Experience from FLASH '9mA' experiments

Gradient and RF Power Overhead

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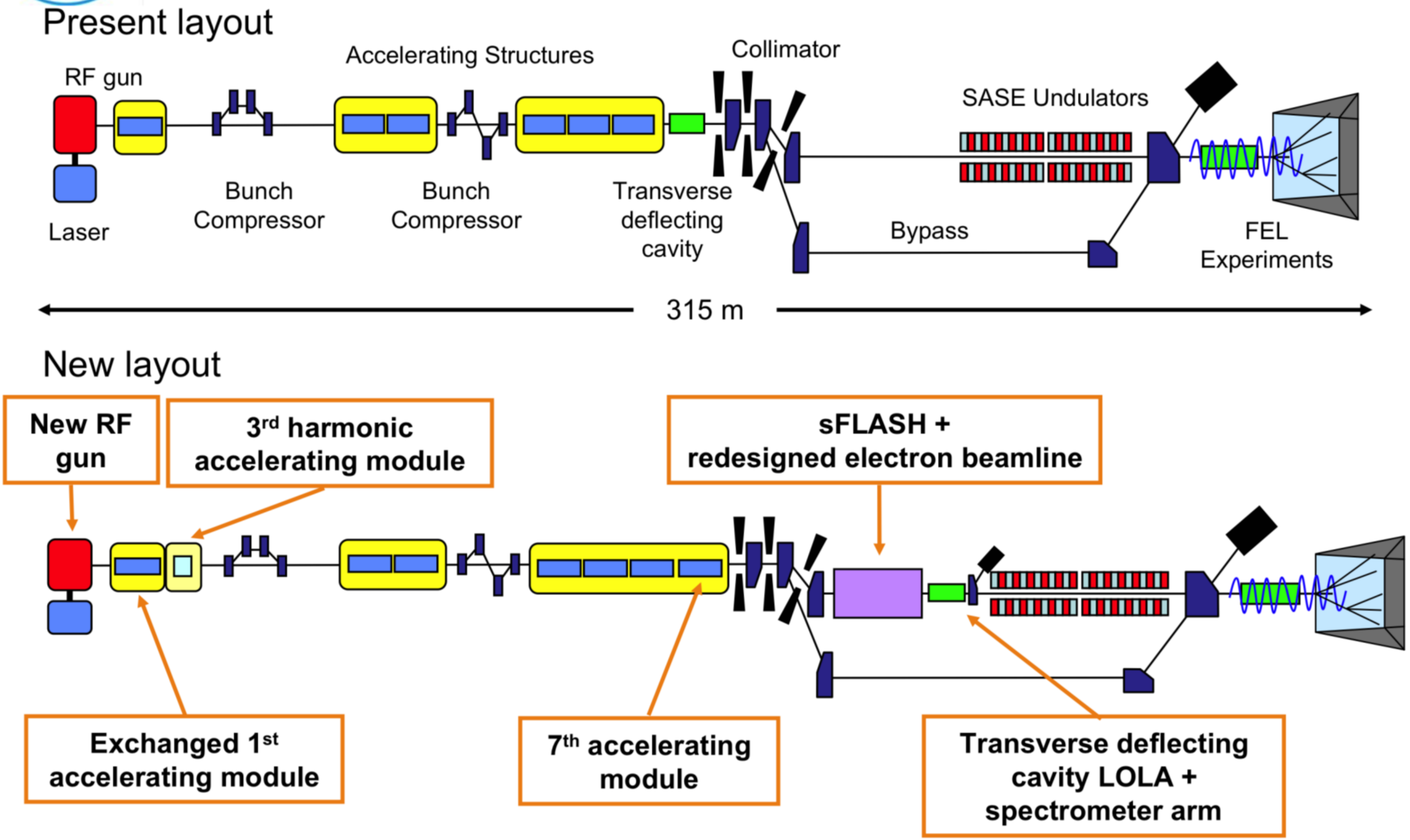
First Baseline Allocation Workshop at KEK
September 2010

Experience from FLASH

FLASH Upgrade 2009/10



Katja Honkavaara, FLASH Seminar, March-31, 2009

Specific objectives for the 9mA study

- Long bunch-train high beam loading (9mA) demonstration
  - 800μs pulse with 2400 bunches at 3MHz, 3nC per bunch
  - Vector Sum control of up to 24 cavities
  - +/- 0.1% energy stability
  - Cavity gradients approaching quench limits
  - Beam energy 700-1000MeV

Demonstrate ILC-like beams

Sept '09

- Characterize operational limits
  - Energy stability limitations and trade-offs
  - Cavity gradient overhead needed for LLRF control
  - Klystron power overhead needed for LLRF control
  - HOM absorber studies (cryo-load)

- Operation close to limits, eg
  - Robust automation of tuning, etc
  - Quench detection/recovery, exception handling
  - Beam-based adjustments/optimization

Studies requiring ILC-like beams

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Awaiting beam time to begin this part of the program – two studies periods expected in 2001

Next 9mA studies shifts are slated for Jan '11 (but 800us pulses likely not possible)

Major achievements
(Sept 2009 studies)

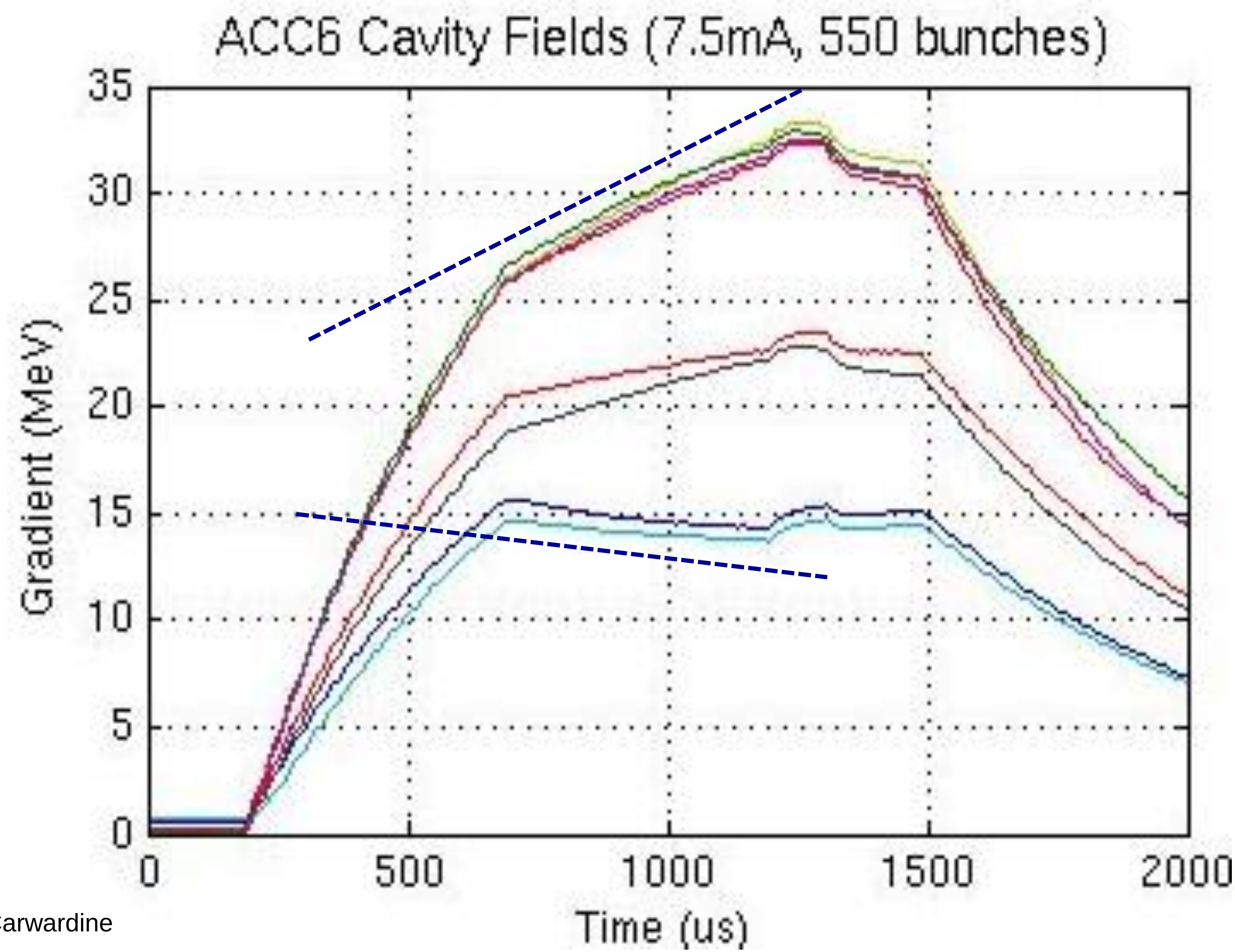
Metric	Goal	Achieved
Bunches per pulse	800 x 3nC (1MHz)	800 x 3nC
	2400 x 3nC (3MHz)	1800 x 3nC 2100 x 2.5nC ~2400 x 2nC
Charge per pulse	7200nC @ 3MHz	5400nC @ 3MHz
Beam power	36kW (7200nC, 5Hz, 1GeV)	22kW (5400nC, 5Hz, 800MeV)
Gradients close to quench	Up to 32Mv/m	Several cavities above 30Mv/m at end of long pulse

- 15 contiguous hours running with 3mA and 800us bunch trains
- Running at ~9mA with bunch trains of 500-600us for several hours
- Full pulse length (800us, ~2400 bunches) at ~6mA for shorter periods

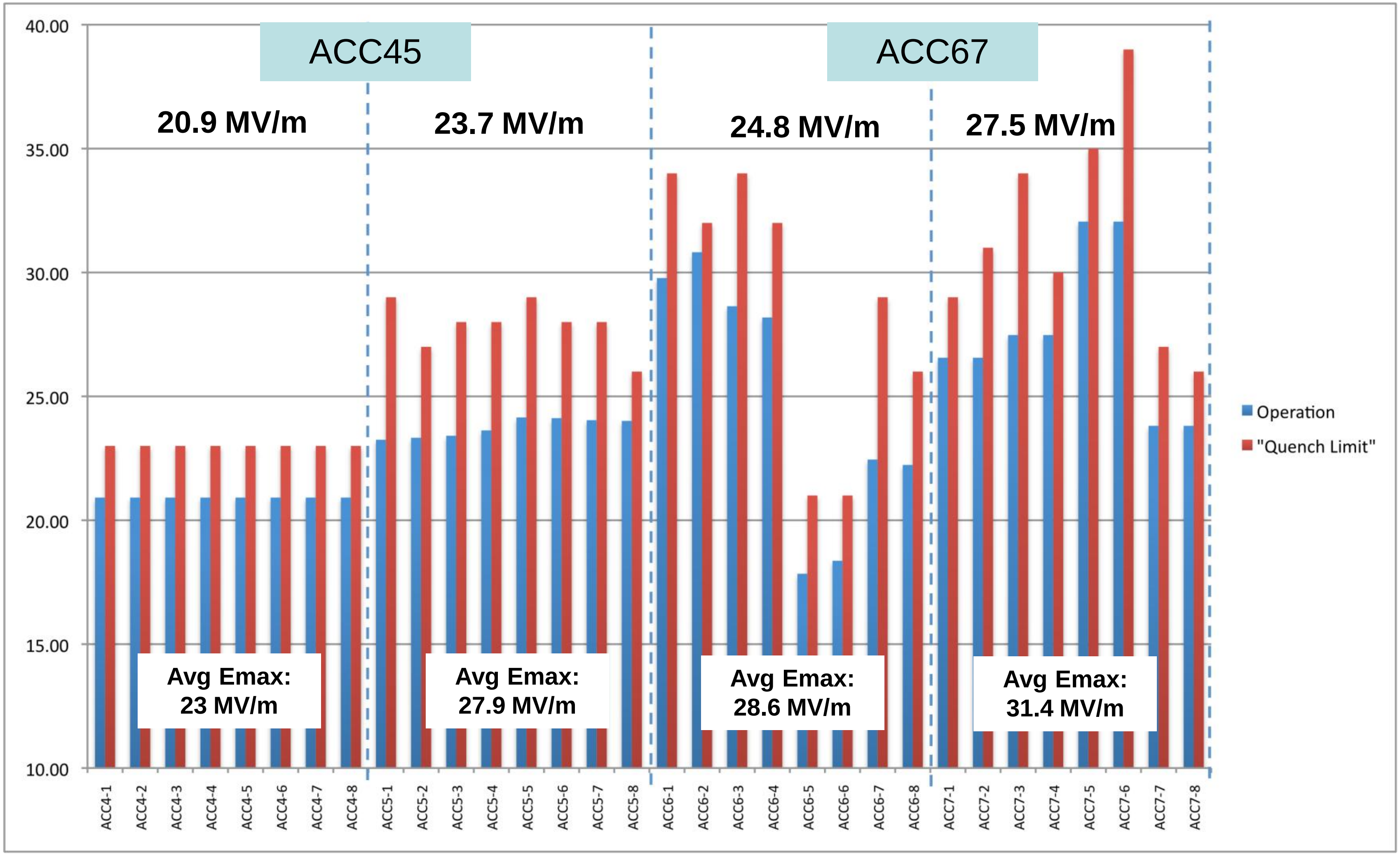
- Energy deviations within long bunch trains: <0.5% p-p (7mA beam)
- Energy jittter pulse-pulse with long bunch trains: ~0.13% rms (7mA)

Measured gradient tilts

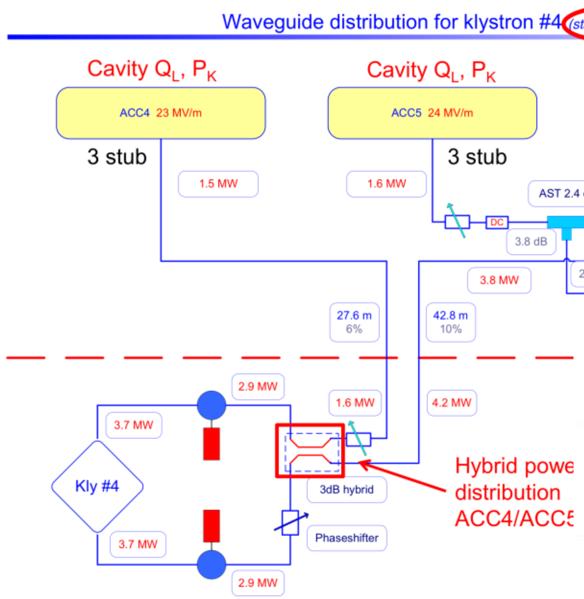
(RF distribution set for flat gradients without beam)



Quench limits and operating gradients for 1.3GeV (FLASH ACC4-7)



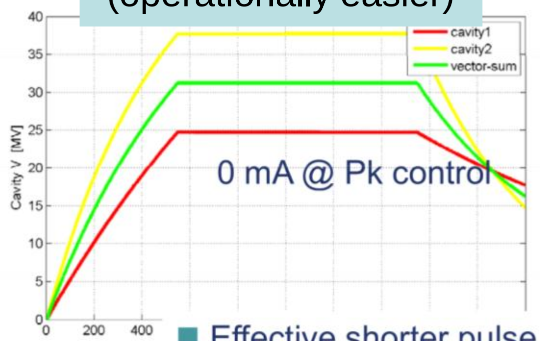
RF distribution 'Pk/Qext' control to minimise gradient slopes over bunch train

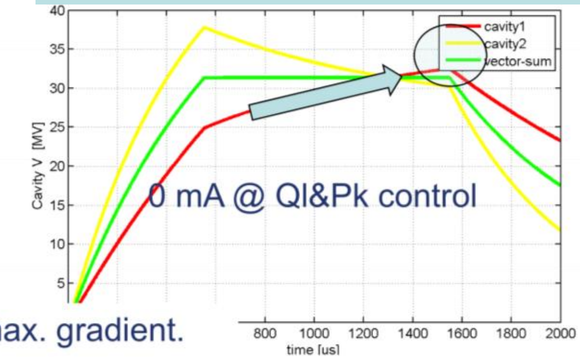


Cavity Q_L & P_K are set up for flat gradients at a particular beam current

FLASH setup
(operationally easier)

ILC Reference Design
(higher average gradient)

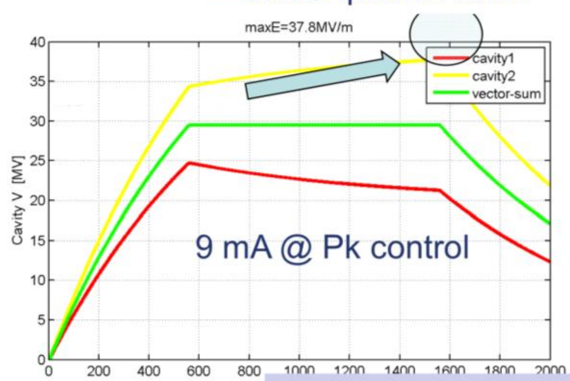


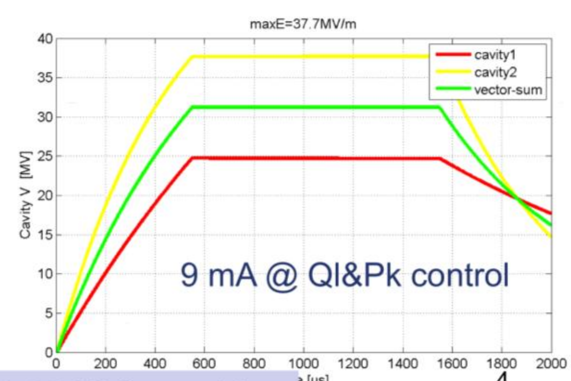


- Effective shorter pulse at max. gradient.
- Same quench limit?

Cavity setup parameters

- Forward power (Pk)
- Loaded Q

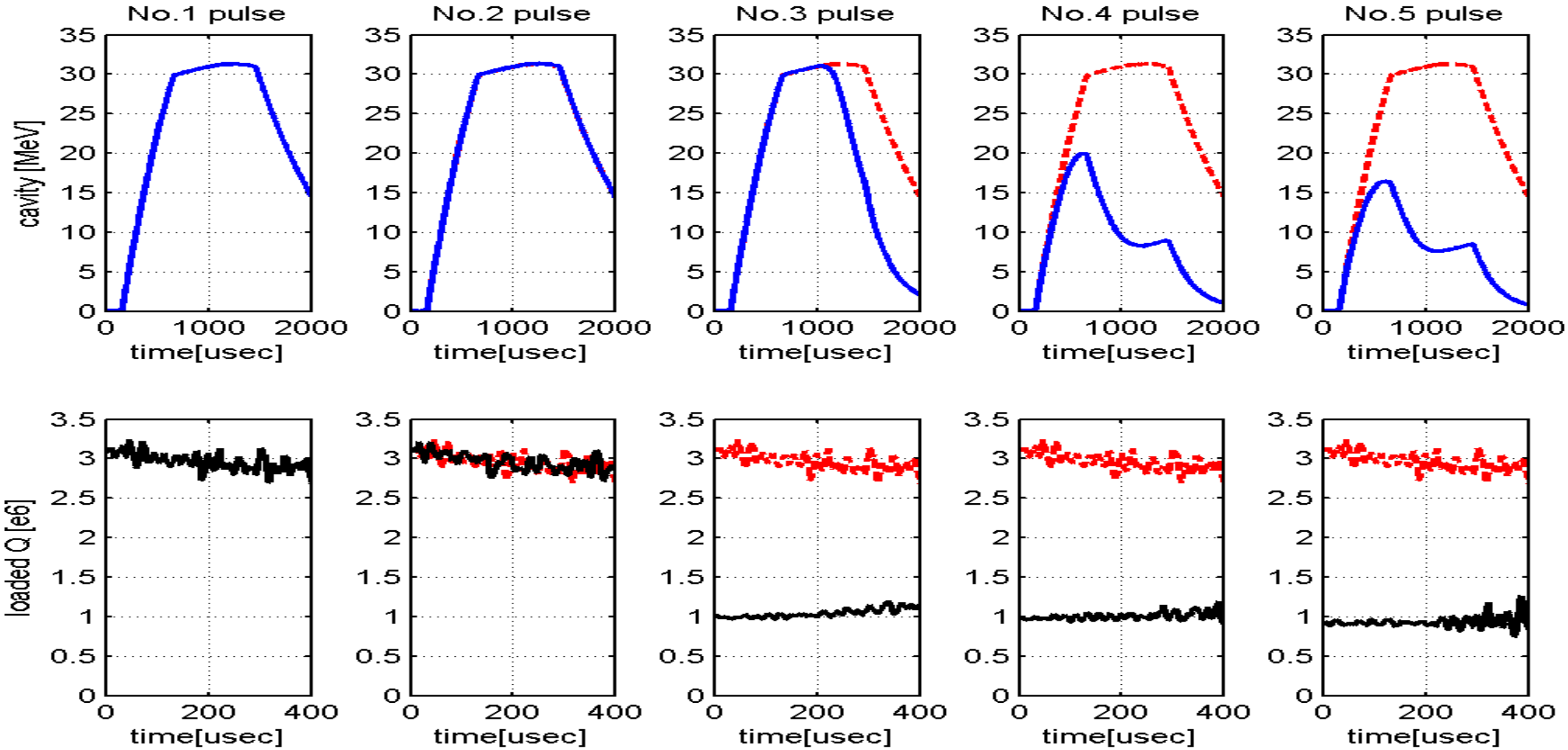




Simulation for 38 MV/m & 25 MV/m cavities

Quenches during 800us RF pulses, no beam

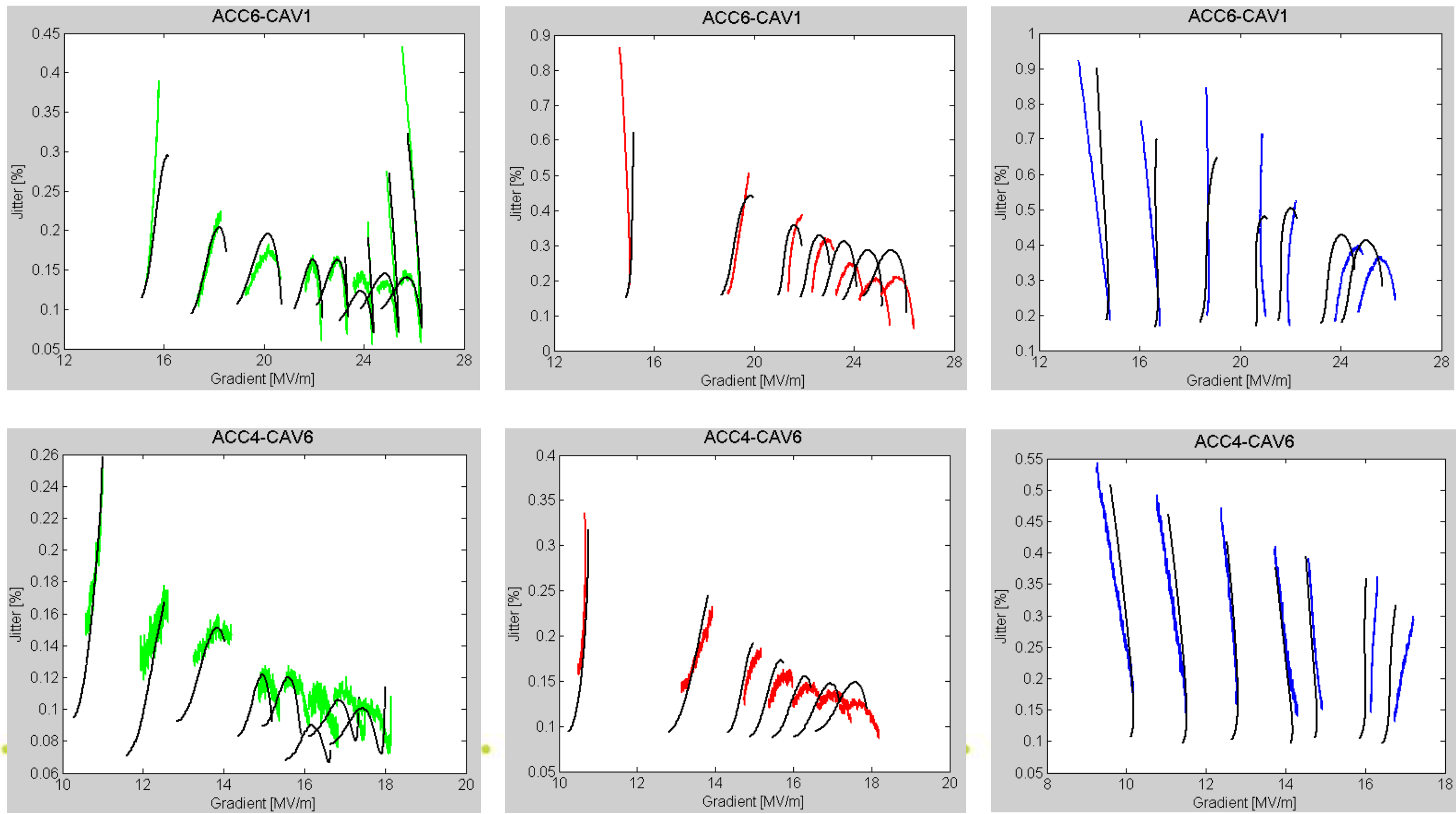
I will also show examples from other operating conditions



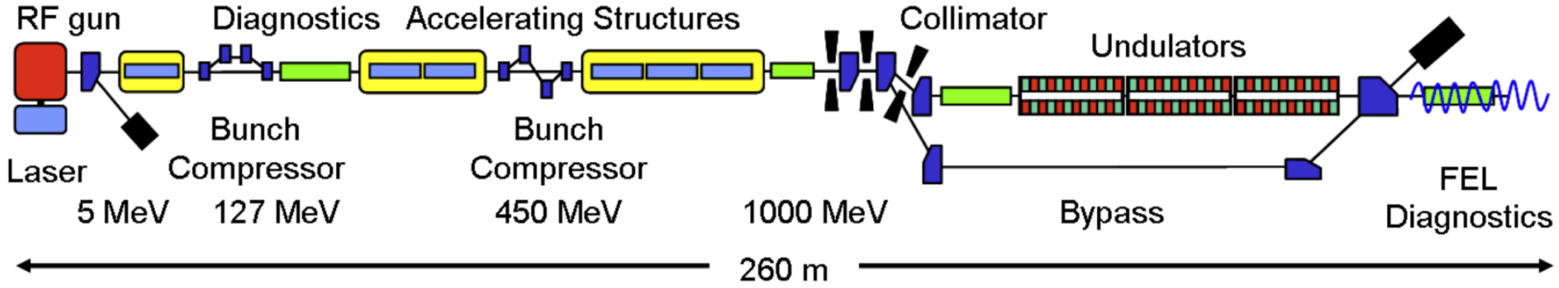
- At longer pulse (~800 us flattop), "quasi-quenches" were not observed.
- Once a quench took place, there was not a quick recovery, probably due to the larger energy deposited in the quenched area.

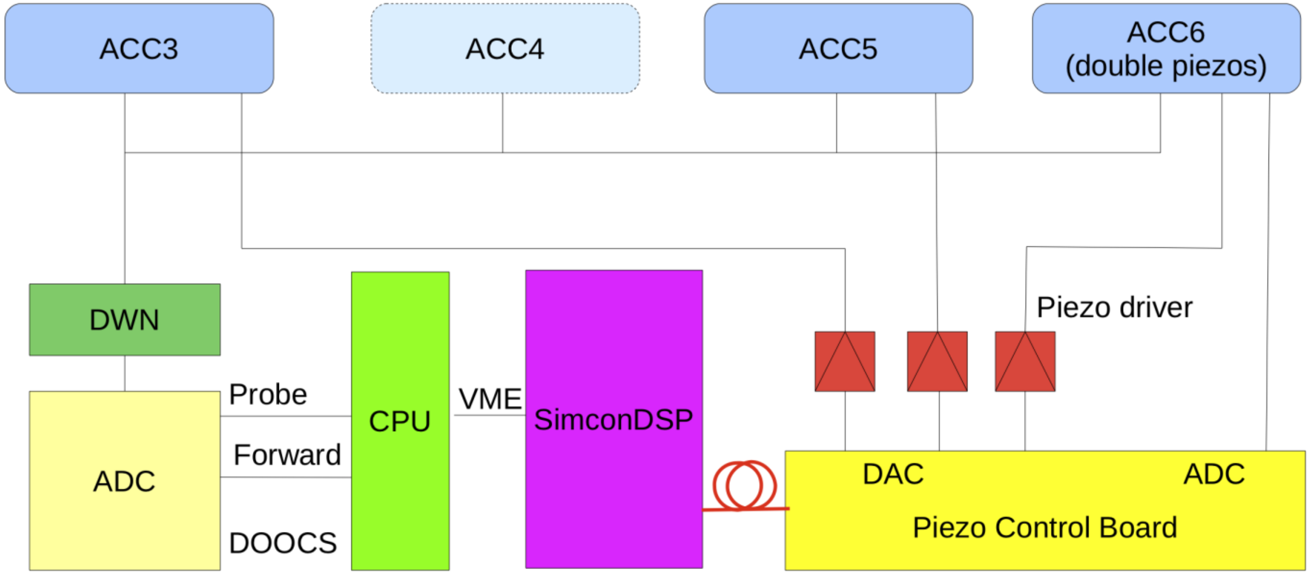
FLASH Cavity Gradient Stability (beam off)

Comparison of beam-off measurements of pulse-to-pulse cavity gradient jitter during the flattop period for different gradients and initial cavity detuning (green, red and blue lines) to a cavity fill model including Lorentz force detuning (black lines) with two degrees of freedom (initial and initial rms detuning)



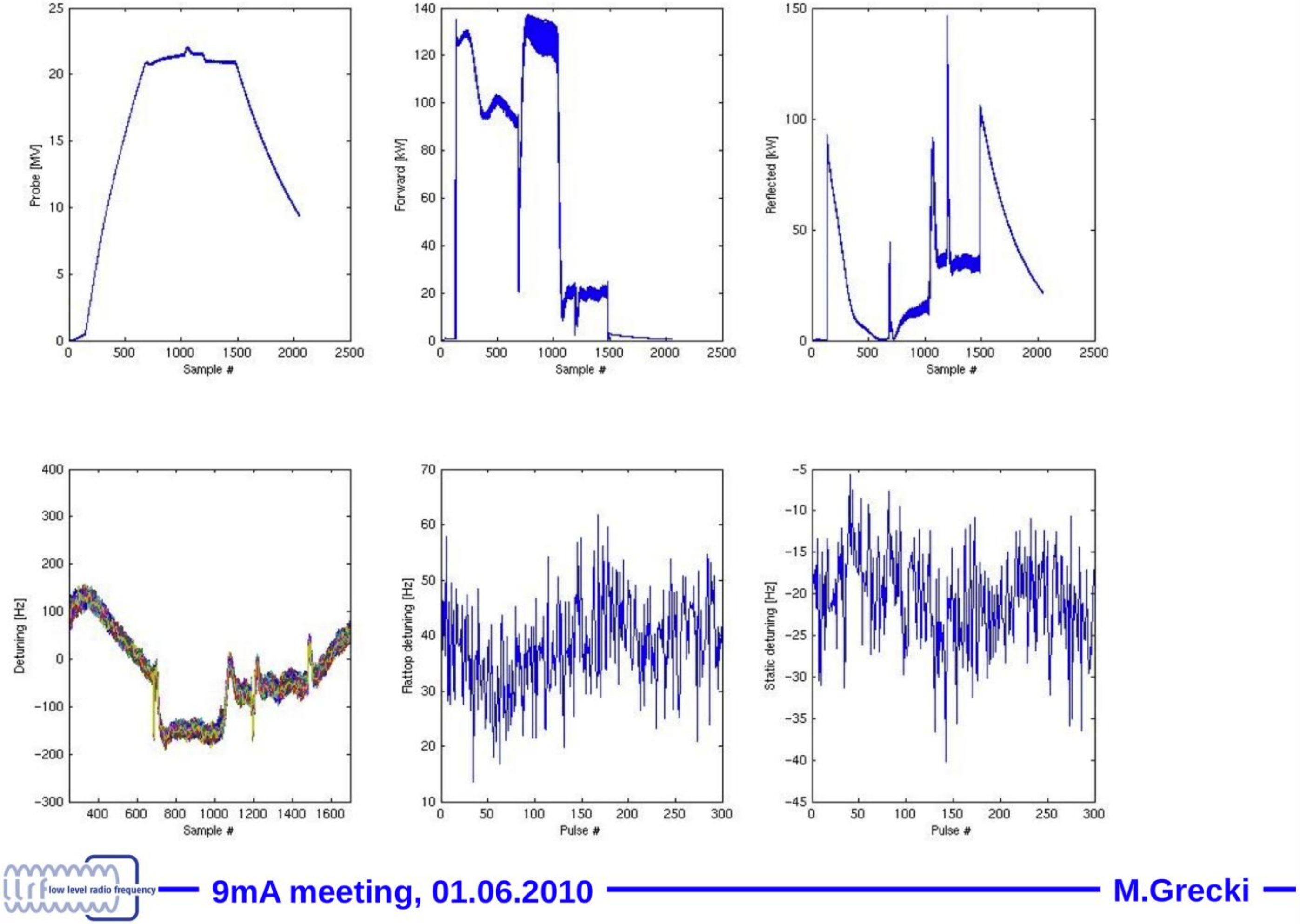
Piezo tuners at FLASH





So far, only limited experience with piezo compensation under beam loading conditions

ACC3 cav 1 with piezos (with beam)



Key topic for TDP-II studies: Characterize operating gradient margins

- ***Demonstrate operation with gradient tilts of better than ~% on all cavities over 800us pulse with spread of gradients and 9mA beam***

- Characterize and understand operating margins needed for, eg…
  - **Random pulse to pulse fluctuations, eg microphonics**
  - **Residual uncorrected LFD**
  - **LLRF tuning – initial turn-on transients,…**
  - **Calibration errors**
  - **Behavior of cavities when operating close to quench**
- Critical preparatory studies
  - **Pk/Qext studies: minimize gradient tilt at desired gradients and current**
  - **Piezo tuner studies: minimize LFD on all 16 cavities in vector sum**

- Measurement and characterization of microphonics:
  - **Cavities in ACC67 have two piezo cells (one used for monitoring)**
  - **Geophones are installed in several locations on the FLASH modules**

Anticipating study time in Jan & Sept 2011 – results (hopefully) by the end of 2011

Gradient and RF power overheads

What do we mean by Gradient Overhead?

- Single cavity quench limit -> S0
- Quench limits for 8 cavities in cryomodule -> S1
- **Remaining items: engineering, integration, operation**

- Main issues are clear
  - **Achievable gradient flatness (lorentz-force detuning, effectiveness of cavity Pk/Qext tuning)**
  - **Operating margin for LLRF regulation**

- To what extent should we take into account issues such as engineering tolerances, environment,…

- Base assumptions significantly impact the required power and gradient overhead – **self-consistent..?**

Impacts on gradient operating margin

- **Engineering; Environmental; Technical/Operational,…**
  - Random pulse to pulse fluctuations, eg microphonics
  - Residual Lorentz-force detuning after piezo compensation
  - Residual errors from minimizing gradient slopes (Pk/Qext control)
  - RF/LLRF control/regulation: turn-on transients, noise sources,…
  - Measurement errors/uncertainties of cavity fields
  - Measurement uncertainties in quench limits at different VTS
  - Engineering tolerances, eg errors in forward rf power ratios
  - Overhead for operational availability

- **Behavior of cavities when operating close to quench…**
  - Stability and shapness of the quench 'knee'
  - Do all cavities behave the same?
  - How does beam loading change things?

Bounding the problem…

(in response to 1% gradient flatness spec from beam dynamics)

Sources of error (LLRF specific)	**Order of magnitude**	**Targets for 1% max gradient tilt…?**
Lorentz Force Detuning	20%, 20 deg	0.2%, 0.2 deg
Cavity P_k, Q_l and beam loading	2%, 2 deg	0.2%, 0.2 deg
Microphonics	2%, 5 deg	0.2%, 0.2 deg
Static cavity detuning	1%, 2 deg	0.1%, 0.1 deg
Beam loading variations		0.1%, 0.1 deg
Vector sum calibration errors and drifts	0.2%, 0.2 deg	0.1%, 0.1 deg
Receiver linearity and noice		0.1%, 0.1 deg
Residual loop error	0.2%, 0.2 deg	0.02%, 0.02 deg
Reference line drifts		0.3 deg

Message: given only 5% gradient margin, even 'small' effects become important

These were 'discussion starters' at a previous meeting - do not use!

B. Chase

Uncertainties in measured cavity quench limits from vertical tests…?

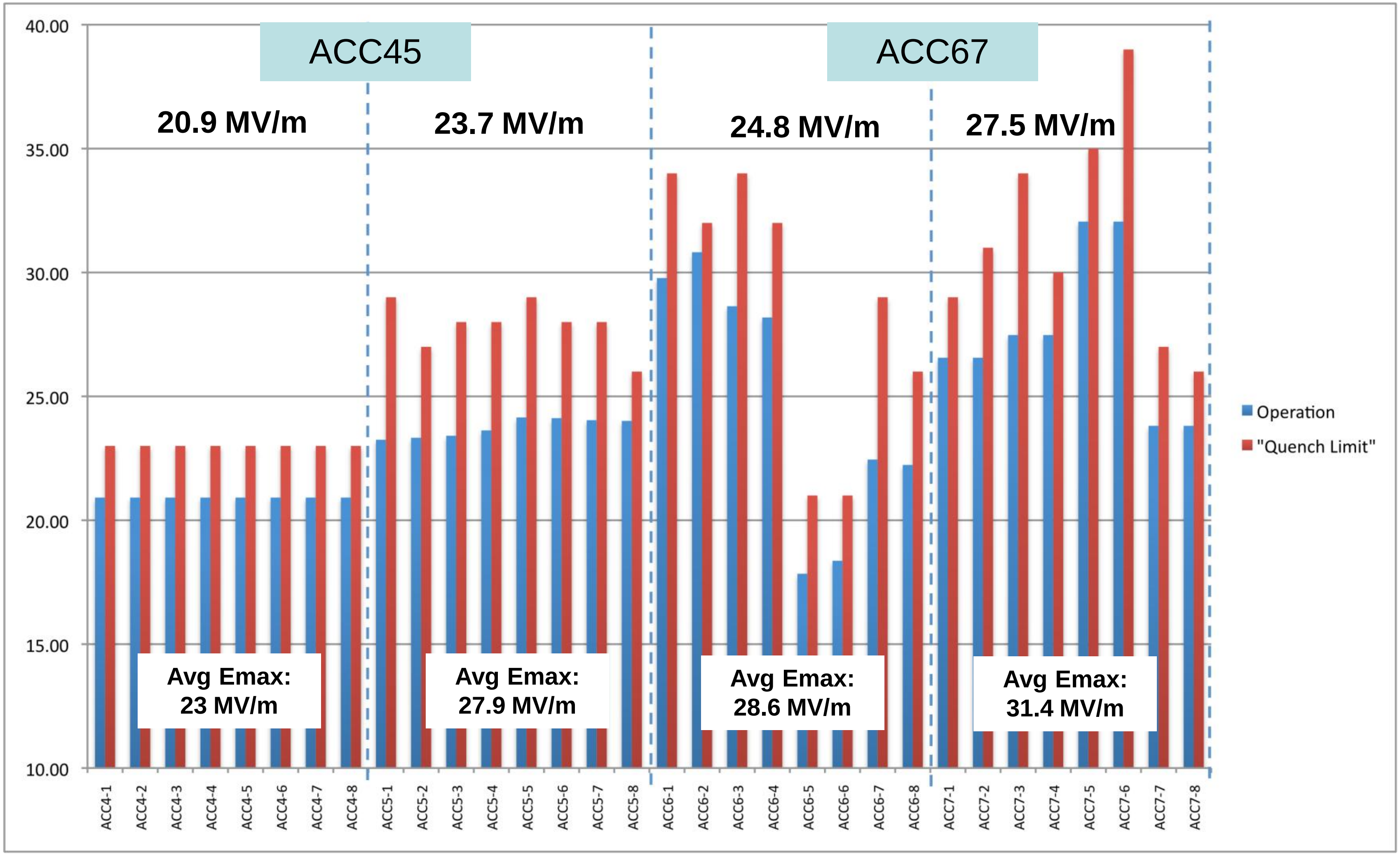
- Absolute calibration, precision, and repeatability of cavity quench limit measurements
  - **On the same cavity…?**
  - **On different cavities…?**
  - **From test stand to test stand…?**

- How to account for the uncertainty in measurement of quench limits?

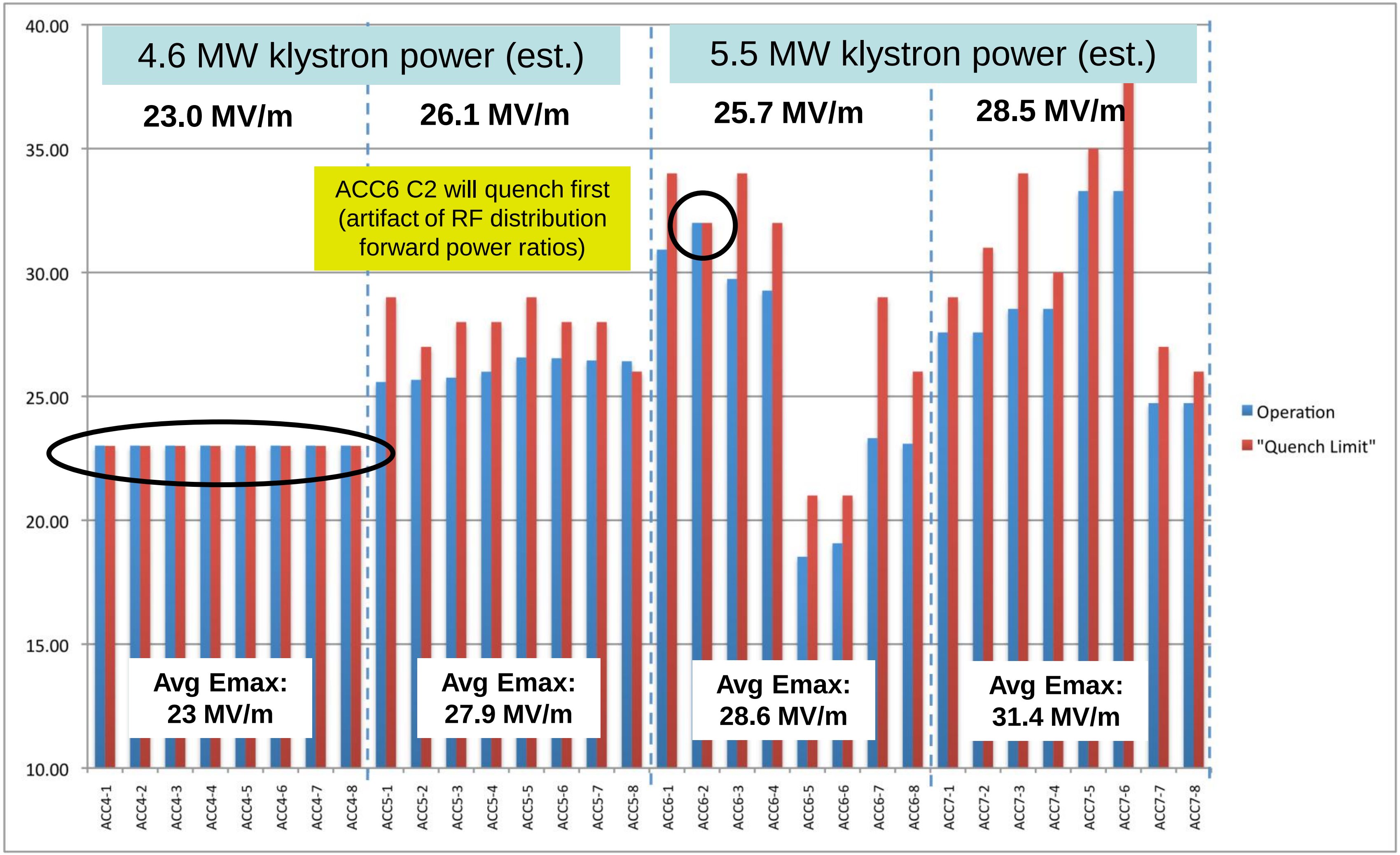
- Experience from the tight loop program?

Impact of tolerances on forward power ratios

FLASH ACC4-6 quench limits and operating gradients for energy of 1.3GeV



Ideally, all cavities reach their respective quench limits at the same forward power

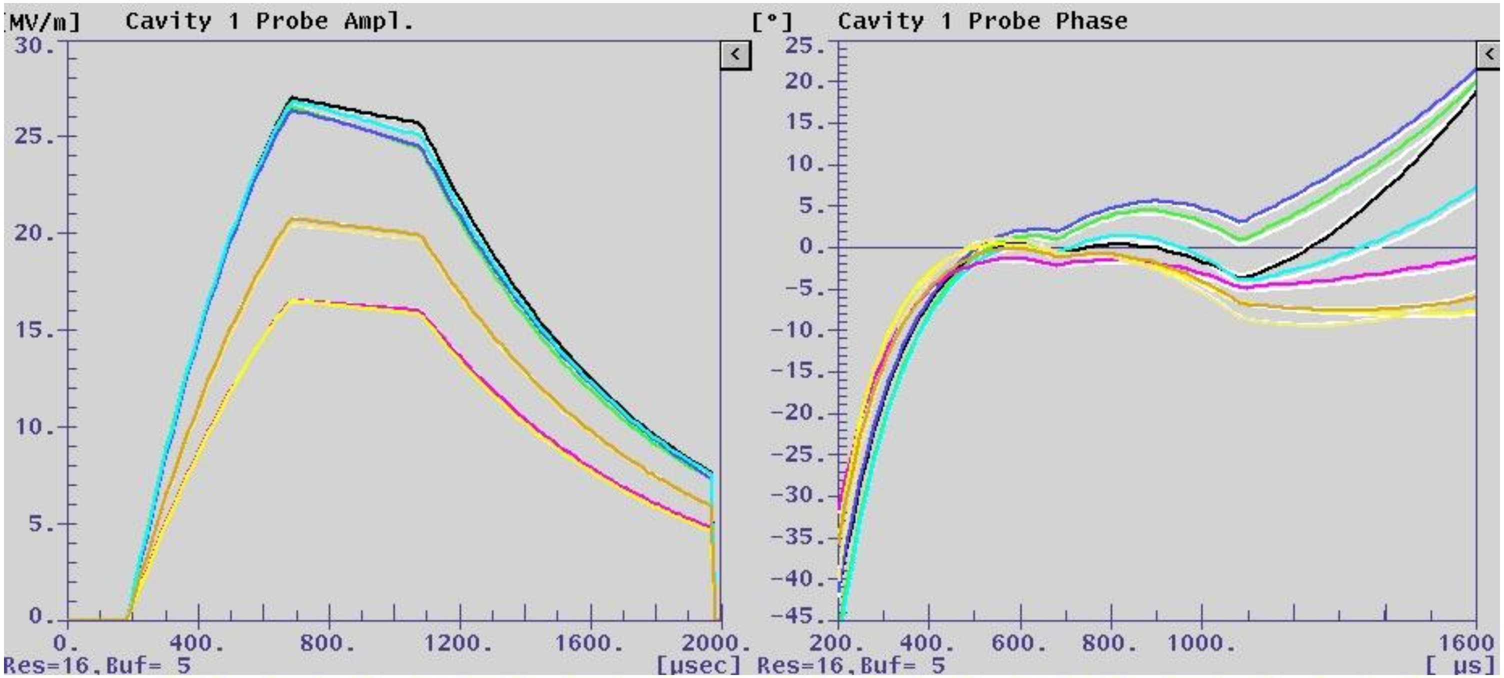


Reality: errors in power ratios due to manufacturing tolerances of rf attenuators (In this case: tolerances are of the order +/-0.1dB)

Difficulty in achieving flat gradients

- In practice, it is non-trivial to establish flat cavity field amplitudes and phases symultaneously (even without beam)
  - **Optimization of mechanical tuners, Qext, piezo feedforward,…**

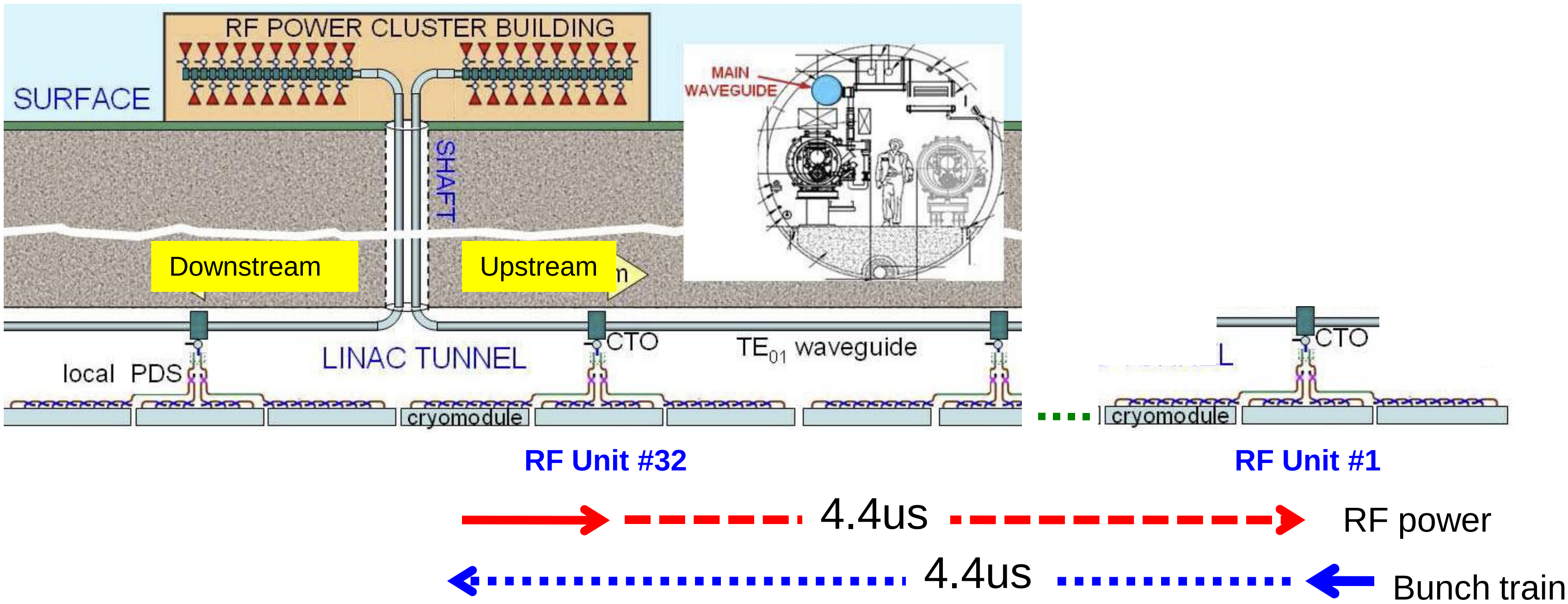
Illustrative example: amplitudes & phases for 8 cavities (without beam and LLRF feedback off)



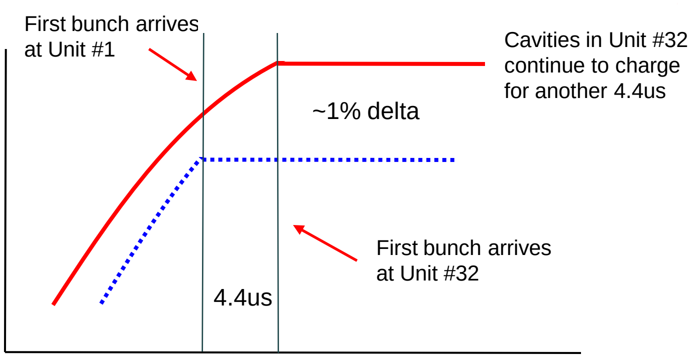
What can be actually demonstrated today is limited by…

- ‘Primary’ limitations (essentially invariant)
- Test facilities (availability thereof, schedule,…)
- Enginering know-how
- Operations ‘learning curve’ – some things are just hard

KCS propogation delays



Cavity field amplitude during fill (upstream side)



Transit delays]apply to vector sum readbacks and power flow – impacts achievable LLRF regulator gain-bandwidth

Not an issue if the baseline assumption is that random disturbances are 'small'

Gradient spread (sorting)

- Present model assumes a random distribution of cavity quench limits over +/-20% spread (26MV/m to 38MV/m) (no sorting)
- KCS and DRFS both assume cavities will be sorted (2's or 4's)
- 'Optimal' sorting:
  - **All cavities on a given RF source have the same quench limits**
- 'Sub-optimal sorting'
  - **All cavities on a given RF source have the same quench limits within some tolerance**
  - **All cavities operated at the same gradient**
- Using the same operating gradients in an RF unit => similar lorentz-force detuning => cavities have similar characteristics
  - **Common-mode components can be removed by feed-forward**

Sorting models

- KCS model
  - **Sort within each group of 26 cavities in an rf unit to get closest matched cavity hybrid pairs**
- DRFS model
  - **Sort into groups of four**

- Cost of sorting:
  - **Warehousing enough cavities for the required sample size and tolerance**

- Manufacturing models & logistics
  - **We get some warehousing for free (how much?), so sorting should be a simple extension**

If we really need detailed optimizations: must do trade-studies (work!)

- RF power overhead vs gradient overhead
  - **RF power is much cheaper than gradient overhead**

- Cavity sorting vs spread in operating gradients

  …in each hybrid cavity pair, across entire RF unit
  - **(hybrids vs circulators?)**
  - **(range of adjustment of Pk and Qext?)**

- Environmental (vibration => microphonics)
  - **Influences LLRF regulation requirements**
  - **We should use consistent assumptions for the three RF schemes**

- The three HLRF alternatives presumably have different optimizations: RDR-prime, KCS, DRFS

Final slide…

- A detailed bottom-up analysis shows there are many factors that could claim part of the 5% operational margin
  - **Over-estimatation?**
- To what degree of accuracy do we really need to estimate the required overhead?
  - **Especially given the apparent lack of 'objective' metrics**
  - **Is there compelling evidence to change the 5% margin?**
- General agreement is that sorting cavities is a good idea
- Underlying assumptions must be self-consistent when comparing schemes (at least differences should be understood)

Thank you