TTF/FLASH 9mA Experiment
Recent Machine Studies and Results

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For the TTF/FLASH 9mA Studies Team

November 18, 2008

The (International) Shift Team

- **FLASH Experts (DESY)**
  - Siggi Schreiber - laser/gun injector set-up
  - Bart Faartz - general set-up
  - Lars Froehlich - TPS installation / commissioning, BLM calibration
  - Florian Loehl - optics matching & emittance
  - Holger Schlarb - optics & steering
  - Nina & Vladimir - optics calculations
  - Valeri Ayvazyan - LLRF set-up and tuning
  - Mariusz Grecki - LLRF set-up and tuning
  - Waldemar Koprek - LLRF set-up and tuning (mostly gun)
  - (Jacek Sekutowicz - HOM absorber measurements)
  - Nick Walker - overall coordination
- **ANL**
  - John Carwardine - LLRF / overall coordination
- **FNAL**
  - Brian Chase - LLRF (experiment & data analysis)
  - Gustavo Cancelo - LLRF (experiment & data analysis)
  - Michael Davidsaver - DAQ applications programming
  - Jinhao Ruan - laser setup
- **KEK**
  - Shinichiro Michizono - LLRF (experiment & data analysis)
  - Toshihiro Matsumoto - LLRF (experiment & data analysis)
- **SLAC**
  - Shilun Pei - LLRF (experiment & data analysis)
- **SACLAY**
  - Abdallah Hamdi - TPS installation / commissioning

Program Overview

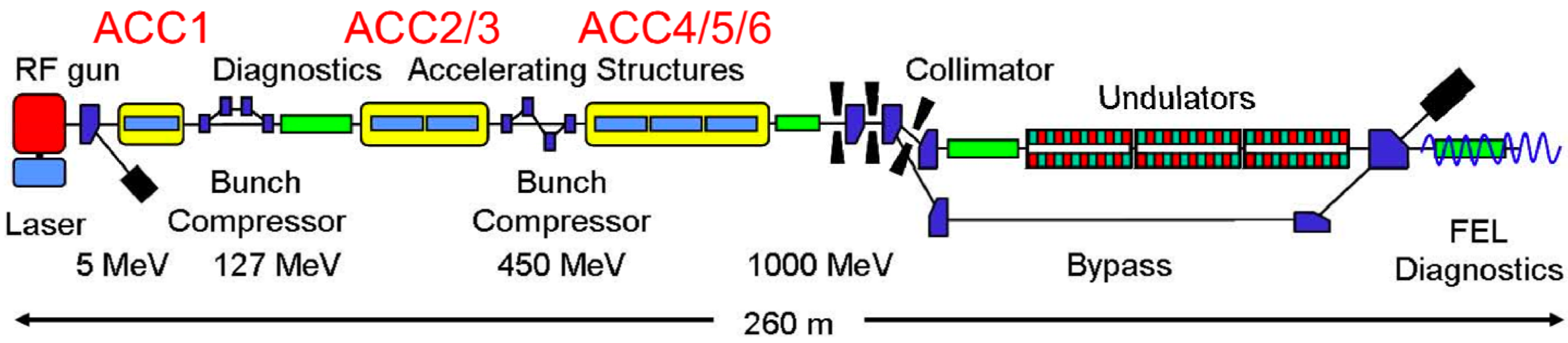
9mA Experiment at TTF/FLASH

- Long-pulse high beam-loading (9mA) demonstration
  - 800μs pulse with 2400 bunches (3MHz)
  - 3nC per bunch
  - Beam energy 700 MeV ≤ E_{beam} ≤ 1 GeV
- Primary goals
  - Demonstration of beam energy stability
    - Over extended period
  - Characterisation of energy stability limitations
    - Operations close to gradient limits
  - Quantification of control overhead
    - Minimum required klystron overhead for LLRF control
  - HOM absorber studies (cryoload)
  - …

Primarily a LLRF experiment

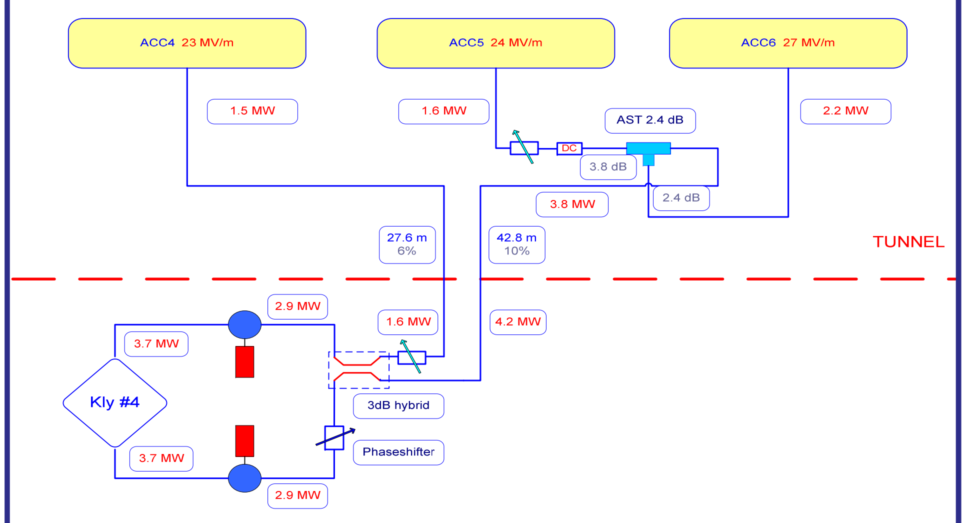
- Major challenge for FLASH
  - Pushes many current operational limits
  - Planning and preparation has already begun

FLASH layout + LLRF block diagram



Comparison of machine parameters

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



ACC456 is main focus of 9mA RF studies

ACC456 Cavity parameters (9mA loading)

ACC4	20.9 MV/m		173 MeV			Max	191	Mev		Δ	17
Pin, MW	1.38		RF power	OK							
Qext	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0			
A, dB	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	*not measured*		
Pcav, kW	155.2	155.2	155.2	155.2	155.2	155.2	155.2	155.2		1241.7	142
Ecav, MV/m	20.89	20.89	20.89	20.89	20.89	20.89	20.89	20.89		20.9 MV/m	
Ecav, max	23	23	23	23	23	23	23	23		23.0	
	Cav 1	*Cav 2*	*Cav 3*	*Cav 4*	*Cav 5*	*Cav 6*	*Cav 7*	*Cav 8*			
Δφ	*not measured*									*beam - forward RF*	

ACC5	26.4 MV/m		219 MeV			Max	231	Mev		Δ	12
Pin, MW	2.20		RF power	OK							
Qext	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0			
A, dB	9.67	9.64	9.61	9.53	9.34	9.35	9.38	9.39	*measured*		
Pcav, kW	237.5	239.1	240.8	245.3	256.2	255.7	253.9	253.3		1981.8	219
Ecav, MV/m	25.84	25.93	26.02	26.26	26.85	26.81	26.72	26.69		26.4 MV/m	
Ecav, max	29	27	28	28	29	28	28	26		27.9	
	Cav 1	*Cav 2*	*Cav 3*	*Cav 4*	*Cav 5*	*Cav 6*	*Cav 7*	*Cav 8*			
Δφ	0	-6	11	1	15	6	6	20		*beam - forward RF*	

ACC6	26.7 MV/m		222 MeV			Max	238	Mev		Δ	16
Pin, MW	2.21		RF power	OK							
Qext	2.95	2.97	3.00	2.98	3.00	2.98	2.99	2.98	11/21/07		
A, dB	7.85	7.54	8.16	8.31	12.27	12.03	10.28	10.37	*measured*		
Pcav, kW	362.8	389.7	337.8	326.4	131.1	138.6	207.4	203.1		2096.9	115
Ecav, MV/m	32.05	33.17	30.83	30.34	19.20	19.77	24.17	23.93		26.7 MV/m	
Ecav, max	34	32	34	32	21	21	29	26		28.6	

9mA Experiment: Context

- Addresses needs of ILC, XFEL, FLASH, Project-X
  - ILC: International GDE stated milestone
    - primary driver: important and visible deliverable for international effort
  - XFEL: Close collaboration with world-wide LLRF groups
    - Focus (potentially accelerate) development and planning for XFEL
    - "Operation at limits" experience provides important Input for future XFEL development
      - Important demonstration also for XFEL
  - FLASH: Addresses many operational issues
    - Automated exception handling and recovery
    - Better characterisation of machine
    - Towards routine high-power long-pulse operation for users.

- Growing International Collaboration (ILC-driven)
  - SLAC, FNAL, KEK, SACLAY, ANL,DESY…
  - TTF2/FLASH remains a unique facility world-wide

S2 context of 9mA studies

Item #	S2 Goals
2	Beam-based feedback and controls
4	RF ‘fault-recognition’ software
5	Quench rates and recovery times
7	Gradient spread
9	HOM heating
12	Produce a ‘spec RF Unit’
10	Check beam phase and energy stability

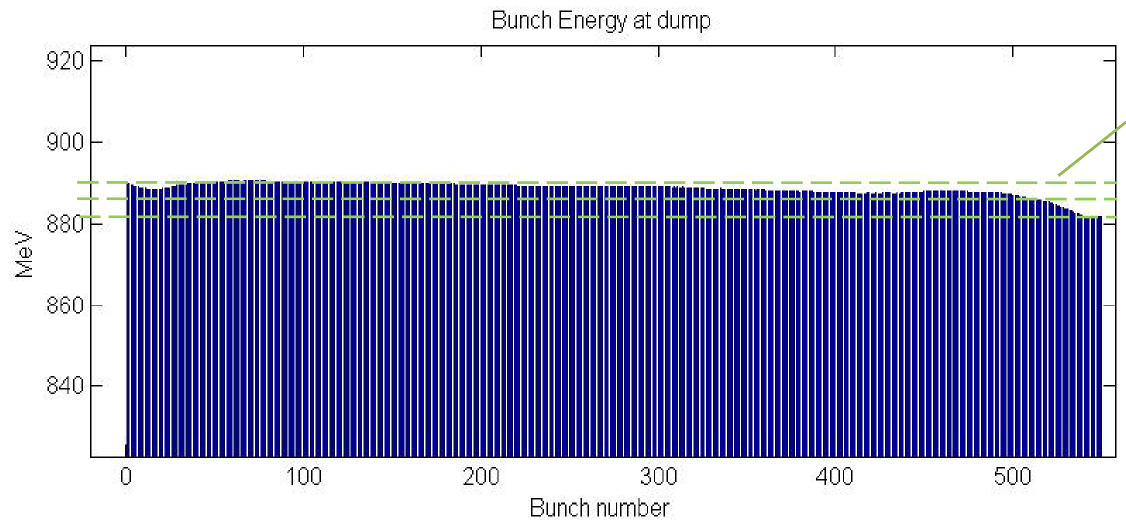
9mA Goals
Operation close to gradient limits
Demonstration of beam energy stability over extended period
Characterisation of energy stability limitations
HOM absorber studies (cryoload)
Long-pulse operation with full beam loading
Quantification of control overhead

Accomplishments in September Studies

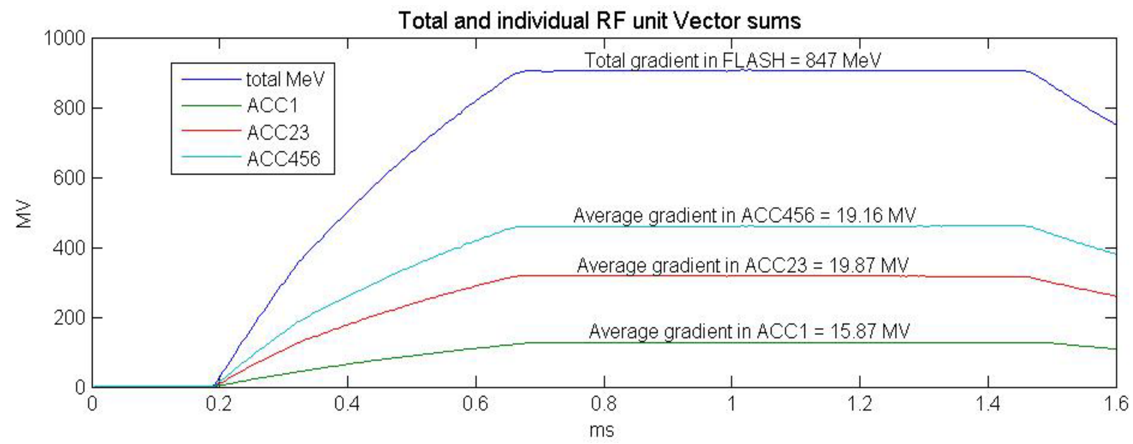
Goal			
Calibrate by-pass BLM	1.5 shifts	✓	
Install/commission by-pass TPS	1.5 shifts	✓	software mask problem prevented long-pulse operation until Friday AM
Injector set-up for 3nC bunches (laser/gun set-up) Loss-free transmission to dump via bypass (optics & steering)	3 shifts	✓	Achieved complete loss-free transmission up to our max of 550 bunches (after LLRF tuning)
Gradually increase bunch number @ 1MHz (3mA) as far as possible; identify problems and constraints. HOM absorber measurements	3 shifts planned ¾ shift achieved	✓ ✗	• Actually achieved* ~2.5 mA with (max) 550 bunches (μs) at ~880 MeV to dump after about four-hours tuning (LLRF). • An average beam power of ~6 kW (final goal 36 kW). • ΔT reported on HOM absorber consistent with current.
Not planned!!		✗	Dump vacuum failure at ~13:00 on Friday 26.09

*) 3nC at gun – but ~20% was estimated to be lost at gun collimator to reduce downstream losses

High Beam Loading Long Pulse Operation



10 MeV over 550 bunches (~1%)
(~4 MeV over 1st 500)



Stable operation with 450 bunches
- Several hours of data
- Currently under analysis

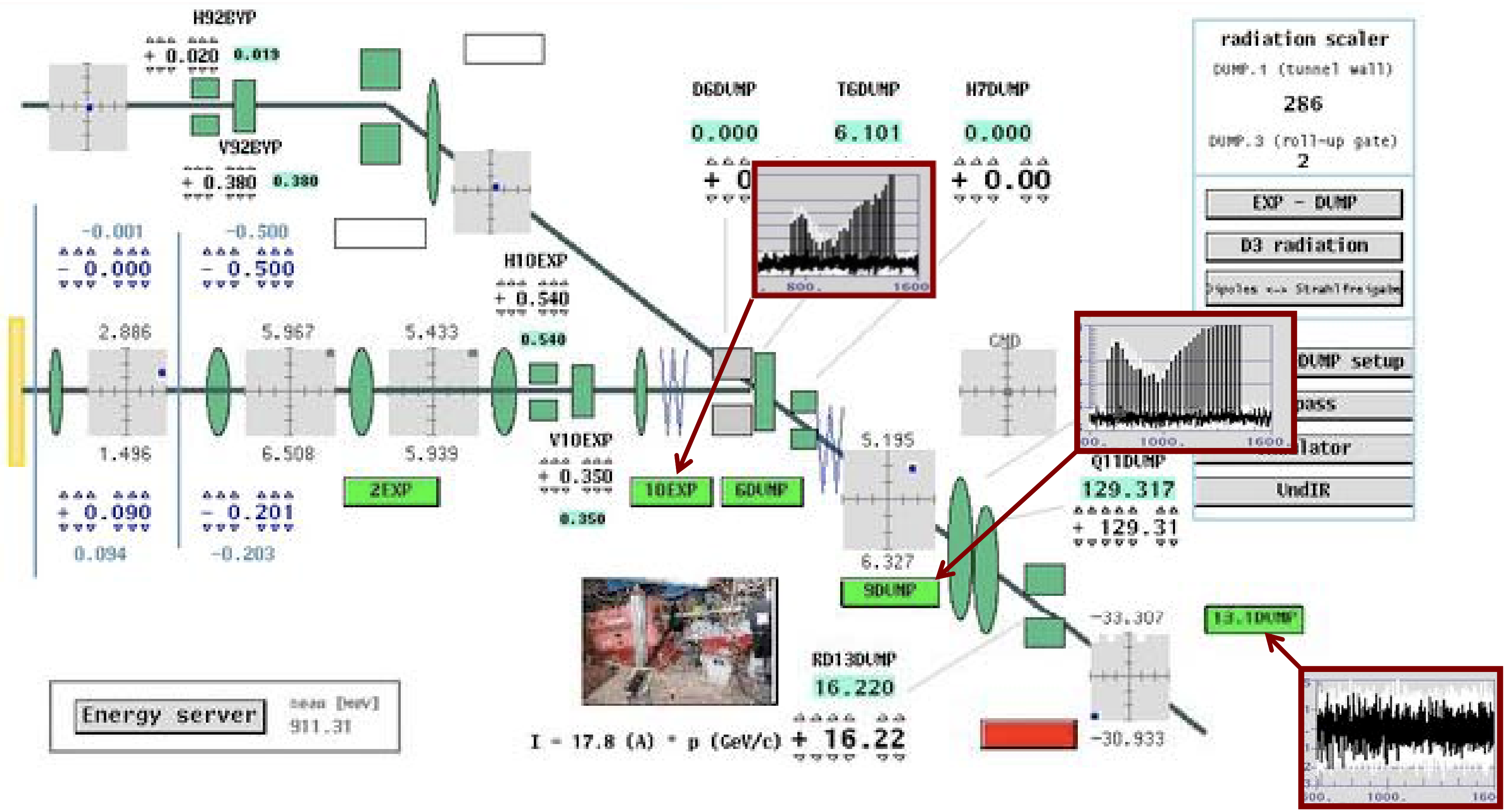
Long bunch trains (~2.5 nC/bunch)
- 550 bunches at 1MHz
- 300 bunches at 500KHz
- 890 MeV linac energy

All modules (RF) running with 800us flat-top and 1GeV total

- Increase from 450 to 550 bunches eventually caused vacuum event

Beam losses signatures in dump region during tuning

(30 bunches @ 50KHz)



FLASH dump-line photo

Dump repair…

- Temporary dump repair in place
  - But limits operation to ~30nC/pulse (eg 30 bunches, 1nC)

- For full-power beam operation
  - Install a new all-titanium 3m dump-line section
  - Must better instrument dump line and improve machine protection for subsequent studies

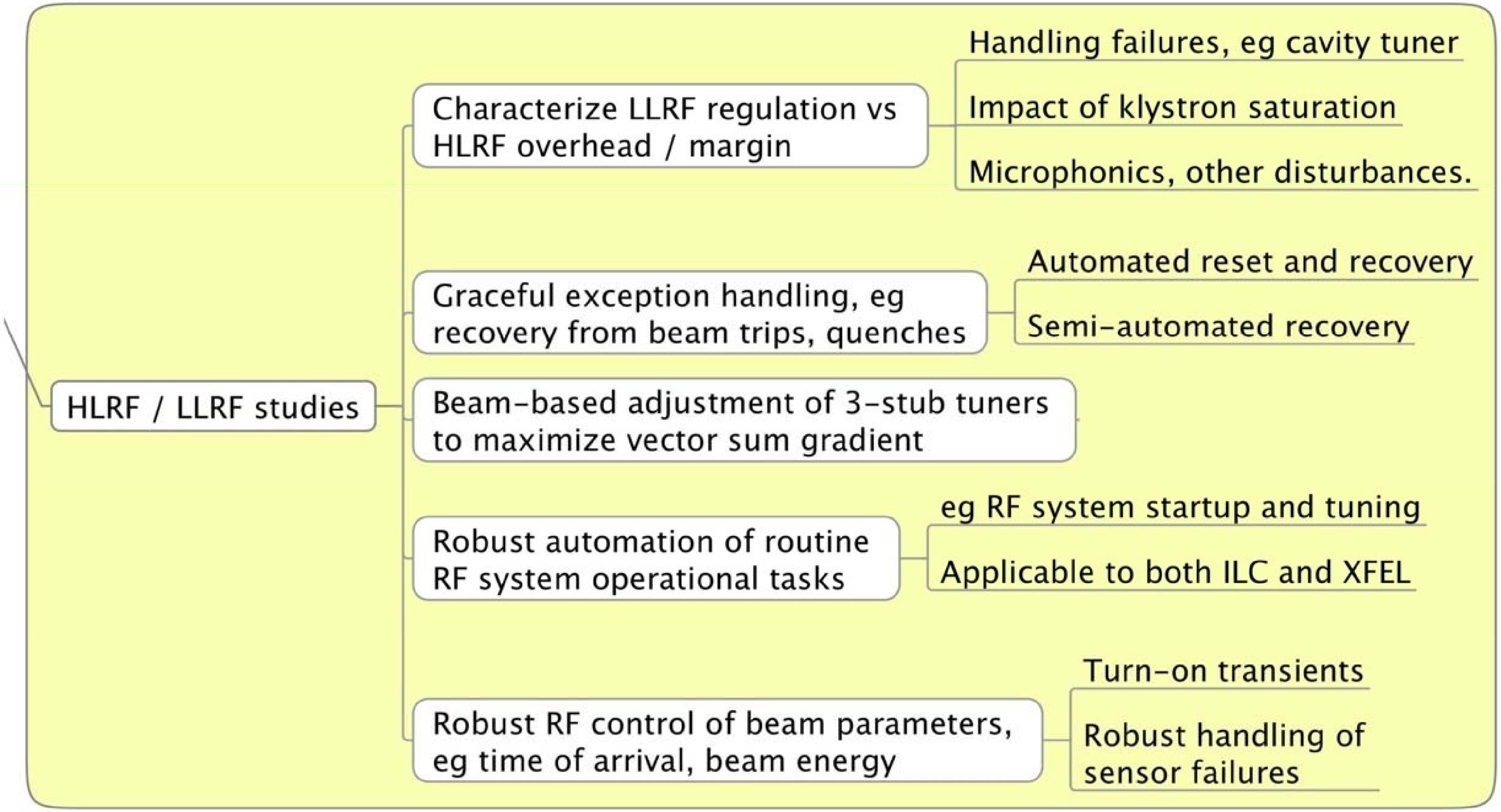
- Dump repair will not be possible before April/May 2009
  - Parts will not be ready for January shutdown
  - An additional 2-3 week shutdown must be scheduled

January 2009 studies proposals

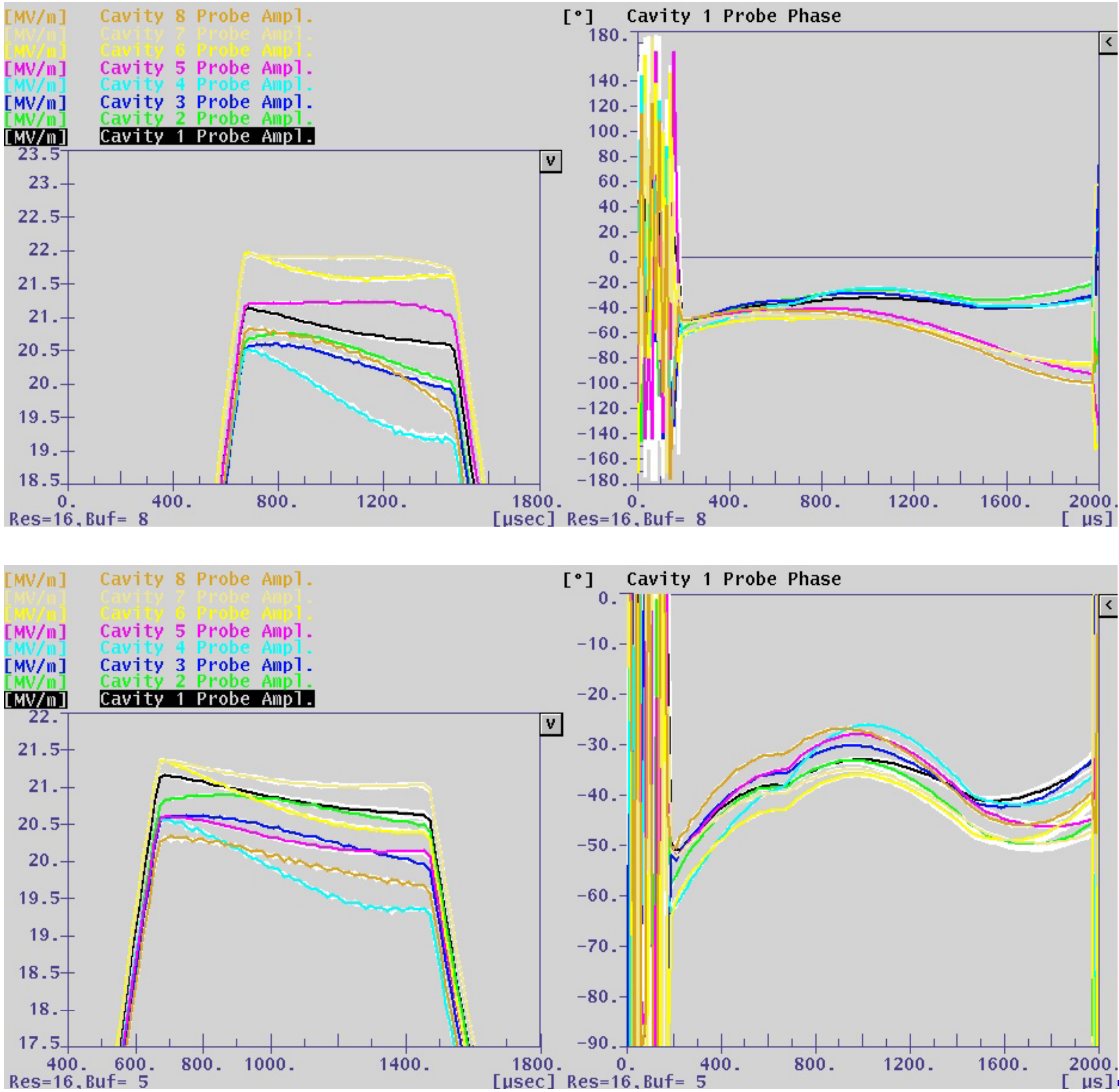
- Temporary limit: 30nC per pulse (eg 30x 1nC, 10x 3nC)
- Main studies objectives
  - Better understand beam loss scenarios in the dump line
  - Correlate losses with LLRF and beam measurements
  - Test beam loss monitor devices in the beam dump area
  - Continue to prepare for 9mA demo, eg
    - Improving LLRF system performance for long pulses
    - Commission 3MHz bunch repetition rate
    - Run cavities in ACC456 close to quench limits
  - Make further LLRF & beam measurements to understand RF overhead requirements

HLRF/LLRF Integration studies

Near- and longer-term goals



Cavity tuning: candidate for automation…?



Cavity tuners adjusted to get ideal field profile for pulse length and gradient

Idea field profile:

- Pre-detune to get same phase at start and end of flat top
- Flat amplitude

Limitations

- Single knob (tuner) means a compromise
- Adjusting 3-stub tuners is time-consuming

Notes…

- We made a lot of progress in September studies
  - 550 bunches, 3nC/bunch, 1MHz.
  - Still a long way to go to the full 9mA demo

- Critical items
  - Schedule for repairing the dump line
  - Better instrumentation and machine protection

- There will no longer be a 3-cryomodule RF unit available after the FLASH shutdown (starts Sept 2009)

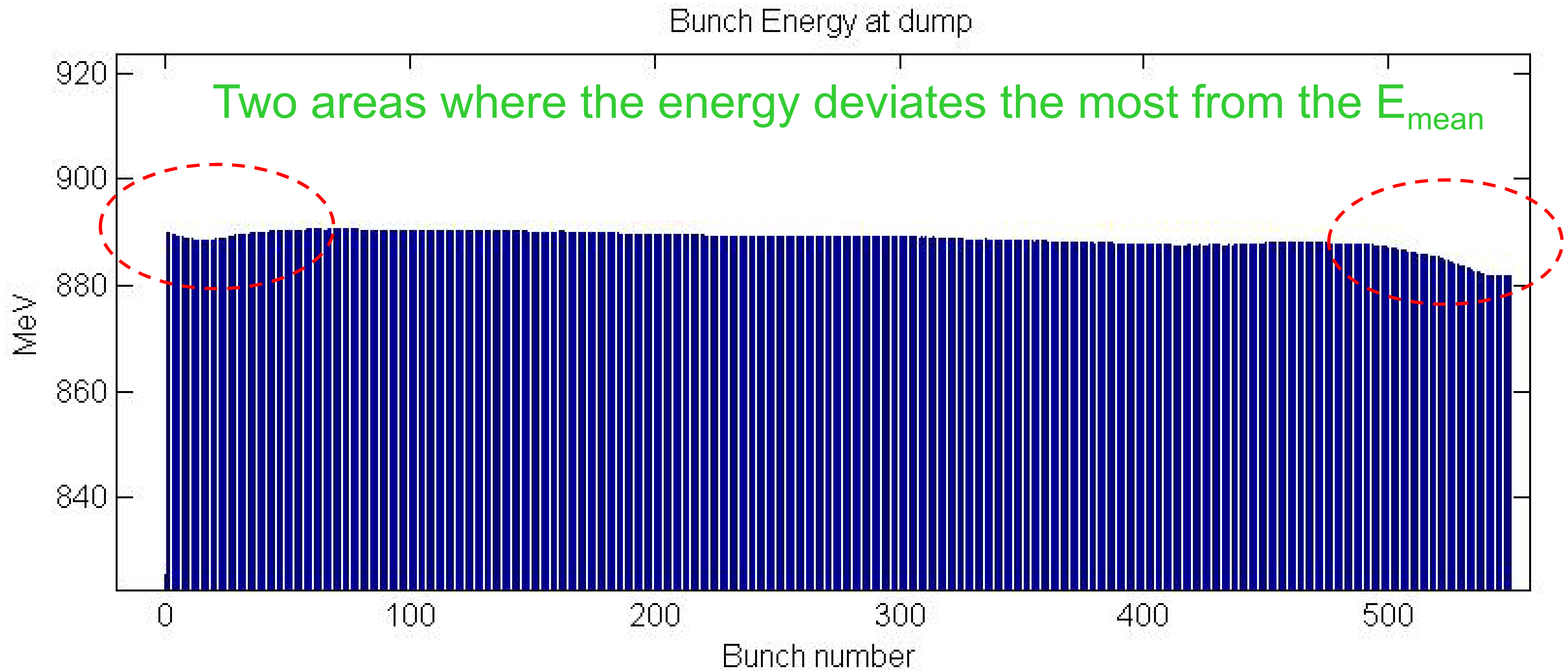
LLRF results and analysis

Outline

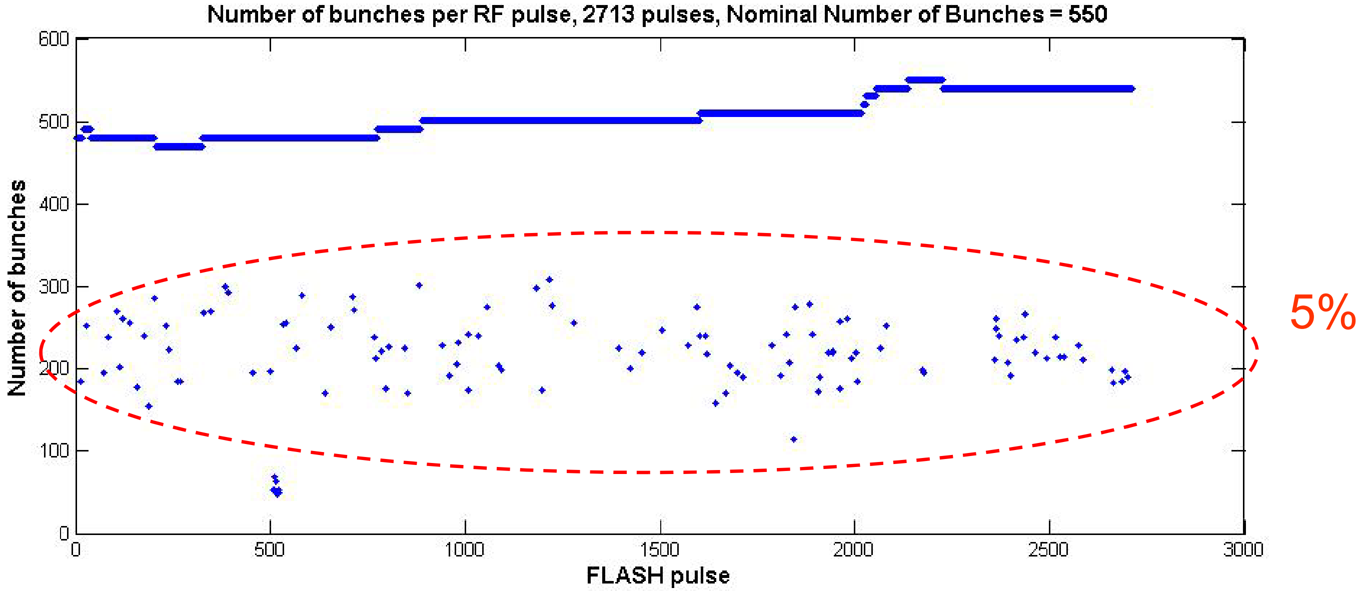
- Beam Energy studies
- Gradient studies
- LLRF Noise studies
- RF power studies
- Desired LLRF improvements for FLASH

Beam Energy studies: Single RF pulse

- On September 26 2008, the ILC-9mA test collaboration run FLASH increasing the number of 3nC bunches up to a maximum of 550.
- The picture below shows a fairly flat bunch energy profile for a single RF pulse.

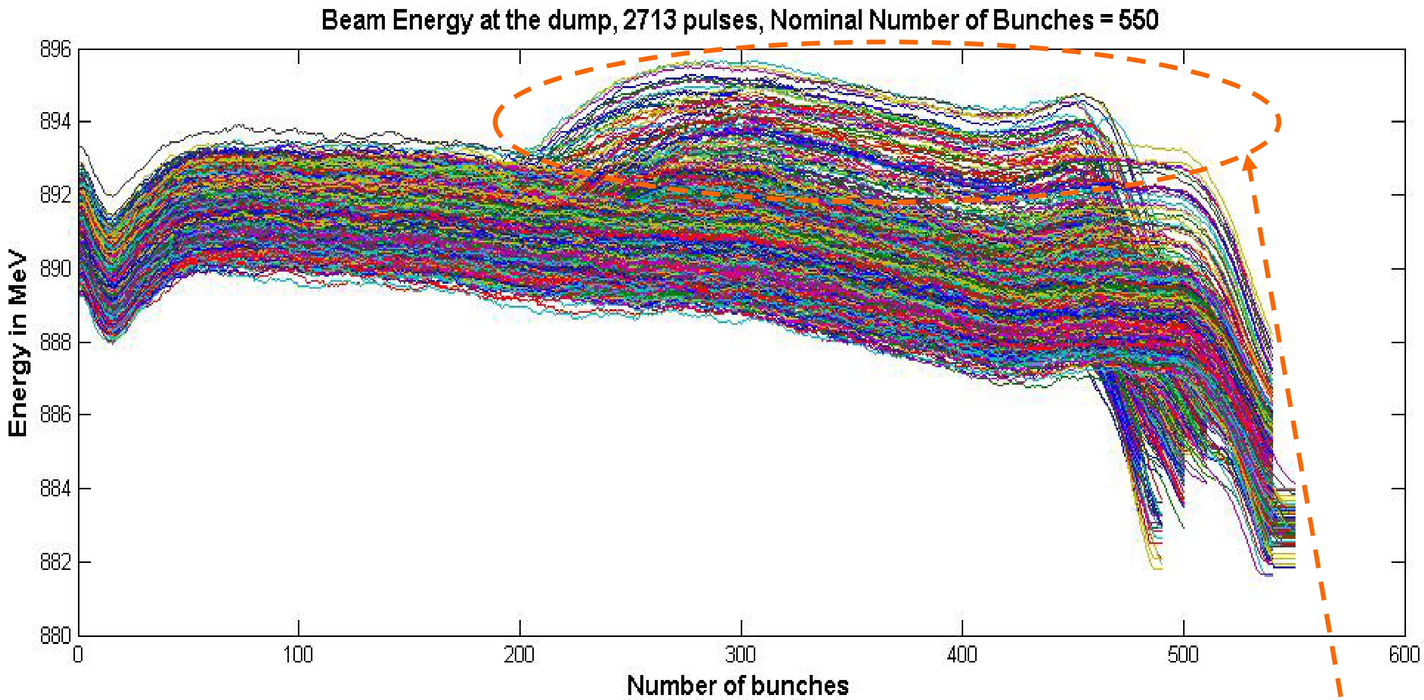


Multi RF pulses: Number of beam bunches at dump



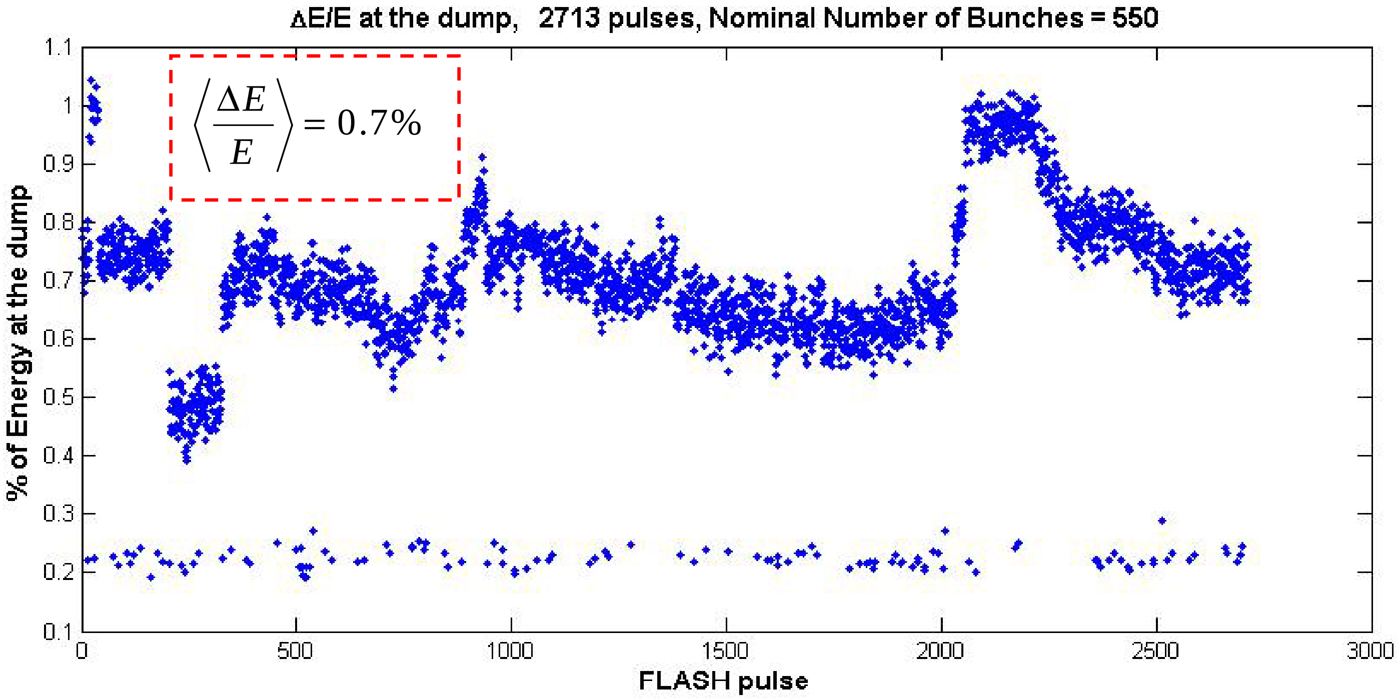
- 2713 RF pulses at 5Hz equals 10 minutes worth of data taken on Sept. 26 between hs 13:00 and 13:10.
  - The plot shows how we were trying to increase the number of bunches per pulse.
    - Sometimes we had to back down and tune machine optics or LLRF parameters before going back up.
  - 5% of the pulses are shorter than the nominal due to machine trips.

Beam Energy at the dump



- This is a similar picture but includes energy plot for a total of 2713 pulses.
  - Not all pulses reach 550 bunches, but most reach 480.
  - For every pulse we see the same two areas where the energy deviates the most from the Emean.
  - We also see an energy increase in the middle of some pulses.

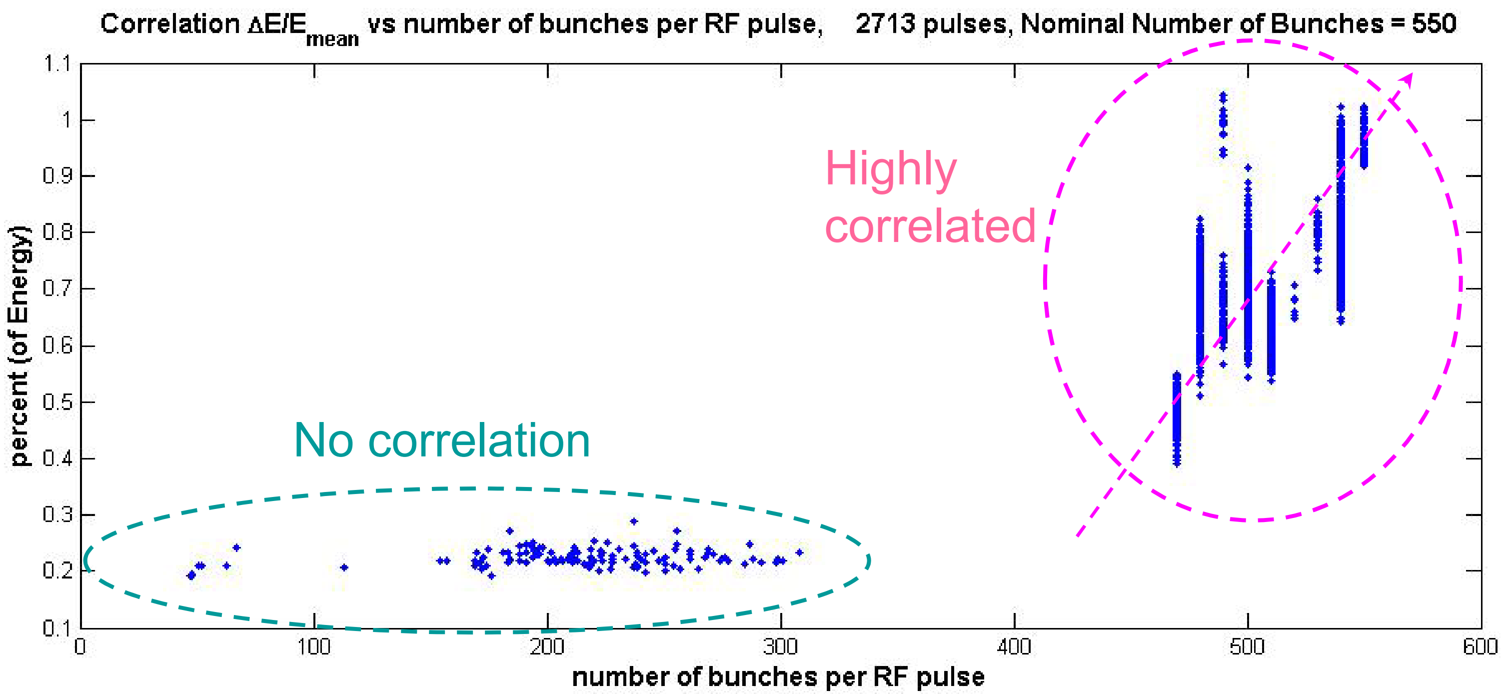
ΔE/E at the dump



- Small number of pulses have ΔE/E ~0.2%. Also some are around 1%.
- Mean ΔE/E = 0.7% still far from the 0.1% specification.

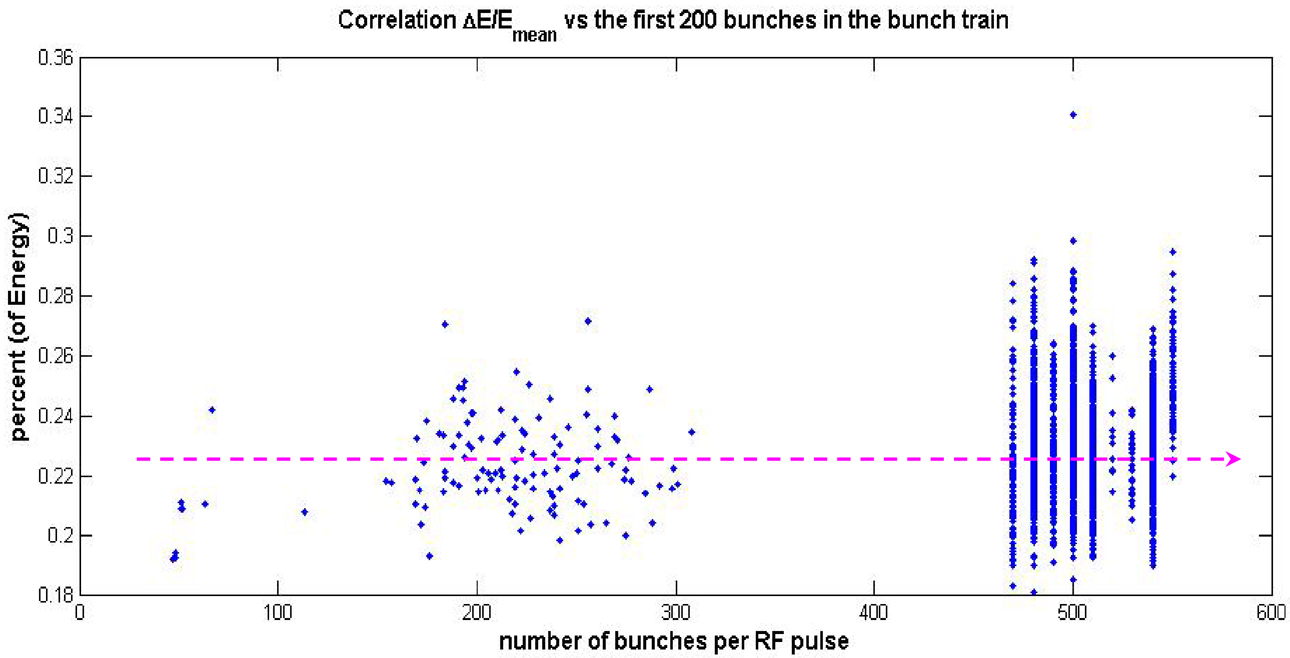
- Are there any interesting correlations here?

Correlation of ΔE/E versus number of bunches



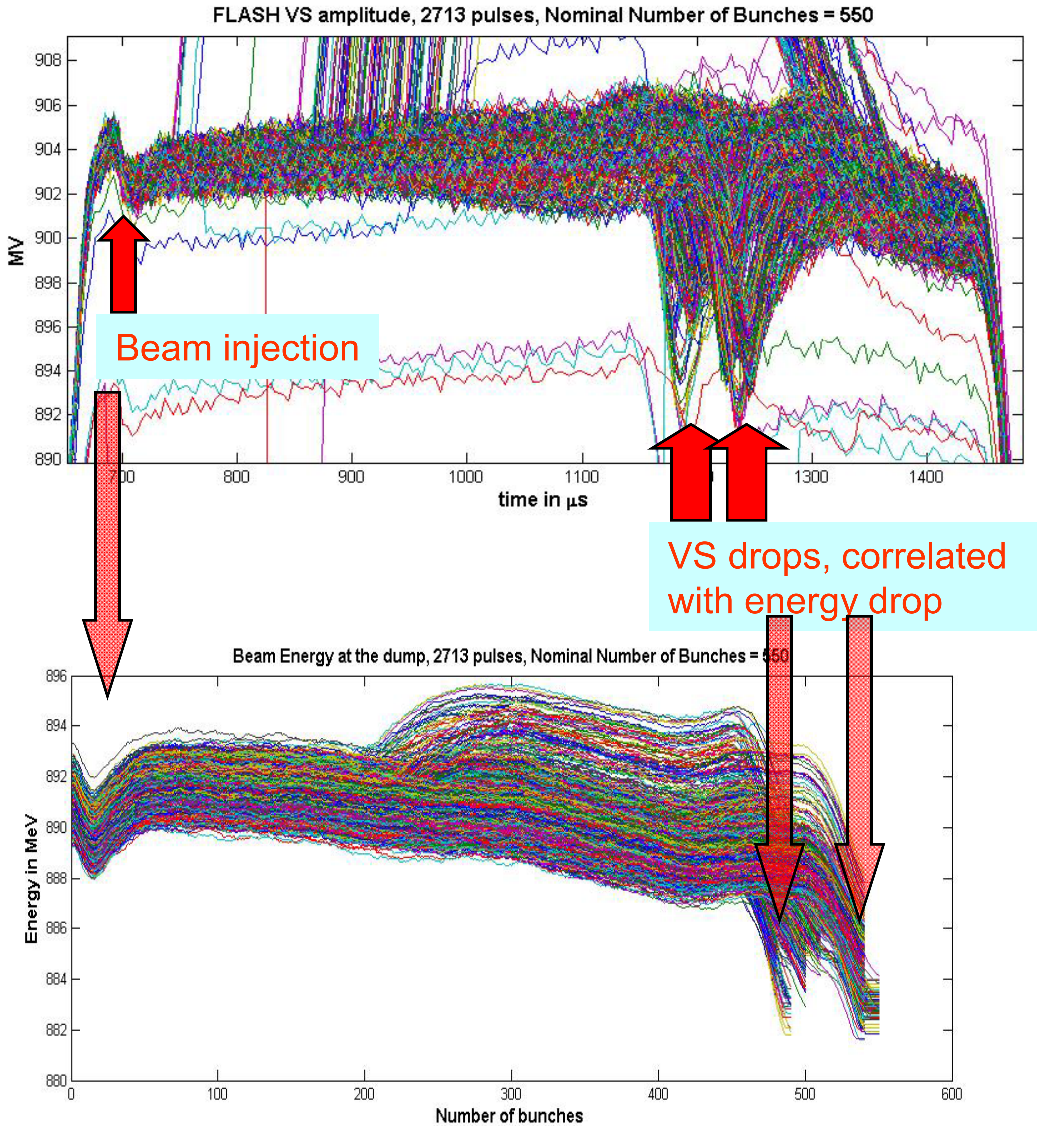
- There is a strong positive correlation between the energy spread and the number of bunches for long bunch trains of N>450.
- There is no correlation for short bunch trains.

Correlation of ΔE/E versus number of bunches (2)



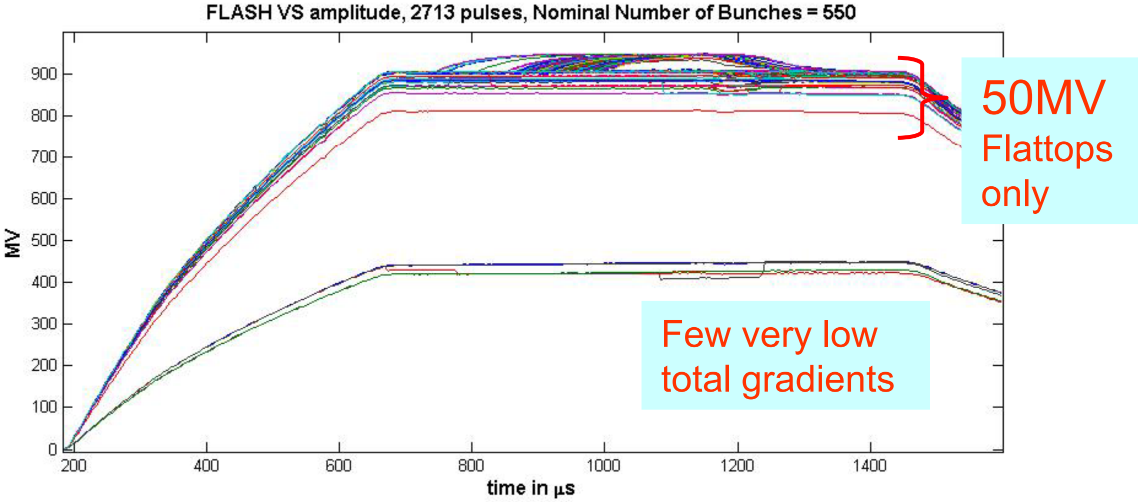
- If we look at the 1st 200 bunches in each bunch train the correlation and energy spread are much smaller.
  - So, the problem seems to be in the RF field, because the energy spread grows with time during the flattop.

Total VS gradient (Amplitude)



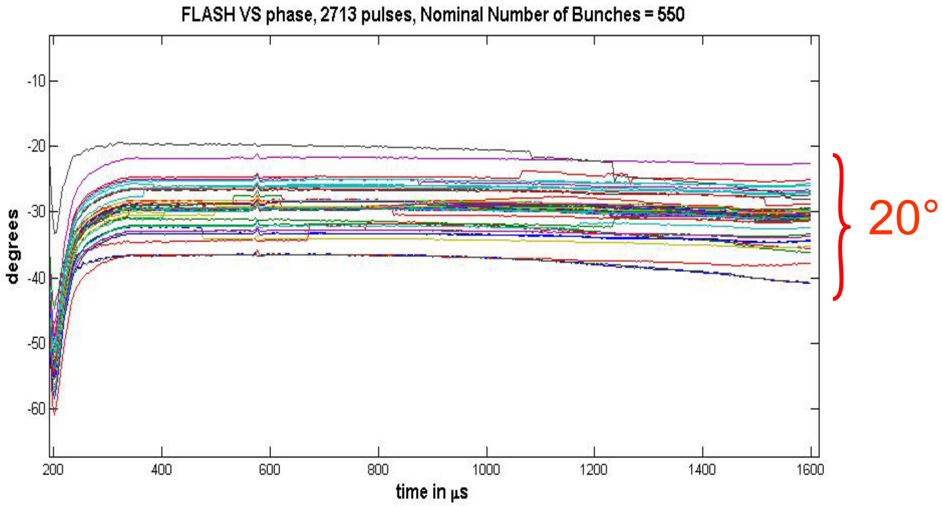
- The VS amplitude drops by 12MV.
- If we take the phase into consideration the V_{acc} drop is 9MV.
- The energy drops by 7MeV on average at the end of the RF pulse coincident with the VS drop.

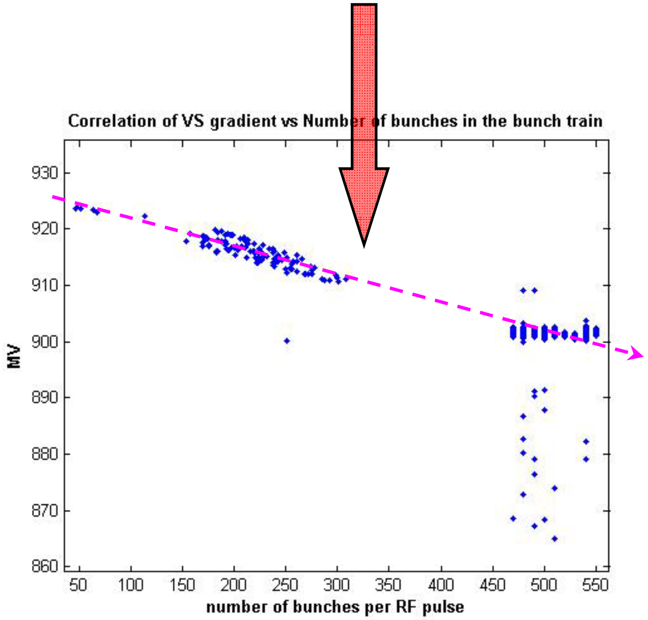
Gradient studies (1)



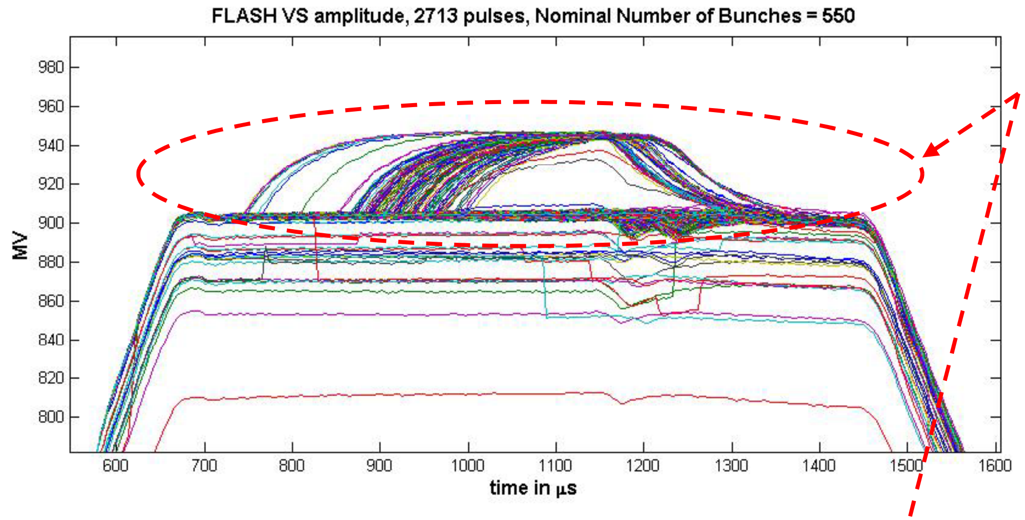
VS amplitude and phases jump from pulse to pulse, although jumps are small 90% of the time.

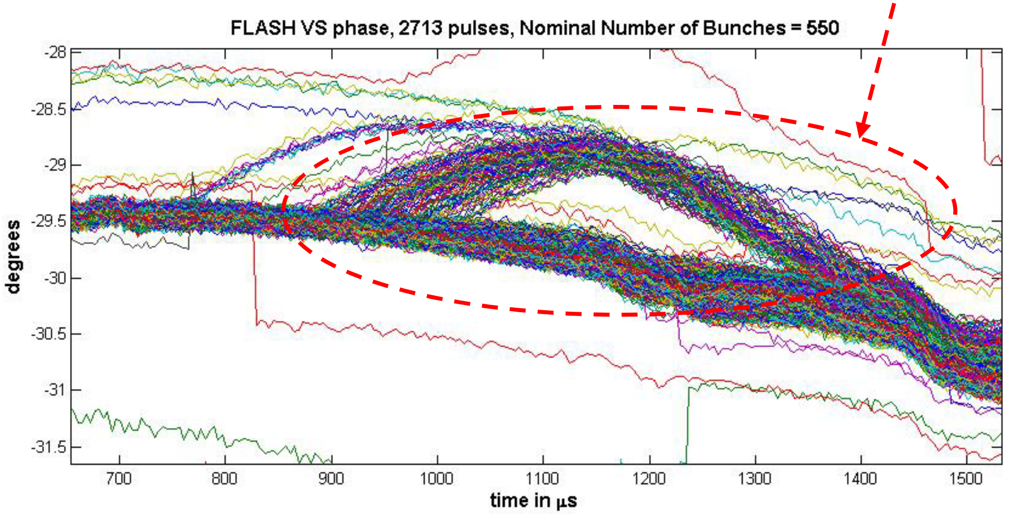
The amplitude of the jumps are also correlated to the number of bunches in the bunch train.





Short bunch trains



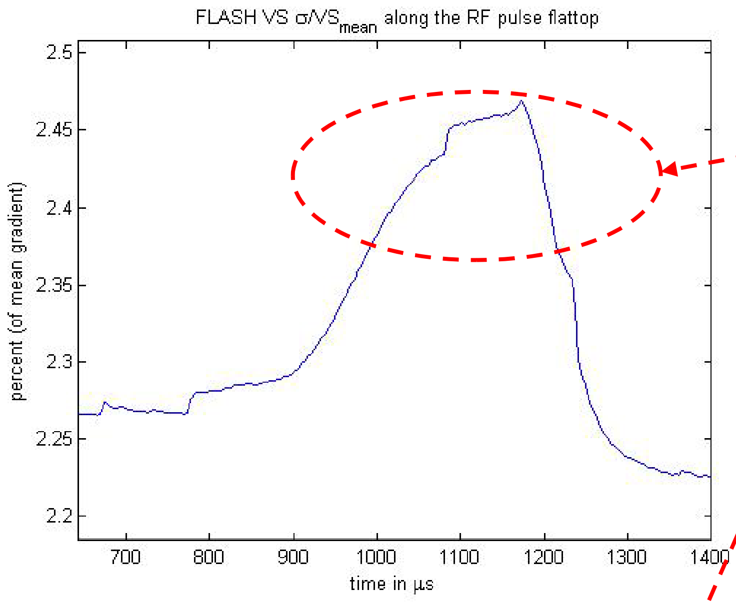


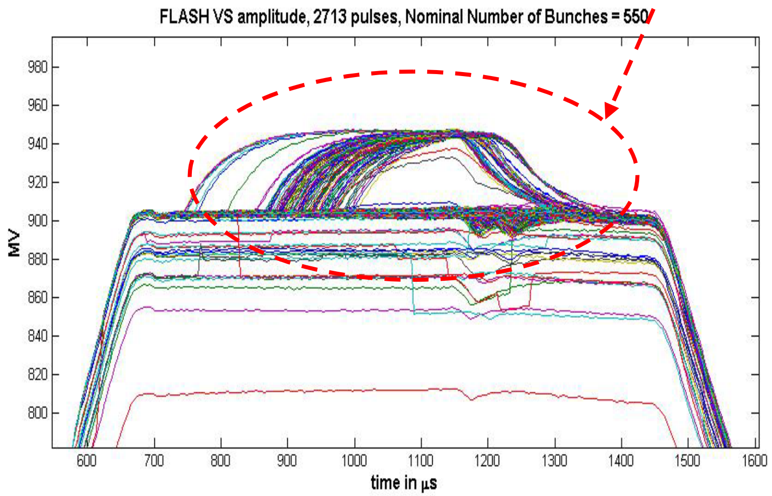
Bunch train is shortened. VS overshoot caused by feed forward being too large.
The phase is affected likewise.
The shorter bunch is a disturbance to the LLRF control.

The Adaptive Feed Forward cannot do anything about it.

The feedback control deals with it but the gain is only 20.

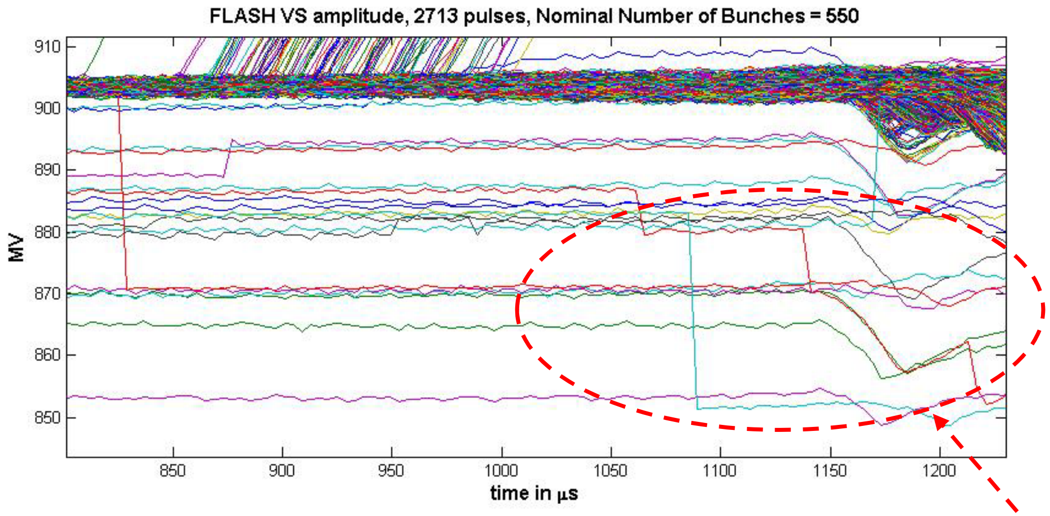
FLASH VS amplitude rms

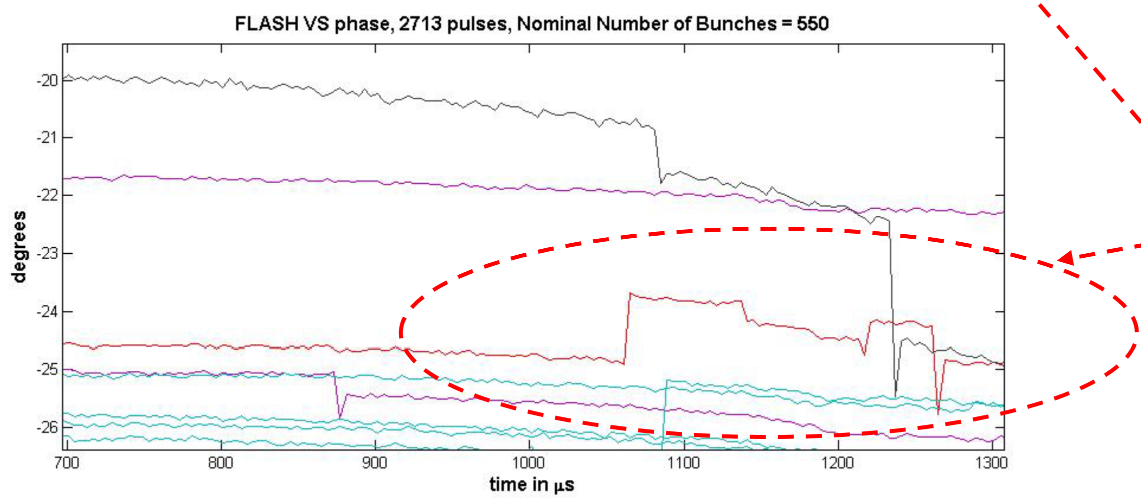




- Part of the error is due to the gradient overshoots in some RF pulses.
- The gradient rms error is computed for 2713 pulses along the flattop.

Gradient studies (4)





- Amplitude and phase suddenly jump, i.e. 30MV, 1°, during the RF pulse in 4us.
- This is not correlated with beam behavior.
- ???
- Is this real or DAQ artifact?

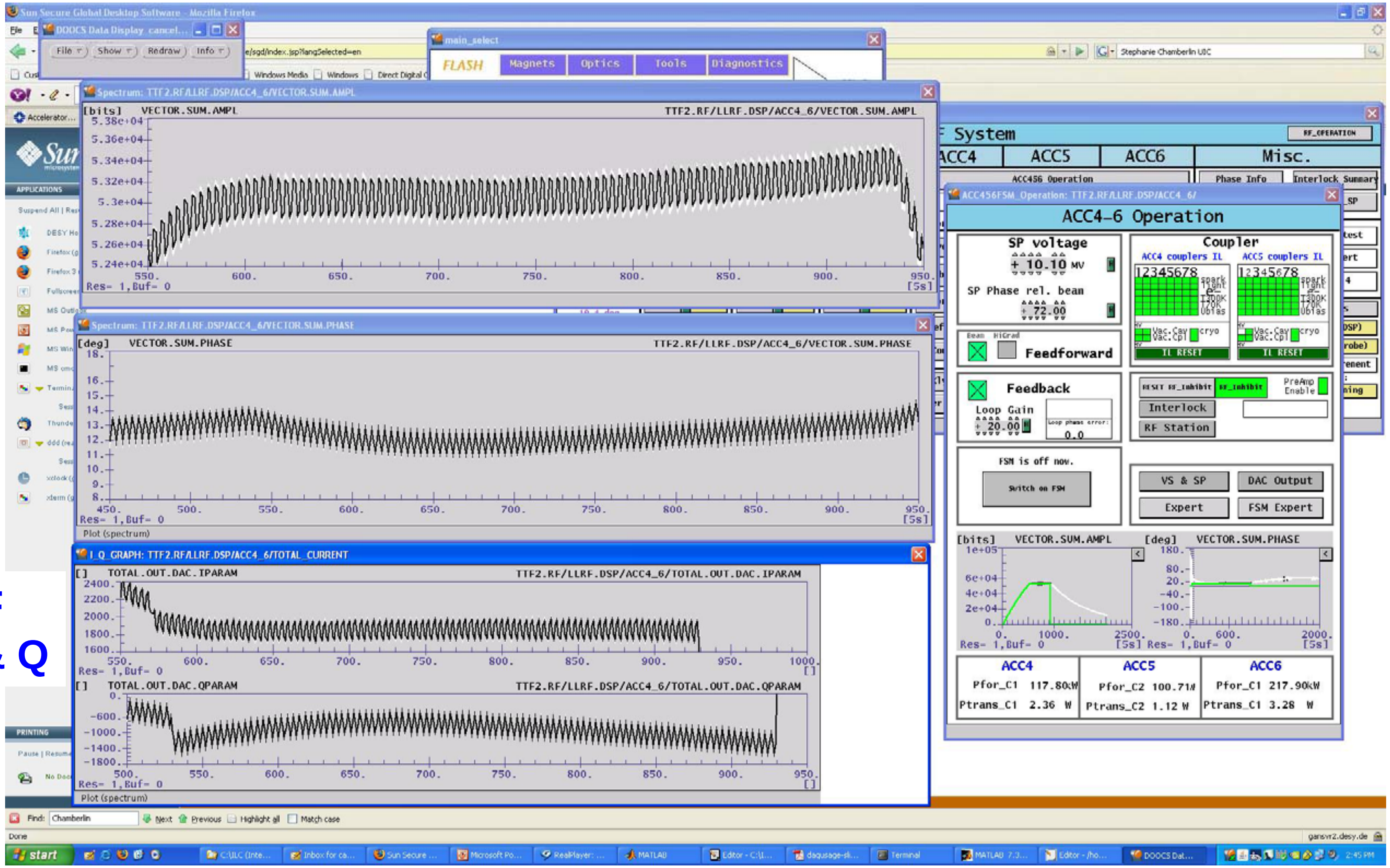
Conclusions of Beam Energy & Gradient studies

- About 5% of the pulses are shortened by machine trips.
- $\Delta E/E = 0.7\%$
- $\Delta E/E$ increases for long bunch trains due to poor LLRF regulation.
- Cavity gradients jump in A and phi for long bunch trains.
- VS overshoot in A and phi when bunch trains get shortened.
- VS Ampl. rms is 2.45% at the end of a bunch train (~550 bunches).
- Small A and phi jumps uncorrelated with beam.

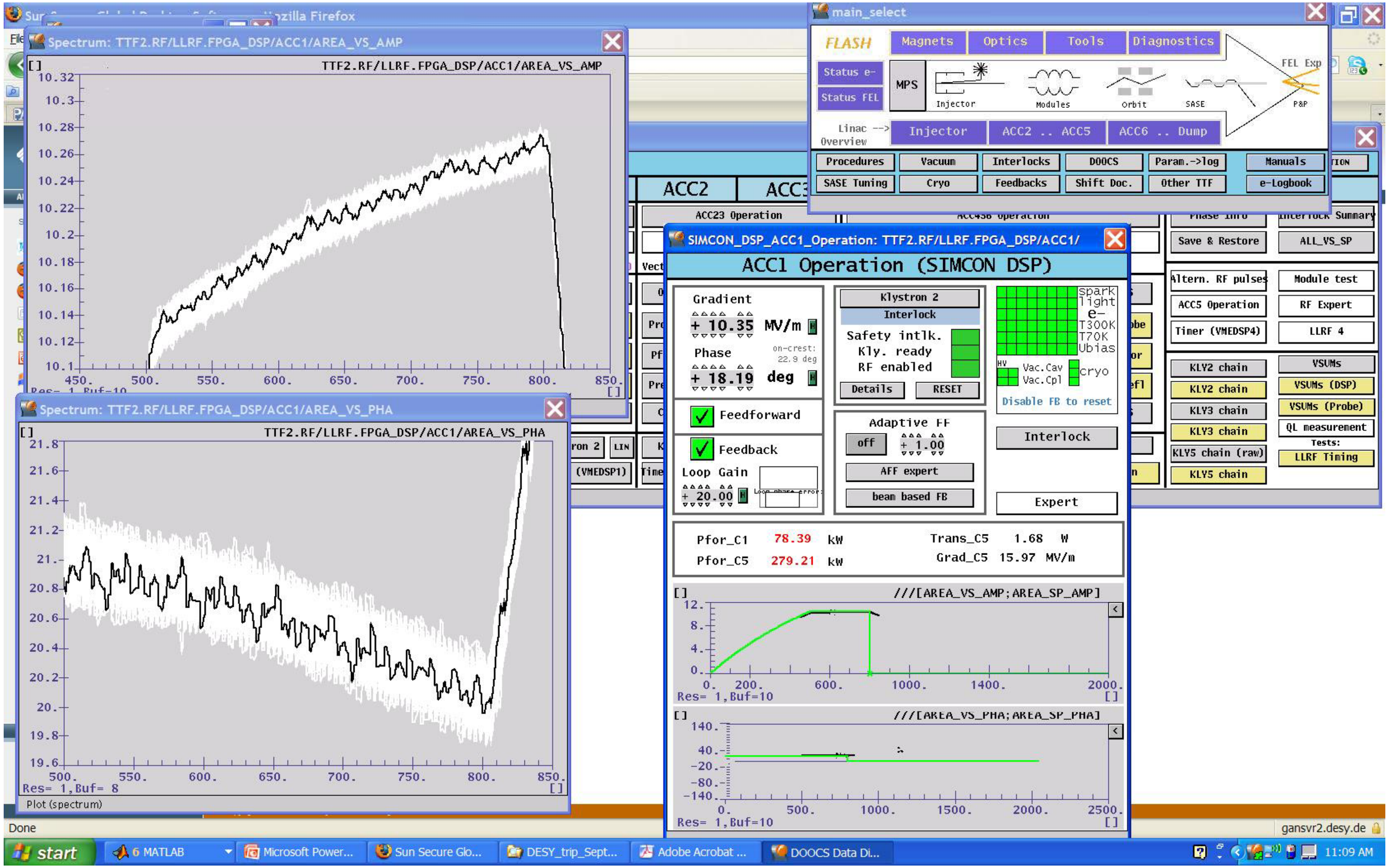
Gradient studies (4): 250 KHz noise in the loop

- ACC456: 1%, 1.5° at Kp=20,

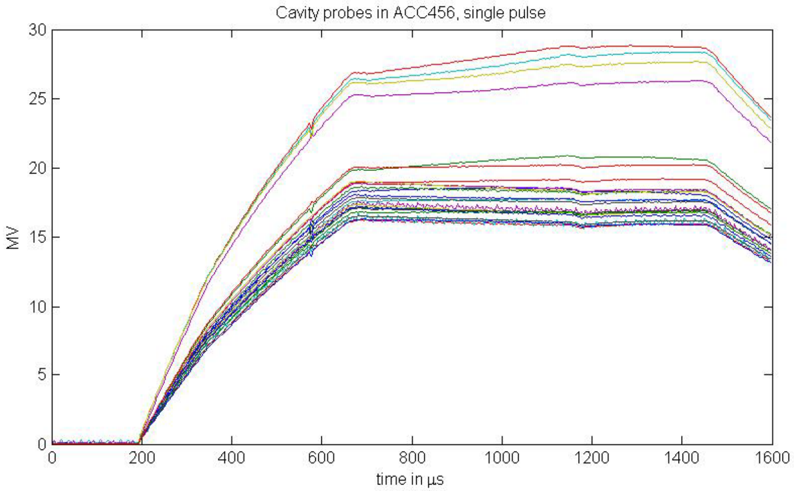
FF
I & Q



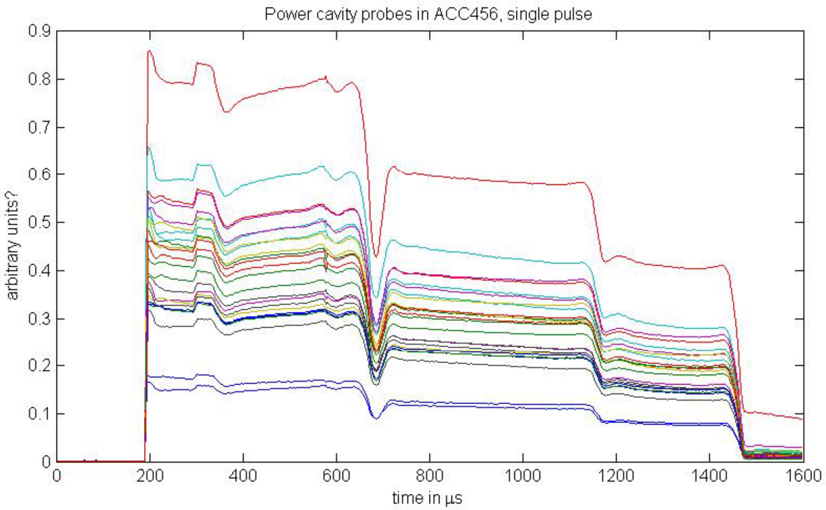
Gradient studies: 250 KHz noise in the loop

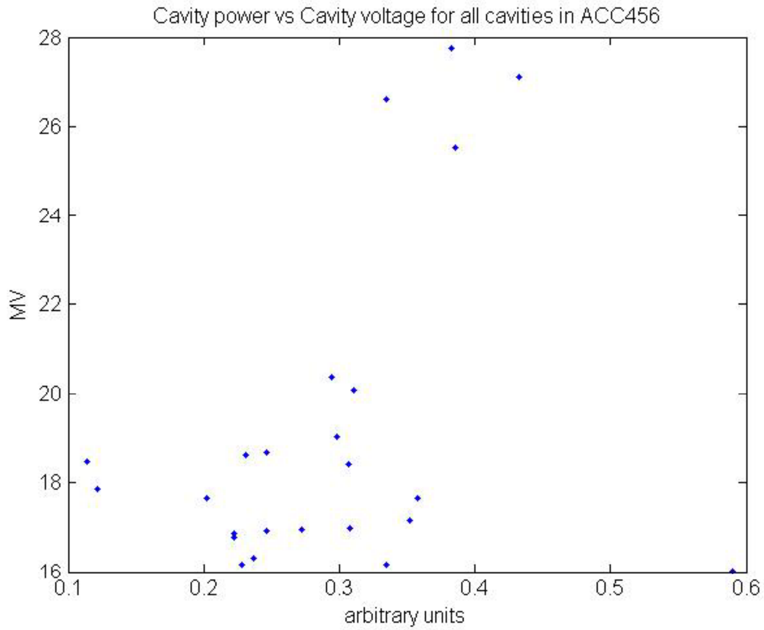


Power studies

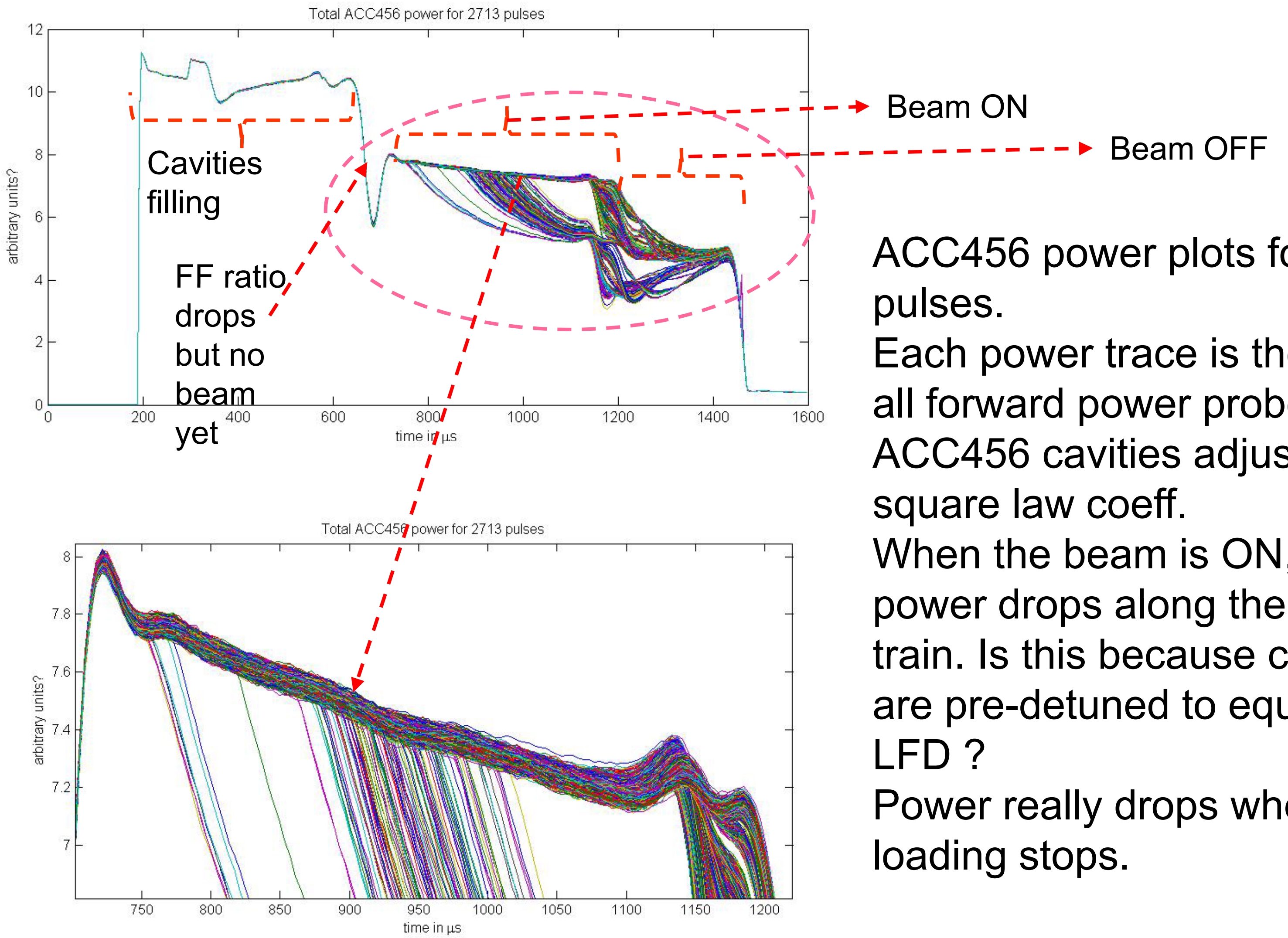


Power probes in ACC456 cavities are not calibrated. Cavity Qs are close to each other. If calibrated there should be a quadratic relationship between power and voltages. So, I normalized power levels to voltage levels using a quadratic law. However, power s will not show in units of watts.



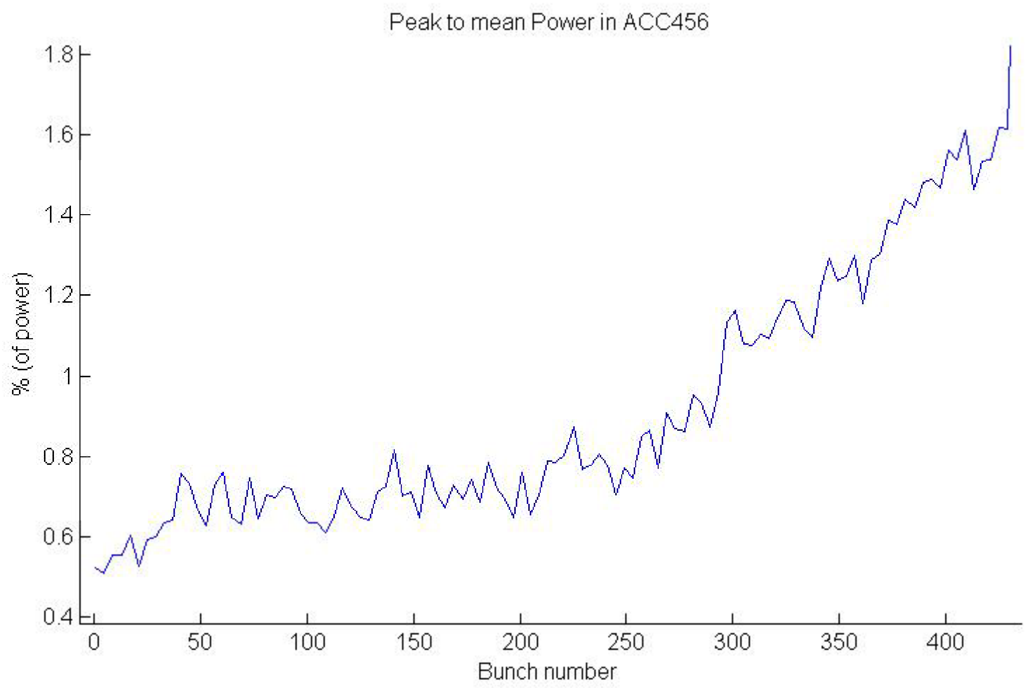


Power studies



ACC456 power plots for 2713 pulses.
Each power trace is the sum of all forward power probes in ACC456 cavities adjusted by a square law coeff.
When the beam is ON, the power drops along the bunch train. Is this because cavities are pre-detuned to equalize LFD ?
Power really drops when beam loading stops.

Power studies



Peak to mean difference of total forward power measured using the sum of all forward power probes in ACC456 cavities adjusted by a square law coeff.

The peak to mean power increase faster after 200 bunches as seen in the energy studies

A slide about control

- There is a talk about control in the breakout session of Wednesday.
- Summary of control issues:
  - The main roll should be played by the FF and the FB controllers.
  - The FB control should increase the proportional gain above 100.
  - An integrator is desired to improve the time response and steady state error. Maybe a PID if overshoot becomes a problem.
  - Minimize measurement error in the feedback loop.
  - The AFF should play a secondary roll.

Desired LLRF improvements for FLASH

- 1) Simcon-DSP based systems for ACC456 and ACC23. This seems easier to implement for ACC456 and not so for ACC23. Maybe a temporary installation of Simcon-DSP can be done in ACC23 for the Jan test.
- 2) Increase the gain of the proportional controller as much as possible. A gain of 100 to 150 is a nice goal. This goal may require to look at the group delay and a new digital filter to notch the 8/9pi mode.
- 3) Unify the AFF algorithms. Currently there are 3 different algorithms, one for each klystron loop.
- 4) Incorporate beam information into the control, so the AFF does not over or under compensate.
- 5) Calibrate power probes.
- 6) Understand vectorsum calibration. Even with 30 1nC bunches we can test the vectorsum calibration.
- 7) Move away from 250KHz IF. I do not know if this is possible for Jan. But we think that it may be required for the 9mA test.

- I think that it would also be nice to look at the RF parameter configuration and understand weather we can improve it in order to minimize the tilt in individual cavities. Of course we won't have heavy beam loading, but at least we can use the September data and draw some conclusions.

LLRF session on Wednesday

Wednesday 19 November 2008

top

08:30->*10:00* **ILC: Main Linac 2** (Convener: Chris Adolphsen (*SLAC*) , Norihito Ohuchi (*KEK*) , John Carwardine (*Argonne*) , Hitoshi Hayano (*KEK*)) (UIC Forum Meeting Room I)

08:30	LLRF progress report from KEK (20')		Shinichiro Michizono (*KEK*)
08:50	LLRF progress report from DESY (20') (Slides)		Stefan Simrock (*DESY*)
09:10	LLRF progress report from FNAL (20')		Brian Chase (*FNAL*)
10:00		coffee break	

10:30->*12:00* **ILC: Main Linac 2** (Convener: Chris Adolphsen (*SLAC*) , Norihito Ohuchi (*KEK*) , John Carwardine (*Argonne*) , Hitoshi Hayano (*KEK*)) (UIC Forum Meeting Room I)

10:30	(Some) LLRF top-level performance requirements (20')		Nicholas Walker (*DESY*)
10:50	Discussion: LLRF performance specifications (20')		Brian Chase (*FNAL*)
11:10	LLRF feed-forward and feedback (20')		Gustavo CANCELO (*FNAL*)
11:30	Discussion: metrics for assessing HLRF overhead requirements (20')		
12:00		lunch	

13:30->*15:30* **ILC: Main Linac 2** (Convener: Chris Adolphsen (*SLAC*) , Norihito Ohuchi (*KEK*) , John Carwardine (*Argonne*) , Hitoshi Hayano (*KEK*)) (UIC Forum Meeting Room I)

13:30	LLRF for the FLASH 9mA program (30')		Stefan Simrock (*DESY*)
14:00	Experience with the FLASH DAQ / Archiver (20')		Michael Davidsaver (*FNAL*)
14:20	Discussion: next LLRF 9mA studies at FLASH (30')		John Carwardine (*Argonne*)
14:50	Discussion on parameters for an ILC cavity model (15')		
15:30		coffee break	

16:00->*18:00* **ILC: Main Linac 2** (Convener: Chris Adolphsen (*SLAC*) , Norihito Ohuchi (*KEK*) , John Carwardine (*Argonne*) , Hitoshi Hayano (*KEK*)) (UIC Forum Meeting Room I)

16:00	Informal tutorial on FLASH DAQ / Archiver (1h00')	