Study proposal of PkQI like configuration at FLASH

PkQl like control at FLASH

- In case of the Pk-Ql control near the quench limit condition, the values of Pks and Qls are calculated as followings.

1. Select operational gradient of each cavity (Vcav)
2. Find out the Pk and Ql of each cavity under the specific beam current (Ibeam) and injection timing (Tinj).

$$\mathrm{Igen} = \mathrm{Ibeam} \cdot \exp\left(\frac{T_{inj}}{\tau}\right)$$

$$V_{cav} = \frac{r}{Q} Q_L \mathrm{Igen} \cdot \left(1 - \exp\left(-\frac{T_{inj}}{\tau}\right)\right) \longrightarrow \mathrm{Pk} = \frac{1}{4}\frac{r}{Q} Q_L (\mathrm{Igen})^2$$

- In case of FLASH, the Pks are not 'knob' (these are fixed.). Thus the Ql is the only free parameter. The selection of the cavity Ql is as followings.

1. Select the operational cavity input power (Pk)
2. Find out the Ql of each cavity under Ibeam and Tinj.
3. Check that the calculated cavity gradient is under the quench limit.

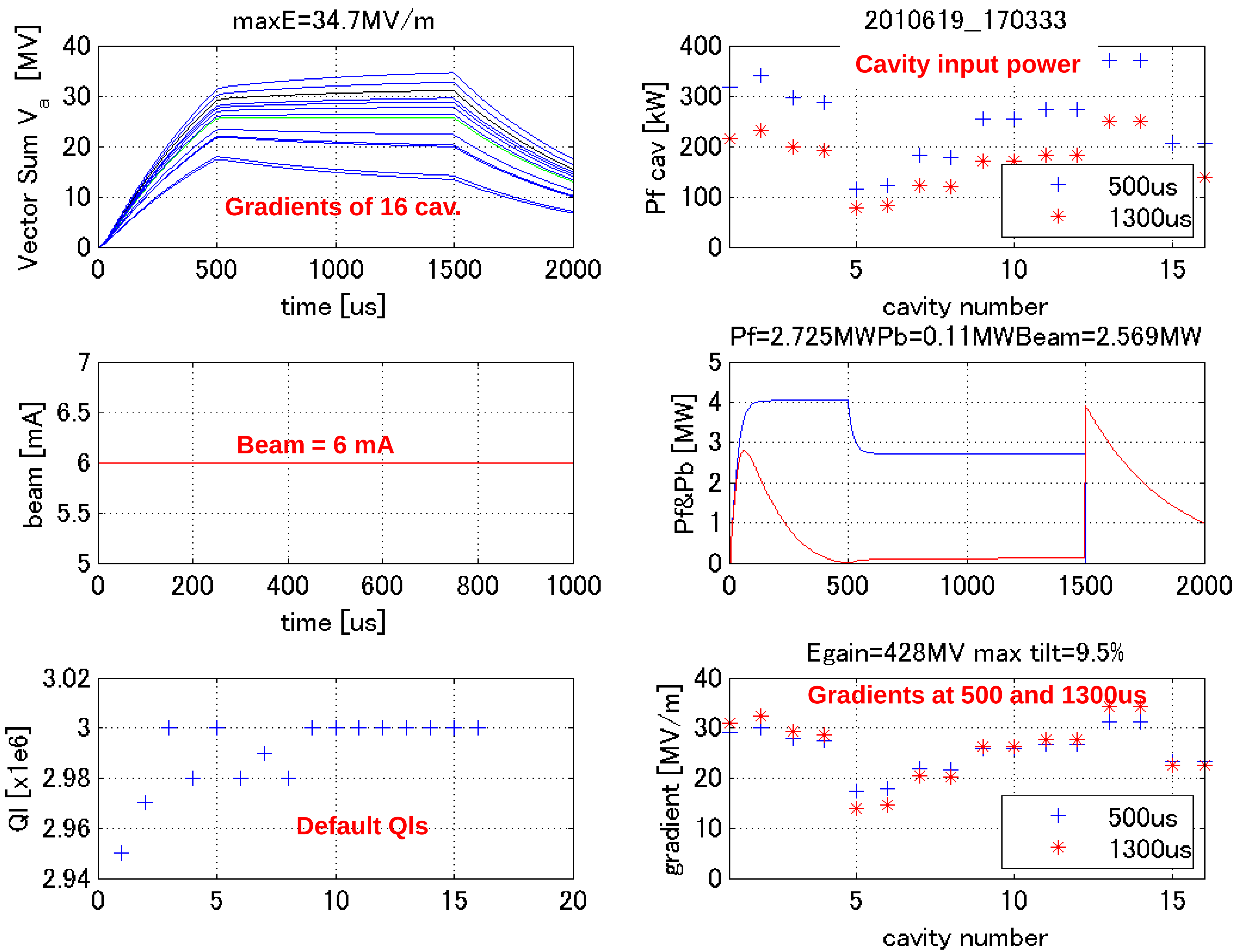
$$\mathrm{Pk} = \frac{1}{4}\frac{r}{Q} Q_L (\mathrm{Igen})^2$$

$$\mathrm{Igen} = \mathrm{Ibeam} \cdot \exp\left(\frac{T_{inj}}{\tau}\right) \longrightarrow V_{cav} = \frac{r}{Q} Q_L \mathrm{Igen} \cdot \left(1 - \exp\left(-\frac{T_{inj}}{\tau}\right)\right)$$

Default PkQI configuration

Waveguide Distribution for ACC6 and ACC7									Klystron 4		
										2010/2/5	V.Katalev
Eacc, MeV	434		Pkly_4	5.1	MW		without beam		Elinac	1347	Mev
			15% waveguide losses + 10% circulator								
								Hybrid	(power divider)		
tinj, mks				P_ACC6, MW		P_ACC7, MW		S41, dB	S31, dB	S41*S41	S31*S31
500				1.9		2.2		3.30	2.74	0.468	0.532
		there are the editing data in green cells						Pcirc_max	370	Lcav =	1,038 m
ACC6	24.8 MV/m			206 MeV			Max	238	Mev	?	32
Pin, MW	1.91		RF power	OK							
Qext	2.95	2.97	3.00	2.98	3.00	2.98	2.99	2.98	2007/11/21		
A, dB	7.85	7.54	8.16	8.31	12.27	12.03	10.28	10.37	measured		
Pcav, kW	313.1	336.2	291.5	281.6	113.2	119.6	178.9	175.3		1809.4	99
Ecav, MV/m	29.77	30.81	28.63	28.18	17.84	18.36	22.45	22.23		24.8	MV/m
Ecav, max	34	32	34	32	21	21	29	26		28.6	
ΔE	4.2	1.2	5.4	3.8	3.2	2.6	6.6	3.8		Ecav max - Ecav	
	Cav 1	Cav 2	Cav 3	Cav 4	Cav 5	Cav 6	Cav 7	Cav 8			
ACC7	27.5 MV/m			228 MeV			Max	261	Mev	?	32
Pin, MW	2.17		RF power	OK							
Qext	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00			
A, dB	9.38	9.38	9.08	9.08	7.74	7.74	10.32	10.32			
Pcav, kW	250.7	250.7	268.3	268.3	365.2	365.2	201.5	201.5		2171.6	0
Ecav, MV/m	26.56	26.56	27.47	27.47	32.05	32.05	23.81	23.81		27.5	MV/m
Ecav, max	29	31	34	30	35	39	27	26		31.4	
ΔE	2.4	4.4	6.5	2.5	3.0	7.0	3.2	2.2		Ecav max - Ecav	
	Cav 1	Cav 2	Cav 3	Cav 4	Cav 5	Cav 6	Cav 7	Cav 8			

Default PkQl (6 mA beam)



BAW1 (Sep.,2010)

PkQI configuration with 9 mA loading

Waveguide Distribution for ACC6 and ACC7									Klystron 4		
										2010/2/5	V.Katalev
Eacc, MeV	389		Pkly_4	4.8	MW		without beam		Elinac	1301	Mev
			15% waveguide losses + 10% circulator								
								Hybrid	(power divider)		
tinj, mks				P_ACC6, MW		P_ACC7, MW		S41, dB	S31, dB	S41*S41	S31*S31
500				1.8		2.1		3.30	2.74	0.468	0.532
		there are the editing data in green cells						Pcirc_max	370	Lcav =	1,038 m

ACC6	20.0 MV/m			166 MeV			Max	238	Mev	?	72
Pin, MW	1.81		RF power	OK							
Qext	2.18	2.02	2.39	2.51			4.08	4.08	2007/11/21		
A, dB	7.85	7.54	8.16	8.31	12.27	12.03	10.28	10.37	*measured*		
Pcav, kW	297.4	319.4	276.9	267.5	107.5	113.6	170.0	166.5		1718.9	94
Ecav, MV/ı	30.37	31.69	28.98	28.29	0.00	0.00	20.34	20.13		20.0	MV/m
Ecav, max	34	32	34	32	21	21	29	26		28.6	
ΔE	3.6	0.3	5.0	3.7	21.0	21.0	8.7	5.9		*Ecav max - Ecav*	
	Cav 1	*Cav 2*	*Cav 3*	*Cav 4*	*Cav 5*	*Cav 6*	*Cav 7*	*Cav 8*			

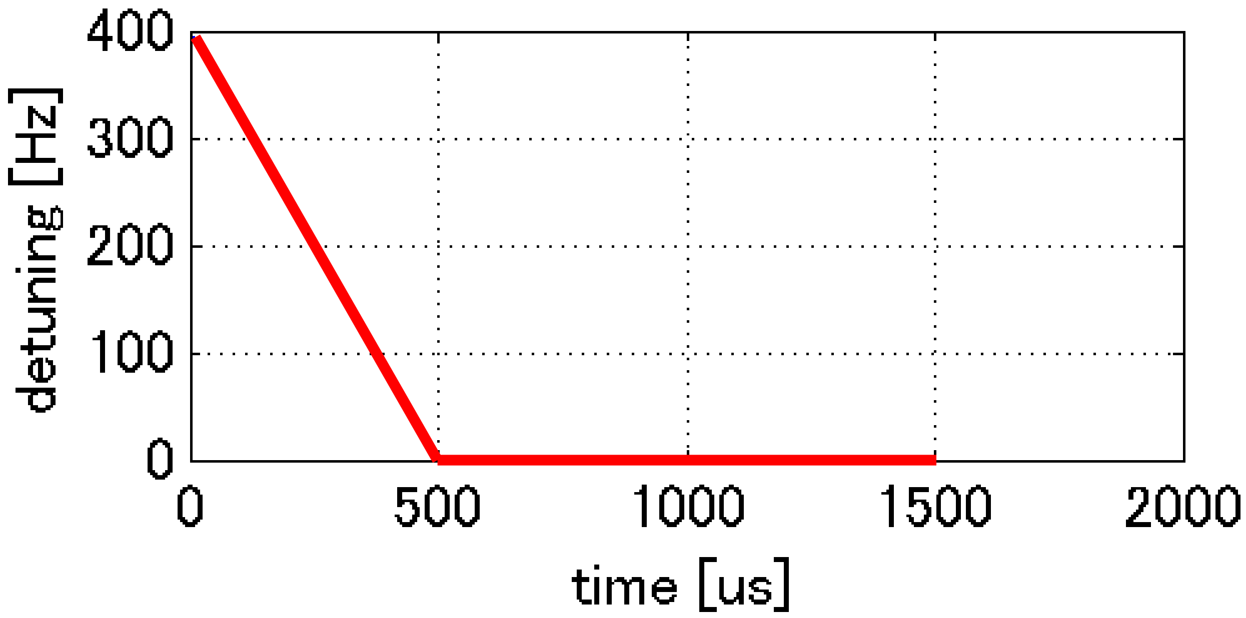
Cavities #5 & #6 are detuned.

ACC7	26.8 MV/m			223 MeV			Max	261	Mev	?	38
Pin, MW	2.06		RF power	OK							
Qext	3.35	3.35	2.75	2.75	1.88	1.88	4.08	4.08			
A, dB	9.38	9.38	9.08	9.08	7.74	7.74	10.32	10.32			
Pcav, kW	238.2	238.2	254.9	254.9	347.0	347.0	191.5	191.5		2063.1	0
Ecav, MV/ı	25.28	25.28	27.21	27.21	33.18	33.18	21.58	21.58		26.8	MV/m
Ecav, max	29	31	34	30	35	39	27	26		31.4	
ΔE	3.7	5.7	6.8	2.8	1.8	5.8	5.4	4.4		*Ecav max - Ecav*	
	Cav 1	*Cav 2*	*Cav 3*	*Cav 4*	*Cav 5*	*Cav 6*	*Cav 7*	*Cav 8*			

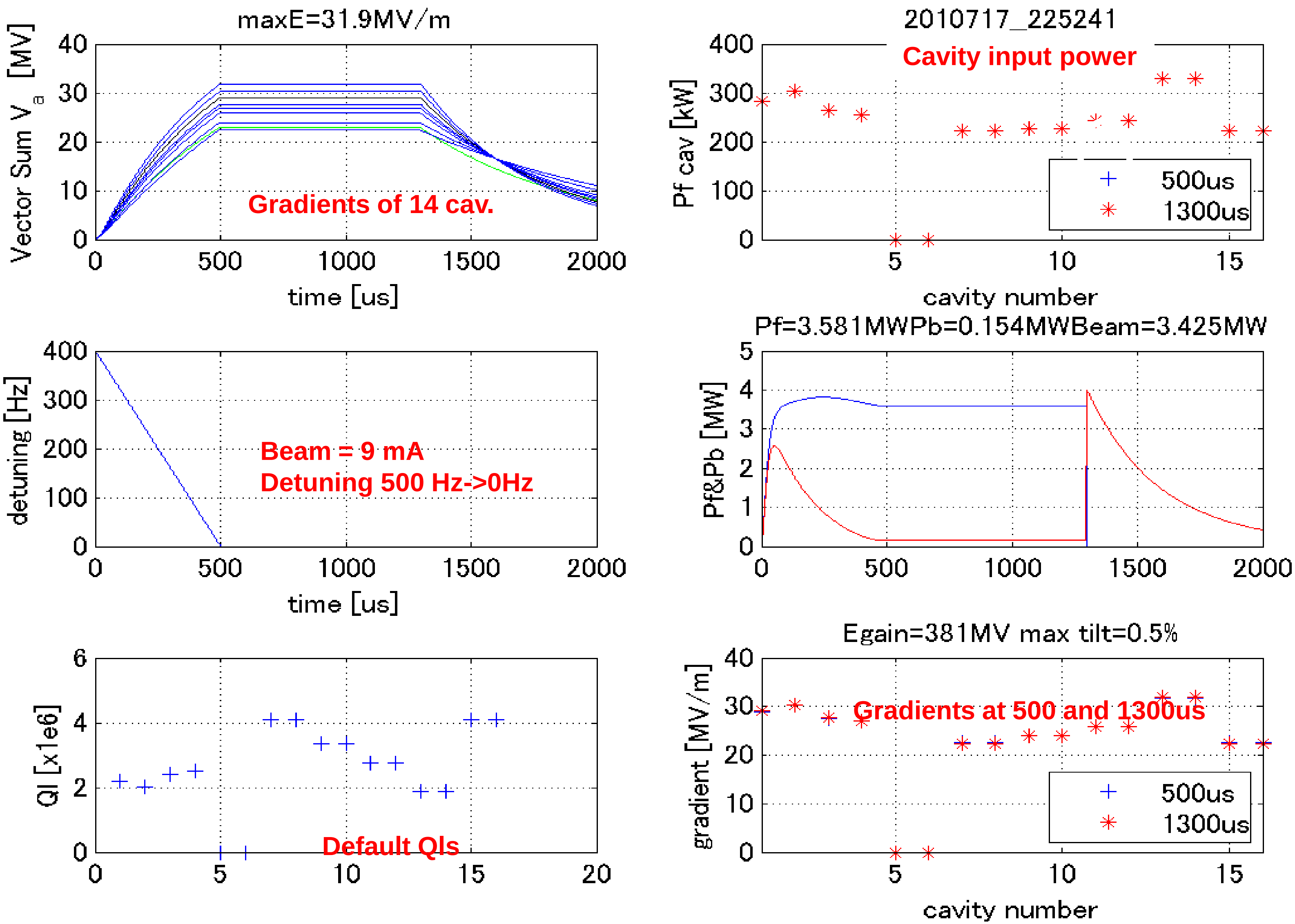
Lorentz force detuning

■ The linear change in detuning from +400 Hz to 0 Hz (during the filling time) is introduced in the simulation.

■ All the cavities are supposed to be same detuning; simplest approximation).



Feedback with Lorentz detuning



Tolerance at P k QI control

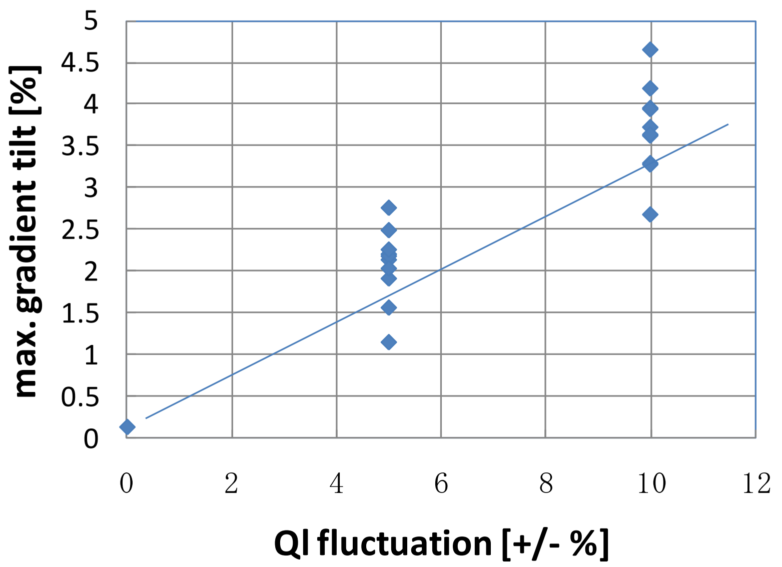
RF configuration

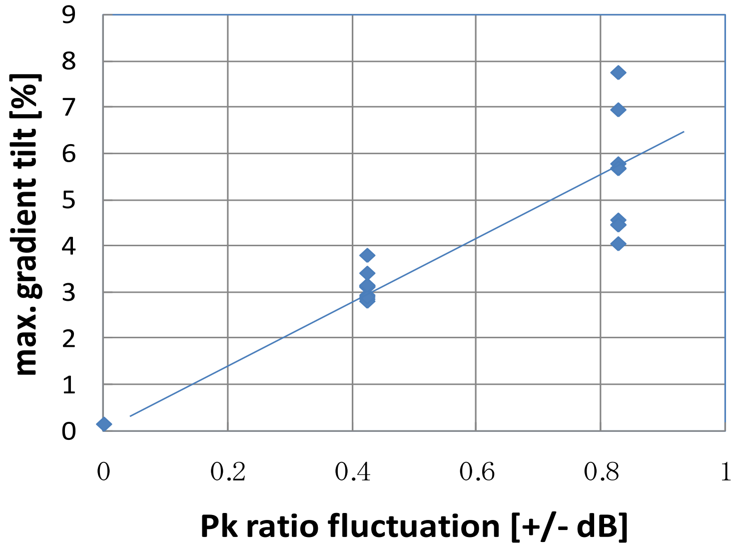
	Cavity grouping	Pk-Ql control
Ql	constant	Remote change depending on the beam current, gradient
RF distribution (Pk)	constant	Remote change depending on the beam current, gradient
Flatness of each cavity	Flat at any beam current.	Flat if Pk & Ql are changed.
comment		Need study because of its complexity

- Pk-Ql control is one of the candidate. (but rather complex and need more study.)
- If we know the cavity performance in advance, same gradient control of each rf unit is preferable.

Tolerance of PkQl at FLASH

- Effects on tolerance of the PkQl control is estimated for FLASH beam test.
- Fourteen cavities are set to PkQl-like control
- Random fluctuation is added to Pk, Ql and detuning
- Each parameter should <1.5% tilt if total 5% tilt is required.

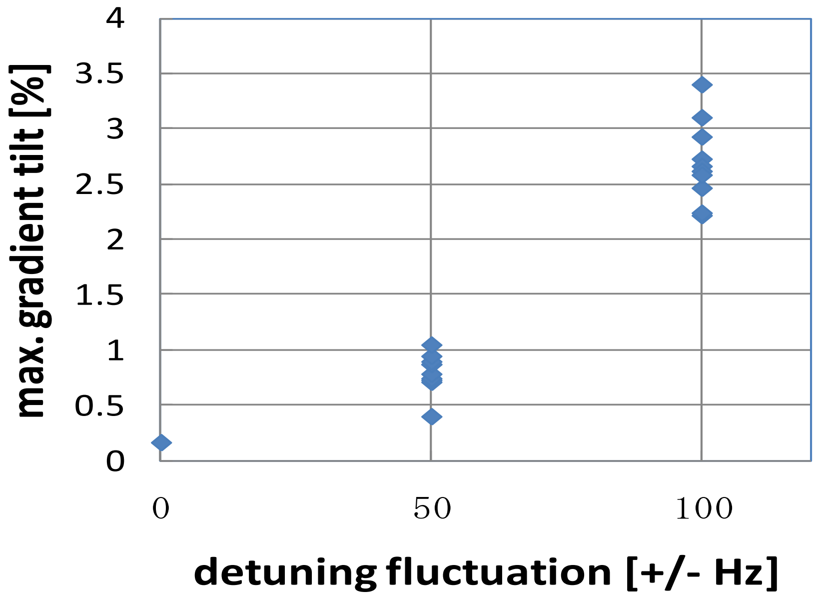


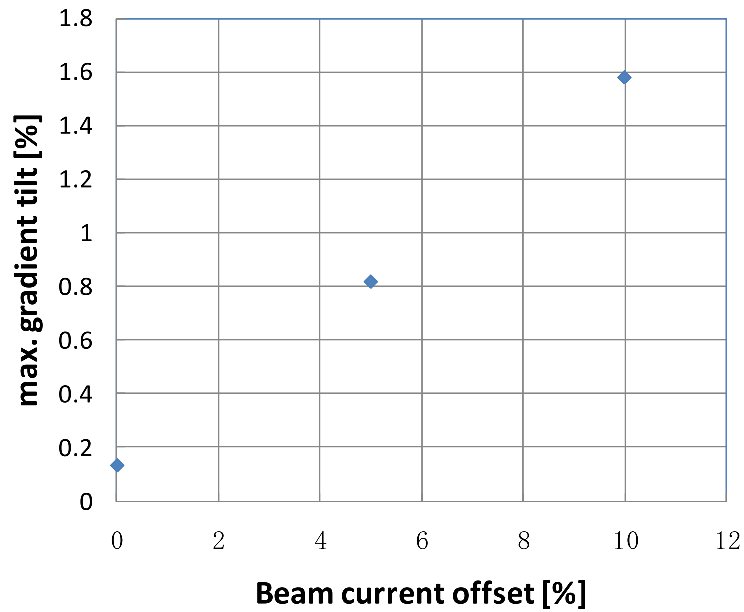


- Fluctuation of Qls should be <5%
- Fluctuation of Pk should be <0.2dB

Tolerance of PkQl at FLASH

- detuning fluctuation (like microphonics, pre-detuning) and beam current are estimated.





- In order to satisfy <1.5% of each parameter,
  - detuning fluctuation should be <60Hz
  - beam current offset should be <8% (X9mA=0.72mA)

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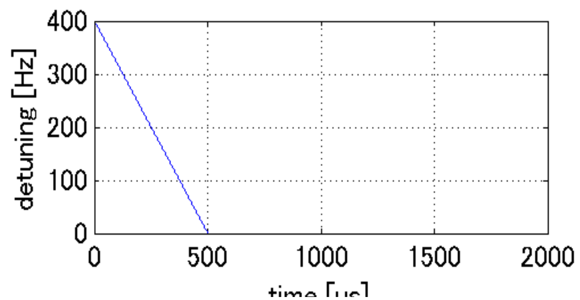
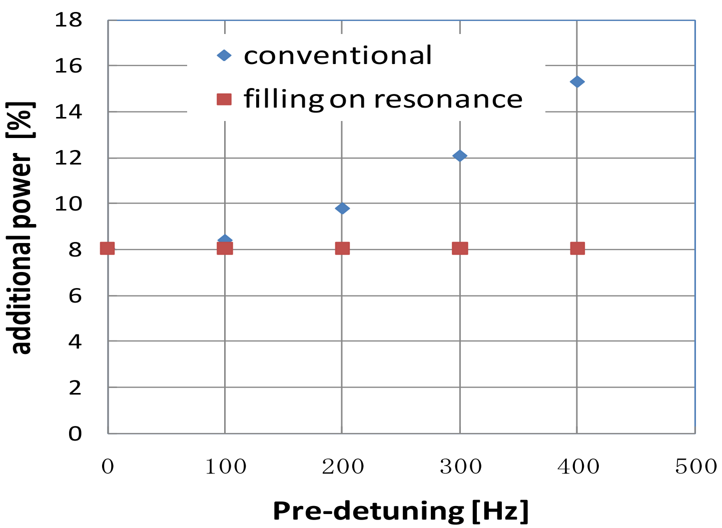
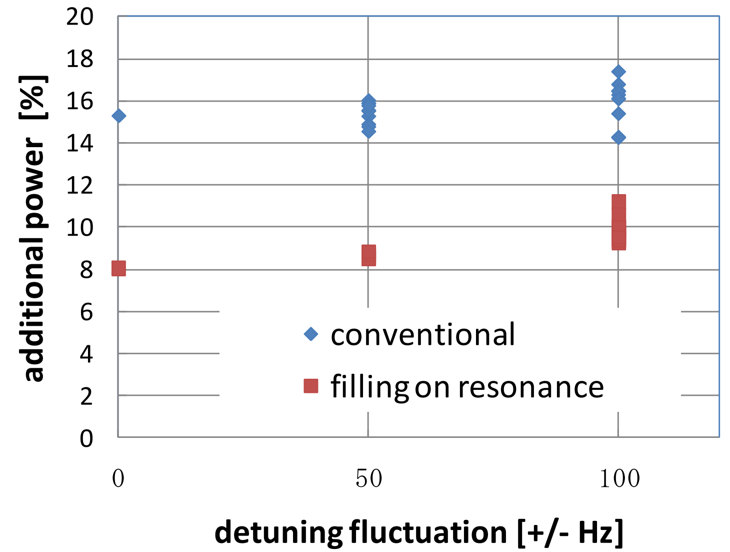
Additional power on PkQl at FLASH

- PkQl like control requires more power than ideal beam loading.
- 8% more power is required at FLASH.
- During the filling time, resonance is different from 1.3GHz.
- 15% more power is necessary when pre-detuning is 400Hz.
- Filling on resonance (change the set-phase during filling) is effective.
- However, if there is fluctuations of pre-detuning, additional power is necessary.







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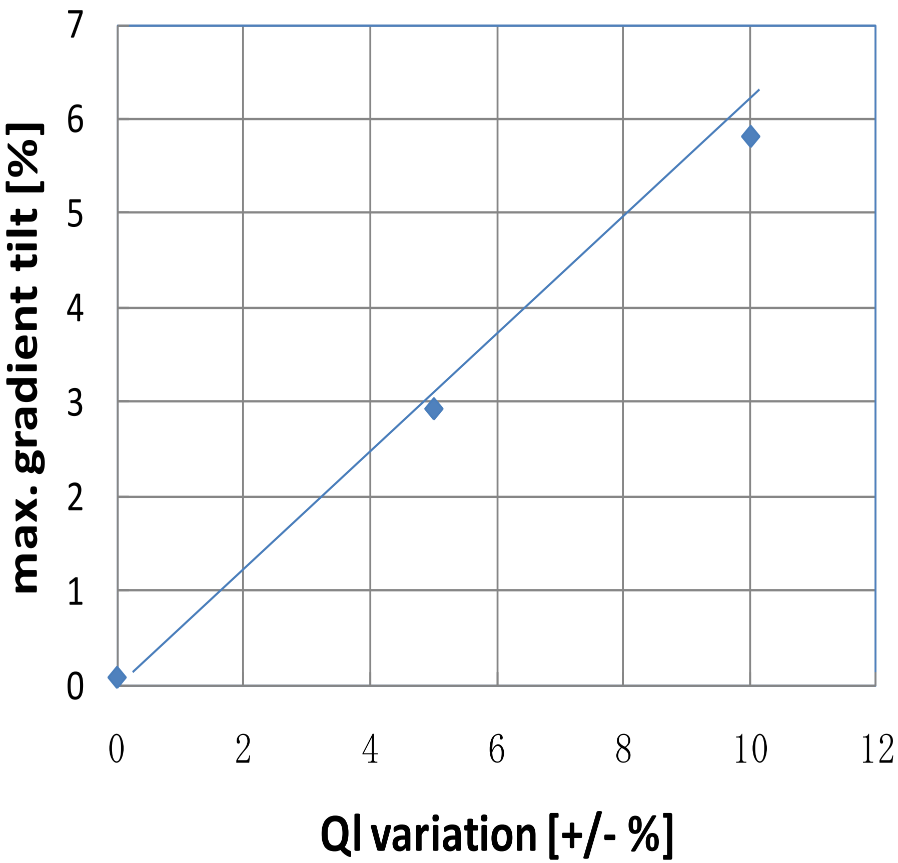
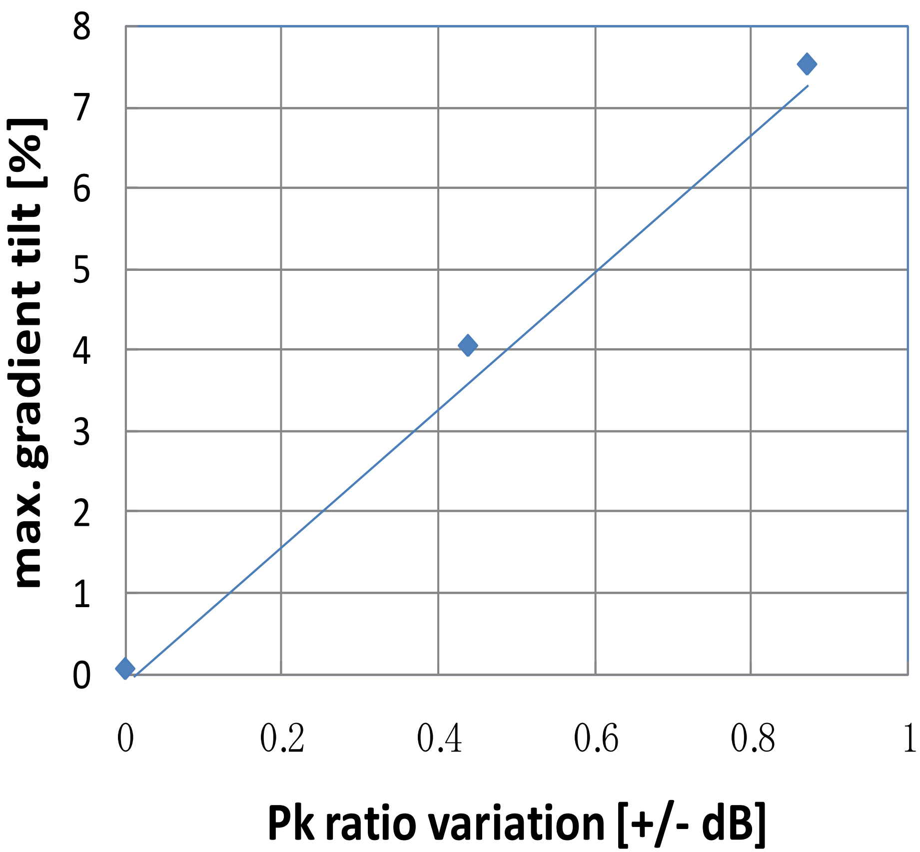
PkQl control

- The gradient tilt by Pk, Ql, detguning fluctuation is simulated when PkQl control is carried out at DRFS.

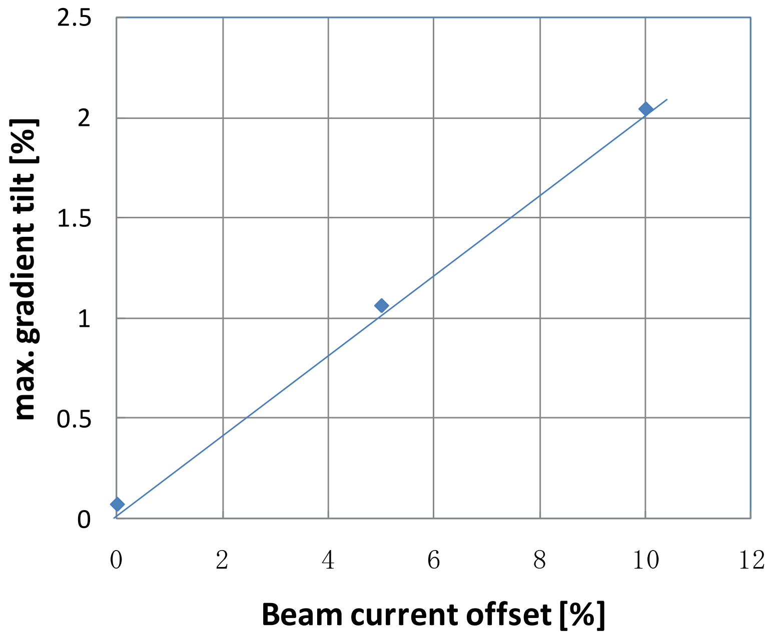


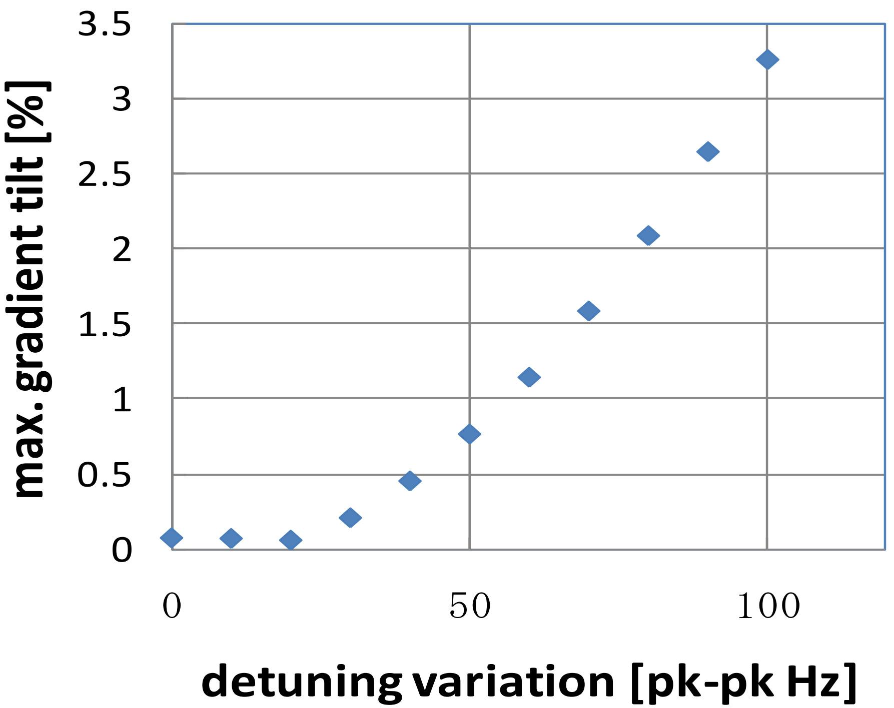


- If the max. tilt is <5%, each component of fluctuation source should be <1.5%.
- Ql fluctuation should be 3%, Pk fluctuation should be 0.2dB.

PkQl control(2) pulse-to-pulse fluctuation

■The gradient tilt by Pk, Ql, detguning fluctuation is simulated when PkQl control is carried out at DRFS.





■ If the max. pulse-to-pulse fluctuation is <1%, each component of fluctuation source should be <0.3%.

■ Beam current offset (average current) should be <2%.

■ **Detuning fluctuation (between cavities) should be <30Hz pk-pk.**

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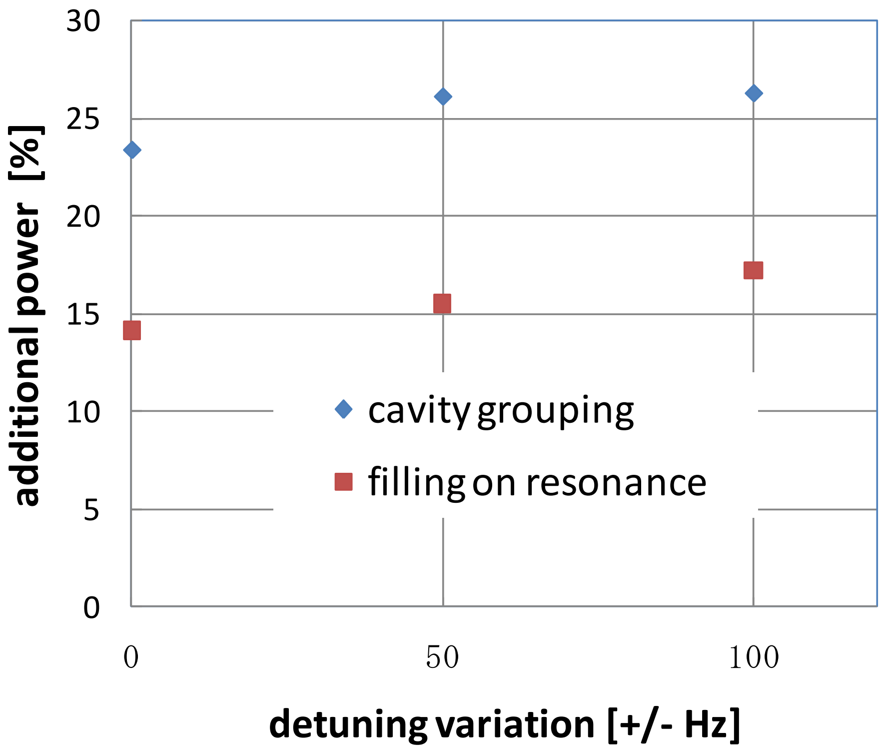
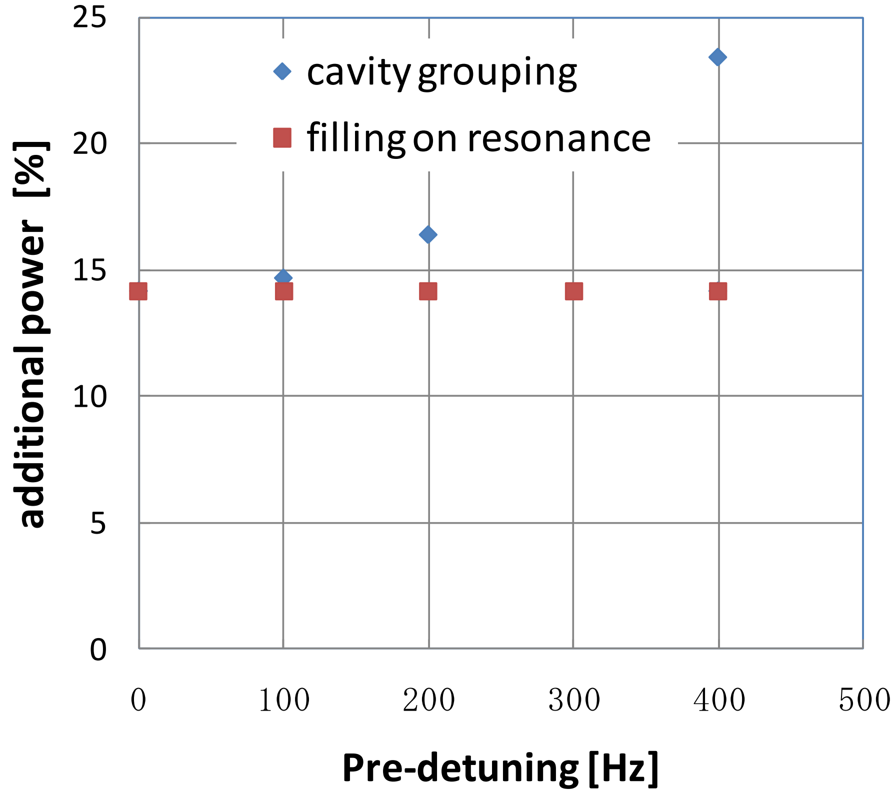
PkQl control(3)

■ Additional rf power when the pre-detuning and detuning fluctuation exist.





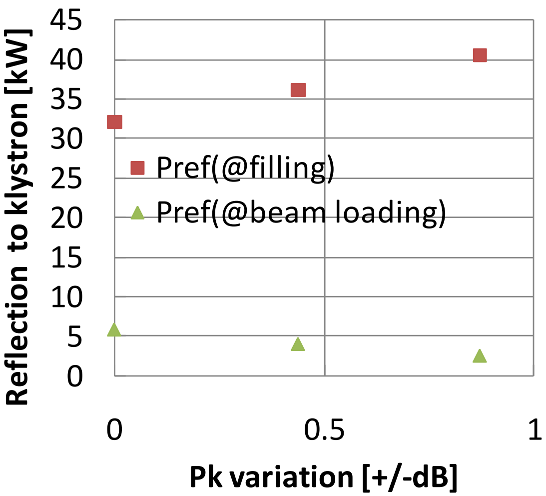
■ When the resonance filling can apply perfectly, we will not lose rf power.

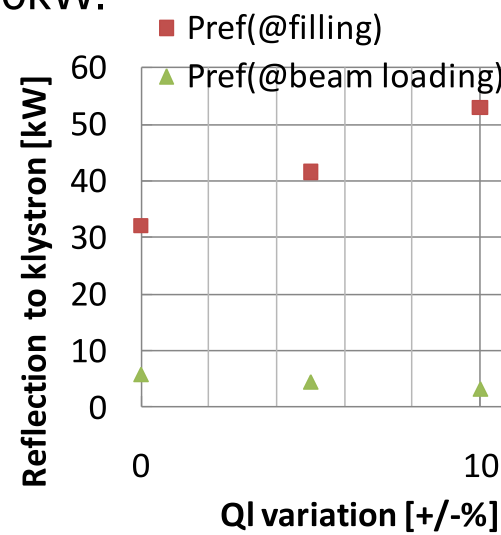
■ The additional rf power when 50Hz fluctuation exist is ~2%.

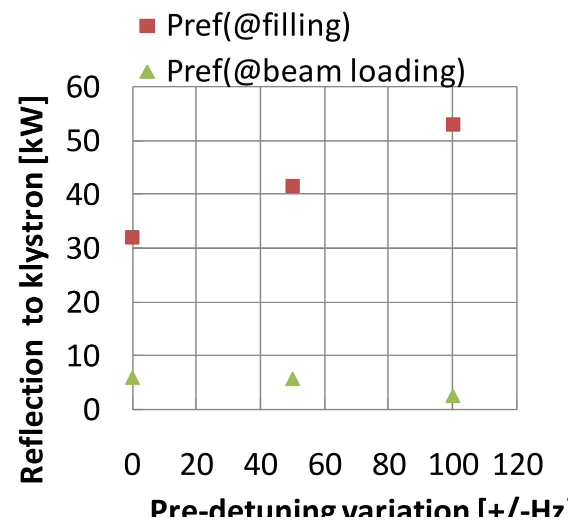
■ We have to examine the PkQl control at the beam operation machine (FLASH) and get the feel for this procedure.

RF reflection (@PkQl)

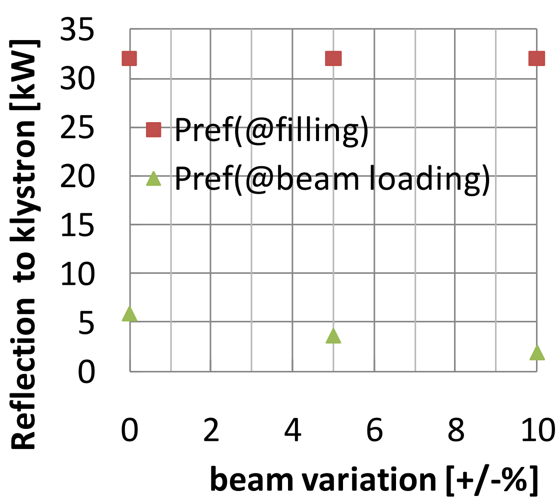
- In addition to Pk, Ql, predetuning and waveguide length, beam current variation is also considered.
- Typical input power is ~700kW.

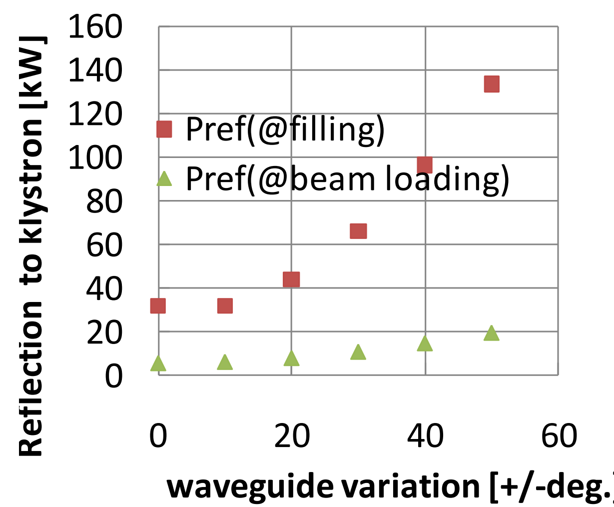






- The reflection is 5x larger.
- but maybe we can operate without circulators.
- Need to measure the sensitivity of kly. output.





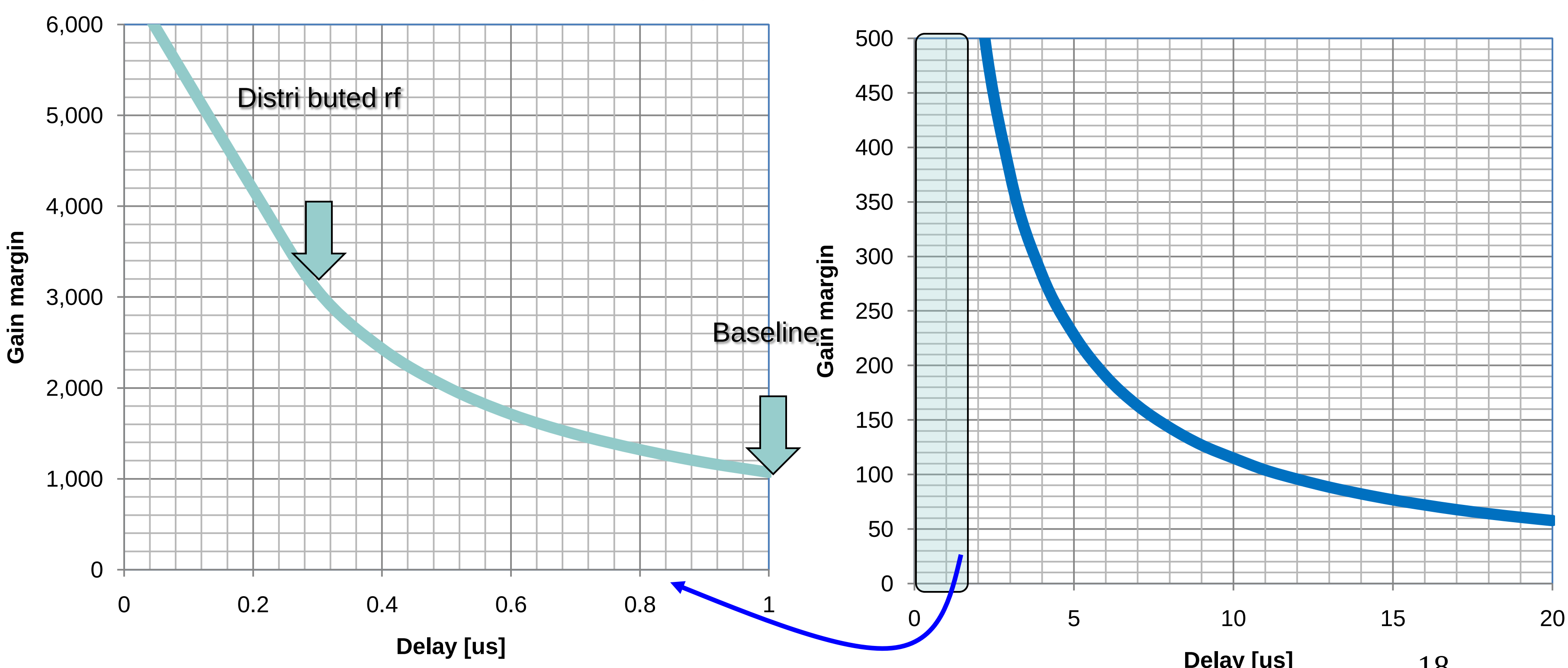
Feedback performance

Operational gain

- Error is only compressed by a factor of gain
- Gain margin is calculated from Bode-plot.

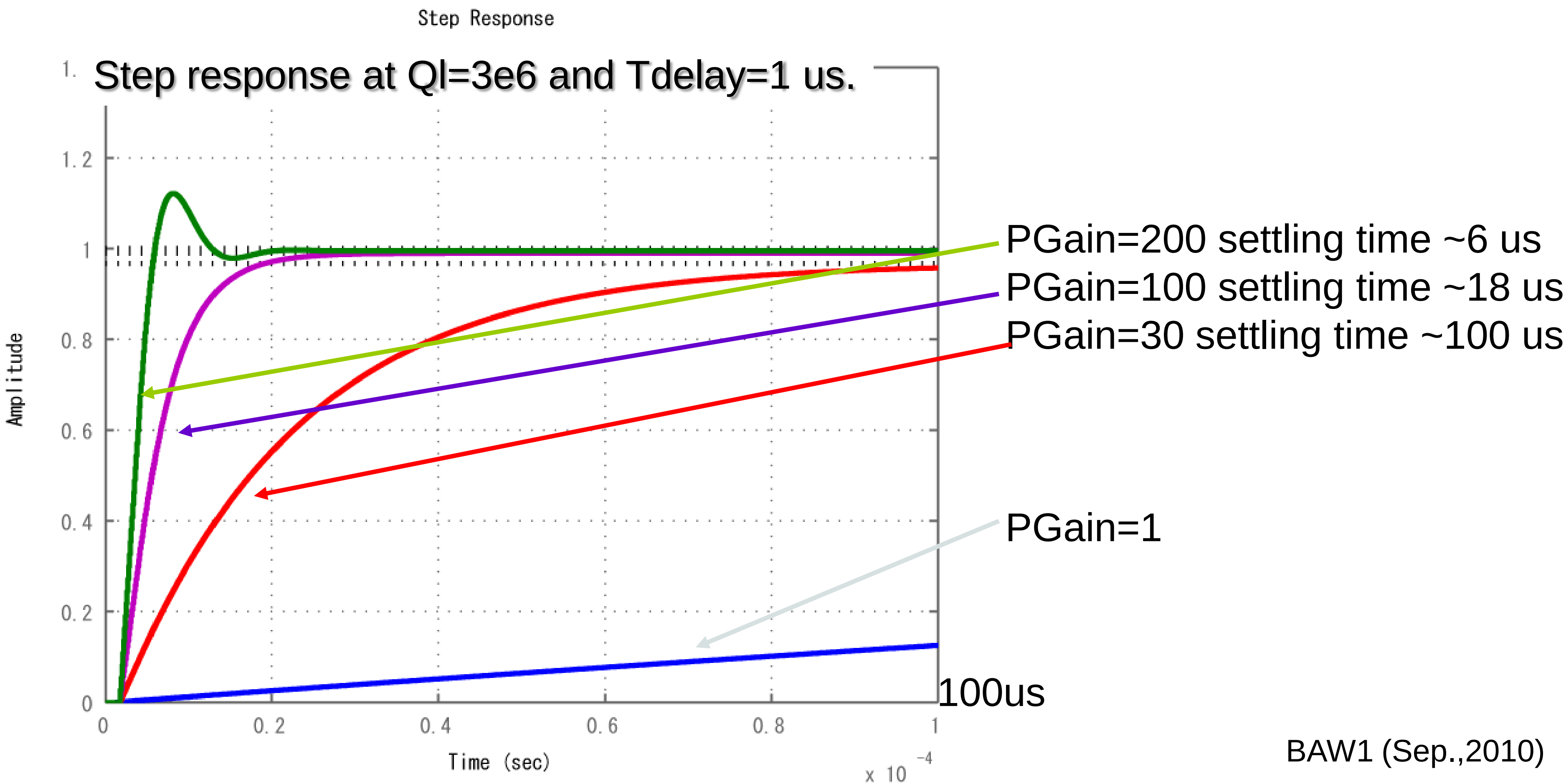
- Operational gain can become ~1000 in case of distributed rf owing to its short latency (such as total loop delay of 0.3 us).

Gain-margin (Gain just before oscillation)



Step response

- If there is an error present, then the RF system must add energy to recover. (Additional power depends on Proportional gain.)
- Any time the klystron and therefore the control loop are saturated there will be no regulation of any disturbance such as beam loading.
  - If multiple stations are saturated then amplitude errors will be correlated.



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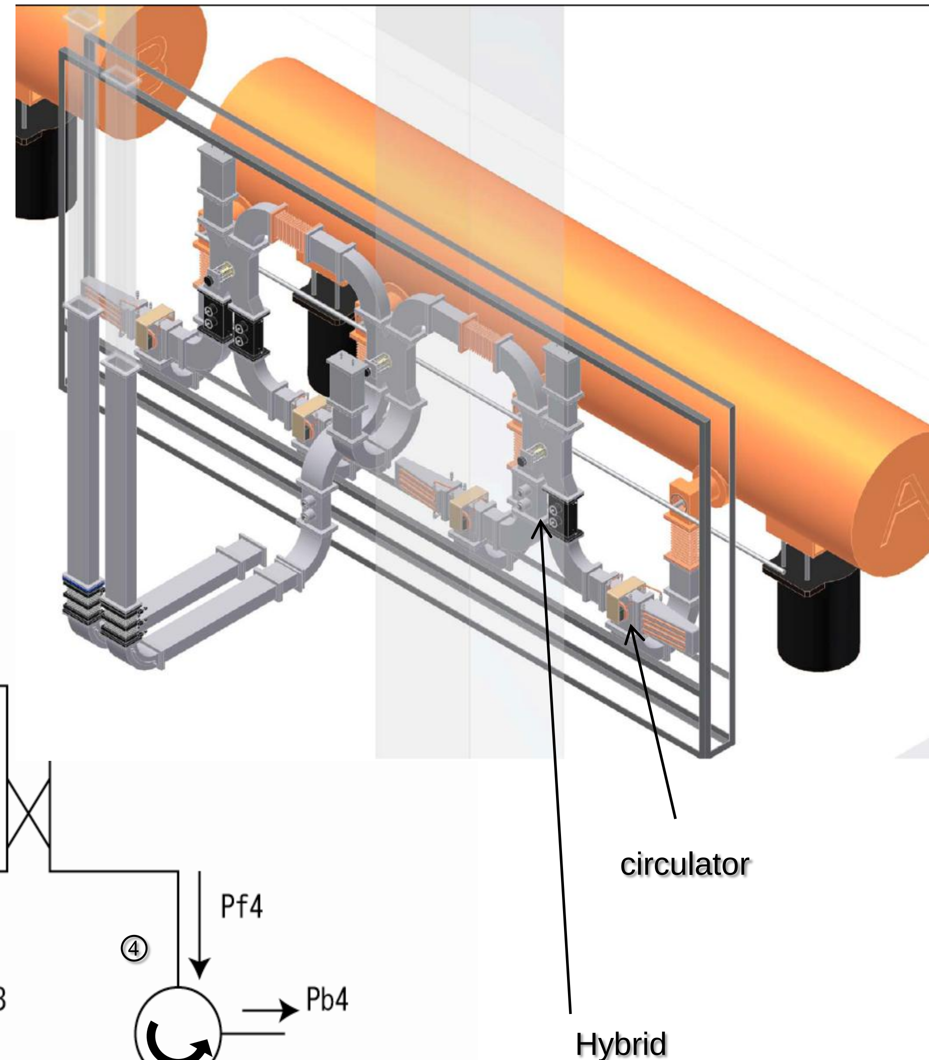
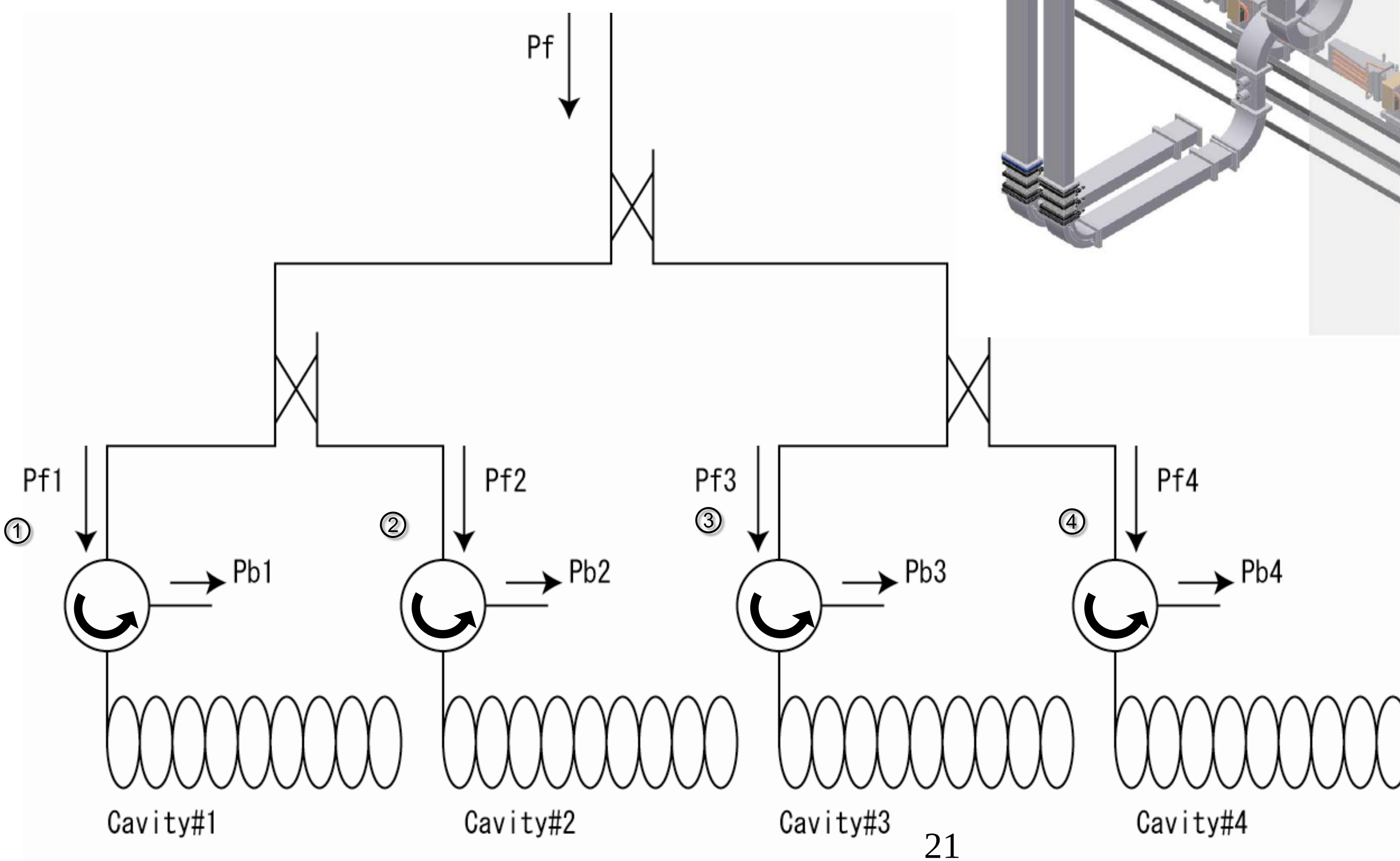
Circulator elimination

Circulator elimination

- A klystron drives 4 cavities via hybrid.
- Circulators are installed before the cavities.





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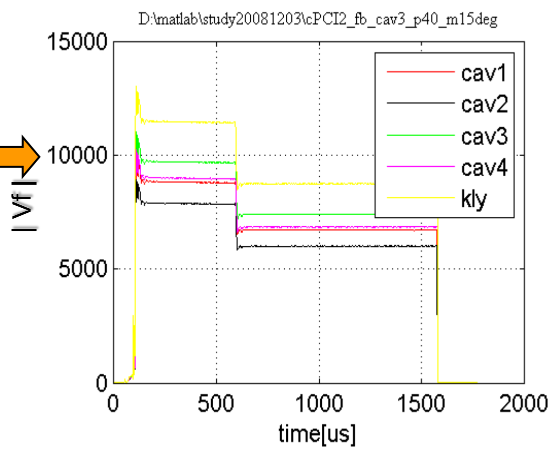
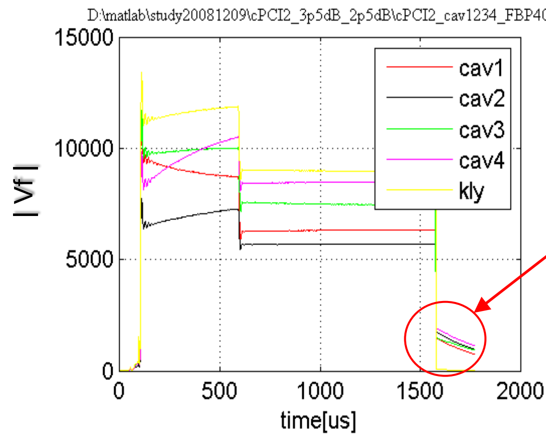
Cavity Input Signals

With circulators ***Without circulators***

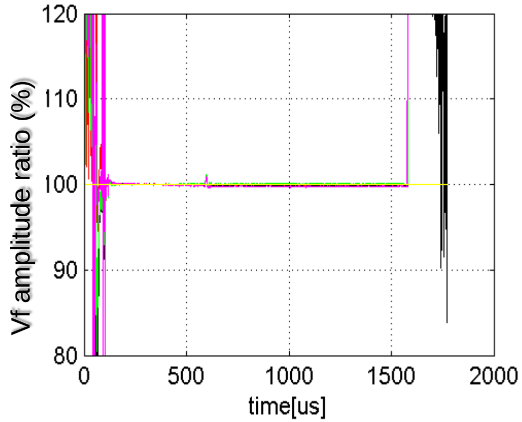
Cavity input

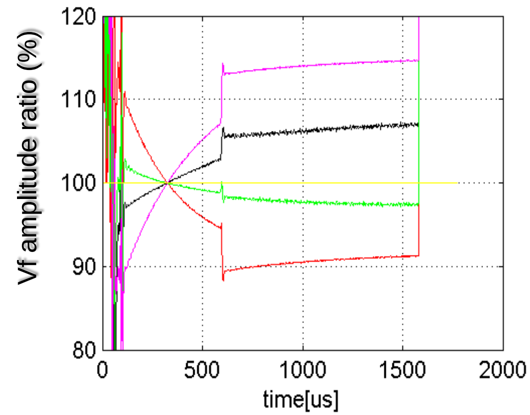




Cavity input exists even after RF off

Normalized by klystron output





Cavity input power is different due to the reflection

Circulator effects

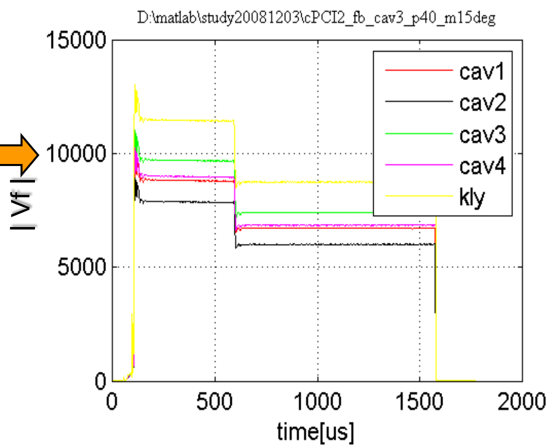
■The previous study (STF-1) indicate high isolation will be required at hybrid in order to estimate the cavity parameters (such as Ql and detuning).

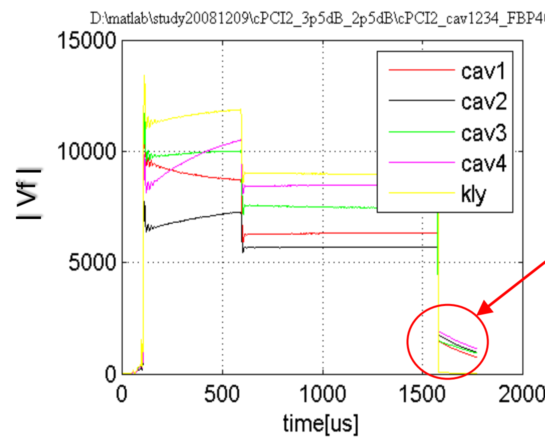
Study goal

■ Study of the rf isolation with new hybrid system suitable for DRFS

With circulators ***Without circulators***

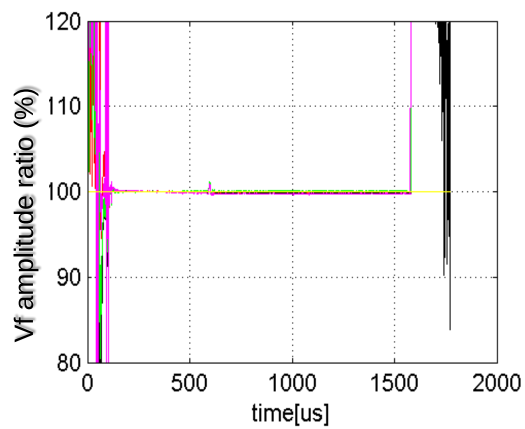
Cavity input

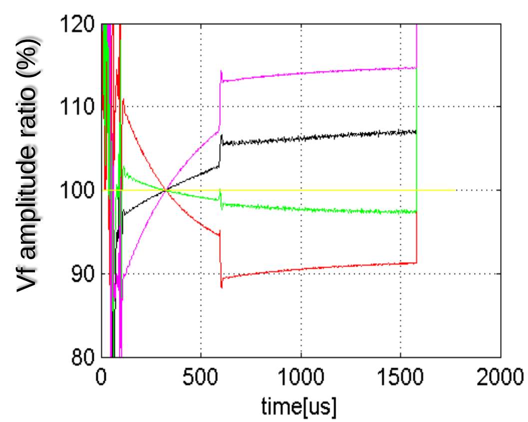




Cavity input exis
even after RF of

Normalized by klystron output





BAW1 (Sep.,2010)

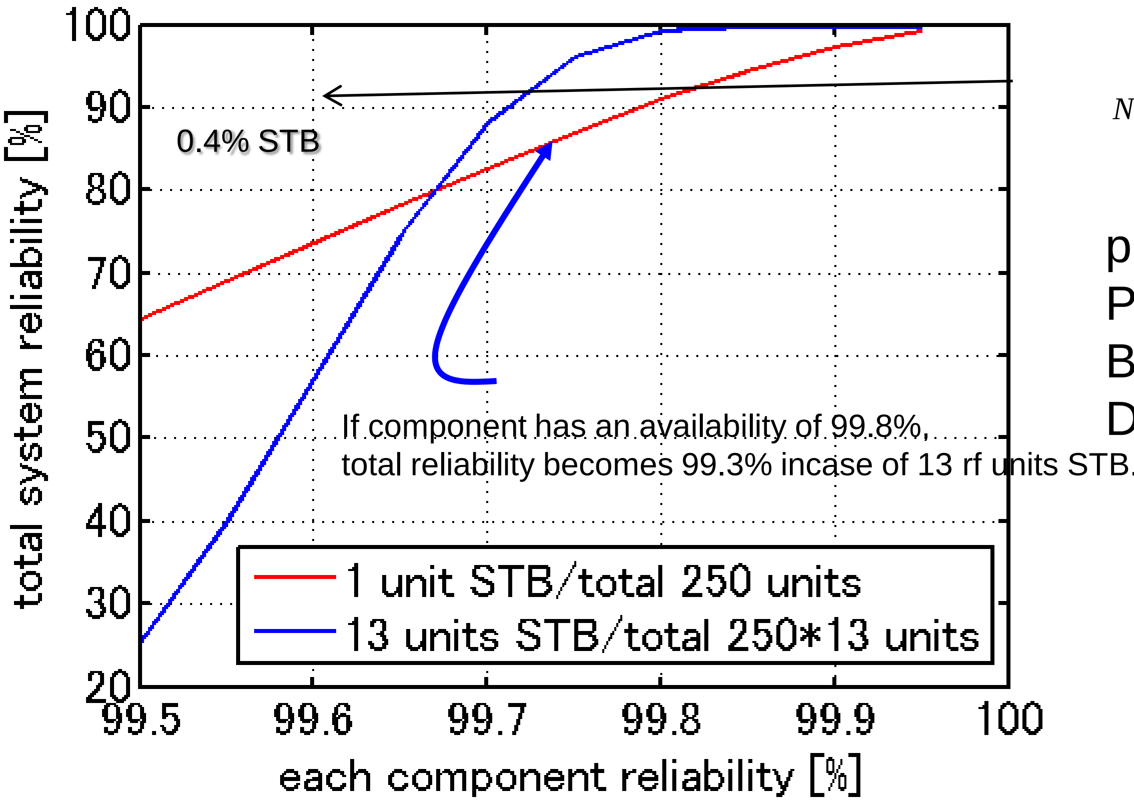
Availability

High Availability @ distributed rf

Assumption:
There is a 0.4% standby cavities (1/250:corresponding to roughly 1 rf unit in baseline and 13 units in DRFS).

$$P_{total} = p^N + \sum_{k=1}^{m} {}_N C_m p^{N-k} (1-p)^k$$

$${}_N C_m = \frac{N!}{(N-m)!m!}$$



p: each rf unit reliability
Ptotal: total reliability
Baseline: N=250,m=1
DRFS: N=250*13=3,250, m=13

BAW1 (Sep.,2010)

High Availability @ distributed rf (2)

- Each rf unit has a reliability of 99.8%? Maybe yes.

: 99.8% corresponds to 20 min./week, 5 hrs/yr (5,000 hrs op.)

From the experience of KEKB injector linac (60 units, 7,000 hrs operation/yr.), the downtime of the unit is<5min./week.

- In addition, we can neglect one cavity failure. (because its energy contribution is negligibly small (0.015%).

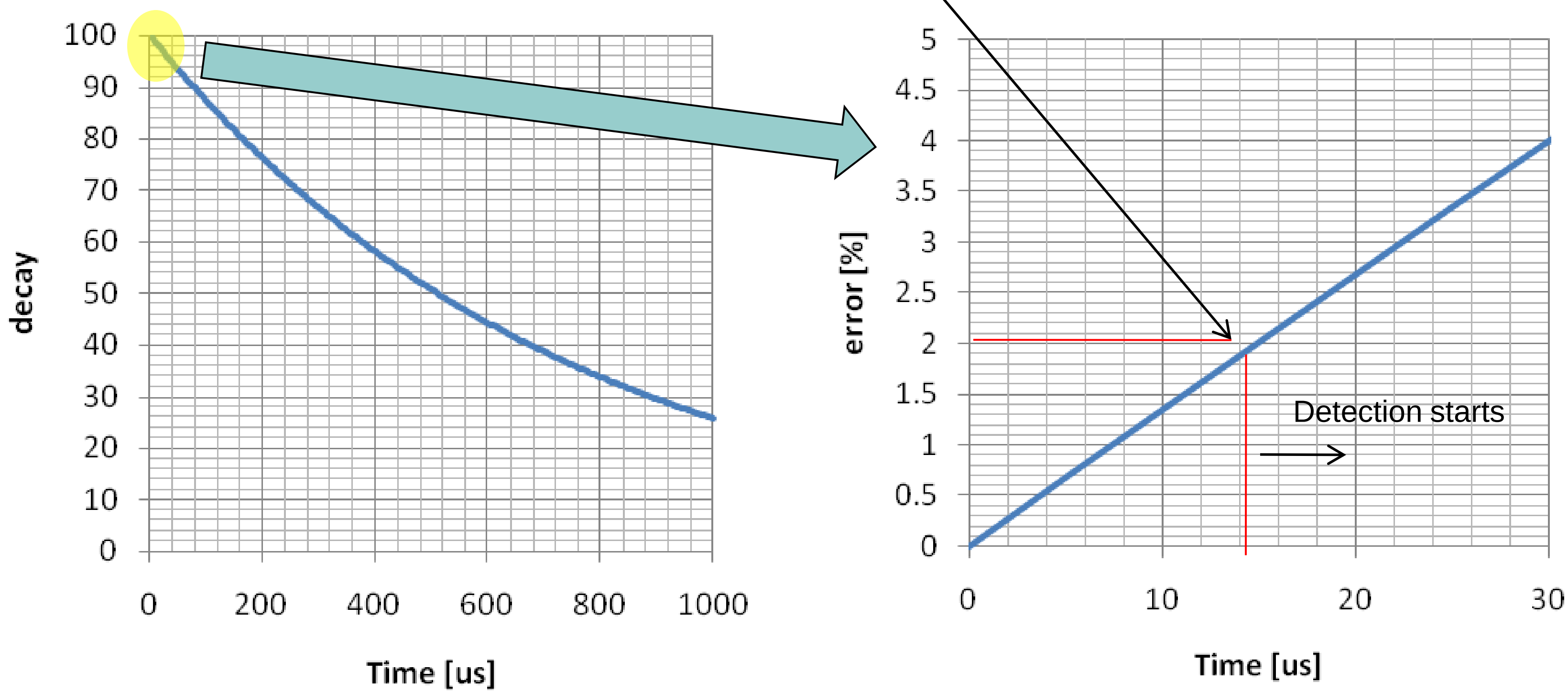
-> We can make some diagnostics even during luminosity operation!

-> Exception handling becomes quite simple.

(Fast recovery of beam energy is not necessary even when quench or rf failure happen.)

FB latency and llrf performance

- Assumption
  - Cavity Q:3e6 -> decay time constant=462us and f1/2=217Hz
  - All signals change in this time constant
  - After 15us of blind time, system changes 2% of perturbation (still large even though the time constant is slow).
  - Rough estimated delay would be 30us dead time (4%) including the slow response time.
- Example 1: Detuning changes (microphonics or Lorentz force) by 20Hz (5 deg in phase) during rf operation.
  - Cavity phase changes by 0.2deg. (=5 deg.*4%) and all the error budget is used for this.



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