SCRF Session: Results of recent 9mA beam studies at FLASH

Presentations

- Summary of the Feb 2011 beam studies (J. Carwardine, Argonne)
- Detuning & detuning compensation (M. Grecki, DESY)
- Pk/Ql studies to flatten cavity gradients (J. Branlard, FNAL)
- Outlook for future 9mA studies (B. Chase, FNAL)

Summary report from 9mA beam studies at FLASH: February 2011

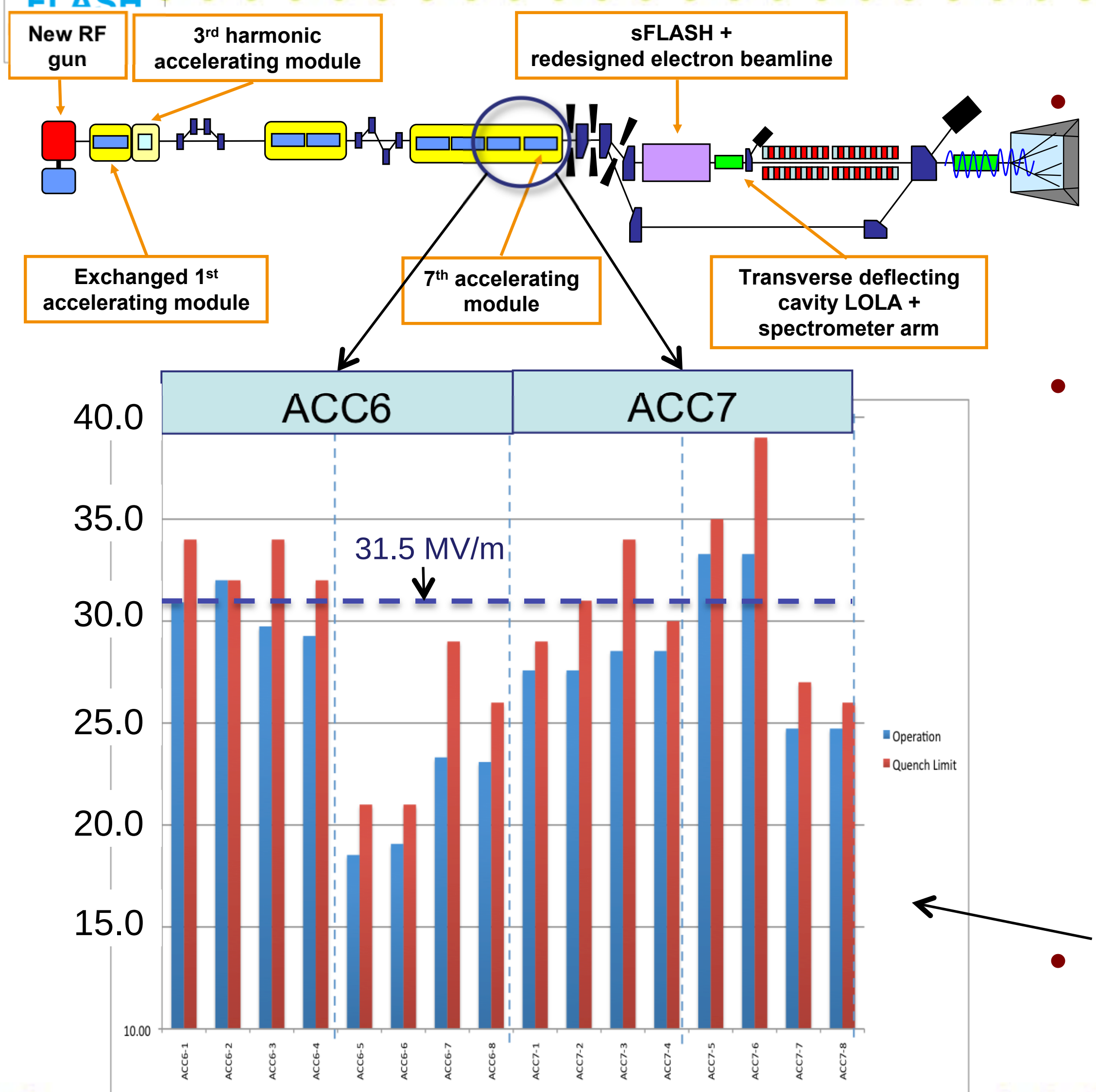
John Carwardine

ALCPG – 22 March, 2011

Outline

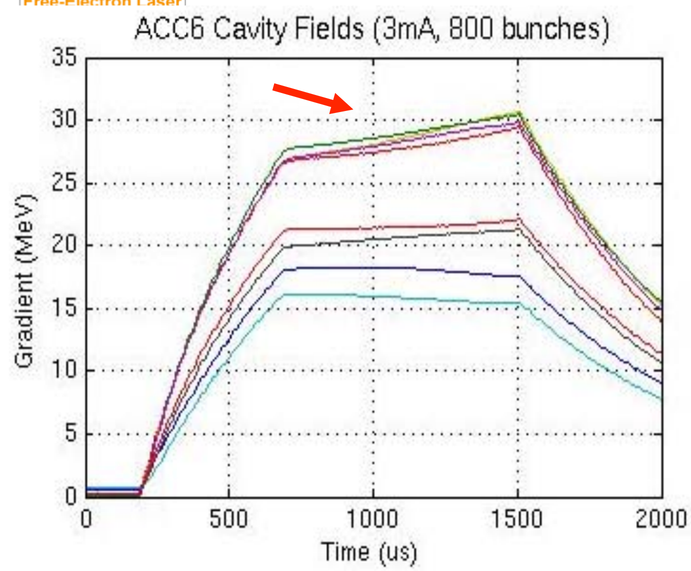
- **Study goals**
- **A few selected results**
  - Pk / QL studies
  - Detuning studies
- **FLASH operation**
- **Future studies**

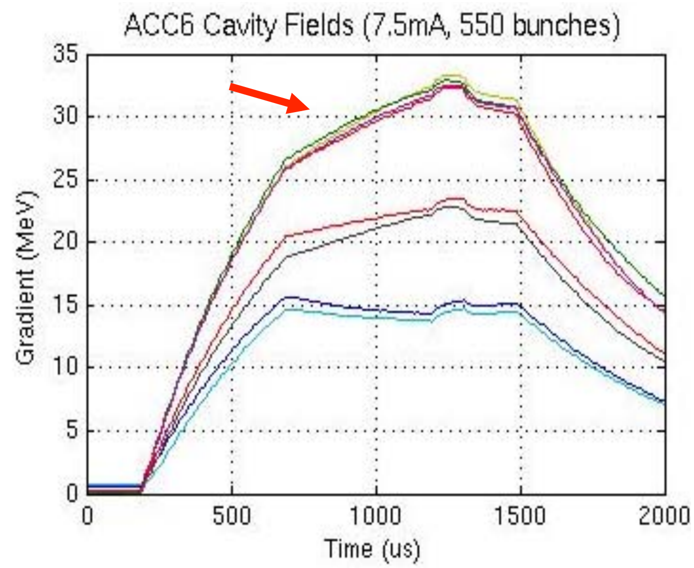
Main TDP R&D goal driving the 9mA studies in February 2011



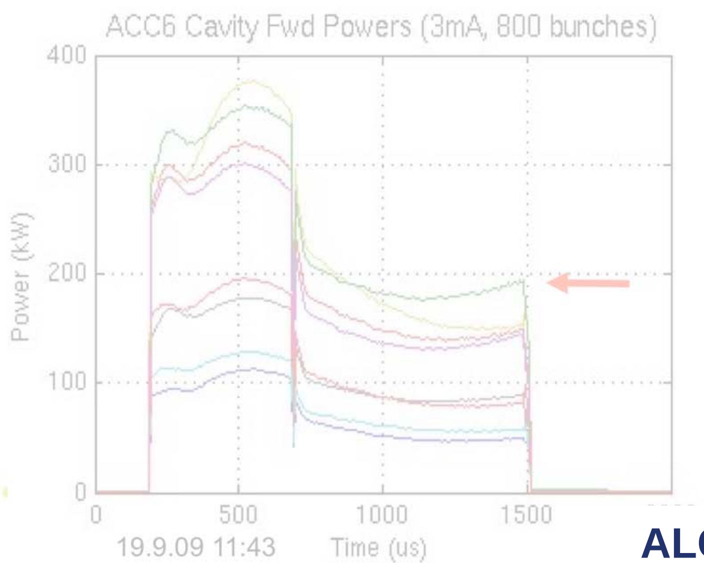
- **Operation with <u>Gradient Spread</u>**
  - From single RF source
- **Specifically: achieving constant gradients <u>for each individual cavity</u> during beam pulse**
  - to within few percent
  - close to gradient limits
  - 'Effective usable gradient'
- **ACC67 modules at FLASH have operating gradient spread around +/-25%**

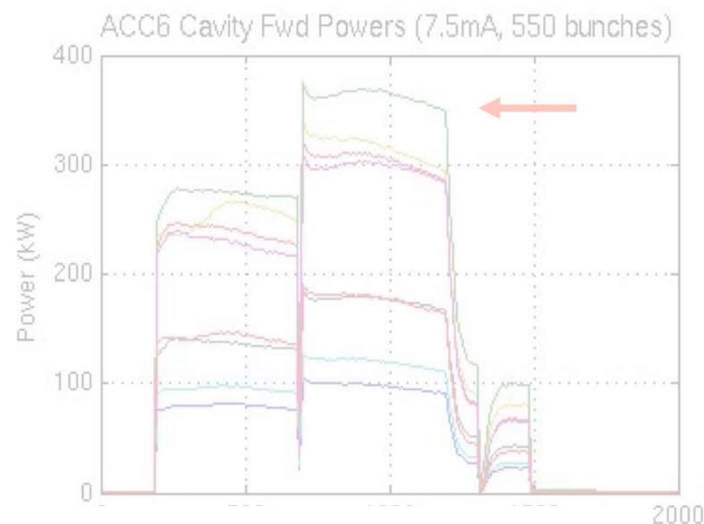
Comparison of ACC6 cavity gradients and forward powers for 3mA and 7.5mA (Sept '09 data)





Substantial increase in gradient 'tilts' with 7.5mA (would have quenched with 800us flat-top)





Power during flat-top is higher than the fill power for the 7.5mA case

Gradient had been lowered in 7.5mA case to reduce peak power and prevent klystron trips

Adaptive feed-forward was ON for the 3mA case

Successful studies!!

- ***Can we actually operate the machine with all cavities within 3% of their quench limits?***

- **15 Shifts: 4th – 8th February**
  - ‘Parallel’ tasks: machine tuning; Pk/Ql studies; Piezo studies

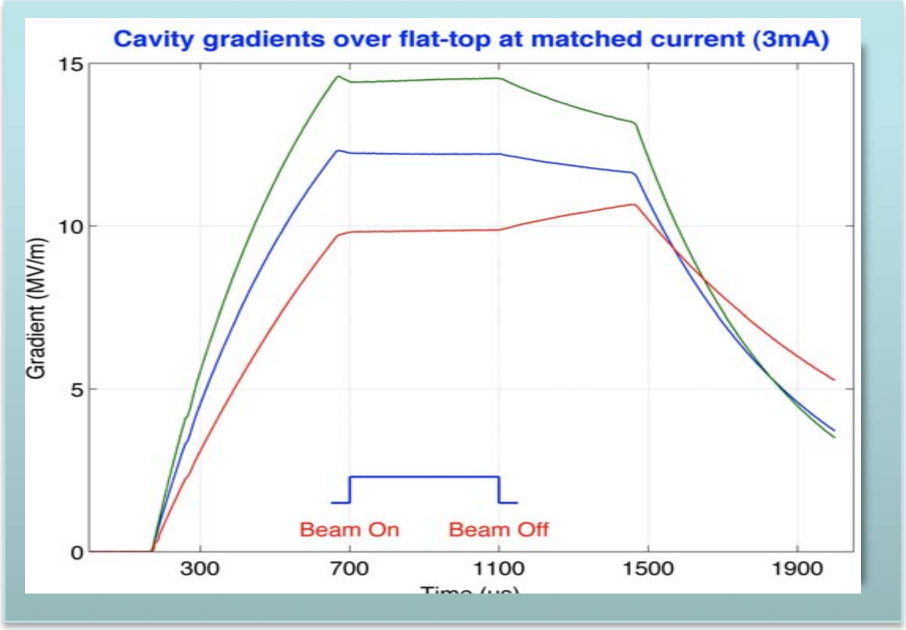
- **The accelerator ran flawlessly**
  - 1GeV, 400us bunch-trains, beam current from 1.5mA to 4.5mA
  - 400us bunch-trains were available within 10mins, always!
  - Energy stability with beam loading over periods of hours: ~0.02%

- **A lot of progress with the 9mA experiments + good results**
  - Achieved flat gradients within few % at 1.5mA, 3mA, 4.5mA

And of course…we have a lot of data ☺

Pseudo-Pk/QL studies

- **Understand RF param solutions**
  - RF power to cavities
  - Adjustment of loaded Q
- **Compensation of Lorentz-Force Detuning via fast piezo-tuners**
  - LFD is proportional to g^2
- **Calibration (benchmarking) of simulation model(s)**
- **Better characterisation of errors, calibration and tuning precision**
- **Establishing best-approach tuning algorithms close to gradient limits**
  - with a view to automation
  - without quenching cavities



Gradients of three cavities over rf flat-top at matched current (3mA)

*note: 400μs beam pulse limited by RF gun

Achieved: flat cavity gradients to +/-few percent over a range of conditions

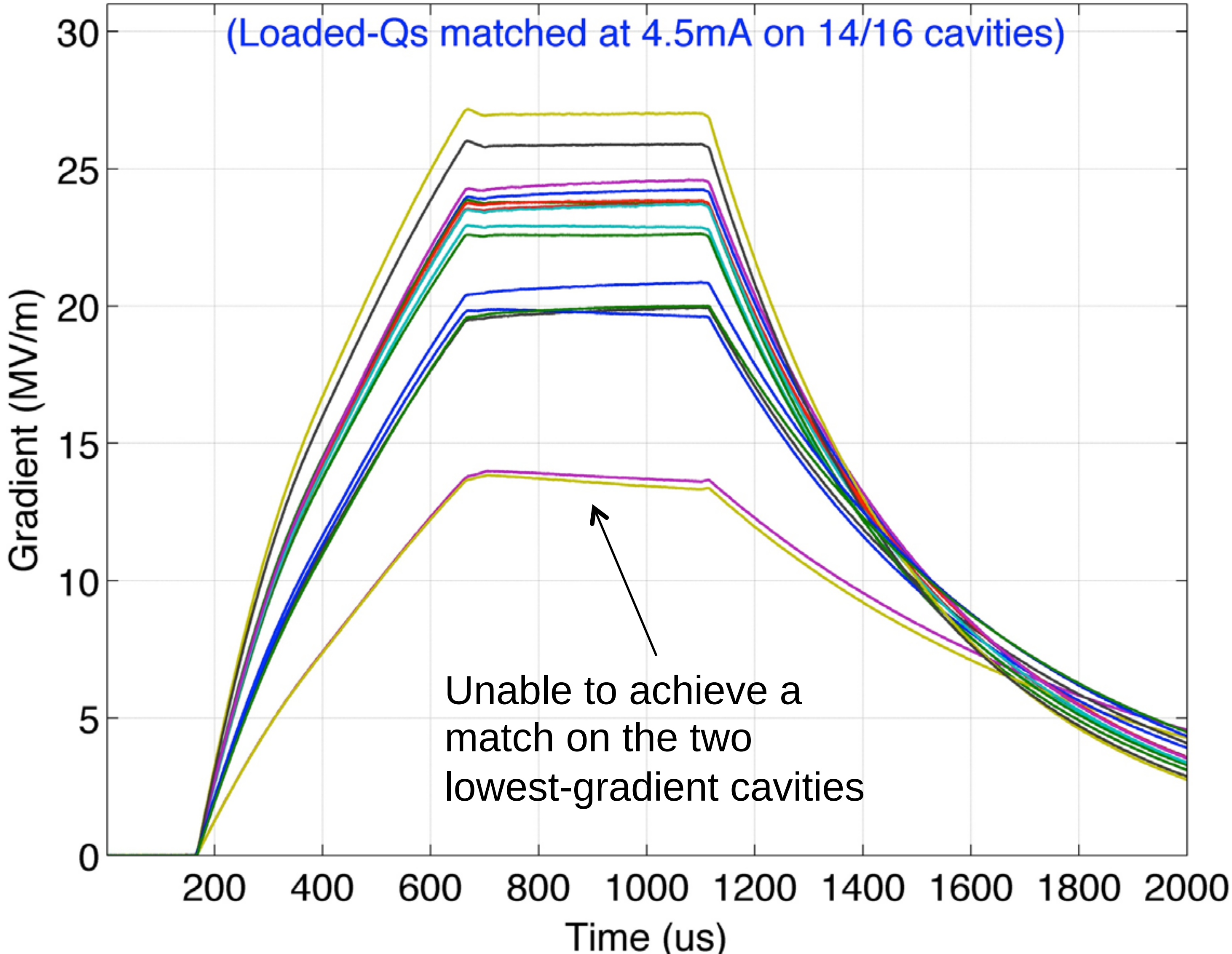
Matched current for 16 cavities	16-cavity Vector Sum	Approx. range of cavity gradients	Beam pulse length	RF flat-top length	Range for current scan
1.6mA	200MeV	7-24MV/m	400us	800us	0.6-1.6mA
3mA	200MeV	7-24MV/m	400us	800us	1.8-4.5mA
4.5mA	290MeV	10-20MV/m	400us	800us	1.5-4.5mA
4.2mA (14 of 16 cavities)	360MeV	17-25MV/m	400us	400us**	1.5-4.5mA

** RF flat-top length was reduced to prevent cavities quenching

- **QLs adjusted on ACC67 cavities to obtain flattest gradient profile over the duration of the bunch train**
- **Beam current scans used to evaluate the optimizations**

First-time demonstration of tailoring Pks/Qls to achieve flat gradients..?

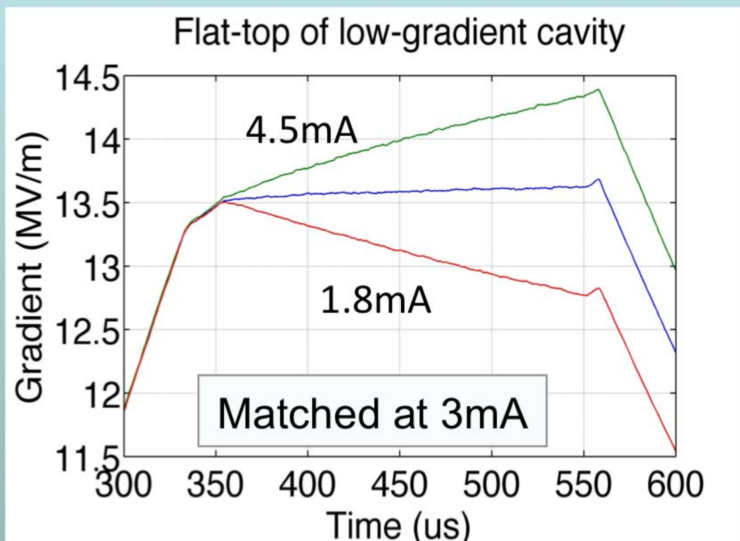
Flat gradient achieved at 360MV Vector Sum and beam current of 4.5mA (400us beam pulse)



Bounding sources of errors from beam current scans (Example of match at 3mA)

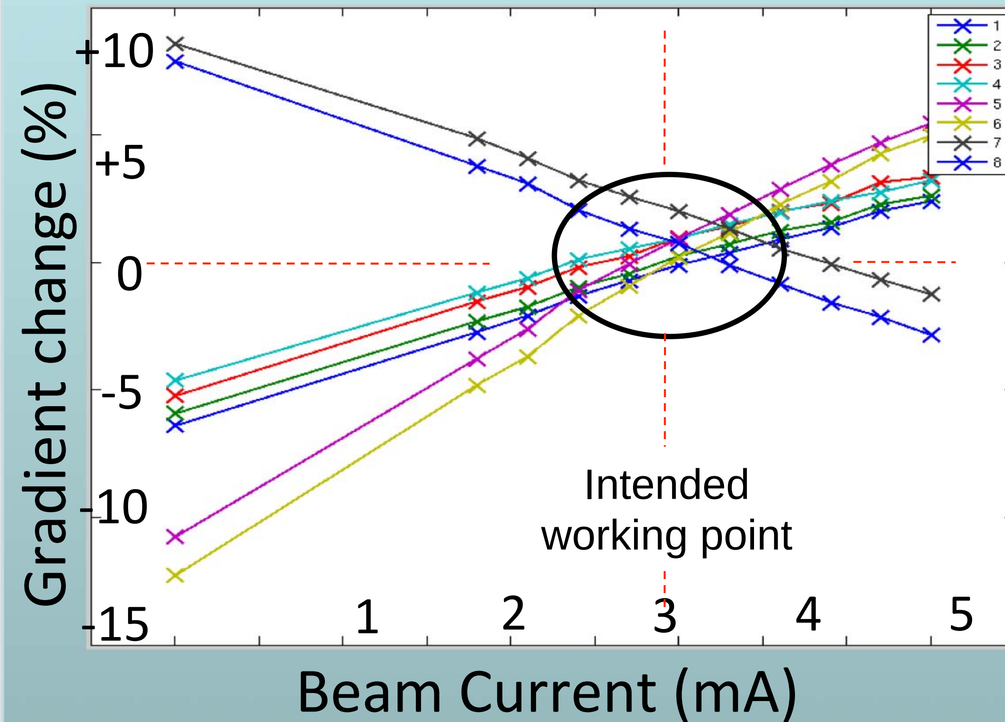
For analysis

As the beam current is scanned, the tilt changes from negative to positive. At some current, the cavity tilt is zero



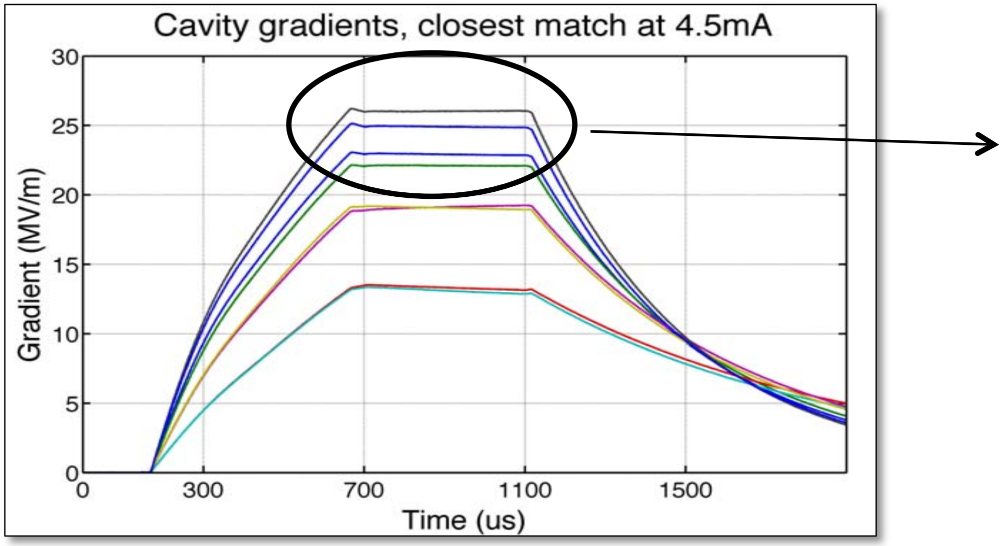
Should get insight into sources of error from the discrepancies in the currents where cavity gradient tilts were zero

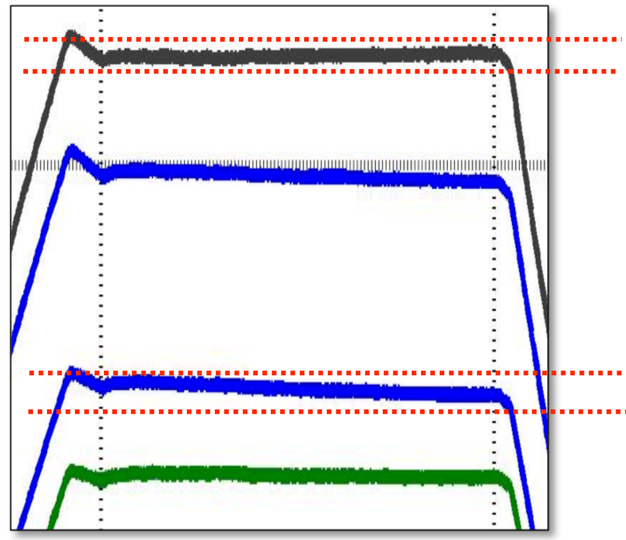
Gradient Tilts vs Beam Current (ACC7)



Evaluate gradient margins (effective usable gradient)

For analysis

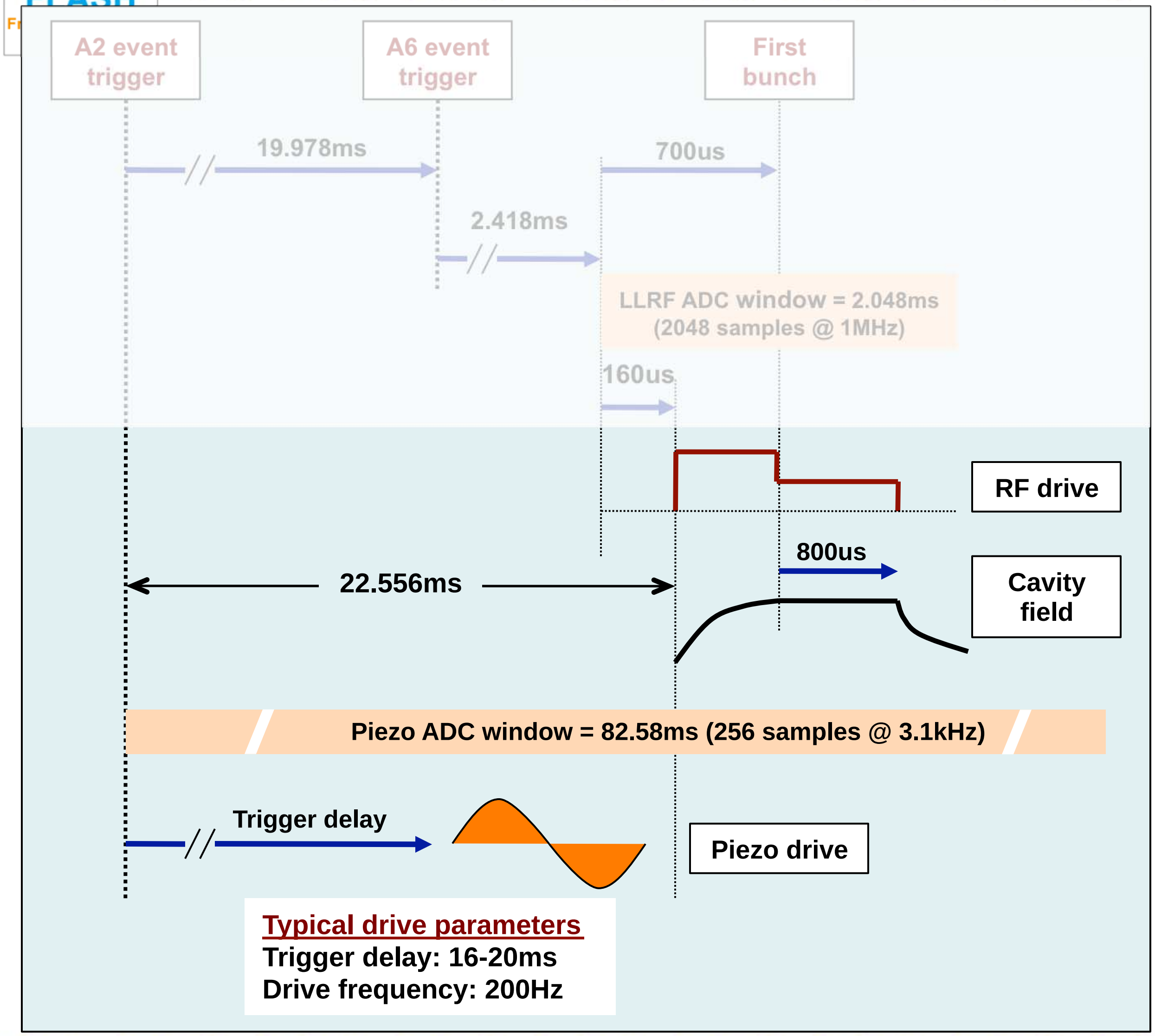


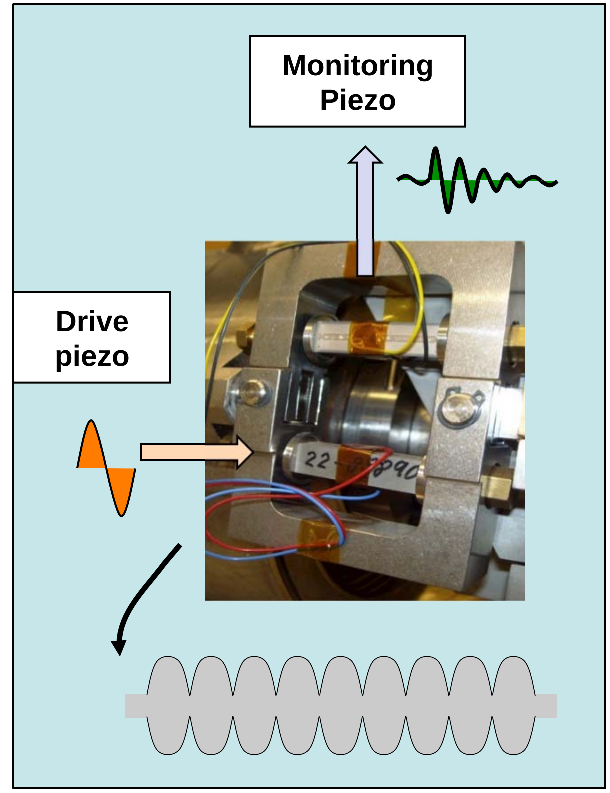


- **For each cavity, take the maximum gradient over the flat top and add the maximums together for all the cavities to get a maximum available vector sum.**
- **The fraction of usable gradient would the ratio of actual vector sum and the sum of the maximum gradients**
- **Factor in pulse-to-pulse jitter & drift to get an assessment of the needed gradient margin**

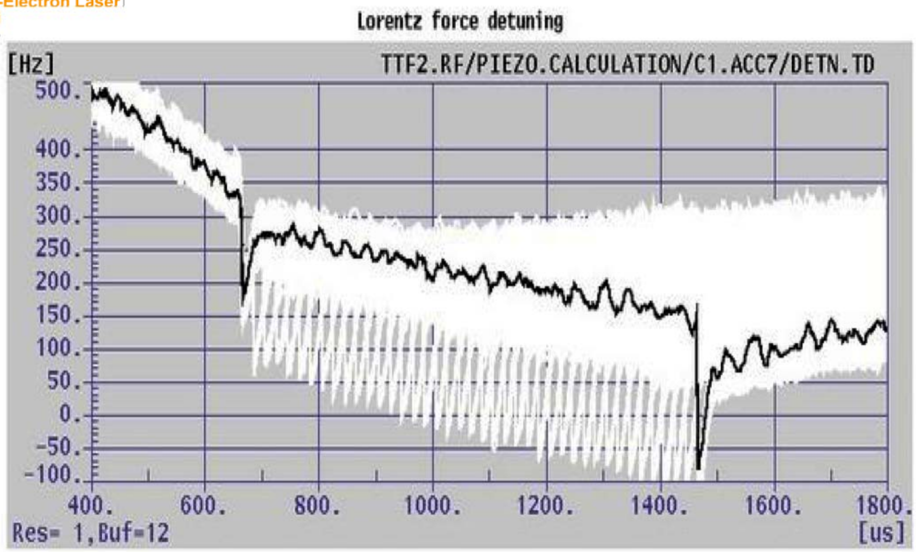
Detuning studies

Trigger timing for the piezo tuners
(nominal setup)





Two methods for measuring cavity detuning profiles

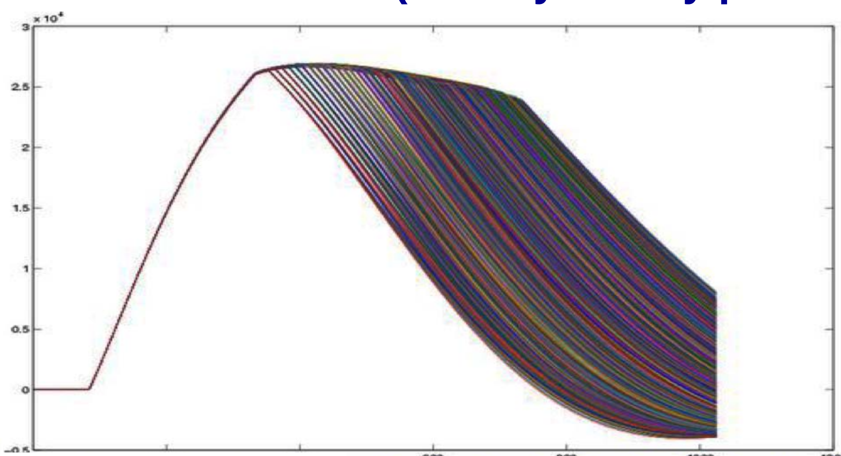


For analysis

Detuning over the rf pulse as computed by piezo controller from the cavity equations

This is an online non-invasive computation – used as basis for piezo tuner optimization

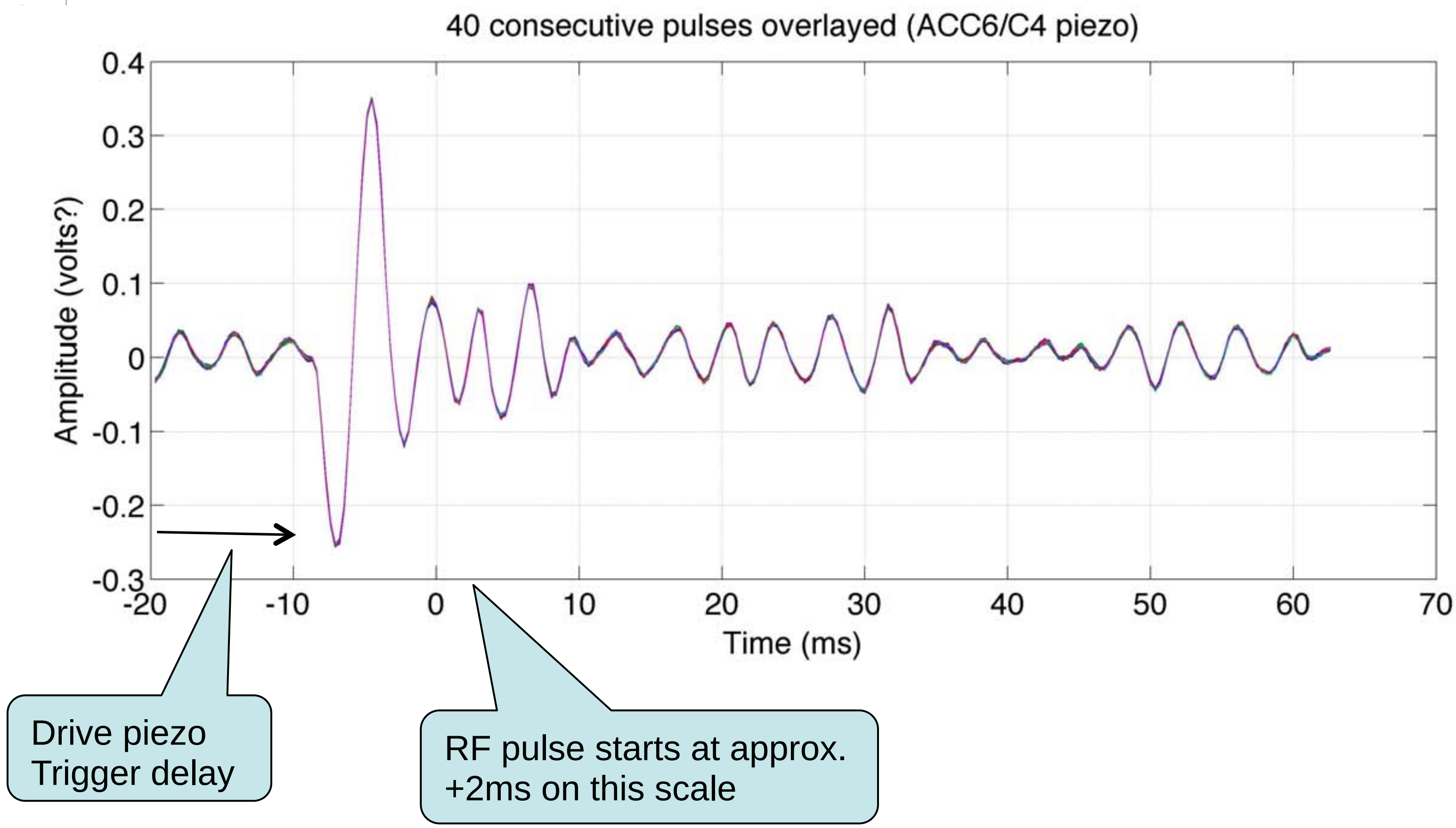
ACC67 Vector Sum (overlay of may pulses)



Length of rf flat-top was reduced in 20us steps from 800us to 20us and detuning computed from the decay at the end of each pulse

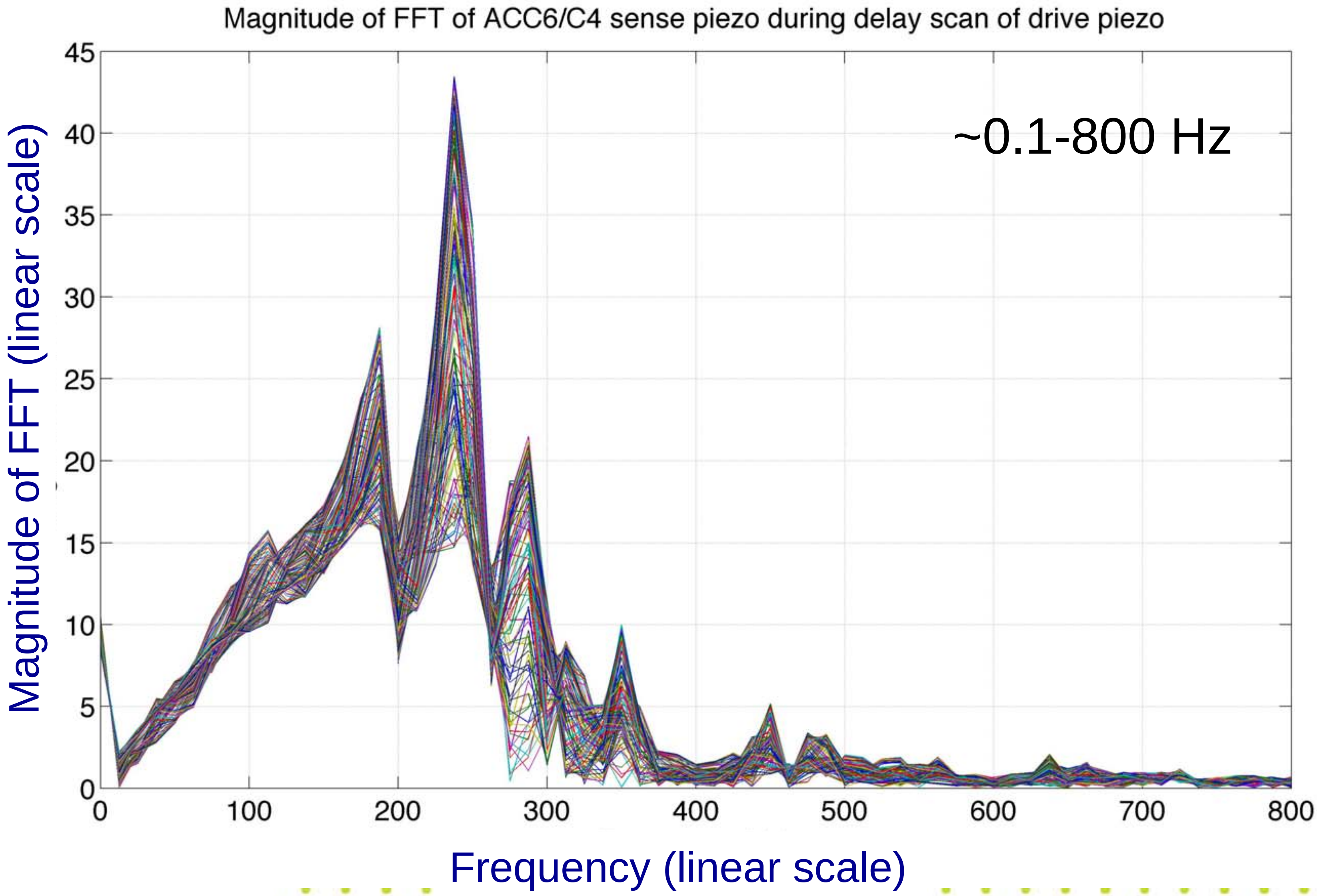
Invasive measurement - for cross-checking the online computation

Example signal from monitoring piezo (ACC6/Cavity4)

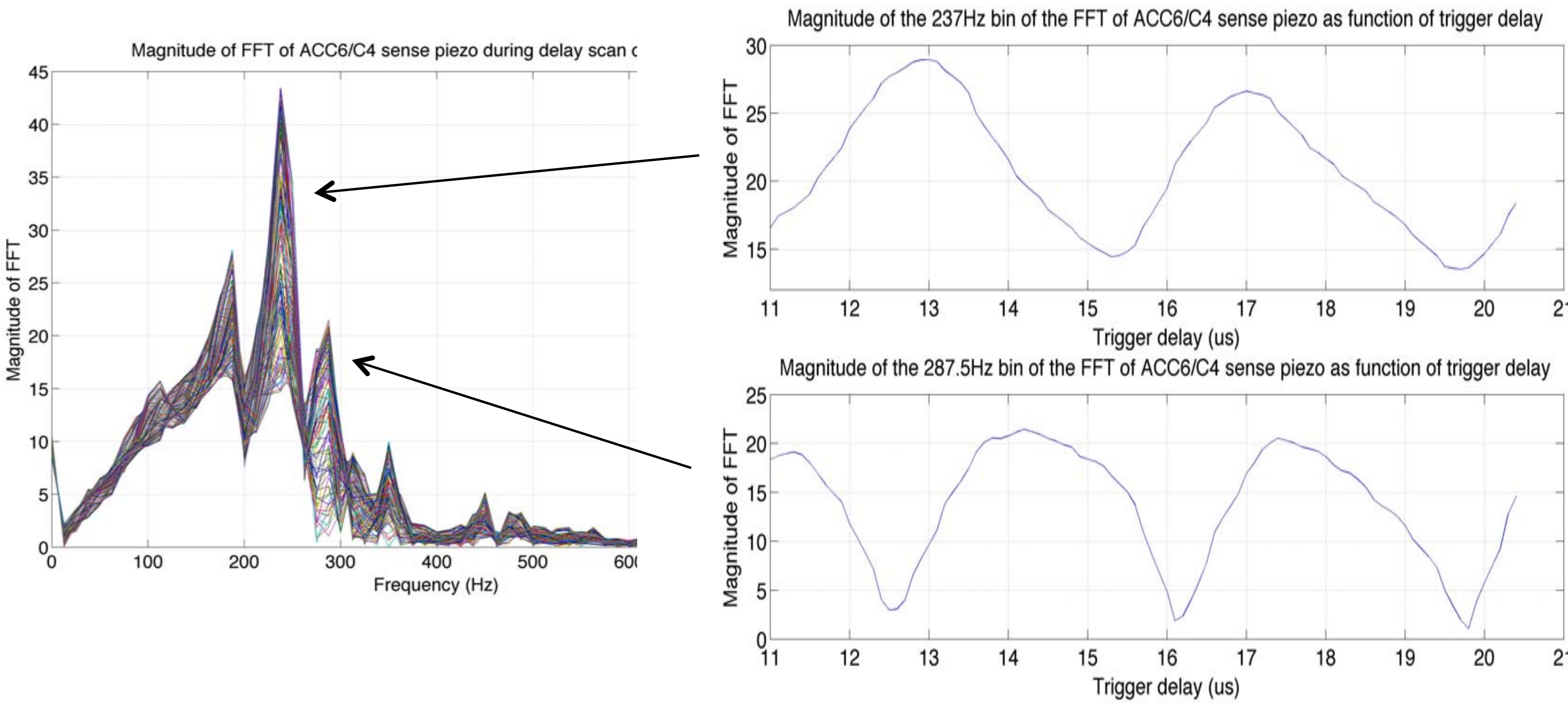


- **Both drive piezo and rf are active in this example**
- **Drive piezo settings:** Freq=200Hz; AC=20v, Cycles=1, delay=11ms

Frequency spectra of monitoring piezo signal during scan of drive piezo trigger delay (many pulses overlaid)

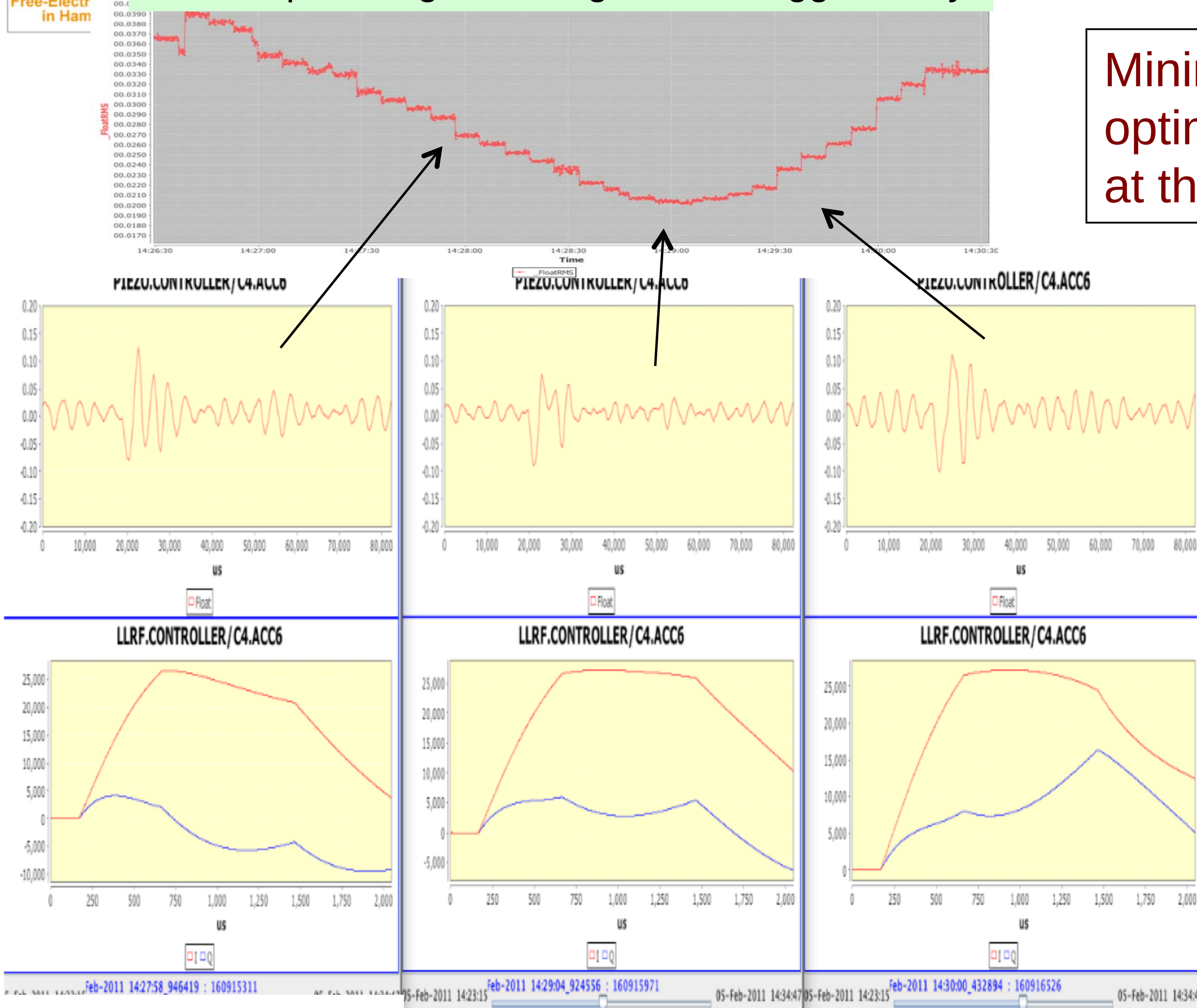


Magnitudes of two main tones as function of drive piezo trigger delay



RMS of the monitoring piezo signals during scan of drive piezo trigger delay

RMS of piezo signal during scan of trigger delay



Minimum RMS and optimal detuning occurred at the same trigger delay

Monitoring piezo signal (80ms)

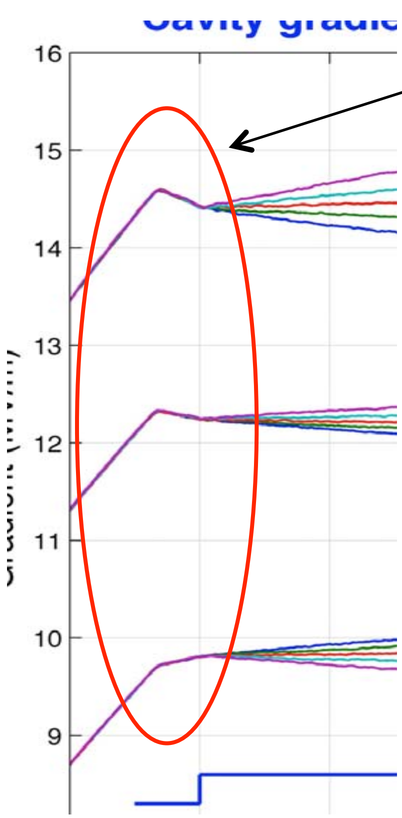
Cavity field probe I&Q (2ms)

(I = Red, Q = Blue)

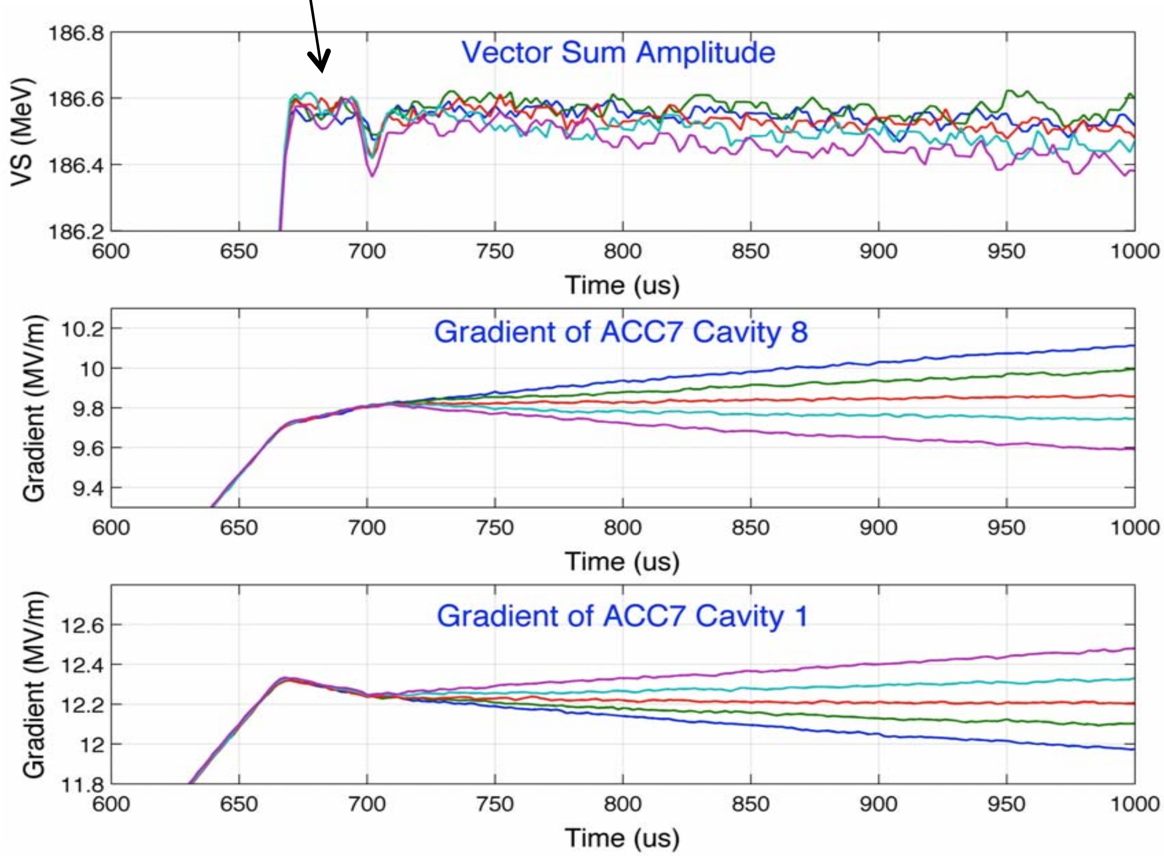
For analysis

FLASH operations

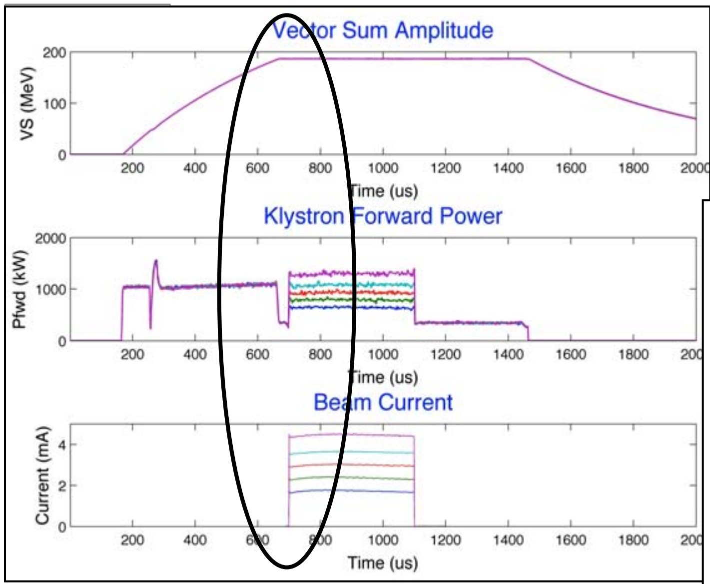
Initial transient on individual cavity gradients…



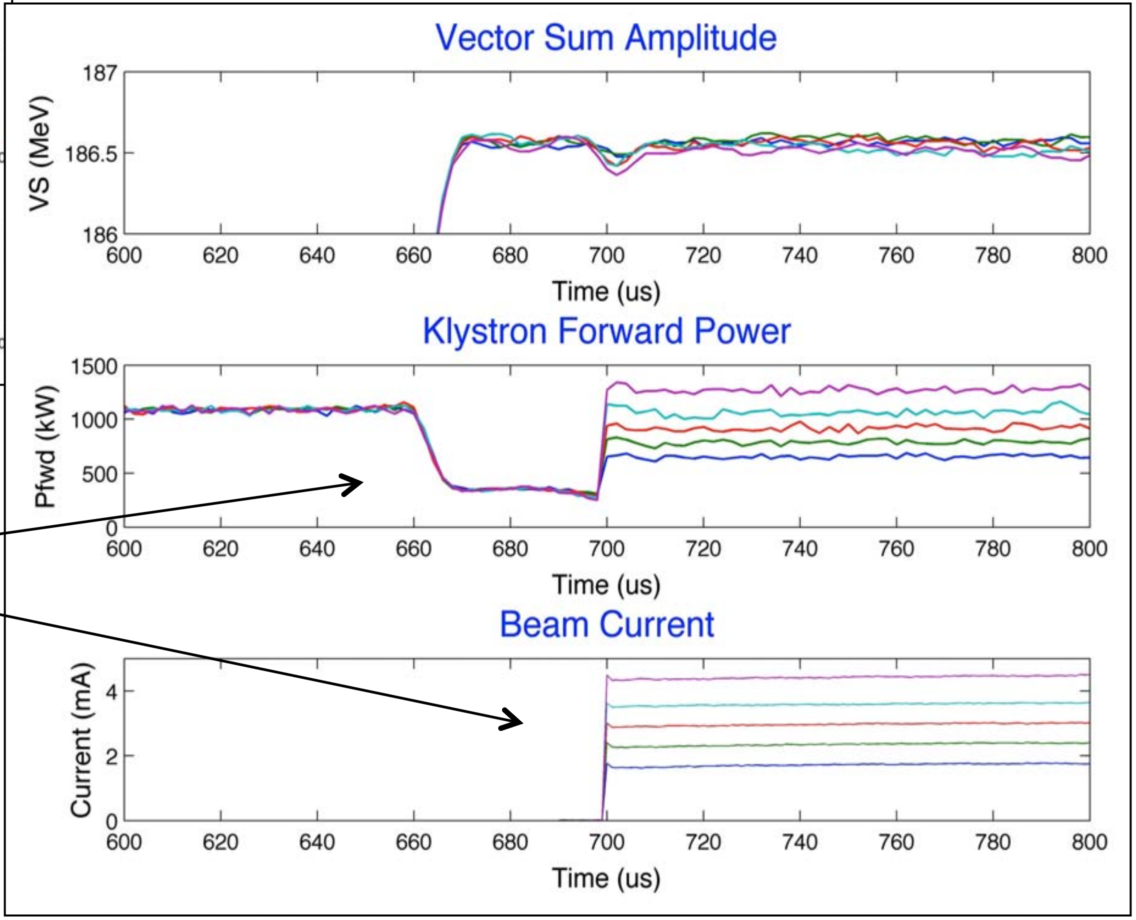
- **Higher gradient cavities overshoot at end of fill, lower gradient cavities undershoot**
- **Vector sum is flat**



Stabilization of vector sum before beam arrival

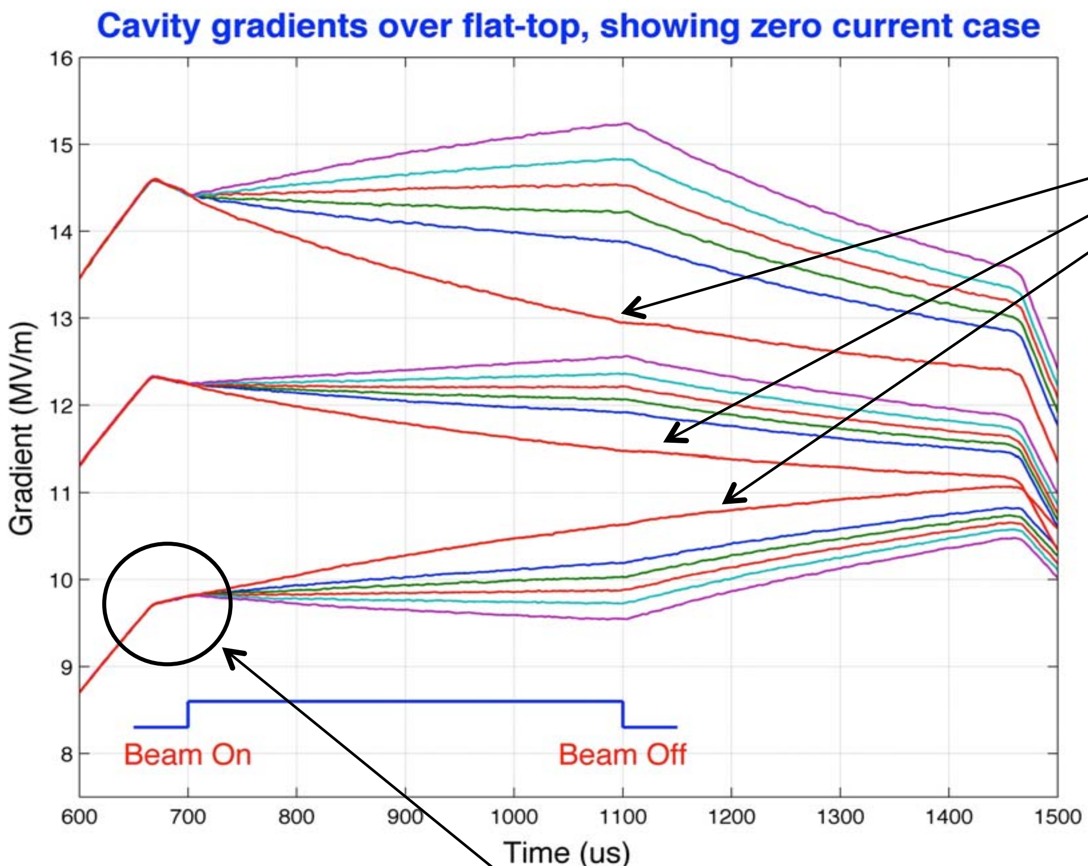


Learning feed-forward + beam loading compensation gives a very flat vector sum



First bunch is timed to after the transition to the RF flat-top to allow time for Learning Feed-forward to stabilize the vector sum

Effect of the initial no-beam period on QL matching

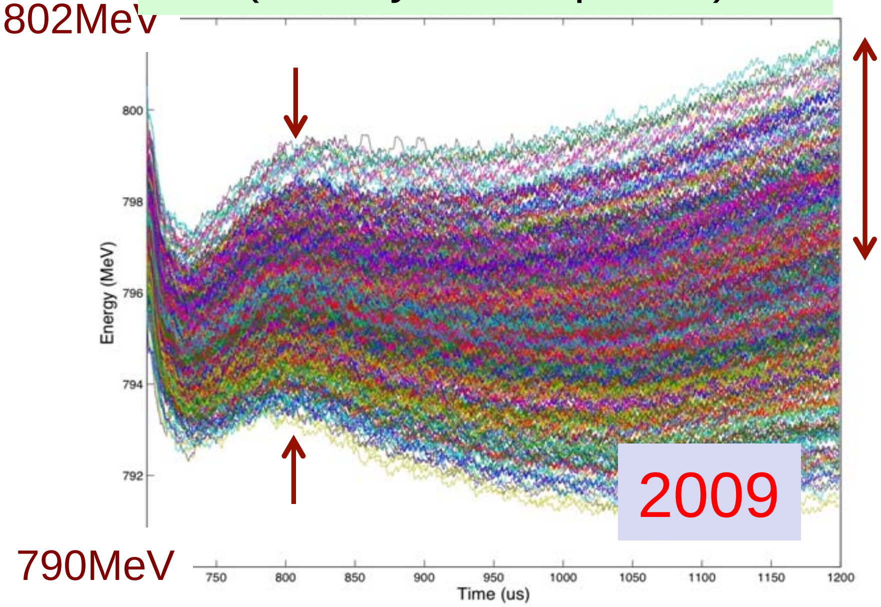


Gradients follow the no-beam trajectory during the initial 40us before the beam arrives

The change in gradients from end of fill to start of beam causes a systematic error in the matched conditions for flat gradients

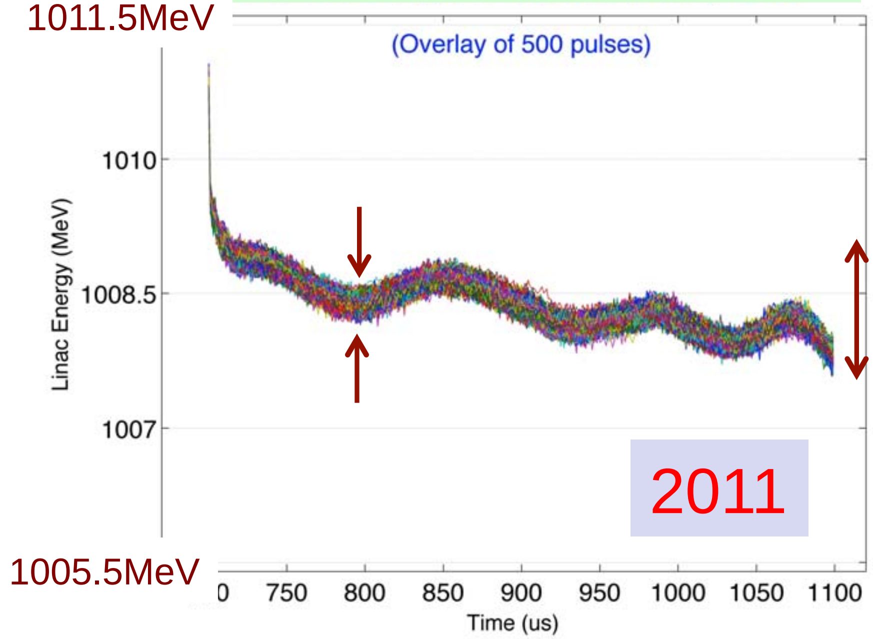
Significantly better performance than in Sept 2009

Linac energy, 3mA, 500us
(overlay of 200 pulses)



Delta-E over bunch-train: ~5MeV
Pulse-to-pulse jitter (p-p): ~4MeV

Linac energy, 4.3mA, 400us
(overlay of 500 pulses)



Delta-E over bunch-train: ~1.5MeV
Pulse-to-pulse jitter (p-p): ~0.4MeV

Future studies

Why didn't we push for 9mA for the Feb '11 studies?

- **Operations rationale**
  - Achieving stable long bunch-train operation at 3nC could have taken a large fraction of the 15 shifts available
  - Much could still be learnt with beam current less than 9mA
  - We operated in 'FEL Mode' with bunch charge up to ~1.7nC
  - It was a good decision to operate in FEL mode!

- **Achieving flat gradients with moderate current was already expected to be quite difficult**

- ***Open issue for future studies: when to next push for 9mA***

Achieved / still to do to in TDP…

- **Demonstrate principles of tailoring Pks/Qls to flatten cavity gradients with beam loading**

Done!

- **Module operation close to quench with ILC-like gradients & gradient spread and ILC-like beams**

Significant progress

- **Next logical steps**
  1. Flatten gradients on all 16 cavities with 6mA / 800us bunch-trains, including
     - Better control of systematic errors
     - Automated procedures for Pk/Ql optimization
  2. Operation of all 16 cavities within a few percent of quench with 6mA / 800us bunch-trains

Preparatory studies at NML...?

Specific requisites / issues for next studies

1. **Flattening gradients on all 16 cavities with 6mA / 800us bunch-trains would require:**
   - Changing Pfwd ratios for low gradient cavities (new ASTs)
   - RF gun conditioned for 800us pulses (FLASH ops)
   - Machine studies to establish 2nC/1200-bunch operation

2. **Operating all 16 cavities within a few percent of quench limits with 6mA / 800us bunch-trains would also require:**
   - A viable methodology for ramping to 6mA / 800us pulses at maximum gradients without quenching the cavities

- **In both cases, would require**
  - Better characterization and control of systematic errors
  - Perhaps finer resolution control of QLs

Last item…

Second Workshop on linac operations with long bunch-trains

- **Nominally 2-1/2 days, June 6th to 8th at DESY**
- **Monday afternoon to Wednesday afternoon would be the best compromise for remote participation**
- **This time, no parallel sessions (just plenary), but we still want it to be a workshop and not a mini conference**
- **Anticipate a lot of results an analysis from the Feb '11 studies and from long bunch-train studies for FEL users**
- **Comments and suggestions on workshop topics are invited**

Summary

- **Flawless operation of the FLASH accelerator**
- **Good progress towards TDP R&D goals**
  - Achieved flat gradients +/-few % at 1.5mA - 4.5mA
  - Gradient spreads up to 17-25MV/m
  - Lorentz-force detuning compensation with beam loading
- **Significant operational experience, insight into practical issues:**
  - Fine control of and repeatability of setting Loaded-Q
  - Absolute measurements: Loaded Q, Detuning
- **Next studies (likely early 2012): refine procedures, aim for higher currents + gradients closer to quench**

BACKUPS

Long bunch-train studies at TTF/FLASH

2002		z	750 bunches	2.8nC	Feasibility	
2007		z	800 bunches	0.6nC	Lasing	
Sept 08	F2/FLASH	1MHz	550 bunches	2.7nC	9mA Expt.	
Sept 09	TTF2/FLASH (Bypass mode)	1MHz 3MHz	800 bunches 2400 bunches	3nC 2nC	9mA Expt.	42 shifts
Feb '11	TTF2/FLASH (FEL mode)	1MHz 3MHz	400 bunches 1200 bunches	1.7nC	9mA Expt.	15 shifts
(Early '12)						

Establish high-power, long beam-pulse operation

Achieve constant gradients <u>for each individual cavity</u> during the long beam pulse

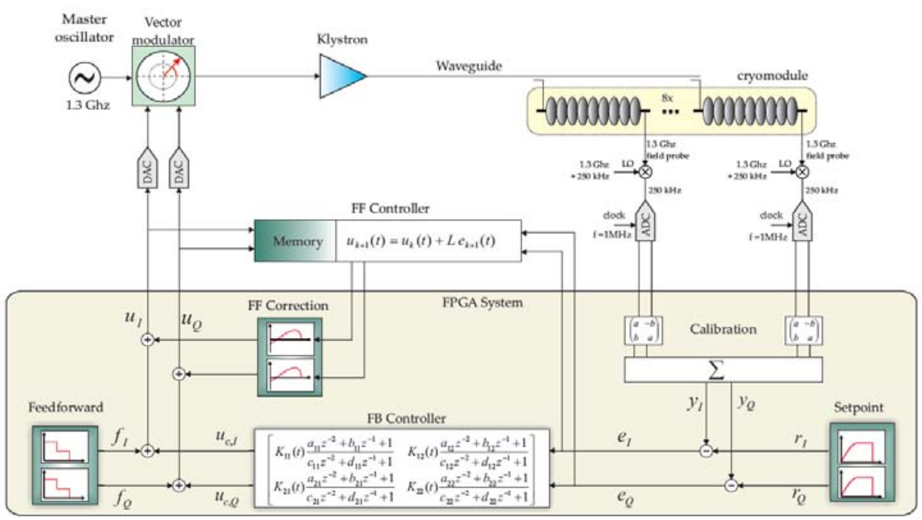
FLASH FEL user op. typical in 2010 (bunch charge ≤1nC)	1-30 bunches @ 1MHz 80 bunches @ 100kHz 200 bunches @ 250kHz

European XFEL

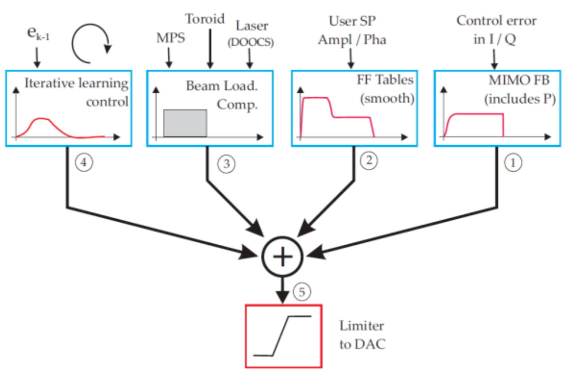
Upgrade of LLRF system

- Upgrade of all RF stations using SimconDSP controller
- RF control for 3.9GHz
- New cabling in injector racks
- **Upgrade & unified FPGA controller firmware**
  - Multiple feed forward table (main/beam loading/correction)
  - Multiple setpoint table (main/beam based correction)
  - Model based Multiple In Multiple Out (MIMO) controller
  - Charge correction & intra-train beam based feedback
  - Exception & Error handling, limiters
  - Error and status displays

Scheme of LLRF RF controller

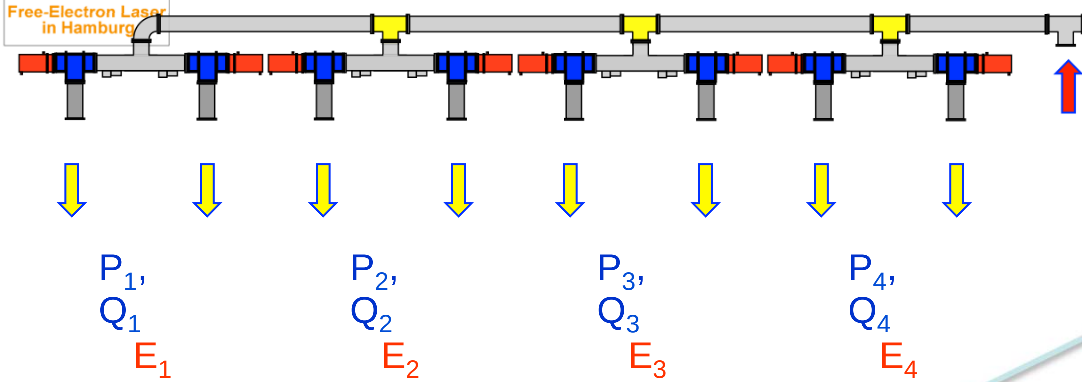


Feed forward table architecture

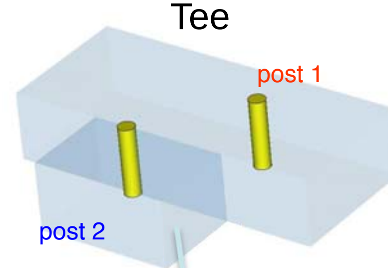


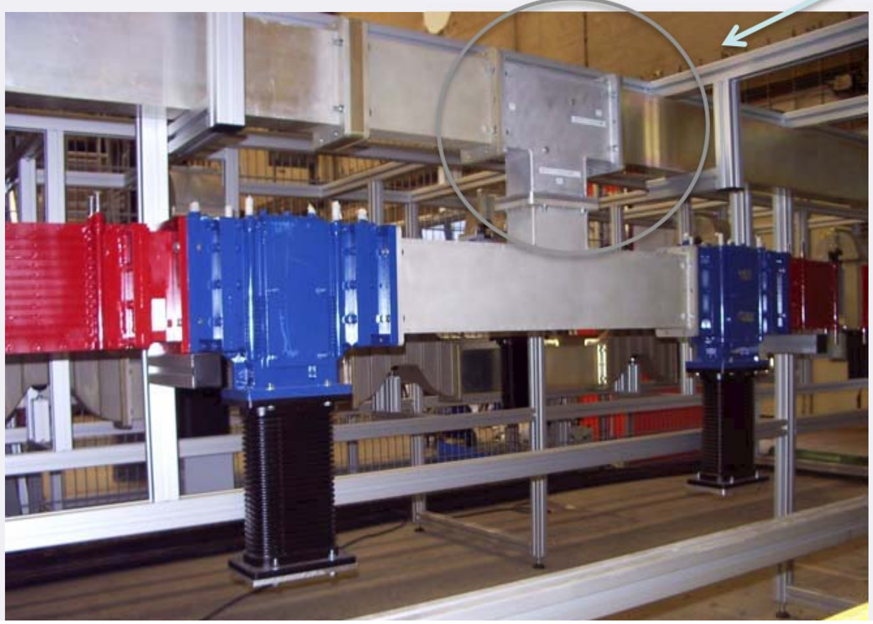
Courtesy: LLRF team

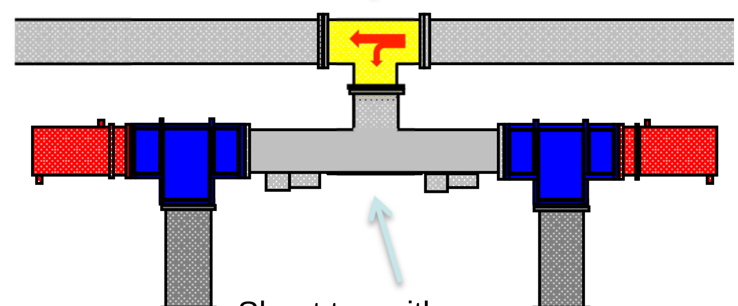
Waveguide distribution system for ACC6 (ACC7 similar)



Asymetric Shunt Tee







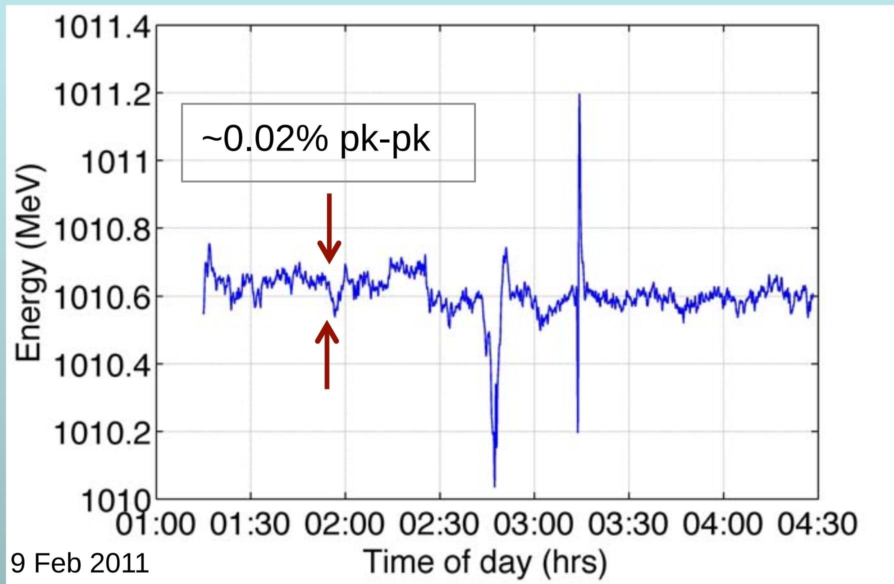
Shunt tee with integrated phase shifter

Posts in AST are fixed in place during manufacture – locations are determined analytically from the desired power ratio.

Measured power ratio is typically within +/-0.1dB of the design value

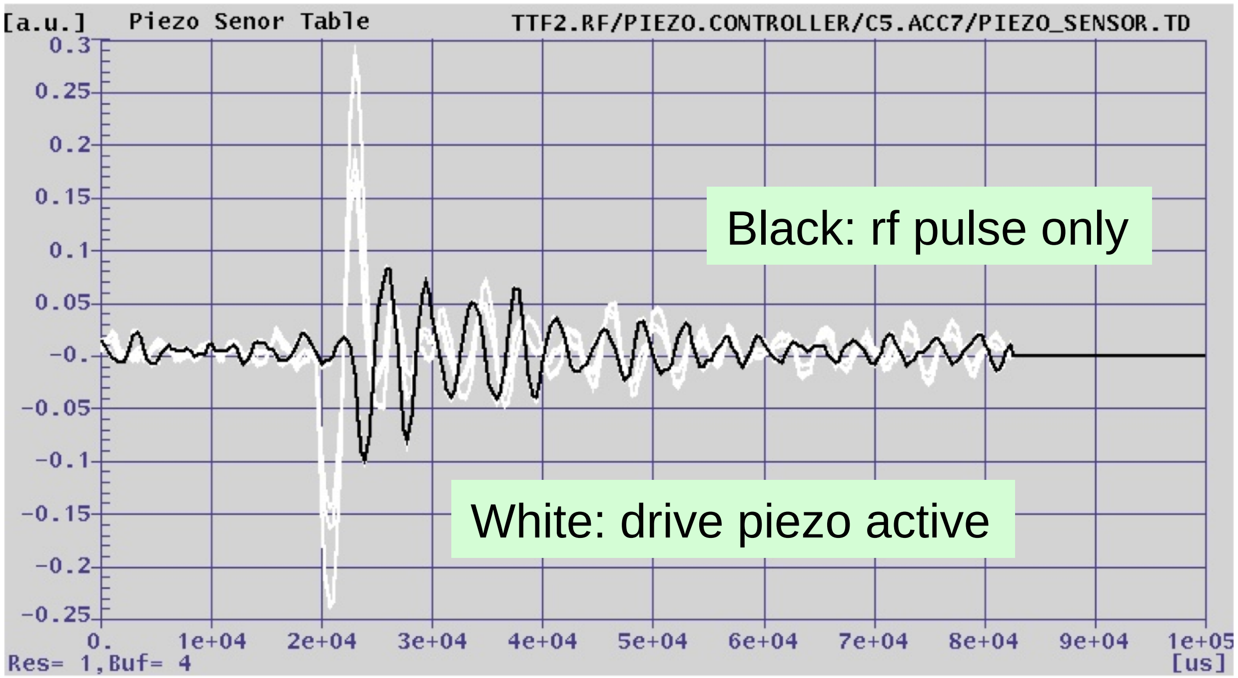
To change the power ratio, would have swap out the ASTs with a new set (requires 2-3 days tunnel access)

Energy stability over 3hrs with 4.5mA



- **15 consecutive studies shifts (120hrs), and with no downtime**
- **Time to restore 400us bunch-trains after beam-off studies: ~10mins**
- **Energy stability with beam loading over periods of hours: ~0.02%**
- **Individual cavity “tilts” equally stable**

Comparison of piezo signal from rf pulse ping only and ping from drive piezo



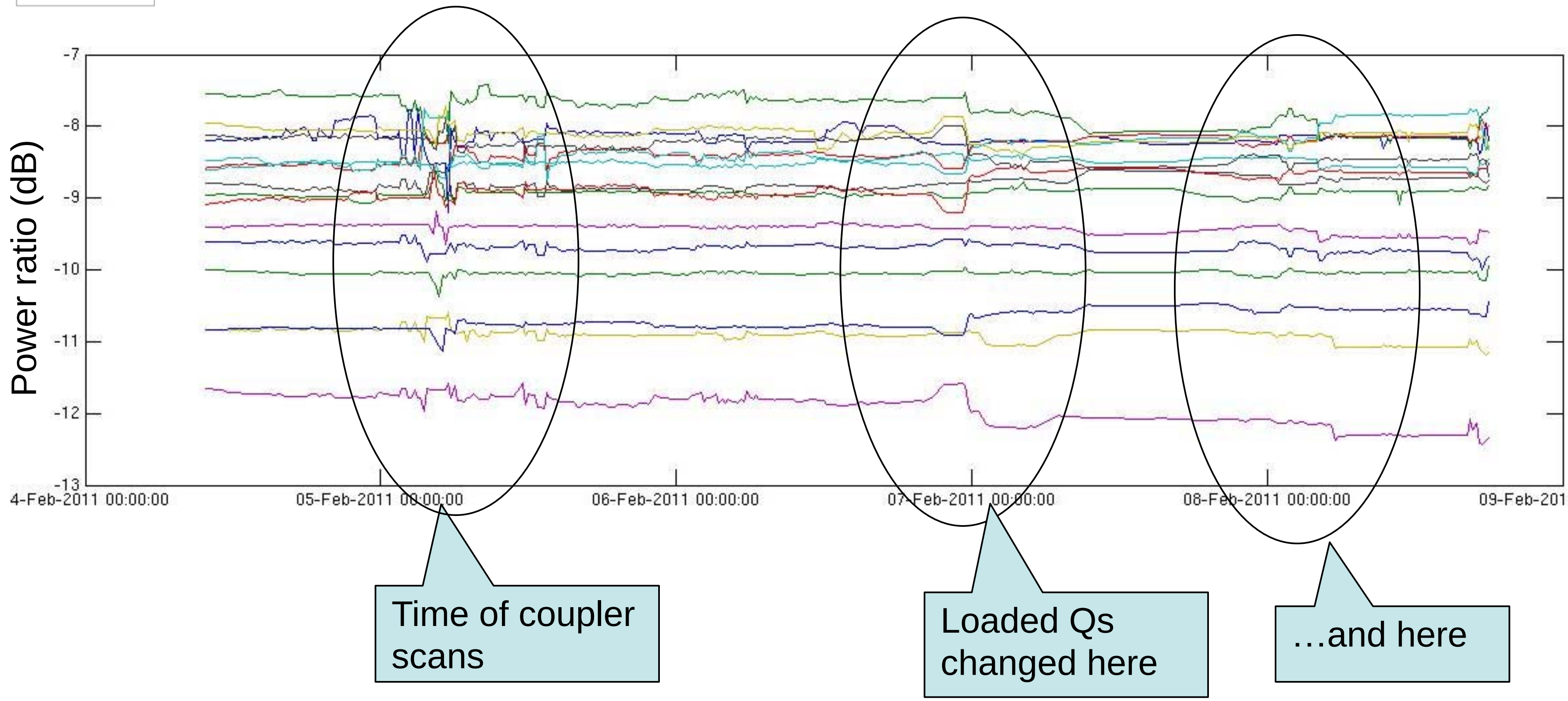
- **The ping used for Lorentz-force detuning compensation is quite large compared with the ping from the cavity itself**
- **But what's important for LFD compensation is the detail during the rf pulse itself**

What else can we learn from the results of the beam current scans?

- **Slopes of the relationship between gradient tilts and beam current**
  - A linear relationship is expected analytically.
  - The slope is a function of the loaded Q
  - Calibration errors in the beam current measurement would show up self-consistently in the slopes of all the cavities
  - What role does detuning play?

- **Self-consistency check of measured parameters**
  - Back-calculate forward power from gradient, loaded Q, beam current scans. Compare the result with the measured Pfwd.
  - Repeat this exercise by computing each parameter in turn from all others and comparing results with measurements

ACC67 Forward Power Ratios during 9mA study: 4th to 8th February



For analysis

Components of the RF Power feed-forward

RF power for fill and flat-top are pre-computed from the required vector sum

Learning FF controller fine-tunes the RF power waveform to minimize repetitive errors in vector sum

Beam-loading compensation feed-forward is added during beam-on period (scaled by the bunch charge)