9 mA study at FLASH on Sep., 2012

Shin MICHIZONO (KEK)

Outline

I. Achievement before Sep.2012
II. Study items for ILC
III. Study plan
IV. Study results
- Gradient study for near quench limit operation
- Klystron output linearization
- RF operation near klystron saturation

V. Summary and future plan

R&D results (upto Feb. 2012)

High beam power and long bunch-trains *(Sept 2009)*

Metric	ILC Goal	Achieved
Macro-pulse current	9mA (5.8mA)	9mA
Bunches per pulse	2400 x 3nC (3MHz)	1800 x 3nC 2400 x 2nC
Cavities operating at high gradients, close to quench	31.5MV/m +/-20%	4 cavities > 30MV/m

Gradient operating margins *(updated following Feb 2012 studies)*

Metric	ILC Goal	Achieved
Cavity gradient flatness (all cavities in vector sum)	2% ΔV/V (800μs, 5.8mA) (800μs, 9mA)	<0.3% ΔV/V (800μs, 4.5mA) *First tests of automation for Pk/Ql control*
Gradient operating margin	All cavities operating within 3% of quench limits	Some cavities within ~5% of quench (800us, 4.5mA) *First tests of operations strategies for gradients close to quench*
Energy Stability	0.1% rms at 250GeV	<0.15% p-p (0.4ms) <0.02% rms (5Hz)

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Study items for ILC

- High beam current
  - From 4.5 mA (Feb. 2012) to 6 mA
- Gradient study for near quench limit operation
  - PkQl control was carried out on Feb. 2012.
  - In February, we had some cavities within 10% of quench, ILC design parameters assume all cavities operate within 5% of quench
- Klystron output linearization
  - To operate the klystron near saturation, linearization would be essential for high gain feedback operation.
- RF operation near klystron saturation
  - In February, we got to within 7% of the saturation power by reducing the klystron anode voltage
  - The ILC design assumes 5% power overhead
- Combination of these results
  - High beam (6 mA), rf operation near saturation, cavity gradient near quench limit

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Intended studies program

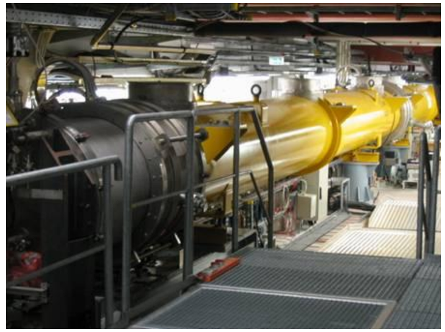
	Sep. 17 Mon	Sep.18 Tues	Sep.19 Wed	Sep.20 Thurs	Sep.21 Fri	Sep.22 Sat
M	Switch to 3MHz/5Hz	Set up long fill time, flat rf pulse	Gradient studies	Gradient studies	Integrate main studies tracks, with goal of high current operation close to quench with klystron saturation	
A	Set up machine with high charge long pulses	Set up long fill time, flat rf pulse	Klystron saturation studies	Klystron saturation studies		
N	Tuning towards 6mA, 2400 bunches	Tuning towards 6mA, 2400 bunches	Saturation studies, machine tuning	Saturation studies, machine tuning		

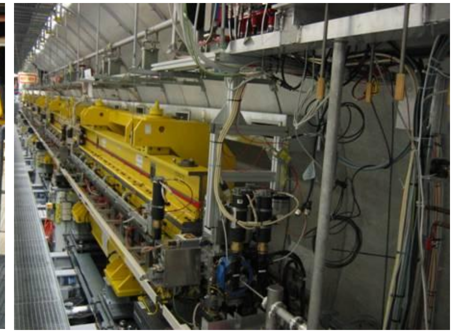
Actual studies

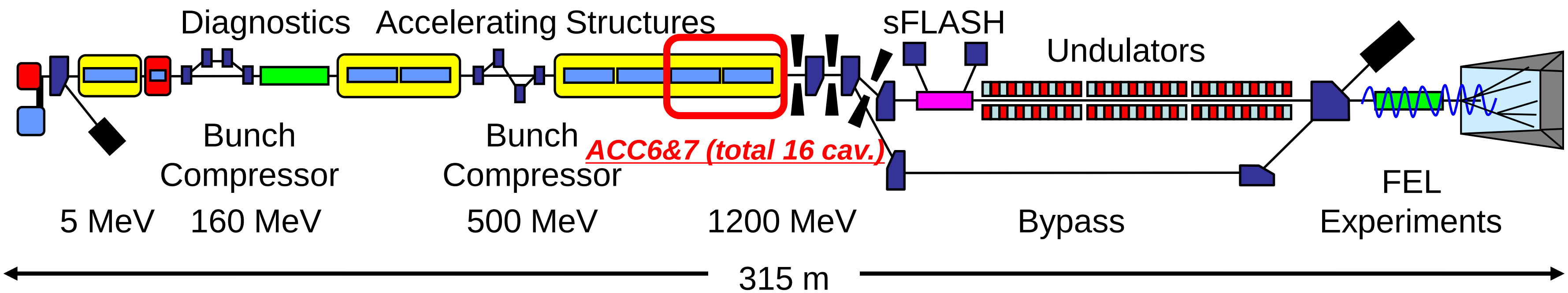
	Sep. 17 Mon	Sep.18 Tues	Sep.19 Wed	Sep.20 Thurs	Sep.21 Fri	Sep.22 Sat
M	Switch to 3MHz/5Hz	RF studies (waiting for beam)	Gradient studies	Gradient studies	Integrate n tracks, with Gradient studies (partial)	Gradient studies (partial)
A	Set up machine with high charge long pulses	Set up long fill time, flat rf pulse	Klystron saturation studies	Klystron Klystron studies		Klystron studies (partial)
N	Tuning towards 6mA, 2400 bunches	Tuning towards 6mA, 2400 bunches	Saturation studies, machine tuning	machine tuning		

About 6 shifts were available and these were not sufficient to complete the studies.

FLASH layout







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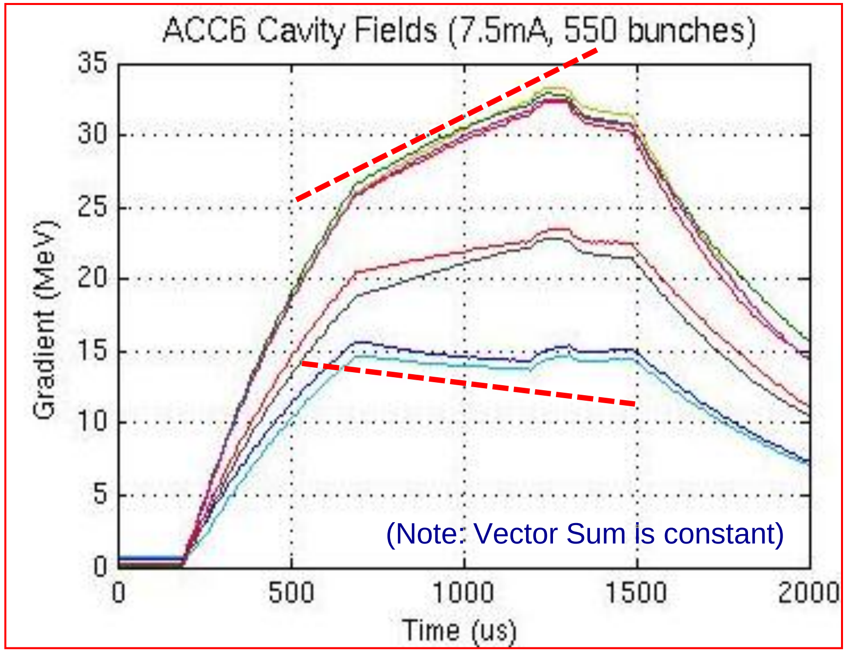
Cavity gradient tilts from beam loading



A 'feature' of running cavities with a spread of gradients when the are all fed from same RF source

Steady-state cavity voltage

$$V = \sqrt{P_{for}\left(\frac{r}{Q}\right)Q_{ext}} - I_b\left(\frac{r}{Q}\right)Q_{ext}$$

Solution: adjust individual Pks and Qls so each cavity is 'matched' for the same beam current

Ratios of power required by each cavity are different between beam off and beam on

Klystron power increases linearly with beam current

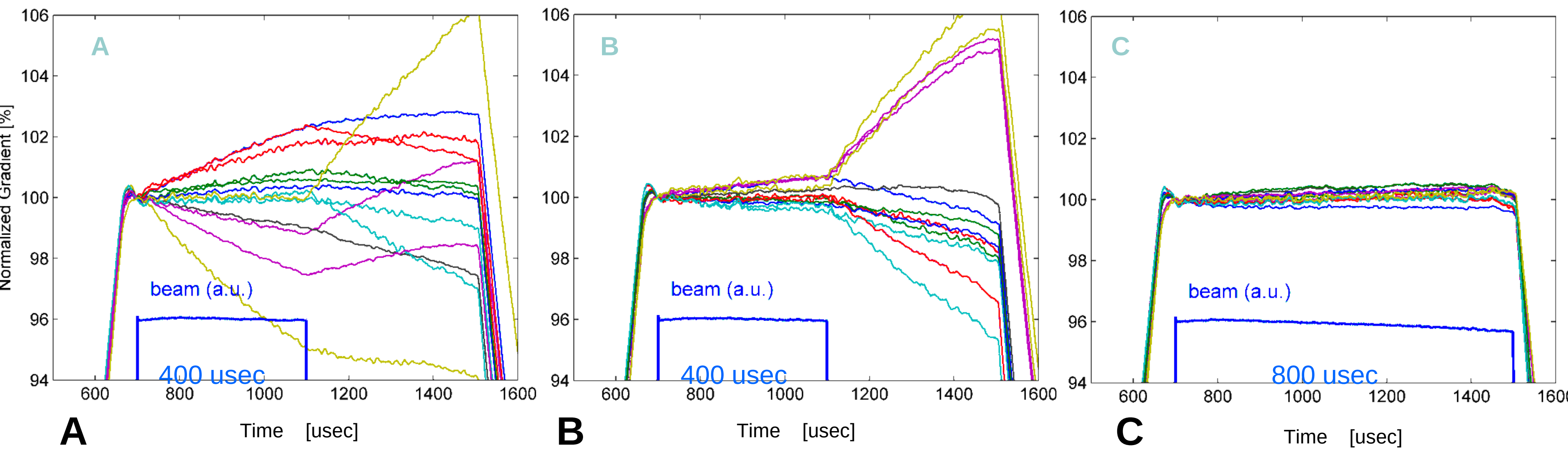
- Higher gradient cavities get too much extra power
- Lower gradient cavities get not enough extra power

$$I_{matched} = \frac{V_k}{\left(\frac{r}{Q}\right)Q_{ext}}$$

Must be solved uniquely for a given beam current and set of gradients

ILC: 9mA @ FLASH: Gradient Study

Results from FLASH 9mA study (Feb. 2012): I_{beam} = 4.5 mA



A
- short bunch train
- default Q_L = 3x10^6

B
- short bunch train
- optimized Q_L

C
- long bunch train
- optimized Q_L

Results from FLASH 9mA study (Sep. 2012):

QL optimization algorithm now includes **exception handling** (Piezo, Ql,…)

Still not fully understood about optimization procedure **(next study)**:

LCWS12(Sep.24) Shin MICHIZONO

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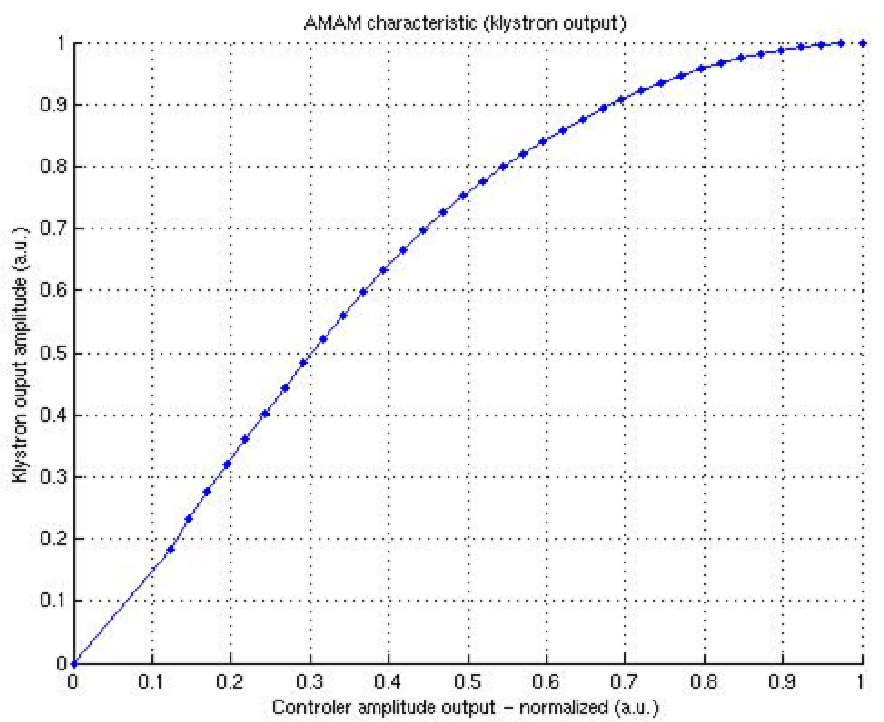
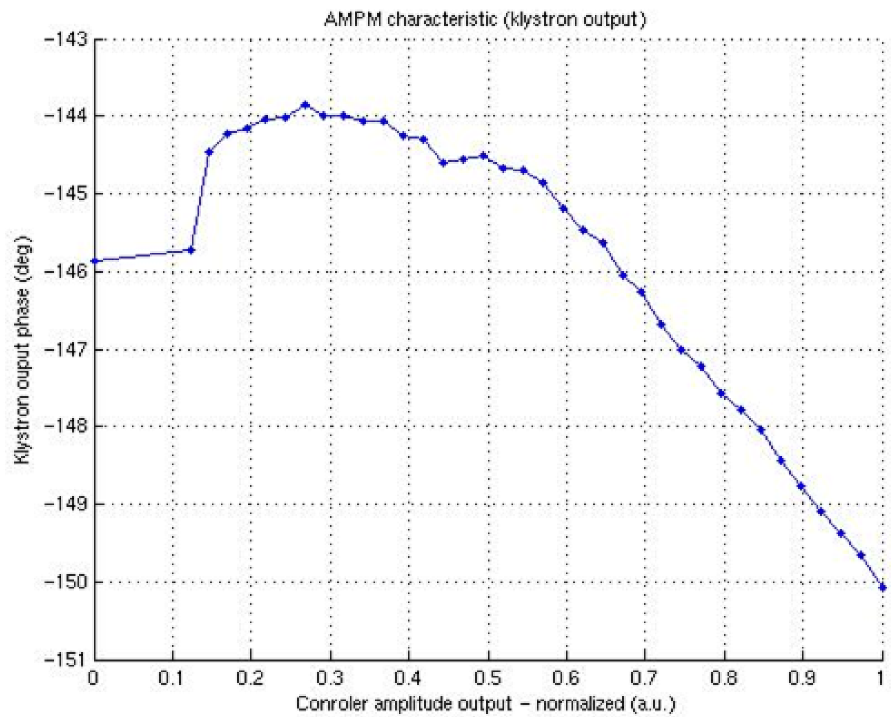
Measured input-output characteristics of klystron

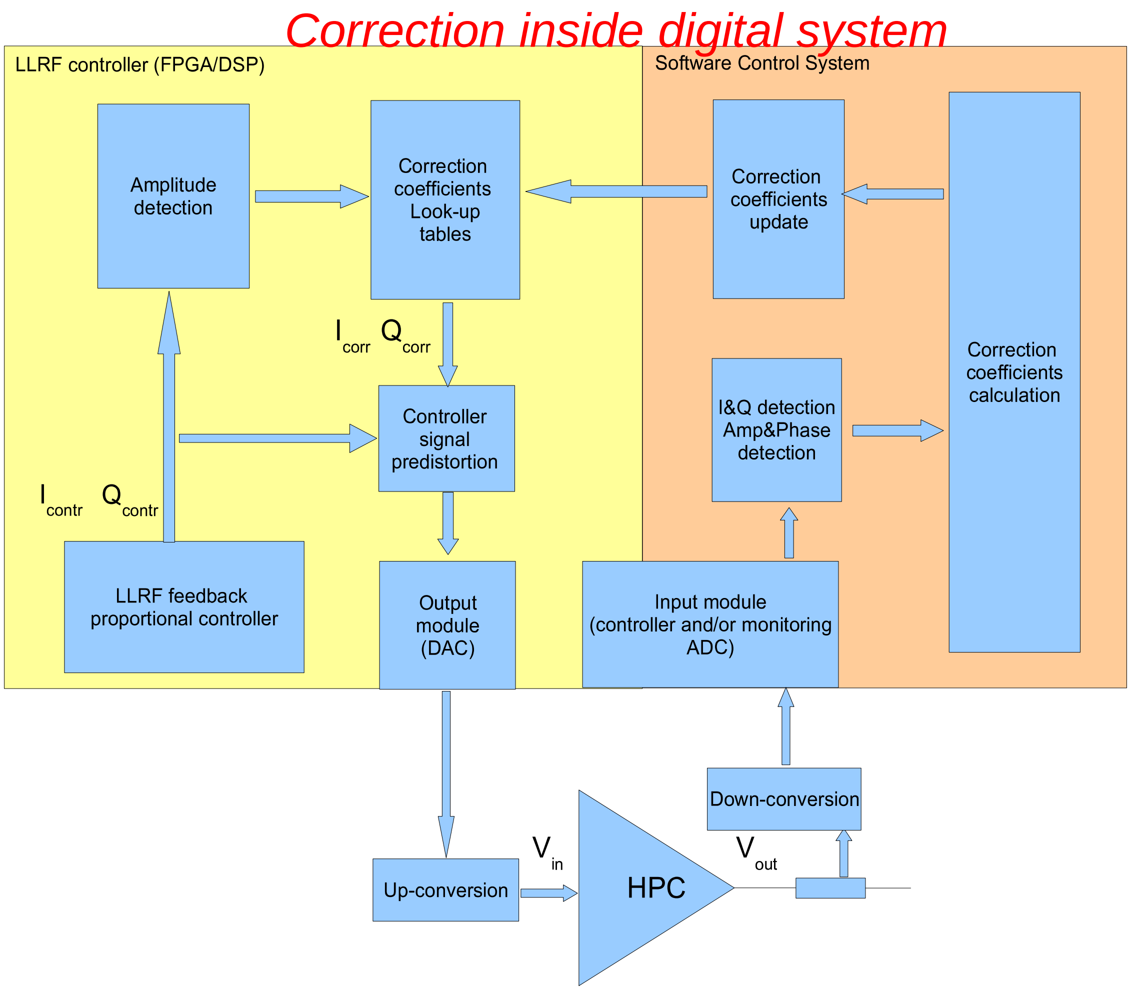
One of the key assumption for ILC design is to operate the RF station near to klystron saturation region (about 5% below hard saturation). In order to determine such inconvenient range of operation (where gain rapidly decreases to 0) the set of measurement has been performed to characterize system behavior (gain change) in function of controller (input) signal change.

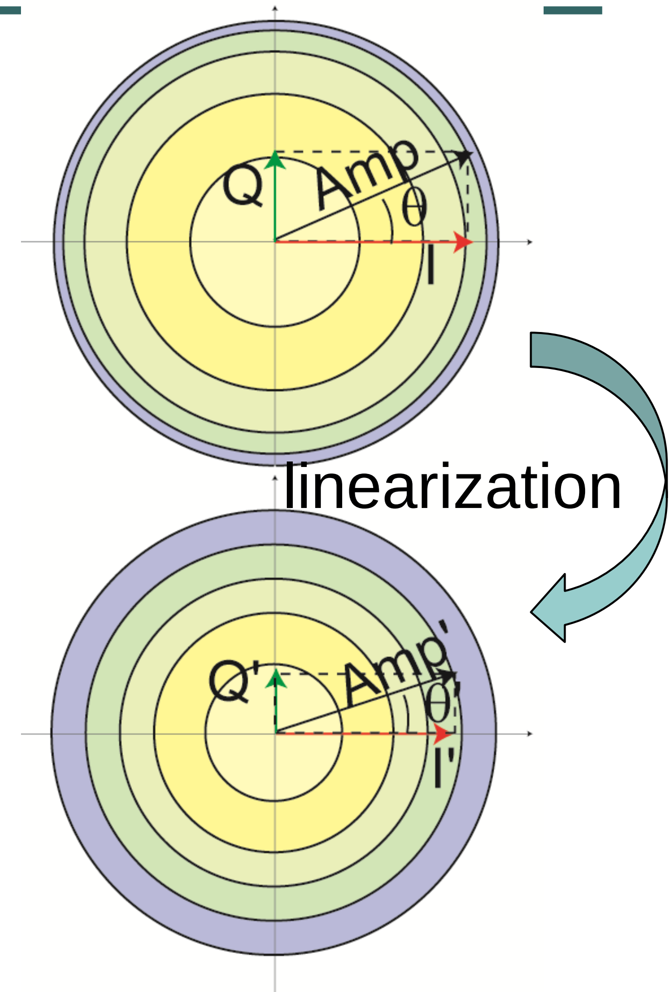




Transfer characteristics achieved for high power chain for modules ACC67 @ FLASH (for reduced cathode voltage value =~86kV) revealed saturation points for given controller output level.
As the nonlinearity and saturation issue is only signal amplitude level dependent – figures shows measured dependence between controller signal amplitude and klystron output (for amplitude and phase). It has to be emphasize that transfer characteristics includes not only klystron behavior but also gain and phase modification caused by preamplifiers.

Linearization tool concept and implementation

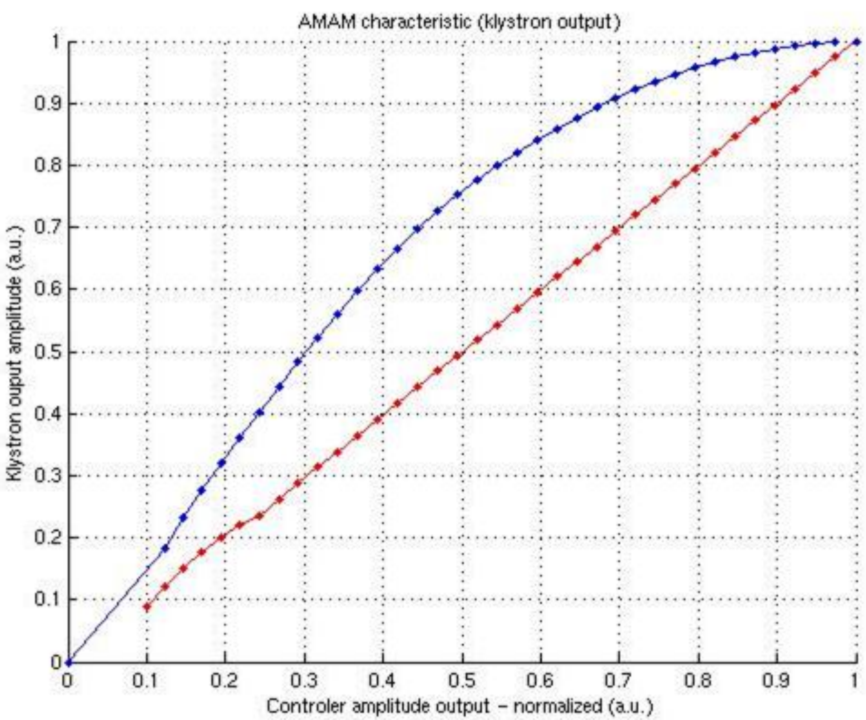


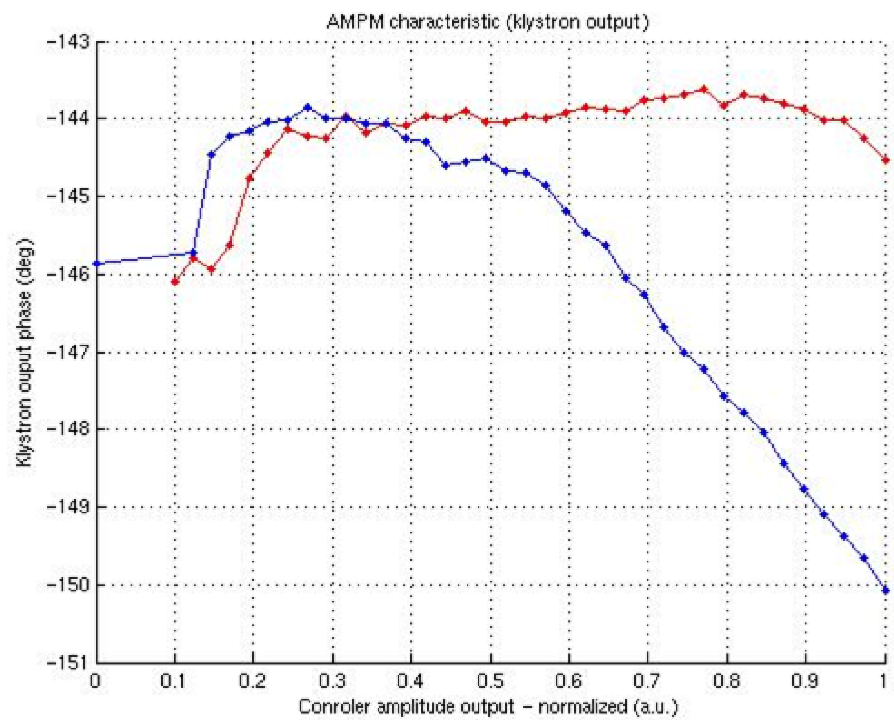


The nonlinearities identified during the system characterization has been used to find inverse function that is described in look-up tables in LLRF controller (FPGA side). The LUT table is indexed by calculated controller signal amplitude. Complex multiplication of the control signal with correction signal from LUT's result in corrected signal generation. This signal is amplified by nonlinear klystron and is distributed.

Linearization results

The results of linearization achieved during last high beam current studies at FLASH (RF station for accelerating modules ACC67 – 10 MW klystron) (red characteristics).





Proposed and implemented method allowed for klystron behavior linearization. Although some system weak points can be recognize (eq. poor phase detection for low signal levels) amplitude and phase characteristic correction can be considered as satisfactory.

The main benefit of constant gain maintenance can be clearly noticed especially for operation with wide working point range (eq. high feedback gain control).

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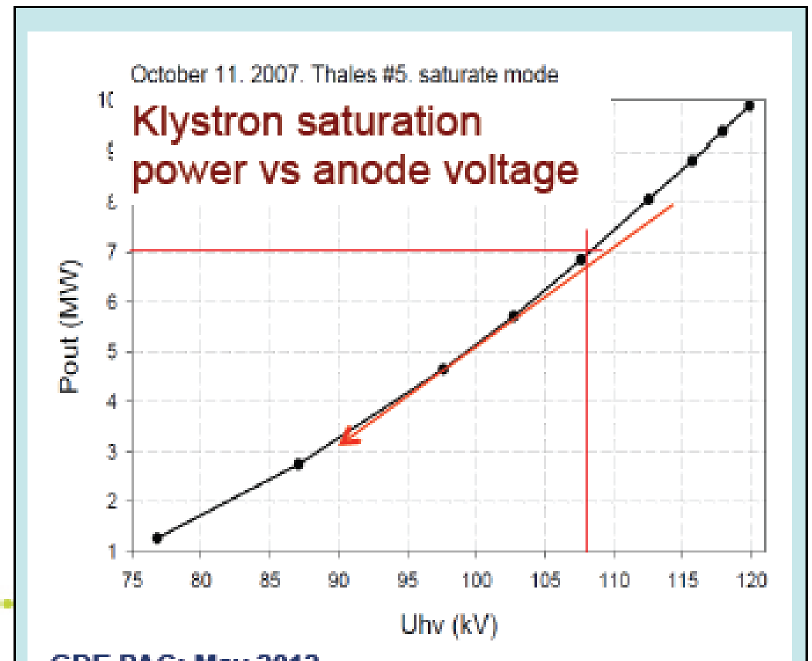
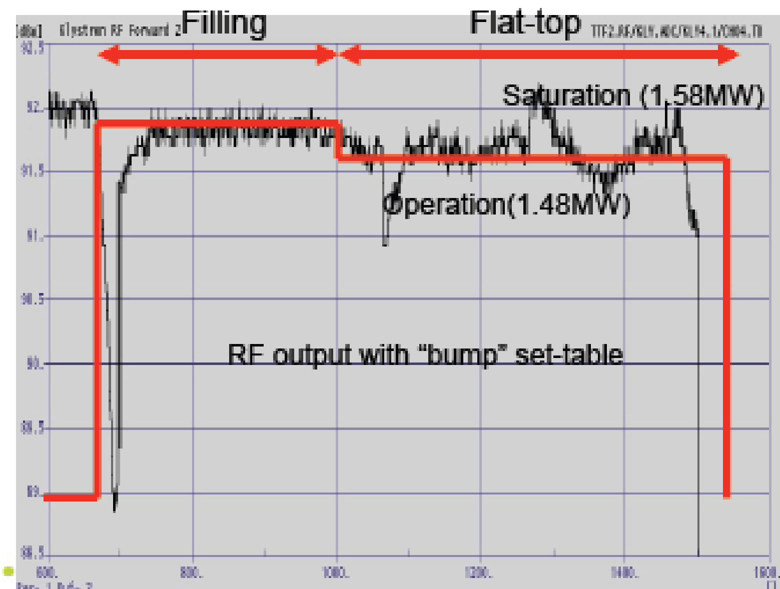
RF operation condition for klystron saturation studies

- Under normal 9mA studies conditions, the klystron forward power is not sufficient to put the klystron into saturation
- Saturation point of the klystron was artificially reduced by lowering the HV
- Beam pulse: 4.5 mA / 800us
- Filling time was adjusted to have ~rectangular output.(500us ->660us)
- Operation point during beam-on was about 7% (in power) from saturation.





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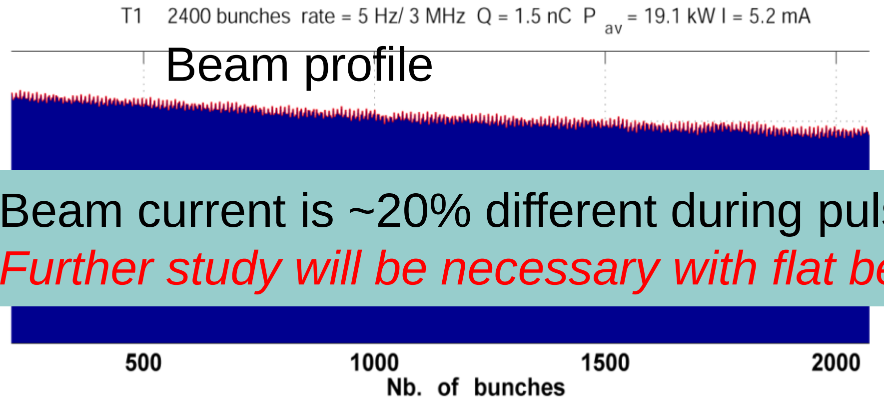
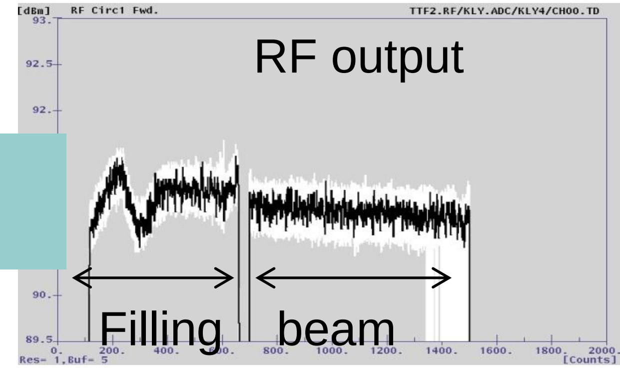
43

Preparation for saturation study

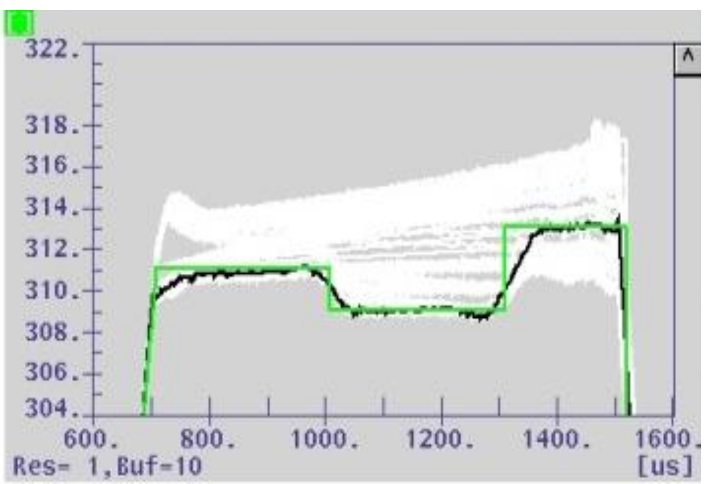
- We adjust filling time (550 us or 590 us) to have a flat rf output at 5.2 mA (800 us).

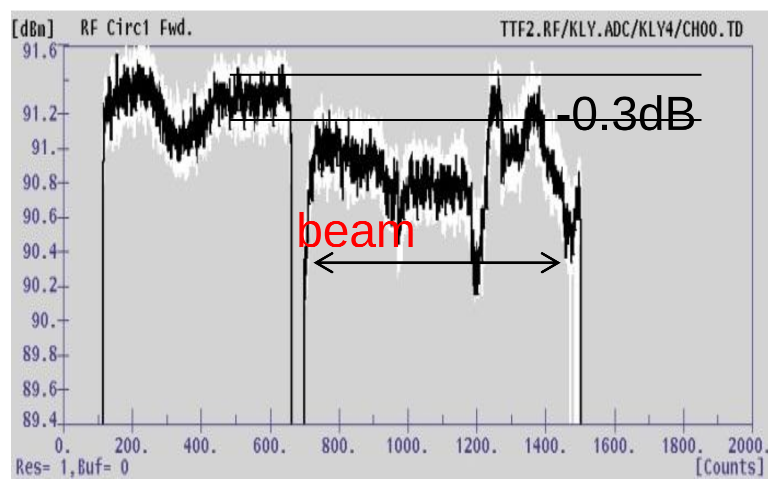




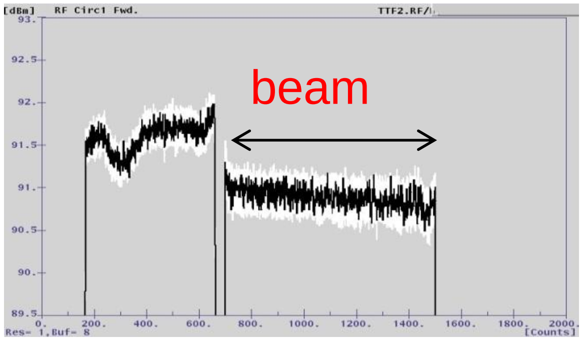
Beam current is ~20% different during pulse.
Further study will be necessary with flat beam

- We decrease HV of the klystron to operate near saturation.
- ILC specification requires to operate -0.22dB (-5%) from saturation.
- Artificial step is introduced to confirm the saturation point during rf pulse

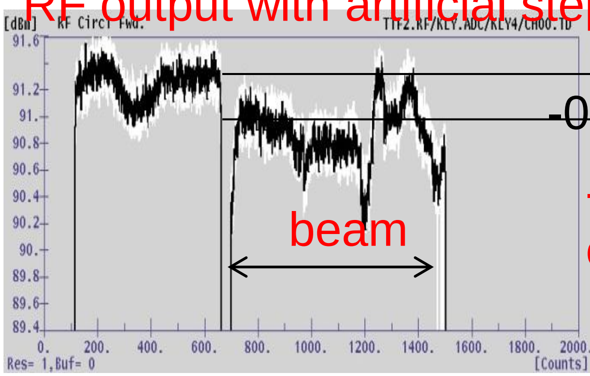




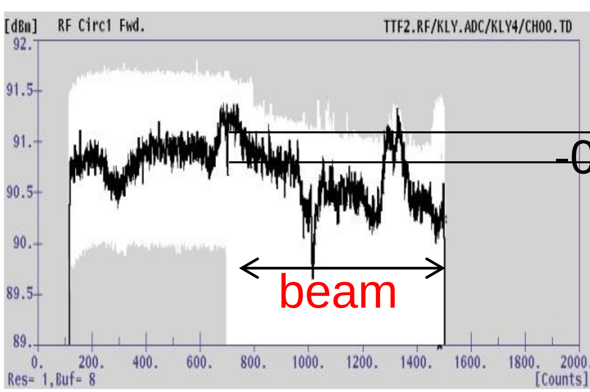
Measured stability



RF output with artificial step



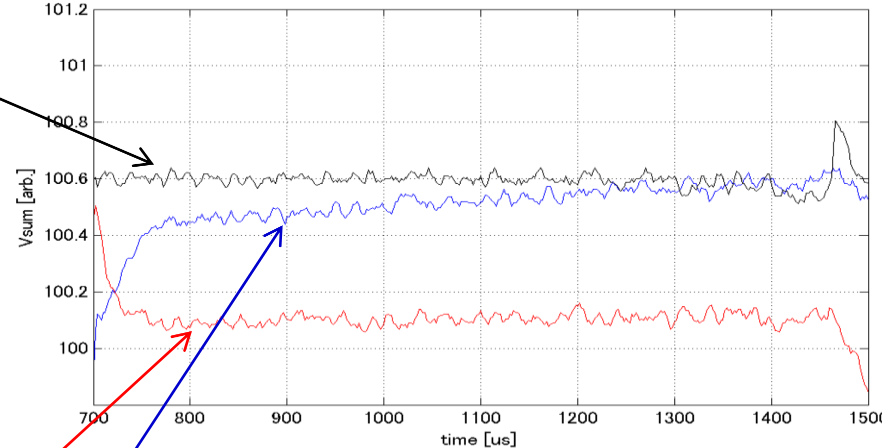
-0.3dB operation



-0.2dB operation

Vector sum amplitude [arb.]

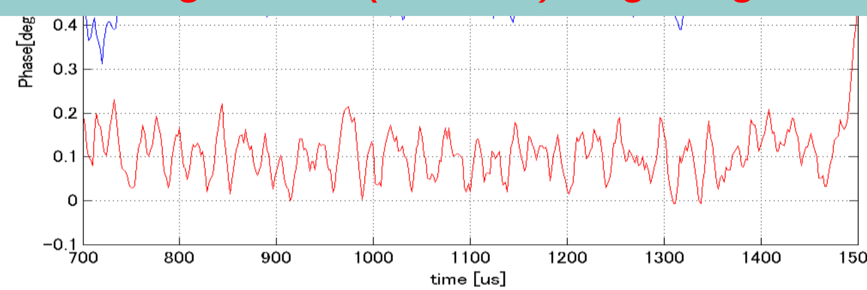
nominal



Stability just after the beam is insufficient probably due to the limited FB gain.

Further study will be necessary.

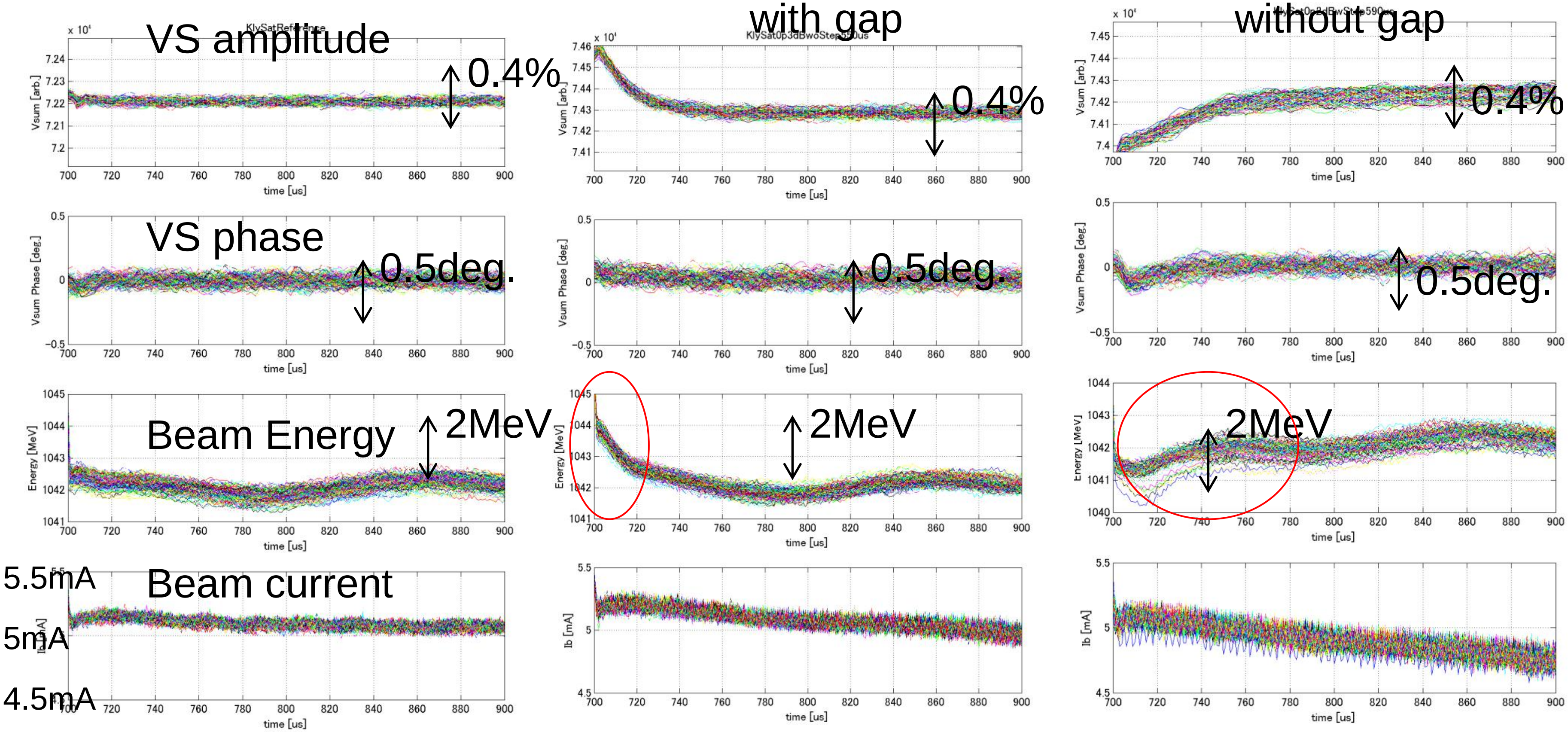
with longer time (> hours), higher gain



150 pulse envelope

- Amp., phase, beam energy, current are compared. (initial 200us of pulse)
- VS amplitudes at the beginning of -0.3dB and -0.2dB show some slope due to the limited beam loading suppression. -> Further study will be necessary.

Nominal | -0.3dB operation with gap | -0.2dB operation without gap



- “nominal” and “-0.3dB” have a gap between filling and beam.
- “-0.2dB” has no gap between filling and beam. -> response is opposite.

Summary and future plan

- Several studies have been carried out at FLASH for technical demonstration of ILC specification.
  - PkQl control (Ql adjustment) for near quench limit operation

  -> strategy for automation (reach near quench limit without exceeding etc.)
  - Klystron linearization and rf operation near saturation

  -> Beam energy stability, long term stability with flat beam current
  - High current beam loading with long bunch train.

  -> High beam, high gradient, near klystron saturation study
- For the engineering phase (post TDR), we need to accumulate more experience for stable operation.
- XFEL and ILC have many common study items because of the similar beam parameters.

	EU-XFEL	ILC (250GeV)
Gradient	23.6 MV/m	31.5 MV/m +-20%
Bunch charge	1 nC	3.2 nC
Beam current	5 mA	5.8 mA
Energy stability	2.5MeVrms/20GeV (0.013%)	0.1% rms