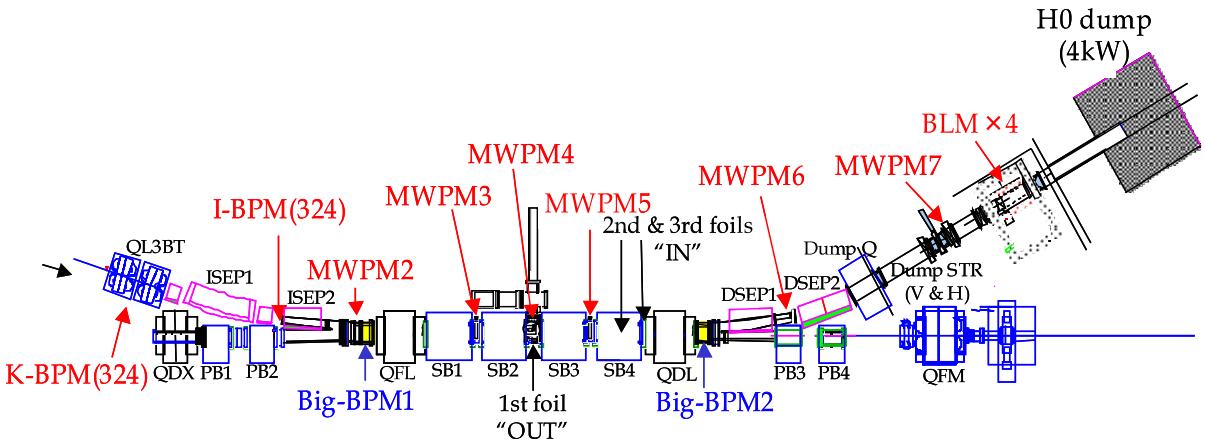
RCS beam commissioning began in October 2007,
MR first beam is to be in May 2008.

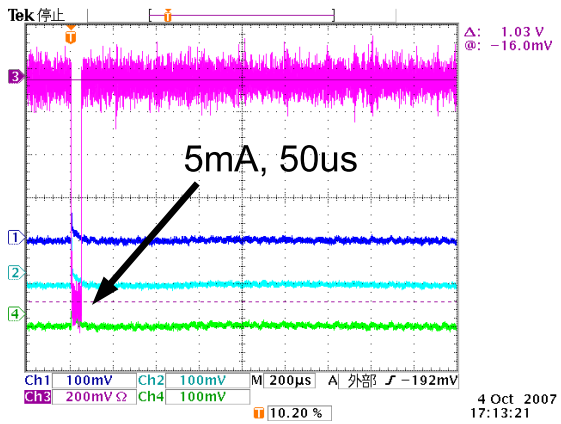
RCS status

The first run was injection orbit commissioning.



- the beam will be circulating from end of this week
- Nov.–Dec.: 3 GeV acceleration





Beam has not come to RF section yet!

Synchrotron RF systems (1)

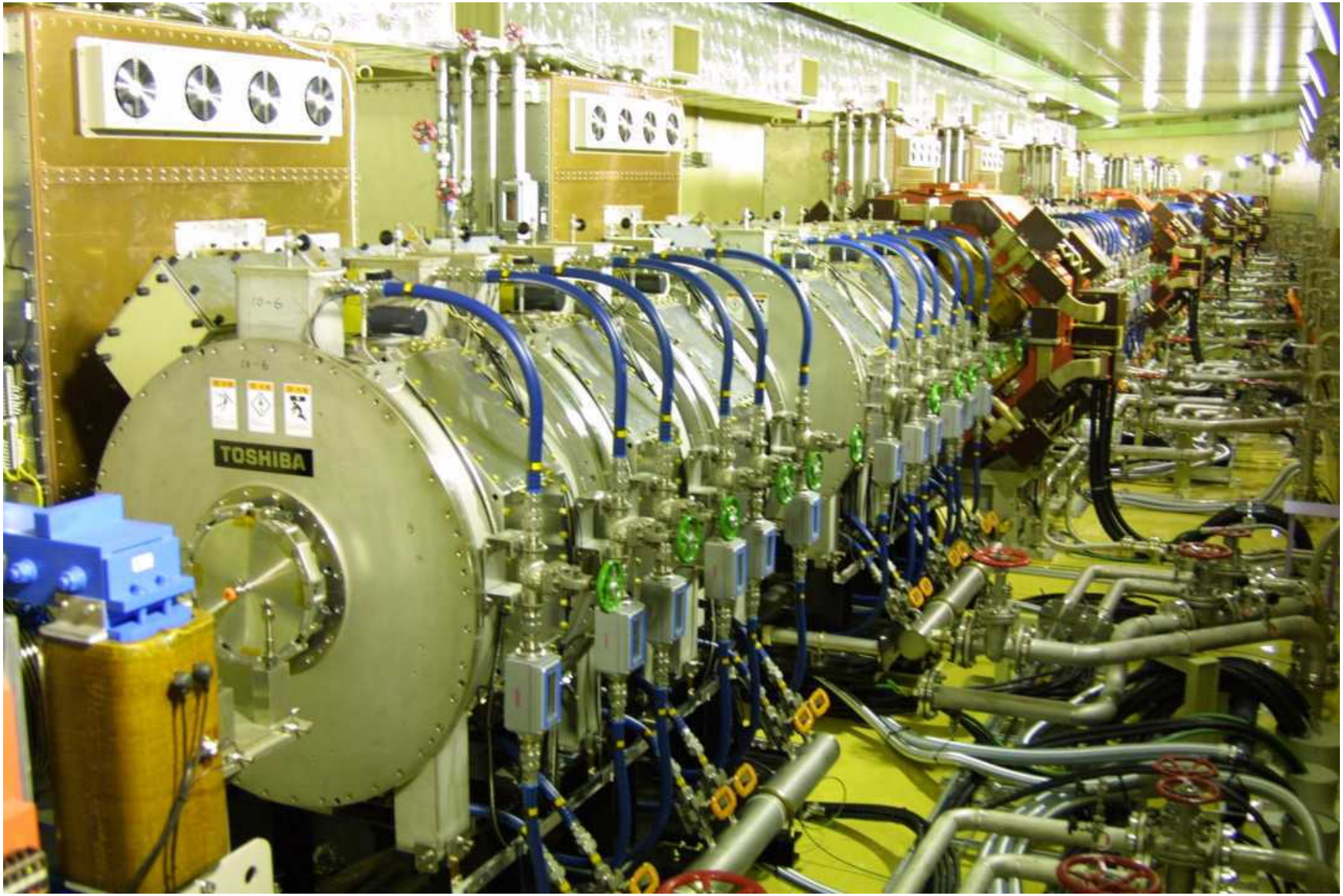
parameter	RCS	MR
circumference	348.3 m	1567.9 m
energy	0.181–3 GeV	3–50 GeV
accel. freq.	0.94–1.67 MHz	1.67–1.72 MHz
harmonic number	2	9
max circ. beam current	11 A	12.7 A
max RF-voltage	450 kV	280 KV
repetition period	40 msec	3.64 sec
duty (power)	30%	60%
No. of cavities	12 (10)	6 (5)
Q-value	2	20
No. of gaps	3 per cavity	3 per cavity
average power	120 kW/cavity	240 KW/cavity

Table 1: Parameters of the J-PARC synchrotron RF

Synchrotron RF systems (2)

- Ultra-high intensity proton beam:
  - Magnetic Alloy (MA) loaded cavities for high accelerating voltages (25 kV/m)
    - more than twice as ferrite cavities (10kV/m)
  - full-digital LLRF control systems: stable, precise control

Synchrotron RF systems (3)



Cavities and tube amplifiers in the RCS tunnel

LLRF for synchrotrons (1)

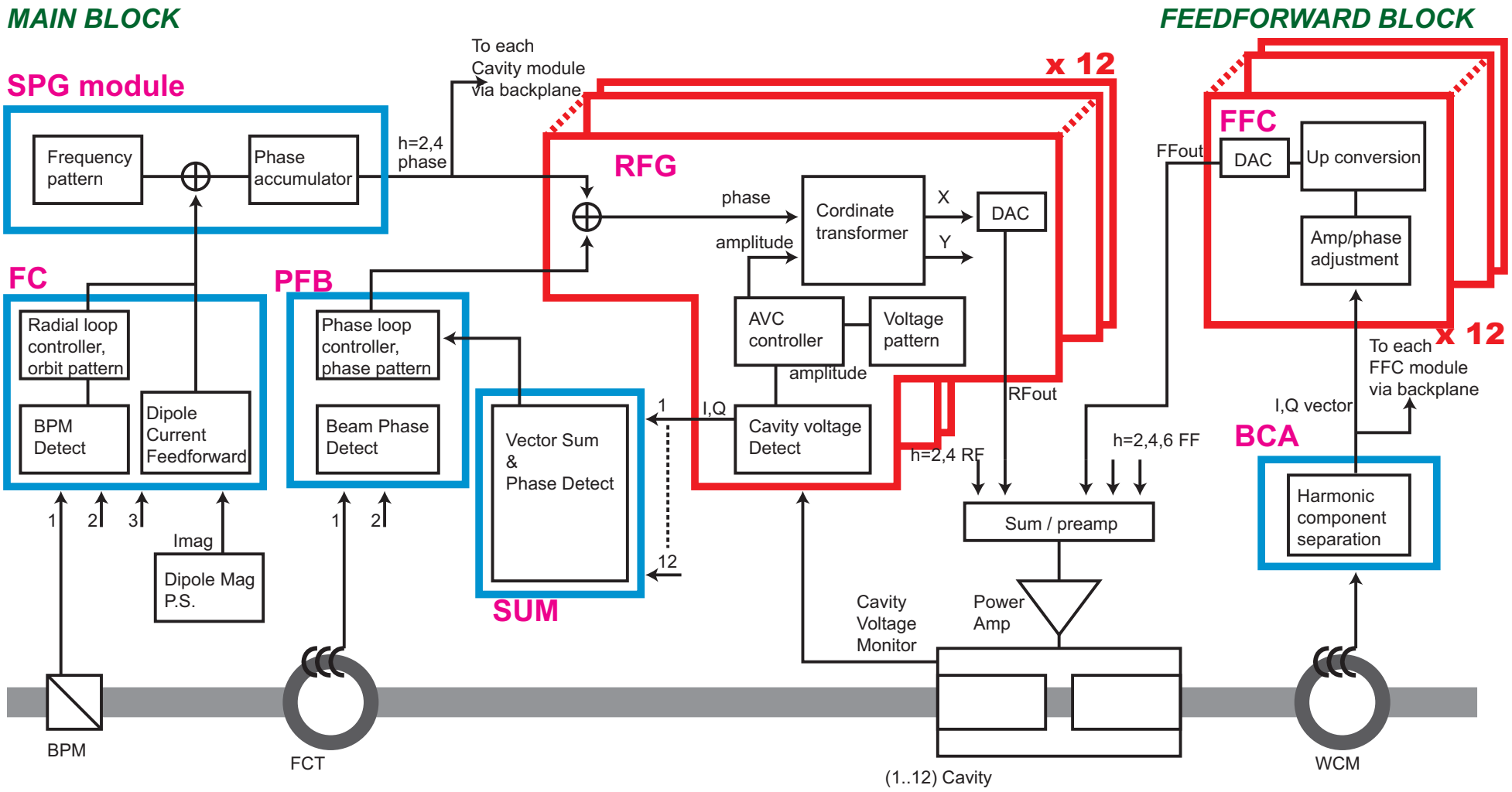
- Cavity Q-value:
  $Q = 2$ for RCS, $Q = 20$ for MR
  - no tuning loop for covering the frequency sweep
- RCS: cavity is driven by dual-harmonic
- MR: single-harmonic cavity ($h = 9$), adding the second harmonic cavity is planned. Due to empty bucket, ($h = 8$) and ($h = 10$) wake voltages are induced
- Both: beam-loading compensation is multi-harmonic

The LLRF systems are designed for handling multi-harmonic RF signals.

LLRF for synchrotrons (2)

- LLRF functions:
  - DDS (direct digital synthesis)-based multi-harmonic RF generation for cavity drive and signal detection
  - Common feedbacks for stabilizing the beam
    - AVC, cavity voltage control
    - phase FB (RF phase)
    - radial FB (frequency)
  - Beam feedforward system for compensating the heavy beam loading
  - misc. functions; synchronization, chopper timing

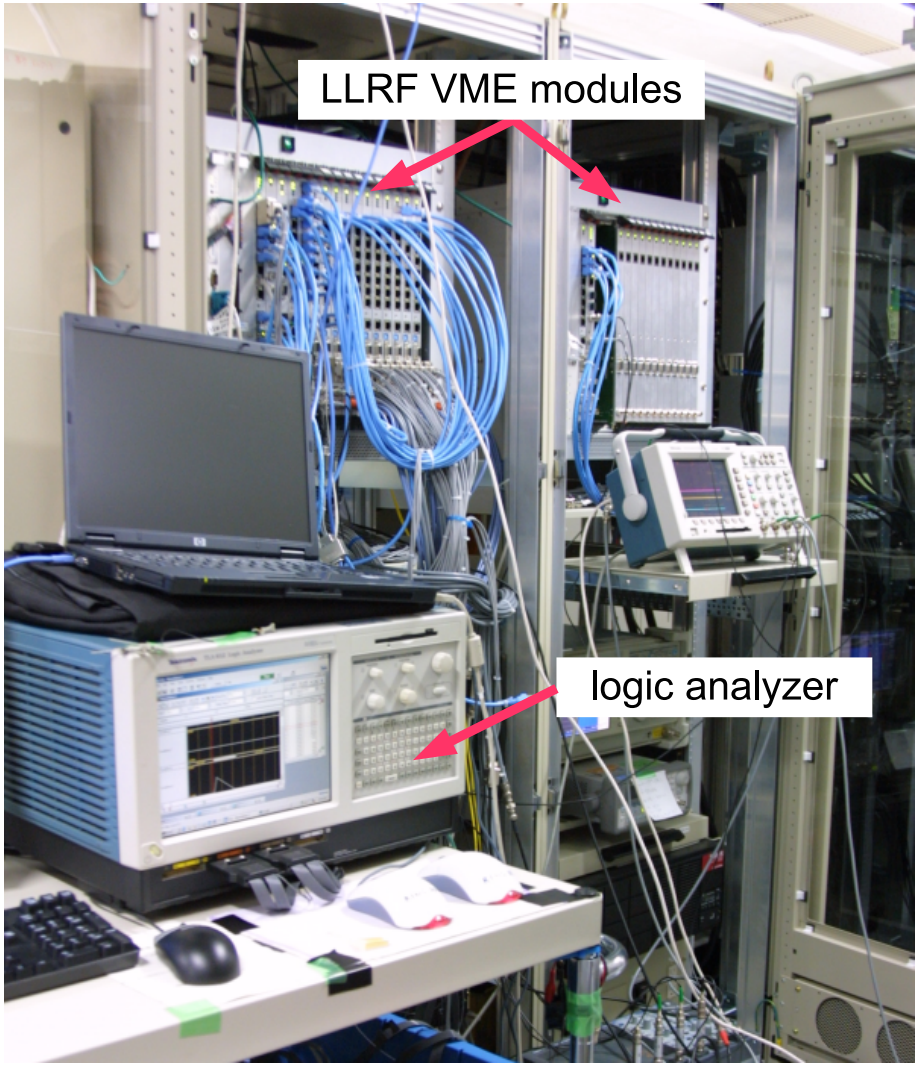
LLRF for synchrotrons (3)

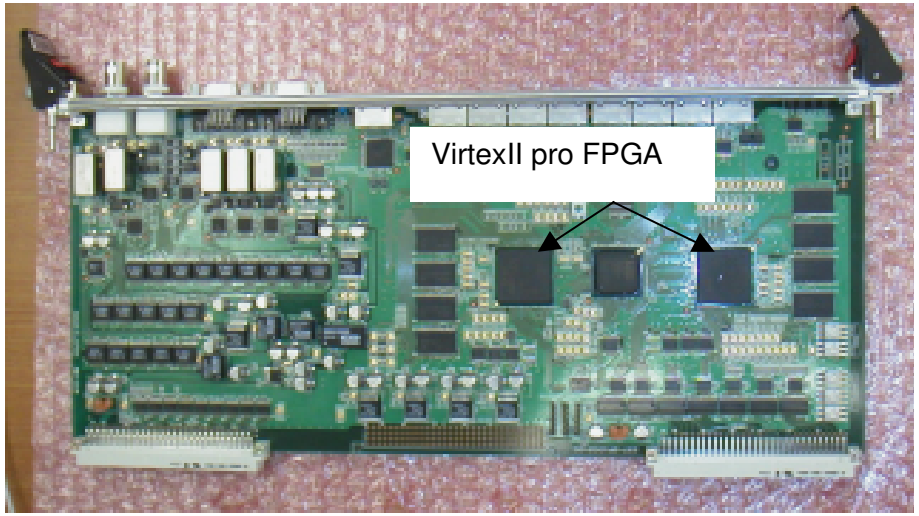


Block diagram of RCS LLRF system (MR LLRF has similar blocks)

Blue: common for the whole system, Red: for each of the 12 cavities

LLRF for synchrotrons (4)



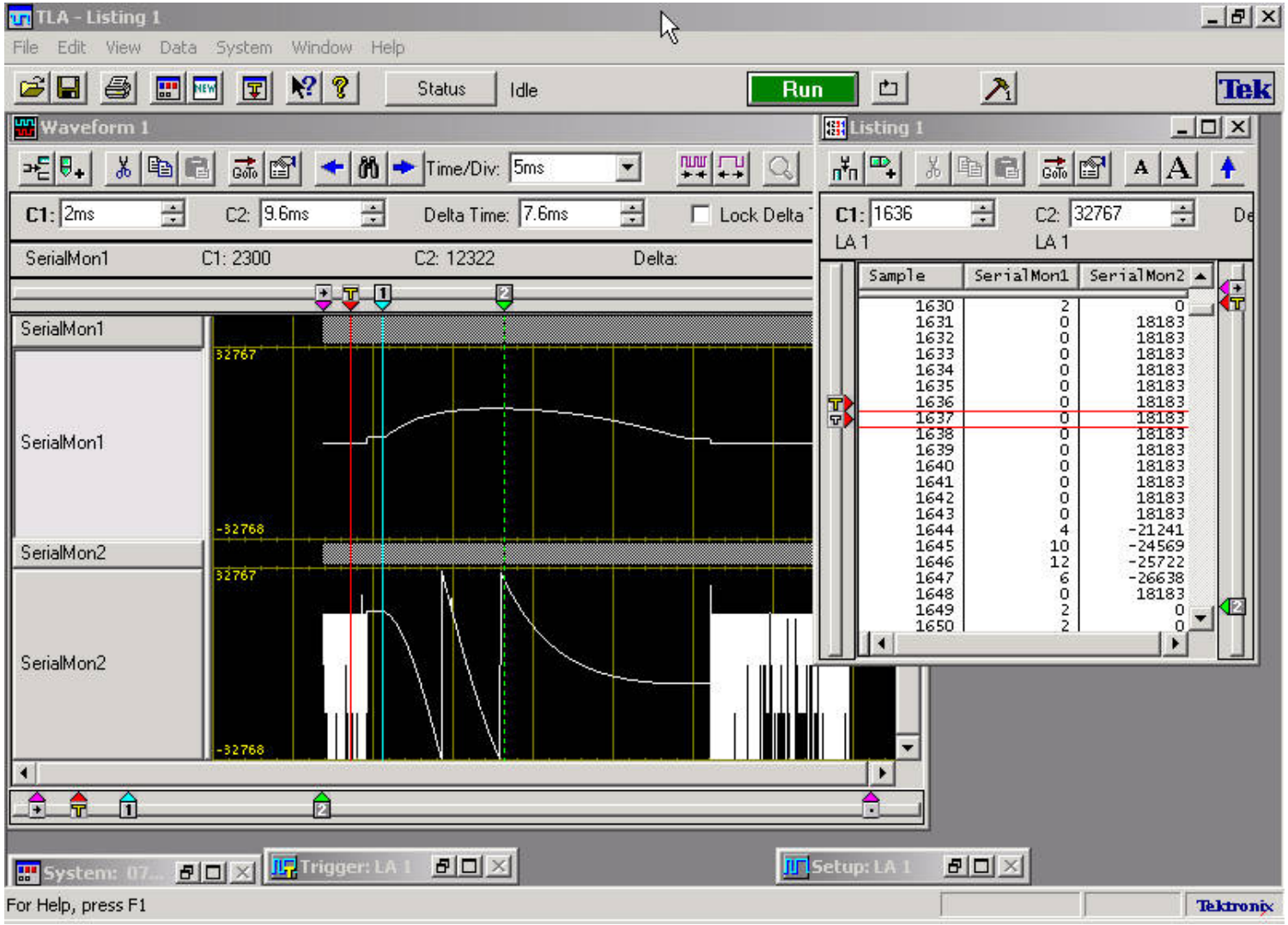


RFG board

- RCS hardware completed, MR ongoing
- VME based, 9U boards
- FPGA (Virtex-II etc.)
  - strong computing power

LLRF for synchrotrons (5)

- Digital monitor outputs are watched by the logic analyzer
  - Strong visualization tool for debugging and commissioning



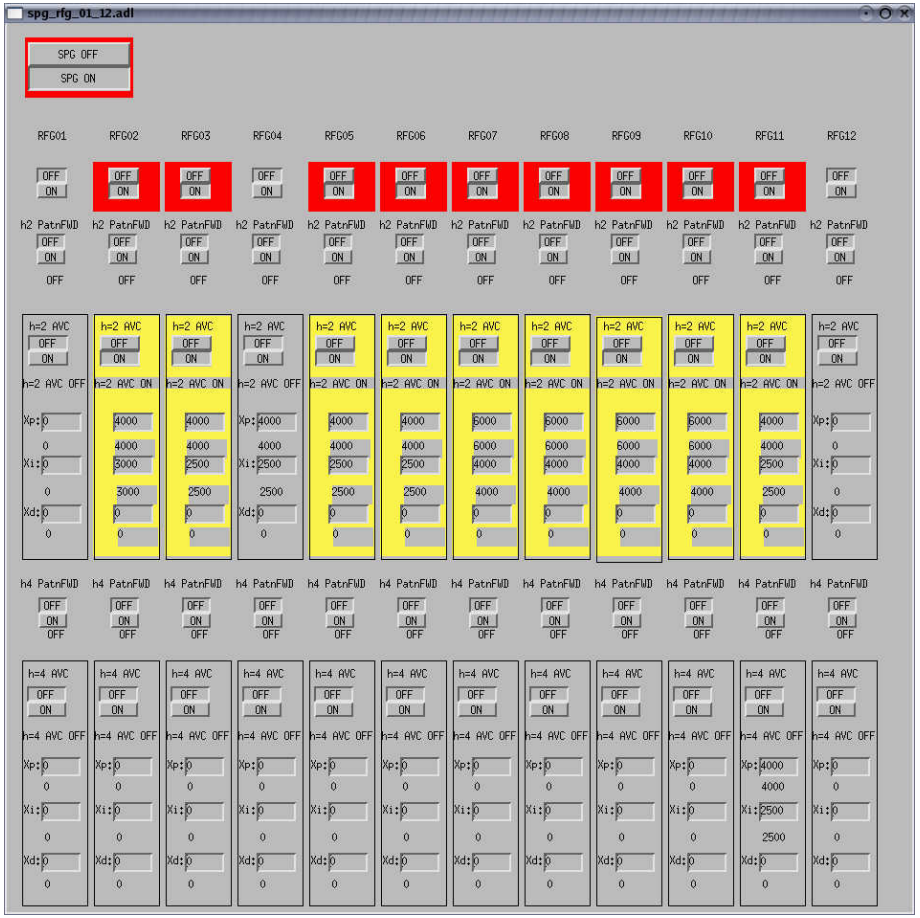
Software (1)

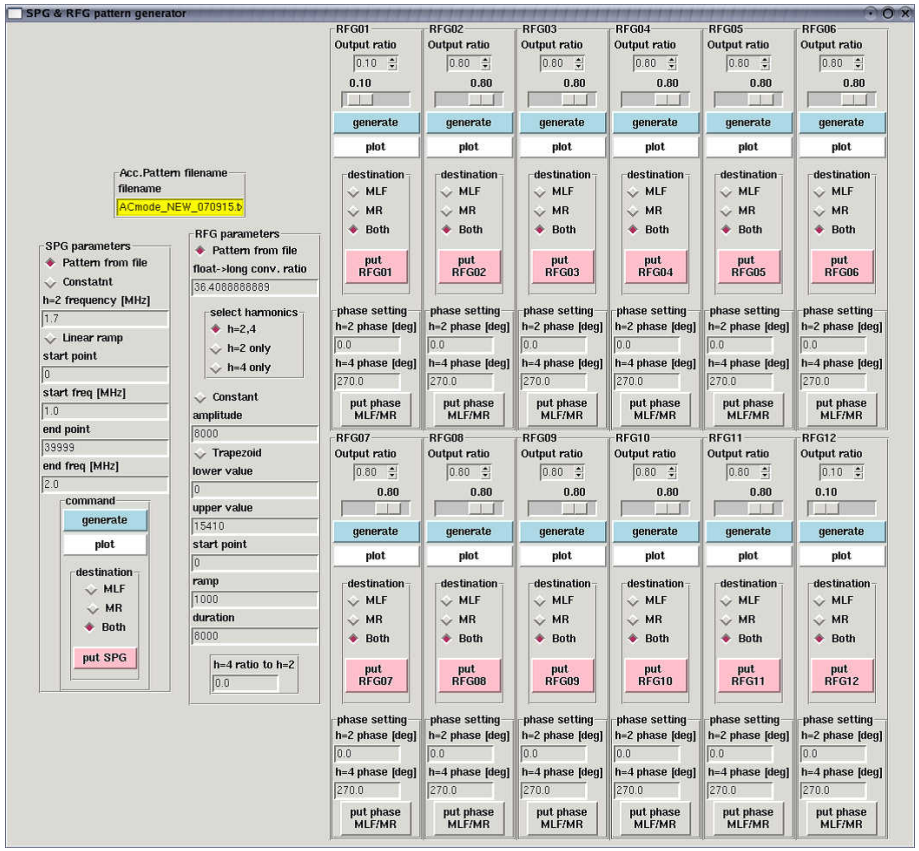
- System is controlled by using EPICS, as well as the other subsystems of J-PARC
  - Setting parameters, monitoring
  - EPICS device support: developed with hardware by company (Nichizou)
  - OPI, GUI: by J-PARC (Tamura)
    - Python-CA, easy / fast programming
    - medm

Software (2)

Example 1:

AVC parameter setting (medm)





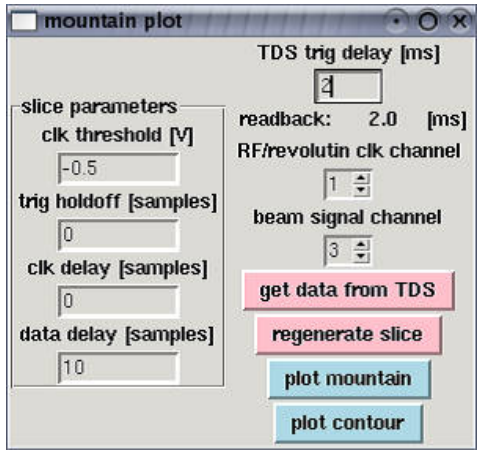
Example 2:

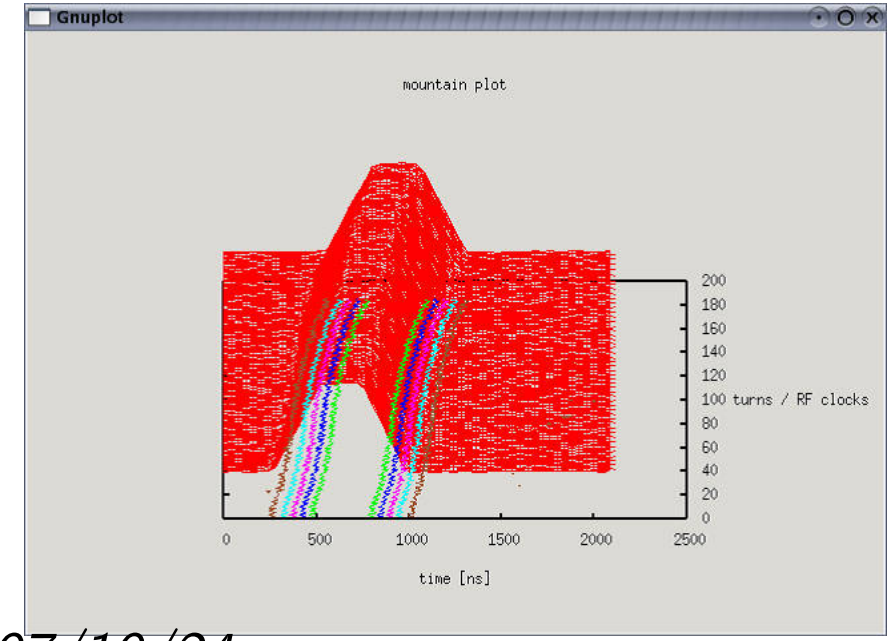
freq/voltage pattern generator (python-CA)

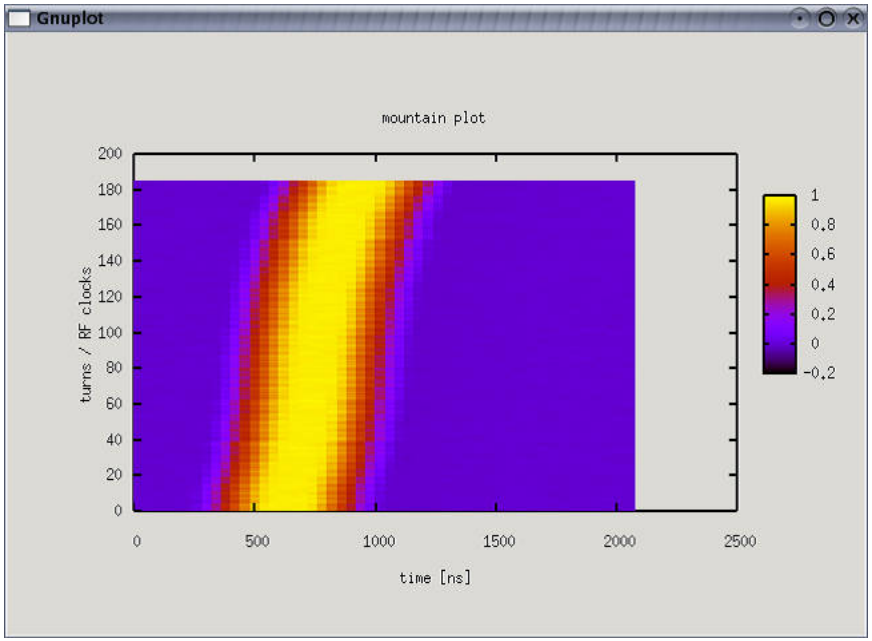
Software (3)

Example 3:

Mountain plot





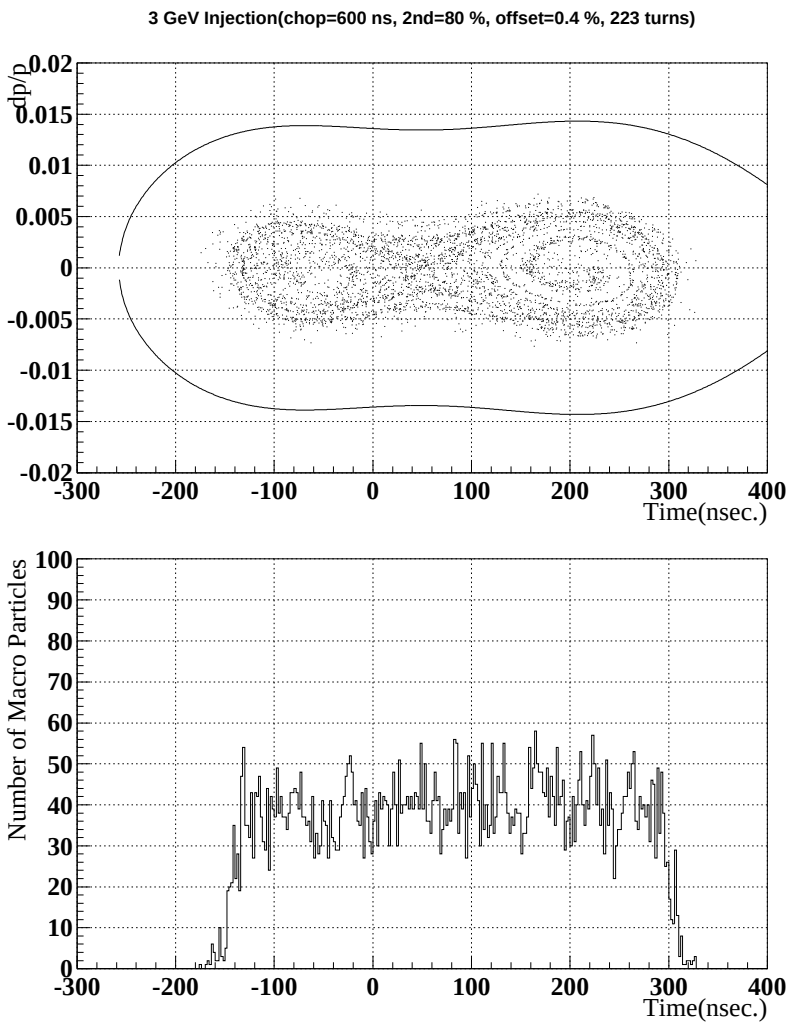


- Waveforms from TDS3014B are received via EPICS CA
- This is a simulated beam signal by a function generator

Dual-harmonic AVC (1)

- RCS: wide-band cavity, $Q = 2$
  - No tuning loop
  - A single cavity is driven by the superposition of multi-harmonic RF signals
    - the fundamental RF ($h = 2$): for acceleration of the beam
    - the second harmonic RF ($h = 4$): for the bunch shape control by modifying the RF bucket.

Dual-harmonic AVC (2)

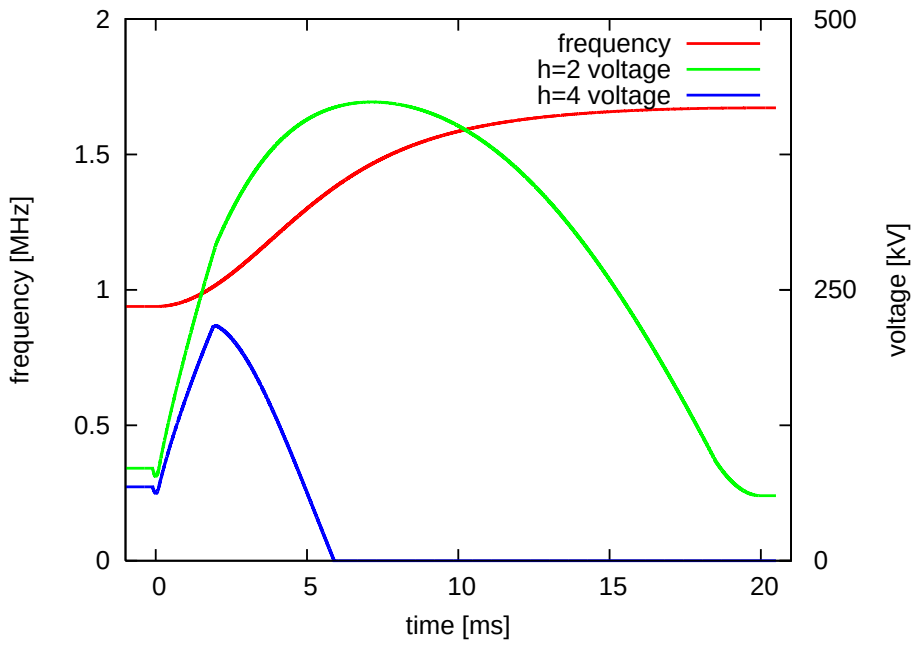


- Space charge effects
  - high beam current
  - especially severe in the injection period
- Increasing the bunching factor, we can alleviate the effects
- Combination:
  - dual-harmonic operation
  - momentum-offset injection
- Simulated flat bunch, low peak current, large bunching factor
  - the ratio of the second harmonic voltage to the fundamental is 80 %

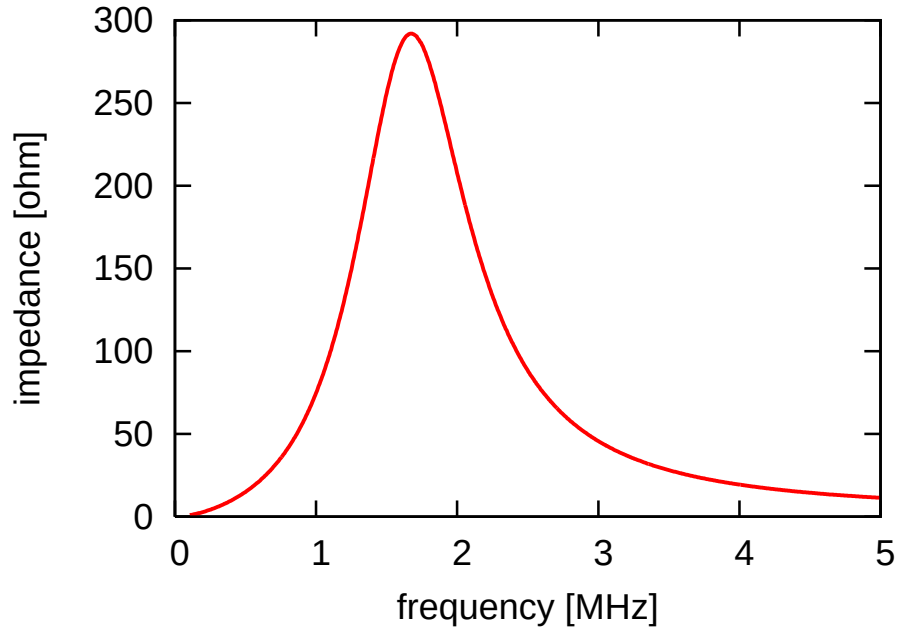
Dual-harmonic AVC (3)

Dual-harmonic operation is very useful for the stable acceleration of the ultra-high intensity beams.

Dual-harmonic AVC (4)



freq. and volt. pattern of RCS



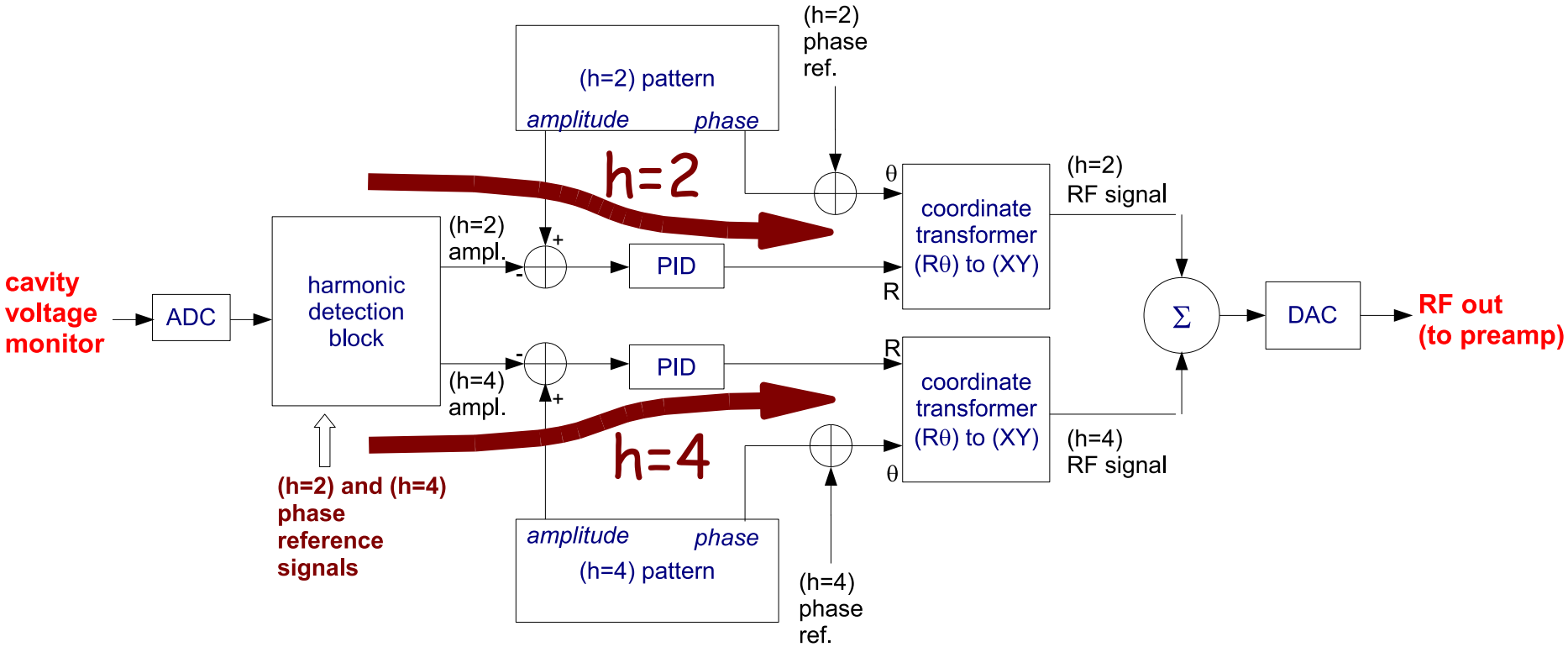
cavity impedance

- the voltage ratio of the accelerating RF $(h = 2)$ and the second harmonic $(h = 4)$ varies in the cycle
- the impedance of the MA-loaded cavity (no tuning) changes according to the frequency sweeps

Dual-harmonic AVC (5)

The dual-harmonic AVC (Auto Voltage Control), which controls the voltage of $(h = 2)$ and $(h = 4)$ independently, is necessary to follow the RCS voltage programs.

AVC block (1)

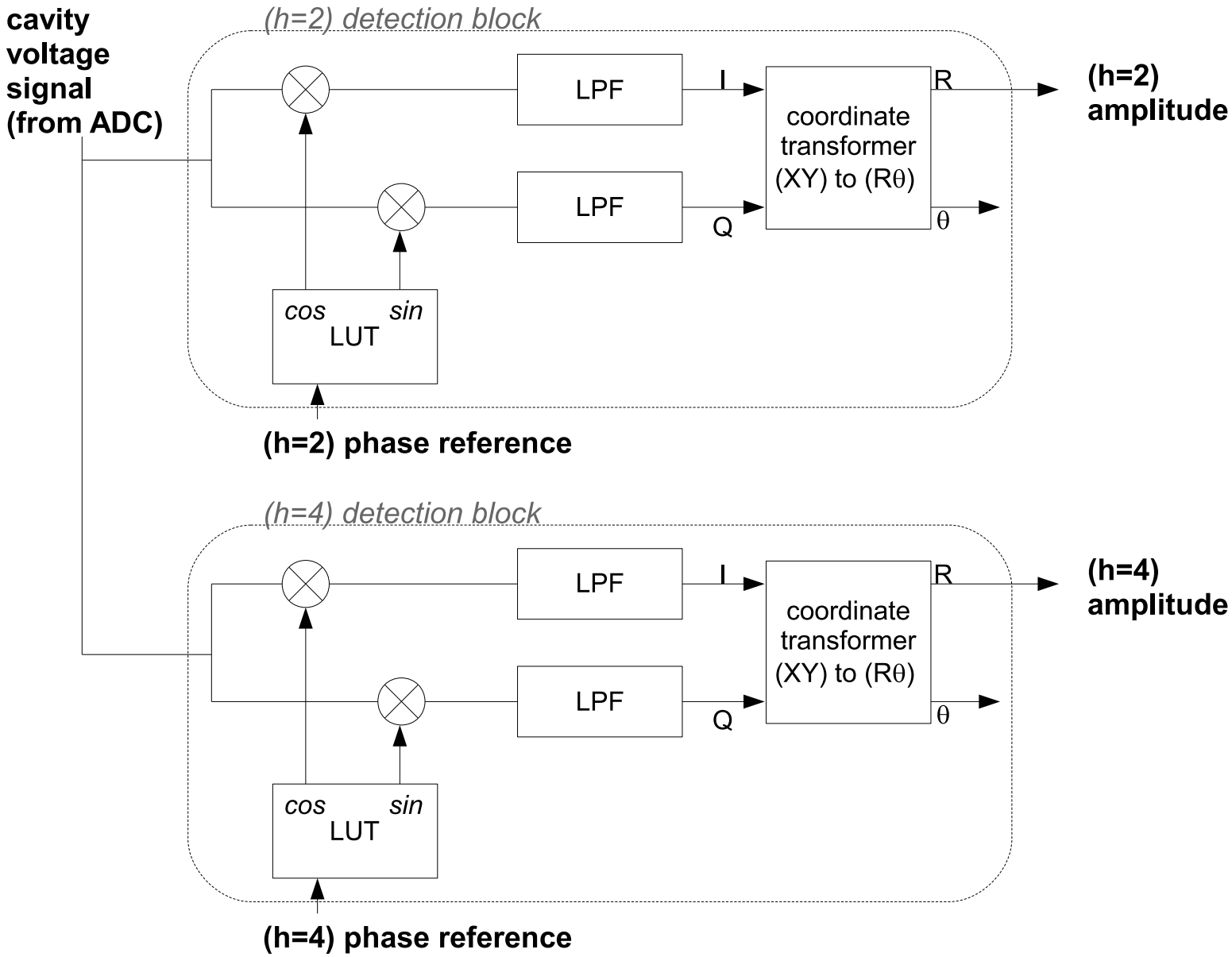


- Frequency is low (several MHz)
  - cavity voltage signal is directly converted into digital by ADC (36 Msample/s)

AVC block (2)

- Harmonic detection blocks
  - amplitudes of $(h = 2)$ and $(h = 4)$ are detected
- Compared with the amplitude patterns
- PID (Proportional-Integral-Derivative) controllers
- Coordinate transformer, (R, θ) to (X, Y)
  - RF signal is generated
  - phase pattern
- $(h = 2)$ and $(h = 4)$ RF signals are summed
  - dual-harmonic RF signals
- DAC

Harmonic detection (1)



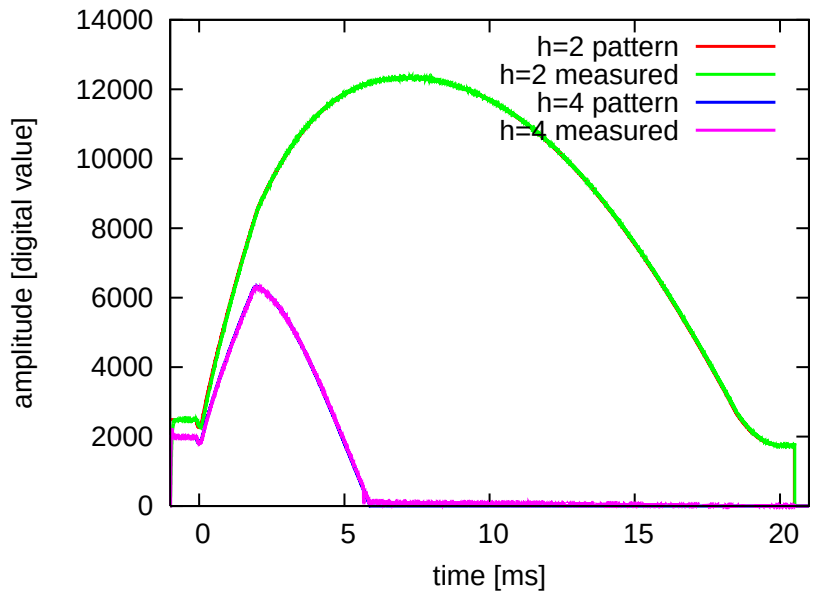
Harmonic detection (2)

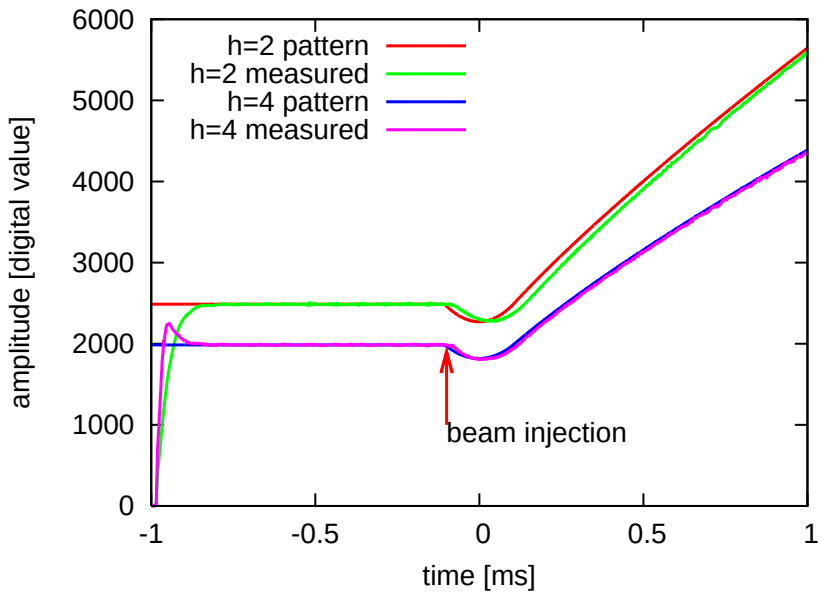
- I/Q demodulation technique is used
- the LPF must reject the nearest harmonics
  - $(h = 1)$ and $(h = 3)$
  - smallest at the injection, 0.47 MHz
- I/Q vector:

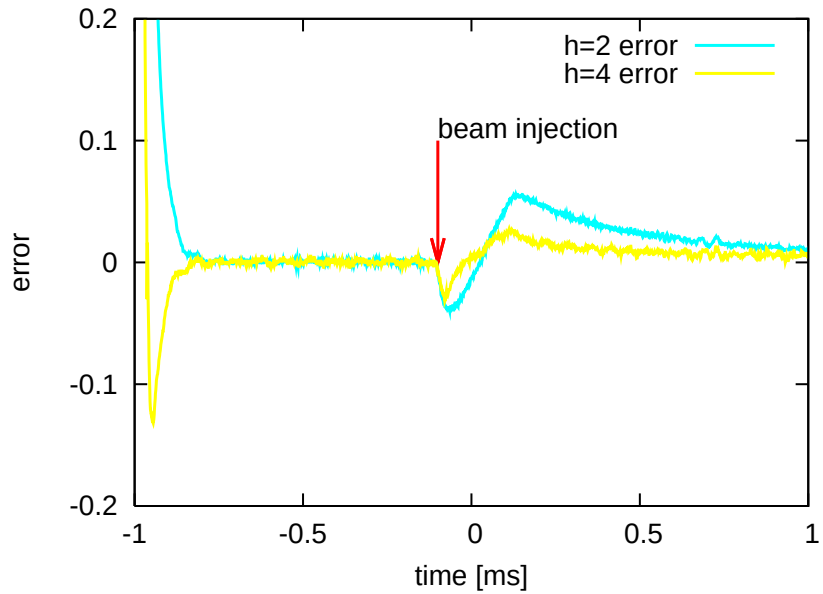
$$\begin{aligned} I_{(2,4)} &= A_{(2,4)} \sin(\phi_{(2,4)}), \\ Q_{(2,4)} &= A_{(2,4)} \cos(\phi_{(2,4)}). \end{aligned}$$

- Coordinate transformer, (X, Y) to (R, θ)

AVC high power test (1)



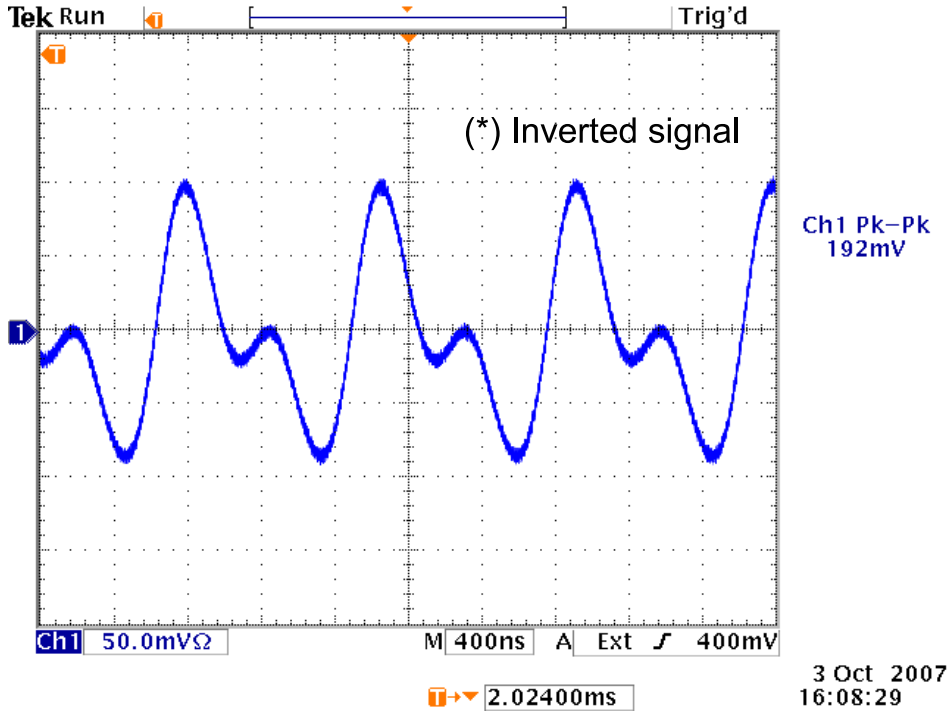




Cavity volt. follow the pattern

- most of cycle, error less than a few %
- max error near Bmin (7%)
- delay: 12 μs, FIR filter

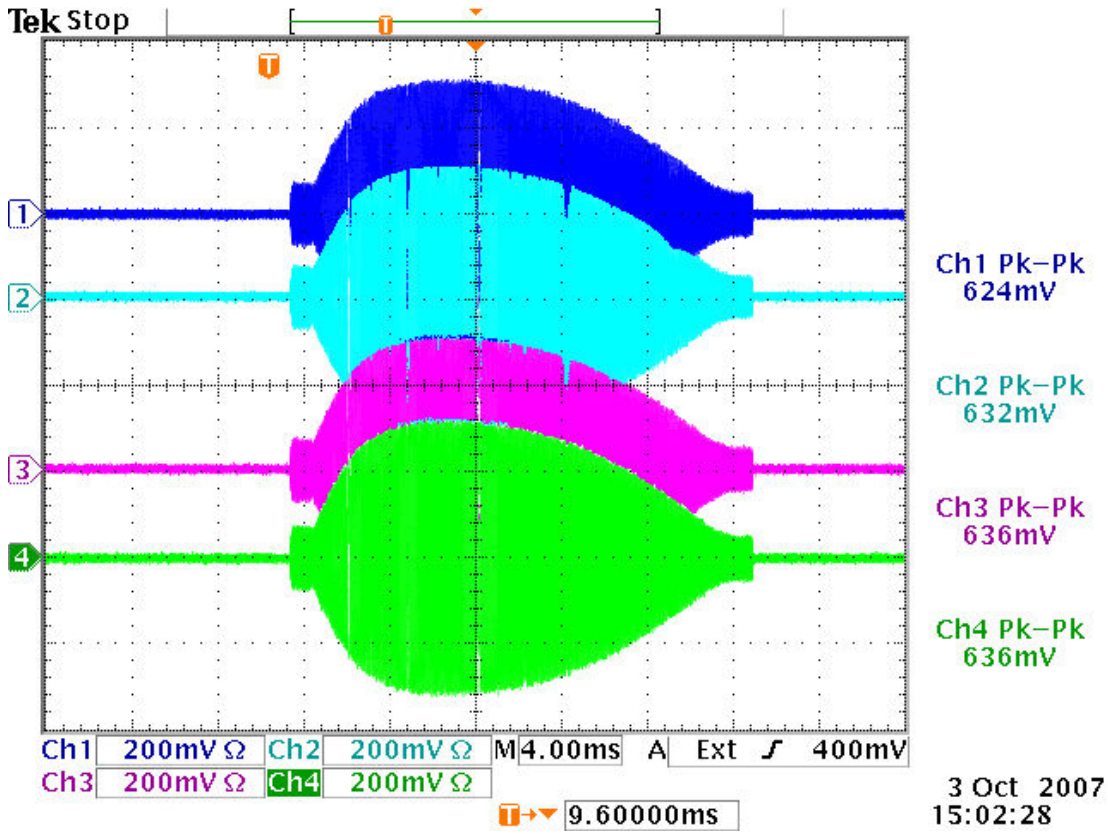
AVC high power test (2)



signal of cavity #1 gap divider

Dual-harmonic AVC works successfully

AVC high power test (3)



Typical cavity voltage signals of four cavities, $\boldsymbol{V_{\mathrm{gap}} = 12.5\ \mathrm{kV_{peak}}}$ *(single harmonic operation for day-1)*

RF systems are waiting the beam!

Summary

- J-PARC RCS beam commissioning began in October 2007, MR first beam is to be in May 2008
- Full-digital LLRF systems are designed and built
- Controlled by EPICS
- Dual-harmonic AVC works successfully