System Tests: 9mA studies at FLASH

John Carwardine (Argonne)

ILC GDE PAC Review, Fermilab 15-16 May, 2012

Outline

- **Brief recap of achievements to date**
- **Results from beam studies in Feb 2012**
- **Tests at FNAL and KEK**
- **Assessment of results / extrapolation to ILC parameters**
- **System test program, post TDR**

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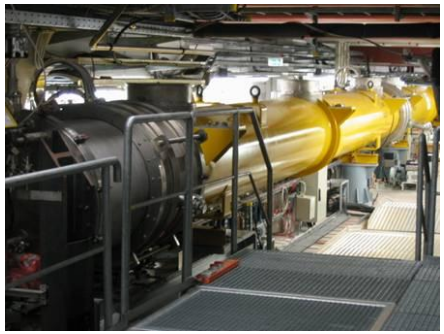
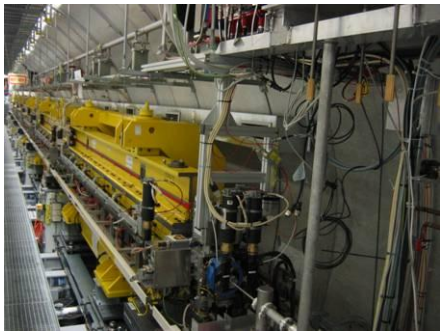
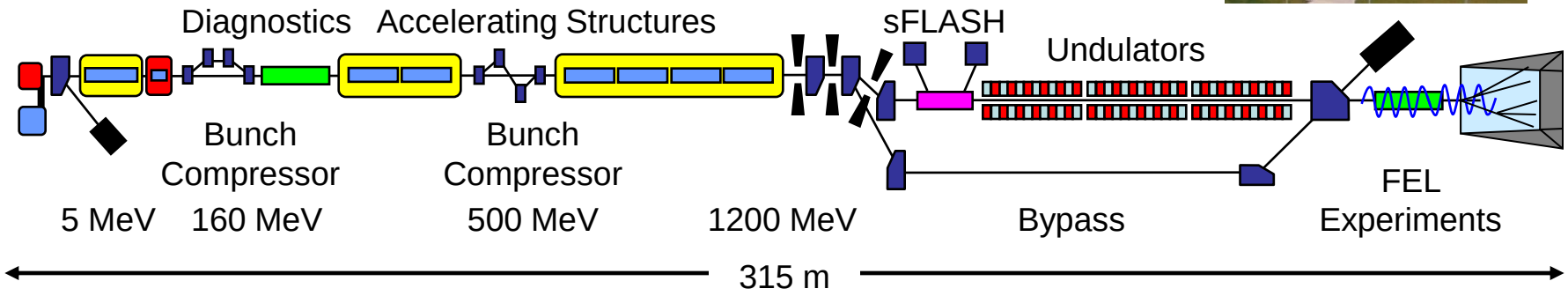
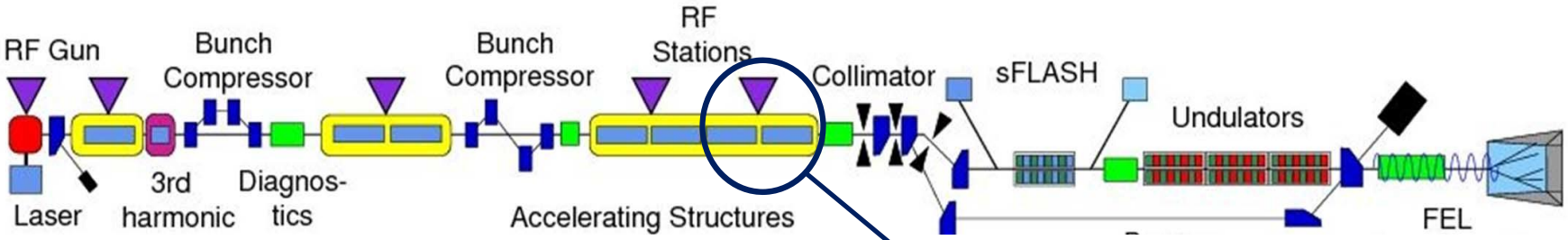
FLASH layout

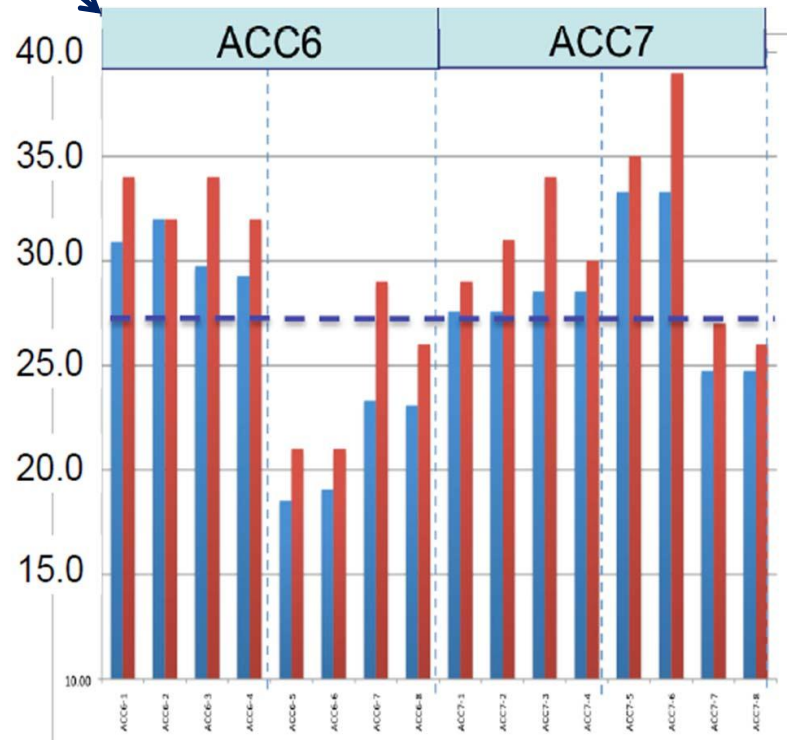





TTF/FLASH layout 9mA Experiment



- 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



FLASH 9mA Experiment achievements: pre-2012

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

Metric	ILC Goal	Achieved
• **Macro-pulse current**	9mA	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 *(Feb 2011)*

Metric	ILC Goal	Achieved
• **Cavity gradient flatness (all cavities in vector sum)**	2% ΔV/V (800μs, 9mA)	2.5% ΔV/V (400μs, 4.5mA) *"Methodology established"*
• **Gradient operating margin**	All cavities operating within 3% of quench limits	*(Focus of early 2012 run)*
• **Energy Stability**	0.1% rms at 250GeV	<0.15% p-p (0.4ms) <0.02% rms (5Hz)

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9mA studies (Feb 2012)

- Study topics
  - **How well can we flatten the individual cavity gradients**
  - **How close to quench can we run the cavities with beam**
  - **How close to saturation can we run the klystron**
  - **How to ramp up to the maximum current, pulse length, and gradient without quenching**

- Machine conditions used
  - **800us bunch-trains (2400 bunches)**
  - **Average current over 800us: ~4.5mA (1.5nC/3MHz)**
  - **Beam energy: 1GeV**
  - **Energy gain on ACC67: 380MeV with 13 cavities**
  - **Operating gradients on ACC67: 29MV/m average, four cavities running above 31MV/m**

Key Results

- Beam operation with 800us/4.5mA bunch trains, and…
  - **Gradients of all cavities in vector sum flat within +/-0.3%,**
  - **All cavities in vector sum operating within 5-10% of quench**

- First experience of ‘high gradient operations management’
  - **Quench detection / exception handling**
  - **Gradient ‘soft limiter’ to dynamically prevent quenching**
  - **Data-point of running machine into quench with 800us/4.5mA**

- Beam operation with 800us/4.5mA bunch trains, and..
  - **RF forward power within ~7% of klystron saturation**

- Ramp-up from ~zero to 800us/4.5mA pulses without quenching
- Rapid recovery (‘crash test’): 800us/4.5mA -> trip -> 800us/4.5mA

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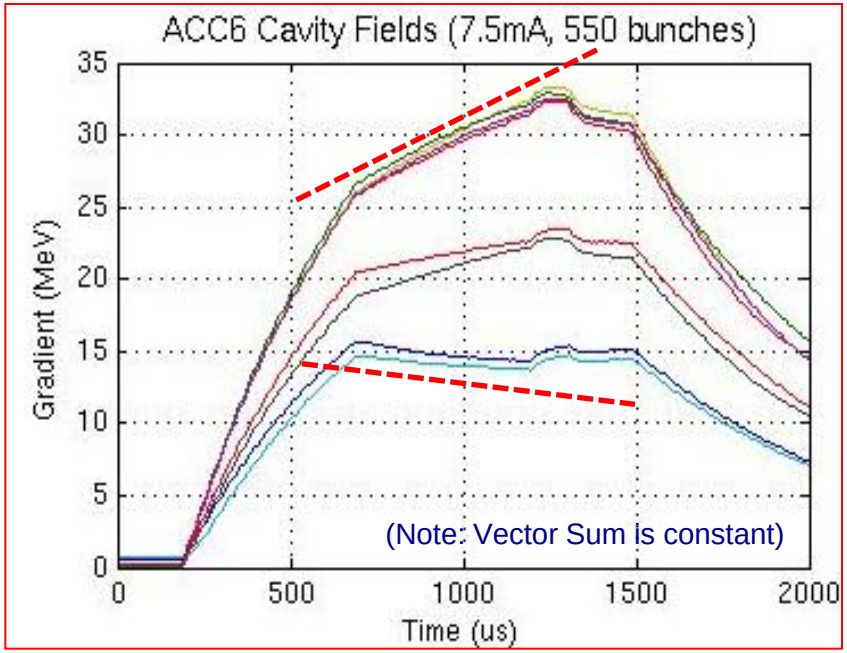
Cavity gradient tilts from beam loading



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

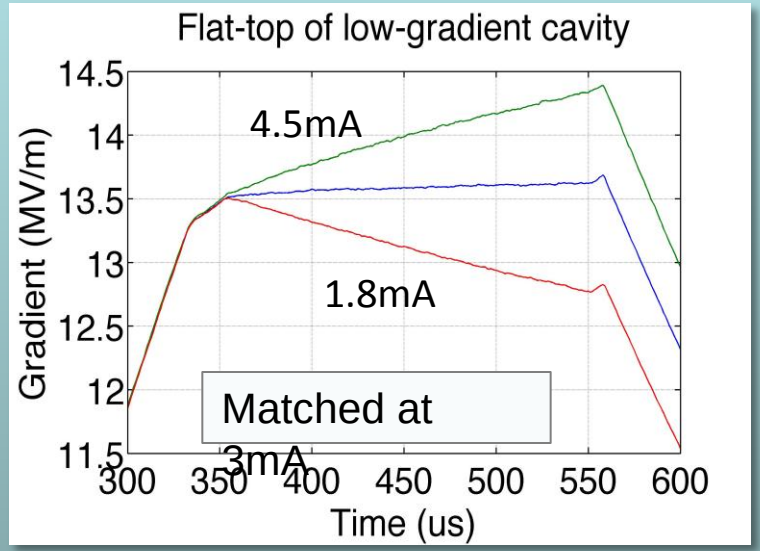
$$I_{matched} = \frac{V_k}{\left(\frac{r}{Q}\right)Q_{ext}}$$

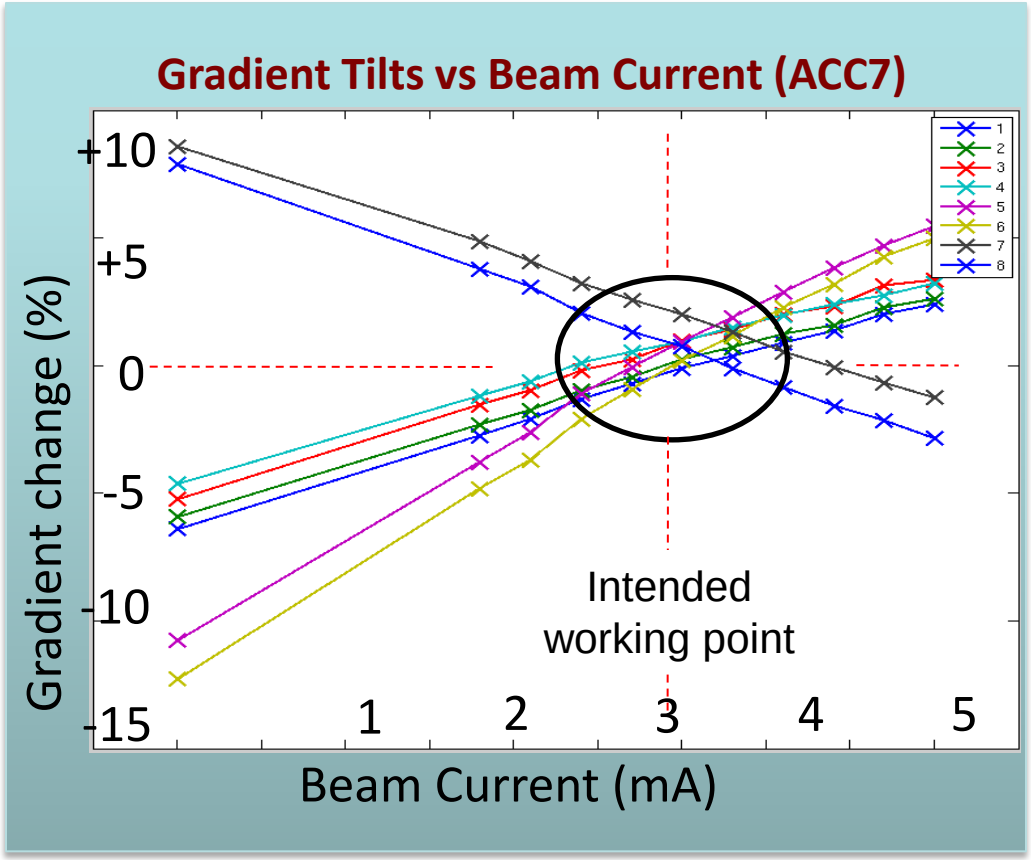
Must be solved uniquely for a given beam current and set of gradients

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

Feb 2011

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





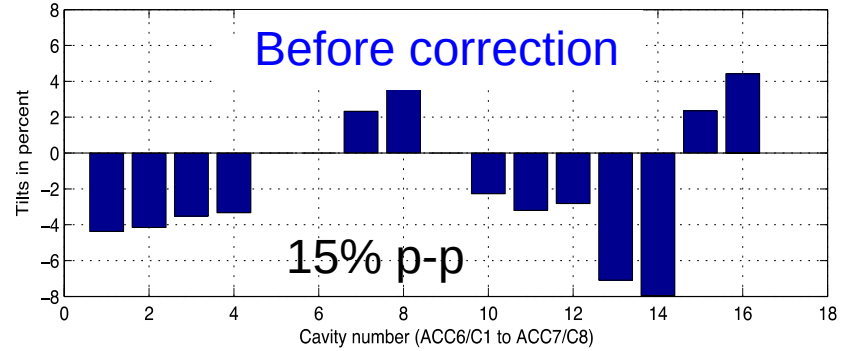
During Feb 2011 studies, cavity Loaded-Qs were adjusted manually
(Quality of the results were a function of the patience of the studiers)

Operation close to the limits: Iterative QL optimization for flattest gradients

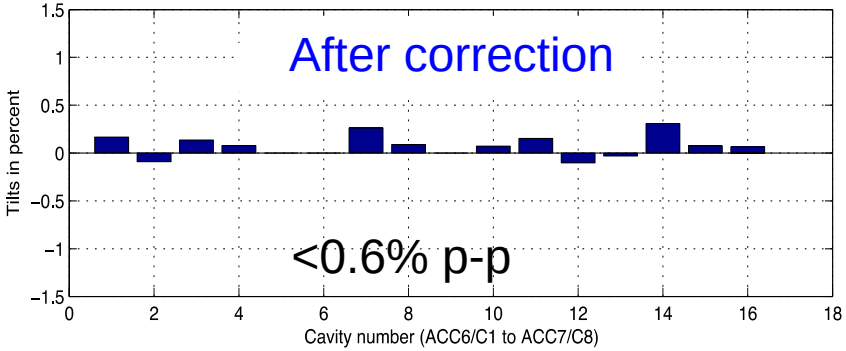
Feb 2012

- Set up Qls using analytically determined values
- Then use iterative algorithm to fine-tune to find optimum
- Gradient flatness far better than needed tolerances of ~few %

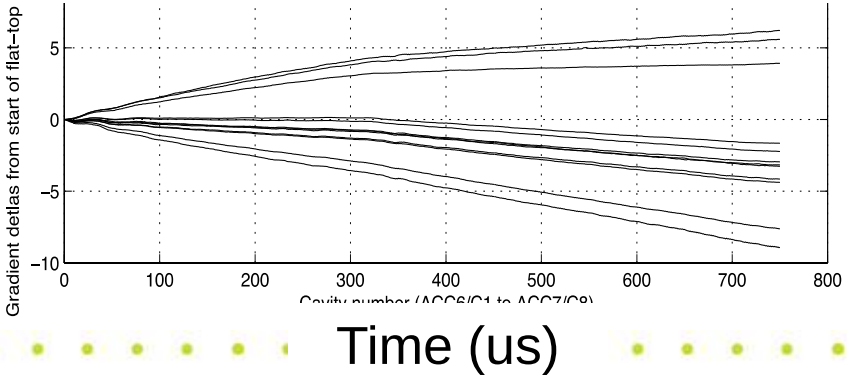
Gradient tilts by cavity (%)



Gradient tilts by cavity (%)



Gradient flat-tops over 800us pulse



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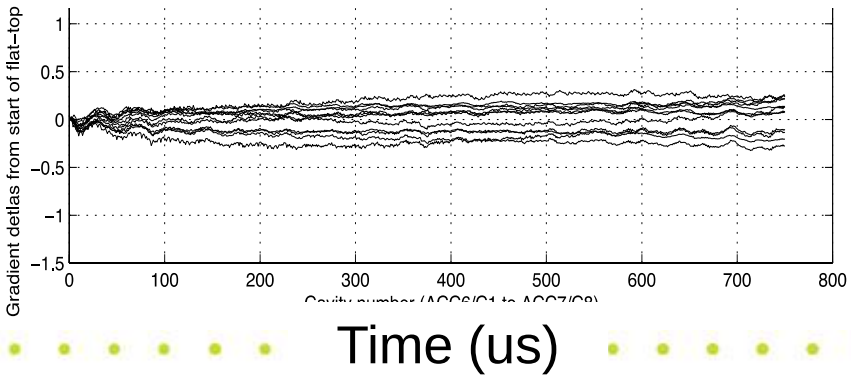


Operation close to the limits: ramping up to full beam power at maximum gradients

The optimal QL settings to achieve flat gradients are different for each beam current and gradient vector sum

- **Changing current without re-optimizing causes gradient tilts**
- **If gradients are already close to the limits ➔ QUENCH**

How to ramp up to full current/pulse length without quenching..?

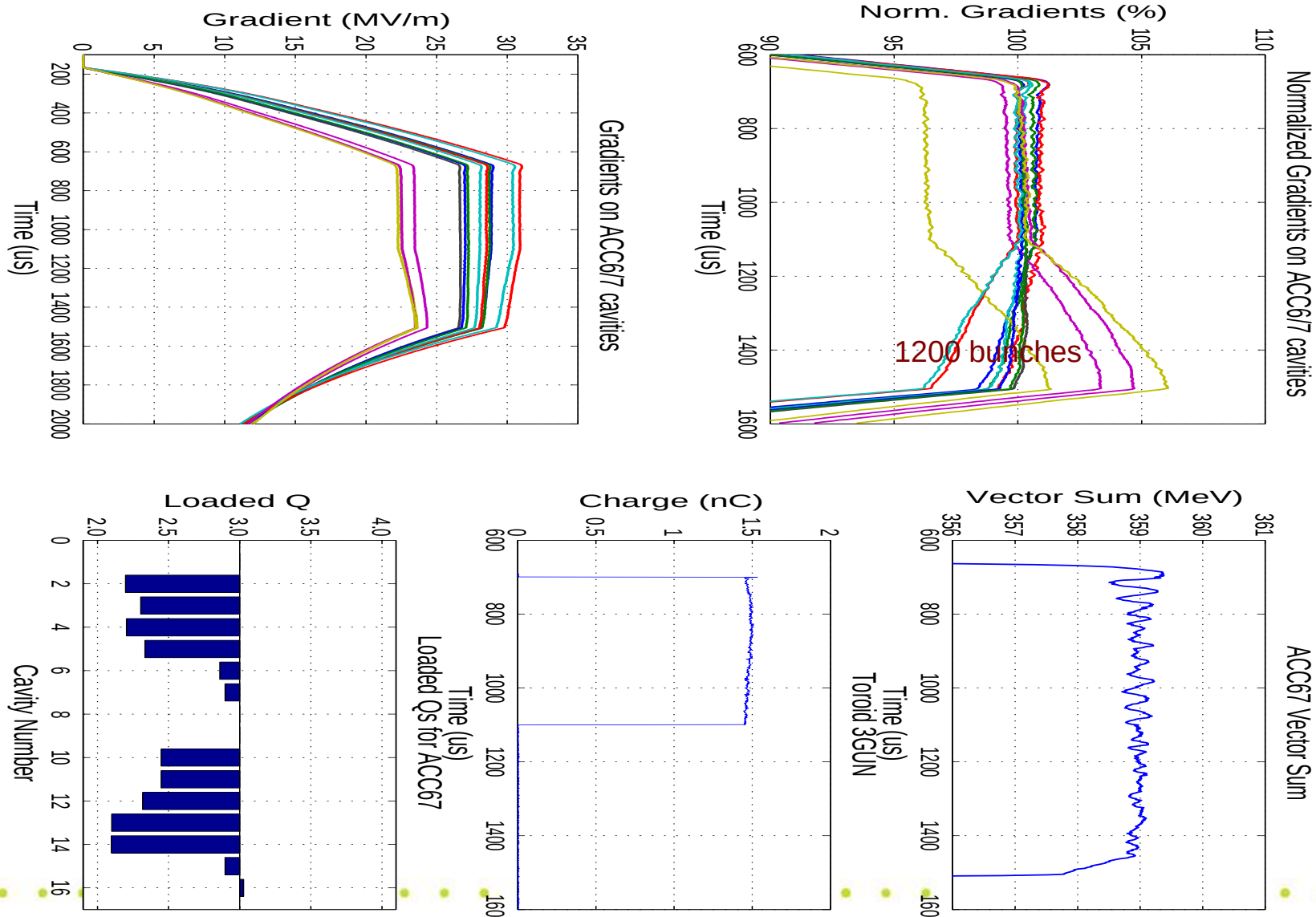
Proposal #1: start with maximum current but short bunch train

- Correct QLs to achieve flat gradients with short bunch train
- Progressively increase length of bunch train
- Ideally, there would be no corrections to QLs needed

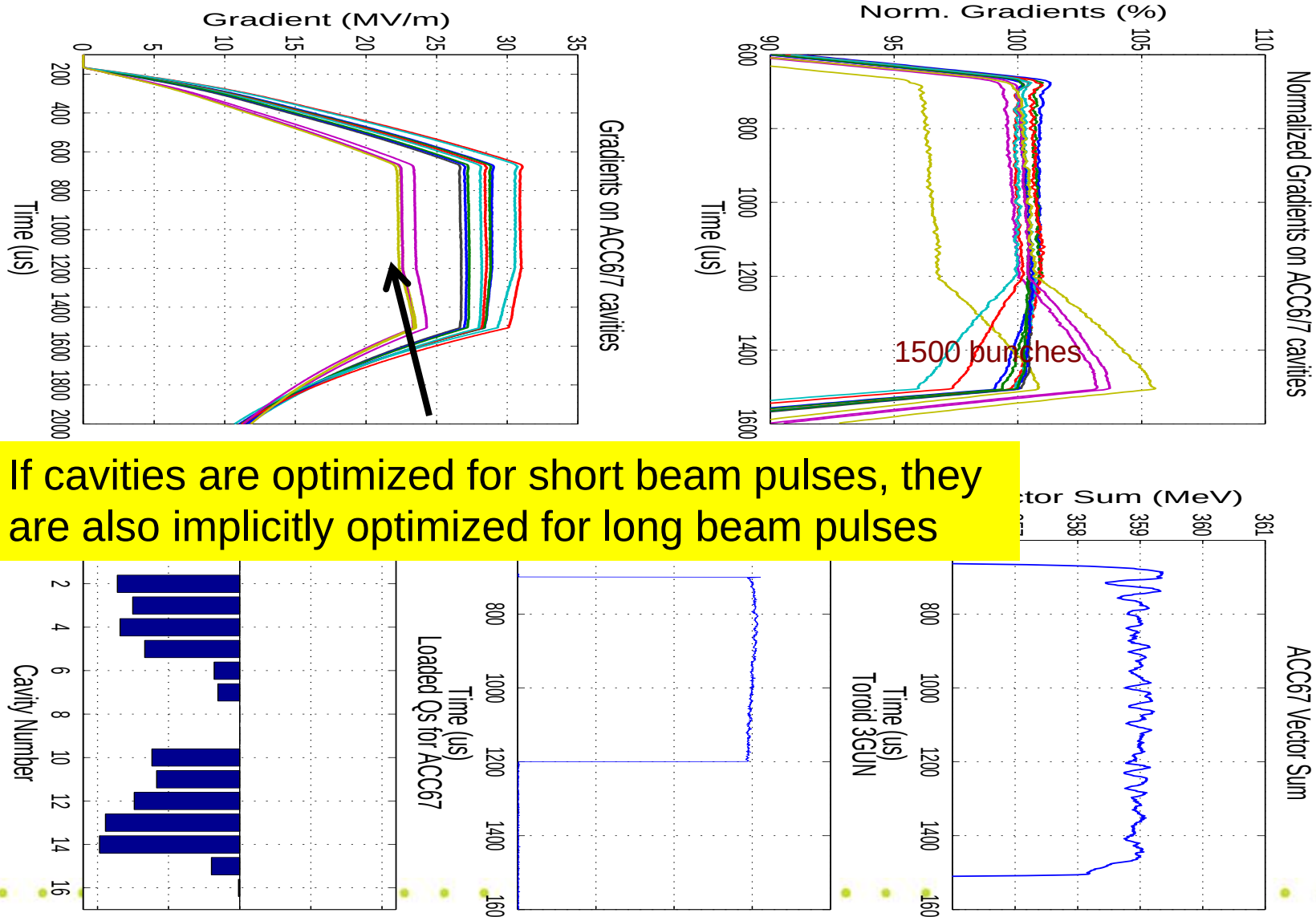
Proposal #2: start with full bunch train, but low charge

- Correct QLs to achieve flat gradients with the lower charge
- Progressively increase charge
- Continue to adjust QLs to maintain flat gradients as charge is increased

Ramp-up of the beam pulse length (400us)

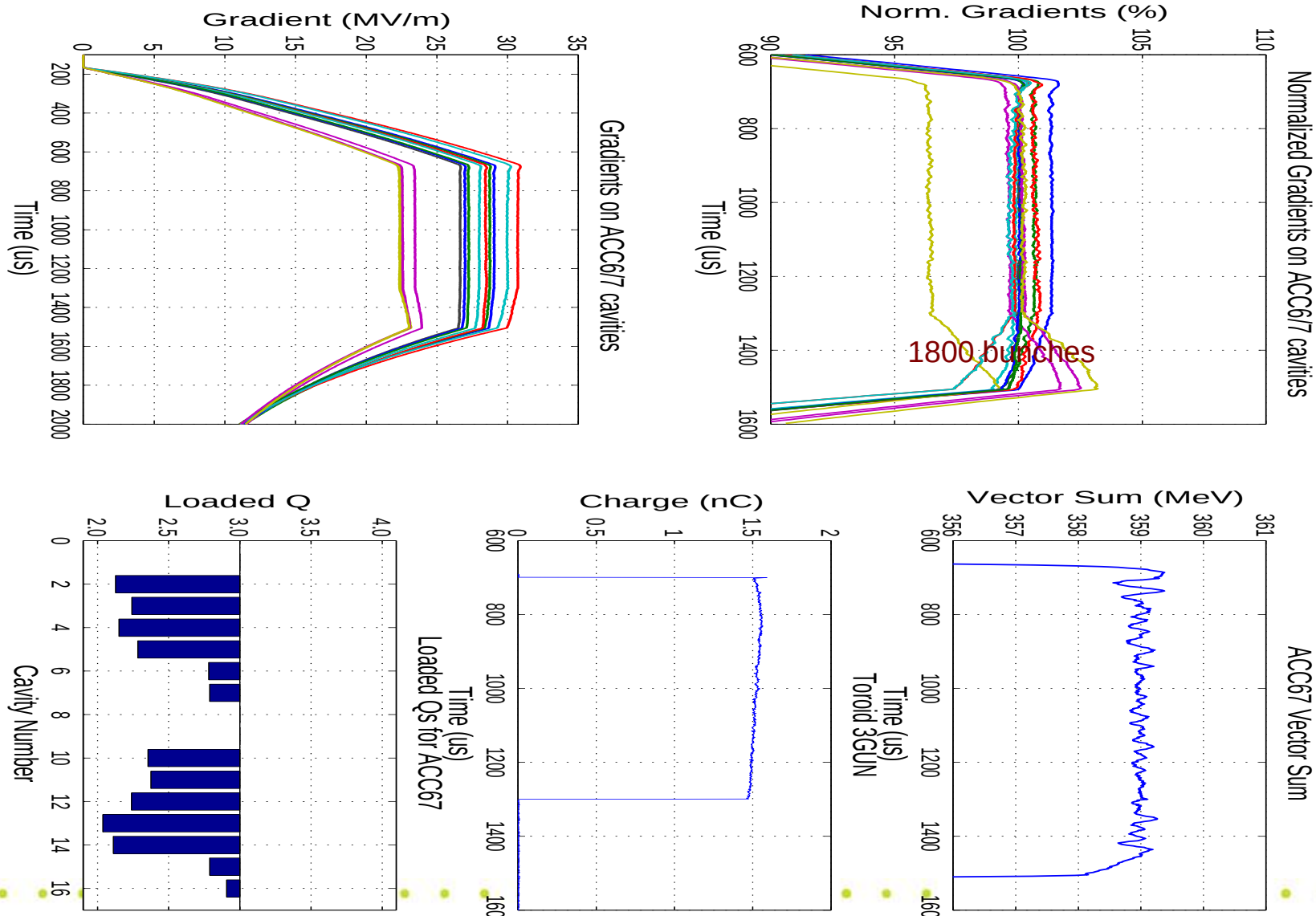


Ramp-up of the beam pulse length (500us)

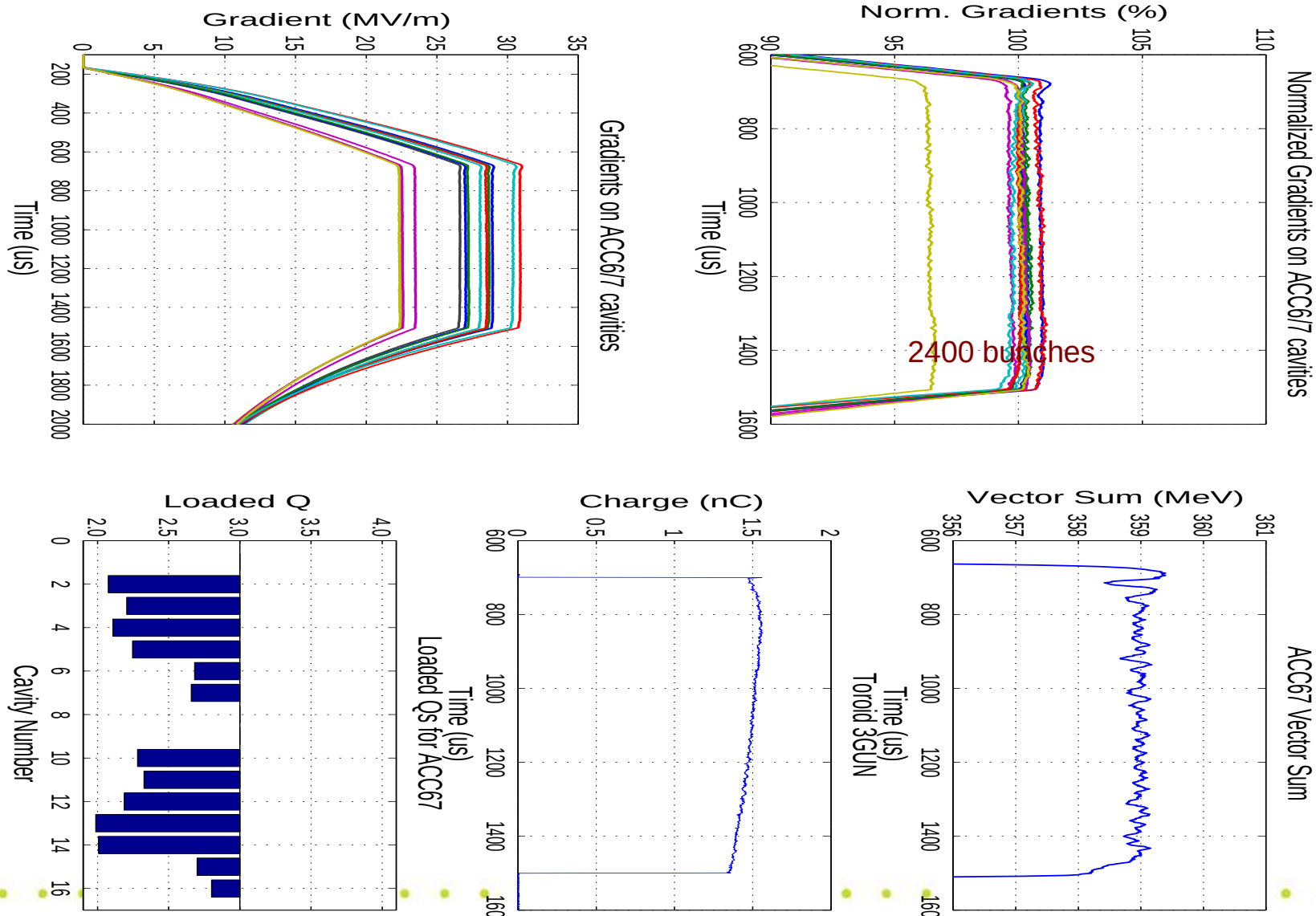


If cavities are optimized for short beam pulses, they are also implicitly optimized for long beam pulses

Ramp-up of the beam pulse length (600us)



Ramp-up of the beam pulse length (800us)



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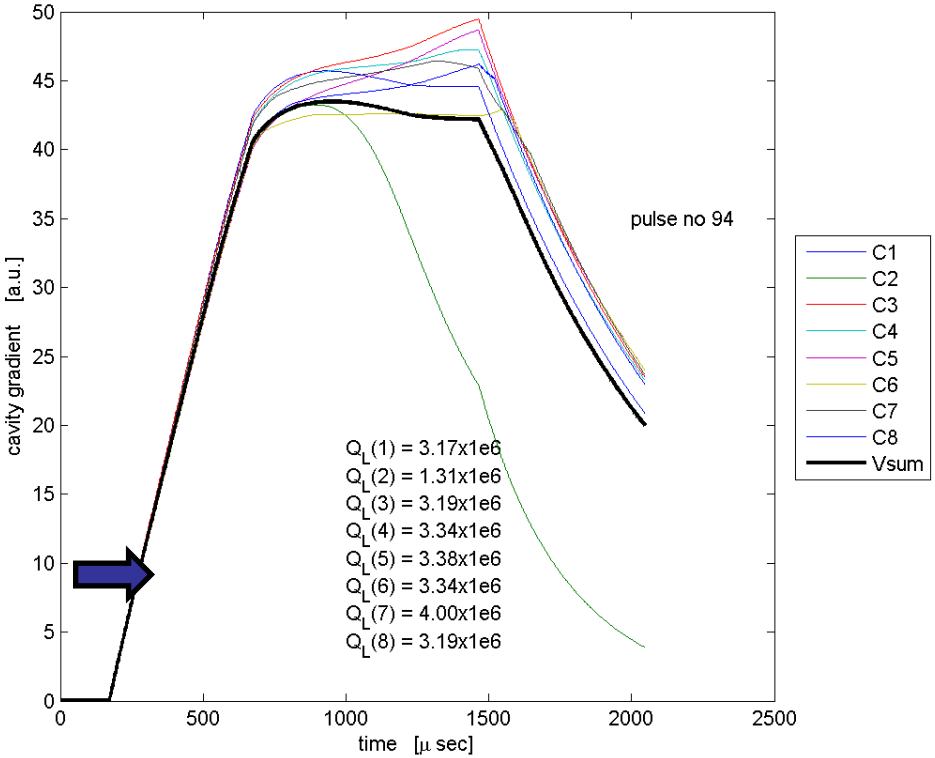
Operation close to the limits: gradient limit studies

Planned studies

- Measure in-situ gradient limits with and without beam, compare with test stand data
- Determine the maximum usable vector sum for 16 cavities with beam loading
- Evaluate quench detection / protection tools
- Ramp from zero to full current and full gradient (see earlier)

Typical quench signature:
a sudden drop in Ql : ΔQl> 5e5



Julien Branlard

Quench limit study: In-situ measured quench limits (no beam)

ACC6	C1	C2	C3	C4	C5	C6	C7	C8
Measured	**36.2**	32.3	Skipped (>30MV/m)	Skipped (>30MV/m)	> 17	**18.6**	29.1	25.1
Reported (Katalev)	**34**	32	34	32	21	**21**	29	26

ACC7	C1	C2	C3	C4	C5	C6	C7	C8
Measured	28.5	Skipped (>30MV/m)	Skipped (>30MV/m)	Skipped (>30MV/m)	Skipped (>30MV/m)	Skipped (>30MV/m)	27.35	26.7
Reported (Katalev)	29	31	34	30	35	39	27	26

- The cavities which were skipped perform better than 30 MV/m
- Some cavities performed slightly better than expected
- High performing cavities were skipped for reasons explained later
- Globally, good agreement with previously reported limits and recently measured ones

Operating close to the limits: quench protection

Goal is to operate close to gradient limits, so we must protect against quenching but without causing frequent pulse terminations

Three levels of detection/prevention of quenches

1. **Quench detection (Quench Server)**
   - **Look for sudden drop in Loaded-Q at end of rf pulse**
   - **Inhibit subsequent pulses**

Interlock

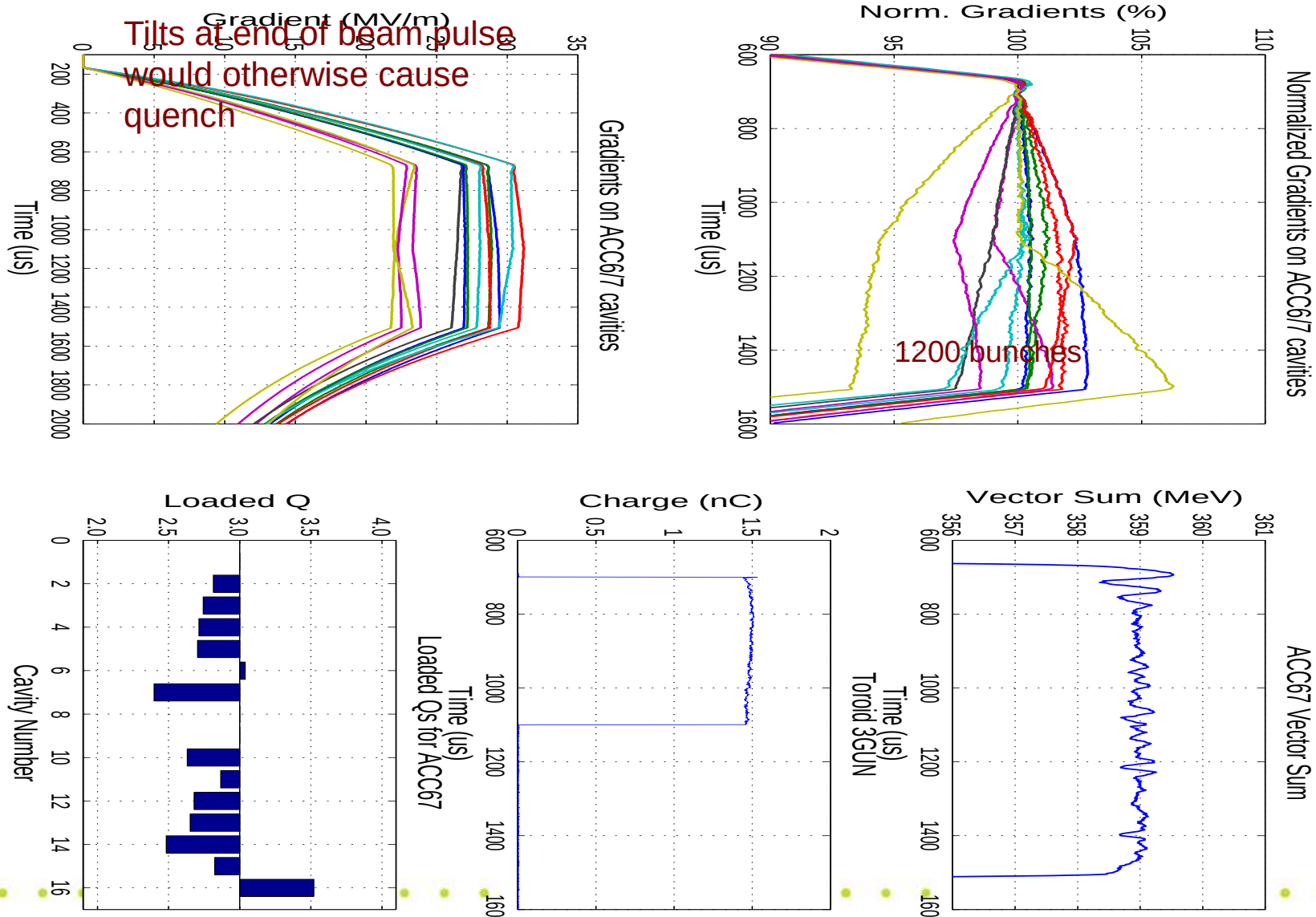
2. **Over-voltage protection during rf pulse ('hard limiter)**
   - **Gradient Limit alarm threshold for each cavity**
   - **Terminate rf pulse as soon any cavity exceeds its threshold**

Interlock

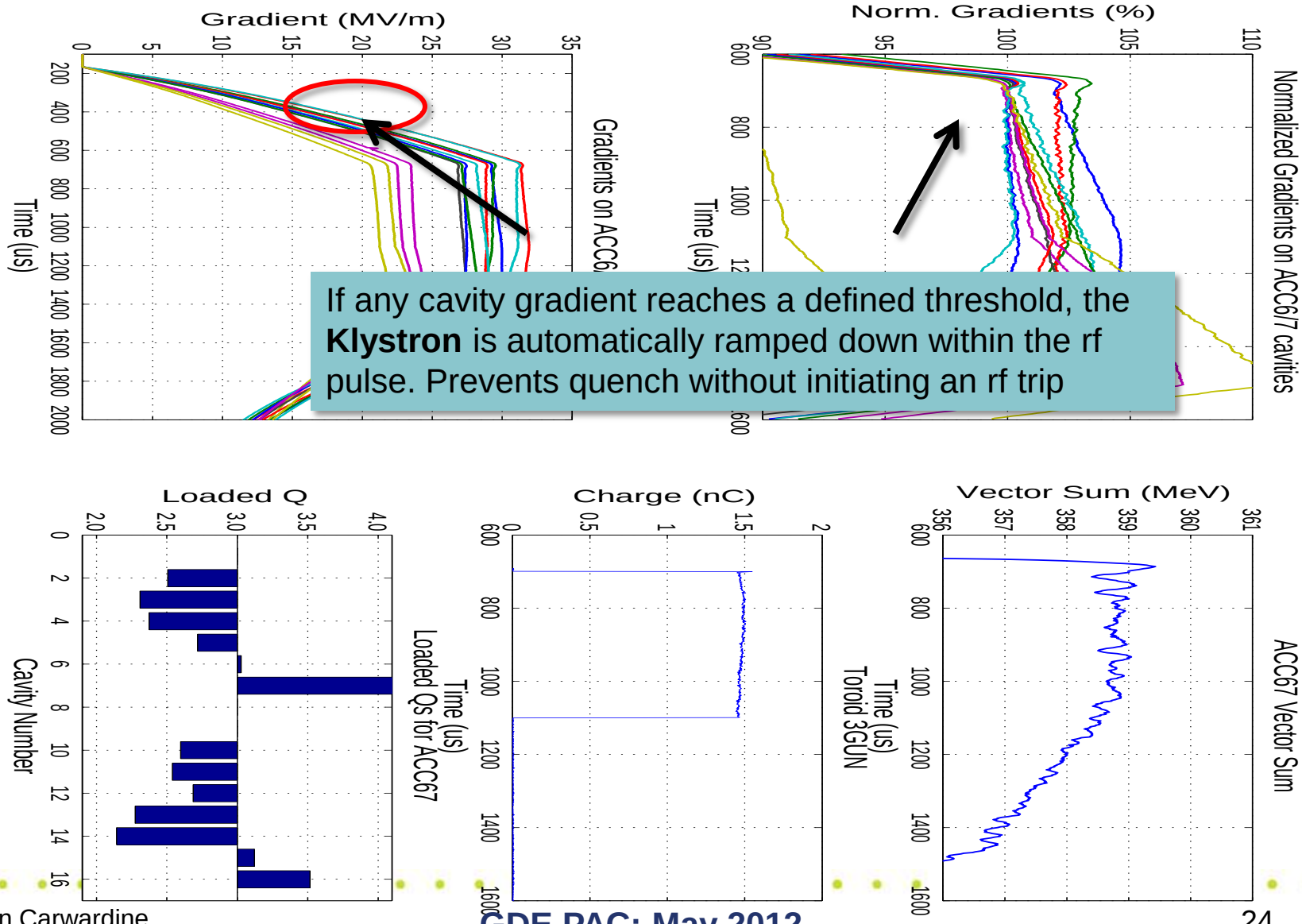
3. **Over-voltage soft-limiter during rf pulse ('soft limiter')**
   - **Gradient Pre-limit threshold for each cavity**
   - **Dynamically ramp down the klystron drive setpoint if any cavity reaches a predefined limiter threshold threshold**

Gradient management

‘Gradient operations management’: quench prevention



Gradient operations management: ‘Soft-limiter’ dynamically prevents quenches



If any cavity gradient reaches a defined threshold, the **Klystron** is automatically ramped down within the rf pulse. Prevents quench without initiating an rf trip

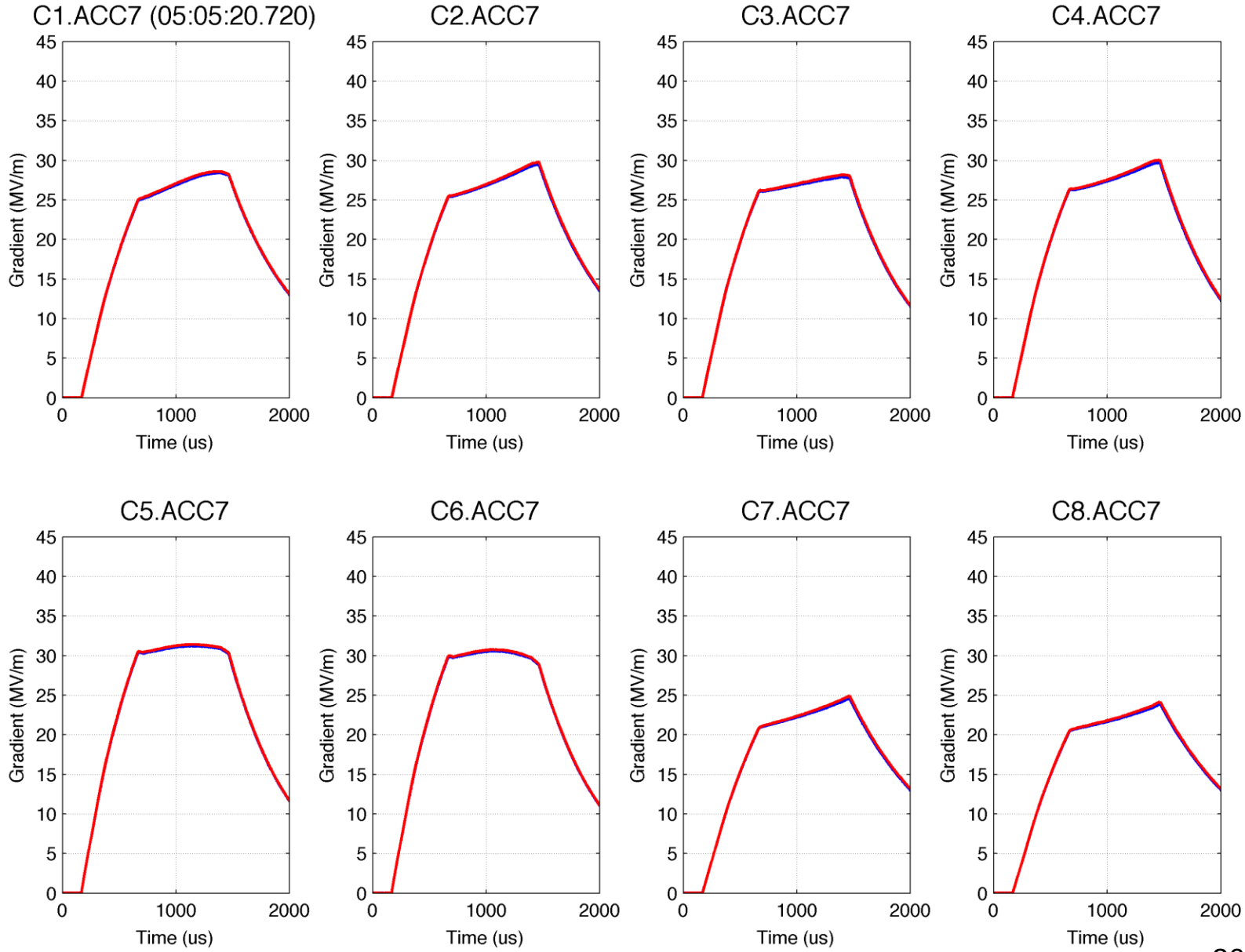
‘Mombo’ quench event: 25 Feb 05:05:21

What happens if quenches are not detected & acted upon…?

- Quench detection was temporarily disabled
- Beam was enabled - 700us bunch trains
- Ramped up Vector Sum on one module (ACC7) small steps

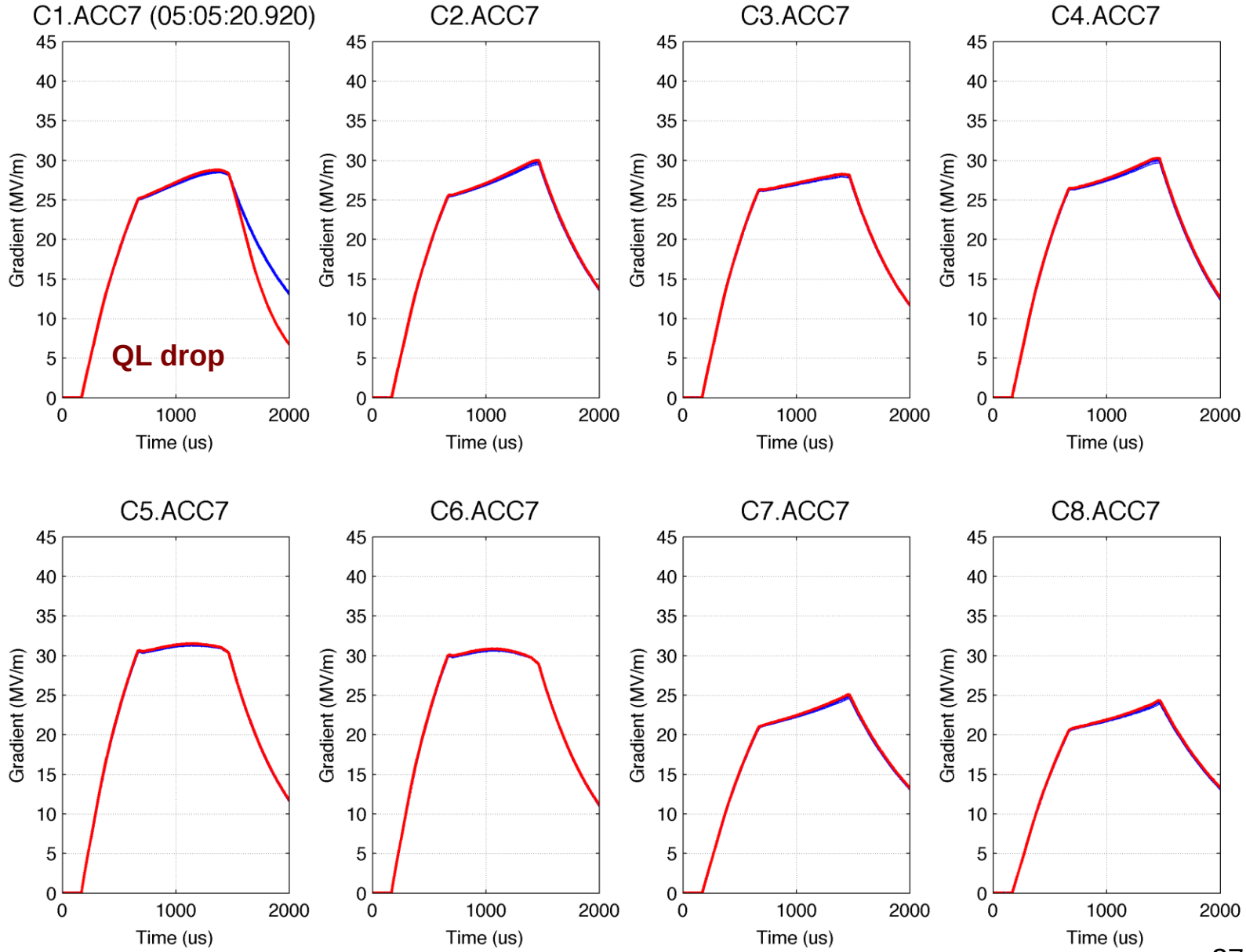
- **ACC7 Cavity 1 was the first to quench**
  - Initially, the LLRF controller was able to maintain the Vector Sum by increasing the klystron power
  - (There was even a full-energy beam pulse)
  - **Then, a cascade of quenches followed as the klystron was driven progressively harder…**

Event #14427309: ACC7 cavity gradients before first quench



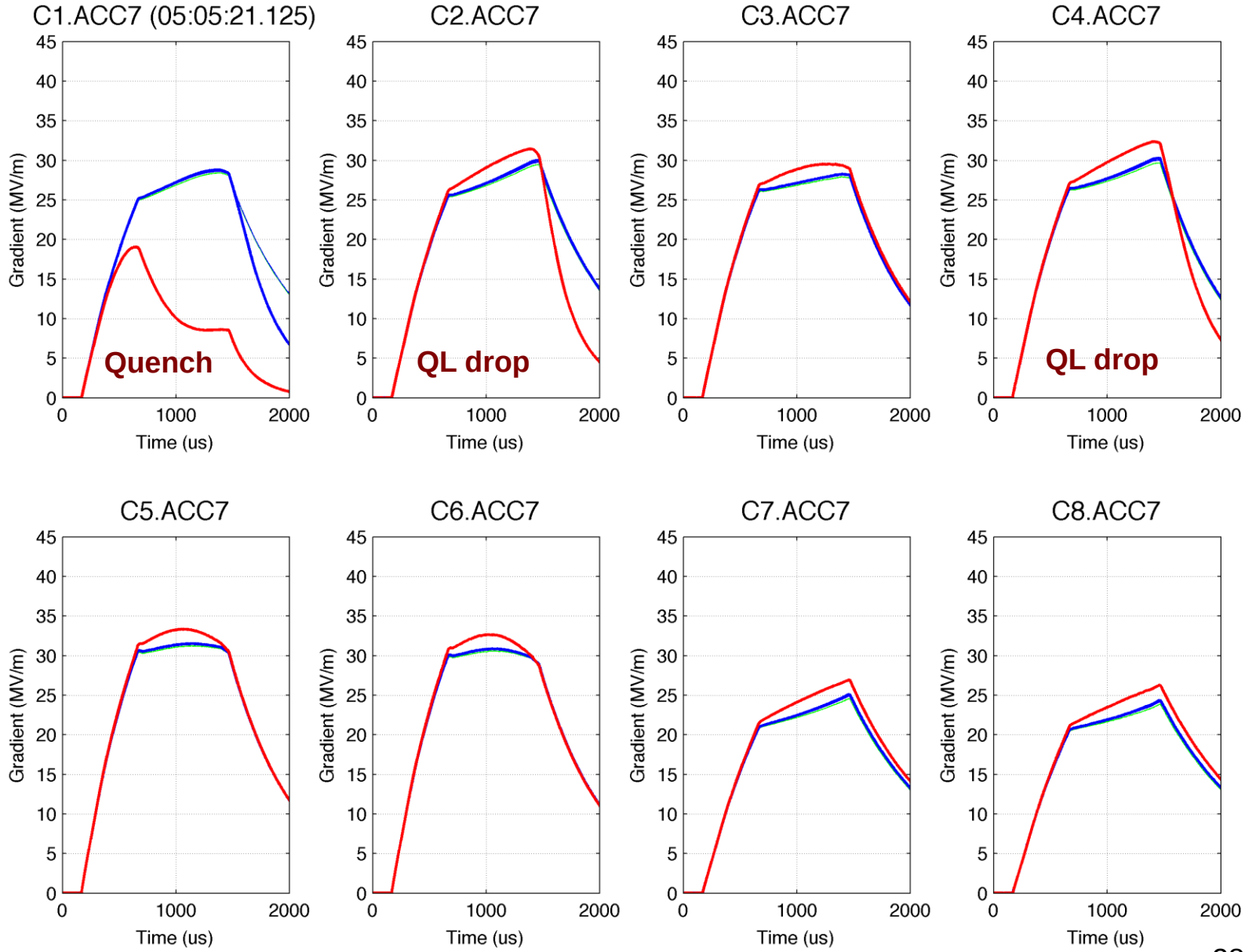
Red: this event, Blue: previous event, Green: nominal

Event #14427310: Raised gradient setpoint by ~2%



Red: this event, Blue: previous event

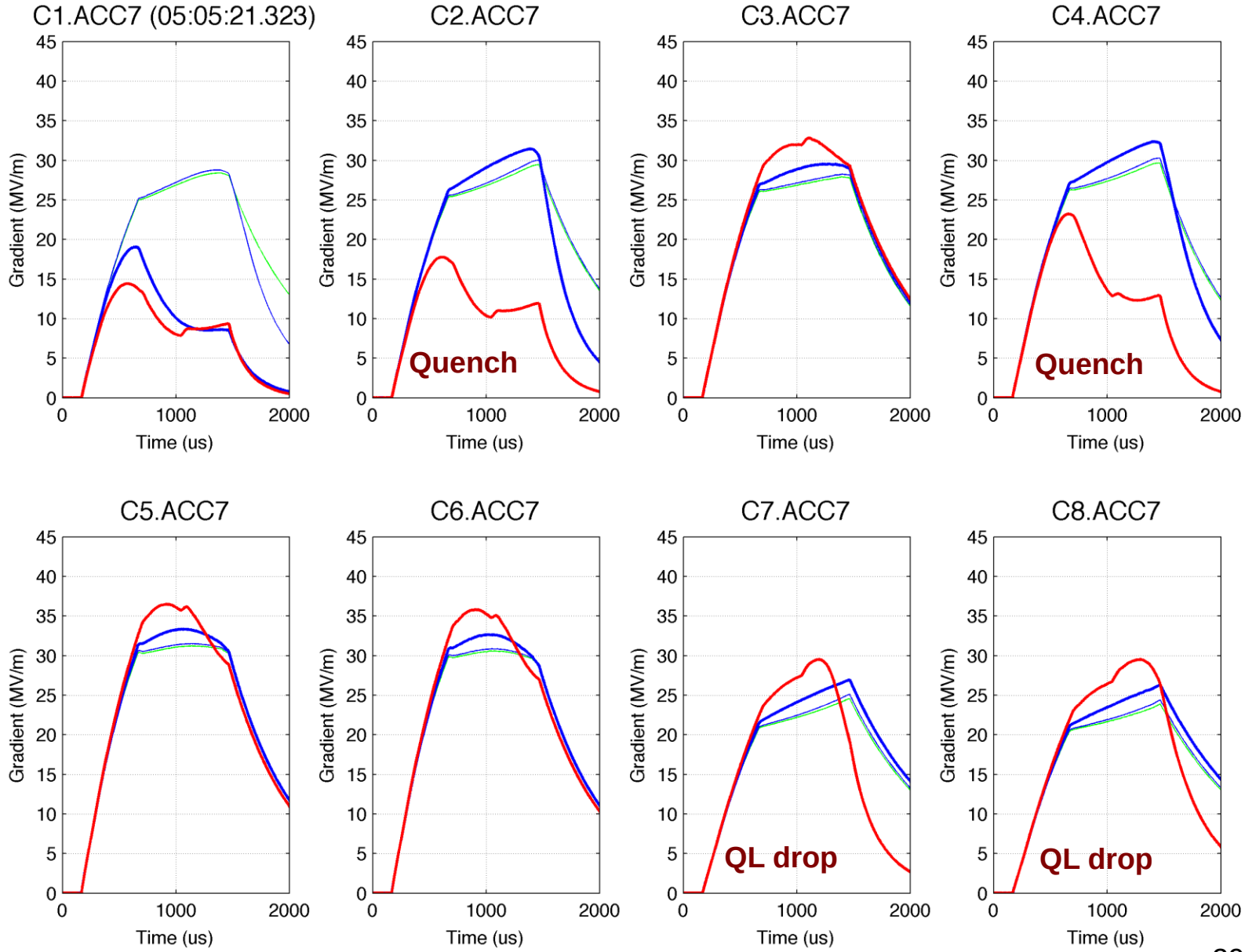
Event #14427311: C1 quenched, QL drop on C2 and C4



Red: this event, Blue: previous event, Green: nominal

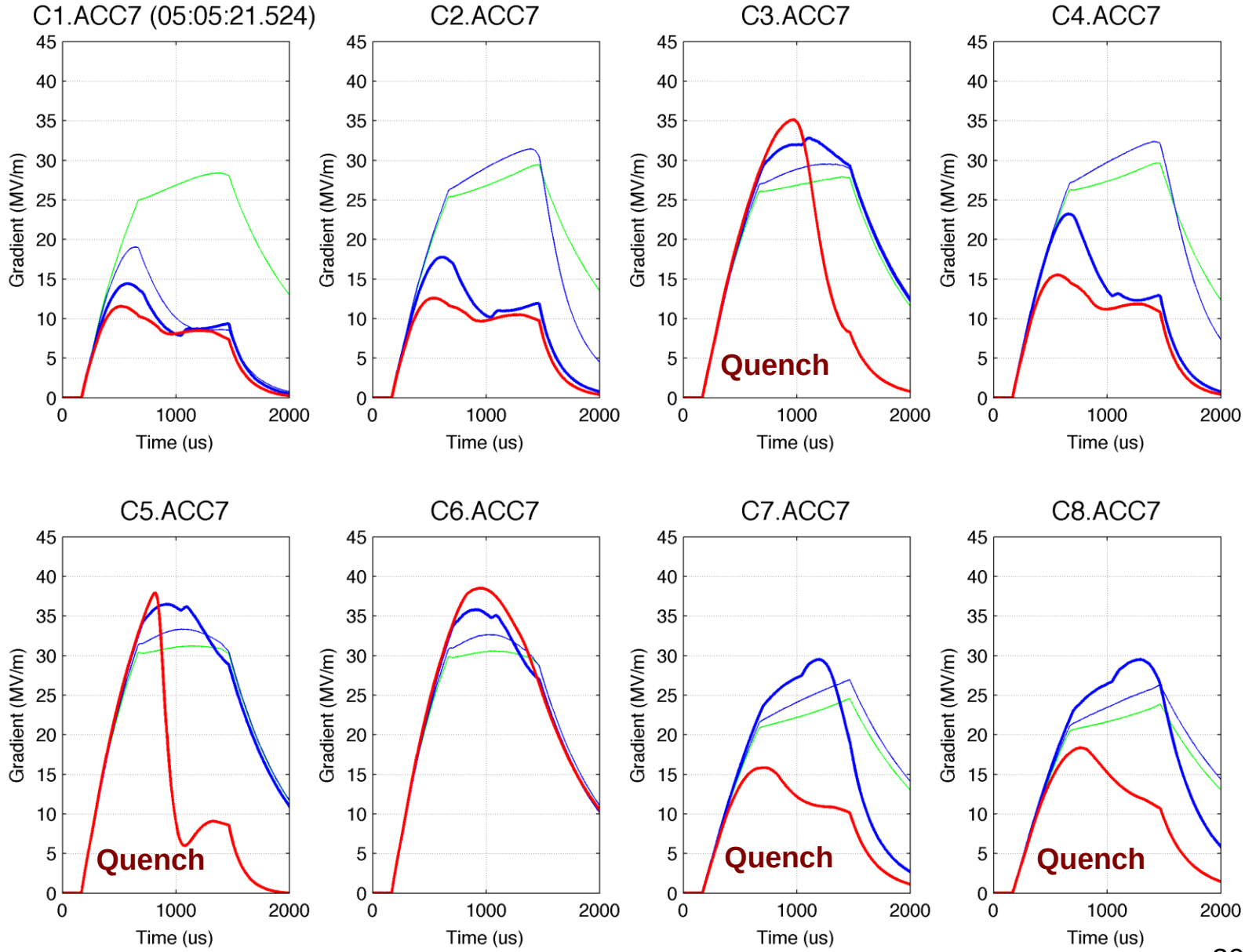
Vector Sum is maintained by driving the other cavities harder

Event #14427312: C2 & C4 quenched, QL drop on C7 & C8



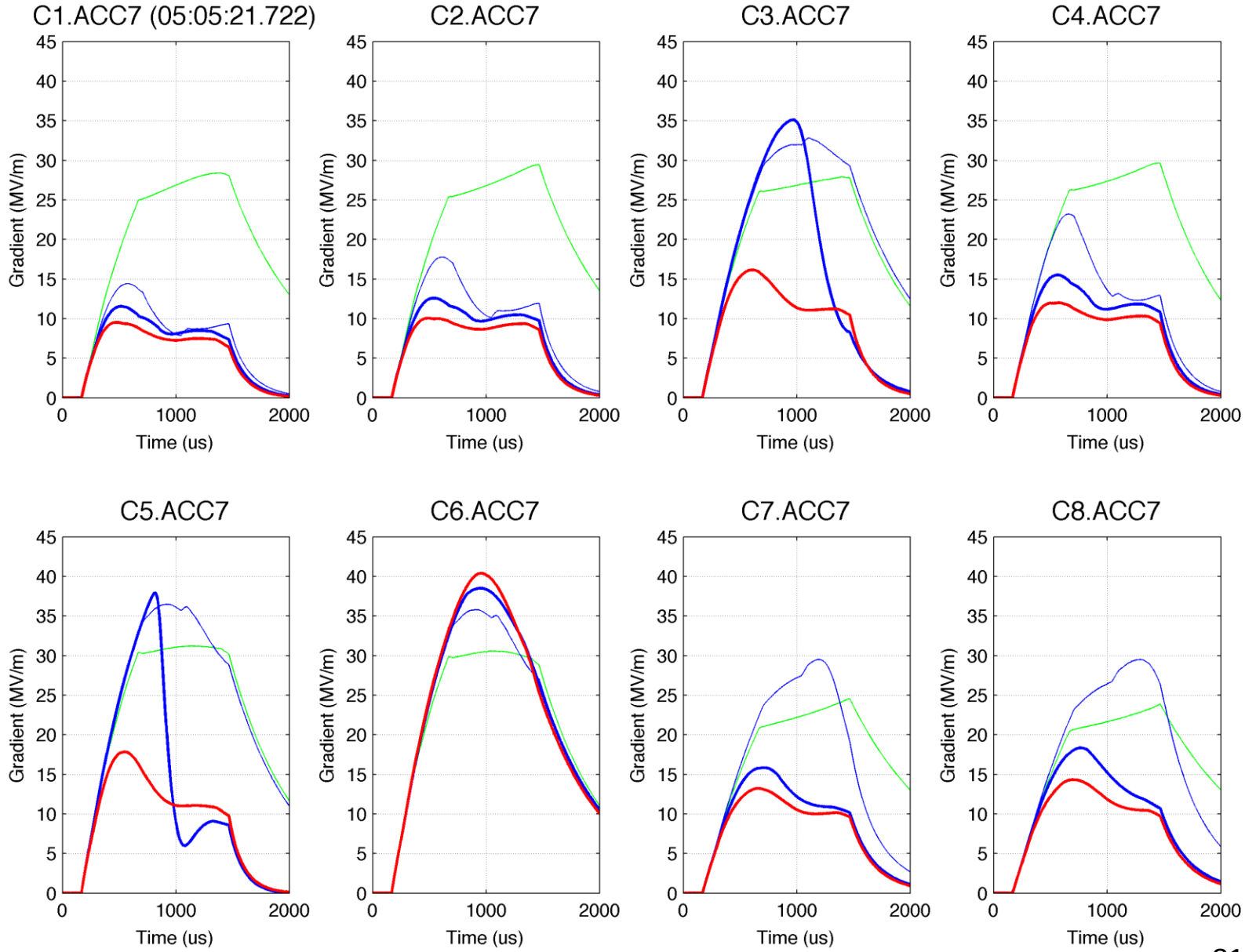
Red: this event, Blue: previous event, Green: nominal

Event #14427313: quenches on C7, C8, C5, C3



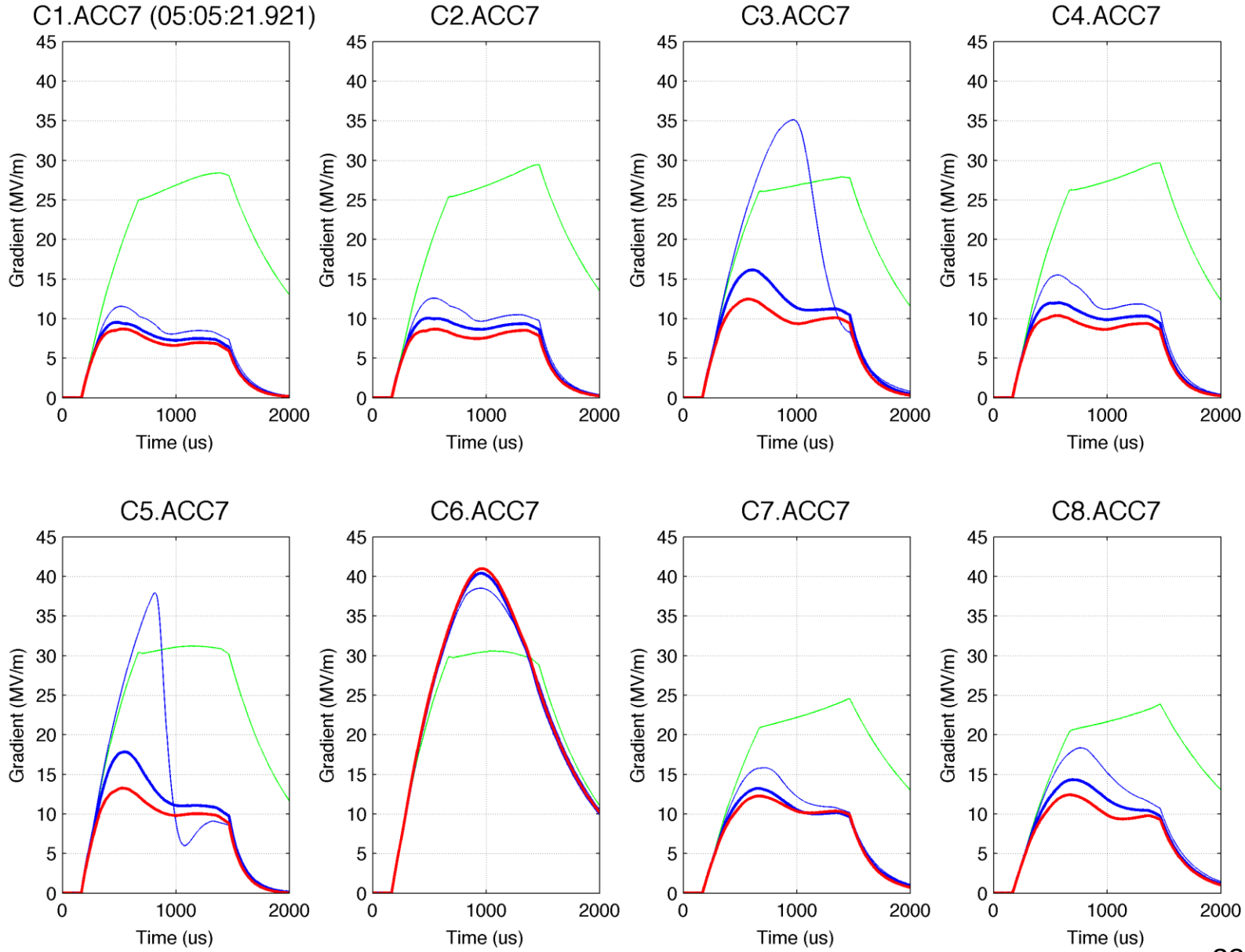
Red: this event, Blue: previous event, Green: nominal

Event #14427314: all cavities quenched, except C6



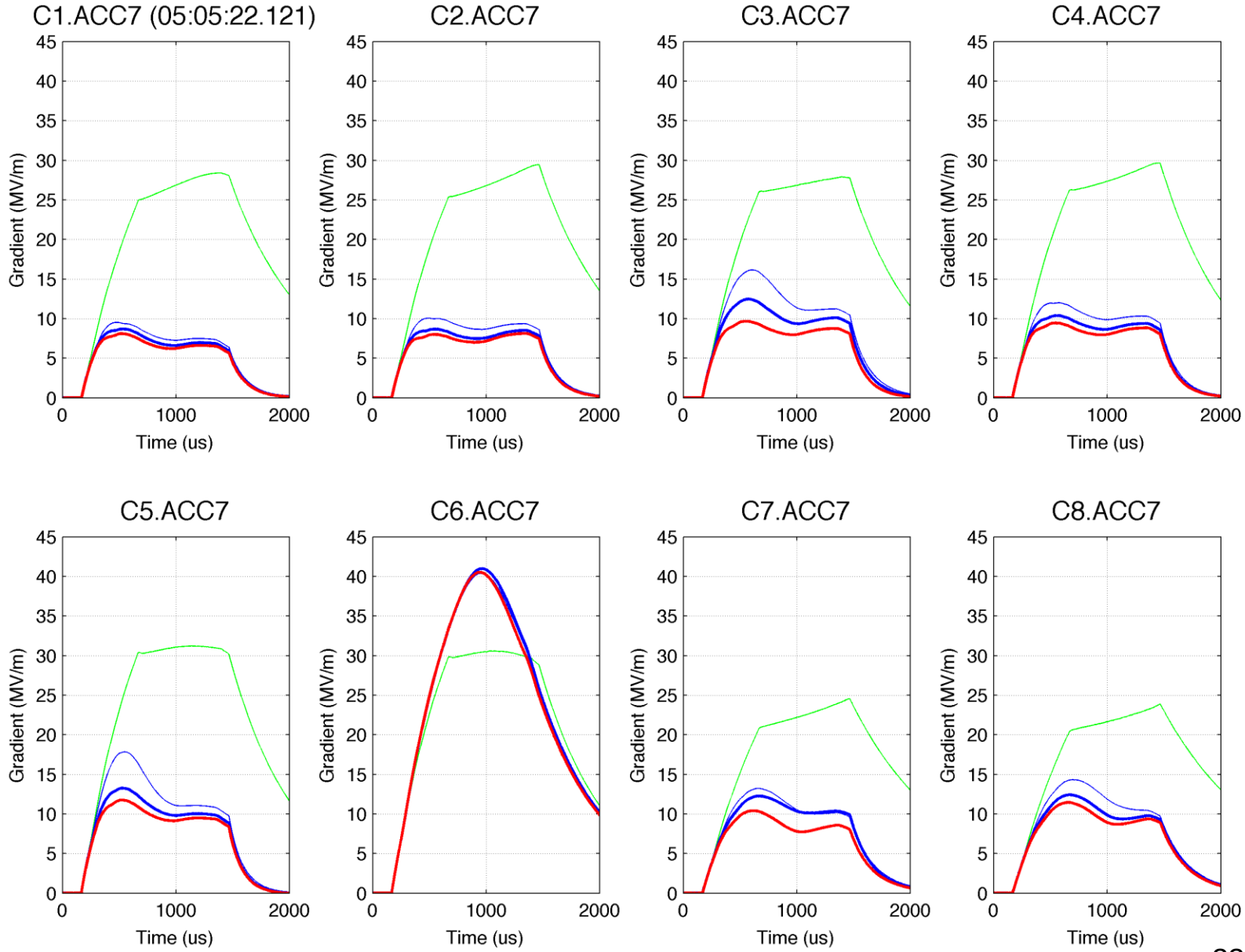
Red: this event, Blue: previous event, Green: nominal

Event #14427315



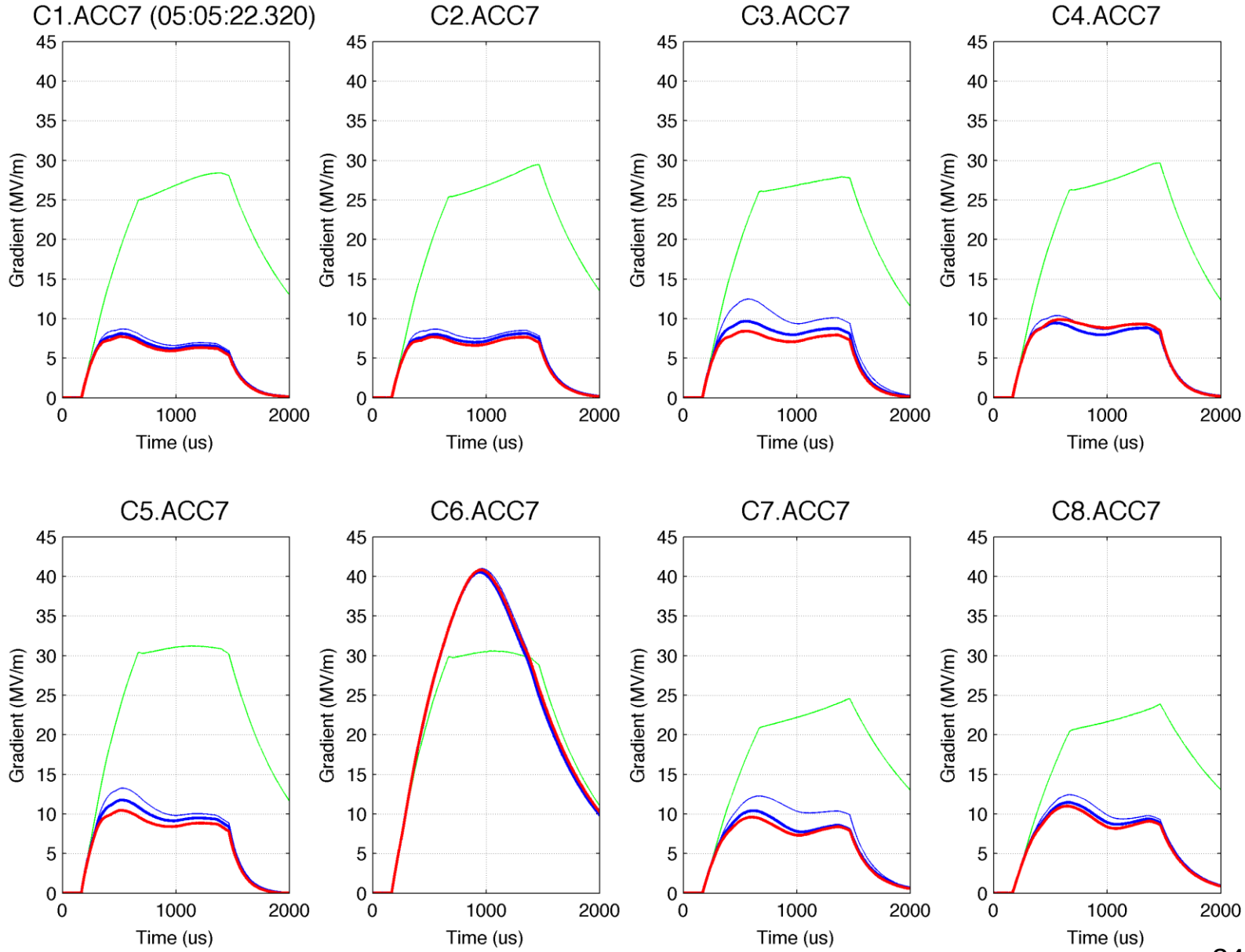
Red: this event, Blue: previous event, Green: nominal

Event #14427316



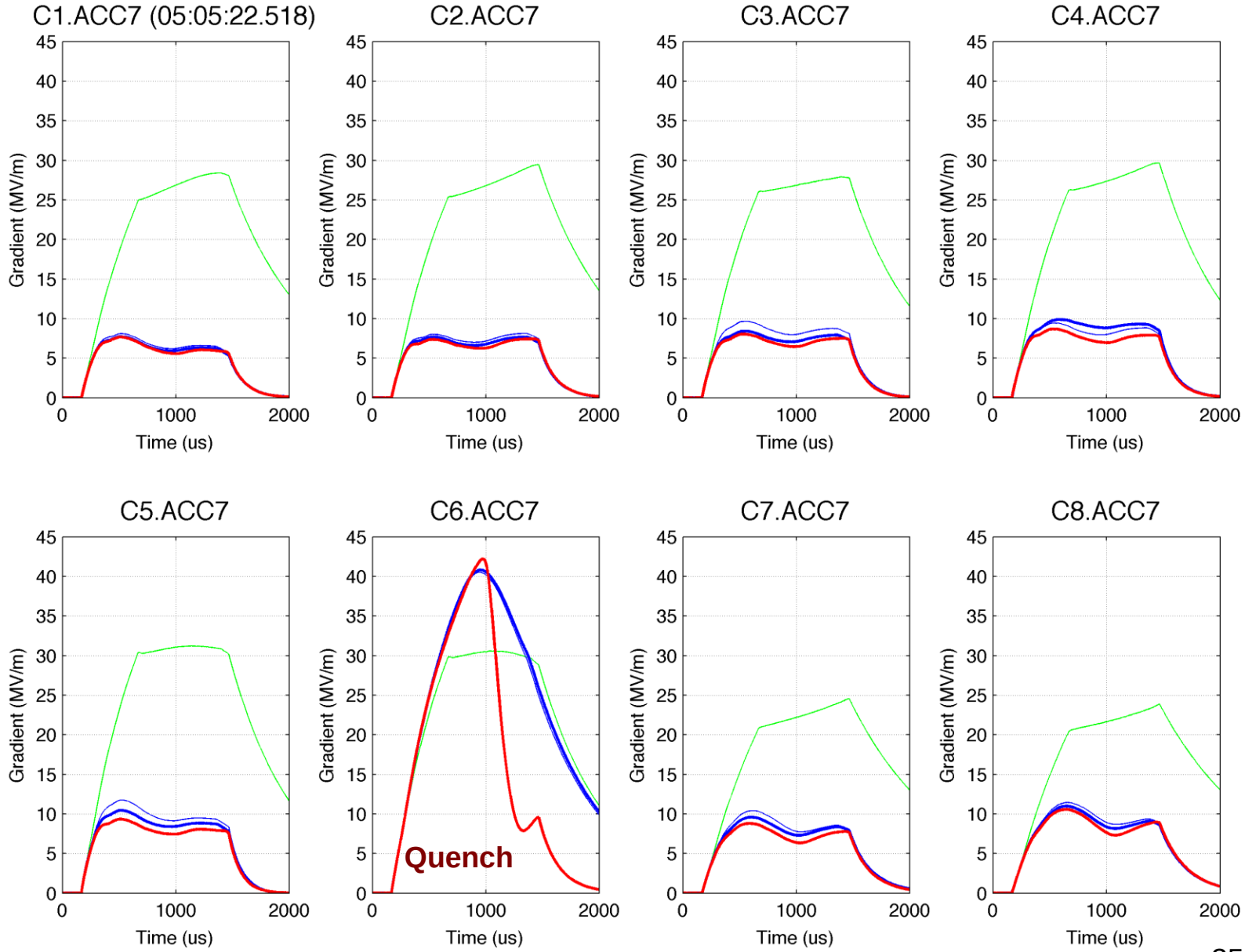
Red: this event, Blue: previous event, Green: nominal

Event #14427317



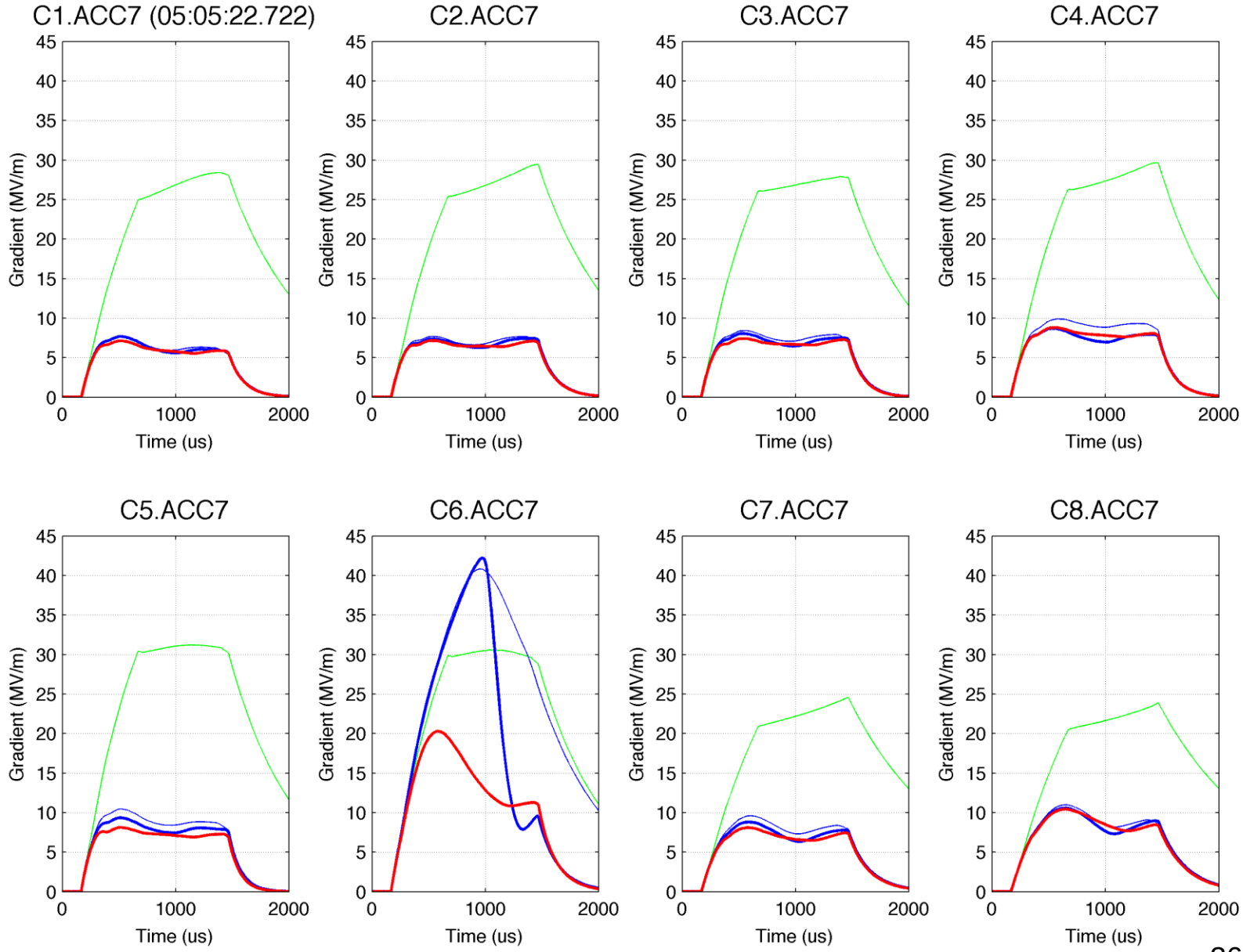
Red: this event, Blue: previous event, Green: nominal

Event #14427318: C6 finally quenches



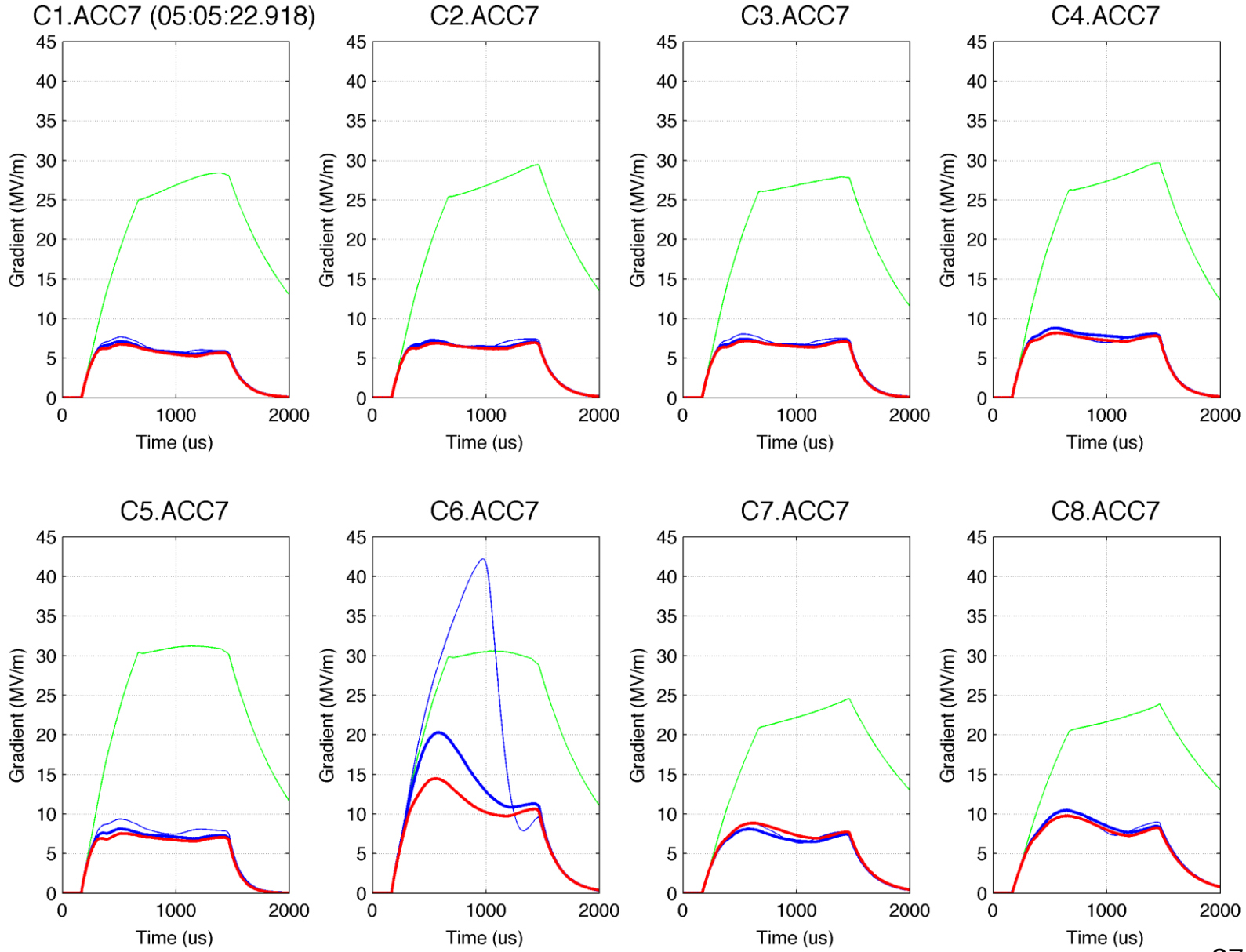
Red: this event, Blue: previous event, Green: nominal

Event #14427319: all cavities quenched



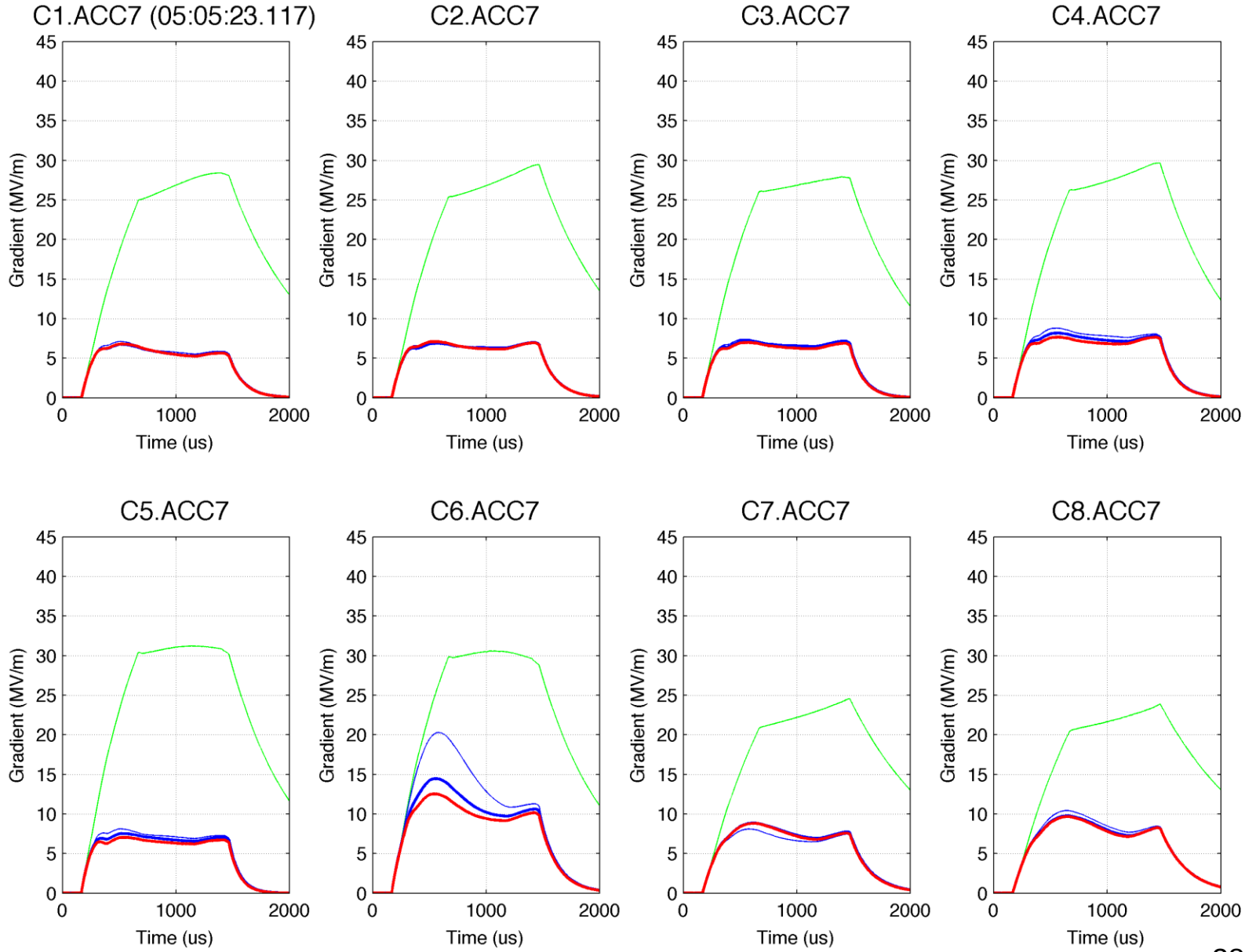
Red: this event, Blue: previous event, Green: nominal

Event #14427320: all cavities quenched



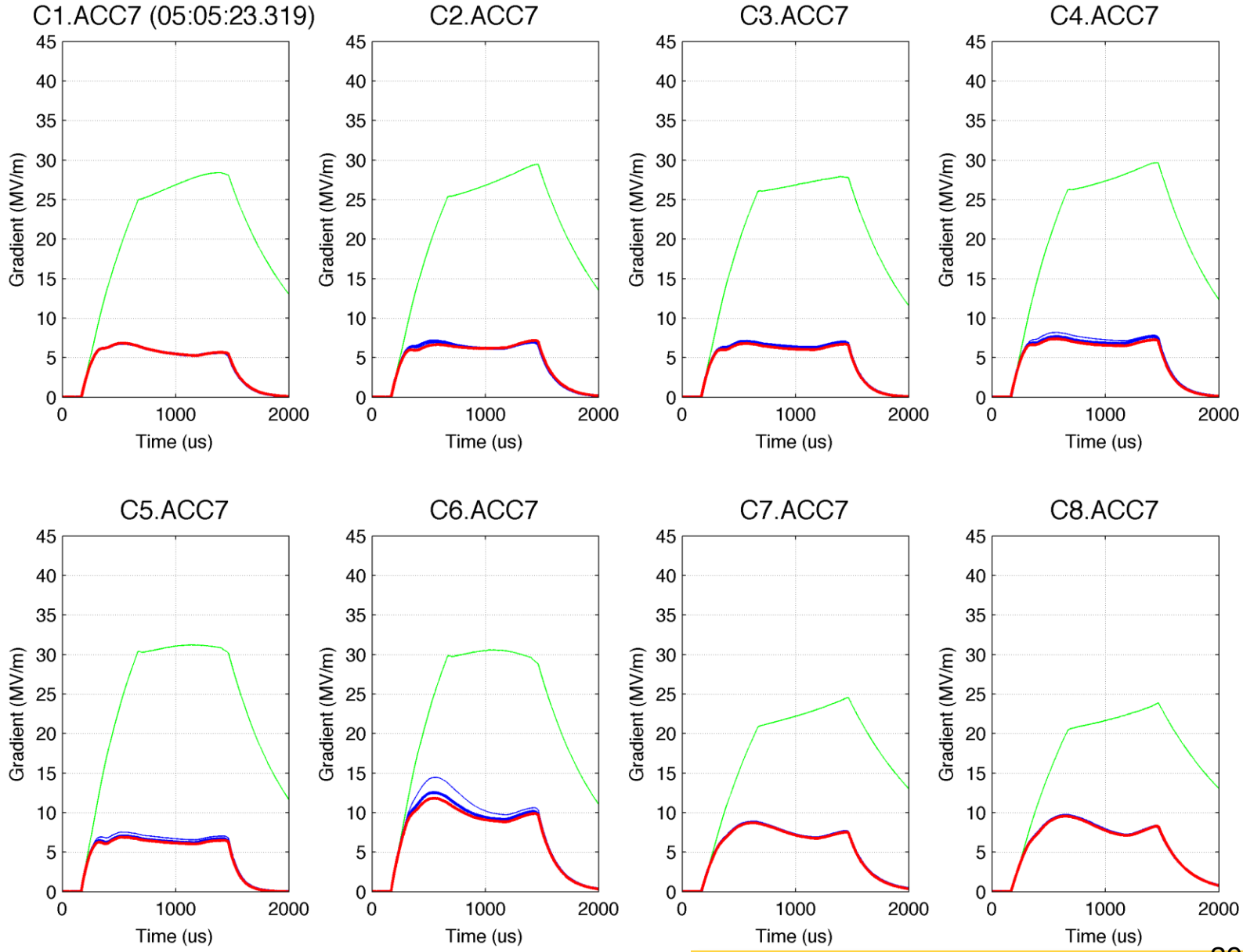
Red: this event, Blue: previous event, Green: nominal

Event #14427321: all cavities quenched



Red: this event, Blue: previous event, Green: nominal

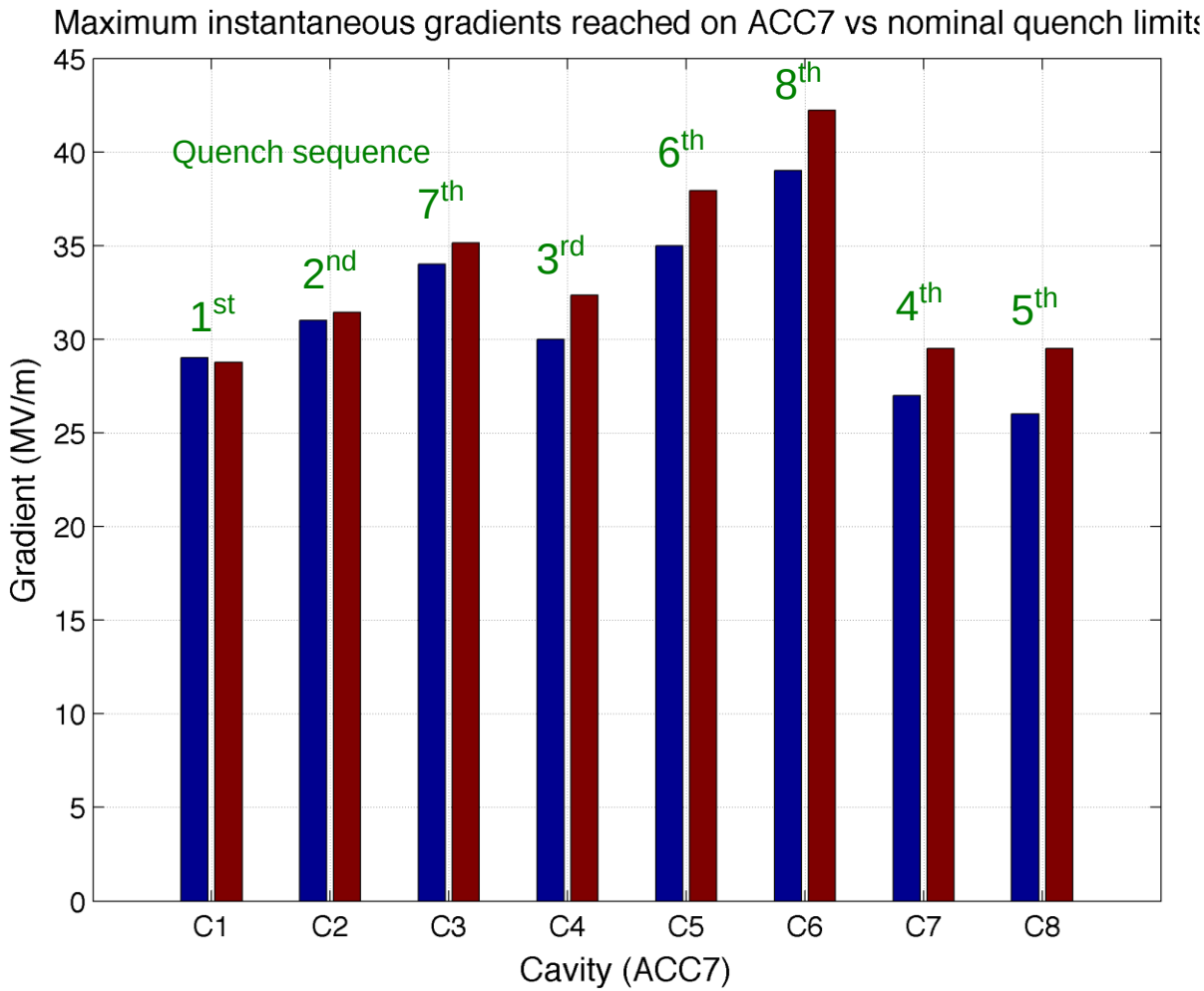
Event #14427322: all cavities quenched



Red: this event, Blue: previous event, Green: nominal

RF is turned off by a cryo alarm at ~5:06:20

Maximum instantaneous gradients during Mombo quench event



Blue: Limits from Katalev spreadsheet

Red: maximum gradient during quench event

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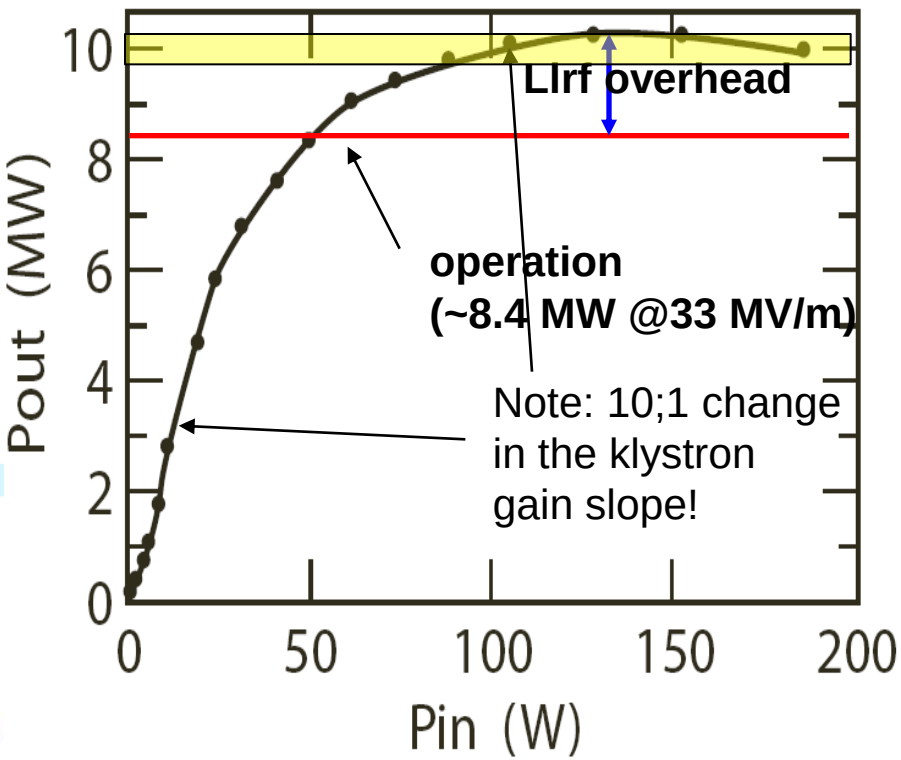
LLRF tuning overhead

- As in RDR, llrf tuning overhead is 16% in power.
- Further suppression of rf overhead is requested.
- LLRF overhead covers such as
  - (dynamic) microphonics, fluctuation of HV (klystron), beam current, …
  - (static) Pk and Ql tolerance, HV ripple, …

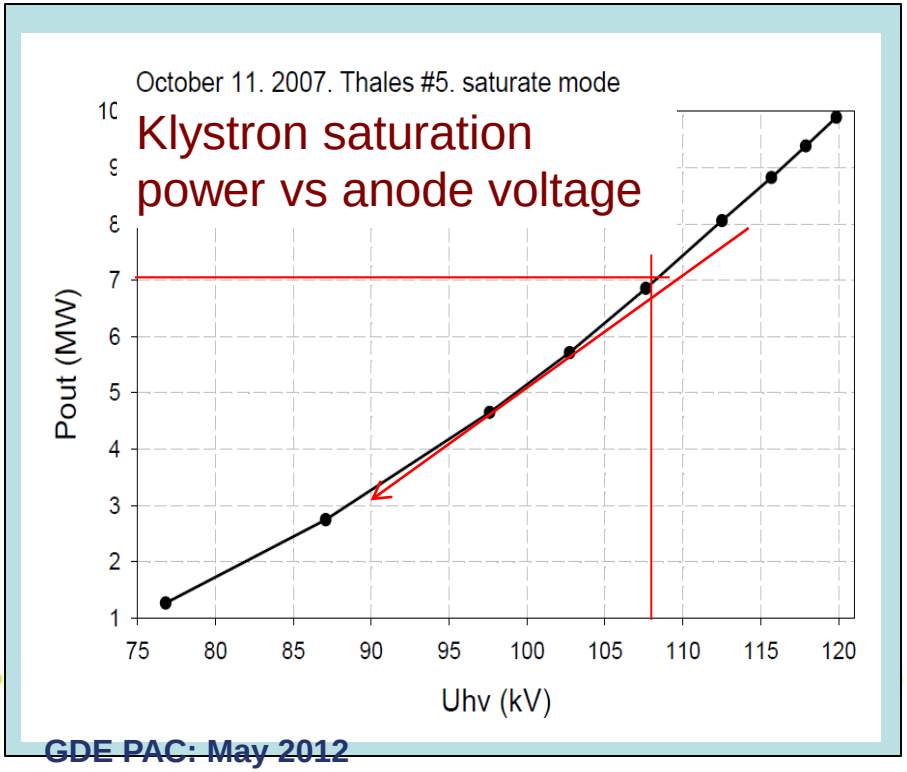
LE 2.6-2
nit parameters.

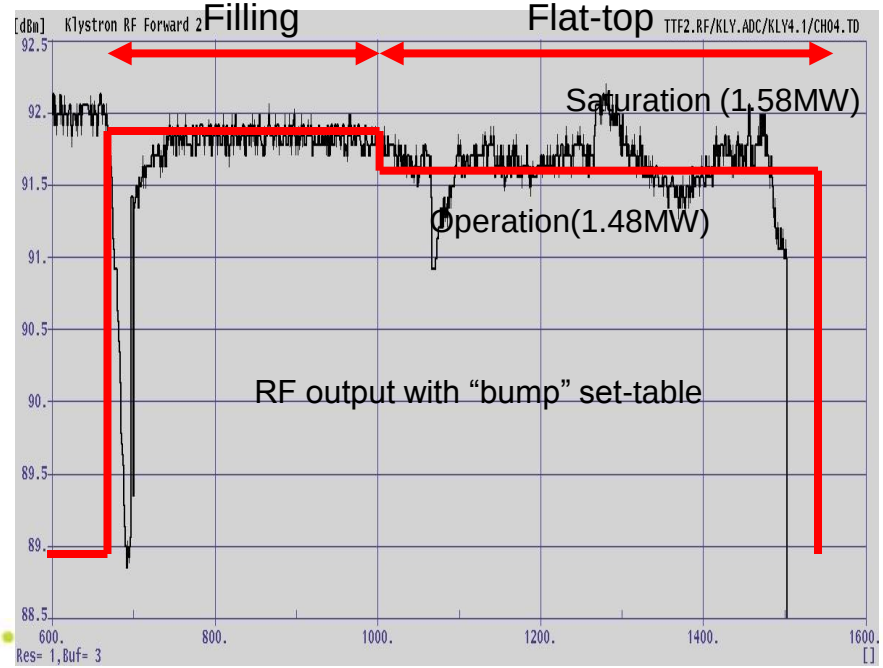
Parameter	Value	Units
Modulator overall efficiency	82.8	%
Maximum klyston output power	10	MW
Klystron efficiency	65	%
RF distribution system power loss	7	%
Number of cavities	26	
Effective cavity length	1.038	m
Nominal gradient with 22% tuning overhead	31.5	MV/m
Power limited gradient with 16% tuning overhead	33.0	MV/m
RF pulse power per cavity	293.7	kW
RF pulse length	1.565	ms
Average RF power to 26 cavities	59.8	kW
Average power transferred to beam	36.9	kW



RF operation condition for klystron saturation studies

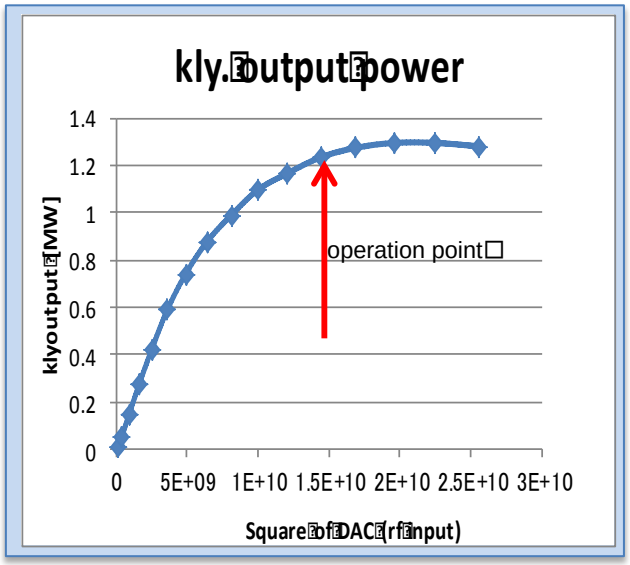
- Under normal 9mA studies conditions, the klystron forward power is not sufficient to put the klystron into saturation
- Saturation point of the klystron was artificially reduced by lowering the HV
- Beam pulse: 4.5 mA / 800us
- Filling time was adjusted to have ~rectangular output.(500us ->660us)
-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

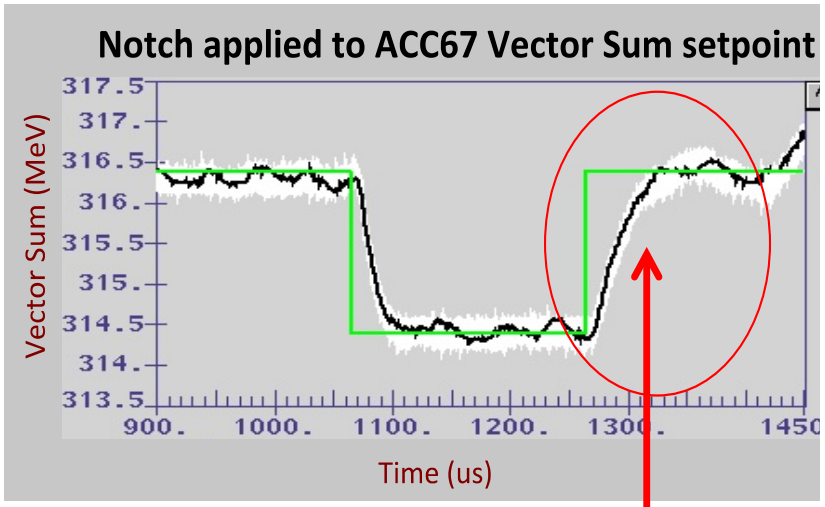


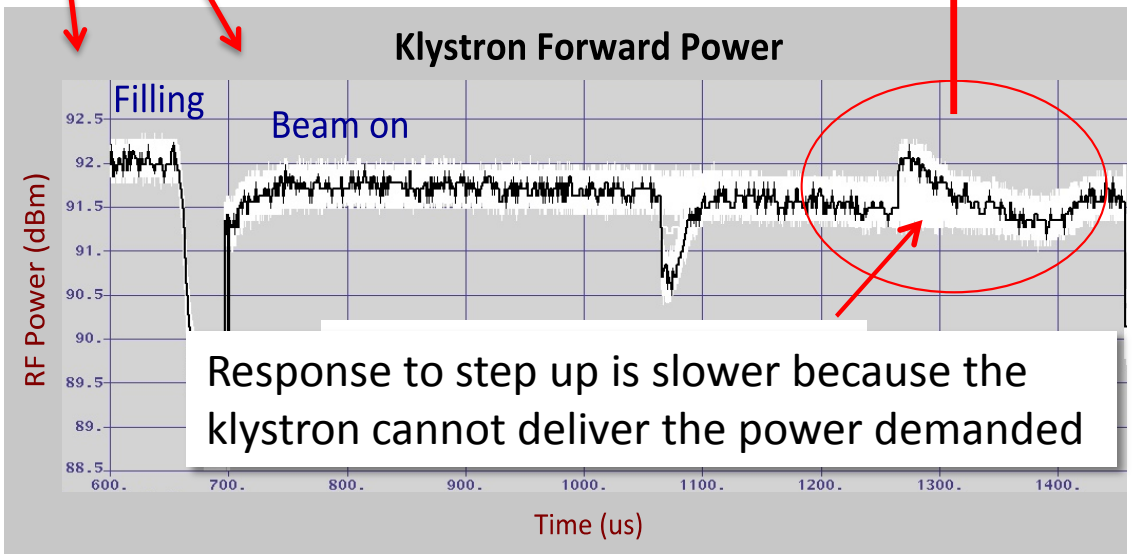


9mA Studies: evaluating rf power overhead requirements
(4.5mA/800us bunch trains)

- Klystron high voltage was reduced from 108KV to 86.5KV so that the rf output just saturated during the fill
- The required beam-on power ended up being ~7% below saturation







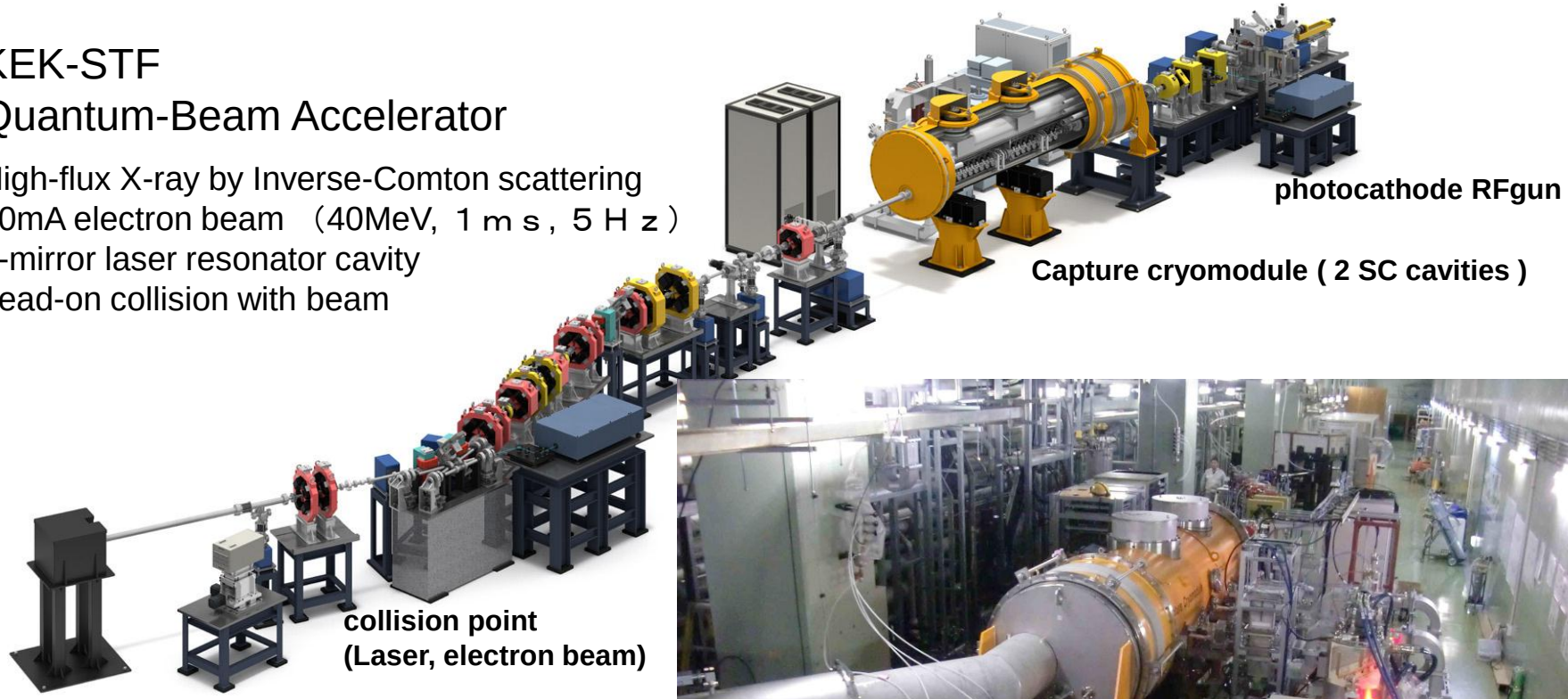
Outline

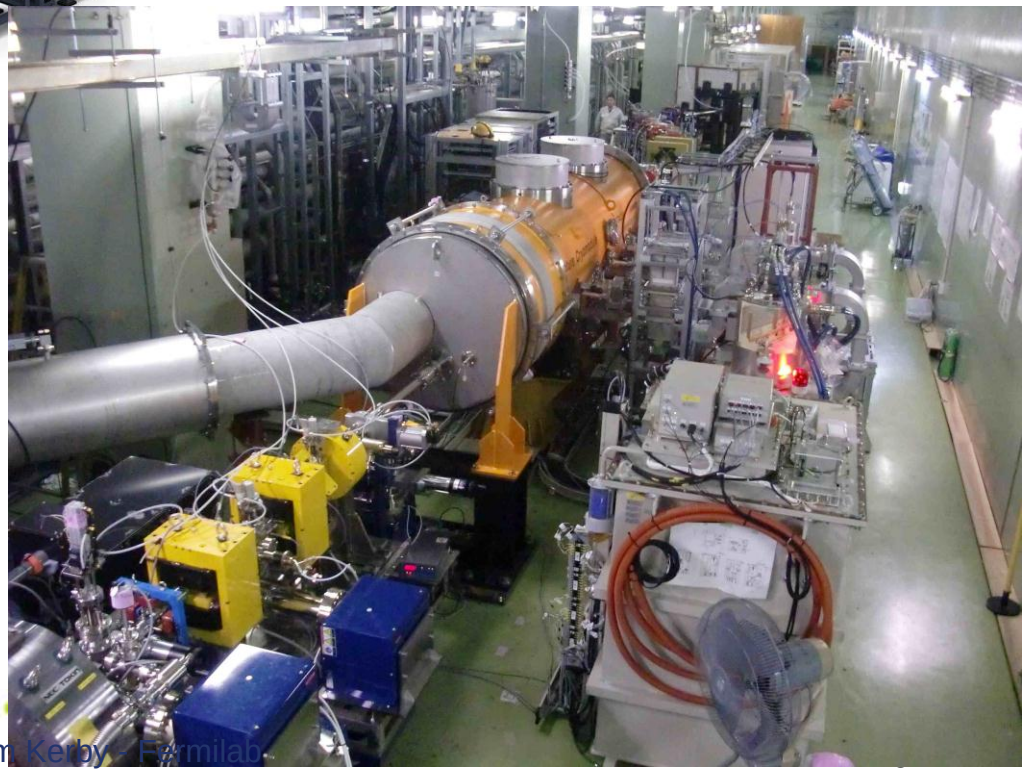
- Brief recap of achievements to date
- Results from beam studies in Feb 2012
- **Quantum Beam at KEK**
- Assessment of results / extrapolation to ILC parameters
- System test program, post TDR

STF Quantum-Beam experiment

KEK-STF
Quantum-Beam Accelerator

High-flux X-ray by Inverse-Comton scattering
10mA electron beam （40MeV, １ｍｓ, ５Ｈｚ）
4-mirror laser resonator cavity
head-on collision with beam





Target: 1.3 x 10^{10} photons/sec 1%bandwidth

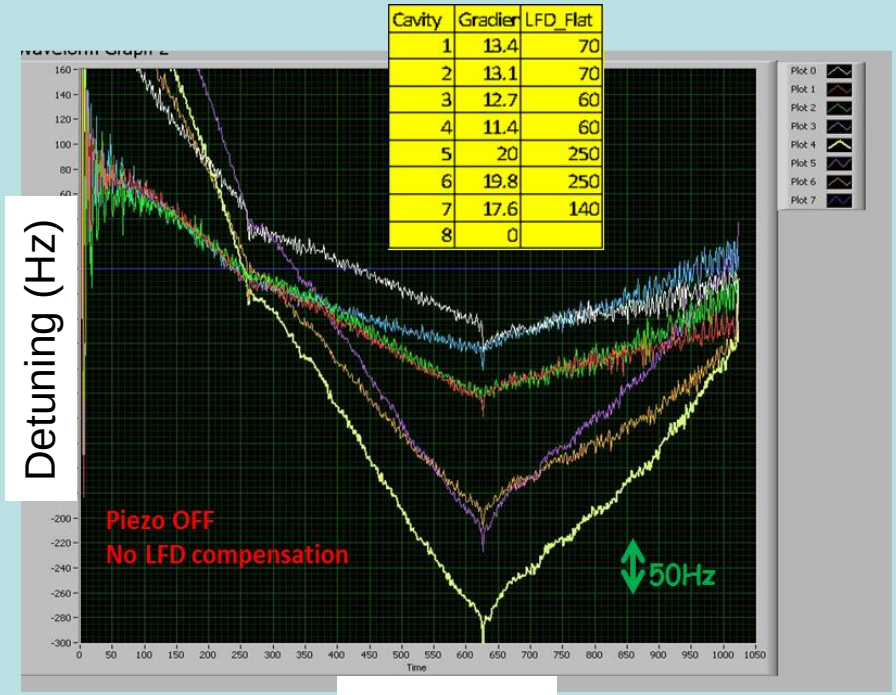
2012. Feb : cool-down started,
April : beam acceleration

Outline

- Brief recap of achievements to date
- Results from beam studies in Feb 2012
- **Lorentz-force detuning compensation at NML**
- Assessment of results / extrapolation to ILC parameters
- System test program, post TDR

Lorentz-force detuning compensation

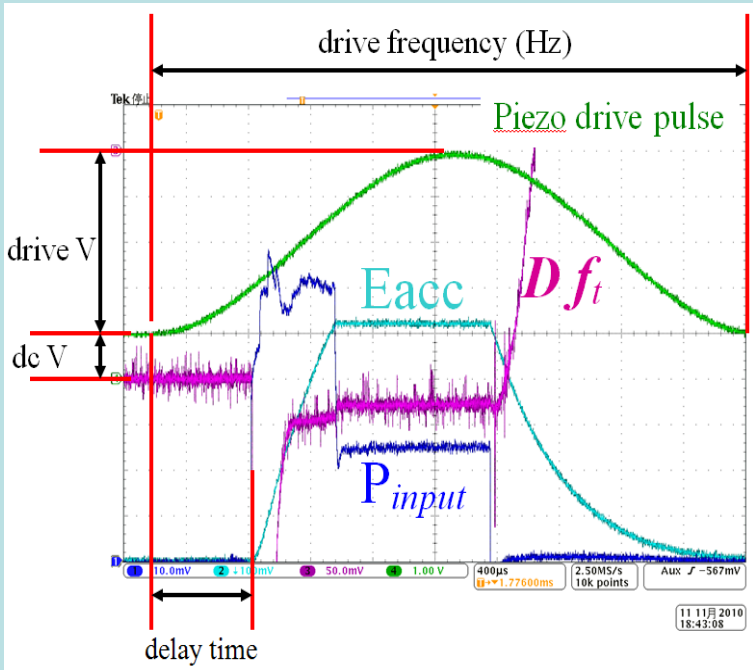
Uncompensated Lorentz-force detuning during rf pulse



Cavity	Gradier	LFD_Flat
1	13.4	70
2	13.1	70
3	12.7	60
4	11.4	60
5	20	250
6	19.8	250
7	17.6	140
8	0	

Standard compensation method

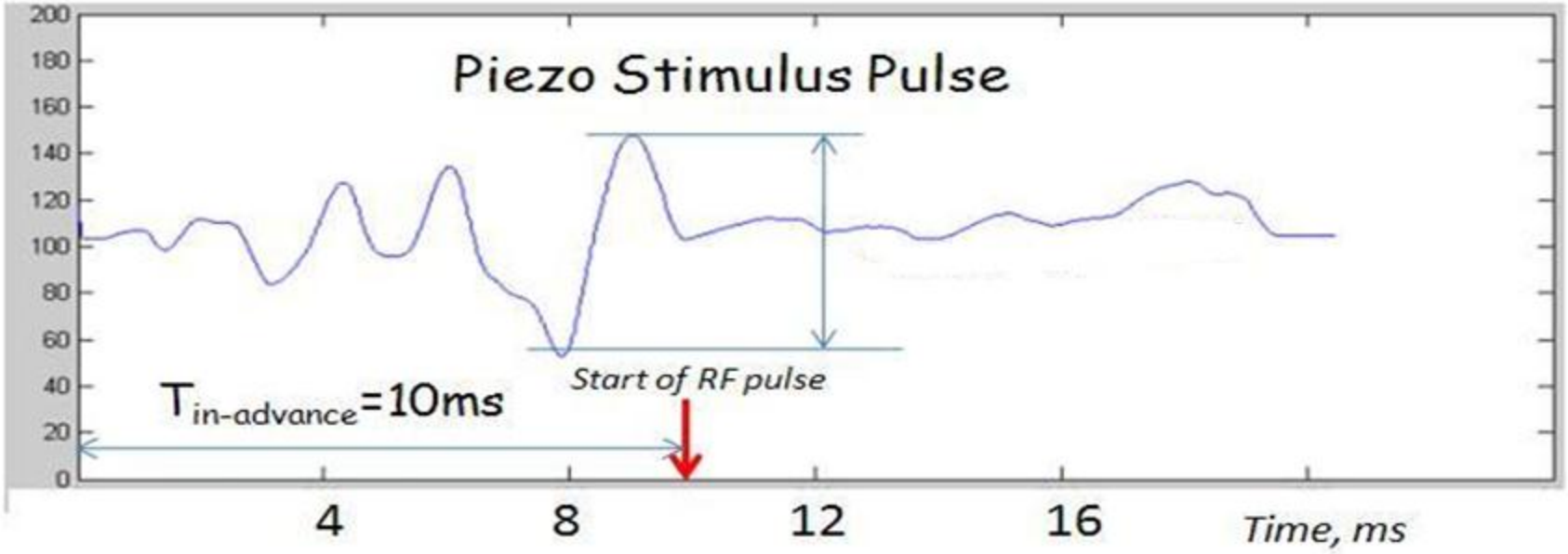
- Half-sine impulse applied to piezo tuner prior to the RF pulse
- Optimize pulse parameters (amplitude, delay, frequency, etc)
- Can give excellent results for short pulses. The method used at FLASH



W. Schappert

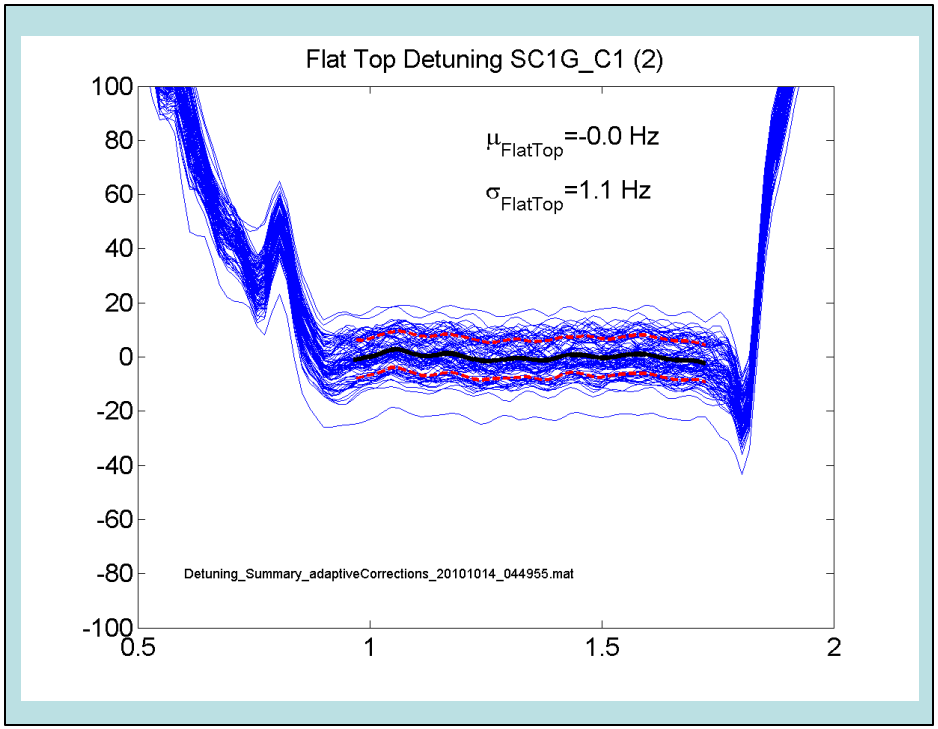
Fermilab/NML: adaptive learning feed-forward

- Use measured transfer function from piezo to LFF
- Accurate measurements of the detuning due to Lorentz force
- Accurate characterization of the detuning response to piezo impulses at various delays
- Use least-squares to determine the combination of piezo impulses required to cancel out the Lorentz force detuning
- Linear problem: Invert Response Matrix using standard matrix algebra



Adaptive LFF compensation at S1-Global

- Single cavity system deployed to KEK during LFD studies of S1-G cryomodule
- Successfully reduced LFD to less than 16 Hz in cavities with
  - **KEK Slide Jack Tuners**
  - **DESY/Saclay Tuners**
  - **INFN/FNAL Tuners**



Aim to test this method at FLASH during the next 9mA studies

Outline

- Brief recap of achievements to date
- Results from beam studies in Feb 2012
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TD Phase R&D results (updated mid 2012): System Tests with Beam at FLASH

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)

Check-list of TD Phase accomplishments

- Long bunch trains, heavy beam loading demonstration
  - **6mA / 800us demonstrated (TDR Baseline)**
  - **9mA / 800us marginally achieved (luminosity upgrade)**

- Vector Sum control of RF unit
  - **Operation of RF units comprising 16 and 24 cavities**
  - **Intra- and inter-pulse stability better than 0.02%**

- Operating gradients
  - **Operation up to average of 29MV/m (24MV/m to 33MV/m)**
  - **Lorentz-force detuning compensation on all cavities simultaneously**

Check-list of TD Phase accomplishments

- Pk/Ql control for optimizing gradient profiles
  - **Demonstrated flat gradient solutions to +/-0.3%**
  - **ILC baseline has more knobs (power ratios), so easier**

- Operation close to quench
  - **Several cavities within 5-10% of quench at 4.5mA, 800us**

- Klystron overhead
  - **First results: beam operation within 7% of saturation**
  - **(Need to evaluate effect on energy stability)**

- HOM coupler
  - **Beam tests during high power 9mA/800us tests in 2009**
  - **Excellent agreement between model and measured data**

Check-list of TD Phase accomplishments

- Operation close to quench (operability)
  - **Ramp-up to 4.5mA, 800us within 10% of quench demonstrated without quenching**
  - **Rapid recovery after quench**
  - **Quench detection / prevention with beam loading**

- FLASH FEL operations…
  - **Many 1000's hours of routine operation for FEL users under a wide range of operating conditions**

Outline

- Brief recap of achievements to date
- Results from beam studies in Feb 2012
- Tests at FNAL and KEK
- Assessment of results / extrapolation to ILC parameters
- **System test program, post TDR**

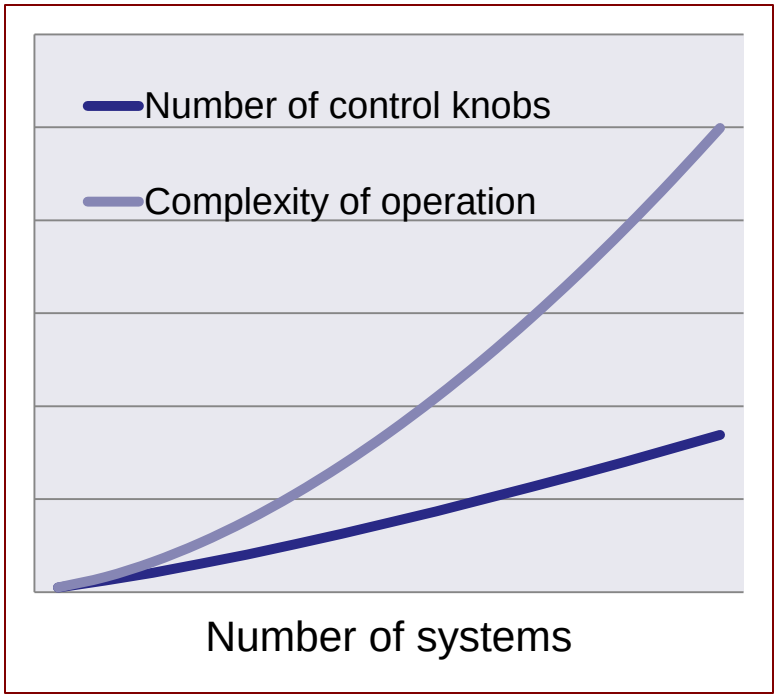
System Tests, post 2012

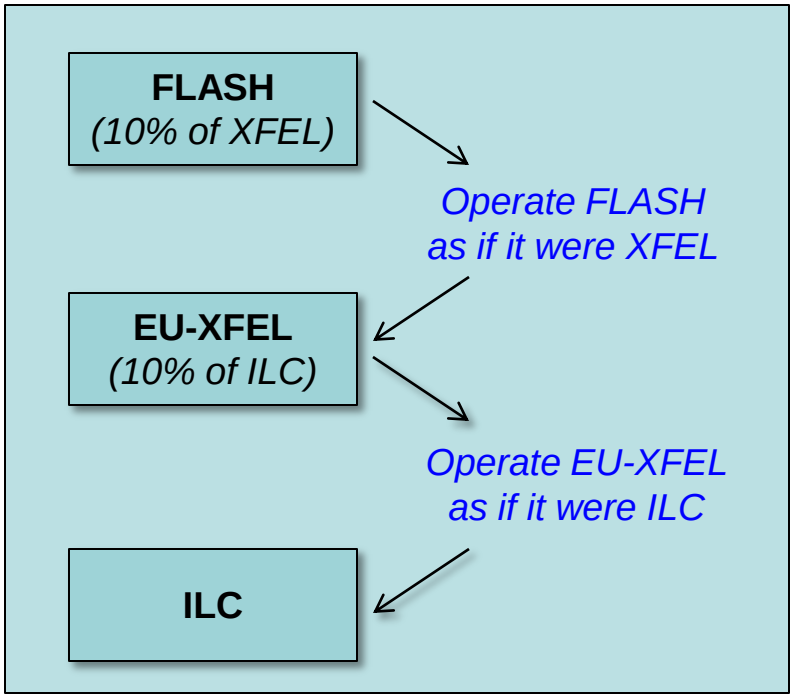
- During the TD Phase, we have verified the key fundamental technology issues of operating an SC linac at ILC-like parameters
  - **Long pulse high power beam operation**
  - **High average gradient, gradient spread**
  - **Operation close to limits of gradient and rf power**

- Post-2012, we move from technology issues to engineering and system integration
  - **Establish a base of experience for building and operating a large-scale high power linear collider, eg**
    - Machine protection, exception handling
    - ‘Gradient management’
    - Startup & machine tuning, achieving stable operation
    - Automation
    - … etc

Scalability of machine operations

- The number of knobs scales ~linearly with the scale of the machine
- Complexity of operation increases exponentially (system interactions)
- Operation becomes unmanageable beyond some level of complexity
- Use automation to contain the level of complexity in the control room
  - Learn how to do this incrementally





Summary

- New study results from FLASH in Feb 2012
  - **Encouraging results from first beam tests with klystron operating close to saturation**
  - **Significant improvements over the Feb 2011 results for cavity gradient flatness (now < 0.6% p-p)**
  - **Demonstrated ramp-up procedures**
  - **Successfully automated some key tasks (just starting)**

- We should be ready to declare success on the TD Phase R&D goals for System Tests with Beam

- Program post 2012: engineering and system integration issues for operating large-scale high-power linear accelerator facilities