SPring-8 Closed Orbit Feedback System, a Challenge for Suppression of the Closed Orbit Vibration Down to Sub-micron Level

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2002.Dec.6 at Workshop on Beam Stabilization

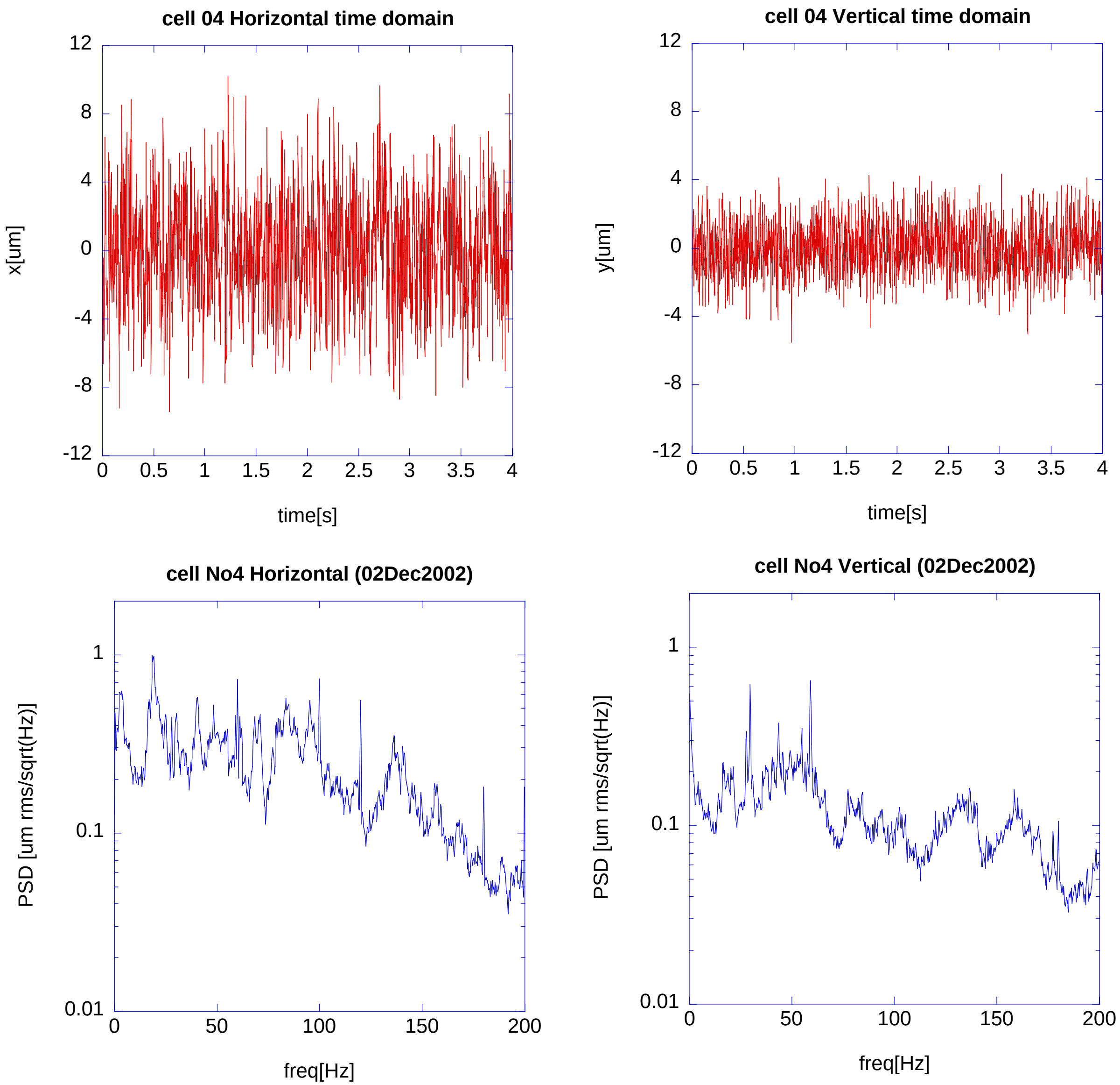
about the plan of a fast global COD correction for the SPring-8 storage ring.

- target performance of the feedback

- requirements to the BPM electronics
  - noise and bandwidth, measurement speed
  - effect of nonlinearity

example of COD motion observed at a certain point in the storage ring

$\mathrm{rms}_x = 3\mu\mathrm{m}$, $\mathrm{rms}_y = 1.4\mu\mathrm{m}$



target performance of the feedback system

- suppression of closed orbit vibration down to sub-micron level
- the frequency range is up to 100 Hz

major components of feedback system

sensor : BPM

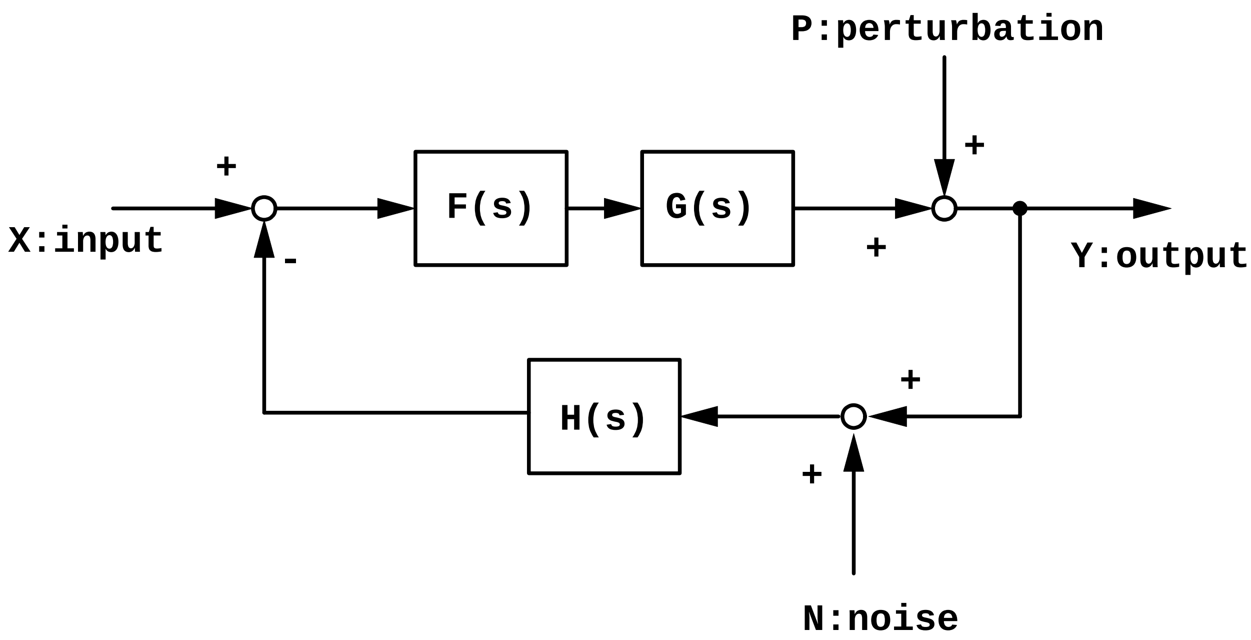
corrector: steering magnets and their power supplies, vacuum chamber response

controller: data acquisition, calculation of the amount of correction from the difference between the measured COD and the reference COD

The feasibility for the BPM electronics will be discussed.

requirements to the position measurement

- ◇ position resolution $< \mu$m $\Rightarrow$ S/N $>$ 80dB$\sim$100dB
- ◇ measurement period $<$ 0.1 ms $\Rightarrow$ BW $>$ 10 kHz



transfer function

$$Y = \frac{FG}{1+FGH}X + \frac{1}{1+FGH}P - \frac{FGH}{1+FGH}N$$

$F(s)$: Orbit difference to correction strength calculation
$G(s)$: power-supply, steering-magnet response, and vacuum chamber response
$H(s)$: Beam position measurements

coefficients for Perturbation and Noise:

$$\frac{1}{1+FGH} + \frac{FGH}{1+FGH} = 1 \Rightarrow \left|\frac{1}{1+FGH}\right| + \left|\frac{FGH}{1+FGH}\right| \geq 1$$

making both coefficients small simultaneously is not possible

conditions for the feedback to be effective:

$$\left|\frac{1}{1+FGH}\right| \ll 1,\ \left|\frac{FGH}{1+FGH}\right| \approx 1,\ |N| \ll |P|$$

for the desired frequency range

$\Rightarrow$ fluctuation of Y become the same order of N; $< Y^2 > \approx < N^2 >$

first step estimation:

$F(s) = K$: constant multiplication (fixed gain),

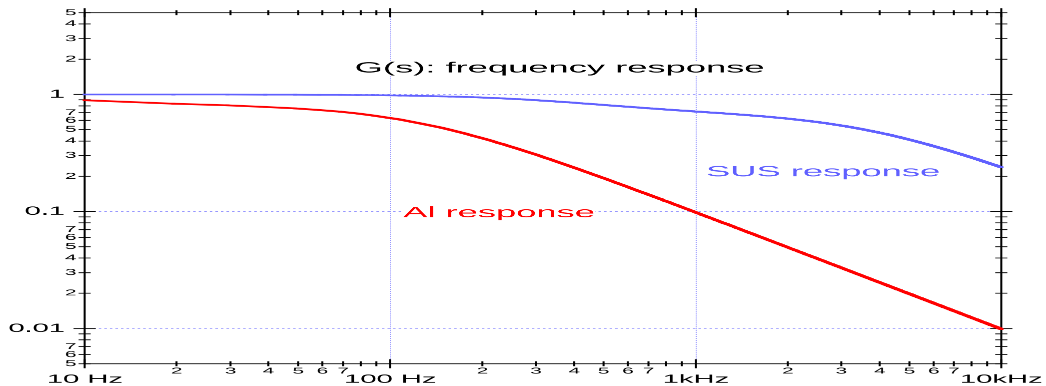
$H(s) = \mathrm{e}^{-sT}$: constant time delay (the time necessary for position measurement or the feedback cycle time),

$G(s)$: calculated response of the vacuum chamber including eddy current effect

$G(s)$: calculated response of the vacuum chamber including eddy current effect for the eliptic cross section with the minor axis of 40 mm, and major axis of 90 mm

$$G(s) = 1 - s\frac{0.2}{s+53.55} - s\frac{0.8}{s+764.75},$$ for 3-mm thick Aℓ chamber

$$G(s) = 1 - s\frac{0.34}{s+2412.2} - s\frac{0.66}{s+22918},$$ for 3-mm thick SUS chamber

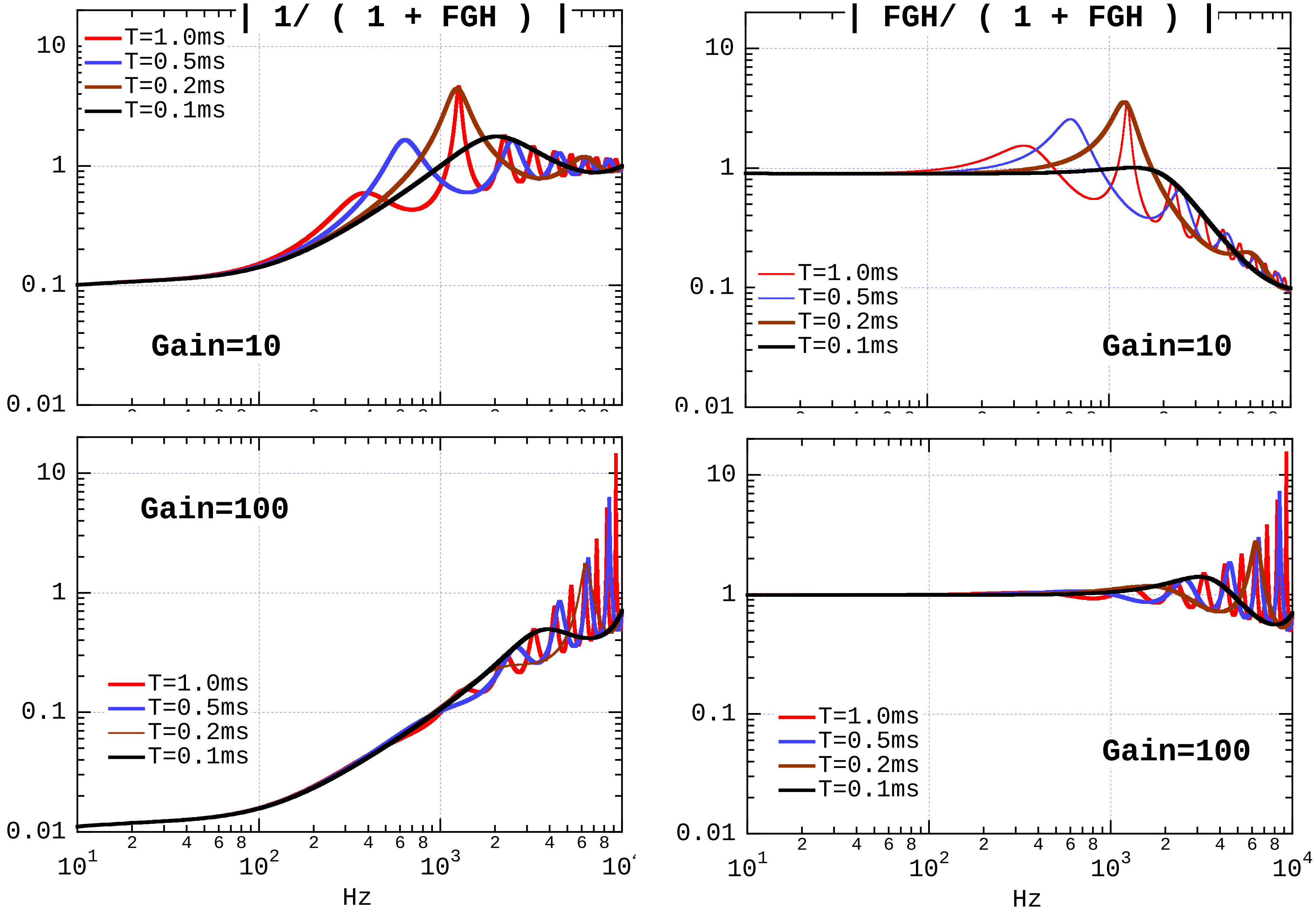


$53.55 = 2\pi\times 8.52$, $764.75 = 2\pi\times 121.7$

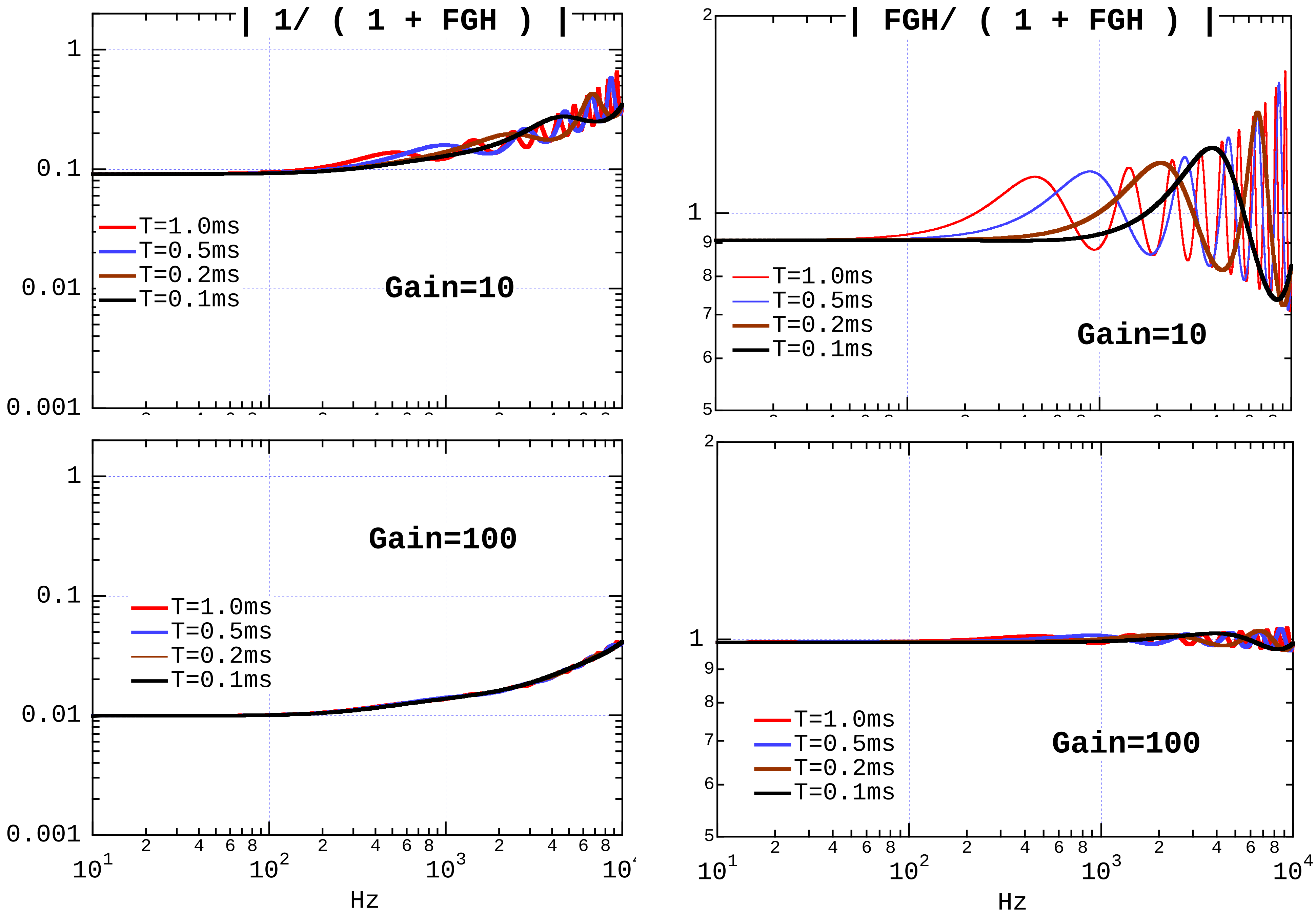
$2412.2 = 2\pi \times 383.9$, $22918 = 2\pi \times 3,647.5$

calculation of frequency response $s \rightarrow j\omega$

G(s): Al 3mm resoponse



G(s): SUS 3mm resoponse



error propagation from signal amplitude on the BPM electrode to beam position measurement

$$\begin{aligned}
x &= \left(\frac{1}{S_x}\right)\left(\frac{1}{2}\right)\left(\frac{A_1 - A_2}{A_1 + A_2} + \frac{A_4 - A_3}{A_4 + A_3}\right) \\
\frac{\partial x}{\partial A_1} &= \left(\frac{1}{S_x}\right)\left(\frac{1}{2}\right)\frac{(A_1 + A_2) - (A_1 - A_2)}{(A_1 + A_2)^2} = \frac{1}{S_x}\frac{A_2}{(A_1 + A_2)^2} \\
& \quad \text{estimate around } A_1 = A_2 = A_3 = A_4 = A \\
\frac{\partial x}{\partial A} &= \left(\frac{1}{S_x}\right)\left(\frac{1}{4A}\right), \\
|\delta x| &= \left|\frac{1}{S_x}\right| \left|\frac{\delta A}{4A}\right| \sqrt{4} = \frac{1}{2}\left|\frac{1}{S_x}\right| \left|\frac{\delta A}{2A}\right|
\end{aligned}$$

$S_x \approx 0.05$ mm^{-1}; $1/S_x \approx 20$ mm;

for vacuum chambers of SPring-8, or the chambers about the same apertures

$|\delta x| \approx 10$ mm $\times\ |\delta A/A|$.

For the $|\delta x|$ to be sub-μm, relative error $\delta A/A \approx 10^{-4}$ or smaller is necessary;

S/N $\approx$ 80dB or more

S/N feasible ?

NOISE: thermal noise

-174 dBm/Hz at room temperature (r.t.)

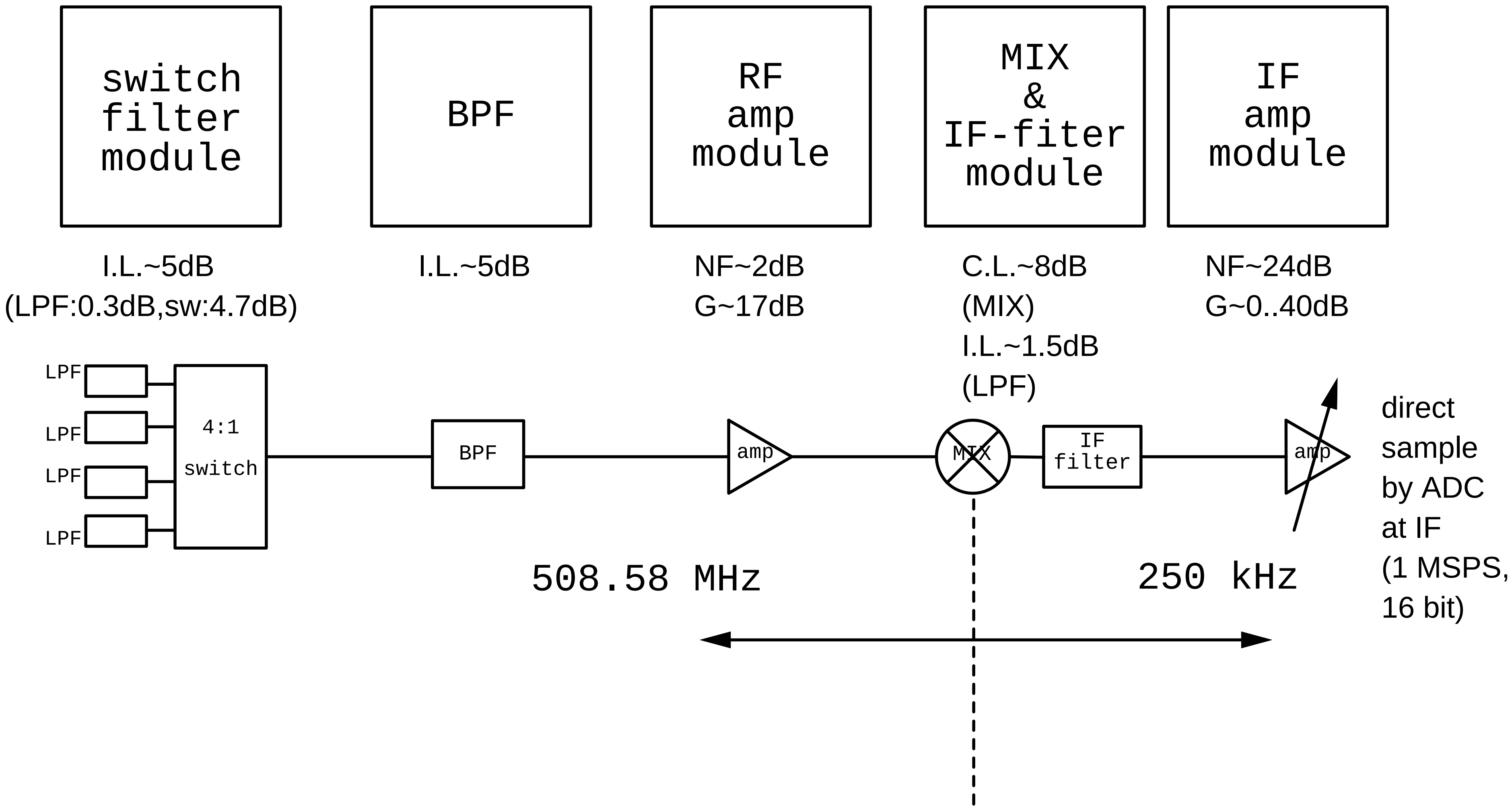
-134 dBm for 10-kHz band width(BW)

SIGNAL: for the SPring-8 storage ring BPM button pickup

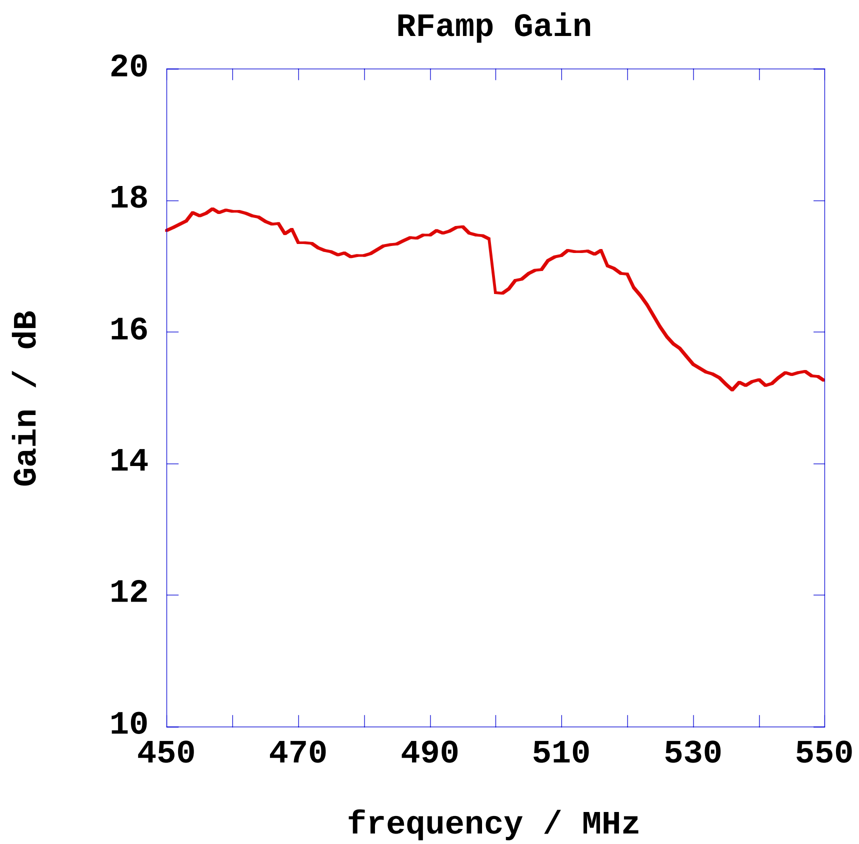
single spectrum line intensity at 508.58 MHz (f_{RF})

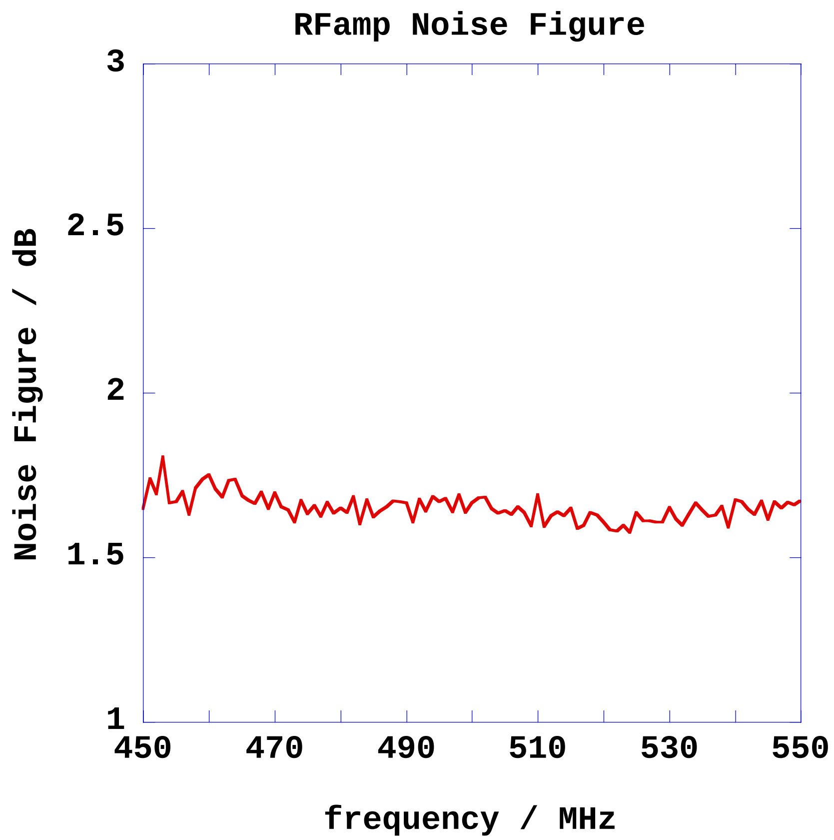
beam current	signal amplitude	NF margin for 80-dB S/N	NF margin for 100-dB S/N
1 mA	-60 dBm	—	—
10 mA	-40 dBm	14 dB	—
100 mA	-20 dBm	34 dB	14 dB

Block Diagram of R&D electronics



Noise figure analyzer data





estimation of the NF for the R&D circuit, with the measured values for each component

component		LPF		BPF		RFamp		MIX		LPF		IFamp
stage NF(dB)						2						24
stage gain(dB)		-0.3		-5		17		-8		-1.5		20
cumulative NF(dB)	22.0		21.7		16.7		33.5		25.5		24.0	

IFamp NF was estimated by output noise level(-130dBm/Hz) observed with a spectrum analyzer for terminated input, with gain 20dB; -174 dBm + 20dB + NF = -130 dBm

NF for cascaded stage:

$$NF_{tot} = NF_i + \frac{NF_{i+1} - 1}{G_i};$$ NF_i, Gain$_i$ expressed in ratio [not in dB]

-134 dBm + 22 dB = -112 dBm: effective noise at input (10-kHz BW)

beam current	S/N	$\|\delta A/A\|$	$\|\delta x\|$
100 mA	92 dB	2.5×10^{-5}	$\approx 0.3\mu$m
80 mA	90 dB	3.2×10^{-5}	$\approx 0.3\mu$m
25 mA	80 dB	1.0×10^{-4}	$\approx 1\mu$m
10 mA	72 dB	2.5×10^{-4}	$\approx 3\mu$m

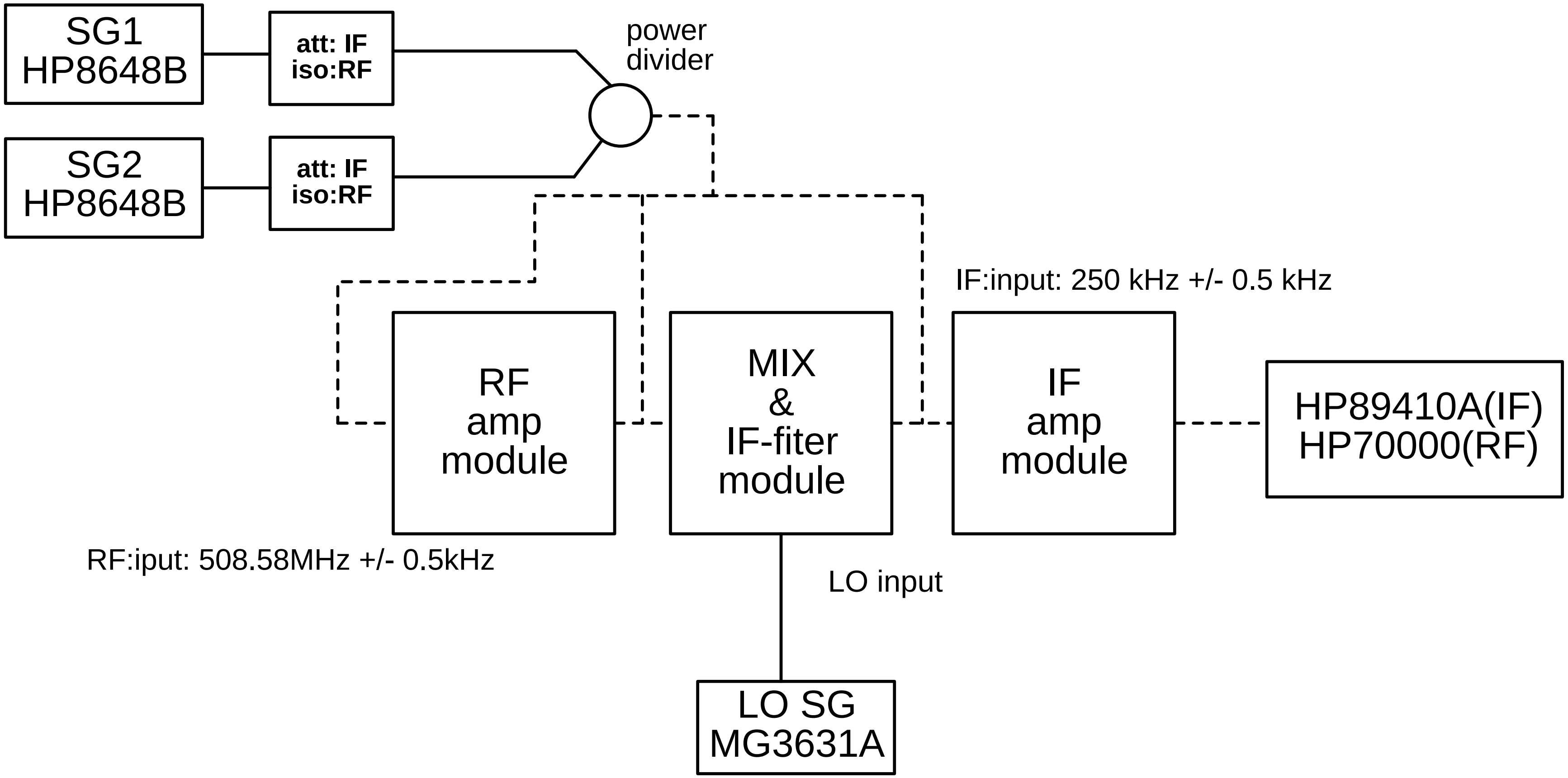
dynamic range: linearity
non linearity was estimated by 2 tone test

$$
\begin{aligned}
y &= a_0 + a_1 x + a_2 x^2 + a_3 x^3 + \cdots \\
x &= A\cos\omega t \\
y &= \left(a_0 + \frac{1}{2}a_2 A^2\right) + \left(a_1 + \frac{3}{4}a_3 A^2\right) A\cos\omega t + \frac{1}{2}a_2 A^2 \cos 2\omega t + \frac{1}{4}a_3 A^3 \cos 3\omega t + \cdots \\
y|_{\omega t} &= \left(a_1 + \frac{3}{4}a_3 A^2\right) A\cos\omega t
\end{aligned}
$$

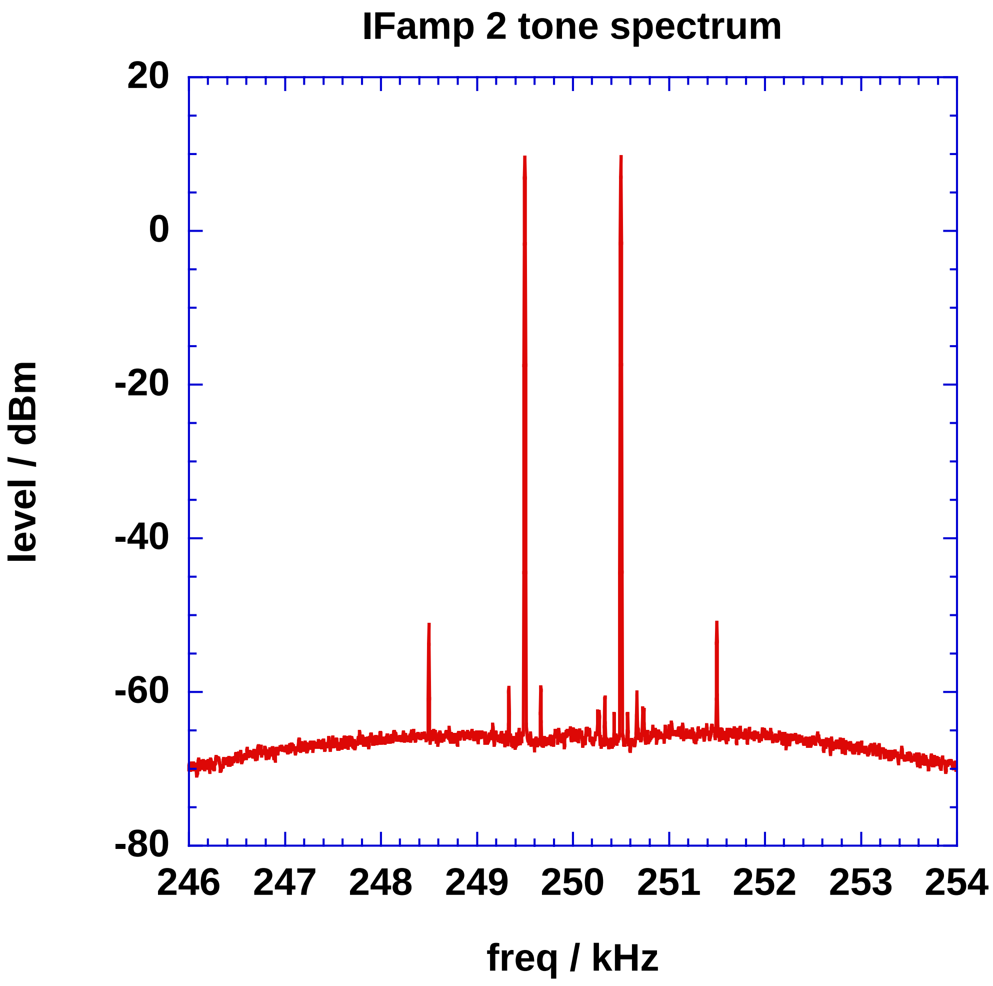
$$
\begin{aligned}
x &= A\left(\cos\omega_1 t + \cos\omega_2 t\right) \\
y &= a_0 + a_1 A\left(\cos\omega_1 t + \cos\omega_2 t\right) + a_2 A^2 \left(\cos\omega_1 t + \cos\omega_2 t\right)^2 + a_3 A^3 \left(\cos\omega_1 t + \cos\omega_2 t\right)^3 + \cdots \\
y|_{\approx\omega t} &= \left(a_1 + \frac{9}{4}a_3 A^2\right) A\left[\cos\omega_1 t + \cos\omega_2 t\right] + \frac{3}{4}a_3 A^2 A\left[\cos(\omega_1 - \delta)t + \cos(\omega_2 + \delta)t\right] \\
\delta &= \omega_2 - \omega_1,\ \ \omega_2 > \omega_1
\end{aligned}
$$

configuration for 2-tone measurements

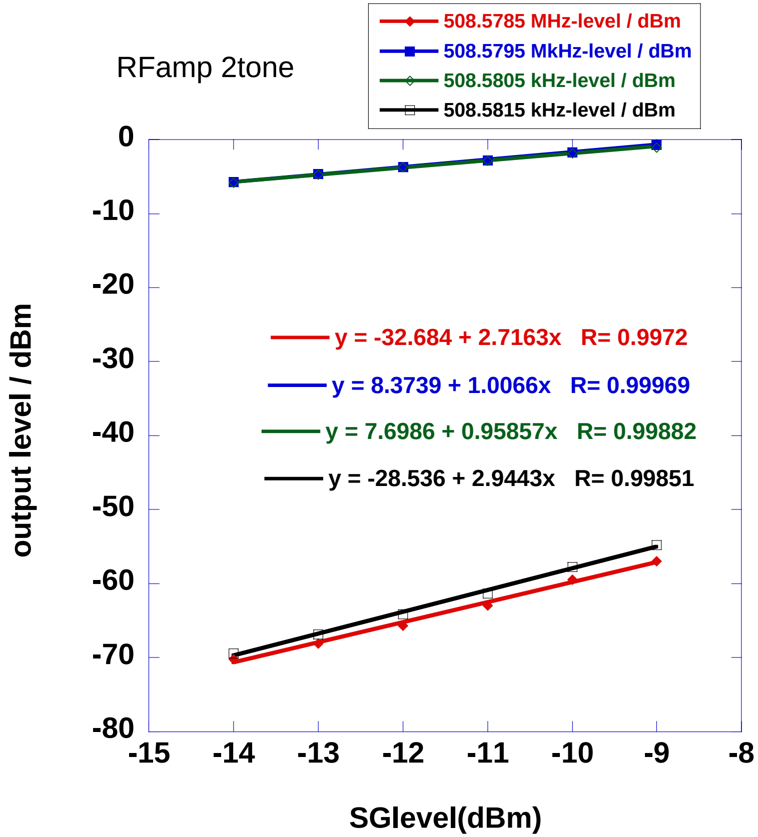
SG1 and SG2 outputs were combined with resistive power divider,
and the combined singnal was connected to IFamp, MIX, and RFamp
for each case of 2-tone measurement.

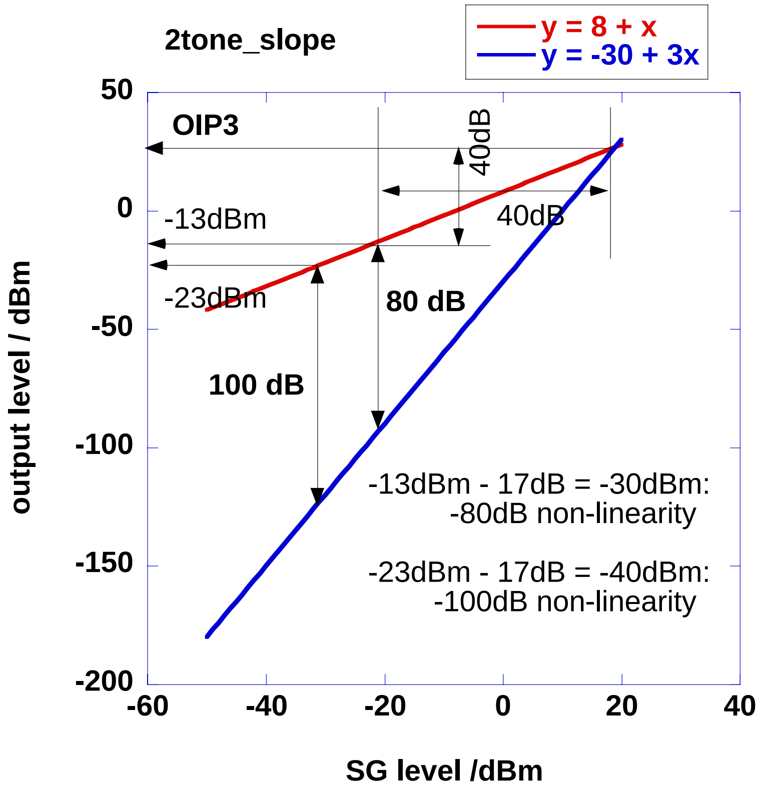


an example of 2 tone spectrum

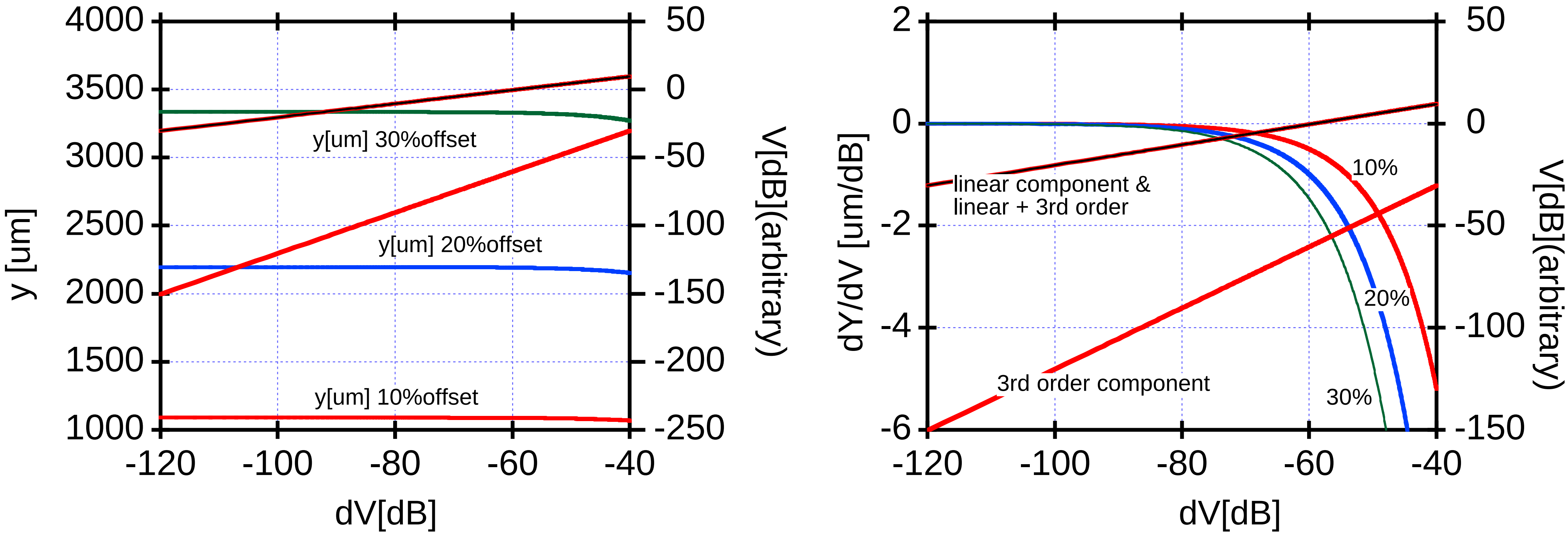


an example of 2 tone test data





estimation of effect of nonlinearity



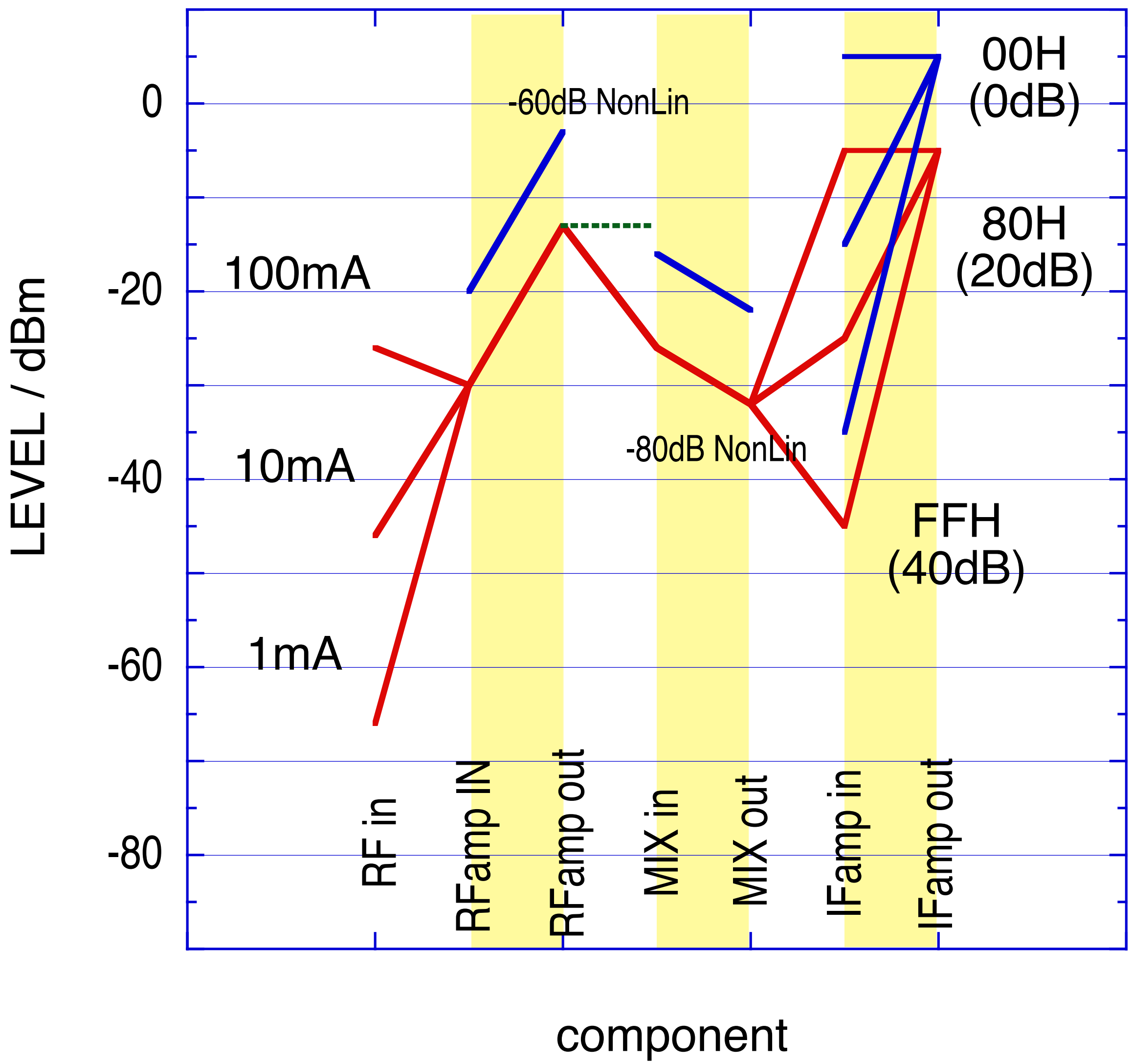
$$y = (1/S_y)(1/2)\left(\frac{V_1^o - V_4^o}{V_1^o + V_4^o} + \frac{V_2^o - V_3^o}{V_2^o + V_3^o}\right),\ V_k^o \propto a_1 V_k^i + (3/4)a_3 (V_k^i)^3,\ k = 1\cdots 4$$

10%offset: $V_1^i = 1.1V_2^i, V_2^i = V_4^i, V_3^i = 0.9V_2^i$

20%offset: $V_1^i = 1.2V_2^i, V_2^i = V_4^i, V_3^i = 0.8V_2^i$

30%offset: $V_1^i = 1.3V_2^i, V_2^i = V_4^i, V_3^i = 0.7V_2^i$

-80dB/-60dB non-linear level



summary for the present status of feedback system design work

Prototype circuits for BPM electronics analogue part were made, and some of the test data were taken with the prototype ciru-cuits;

- S/N $>$ 90 dB is feasible if the range of Ib is limited around 100mA or larger;
  Since the -2-dB change of 100mA is 80mA; for Ib $>$ 80mA $|\delta x| \approx$ 0.3 μm
- Effect of non linearity is about 3μm for 3rd order contribution $\approx$-60dB with the offset of 30% and the 2-dB Ib change; however, the -60-dB nonlinear level is marginal for mixer part for the input signal amplitude corresponding to the 100-mA beam current.

  The condition can be relaxed if the input amplitudes are trimmed to be equalized.

things to be done

for BPM electronics

- design and test for data acquisition part of the electronics; digital demodulator part
- estimate the cycle time for feedback

other than electronics

- measure the magnetic field response in the vacuum chamber, and compared the calculated $G(s)$
- determine the locations of BPM and steering magnets for the feedback
- develop an argorithm for orbit correction