R&D Program at FLASH (DESY)

Beam Test Facility effort in support of ILC R & D

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An update to the report given to PAC Nov 2010, Eugene

SRF test linac objectives

- ***Demonstration of:***
  - *accelerating gradient*
- ***With specified:***
  - *Beam phase and energy stability at full current; with gradient spread*
  - *Gradient and RF power overhead*
- **to establish technology for:**
  - controlling beam loading effects
  - 'Lorentz – Force' detuning compensation
  - *in both static and dynamic conditions*

Outline:

- **Beam Operation:**
  - DESY LLRF team success
- **High gradient / high current operation**
  - what power / gradient overhead is required?
- **Lorentz force detuning**
  - stabilizing cavity motion
- **Reducing initial pulse transient**
  - application of “Learning Feed-Forward”
- **Next steps**

Eugene

High power long bunch-train operation
(During 2 weeks of studies in Sept 2009)

Metric	ILC Goal	Achieved
Bunches per pulse	800 x 3nC (1MHz)	800 x 3nC
	2400 x 3nC (3MHz)	1800 x 3nC 2100 x 2.5nC ~2400 x 2nC
Charge in macro-pulse	7200nC @ 3MHz	5400nC @ 3MHz
Average beam power	36kW (7200nC, 5Hz, 1GeV)	22kW (5400nC, 5Hz, 800MeV)
Cavties operating at high gradients, close to quench	Up to 38Mv/m	Several cavities above 30MV/m

- **15 contiguous hours running with 3mA and 800us bunch trains**
- **Running at ~9mA with bunch trains of 500-600us for several hours**
- **Full pulse length (800us, ~2400 bunches) at ~6mA for shorter periods**

- **Energy deviations within long bunch trains: <0.5% p-p (7mA beam)**
- **Energy jittter pulse-pulse with long bunch trains: ~0.13% rms (7mA)**

SRF Linac Summary - *Eugene*

1) ***Intra-pulse*** **beam based RF Feedback**
   - Now working ***7 x improvement*** observed
   - ~ high current energy jitter results 2010

2) **Flatten tilt - compensate for *Gradient Spread***
   - coming late 2010 / early 2011

3) **Precision *LF Detuning compensation***
   - S1 Global – Fermilab / KEK: ***20 Hz p/p at 37 MV/m***
   - to be applied at FLASH ~ 2011

4) **Cavity gradient limits – (Field emission)**
   - ***diagnosis required:*** change observed after Cryomodule assembly

Long bunch-train studies at TTF/FLASH

2009	FLASH (typical for users)		1-30 bunches	≤1nC	FEL op.

2002	TTF	3MHz	750 bunches	2.8nC	
2006	TTF2/FLASH	1MHz	800 bunches	0.8nC	(400 lasing)
2007	TTF2/FLASH	1MHz	800 bunches	0.6nC	lasing
Sept 08	TTF2/FLASH	1MHz	550 bunches	2.7nC	9mA exp.
Aug 09	*3-week shutdown to repair beam dump and install new diagnostics*				
Sept 09	TTF2/FLASH	1MHz 3MHz	800 bunches 2400 bunches	3nC 2nC	9mA exp
Feb 2011	TTF2/FLASH	3MHz	1200 bunches	<2nC	9mA exp
early 2012	TTF2/FLASH	Planned: Gradient margin and rf power overhead studies			
2012->		…Continue…			

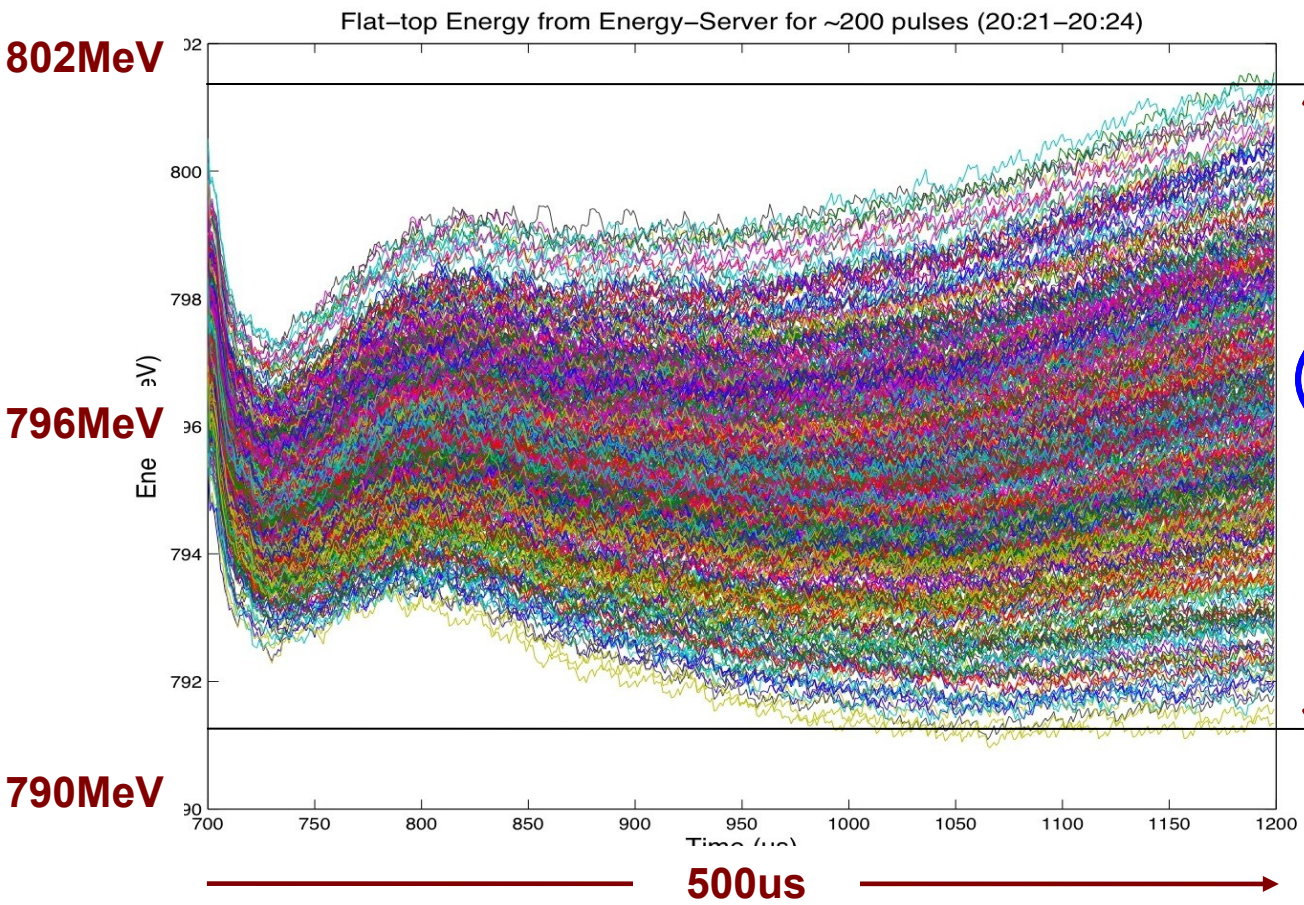
Dedicated long – train operation:

February 2011 Studies

- **Modeling and Control of each cavity**
  - input power (P_k), ***loaded Q (Q_L),*** (and RF/beam timing)
  - simulate beam loading etc
- **Calibrate simulation to establish control method**
  - approach quench point – with practical margins
  - automation
- **400 us pulse (gun limit!)**
  - <2nC/bunch (3 – 5 mA) – focus on tuning process
  - use primary undulator beamline (not bypass)

Close-up Example – 200 pulses: Energy vs time along pulse

Shown at Eugene PAC Review, 11.2010

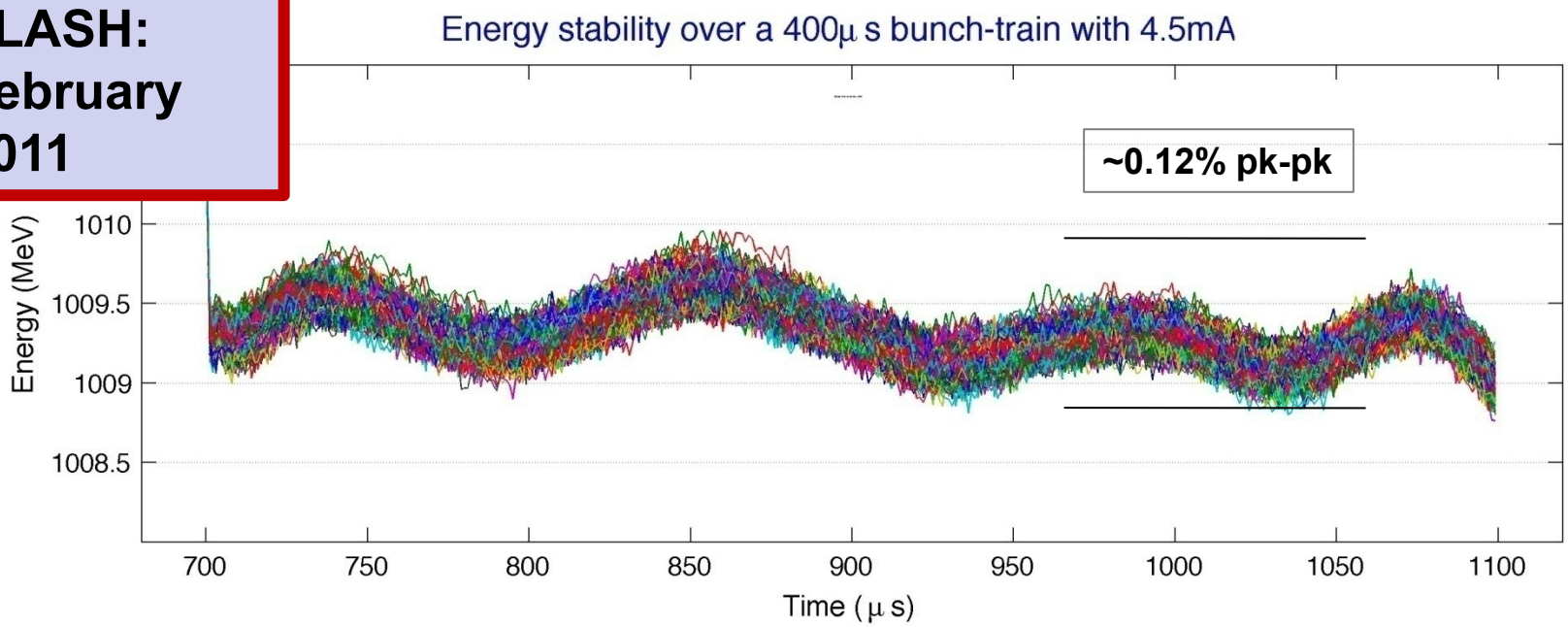


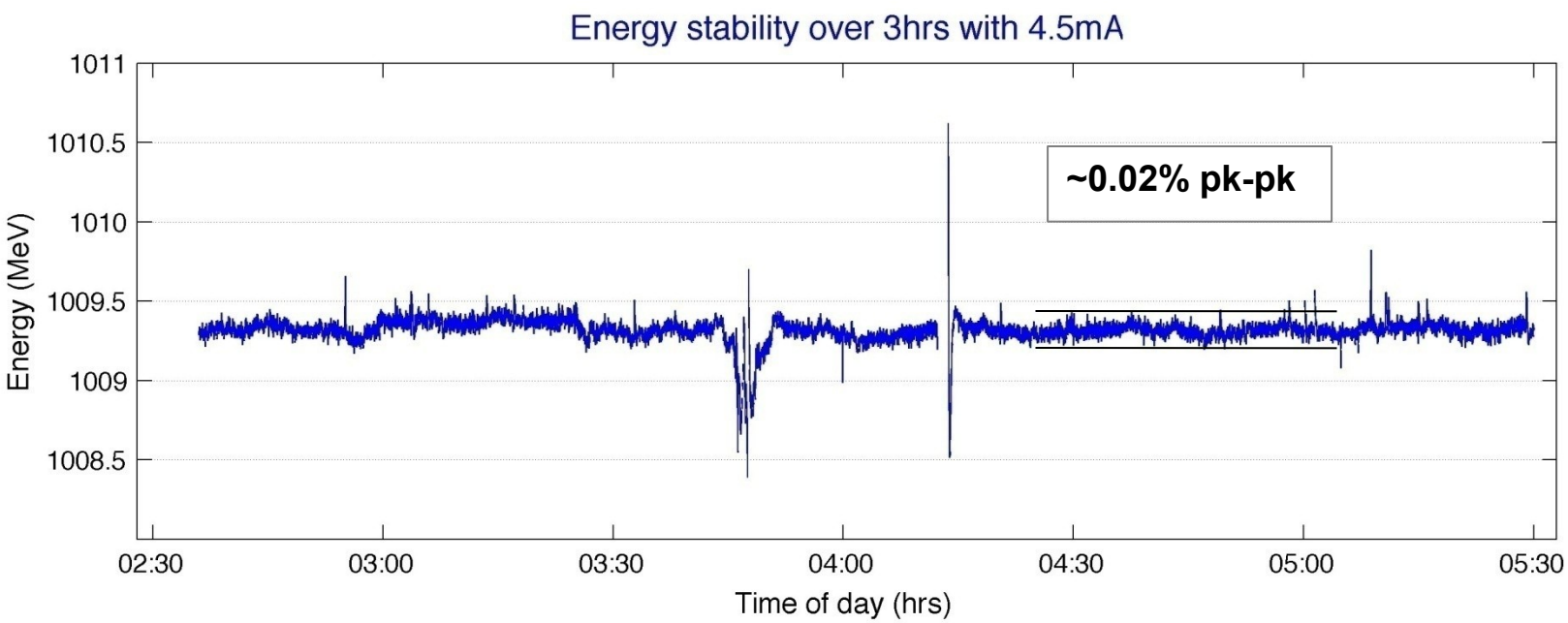
+/- 0.6%

showing pulse-to-pulse energy jitter

(500us, ~3mA, 200 pulses overlaid)

FLASH: February 2011





Achievements: SRF Linac – FLASH (DESY)

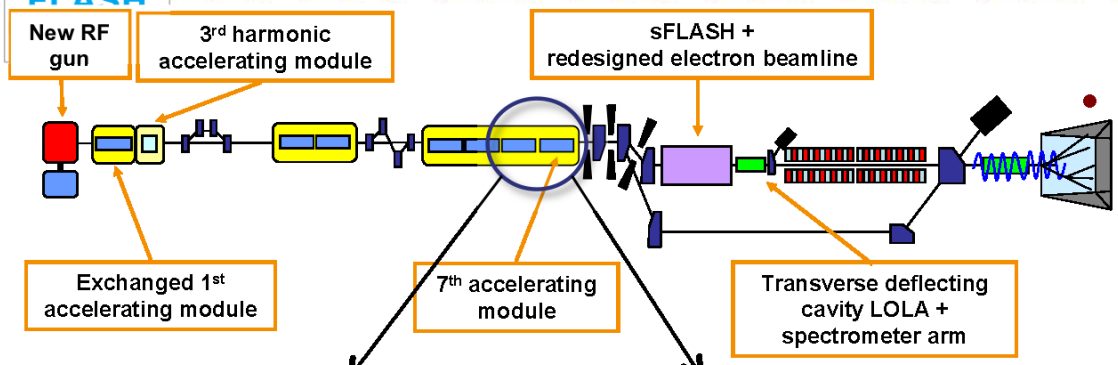
High beam power and long bunch-trains *(Sept 2009)*

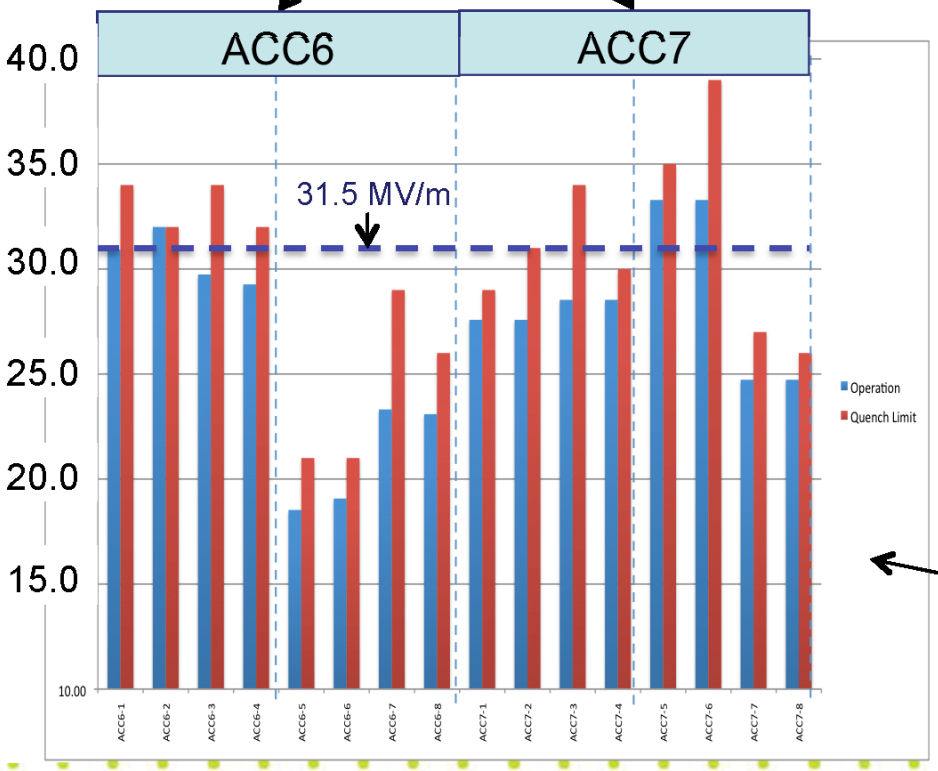
Metric	ILC Goal	Achieved
• **Macro-pulse current**	9mA	9mA
• **Bunches per pulse**	2400 x 3nC (3MHz)	1800 x 3nC 2400 x 2nC
• **Cavities operating at high gradients, close to quench**	31.5MV/m +/-20%	4 cavities > 30MV/m

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% at 250GeV	<0.15% p-p (0.4ms) <0.02% rms (5Hz)

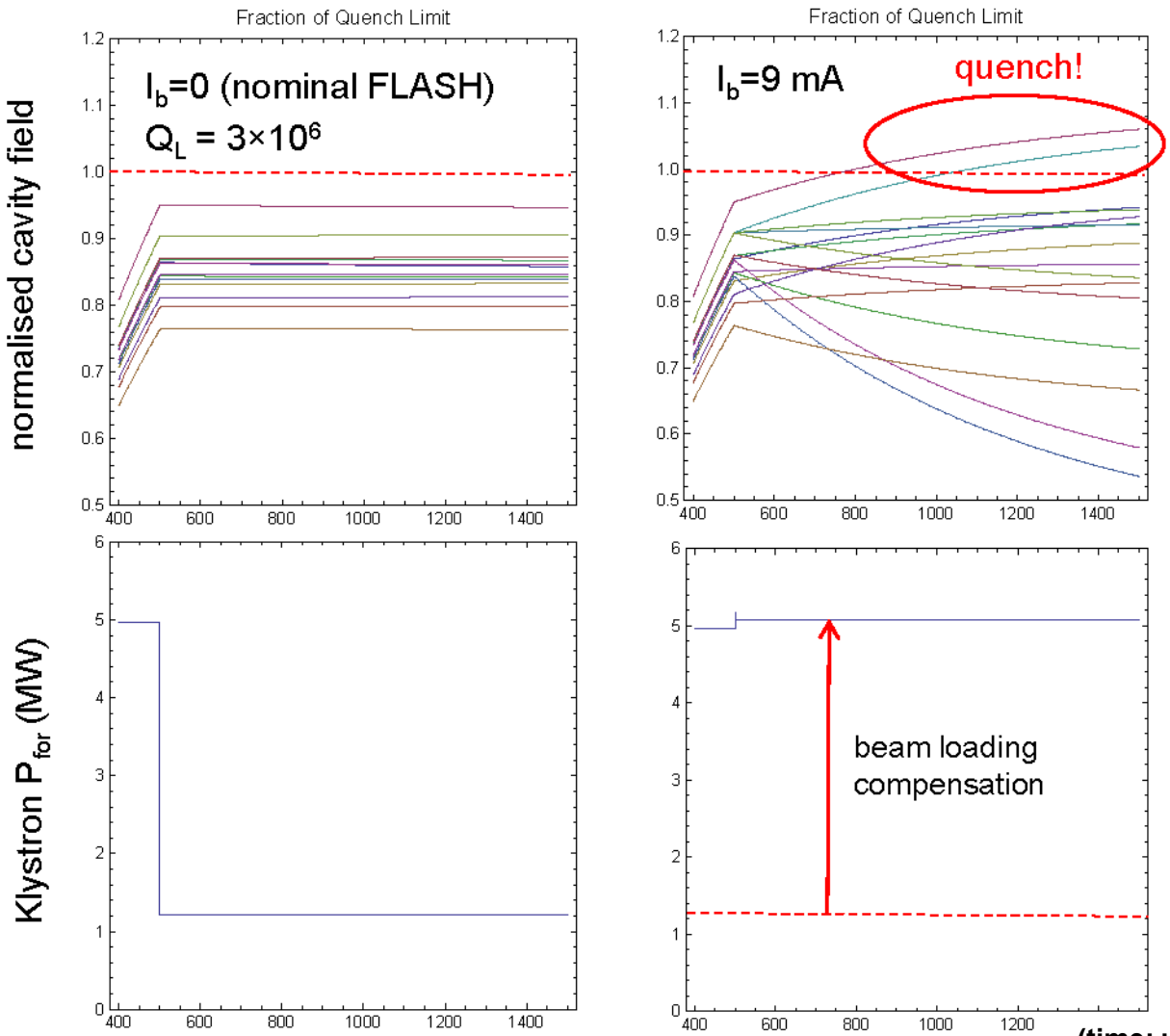
Main TDP R&D goal driving the 9mA studies in February 2011





- **Operation with <u>Gradient Spread</u>**
  - From single RF source
- **Specifically: achieving constant gradients <u>for each individual cavity</u> during beam pulse**
  - to within few percent
  - close to gradient limits
  - 'Effective usable gradient'
- **ACC67 modules at FLASH have operating gradient spread around +/-25%**

Flat Gradients?

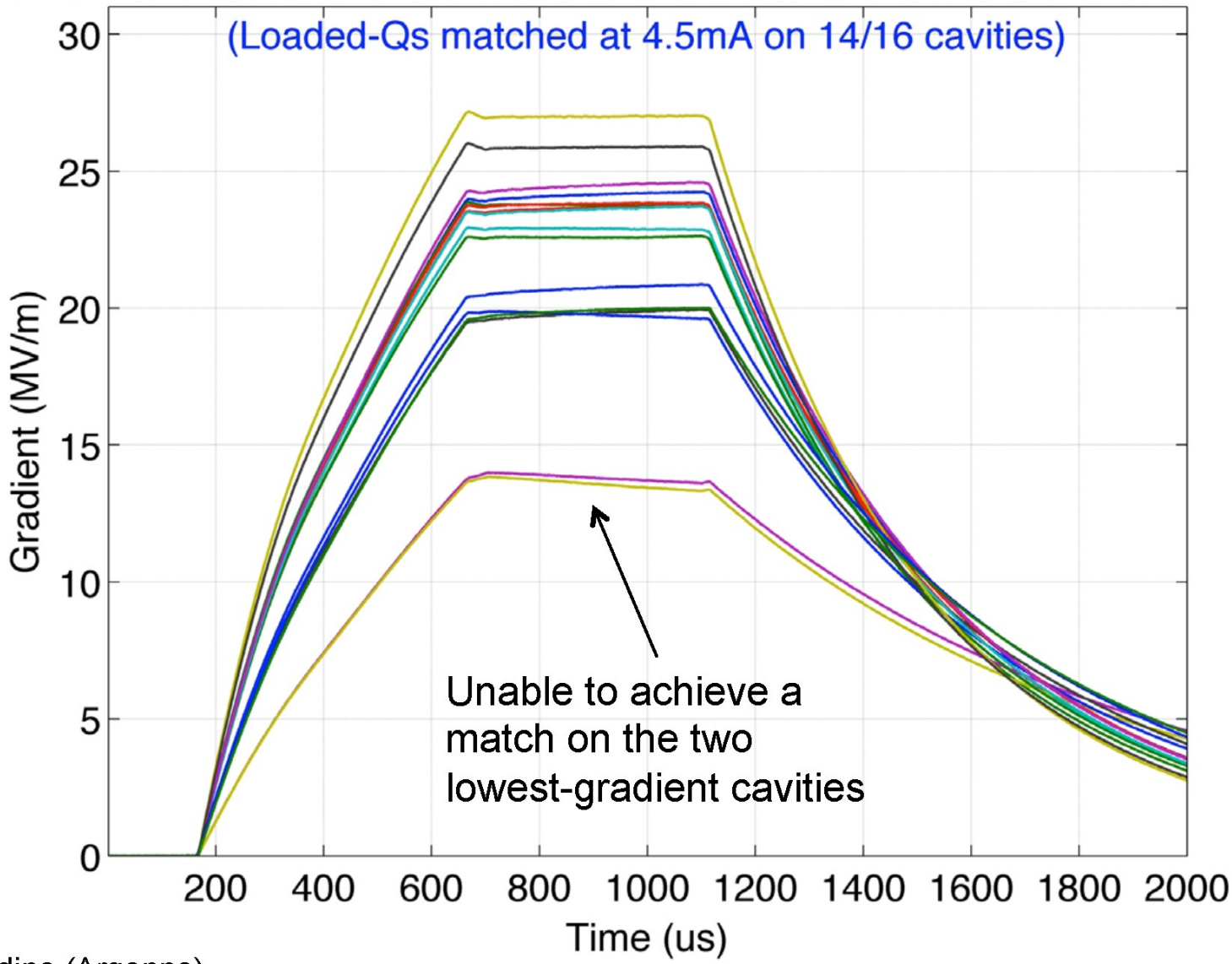


(time: us from start of fill)

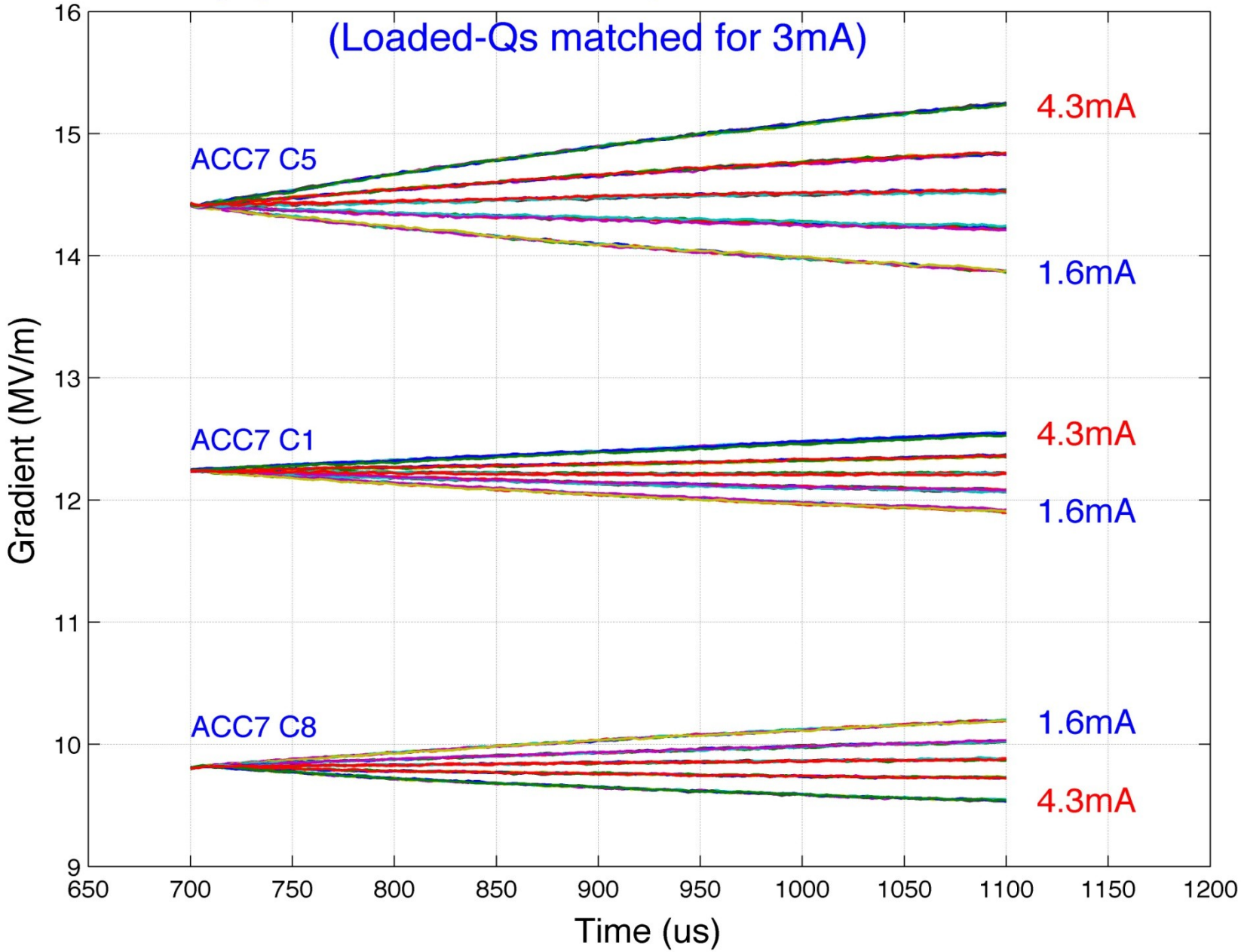
Simulation

- vector sum held constant (flat)
- Individual cavity fields vary (tilts)
- Implications for
  - max. operation gradient
  - beam dynamics
- Flat gradient solution unique to I_b
  - Need to adjust power to cavities *and individual* Q_L
- Control of Lorentz-Force Detuning (LFD) becomes critical
  - Fast piezo tuners

Flat gradient achieved at 360MV Vector Sum and beam current of 4.5mA (400us beam pulse)



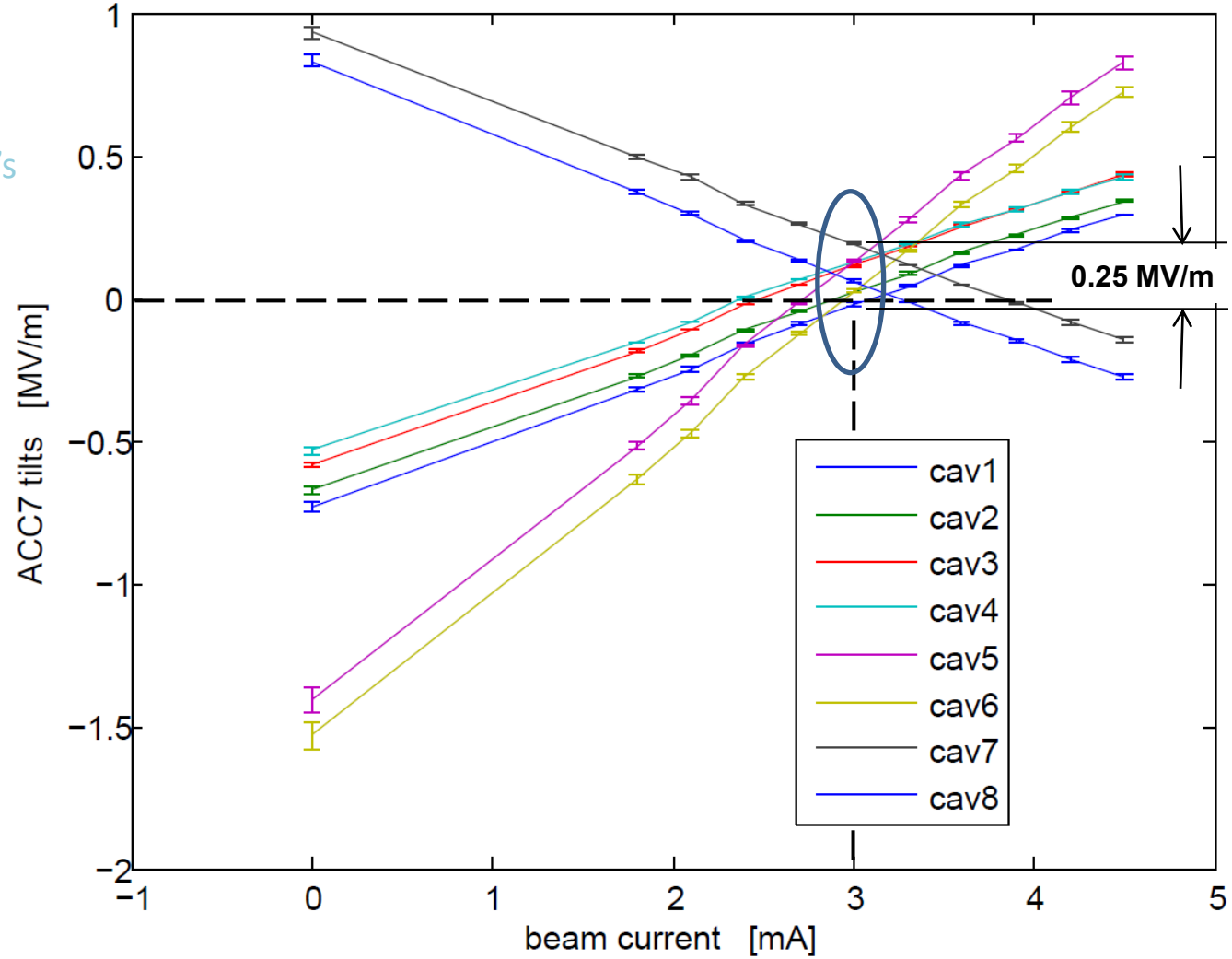
Cavity gradients over flat-top at different beam currents



Assessing the accuracy of the model

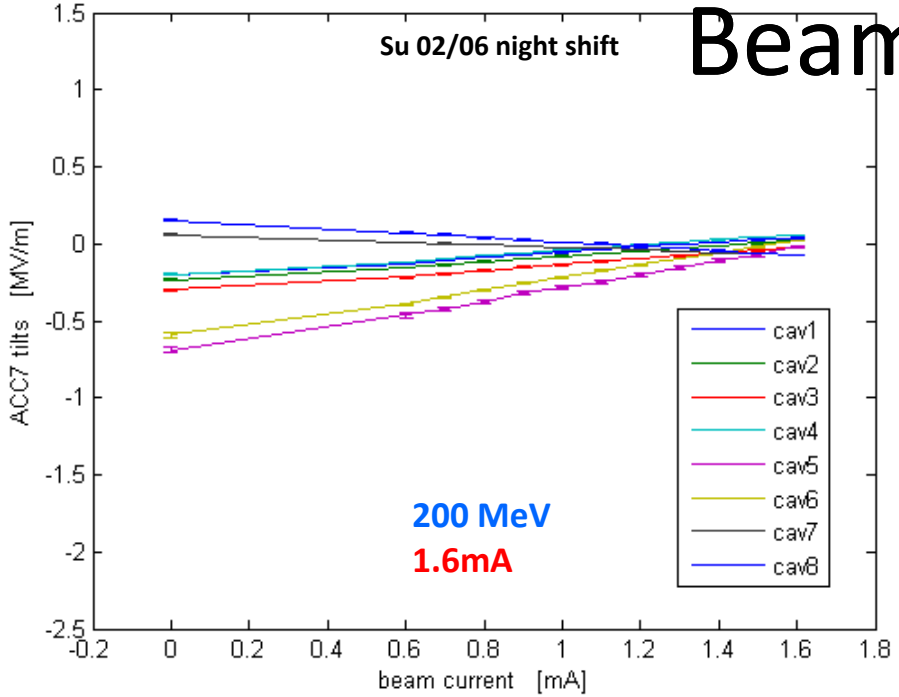
- Q_L scan
  → Keep beam current constant but walk Q_L's around optimized value

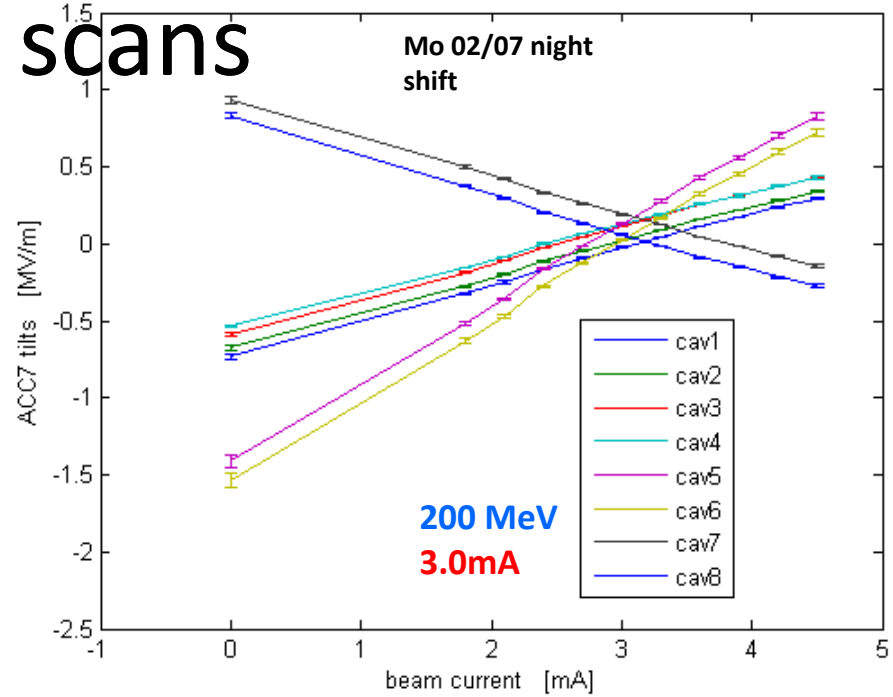
- I_B scan
  → Keep optimized Q_L's but ramp beam up/down

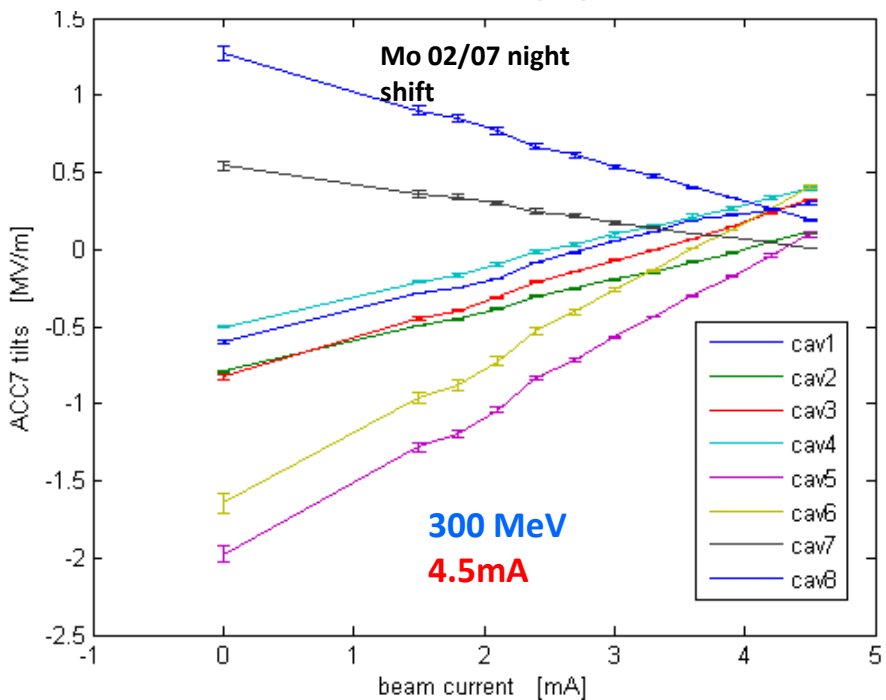


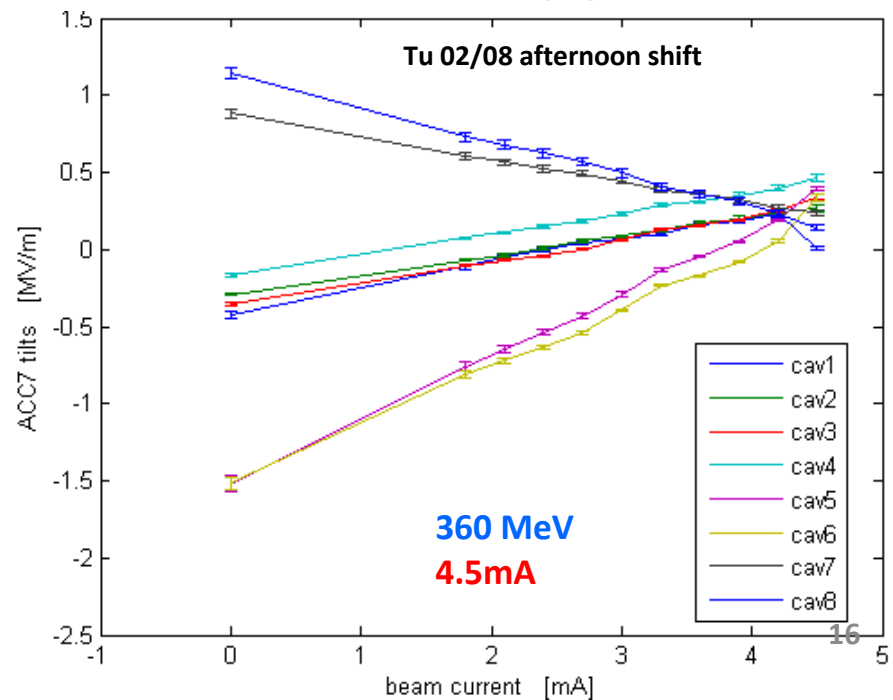
(Tilt: gradient change during 400 us beam pulse)

Beam scans


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


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


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


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

Achieved: flat cavity gradients to +/-few percent over a range of conditions

Matched current for 16 cavities	16-cavity Vector Sum	Approx. range of cavity gradients	Beam pulse length	RF flat-top length	Range for current scan
1.6mA	200MeV	7-24MV/m	400us	800us	0.6-1.6mA
3mA	200MeV	7-24MV/m	400us	800us	1.8-4.5mA
4.5mA	290MeV	10-20MV/m	400us	800us	1.5-4.5mA
4.2mA (14 of 16 cavities)	360MeV	17-25MV/m	400us	400us**	1.5-4.5mA

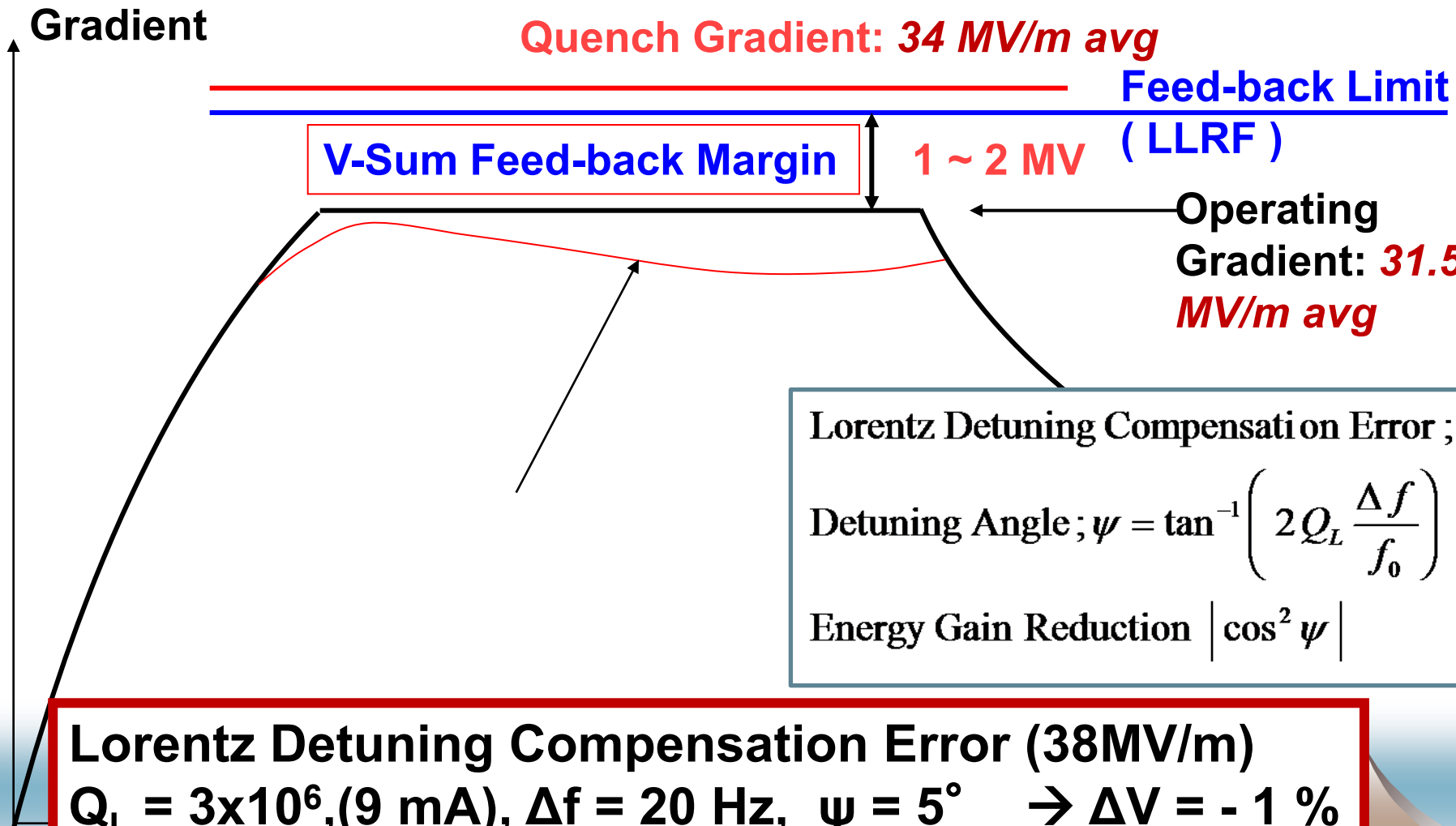
** RF flat-top length was reduced to prevent cavities quenching

- **QLs adjusted on ACC67 cavities to obtain flattest gradient profile over the duration of the bunch train**
- **Beam current scans used to evaluate the optimizations**

First-time demonstration of tailoring Pks/QIs to achieve flat gradients..?

NOGUCHI, KEK

Highest Gradient Operation



Lorentz Detuning Compensation Error ; Δf

Detuning Angle ; $\psi = \tan^{-1}\left(2Q_L \frac{\Delta f}{f_0}\right)$

Energy Gain Reduction $\left|\cos^2\psi\right|$

Lorentz Detuning Compensation Error (38MV/m)

Q_L = 3x10^6,(9 mA), Δf = 20 Hz, ψ = 5° → ΔV = - 1 %

Q_L = 7x10^6,(5 mA), Δf = 20 Hz, ψ = 12° → ΔV = - 4 %

ILC-ML SCRF Cavity Gradient Specifications Update

Cost-relevant design parameters for TDR	ML cavity gradient Specification	R&D Milestone
9-cell Cavity Gradient in vertical test	35 MV/m, average - Spread: 28 – 42 MV/m (+/- 20 % or less)	35 MV/m at 90 % yield including 2nd pass, (eq. > 38 MV/m, average)
Cryomodule Operational Gradient	34 MV/m, average	34 MV/m, average CM Obs. G. Limit = 3 %
Accelerator Operational Gradient	**31.5 MV/m, average** - Spread: 25 – 38 MV/m (+/- 20 % or less: TBD)	31.5 MV/m, average Op. G lim = 1.5 MV/m Cntrl margin = 3 %**
Required RF power overhead for control	1	

Few % (~1 MV/m) achieved at FLASH gradients/gradient spread

Bringing up a linac

Traditional approach (i.e. FLASH)

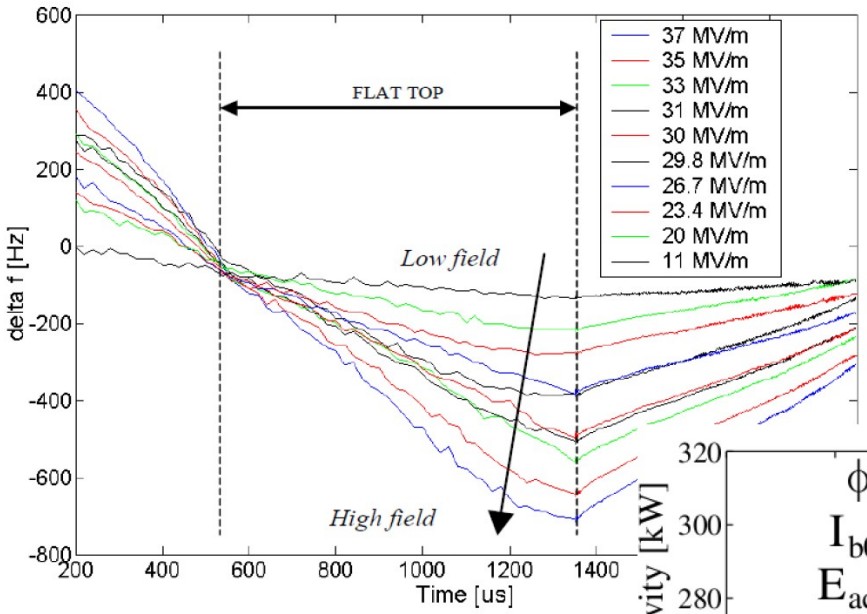
1. Make target gradient with FF
2. Turn FB on
3. Compensate for LFD
4. Send a couple of pilot bunches (~10)
   (automated beam loading compensation)
5. Minimize losses
6. Gradually increase bunch length to full train
   (while minimizing beam losses)
7. Learning feed forward

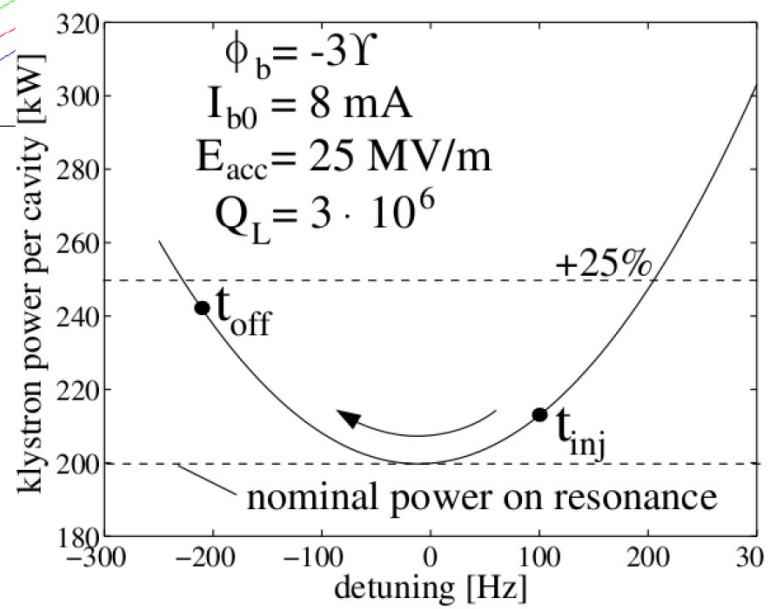
One "possible" scenario for flat gradients

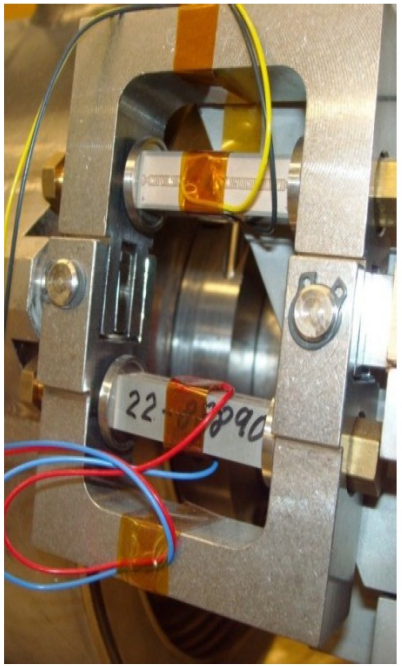
1. Bring cavity to their nominal gradient
   - ➔ typically: quench gradient -2-3 MV/m
2. Adjust Q_L so cavities are flat with beam
   - ➔ cavity will quench (because no beam)
3. Shorten pulse length to avoid quench
   - ➔ typically <200 usec for high beam currents Q_L's
   - ➔ can't see LFD effects (can't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

Slide - J. Branlard

Lorentz Force Detuning



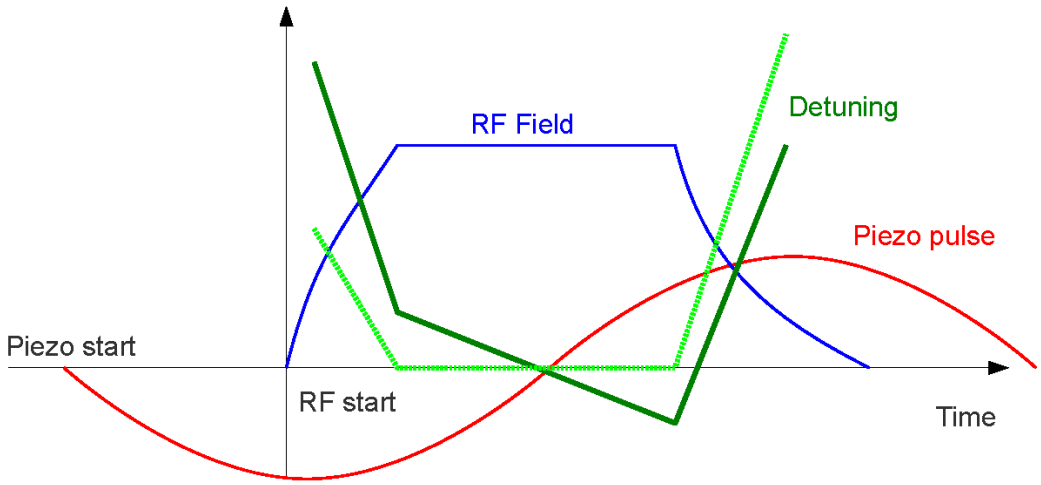




Dimensions: **10x10x36mm**
Manufacturer: **PI**

Piezo control for LFD compensation

- Sinusoidal excitation with adjustable
  - Frequency
  - Pulse number
  - Amplitude
  - Time position
  - DC pedestal



- Amplitude → dynamic detuning
- DC pedestal → static detuning
- Time position → curvature

Trigger timing for the piezo tuners
(nominal setup)

A2 event trigger

A6 event trigger

First bunch

19.978ms

700us

2.418ms

LLRF ADC window = 2.048ms
(2048 samples @ 1MHz)

160us

RF drive

800us

22.556ms

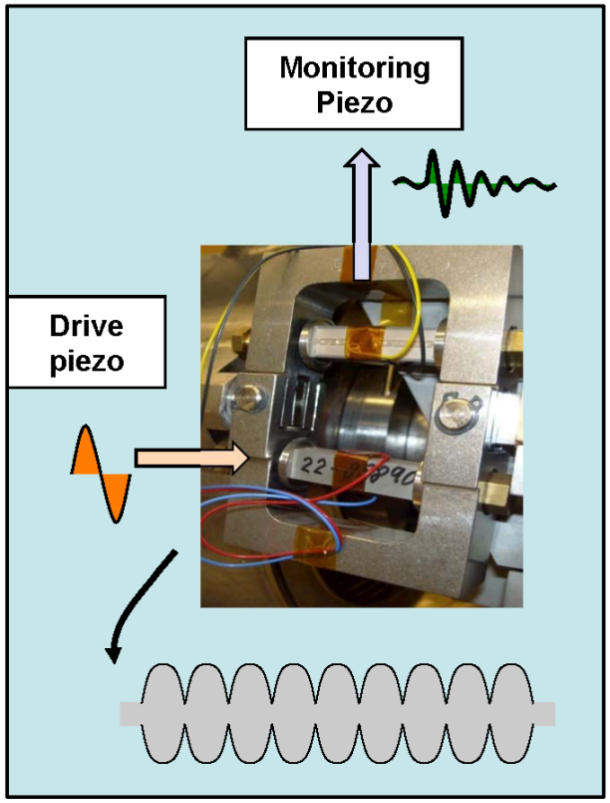
Cavity field

Piezo ADC window = 82.58ms (256 samples @ 3.1kHz)

Trigger delay

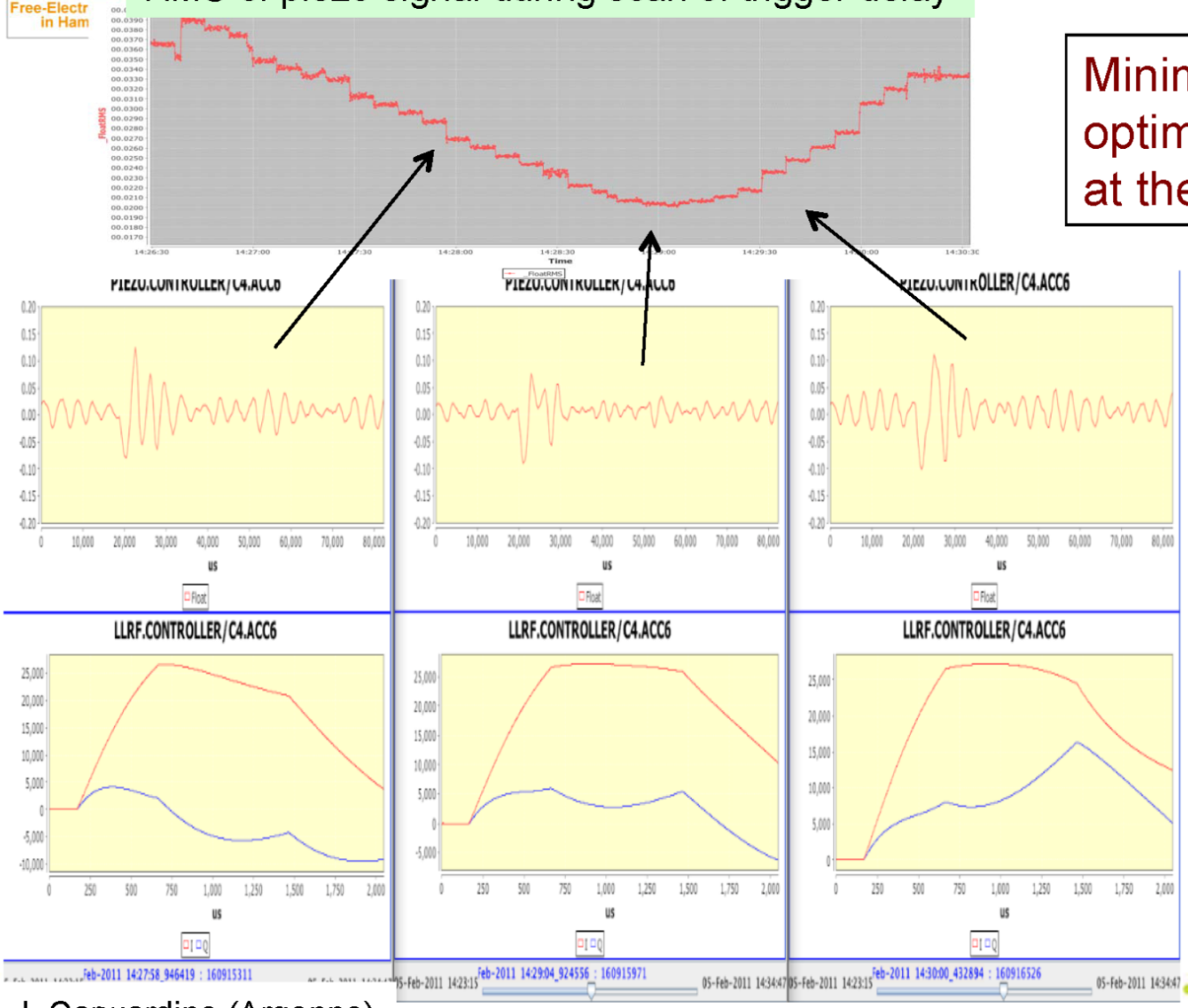
Piezo drive

Typical drive parameters
Trigger delay: 16-20ms
Drive frequency: 200Hz



RMS of the monitoring piezo signals during scan of drive piezo trigger delay

RMS of piezo signal during scan of trigger delay



Minimum RMS and optimal detuning occurred at the same trigger delay

Monitoring piezo signal (80ms)

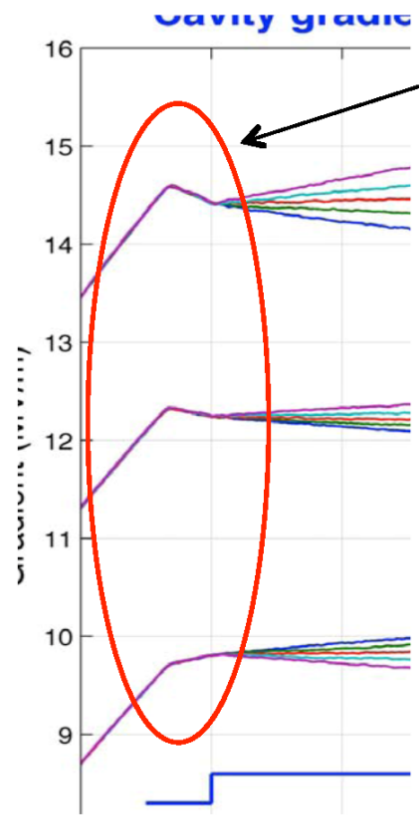
Cavity field probe I&Q (2ms)

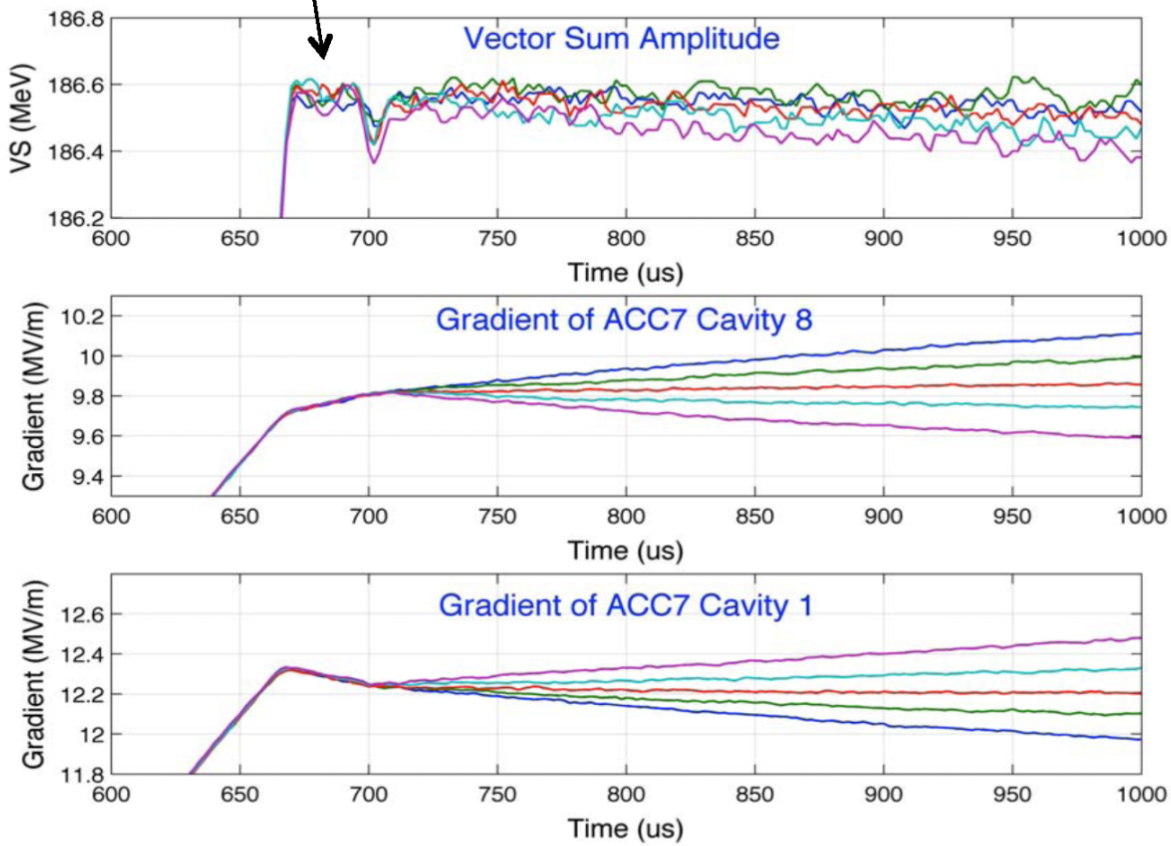
(I = Red, Q = Blue)

For analysis

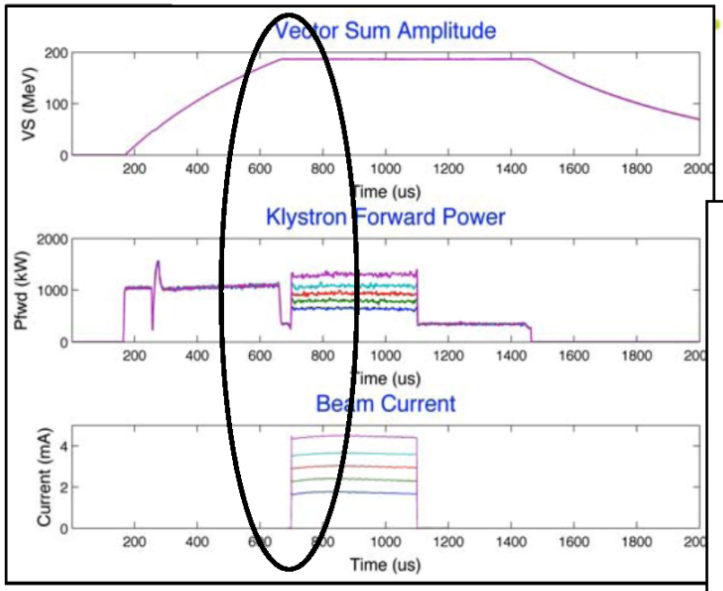
Initial transient on individual cavity gradients…

- **Higher gradient cavities overshoot at end of fill, lower gradient cavities undershoot**
- **Vector sum is flat**

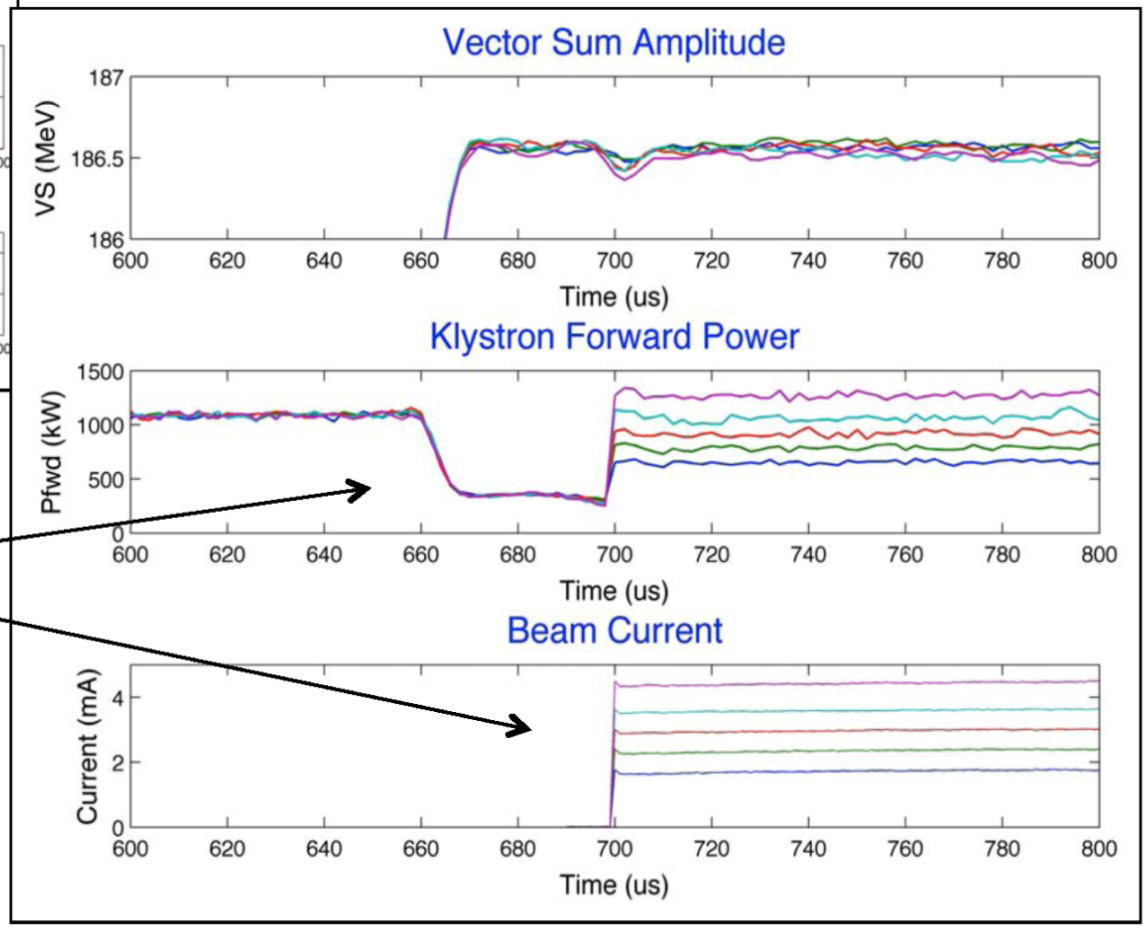




Stabilization of vector sum before beam arrival



Learning feed-forward + beam loading compensation gives a very flat vector sum



First bunch is timed to after the transition to the RF flat-top to allow time for Learning Feed-forward to stabilize the vector sum

Next steps:

- **Operation close to quench with ILC-like gradients / gradient spread**

- **Flatten gradient (16 cavities) with 6 mA, 800us**
  - automated adjustment of coupling (Q_L)
  - correction of systematic errors
- **Operation within few % of quench limit**