Results from the Feb 2012 9mA studies

John Carwardine

For: Nick Walker, Gustavo Cancelo, Shin Michizono, Julien Branlard, Christian Schmidt, Valeri Ayvazyan, Vladimir Vogel, Siggi Schreiber, Holger Schlarb, Bart Faatz, Mathias Vogt, Warren Schappert, Wojciech Cichalewski, Olaf Hensler, and others

Outline

- ILC context for the February 2012 studies
- Goals for February 2012
- Achieving flat gradients ('Pk/Ql' studies)
- Quench studies
- Klystron saturation studies
- Long pulse operation close to gradient limits
- Wrap-up

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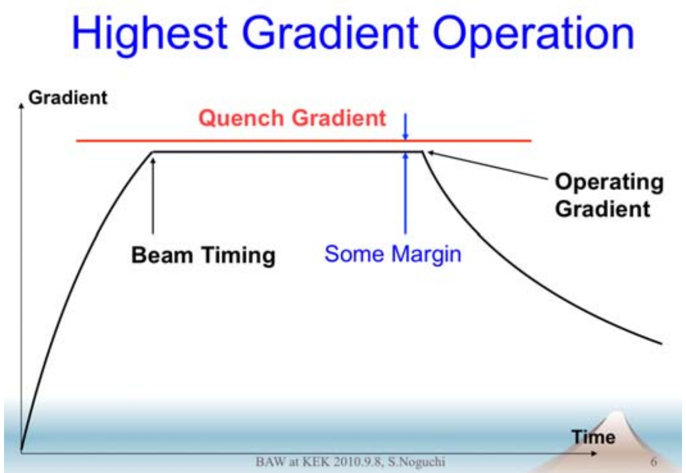
- **Wrap-up**

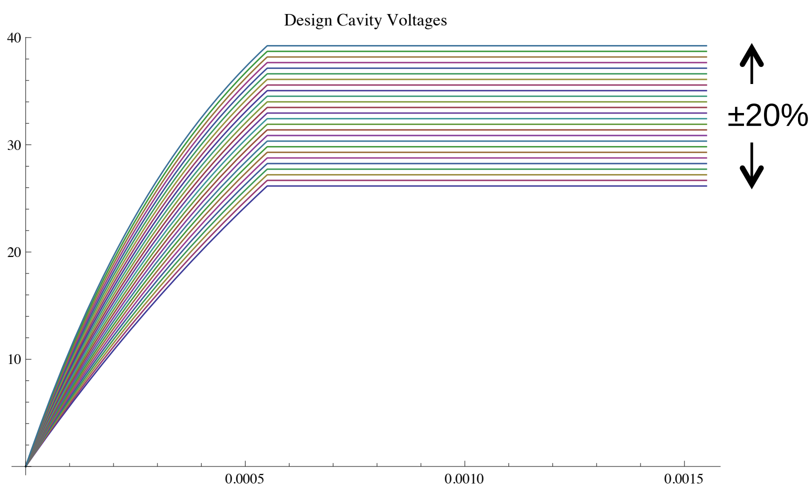
Background to February 2012 studies

- **Cost minimization for the ILC**
  - High cost of gradient -> keep gradient overhead to minimum
  - High cost of RF power -> keep rf power overhead to minimum

- **Minimize emittance growth due to orbit changes from cavity kicks**
  - Minimize changes in cavity kicks -> minimize changes in cavity gradients over the duration of the beam pulse
  - Spread of operating gradients on same RF klystron

ILC: Maximising Energy





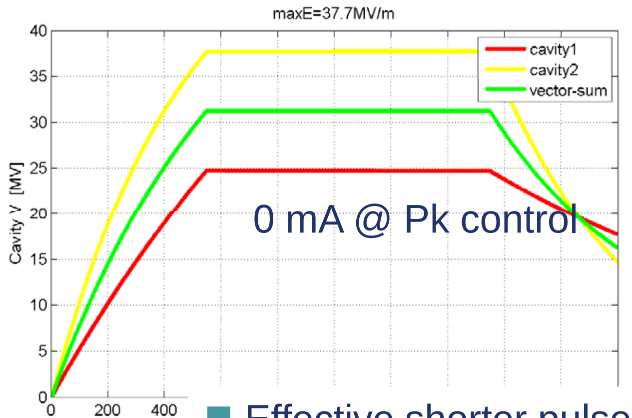
VT Observed Gradient Limit		35.0 MV/m avg
CM Observed Gradient Limit	3%	34.0 MV/m avg
Operation Gradient Limit	1.5 MV/m	32.5 MV/m avg
Controls margin	3%	31.5 MV/m avg

- **ILC baseline parameter: 31.5±20% MV/m accelerating gradient (25-38 MV/m)**
- **Full individual cavity P_{for} and Q_L control foreseen**
  - but not cheap!
  - FLASH only has Q_L adjustment
  - Flat gradient solutions I_B dependent!
- **(Positive) slopes on individual cavity gradients 'eat away' gradient overhead**
- **Goal: <3% change in V over flat top**
  - including during turn-on

Cavity gradient tilts due to spread in operating gradients on same vector sum

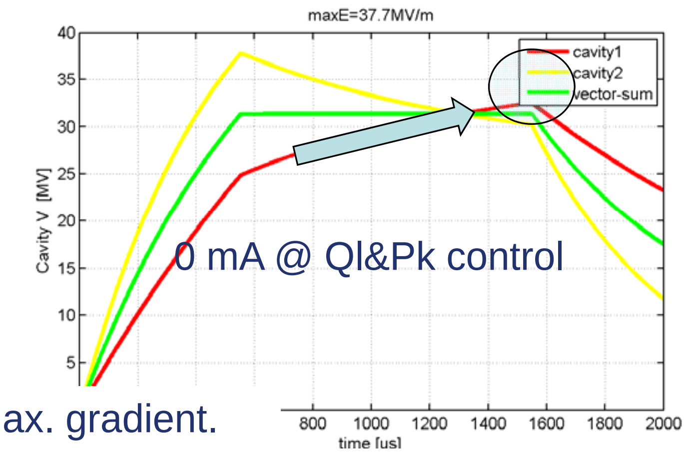
All Qext equal

(FLASH standard setup)



Individually adjusted Qext

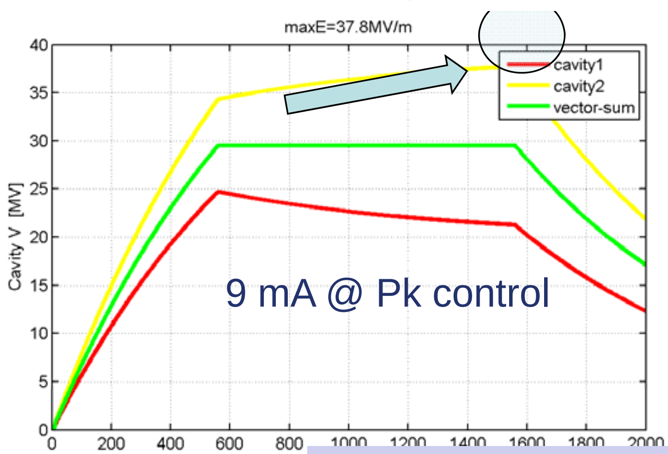
(ILC Reference Design)

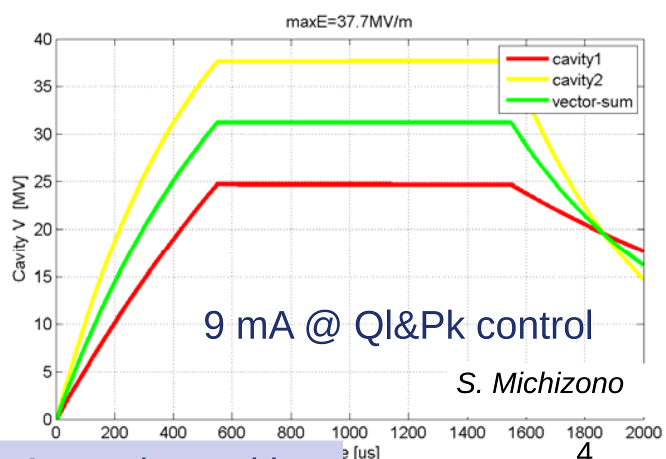


Matched beam current with constant Pk:

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

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





FLASH cavities have remotely adjustable Loaded Qs (ACC67)

Solutions modeled to achieve flat gradients without adjusting Pk

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

ILC: Beam Dynamics

$$\delta y'(t) \approx \frac{1}{2}\frac{V_a(t)}{E_{beam}} \cdot \alpha_{cav}$$

Cavity alignment pitch: **300 μr RMS**

$\gamma\varepsilon_y$ = 30 nm

1.5% RMS 'voltage tilt' $\rightarrow$ 1 nm $\gamma\varepsilon_y$ growth (for entire ILC linac)

Note: $\Delta(\gamma\varepsilon_y) \propto \Delta V_a(t)^2$

Tolerance similar to quench limit overhead (few %)

- **Impacts of random cavity misalignments (tilt) α_{cav}**
- **Transverse kick to the beam**
  - time dependent due to voltage 'slope' $V_a(t)$
- **Resulting betatron oscillations cause *emittance growth***
  - *different for different bunches along train*

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- **Study questions**
  - How well can we flatten the cavity gradients?
  - How close to quench can we run the cavities?
  - How close to saturation can we run the klystron?
  - How do we reach full current and full gradient without quenching?

  - All the above must be achieved while running maximum current and 800us bunch trains

- **Machine conditions**
  - 800us bunch-trains (2400 bunches)
  - Average current over 800us: ~4.5mA (1.5nC/3MHz)
  - Beam energy: 1GeV
  - Average gradients (ACC67): 26.7MV/m avg (13 cavities)
  - Max operating gradients (ACC7): 4 cavities above 31MV/m

- **ACC67 was focus of study**
  - We chose to use only 13 of the 16 cavities: ACC6 C5/C6 and ACC7/C1 were detuned

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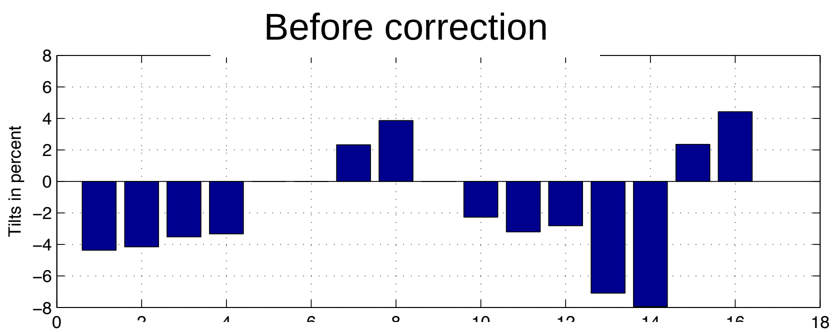
Iterative flattening of cavity gradients (better than +/-0.3% achieved)

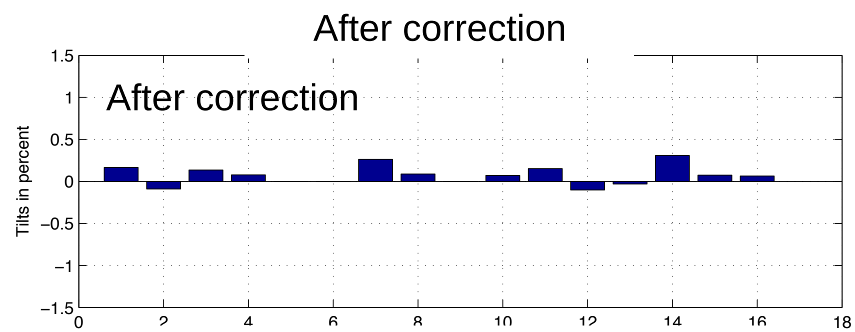
Algorithm

- **Measure gradient tilt (linear fit)**
- **Make small change to QL of cavity with worst tilt**

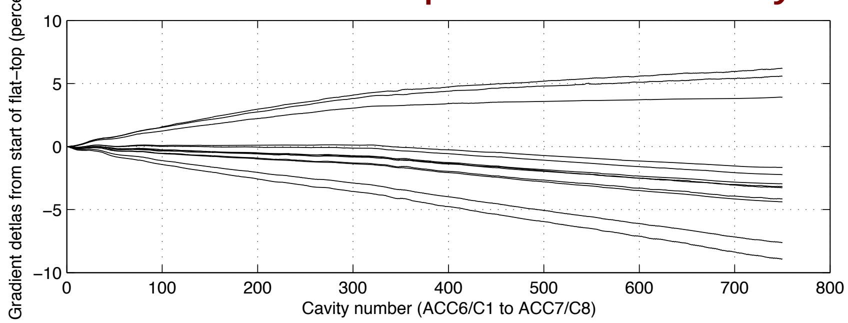
Gradient tilts by cavity (%)



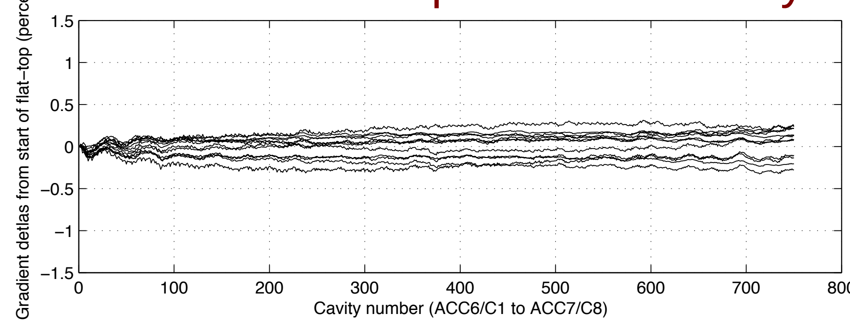
Gradient tilts by cavity (%)



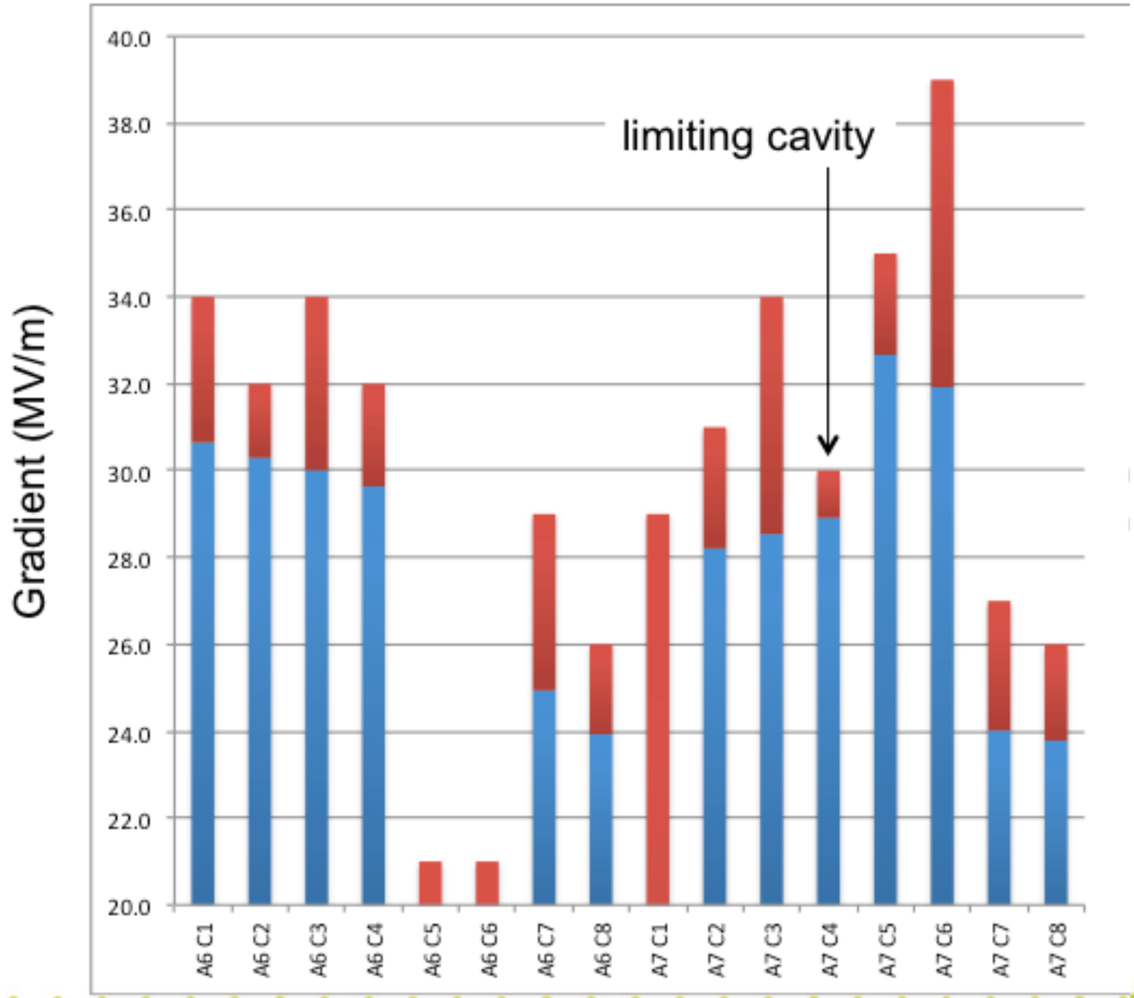
Gradient flat-tops for each cavity



Gradient flat-tops for each cavity



Limits achieved (380 MV)

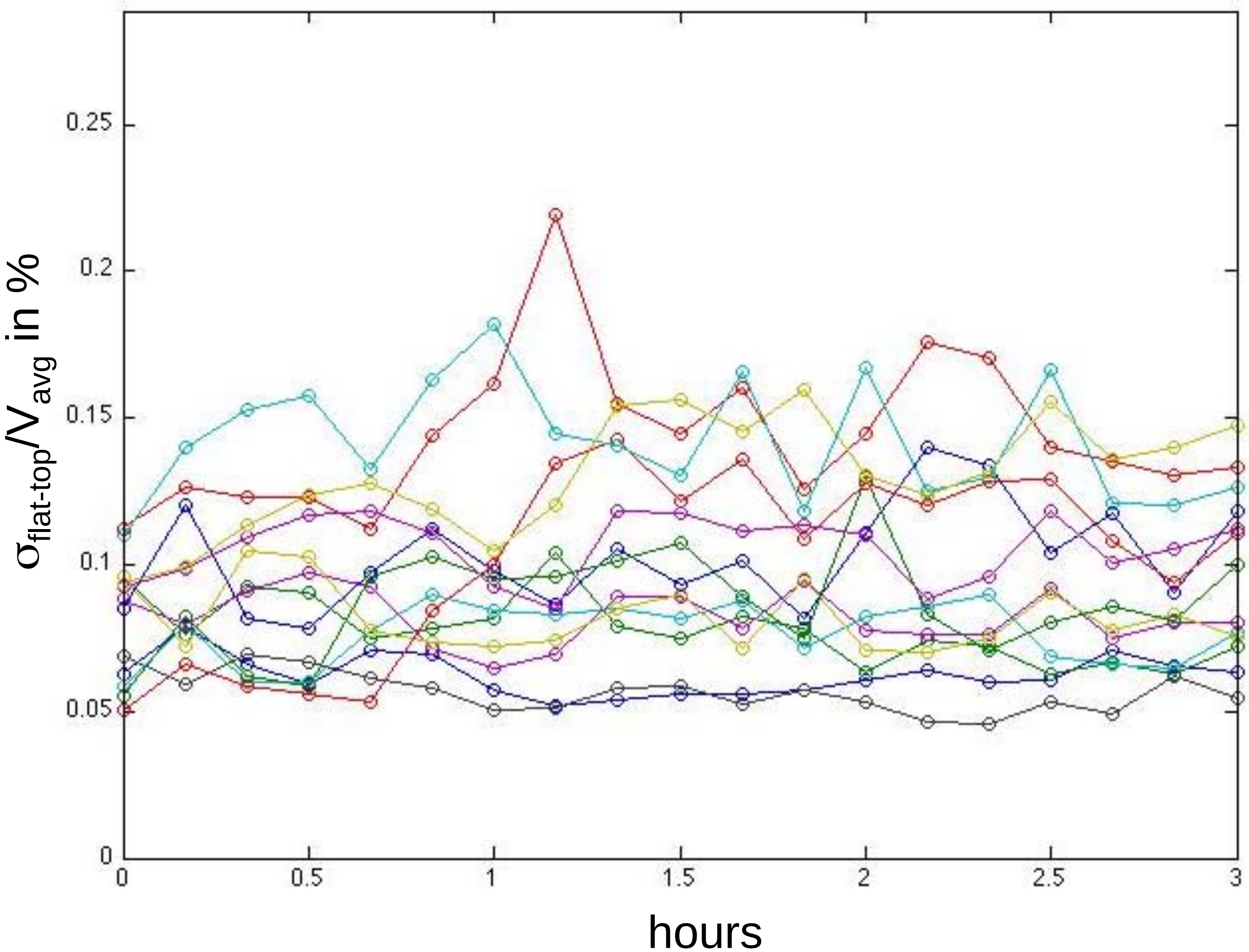


Long-term stability: cavity flat-top RMS

13 cavities plotted

Each data point is average over
- RMS over flat-top divided by average voltage.
- 100 pulses averaged (20 seconds)

Scale is equivalent relative rms for 1% voltage change over flat-top (tilt)
[= 1% / (2*sqrt(3)) ~ 0.29%]

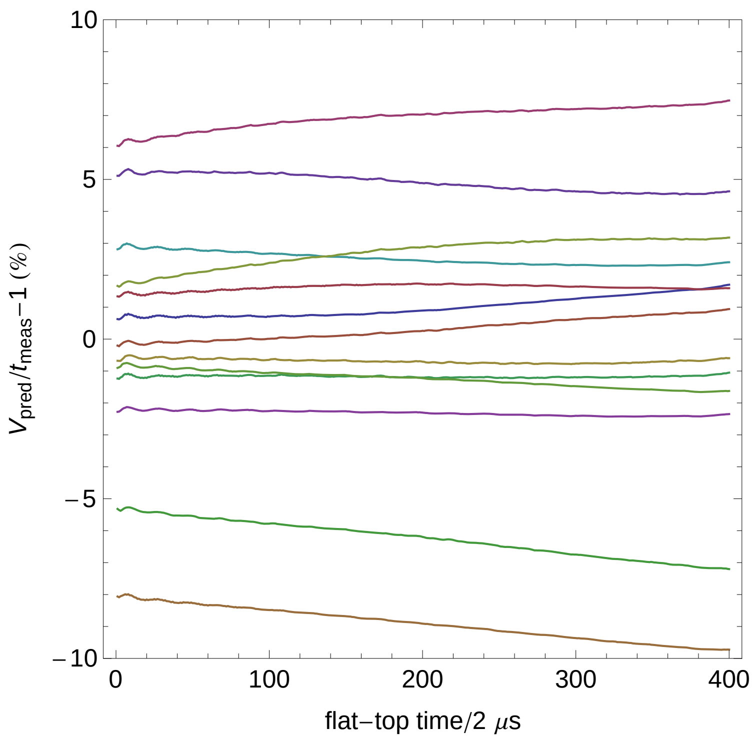


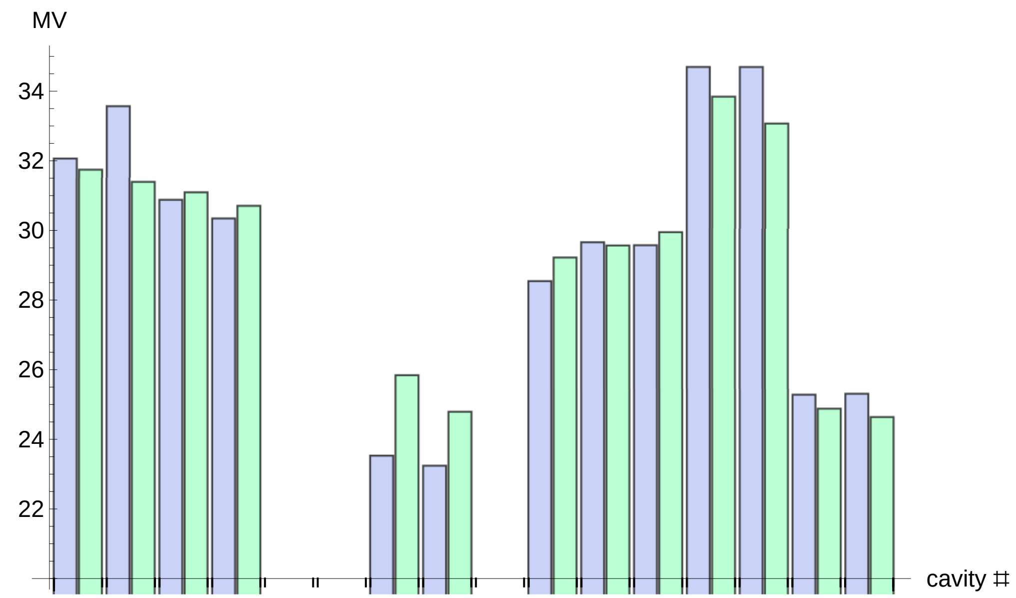
A380 point

Assumed 4.5mA beam current (flat pulse)
Power distribution taken from V. Katalev
Used measured Q_L values (from e-logbook)
Model P_{for} adjust to give VΣ=381.5 MV:

P_{fill} = 4.95 MW, P_{ft} = 3.37 MW

	ACC6	ACC7
1	1.99099×10^6	2.03805×10^6
2	2.06199×10^6	2.20636×10^6
3	2.03625×10^6	2.17752×10^6
4	2.07755×10^6	2.1208×10^6
5	2.93182×10^6	1.87928×10^6
6	3.01973×10^6	1.87887×10^6
7	2.52372×10^6	2.5007×10^6
8	2.55806×10^6	2.60172×10^6





Model = blue
Measured = green

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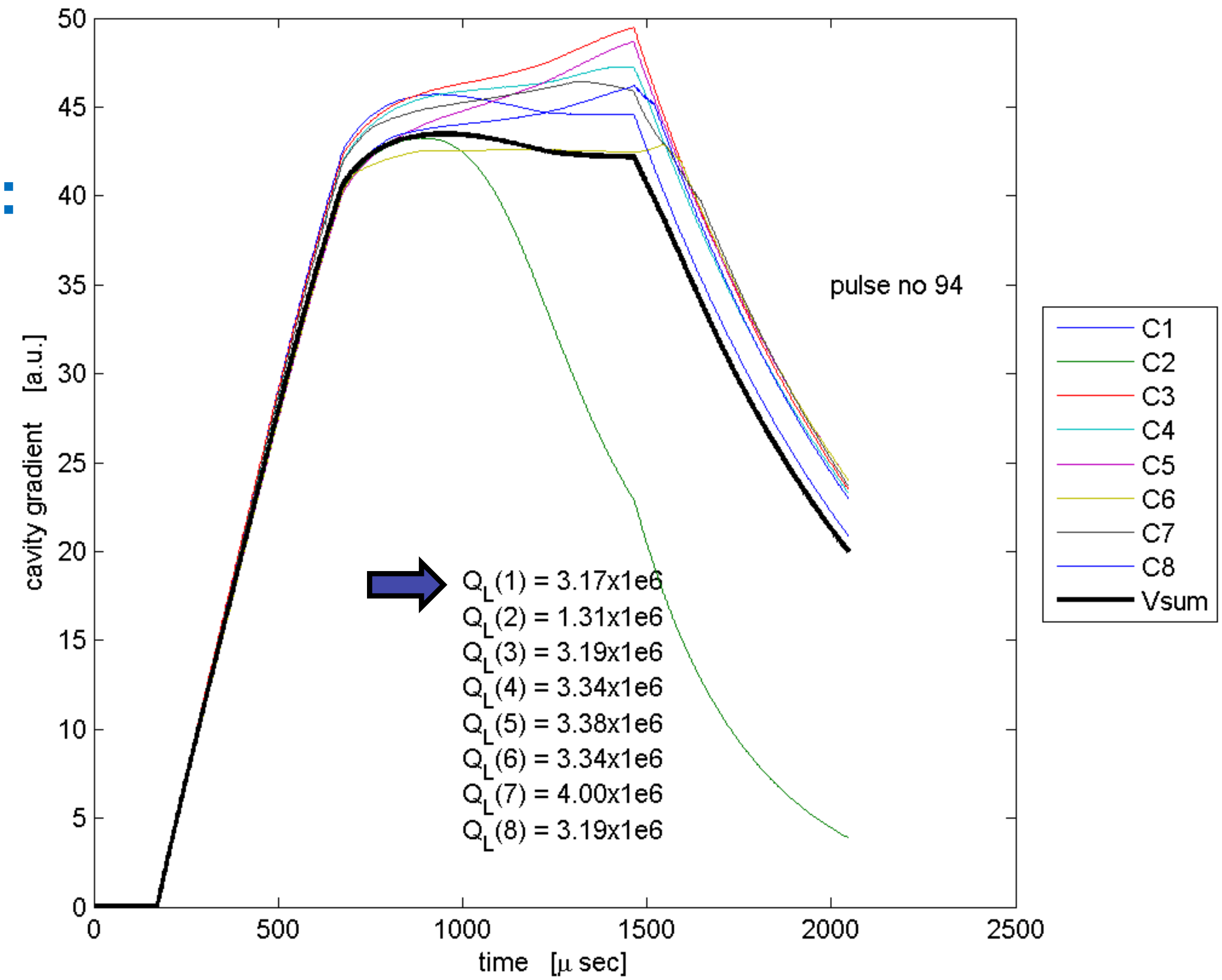
- **Quench studies**
  - Measurement of quench limits
  - Quenches!
- Klystron saturation studies
- Long pulse operation close to gradient limits
- Wrap-up

Quench limit study: approach

Typical quench signature :

Sudden drop in Ql :

ΔQl> 5e5



Quench limit study: approach

- **Measurement approach**
  - Detune all cavities but cavity being tested
  - Only include cavity i in vector sum, run with feedback on
  - Increase power below expected quench limit
  - Slowly approach limit gradient until quench
  - Report quench gradient

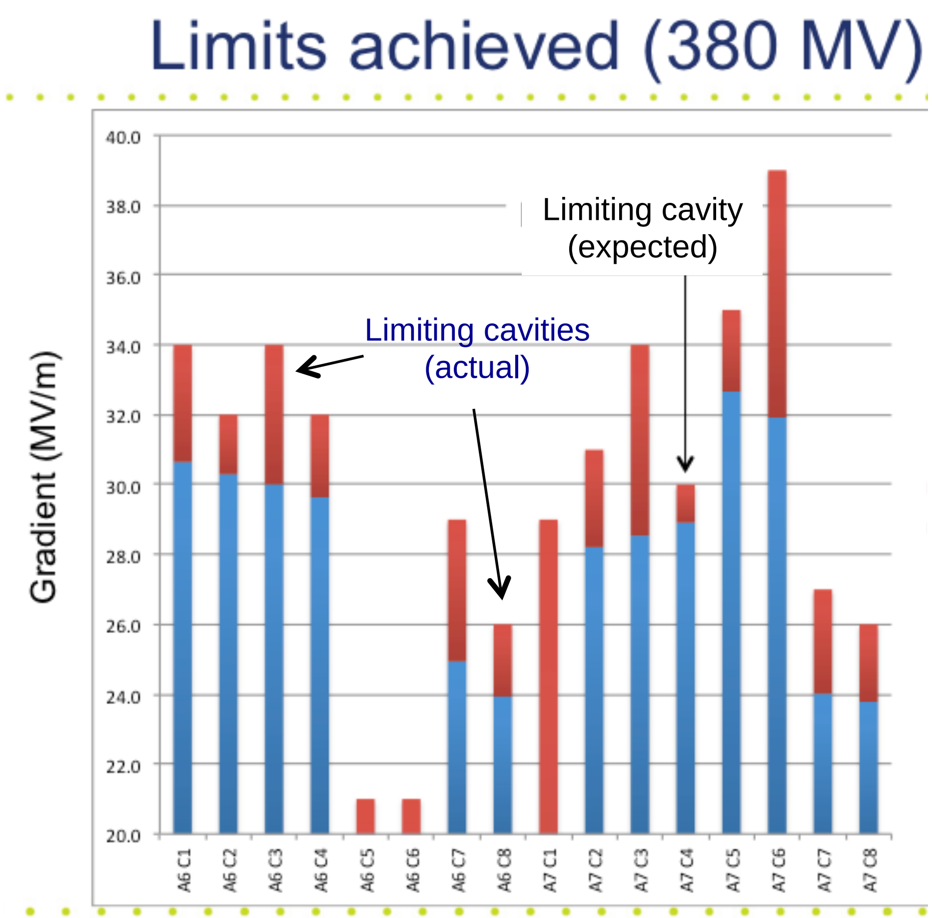
Quench limit study : results

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

Quench event during high gradient operation (26 Feb, 21:57)



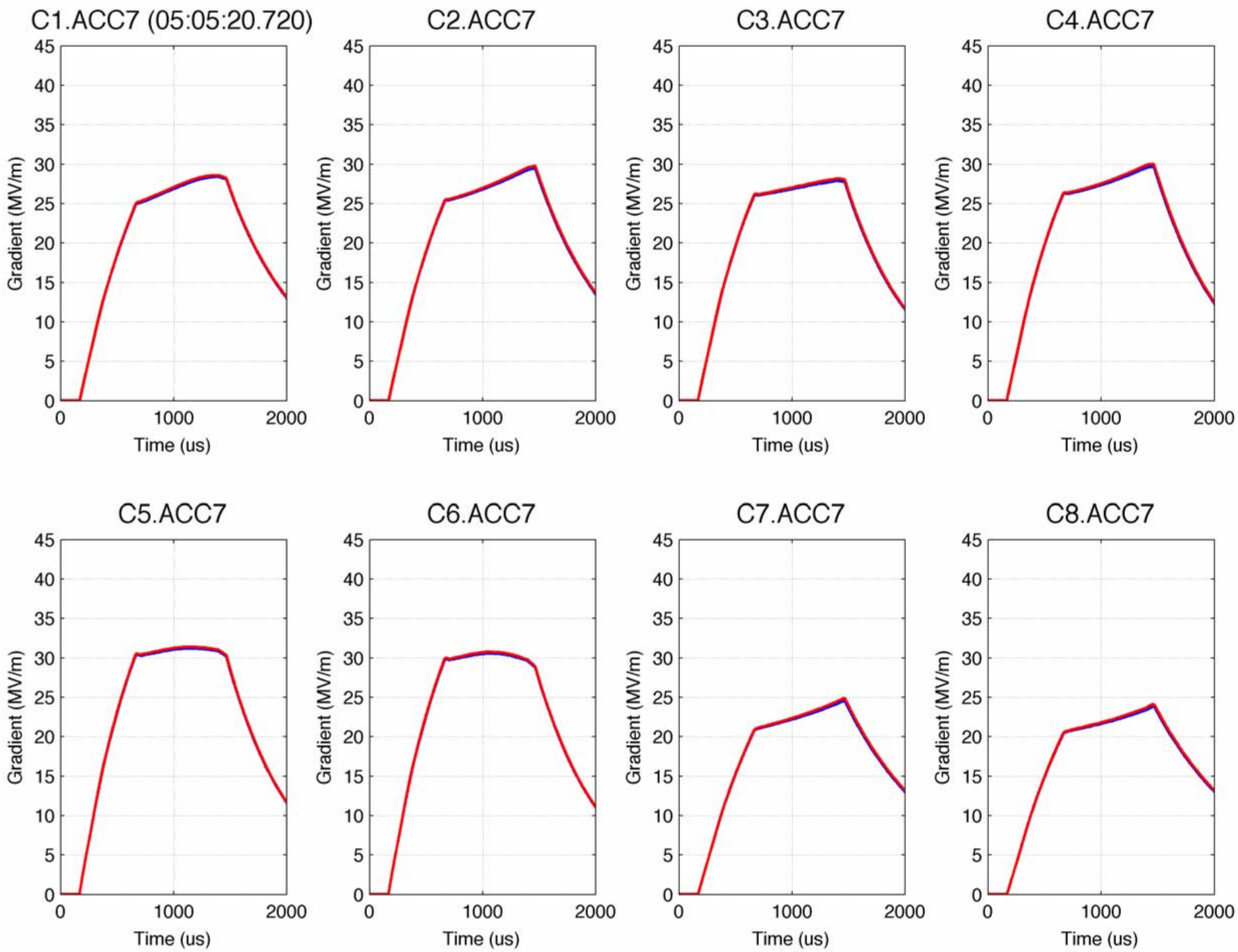
Comparison of quench limits from Katalev Spreadsheet (red) with gradients in 380MeV vector sum(blue) indicate that ACC7/C4 is closest to its quench limits

But… ACC6/C3 and ACC6/C8 were actually the first cavities to quench (…?)

‘Mombo’ quench event: 25 Feb 05:05:21

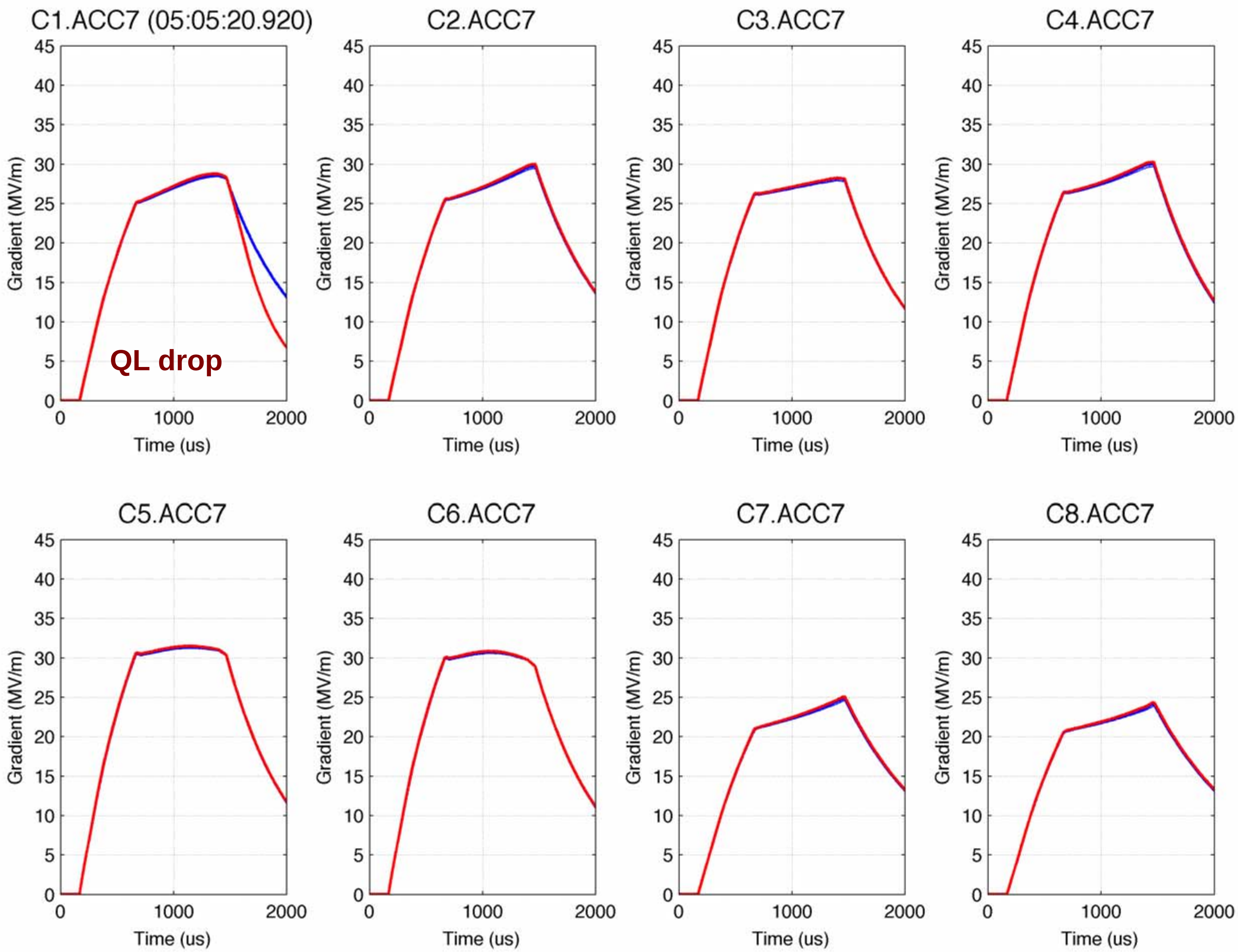
- **We were adjusting the relative powers to ACC6 and ACC7 to find the maximum usable partial vector sum on ACC7**
  - Beam was enabled - 700us bunch trains
  - Quench detection was disabled
- **ACC7 Cavity 1 was the first to quench**
  - Initially, the LLRF controller successfully maintained the ACC67 Vector Sum by increasing the klystron power
  - We even got a full-energy beam pulse with C1 quenched
- **There was a cascade of quenches as the LLRF controller tried to maintain the VS by driving the other cavities harder and eventually into quench**
- **Finally, RF was turned off by a cryo alarm ~1min later**

Event #14427309: ACC7 cavity gradients before first quench



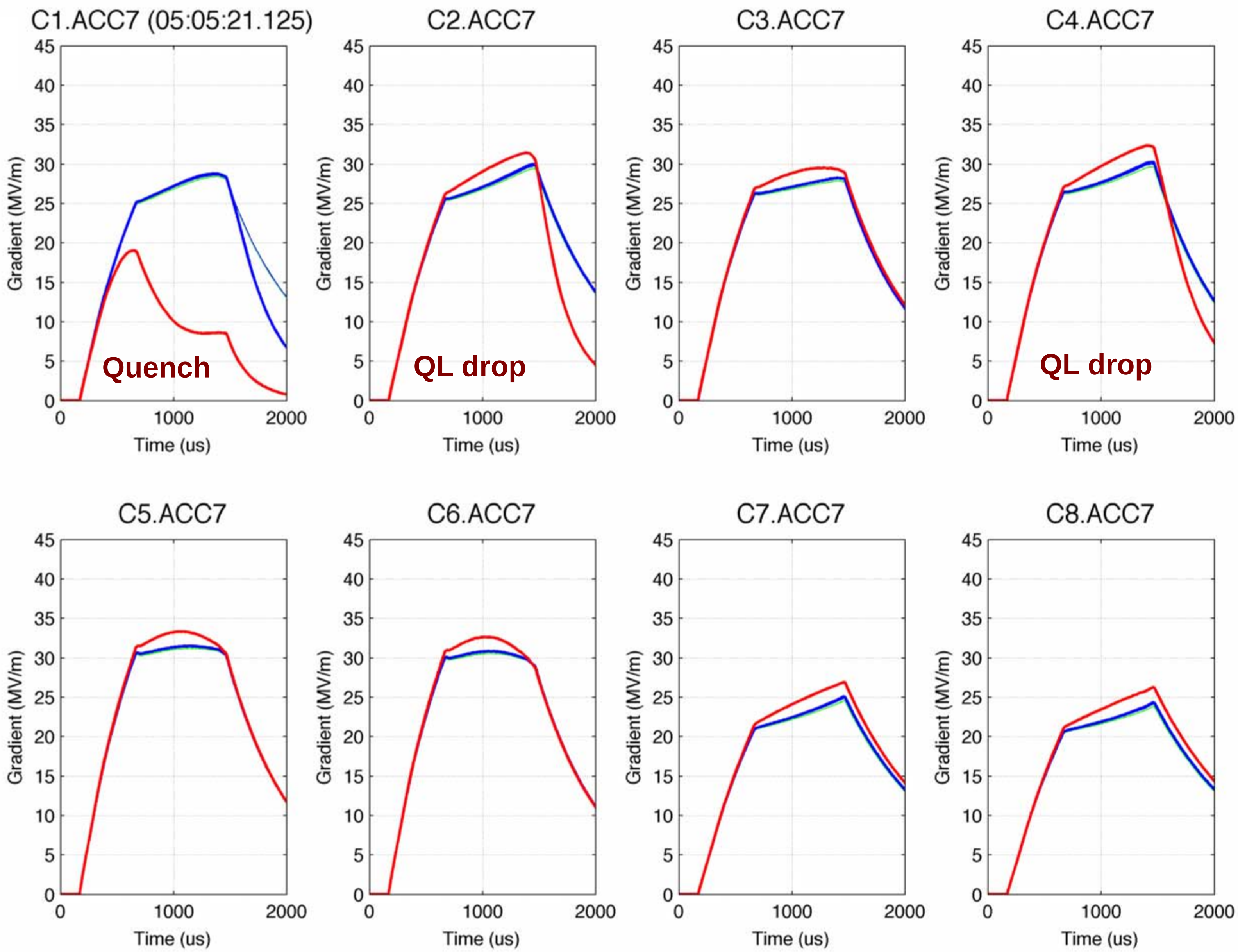
Red: this event, Blue: previous event, Green: nominal

Event #14427310: QL drop on C1



Red: this event, Blue: previous event

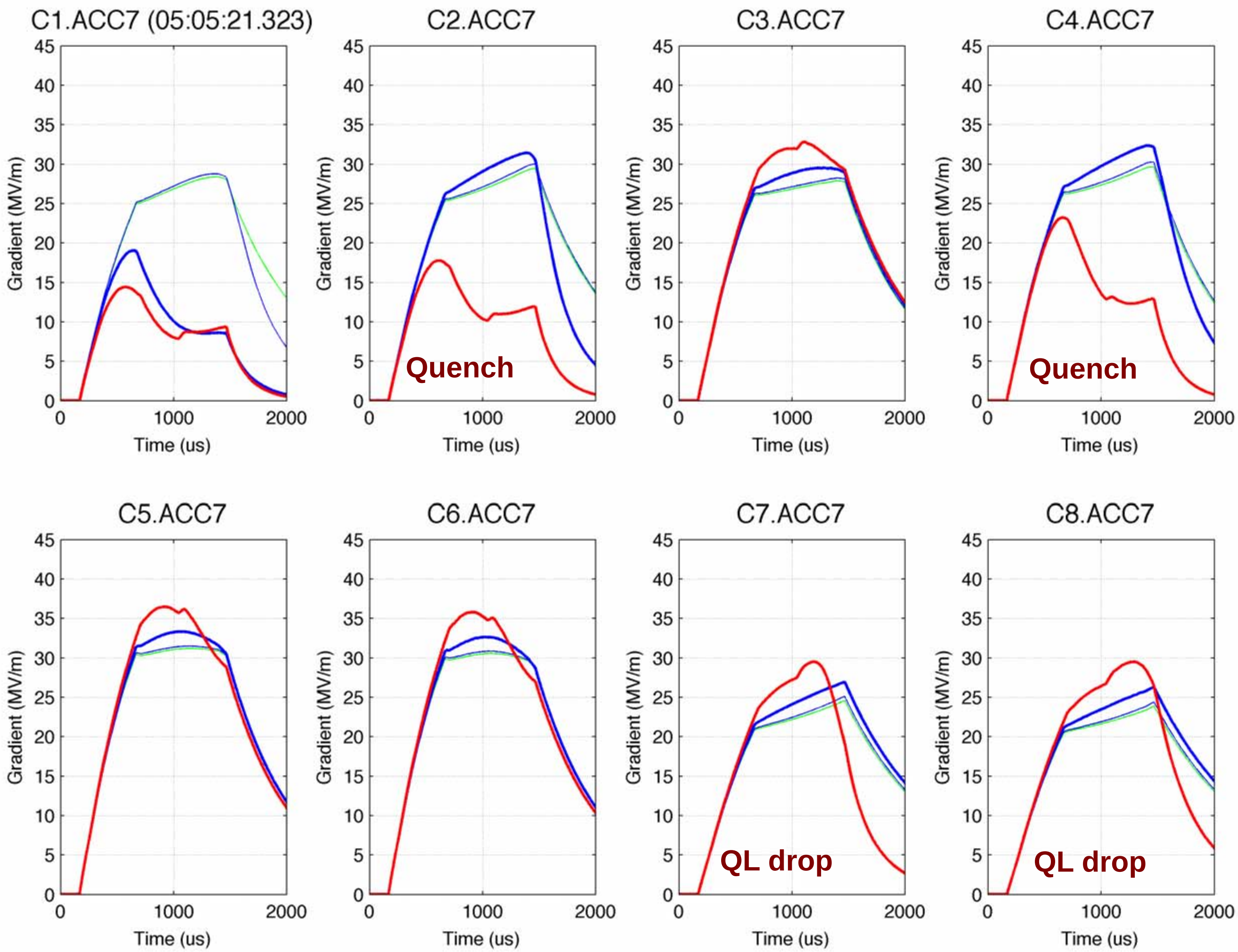
Event #14427311: C1 quenched, QL drop on C2 and C4



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

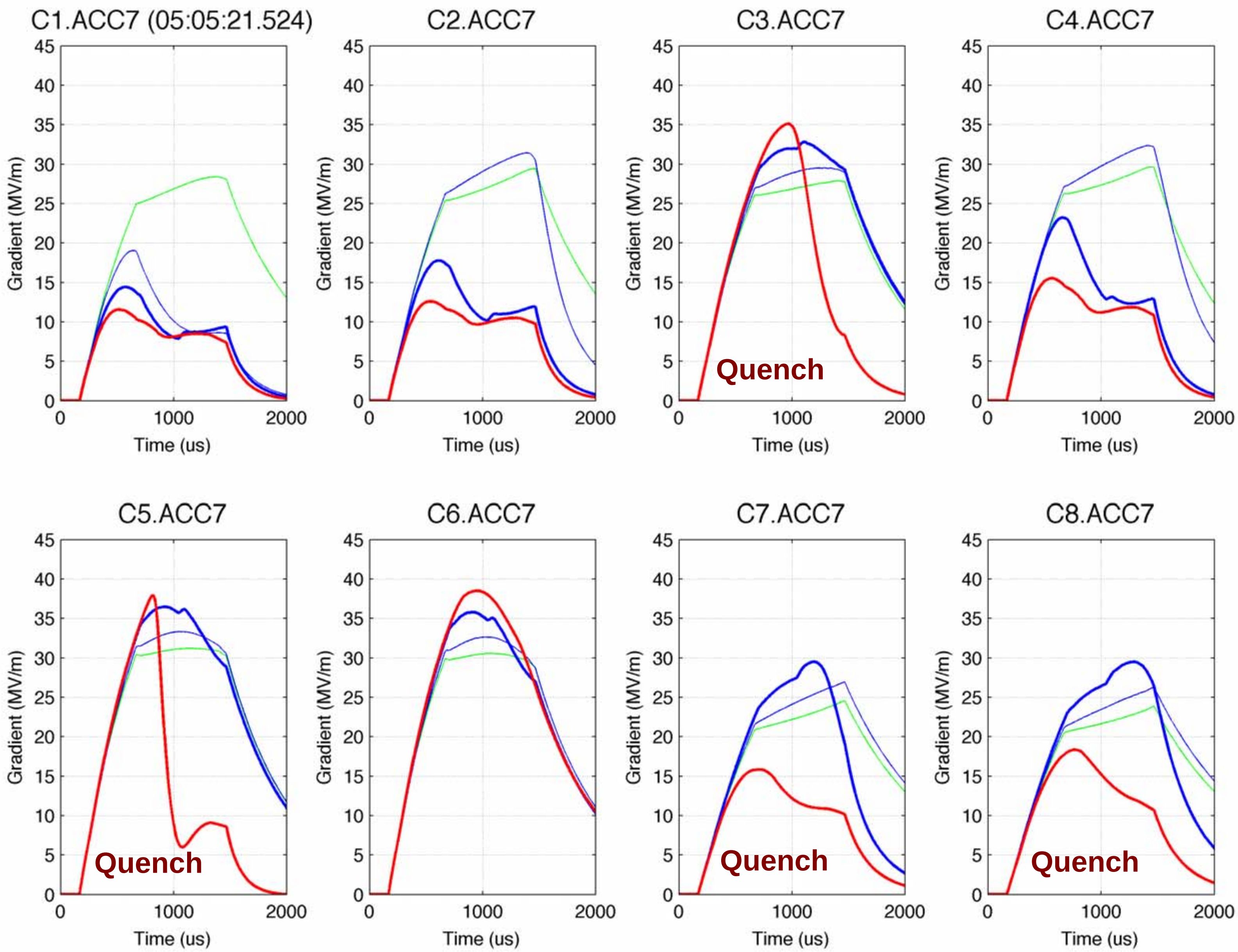
Vector Sum is maintained by driving the other cavities harder

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



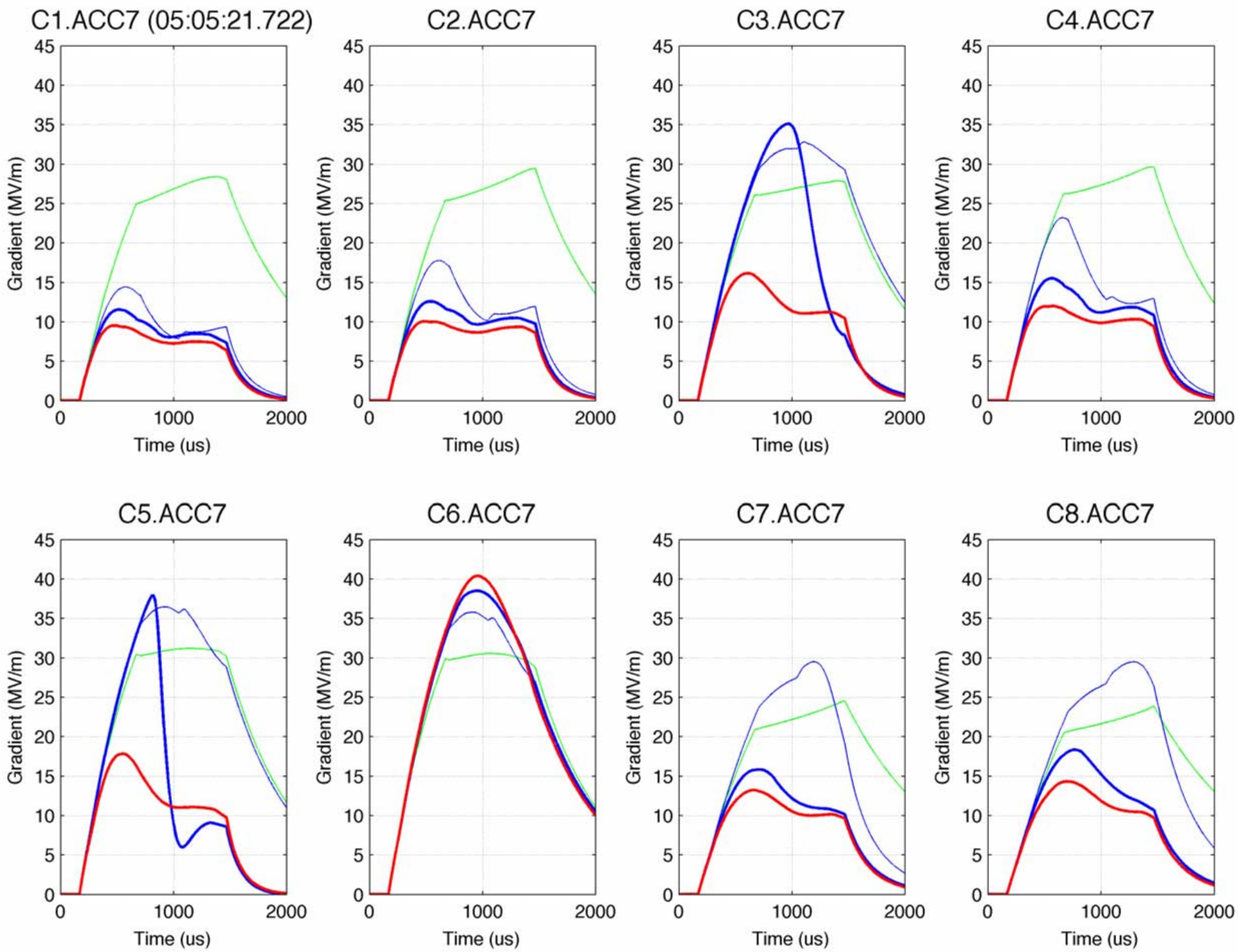
Red: this event, Blue: previous event, Green: nominal

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



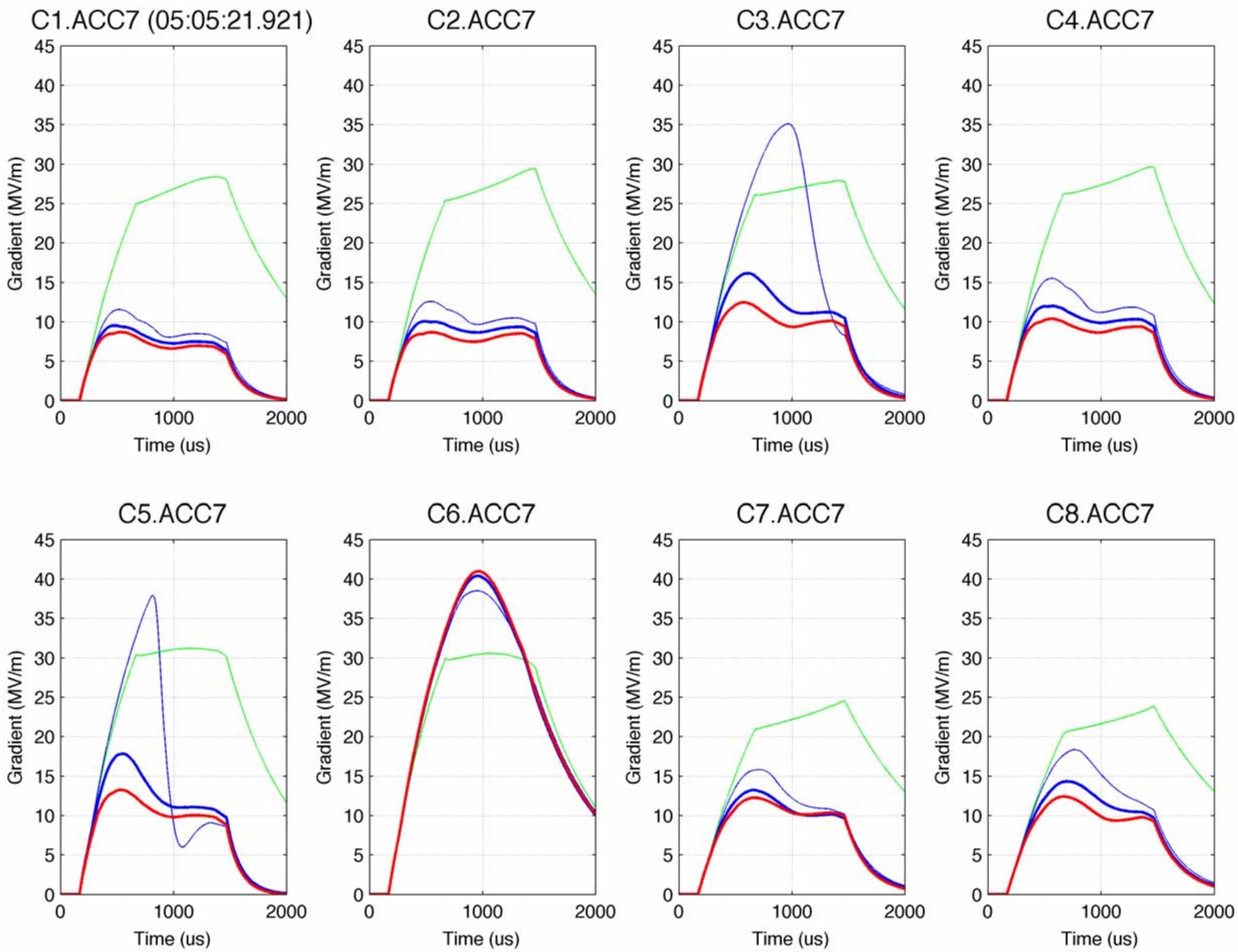
Red: this event, Blue: previous event, Green: nominal

Event #14427314: all cavities quenched, except C6



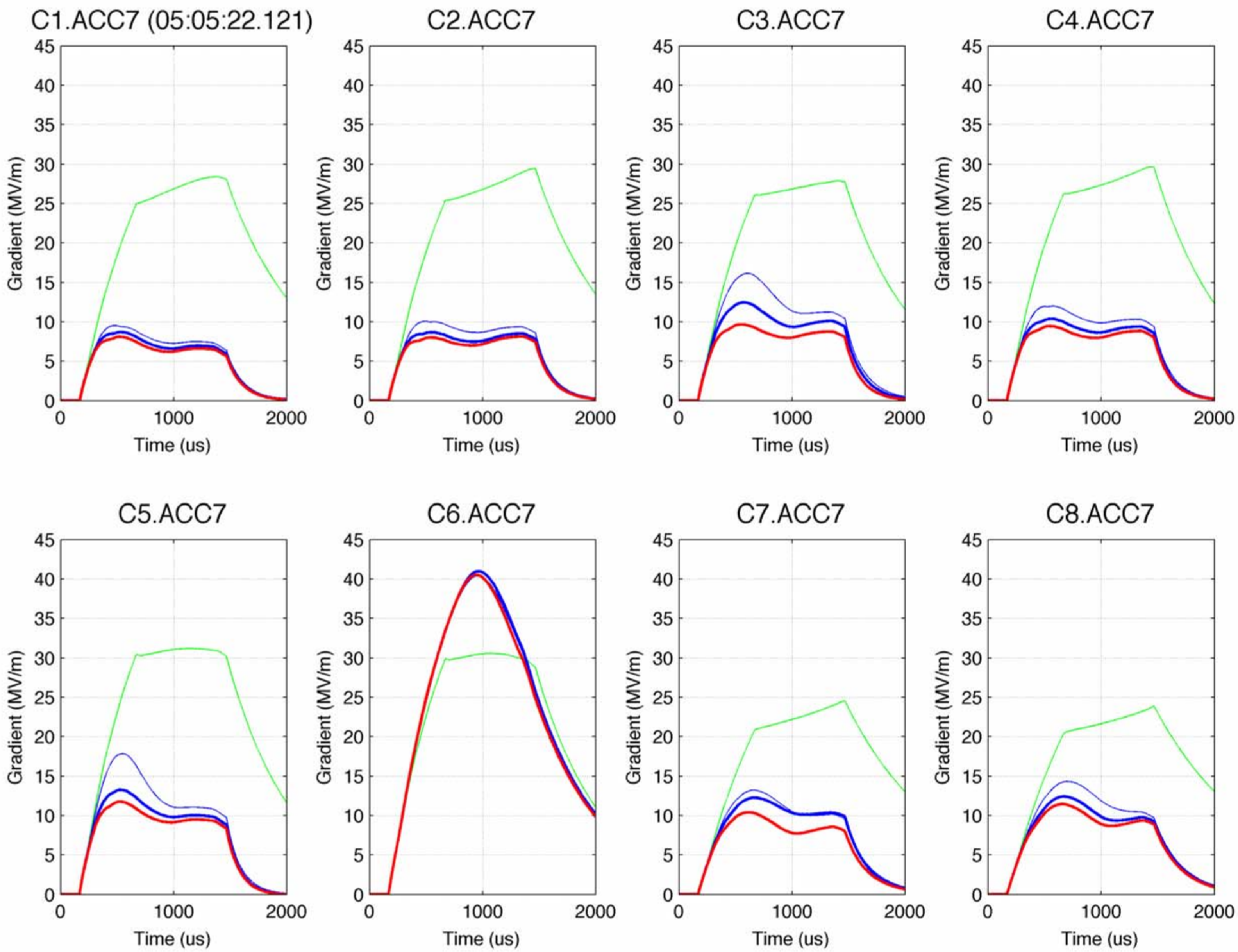
Red: this event, Blue: previous event, Green: nominal

Event #14427315



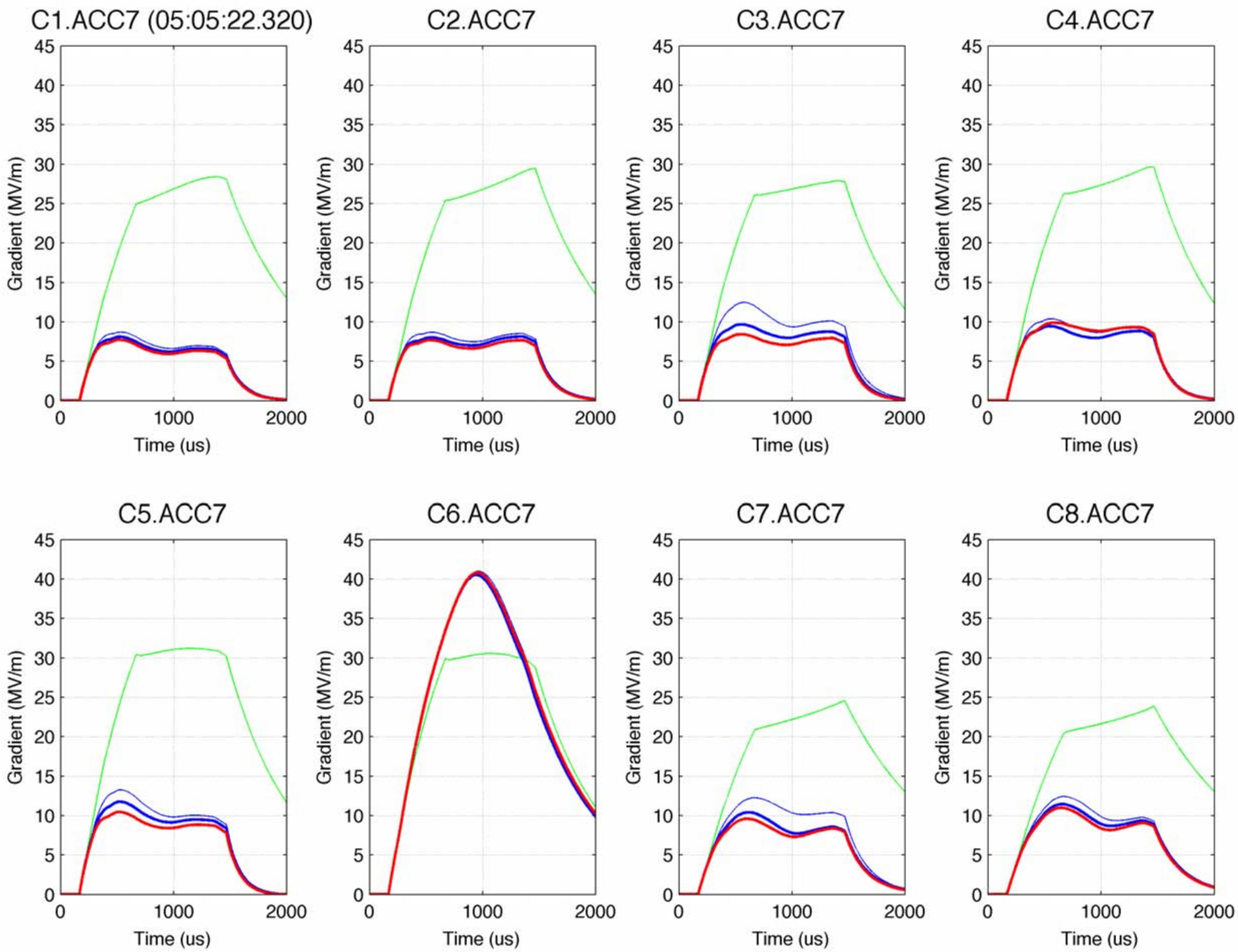
Red: this event, Blue: previous event, Green: nominal

Event #14427316



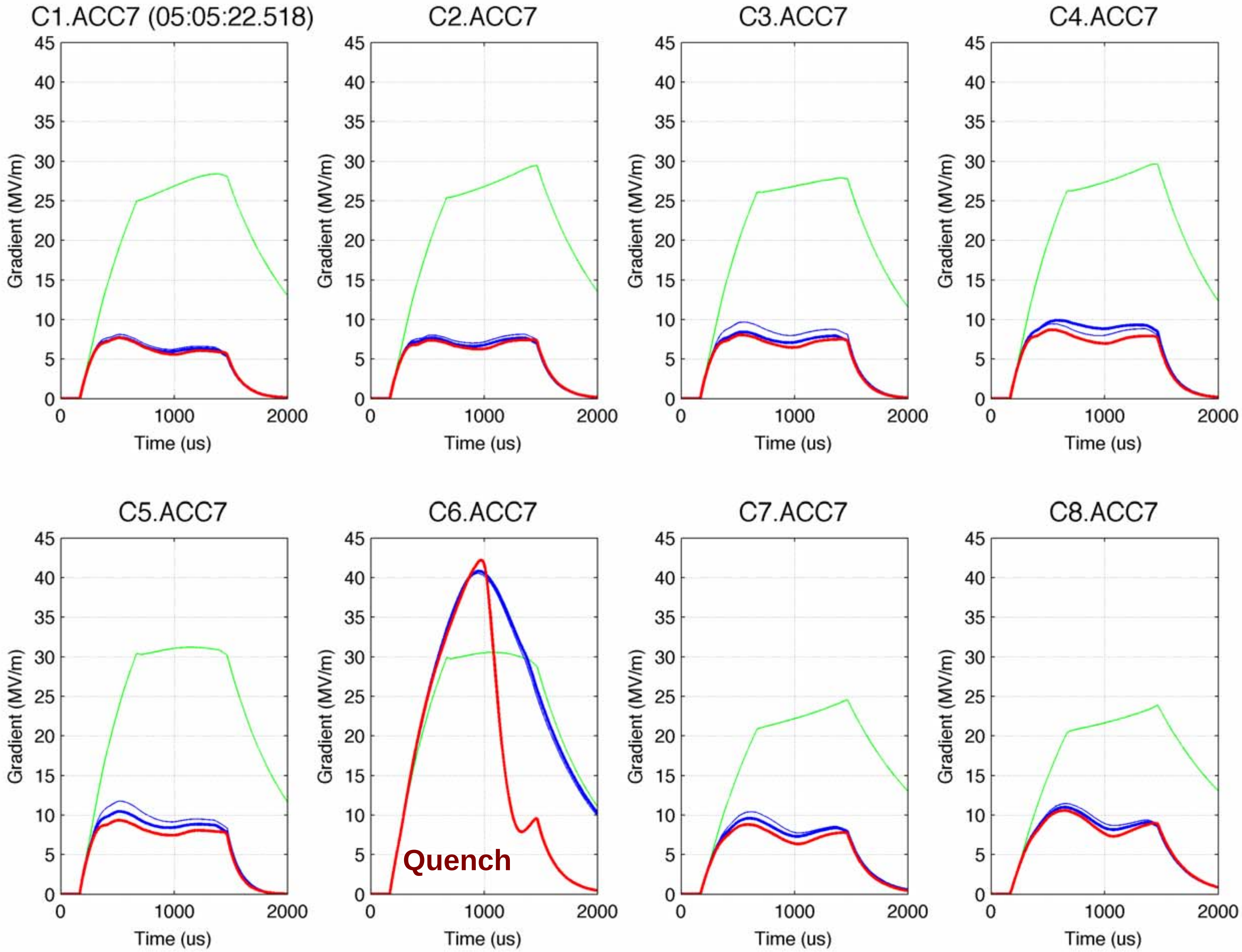
Red: this event, Blue: previous event, Green: nominal

Event #14427317



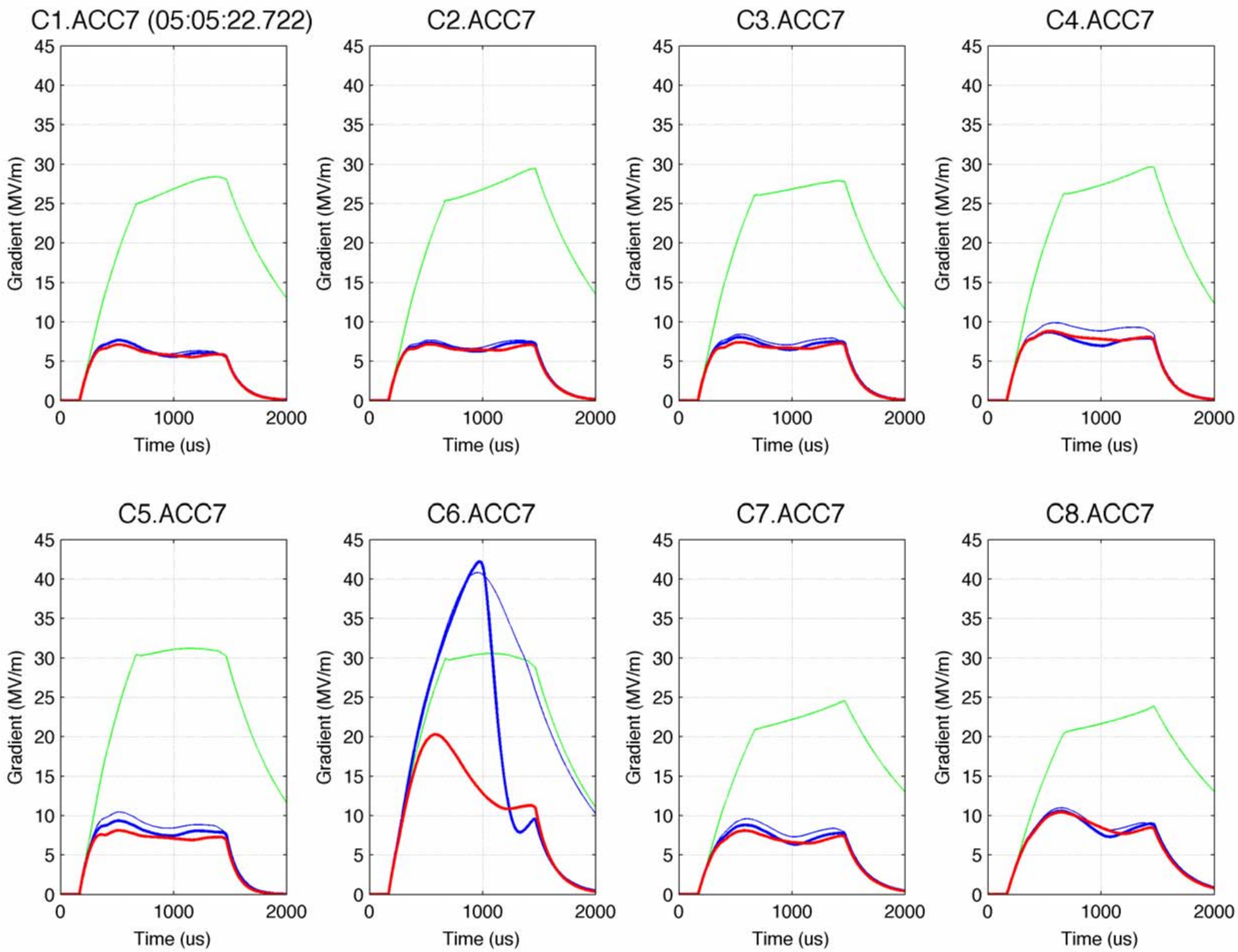
Red: this event, Blue: previous event, Green: nominal

Event #14427318: C6 finally quenches



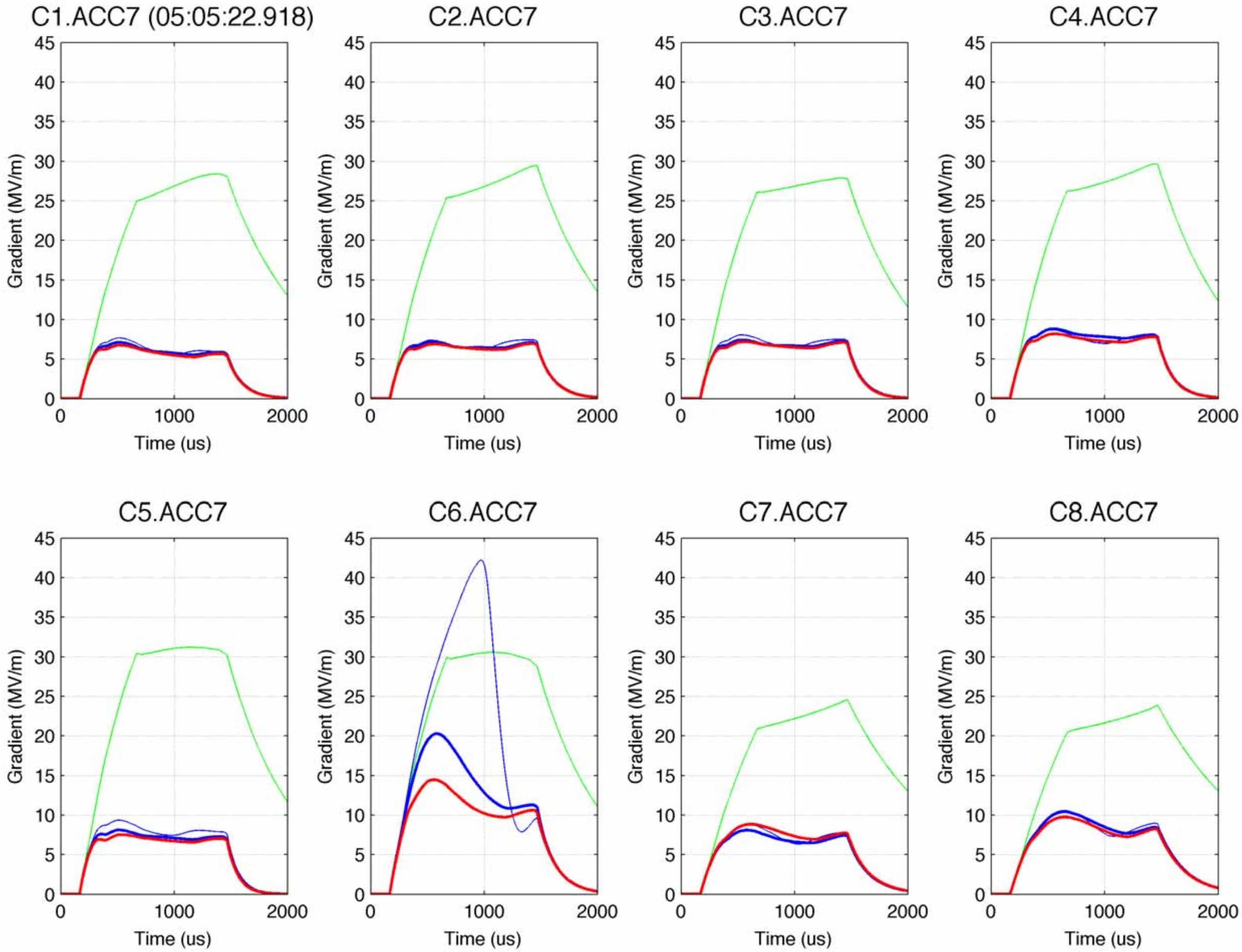
Red: this event, Blue: previous event, Green: nominal

Event #14427319: all cavities quenched



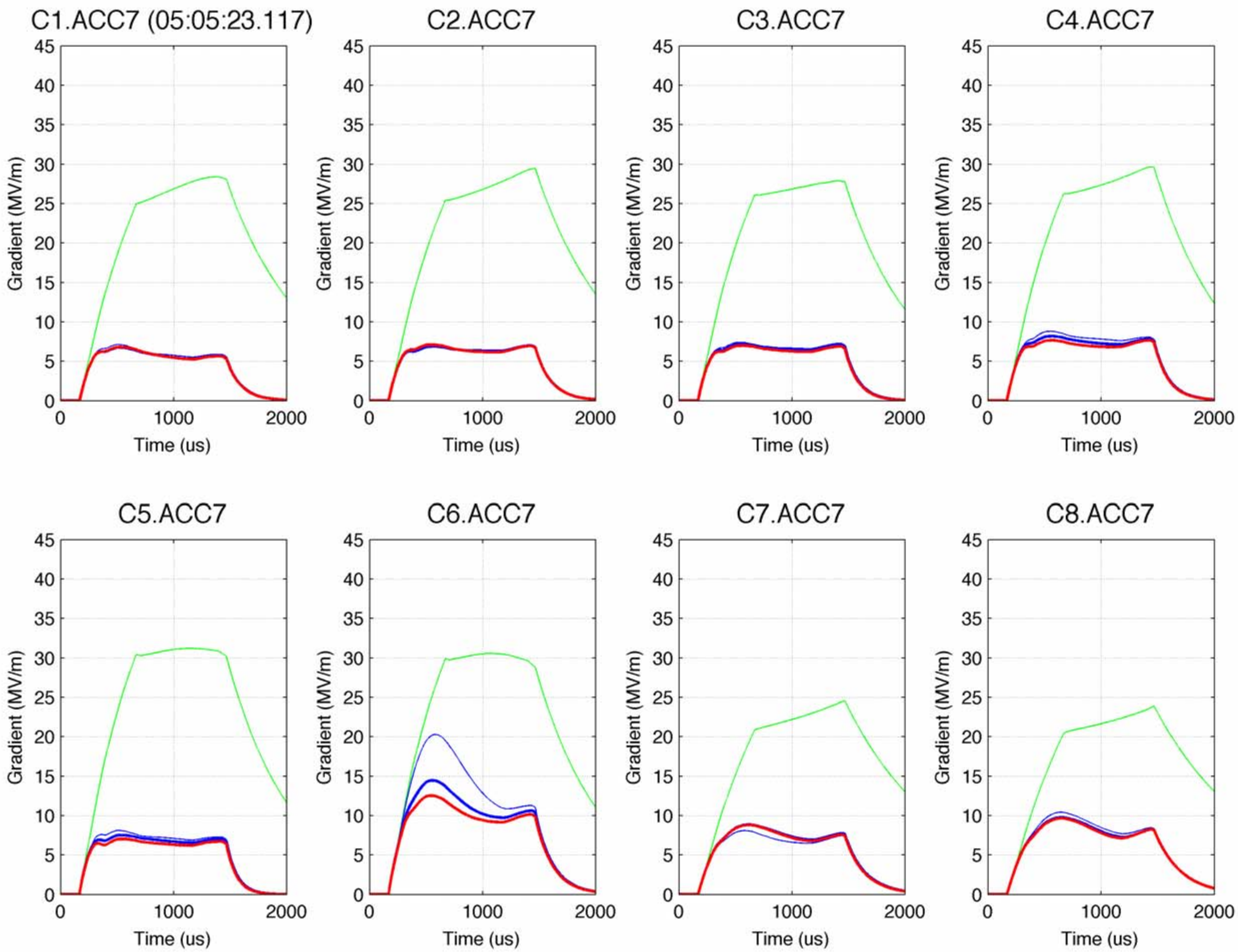
Red: this event, Blue: previous event, Green: nominal

Event #14427320: all cavities quenched



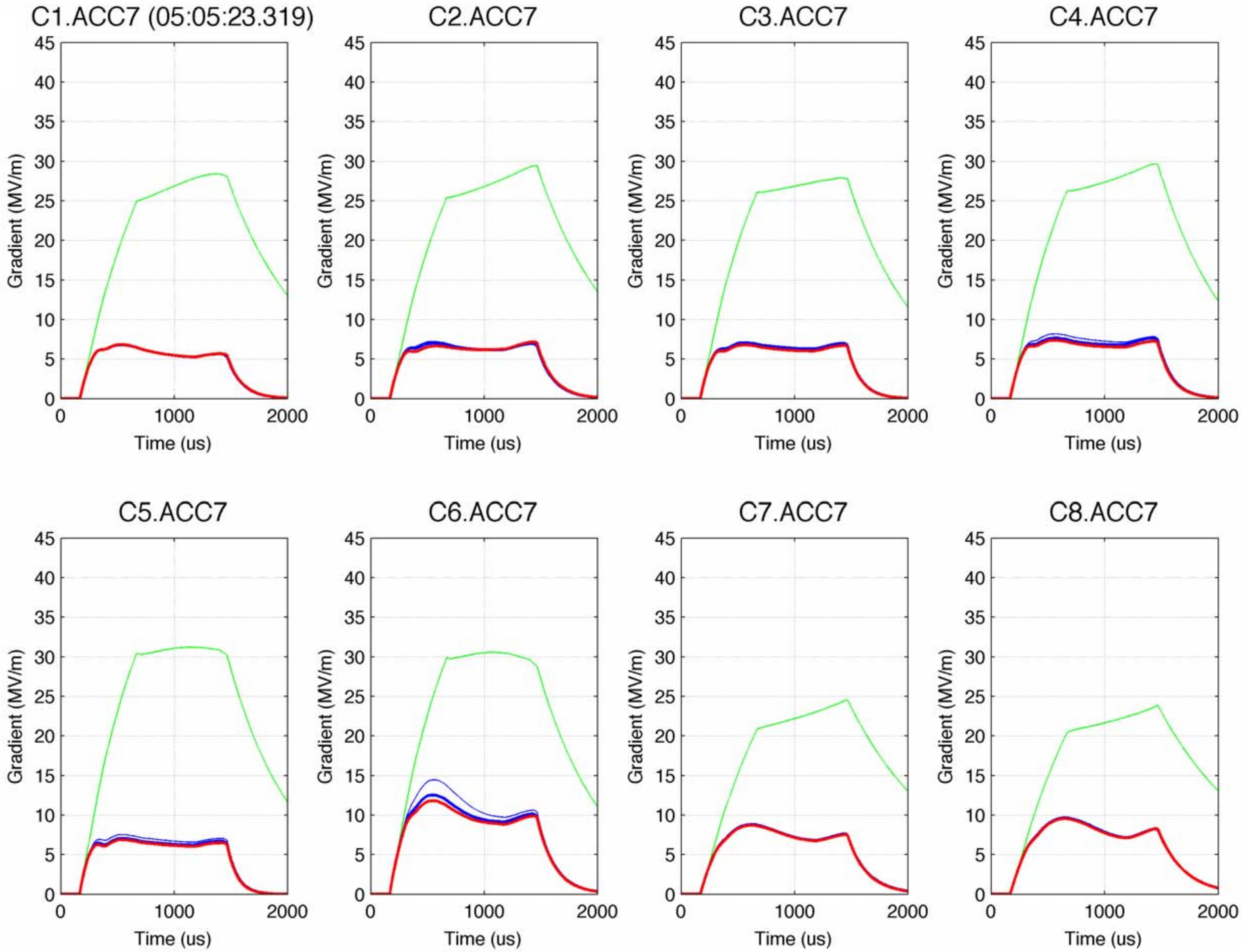
Red: this event, Blue: previous event, Green: nominal

Event #14427321: all cavities quenched



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

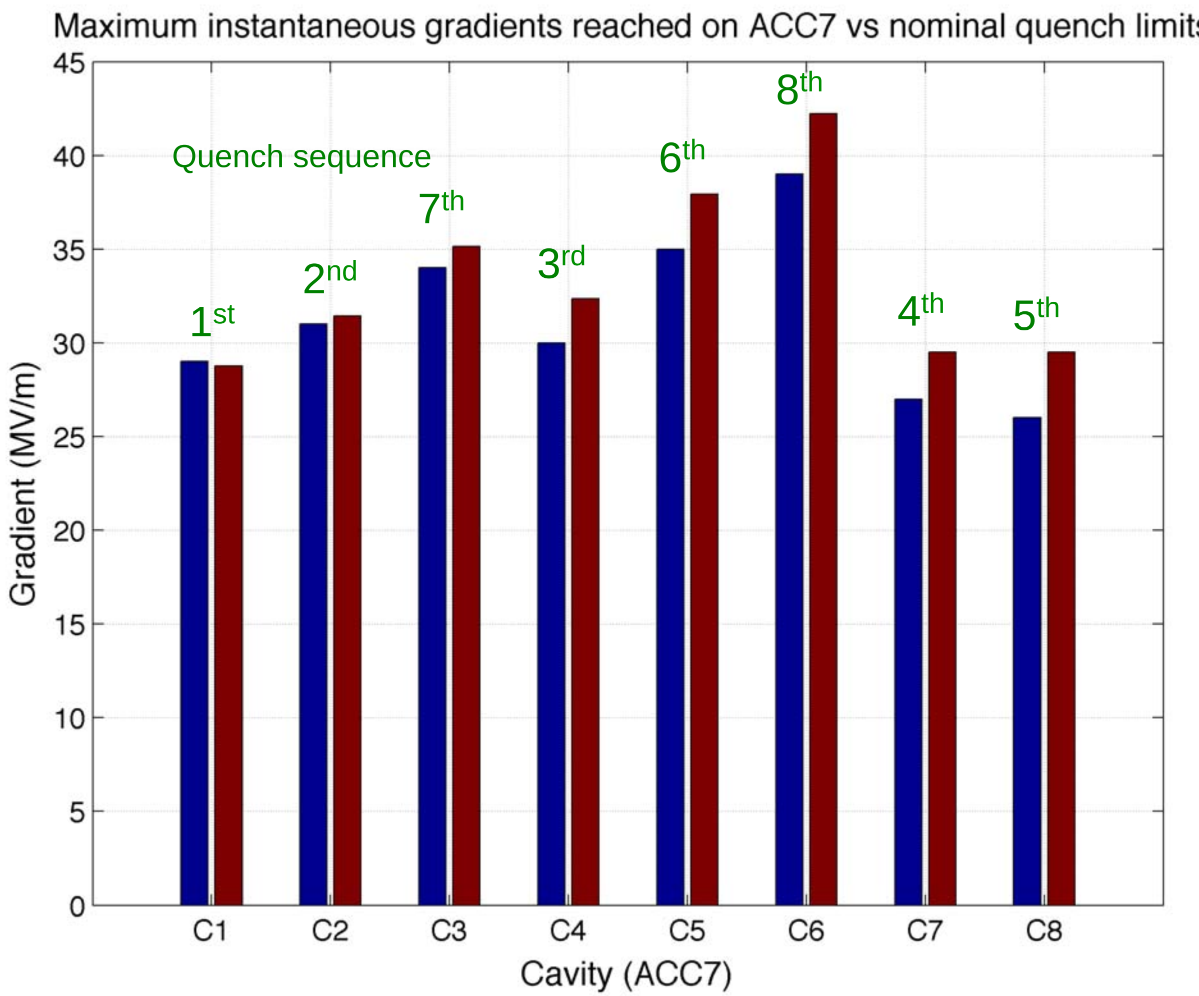
Event #14427322: all cavities quenched



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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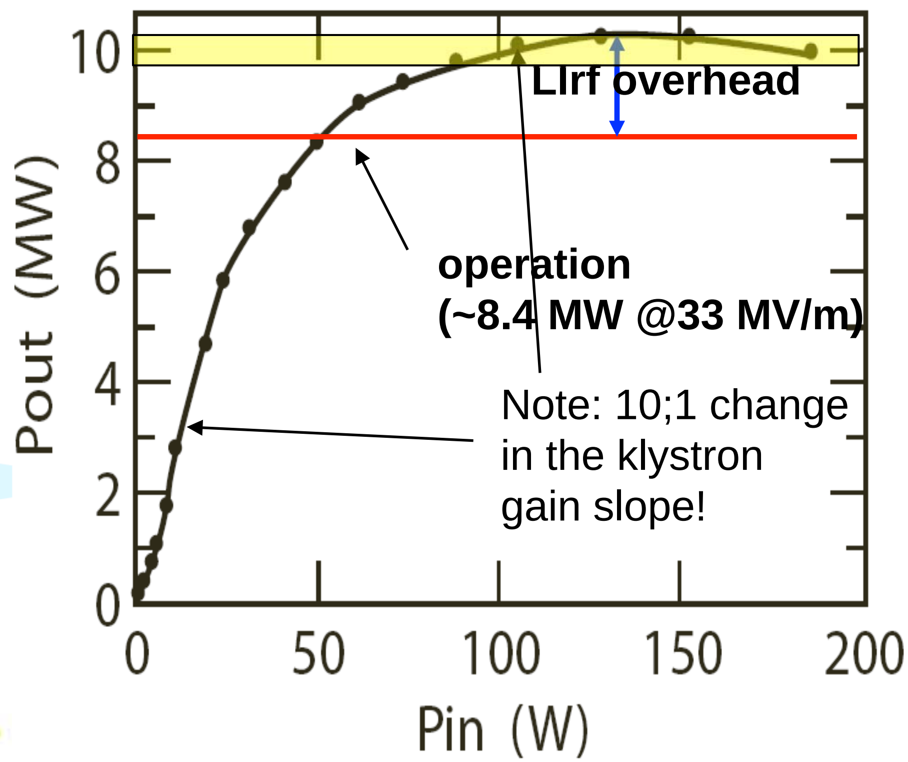
Llrf tuning overhead

- 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, …

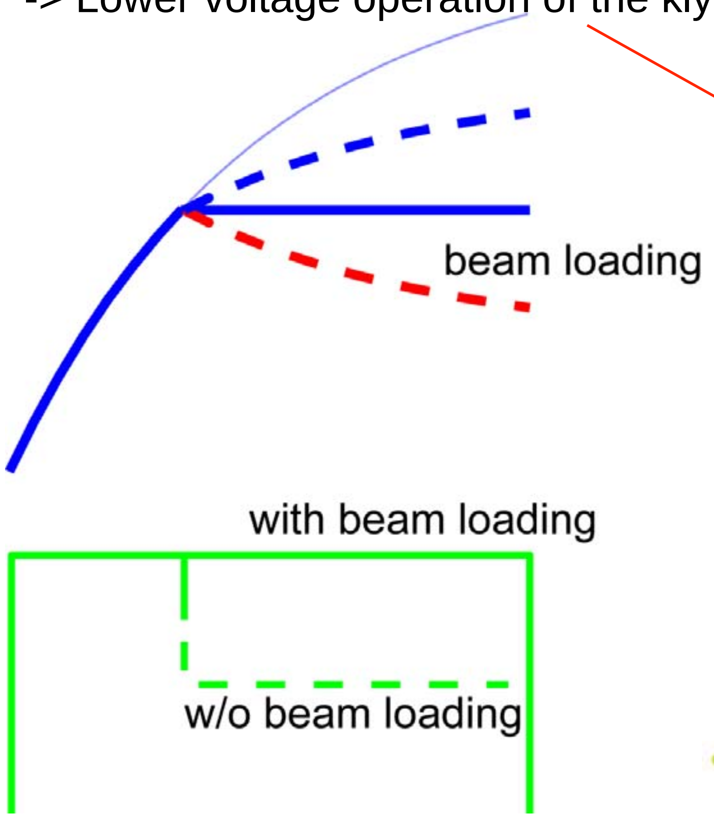
.E 2.6-2
nit parameters.

Parameter	Value	Units
Modulator overall efficiency	82.8	%
Maximum klystron 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

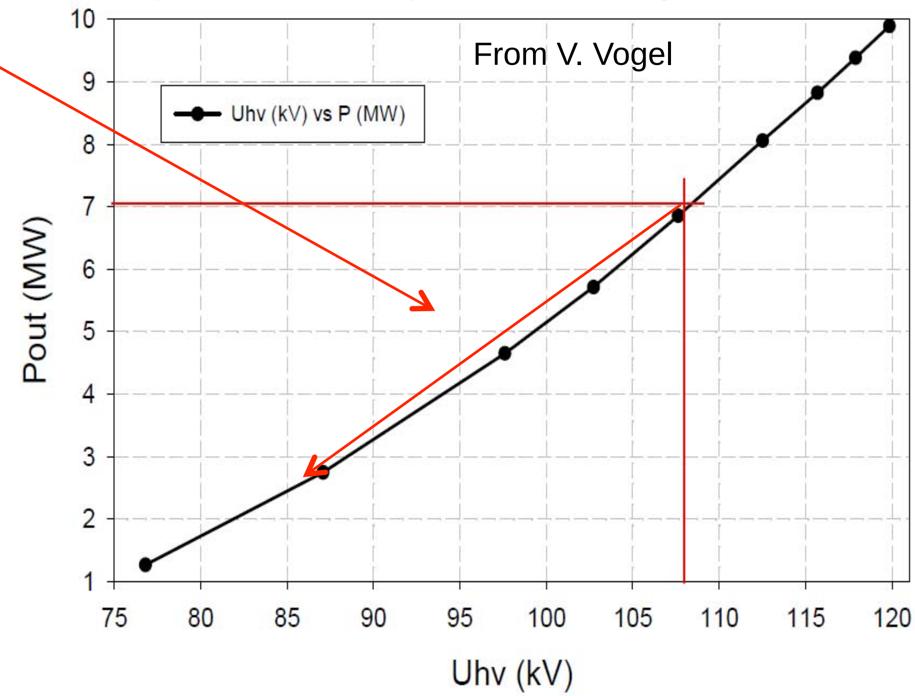


Preparation for RF overhead study

•Rectangular rf output (not “Step-like”) is required because the rf overhead should be examined at flat-top.
-> high current beam is desired.
-> filling time should be optimized.
• Near saturation operation is required.
-> Lower voltage operation of the klystron

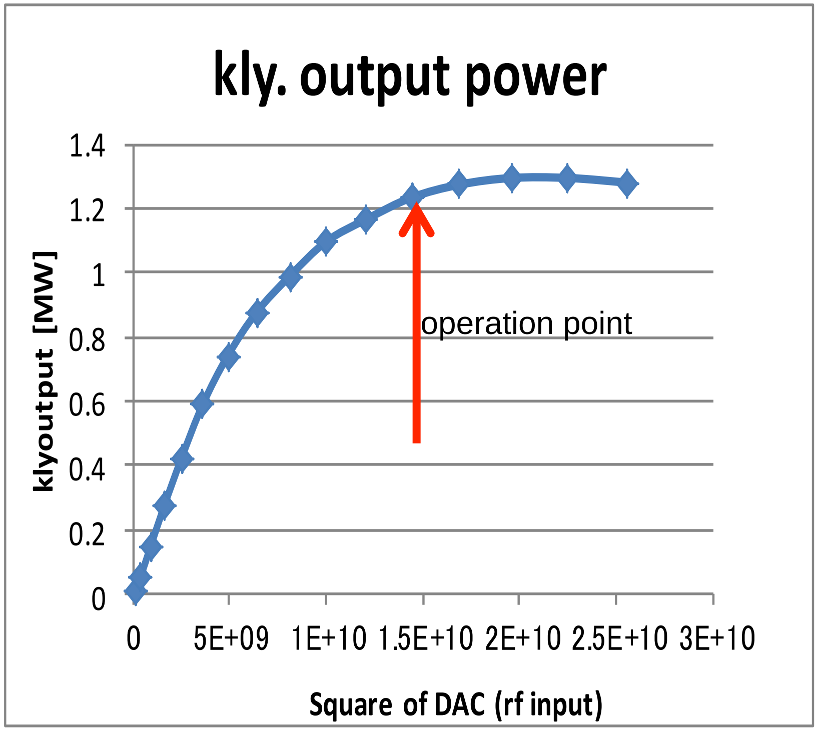


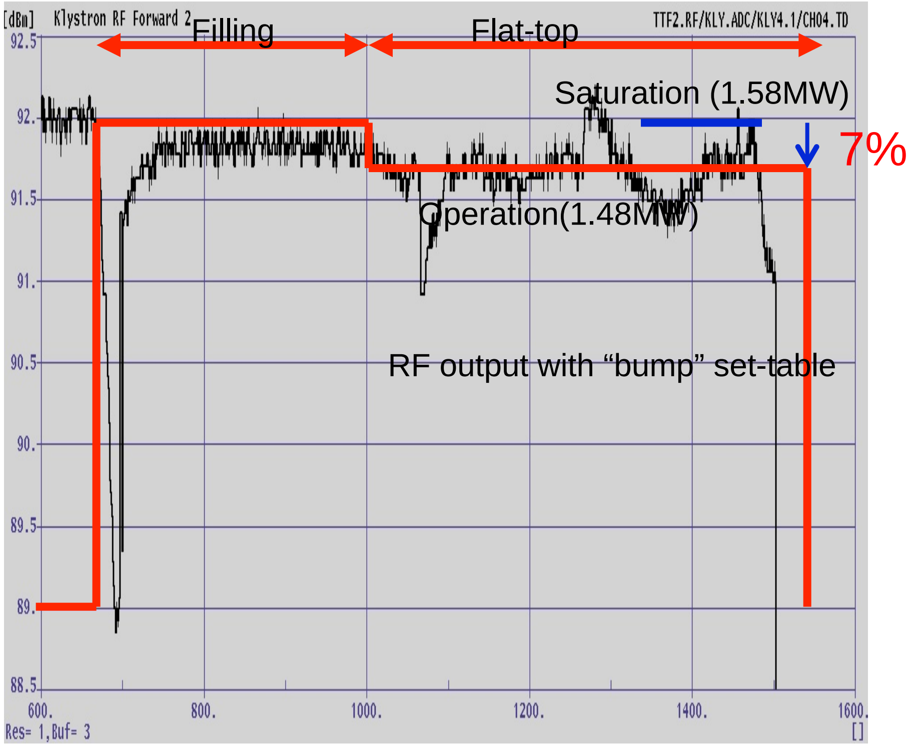
Klystron voltage v.s. rf output



RF operation condition

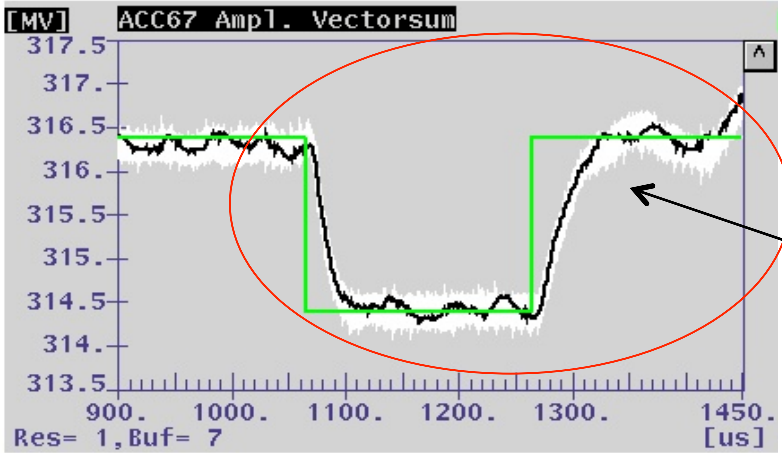
- HV of klystron was decreased from 108 kV to 86.5 kV.
- 4.5 mA beam was used.
- Filling time was adjusted to have ~rectangular output.(500us ->660us)
- Operation point is about -7% (in power) from saturation.



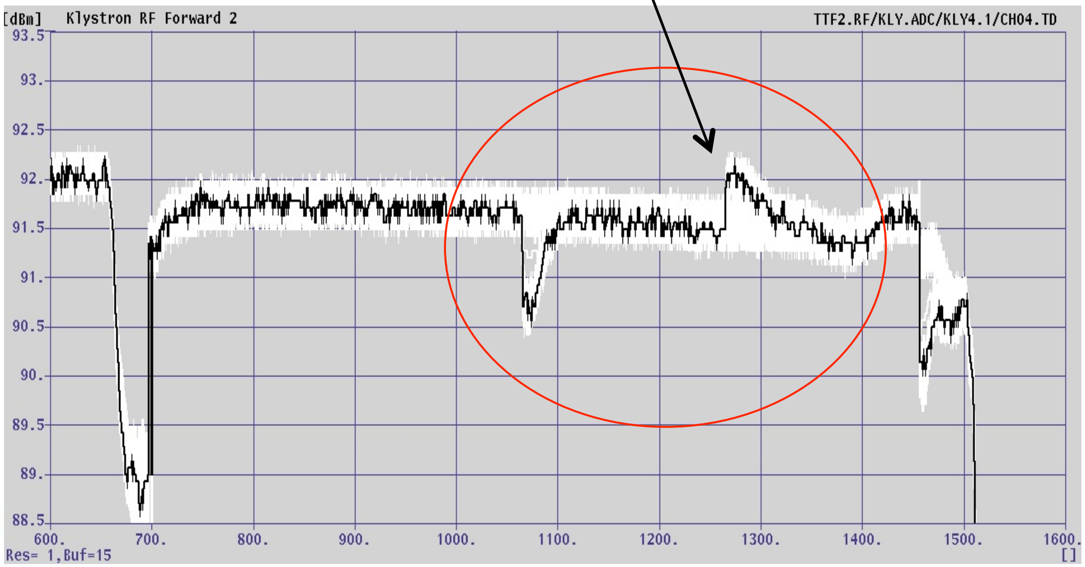


Klystron saturation: disturbance test

Notch applied to Vector Sum setpoint

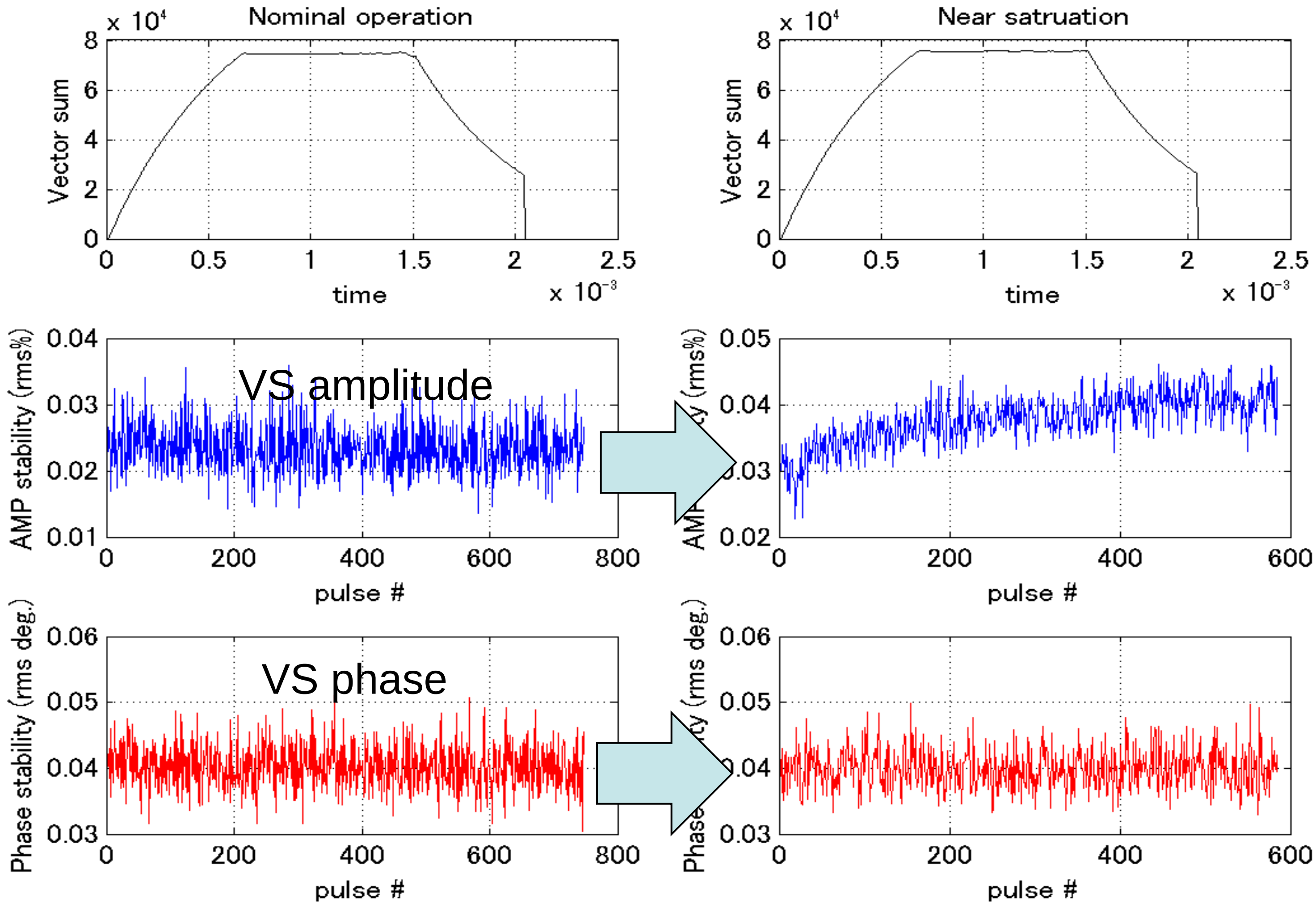


Forward power shows slower response on step up because the klystron cannot provide the power demanded due to saturation



Stabilities at nominal and near sat.

- Amplitude stability was worse twice at near sat. because of the limitation of rf.
- But 0.05%rms in amplitude can satisfy the requirements (~0.1% in amplitude)
- Phase stability was almost same between nominal and near saturation.



Timeframe: 02-26-2012 08:00:00 – 08:10:00

Timeframe: 02-26-2012 05:57:00 – 06:05:00

Klystron saturation study summary

- It was possible to operate near saturation (~7% below saturation).
  - Performance (amplitude and phase stabilities) satisfy the requirements

- Dynamic fluctuations can be compensated
  - Klystron HV fluctuation
  - Beam current fluctuation
  - Dynamic detuning (microphonics+ Lorentz force detuning) can be compensated.

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- **Long pulse operation close to gradient limits**
  - Quench prevention
  - Ramping pulse length with full current
  - Ramping beam current with full pulse length
- Wrap-up

Operating close to the limits: quench protection

Goal is to operate close to gradient limits, need to protect against quenching without causing frequent pulse terminations

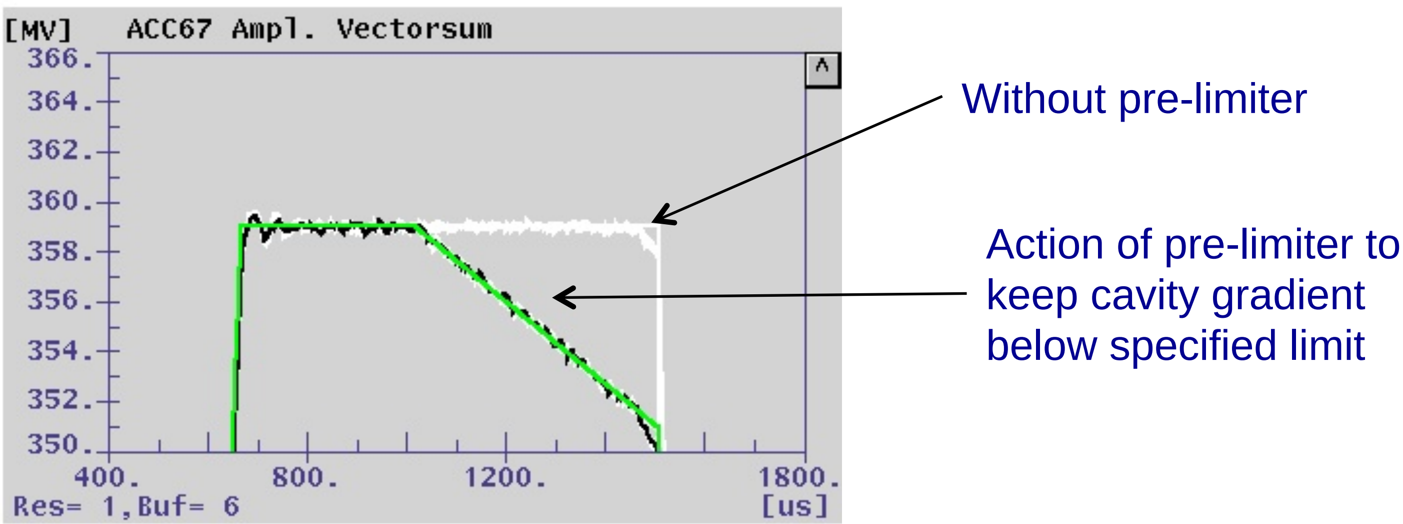
Three-pronged approach

1. **Quench detection (Quench Server)**
   - Look for sudden drop in Loaded-Q at end of rf pulse
   - Inhibit subsequent pulses
2. **Over-voltage protection during rf pulse (Gradient Limiter)**
   - Gradient Limit alarm threshold for each cavity
   - Terminate rf pulse as soon any cavity exceeds its threshold
3. **Over-voltage soft-limiter during rf pulse (Gradient ‘Pre-limiter’)**
   - Gradient Pre-limit threshold for each cavity
   - Dynamically ramp down the VS setpoint if any cavity reaches its threshold

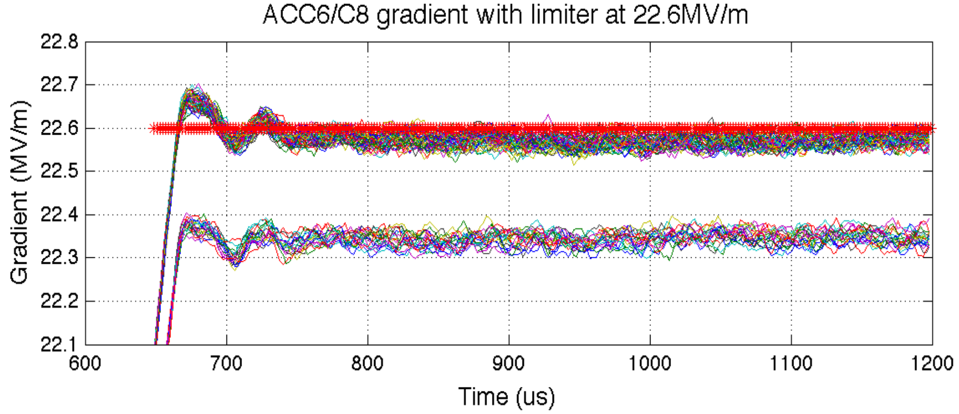
Gradient pre-limiter

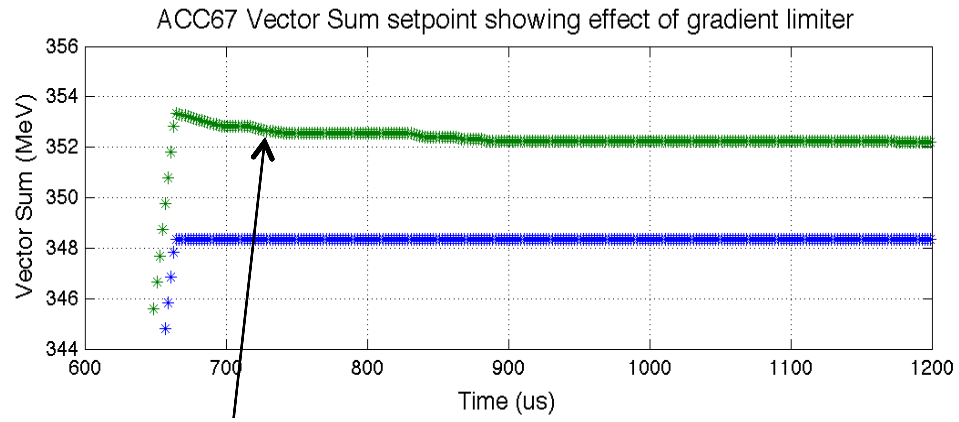
- Dynamically ramp down the VS setpoint if any cavity reaches its gradient ‘pre-limiter’ threshold
  - Implemented on ACC6 just before the start of the 9mA studies
  - It works beautifully!

Vector Sum setpoint and readback



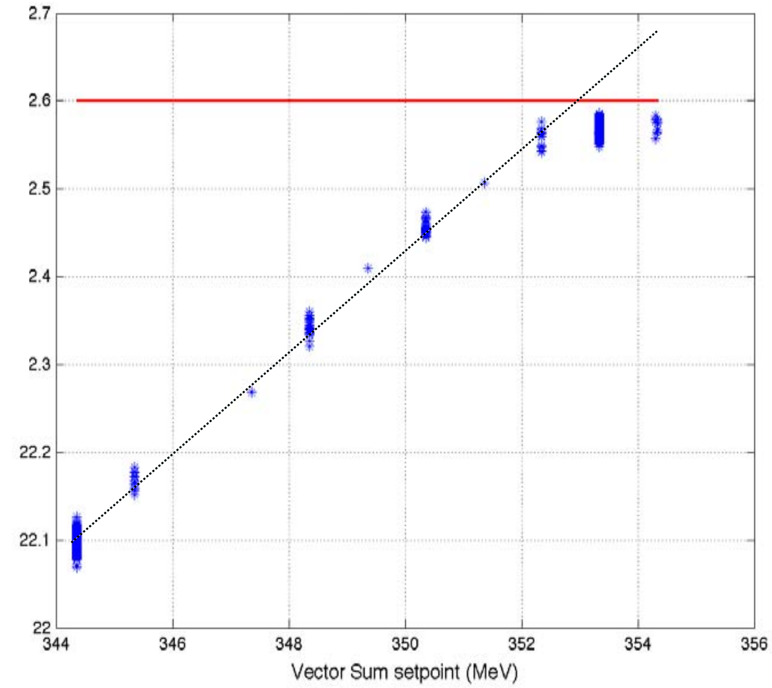
Gradient pre-limiter operation





Vector Sum setpoint is dynamically ramped down as long as any cavity gradient is above its pre-limit threshold

Limiter effect: ACC6/C8 Gradient vs Vector Sum setpoint



Analysis timeframe: 26-02-2012 17:00-17:02

Automated ramp-up to full current by extending length of bunch-train

How to ramp up from zero to full current/pulse length with gradients at their limits?

- Without quenching cavities

Option One: start with maximum current but short bunch train

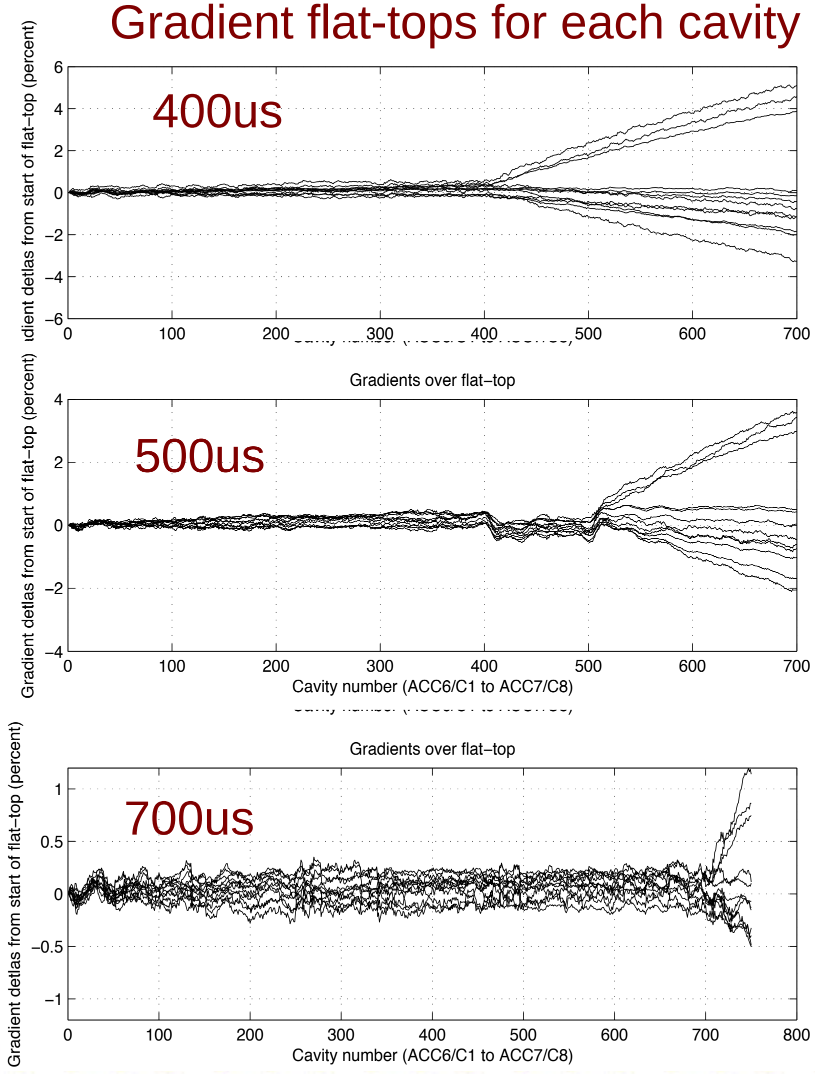
- Correct QLs to achieve flat gradients with short bunch train
- Progressively increase length of bunch train
- Ideally, there would be no corrections to QLs needed

Option Two: 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

Automated ramp-up to full current by extending length of bunch-train

Gradient flat-tops for each cavity



Study of Method One : start with maximum current but short bunch train

- Iterative algorithm used to correct gradient flat-tops with 400us bunch train
- Increased number of bunches in steps
- Minimal changes required to QLs when number of pulses was increased

- Used gradient pre-limiter to keep gradients below thresholds for beam off period – it worked beautifully!

Bottom line: Method One works!!

By the way, Method Two also works

- *Gradient Pre-limiter is the key*

Outline

- ILC context for the February 2012 studies
- Goals for February 2012
- Achieving flat gradients (‘Pk/Ql’ studies)
- Quench studies
- Klystron saturation studies
- Long pulse operation close to gradient limits
- **Wrap-up**

- **Studies highlights**
  - Operated full beam current within ~7% of klystron saturation
  - Flattened individual gradients to <<1% peak-peak and 4.5mA/800us operation within 5% of quench
  - ‘Crash test’: 800us/4.5mA -> beam off -> 800us/4.5mA
  - Ramped up current from ~zero to 4.5mA with ACC67 gradients approaching quench
  - Operated machine into quench with 800us / 4.5mA
  - ‘Cavity gradient limiter’ for dynamically preventing quench

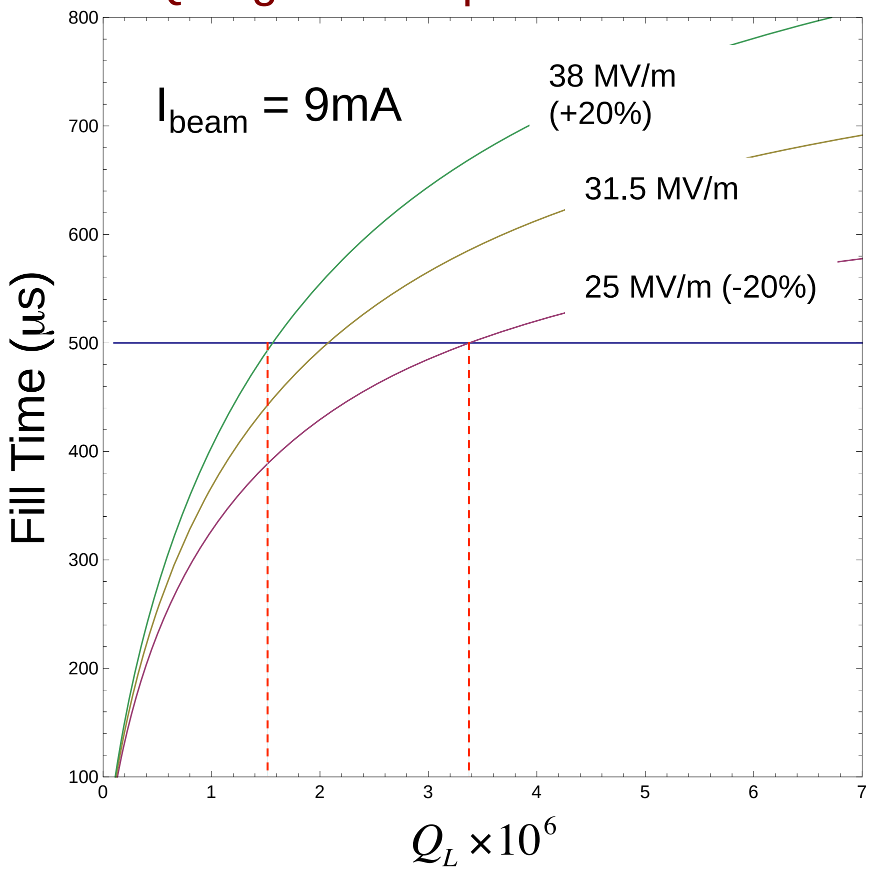
A few lessons

- **Lessons**
  - Loaded-Q server worked well - we also need some changes
  - Various servers and control functions fight each other during recovery (detuning, loaded-Q, gradient flattening,…)
  - Were able to recover, but also failed a few times because we did things in the wrong order

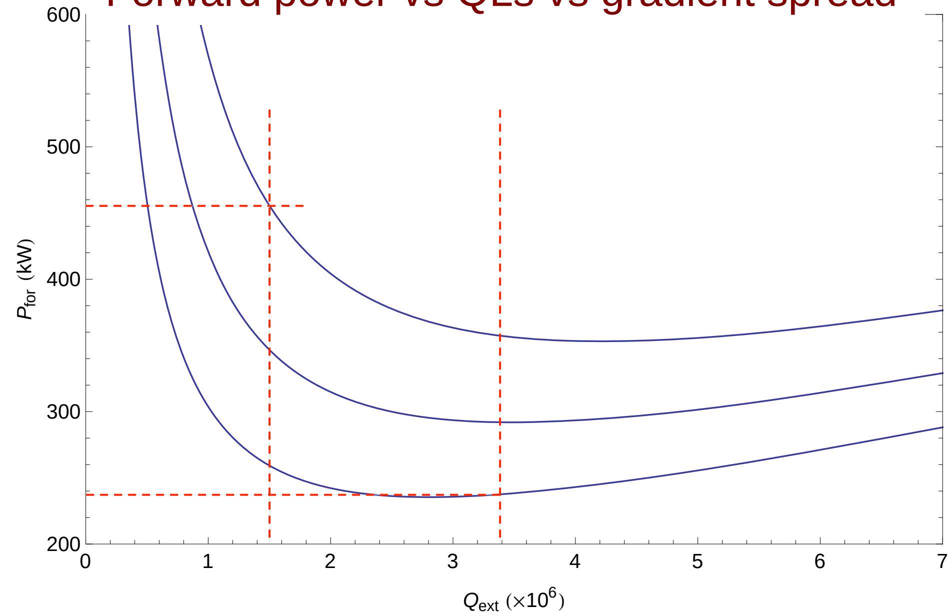
Thank you for your attention

Flat Voltage Solutions

QLs gradient spread vs fill-time



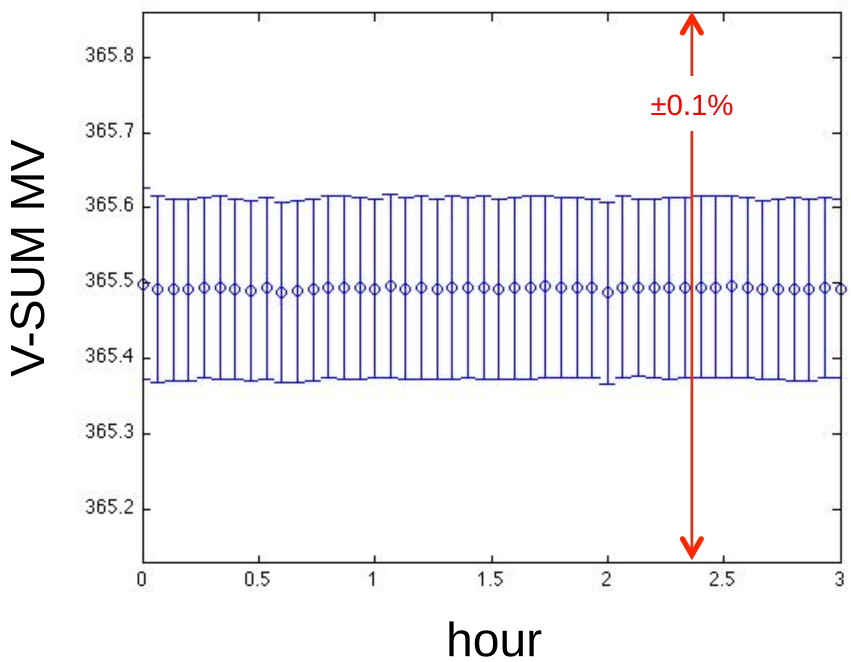
Forward power vs QLs vs gradient spread

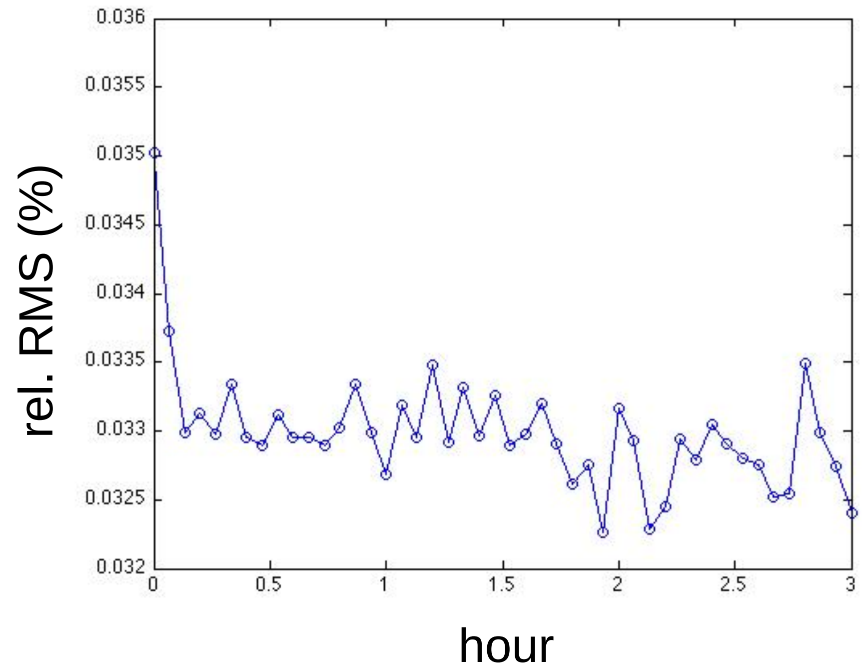


With full P_{for} – Q_L control solutions for different currents can be found

For FLASH, power distribution on ACC6-7 is fixed (no individual P_{for} control). However solutions can still be found for a limited range of currents (<6mA)

Vector sum stability





Same time period as cavity stability plots
100 pulses averaged per time step
error bar = ±1σ

Same data as LH plot.
rms / mean (over 100 pulses) in %

Quench limit study: limitations

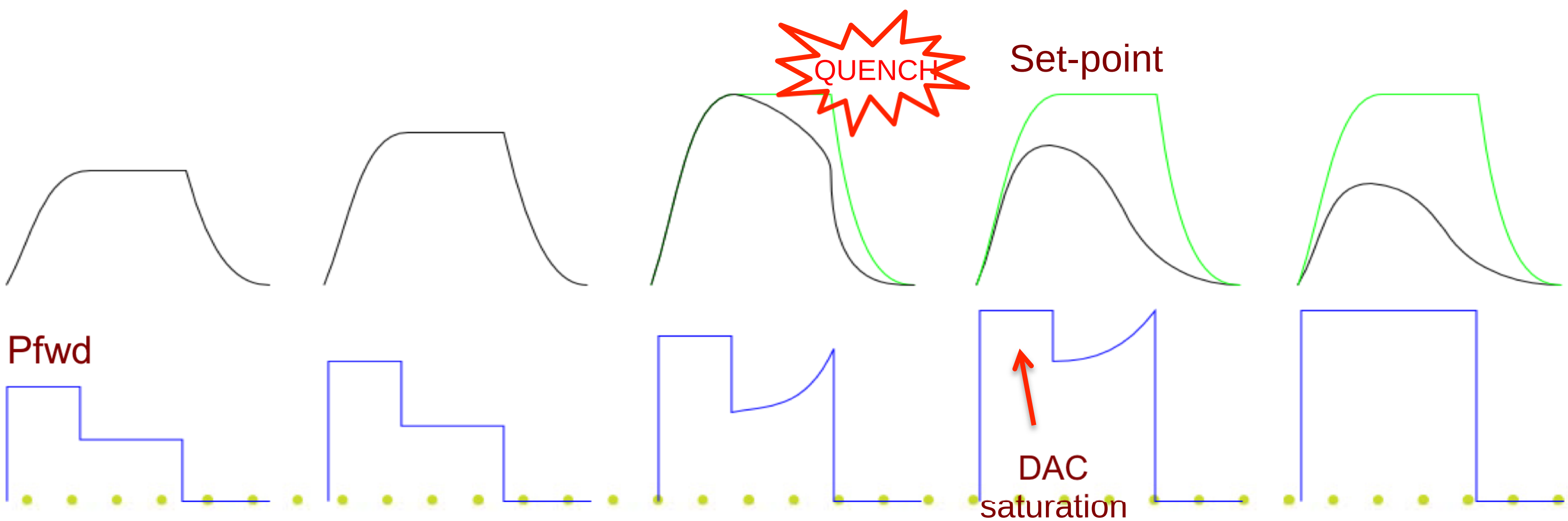
- **FF is scaled with set point for 16 cavities vector sum, while this approach uses 1 cavity vector sum**
  → extreme proportional gains are required, Kp = 1000

- **FLASH waveguide system is not conditioned for quenches**
  → nominal waveguide power is 5 MW
  → a high gradient cavity quench might require 7-8 MW
  → might generates coupler and waveguide sparks

Quench limit study: limitations

- FLASH LLRF system is not calibrated for quench threshold identification
  →DAC saturation, ADC saturation

- Running in FB around a single cavity can generate a maximum power request to the klystron
  →FB is useful to maintain flat gradient and compensate for LFD
  →if quench not detected immediately, LLRF request can be max klystron power for next pulse (should always be avoided)



Julien Branlard

Cryo flow during mombo quench event