Outline(3)

Machine Protection and Interlock Systems – Linear Machines

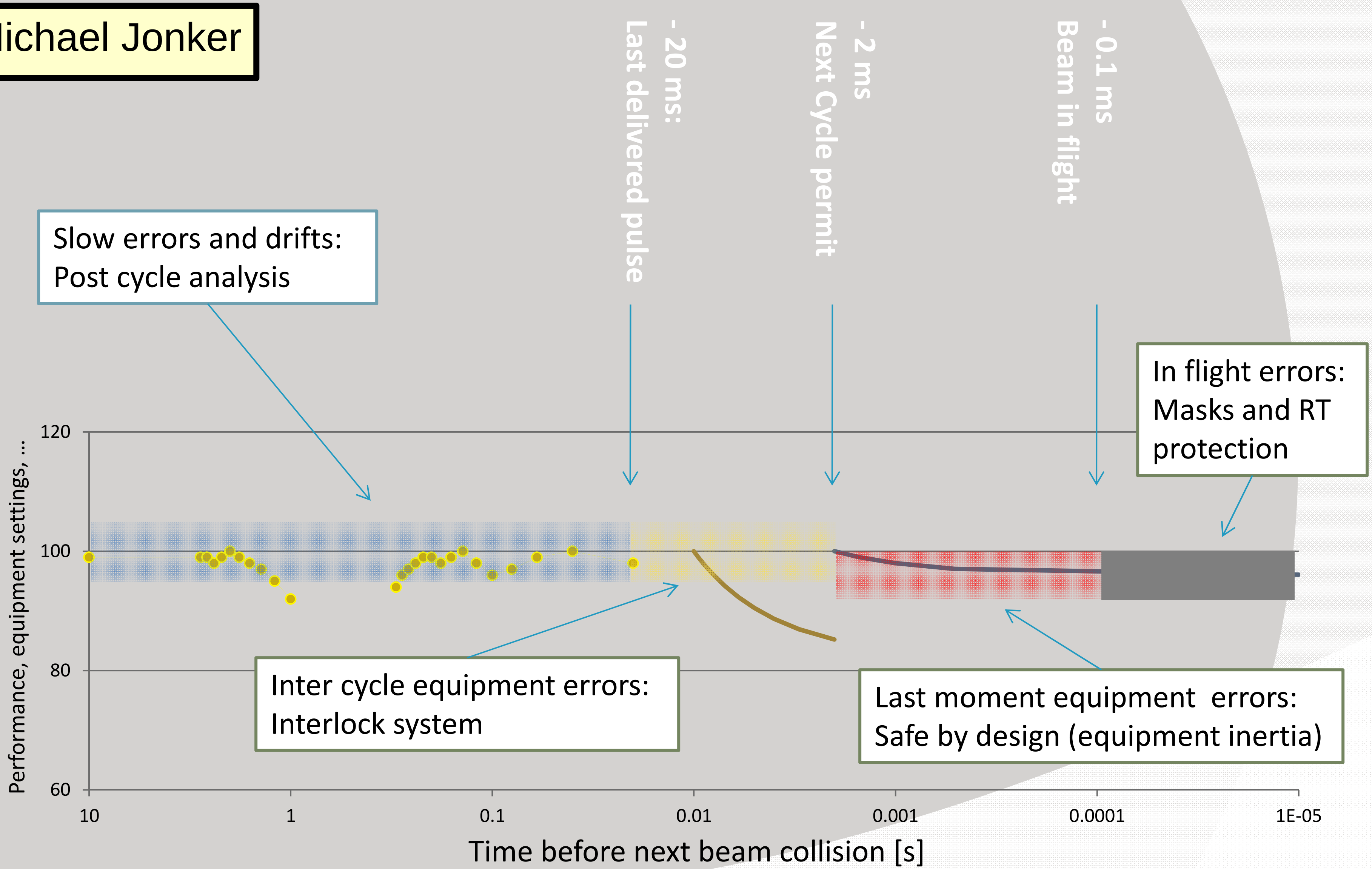
- **Linacs**
- **What protections are needed?**
- **Protection Systems:**
  - series of abort kickers and low power dumps,
  - a beam permit system / restart ramp sequence → operations
  - fault analysis recorder system,
  - a strategy for limiting the *rate-of-change* of magnetic fields and insertion device positions
  - a sequencing system that provides for the appropriate level of protection depending on machine mode or state
- **Recovery / Reliability- *Operations***

Linac Cycles:

- LCLS: CW 1 MHZ
  - Preferred; constant beam-surveillance
  - (But low power operation will be at much lower rates)
- SNS: 60 Hz with 1 ms macro pulses
- E-XFEL: 10 Hz with 1 ms macro pulse; ~10 MHz bunch-rate
  - Low power operation by reducing 10 MHz (factor 1e-4)
- ILC: 5 Hz with 1 ms macro pulse; 3 MHz bunch-rate
- CLIC: 100 Hz with 100 ns macro pulses; ~ 1GHz bunch-rate →

Machine Protection Timeline

Michael Jonker



Failure types and Protection strategies

Michael Jonker

Slow Failures

Time scale larger than the machine cycle period (10 ~ 20 ms) .

– Temperature drifts
– Alignment drifts
– Beam feedback saturations.

N.B.: Normally, the beam feedback system should keep drifts under control. Any deviation of the expected behaviour is potentially dangerous.

Inter-Cycle Failures

Time scale comparable to machine cycle period (10 ~ 20 ms).

– Power supply failures
– Positioning system failures
– Vacuum system failures

Last moment Equipment Failures

As above but to late for the Interlock system to react (< 2 ms).

Fast Failures

Time scale of beam flight time through the accelerator complex (*in flight < 0.2 ms*).

– RF breakdown: (transversal kicks...)
– Kicker misfiring: (damage to septum magnet).
– RF klystron trip. (disrupt beam, large losses)

N.B. the drive beam linac: 1.5 drive beam train in the pipeline: i.e. two orders above damage level.

Next Cycle Permit | **Safe by construction**

Post Cycle Analysis

Equipment Interlock | **Static Protection**

Next Cycle Permit

– Systematically **revoked after every cycle**
– **Re-established** if predefined beam and equipment **quality checks** have passed: ≈10 ~ 20 ms to analyse the previous cycle and to decide if OK for next cycle.

Static Protection

In flight failures:

– Difficult to detect beam failures and dump the misbehaving beam.
– Impossible for the head of the beam (causality, speed of light).

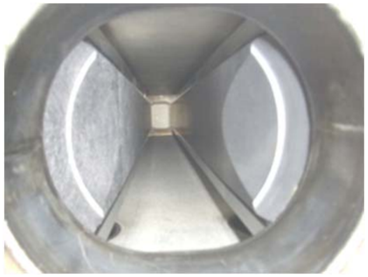
Passive protection: masks and spoilers.

Make passive protection robust enough to provide full protection for the whole pulse.

Many of the systems are already designed along this principle.

Locations (mostly associated with kickers)

- Extraction channels damping ring
- Extraction from combiner rings
- Drive Beam turn around



Protective masks. (Picture of an LHC Collimator)

4 ... minal).

Decision time: 2 ms before next pulse

Protection/Interlock Systems:

- series of abort kickers and low power dumps,
- a beam permit system / restart ramp sequence → operations
- fault analysis recorder system,
- a strategy for limiting the *rate-of-change* of magnetic fields and insertion device positions
- a sequencing system that provides for the appropriate level of protection depending on machine mode or state

The MPS interlocks consists of:

1) a single bunch damage mitigation system,
2) an average beam loss limiting system,
3) a series of abort kickers and low power dumps,
4) a restart ramp sequence,
5) a beam permit system,
6) a fault analysis recorder system,
7) a strategy for limiting the rate with which magnetic fields (and insert-able device positions) can change,
8) a sequencing system that provides for the appropriate level of protection depending on machine mode or state, and
9) a protection collimator system.

Rapidly changing fields / devices – Slew rate limits and locks

- Some critical devices have fields (or positions) that can change *quickly*
  - during the pulse, or between pulses.
- Need:
  - 1) special controls protocols,
  - 2) redundancy or
  - 3) external stabilization and verification systems.
- *Depending on the state* of the machine
  - programmed (perhaps at a very low level) ramp rate limits
- Example: dipole magnet is not allowed to change its kick by more than a small fraction of the aperture between beam pulses
  - (full power operation)
- (may have an impact on the speed of beam based feedback)
- Some devices, such as collimators should be effectively frozen in position at the highest beam power level

Michael Jonker

Fast Failures

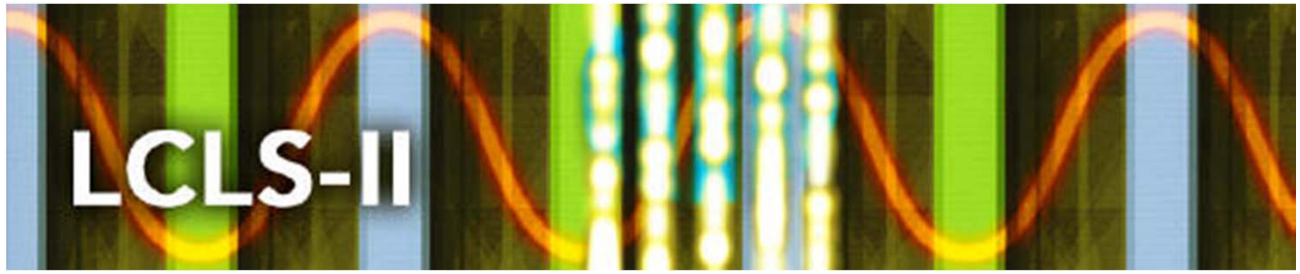
Critical, high power, high speed devices will need some level of redundancy in order to reduce the consequence of failure. For example the bunch compressor RF will have more than one klystron / modulator system powering a given cavity through a tee.

- RF breakdown. An RF breakdown could potentially produce enough transversal kick to send the drive beam or the main beam off trajectory into some accelerator component.
- Kicker misfiring. A misfiring of a kicker can send the beam off trajectory into the extraction channel (most critical element: the septum magnet).

In the case of the extraction kicker, this will be done by having a sequence of independent power supplies and stripline magnets that have minimal common mode failure mechanisms.

Common mode failures

- **Timing and phase distribution system need specially engineered controls.**
- **Linac common phase cannot change drastically compared to some previously defined reference,**
  - even if commanded to do so by the controls, unless the system is in the benign – beam tune up mode.



Machine Protection and Operation – Linear Machines

Machine Protection and Operation – Linear Machines
Marc Ross

Case-Study:

- **SLAC Linear Collider (SLC) operated from 1987 to 1998**
- **Topics:**
  - Source intensity instability
  - Damping Ring bunch lengthening and instability
  - Linac / collimator instability ‘amplification’

SLC Parameters

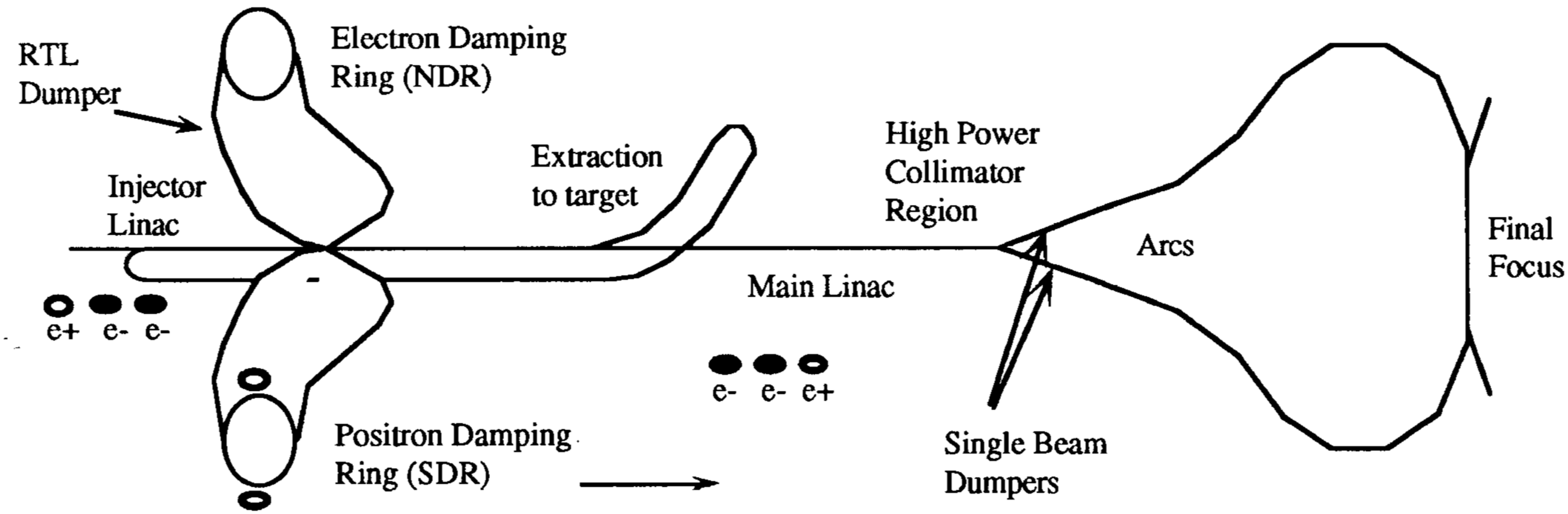
E_cm	92 GeV	Z_0 resonance
n_b +/-	3-4e10	At collision point; source intensities much higher
f_rep	120 Hz	MPS rate limit to either 10 or 1 Hz
P_beam	35 kW	single bunch, full energy
sig_x/y	100/10	microns at the end of the linac
sig_z	1 mm	
Lumi	3e30	

Parameter 'performance' Summary

Table 1: Design and achieved SLC beam parameters

	Design	Achieved	Units
Beam charge	7.2e10	4.2e10	$e^{\pm}$/bunch
Rep. rate	180	120	Hz
DR ε_x	3.0e-5	3.0e-5	m rad
DR ε_y	3.0e-5	3.0e-6	m rad
FF ε_x	4.2e-5	5.5e-5	m rad
FF ε_y	4.2e-5	1.0e-5	m rad
IP σ_x	1.65	1.4	µm
IP σ_y	1.65	0.7	µm
Pinch factor	220%	220%	Hd
Luminosity	6e30	3e30	$cm^{-2}sec^{-1}$

e+ / e- bunches in SLC

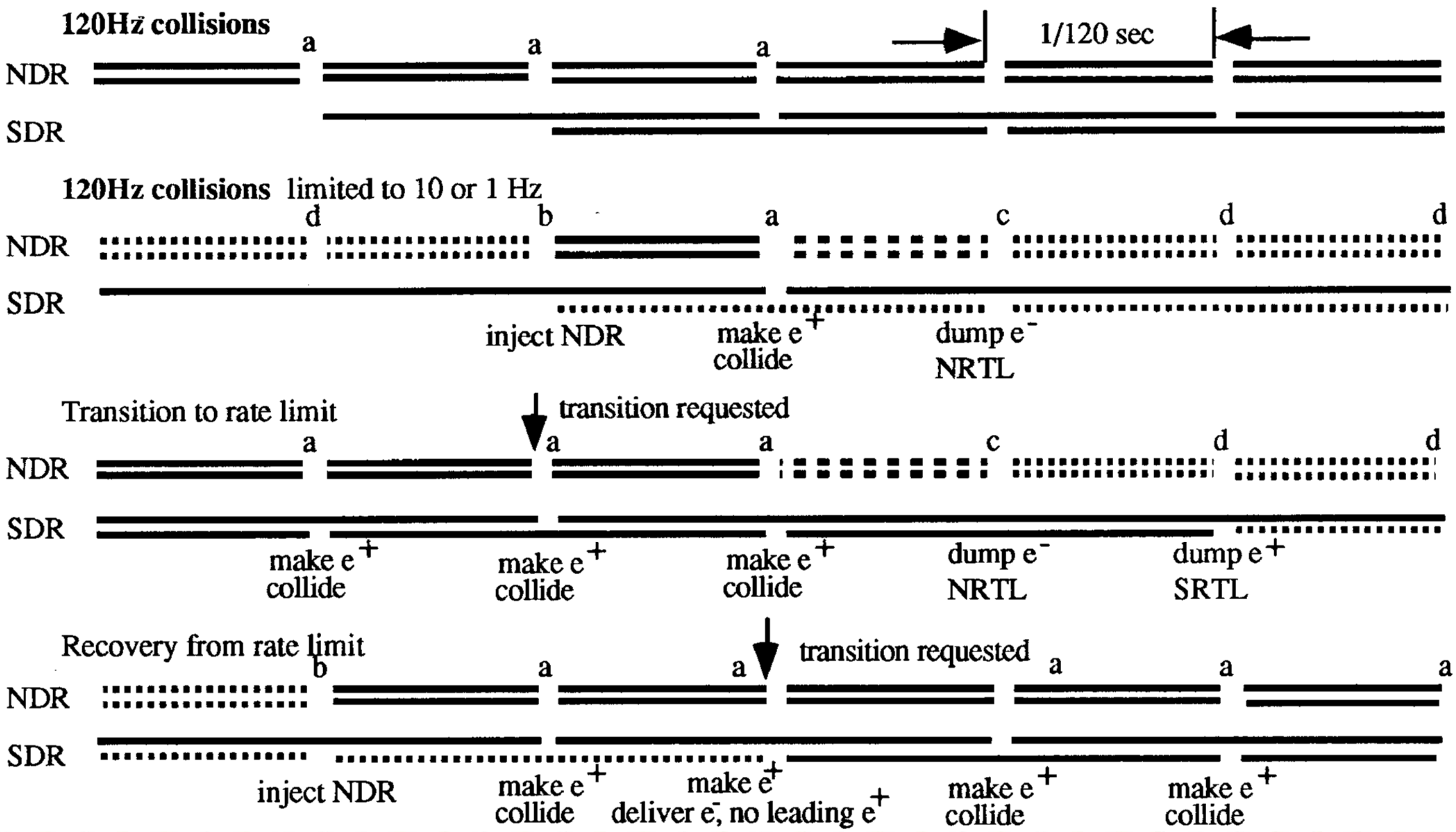


- e+ are both delivered and generated on a given pulse
- e+ from pulse *n* will collide on pulse *n*+2
- extraction line, high power collimators (linac end), arc and beam delivery entrance are critical locations

Limiting beam power

- **Assumption: Damage is less likely when all systems are functioning properly**
  - (marginal for beam-defining devices – collimators)
- **sometimes 'errant beam detector' (EBD) will indicate problem even when all systems seem to function properly**
  - (→beam dynamics← this case-study)
- **low power copy of the nominal beam may be required to allow study / testing mitigations**
- **transition between low / nominal power must be 'perfect'**
- **At SLC – low power copy was made by lowering the repetition rate**
  - (average power the main concern - rather than single pulse damage)
- **vicious circle or 'Catch-22' can easily happen**

Damping Ring in transition

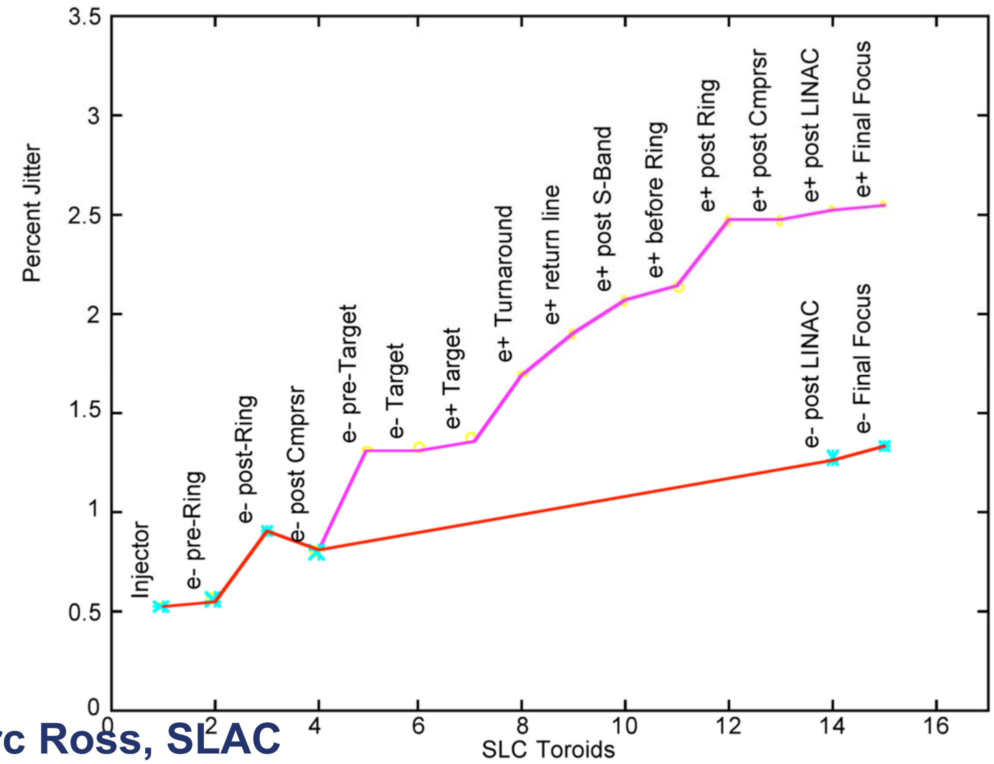


Intensity jitter

- **jitter ≡ pulse-to-pulse stability of the machine**
  - intensity, energy and trajectory jitter
  - collimation, collimator-wakes, ring beam dynamics, linac long-range wakes couple all three tightly

- **e+ and e- intensity jitter**

sig_I/I for ~ 100 pulses (full rate – 1 sec) vs position in entire complex



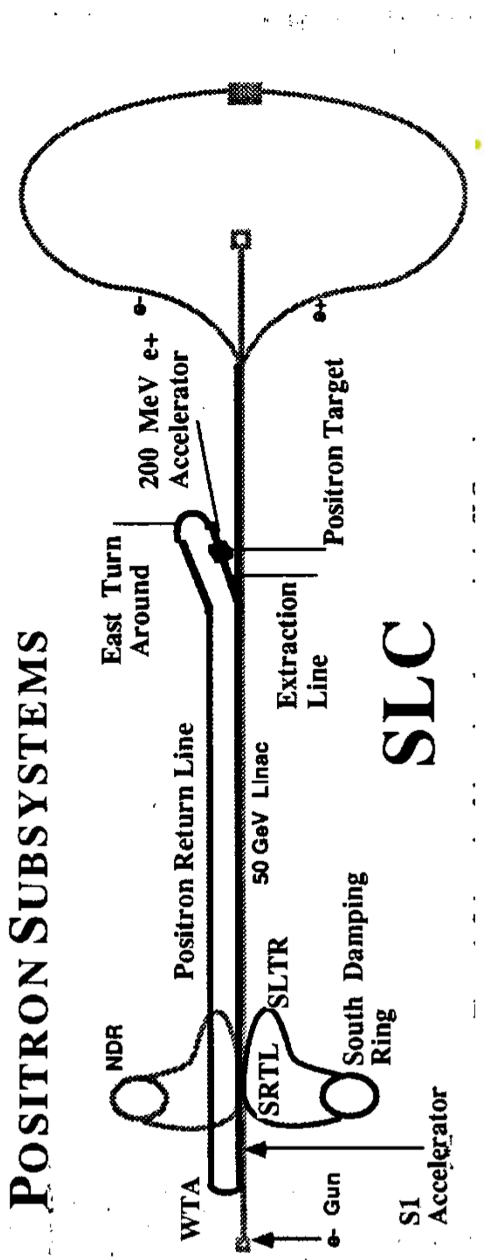
e+ jitter grows 3x (losses!)
e- jitter grows 1.5x
e- (target) 1.5x

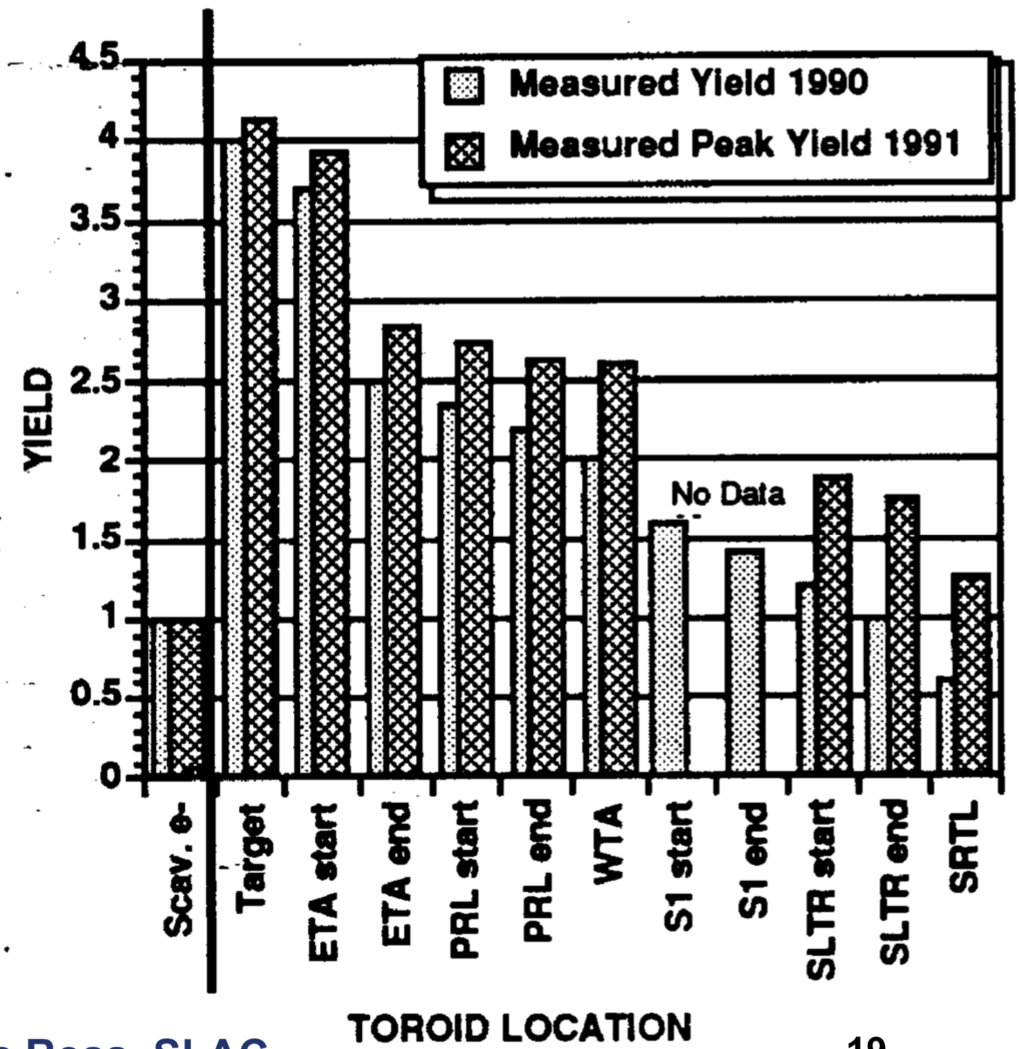
Marc Ross, SLAC

SLC Positron Source

E_targ	30 GeV	2/3 point 47 GeV linac
n_b +	8e10	at 250 MeV
loss locations		1. incoming target energy definition – target bunch last of 3 2. outgoing target energy 3. 1.2 GeV S-band linac – positron bunch last of 3 4. damping ring injection
emit_n	0.01	m-radians normalized
sig_z	4 mm	

SLC Positron system beam loss pattern





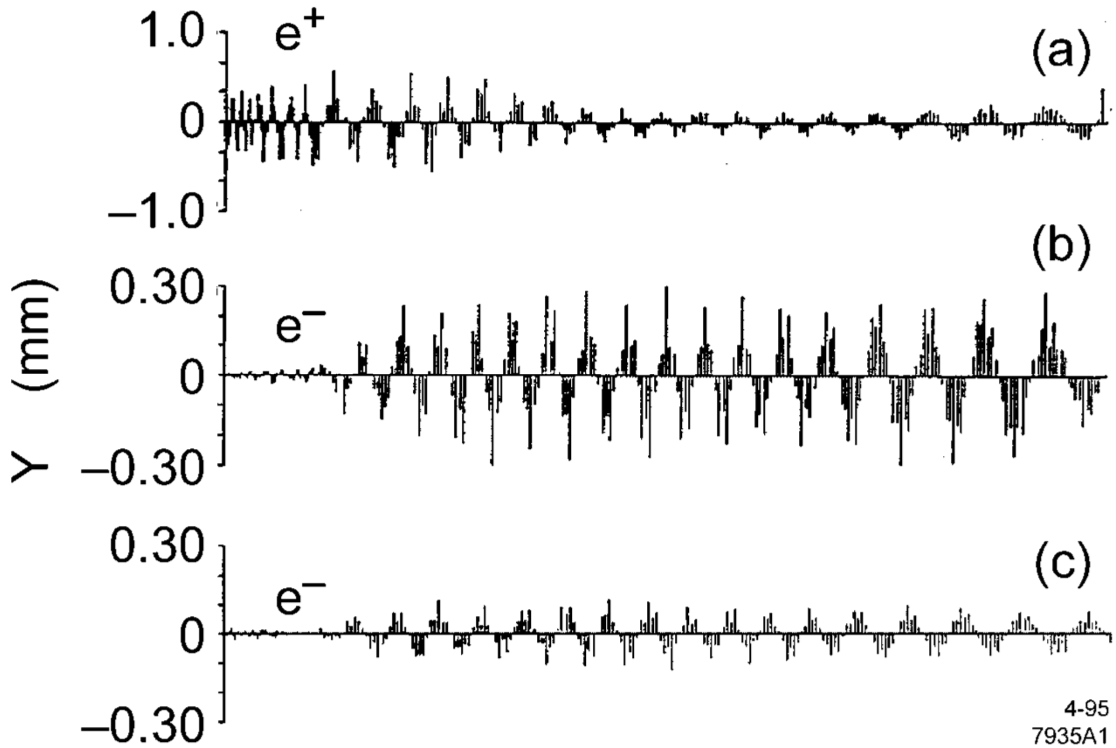
Linac long range wake

- **Couples intensity jitter of lead bunches to**
  - energy (0^{th} order) and
  - trajectory (1^{st} order) of trailing bunches
- **Also couples trajectory jitter**

Linac 'y' trajectory

e+ (leading) coupled to e- (following)

after 'split tune' (c)



SLC Damping Rings

- **impedance-driven bunch lengthening and transverse mode-coupling instability (TMCI)**
  - primary deficiency
  - also acceptance
- **Complete vacuum chamber replacement mid-life (1992)**
- **Longer bunch → outside compressor acceptance → non-linear compression 'tails'**
  - compression-related beam-loss
  - distorted linac phase space
  - strong collimator kicks
  - mitigated using internal 'pre-compression' →
- **TMCI**
  - intensity, energy and trajectory jitter
  - instability → 'errant beam' collimator losses / coll. damage

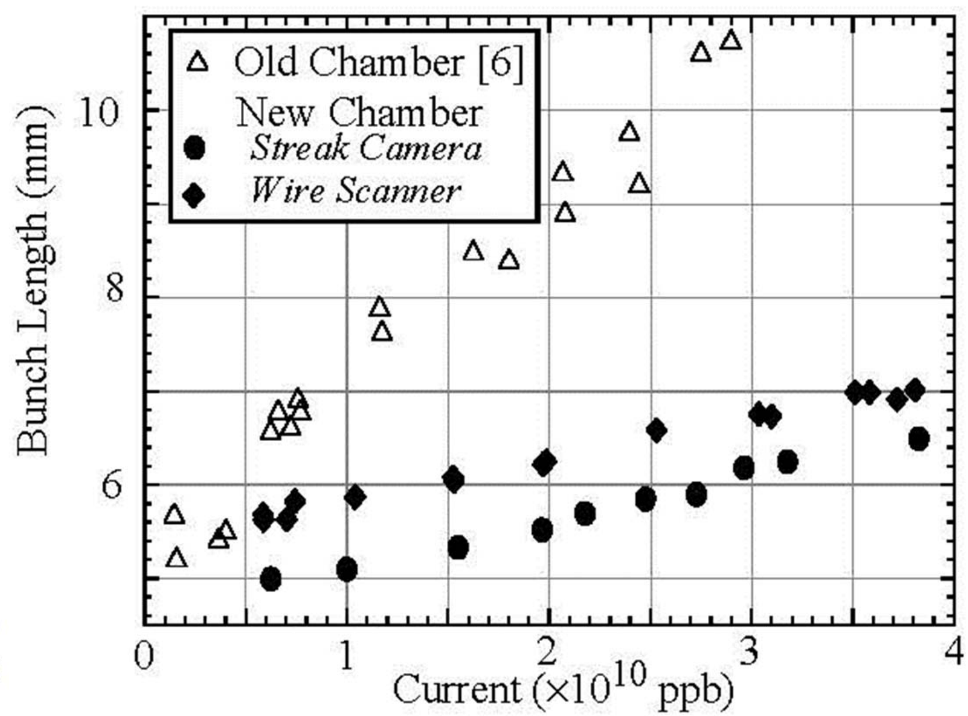
Damping Ring Vacuum Chamber:

Table I. Vacuum Chamber Inductance (nH)

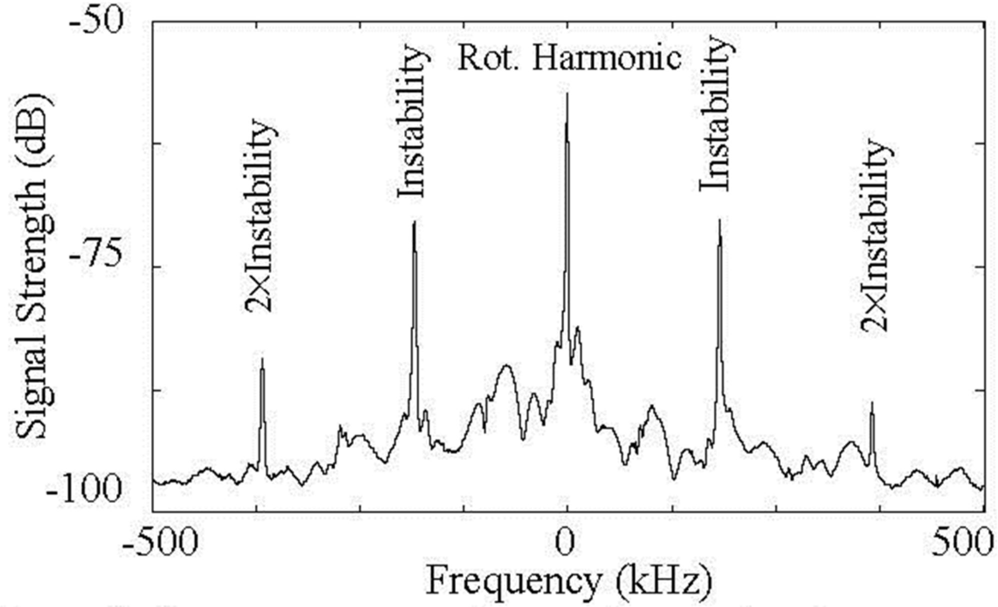
Element	Old Chamber*	New Chamber*
Synch. Radiation Masks	9.5	----
Bellows	----	1.1
Quadrupole to Dipole Chamber Transitions	9.3	2.4
Ion Pump Slots	0.2	0.05
Kicker Magnet Bellows	4.1	----
Flex Joints	3.6	----
Beam Position Monitors	3.5	0.2
Other	2.4	2.4
TOTAL	33	6

- Inductance reduced 5x
- before: 2x bunch lengthening
- after: 1.3x

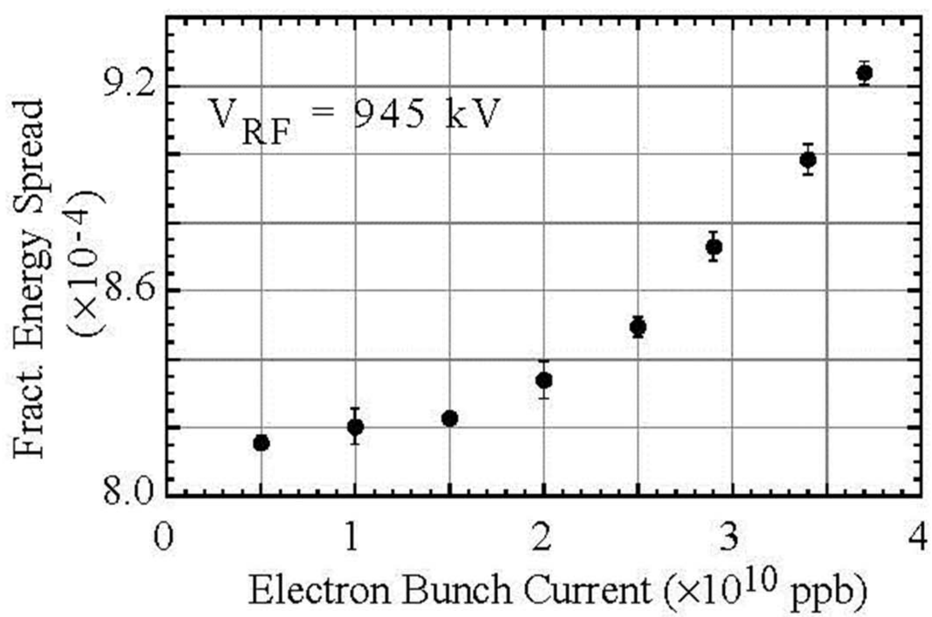
- New chamber showed instability threshold ~ 3e10

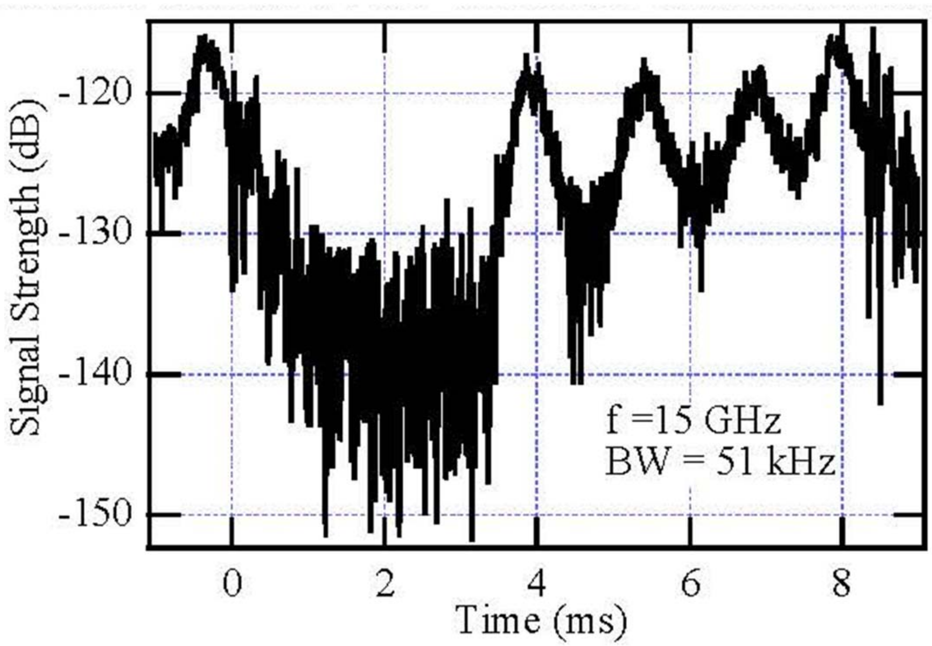


Longitudinal instability



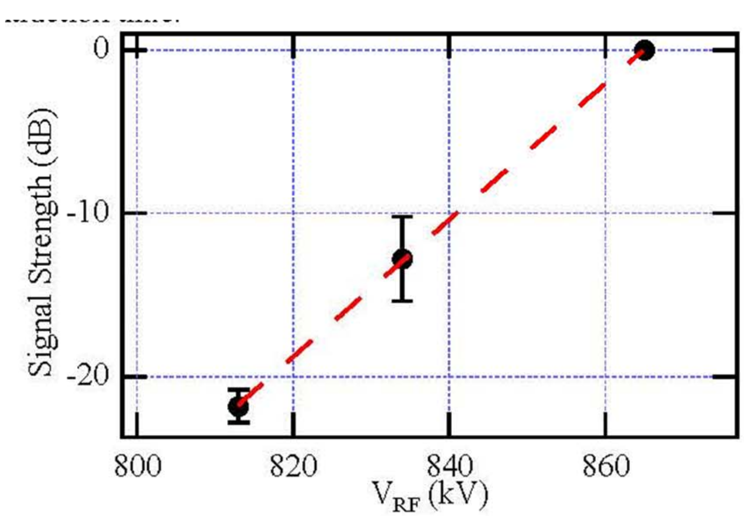
- detected using rotation side-bands at 1/sig_z (25 GHz)

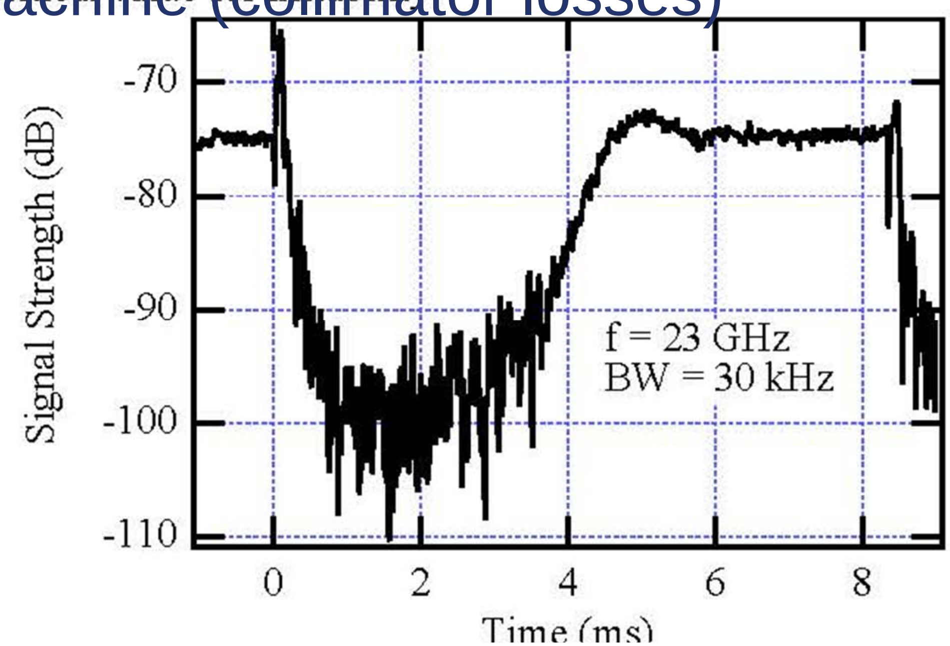




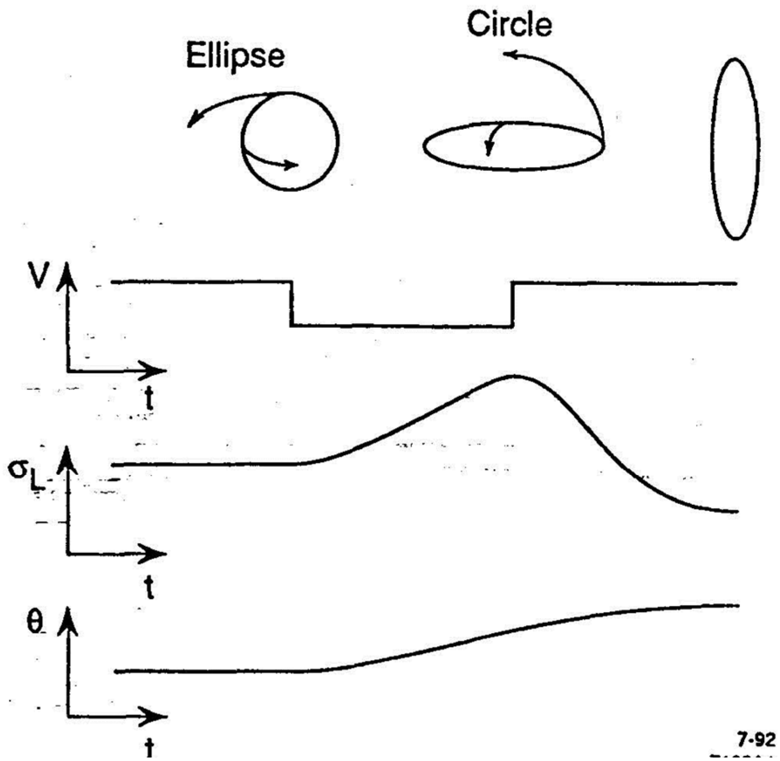
Instability during damping cycle

- arbitrary instability 'phase' at extraction was single largest source of full-power machine (collimator losses) protection trips





Pre-compression:



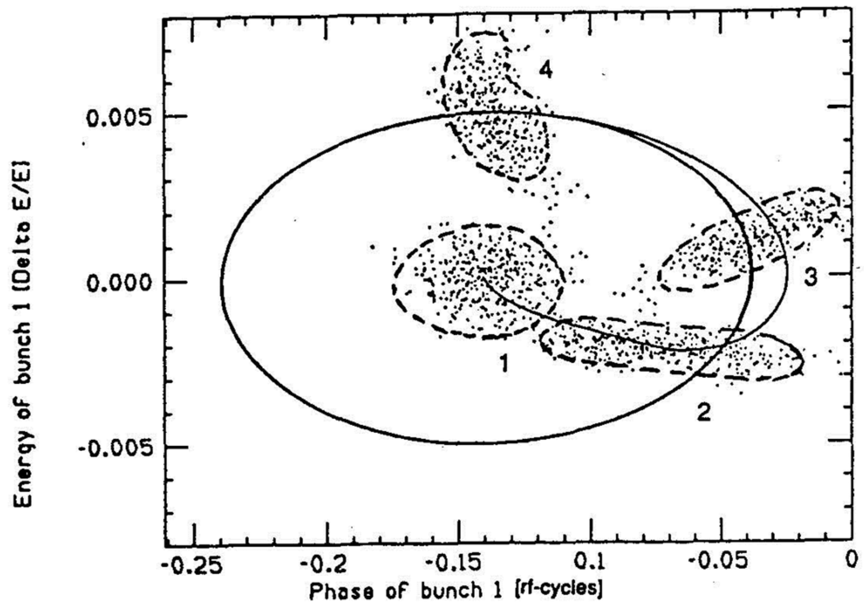


Figure 2: Pre-compression simulation.

A sample of 200 particles is tracked in the presence of the changing rf-voltage. The rf is switched off first and the

Pre-compression in action:

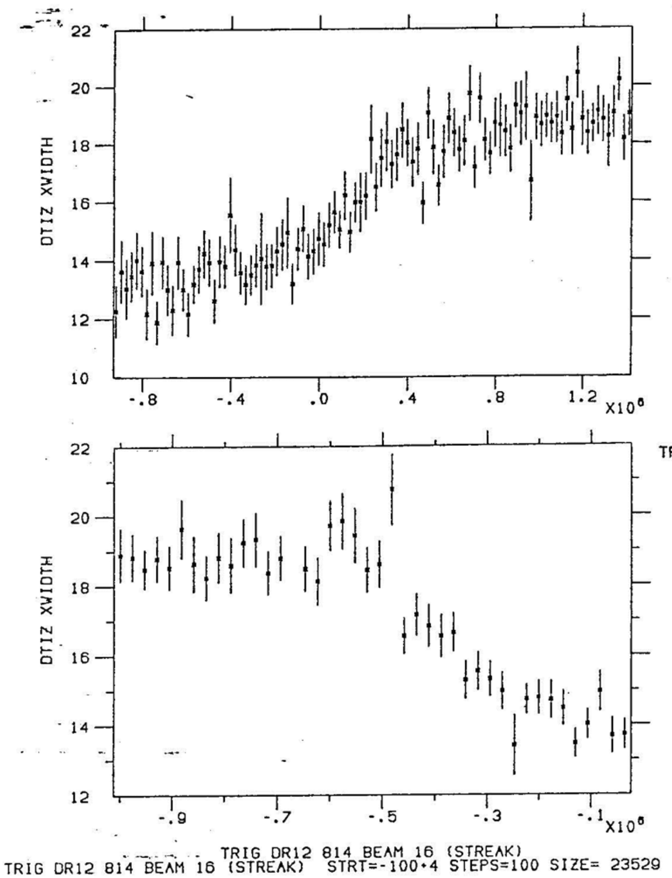


Figure 4: Bunch length during the DR RF ramp.

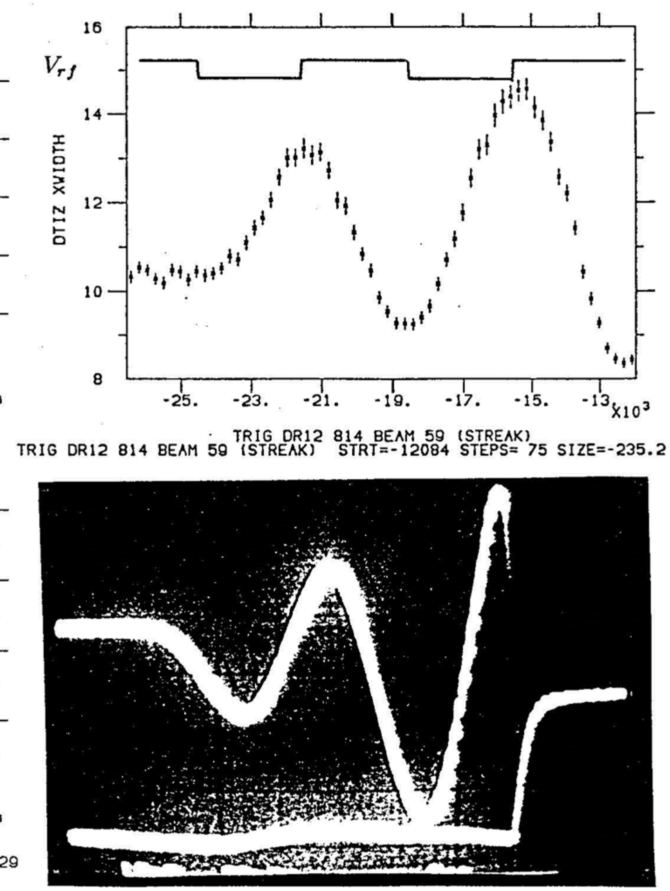


Figure 5: Pre-compression of the bunch length.

helped reduce bunch length to closer to compressor acceptance and 'synchronize' instability phase

Linac Collimation:

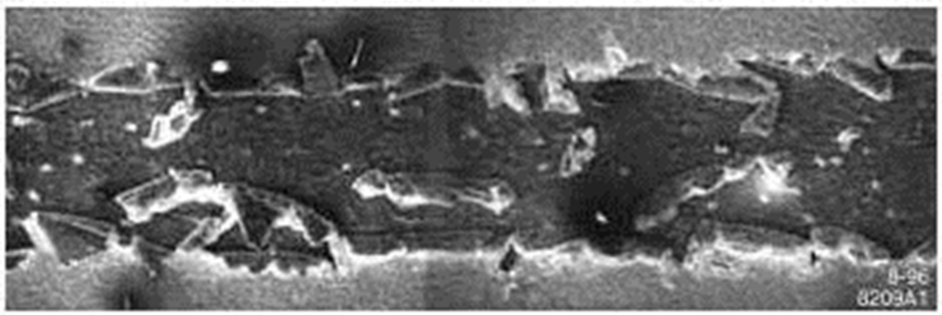
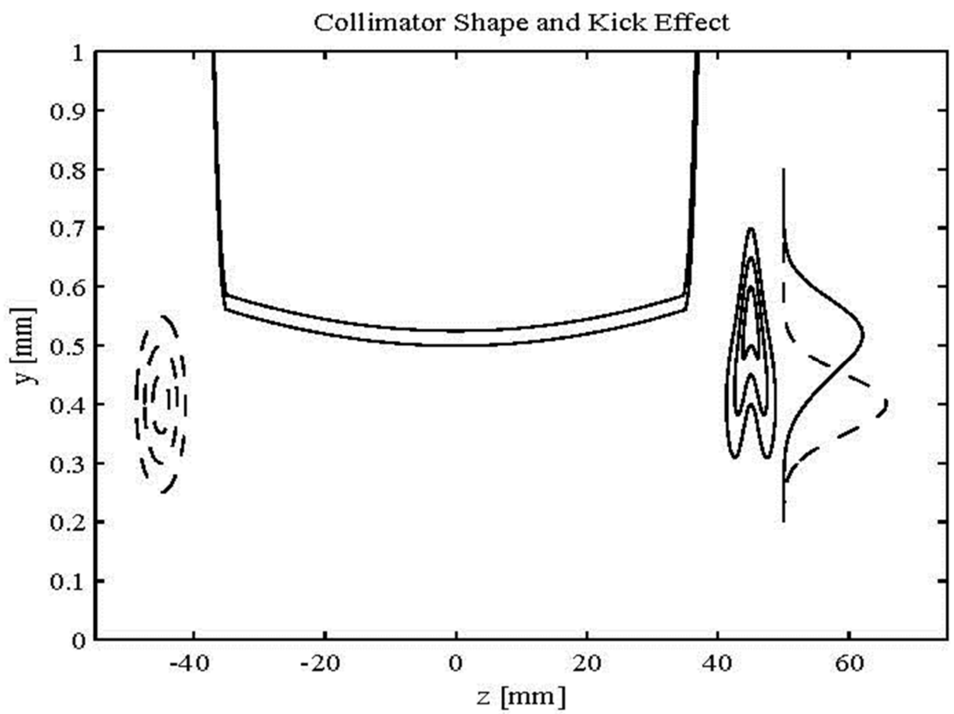


Fig. 1: Damaged collimator surface (stripe width ≈1 mm). The beam enters at the left, creating gold flakes and spherules.

- 47 GeV (max) collimation system
- typical gap <1mm

- Collimator surface damage →
- de-lamination
- (Au coated to reduce resistive wake)



Centroid kick from a collimator:

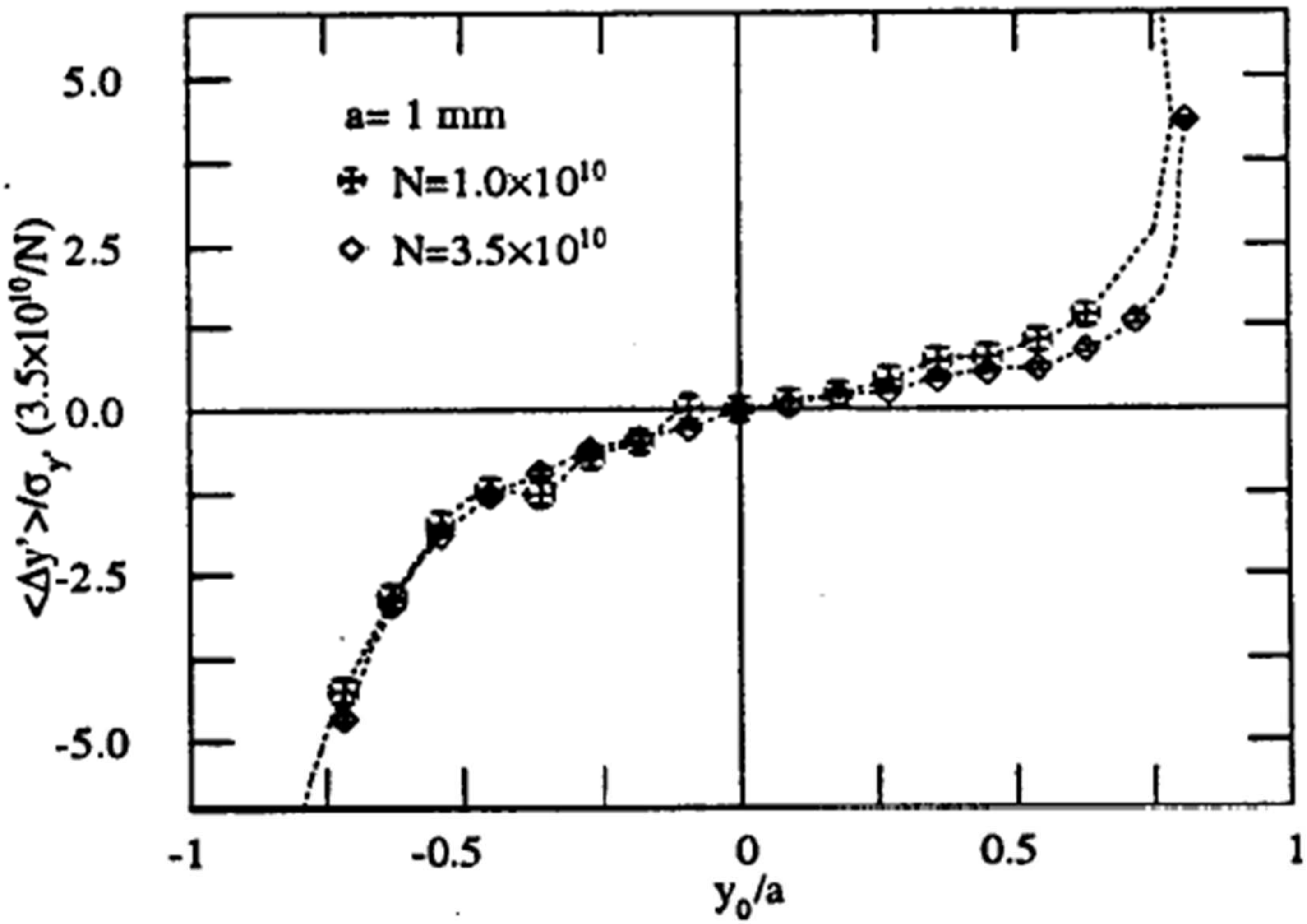


Figure. 2. Kick of the beam, but scaled inversely as N, *vs.* y_0/a, for $N/10^{10} = 1$ and 3.5; $a = 1$ mm.

SLC – a case study

- The SLAC Linear Collider (SLC) was intended in part to demonstrate that linear colliders could work.
- Even though it did not meet luminosity goals, physics goals were met and remain comparable to LEP results.
- **Stabilizing the SLC was the most difficult challenge and transitions in beam power, caused by frequent machine protect system faults were the most serious source of instability.**
- **MPS faults, in turn, were caused through amplification of relatively small damping ring impedance-related longitudinal instabilities in a kind of chain reaction that involved the ring, bunch compressor, normal-conducting linac and collimation systems.**

MP and Operations: Outline

- Linac Segmentation and ‘Bifurcation’
  – Complex topology
- Turn-on / Recovery following a stop
- Failure modes
- Availability

Segmentation

- Key implementation of ***multiple user-stations (hutches)***
  - Present LCLS user-time is 5x over-subscribed
  - New undulator-lines to fix this! ←
  - Operation of each should not interfere with any other
- *N* completely logically independent machines!
  - Each user has own stability criteria (including optimum limiting strategy)
- Parallel high power operation
  - (problem faced by SLAC fixed-target in 1970's)

Future Facility Expansion Options

- SLAC has extensive infrastructure that will allow expansion
  - **New tunnels are possible north and south of existing LCLS tunnel and could be optimized for long, high pulse energy, hard X-ray FEL's**
  - **Five separate undulator complex**

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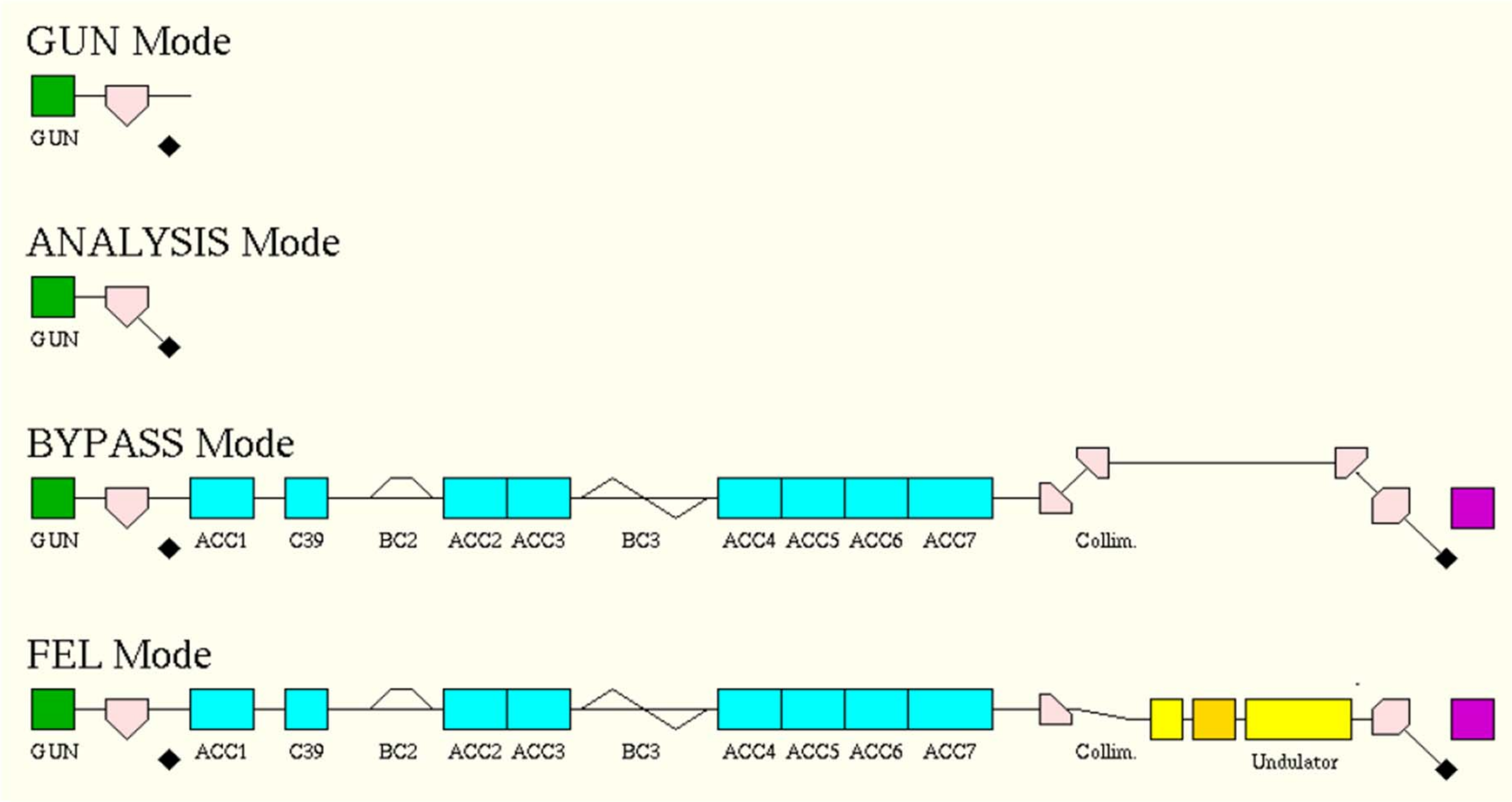
Marc Ross, SLAC

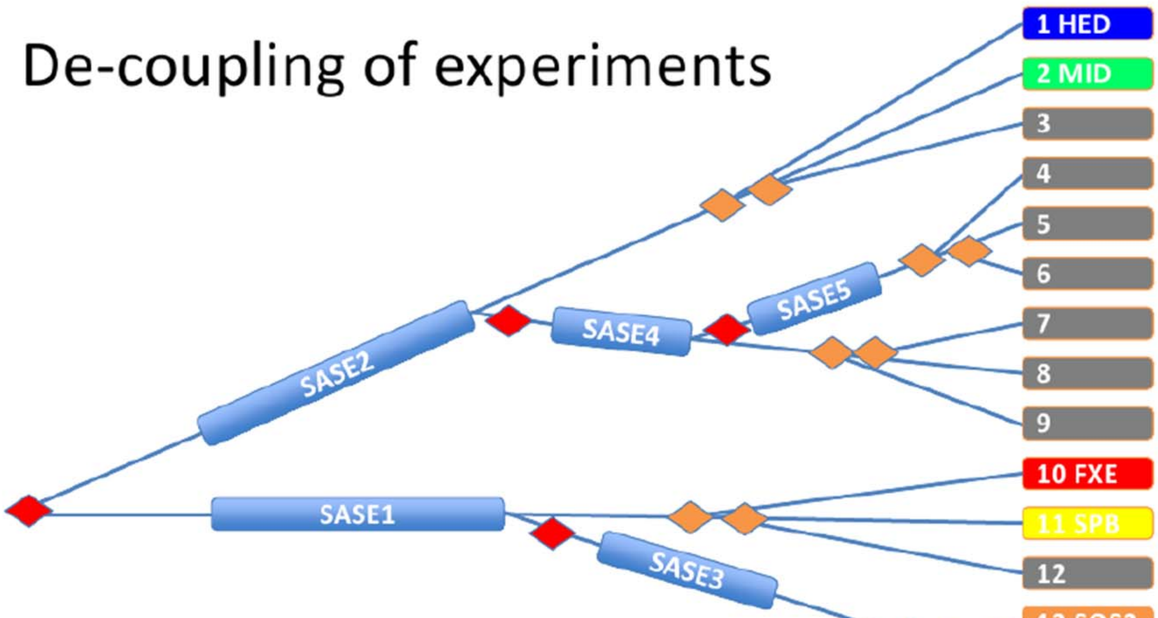
FLASH: Operation Modes



- MPS determines operation mode from machine settings
- Operators set magnets and vacuum valves, MPS reacts

Beam Modes (3)

De-coupling of experiments



MPS needs to know which branch is active
MPS needs to know where pulse lases (requires R&D)
Beam Transport PLC needs to know which experiment active (max 10 Hz switching)

- 15 experiments in 5 SASE beamlines, 5 experiments with different beam requirements operated at the same time
- SASE 1 and SASE 3 get the same electron beam

Linac Cycles:

- LCLS: CW 1 MHZ
  - Preferred; constant beam-surveillance
  - (But low power operation will be at much lower rates)
- SNS: 60 Hz with 1 ms macro pulses
- E-XFEL: 10 Hz with 1 ms macro pulse; ~10 MHz bunch-rate
  - Low power operation by reducing 10 MHz (factor 1e-4)
- ILC: 5 Hz with 1 ms macro pulse; 3 MHz bunch-rate
- CLIC: 100 Hz with 100 ns macro pulses; ~ 1GHz bunch-rate

Linac Cycles:

- E-XFEL: 10 Hz with 1 ms macro pulse; ~10 MHz bunch-rate
  - Low power operation by reducing 10 MHz (factor 1e-4)
- 15 Users – 5 FE Laser beamlines
  - Macro rate independent
  - n_bunches independent
    - One to ~2 k (present FLASH experience)
  - N_ppb probably fixed
  - (could be done….)
- ILC: must apply all of the above and also reduce N_ppb

MP and Operations: Outline

- Linac Segmentation and ‘Bifurcation’
- Turn-on / Recovery following a stop
  - Transitions from low to high power happen much more frequently in today’s linacs – than in a storage ring
  - Sequencing: SRF example
- Failure modes
- Availability

Relaxation oscillator mode

Cycle Start:

- Low power operation
- Transition to higher beam power
- Beam loss unacceptable
  - Root cause may be beam-power heating?
  - Or controls – related interference?
  - Or BLM malfunction (usually saturation)
  - Or flaw in the sequence (many examples)
- Transition back to low beam power

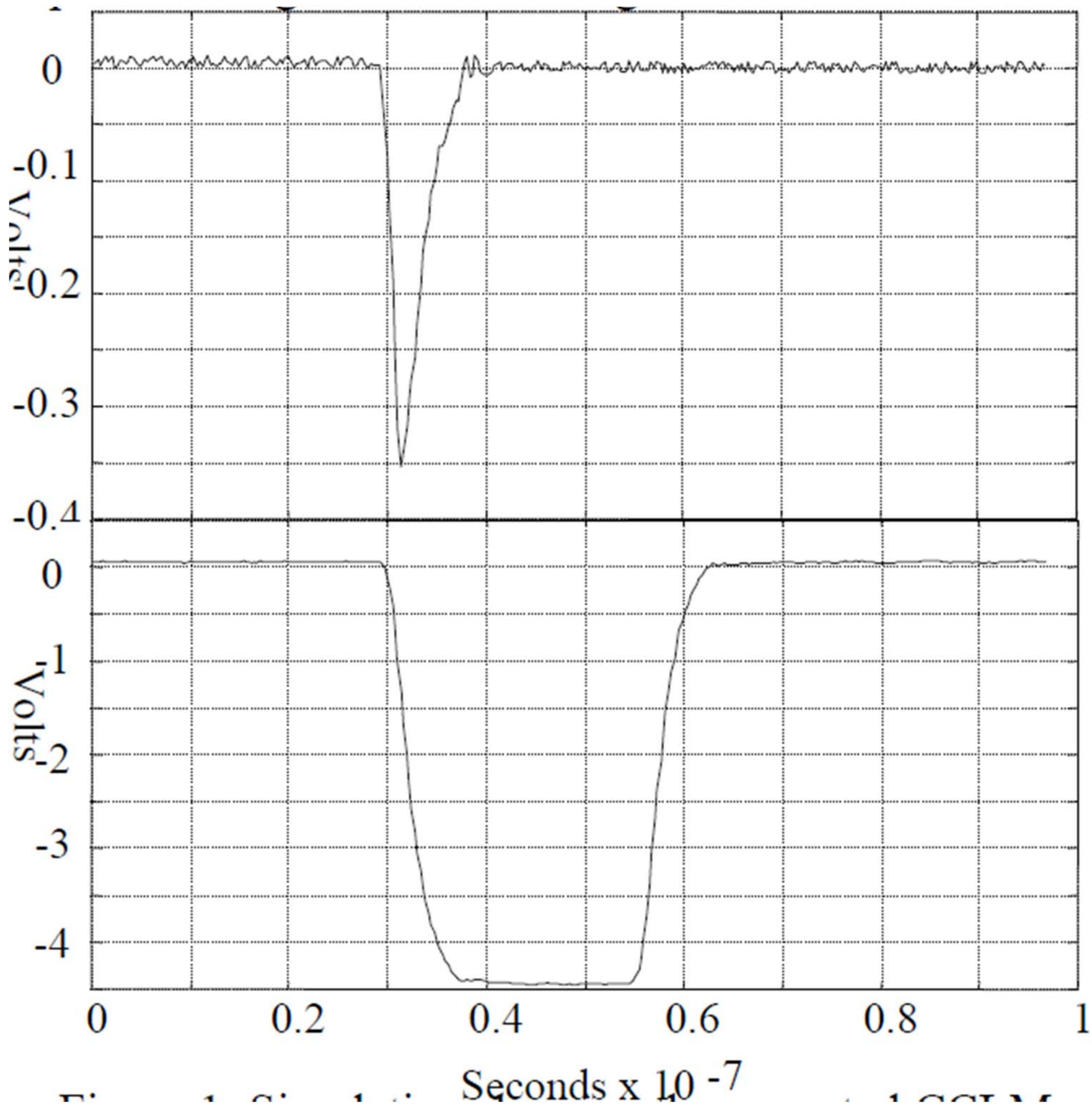
Repeat

How to diagnose? (break the cycle?)

Linac Loss Monitor

Comparing a single bunch loss vs the same per-bunch loss at full power

Integrated signal increases >100 x



Linear Collider (NLC/CLIC) Sequence

1) Rate, 2) Intensity, 3) Emittance

Step	Parameters n_b, I_b, typ. $\sigma_{x,y}$	Charge density (C/m^2)	Average beam power
Pilot beam	1, 1 x 10^9, 30µm(1Hz)	.04	80
Full rate	120 Hz	.04	10KW
Nominal I	1, 1 x 10^{10}, 30µm	.3	100KW
Nominal ε and I	1, 1 x 10^{10}, 3µm	23	100 KW
Nominal	90, 1 x 10^{10}, 3µm	2100	8MW

ILC restart sequence

- Depending on the beam dynamics of the long trains, it may be advisable to program short trains into a restart sequence.
- There may also be single bunch, intensity dependent effects that require an intensity ramp.
- In order to avoid relaxation oscillator performance of the average beam loss MPS, the system will be able to determine in advance if the beam loss expected at the next stage in the ramp sequence is acceptable.
- Given the number of stages and regions, the sequence controller must distribute its intentions so that all subsidiary controls can respond appropriately and data acquisition systems are properly aligned.
- The sequence may need to generate a ‘benign’ bunch sequence with the nominal intensity but large emittance.
- The initial stages of the sequence will be used to produce ‘diagnostic’ pulses to be used during commissioning, setup and testing.

‘NLC’ restart sequence strategy detail

Table 1: Linac MPS Transition Sequence from pilot beam to nominal full power operation. Only step 4 has n_b>1. The peak charge density ρ is computed using $2\pi\sigma_x\sigma_y$ as the peak density. The beam sizes, σ_x and σ_y are estimated using the linac quadrupole magnet spacing and the optical phase advance to estimate the geometric mean ($\sqrt{\beta_x\beta_y}$). Step 4.1 shows parameters associated with the n_b =190, 1.4 ns inter-bunch time operation.

Step #	I /pulse e±/pulse	$\gamma\epsilon_{x,y}$ (m-rad)	$\sigma_x\ \sigma_y$ begin (μm^2)	$\sigma_{x,y}$ begin (μm)	ρ begin pCb/μm^2	$\sigma_x\ \sigma_y$ end (μm^2)	$\sigma_{x,y}$ end (μm)	ρ end pCb/μm^2	ΔT max (°C)
1	1.1E+09	3.0E-05	13,000	110	.0022	780	28	.036	180
1.1	0.70E+08	1.5E-06	650	26	.0022	39	6.2	.036	180
1.2	1.0E+10	2.7E-04	117,500	340	.0022	7016	84	.036	180
2	1.0E+10	3.0E-05	13,000	110	.019	780	28	.36	1800
		$\gamma\epsilon_x\ \gamma\epsilon_y$							
3	1.0E+10	3.0E-06 x 3.0E-08		31.3 x 4.4	1.4	11.0	7.7x 1.1	23	1.1E+05
4	9.0E+11	3.0E-06 x 3.0E-08		31.3 x 4.4	120	11.0	7.7x 1.1	2100	1E+07
4.1	1.4E+12	3.0E-06 x 3.0E-08		31.3 x 4.4	190	11.0	7.7x 1.1	3325	1.6E+07

Superconducting RF vs Magnets: a comparison

Accelerator SRF

- Large-scale commercialization a possibility
- Minimal (~zero) stored energy
  - **Quench recovery easy**
- Cryogenic dynamic load can be cost-driver
- Radiation can be a problem

Accelerator SC Magnets (SCM)

- Commercialization is very unlikely
- Truly enormous stored energy
  - **Complicates quench recovery**
- Minimal intrinsic dynamic load
- -

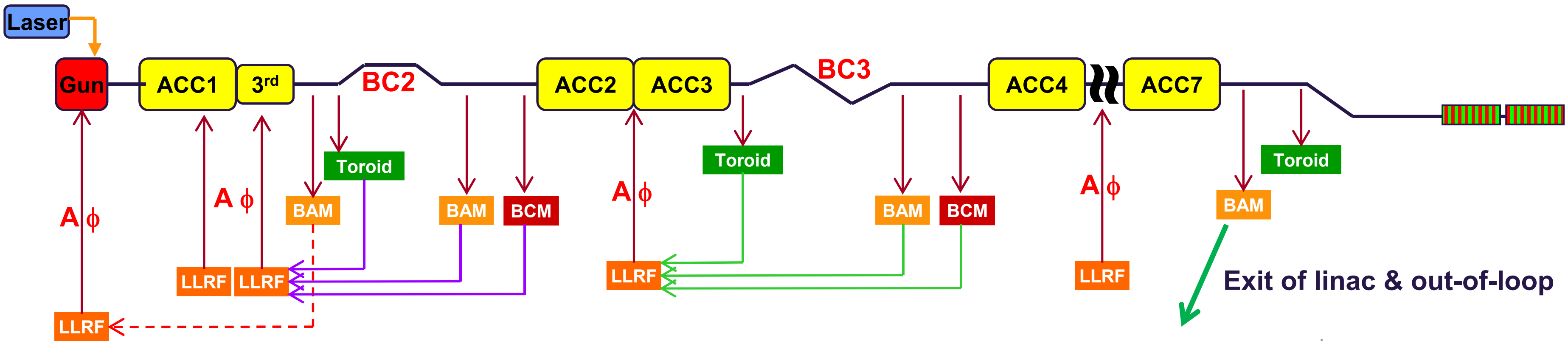
SRF Basics: Resonator Control

- Example: Pulsed operation (SNS, XFEL, ILC, ESS, …)

1. Pulses are long → Controls (incl MPS have time to react)
2. Beam-loading very important (for CW less important)
3. High fields – Lorentz Force can be important
4. RF economics drive single-source:multi-cavity layout
5. Tuning done electro-mechanically
6. Active stabilization required

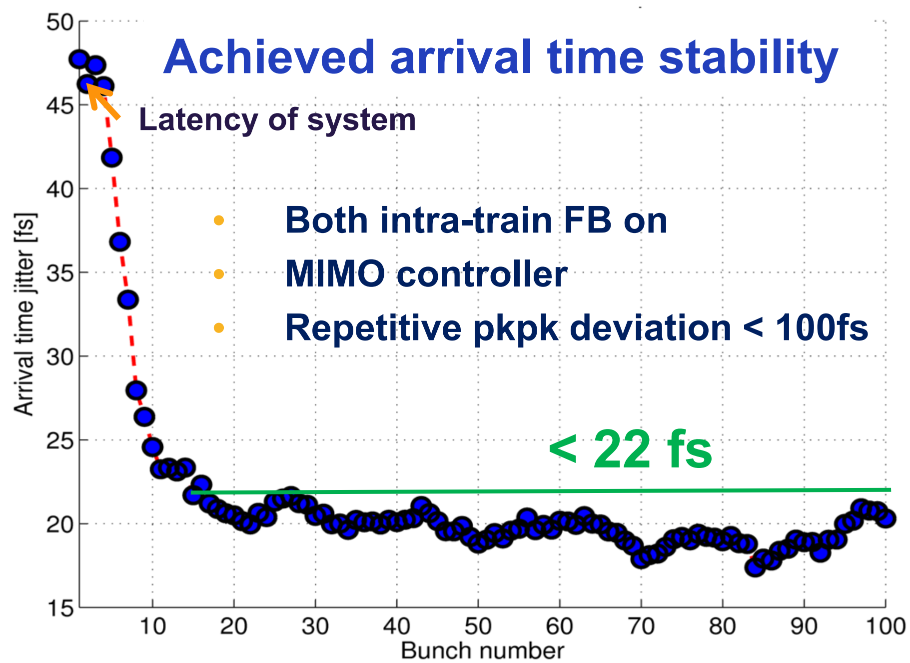
Characteristic: ***Q_external*** determines system bandwidth and power-flow

Performance of LLRF system after upgrade



Beam Based Feedbacks:

- BAM before BC2 corrects phase in RF-Gun
- BAM and BCM after BC2 simultaneously correct amplitude and phase in ACC1 and 3rd harmonic
- BAM and BCM after BC3 correct amplitude and phase in ACC23

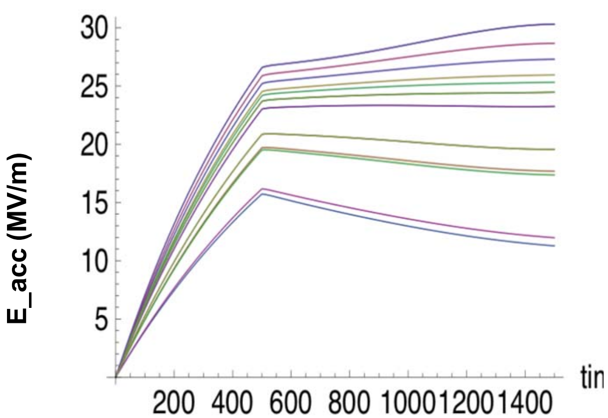


Methodology for ramping to maximum gradient and full beam loading (16 cavities FLASH ACC6/7)

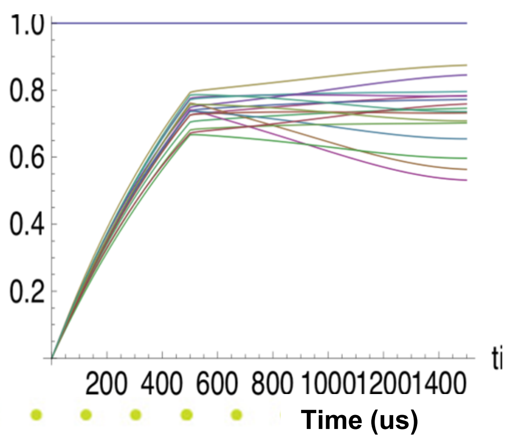
Step 1 → Adjust Q_l → **Step 2** → Raise Power → **Step 3**

Step 1

Cavity Voltages: 6mA
Default Qexts, 3.5MW

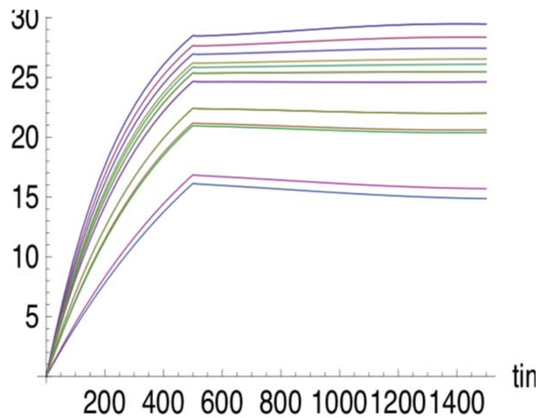


Fraction of quench limit

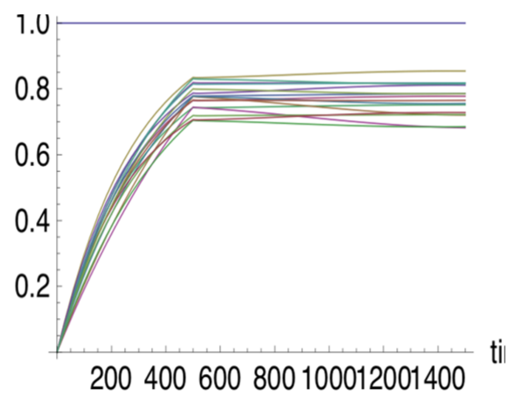


Step 2

Cavity Voltages: 6mA
Shin's Qexts, 3.5MW

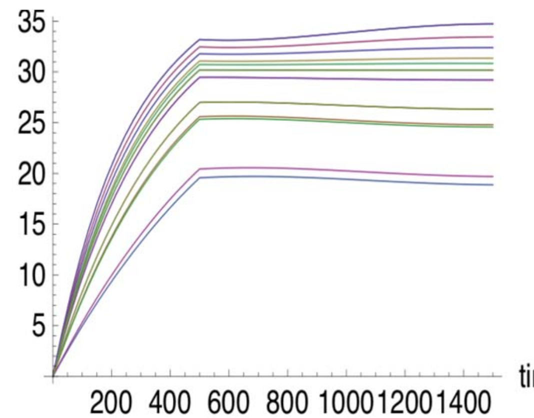


Fraction of quench limit

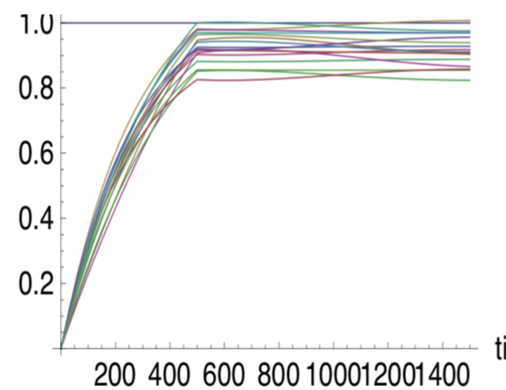


Step 3

Cavity Voltages: 6mA
Shin's Qexts, 5.1MW



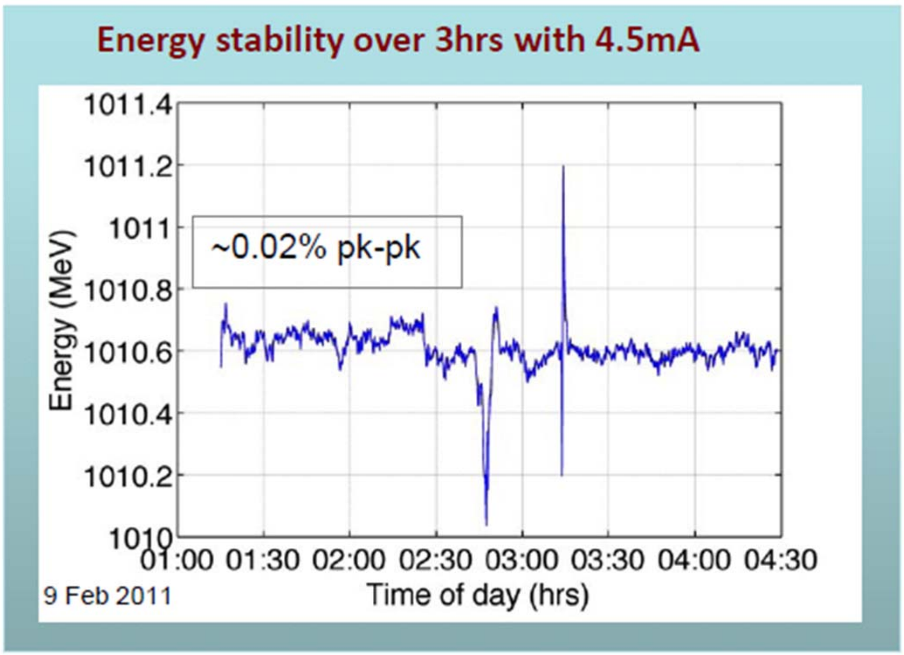
Fraction of quench limit



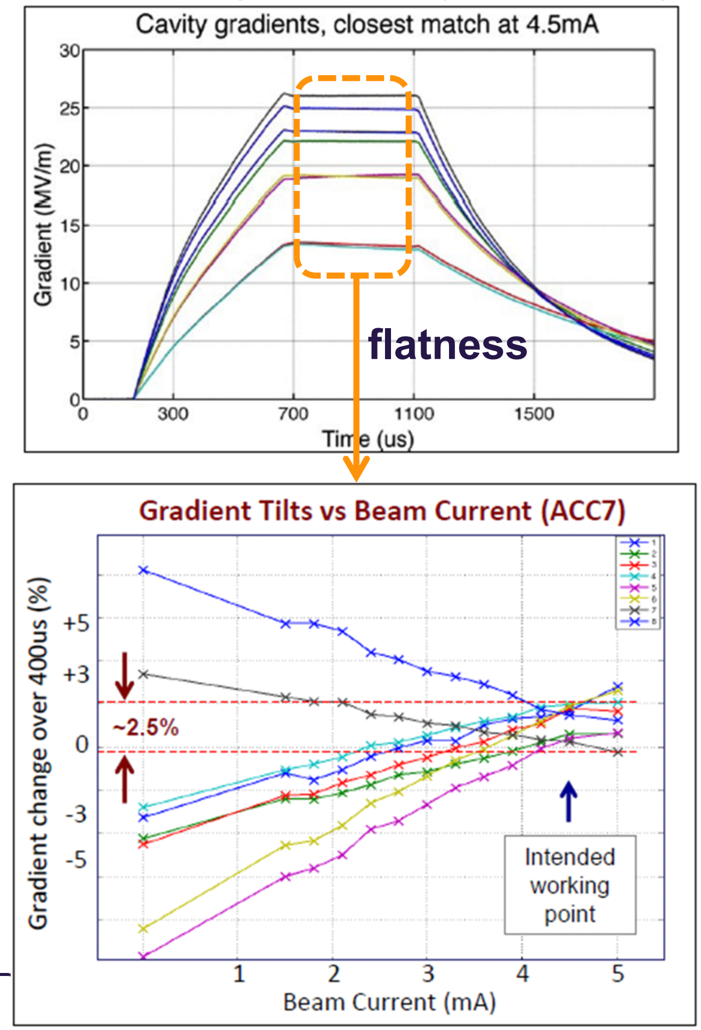
Performance of LLRF system after upgrade

ILC studies: energy stability / gradient flatness / gradient limit

Energy stability exit of accelerator



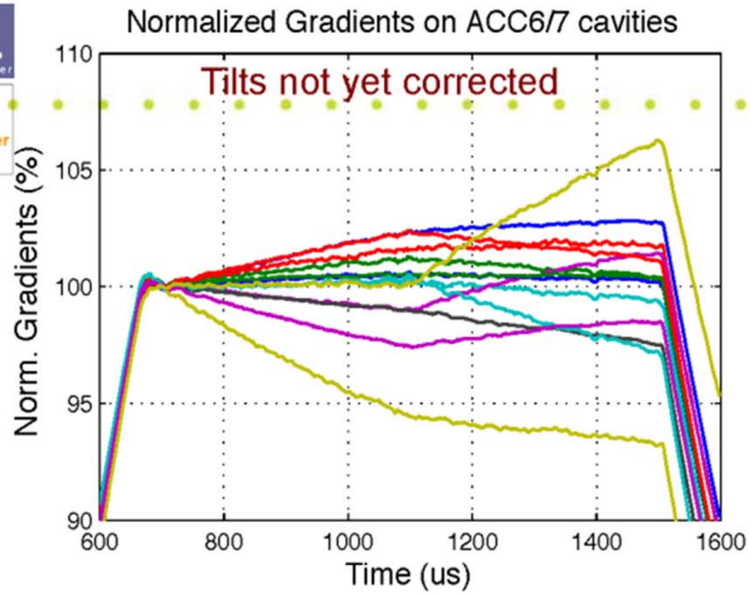
Minimizing slopes by QL tuning



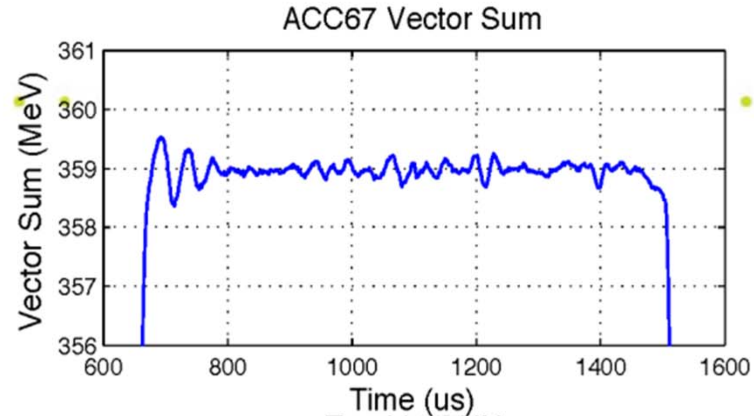
Important studies for FLASH & XFEL

- Impacts orbit variation and orbit slopes
- Achievable energy gain

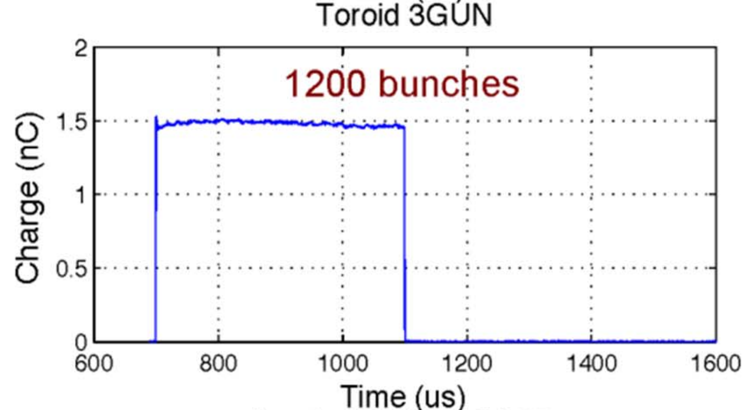
ILC study results → Poster J. Branlard



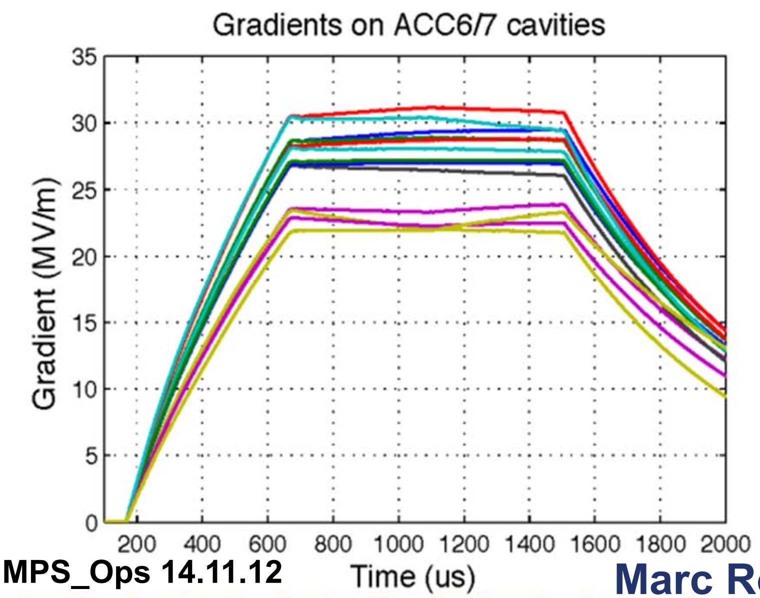
Normalized Gradients on ACC6/7 cavities
Tilts not yet corrected
Norm. Gradients (%)
Time (us)



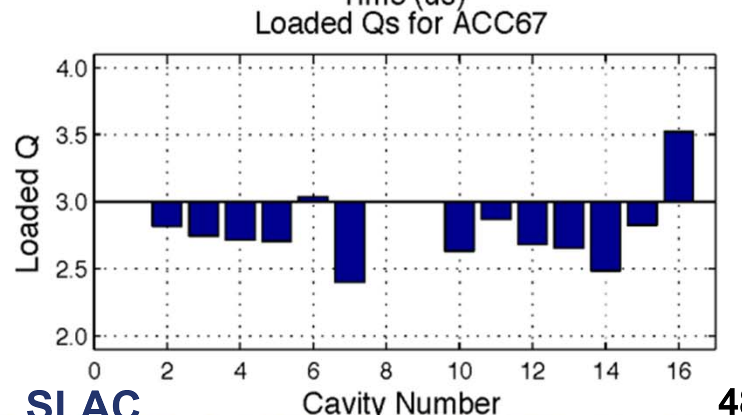
ACC67 Vector Sum
Vector Sum (MeV)
Time (us)



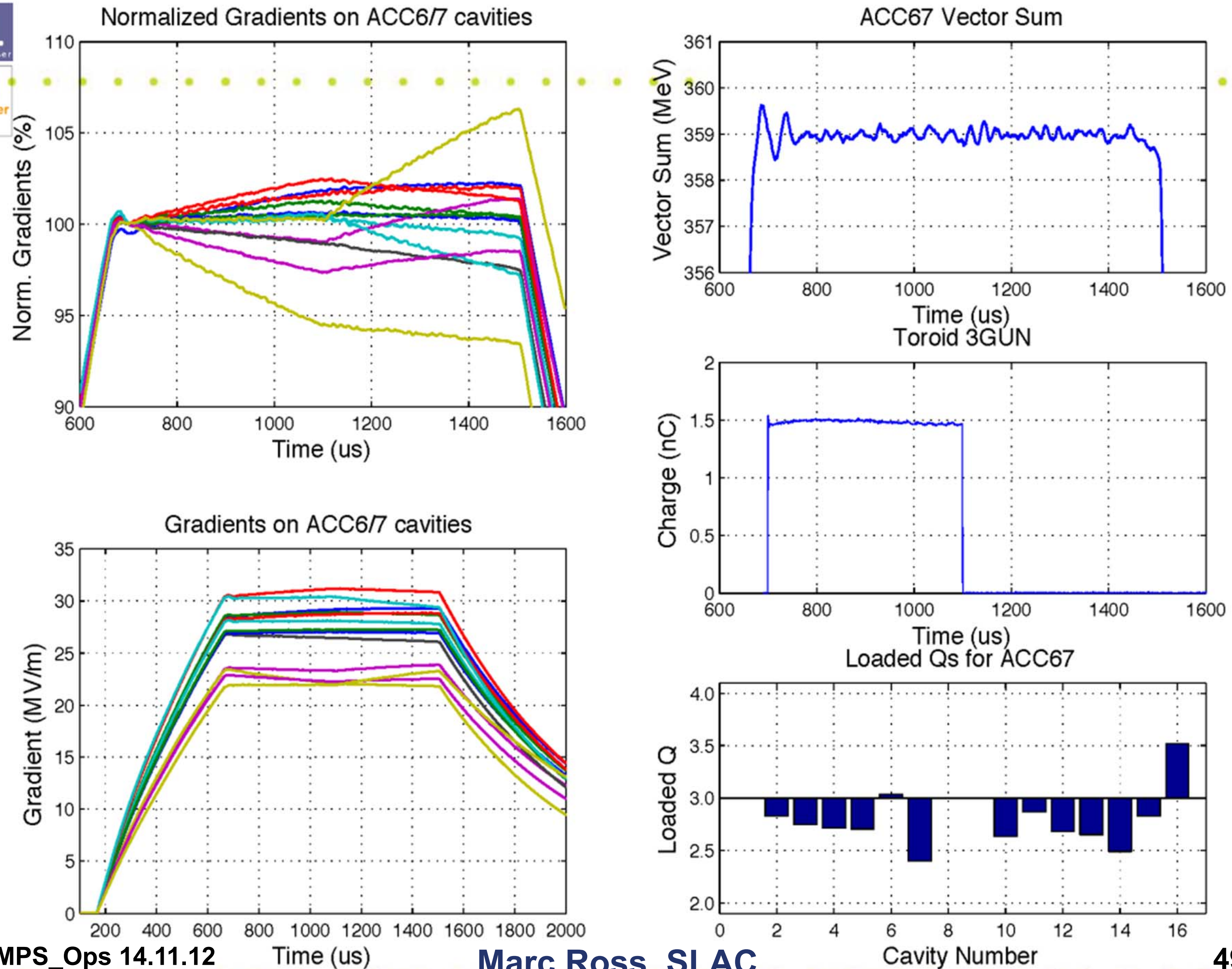
Toroid 3GUN
1200 bunches
Charge (nC)
Time (us)

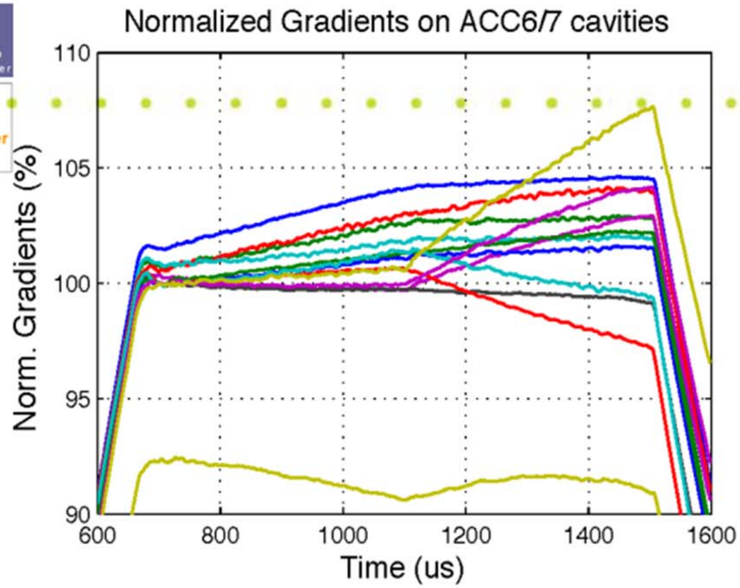


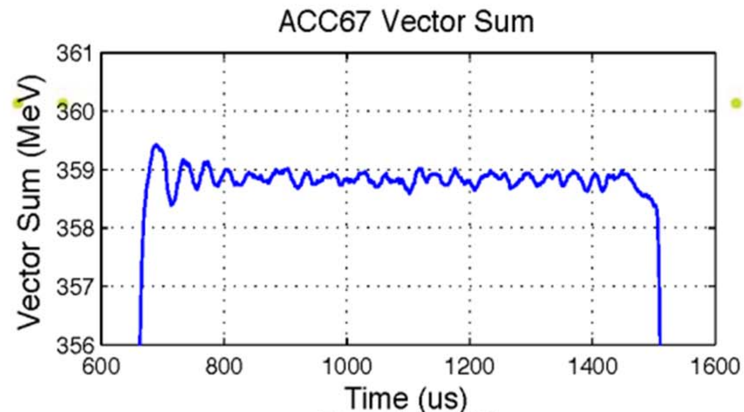
Gradients on ACC6/7 cavities
Gradient (MV/m)
Time (us)

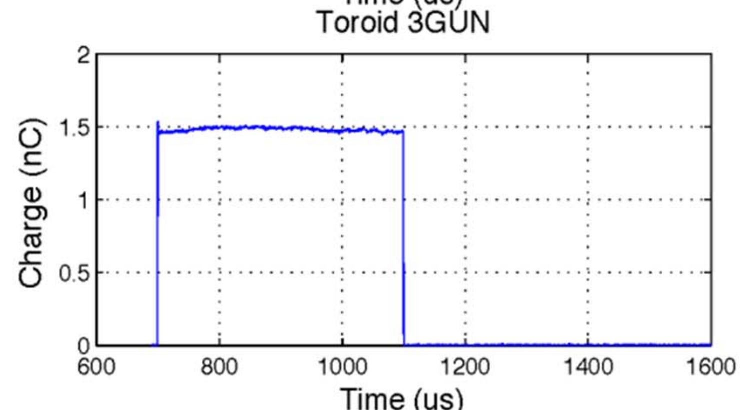


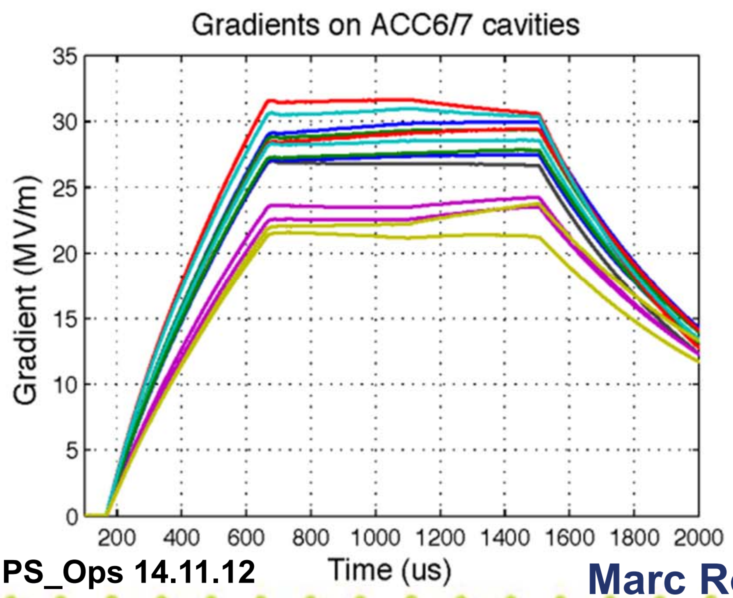
Loaded Qs for ACC67
Loaded Q
Cavity Number

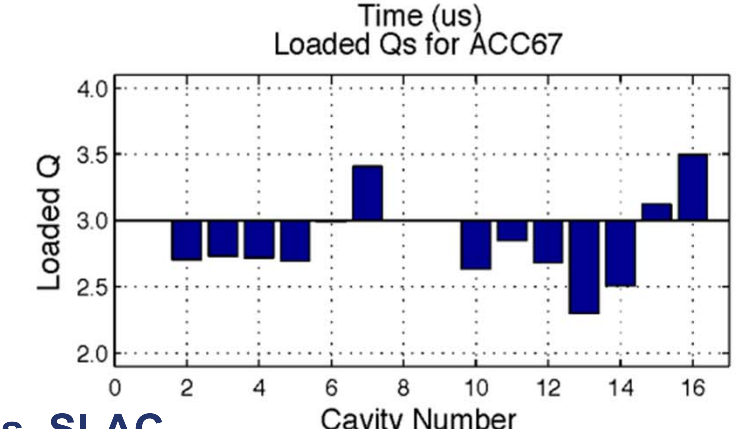

Normalized Gradients on ACC6/7 cavities
Norm. Gradients (%)
Time (us)
ACC67 Vector Sum
Vector Sum (MeV)
Time (us)
Toroid 3GUN
Charge (nC)
Time (us)
Loaded Qs for ACC67
Loaded Q
Cavity Number
Gradients on ACC6/7 cavities
Gradient (MV/m)
Time (us)

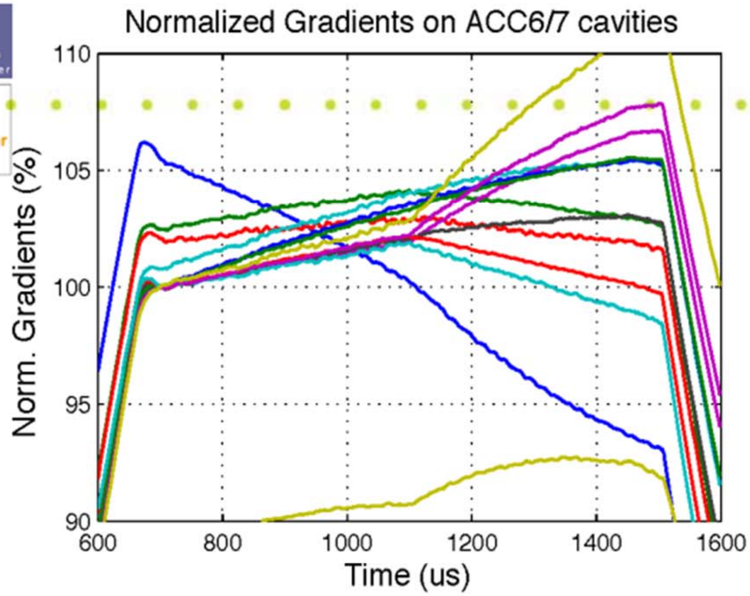

Normalized Gradients on ACC6/7 cavities
Norm. Gradients (%)
Time (us)

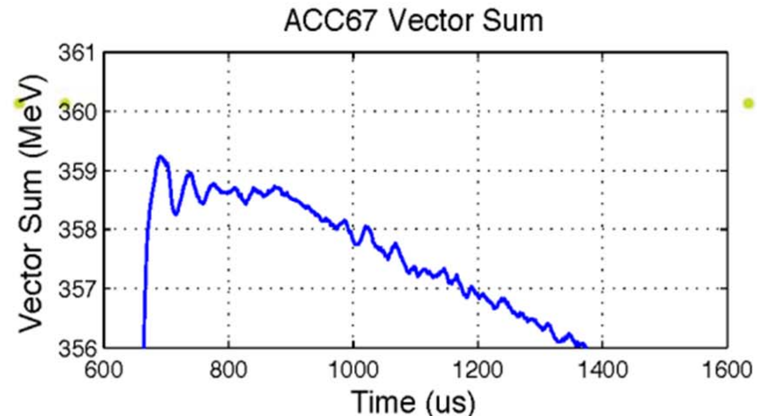

ACC67 Vector Sum
Vector Sum (MeV)
Time (us)

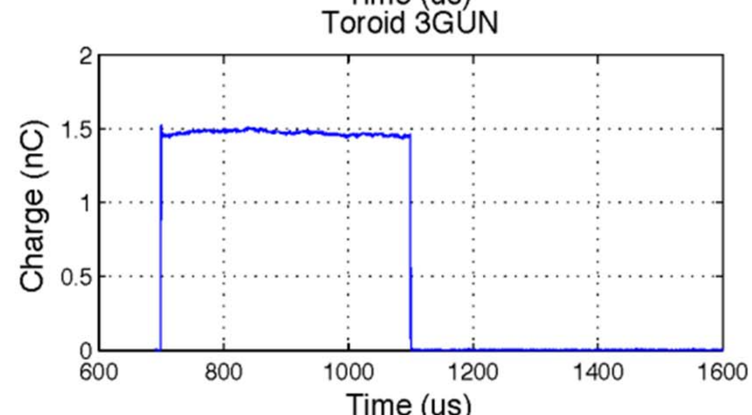

Toroid 3GUN
Charge (nC)
Time (us)

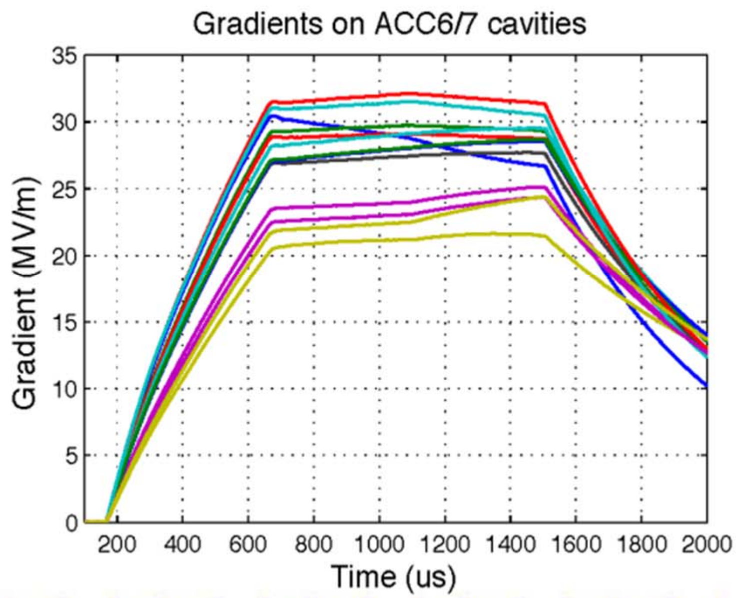

Gradients on ACC6/7 cavities
Gradient (MV/m)
Time (us)

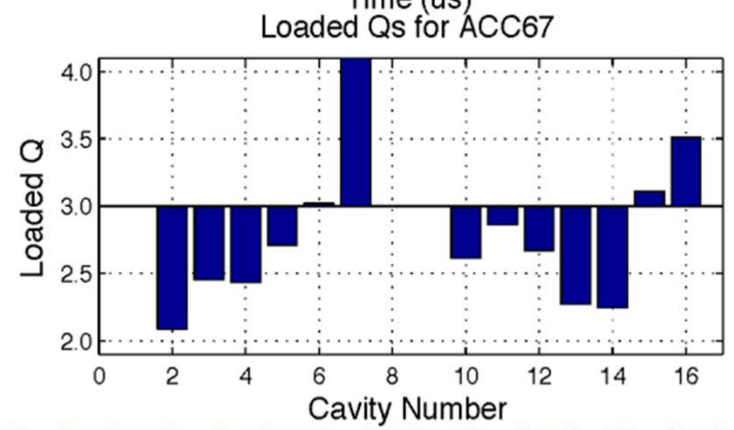

Loaded Qs for ACC67
Loaded Q
Cavity Number

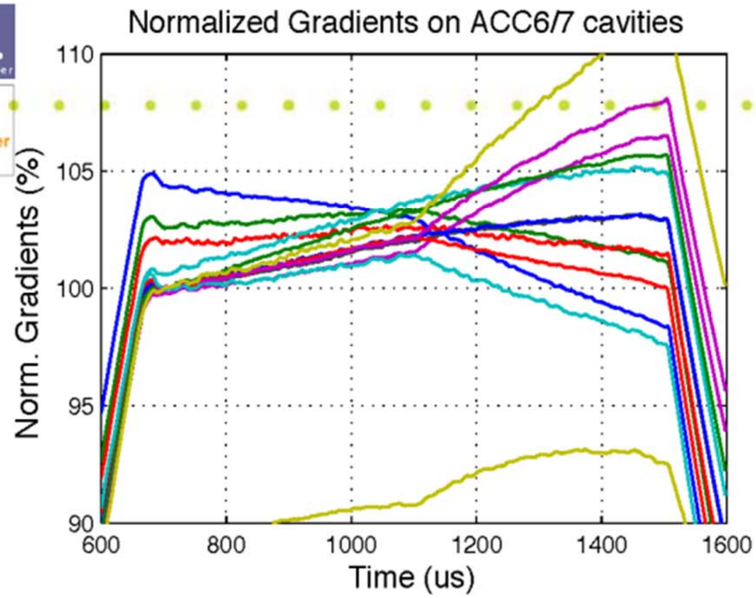

Normalized Gradients on ACC6/7 cavities
Norm. Gradients (%)
Time (us)

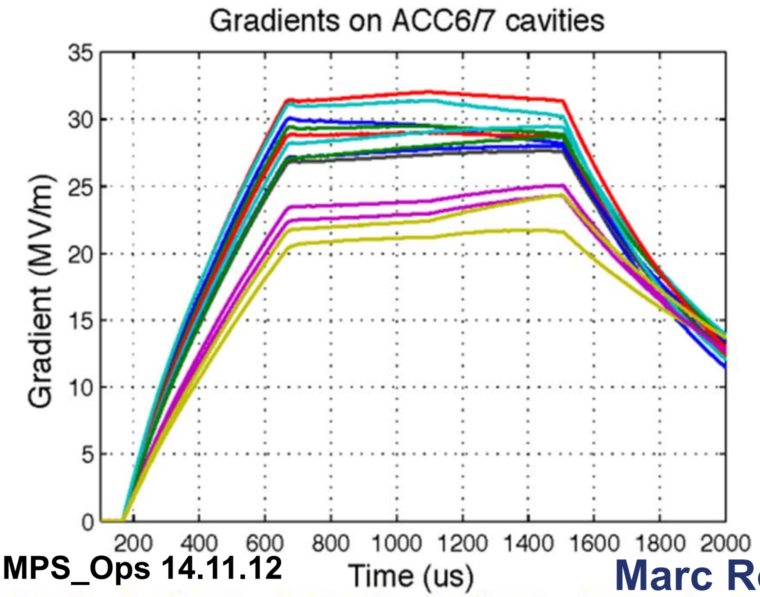

ACC67 Vector Sum
Vector Sum (MeV)
Time (us)

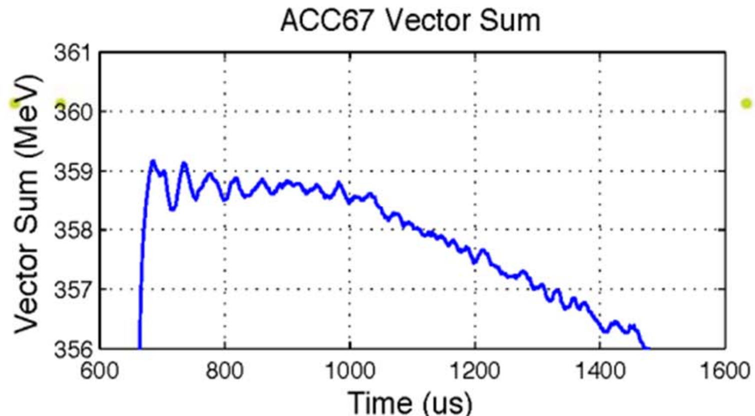

Toroid 3GUN
Charge (nC)
Time (us)

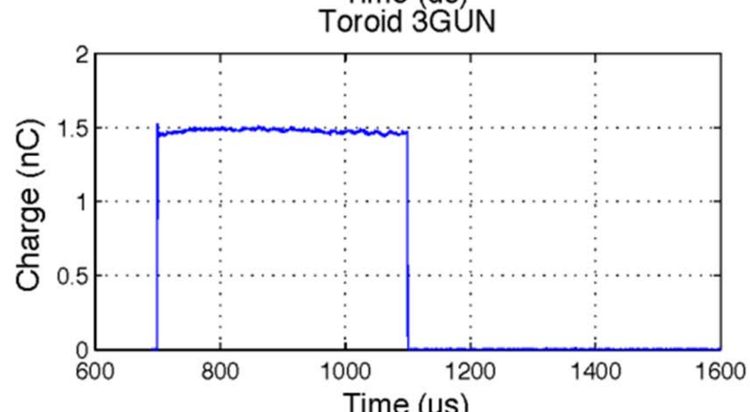

Gradients on ACC6/7 cavities
Gradient (MV/m)
Time (us)

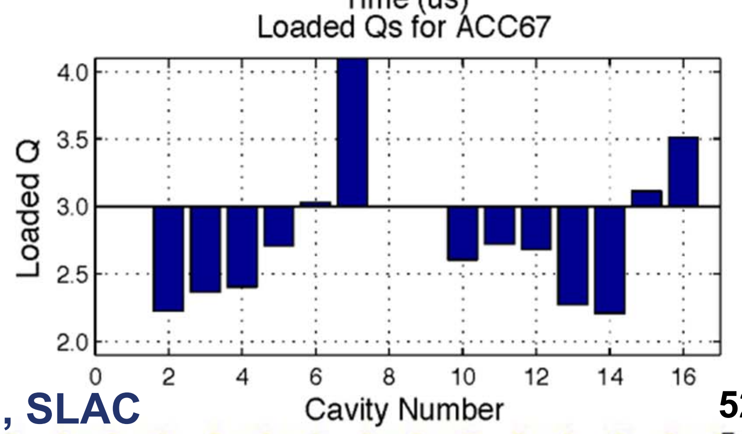

Loaded Qs for ACC67
Loaded Q
Cavity Number

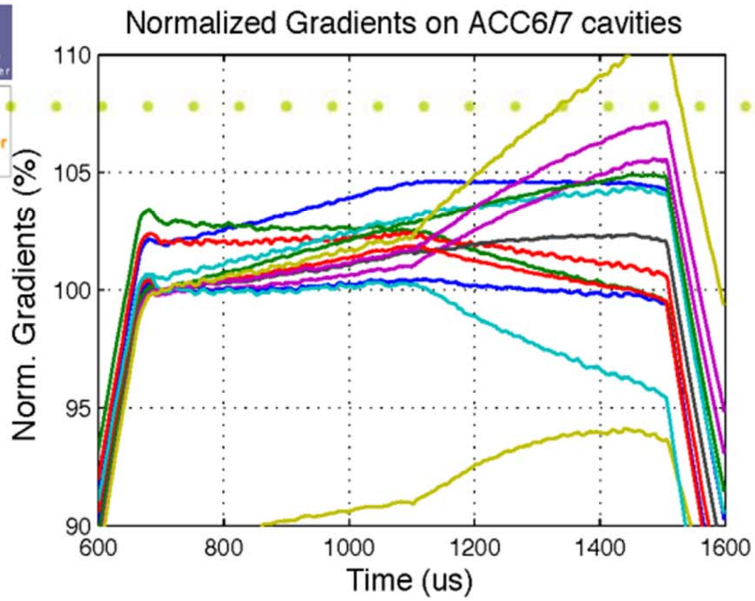

Normalized Gradients on ACC6/7 cavities
Norm. Gradients (%)
Time (us)

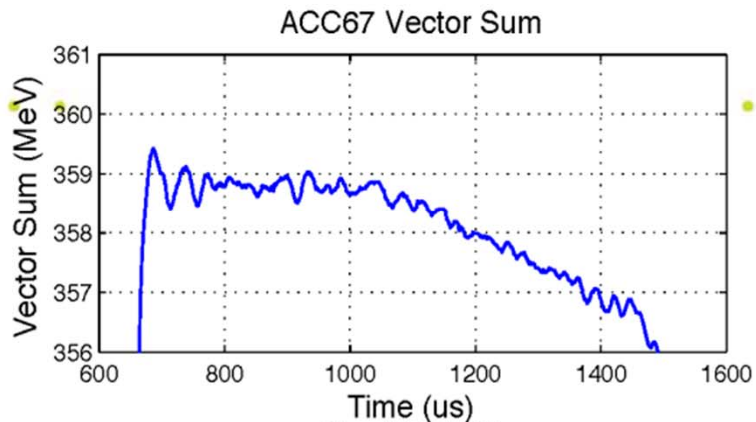

Gradients on ACC6/7 cavities
Gradient (MV/m)
Time (us)

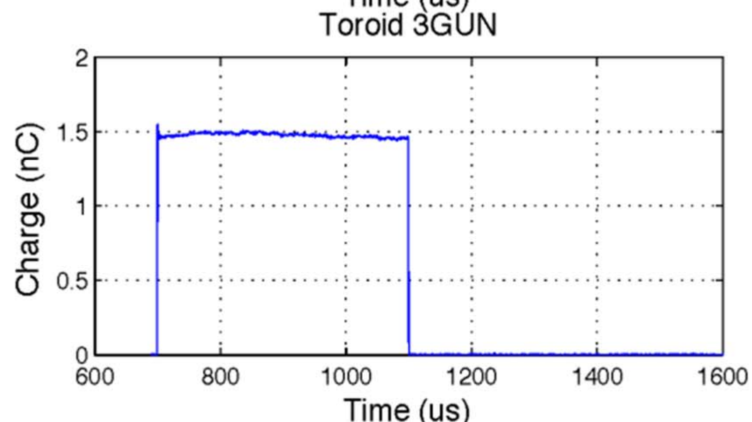

ACC67 Vector Sum
Vector Sum (MeV)
Time (us)

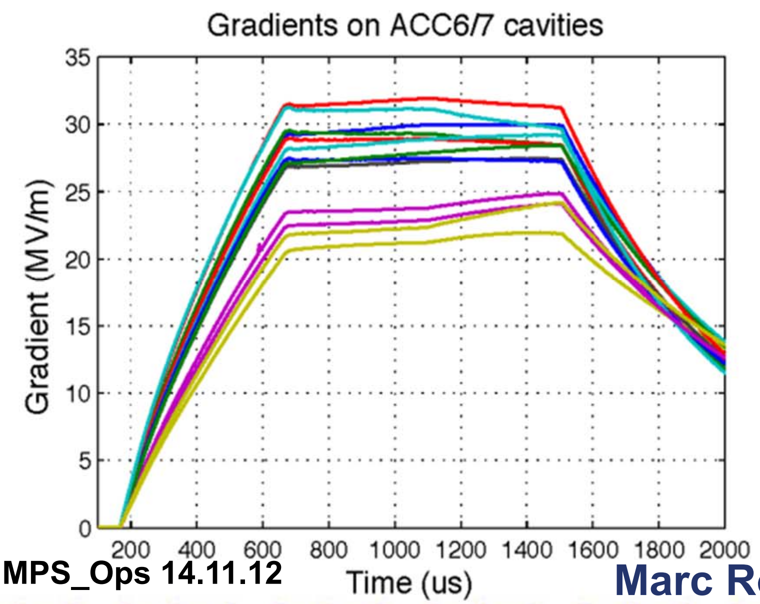

Toroid 3GUN
Charge (nC)
Time (us)

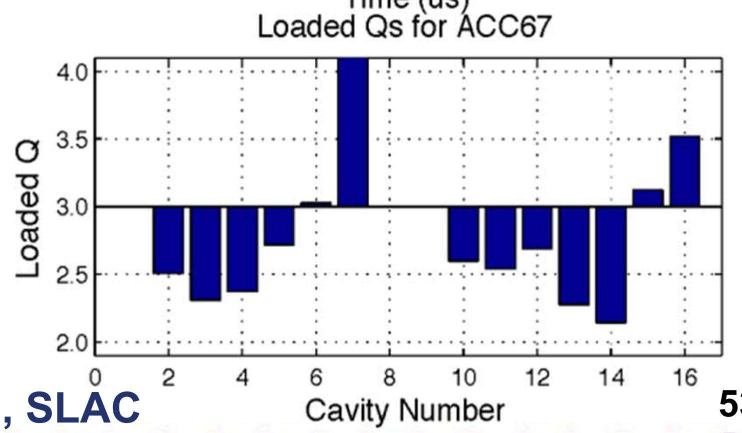

Loaded Qs for ACC67
Loaded Q
Cavity Number

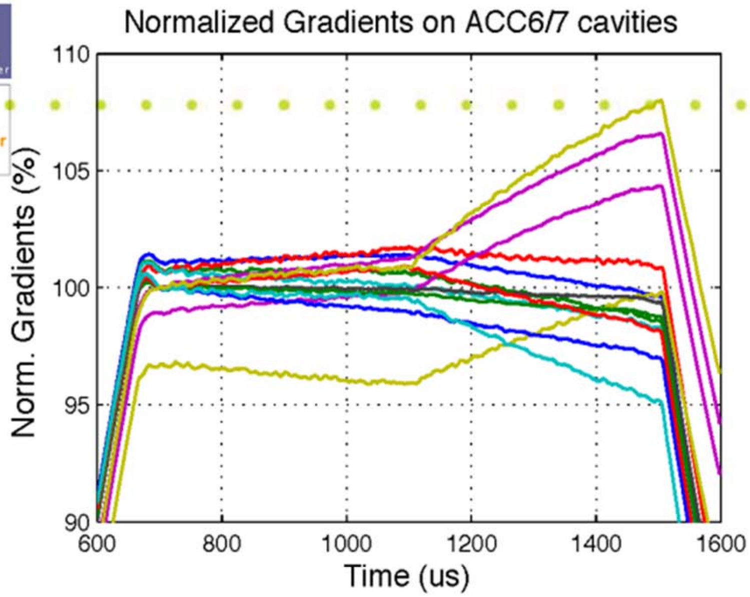

Normalized Gradients on ACC6/7 cavities
Norm. Gradients (%)
110
105
100
95
90
600
800
1000
1200
1400
1600
Time (us)

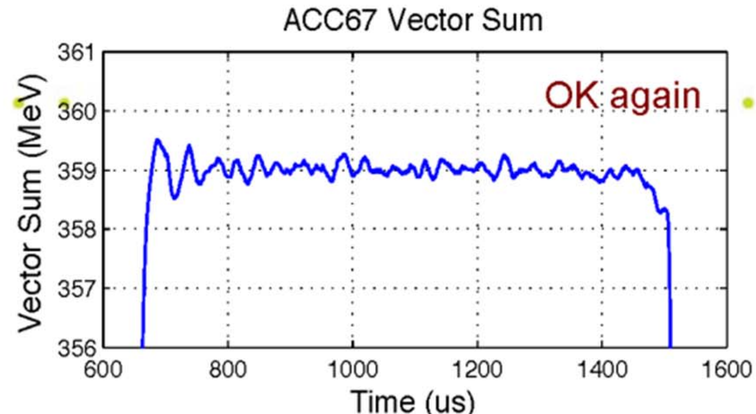

ACC67 Vector Sum
Vector Sum (MeV)
361
360
359
358
357
356
600
800
1000
1200
1400
1600
Time (us)

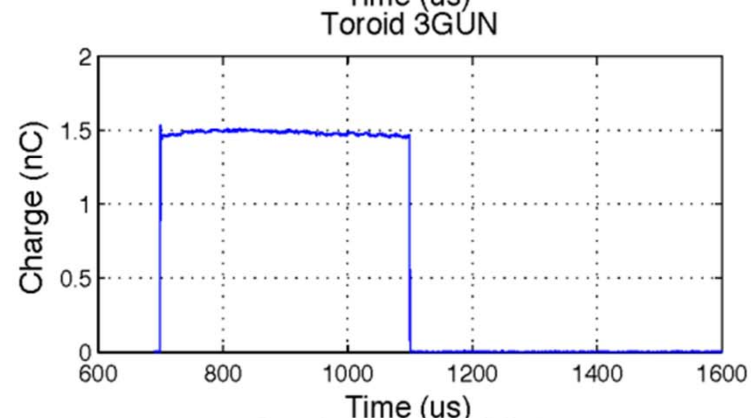

Toroid 3GUN
Charge (nC)
2
1.5
1
0.5
0
600
800
1000
1200
1400
1600
Time (us)

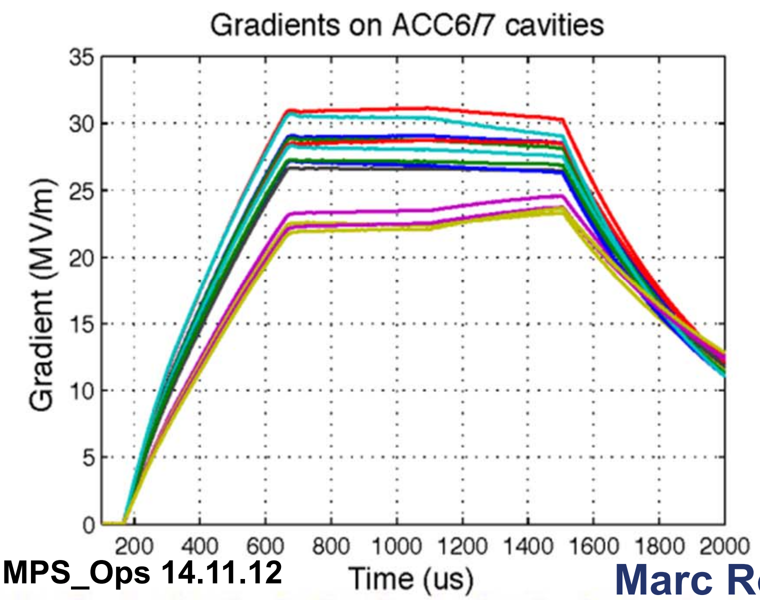

Gradients on ACC6/7 cavities
Gradient (MV/m)
35
30
25
20
15
10
5
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (us)

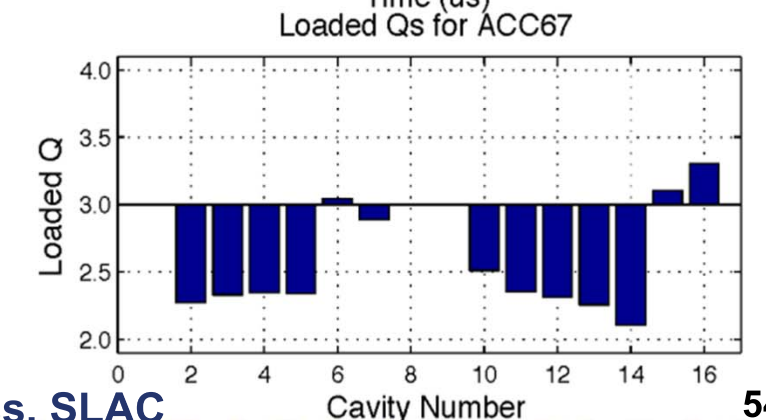

Loaded Qs for ACC67
Loaded Q
4.0
3.5
3.0
2.5
2.0
0
2
4
6
8
10
12
14
16
Cavity Number

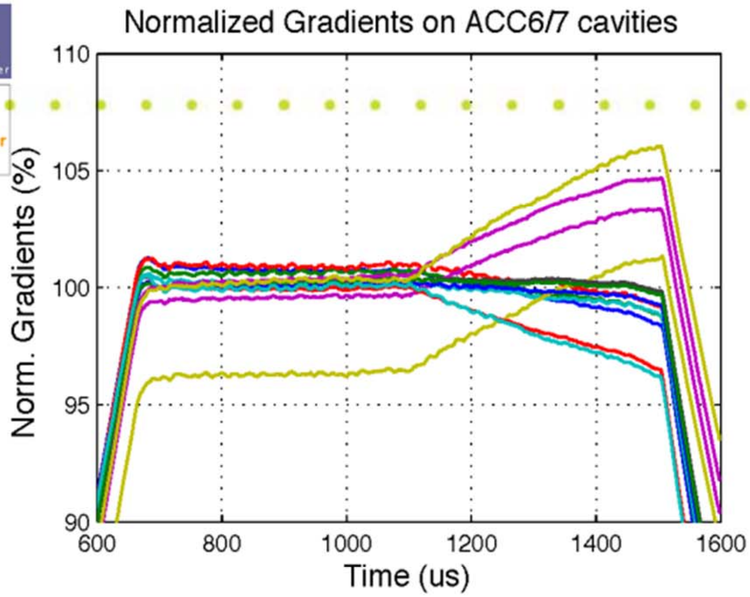

Normalized Gradients on ACC6/7 cavities
Norm. Gradients (%)
110
105
100
95
90
600
800
1000
1200
1400
1600
Time (us)

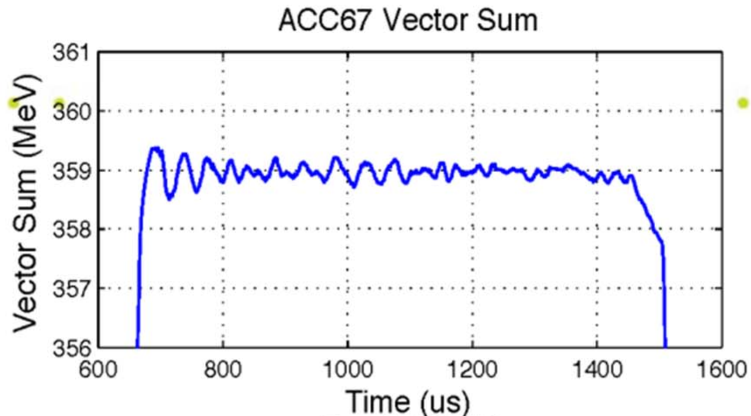

ACC67 Vector Sum
OK again
Vector Sum (MeV)
361
360
359
358
357
356
600
800
1000
1200
1400
1600
Time (us)

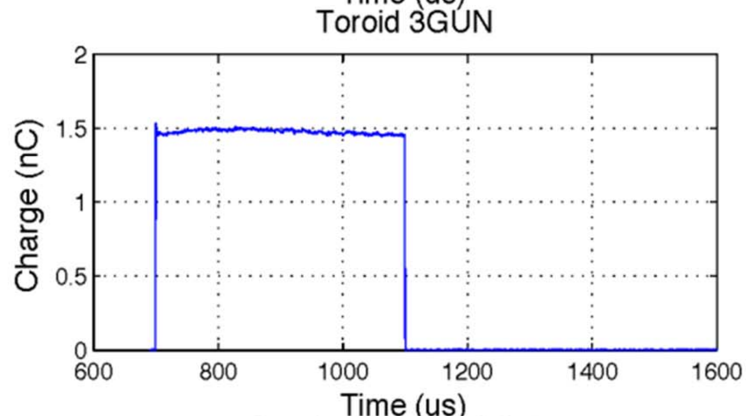

Toroid 3GUN
Charge (nC)
2
1.5
1
0.5
0
600
800
1000
1200
1400
1600
Time (us)

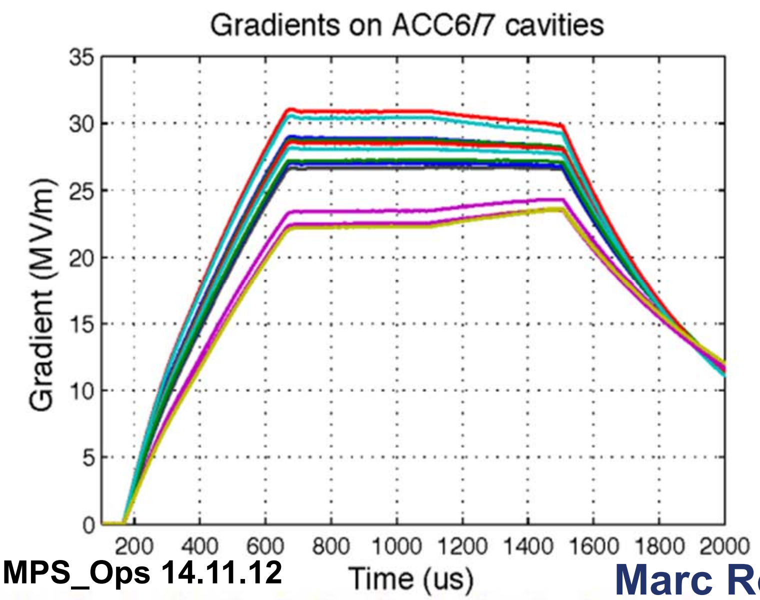

Gradients on ACC6/7 cavities
Gradient (MV/m)
35
30
25
20
15
10
5
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (us)

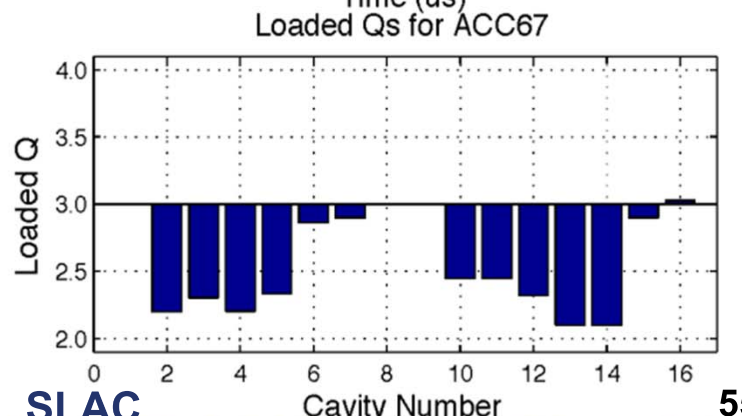

Loaded Qs for ACC67
Loaded Q
4.0
3.5
3.0
2.5
2.0
0
2
4
6
8
10
12
14
16
Cavity Number

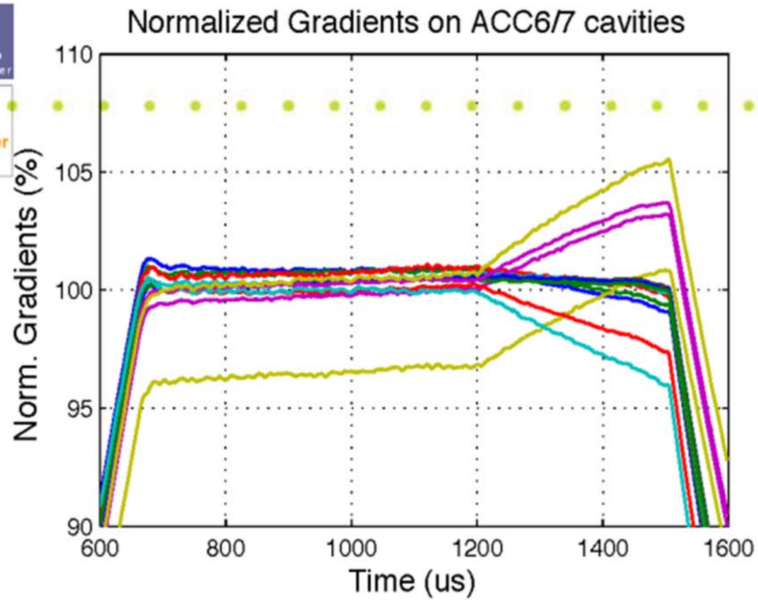

Normalized Gradients on ACC6/7 cavities
Norm. Gradients (%)
110
105
100
95
90
600
800
1000
1200
1400
1600
Time (us)

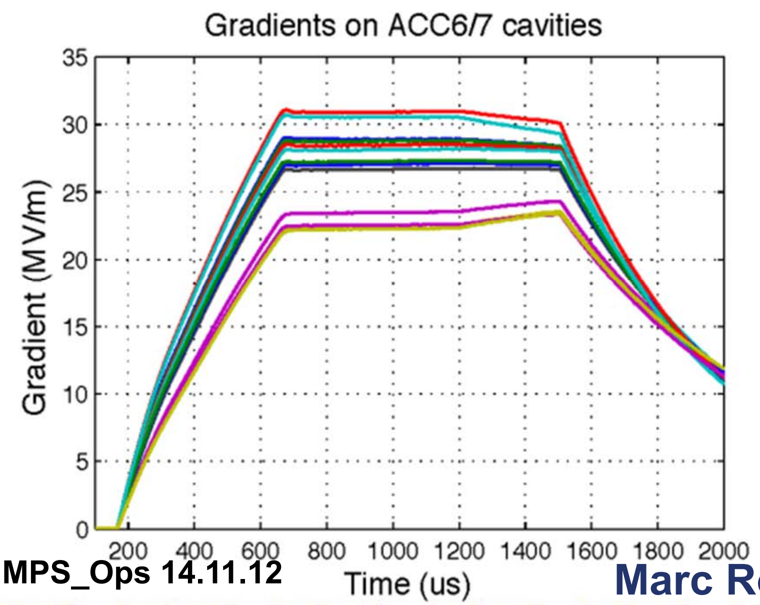

ACC67 Vector Sum
Vector Sum (MeV)
361
360
359
358
357
356
600
800
1000
1200
1400
1600
Time (us)

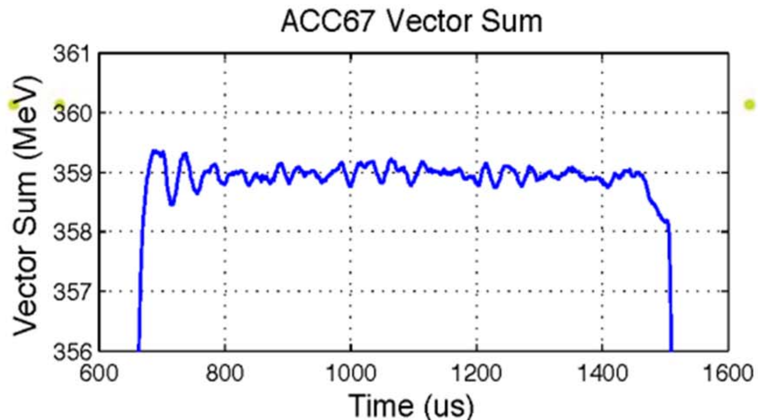

Toroid 3GUN
Charge (nC)
2
1.5
1
0.5
0
600
800
1000
1200
1400
1600
Time (us)

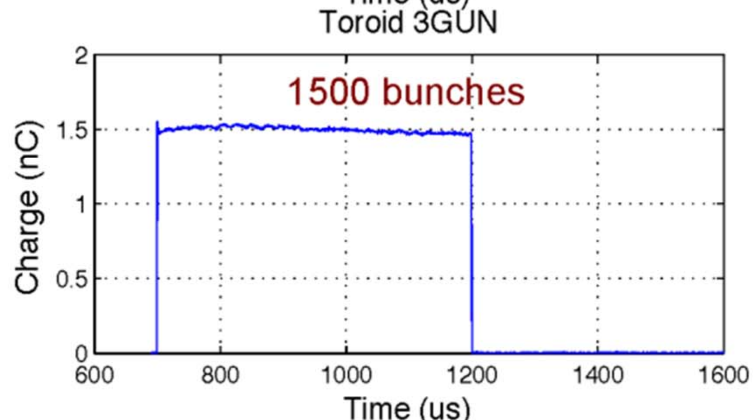

Gradients on ACC6/7 cavities
Gradient (MV/m)
35
30
25
20
15
10
5
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (us)

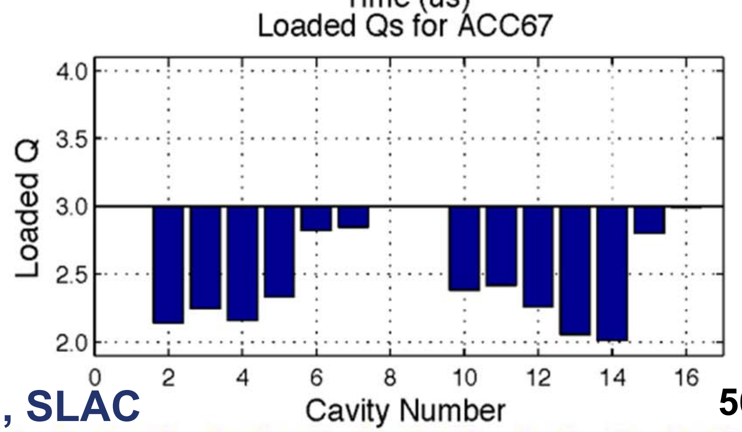

Loaded Qs for ACC67
Loaded Q
4.0
3.5
3.0
2.5
2.0
0
2
4
6
8
10
12
14
16
Cavity Number

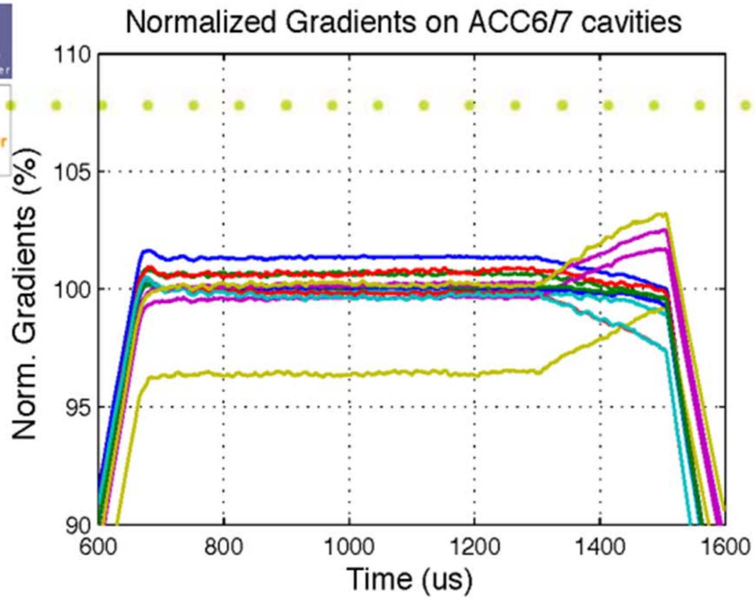

Normalized Gradients on ACC6/7 cavities
Norm. Gradients (%)
Time (us)
110
105
100
95
90
600
800
1000
1200
1400
1600

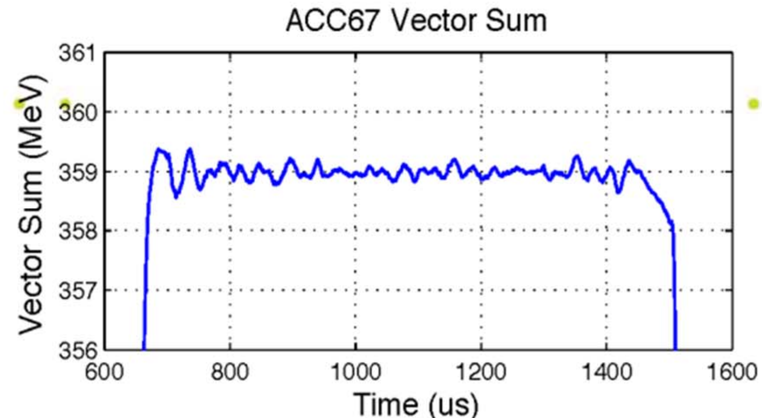

Gradients on ACC6/7 cavities
Gradient (MV/m)
Time (us)
35
30
25
20
15
10
5
0
200
400
600
800
1000
1200
1400
1600
1800
2000

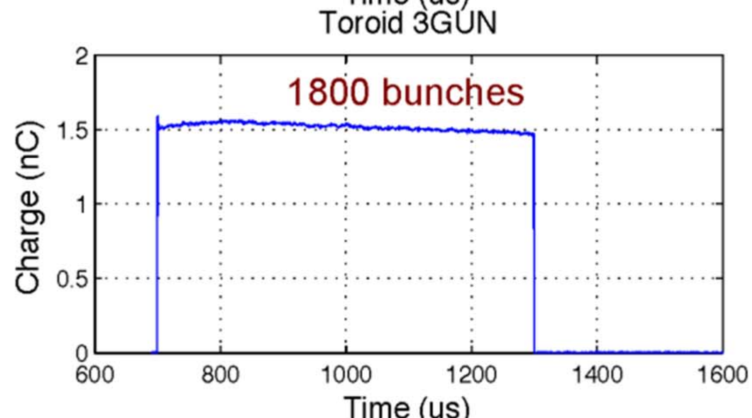

ACC67 Vector Sum
Vector Sum (MeV)
Time (us)
361
360
359
358
357
356
600
800
1000
1200
1400
1600

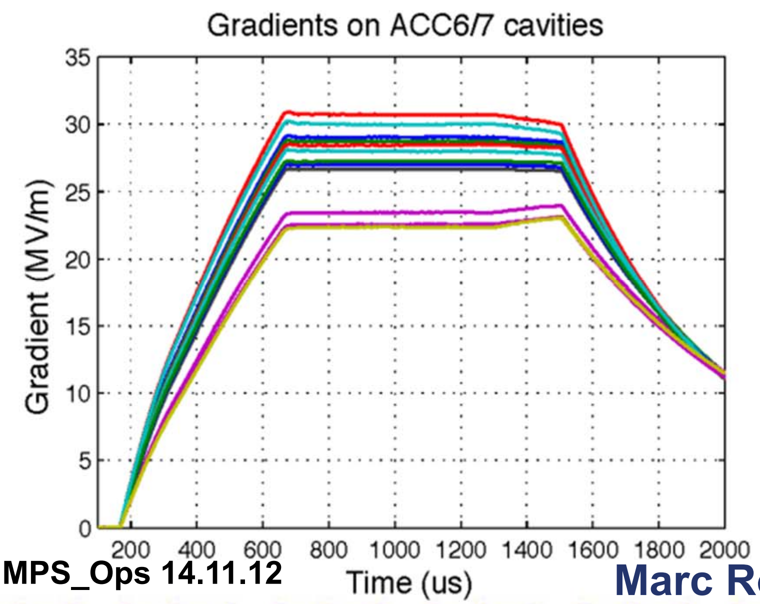

Toroid 3GUN
1500 bunches
Charge (nC)
Time (us)
2
1.5
1
0.5
0
600
800
1000
1200
1400
1600

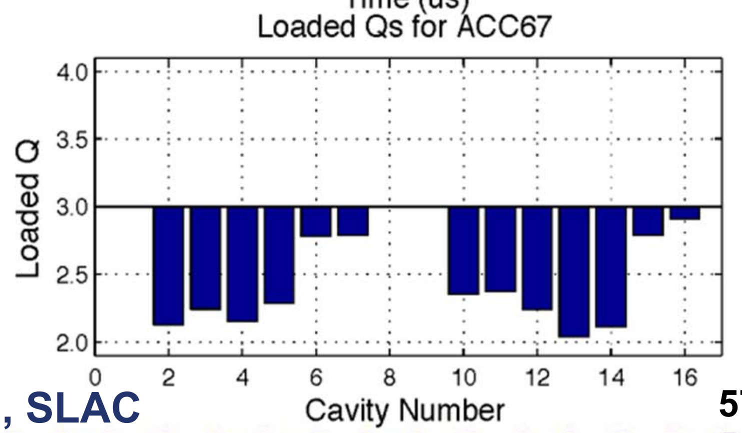

Loaded Qs for ACC67
Loaded Q
Cavity Number
4.0
3.5
3.0
2.5
2.0
0
2
4
6
8
10
12
14
16

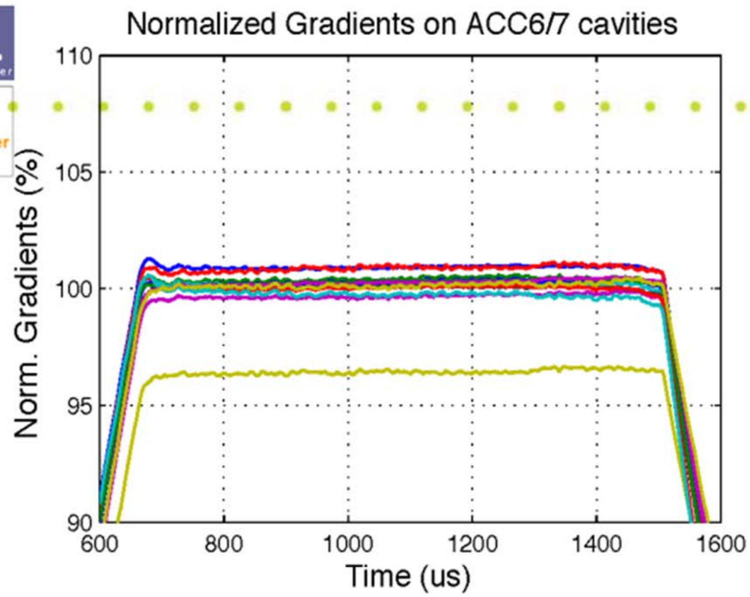

Normalized Gradients on ACC6/7 cavities
Norm. Gradients (%)
110
105
100
95
90
600
800
1000
1200
1400
1600
Time (us)

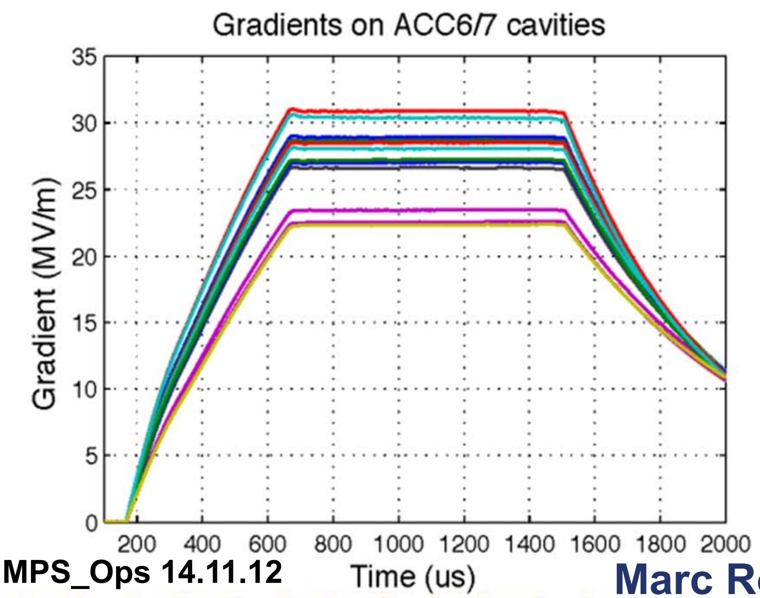

ACC67 Vector Sum
Vector Sum (MeV)
361
360
359
358
357
356
600
800
1000
1200
1400
1600
Time (us)

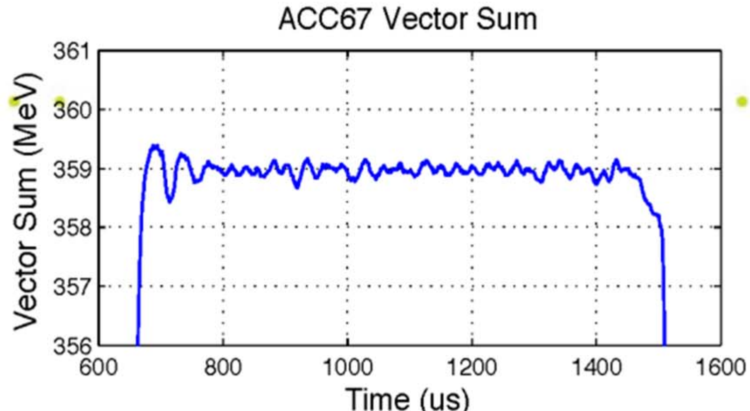

Toroid 3GUN
1800 bunches
Charge (nC)
2
1.5
1
0.5
0
600
800
1000
1200
1400
1600
Time (us)

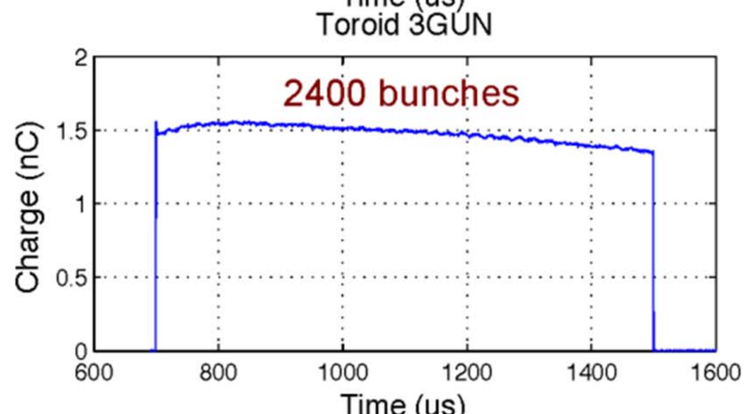

Gradients on ACC6/7 cavities
Gradient (MV/m)
35
30
25
20
15
10
5
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (us)

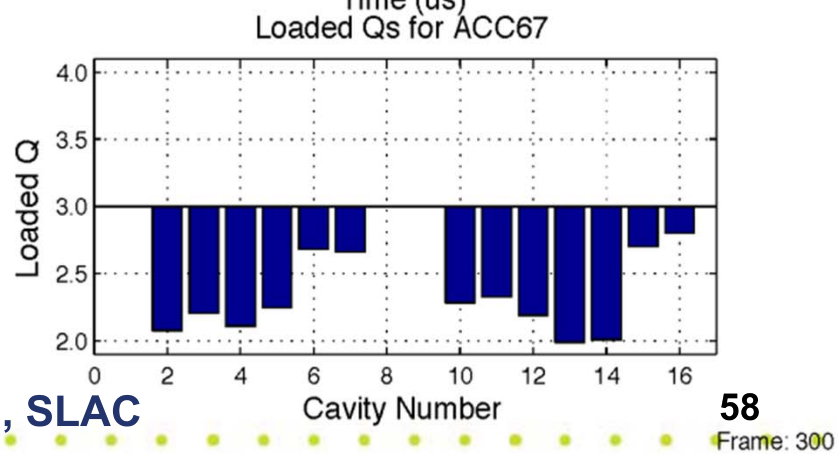

Loaded Qs for ACC67
Loaded Q
4.0
3.5
3.0
2.5
2.0
0
2
4
6
8
10
12
14
16
Cavity Number


Normalized Gradients on ACC6/7 cavities
Norm. Gradients (%)
110
105
100
95
90
600
800
1000
1200
1400
1600
Time (us)

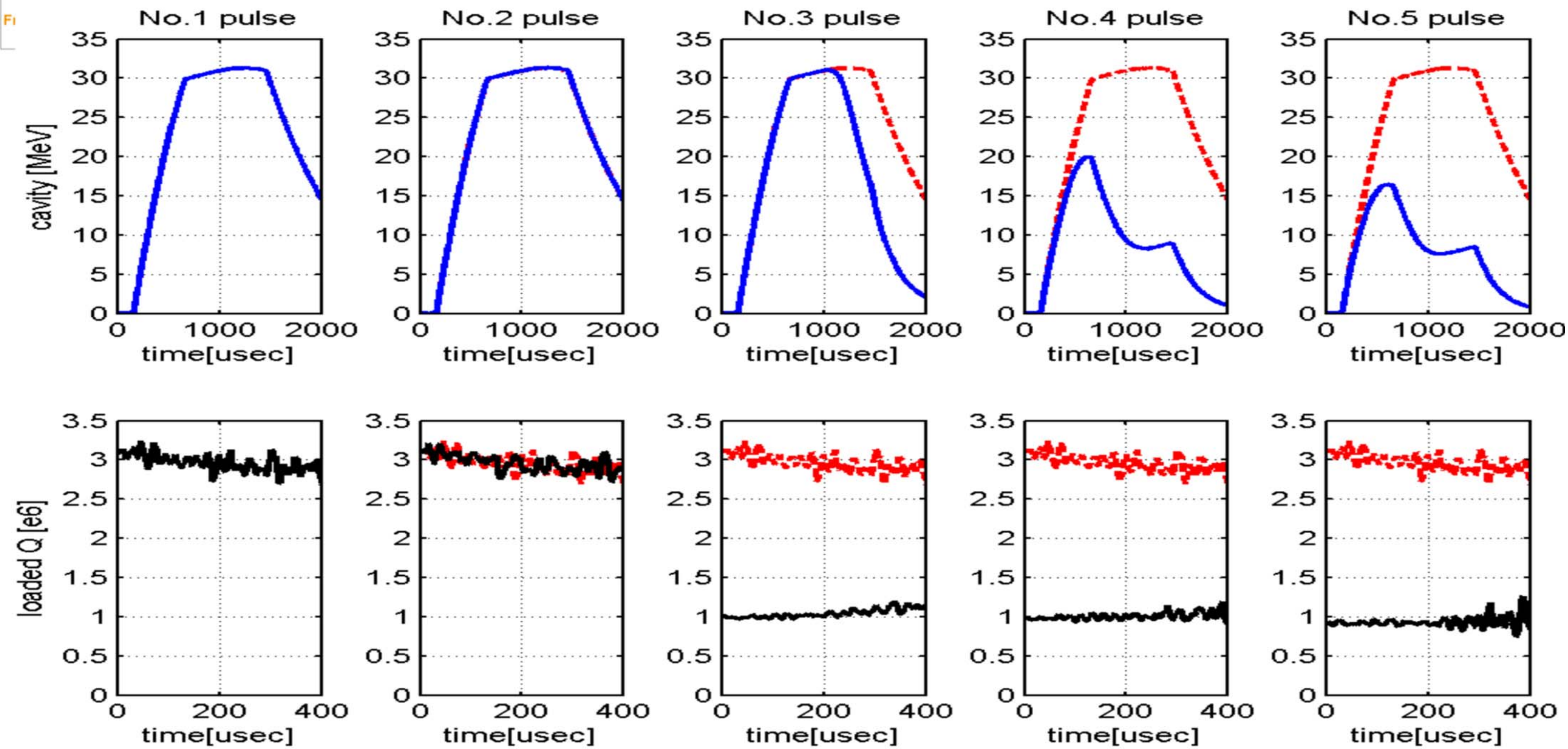

Gradients on ACC6/7 cavities
Gradient (MV/m)
35
30
25
20
15
10
5
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (us)


ACC67 Vector Sum
Vector Sum (MeV)
361
360
359
358
357
356
600
800
1000
1200
1400
1600
Time (us)


Toroid 3GUN
2400 bunches
Charge (nC)
2
1.5
1
0.5
0
600
800
1000
1200
1400
1600
Time (us)

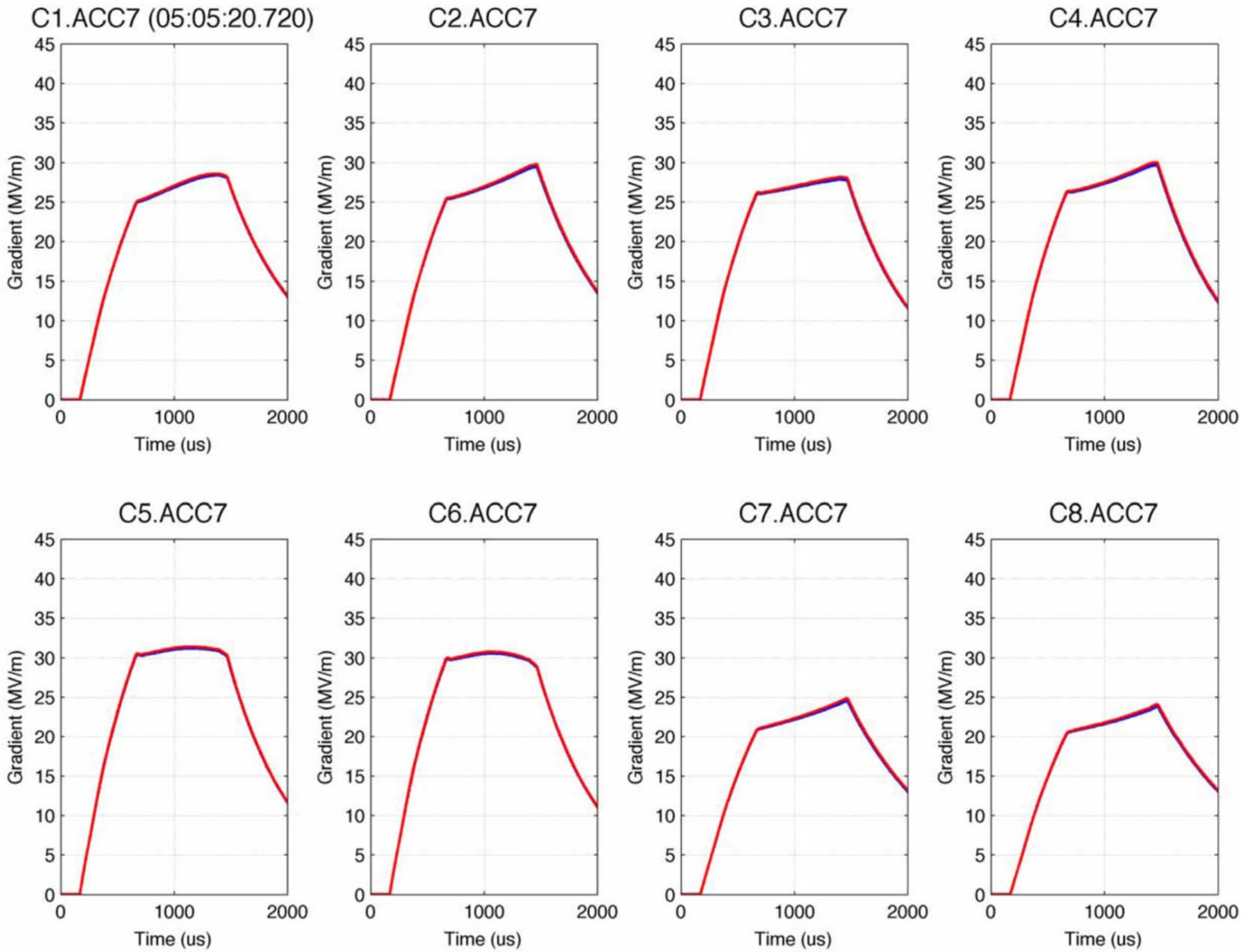

Loaded Qs for ACC67
Loaded Q
4.0
3.5
3.0
2.5
2.0
0
2
4
6
8
10
12
14
16
Cavity Number
Frame: 300

Quenches during 800us RF pulses, no beam



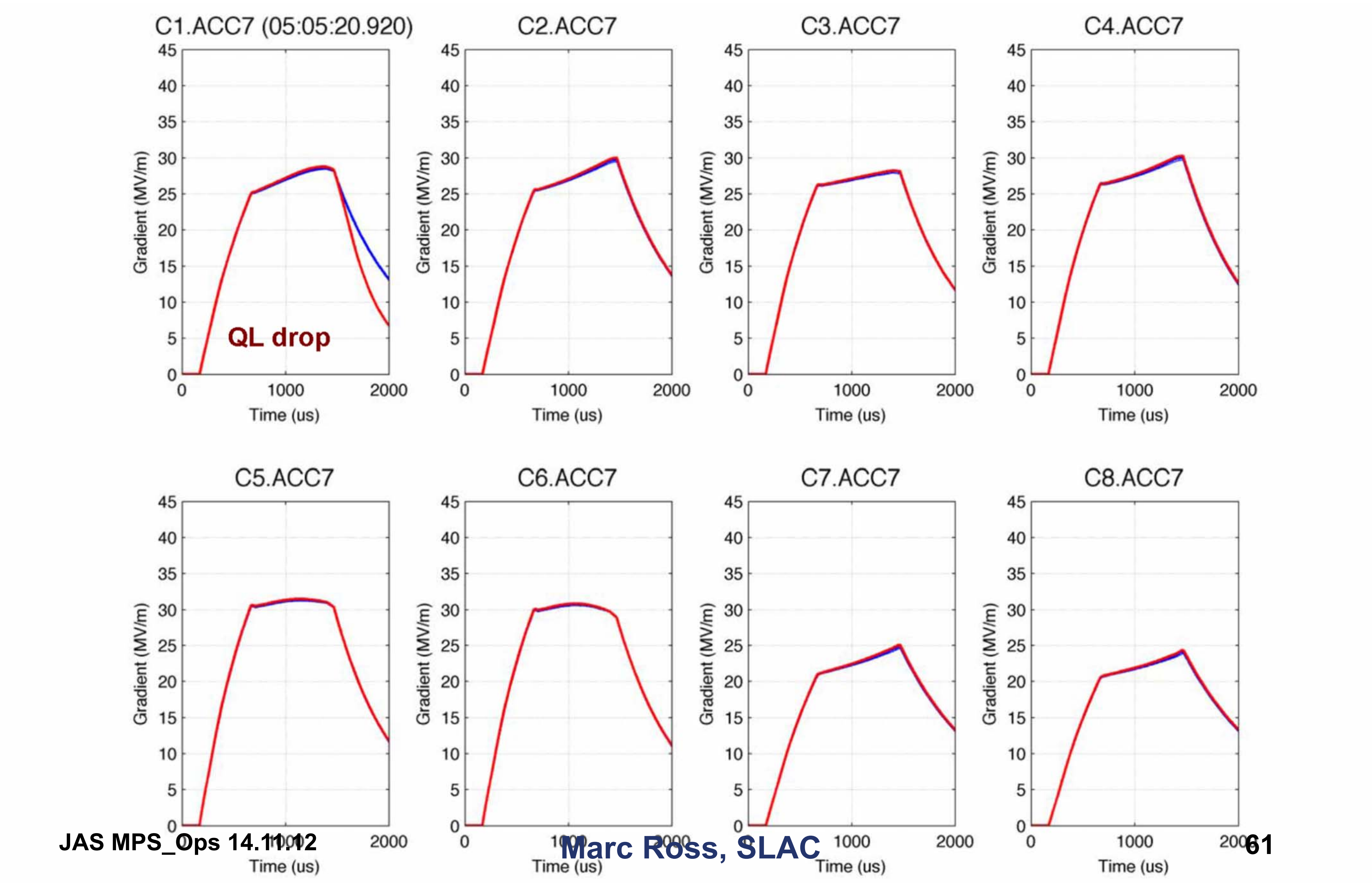
- At longer pulse (~800 us flattop), "quasi-quenches" were not observed.
- Once a quench took place, there was not a quick recovery, probably due to the larger energy deposited in the quenched area.

Event #14427309: ACC7 cavity gradients before first quench

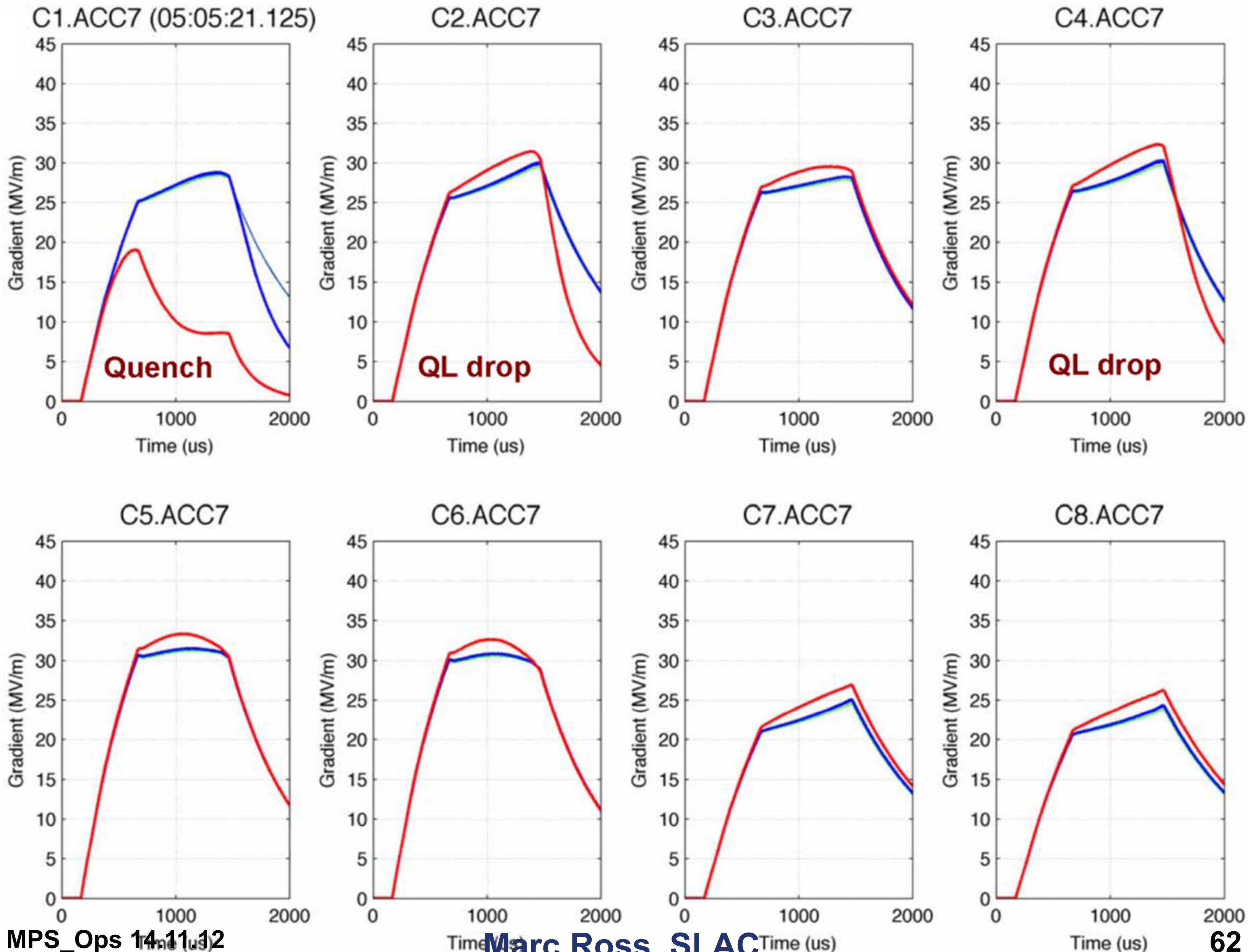


Red: this event, Blue: previous event, Green: nominal

Event #14427310: QL drop on C1



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

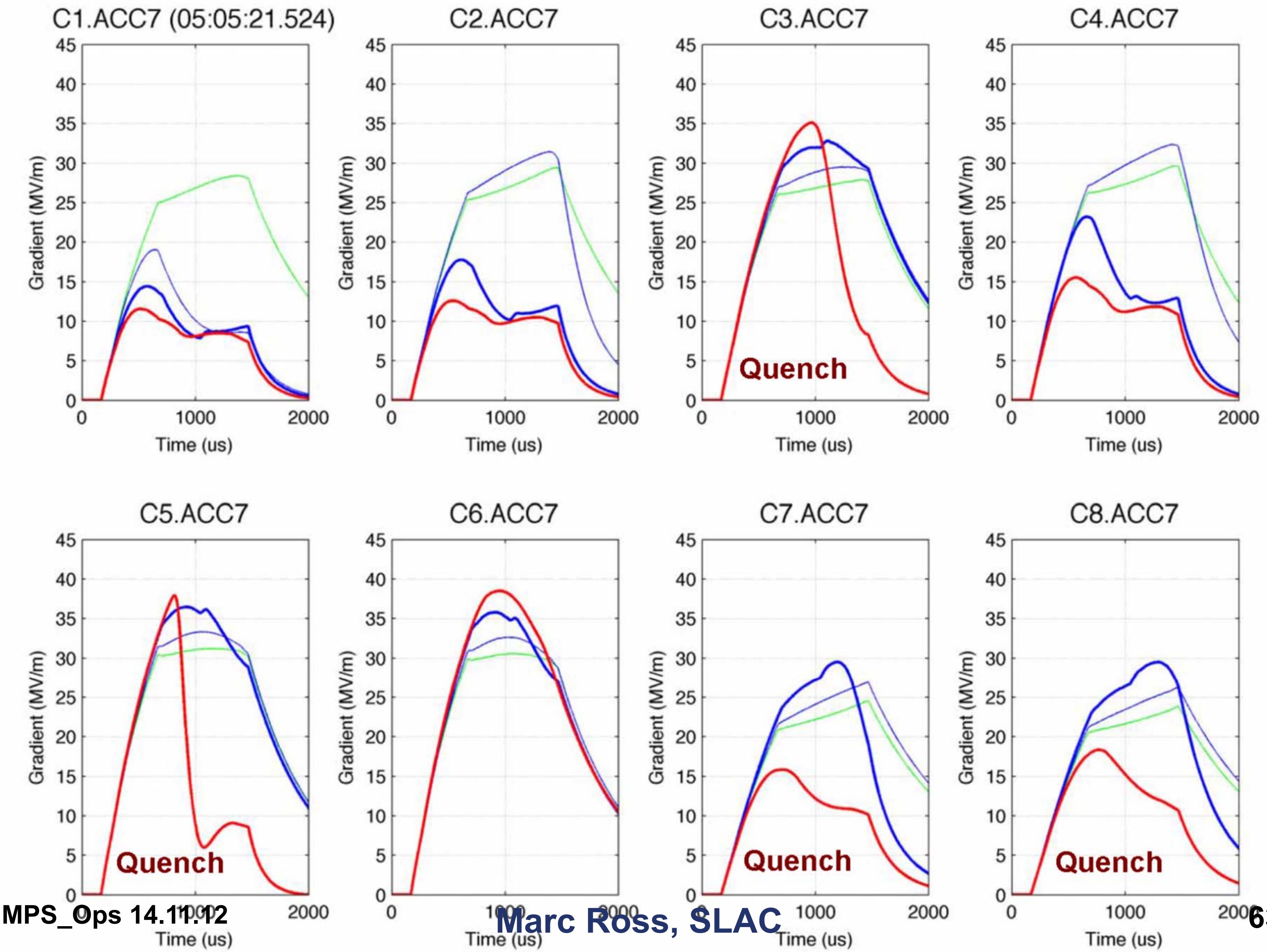


Red: forward, Blue: probe, Green: nominal

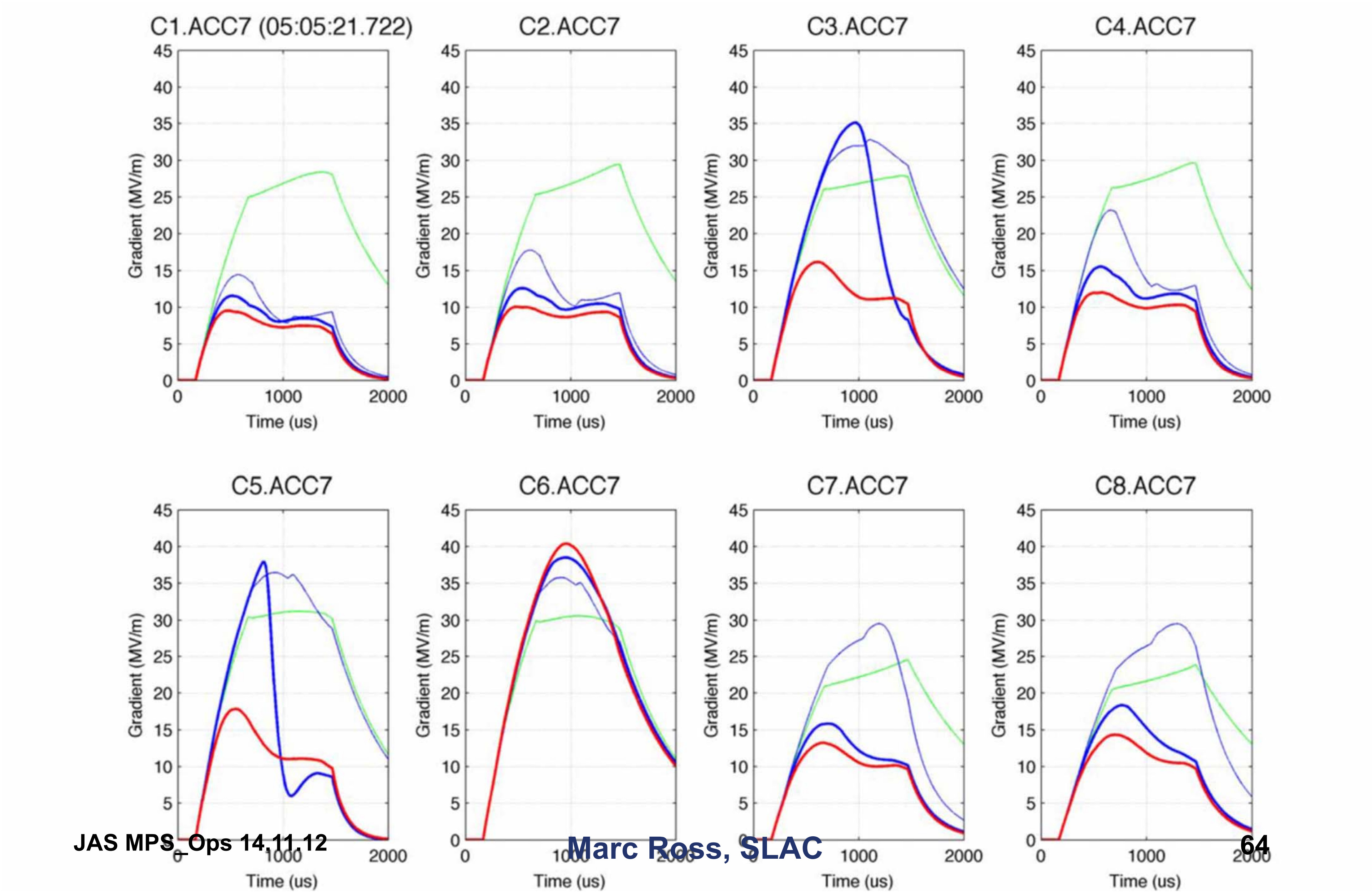
J. Carwardine, MSK Seminar 16 March 2012

Vector Sum is maintained by driving the other cavities harder

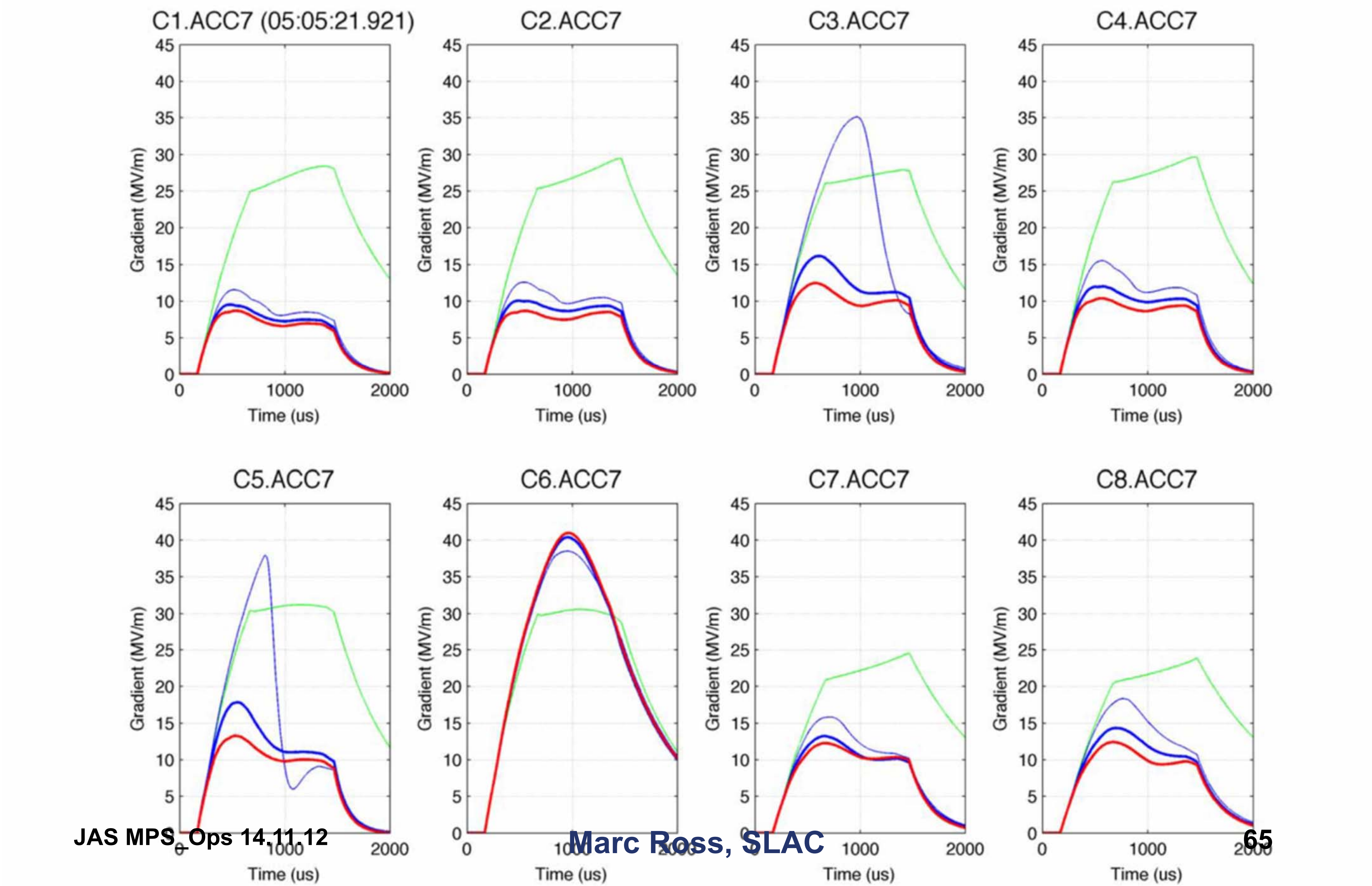
Event #14427313: quenches on C7, C8, C5, C3



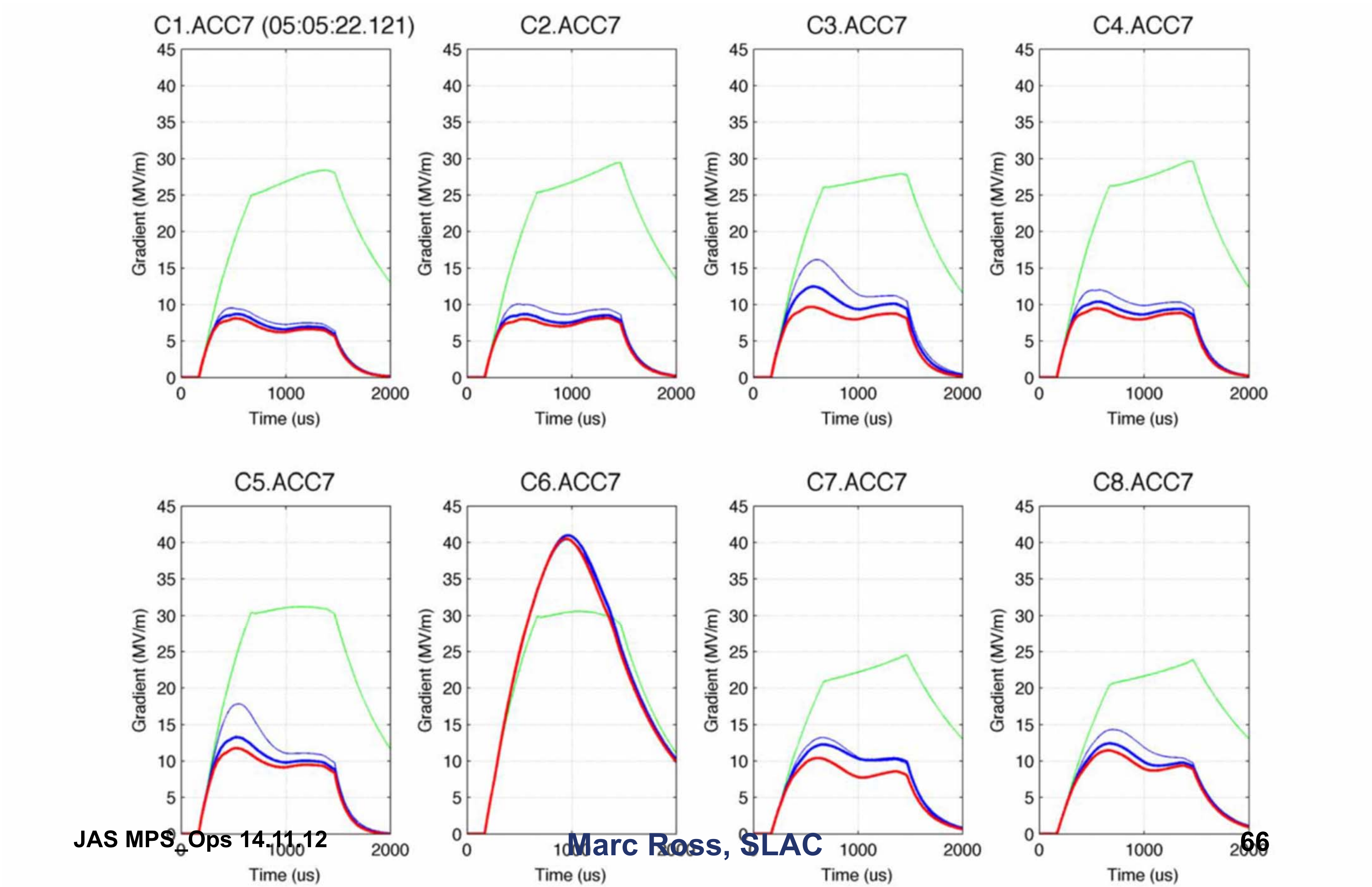
Event #14427314: all cavities quenched, except C6



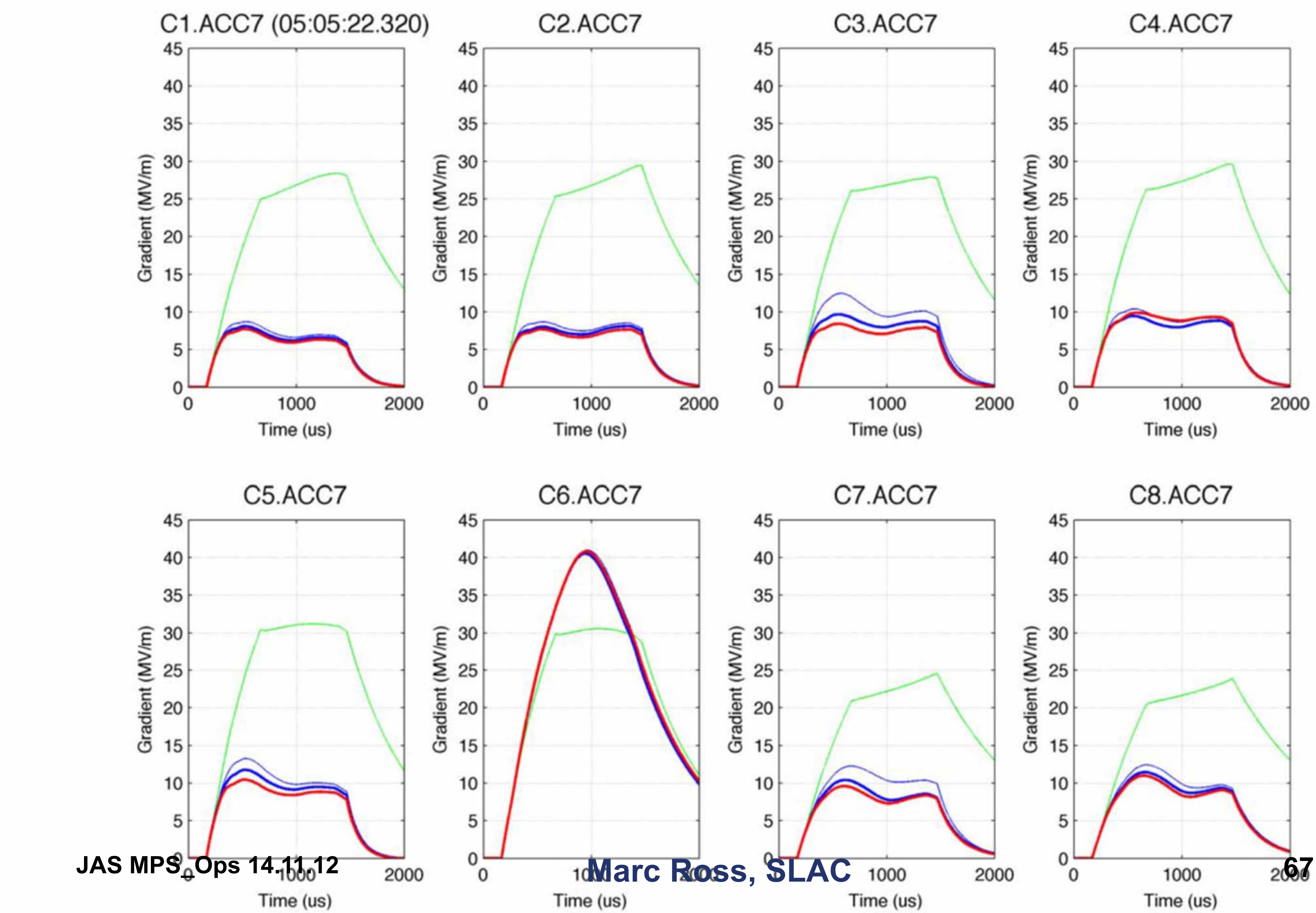
Event #14427315



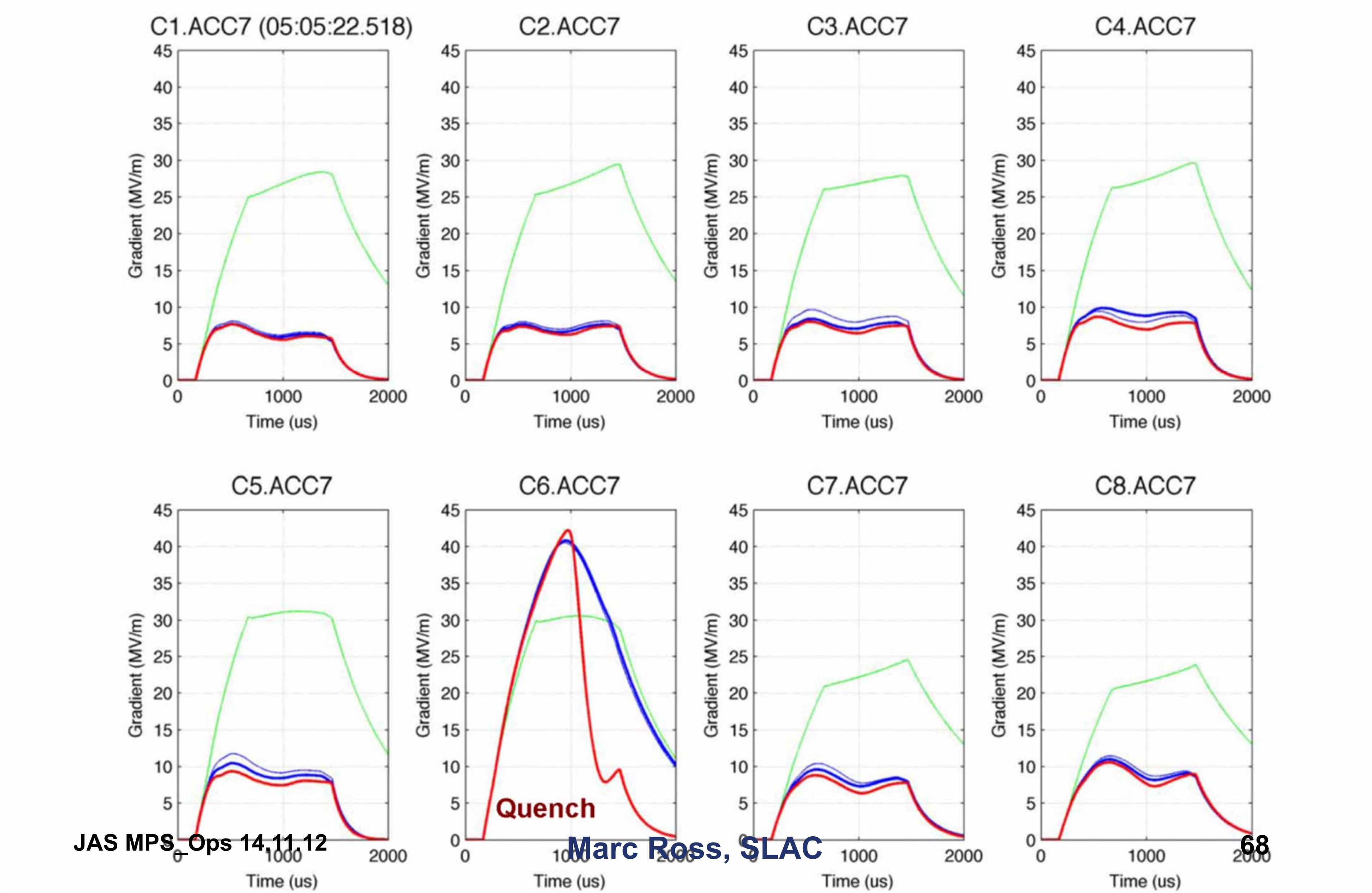
Event #14427316



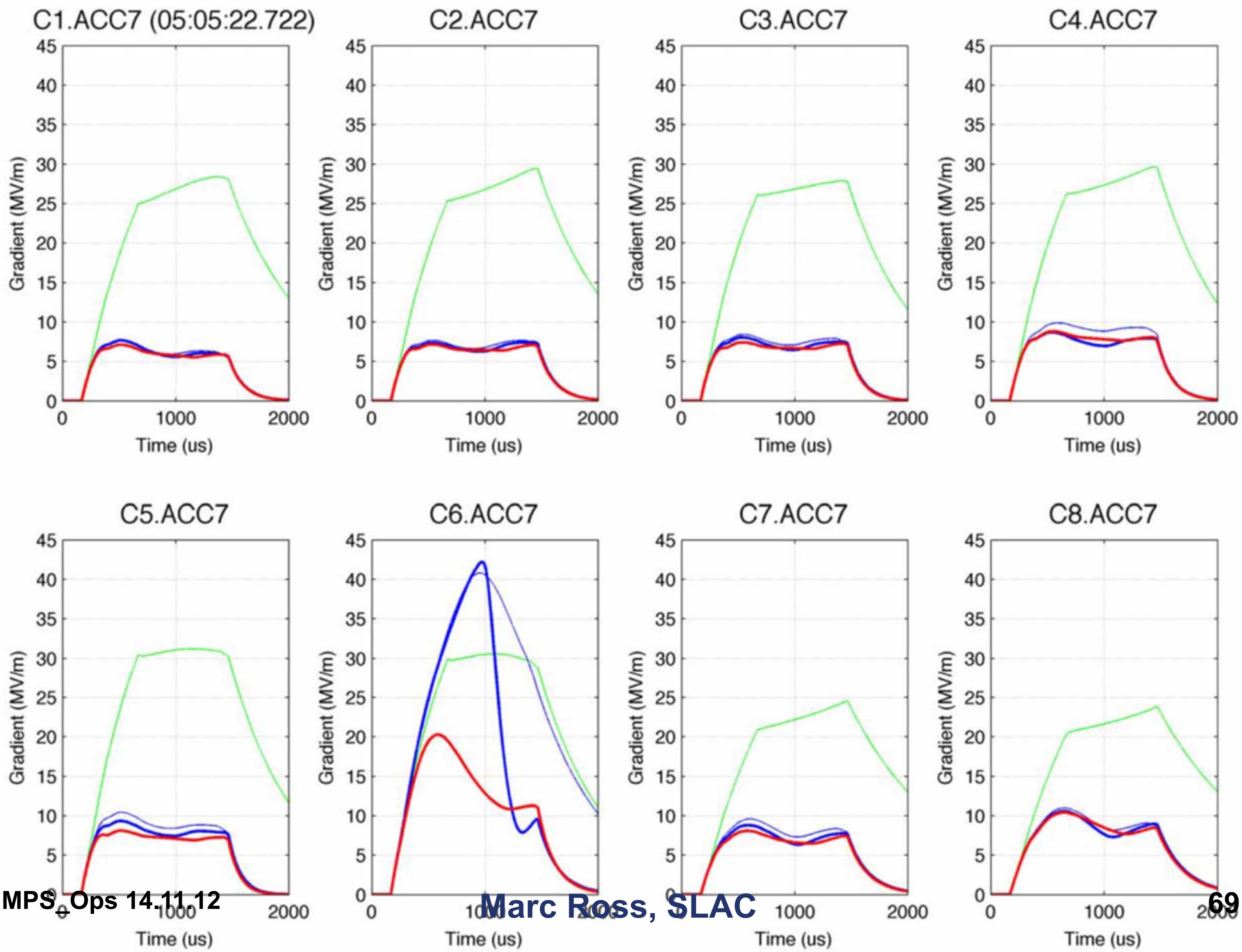
Event #14427317



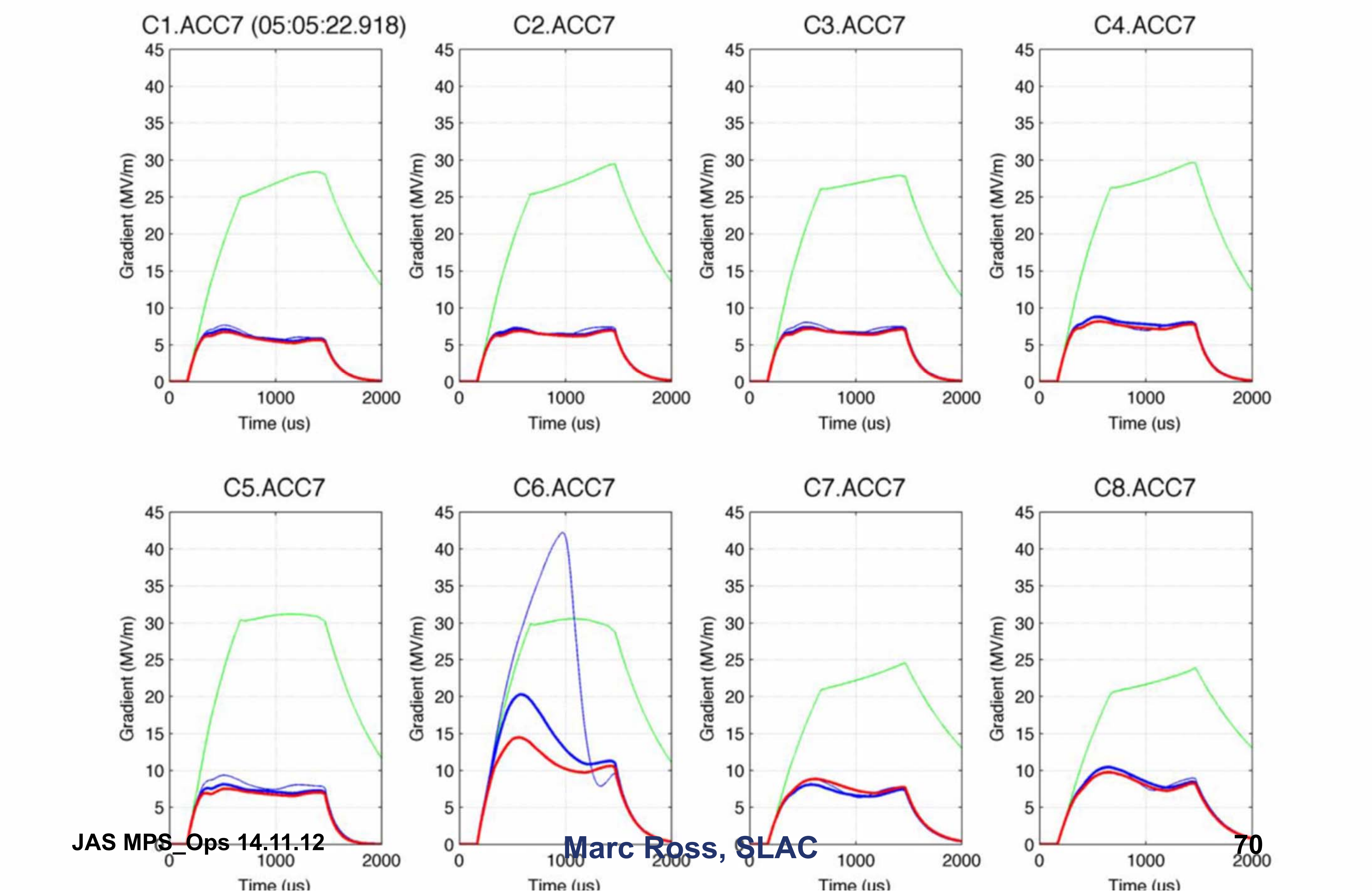
Event #14427318: C6 finally quenches



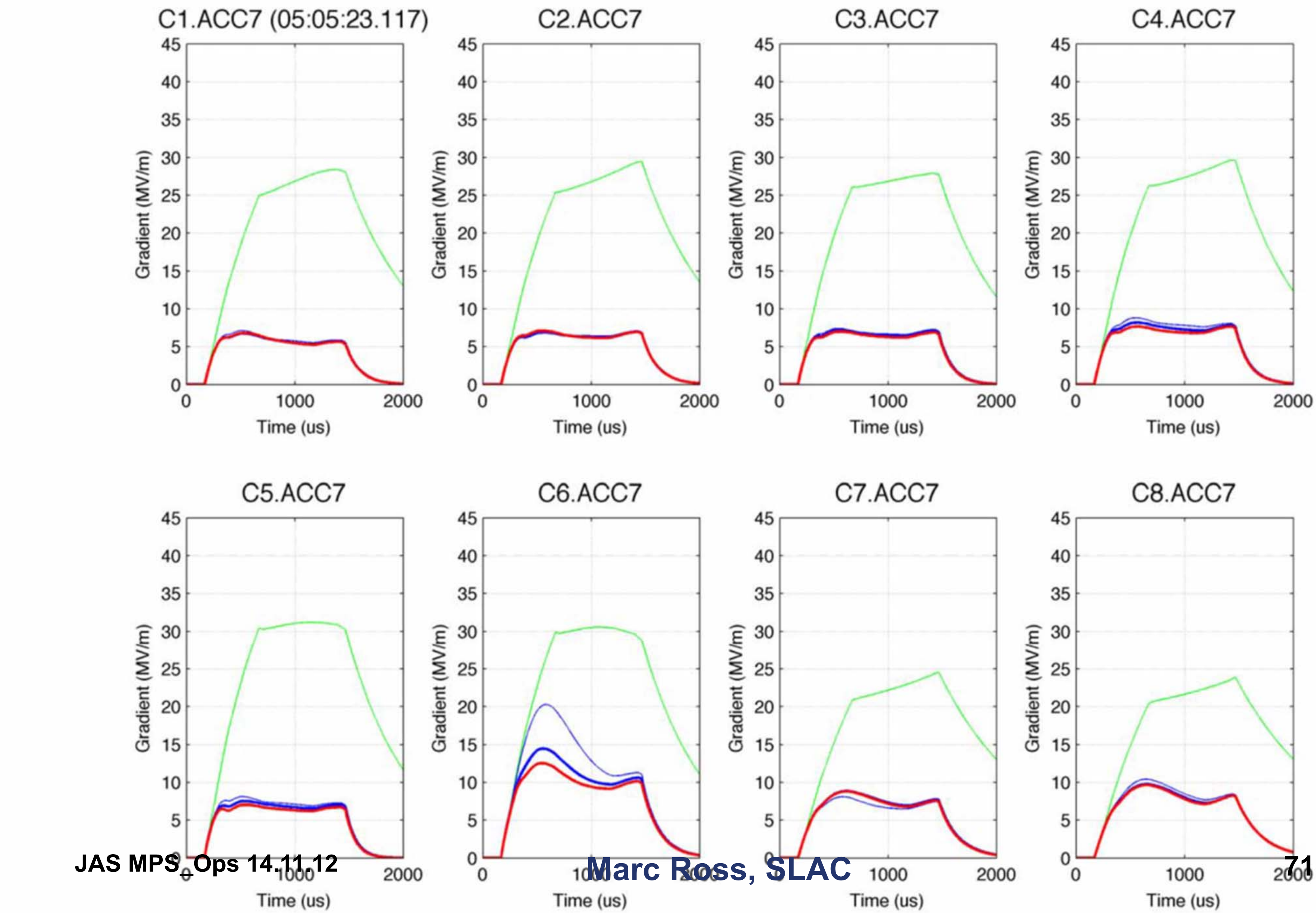
Event #14427319: all cavities quenched



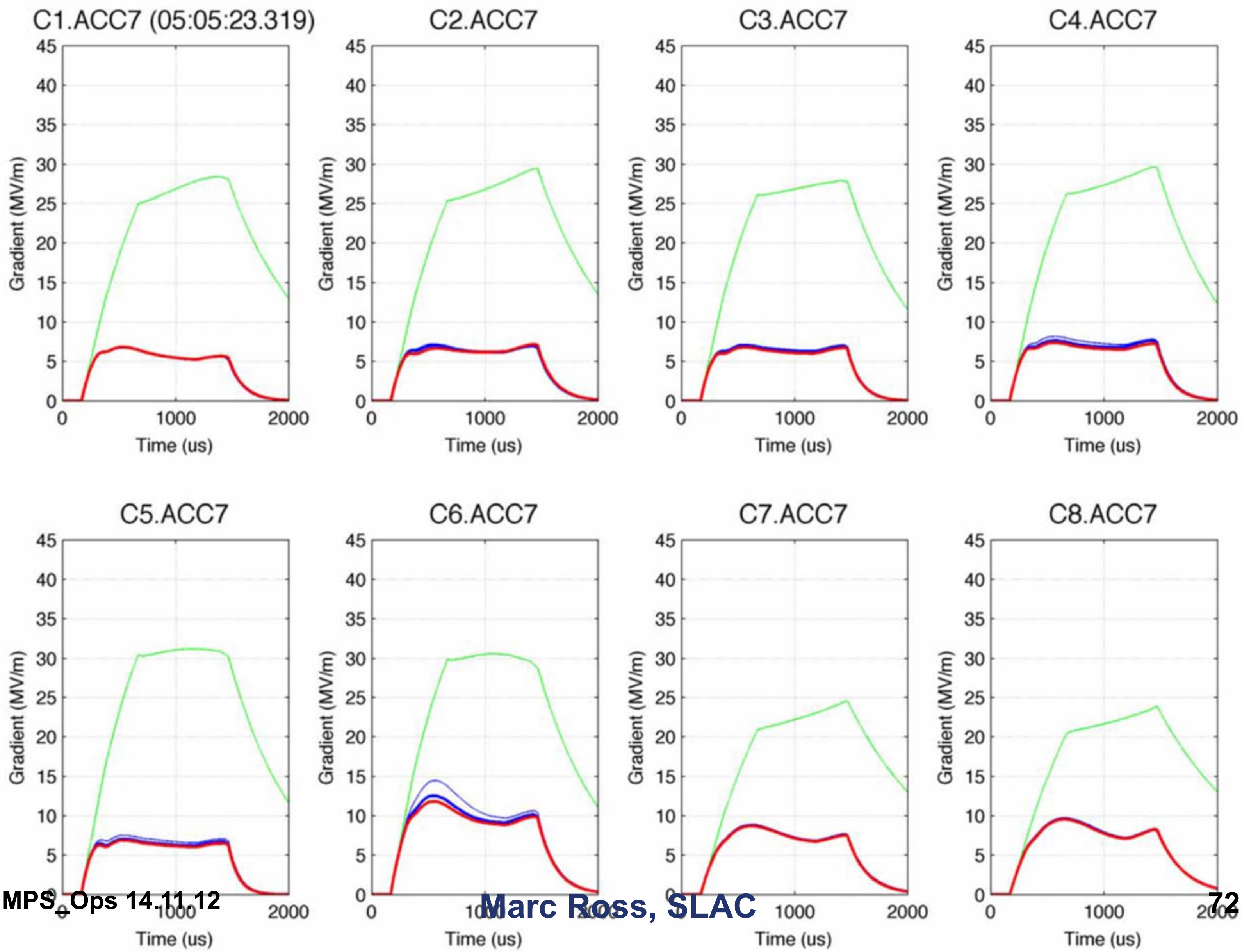
Event #14427320: all cavities quenched



Event #14427321: all cavities quenched



Event #14427322: all cavities quenched



MP and Operations: Outline

- Linac Segmentation and ‘Bifurcation’
- Turn-on / Recovery following a stop
- Failure modes
  - Linac modeling
  - Finding the worst case
- Availability

Failure Mode models: Conclusions

- A single quadrupole failure will not direct the beam outside the cavity aperture. About 8 failing quadrupoles at random positions along the ILC main linac are necessary.
- A common klystron phase shift must become larger than 53^0 to lose more than 50% of the beam particles.
- A common feature in the studied examples is that the beam emittance is largely increased before the beam is lost.
- The particle densities observed in the cavities a than $10^{12}/mm^2$/cavity. There is no need for a system along the length of the linac.

For a SC module with 9 cells and a typical ILC bunch with $2 \cdot 10^2$ particles per bunch and 3000 bunches per train:

$$10\ \% \cdot 2 \cdot 10^{10} \cdot 3000/9 = 7 \cdot 10^{11} \text{ particles}$$

The typical particle density to generate a hole (copper) is $10^{13}/mm^2$. We are still more than an order of magnitude away from the critical value. Furthermore the above argument overestimates the particle density because two bunches will probably not hit exactly the same spot. Since the particles in different bunches are uncorrelated the the average density will be smaller. A reasonable control system that can abort the beam early will be able to reduce this value even further

Failure modes

Identification:

- machine operation modes (tuning mode, positron production mode, etc…)
- beam modes (low power, high power, …)
- Machine segmentation for MPS

Failure catalogue… hazards etc… to be established

For each failure accident :

- Timing:
    - fast ~us) - bunch by bunch
    - medium (~ms) - inside train
    - slow (~sec) – longer then one train
- Diagnostics to identify failure event
- Potential damage scenario (need beam physics modeling)
- Reaction to accident and required devices
- Recovery from accident

Some failure modes in ML

HLRF:
- Trip in klystron / modulator/ drive amplifier (fast)
- Timing/phase synchronization system failed

LLRF:
- Phase / amplitude control failed, coherent phase shift (worst case)

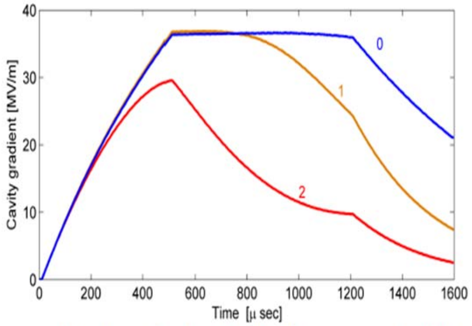
Cavities:
- Quench (~0.5ms)
- Dark current
- Coupler breakdown

Magnets/dipole:
- Trip / Quench (~1s)
- Misalignment

Vacuum:
- Lost of vacuum is segment (stop machine)

BPM/Toroid:
- Failure/ wrong signal

BC:
- RF system (trip, phase shift
- Magnets (trip, misalignment)

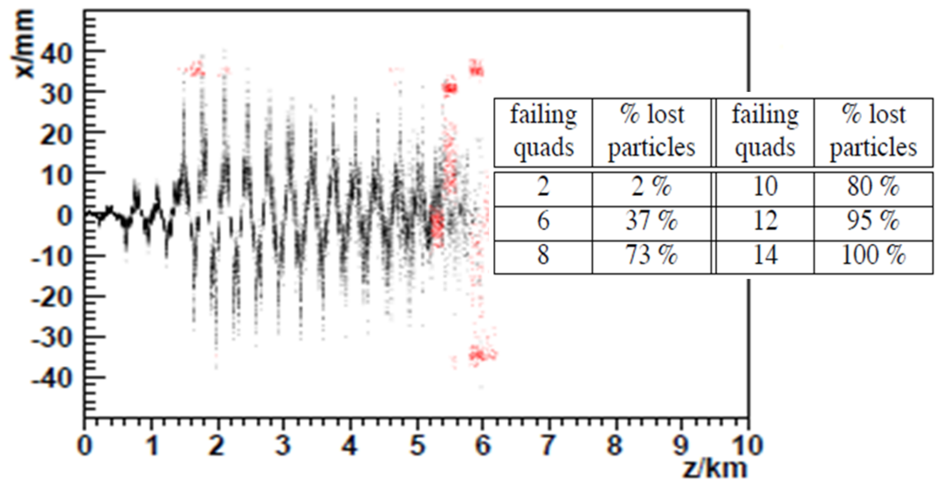


Cavity gradient profile for three successive RF pulses, before (0) and during quench (1) and (2).

Failure modes studies in Main Linac

Some studies, done in past

1. P.Eliasson, et.al., “Studies of Failure Modes in the ILC Main Linac”, EUROTeV-Report-2008-075
2. E. Adli et.al., “Studies of Selected Failure Modes in the ILC and CLIC Linear Colliders”, EUROTeV-Report-2006-040



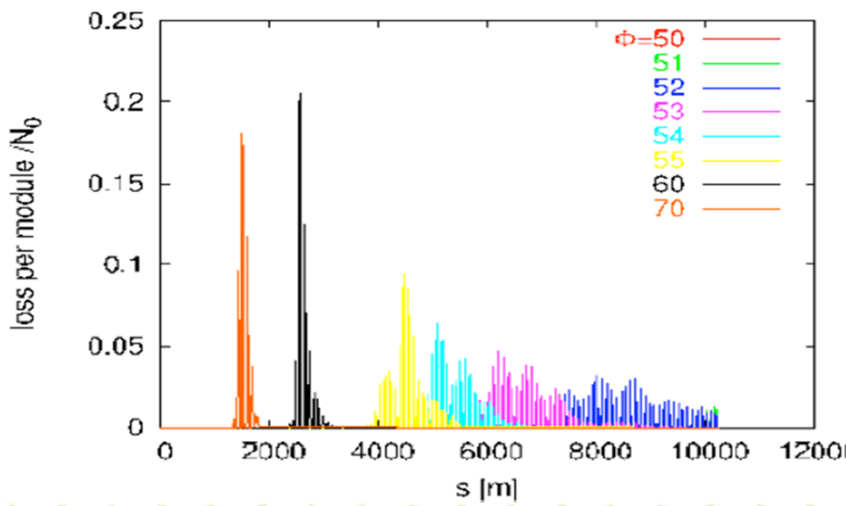
- Studies of quadrupole failure and errors
- Studies of klystron phase errors and their impact on the machine

ϕ	0^0	9^0	18^0	27^0	36^0
E_ϕ/GeV	251.5	248.6	240	225.9	206.4
45^0	54^0	63^0	72^0	81^0	90^0
182.3	154.0	(56.3)	(29.3)	(19.4)	(15.0)

Critical coherent energy shift: δ_x =−0.39; δ_y = −0.46

- In the BDS 50% of the beam is already lost when the phase is below 3∘ or above 7∘.
- Max particle density when beam is lost (klystron phase errors + nominal misalignments)

  ~10% of nominal or < 10^{12}/mm^2/cavity (below damage level),no need for abort system in ML



Linac Simulated Beam Loss vs Φ and z

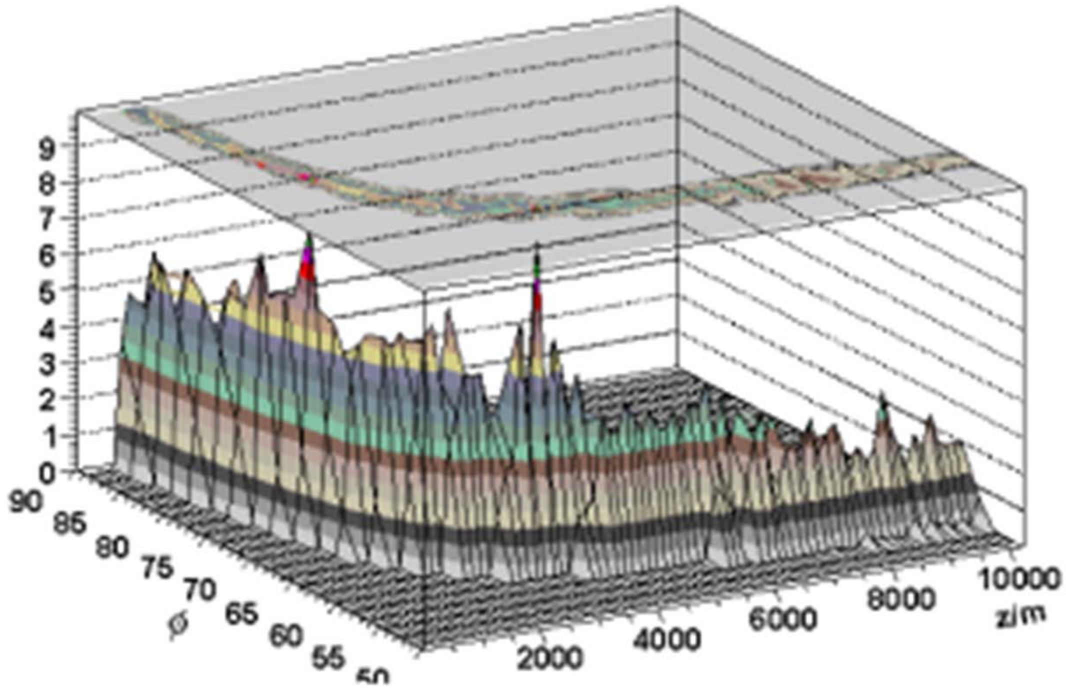


Figure 3: Maximum relative density of lost particles per cavity and mm^2 collected from 500 different configurations of misalignment.

Linac Simulated Beam Loss vs Φ and z (2)

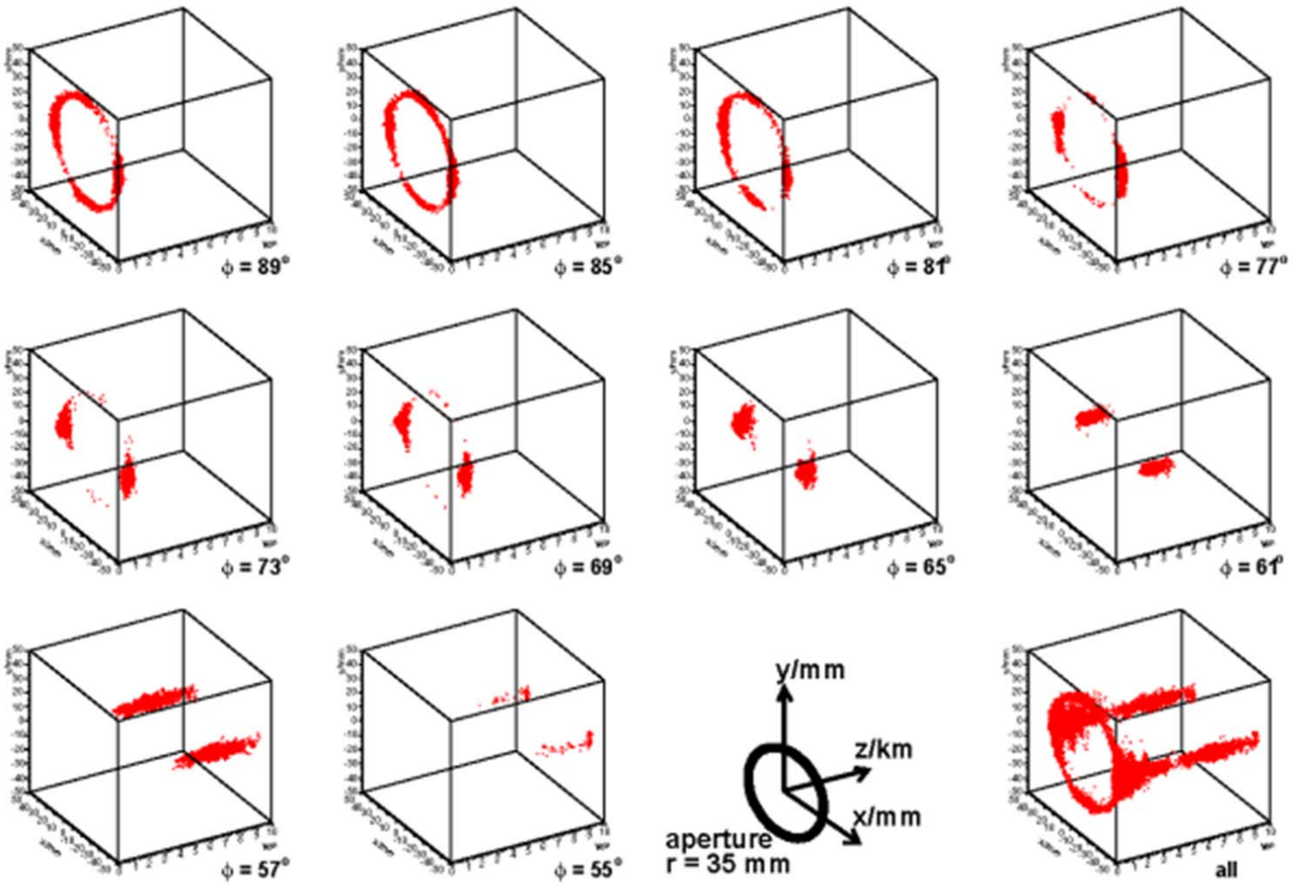


Figure 3: *Spatial distribution of lost particles for different klystron phase shifts ϕ. The beam will only be lost in the ML when the phase error becomes large. Still at 55^0 (second plot, last row) only a few particles hit the cavity aperture. The upper left plot shows the case of an RF phase error of almost 90^0. In such an extrem case the particles are lost immediately at the entrance of the linac.*

MP and Operations: Outline

- Linac Segmentation and 'Bifurcation'
- Turn-on / Recovery following a stop
- Failure modes
- Availability
  - 'Failure-mode catalog' is not enough to understand risk
  - Budgeting and Modeling
  - Fusion: RAMI (Reliability, Availability, Maintainability, Inspectability)
  - Accelerator: Availsim → Operations Monte-Carlo

Motivation and Availability defined

- LCLS II X-Ray source is planned to be a user facility; as such is expected to operate with high availability.
- Third generation light sources as well as LCLS I FEL typically operate with user availabilities between 95% and 99%
- Availability: The percentage of time the facility is running and capable of supporting user operations when user operations are scheduled. (Availability definition varies among labs)
- If one tracks downtime events, then reliability (%) can be calculated: R = MTTF/(MTTF+MTTR)
- MTTF: Mean Time To Fail
- MTTF: Mean Time to Repair

http://www.weibull.com/hotwire/issue94/relbasics94.htm

Reliability Tracking Uncertainties

- Assigning downtime to a given system can at times be difficult. Root cause for a problem is not always discovered. Without accurate diagnostics experts from two different systems may disagree on root cause.
- Downtime accounting can be sometimes subjective:
  - Electrical power glitches can be accounted as power distribution faults or charged to the equipment that trips due to a few millisecond line glitch.
  - Maintainability is important here: When your system trips due to a power glitch, don't design it so that an expert is needed to drive onsite for the system to be fully recovered.
- Tuning may be needed after a difficult to identify hardware fault that degrades beam conditions.
  - For example injector gun probe affecting RF amplitude measurement , degrading injector emittance and beta match.

LCLS I Availability Program

- Any event longer than 3 minutes is recorded in downtime accounting database with 0.1 of one hour granularity. (We don't really track fast trips)
- Each downtime event gets assigned a system and sub-system code. (i.e. 7.3.2 = Controls (7), Safety (3), PPS(2));
- Root cause information is recorded if known.
- Sub-system MTTF and MTTR are tracked over time.
- Accelerator Improvement Program (AIP) projects are proposed based on downtime trends.

Beam time accounting categories:

Delivered	User Off	Configuration change	Tuning	Down
Users taking data.	Beam is delivered but hutch stopper is closed	Photon wavelength, bunch length, electron charge, etc.	Hardware is up BUT a beam parameter is not to specifications	Hardware/ software downtime.

LCLS I last 4 month performance:

Photon Availability 95.2 (%)

Electron Availability 97.9 (%)

Photon Availability = Delivered + User Off + Configuration Change

Electron Availability = Delivered + User Off + Configuation Change + Tuning

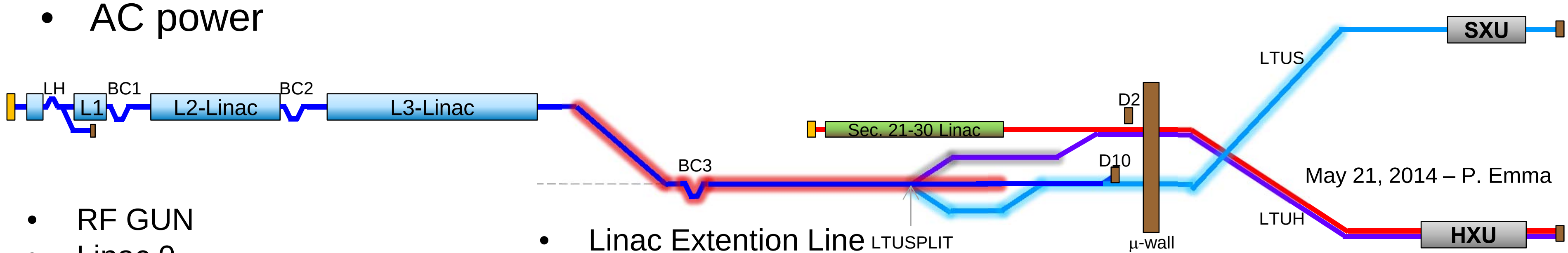
Preliminary Availability Target Setting

- Start with documented reliability of systems at operating machines. (LCLS I, CEBAF, SNS, CERN, etc.)
- Compare these systems to proposed LCLS II systems.
- Two different approaches:
  - Scale and repartition availability expectations so that total comes to ~95%. (i.e. work under a given budget)
  - Use measured **BEST** availability performance as expectation for LCLS II availability performance.
- Once system availability requirements are set, area requirements can be computed.
- Communicate these expectations to **ALL** individuals involved.

Systems and Areas

- Lasers
- Magnets
- PS Controllers
- Vacuum
- Water
- AC power

- RF power Sources
- RF structure
- Cryogenics Plant
- Controls



- RF GUN
- Linac 0
- Laser Heater
- Diagnostic Line 0
- Collimation 0
- Linac 1
- BC1

- Diagnostic Line 1
- Collimation 1
- Linac 2
- BC2
- Collimation 2
- Linac 3

- Linac Extention Line
- Dog Leg
- BC3

- Bypass Line
- Spreader

- SXR Undulator
- HXR Undulator

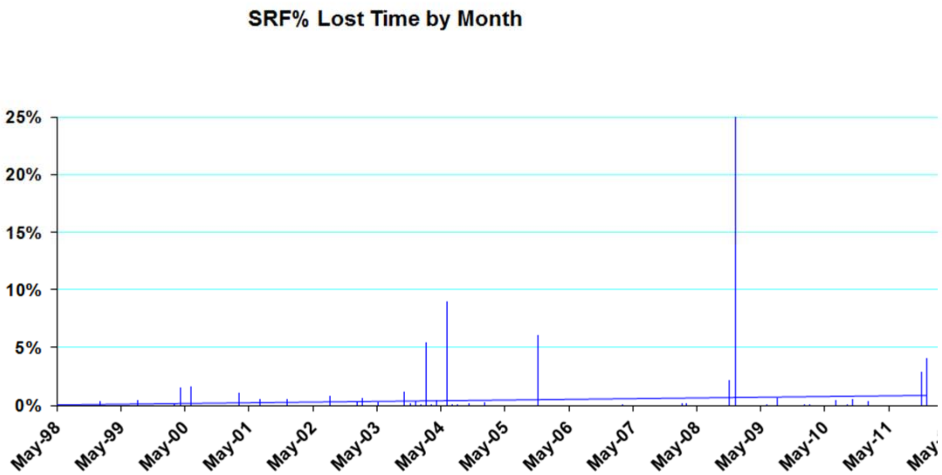
- Global

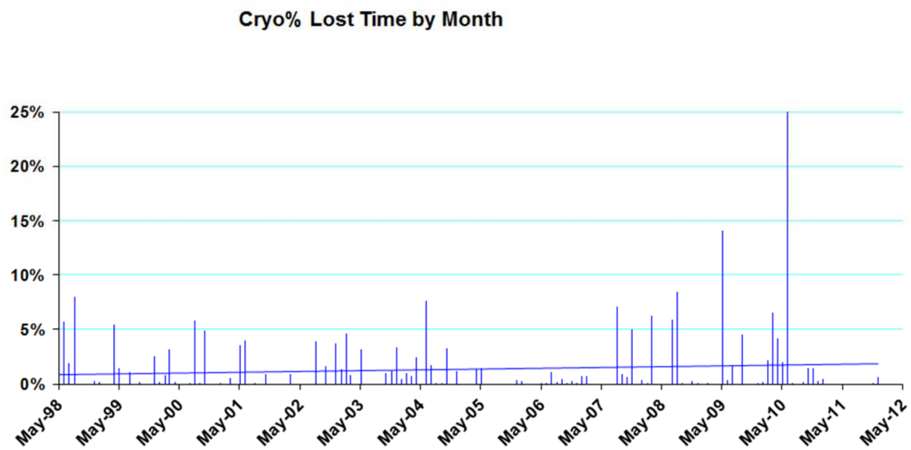
Preliminary Systems' Availability Targets

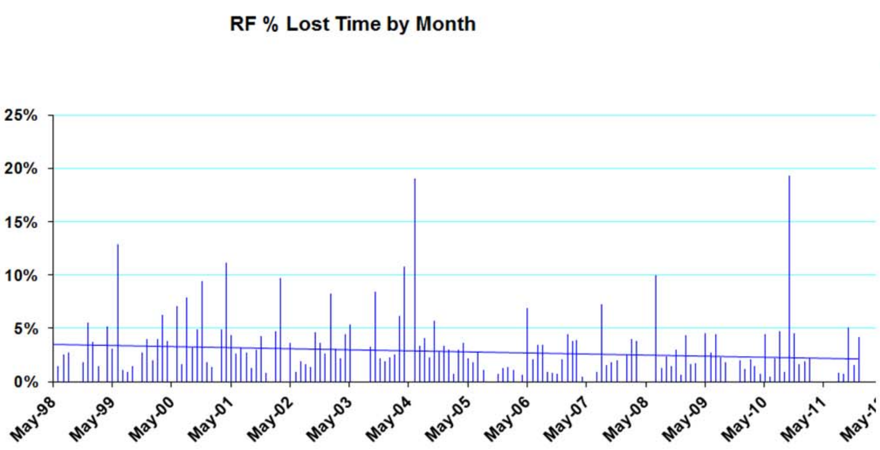
System	Availability	Description
Lasers (1,2)	99.43%	Injector Laser and Laser Heater
Magnets (1)	99.66%	Bends, Quadrupole, Horizontal and Vertical Correctors, Kickers.
PS (1) controllers	99.47%	Power Supply controllers for magnets.
RF power sources (3)	99.63%	Klystrons, Solid State Amplifiers and high power RF distribution .
RF structure (4)	99.80%	Cavities, cavity tuner, Cryomodule vacuum.
Vacuum (1)	99.91%	Vacuum pumps, valves, gauges and controllers.
Tuning and Diagnostic(5)	99.00%	Beam Position Monitor, Wire Scanner and Time spent tuning machine performance to previously defined X-Ray parameters.
Water system (1)	99.86%	Water pumps, cooling water temperature regulation.
AC power (1)	99.80%	Power distribution system
Cryogenics Plant (6)	99.36%	
Controls (1)	98.62%	Input/output controllers, Machine Protection System, Personnel Protection System, controls backbone, timing , feedback, LLRF.
All	94.68%	

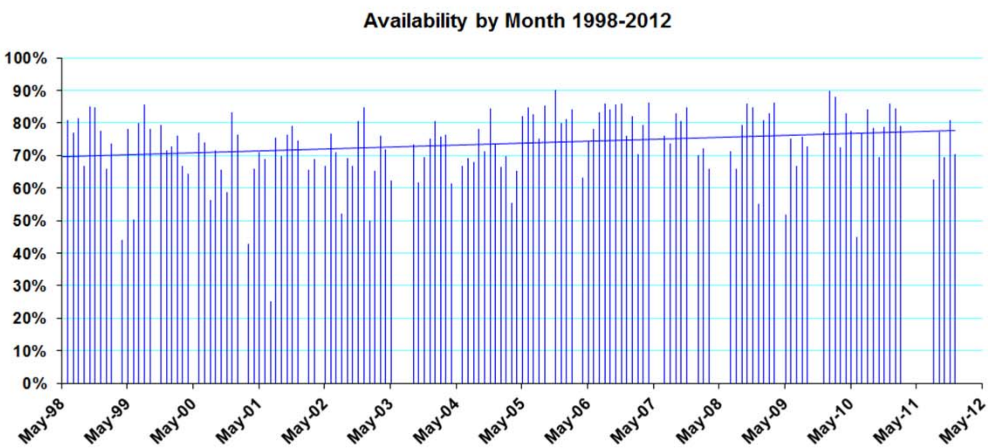
1. LCLS I systems' availability goals are used (overall goal is 95%).
2. Assumes spare laser.
3. RF power sources goal includes LCLS I availability goals for Modulators, Sub-boosters (including solid state amplifiers), and X/S band klystrons. Any technology used that may replace klystrons is expected to have similar or better reliability.
4. Cryomodule availability from ILC and XFEL simulations as used in AvailSim.
5. Time spent tuning the beam is tracked as downtime to the User program. Diagnostics used to tune the beam are therefore required to work.
6. Cryogenics plant availability target is derived from CEBAF and CERN performance. CERN's eight cryogenics plants have a combined availability target of 95%. LCLS II will have one such plant, our value is scaled by the eighth root of 0.95. CEBAF 2006 cryogenics plant availability was 99.25%

CEBAF Lost Time and Availability by Month









JLAB Hurricane recovery

- “Most Cryomodules had never been warmed up since installation.”
- Warm up can lead to indium vacuum seal problems. (64 seals per cryomodule at CEBAF; Zero for LCLS II)

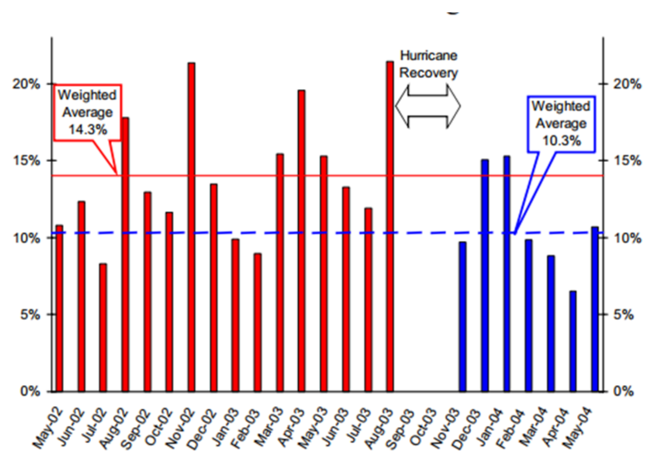


Figure 3: “Accelerator Down” versus time, showing monthly data before (in red) and after (in blue) hurricane recovery

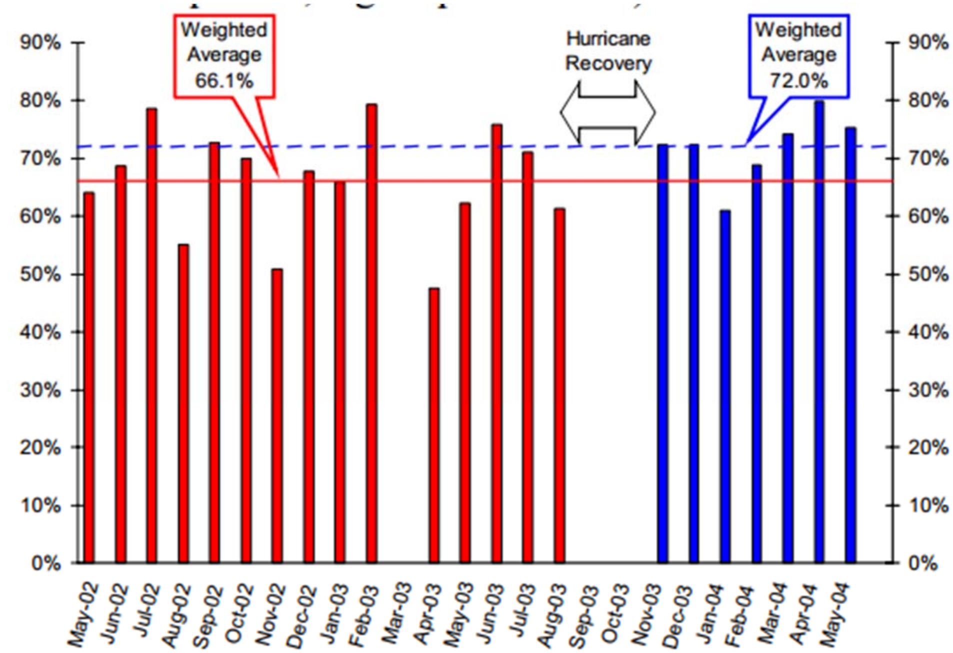


Figure 4: “Availability for Physics”, showing monthly data before (in red) and after (in blue) hurricane recovery

http://accelconf.web.cern.ch/AccelConf/e04/PAPERS/TUPKF068.PDF

Understanding Cryomodule Availability

AvailSim: 99.798%

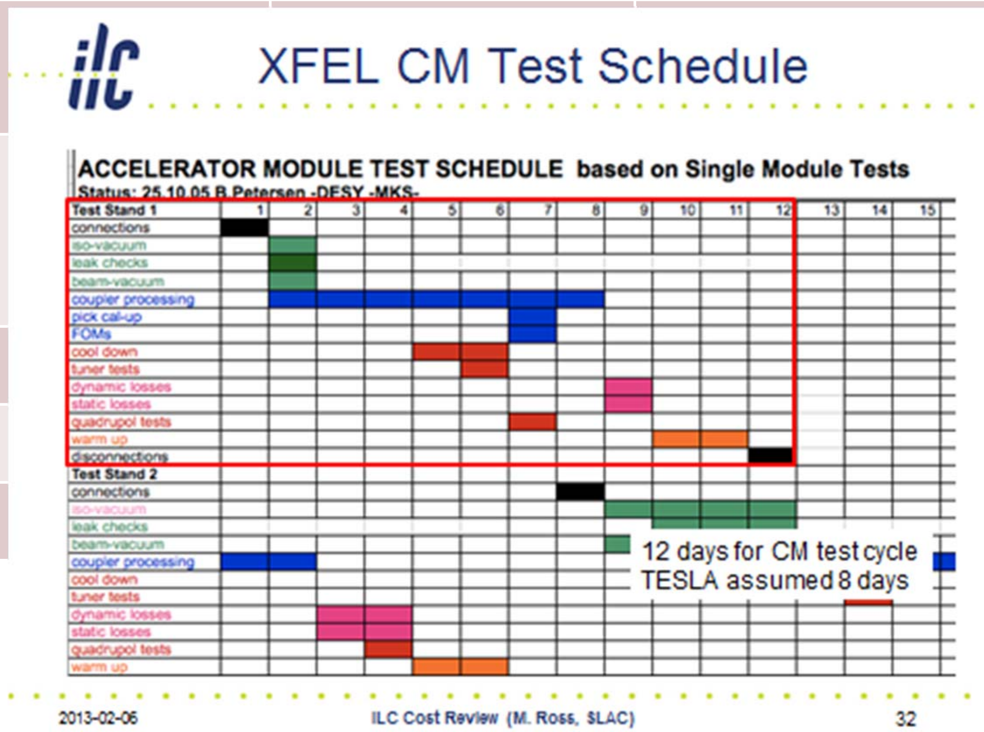
	MTTF (hours)	MTTR (hours)	Availability (%)	Notes
Cavities	1.0E+08	672	99.9993	
Cavity tuner	1.0E+06	672	99.9328	Given sufficient RF power overhead operations can be re-established by adjusting RF feedback or moving master oscillator away from stuck tuner resonance frequency.
Cavity piezo tuner	5.0E+05	672	99.8658	
Power coupler	1.0E+7	2	100.000	Kludge fix by disconnecting the coupler, so only lose one cavity not the whole module.
RF Control instabilities				
Vacuum valve and Pump				
Failed Turbines				
Unstable cryogenic liquid levels				
Fast shut down or protection interlock trips				Quench, Arc interlock.
			99.798	

Need comprehensive list of failure modes and failure rates.

Understanding Cryomodule MTTR

Downtimes till full recovery if:	SNS	LCLS II		XFEL test stand
Warm-up Needed	7-10 days	~12 days + Repair time.		About 12 days
2K Cold box trips	10 hours			
More coupler flow needed	2-4 hours			
Small part/board change	1-3 hours			
SCL retuning	0.5-1 hours			

Working on filling out this table…



CM2014 – Workshop on Cryomodule Maintenance

	KEKB	SNS	CEBAF	INFN	ATLAS	TRISTAN	FRIB
Trips/Day	0.5	<1				Large	
# Cavities	8		300+		47	32	
Warm up/Year	2	2.9	<?		Yes	Yes	"Too Many"
Conditioning/ Month	2						
Gradient Degradation	~0.5 (MV/m-decade)		0.14 (MV/m-yr)				
Q_0 Degradation	Yes	Yes	Yes			Yes	Yes
Q_0 Recovery	Yes (2/2 modules)	Yes (1 cav. No)					

It would be nice to quantify Q_0 degradation rates

Cryomodule Operations at SLAC: Long-term simulation

Availability modelling (AvailSim)

- Monte-Carlo simulation tool (by Tom Himel)
- Generates a timeline of operation of a large accelerator complex.
- Uses tables of accelerator components with MTTF and MTTR estimates from real machines, typ. HEP in 1990's
- Uses segmentation so that repairs can be done in one segment; includes recovery time
- AvailSim is a useful tool for machine design,
  - *equipment location (in /out of tunnel), access and operations segmentation and redundancy*.

Assumptions, sample cryomodule components (klystron - old model).

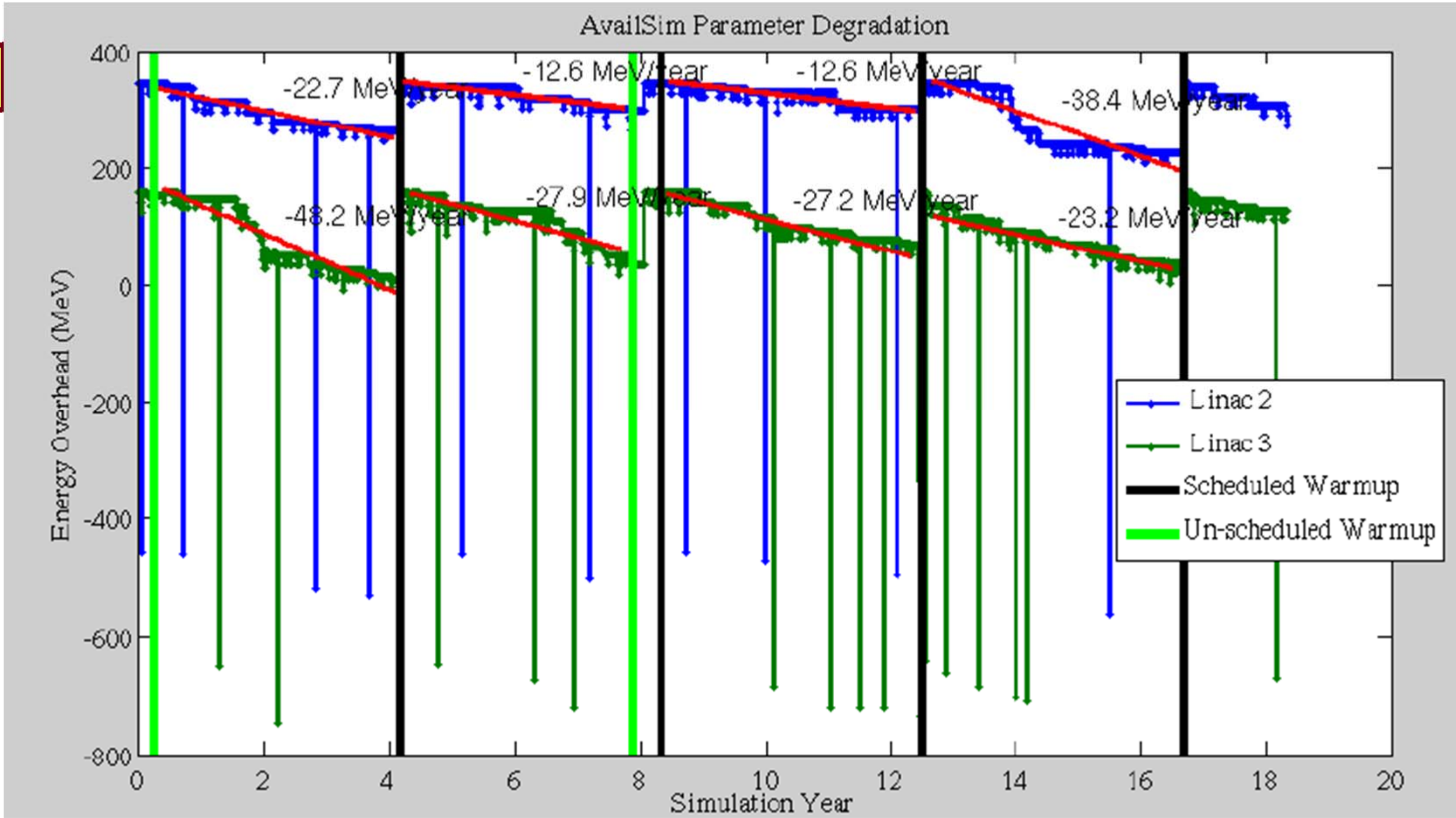
Event	Energy Overhead loss (MeV)	MTTF (Years)	MTTR (hours)
Cavity degraded	6.4	11416	672
Cavity Broken	16.6	11416	672
Power Coupler degraded	307.2	1142	2
Power Coupler broken	797.2	1142	2 (Kludge fix by disconnecting cavity)
Piezo tuner	5.0	114	672
Cryo JT valve	2391.5	34	2
Insulating Vacuum Pump	2391.5	11	8
Klystron	797.2	5	6
RF Power source Vacuum Gage	797.2	11	1

AvailSim Results

Energy overhead vs time for 18yrs

E_acc ▼ 1.3%/yr

- Both strings repaired during each schedule downtime and during un-scheduled downs.
- To be used to assess CM design choices



Availability and MPS

- Impact on Availability of Machine Protection:
  - Trips themselves
  - Understanding and Correction root-cause
  - Recovery back to full operation
  - Secondary (thermal?) delays
  - Stabilization
- Example:
  - FEL Xrays (very low average power)
  - Mirror deformation due to incident power – very small critical to users
  - Slow (10’s minutes) recovery