HB 2023 workshop, CERN, Geneva, Switzerland

RF systems of J-PARC proton synchrotrons for high-intensity longitudinal beam optimization and handling

Fumihiko Tamura

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J-PARC Center, JAEA & KEK

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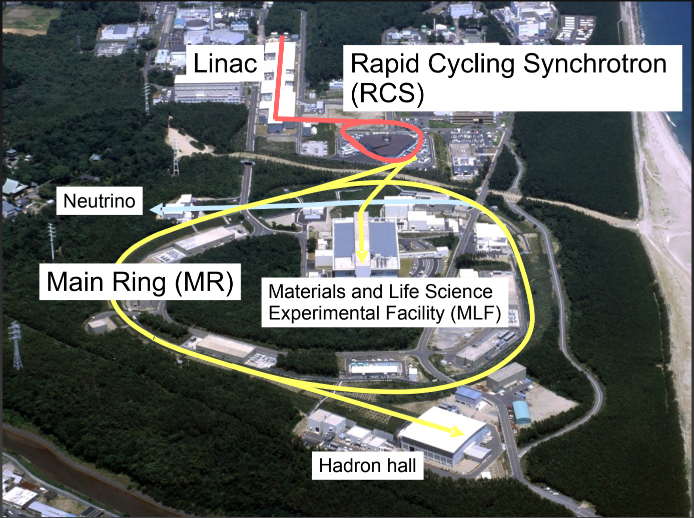
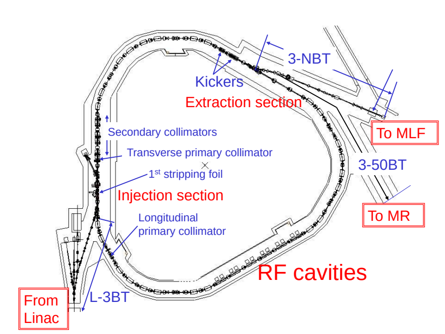
Contents

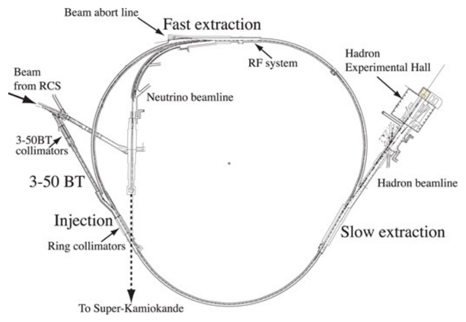
Japan Proton Accelerator Research Complex (J-PARC)



- Consists of 400 MeV linac, 3 GeV RCS, 30 GeV Main Ring, and experimental facilities (MLF, Hadron, Neutrino)

RCS and MR: very high intensity synchrotrons

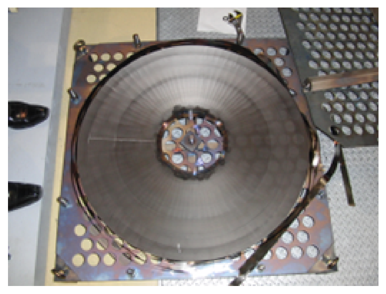


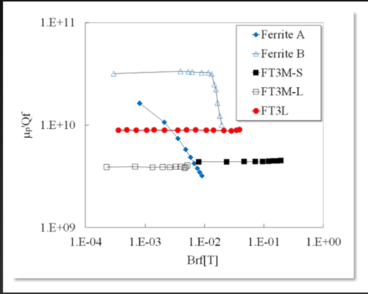


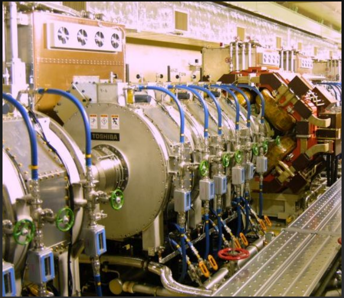
circumference	348.333 m
energy	0.400-3 GeV
beam intensity	8.3×10^{13} ppp
output beam power	1 MW
accelerating frequency	1.227-1.671 MHz
harmonic number	2
maximum rf voltage	440 kV
repetition rate	25 Hz
No. of cavities	12
Q-value of rf cavity	2

circumference	1567.5 m
energy	3 - 30 GeV
beam intensity	2.5×10^{14} ppp
output beam power	(design) 750 kW
accelerating frequency	1.67-1.72 MHz
harmonic number	9
maximum rf voltage	480 kV
repetition period	1.16 - 5.2 s
No. of cavities (Fund. + 2nd)	9+2
Q-value of Fund. rf cavity	22

Finemet / Magnetic Alloy (MA) cavity







Nano-crystalline material Finemet:

- $B_s \sim 1.2$ T, stable at high rf voltage
  → twice higher accelerating gradient than ferrite cavities
- Very high permeability → wideband

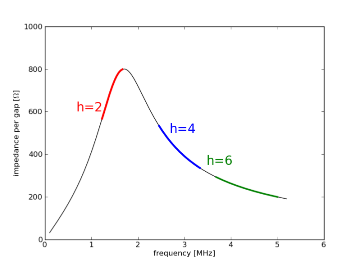
RCS MA cavity: 440 kV /12 cavities, Q = 2

MR MA cavity: 480 kV / 9 cavities, Q = 20, 2nd harmonic 120 kV / 2 cavities

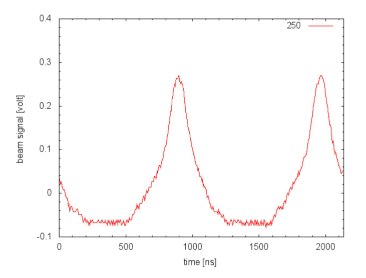
- Both cases, frequency sweep without tuning is possible

Wideband MA cavity for RCS

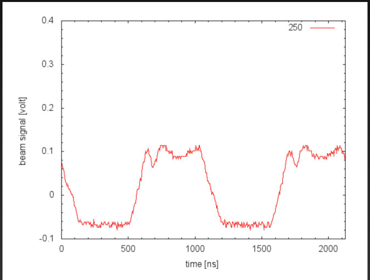
Q = 2 response:



Single harmonic:



Dual harmonic:



Wideband frequency response (Q = 2) enables the dual harmonic operation:

- A single cavity is driven by superposition of fundamental (h2) and 2nd harmonic (h4) rf signals
- Bunch shaping is indispensable for high intensity beam acceleration, alleviating space charge effects

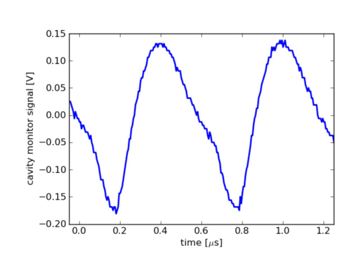
Drawbacks of wideband cavity

(1) Wake voltage is multiharmonic.

- RCS: contains higher harmonic
- MR: narrower bandwidth (Q = 20) but still wide enough that wake contains neighbor harmonics (h8, h10), which can be source of coupled bunch instabilities

Multiharmonic beam loading compensation is mandatory.

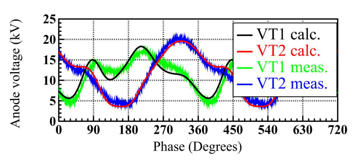
Measured wake voltage in RCS cavity:



(2) The tetrode tube operation is not trivial with the wideband RCS cavity.

- Output current of the final stage tetrode amplifier is distorted, contains higher harmonics
- Tube operating condition is a limiting factor of the maximum beam intensity

Anode voltages at 1 MW beam acceleration:



We present our efforts against these issues.

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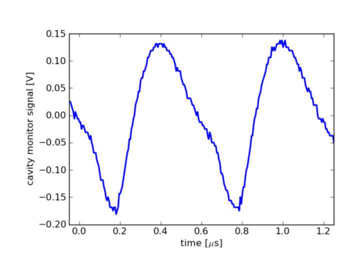

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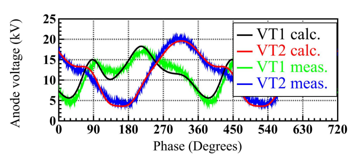


We present our efforts against these issues.

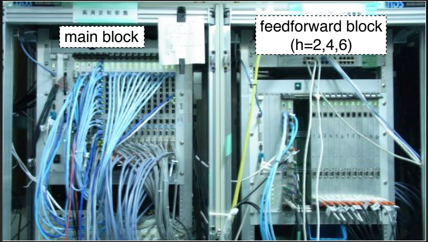
1. Introduction – J-PARC and magnetic alloy cavity

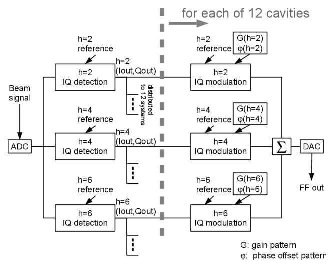
2. Low Level rf

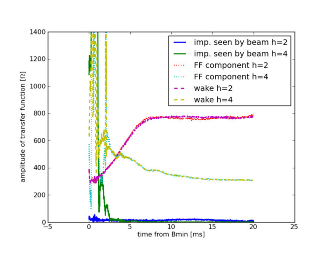
3. High power rf

4. Conclusions and outlook

Multiharmonic feedforward in original RCS LLRF control system (-2019)







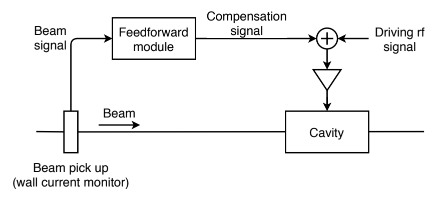
The original LLRF features Multiharmonic feedforward beam loading compensation:

(Phys. Rev. ST Accel. Beams 14, 051004, 2011, Phys. Rev. ST Accel. Beams 16, 051002, 2013, Phys. Rev. ST Accel. Beams 18, 091004, 2015)

- Commissioning methodology established
- Works perfectly at 300 kW, impedance reduction 1/30
- Still works at 1 MW

We switched compensation method from FF to FB with renewal of LLRF, because...

FF is open-loop



RF feedforward generates compensation signal using beam signal:

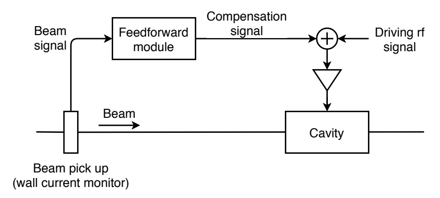
- It relies on linearity of system
- Tube amplifier gain changes with beam intensity / tube output current. It is an issue for > 800 kW beams
- Voltage waveform distortion due to tubes cannot be compensated by definition

FB can solve these issues:

- FB works with gain variation within the stability margin
- Voltage waveform distortion is to be compensated

Multiharmonic vector rf voltage control feedback is implemented in next-generation LLRF control system deployed in 2019.

FF is open-loop



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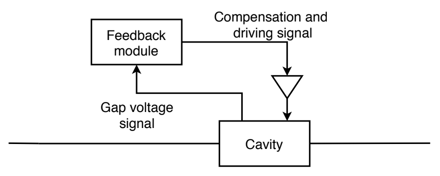

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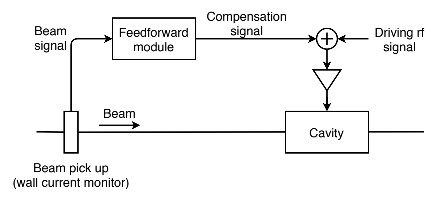

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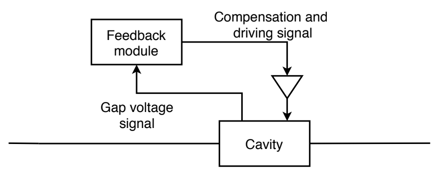

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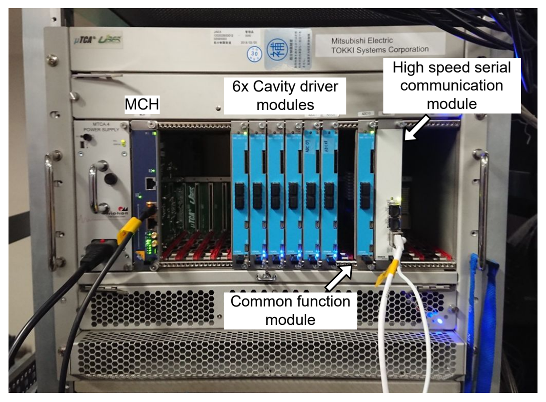
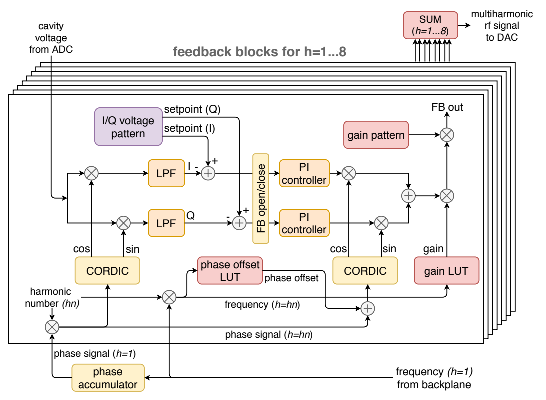
Multiharmonic vector rf voltage control feedback in new RCS LLRF (2019-)





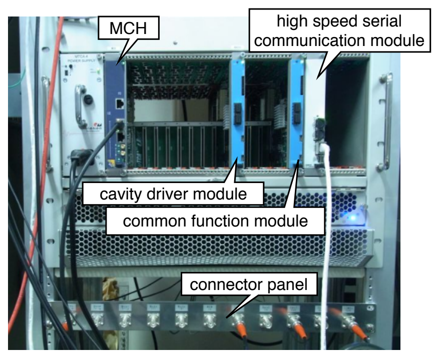
(Phys. Rev. Accel. Beams 22, 092001, 2019)

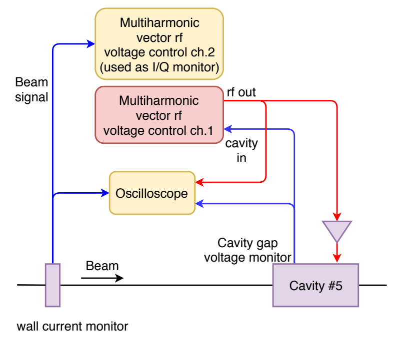
Eight classical I/Q feedback blocks for harmonics (h1...h8).

- Phase offset LUT and gain LUT for wide frequency range (0.4-6.8 MHz)
- LPF design: Tracking CIC by J. Molendijk (CERN) + leaky integrator

Single cavity tests (2018)

Parts of next-generation LLRF were delivered in 2018.



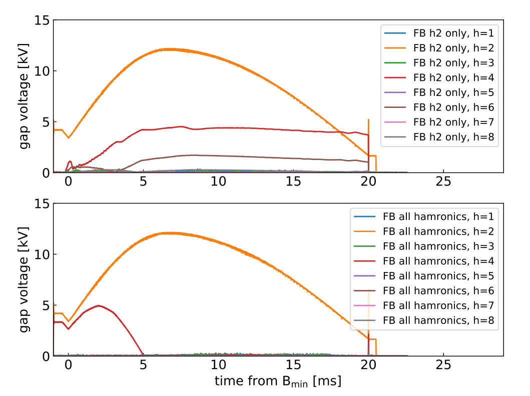


Single cavity tests using Cavity 5 were performed:

- Compensation of other 11 cavities by feedforward
- Harmonic components of beam signal and Cavity 5 voltage signal taken by new LLRF, waveforms by oscilloscope

Single cavity tests (2018): 1 MW beam acceleration

Harmonic components of gap voltages:



(Top)
FB closed for h2 only, other harmonics output off:

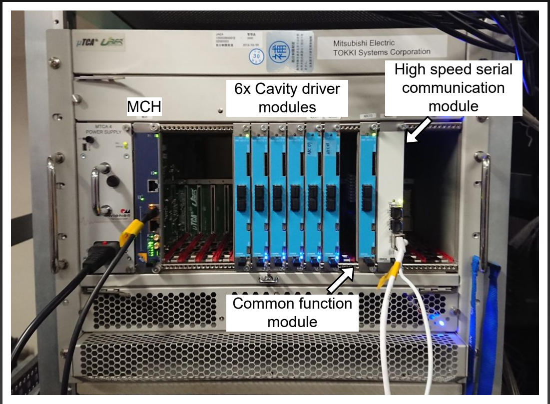
- Amplitudes of h4, h6 are significant, 4.6 kV, 1.7 kV max
- h4, h6 contain mainly wake, distortion due to tubes as well

(Bottom)
FB for all (h1…8) closed:

- h2, h4 as programmed
- Other harmonics well suppressed, below 300 V

It is proved that multiharmonic vector rf voltage control feedback can successfully compensate beam loading of eight harmonics in a single cavity, up to 1 MW.

Full replacement with next-generation system done in 2019



All cavities connected to new LLRF system.

When all of twelve cavities are controlled by the new LLRF control system, the beam loading seen by the feedback can be different.

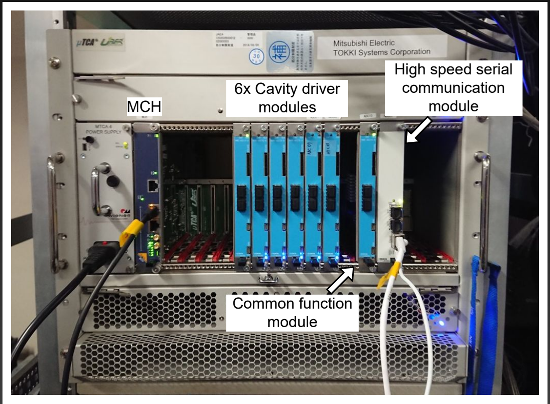
- Previous tests: 1x new FB / 11x FF

We started from 500 kW beam.

- With all of h1–h8 FB blocks ON
- Intensity increased by small steps

What happens?

Full replacement with next-generation system done in 2019



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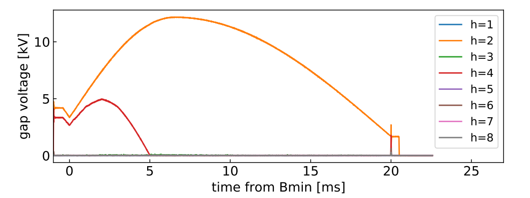
Beam tests with 12 cavities controlled by vector FB (2019)

Harmonic components of Cavity 10 (h1-h8 ON), 620 kW



Up to 620 kW all cavities are well controlled as the single cavity tests

- Driving harmonics (h2, h4) as programmed
- Others (h1, h3, h5-h8) suppressed to < 0.2 kV
- Above this intensity, problems arise

Beam tests with 12 cavities controlled by vector FB (2019)

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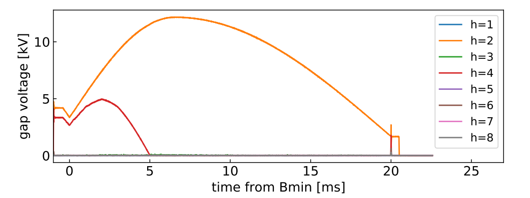
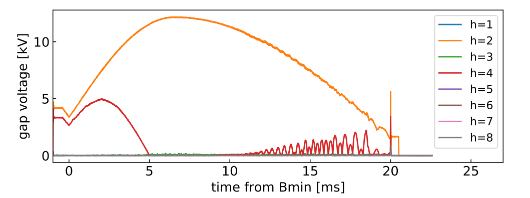


Harmonic components of Cavity 10 (h1–h8 ON), 890 kW



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At 890 kW, Driver amp trips. Regulation of h2, h4 worse after 10 ms. Countermeasure strategy:

1. Feedback block of the cavity is disabled for the higher harmonics (h8, h7. . .)
2. If above does not work, the voltage pattern is reduced by a factor (×0.9, ×0.8 . . .)

Beam tests with 12 cavities controlled by vector FB (2019)

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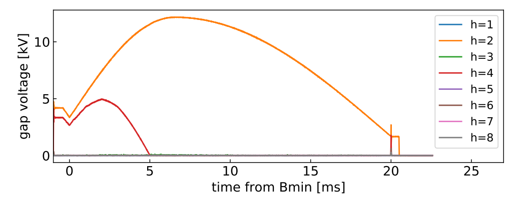

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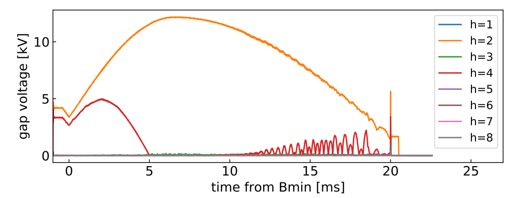
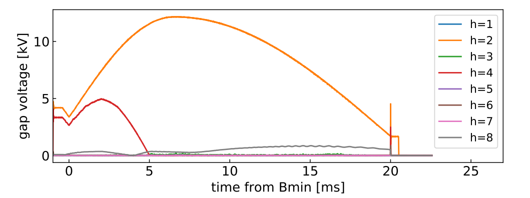


Harmonic components of Cavity 10 (h78 OFF), 890 kW

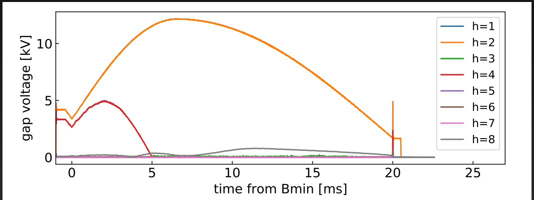


Strategy #1 is applied to overcome the problem. No trip with h78 FB disabled. h8 component clearly seen, ∼ 0.8 kV around 15 ms.

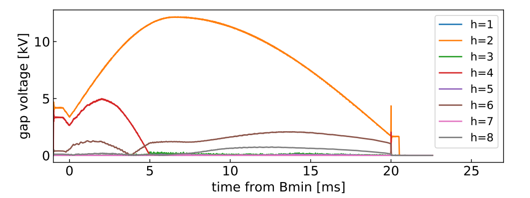
- Applying the strategy, we tried to reach 1 MW

Beam tests with 12 cavities controlled by vector FB (2019), 1 MW

Compensated up to h6 (Cavity 10)



Compensated up to h5 (Cavity 8)

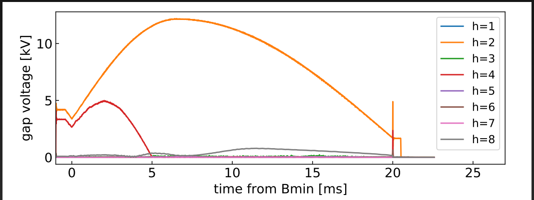


We need compromise:

- h78 FB disabled for all cavities
- h6 disabled for 7 out of 12 cavities, h6 amplitude 2 kV max
- The factor ×0.9 is applied to the voltage program of Cavity 1

Beam tests with 12 cavities controlled by vector FB (2019), 1 MW

Compensated up to h6 (Cavity 10)



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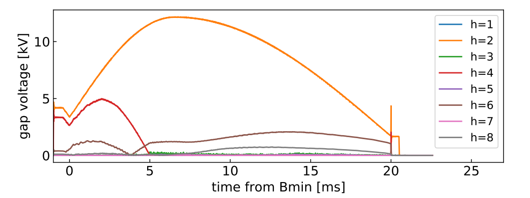

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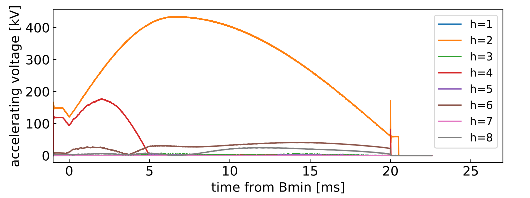
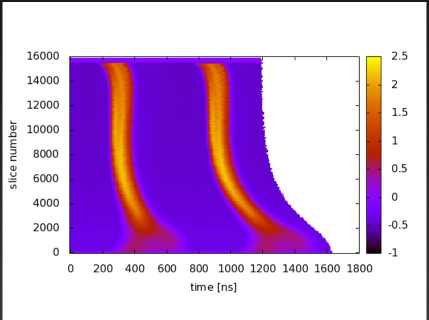
Vector sum voltage of 12 cavities.
Unwanted h6/h8 clearly seen, 40/25 kV.



Although there is a compromise in the feedback setting, stable acceleration of 1 MW beam is achieved.

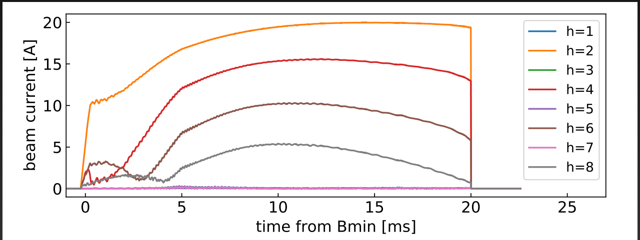
Beam tests with 12 cavities controlled by vector FB (2019), 1 MW

Mountain plot of beam signal:



- No oscillation, stable

Harmonic components of beam signal:

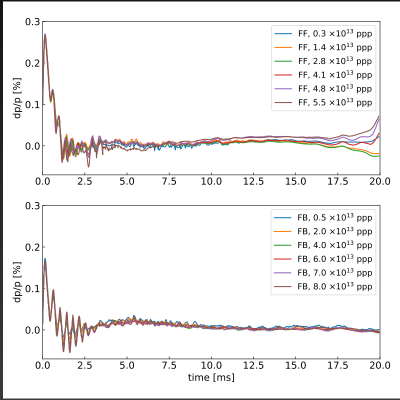


- The harmonic components of the beam vary smoothly without oscillations
- The bunch shape smoothly changes during acceleration with the cavity voltages regulated as programmed.

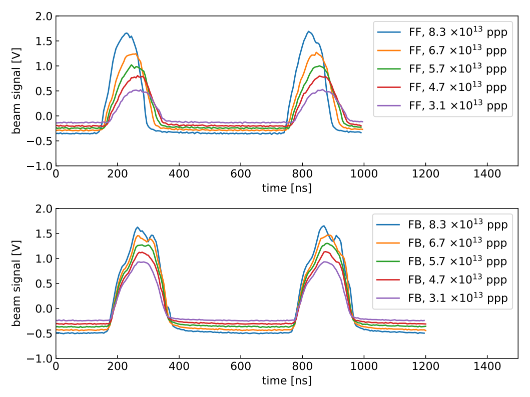
The beam control is more stabilized by the multiharmonic vector rf voltage control feedback than by the feedforward compensation.

Comparisons of intensity dependencies of (top) FF and (bottom) FB

Momentum deviations (dp/p) of the beam



Beam signals just before extraction



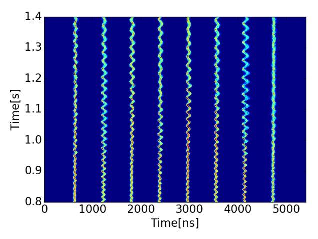
In case of FF, intensity dependencies clearly seen.

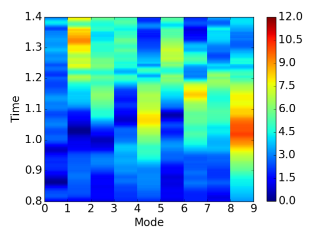
- dp/p ~ 0.1% at extraction
- 40 ns timing change, bunch shapes vary with different intensities

With vector FB, almost no dependencies observed. More stable acceleration is achieved.

MR commissioning results

With feedforward





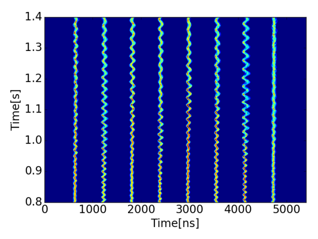
Above 450 kW, coupled bunch instabilities observed in MR.

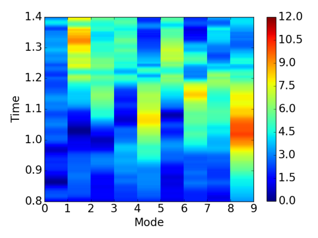
- A limiting factor of the available beam power
- Neighbor harmonic (h8, h10) wake voltages, which are reduced by multiharmonic feedforward by a factor. Not enough reduction
- Mode 1 and 8 are dominant, consistent with wake components

With multiharmonic feedback, wake voltages of h8/h10 and the oscillation are suppressed.

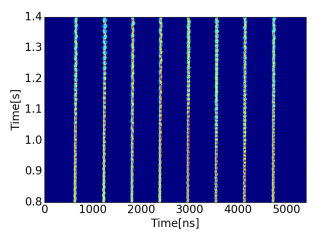
MR commissioning results

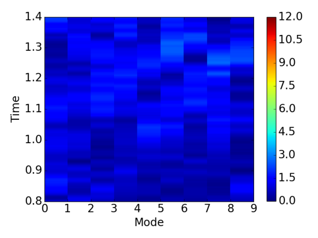
With feedforward





With feedback





Above 450 kW, coupled bunch instabilities observed in MR.

- A limiting factor of the available beam power
- Neighbor harmonic (h8, h10) wake voltages, which are reduced by multiharmonic feedforward by a factor. Not enough reduction
- Mode 1 and 8 are dominant, consistent with wake components

With multiharmonic feedback, wake voltages of h8/h10 and the oscillation are suppressed.

LLRF summary

Performance of multiharmonic vector rf voltage control feedback is satisfactory.

- Can compensate not only wake voltages but also distortion due to tubes
- RCS: Stable acceleration of 1 MW beam is achieved, while there is compromise of feedback setting
- MR: Coupled bunch instability due to wake voltage of neighbor harmonics is suppressed

Lessons learned:

- HPRF determines the final performance, not LLRF
- Analysis of HPRF operation is necessary

1. Introduction – J-PARC and magnetic alloy cavity

2. Low Level rf

3. High power rf

4. Conclusions and outlook

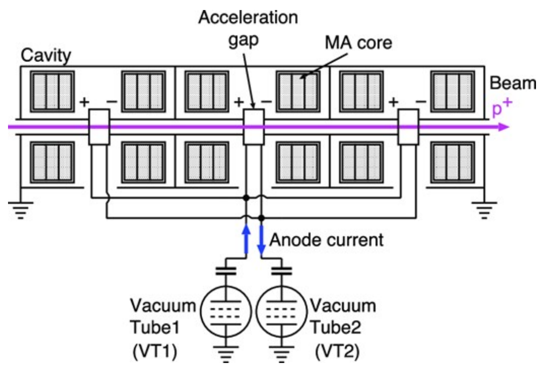
Analysis of the tetrode operating conditions

Rf trips limit the beam intensity.

- Anode OC, SG OC, driver amp trip...

To investigate the tetrode operating condition, a comprehensive simulations have been performed.

RCS cavity has push-pull configuration:

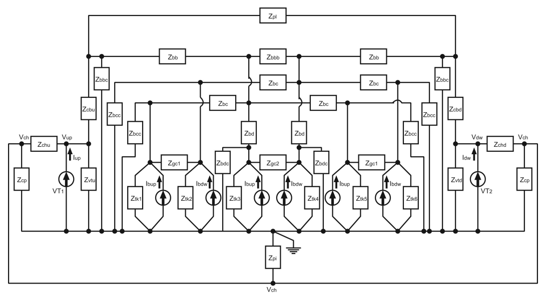


Second harmonic distortion due to tetrode is canceled by push-pull configuration.

- Class AB

Real life is complicated: comprehensive impedance and tetrode models

The impedance model includes cavity, busbar inductance, capacitance, and any possible components.

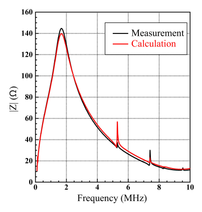


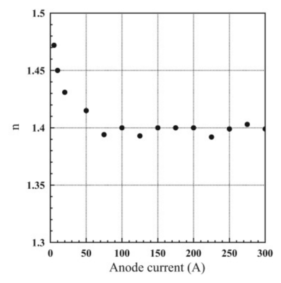
For the downstream acceleration gap,

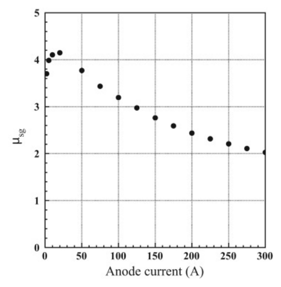
$$V_{\mathrm{aup}} - Z_{\mathrm{cbu}}(I_{\mathrm{aup}} - I_{\mathrm{chu}} - I_{\mathrm{vtu}}) - Z_{\mathrm{bb}}(I_{\mathrm{aup}} - I_{\mathrm{chu}} - I_{\mathrm{vtu}} - I_{\mathrm{pl}} - I_{\mathrm{bbcu}}) - Z_{\mathrm{bc}} I_{\mathrm{b5}} \quad \text{(A.6)}$$
$$= Z_{\mathrm{tk}\,5}(I_{\mathrm{b5}} - I_{\mathrm{bbc}\,5} + I_{\mathrm{bup}} - I_{\mathrm{cg}\,3}) V_{\mathrm{adw}} - Z_{\mathrm{cbd}}(I_{\mathrm{adw}} - I_{\mathrm{chd}} - I_{\mathrm{vtd}})$$
$$- Z_{\mathrm{bb}}(I_{\mathrm{adw}} - I_{\mathrm{chd}} - I_{\mathrm{vtd}} + I_{\mathrm{pl}} - I_{\mathrm{bbcd}}) - Z_{\mathrm{bc}} I_{\mathrm{b6}}$$

$$V_{\mathrm{aup}} - Z_{\mathrm{cbu}}(I_{\mathrm{aup}} - I_{\mathrm{chu}} - I_{\mathrm{vtu}}) - Z_{\mathrm{bb}}(I_{\mathrm{aup}} - I_{\mathrm{chu}} - I_{\mathrm{vtu}} - I_{\mathrm{pl}} - I_{\mathrm{bbcu}}) - Z_{\mathrm{bc}} I_{\mathrm{b5}} \quad \text{(A.7)}$$
$$= Z_{\mathrm{tk}\,6}(I_{\mathrm{b6}} - I_{\mathrm{bbc}\,6} + I_{\mathrm{bdw}} + I_{\mathrm{cg}\,3}) V_{\mathrm{aup}} - Z_{\mathrm{cbu}}(I_{\mathrm{aup}} - I_{\mathrm{chu}} - I_{\mathrm{vtu}})$$
$$- Z_{\mathrm{bb}}(I_{\mathrm{aup}} - I_{\mathrm{chu}} - I_{\mathrm{vtu}} - I_{\mathrm{pl}} - I_{\mathrm{bbcu}}) - Z_{\mathrm{bc}} I_{\mathrm{b5}} - Z_{\mathrm{gc}\,1} I_{\mathrm{gc}\,3}$$

$$V_{\mathrm{aup}} - Z_{\mathrm{cbu}}(I_{\mathrm{aup}} - I_{\mathrm{chu}} - I_{\mathrm{vtu}}) - Z_{\mathrm{bb}}(I_{\mathrm{aup}} - I_{\mathrm{chu}} - I_{\mathrm{vtu}} - I_{\mathrm{pl}} - I_{\mathrm{bbcu}}) - Z_{\mathrm{bc}} I_{\mathrm{b5}} \quad \text{(A.8)}$$
$$= V_{\mathrm{adw}} - Z_{\mathrm{cbd}}(I_{\mathrm{adw}} - I_{\mathrm{chd}} - I_{\mathrm{vtd}}) - Z_{\mathrm{bb}}(I_{\mathrm{adw}} - I_{\mathrm{chd}} - I_{\mathrm{vtd}} + I_{\mathrm{pl}} - I_{\mathrm{bbcd}})$$
$$- Z_{\mathrm{bc}} I_{\mathrm{b6}}$$

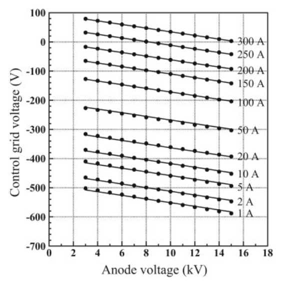






The tetrode model reproduces the constant current characteristics.

$$I_{\mathrm{a}} = k\left(V_{\mathrm{cg}} + \frac{V_{\mathrm{sg}}}{\mu_{\mathrm{sg}}(I_{\mathrm{a}})} + \frac{V_{\mathrm{a}}}{\mu_{\mathrm{a}}}\right)^{n(I_{\mathrm{a}})}.$$

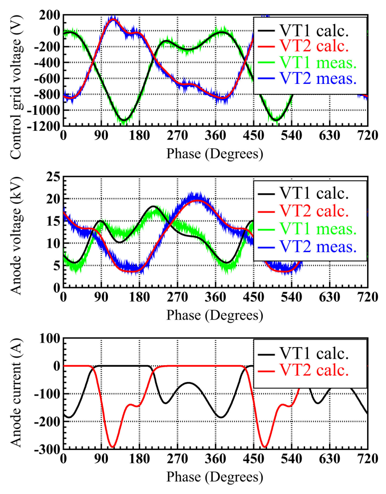


Analysis of the tetrode operating conditions

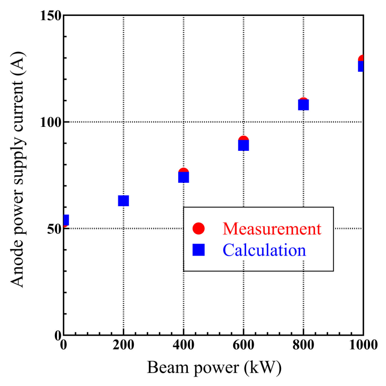
The simulation model well reproduce the tetrode operation at 1 MW beam acceleration.

(Nuclear Instruments and Methods in Physics Research Section A, Volume 835, p.119-135, 2016)

Anode voltage



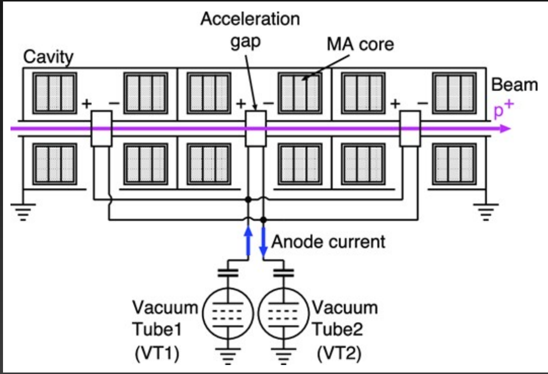
Anode PS current



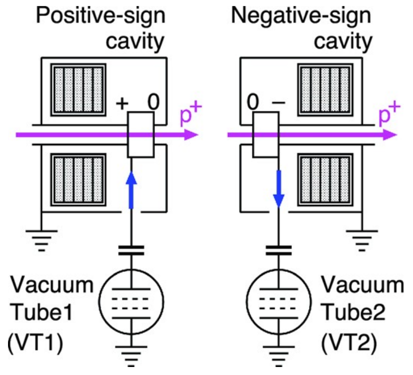
← Anode voltages of VT1/2 are quite asymmetric.

Analysis of the tetrode operating conditions

Push-pull configuration:



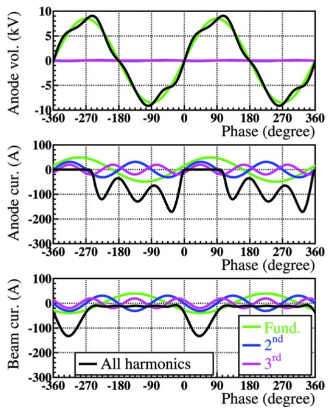
Single-ended cavities for simulation:



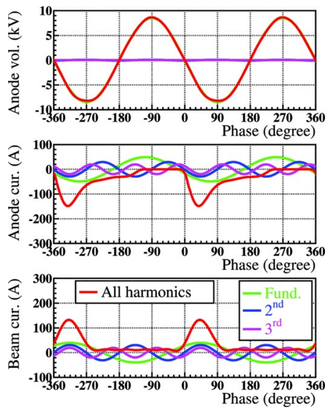
To investigate the source of asymmetry, simulations for single-ended cavities performed.
The push-pull cavity is cut at the center (virtual ground).

Single-ended cavity simulation results

Positive-sign:



Negative-sign:

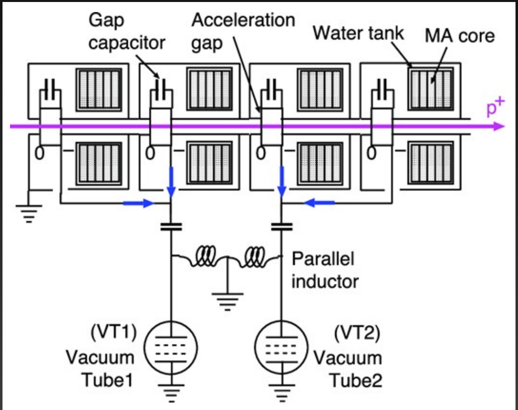


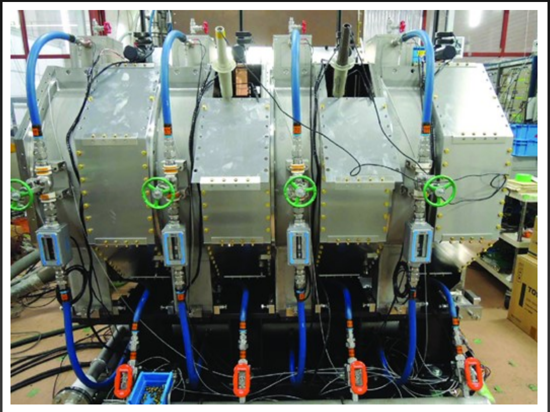
Simulated anode currents are very different:

- Much more anode DC currents for positive-sign cavity. Beam loading for negative-sign cavity seems easier
- Second harmonic component is the source of asymmetry (Progress of Theoretical and Experimental Physics, vol. 2023, no. 7, 073G01, 2023)
- Same condition should occur in the push-pull operation because it is a combination of the positive-sign and negative-sign cavities

We developed a prototype single-ended cavity only with negative-sign cavities.

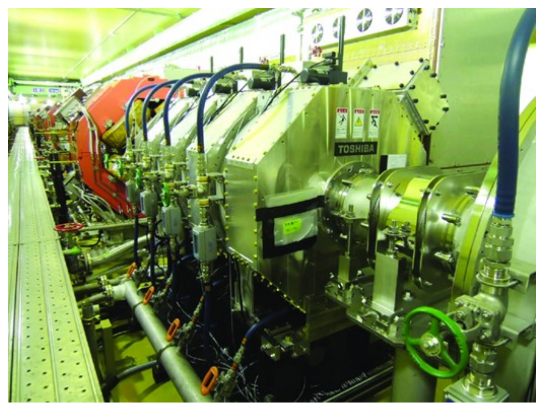
Prototype single-ended cavity



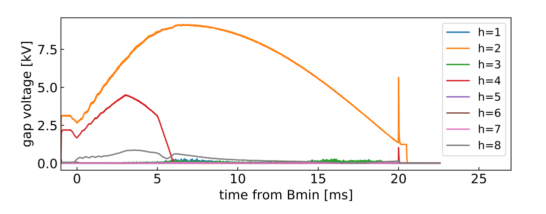


Core type: FT3M → FT3L (C. Ohmori, WEC4C1)
# of electrode 6 (2x3) → 4
Offline high power tests done successfully.

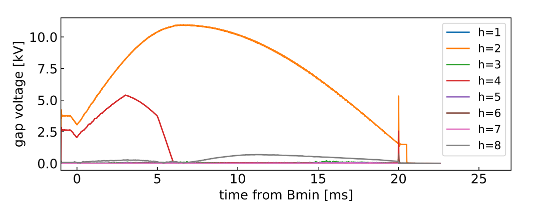
Beam test of prototype single-ended cavity



Cav4 (single-ended):



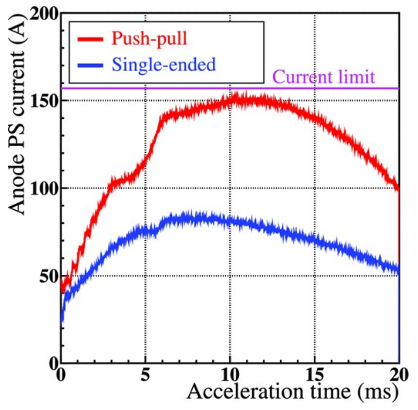
Cav11 (push-pull):



1 MW Beam acceleration with single-ended cavity successfully demonstrated.

- Up to h6 compensated. Different h8 component compared to push-pull cavity, because of different frequency response

Beam test of prototype single-ended cavity



Anode PS current is reduced.

- # of electrodes 6 (push-pull) → 4 (single-ended)
- Negative-sign cavities. FT3L core. No in-phase current
- Max anode PS current: 150 A (push-pull) → 80 A (single-ended). Enough margin
- Average power consumption: 820 kW → 487 kW, 40% reduction

HPRF summary

We developed the comprehensive cavity / amplifier model for RCS.

- Simulation well reproduces the tetrode operation
- The issues of tetrode operation in push-pull configuration identified
- Single-ended cavity is developed and successfully tested
  - Single-ended cavity requires multiharmonic voltage regulation to suppress the intrinsic distortion of waveform

Conclusions and outlook

RCS: We believe that combination of

- Multiharmonic vector rf voltage control feedback, and
- Single-ended cavity

is ultimate solution for application of wideband cavity driven by tube amplifier in high intensity synchrotrons.

- All push-pull cavities are to be replaced with single-ended cavities (3 out of 12 done)
- After completion of replacement, we are ready to accelerate higher intensity beams of more than 1 MW. Studies ongoing (K. Yamamoro, WEC3C1)

MR: High accelerating voltage by MA cavities and new LLRF control system will contribute to

- Shorter repetition cycle to achieve higher beam power of 750 kW
- More stable acceleration

Backup slides

Possible improvements

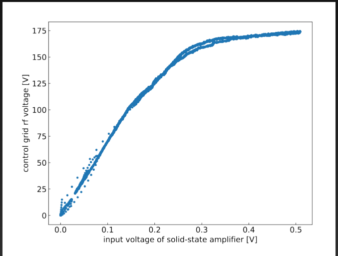
Q: Where the compromise comes from?

Possible improvements

Q: Where the compromise comes from?

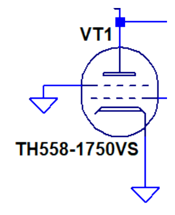
A: Distortion and nonlinearity of amplifier chain.

- Load of the amplifier chain is close to the limit at 1 MW
- Saturation and distortion of the output of driver amp observed



Tetrode parameters modified:

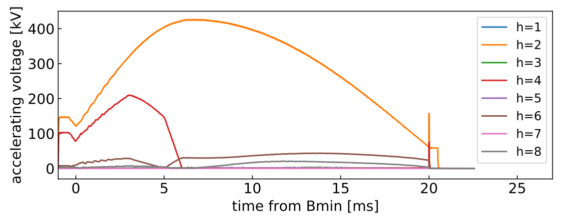
- Filament current: 450 A (longer life setting) → 480 A (spec value), more emission
- Screen grid voltage: 1.75 kV → 2.0 kV



Increased tetrode gain reduces the load of driver amplifier.

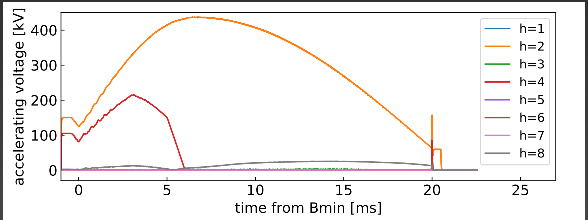
Comparison of vector sum voltages

Fil 450 A / SG 1.75 kV (shown again)



- h78 are all off
- h6 off for 7 out of 12 cavities
- Cavity 1: ×0.9

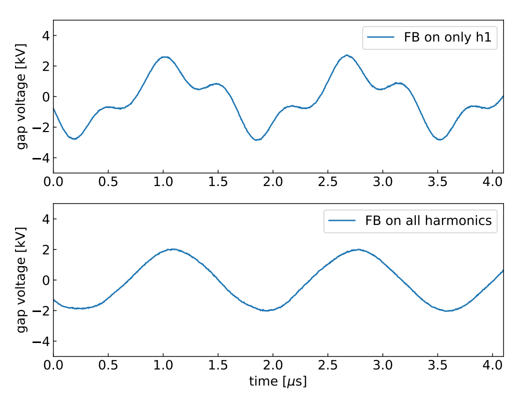
Fil 480 A / SG 2.0 kV

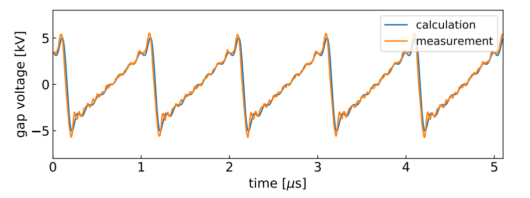


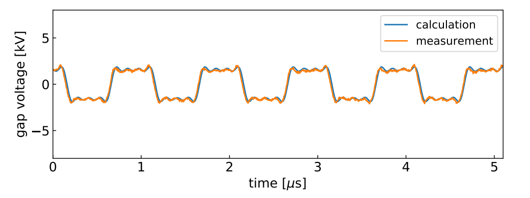
- h78 are all off, same
- h6 ON for all cavities
- Cavity 1: ×1.0
- The load of driver amplifier much reduced, headroom to saturation kept

Components up to h6 are under control for all 12 cavities.

Demonstrations

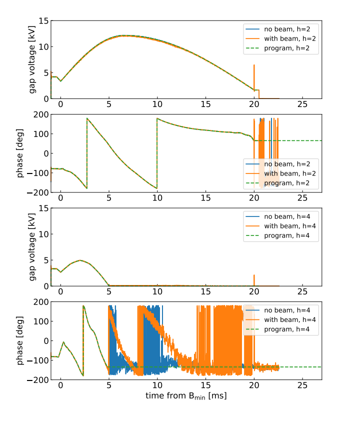




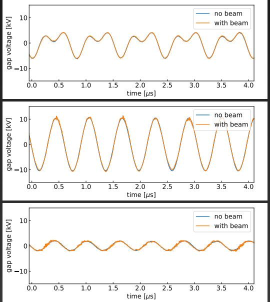


Single cavity tests (2018): 1 MW beam acceleration

Amplitude and phase of driving harmonics (h2, h4):



Voltage waveform:

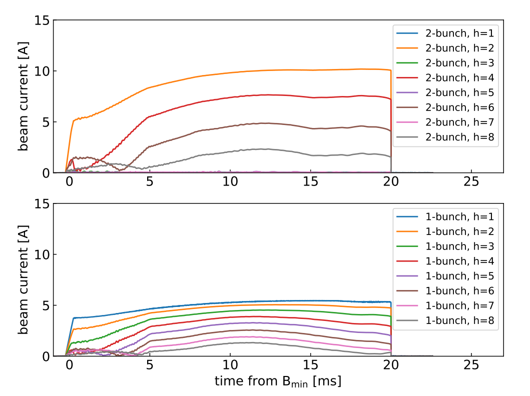


- Amp/phase of no beam / 1 MW beam are very close to program
- Waveforms almost identical

→ Beam loading is well compensated.

Single cavity tests (2018): cancellation of wake voltage

Beam current harmonic components:

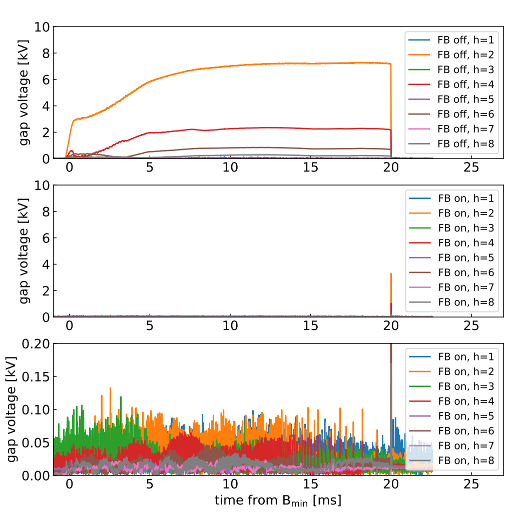


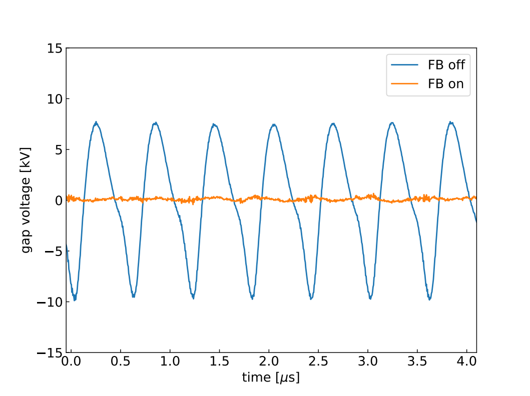
(Top) Acceleration of two bunches at 4.2×10^{13} ppp, 500 kW

(Bottom) Single bunch at 4.2×10^{13} ppp, 250 kW

Single cavity tests (2018): cancellation of wake voltage

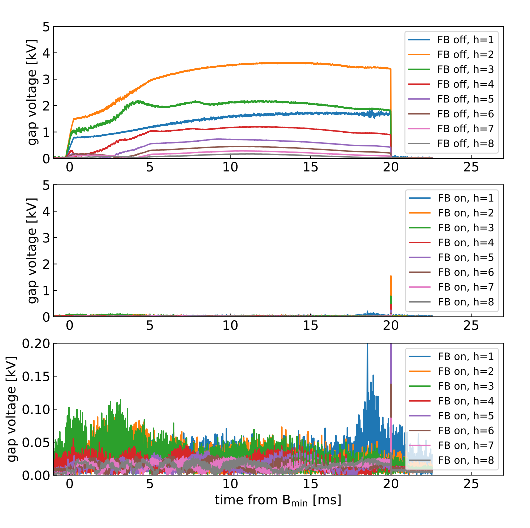
2 bunches

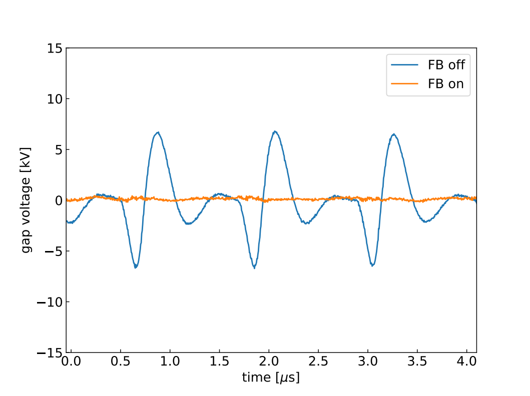




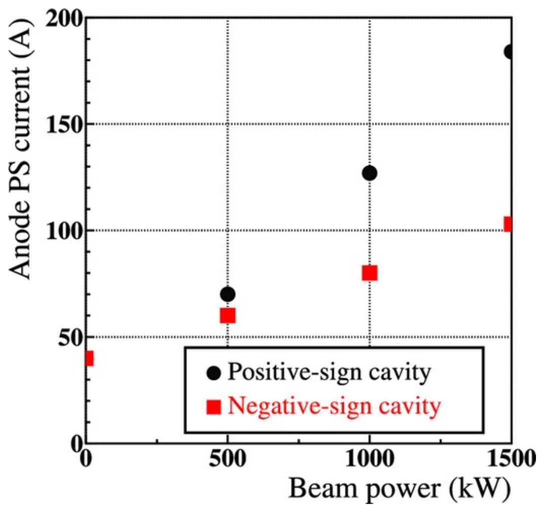
Single cavity tests (2018): cancellation of wake voltage

1 bunch

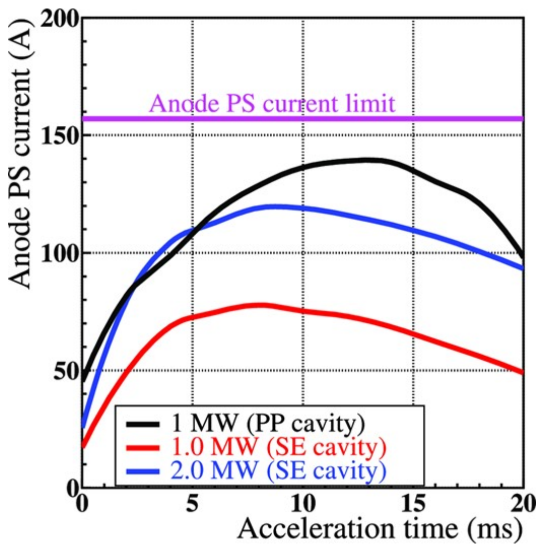




Anode PS currents for positive- and negative- sign cavities

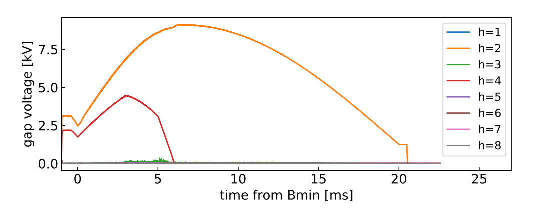


Anode PS currents for push-pull and single-ended cavities

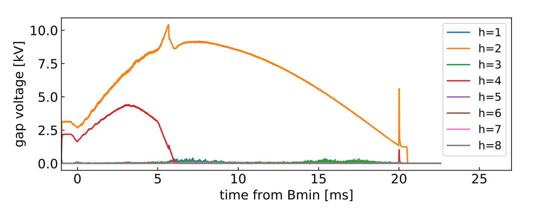


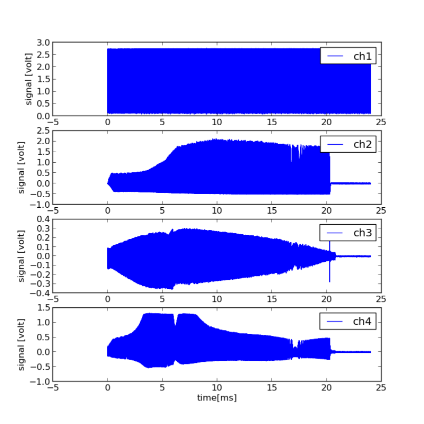
h78 FB?

h78 on without beam:



h78 on with 1 MW beam:

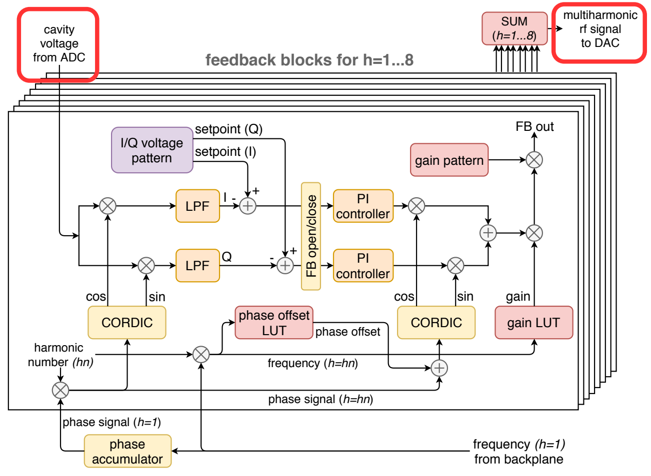




Ch.4 (LLRF output) saturated → h8 gain is not enough

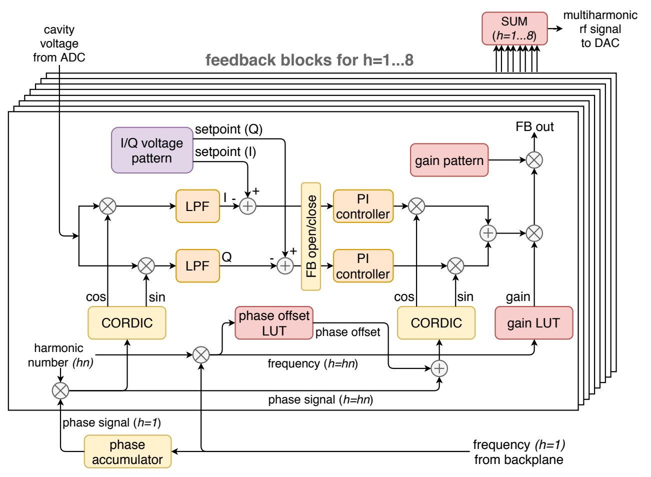
Tetrode condition should be optimized.

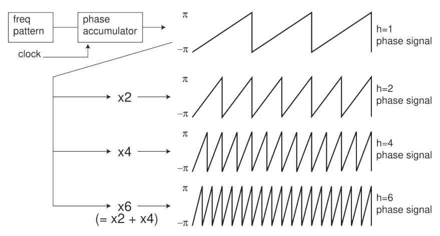
Multiharmonic vector rf voltage control feedback, block diagram



- Input: cavity voltage signal
- Output: multiharmonic rf signal

Multiharmonic vector rf voltage control feedback, block diagram

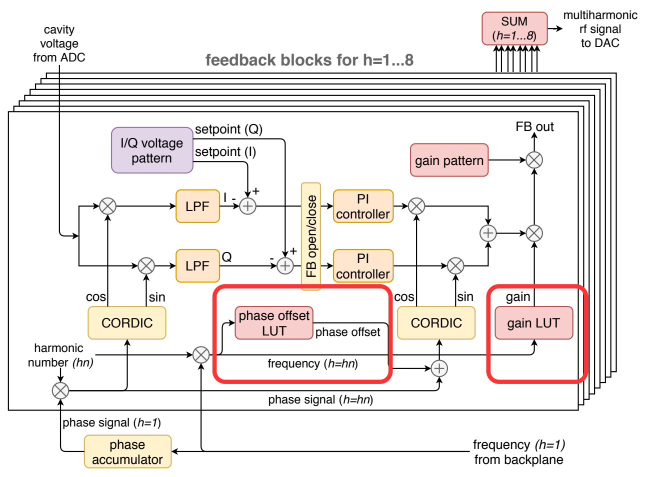




- Perfect synchronization of the harmonics

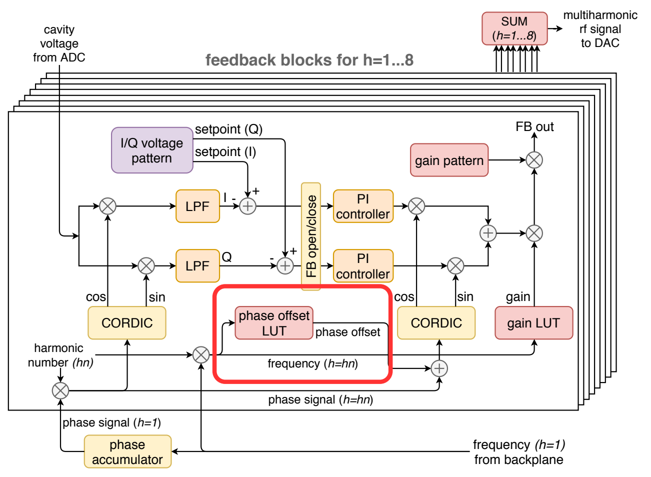
- The feedback consists of eight (h1…h8) feedback blocks. Each block is classical I/Q vector feedback w/ PI controller
- Multiharmonic phase signal is generated from h1 phase signal

Multiharmonic vector rf voltage control feedback, block diagram

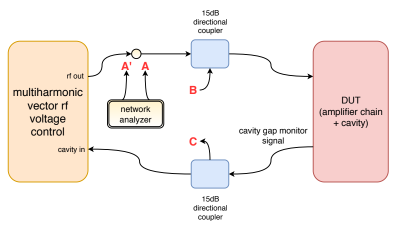


- For wide frequency range (frequency sweep and multiharmonic), it has phase offset LUT and gain LUT
- Frequency is used as address

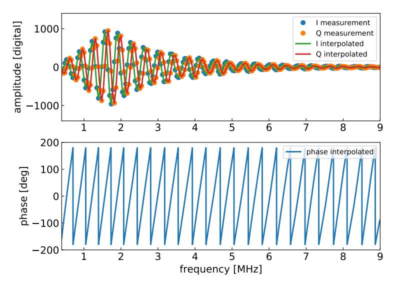
Multiharmonic vector rf voltage control feedback, block diagram



Open loop TF is measured using EPICS I/Q monitor

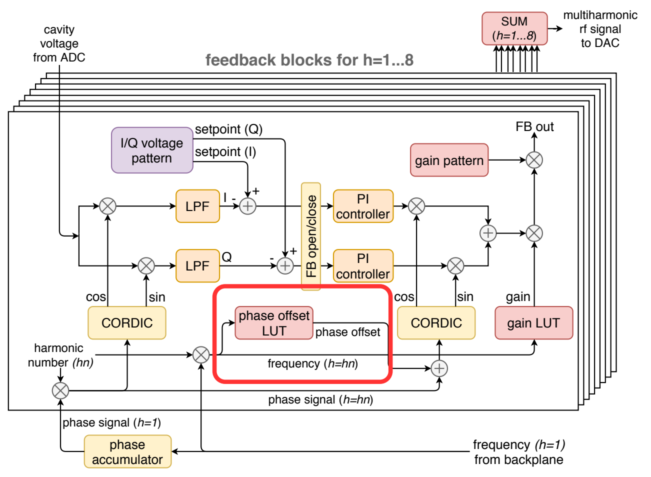


Phase offset LUT: "0" const

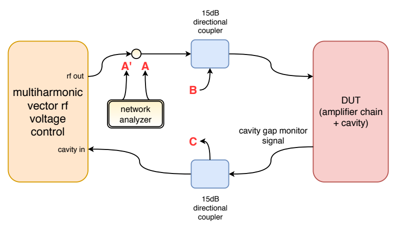


- Phase offset LUT gives phase offset between I/Q demod and mod to control phase transfer function
- Before LUT set, phase shift due to cable delay seen

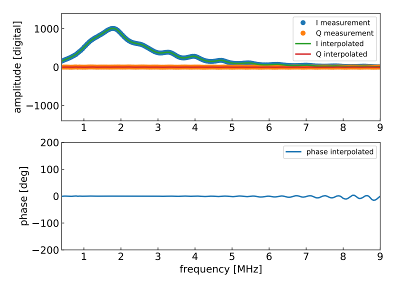
Multiharmonic vector rf voltage control feedback, block diagram



Open loop TF is measured using EPICS I/Q monitor

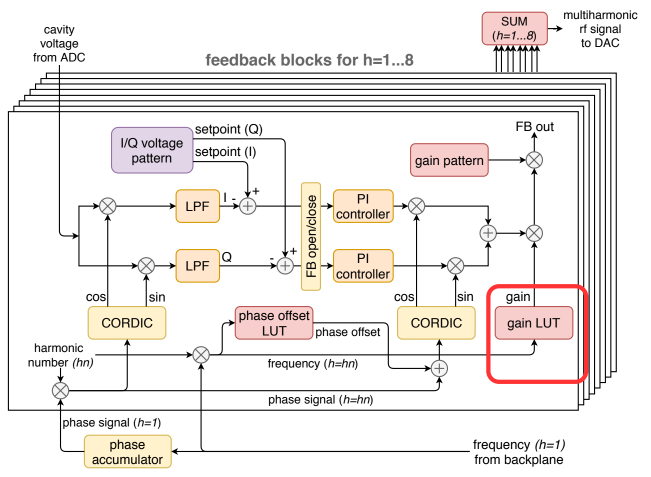


Phase offset LUT set:

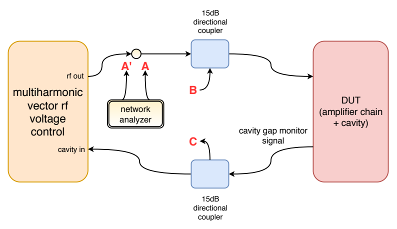


- With phase offset LUT set, the phase response is 0 deg. Feedback can be closed for all frequencies
- Amplitude response due to cav resonance seen → gain LUT

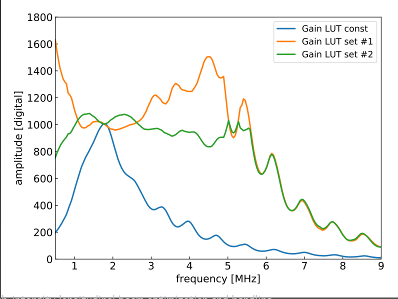
Multiharmonic vector rf voltage control feedback, block diagram



Open loop TF is measured using EPICS I/Q monitor

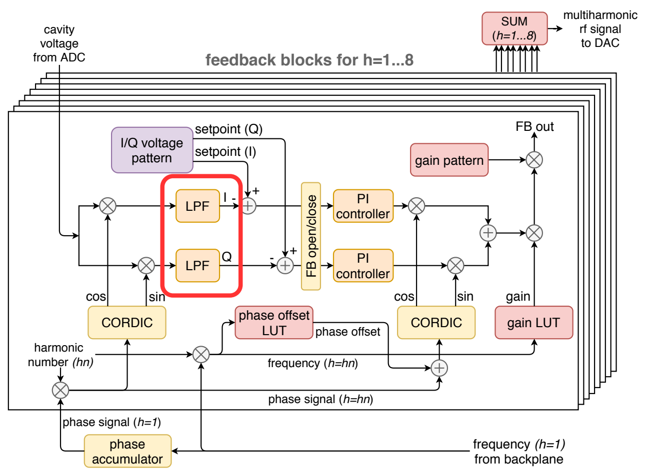


Gain LUT: const and set #1, #2:



- Gain LUT compensates amplitude transfer function, mainly due to cavity response
- Same PI gain setting can be used over frequency range

Multiharmonic vector rf voltage control feedback, block diagram



- LPF response affects performance of feedback
- Need consideration

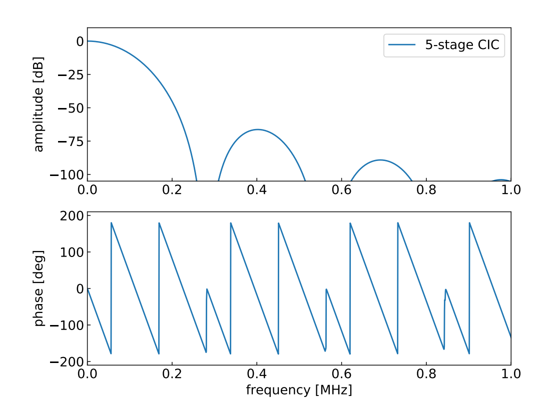
LPF consideration: 5-stage CIC filter

LPF must reject the next harmonic (separation 600 kHz): narrow band LPF necessary.

5-stage CIC filter, used for prototype module

$$H_{CIC}(z) = \left(\frac{1 - z^{-RM}}{1 - z^{-1}} \right)^N$$

- R: decimation factor between integrator and system clock
- M: the number of the delay taps in the comb
- N: the number of stages

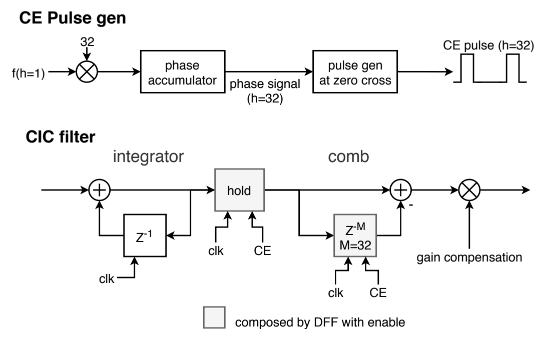


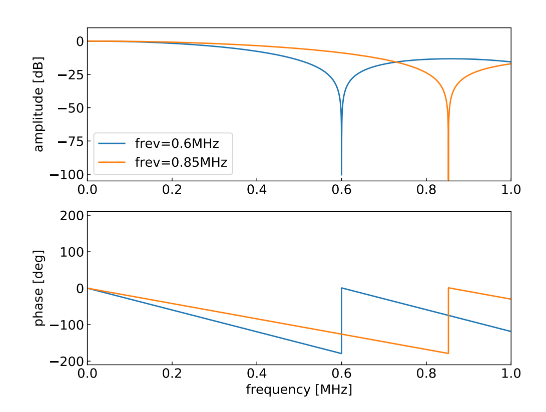
Prototype: R = 2, M = 256, and N = 5

Rejection of the next harmonic is enough, but much phase shift in the passband is an issue.

LPF consideration: tracking CIC filter

Proposed by J. Molendijk (CERN) for CERN PSB, LLRF17





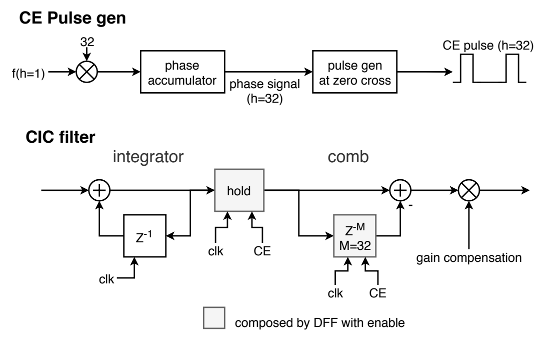
Analogy of sweeping clock implementation:

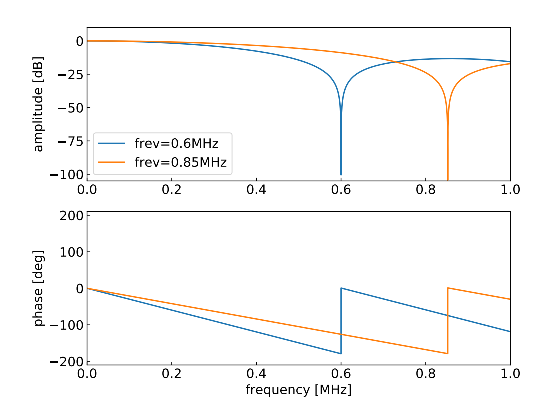
- CE pulse for comb generated by rev clock
- Notches follow the rev frequency change

Rejection of the next harmonic is enough and phase shift is smaller, but bandwidth is too wide for long cable delay (2 μs) in RCS.

LPF consideration: tracking CIC filter

Proposed by J. Molendijk (CERN) for CERN PSB, LLRF17





Analogy of sweeping clock implementation:

- CE pulse for comb generated by rev clock
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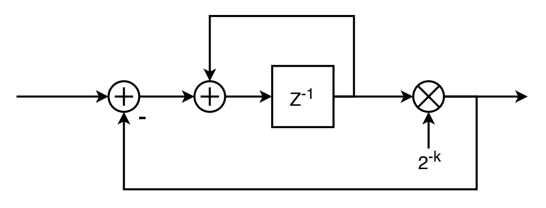
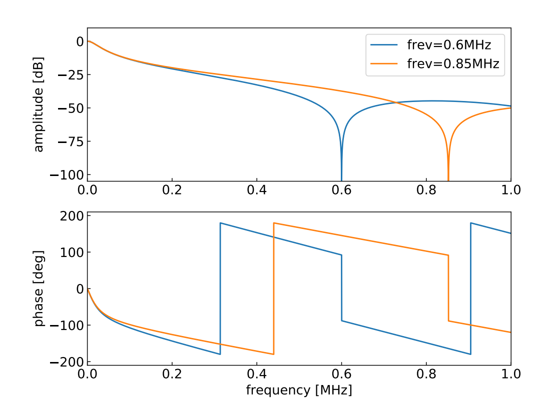
Rejection of the next harmonic is enough and phase shift is smaller, but bandwidth is too wide for long cable delay (2 μs) in RCS.

LPF consideration: Hybrid filter

Hybrid filter = tracking CIC + leaky integrator: implemented in next-generation system





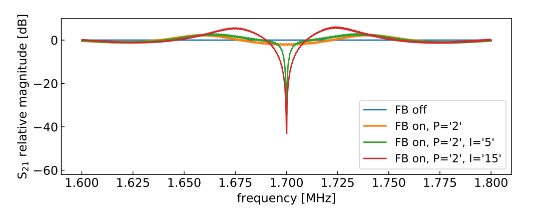
LI has narrow bandwidth and some phase shift.

Hybrid filter:

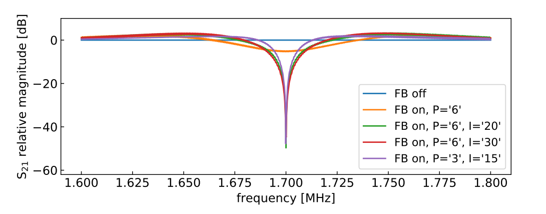
- Rejection of next harmonic is good
- Bandwidth is moderate
- Phase shift is not too much

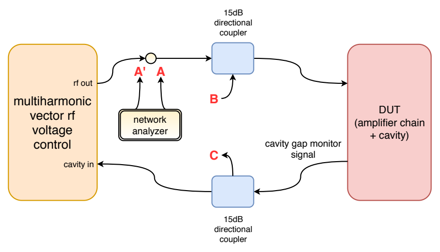
Closed loop gain comparison

5-stage CIC filter (prototype):



Hybrid filter (next-generation system):





Closed loop gain with various PI setting is measured by network analyzer (S_{21}, B to C).

- Higher PI gain is possible w/ hybrid
- Bandwidth w/ hybrid filter is wider
- Comparable bandwidth w/ 5-stage (P=2/I=15): unwanted enhancement

The measurements show the advantage of the hybrid filter over the five-stage CIC filter.