ILC 9mA tests at FLASH

Past results and future plans

Julien Branlard
ILC 9mA tests at FLASH
DESY, 02.07.2012

Overview

> I. The International Linear Collider

- ILC main specification
- The 9mA collaboration
- ILC challenges

> II. Simple key-concepts to understand the 9mA studies

- Single-klystron multiple-cavities
- Vector sum regulation
- Pk / Ql control

> III. Flattening cavity gradients

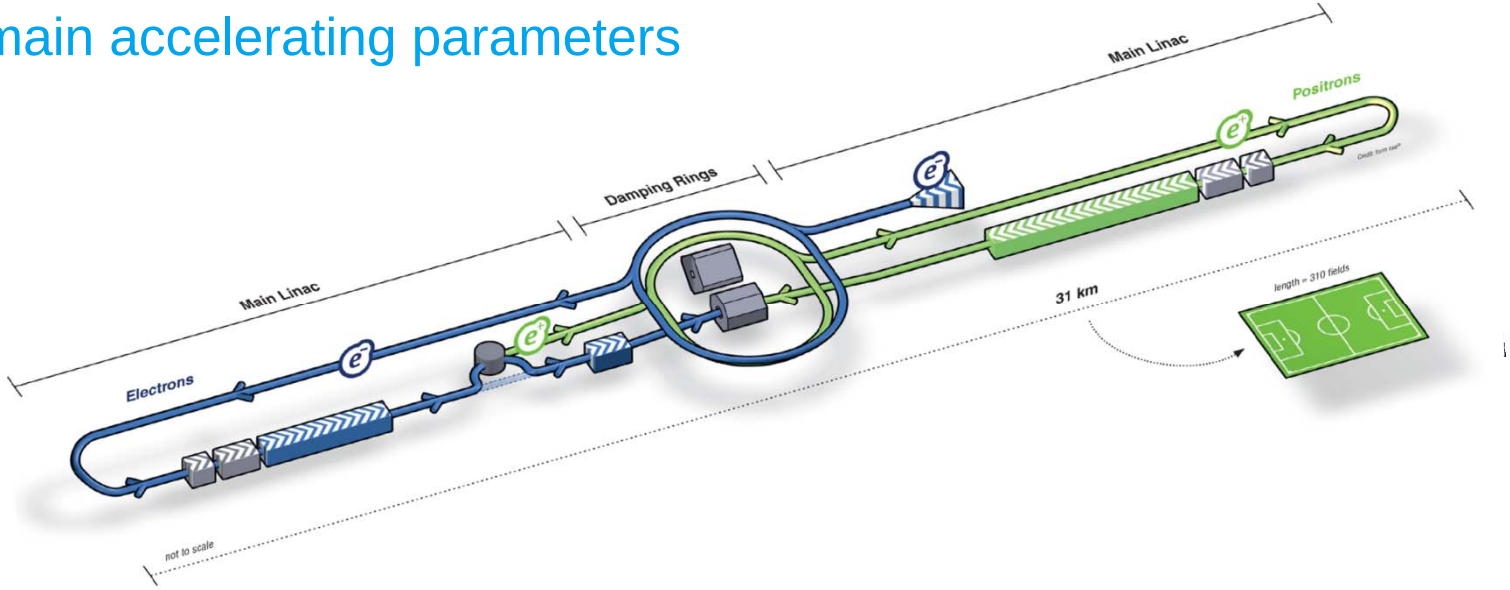
- Analytical approach
- Accuracy assessment

> IV. Conclusions:

- Summary of the 9mA run last year (Feb. 2011)
- Outlook on the next 9mA run (Feb. 2012)

I. The International Linear Collider

> ILC main accelerating parameters



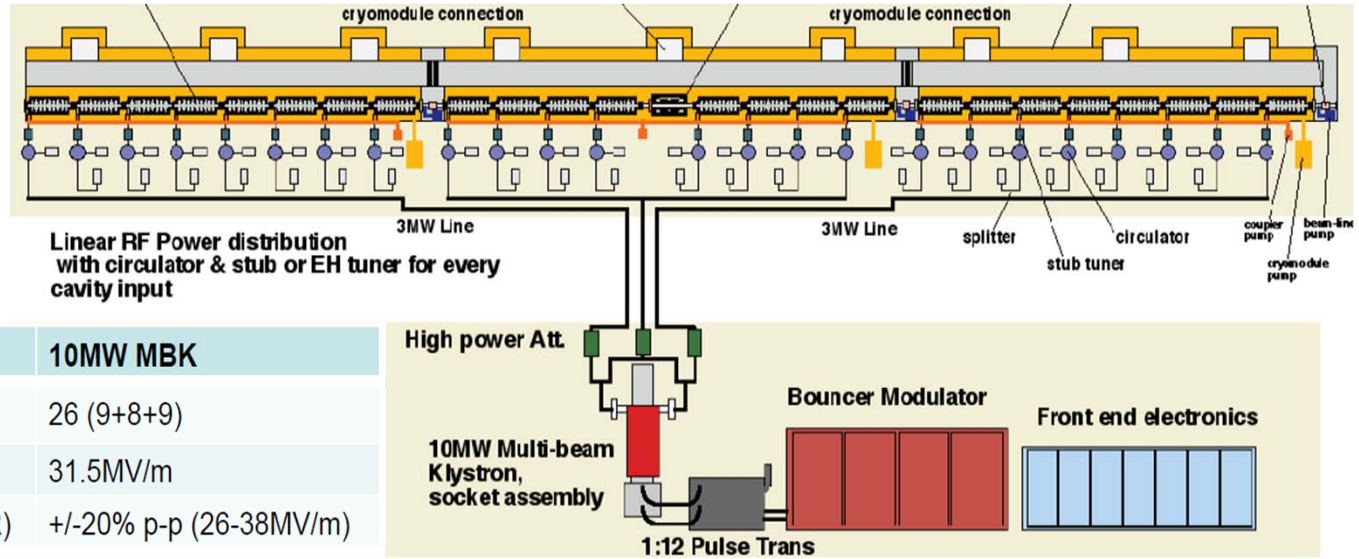
Accel. Params	ILC	FLASH	Unit
Cavity tech.	super conducting	super conducting	
RF freq.	1.3	1.3	GHz
Rep. rate	5	5-10	Hz
Beam current	9	1-9	mA
Average gradient	31.5	26	MV/m
RF station	10 MW klystron for 26 cavities	10 MW klystron for 16 cavities	

Main Linacs	
Energy	2x 250GeV
Cavities (9-cell)	14,560
Cryomodules	1680
RF Units	560
Cavities per RF Unit	26

Courtesy:
J.Cawardine

I. The International Linear Collider

> The reference design RF unit: klystron power distribution scheme



Klystron	10MW MBK
Cavities per RF Unit	26 (9+8+9)
Avg. gradient	31.5MV/m
Gradient spread (post RDR)	+/-20% p-p (26-38MV/m)

> Beam current parameters

		XFEL	ilc	FLASH	FLASH 9mA experiment
Bunch charge	nC	1	3.2	1	3
# bunches		3250*	2625	7200*	2400
Pulse length	µs	650	970	800	800
Current	mA	5	9	9	9

Courtesy:
J.Cawardine

I. The ILC 9mA collaboration

> DESY
- Nick Walker
- Siegfried Scheiber
- Bart Faartz
- Katja Honkavaara
- Holger Schlarb
- Valeri Ayvazyan
- Mariusz Grecki
- Wojciech Jalmuzna
- Wojciech Cichalewski
- Tim Wilksen
- Olaf Hensler
- Christian Schmidt
- Julien Branlard
-
- … and many others

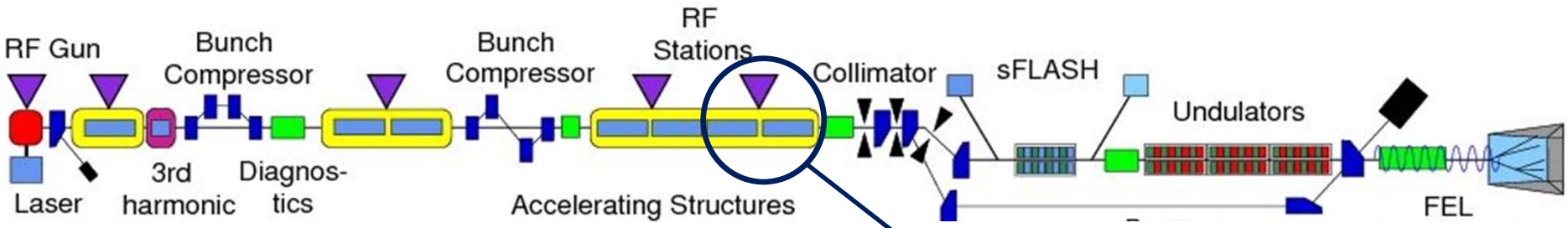
> ANL
- Ned Arnold
- John Cawardine

> FNAL
- Brian Chase
- Gustavo Cancelo
- Warren Schappert
- Yuriy Pischalnikov

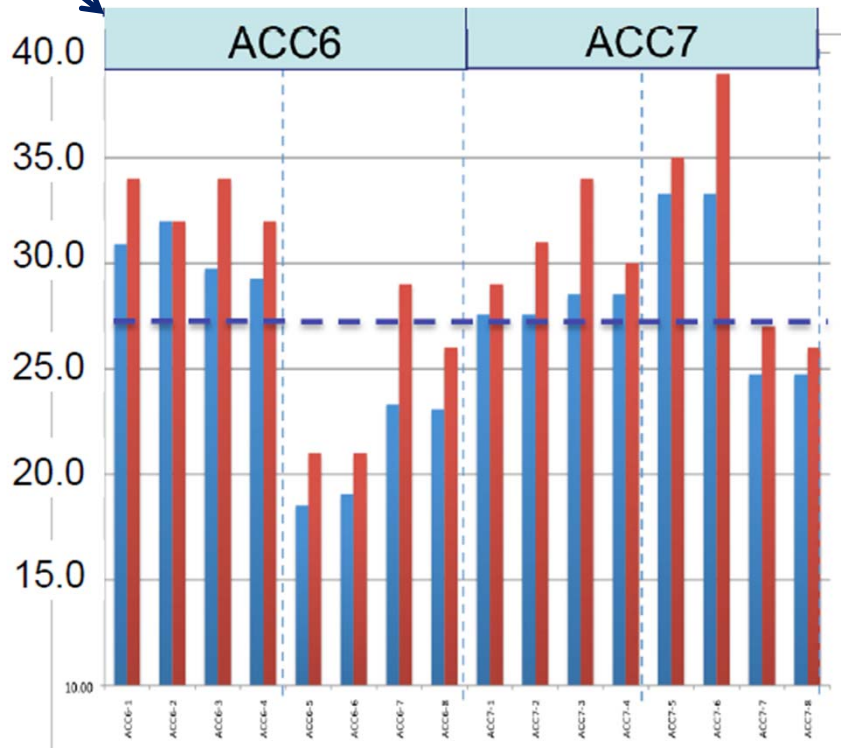
> KEK
- Shinichiro Michizono
- Toshihiro Matsumoto

> SLAC
- Chris Adolphsen
- Shilun Pei

I. Specific objectives for the 9mA study



- Operation with gradient spread from a single source
  - operating gradient spread for ACC67 around +/-25%
- Operation with high beam current
  - gain experience with beam loading
- Operate as close as possible to the quench limit
  - challenges linked to low RF overhead
- Focus on ACC67
  - highest gradient
  - piezo
  - Q_L motors



I. Specific objectives for the 9mA study

> Long bunch-trains with high beam loading (9mA)

- 800µs pulse with 2400 bunches at 3MHz, 3nC per bunch
- Vector Sum control of up to 16 cavities, with +/- 20% gradient spread
- Beam energy 700-1000MeV with +/- 0.1% energy stability
- Beam-based adjustments/optimization

> Operation (very) close to cavity quench limits (1MV/m or less)

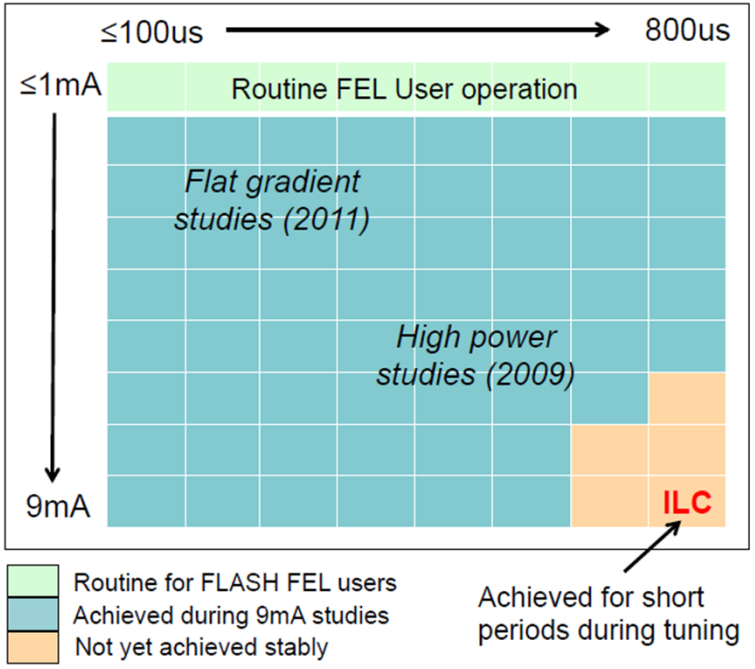
- Robust automation of tuning (Ql, piezo, tuners, etc..)
- Cavity gradients approaching quench limits
- Quench detection/recovery, exception handling

> Characterize operational limits

- Low klystron power overhead
- Klystron saturation regime
- Saturation of control loop
- Energy stability limitations and trade-offs

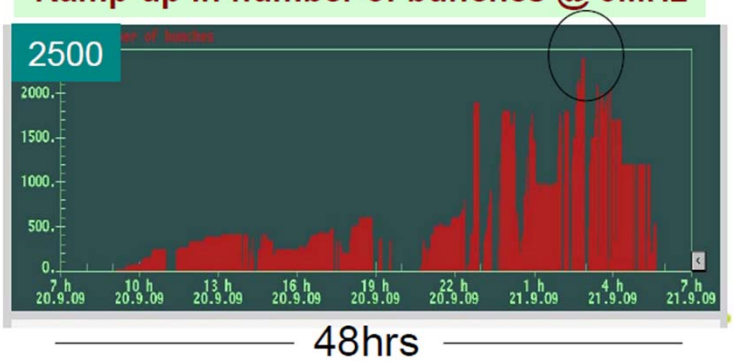
I. Specific objectives for the 9mA study

> Long-pulse + high-current: achieved parameter space



800 bunches at 3mA for 15hrs

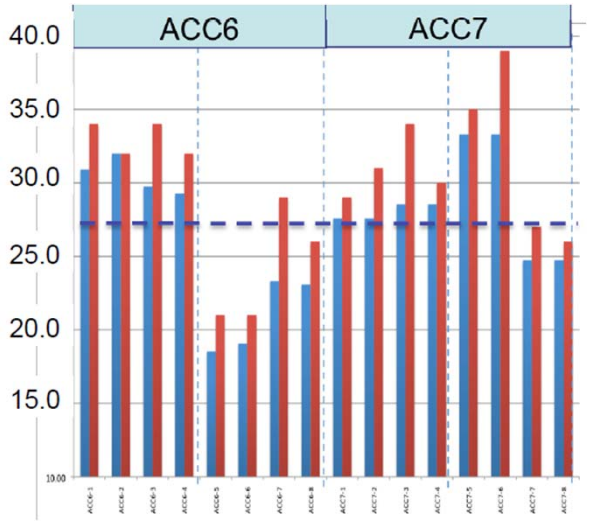
Ramp-up in number of bunches @ 3MHz

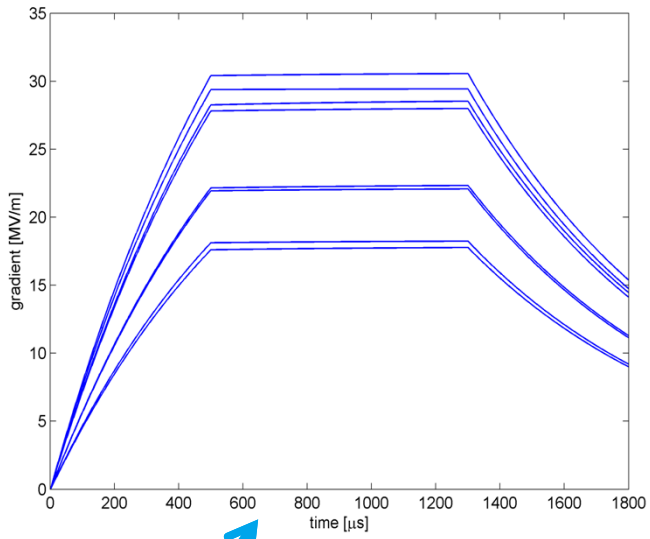


Courtesy:
J.Cawardine

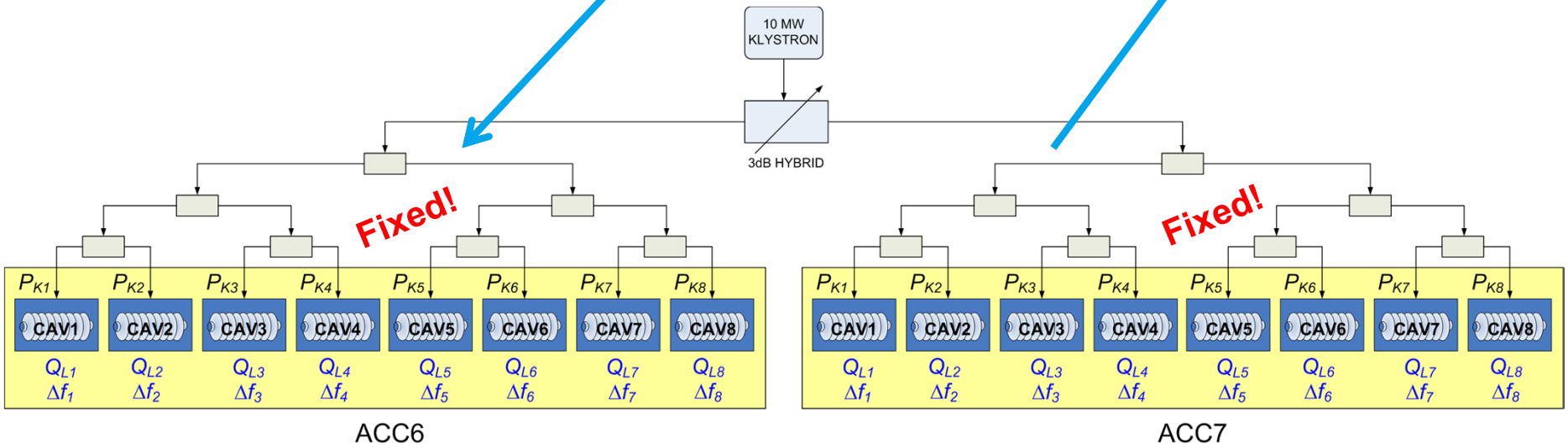
II. Some key concepts to understand the ILC study

> Gradient spread





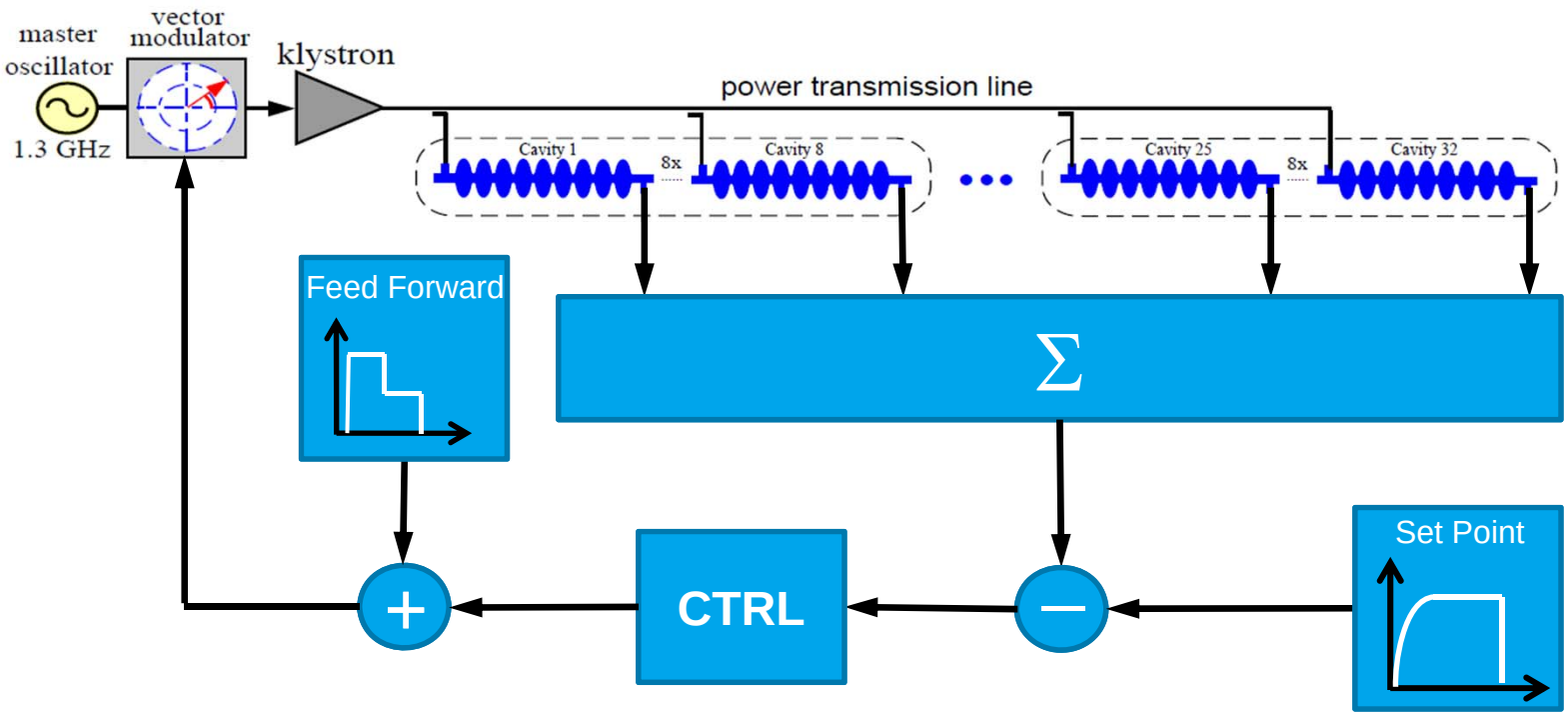
> Power distribution



II. Some key concepts to understand the ILC study

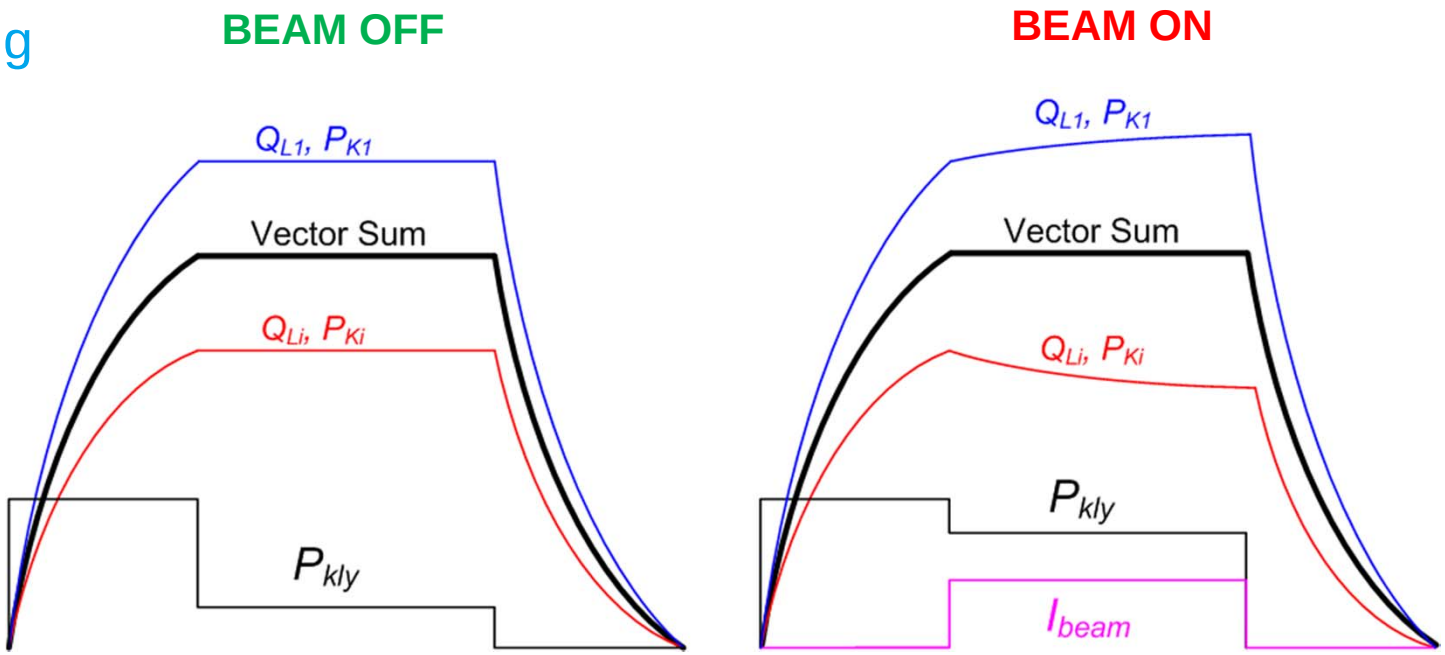
> Vector sum control

Single-klystron multiple-cavities



II. Some key concepts to understand the ILC study

> Beam loading

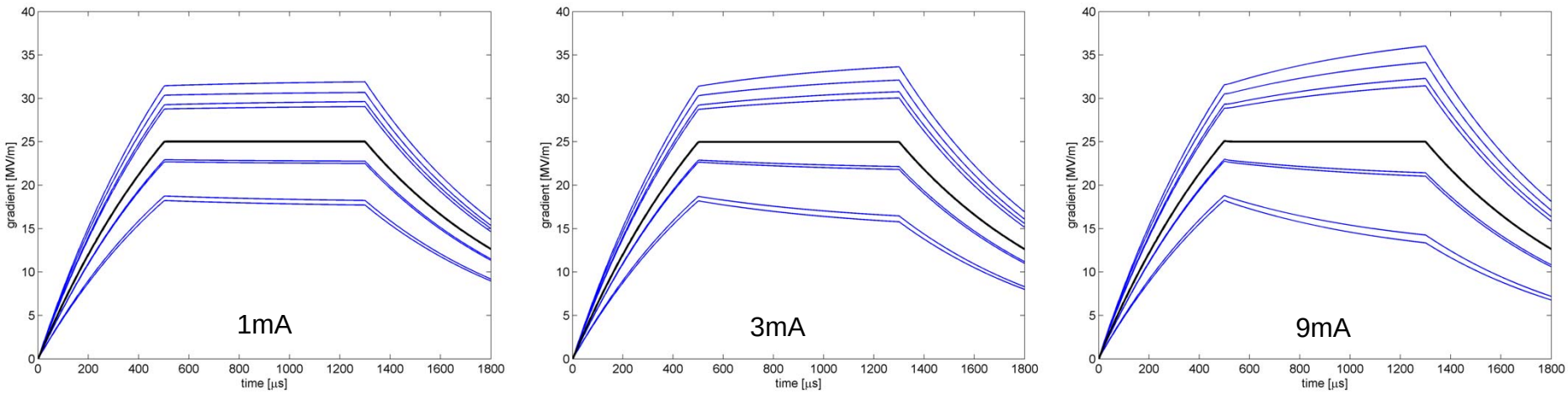


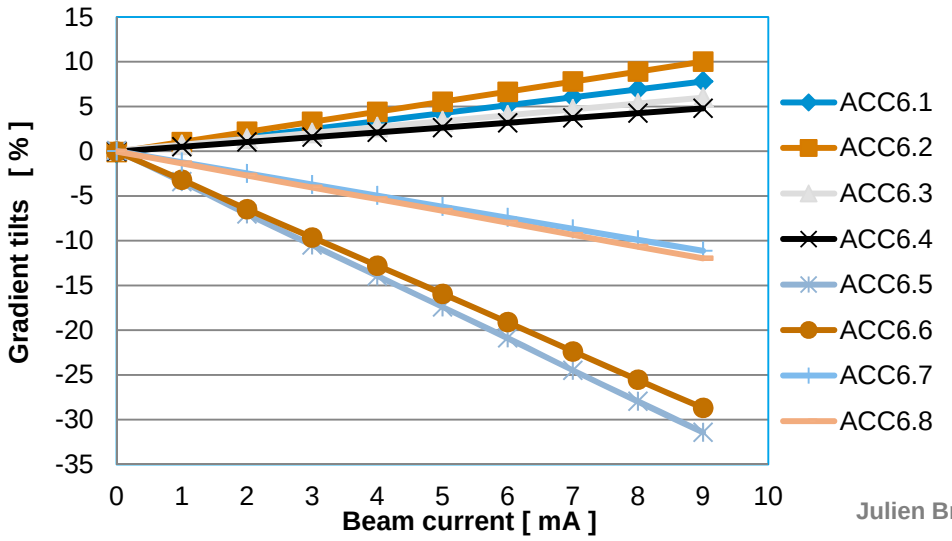
> Why do we care about individual flat gradients?

- "Effect of Cavity Tilt and RF Fluctuations to Transverse Beam Orbit Change in ILC Main Linac" K. Kubo, Jan. 2010

II. Some key concepts to understand the ILC study

> Beam loading tilts scale linearly with beam current





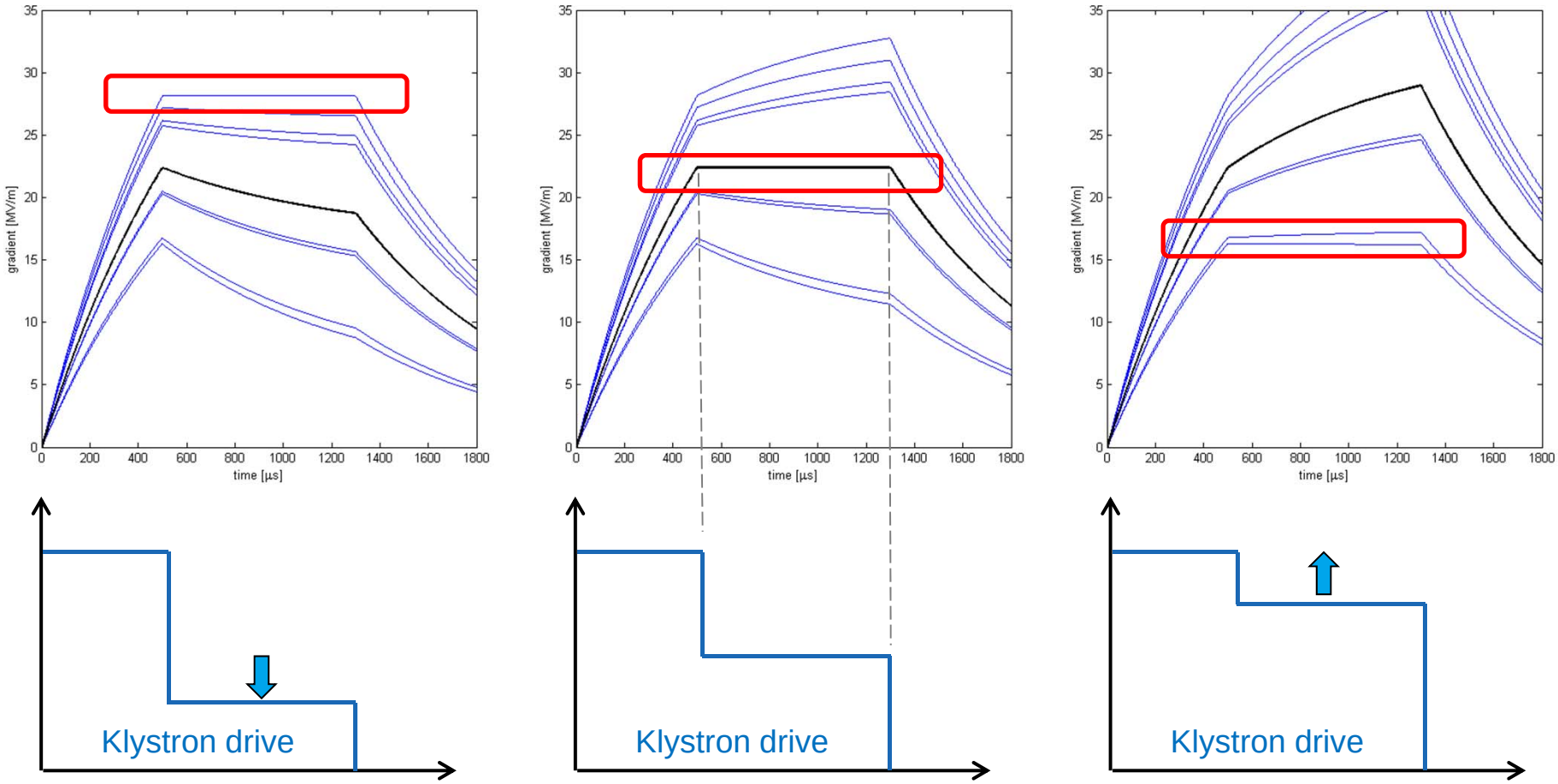
Simulated gradient tilts in ACC6,

for a 800 usec flat top

with current FLASH Q_L setup

II. Some key concepts to understand the ILC study

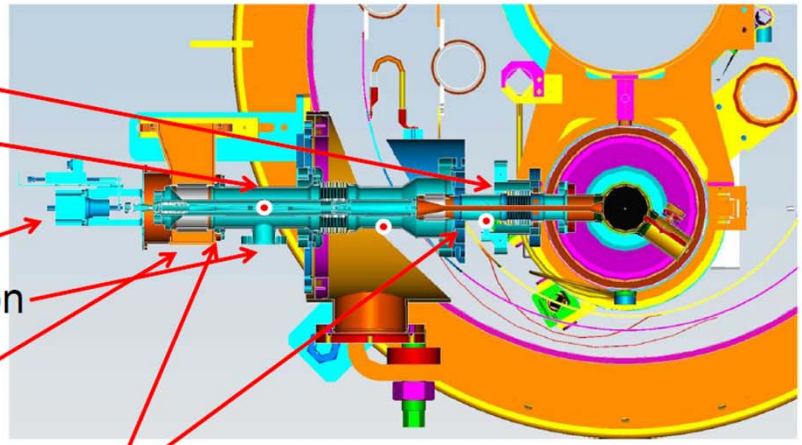
> Single klystron + beam loading = gradient tilts



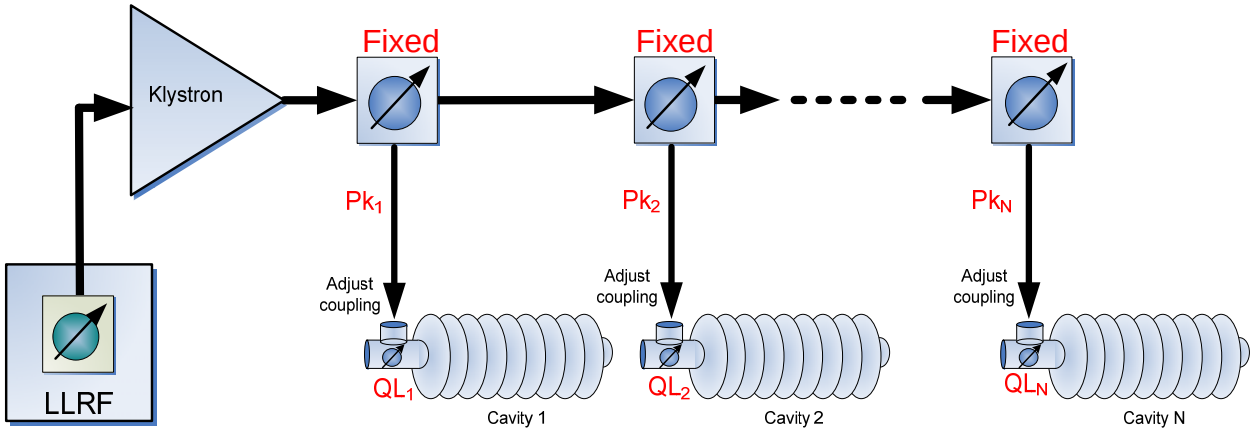
II. Some key concepts to understand the ILC study

> Loaded quality factor: Q_L

- Cold coax
- Warm coax
- Wave guide
- Qext tuner motor
- Vacuum connection
- Wave guide spark detector
- Temperature sensor, 300K and 70K



Courtesy:
W.D. Möller



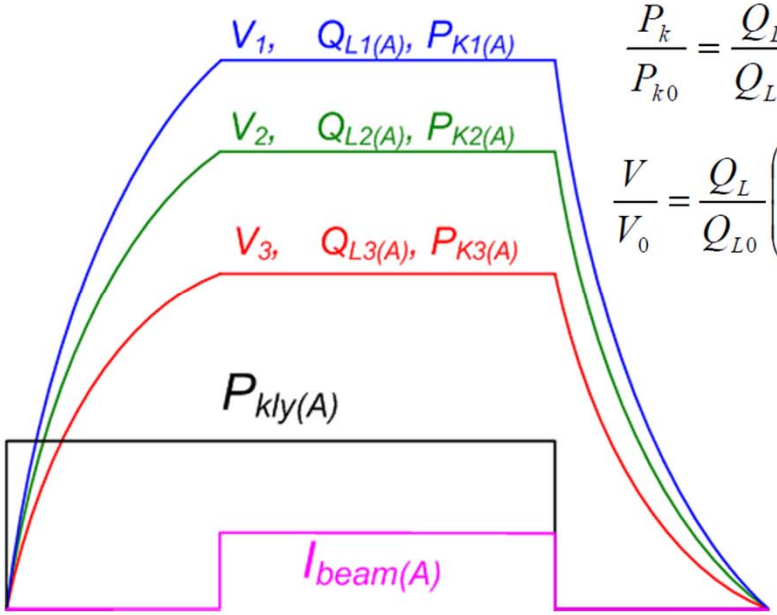
III. Analytical solution: Pk / Ql

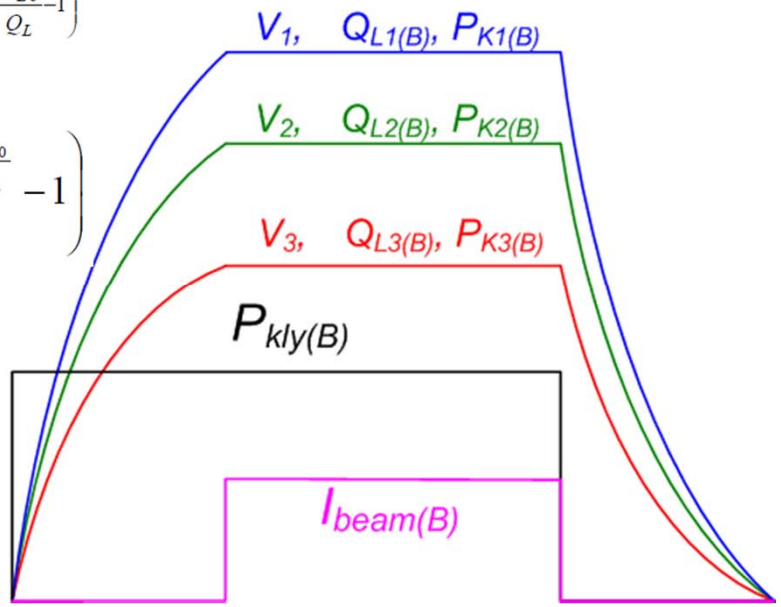
> "Solutions" to flatten cavity gradient with beam

- "RF Distribution Optimization in the Main Linacs of the ILC", Bane, Adolphsen, Nantista – PAC07
- "Optimal Coupler and Power Settings for Superconductive Linear Accelerators", Branlard, Chase - LINAC08
- "Pseudo-Pk/Ql control for ACC6/7 at FLASH", Michizono, unpublished 2010

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

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





III. Analytical solution: “pseudo Pk” / Ql

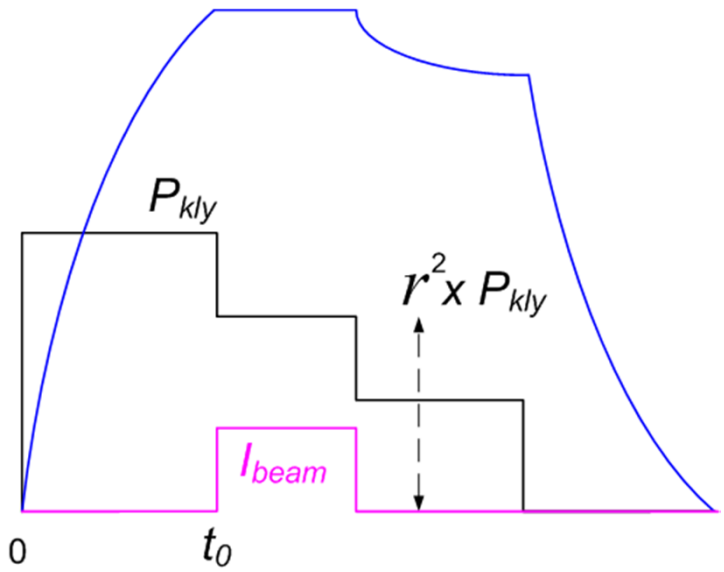
> Analytical ‘solution’ for optimal Q_L

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

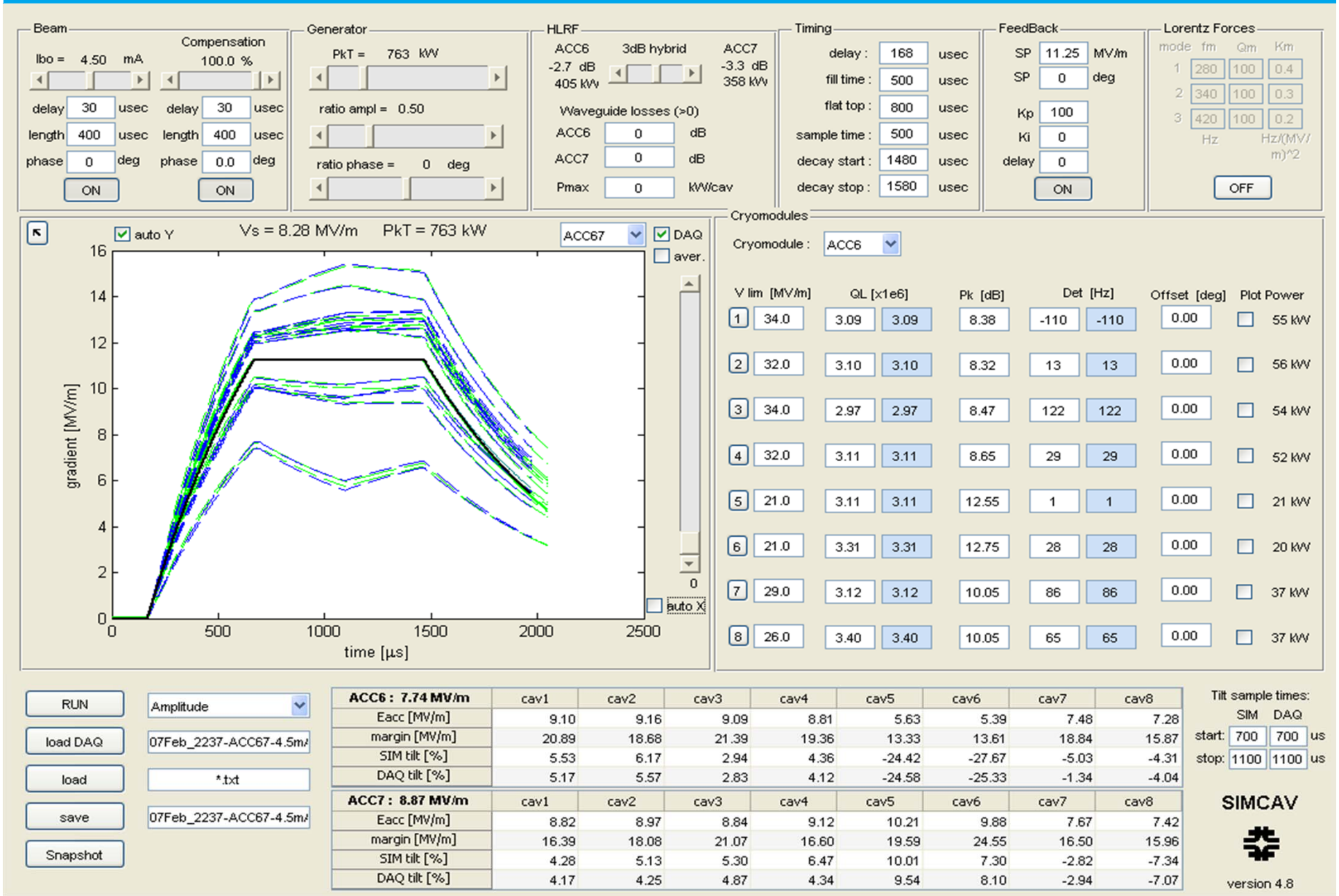
→ assumes “perfect” tuning

→ 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)



III. Analytical solution: SIMCAV, cavity simulator



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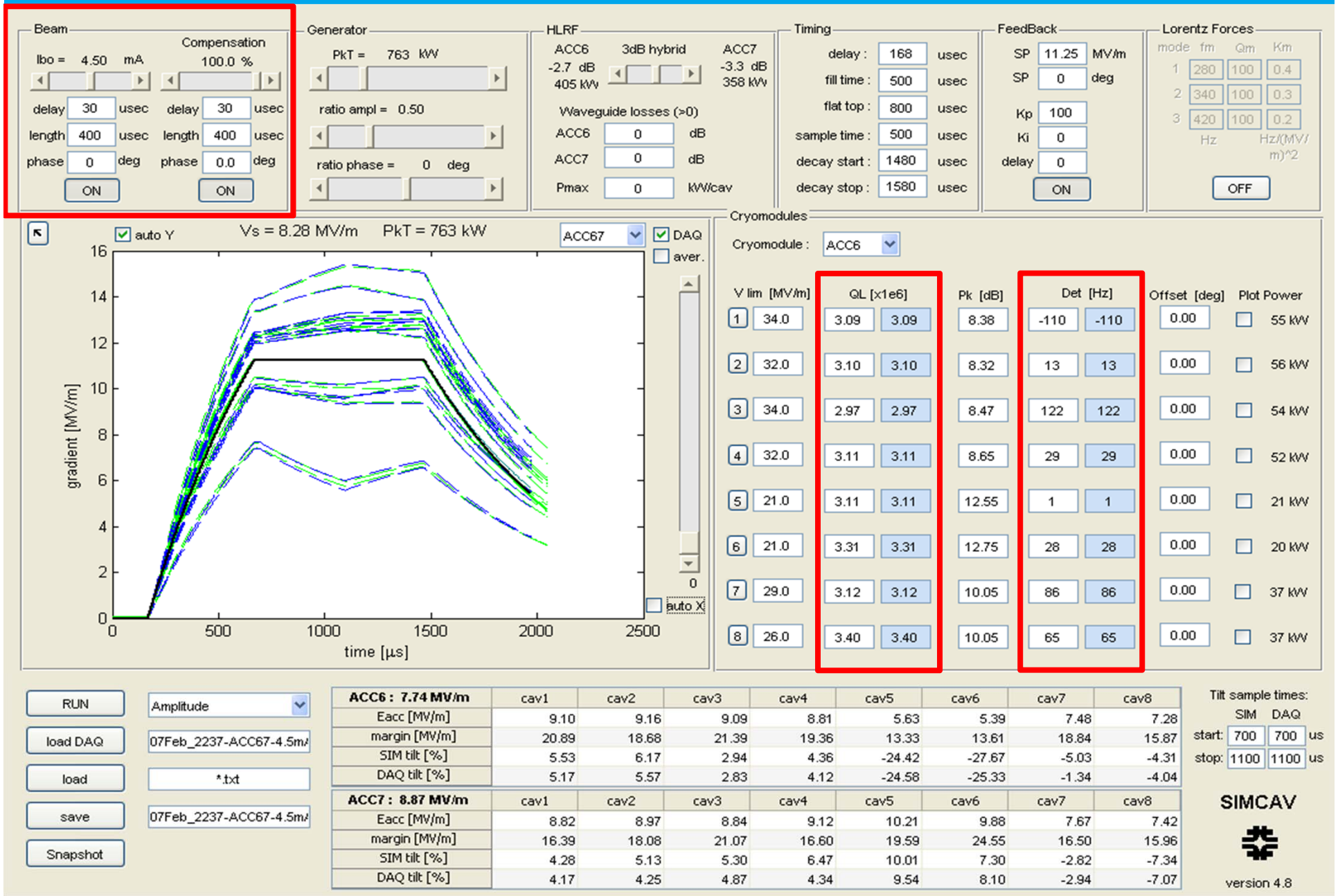
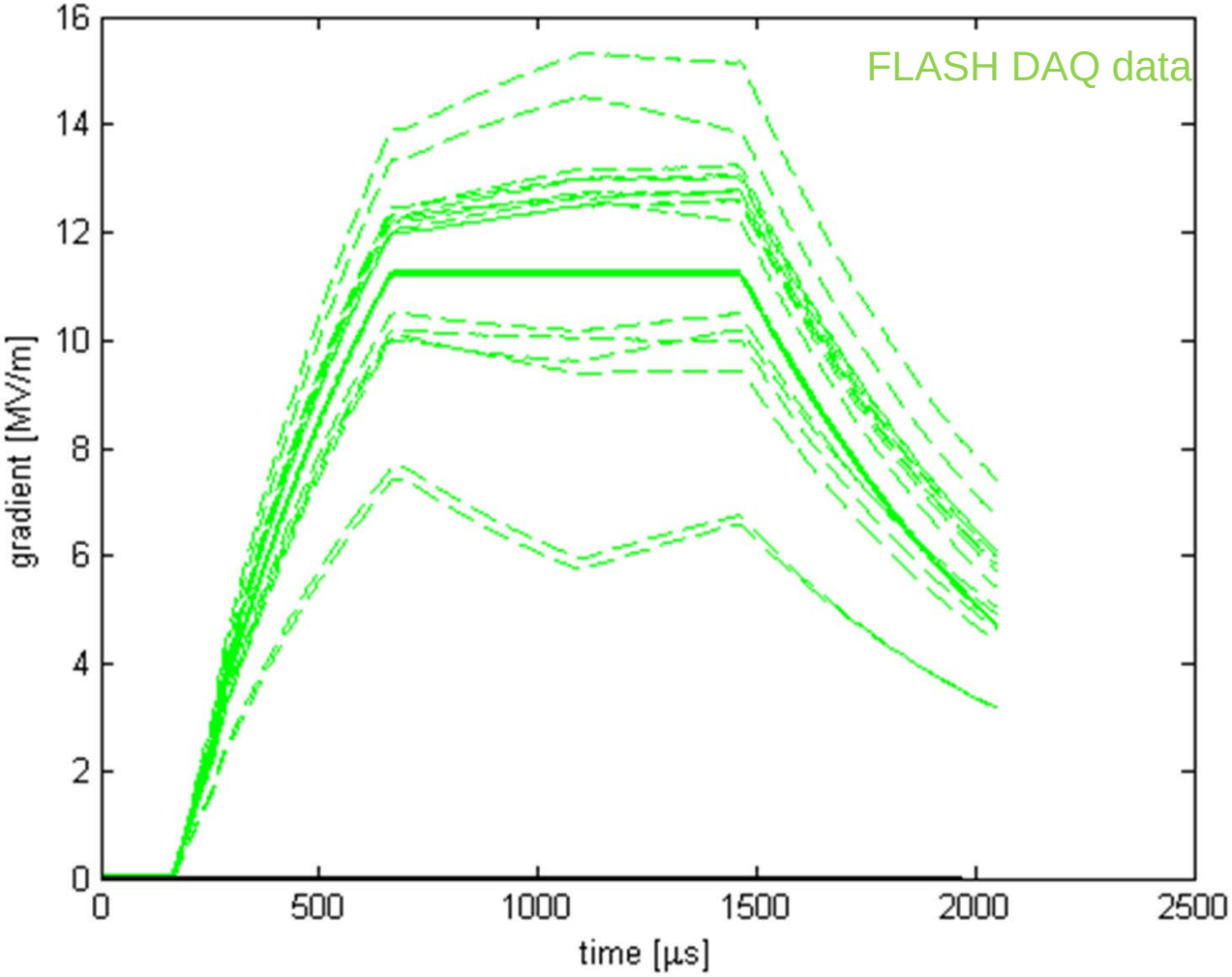


III. Analytical solution: procedure

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

DAQ data: Feb. 07 2011, 22:37



I_b = 4.5 mA

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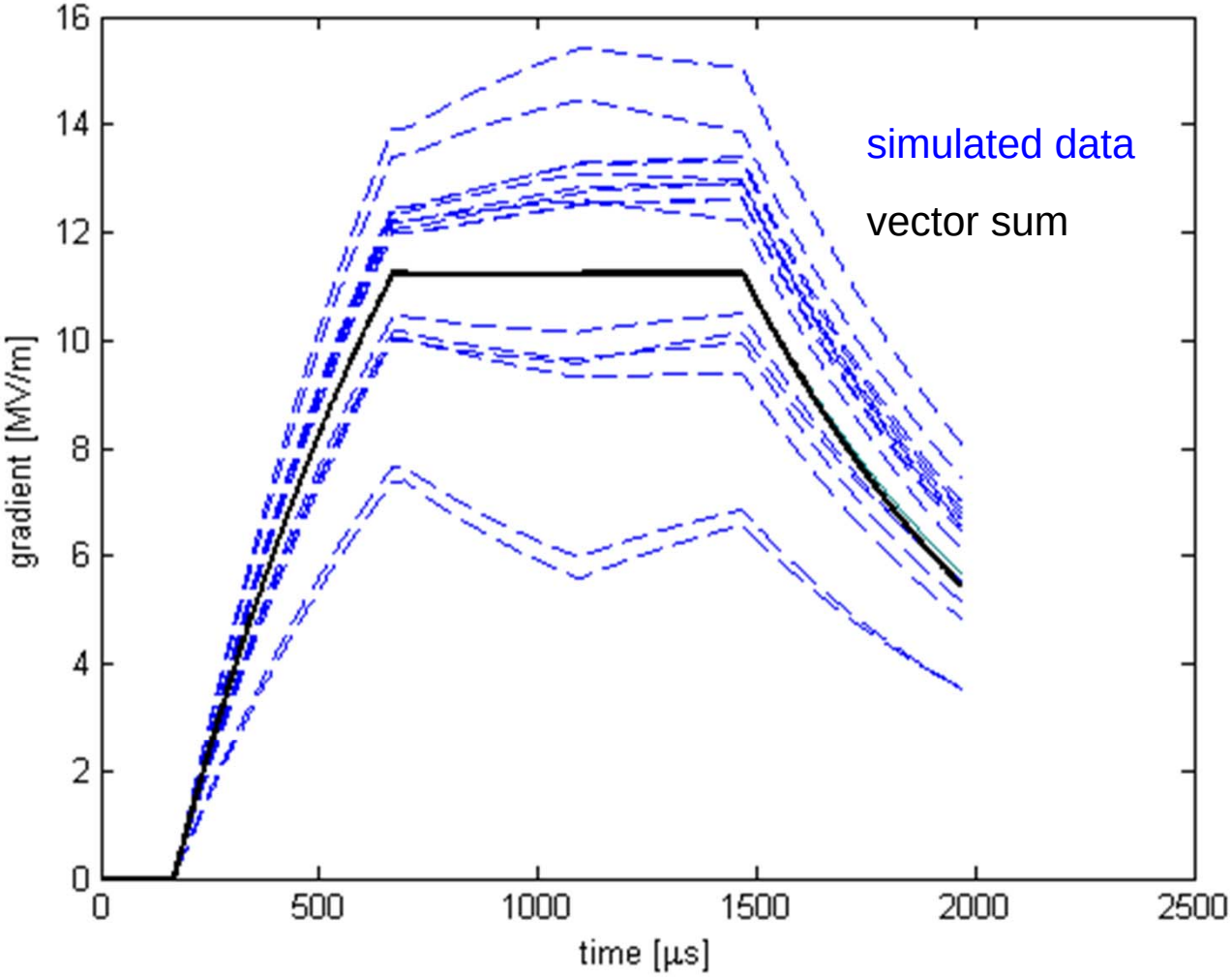

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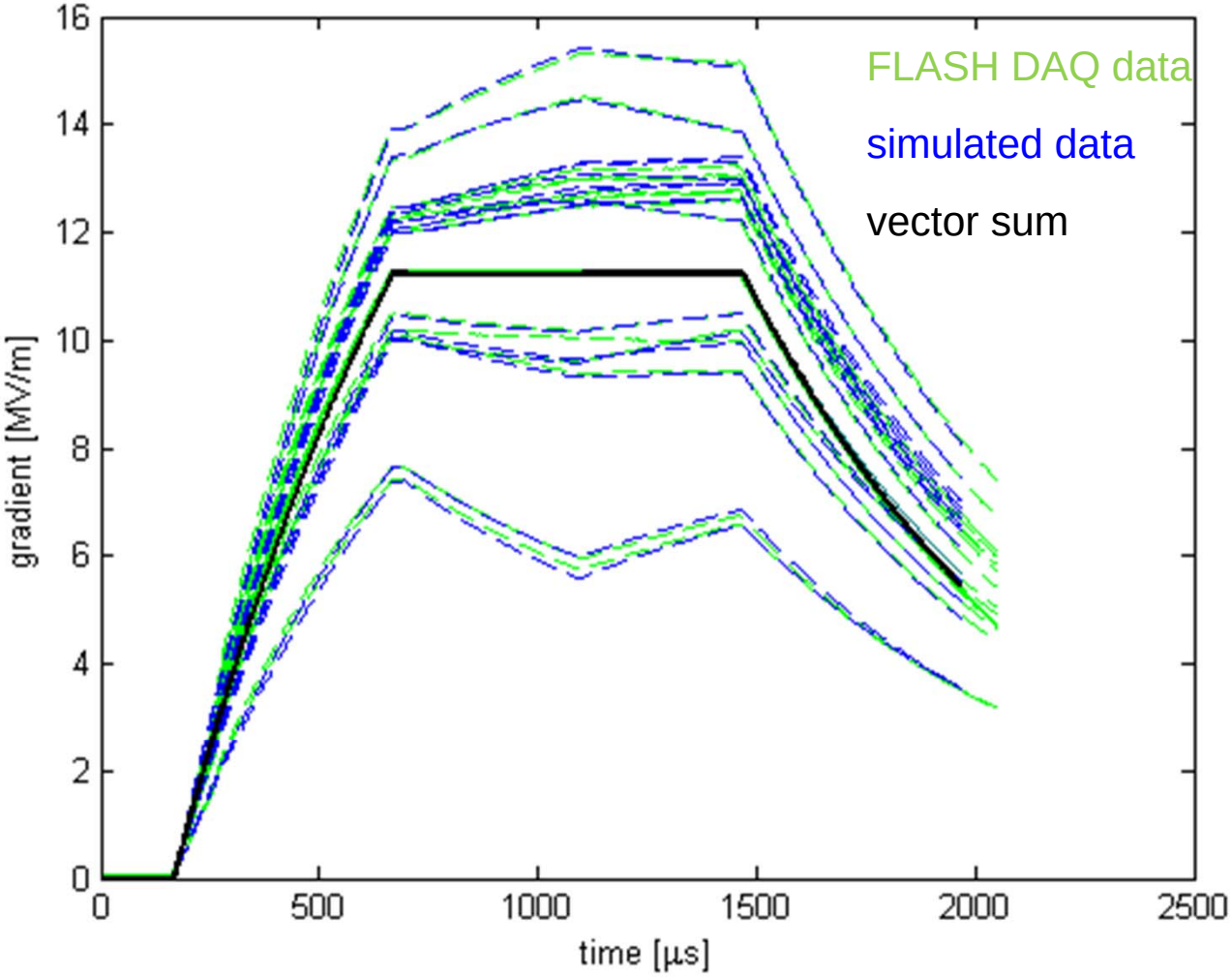

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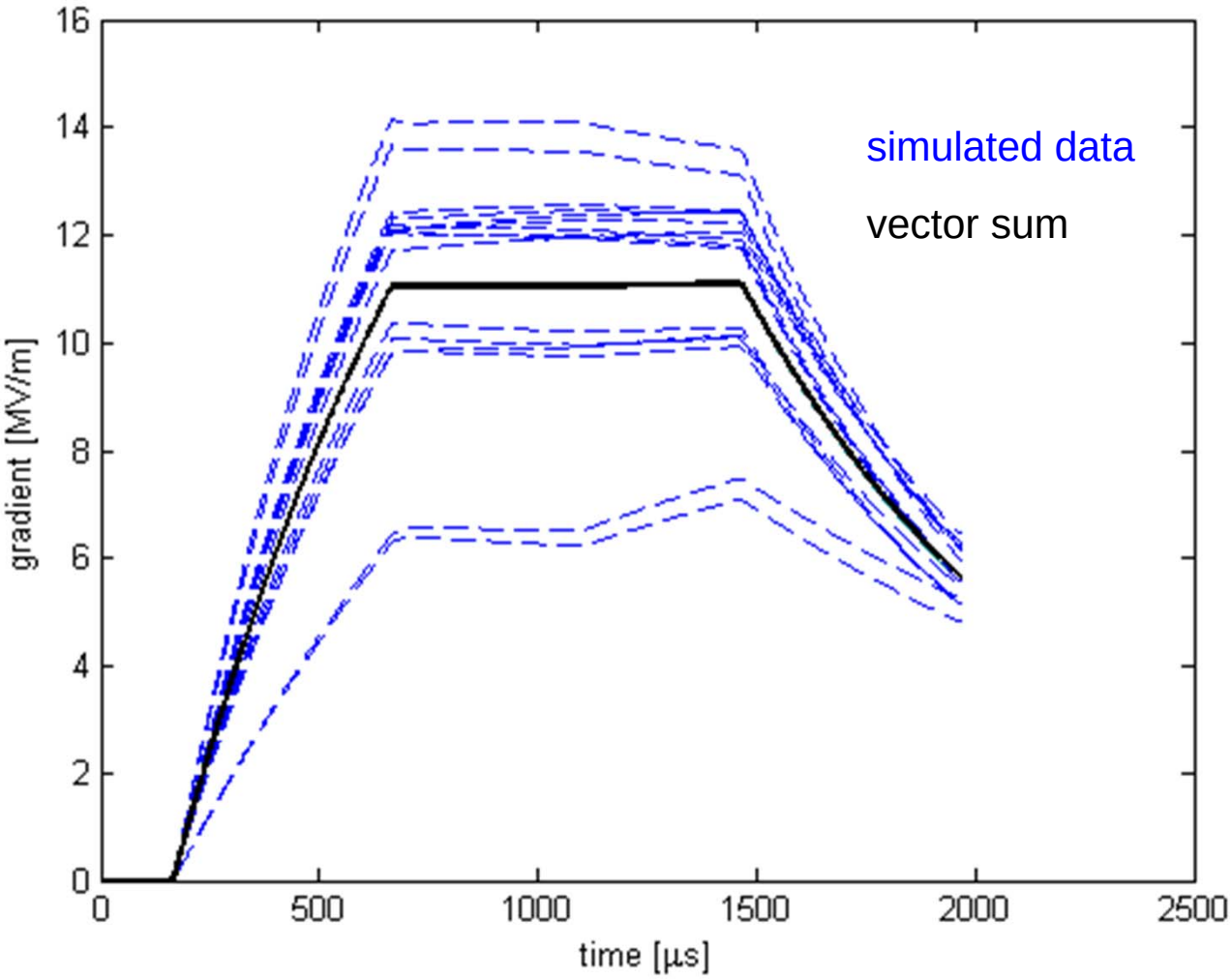

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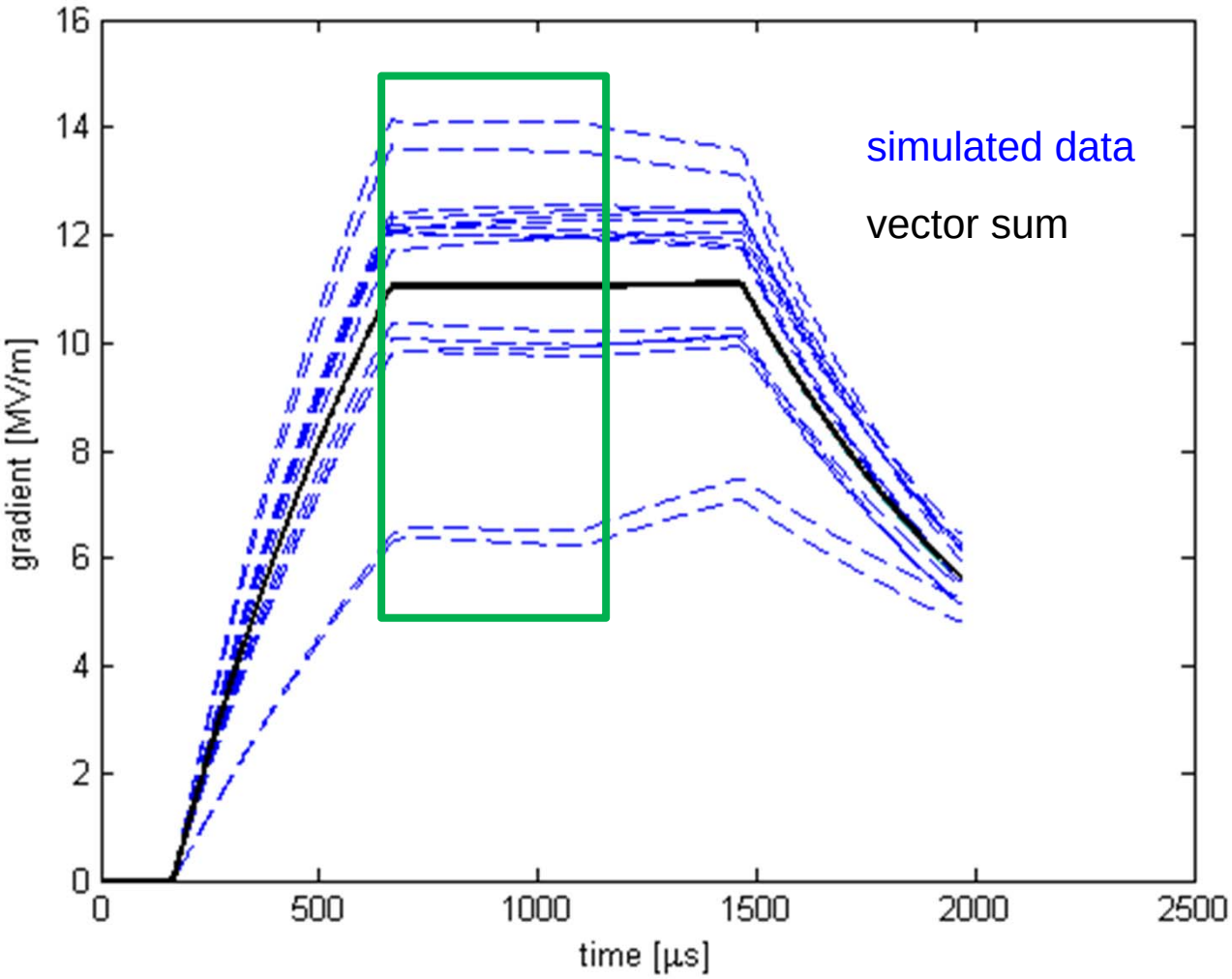

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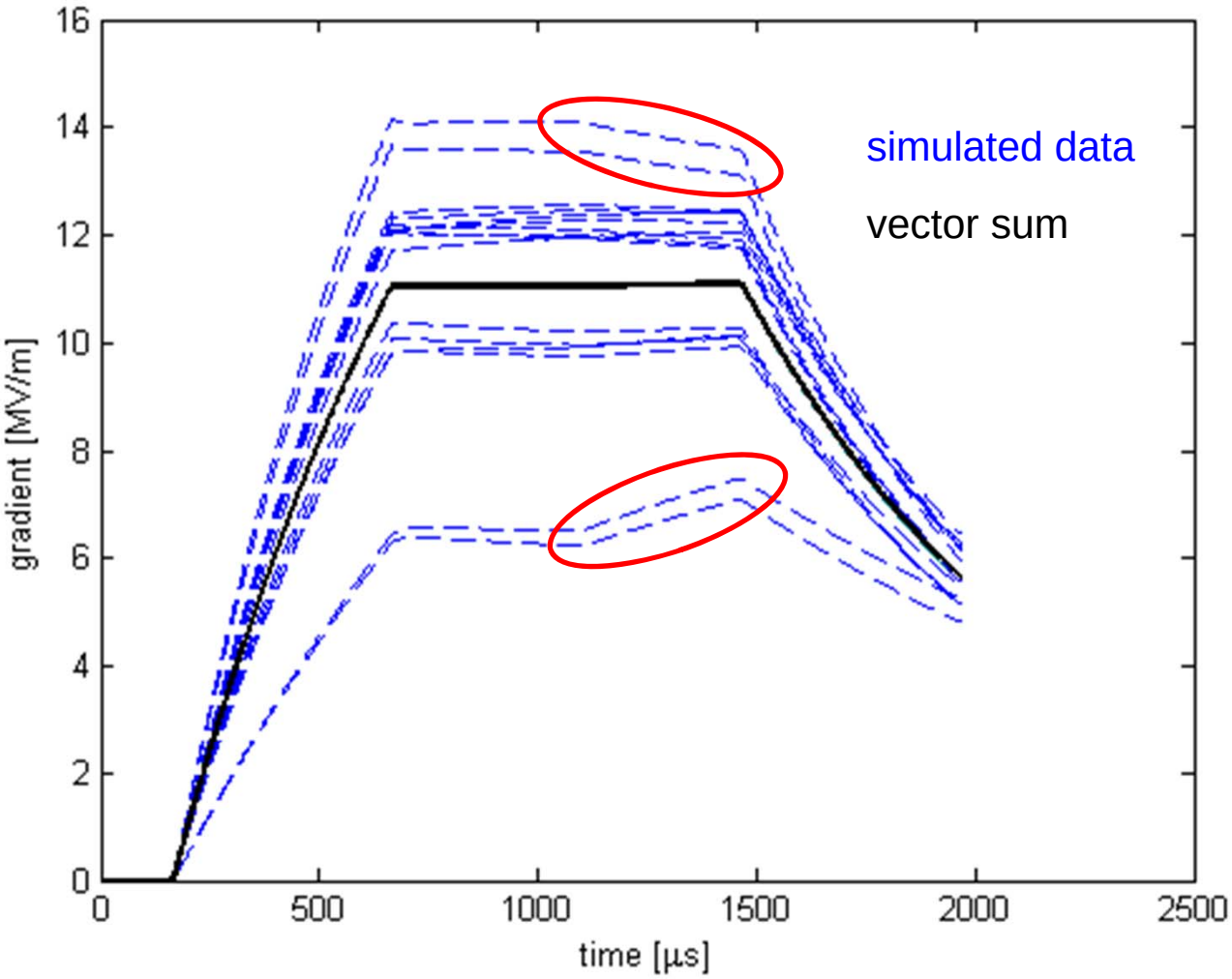

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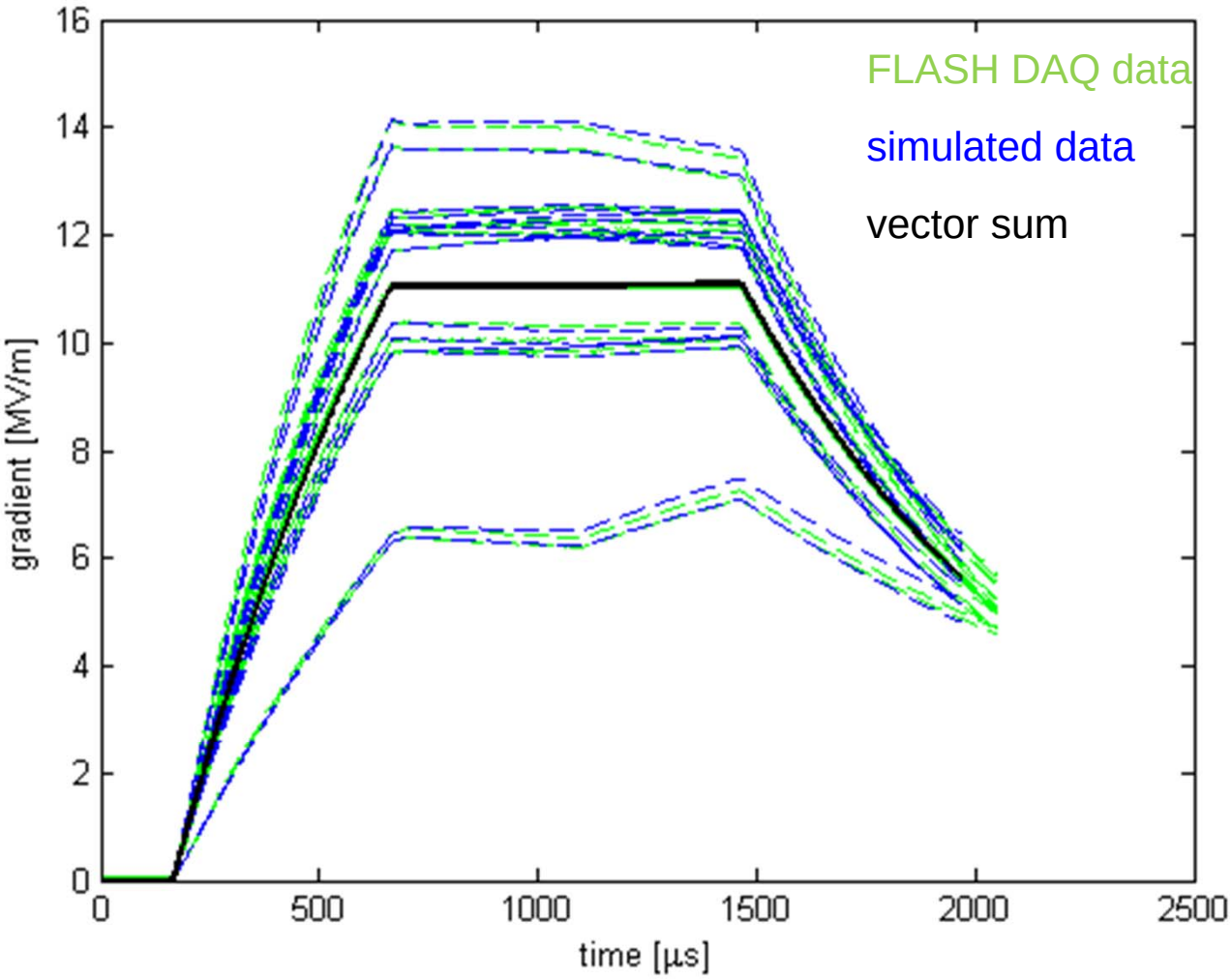

III. Analytical solution: procedure

1. Load *V*
2. Compu
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3. Type in
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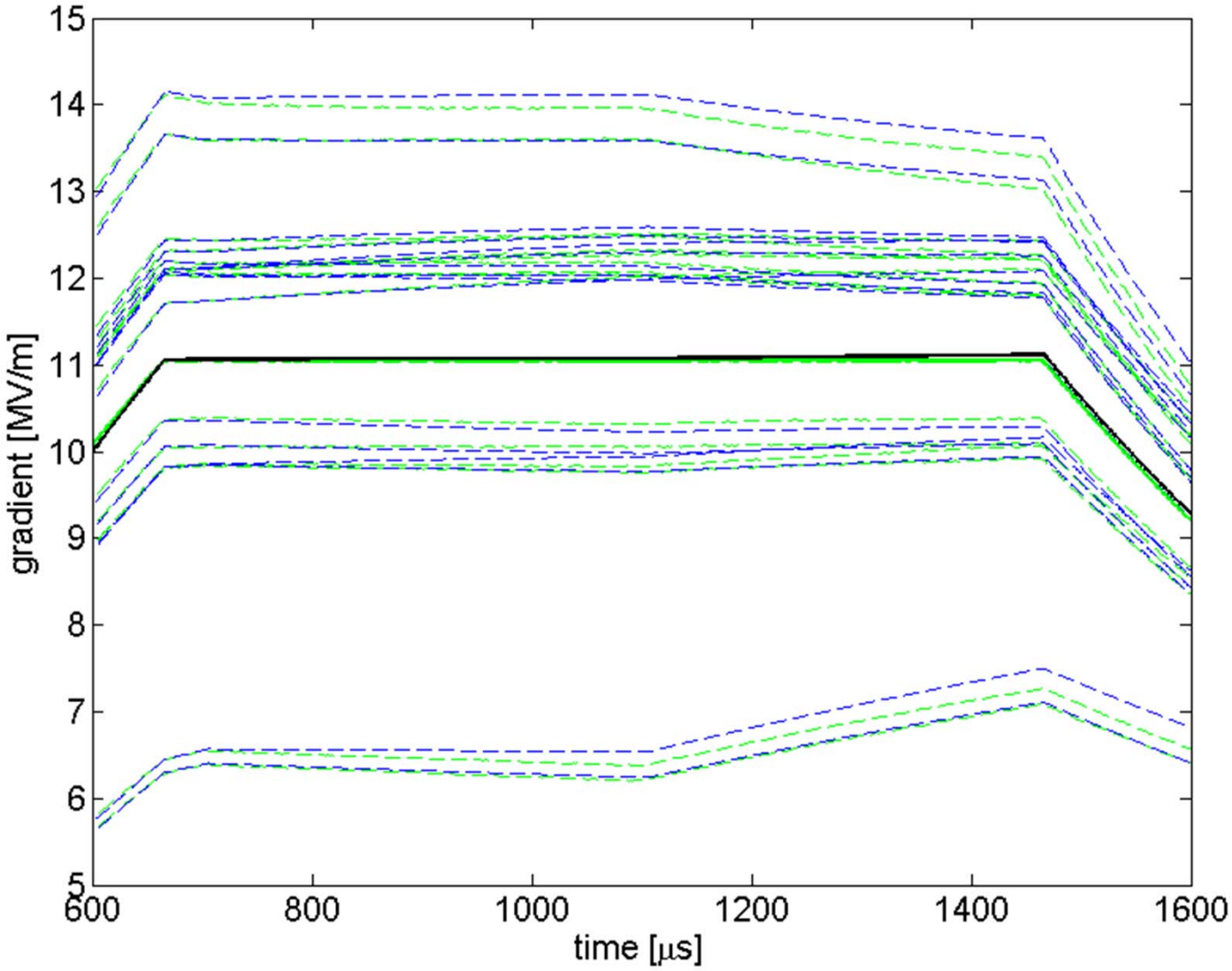


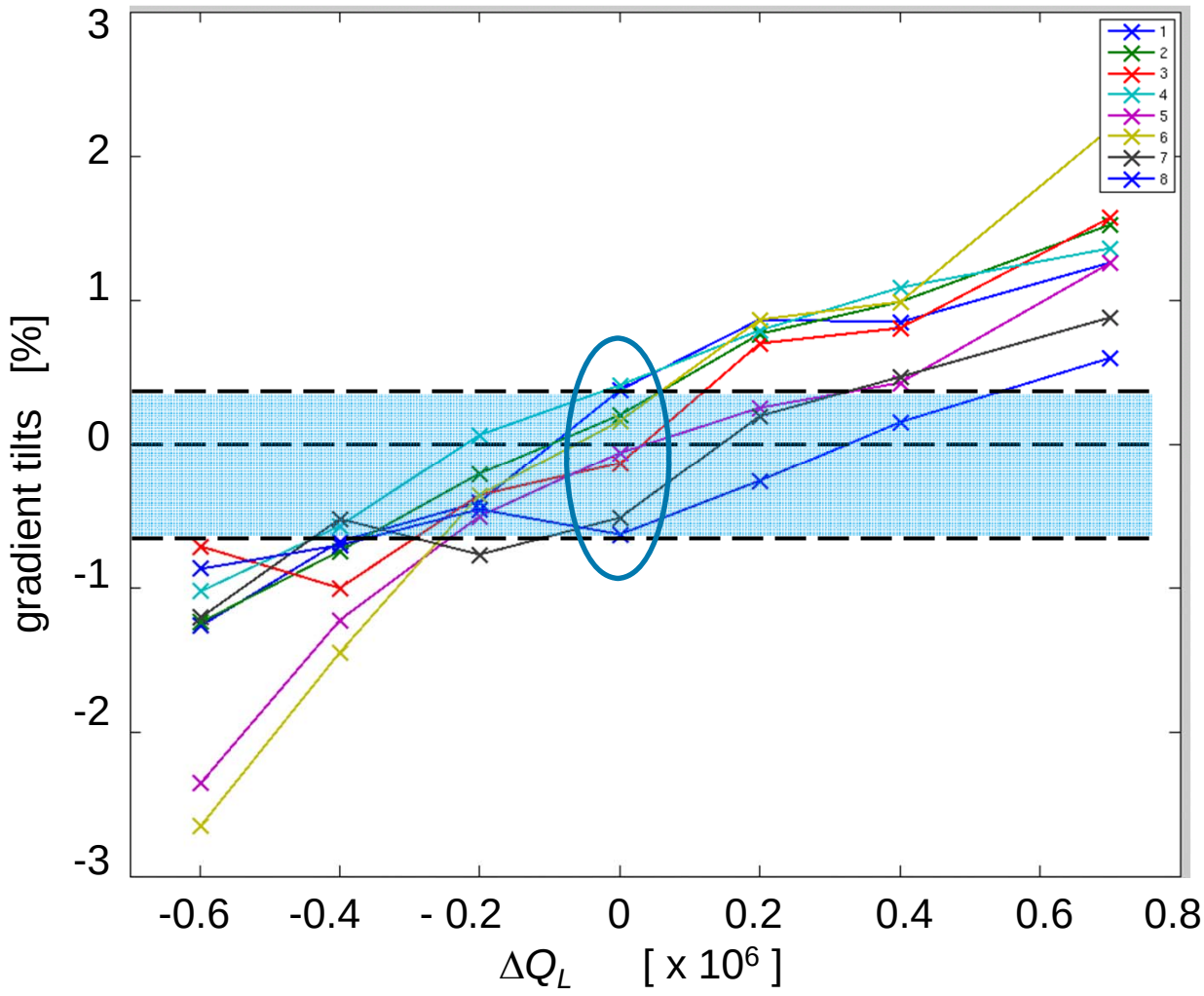
III. Accuracy assessments

> 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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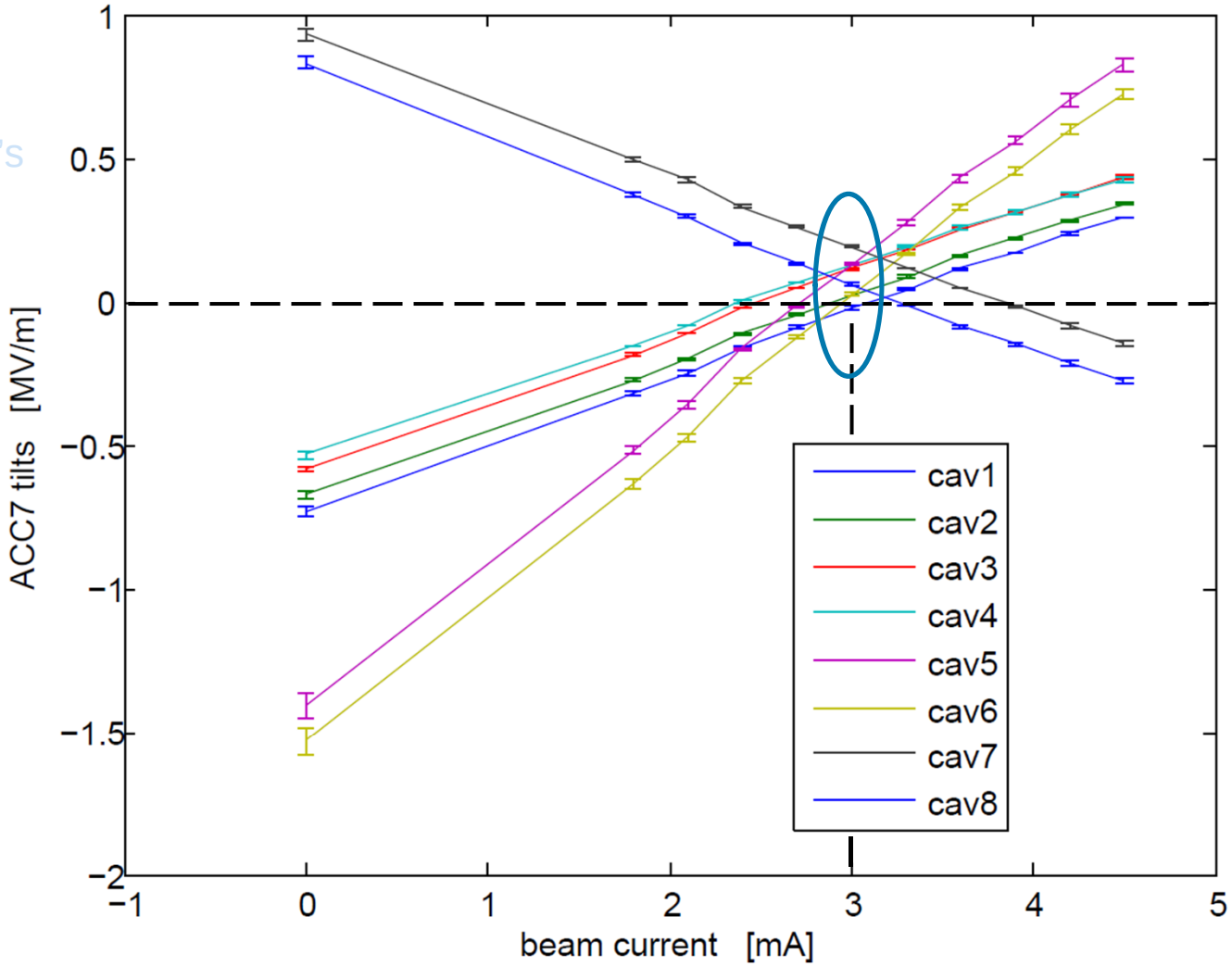

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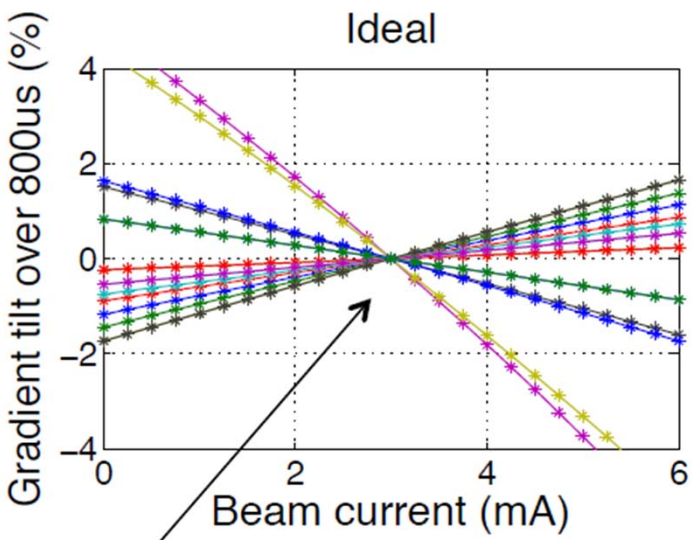
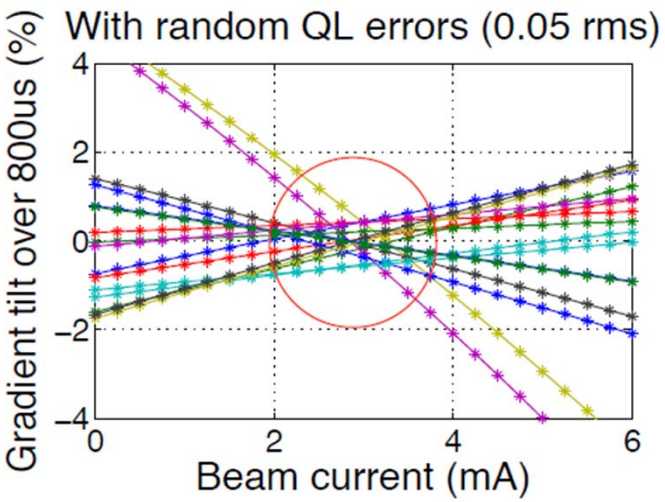
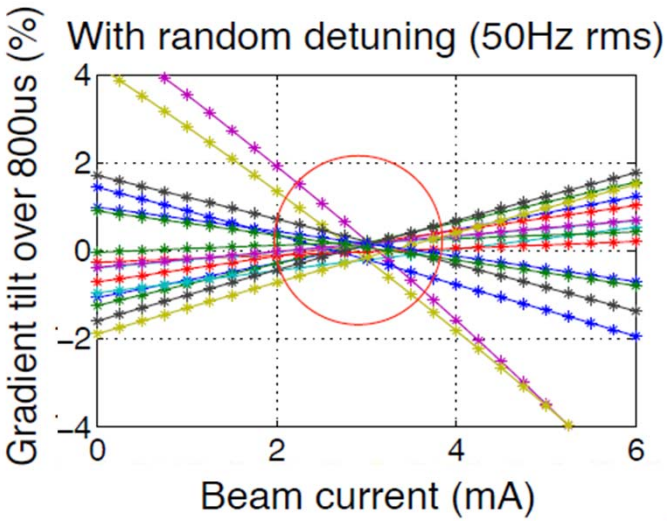


In the ideal case, all cavities have zero tilts at the same exact beam current

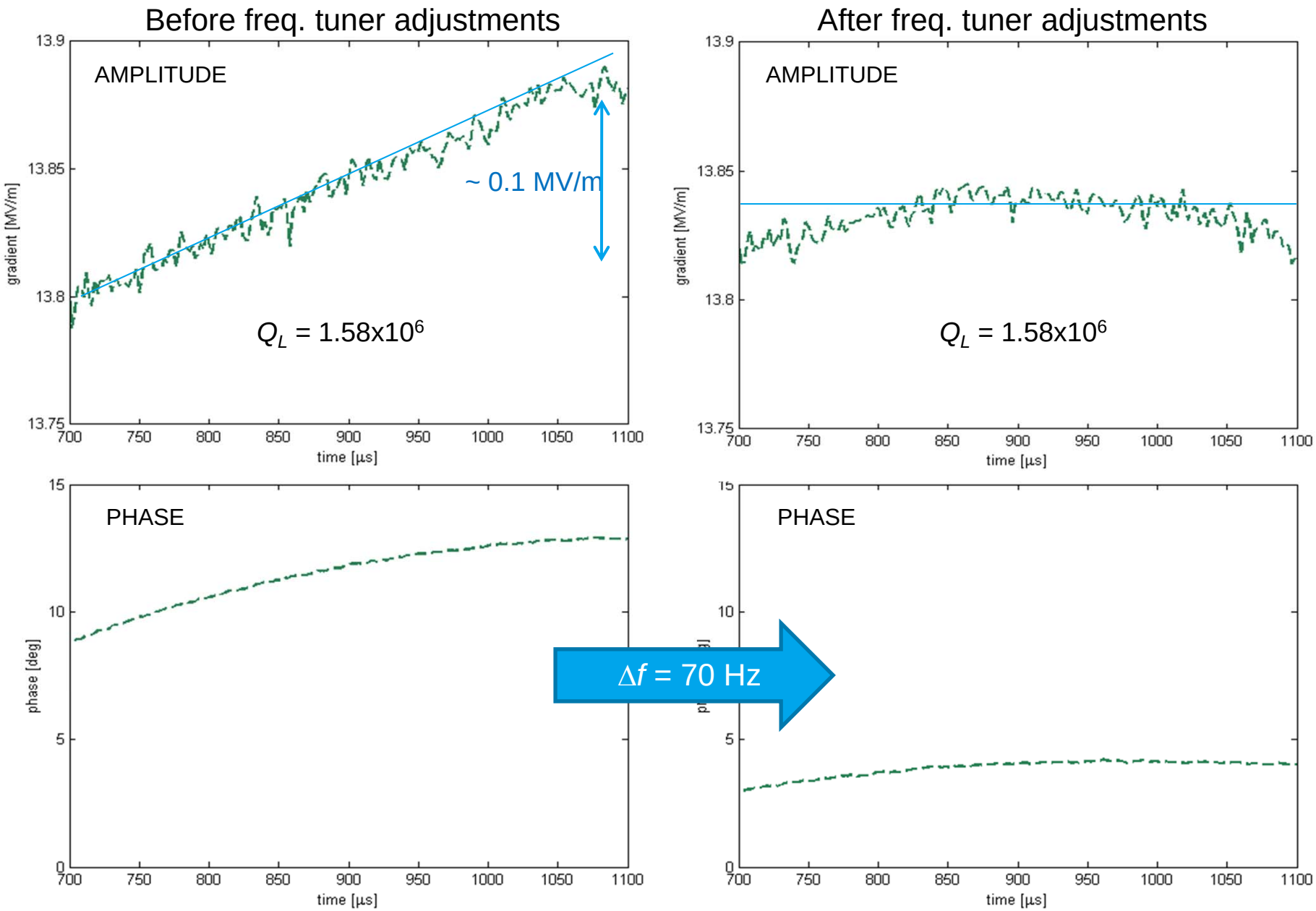




Errors in QL or in detuning will cause cavities to have zero tilts at different beam currents

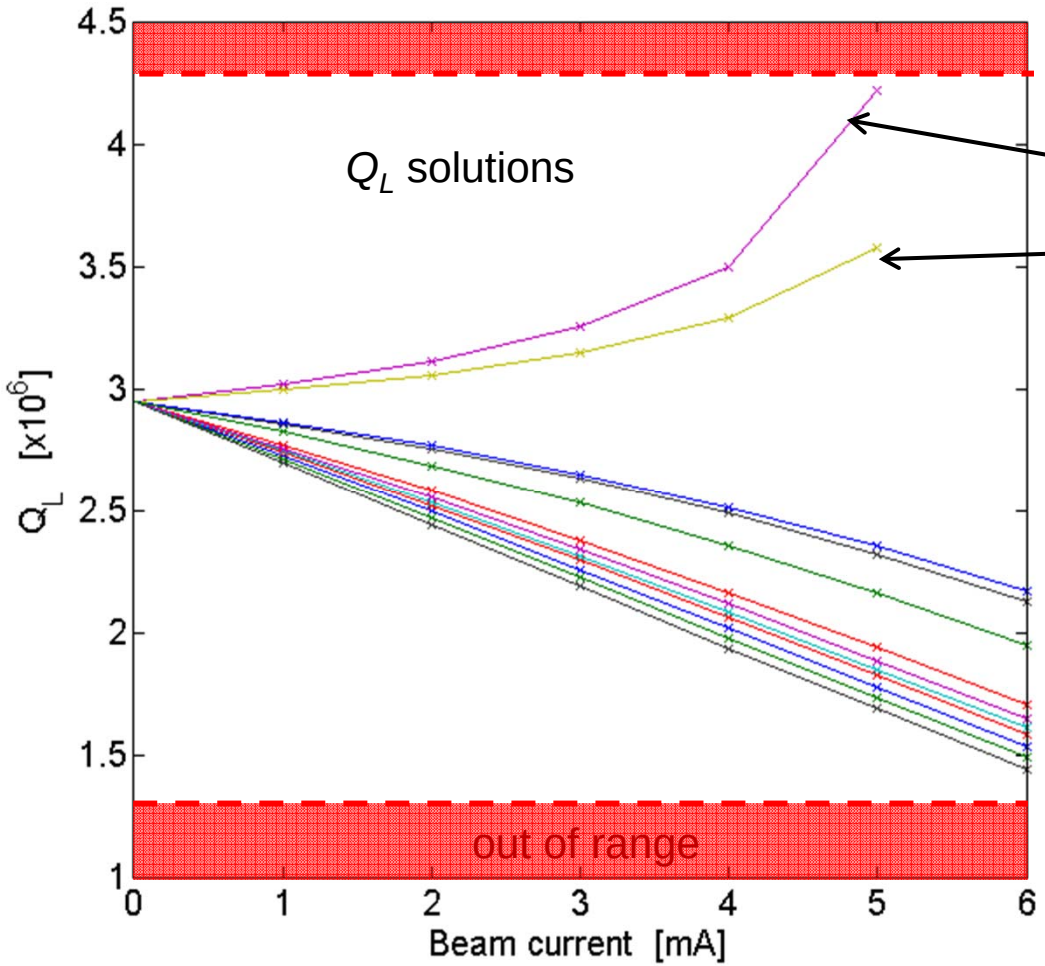
Courtesy:
J.Cawardine

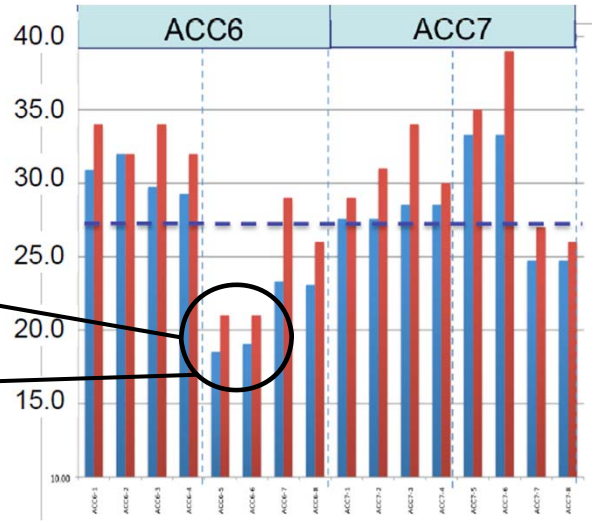
III. Accuracy assessments



III. Accuracy assessments

> Q_L settings are limited: no solution yet for 9mA !





ILC specs : 9 mA !

IV. Conclusions: last 9mA run at FLASH (Feb. 2011)

What went well

- Motorized couplers / tuners
- Analytical approach proved to be 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 analytical approach:
  - How accurately can we compensate for LFD
  - How accurately can we measure and set Q_L's → +/- 2 to 5%

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) → ACC6.C5 and C6
- No solution to bring up the machine at its highest gradient

IV. Conclusions: upcoming 9mA test at FLASH (Feb. 2012)

> Machine automation

- Automatic Q_L settings
- Automatic quench detection
- Automatic piezo compensation

> Machine operation scenarios

- Tuning strategies
- How to ramp up the beam
- How to ramp up the gradient
- How to recover from a quench

> RF power overhead study

- Simulate klystron saturation regime
- Field control regulation saturation

Thank You!

> Further reading:

- FLASH 2011 Highlights

ILC HIGH BEAM CURRENT TESTS AT FLASH.

High beam loading RF operation with flat cavity gradient

The International Linear Collider (ILC) design for the main linac is based on RF stations comprising one 10 MW klystron providing power for 26 cavities housed in 3 cryomodules. The average operating gradient is 31.5 MV/m with a tolerance of 20% gradient spread, (i.e. individual cavities ranging from 25 MV/m to 38 MV/m). To achieve the design average operating gradient, all cavities must operate simultaneously within 3% of their respective gradient limits under full beam current conditions (5mA baseline, 9mA upgrade). FLASH offers an excellent test bench for ILC operating conditions as it is also based on a single-klystron – multiple-cavities scheme, and allows acceleration of beam currents up to 9 mA. An on-going series of tests is carried out at FLASH as part of an international collaboration between DESY, FNAL and KEK, to demonstrate operations at the limits of gradient and RF power in the presence of heavy beam loading. More specifically, the latest one took place in February 2011 as a proof of principle of tuning cavity key parameters to accelerate high beam currents while maintaining flat cavity gradients.

Challenges

In pulsed accelerators, like FLASH or the ILC, the electric field inside a cavity is ramped up at the beginning of each pulse and kept constant both in amplitude and phase for the entire duration of the beam train. This latter time segment where the beam is accelerated is commonly referred to as **flat top**. To meet the luminosity goals, the flat top gradient is regulated and controlled to better than 0.1% in amplitude and 0.1 degree in phase, according to ILC specifications.
At FLASH like in the ILC design, one klystron provides power to several cryomodules. Due to performance disparities among cavities, the klystron RF power is distributed according to the individual cavity gradient limits, i.e. cavities with higher performance will receive more power than cavities of lower performance. At FLASH, this is achieved by using adjustable power couplers, which are set once according to each cavity's performance. The spread in power distribution results in a gradient spread among the cavities within a cryomodule. A consequence of this gradient spread is the different behaviour of each cavity due to the interaction with the beam, which is also known as **beam loading**. Typically, cavities operating above the average gradient will show an increase in gradient (positive tilt), while those operating below average will see their gradient drop during the beam acceleration (negative tilt). While this effect is negligible for low beam currents (below 1 mA), it can induce 10 to 20% tilts on single cavities for high beam currents such as the 9 mA ILC upgrade design, as illustrated in Fig. 1. It was demonstrated that a physical misalignment of cavities combined with a gradient tilt during beam acceleration results in a transverse dispersion of the beam. Due to mechanical limitations, a perfect alignment of all cavities in the accelerator chain is not realistically achievable, only leaving the option of minimizing the cavity tilts to avoid this detrimental beam dispersion effect.

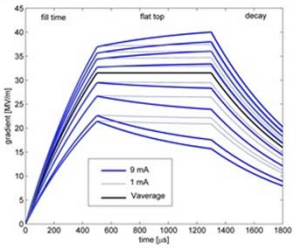


Figure 1: Pulsed cavity gradients for one cryomodule with 1 mA (dashed) and 9 mA (solid) beam currents, illustrating positive and negative tilts during the flat top region. The average gradient is shown in black.

For a multi-cavity single-klystron accelerator, like FLASH or the ILC, the fields of all individual cavities are measured and added up. The feedback control then computes the amplitude and the phase of the sum of all cavity gradients, and regulates the drive of the klystron power to maintain a flat and stable total field accelerating the beam. This control scheme is referred to as **vector sum control** and was first used on a large scale superconducting accelerator at FLASH. One