Results from 9mA studies on achieving flat gradients with beam loading

P_K / Q_L studies at FLASH

during the Feb. 2011 test in DESY

OVERVIEW

- Problem statement and historical background
  - Why do we care about individual flat gradients?
  - What solutions were offered to achieve flat gradients with beam loading?
  - What can we actually implement at FLASH?

- The Feb.'11 study at FLASH
  - What approach have we followed during the FLASH test studies?
  - Results of the P_K / Q_L studies

- Conclusions and lessons learnt
  - Study insights
  - Approach limitations
  - Improvements

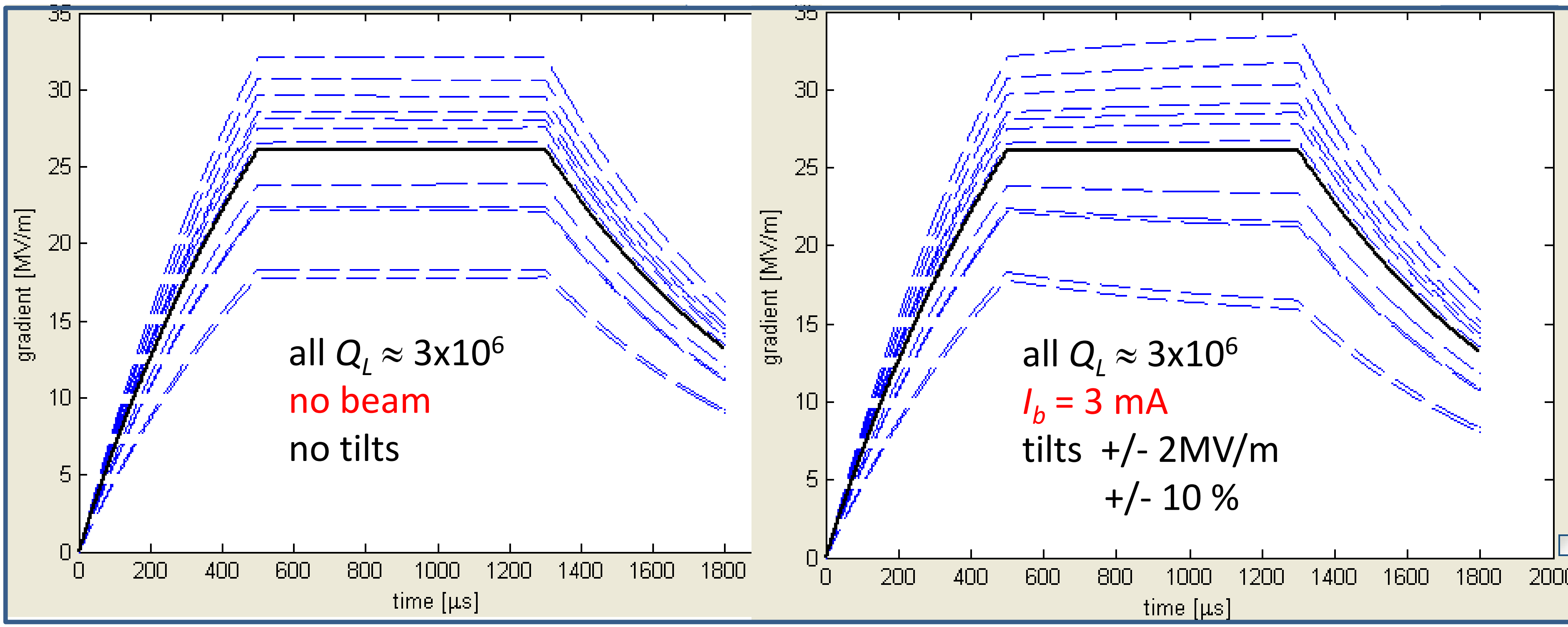
Introduction: problem statement

Why do we care about individual flat gradients?

"Effect of Cavity Tilt and RF Fluctuations to Transverse Beam Orbit Change in ILC Main Linac"

K. Kubo, Jan. 2010

FLASH ACC6 & ACC7



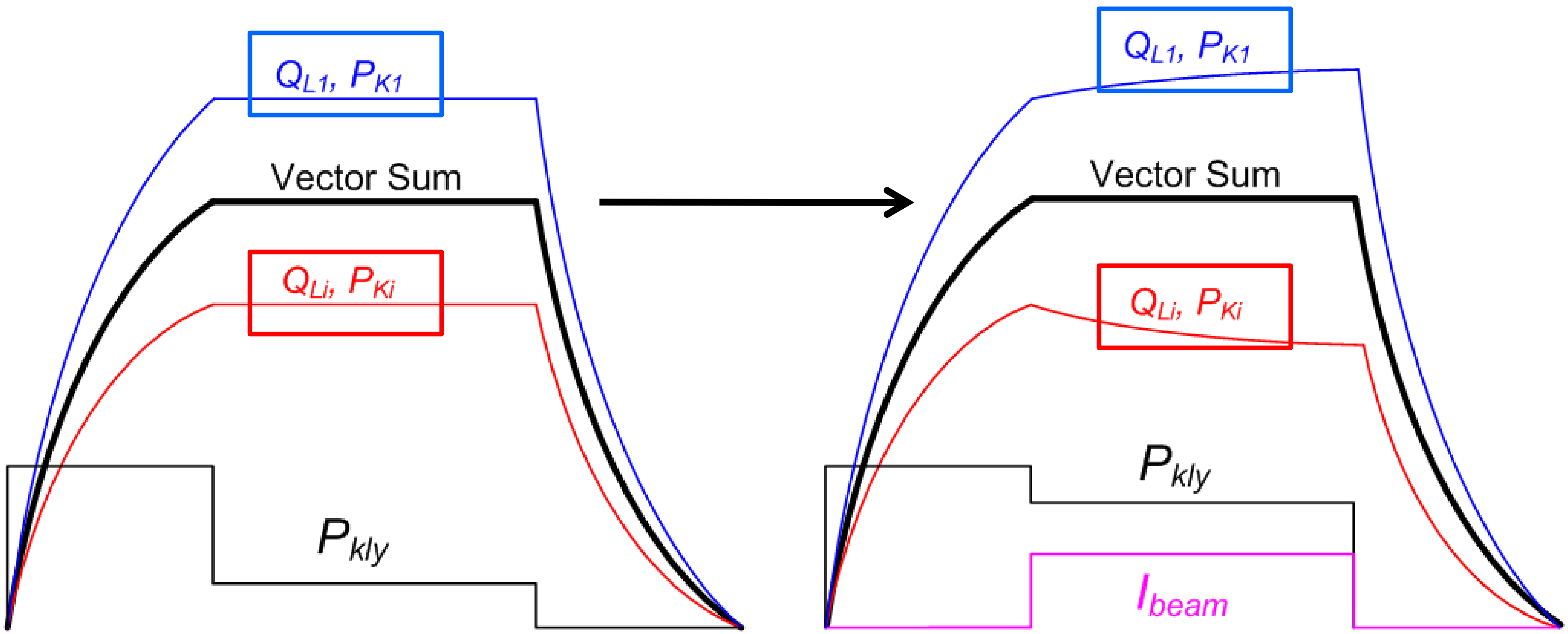
Introduction: problem statement

FNAL approach to cavity quench due to beam ON/OFF operations

"Optimal Coupler and Power Settings for Superconductive Linear Accelerators", J. Branlard, B. Chase, Linac 2008

→ produces fixed P_K/Q_L settings (unique to each cavity) which is safe for all beam loadings
(i.e. no tuning action required to prevent quench)

→ individual cavities gradients have tilts with beam



Beam OFF *Beam ON*

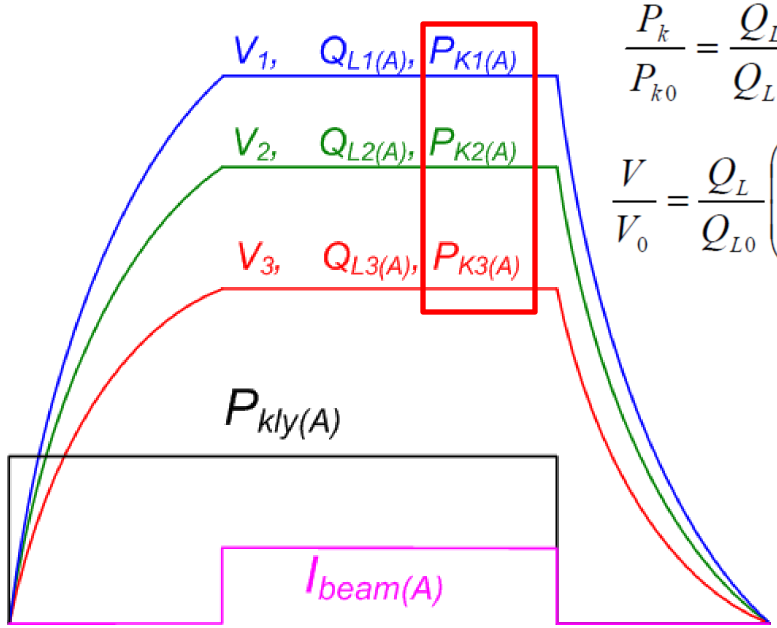
Introduction: problem statement

Published "solutions" to flat cavity gradient with beam

"RF Distribution Optimization in the Main Linacs of the ILC"
Bane, Adolphsen, Nantista - WEPMS037.pdf, 2007

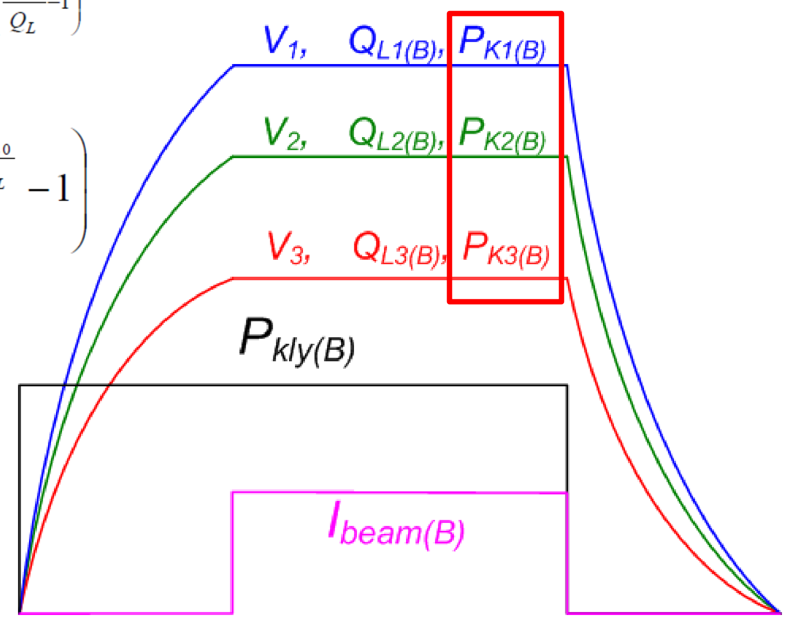
→ Assumes a square forward power pulse

→ Assumes adjustable P_K's



$$\frac{P_k}{P_{k0}} = \frac{Q_L}{Q_{L0}} 4^{\left(\frac{Q_{L0}}{Q_L} - 1\right)}$$

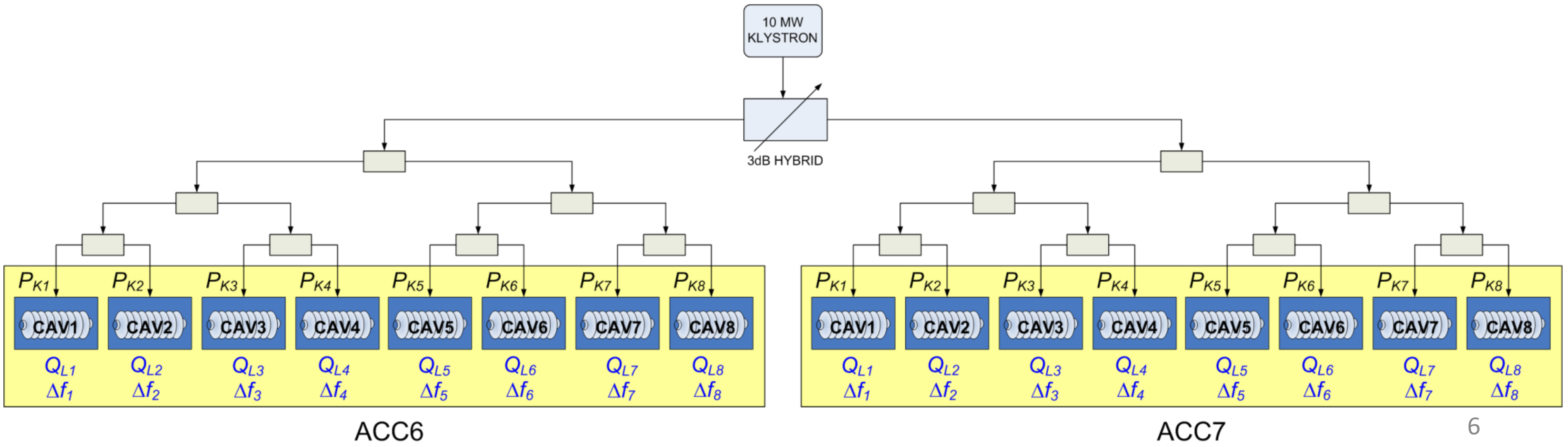
$$\frac{V}{V_0} = \frac{Q_L}{Q_{L0}} \left(2^{\frac{Q_{L0}}{Q_L}} - 1 \right)$$



Introduction: problem statement

Problem space at FLASH

→ Focus on ACC6 and ACC7
→ Motorized couplers (Q_L adjustments, limited range)
→ Fixed power distribution (i.e. P_K), except for 3dB hybrid
→ Motorized static tuners
→ Dynamic cavity resonance control with piezo



Introduction: problem statement

Published "solutions" to flat cavity gradient with beam

"PkQl-like control for ACC6/7 at FLASH" PkQl_FLASHver3.docx — Shin Michizono, Sept. 2010

"To flatten the cavity gradient for ACC6/7" FLASH101022BV2.pdf — Shin Michizono, Nov. 2010

→ solves the same problem but using existing P_K distribution

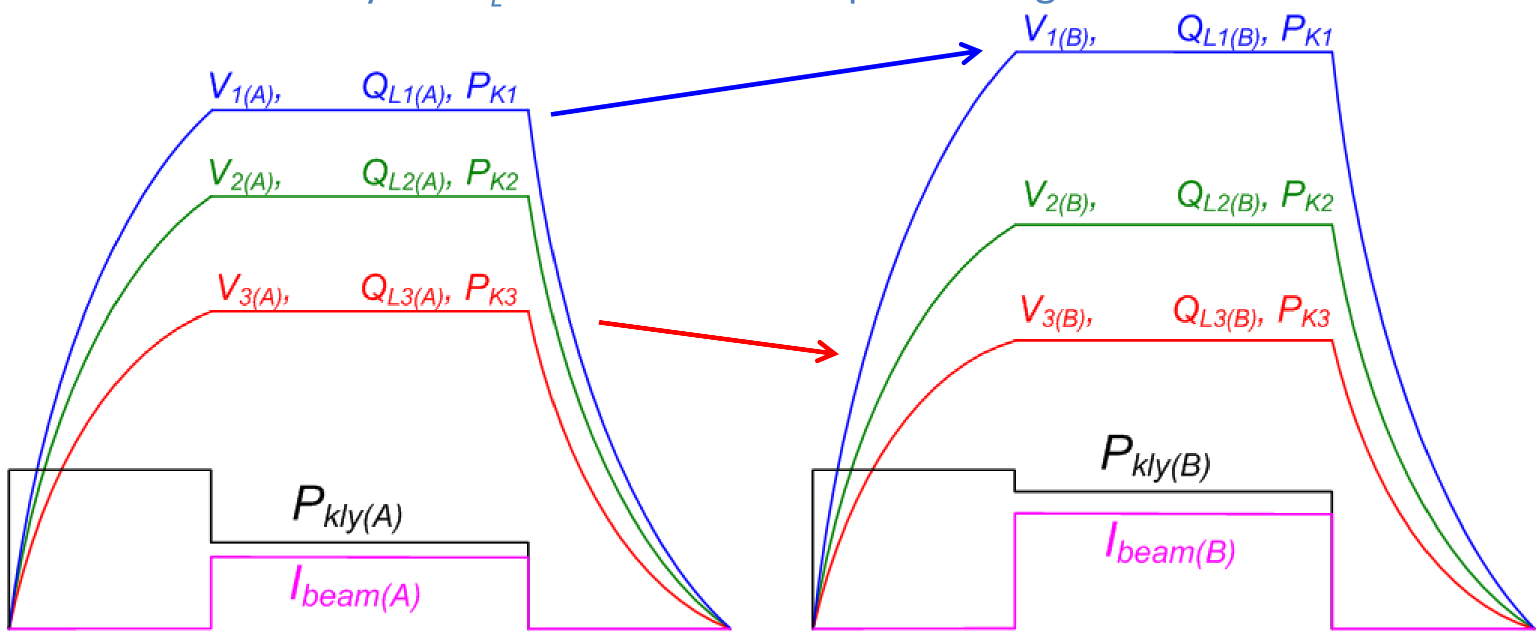
→ no PK adjustments for different beam loading, only Q_L changes

→ version1: assumes a square forward power pulse

yield very low Q_L values

→ version2: assumes a fill time / flat top power step

yield Q_L values within acceptable range



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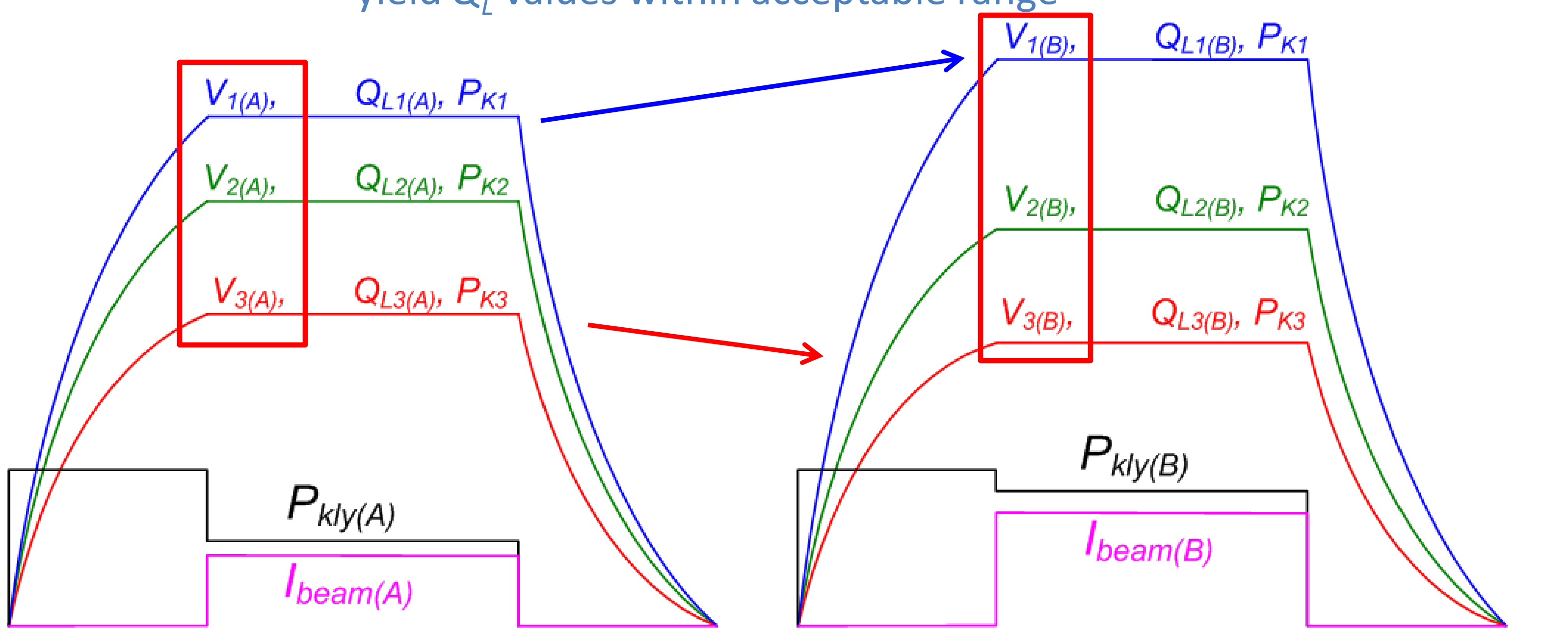


FLASH studies: 5 shift overview

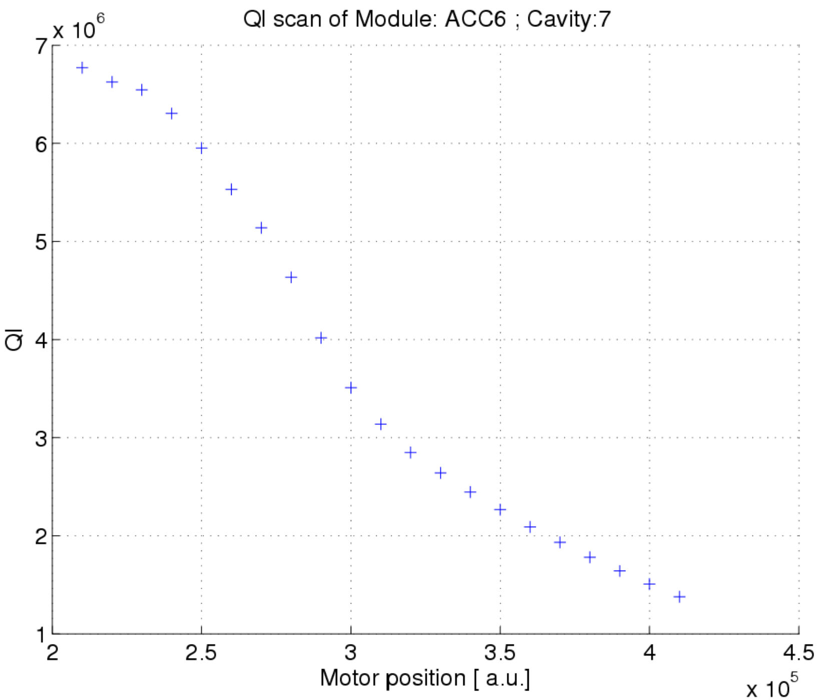
- Friday 2/4 night shift: no beam, low gradient
  - no beam
  - ACC6/7 vector sum calibration 100 bunches, 1 MHz, 1.6 nC
  - QL tuners characterization for ACC6/7
  - simulator calibration to reflect ACC6/7 power distribution
- Saturday 2/5 night shift: 1 mA , low gradient
  - 1mA beam, low gradient (100 MeV – 200 MeV)
  - Successfully implemented QL adjustments to flatten cavity gradients
  - beam loading tilts correction (all tilts below 1%) using simulator predicted values
  - Simulated values are reliable
- Sunday 2/6 night shift: 1.6 mA , mid-gradient
  - 1.6mA beam, low gradient (200 MeV)
  - low gradient, beam loading tilts Q_L correction (below 1%)
  - beam current scan
  - QL scan
- Monday 2/7 night shift: 3.0 mA - 4.5 mA, mid and high gradient
  - 3.0mA beam, 200 MeV
  - QL adjusted for gradient flat at 3mA
  - beam scan from 0.9 to 4.5 mA
  - 4.5mA beam, 300 MeV
  - QL adjusted for gradient flat at 4.5 mA
  - beam current scan
- Tuesday 2/8 afternoon shift: 4.2 mA, highest gradient
  - 4.2mA beam, 360 MeV
  - Lorentz force detuning compensation
  - Use calculator to predict QL → gives very accurate prediction
  - Flatten ACC6/7 gradients tilts to ~ 1.5%
  - beam current scan

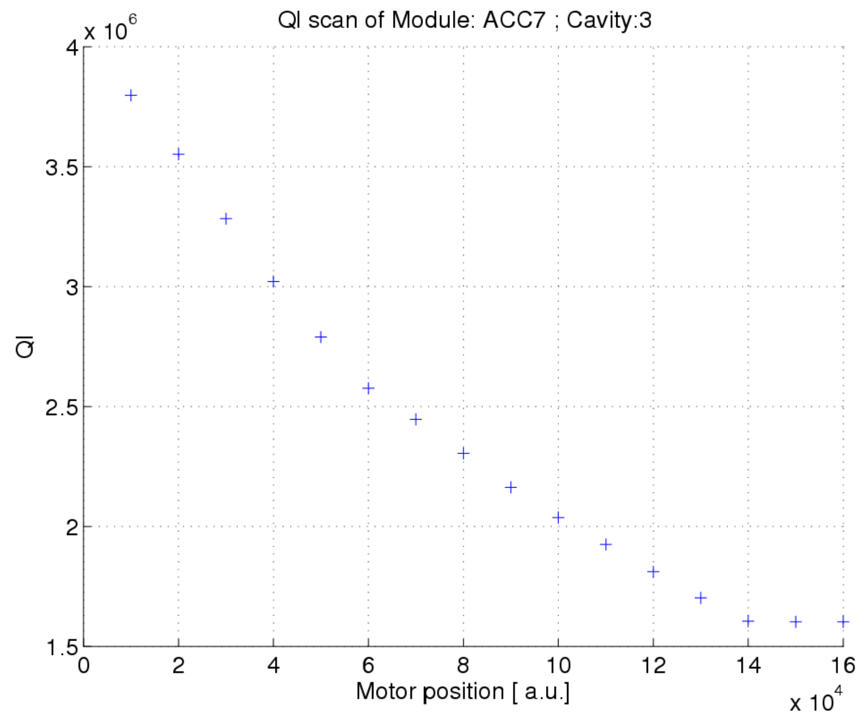
ACC6 & ACC7 Q_L settings limits

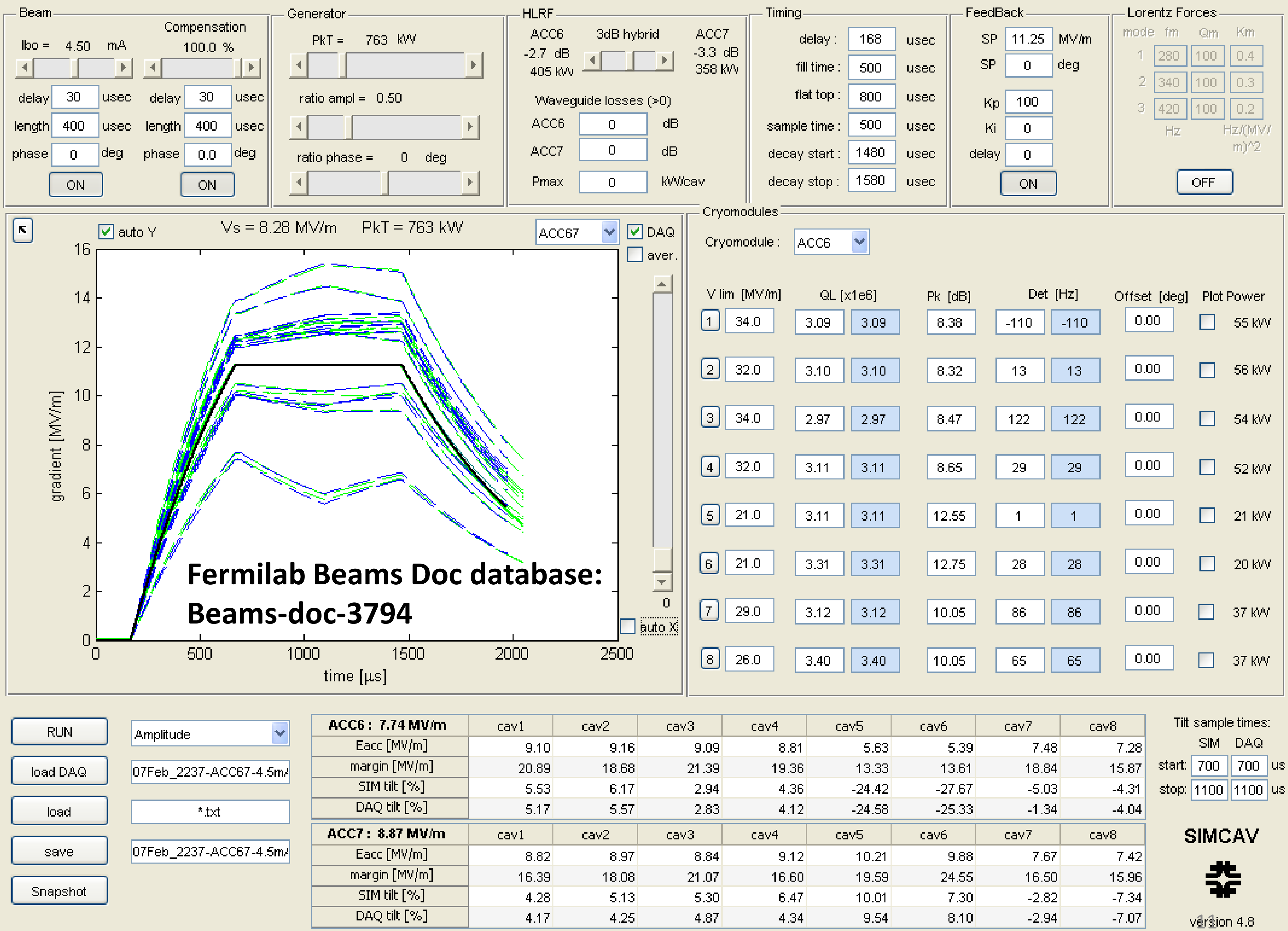
ACC6	cav1	cav2	cav3	cav4	cav5	cav6	cav7	cav8
Q_L min [x10^6]	1.2	1	1.2	1	1.5	1.5	1.5	1
Q_L max [x10^6]	7	5	7.5	5.5	8.5	7.5	6.5	4

ACC7	cav1	cav2	cav3	cav4	cav5	cav6	cav7	cav8
Q_L min [x10^6]	1.1	1.8	1.6	1.3	1.1	1.4	1.7	2.1
Q_L max [x10^6]	3.4	3.8	3.7	3.6	3.3	3.3	3.3	4.6

not "hard" limits







ACC6 : 7.74 MV/m	cav1	cav2	cav3	cav4	cav5	cav6	cav7	cav8
Eacc [MV/m]	9.10	9.16	9.09	8.81	5.63	5.39	7.48	7.28
margin [MV/m]	20.89	18.68	21.39	19.36	13.33	13.61	18.84	15.87
SIM tilt [%]	5.53	6.17	2.94	4.36	-24.42	-27.67	-5.03	-4.31
DAQ tilt [%]	5.17	5.57	2.83	4.12	-24.58	-25.33	-1.34	-4.04

ACC7 : 8.87 MV/m	cav1	cav2	cav3	cav4	cav5	cav6	cav7	cav8
Eacc [MV/m]	8.82	8.97	8.84	9.12	10.21	9.88	7.67	7.42
margin [MV/m]	16.39	18.08	21.07	16.60	19.59	24.55	16.50	15.96
SIM tilt [%]	4.28	5.13	5.30	6.47	10.01	7.30	-2.82	-7.34
DAQ tilt [%]	4.17	4.25	4.87	4.34	9.54	8.10	-2.94	-7.07

Beam

Ibo = 4.50 mA | Compensation 100.0 %

delay 30 usec | delay 30 usec

length 400 usec | length 400 usec

phase 0 deg | phase 0.0 deg

ON | ON

Generator

PkT = 763 kW

ratio ampl = 0.50

ratio phase = 0 deg

HLRF

ACC6 -2.7 dB 405 kW | 3dB hybrid | ACC7 -3.3 dB 358 kW

Waveguide losses (>0)

ACC6 0 dB

ACC7 0 dB

Pmax 0 kW/cav

Timing

delay :	168	usec
fill time :	500	usec
flat top :	800	usec
sample time :	500	usec
decay start :	1480	usec
decay stop :	1580	usec

FeedBack

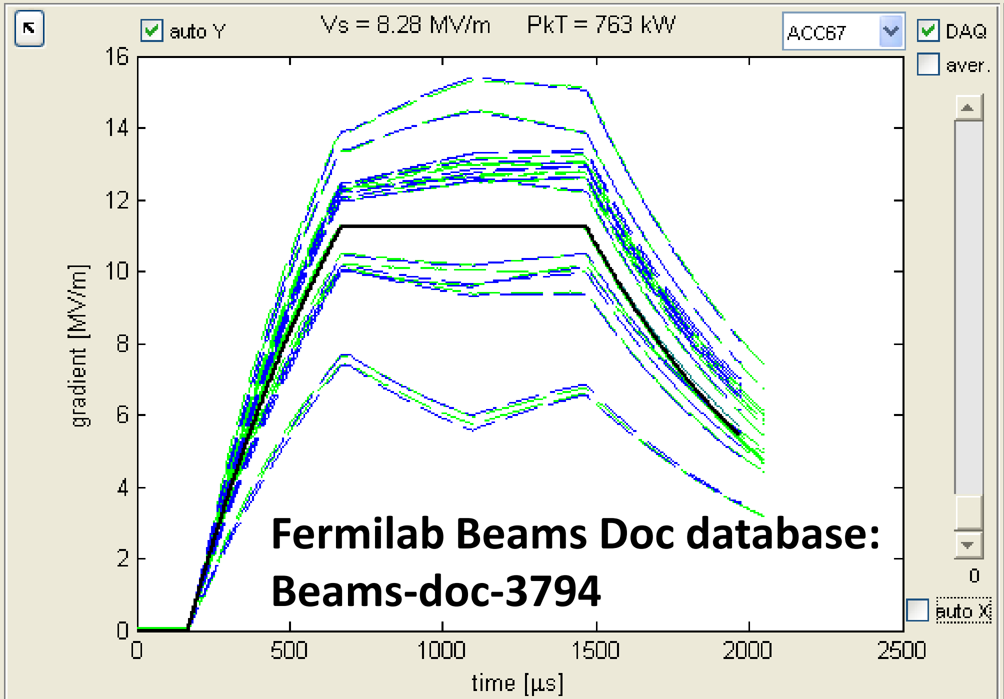
SP	11.25	MV/m
SP	0	deg
Kp	100	
Ki	0	
delay	0	

ON

Lorentz Forces

mode	fm	Qm	Km
1	280	100	0.4
2	340	100	0.3
3	420	100	0.2
	Hz		Hz/(MV/m)^2

OFF



Cryomodules

Cryomodule : ACC6

	V lim [MV/m]	QL [x1e6]		Pk [dB]	Det [Hz]		Offset [deg]	Plot Power
1	34.0	3.09	3.09	8.38	-110	-110	0.00	55 kW
2	32.0	3.10	3.10	8.32	13	13	0.00	56 kW
3	34.0	2.97	2.97	8.47	122	122	0.00	54 kW
4	32.0	3.11	3.11	8.65	29	29	0.00	52 kW
5	21.0	3.11	3.11	12.55	1	1	0.00	21 kW
6	21.0	3.31	3.31	12.75	28	28	0.00	20 kW
7	29.0	3.12	3.12	10.05	86	86	0.00	37 kW
8	26.0	3.40	3.40	10.05	65	65	0.00	37 kW

RUN | Amplitude

load DAQ | 07Feb_2237-ACC67-4.5mA

load | *.txt

save | 07Feb_2237-ACC67-4.5mA

Snapshot

ACC6 : 7.74 MV/m	cav1	cav2	cav3	cav4	cav5	cav6	cav7	cav8
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DAQ tilt [%]	4.17	4.25	4.87	4.34	9.54	8.10	-2.94	-7.07

Tilt sample times:

	SIM	DAQ	
start:	700	700	us
stop:	1100	1100	us

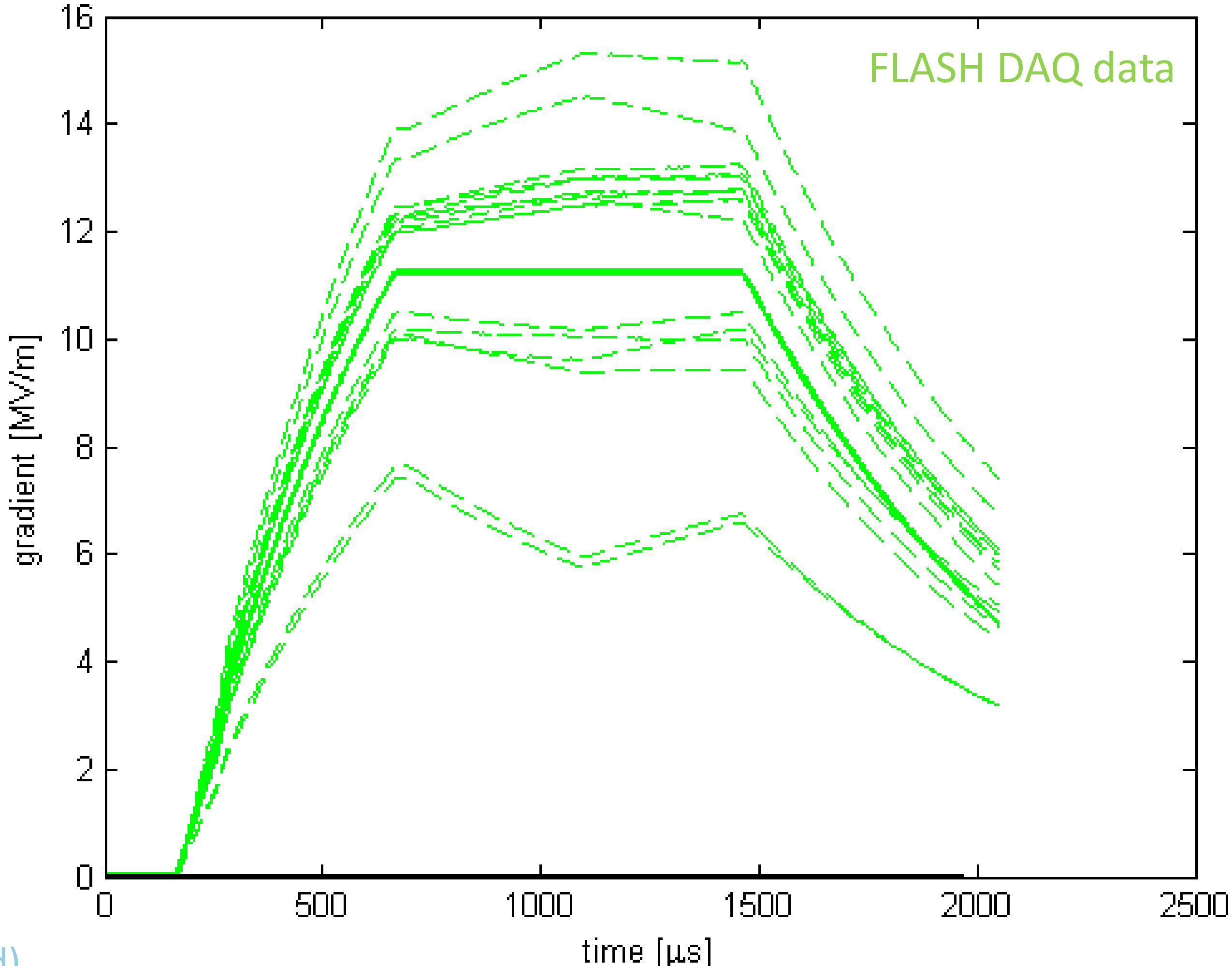
SIMCAV

version 4.8

Calibration procedure

1. Load V_{cav} from DAQ
2. Compute actual Q_L , P_K and Δ_f from DAQ data
3. Type in Q_L, P_K and Δ_f into simulator
4. Check agreement between simulated and FLASH data
5. Adjust Q_L in simulator to flatten tilts
6. Implement Q_L corrections in FLASH
7. Check gradient flatness (retune cavities if needed)

DAQ data: Feb. 07 2011, 22:37



I_b = 4.5 mA

Calibration procedure

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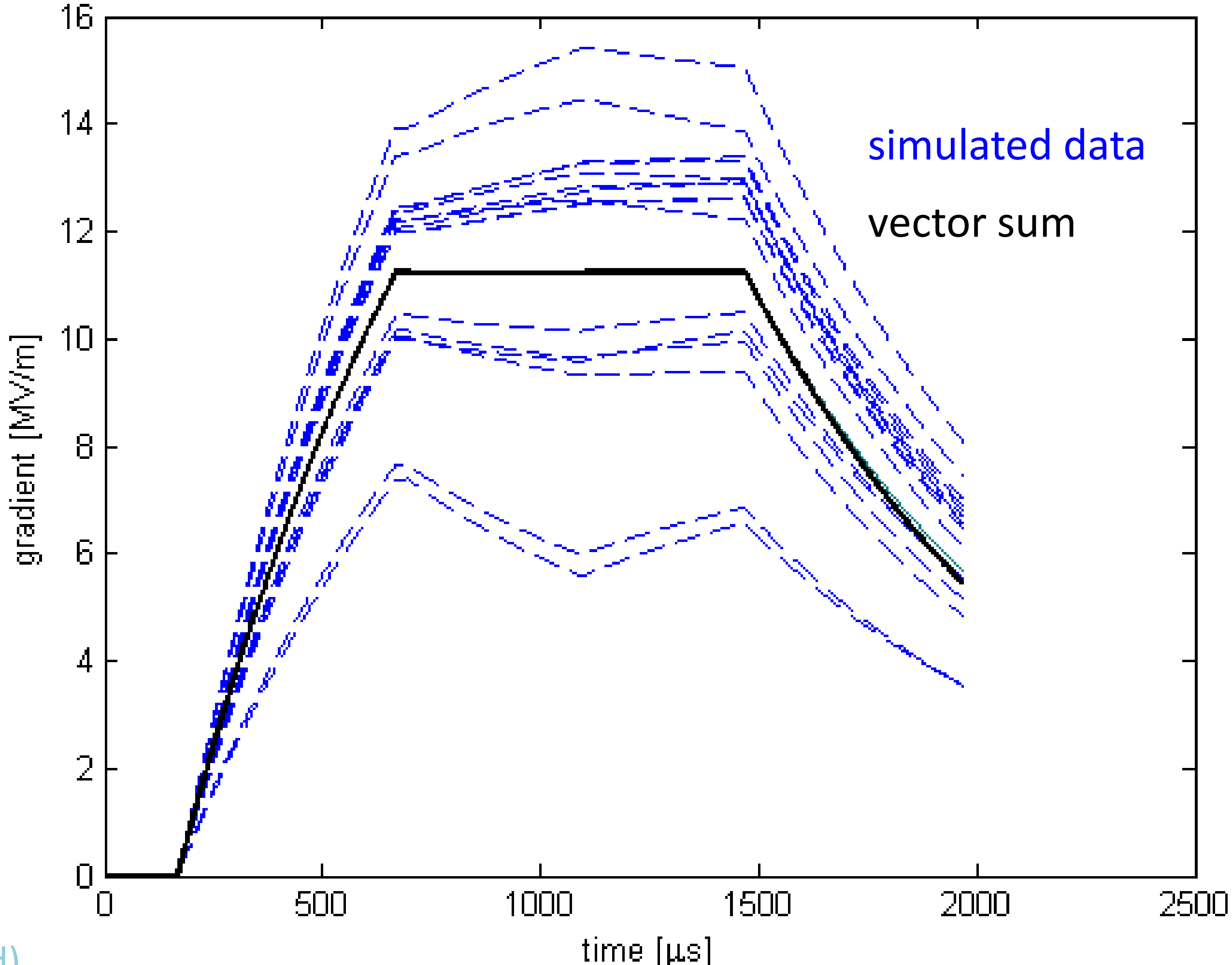

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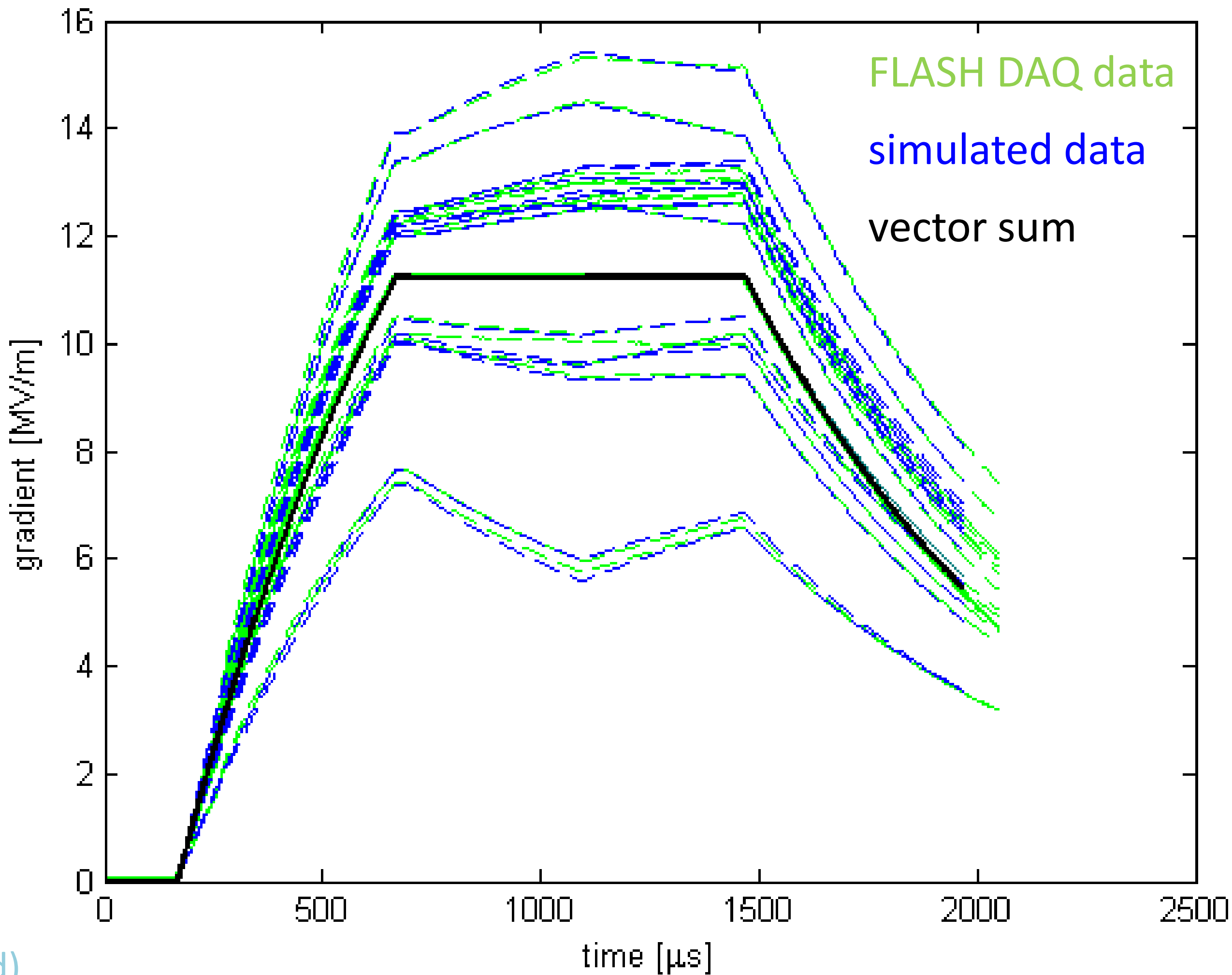

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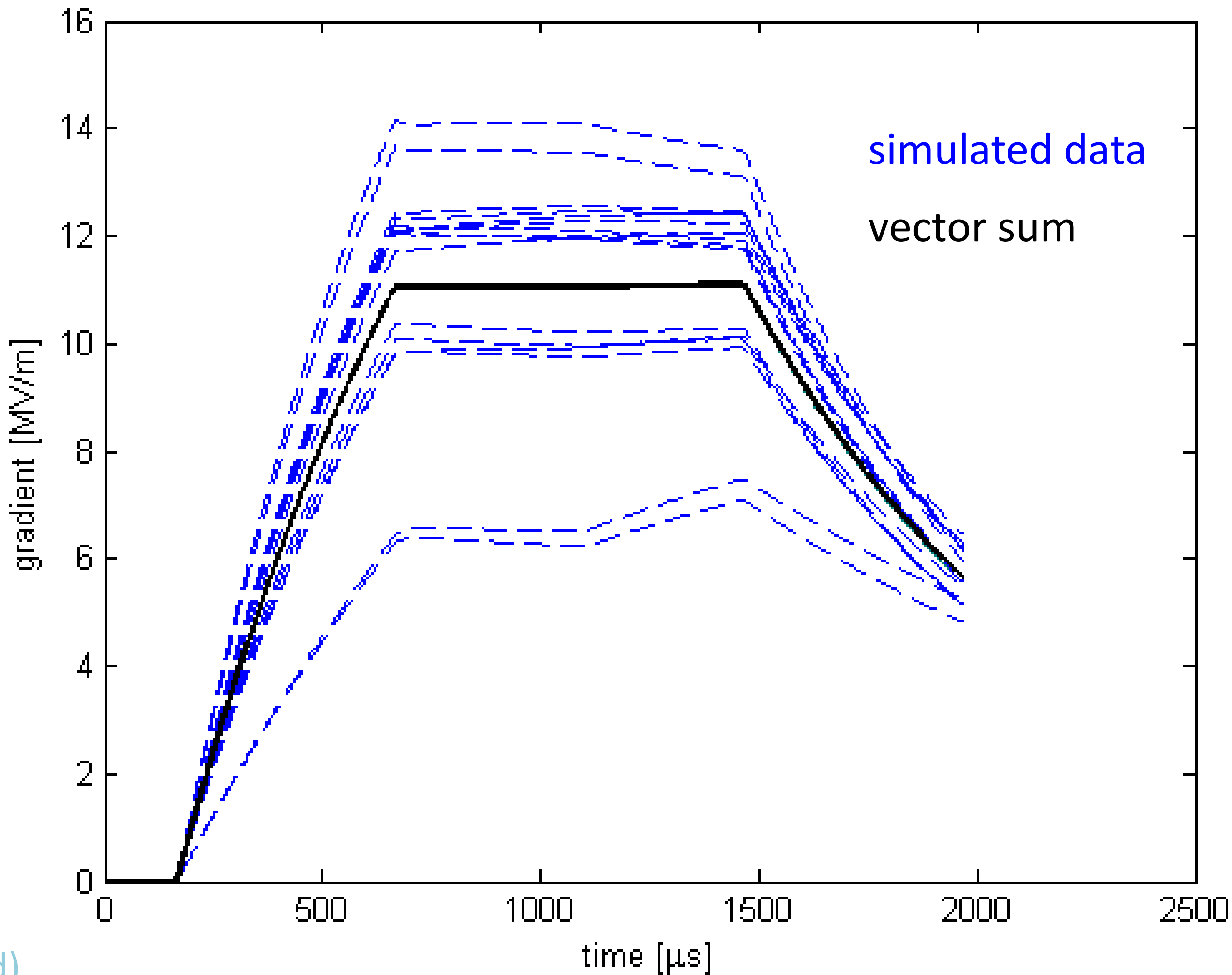

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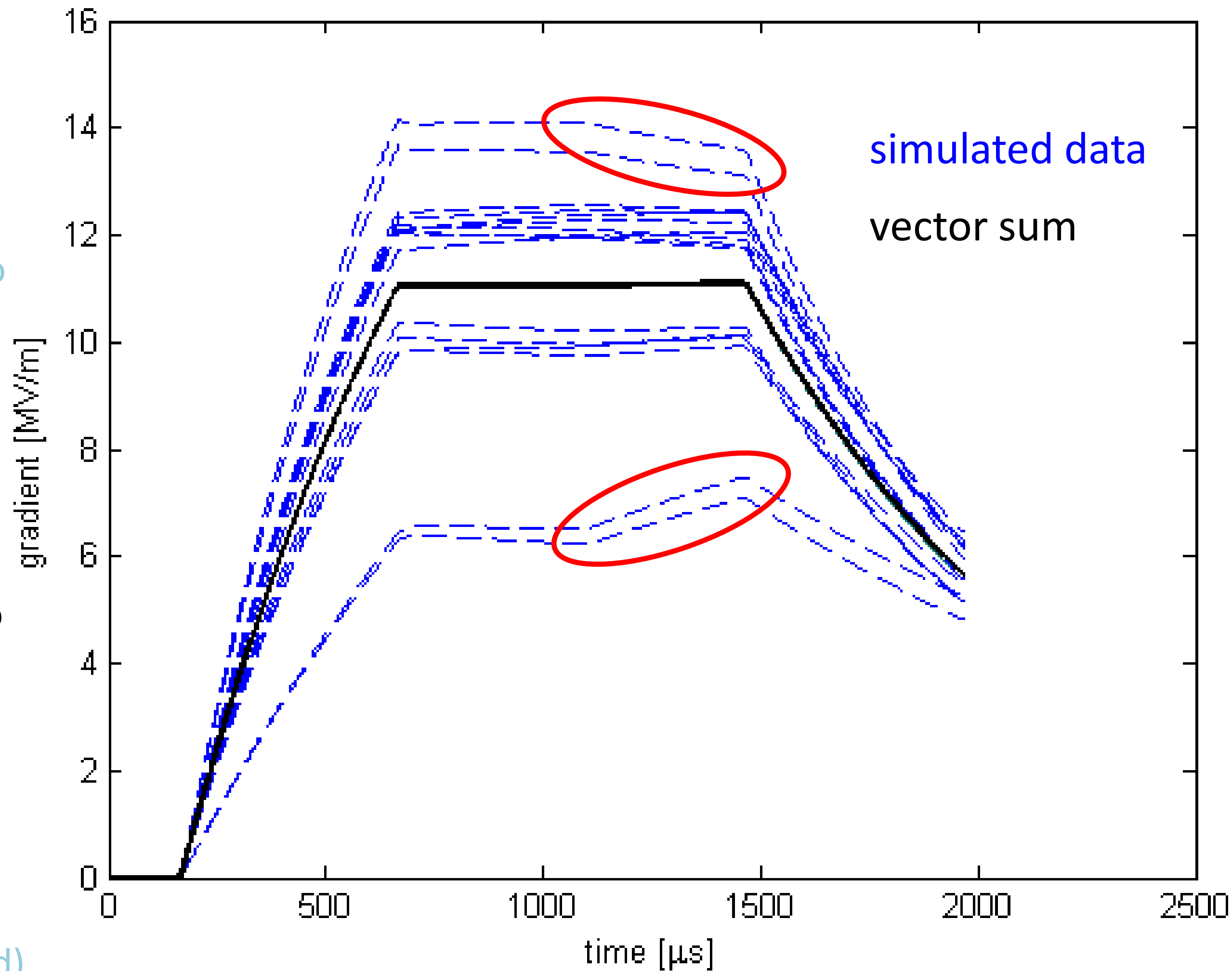

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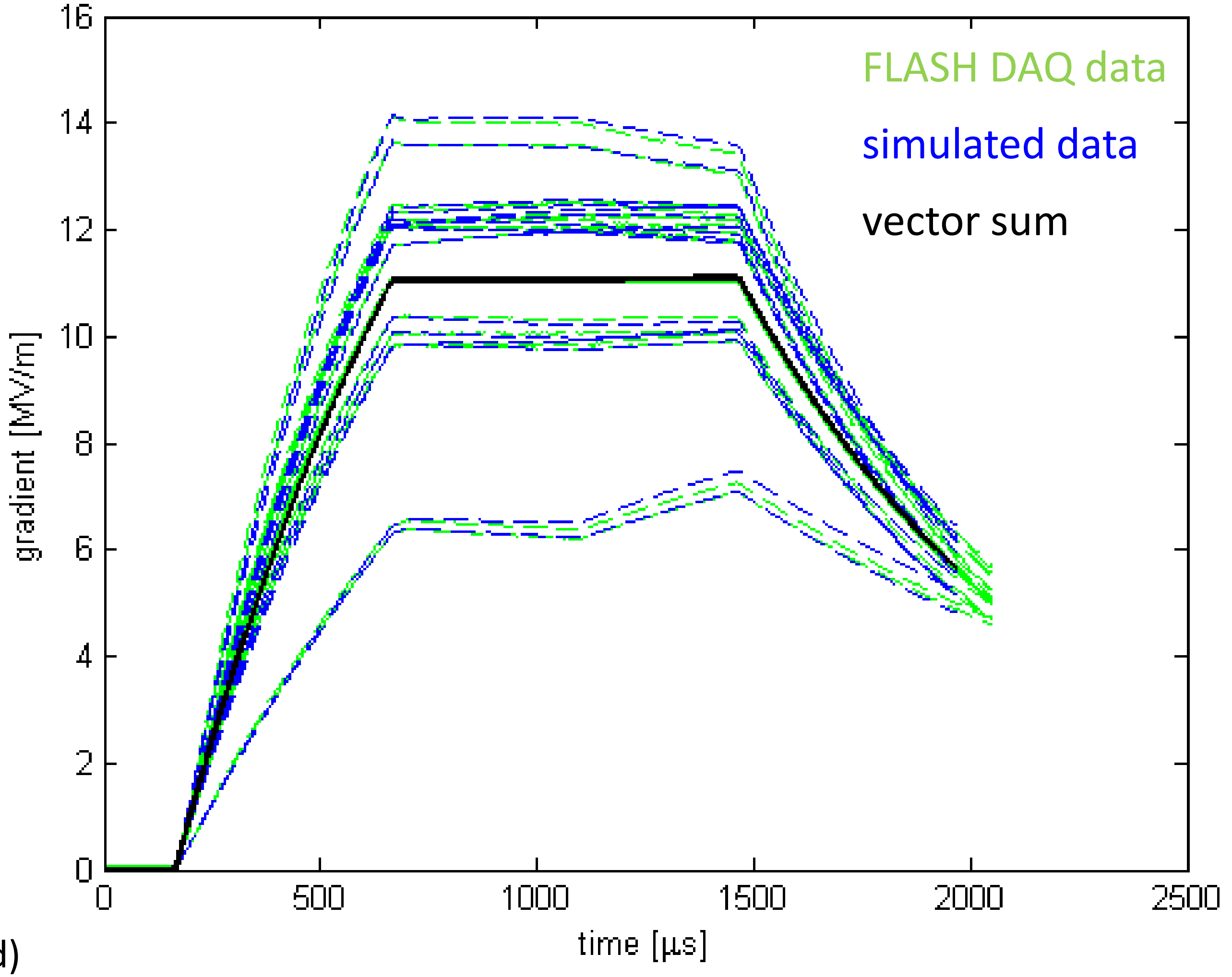
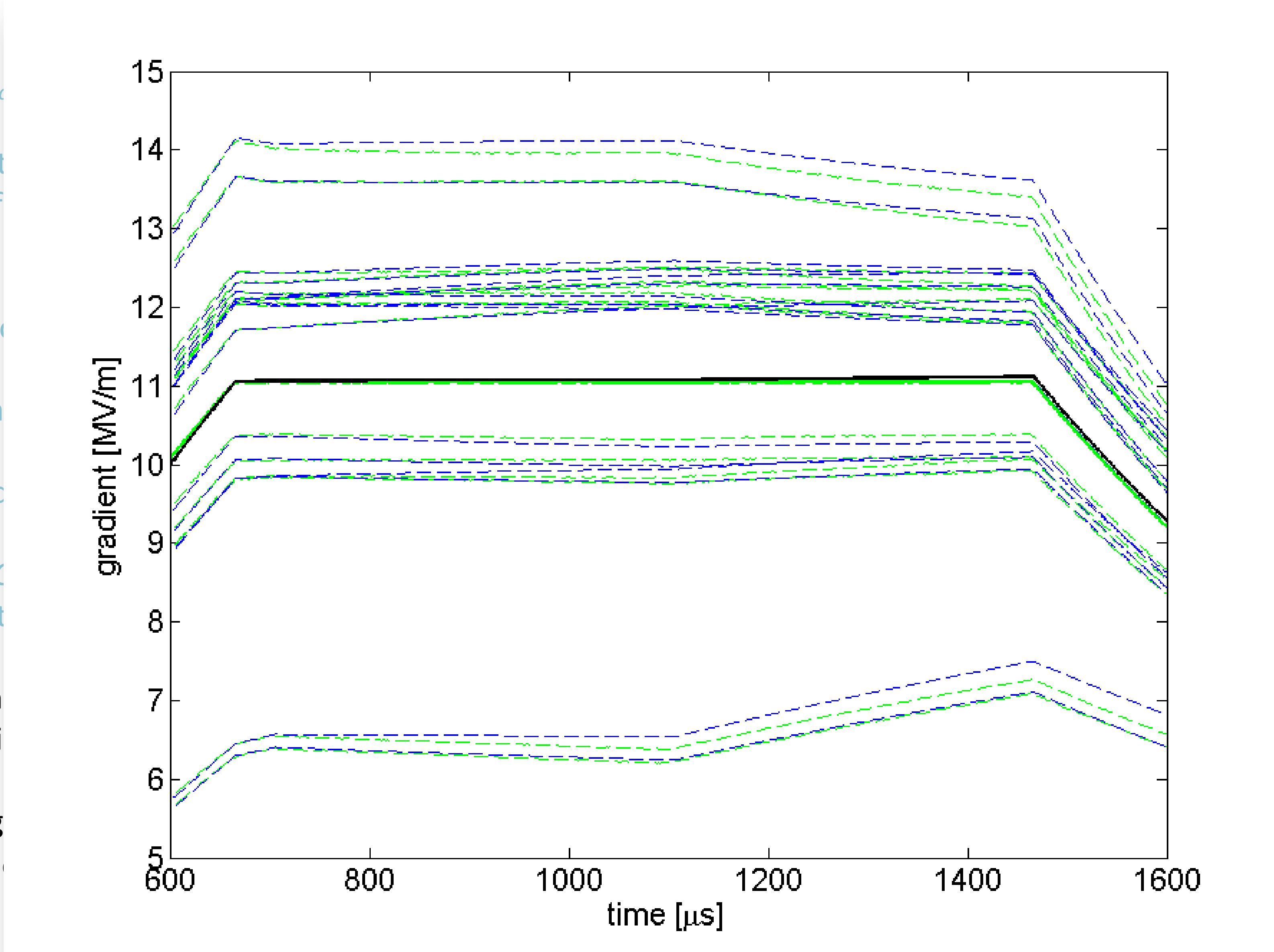


Calibration procedure

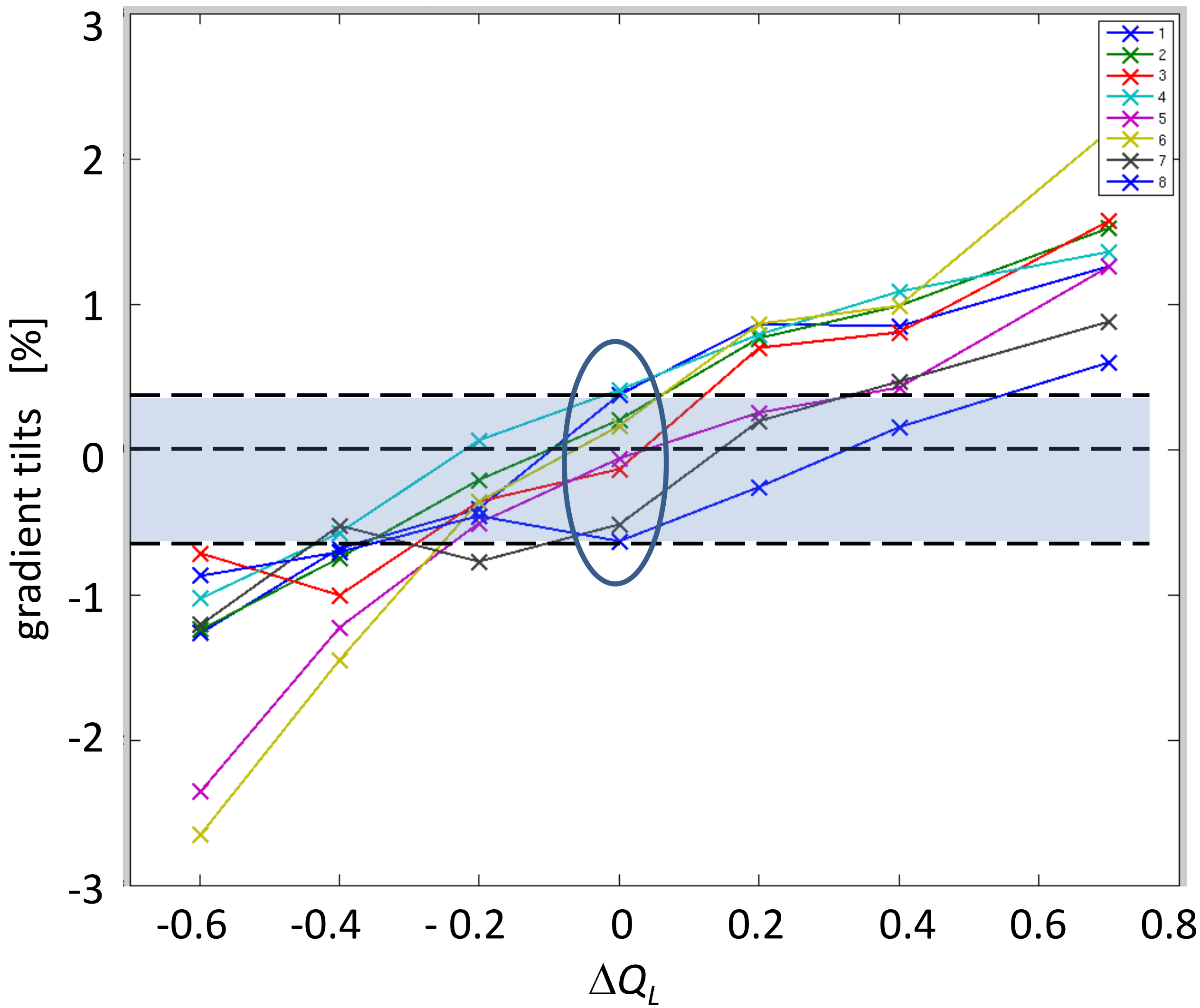
1. Load V_{cc}
2. Comput and Δ_f f
3. Type in simulat
4. Check a betwee FLASH c
5. Adjust (flatten t
6. Implem correcti
7. Check g (retune



Assessing the accuracy of the model

- Q_L scan
  → Keep beam current constant but walk Q_L's around optimized value

- I_B scan
  → Keep optimized Q_L's but ramp beam up/down



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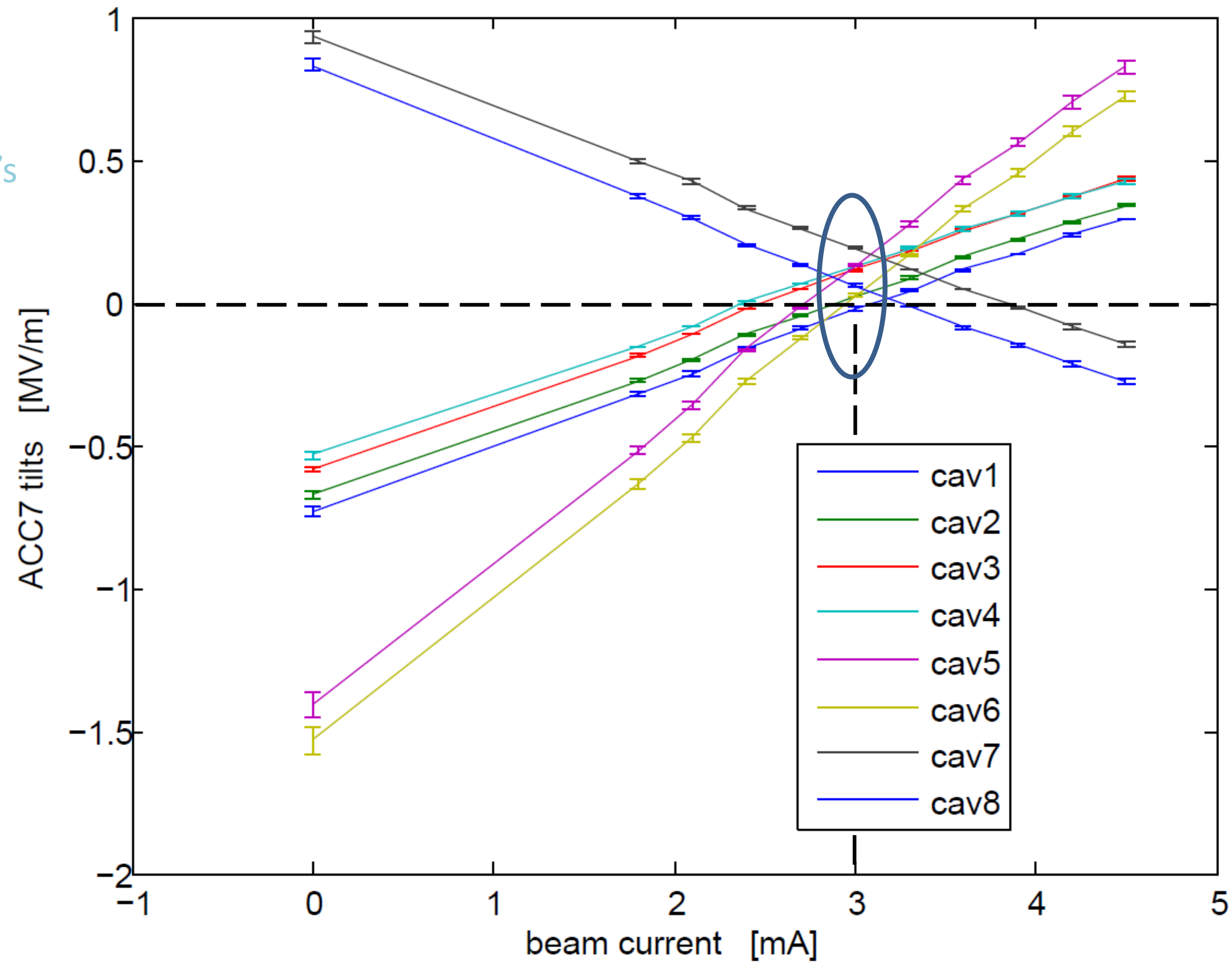
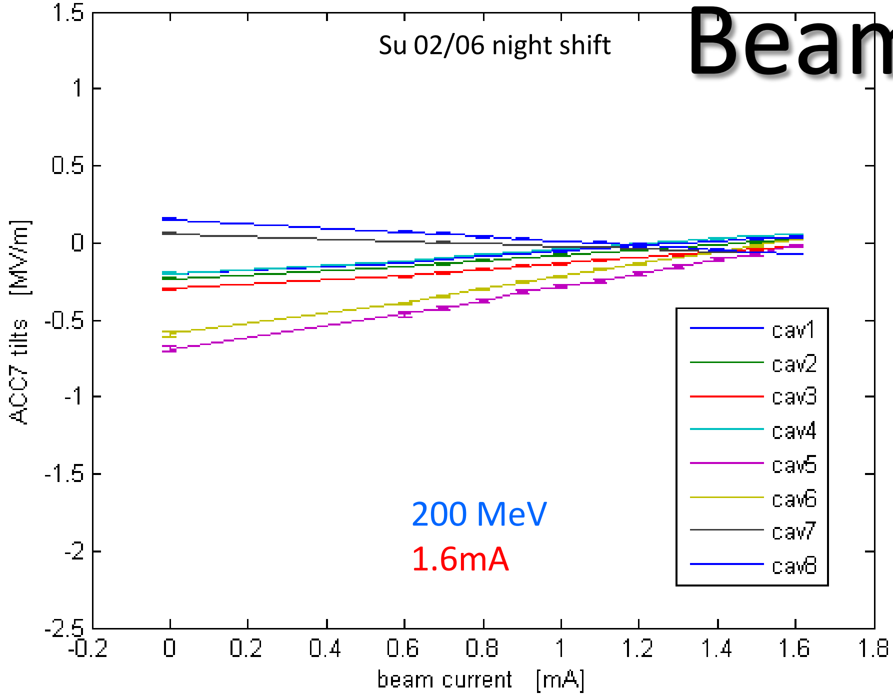
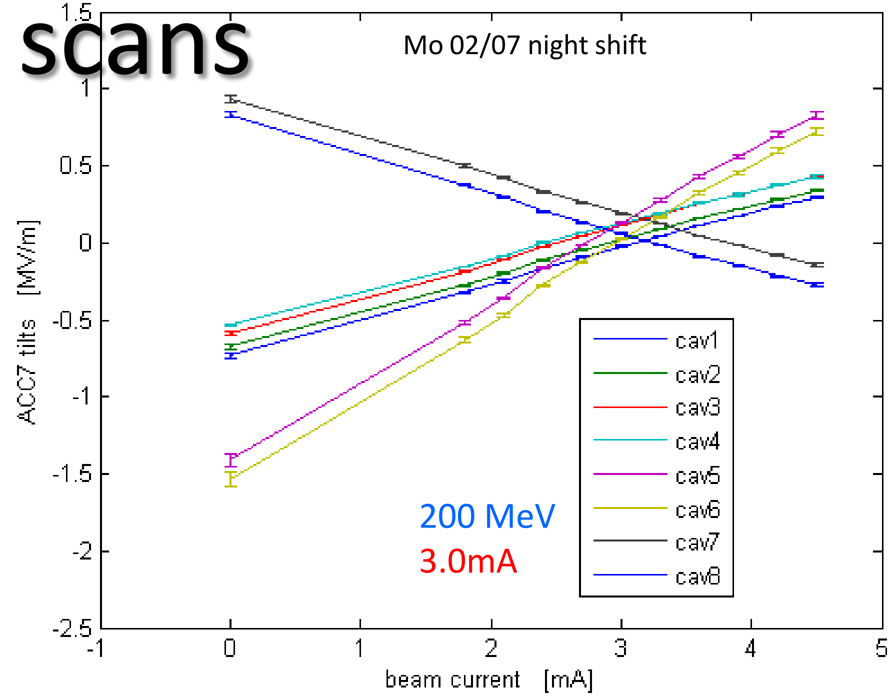
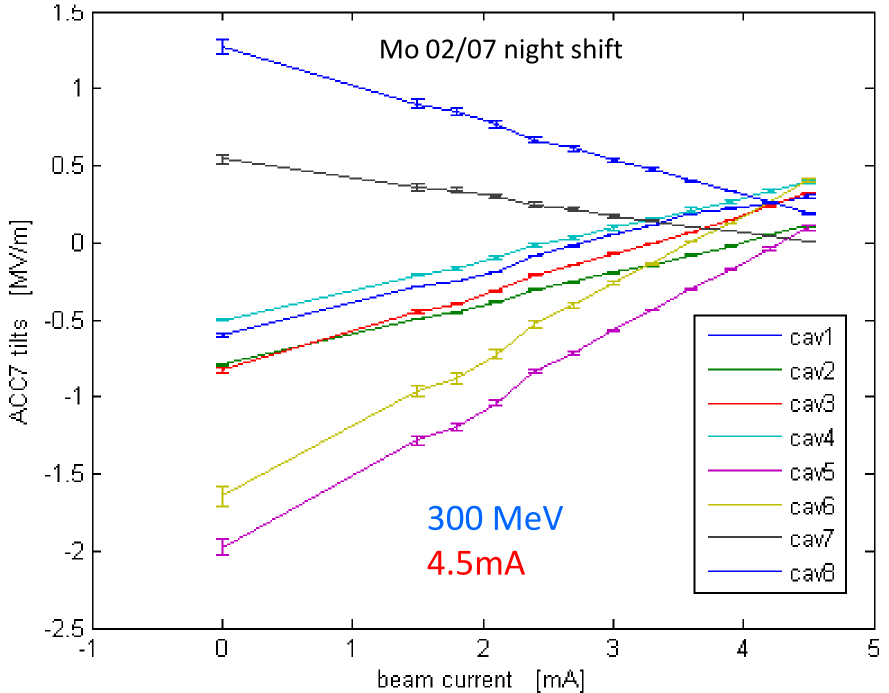
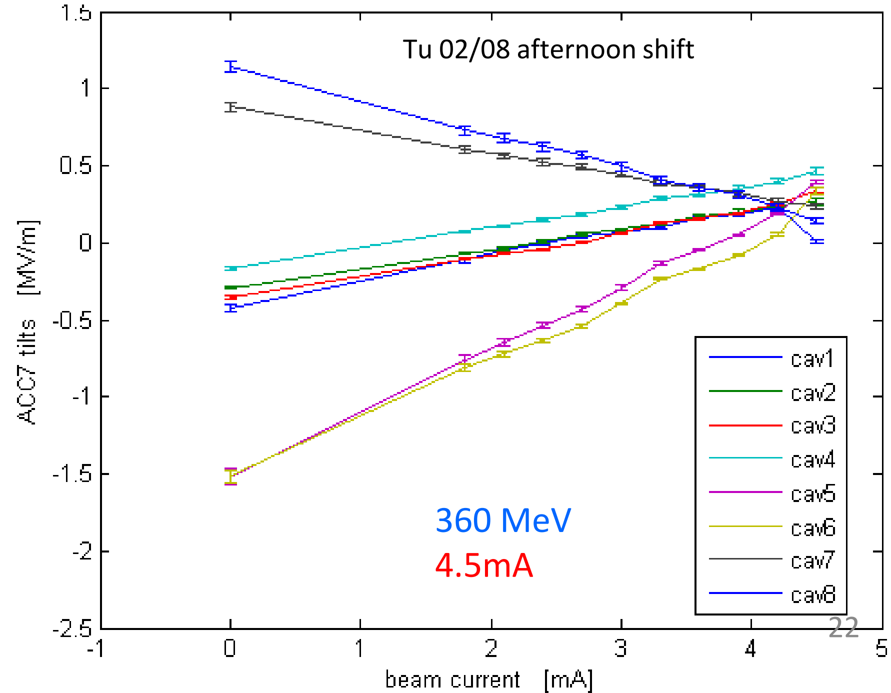


Beam scans


Su 02/06 night shift
ACC7 tilts [MV/m]
beam current [mA]
cav1
cav2
cav3
cav4
cav5
cav6
cav7
cav8
200 MeV
1.6mA


Mo 02/07 night shift
ACC7 tilts [MV/m]
beam current [mA]
cav1
cav2
cav3
cav4
cav5
cav6
cav7
cav8
200 MeV
3.0mA


Mo 02/07 night shift
ACC7 tilts [MV/m]
beam current [mA]
cav1
cav2
cav3
cav4
cav5
cav6
cav7
cav8
300 MeV
4.5mA


Tu 02/08 afternoon shift
ACC7 tilts [MV/m]
beam current [mA]
cav1
cav2
cav3
cav4
cav5
cav6
cav7
cav8
360 MeV
4.5mA

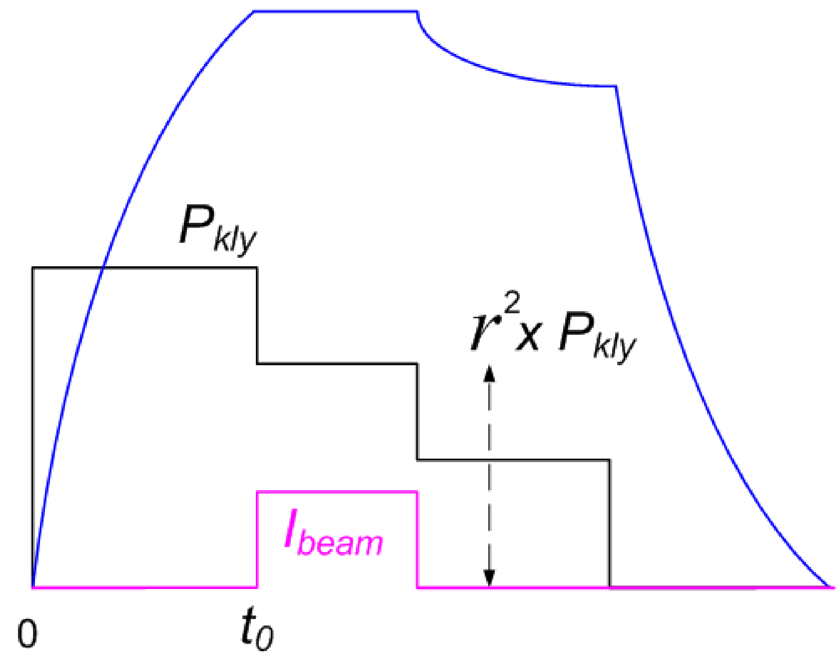
The analytical solution

Given a fixed power distribution, a known beam current and beam compensation, find individual Q_L's that will flatten cavity gradients during beam time

$$e^{-\frac{t_0 \omega_0}{2 Q_{Li}}} - \sqrt{\frac{\frac{1}{4}\frac{R}{Q} Q_{Li} {I_B}^2}{P_{Ki}}} = 1 - r$$ *

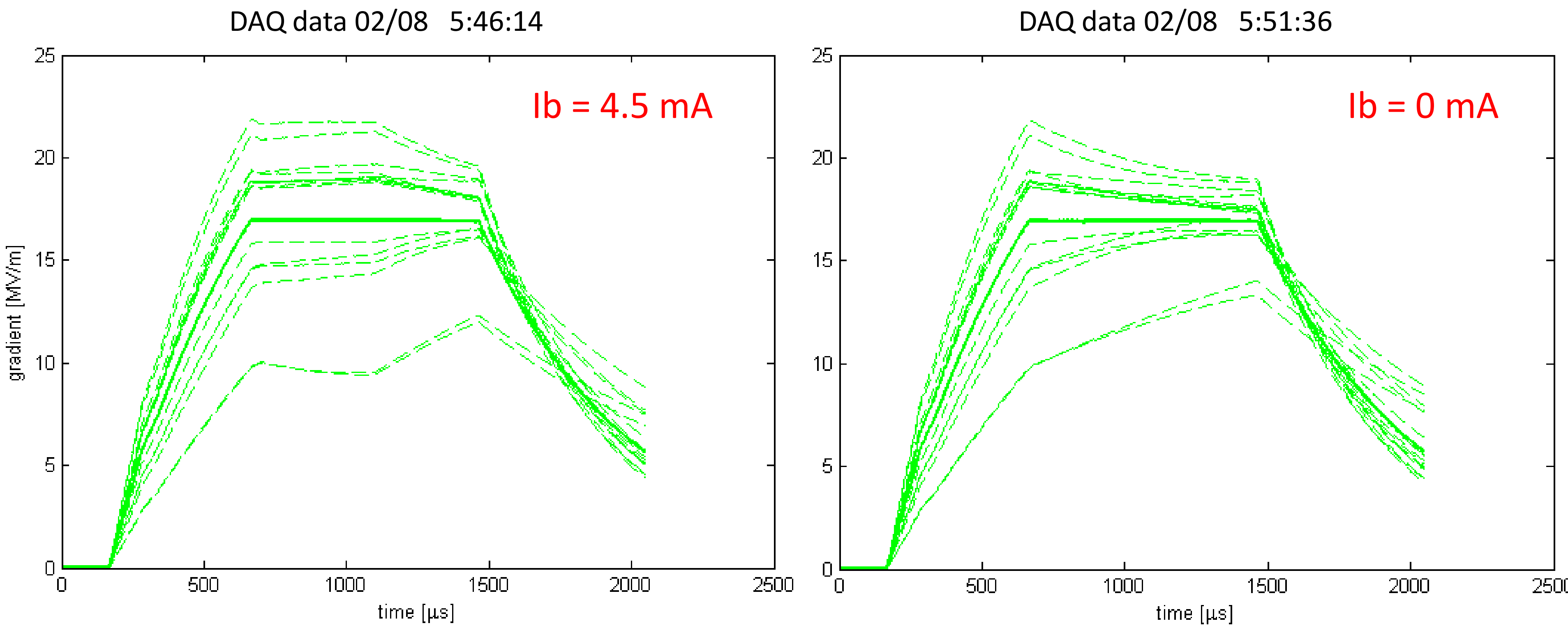
→ assumes "perfect" tuning
→ solve for Q_{Li} when possible

Q_{Li}	cavity i loaded Q
P_{Ki}	cavity i forward power during fill time [W]
I_B	DC beam current [A]
t_0	fill time (~ beam arrival time) [s]
r	fill time to flat top voltage ratio (including beam compensation)



* "Note on solving QL for flat gradients at FLASH ACC6 and ACC7", J. Branlard, Feb 2011, FNAL Beams-doc-3796
"Analytical solution to the cavity tilt problem.docx", G. Cancelo, Feb 2011

Beam ON/OFF



→ Cavities below vector sum rise without beam

→ Cavities above vector sum drop without beam

→ Need for an automatic safety feature to shorten RF pulse to prevent quench

Study insights

What went well

- Very stable machine → long study time
- Motorized couplers / tuners → optimal study conditions
  automated scripts + skilled operators
- Simulator proved to be very useful
- Predicted optimized Q_L values were accurate → to 0.2e6
- Successfully implemented the tuning plan → tilts < 0.1MV/m

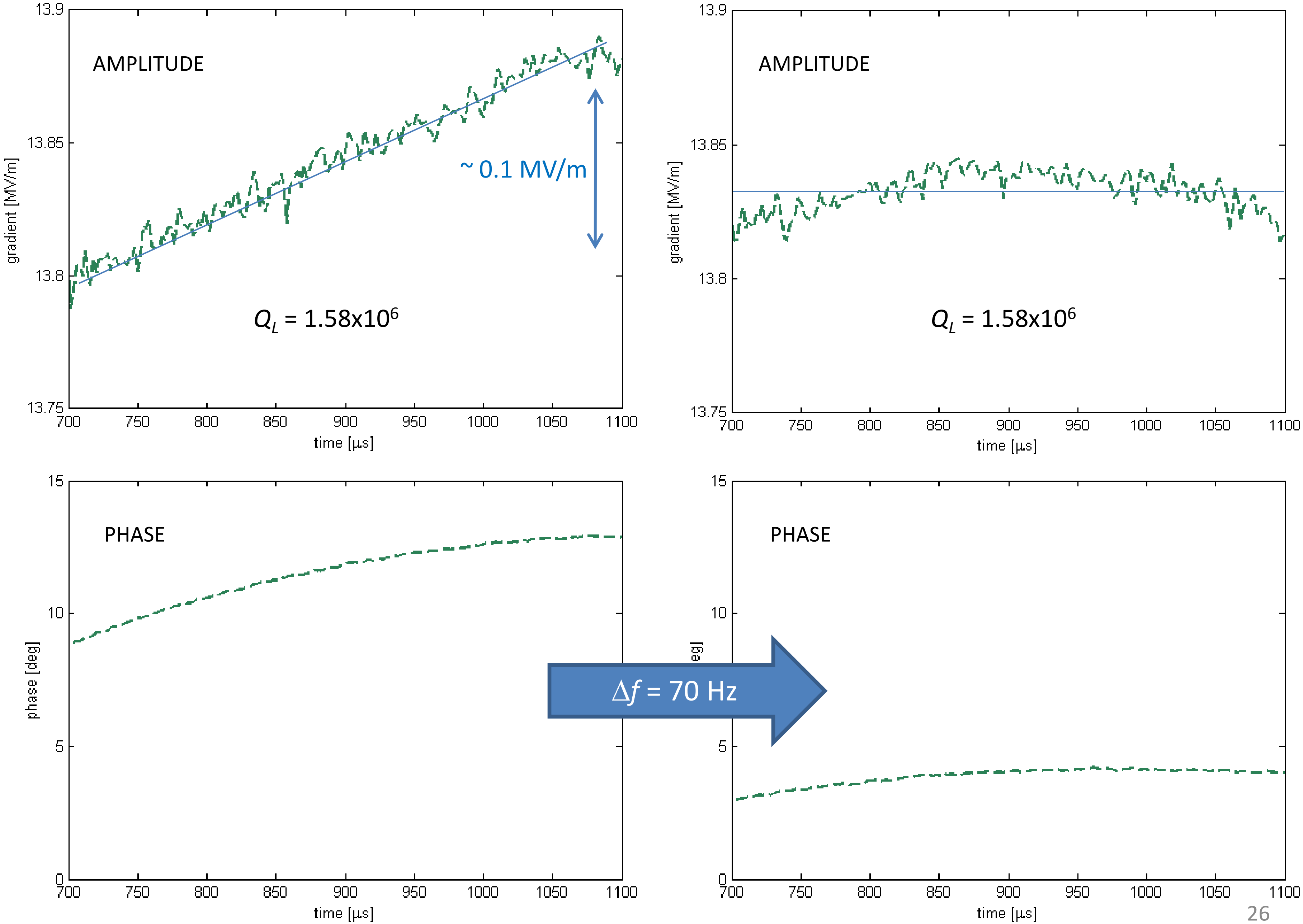
What we've learnt

- Cavity resonance control is crucial for gradient tilts
- Limitations to the simulation approach:
  - How accurately can we measure the power distribution? → John's slide
  - How accurately can we compensate for LFD OR include in model? → next slide
  - How accurately can we measure and set Q_L's → +/- 2 to 5%
  - Fine tuning "by-eye" is compromised by operating in closed loop

What is still unanswered

- No proposed solution for high beam currents (>6mA) implementable at FLASH
- There is not always a solution to flatten all cavities
  (especially when gradient spread is large)
- No solution to bring up the machine at its highest gradient

Before freq. tuner adjustments | After freq. tuner adjustments



Bringing up a linac

Traditional approach (i.e. FLASH)

1. Make target gradient with FF
2. Turn FB on
3. Compensate for LFD
4. Send a couple of pilot bunches (~10)
   (automated beam loading compensation)
5. Minimize losses
6. Gradually increase bunch length to full train
   (while minimizing beam losses)
7. Learning feed forward

One "possible" scenario for flat gradients

1. Bring cavity to their nominal gradient
   - ➔ typically: quench gradient -2-3 MV/m
2. Adjust Q_L so cavities are flat with beam
   - ➔ cavity will quench (because no beam)
3. Shorten pulse length to avoid quench
   - ➔ typically <200 usec for high beam currents Q_L's
   - ➔ can't see LFD effects (can't compensate for LFD)
   - ➔ can't walk pilot bunch across flat top
4. As you increase bunch length
   - ➔ increase flat top length
   - ➔ compensate for LFD
   - ➔ minimize losses
5. The LLRF quench monitoring system should
   - ➔ truncate the flat top length to prevent quenches
   - ➔ every time bunch train is shorter than expected

References

- "RF Distribution Optimization in the Main Linacs of the ILC", Bane, Adolphsen, Nantista - WEPMS037.pdf
- "Optimal Coupler and Power Settings for Superconductive Linear Accelerators", J. Branlard, B. Chase, Linac 2008
- "Optimizing Cavity Gradient in Pulsed Linacs Using the Cavity Transient Response", G. Cancelo, A. Vignoni, Linac 2008
- "Effect of Cavity Tilt and RF Fluctuations to Transverse Beam Orbit Change in ILC Main Linac", K. Kubo, Jan. 2010
- "PkQl-like control for ACC6/7 at FLASH" S. Michizono, PkQl_FLASHver3.docx, Sept. 2010
- "To flatten the cavity gradient for ACC6/7" S. Michizono, FLASH101022BV2.pdf, Nov. 2010
- "Analytical solution to the cavity tilt problem.docx", G. Cancelo, Feb 2011
- "Note on solving QL for flat gradients at FLASH ACC6 and ACC7", J. Branlard, FNAL Beams-doc-3796
- SIMCAV version 4.8 (FLASH ACC6 and ACC7 16 cavity MATLAB simulator), FNAL Beams-doc-3794

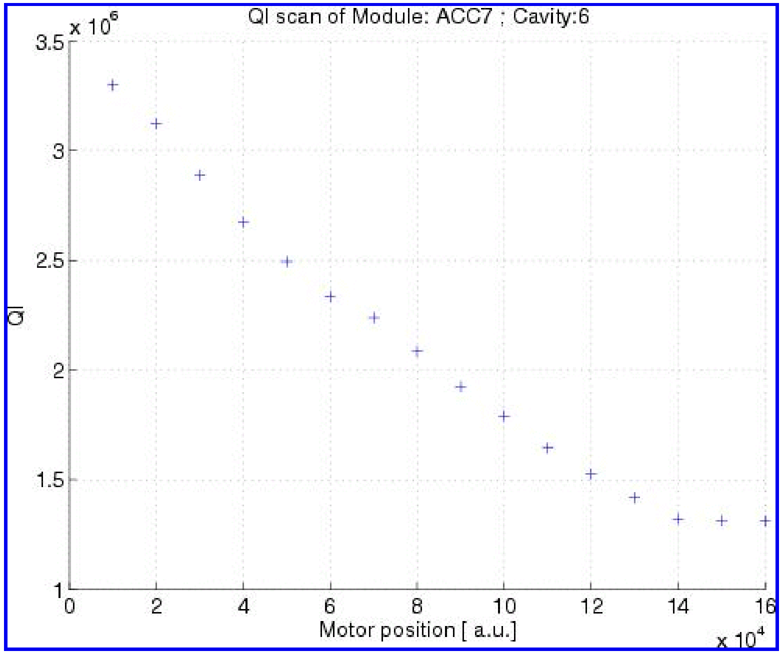
THANK YOU

BACKUP SLIDES

SUMMARY

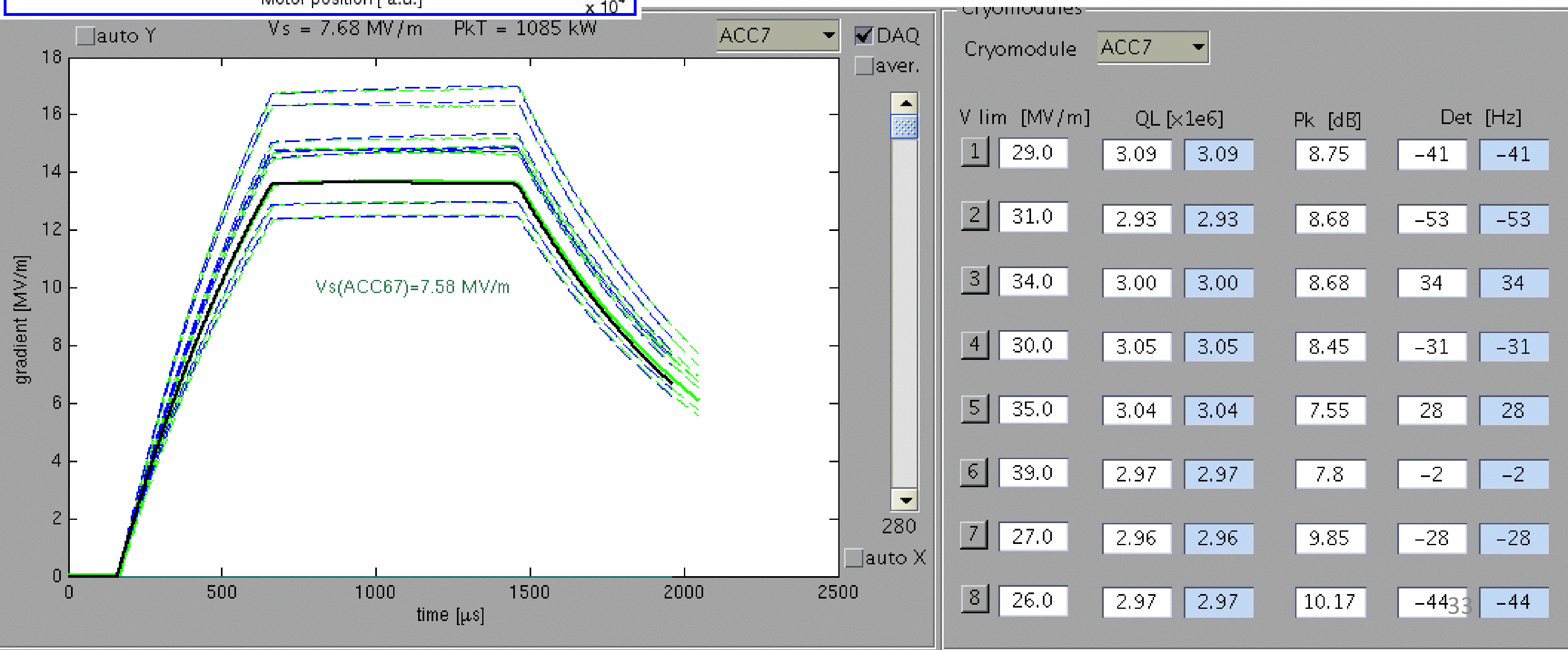
- Why do we care about individual flat gradients?
  - KEK paper
- What can we actually implement at FLASH?
  - No P_K adjustments
  - Only Q_L can be changed
  - Limited range in Q_L changes
- What solutions were offered to achieve flat gradients with beam loading?
  - SLAC paper , using Q_L and P_K adjustments
  - Shin's solution with square P_{fwd} pulse
  - Shin's solution with step ratio P_{fwd} pulse
- What approach have we followed during the FLASH test studies?
  - Procedure (issues with adjusting Q_L when beam is OFF)
  - When beam is ON, beam compensation is ON too
  - Which tools did we use
  - The analytical solution
- Results of the P_K / Q_L studies
  - Assess Q_L ranges
  - Low gradient / mid gradient
  - Low beam / mid beam current
  - Beam scans
  - Q_L scans
- Conclusions and lessons learnt
  - How accurate were the tuning adjustments?
  - What limited the accuracy of tuning adjustments?
  - Difference between solving the problem open / close loop
  - Impact of detuning on tilts (static & dynamic)
  - No solution to bringing the machine up to its maximum gradient

Shift-by shift highlights



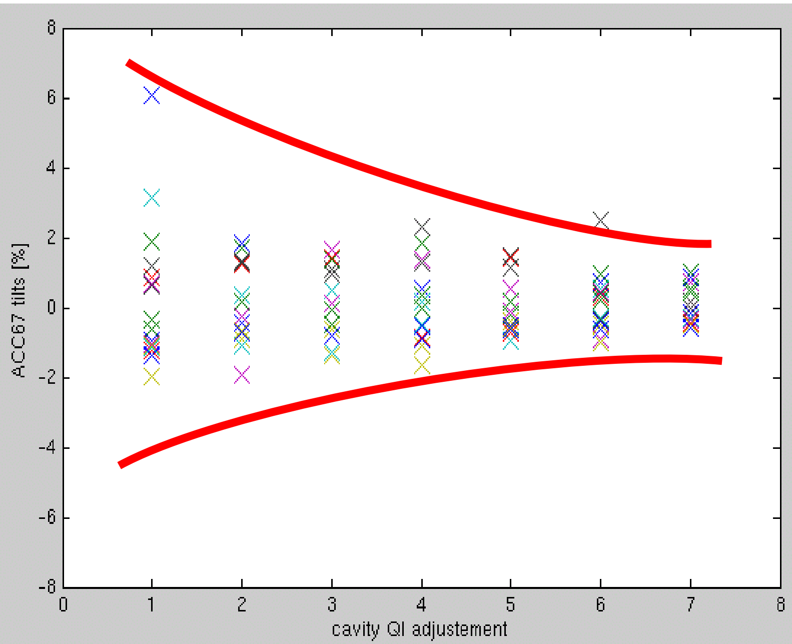
Friday 2/4 night shift – highlights:

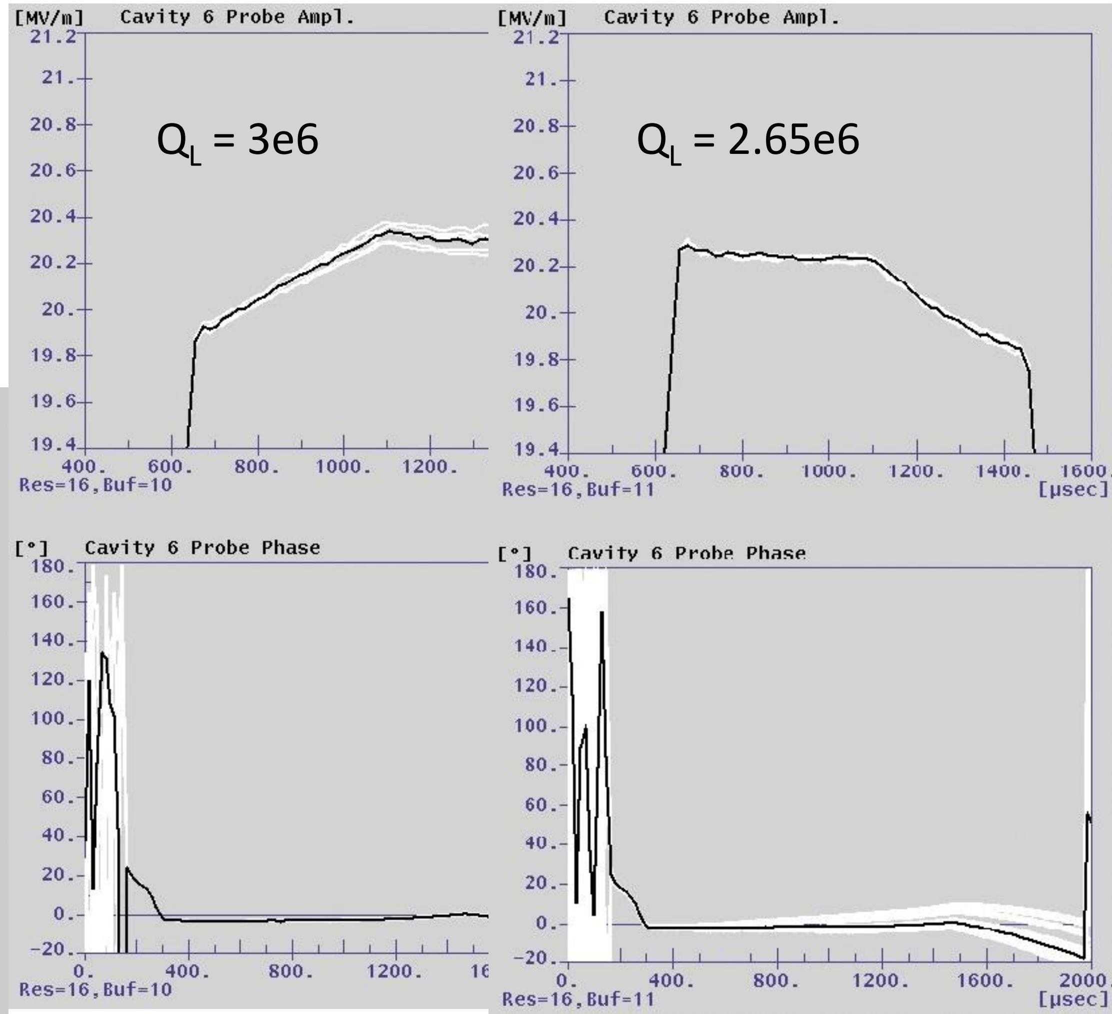
- no beam
- ACC6/7 vector sum calibration 100 bunches, 1 MHz, 1.6 nC
- Q_L tuners characterization for ACC6/7
- simulator calibration to reflect ACC6/7 power distribution



Saturday 2/5 night shift – highlights:

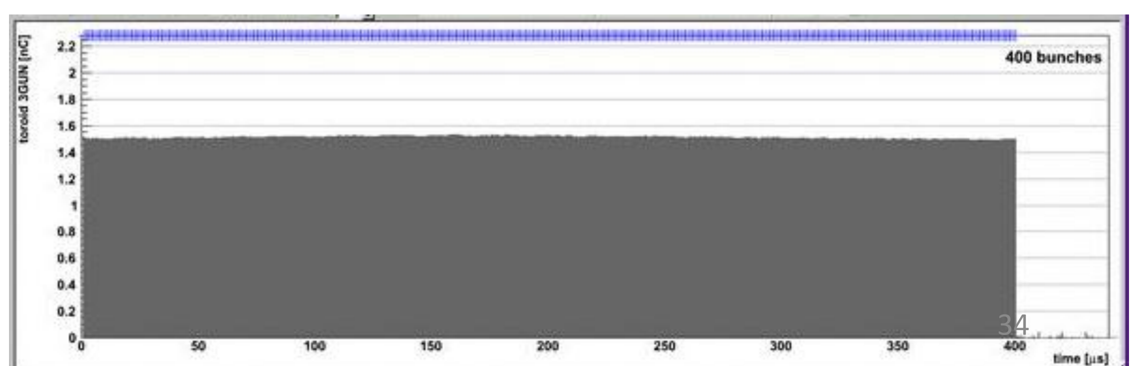
- 1mA beam, low gradient (100–200 MeV)
- Successfully implemented QL adjustments to flatten cavity gradients
- beam loading tilts correction (all tilts below 1%) using simulator predicted values
- Simulated values are reliable

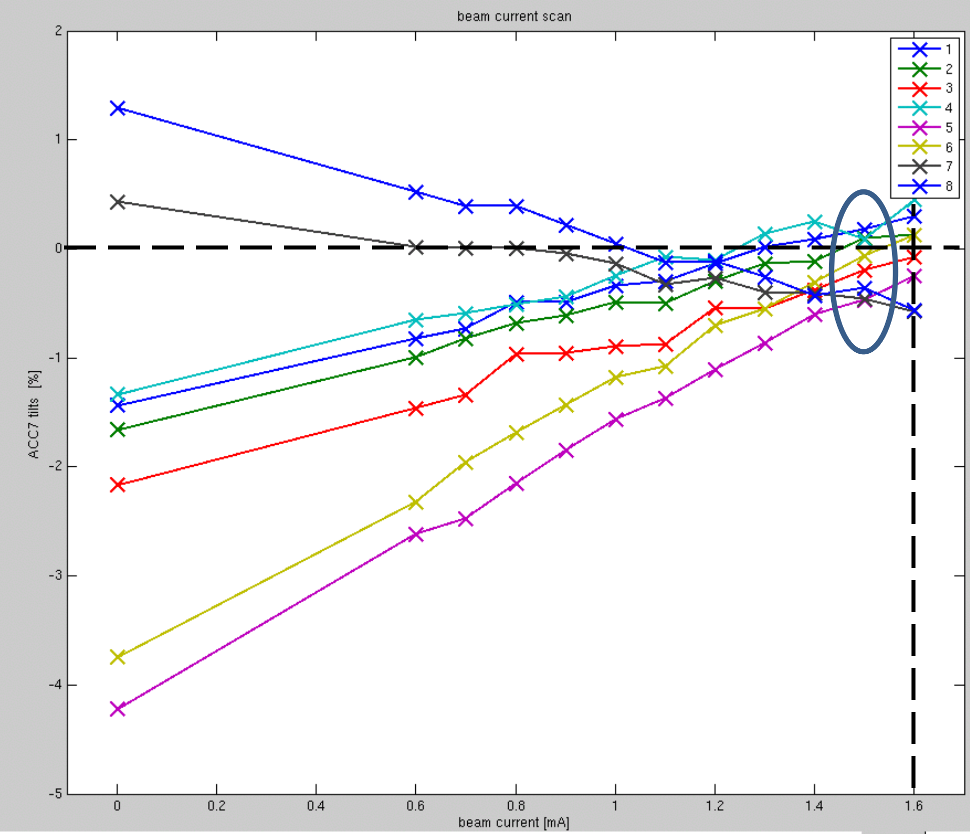




ACC6	cav1	0.87 %
ACC6	cav2	1.01 %
ACC6	cav3	0.44 %
ACC6	cav4	0.70 %
ACC6	cav5	0.71 %
ACC6	cav6	-0.17 %
ACC6	cav7	0.15 %
ACC6	cav8	-0.17 %

ACC7	cav1	0.55 %
ACC7	cav2	-0.43 %
ACC7	cav3	-0.30 %
ACC7	cav4	-0.32 %
ACC7	cav5	-0.50 %
ACC7	cav6	-0.01 %
ACC7	cav7	-0.57 %
ACC7	cav8	0.45 %





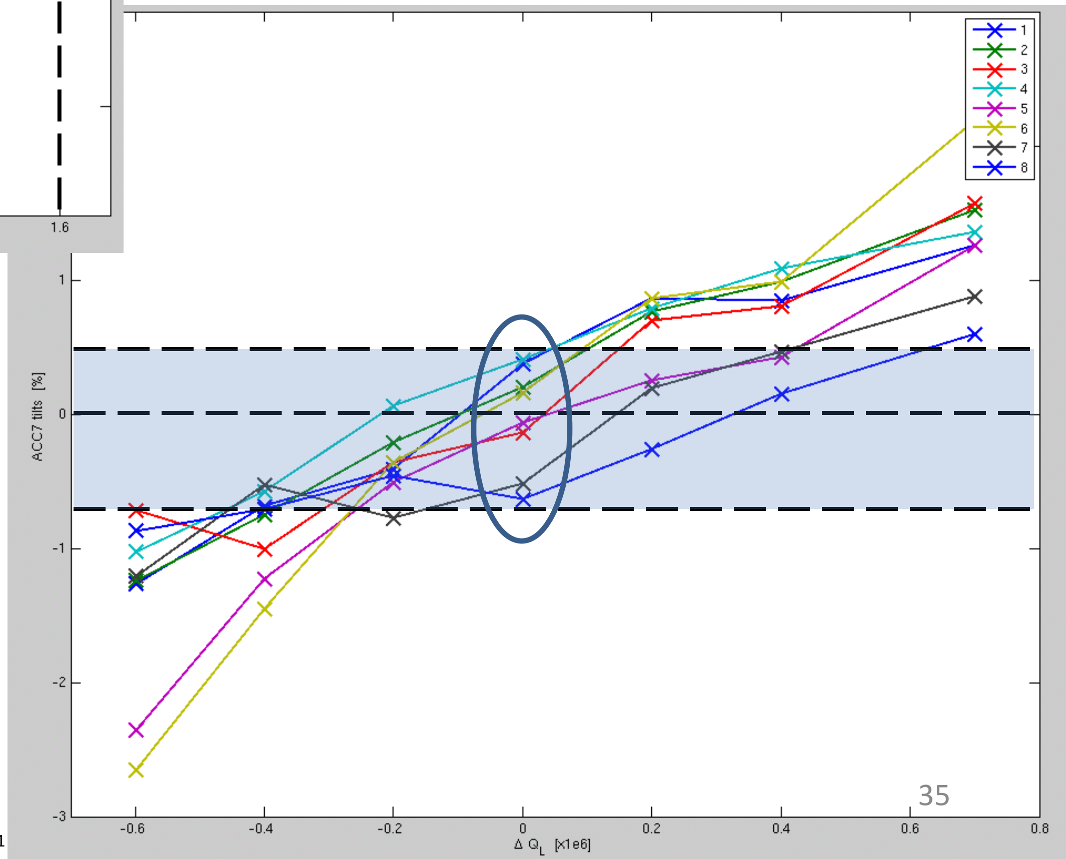
Sunday 2/6 night shift – highlights:

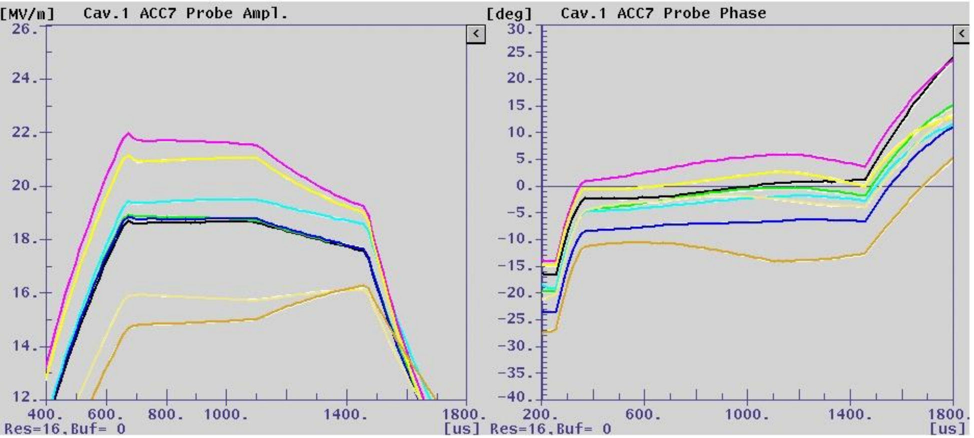
- 1.6mA beam, low gradient (200 MeV)
- beam loading tilts Q_L correction (below 1%) (several cavities at once, with beam on)
- beam current scan
- Q_L scan

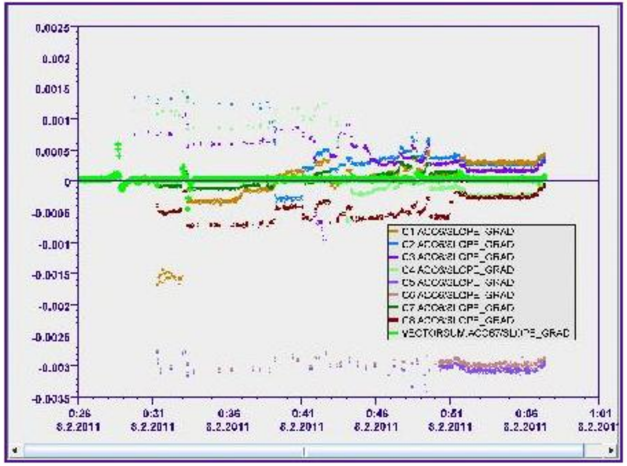
```
ACC7-cav0= -0.23 %
ACC7-cav1= 0.35 %
ACC7-cav2= 0.17 %
ACC7-cav3= -0.03 %
ACC7-cav4= 0.32 %
ACC7-cav5= -0.15 %
ACC7-cav6= 0.15 %
ACC7-cav7= -0.58 %
ACC7-cav8= -0.59 %
```

Ql config is for ACC7:

cav1 : 2.8 e6
cav2 : 2.8 e6
cav3 : 2.8 e6
cav4 : 2.8 e6
cav5 : 2.5 e6
cav6 : 2.5 e6
cav7 : 3.1 e6
cav8 : 3.2 e6



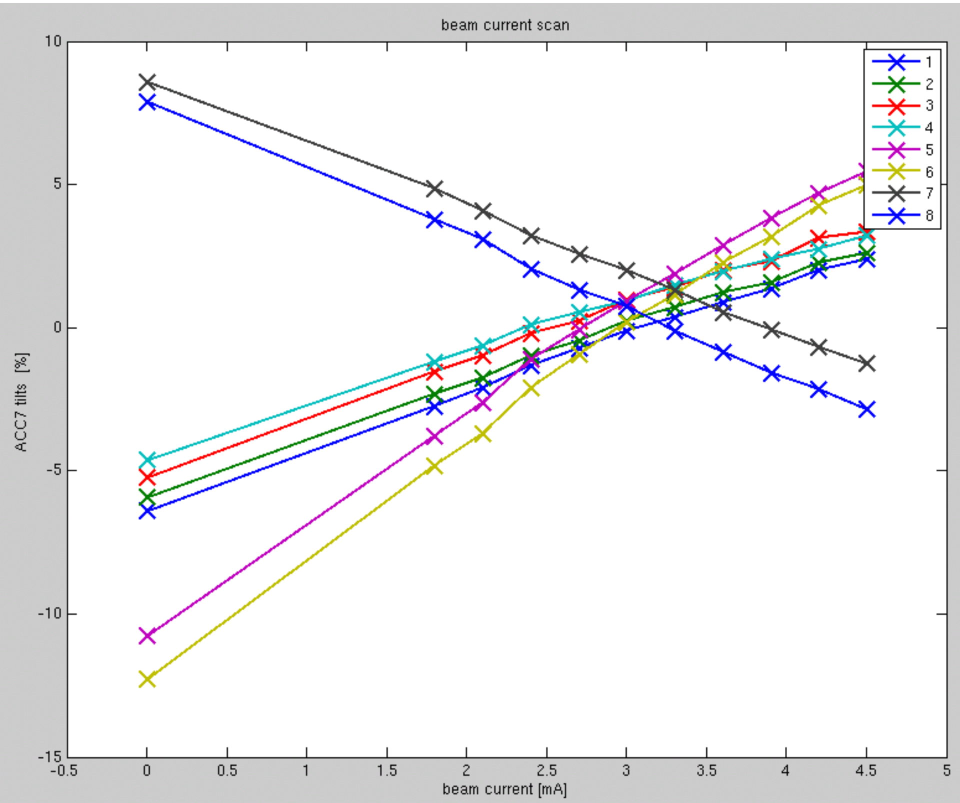


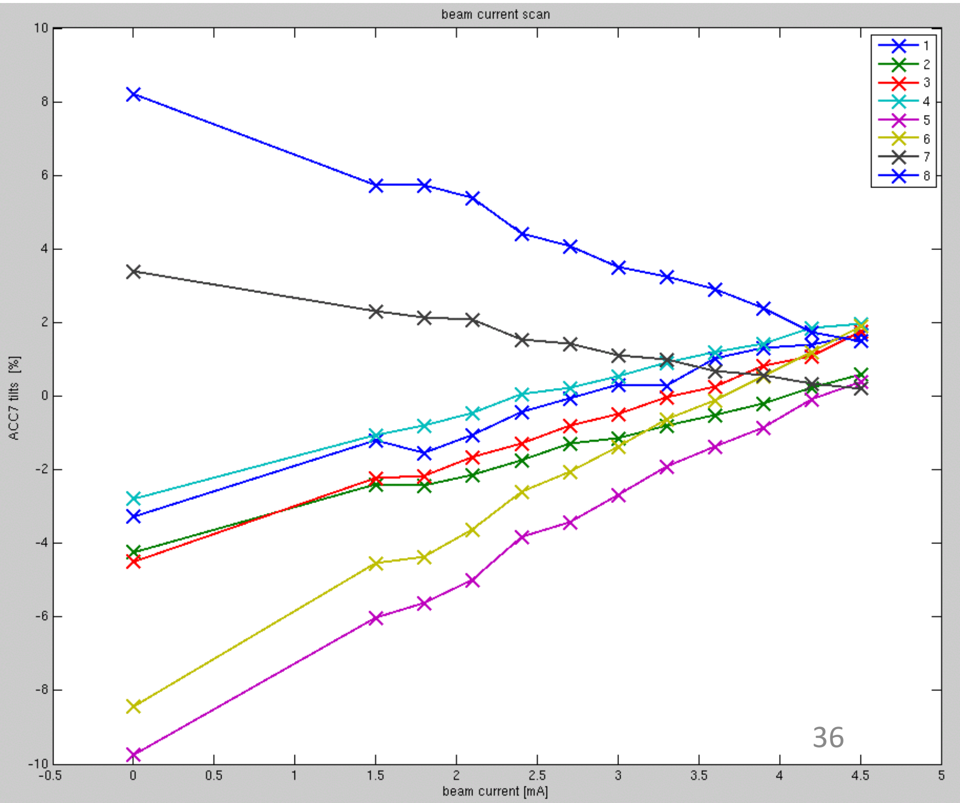


Monday 2/7 night shift – highlights:

- 3.0mA beam, 200 MeV
- Q_L adjusted for gradient flat at 3mA
- beam scan from 0.9 to 4.5 mA

- 4.5mA beam, 300 MeV
- QL adjusted for gradient flat at 4.5 mA
- beam current scan



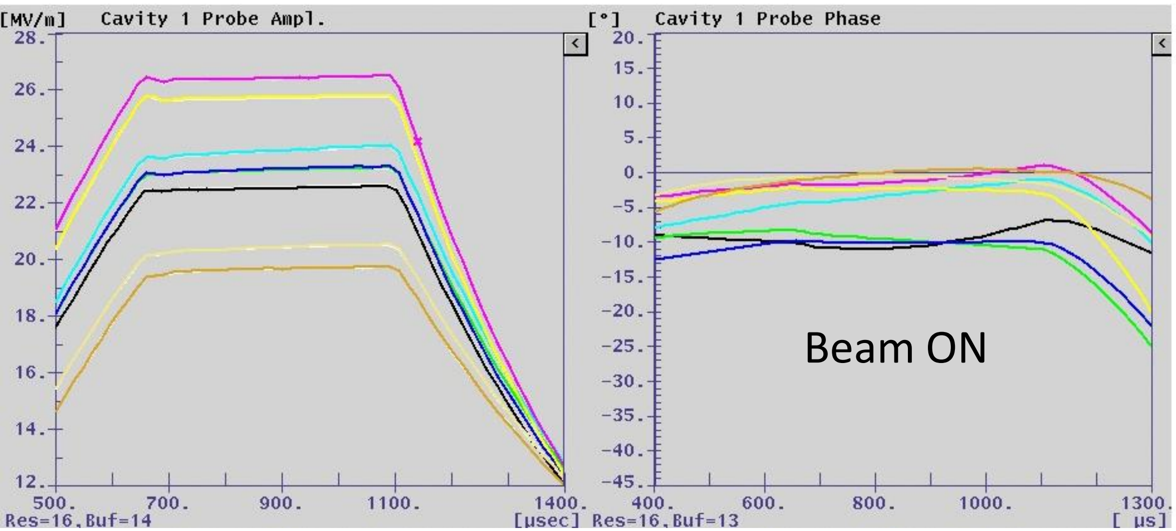


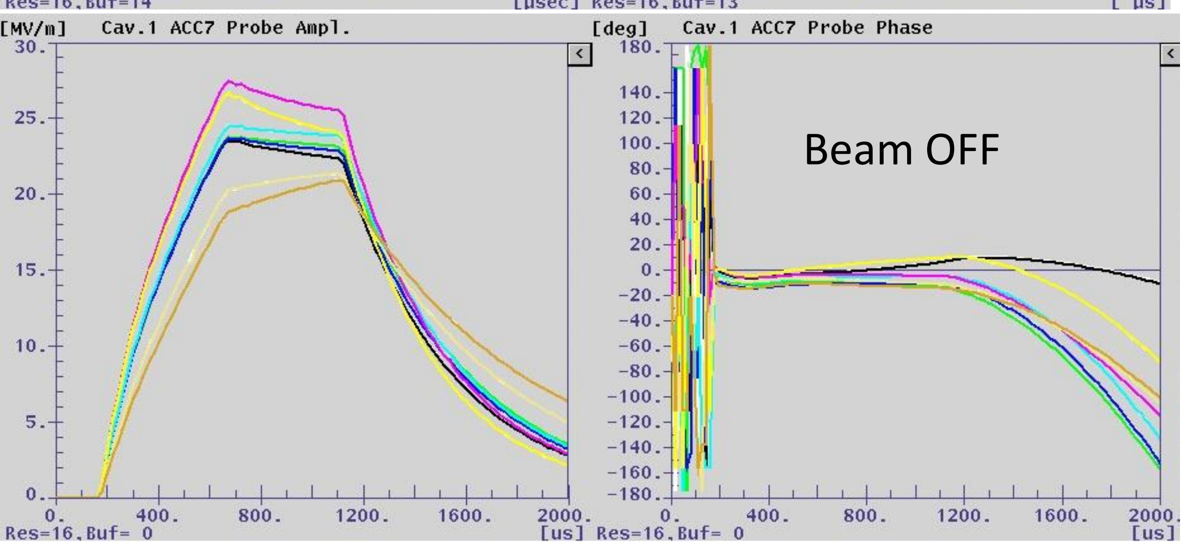
Tuesday 2/8 afternoon shift – highlights:

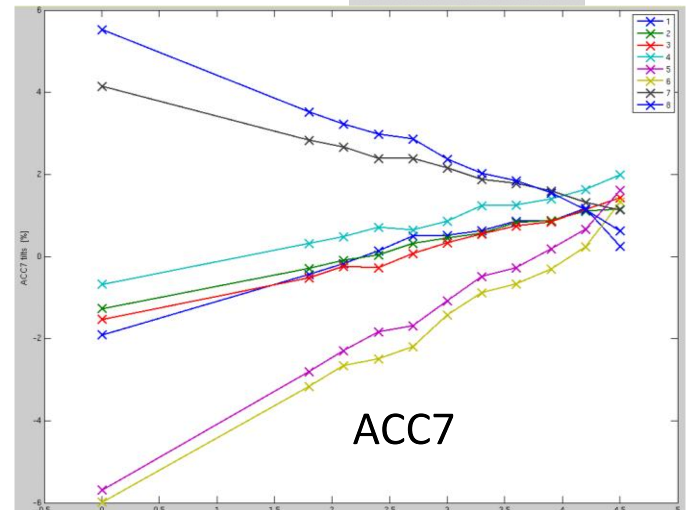
- 4.2mA beam, 360 MeV
- Lorentz force detuning compensation
- Use calculator to predict QL → very accurate prediction
- Flatten ACC6/7 gradients tilts to ~ 1.5% (tuned for 4.2mA)
- beam current scan to 4.5 mA

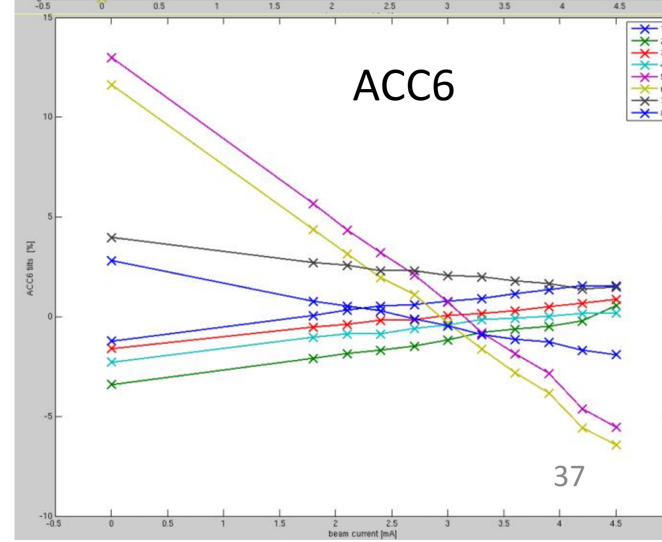
ACC7 Q_L values

Predicted		Implemented: Cavity#	Implemented: Loaded Q
cav1.	1.78 e6	1	1.79e+06
cav2.	1.74 e6	2	1.77e+06
cav3.	1.85 e6	3	1.84e+06
cav4.	1.88 e6	4	1.91e+06
cav5.	3.25 e6	5	3.28e+06
cav6.	3.12 e6	6	3.10e+06
cav7.	2.37 e6	7	2.37e+06
cav8.	2.40 e6	8	2.28e+06

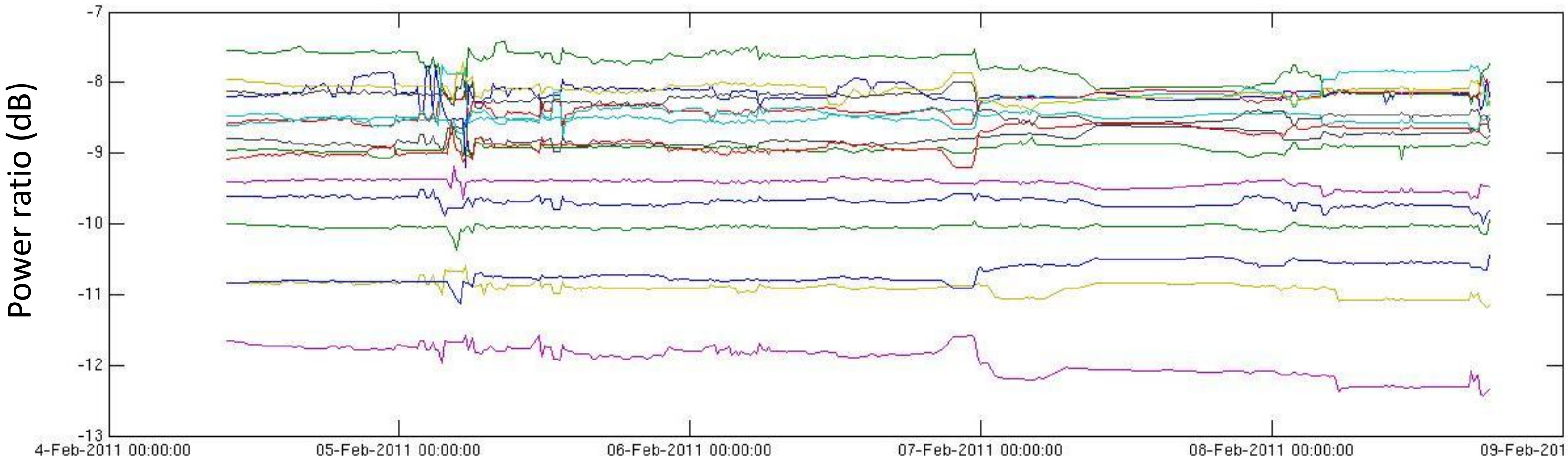


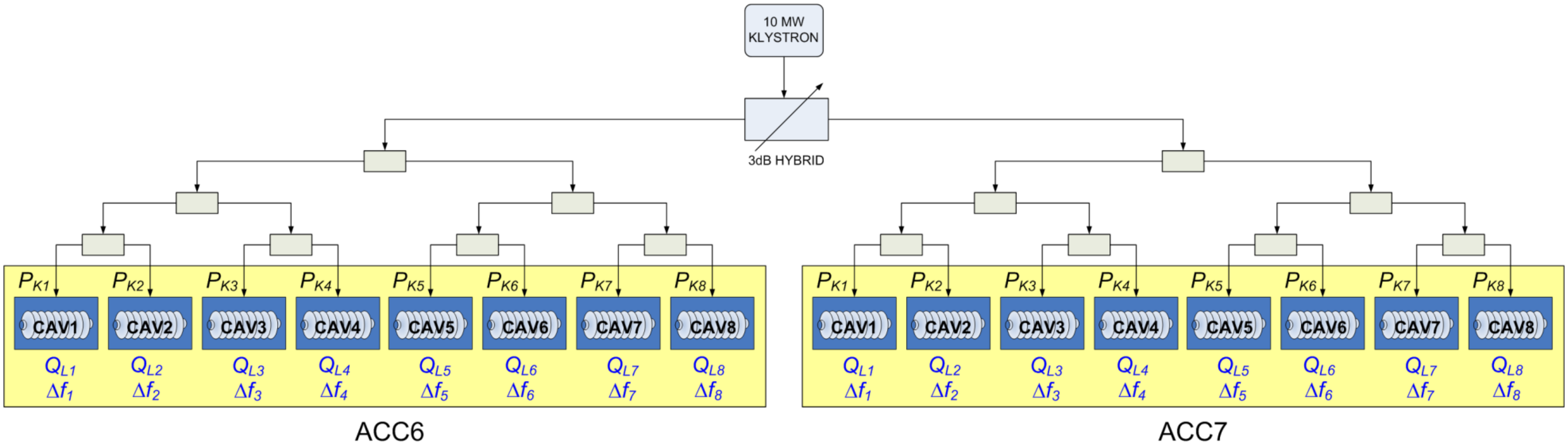




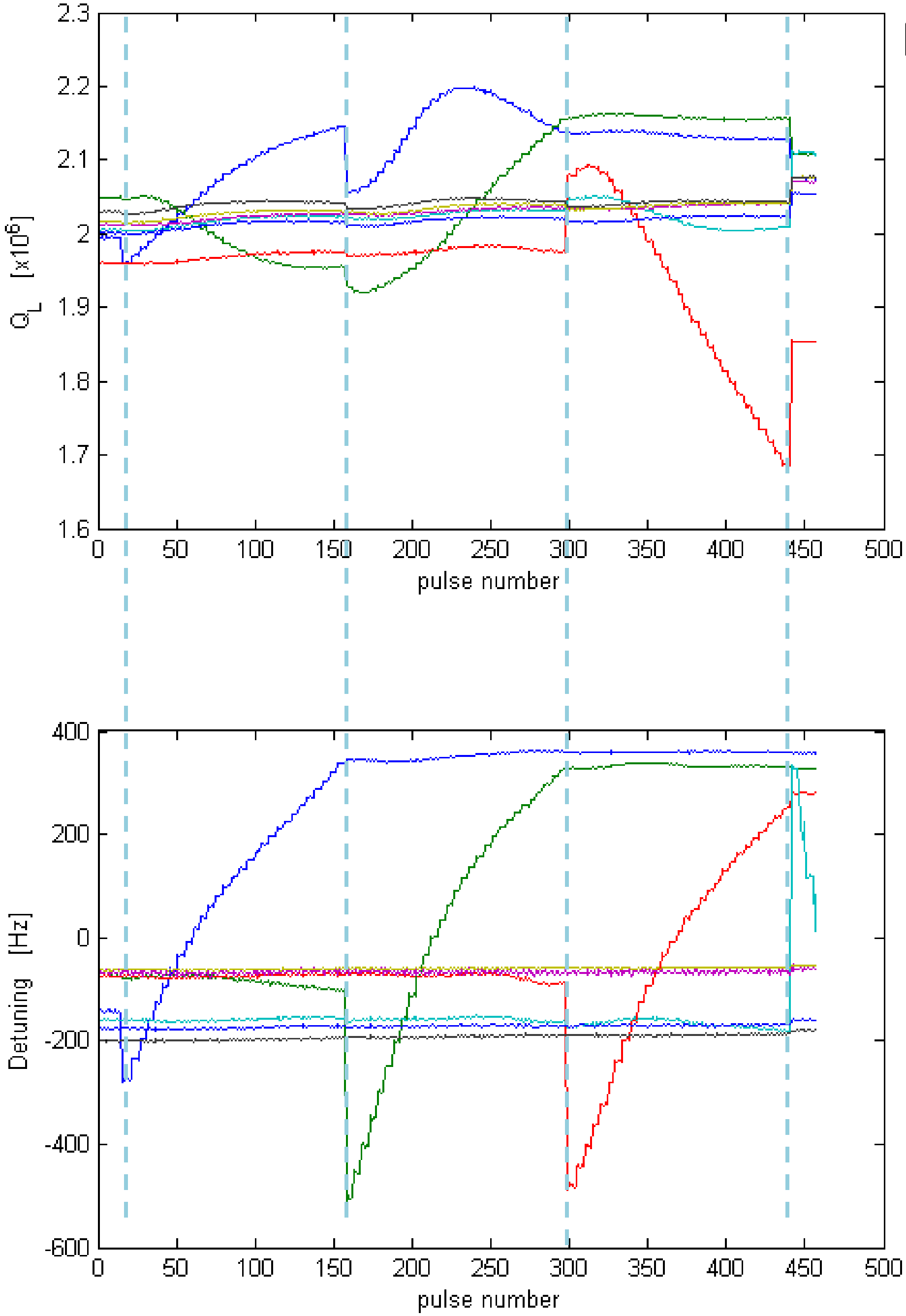


Power ratios





Power coupling between adjacent cavities



- 3 sequences of detuning: cav1, then cav2 then cav3.
- when we reach the end of the detuning range of one cavity, the detuning of the adjacent cavity is affected
- Q_L changes with the detuning for all three cavity (cav1 and 2 in one direction, cav3 in the opposite direction)
- We see that Q_L(cav1) and Q_L(cav2) are coupled.
- Similarly, Q_L(cav3) and Q_L(cav4), but no cav3-cav1 coupling