LLRF requirements/issues for DRFS

Shin MICHIZONO (KEK)

BAW1 (Sep.8, 2010)

Outline

- Three important requirements concerning LLRF:
  1. LLRF feedback overhead (nominal ~15%)
  2. Gradient flatness of each cavity for near-quench-limit operation (5%?)
  3. Pulse-to-pulse stability of each cavity for luminosity operation (~1%rms)
- Tolerance of Pk, Ql and detunings to satisfy these requirements are considered.

- Cavity control schemes are compared (for DRFS):
  1. PkQl control: set rf power ratio (Pks) and external Q (Qls) so that cavity gradients become flat at specific beam current.
  2. Cavity grouping: select same performance cavities and operate at the same gradients.
- DRFS will adopt “cavity grouping” because of
  1. Saving of rf power (PkQl control requires 14% additional power since the cavity Qls are not matched to beam loading.)
  2. Elimination of circulators (Less rf reflection is preferable.)
- Some ideas to operate 38 MV/m (at cavity grouping) are also shown.

RDR concept configuration, overhead and error budget

Required stability

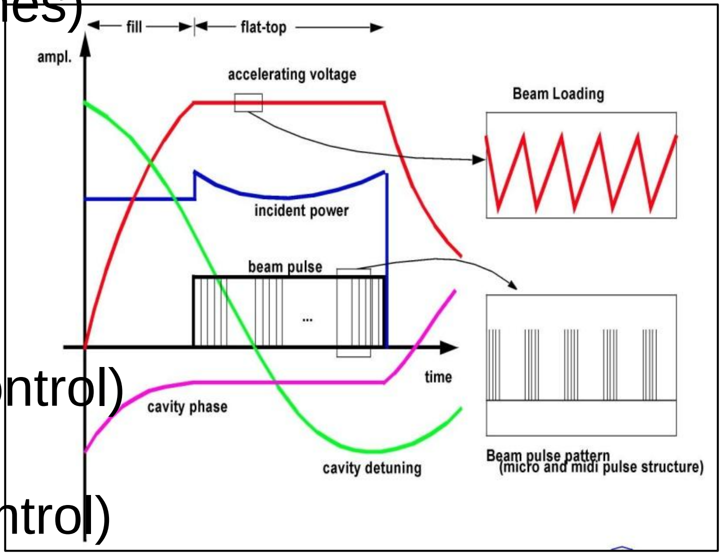
- Llrf stability requirements (@ ML and BC) are < 0.07%, 0.24deg.

TABLE 3.9-1
Summary of tolerances for phase and amplitude control. These tolerances limit the average luminosity loss to <2% and limit the increase in RMS center-of-mass energy spread to <10% of the nominal energy spread.

Location	Phase (degree)		Amplitude (%)		limitation
	correlated	uncorr.	correlated	uncorr.	
Bunch Compressor	0.24	0.48	0.5	1.6	timing stability at IP (luminosity)
Main Linac	0.35	5.6	0.07	1.05	energy stability $\leq 0.1\%$

Power Overhead

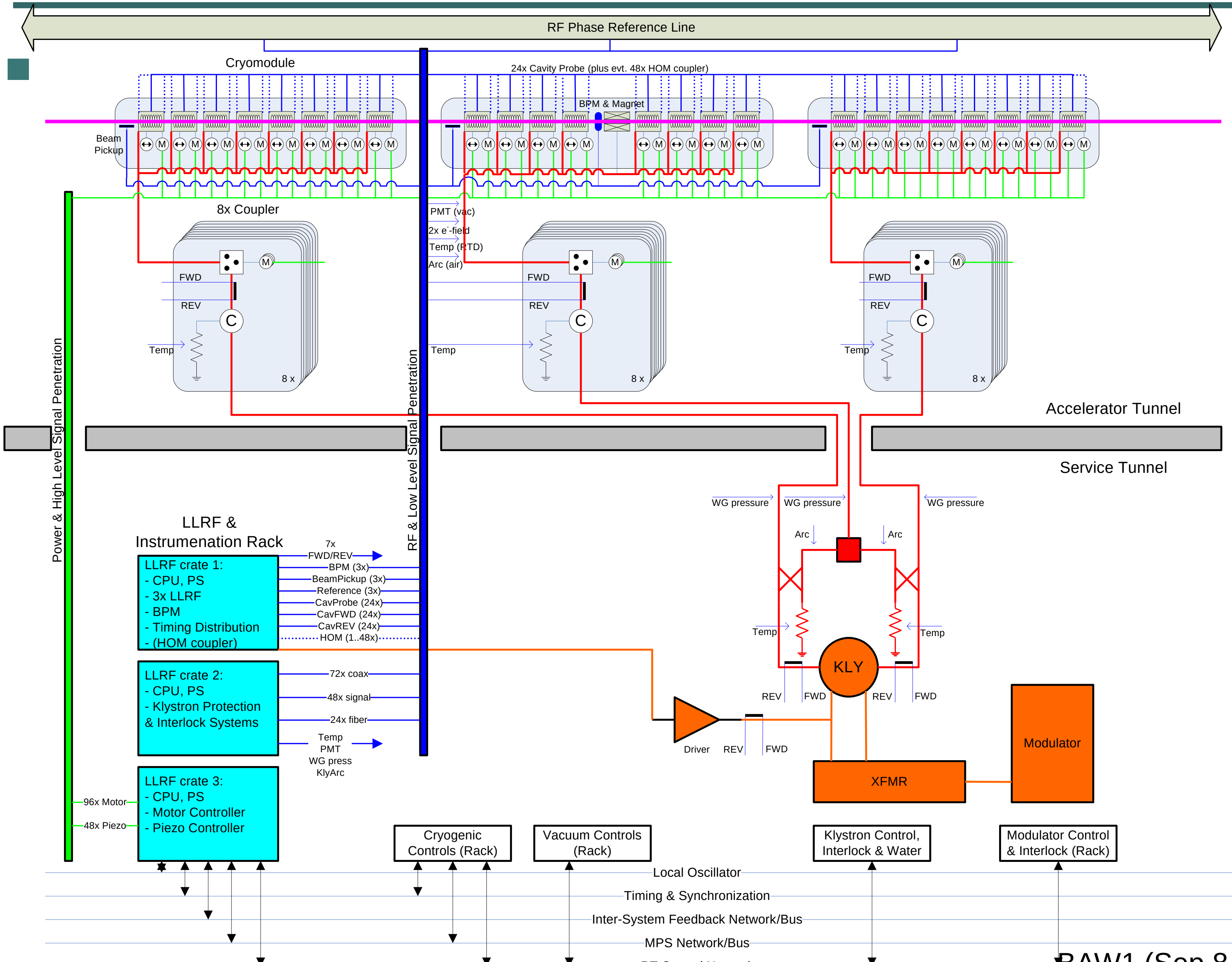
- Static rf losses (use the rf overhead at all times)
  - Klystron HV ripple
  - Ql tolerance
  - Pk distribution tolerance
  - Pre-detuning of each cavity
  - Distribution of pre-detunings
  - Reflection power (in case of the PkQl control)



- Dynamic rf losses (used by the feedback control)
  - Klystron HV fluctuation
  - Beam current fluctuation
  - Dynamic detuning (microphonics+ Lorentz force detuning)

These issues will be covered by the llrf overhead. If the overhead is not enough the regulation of the rf fields will not satisfy the requirements

RDR rf configuration

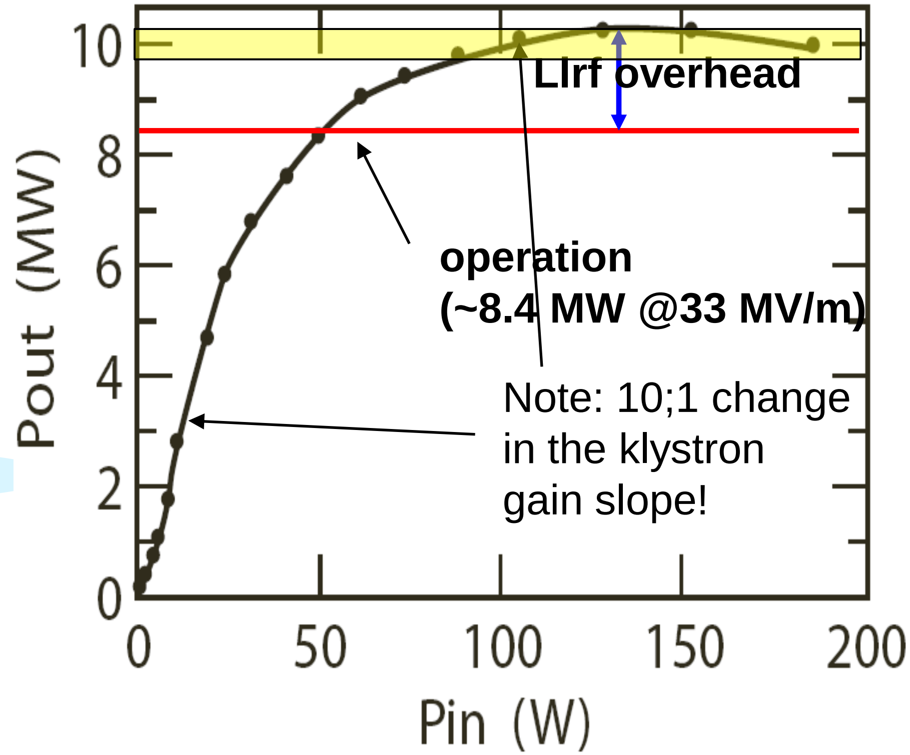


Llrf tuning overhead

- As in RDR, llrf tuning overhead is 16% in power.

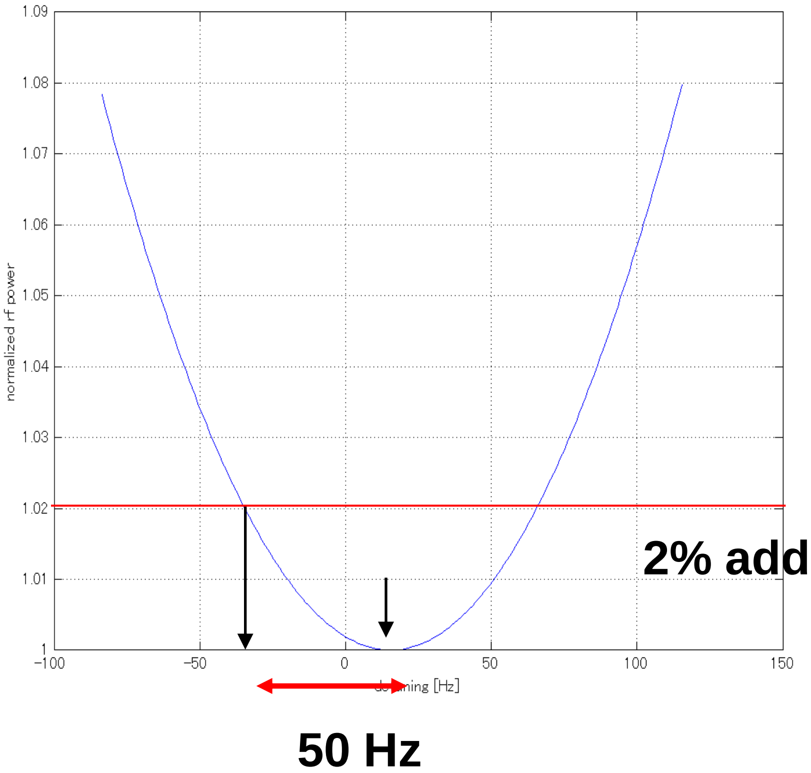
LE 2.6-2
nit parameters.

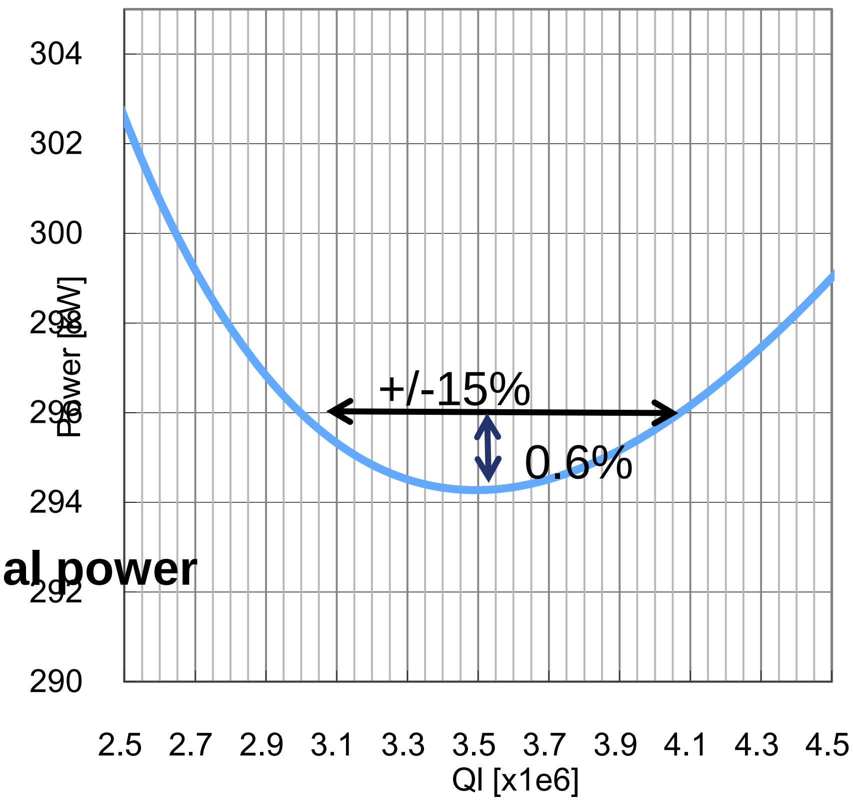
Parameter	Value	Units
Modulator overall efficiency	82.8	%
Maximum klyston output power	10	MW
Klystron efficiency	65	%
RF distribution system power loss	7	%
Number of cavities	26	
Effective cavity length	1.038	m
Nominal gradient with 22% tuning overhead	31.5	MV/m
Power limited gradient with 16% tuning overhead	33.0	MV/m
RF pulse power per cavity	293.7	kW
RF pulse length	1.565	ms
Average RF power to 26 cavities	59.8	kW
Average power transferred to beam	36.9	kW



BAW1 (Sep.8, 2010)

Detuning , Ql tolerance

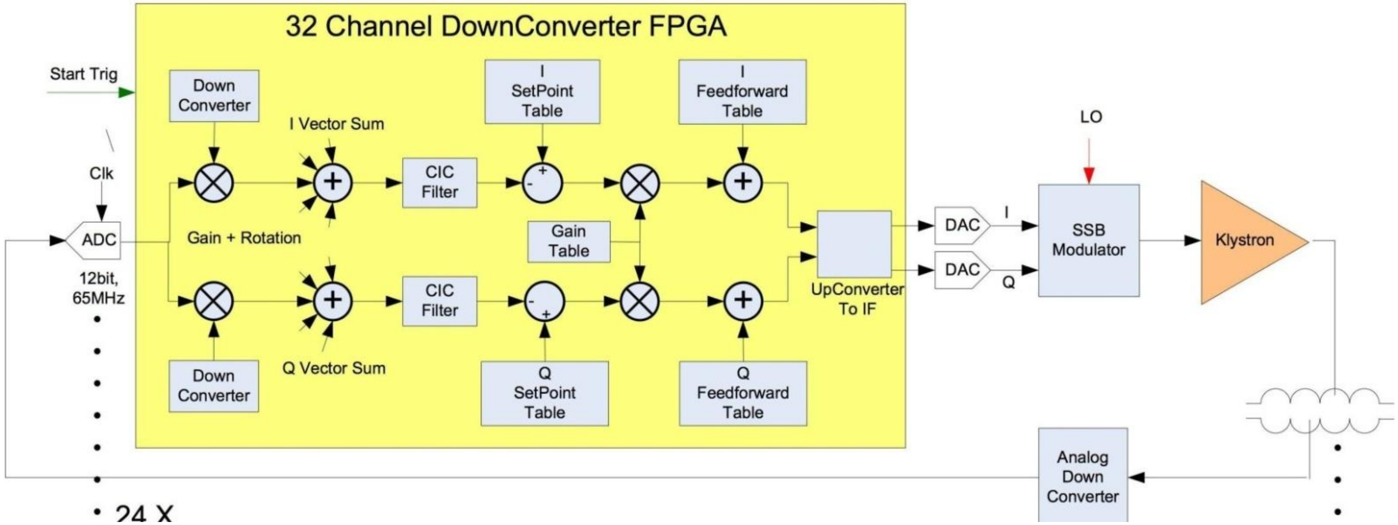




- 50 Hz detuning requires additional 2% rf power
- +/-15% Ql difference requires 0.6% additional power.

Power Overhead Budget @RDR

- llrf overhead (16% @33 MV/m op.) is used for
  - 1% (beam current compensation) (1% fluctuation)
  - 2.5% (HLRF) (1% HV fluctuation)
  - 2% (detuning; microphonics+Lorentz force)(optimistic?)
  - 10.5% Feedback headroom



- Current FB control consists of feed forward and proportional FB.
- Having proportional gain of Pgain, fluctuations can be suppressed 1/Pgain.

(10% fluctuation and Pgain=100, -> 0.1% stability)

- In case of *x*% error, rf amplitude increase x/100*Pgain

(0.05% error and Pgain=100, -> 5% additional amplitude (10% in power)

- Thus 10% is minimum headroom for linear feedback operation.

3, 2010)

Operation of 31.5 MV/m +/-20% gradient cavities

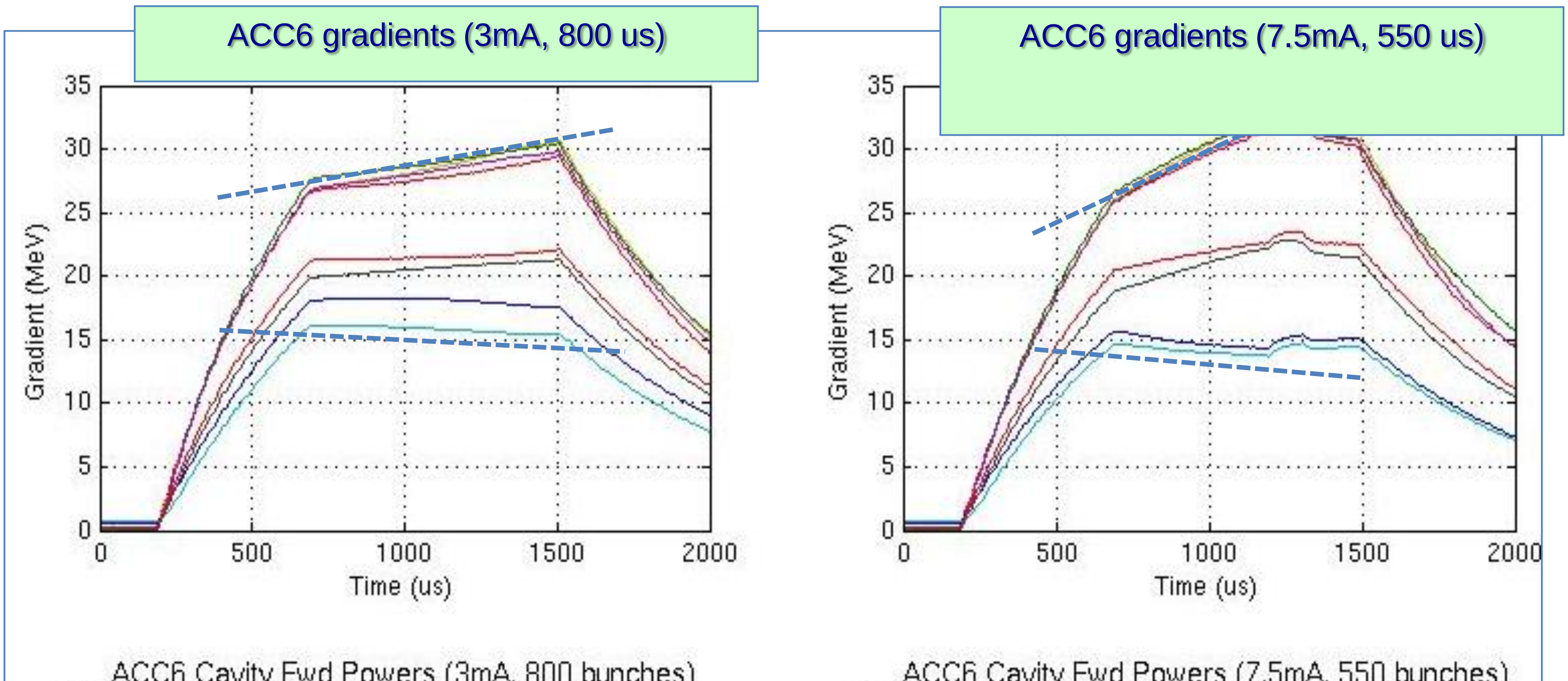
under the requirements of
“near-quench limit operation (~5%)”
“small LLRF margin (~10%)”
“pulse-to-pulse cavity gradient stability (~1%rms)”

31.5 MV/m +/- 20% cavities

- The maximum operational gradient at RDR was 33 MV/m.
- Recently, mainly for using the lower quench cavities, wider variety of cavities are asked to be installed (+/-20%).
- The conventional same-Ql configurations will cause the big gradient tilts due to the difference in beam loading effects.
- In order to operate the cavity efficiently (=operate near quench limit), less tilts of the cavity gradient are preferable.
- In addition, the beam optics group also requires less cavity gradient tilts (~1%rms,pulse-to-pulse) to keep the luminosity at the collision point.
- The strategy for the small tilt configuration is
  (1) Cavity grouping
  (2) PkQl control
  (3) conventional Ql constant control
- (1) and (3) are not realistic at RDR because the rf power source can not drive 38 MV/m cavities.
- PkQl controls requires the remote control of Pk and Ql since the Pk and Ql depend on cavity gradient and beam current.
- If the wide variety of gradients have to be operated, some rf power will not be used (less power efficiency).

Beam loading effects

- The conventional constant Ql distribution is good at non-beam condition.
- In case of the high beam loading, how ever, large gradient tilts appear.
- The gradient tilts are not allowed from the view points of (1) the operational set-point near quench limit and (2) beam dynamics.
- The possible solutions are
  - cavity grouping
  - PkQl control
  - same Ql with same gradient control



Gradient tilt

- Tilts of the cavity gradients should be minimized for
  - beam dynamics (~5%rms repetitive error, ~1%rms pulse-to-pulse error)
  - near the quench limit operation (~5%)

- The sources of the cavity gradient fluctuation are
  - Pk tolerance
  - Ql tolerance
  - Beam current (in case of the PkQl control)
  - Pre-detuning
  - Distribution of pre-detunings
  - Microphonics

Effect on the gradient tilts of each component was estimated by simulation.

PkQl control

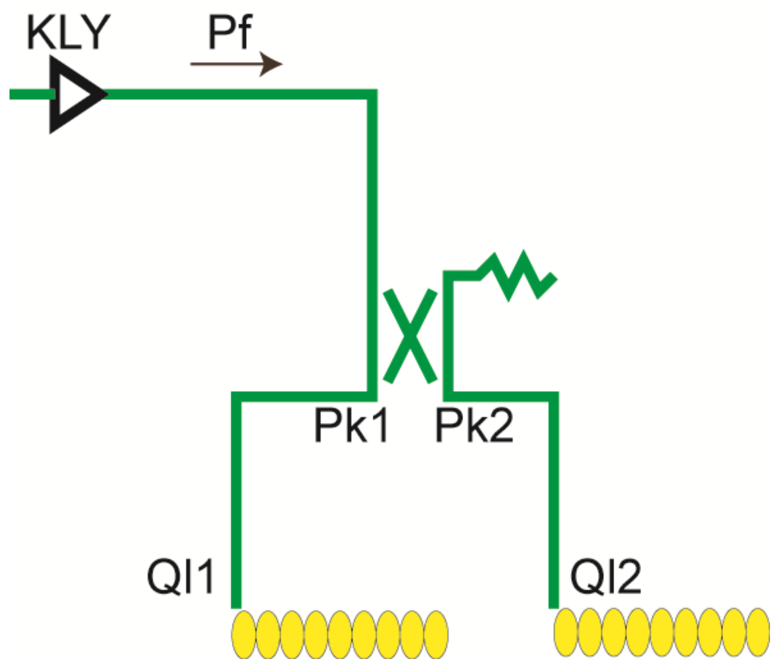
- In case of the Pk-Ql control near the quench limit condition, the values of Pks and Qls are calculated as followings.

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).

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

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

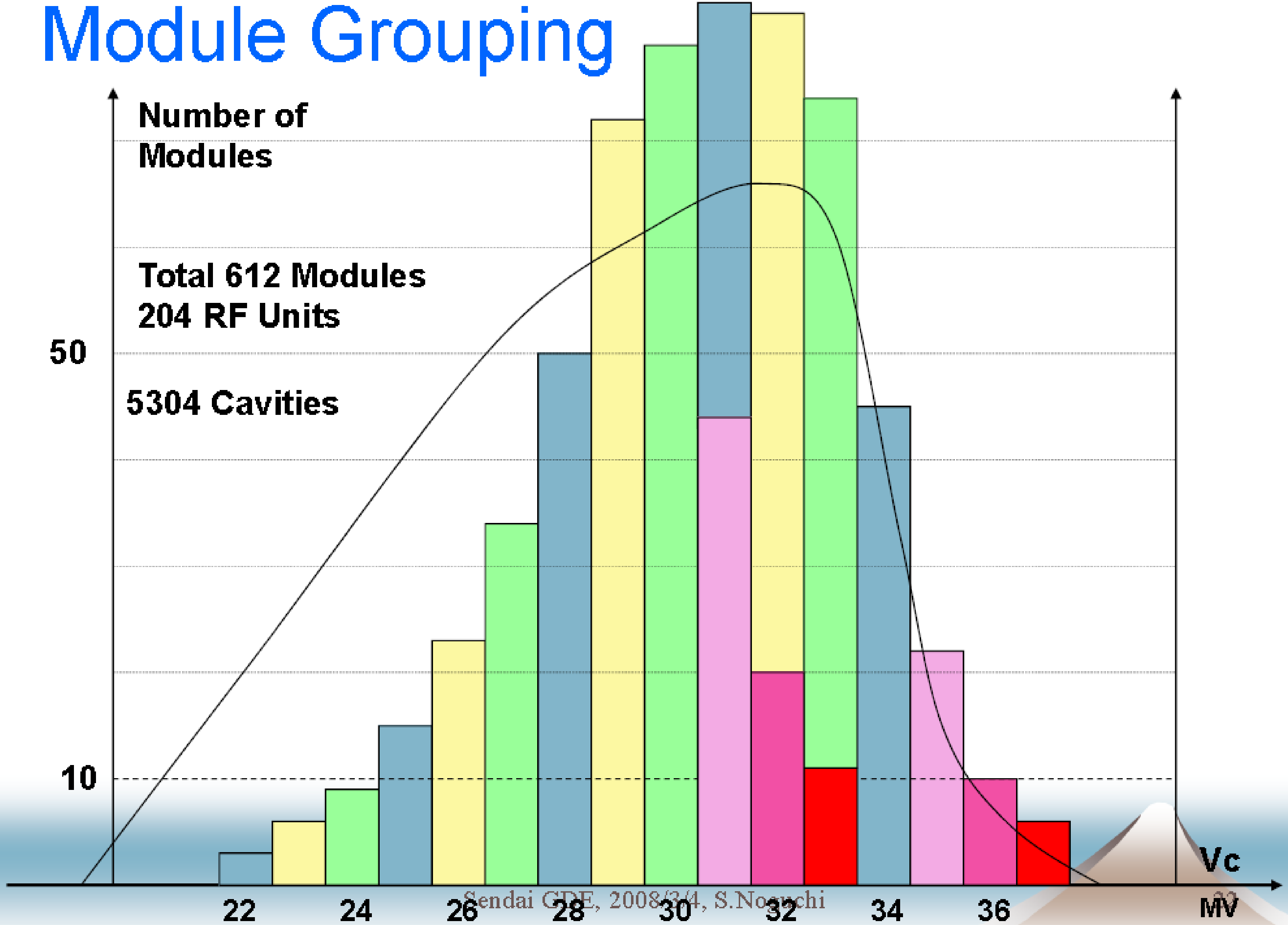
$$\rightarrow \quad \mathrm{Pk} = \frac{1}{4}\frac{r}{Q} Q_L (\mathrm{Igen})^2$$



Cavity Grouping Concept

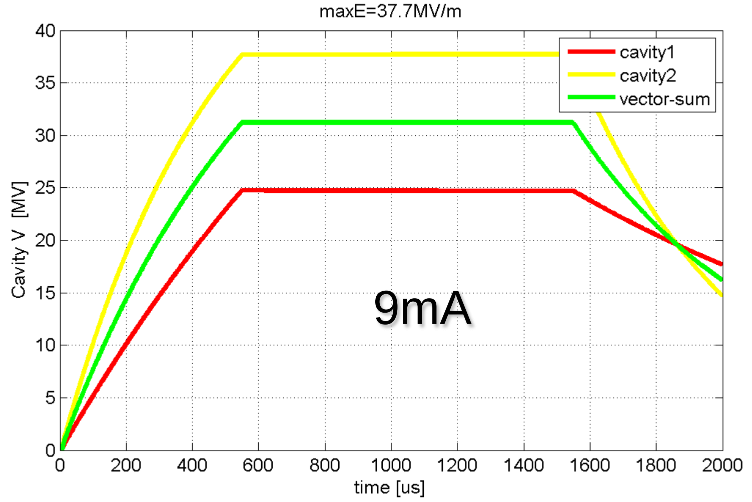
- Install the Cavities having the same Maximum Gradient into the same Cryostat.
- Drive the same Gradient Cryomodules by one Klystron.
- Combine a high Gradient module with two other low Gradient Modules.

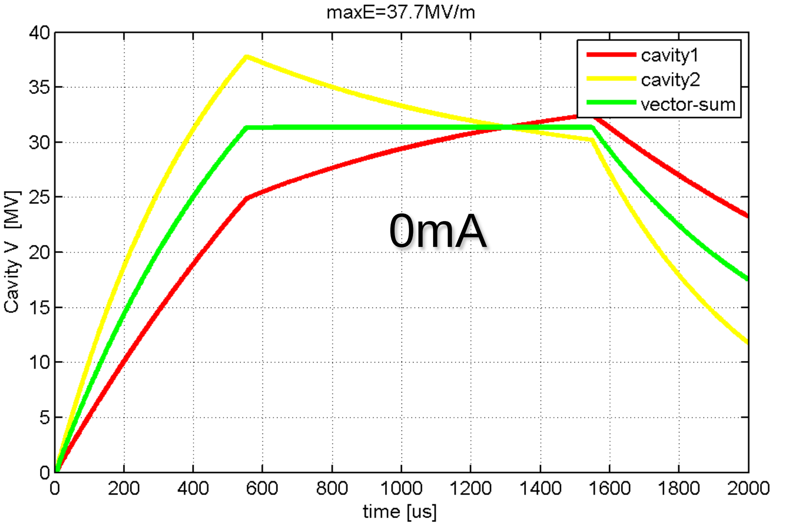
Module Grouping

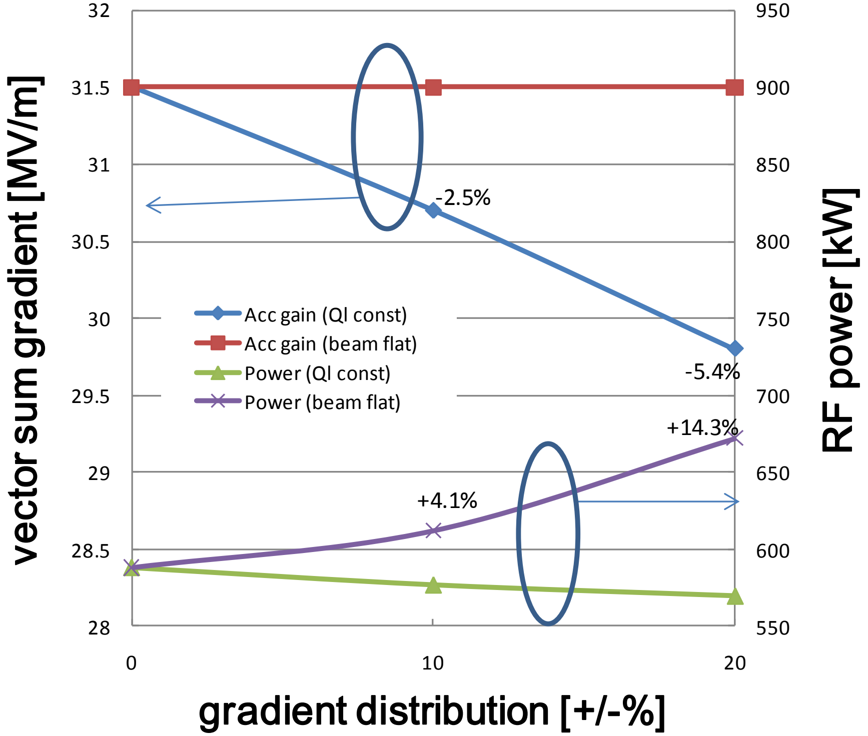


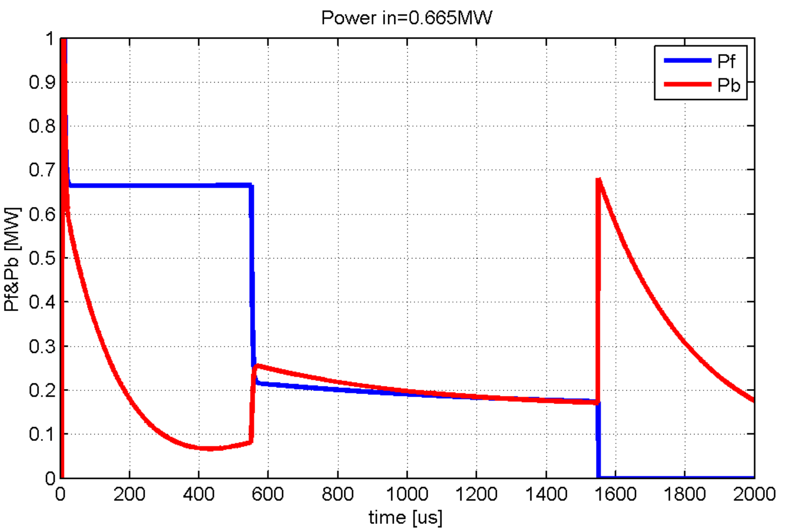
LLRF control at DRFS

PkQl or cavity grouping ?



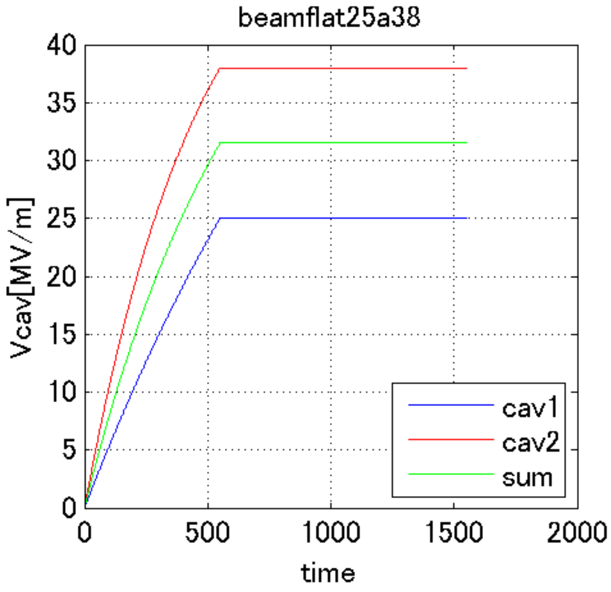


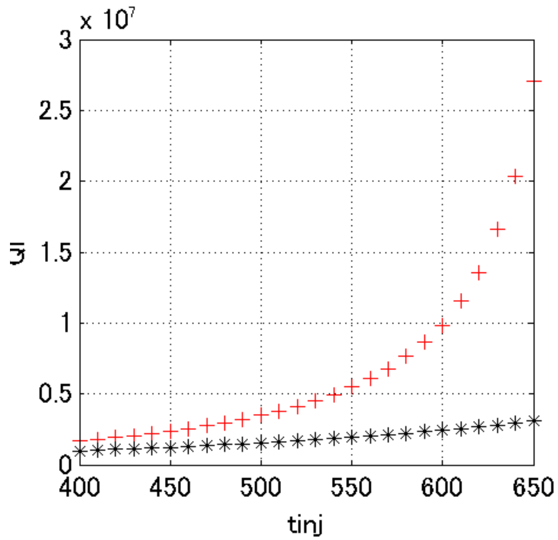


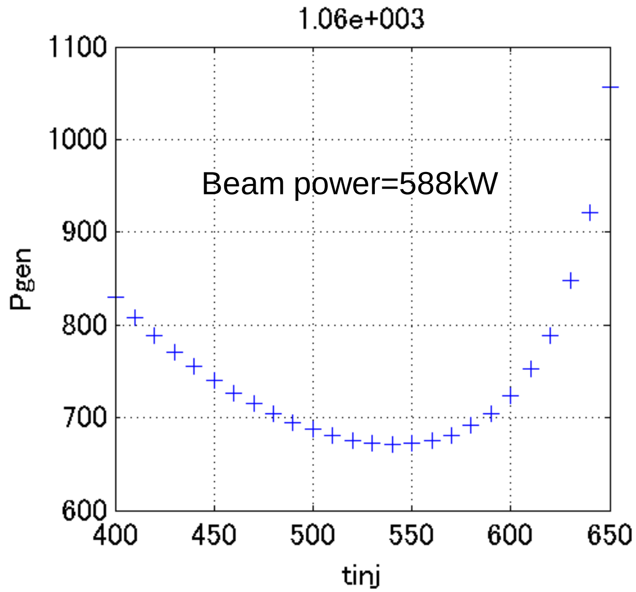


BAW1 (Sep.8, 2010)

PkQI @DRFS







- Two cavities operation at 25 MV/m and 38 MV/m.
- Injection time of ~550us is the best performance but still 14% more than beam power.

LLRF control at DRFS

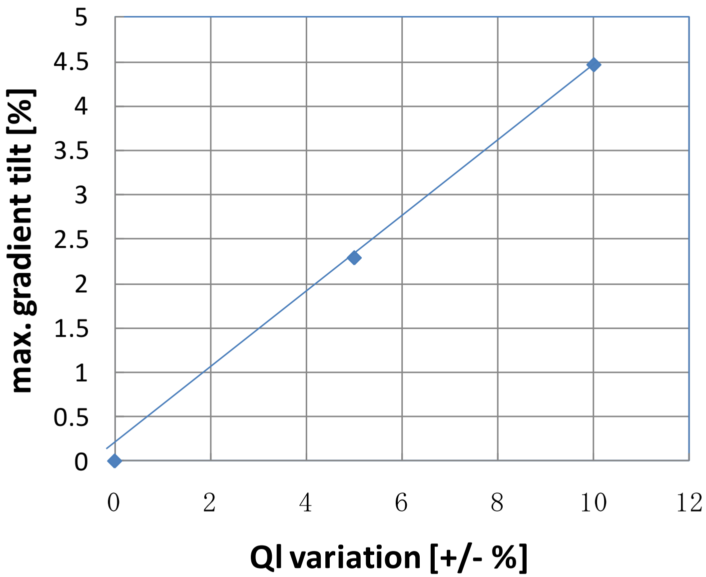
- PkQl control: additional 14% rf power is required when 2 cavity operation with 25MV/m and 38 MV/m. Need circulators and variable Ql, Pk. In addition, flatness is only guaranteed when operated the certain beam current.
- Cavity grouping: no additional power is required. The gradient flatness is guaranteed even when we change beam current. But need to examine the driving of cavities at 38 MV/m.

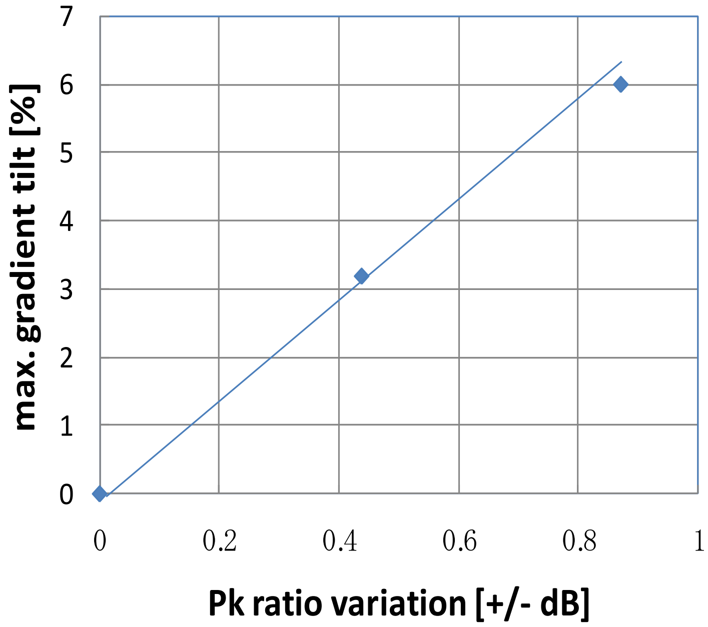
-> We will adopt cavity grouping and propose some ideas to drive 38 MV/m cavities at small overhead.

Tolerance at cavity grouping

Cavity grouping control

- Two cavities are operated from an rf unit.
- Same gradient control is cost saving, because we can operate without circulators (upstream of cavity input coupler).
- In such a case, high gradient operation should be considered (later).
- The gradient tilt by Pk, Ql, detguning variations is simulated.

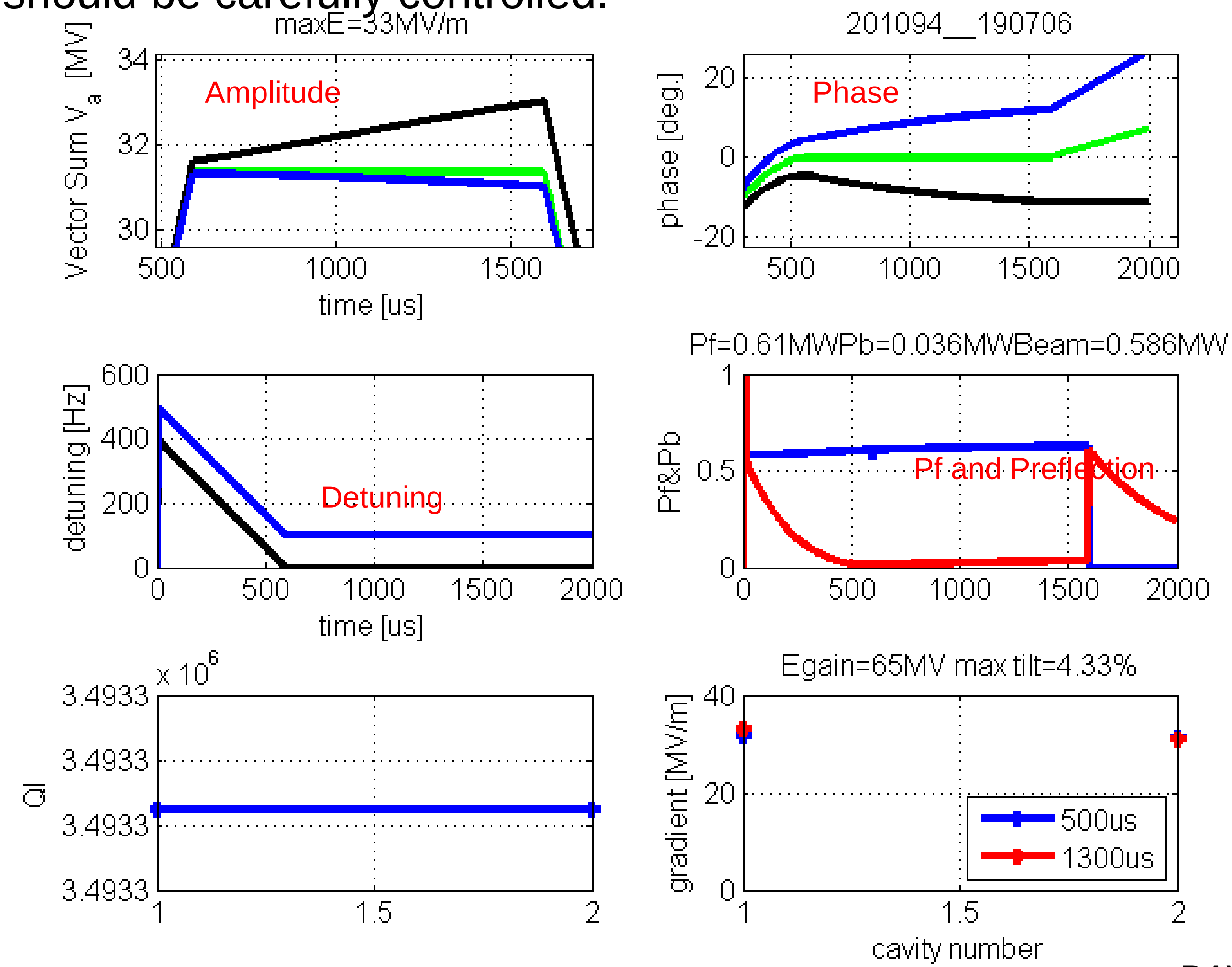




- If the max. tilt is <5%, each component of fluctuation source should be <1.5%.
- Ql variation should be 3%, Pk variation should be 0.2dB, repetitive detuning difference (between cavities) should be <100Hz.

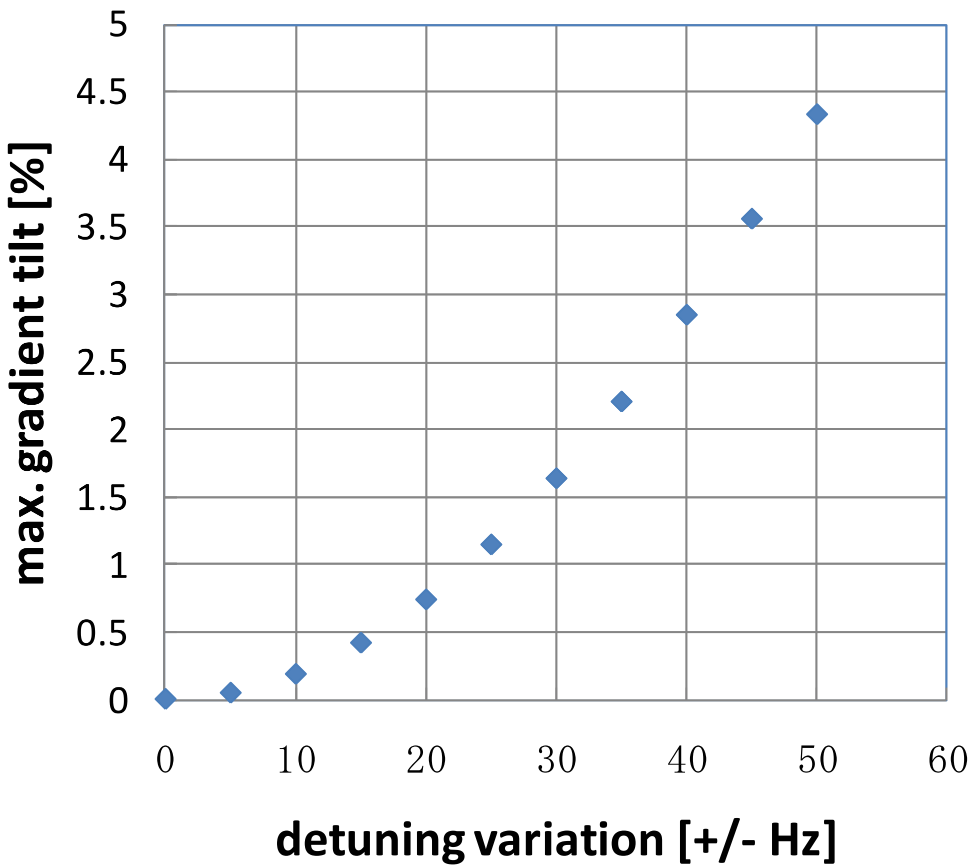
Cavity grouping control(2) pulse-to-pulse

- If the cavity detuning is different +/-50 Hz between cavities, gradient tilt becomes ~4%.
- Even if Qls and Pks are controlled perfectly by remote control, the dynamic detuning should be carefully controlled.



BAW1 (Sep.8, 2010)

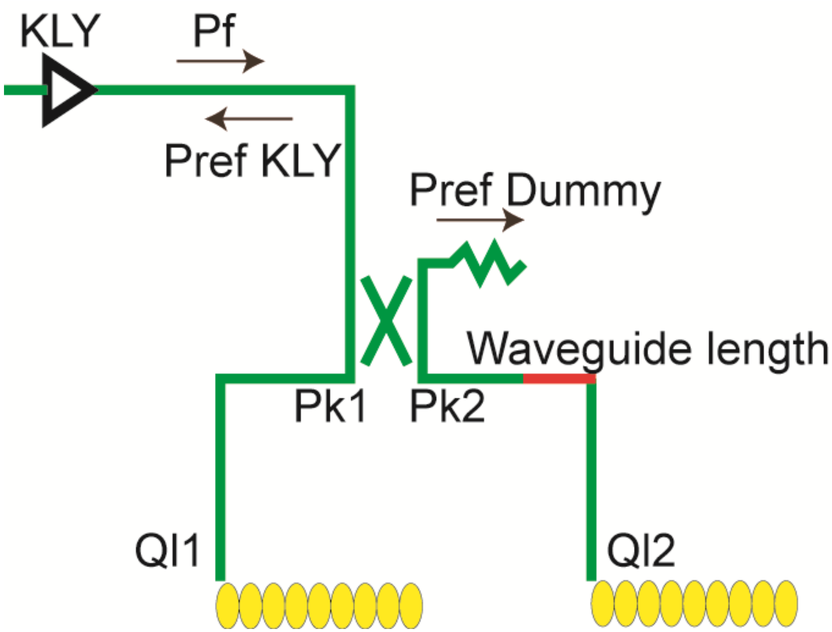
Cavity grouping control(3) pulse-to-pulse

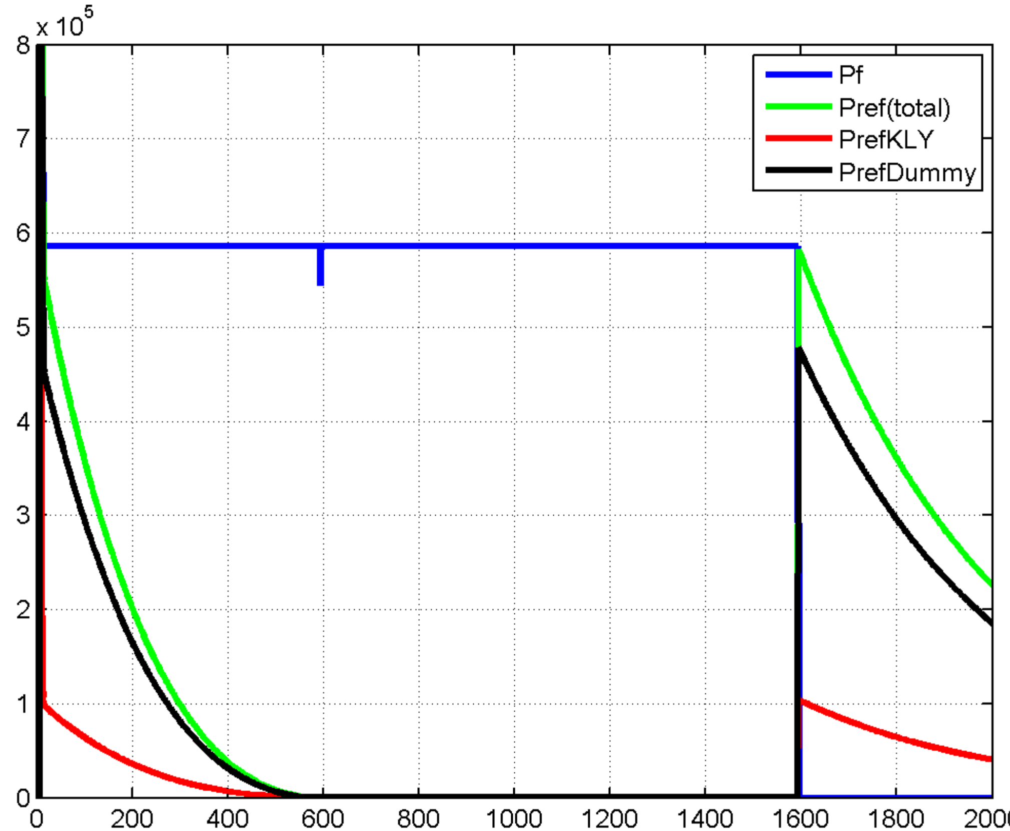


- **If the max. pulse-to-pulse fluctuation is <1%rms, detuning fluctuation (between cavities) should be <20Hz rms.**

RF reflection (@cavity grouping)

- RF reflection is calculated at cavity grouping concept. (without circulators)
- Variation of Qls, Pks, detuning difference and waveguide phase are considered.

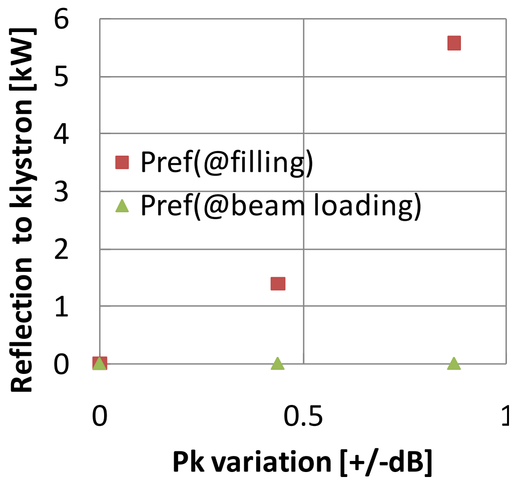


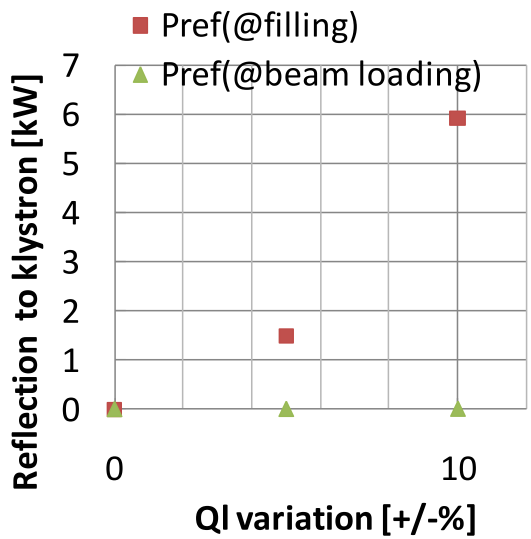


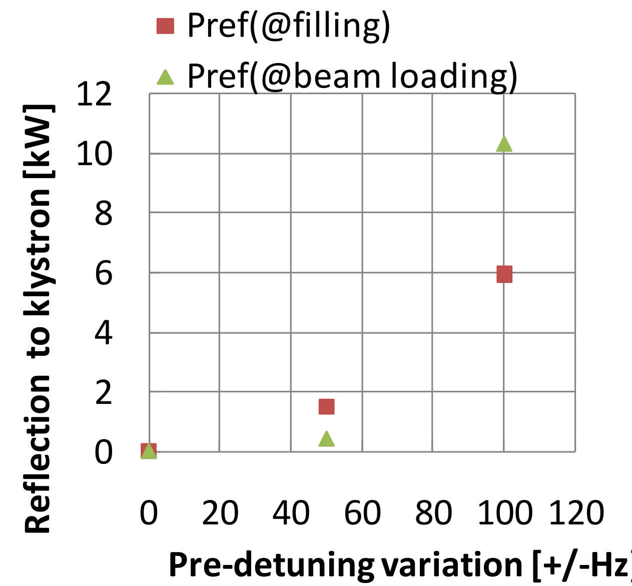
- Max. reflection to the klystron at 600 kW output is 150 kW at worst.

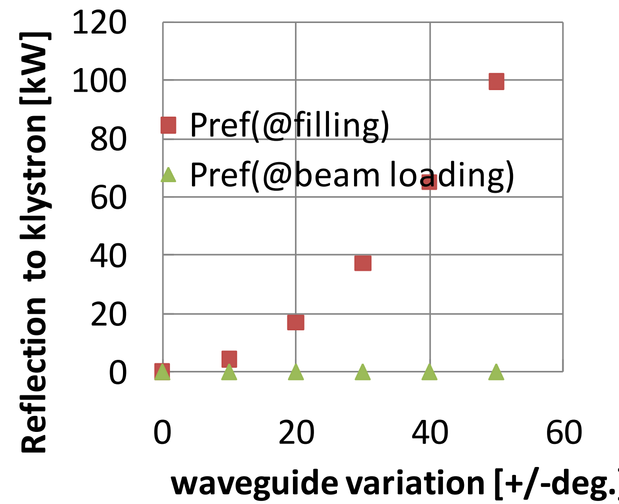
RF reflection (@cavity grouping)

- Reflection to the klystron during the filling and beam operation is calculated.









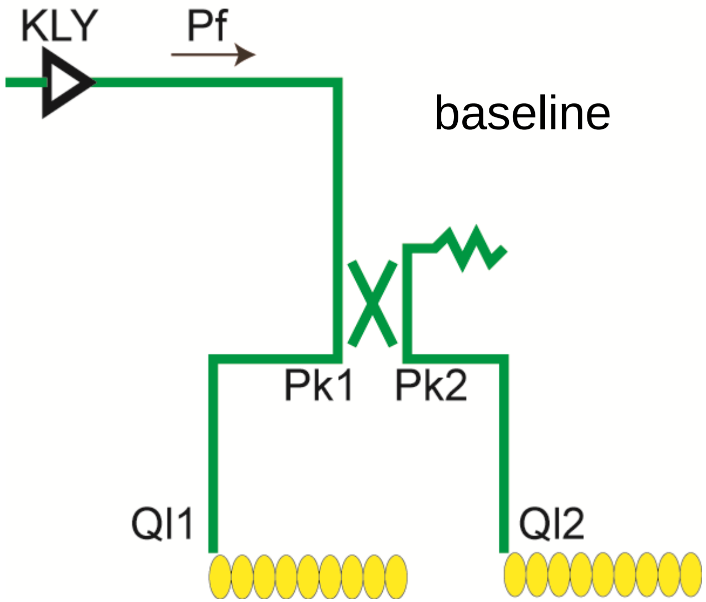
- Waveguide length can be adjusted ~3deg. (~3mm)
- Since the rf reflection is small (~1/100),
  the circulator can be eliminated.

DRFS configuration

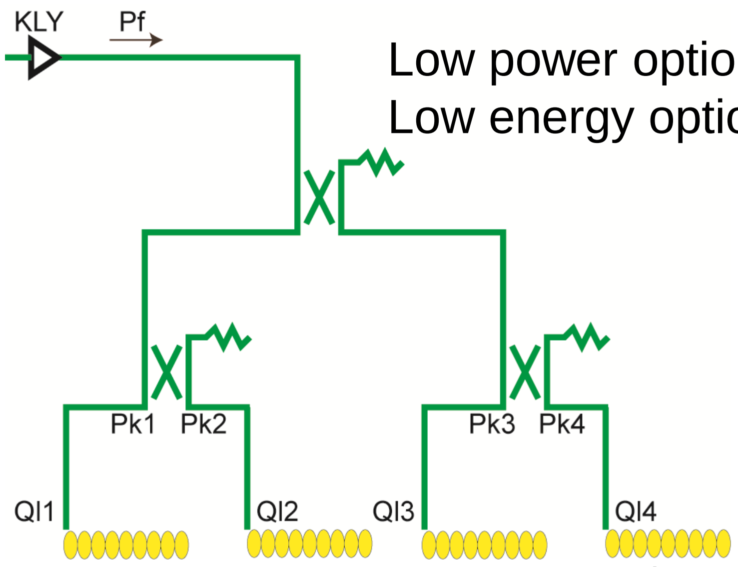
RF configuration

- Baseline: one klystron drives 2 cavities. Max.38 MV/m
- Lowpower 2 is the concept to reduce the filling time but requires 12% additional rf power leading to the lower operational gradient.

	gradient	beam	# of cav.	Ql	Fill time
baseline	31.5 MV/m	9 mA	2	3.5e6	593 us
Low power1	31.5 MV/m	4.5 mA	4	7e6	1186 us
Low power2	(28 MV/m)	4.5 mA	4	3.5e6	593 us
Low energy	15.8 MV/m	4.5 mA	4	3.5e6	593 us



baseline



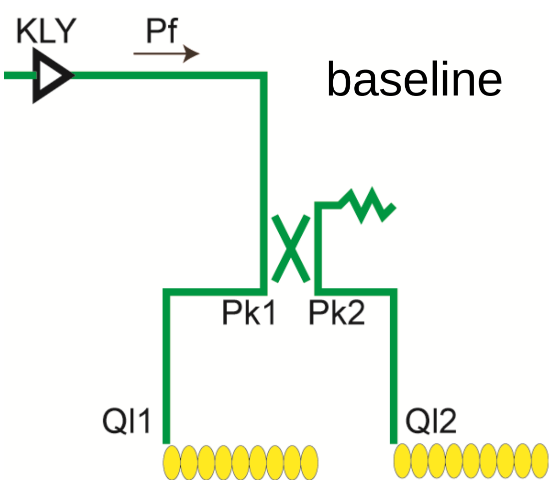
Low power option
Low energy option

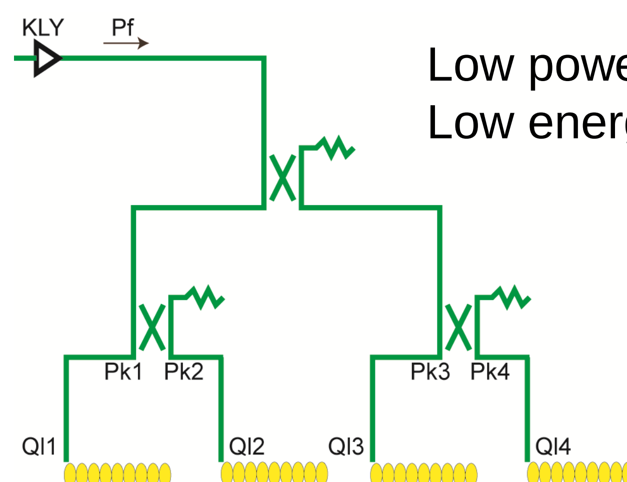
BAW1 (Sep.8, 2010)

Cavity grouping and cavity failure

- If one of the cavities has lower quench limit (25 MV/m), …
- Baseline:
  I. Detune the cavity -> ¼ power (150 kW) reflects to the klystron, lose 25MeV
  II. Operate at lower gradient -> lose 13MeV (38,25 -> 25,25)
  III. Move to PkQl -> can be operated at 30 MV/m ave. (35&25) (lose 3MeV)
- Low power:
  I. Detune the cavity -> 1/16 power (38 kW) reflects to the klystron, lose 25 MeV
  II. Operate at lower gradient -> lose 39MeV (38x3,25 -> 25x4)
  III. Move to PkQl -> can be operated at 30 MV/m ave. (33x3,25) (lose 15 MeV)
- Low energy: operational gradient is half of the final value.

- Remote Pks,Qls are preferable for flexiblity, but it requires larger initial cost…
- Combination of different control scheme (cavity grouping and PkQl) results in the complex llrf control procedure especially when we change the beam current.

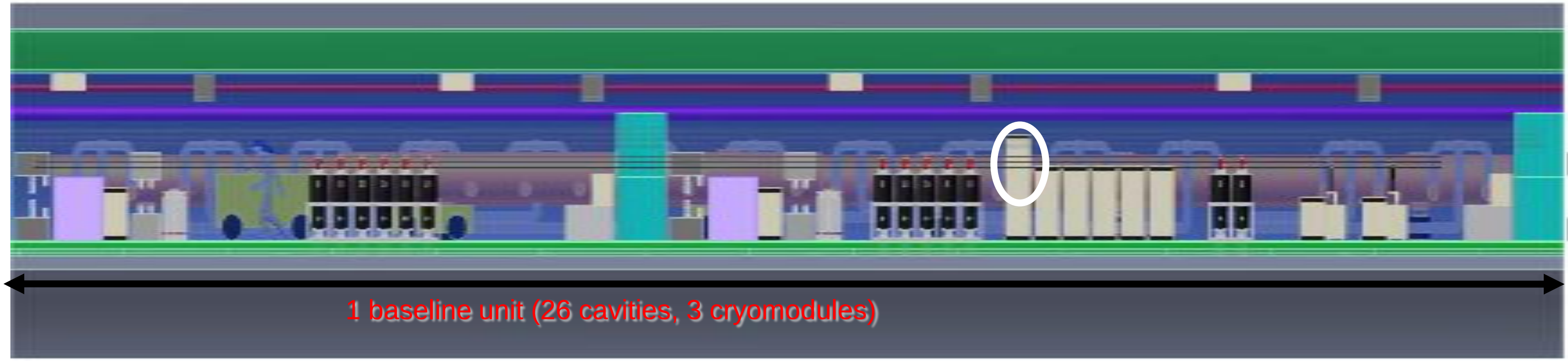




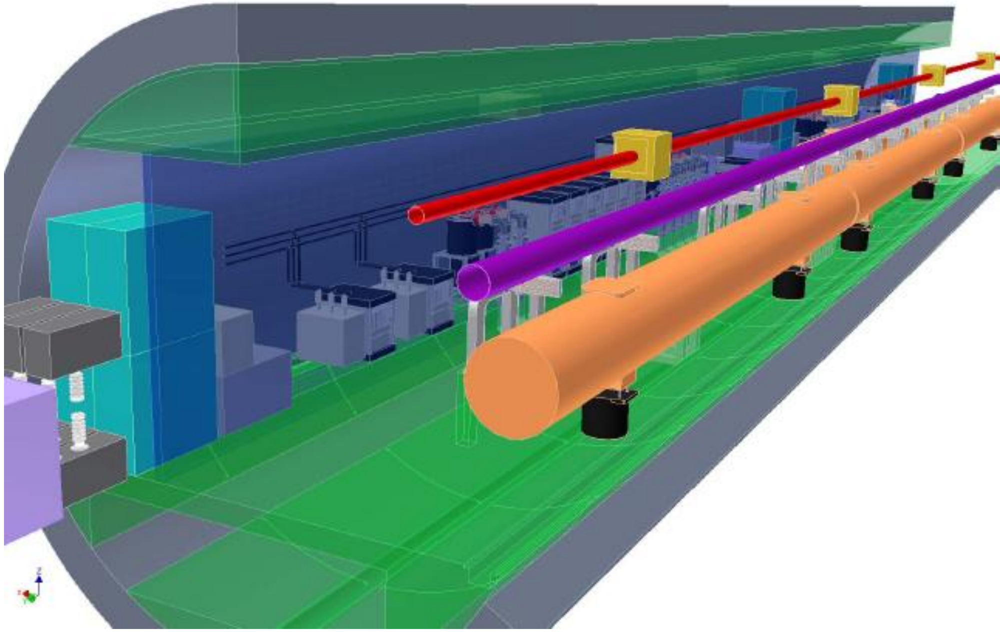
Low power option
Low energy option

Sep.8, 2010)

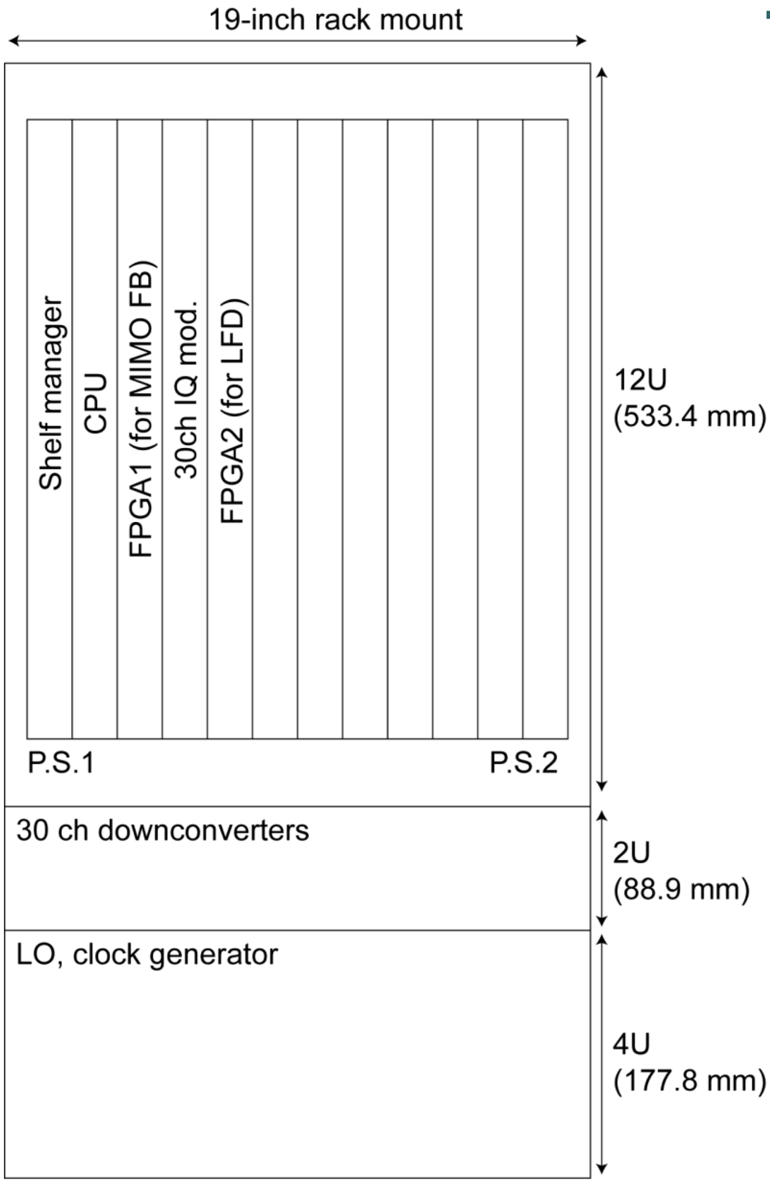
LLRF rack layout for DRFS



- 19 inch rack (total 16U) is located in every 3 cryo-modules.
- Maximum cable length is ~20 m (corresponding to 100ns)

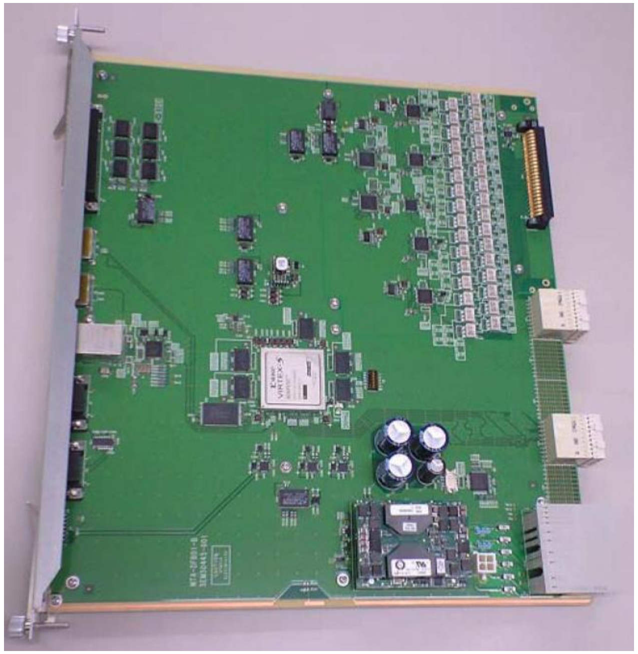


LLRF rack layout for DRFS (2)

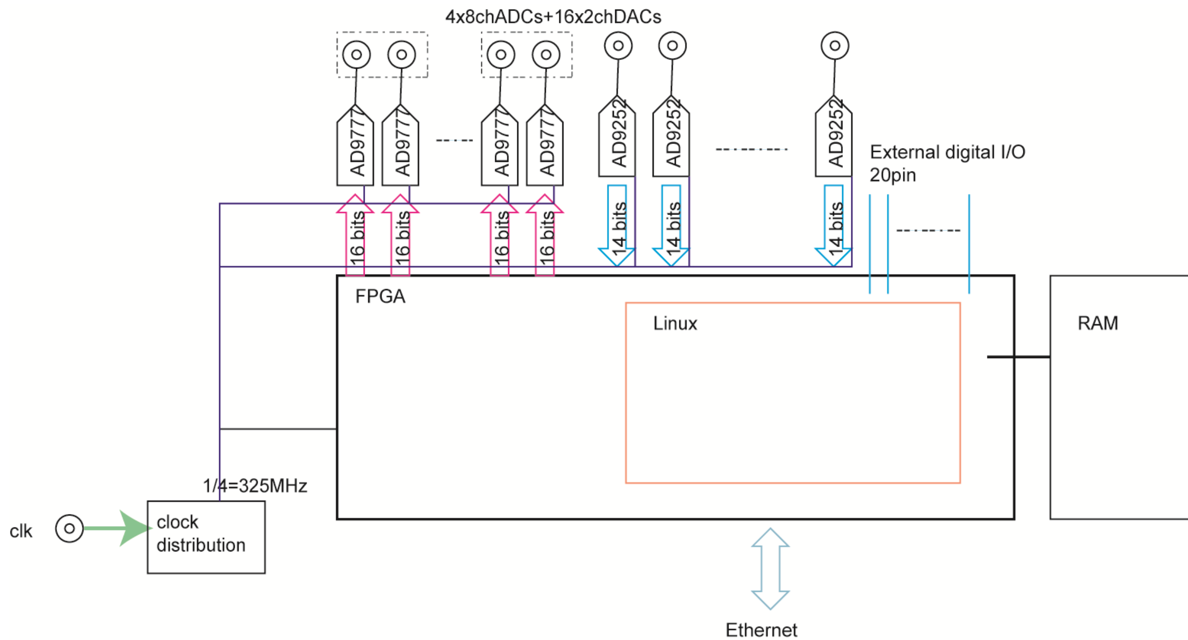


- One big FPGA board (having 30ADCs and 30DACs) is installed.
- ATCA is a candidate of the crate standard for DRFS.
- IQ modulators are also located at ATCA.

ATCA FPGA board for DRFS



32ch ADCs+4ch DACs ATCA-FPGA board



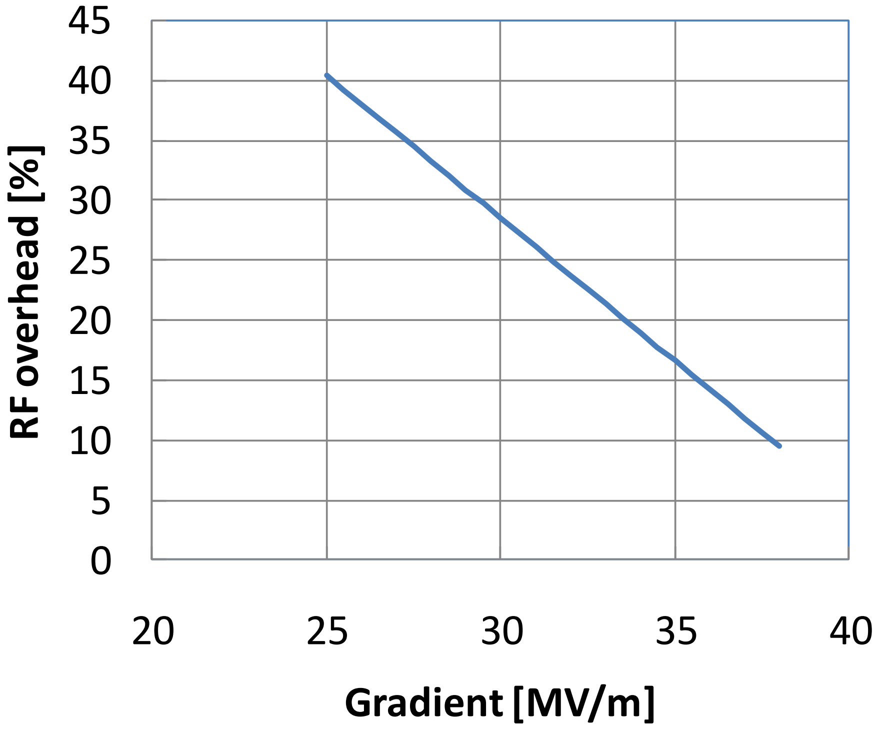
32ch ADCs+32ch DACs ATCA-FPGA board for ILC-DRFA

- One big FPGA board (having 30ADCs and 30DACs) is installed.
- The FPGA board drives all the rf sources in 3 cryomodule (~13).
- This board is suitable for the energy (rf field) regulation.
- MIMO (Vector-sum like) control will be possible.
- One low gradient operation rf-unit will compensate the other rf units.

38 MV/m operation at DRFS

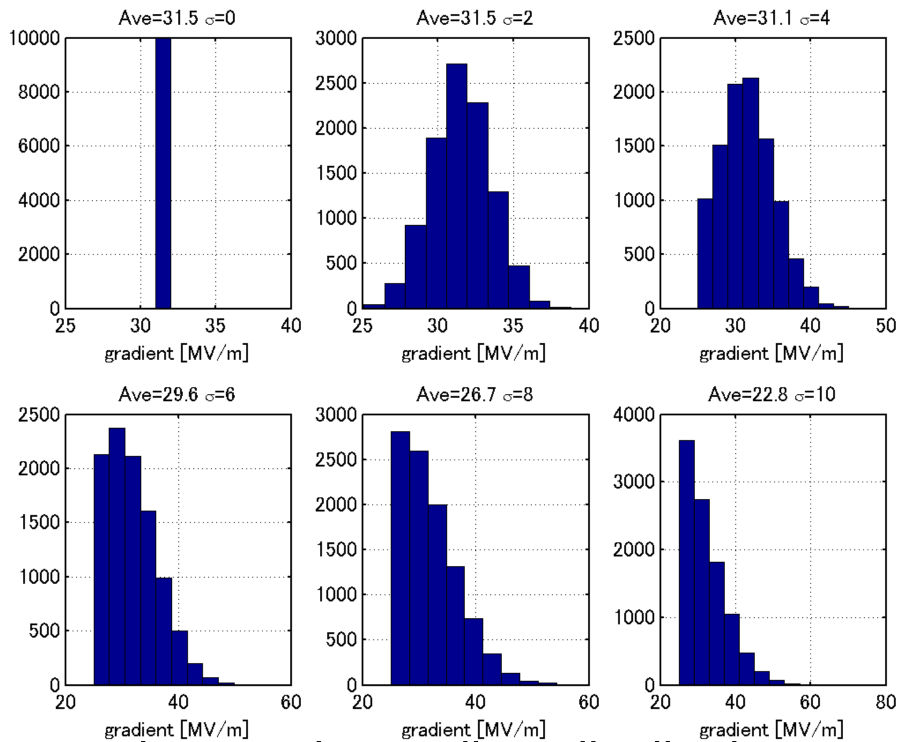
- rf regulation
- power shortage

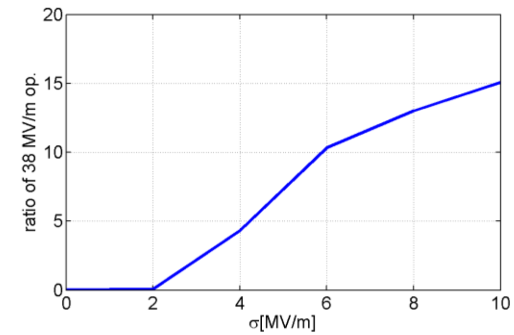
RF overhead

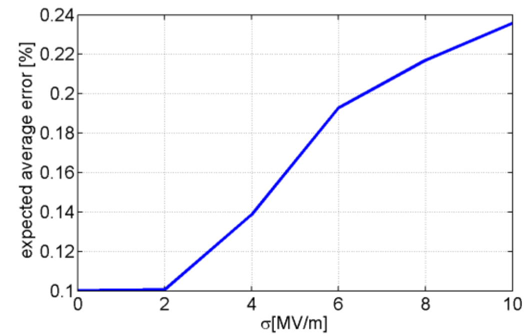


- The max. rf power from the klystron is 800 kW.
- Waveguide loss is supposed to be 2%.
- The rest power (784 kW) is the max. available power.
- At DRFS cavity grouping concept, rf overhead is small ~10% when operated with 38 MV/m.
- The nominal overhead is about 25%.
- The performance at high gradient operation should be considered.

38 MV/m operation



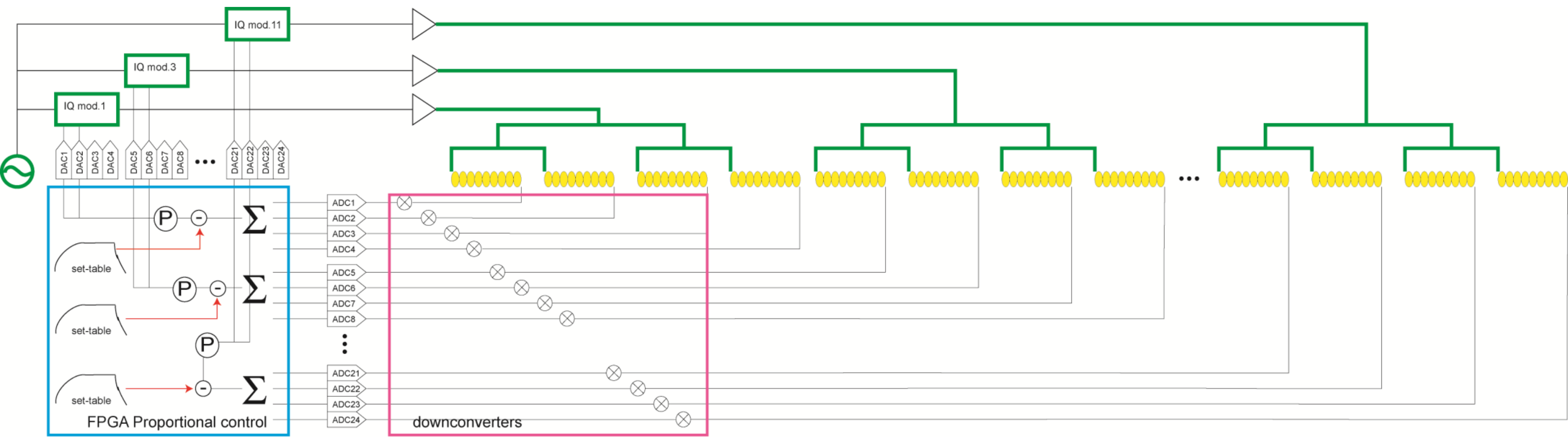


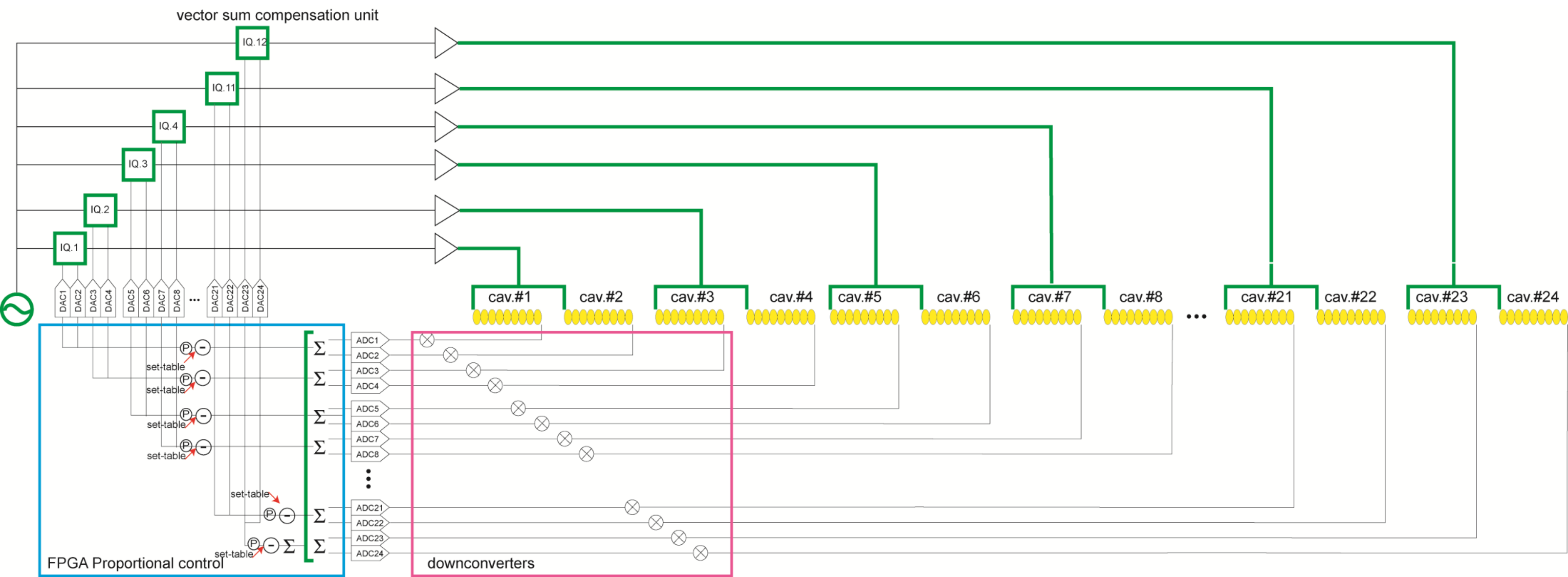


- Various cavity gradient distributions are considered keeping the average gradient of 31.5 MV/m.
- All the cavities can be operated >25MV/m.
- >38MV/m cavities are operated at 38MV/m.
- Stabilities of 38MV/m cavities are 1%, other cavities are regulated 0.1% in amplitude.
- In case of the 10MV/m sigma,15% cavities are operated at 38MV/m.
- Even in this case, the stability is 0.24%.
- The worse performance of 38MV/m cavity can be compensated by other cavities.

BAW1 (Sep.8, 2010)

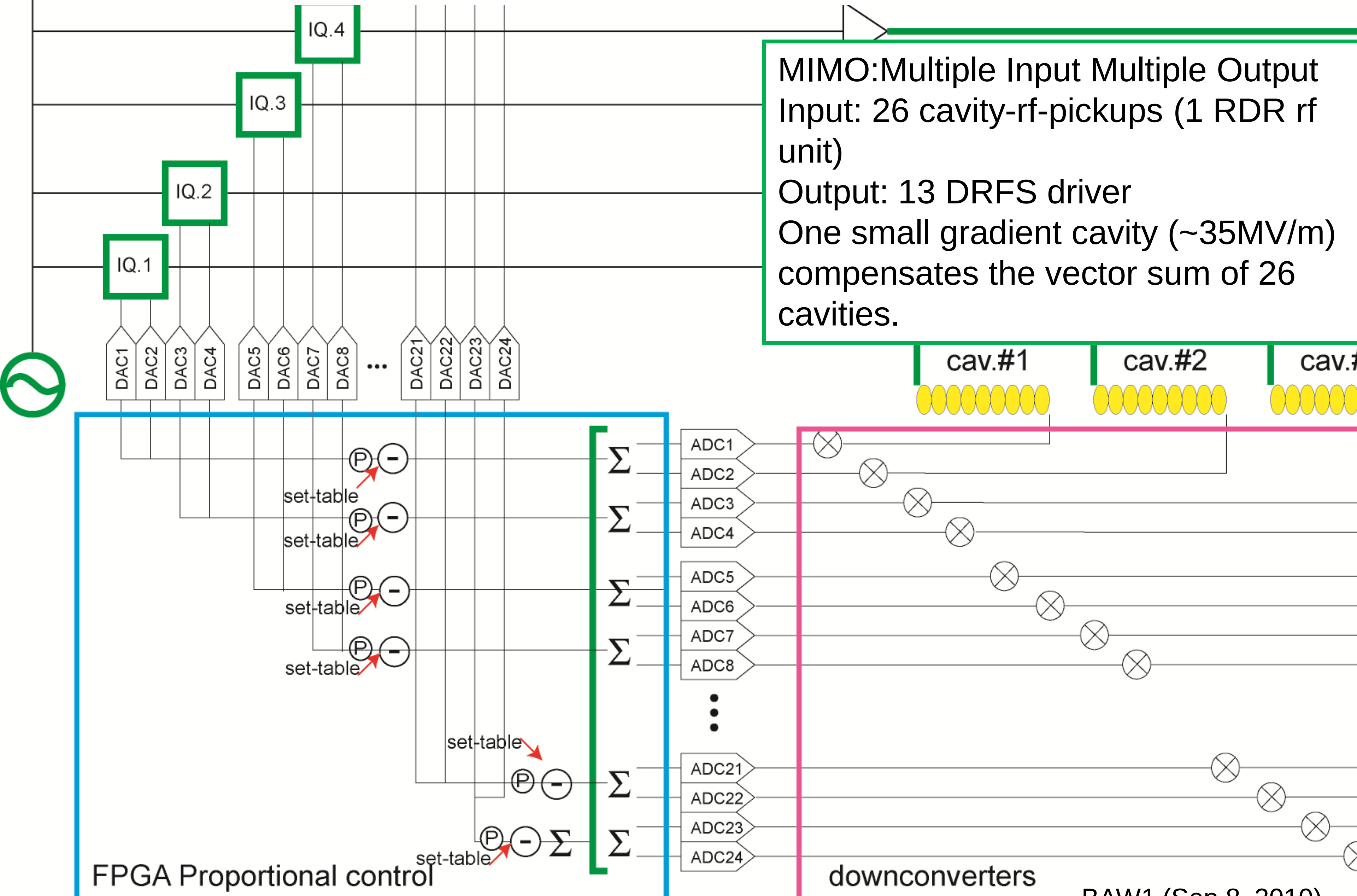
MIMO control (partial vector-sum)





MIMO control (partial vector-sum)

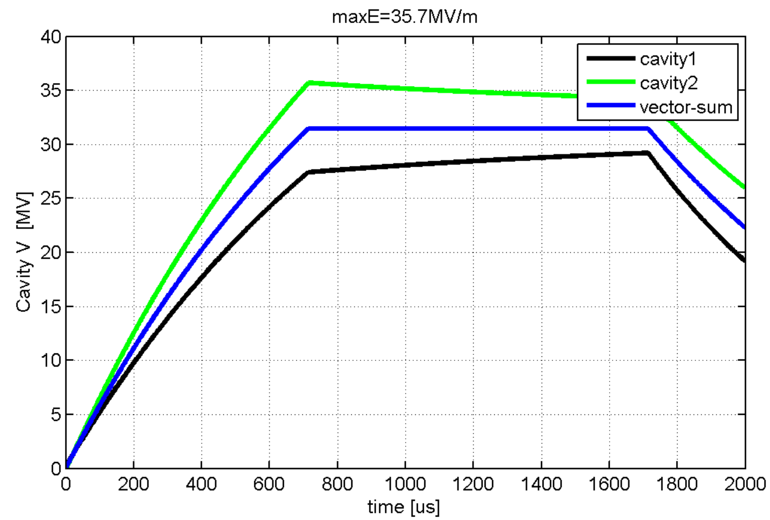
MIMO:Multiple Input Multiple Output
Input: 26 cavity-rf-pickups (1 RDR rf unit)
Output: 13 DRFS driver
One small gradient cavity (~35MV/m) compensates the vector sum of 26 cavities.

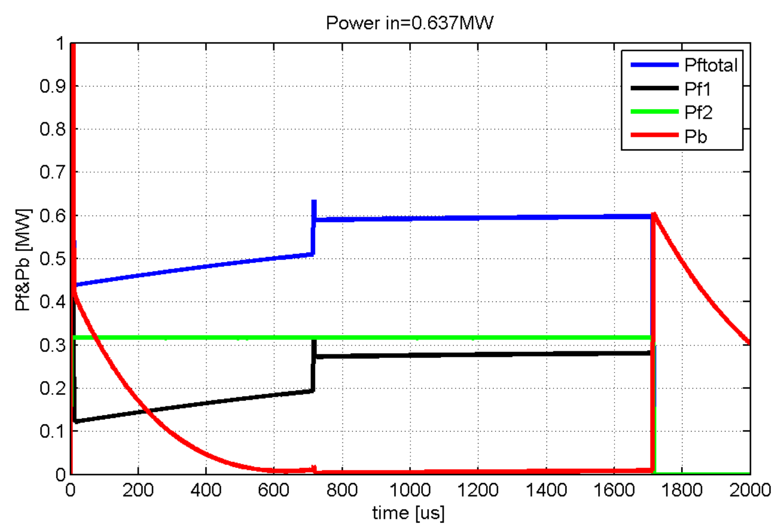


MIMO control (partial vector-sum)

MIMO:Multiple Input Multiple Output
Input: 26 cavity-rf-pickups (1 RDR rf unit)
Output: 13 DRFS driver

One small gradient cavity (~35MV/m) compensates the vector sum of 26 cavities.



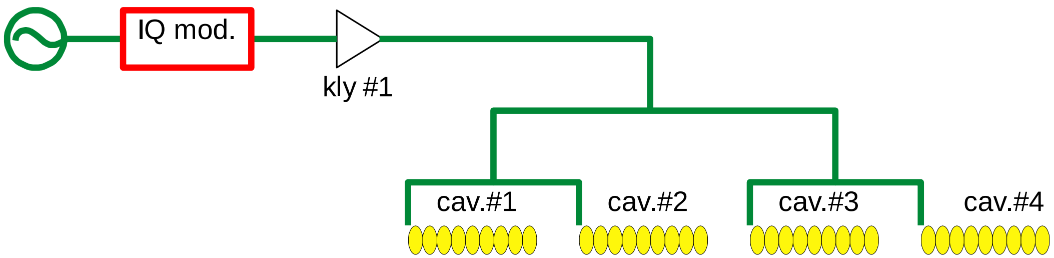


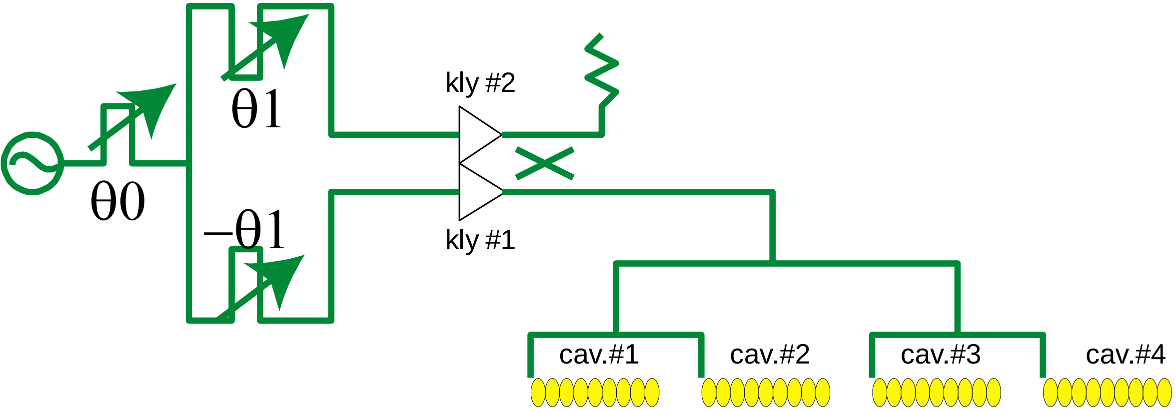
- Simulation of vector-sum like control
- Two rf units (25MV/m and 38MV/m) are driven by two drivers.
- The rf output of high gradient unit is limited.
- The vector sum control is carried out at the rf unit1.
- High gradient cavity has detuning (100Hz) and power-limited. Thus the gradient decrease with time.
- <u>Owing to the vector-sum like control, total gradient is kept constant.</u>

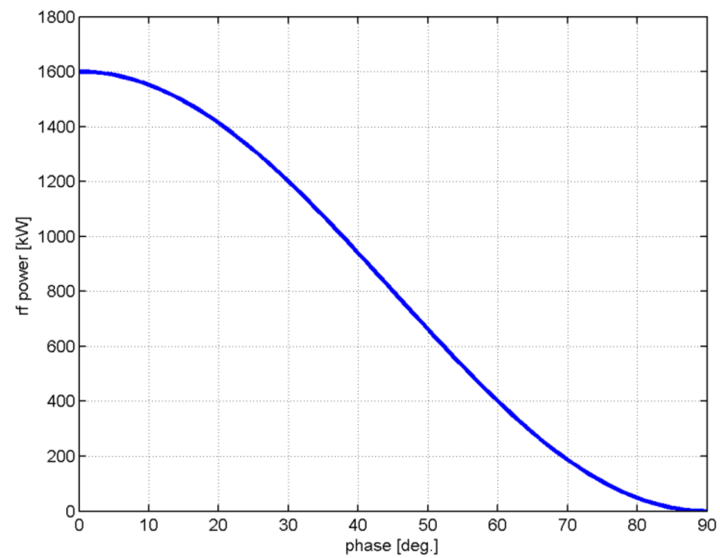
Other concepts

operation at rf saturation
full power filling

Other idea –operation at saturation





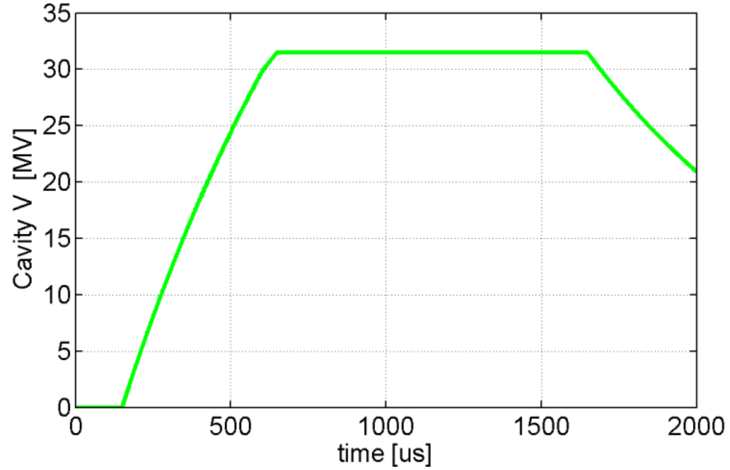


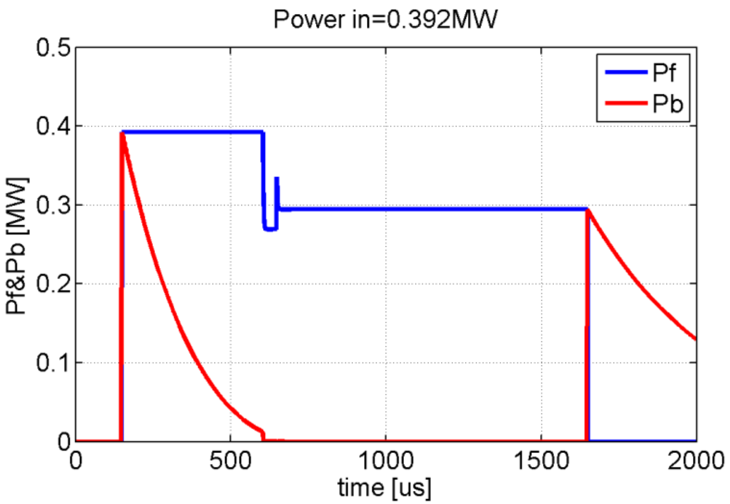
- From low-power operation to high power operation, we add a hybrid.
- Both klystrons are operated at saturation and the cavity driven power can be controlled by changing the phase (θ1)
- Since the phase dependence is cosine curve, it is more easy to control.

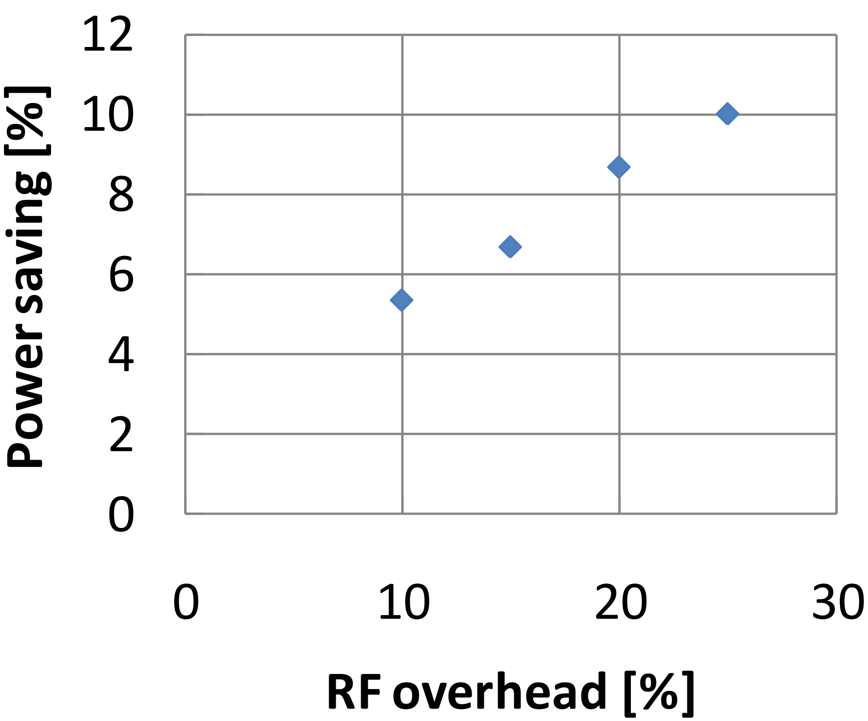
BAW1 (Sep.8, 2010)

Full power filling scheme

- In order to use the rf power, full-power filling scheme is proposed.
- By using the full-power filling, shorter rf pulse will be enabled.

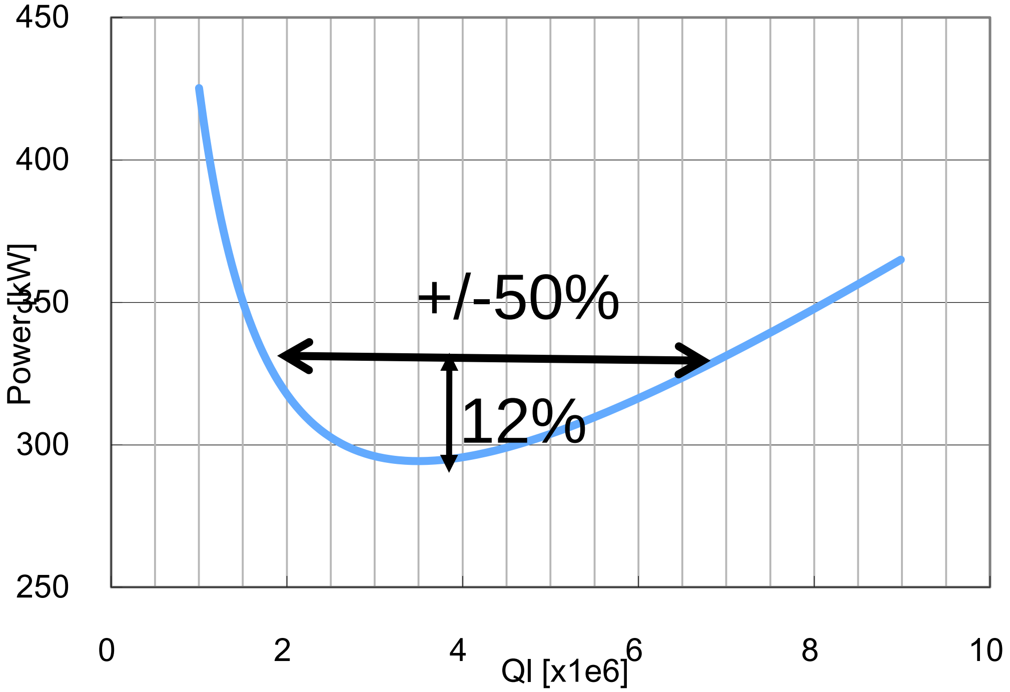






BAW1 (Sep.8, 2010)

Low Ql operation for short filling and insensitive to detuning



(From Prof. Noguchi)

- If the gradient fluctuation of 1% (pulse-to-pulse) is the essential for luminosity operation, and if the detuning control of +/- 20~30 Hz is difficult to achieve, we can decrease the Ql value.
- The half of the Ql requires 12% more rf power but it can relax the detuning requirement (from +/-20Hz to +/-40Hz).
- Low Ql is beneficial from the view point of shorter (half) filling time.

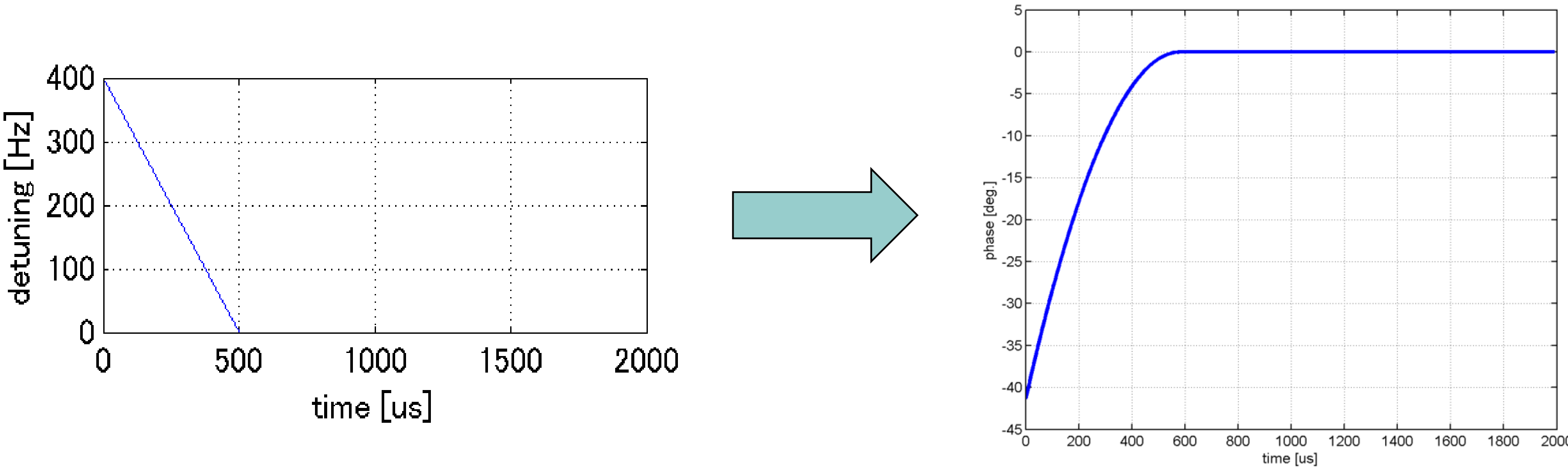
Detuning cavity operation for minimizing the rf power

Filling on resonance (1)

- In order to minimize the driving power,
  (1) keep the detuning to be zero even at the beginning of the filling
  (2) change the phase during the filling time to meet the resonance frequency.

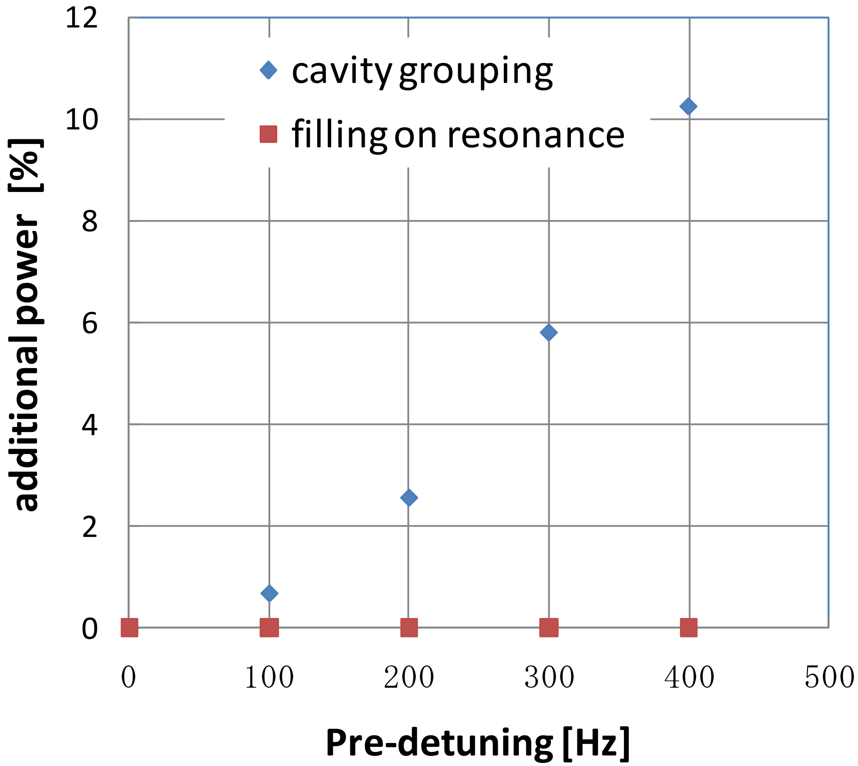
$$\phi = \int_0^t 2\pi\Delta f dt$$

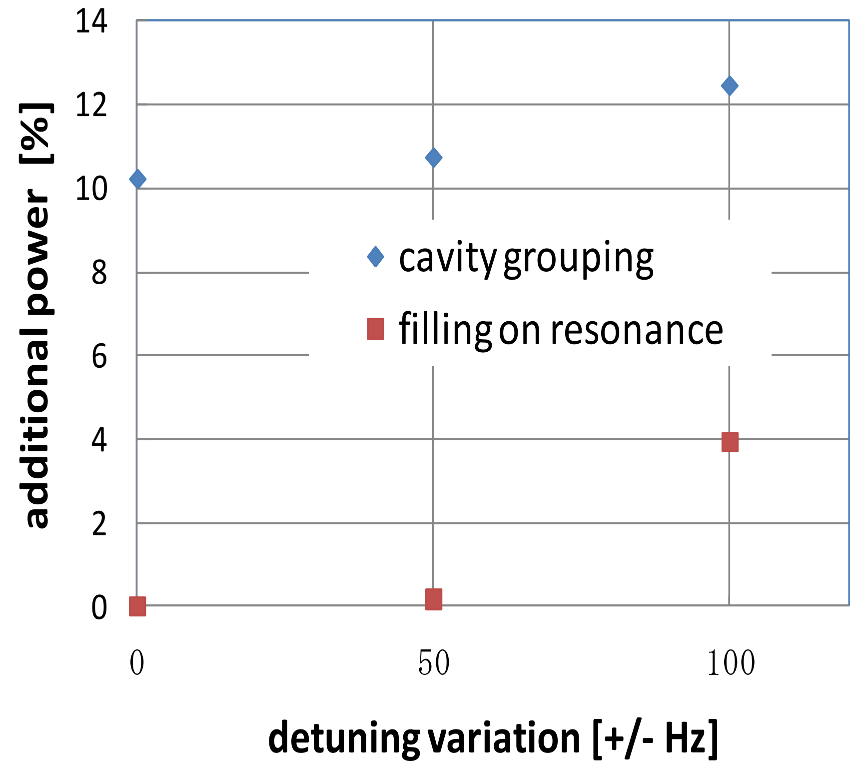
- Changing the set-phase (to be on resonance) is effective when all the cavities are near same detuning.



Filling on resonance

- Filling on resonance is effective to reduce the filling power.
- Additional power due to the fluctuation of the cavities are negligible small when detuning difference is <50Hz.





Filling on resonance (2)

- Resonance filling scheme has been tested at FLASH.

"OPTIMIZATION OF FILLING PROCEDURE FOR TESLA-TYPE CAVITIES FOR KLYSTRON RF POWER MINIMIZATION FOR EUROPEAN XFEL" by Valeri Ayvazyan et al. (presented at IPAC10)

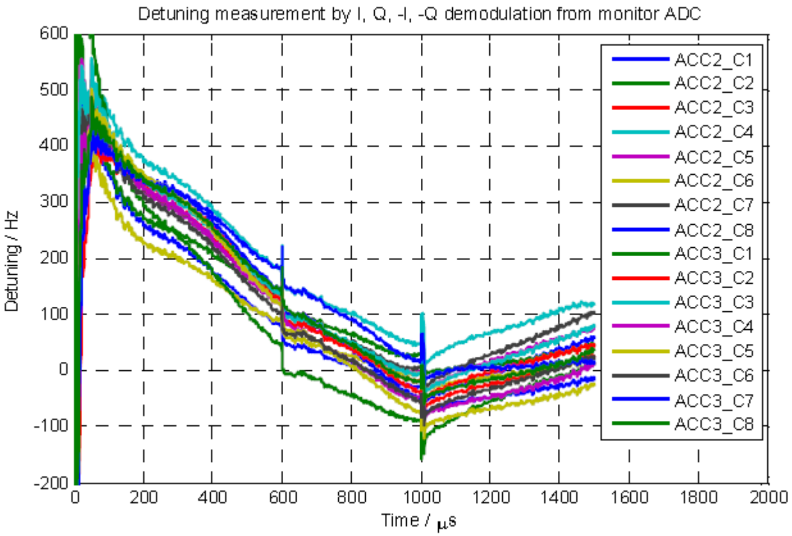


Figure 2: Detuning measurement at FLASH accelerating modules.

Figure 6: Energy gain increase by phase modulation.

- Pre-detunings are 400~500Hz, distribution is +/-100Hz.
- 4% recovered by resonance filling

-> Perfect rf input is rather difficult at the configuration with various detuning cavities.

- Need further study to evaluate the additional power for filling

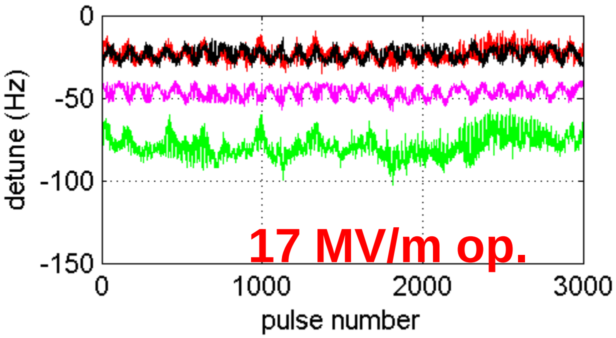
Summary

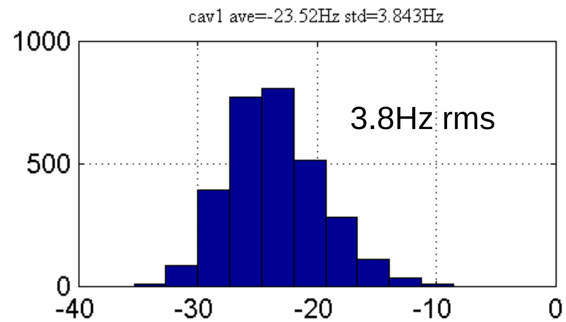
		RDR	DRFS (PkQl)	DRFS(Cavity grouping)
RF power	Operation gradient	Max. 33 MV/m	Average 31.5 MV/m	Max. 38 MV/m
	RF source	10 MW		800 kW
	Waveguide loss	8% power	2% power	2% power
	Static loss (Ql, Pk)	2% power	2% power	2% power
	Kly Hv ripple	2.5% power	2.5% power	2.5% power
	Microphonics	2% power	2% power	2% power
	Reflection	0% power	14% power	0% power
	Other LLRF margin	10% power	10% power	5%~10% power
Tolerance	Ql tolerance		3% (2)	3% (2)
	Pk tolerance		0.2dB (2)	0.2dB (2)
	Detuning tolerance		15Hz rms(3)	20Hz rms (3)
	Beam current offset		2% rms (3)	

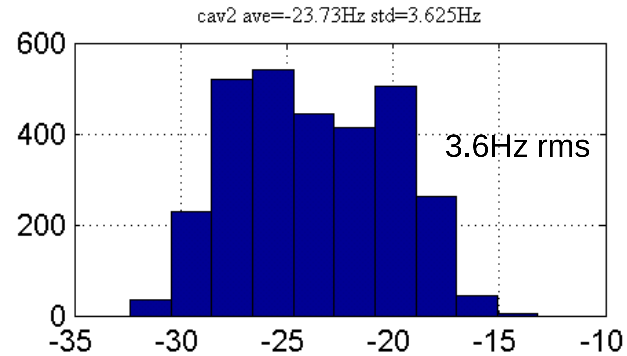
(1) LLRF overhead ~5%
(2) Cavity gradient tilt (repetitive) ~5%
(3) Pulse-to-pulse gradient fluctuation ~1%rms

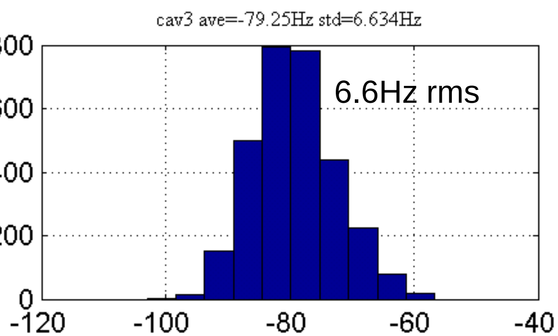
- We have to examine these numbers experimentally.
- Tolerance should be discussed with cavity and HLRF group. If the tolerance is smaller, better gradient tilt would be possible.

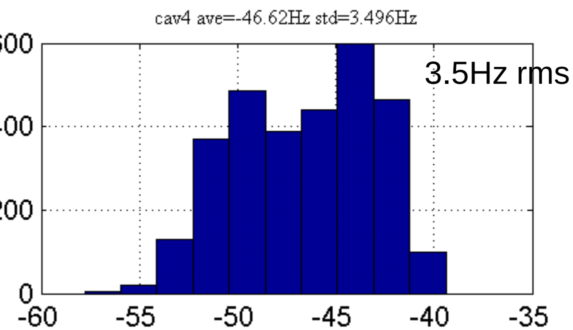
Microphonics











Microphonics @STF-1
4 cavities 1 hour operation
3000 pulses analysis

- Microphonics measured at STF-1 is 3~6Hz
- Similar number was obtained at TTF.
- Lorentz force detunings are not fully included. (due to rather low gradient op.)
- Detuning due to LFD should be studied.

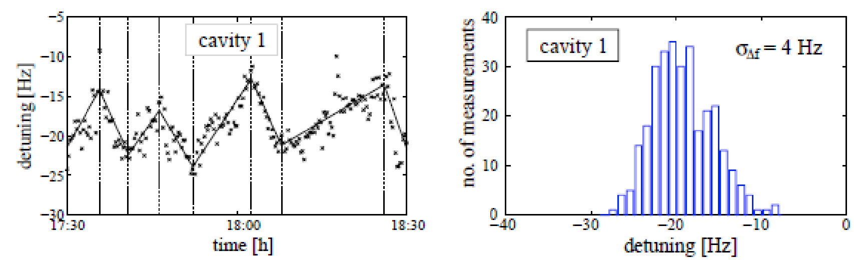


Figure 6.2: Variation of the detuning of a single cavity in the cryomodule. left diagram: The solid line indicates the assumed frequency correction by a mechanical tuner. The residual microphonics is calculated with respect to this line. right diagram: The resonance frequency spread is plotted to demonstrate the resonance frequency variation shown in the left diagram. The mechanical tuner has been in a fixed position, i.e. no tuner control has been applied.

Microphonics @TTF
(from T. Schilcher)

Summary(2)

- LLRF overhead :
  - need further studies including the detuning control.
  - 38 MV/m operation will be tight and some additional idea needs to be tested.
- Cavity gradient tilt (repetitive) ~5%
  - Means that the operational gradient is ~5% lower from the quench limit (at least)
- Pulse-to-pulse gradient fluctuation ~1%rms
  - Will be a tight requirement concerning the detuning regulation (20Hzrms)
  - If this requirement is essential and detuning fluctuation is >20Hz, we can decrease Ql (wideband) but need more rf power (~10%).