Multiharmonic enthusiast
– Applications of multiharmonic feedback in synchrotrons –

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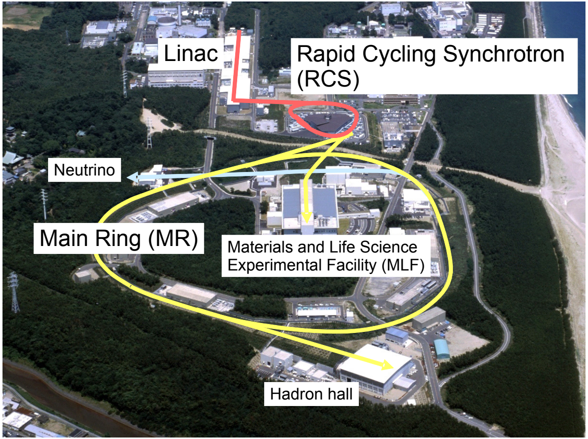
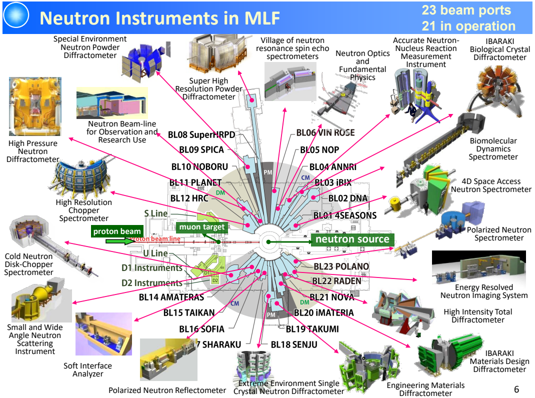
Contents

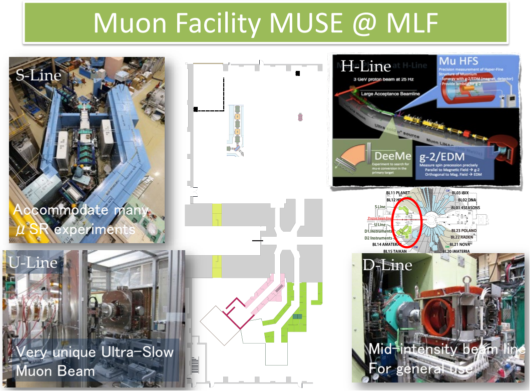
Japan Proton Accelerator Research Complex (J-PARC)



- Consists of 400 MeV linac, 3 GeV RCS, 30 GeV Main Ring, and experimental facilities (MLF, Hadron, Neutrino)
- Very high intensity proton beams are used for generation of secondary particles

Material and Life science Experimental Facility：MLF

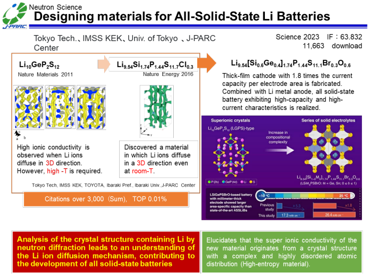


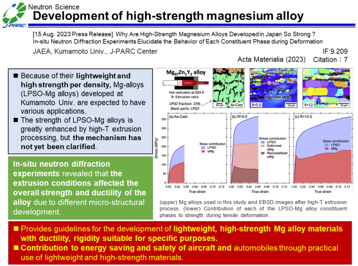


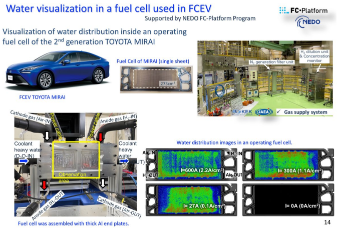
Spallation neutron source and muon source:

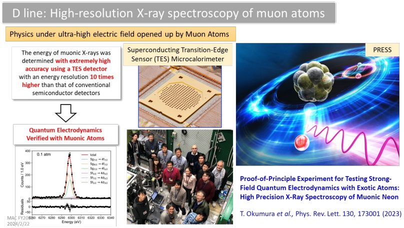
- Neutron: over 20 beamlines
- Muon: four

Only a few of recent outcome from MLF





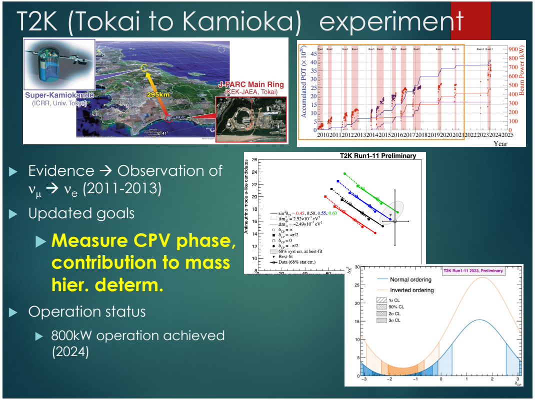


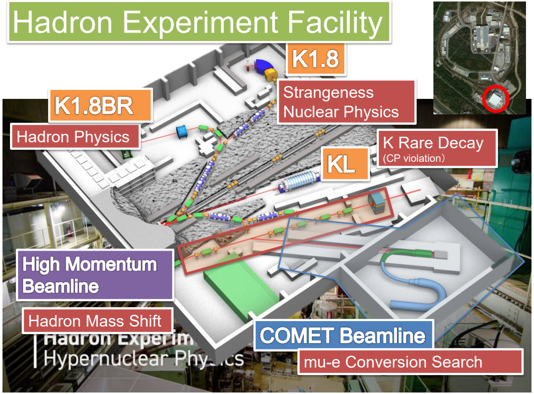


~500 experiments/year

MR beam destination: Neutrino experiments and Hadron hall

MR beams for particle and nuclear physics.

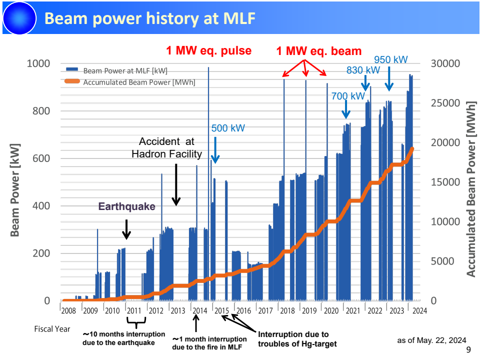


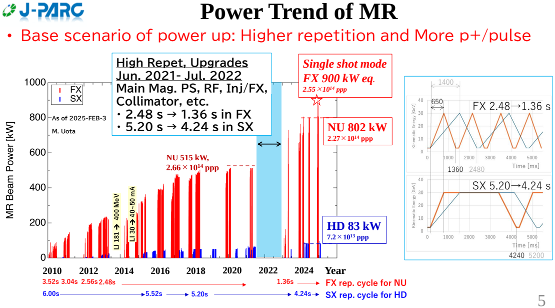


- Fast extraction (FX) by extraction kickers
- Hyper-K will requires 1.3 MW beam (3e14 ppp)

- Slow extraction during 2 s
- Kaon rare decay, strangeness, μe conversion search, etc. . .

Beam power history of RCS and MR

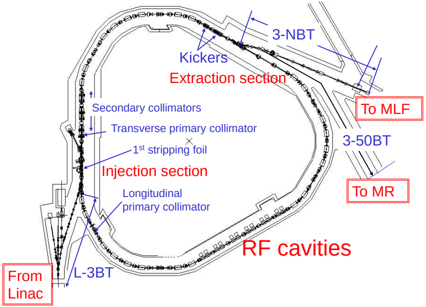


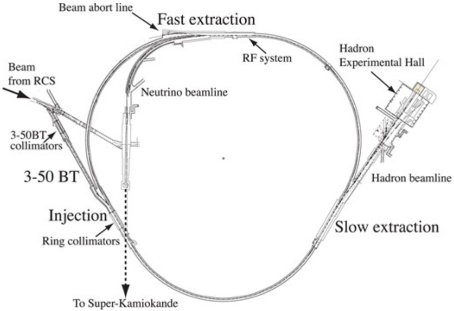


Original design beam powers (RCS: 1 MW, MR: 750 kW) have been achieved.

- We are trying to push beam powers higher

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

Key features of the synchrotrons (RCS and MR)

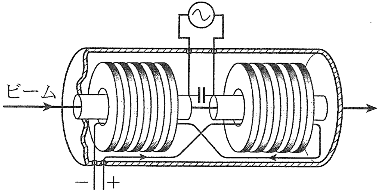
In point of view of rf, two key features:

High (RCS) and imaginary (MR) transition gamma lattice

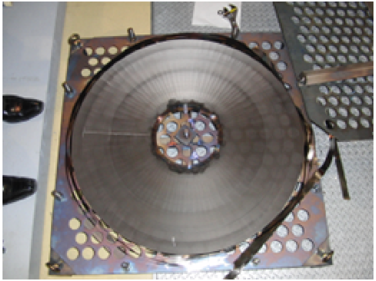
- No transition during acceleration, easy beam handling avoiding beam losses
- Small slippage factor / low synchrotron frequency. Longitudinal beam gymnastics is sometimes difficult

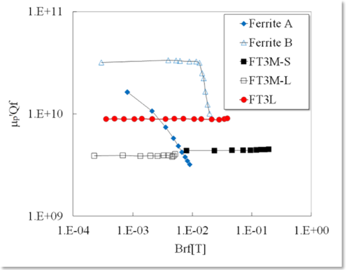
Magnetic alloy (Finemet) cavities

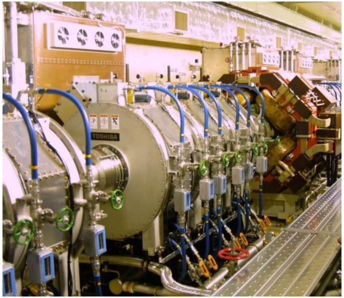
- Magnetic material loaded cavities are used for proton (ion) synchrotrons
- J-PARC synchrotrons employ magnetic alloy instead of conventional ferrite
- Today’s main topic



Finemet / Magnetic Alloy (MA) cavity







Magnetic Alloy:

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

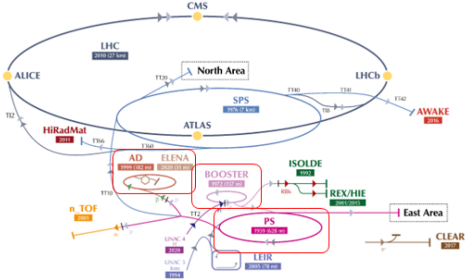
RCS MA cavity: 440 kV /12 cavities, $Q = 2$

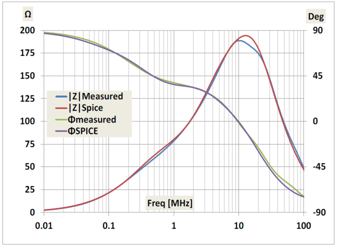
MR MA cavity: 480 kV / 9 cavities, $Q = 20$, 2nd harmonic 120 kV / 2 cavities

- Both cases, frequency sweep without tuning is possible

MA cavities at CERN

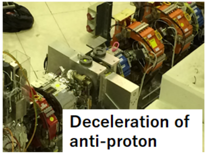
Facilities	Rings	Number of Cavities	Cell per Cavity	Total Voltage	Q-value	Cooling	Core	O.D. of core	Purposes
CERN	LEIR	2	1	8 kV	<1	Direct	FT3M	67 cm	Acc., 2nd
	PSB	3 × 4	2 ×6	24 kV	<1	Indirect	FT3L	33 cm	Acc.,2nd, blow-up
	PS	1	5	5 kV	<1	Indirect	FT3L	33 cm	damper, barrier RF
	ELENA	1	1	500 V	<1	Indirect	FT3L	33 cm	Decel.
	AD	1	5	4 kV	<1	Indirect	FT3L	33 cm	Decel.





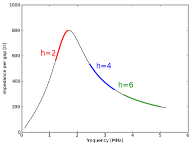

Replacement of all PSB cavity


Damper cavity for CBI in PS

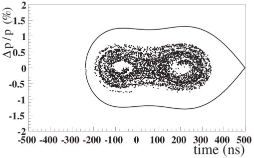

Deceleration of anti-proton

Advantage and disadvantage of wideband MA cavity

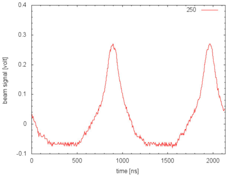
$Q = 2$ response:



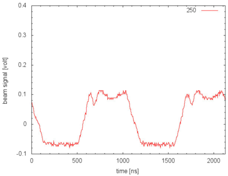
Simulated distribution:



Single harmonic:



Dual harmonic:



Dual harmonic operation for bunch shaping, where a single cavity is driven by superposition of the fundamental and second harmonic voltages, is possible.

- Indispensable for high intensity beam acceleration, alleviating space charge effects

Advantages can also be disadvantages.

- Wake contains higher harmonic. Multiharmonic beam loading compensation is necessary
- Distortion of tetrode output current appears as cavity voltage distortion

Advantage and disadvantage of wideband MA cavity

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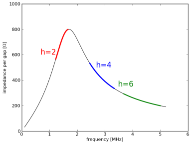
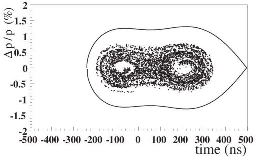
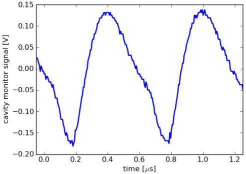


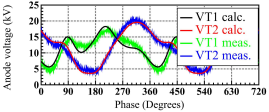
Simulated distribution:



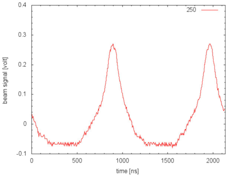
Measured wake voltage in RCS cavity:



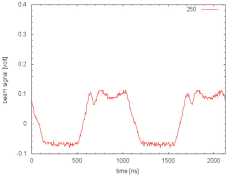
Anode voltages at 1 MW beam acceleration:



Single harmonic:



Dual harmonic:



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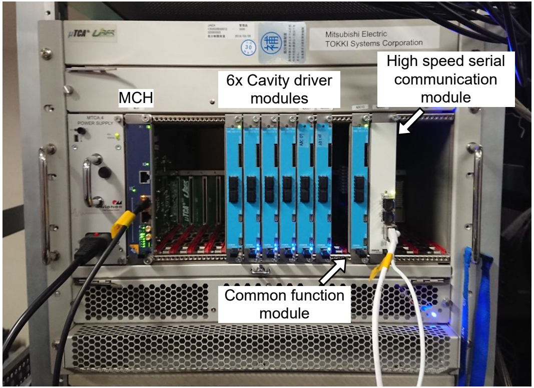
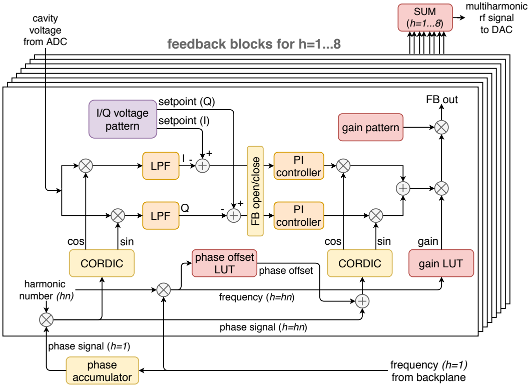
Multiharmonic vector rf voltage control feedback in new RCS LLRF (2019–)





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

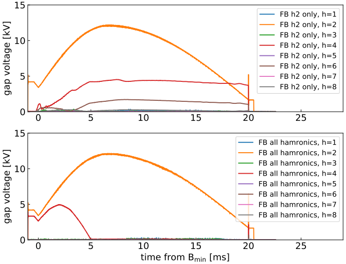
Eight classical I/Q feedback blocks for harmonics (h1. . .h8).

- LPF design is the key: Tracking CIC + leaky integrator
- Phase offset LUT and gain LUT for wide frequency range (0.4-6.8 MHz)

Performance of multiharmonic feedback with 1 MW beams

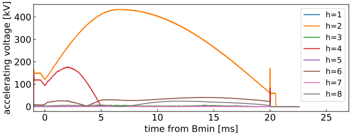
Preliminary test with a single cavity

Harmonic components of cavity gap voltage:



Tests with 12 cavities

Harmonic components of vector-sum voltage:

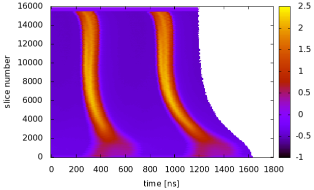


https://doi.org/10.1109/TNS.2019.2899358,

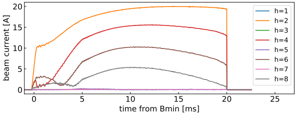
https://doi.org/10.1103/PhysRevAccelBeams.22.092001,

https://doi.org/10.1016/j.nima.2021.165211

Mountain plot of beam signal:



Harmonic components of beam signal:



Single cavity test: Just perfect.

- Wake voltages of 4.6 kV (h4) / 1.7 kV (h6) suppressed by FB below 300 V

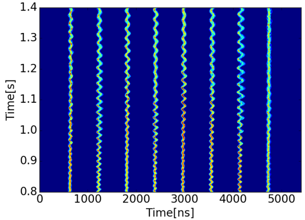
We need compromise for 12 cavities.

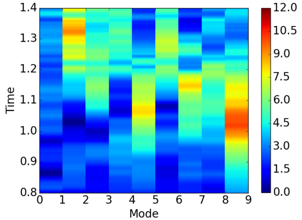
- h78 FB disabled for all cavities. h6 disabled for 7 out of 12 cavities. Because of HLRF trips
- Unwanted h6/h8 clearly seen in vector-sum voltage, 40/25 kV

Although compromises were necessary, stable beam acceleration was achieved.

Similar multiharmonic FB deployed in MR: CBI suppression

With feedforward

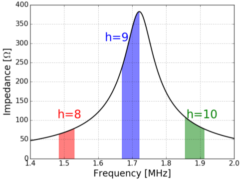




Above 450 kW, coupled bunch instabilities observed in MR.

- CBI limited the available beam power
- Impedance of Neighbor harmonic (h8, h10) is the source of CBI. Mode 1 and 8 are dominant

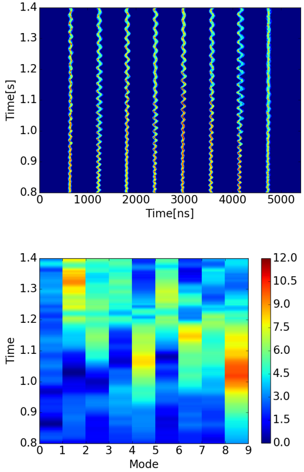
With multiharmonic feedback, wake voltages of h8/h10 and the coupled bunch oscillations are suppressed.



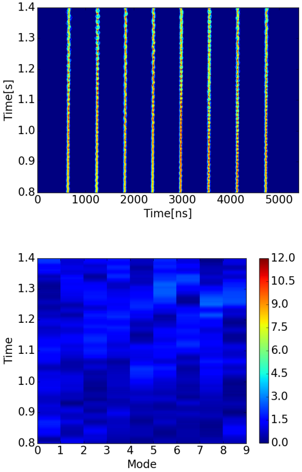
For both RCS and MR, multiharmonic FB serves high intensity beam acceleration.

Similar multiharmonic FB deployed in MR: CBI suppression

With feedforward



With feedback



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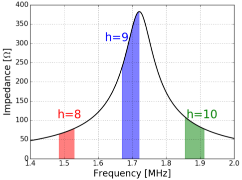

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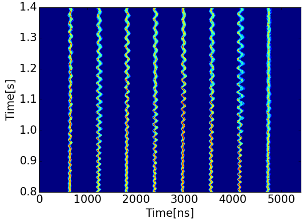

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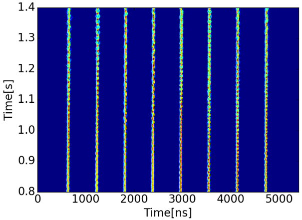

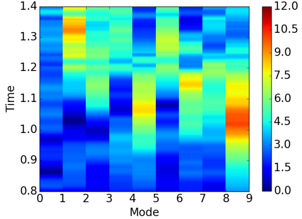

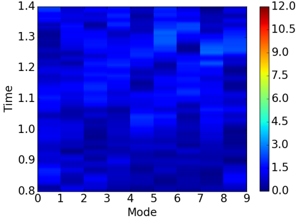

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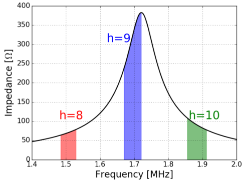
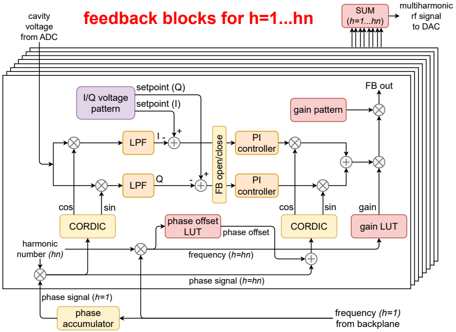
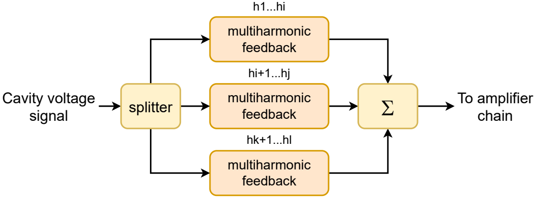


For both RCS and MR, multiharmonic FB serves high intensity beam acceleration.

Multiharmonic FB is scalable

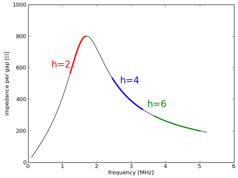




Number of harmonics is (theoretically) not limited.

- J-PARC: 8 harmonics / cavity, CERN PSB (Servo loop): 16 harmonics /cavity
- Adding modules is also possible

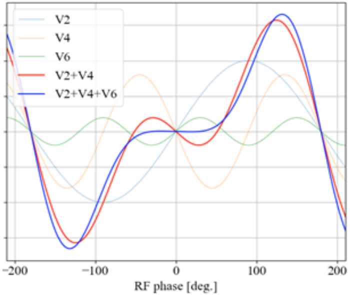
Triple harmonic operation

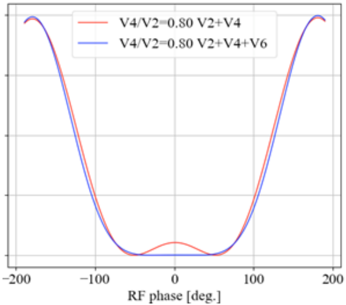


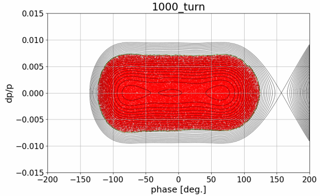
To realize flatter bunch in RCS, triple harmonic operation is considered.

- h6 is covered by the frequency response

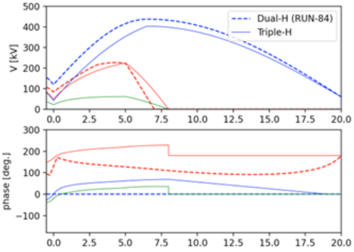
With h6, a wide and flat potential can be formed.







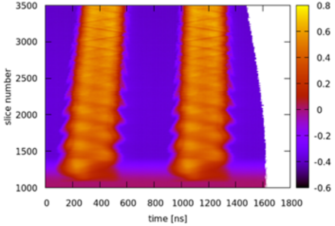
Triple harmonic operation: beam tests

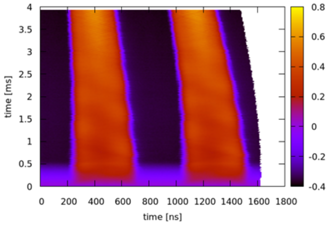


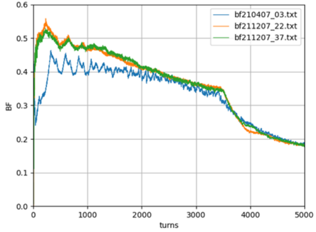
Beam tests performed with 1 MW beams.

- Smoother bunch shape obtained with triple harmonic
- Bunching factor improved

Because of power consumption, triple harmonic is not yet used for normal operation.







1. Introduction

2. Multiharmonic feedback at J-PARC

3. Possible applications of multiharmonic FB

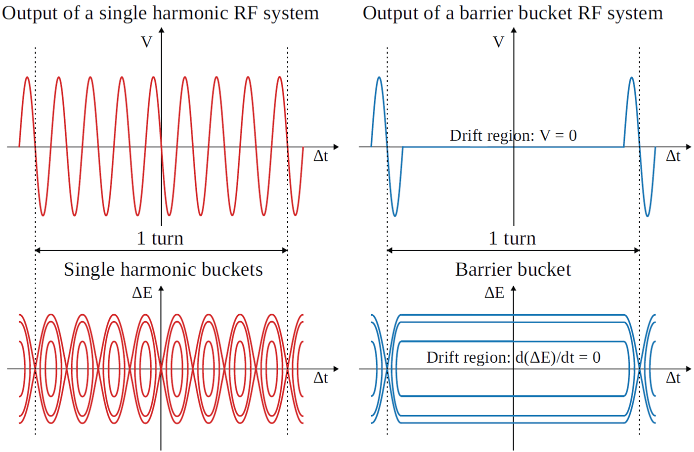
- Triple harmonic operation
- Barrier bucket formation
- Non-integer harmonics

4. Important considerations when using multiharmonic FB

- Frequency response of cavity voltage monitor and cable
- Unwanted voltage jump

5. Final thoughts

What is barrier bucket?

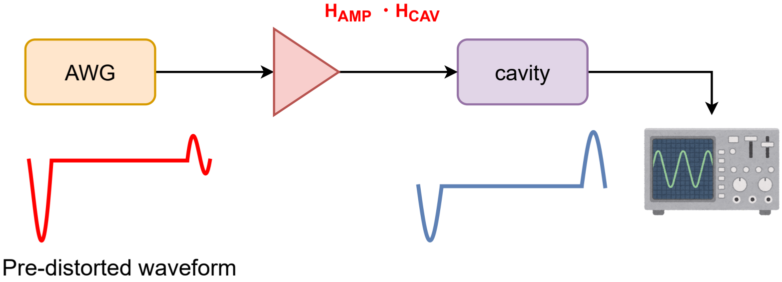


M. Vadai, et. al., EPL, 128 (2019) 14002.

A Barrier bucket voltage has long drift region.

- Preserve a gap for kicker in a debunched beam
- Accumulate intense beam with alleviating space charge effects

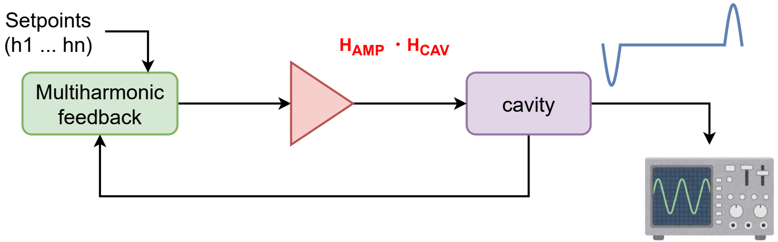
Conventional way to generate barrier voltage



A pre-distorted waveform is generated by AWG so that cavity gap voltage is desired barrier voltage.

- Compensate the transfer function of the system ($H_{\mathrm{AMP}} \cdot H_{\mathrm{CAV}}$)
- Adjustment is not trivial
- It is difficult to keep voltage under beam loading, because the setup is open loop

Barrier voltage generation using multiharmonic feedback

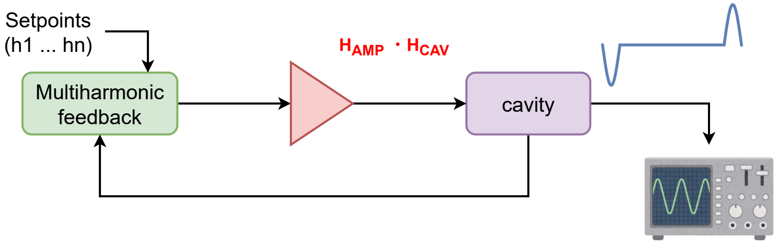


Multiharmonic setpoints are set to generate barrier voltage.

- Relying on the voltage monitor, one can forget about the transfer functions
  - Feedback conditions (phase) must be adjusted for harmonics
- Closed loop. Beam loading and other fluctuation can be compensated

But, how many harmonics are necessary?

Barrier voltage generation using multiharmonic feedback



Multiharmonic setpoints are set to generate barrier voltage.

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  - Feedback conditions (phase) must be adjusted for harmonics
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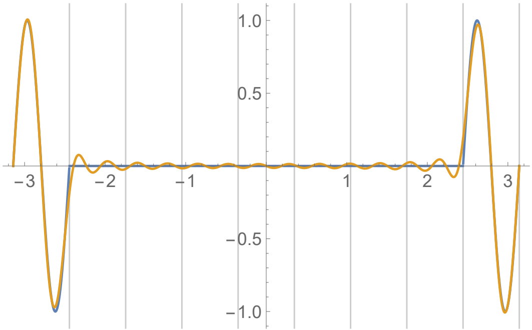
But, how many harmonics are necessary?

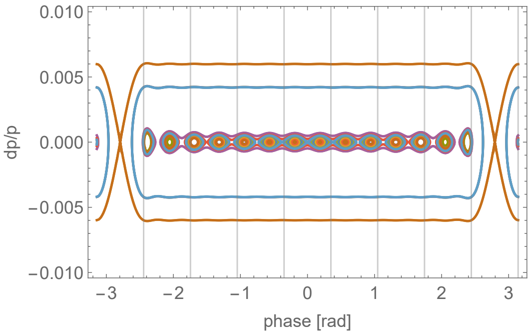
Example of multiharmonic barrier voltage

Out[793]= 0.0460363 Sin[x] - 0.0732796 Sin[2 x] + 0.0689161 Sin[3 x] - 0.0301482 Sin[4 x] -
0.0349934 Sin[5 x] + 0.110266 Sin[6 x] - 0.176329 Sin[7 x] + 0.216641 Sin[8 x] -
0.222222 Sin[9 x] + 0.193837 Sin[10 x] - 0.141063 Sin[11 x] + 0.0787613 Sin[12 x] -
0.0222685 Sin[13 x] - 0.0170403 Sin[14 x] + 0.0344581 Sin[15 x] - 0.032243 Sin[16 x]



With 16 harmonics, barrier voltage can be generated.

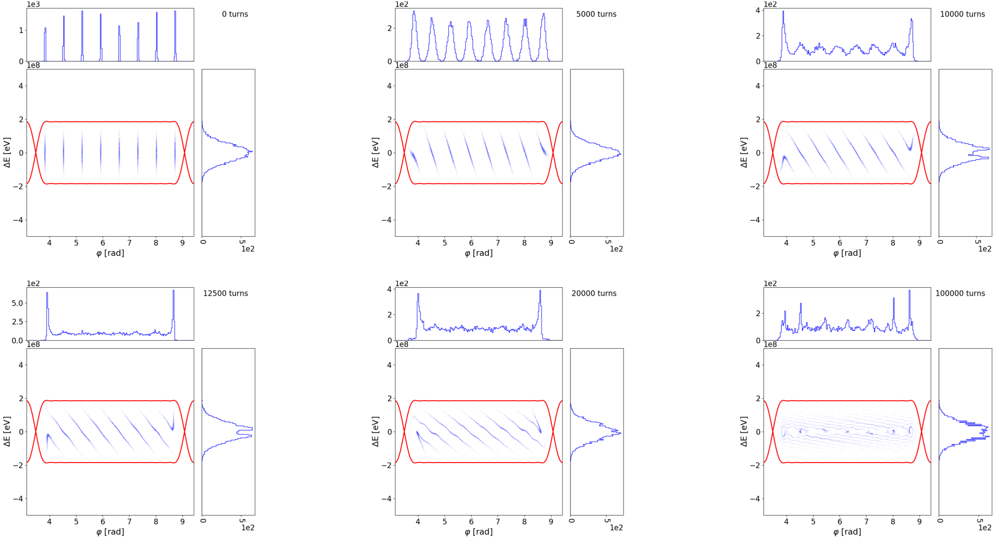
- 16 is a reasonable number



Barrier bucket example for J-PARC MR, $f_{\mathrm{rev}} = 192$ kHz, V_{peak} =30 kV.

- Inner separatrix due to ringing in the drift region seen

Multiharmonic barrier voltage works



Note: MR has no wideband cavity; just consideration.

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- Triple harmonic operation
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- Non-integer harmonics

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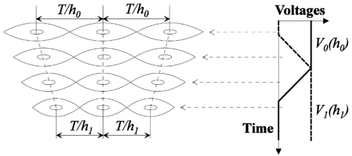
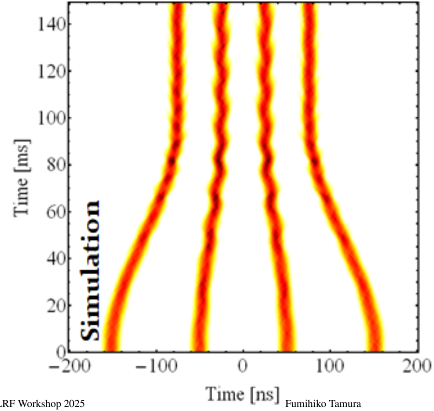
Batch compression



(From Accelerator Handbook) Batch compression is applied to squeeze a set of n bunches into a smaller fraction of the circumference. The number of bunches is unchanged. It can be quasi-adiabatic, preserving shape and emittance of bunches.



Batch compression of lead ion beams from 100 ns spacing to 50 ns is being considered at CERN.

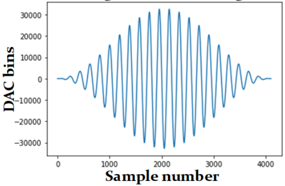
- Selection of harmonics is not trivial
- $h = 21 \rightarrow 21 \rightarrow 25 \rightarrow 30 \rightarrow 36 \rightarrow 42$
- Imperfect compression of (inner) bunch pair, even with non-linear voltage programs

Alternative smooth batch compression

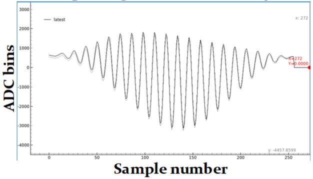
4

- Use amplitude modulated non-integer harmonic sweep
  - → Smooth batch compression for all bunches
  - → $V_{RF}(t) = V_o \cdot f_{envelope}(\text{azimuth}) \cdot \sin(2\pi f_{rev} \cdot h)$, h non-integer
  - → Works with 4 and 6 bunches

Programmed RF voltage



Gap voltage (PS Finemet cavity)



- → No handover between harmonics → all cavities do the same
- → Spectral content only at f_{RF} and $f_{RF} \pm f_{rev}$ (half amplitude)

$$V_{\mathrm{RF}}(t) = 0.25\sin[\omega_{\mathrm{rev}}(h-1)t] + 0.5\sin[\omega_{\mathrm{rev}}ht] + 0.25\sin[\omega_{\mathrm{rev}}(h+1)t] \quad \text{h: non-integer}$$

CERN people trying to use non-integer harmonic directly with open loop configuration.

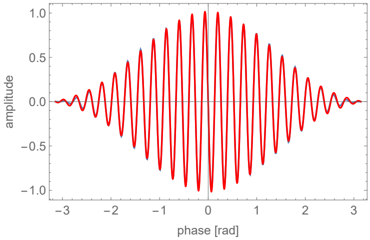
- Is it possible to use multiharmonic FB, which consists of integer harmonics, for this?

Expression non-integer harmonics using integer harmonics

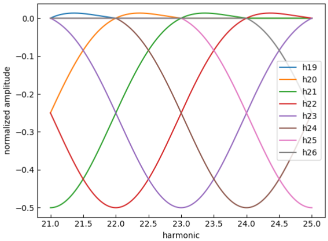
The non-integer waveform can be fitted by up to 5 integer harmonics:

```
In[890]:= (* define target waveform *)
          hh = 23.7(* non integer *)
          usedbucket = hh;
          func = -Sin[hh x] (0.5 - 0.5 Cos[x - π])
          data = Join[Table[{x, func}, {x, -usedbucket / hh π, usedbucket / hh π, π / ( 20 hh)}]];
          p1 = Plot[func, {x, -π, π}, PlotPoints → 10];
          p2 = ListPlot[ data, PlotStyle → {Green}];
          starthh = Floor[hh - 1];
          endhh = Ceiling[hh + 1];
          line = Fit[data, Flatten[Table[{Sin[n x]}, {n, starthh, endhh, 1}]], x] // Chop
          p3 = Plot[line, {x, -π, π}, PlotRange → All, PlotStyle → {Red}];
          Show[p1, p3, AspectRatio → 1 / GoldenRatio, Frame → True,
           FrameLabel → {"phase [rad]", "amplitude"},
           LabelStyle → Directive[Medium, FontFamily → "Helvetica"]]

Out[890]= 23.7

Out[892]= -(0.5 + 0.5 Cos[x]) Sin[23.7 x]

Out[898]= -0.0400731 Sin[22 x] - 0.360671 Sin[23 x] - 0.471644 Sin[24 x] - 0.143545 Sin[25 x]
```

Blue (target) and red (fit) lines are very close.

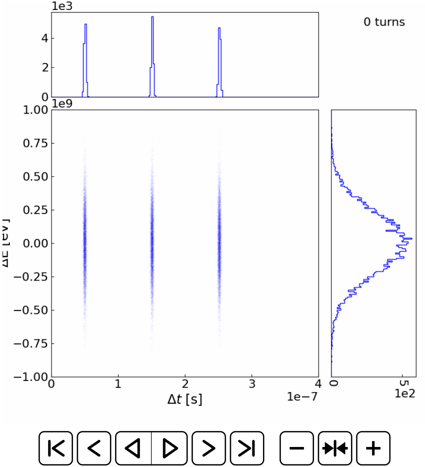


Harmonic amplitude to realize non-integer harmonics:



The harmonic amplitudes vary smoothly according to the target harmonics.

Longitudinal tracking simulation



Preliminary longitudinal tracking simulation was performed.

- CERN PS flattop, lead ion, 6 bunches
- Voltage = 20 kV, duration 180 ms
- The bunches move with non-integer harmonic sweep, while the parameters are not optimized yet

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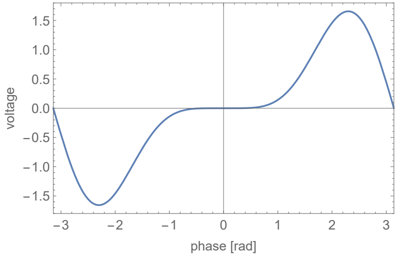
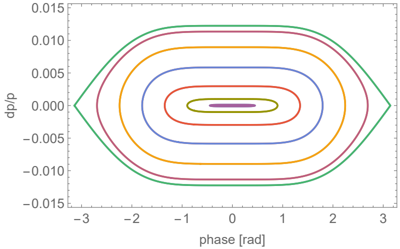
We cannot believe the voltage monitor waveform as is

Voltage monitor signal of nice triple harmonic:





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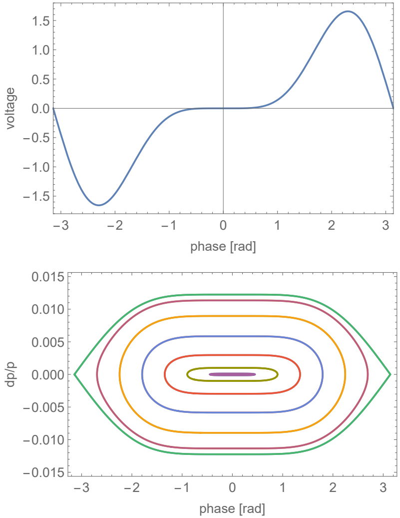
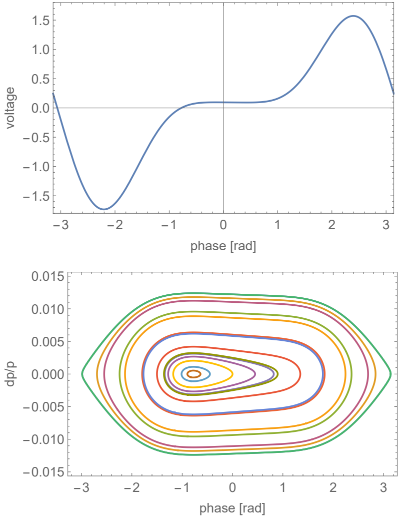
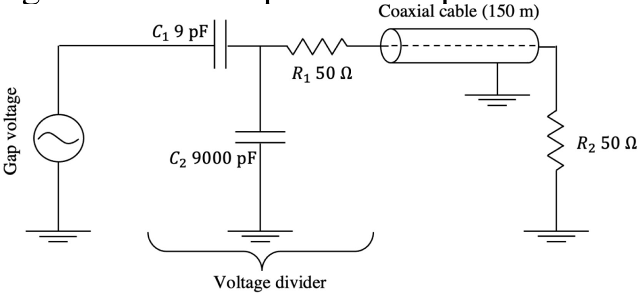


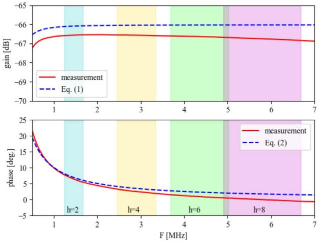
Real gap voltage seen by the beam:



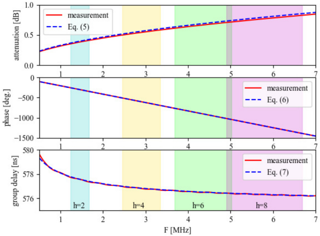
Voltage monitor components: capacitive divider and coaxial cable



C-divider response:



150 m coax cable response:

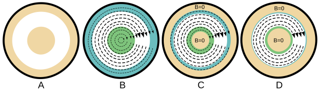


Capacitive divider:

- $G_v = 20\log_{10}\frac{2\pi f C_1 R_1}{\sqrt{1+[2\pi f(C_1+C_2)(R_1+R_2)]^2}}$ dB
- $\phi_v = \arctan\frac{1}{2\pi f(C_1+C_2)(R_1+R_2)}$ radians

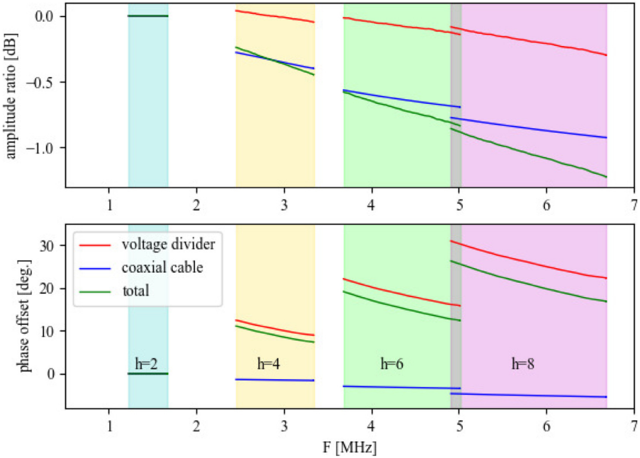
Coaxial cable:

- Due to skin effect, not only attenuation but also group delay varies.



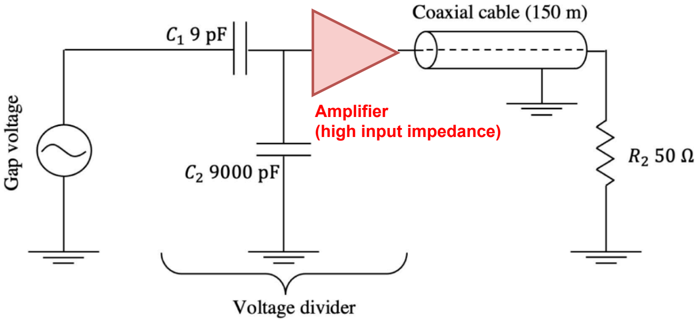
Our operating frequency range (1.2 MHz–6.8 MHz) is in “C”.

Relative frequency response to fundamental accelerating harmonic



- Relative phase offset: $-\phi_{h_n} + \frac{h_n}{h_0}\phi_{h_0}$
- Details: `https://doi.org/10.1016/j.nima.2022.167361`

Countermeasure (1)

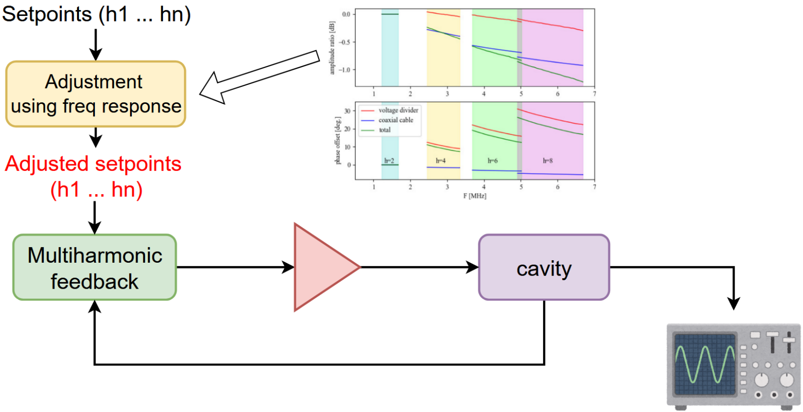


Replace 50 Ω resister with amplifier:

- High input impedance
- $G_v = 20\log_{10}\frac{2\pi f C_1 R_1}{\sqrt{1+[2\pi f(C_1+C_2)(R_1+R_2)]^2}}$ dB $\to 20\log_{10}\frac{C_1}{C_1+C_2}$
- $\phi_v = \arctan\frac{1}{2\pi f(C_1+C_2)(R_1+R_2)}$ radians $\to$ 0 radian

Frequency response of coaxial cable cannot be modified.

Countermeasure (2)

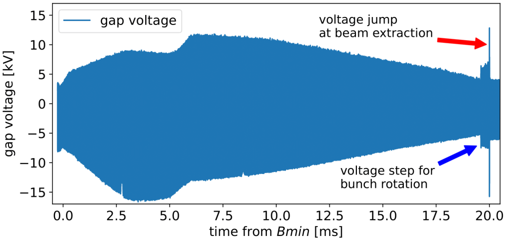


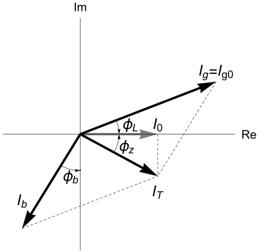
I/Q setpoints are adjusted using frequency response so that the real gap voltage is desired one.

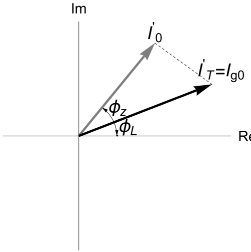
- Beam tests of triple harmonic operation done with this method
- Note: looking at the oscilloscope waveform does not make so much sense. Analysis using frequency response is necessary

Unwanted voltage jump after fast extraction of high intensity beam

Typical gap voltage waveform with accelerating 1 MW beams:





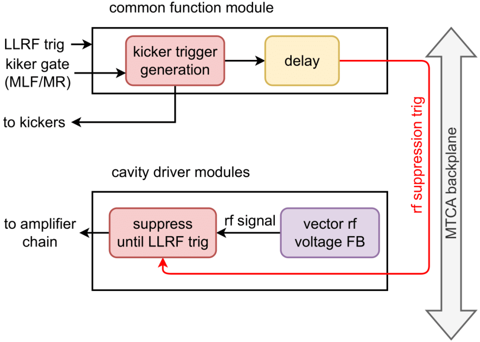


After fast extraction of high intensity beams, voltage jump occurs because of the delay of FB.

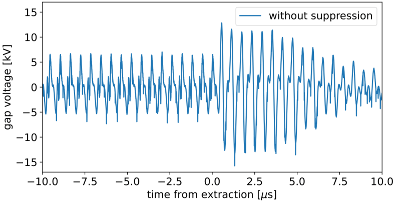
- Steady state before extraction: large generator current (I_g0)
- After extraction, beam current suddenly becomes zero. New total current $I'_T = I_{g0}$, $I'_T > I_T$
- Since the RCS cavity has a very low Q value of 2, the voltage reacts quickly within a few cycles
- Voltage goes to the set value by FB for step response of 10 µs

Countermeasure against voltage jump

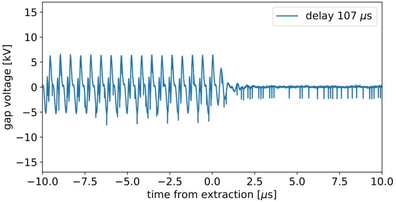
One can turn off the generator current when extraction by turning off the rf output.



No suppression



Delay = 107 μs



Kicker trigger is generated by RCS LLRF.

- rf output is suppressed after kicker trigger output with proper delay

Final thoughts

The combination of wideband MA cavity and multiharmonic rf feedback has a wide variety of applications.

- Dual or triple harmonic operation
- Barrier bucket
- Non-integer harmonics for batch compression
- and more...

One should be aware of frequency responses of voltage monitors.

(Not mentioned in presentation) HLRF determines final performance / limits.

Multiharmonic rf rules!

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Backup slides

Barrier bucket