Progress report on FLASH 9mA studies

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(For the 9mA collaboration)
FLASH Seminar, November 24, 2009

Outline

- Background
- Selected results
- Operational lessons
- Next steps…
- Wrap-up

Background

Primary objectives of the 9mA studies

- Long-pulse high beam loading (9mA) demonstration
  - 800μs pulse with 2400 bunches (3MHz), 3nC per bunch
  - Vector Sum control of up to 24 cavities, ±0.1% energy stability
  - Cavity gradients approaching quench limits
  - Beam energy 700-1000MeV

- Characterize operational limits
  - Energy stability limitations
  - Cavity gradient overhead needed for LLRF control
  - Klystron power overhead needed for LLRF control
  - HOM absorber studies (cryo-load)

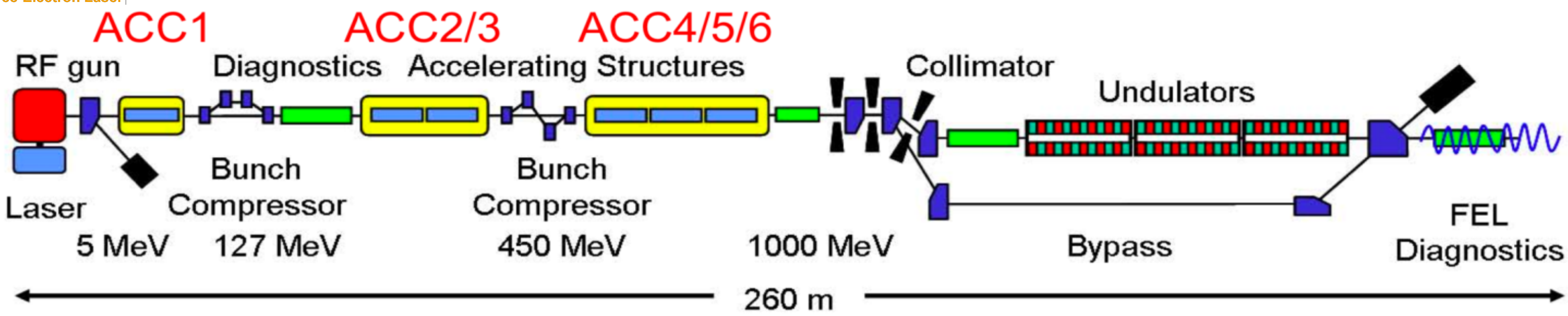
- Operation close to limits, eg
  - Robust automation of tuning, etc
  - Quench detection/recovery, exception handling
  - Beam-based adjustments/optimization

Studies using the high power beam

Operational challenge for FLASH

Well beyond typical beam parameters for photon users

TTF/FLASH 9mA Experiment



Comparison of machine parameters

		XFEL	ILC	FLASH design	9mA studies
Bunch charge	nC	1	3.2	1	**3**
Bunch rate	MHz	5	2.7	9	**3**
# bunches		3250	2625	7200	**2400**
Pulse length	μs	650	970	800	**800**
Current	mA	5	9	9	**9**

Nominal experiment setup

- 3nC/bunch
- Bunch rates: 40kHz – 3MHz
- Laser #1: 40kHz – 1MHz; Laser #2: 3MHz
- RF systems operating nominally on crest
- BC magnets on, but no compression
- Beam through Bypass line to dump
- RF gun: 1.5 cell warm PC gun
- ACC1: 8 SC cavities
- ACC23: 2x 8 SC cavities
- ACC456: 3x 8 SC cavities
- LLRF: digital I/Q control of VS
- Piezo tuners: ACC3, ACC5, ACC6

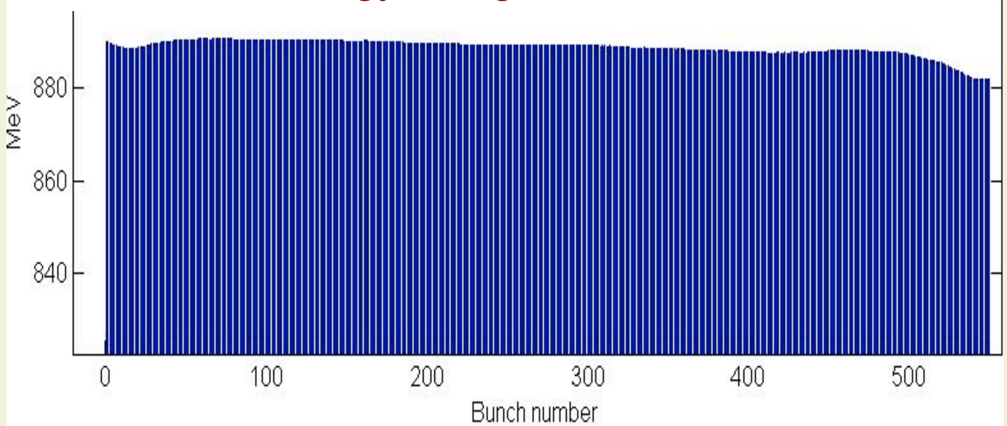
Before Sept 09…

First high power run: Sept 2008

High beam-loading long pulse operation

(550 bunches at 1MHz, ~2.5nC / bunch at dump, 890MeV)

Beam Energy along 550us bunch train



Long bunch trains:

- **450 bunches @ 1MHz**
- **300 bunches @ 500KHz**

… terminated early by vacuum incident in dump line

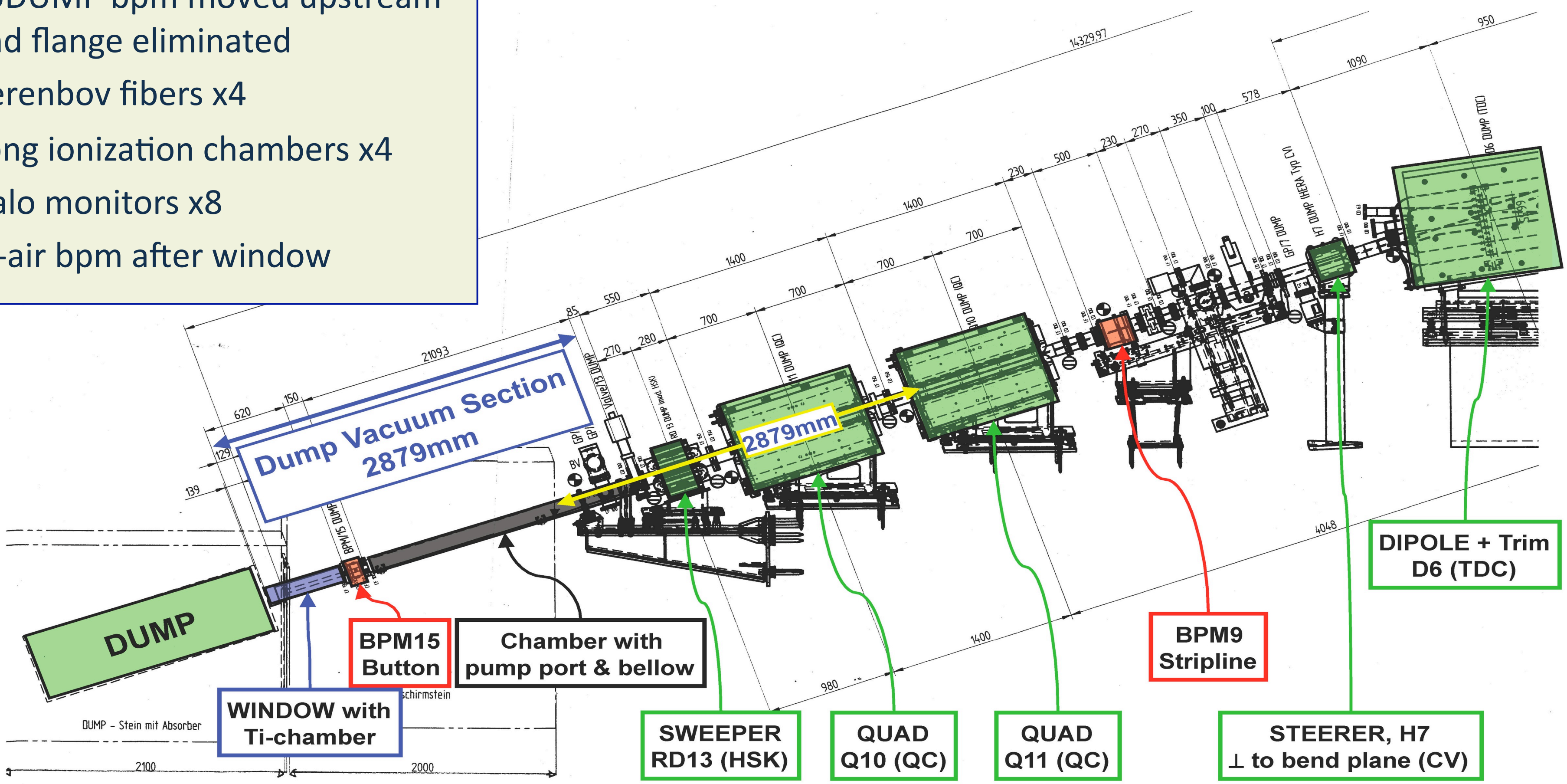
Biggest operational issue: minimizing beam losses

- High beam power (~6kW)
- Narrow energy aperture, sensitive to LLRF tuning
- Insufficient beam loss information from dump line

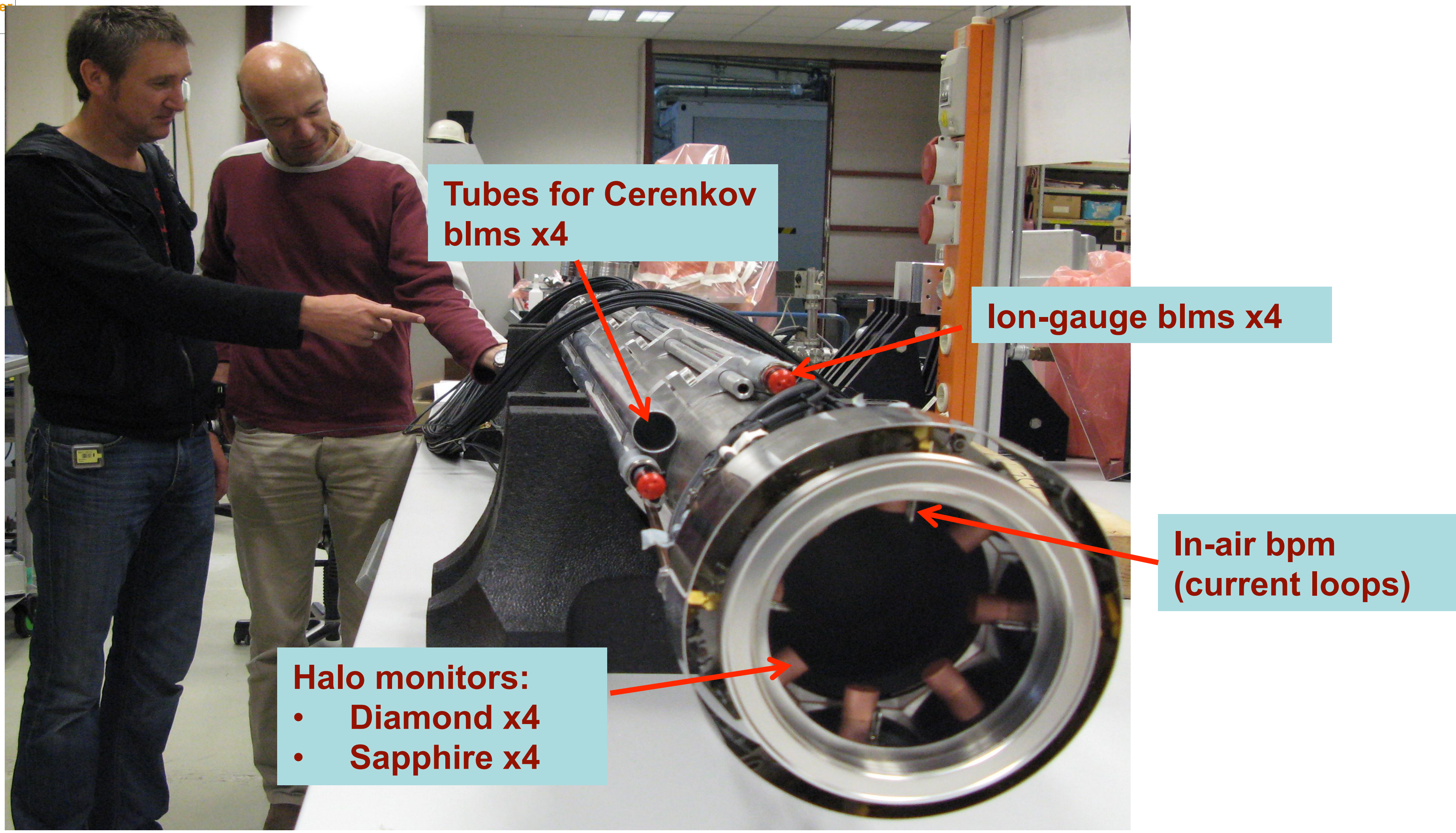
New dump-line section…

New dump line + diagnostics…

- New vacuum pipe
- 15DUMP bpm moved upstream and flange eliminated
- Cerenbov fibers x4
- Long ionization chambers x4
- Halo monitors x8
- In-air bpm after window



New dump-line + diagnostics



Upgrades…

New laser…

- Existing laser (Laser #1) supports bunch rep rates up to 1MHz
- New laser capable of 3MHz rep rate at 3nC (Laser #2) was developed and commissioned for the 9mA studies (Ingo Will)

ACC456 LLRF upgrades...

- Upgrade to latest generation LLRF system (SimconDSP)Hardware / firmware
  - New down-converters (Cryo-electra) with 54MHz IF, 81MHz sample rate
- DOOCS servers

- LLRF system functional improvements
  - New knobs for beam loading compensation
  - Feed-forward waveform generation,...

Ambitious goals…

	Achieved in Sept 08	Goal for Sept 09
Bunch charge to dump	2.5nC @ 1MHz	3nC @ 3MHz
Bunches/pulse	550 @ 1MHz	2400 @ 3MHz
Beam pulse length	550uS	800uS
Beam power	6kW (550x3nC/200mS @ 890MeV)	36kW (2400x3nC/200mS @ 1GeV)
Gradient in ACC4-6	Ensemble avg: ~19MV/m	Ensemble avg: to ~27MV/m Single cavities: to ~32MV/m

Plus, series of other studies:

- RF overhead studies: cavity data, operation with reduced klystron voltage
- Gradient studies: operating close to quench
- Power distribution studies: Loaded-Q,…
- Make time available for other studies with the high power beam (eg RTML)

Major achievements

Major achievements
(Sept 2009 studies)

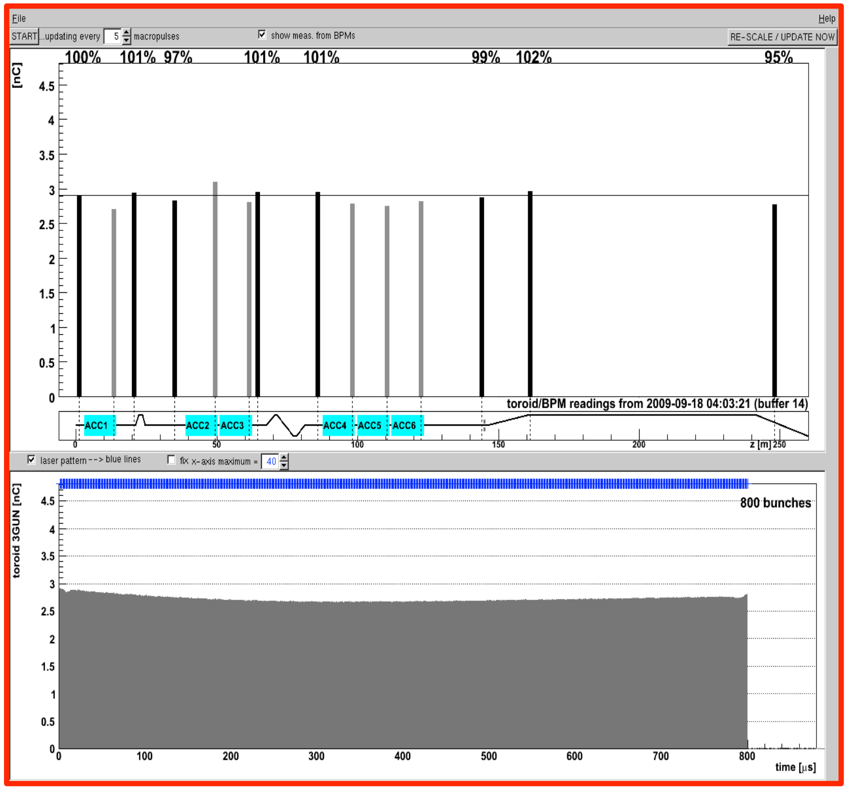
Metric	Goal	Achieved
Bunches per pulse	800 x 3nC (1MHz)	800 x 3nC
	2400 x 3nC (3MHz)	1800 x 3nC 2100 x 2.5nC ~2400 x 2nC
Charge per pulse	7200nC @ 3MHz	5400nC @ 3MHz
Beam power	36kW (7200nC, 5Hz, 1GeV)	22kW (5400nC, 5Hz, 800MeV)
Gradients close to quench	Up to 32Mv/m	Several cavities above 30Mv/m at end of long pulse

- 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)

800 bunches, 3nC/bunch, 1MHz

Toroids for 800 bunches at ~3mA

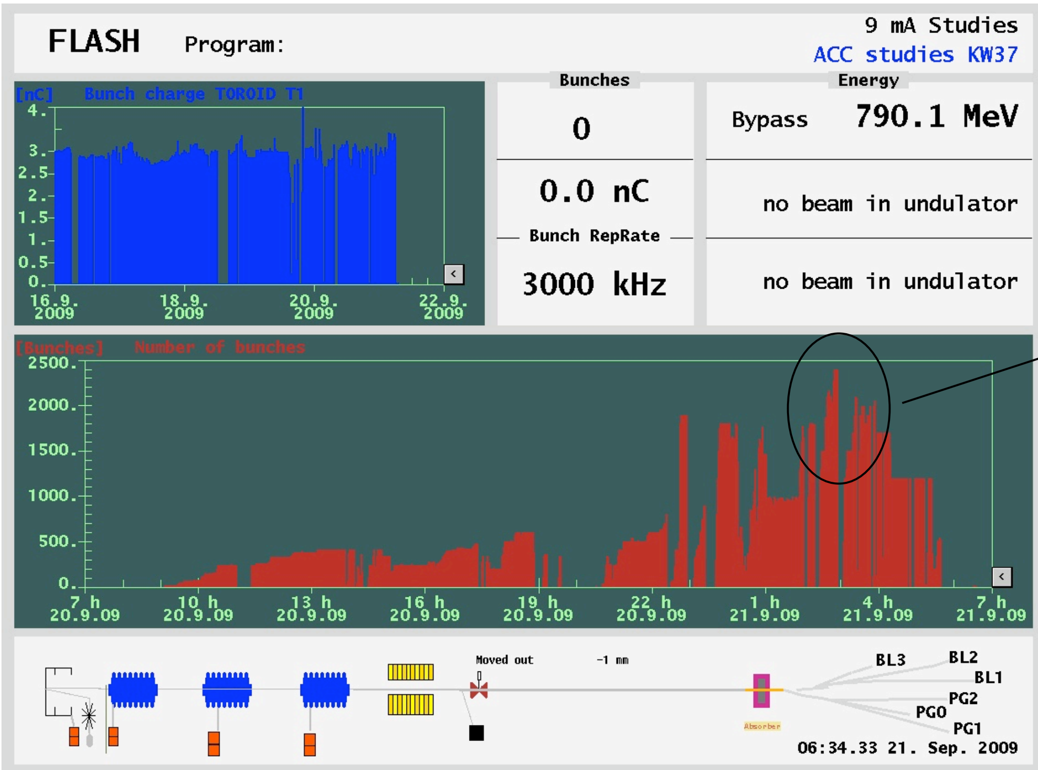


800 bunches at ~3mA for 15hrs

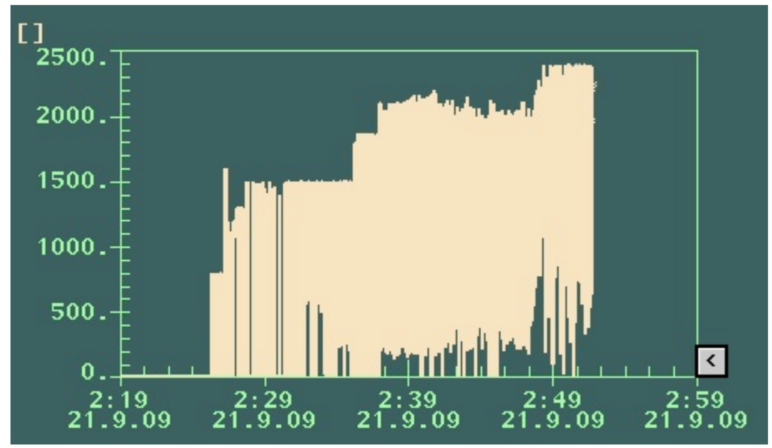
Zero to 800 bunches in 50mins

Last 24hrs: ~2400 bunches, 9mA

Number of bunches and charge for Sept 20/21



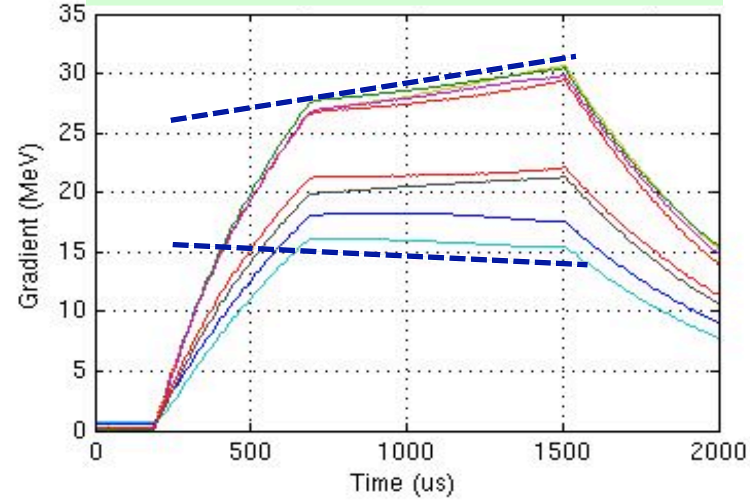
~2400 bunches, 9mA



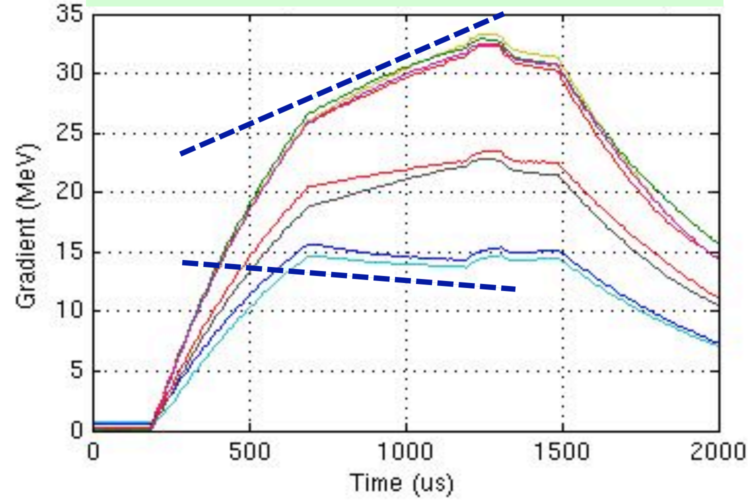
Some data…

Cavity tilts with long bunch trains and heavy beam loading (3mA and 7.5mA, long bunch trains)

ACC6 gradients (3mA, 800 us)



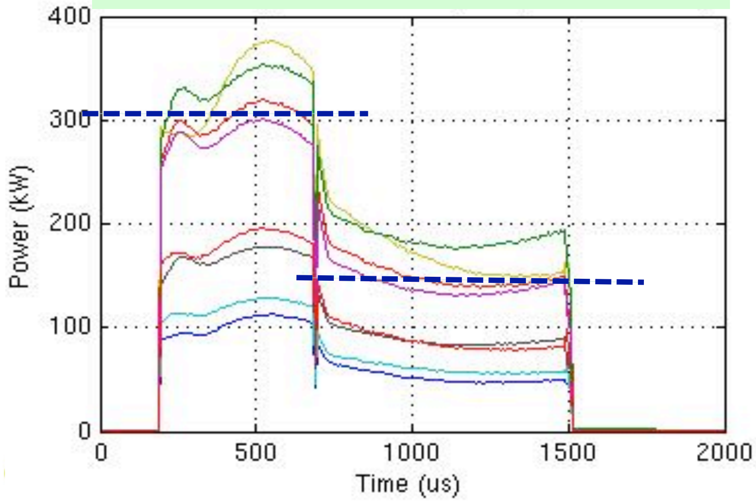
ACC6 gradients (7.5mA, 550 us)



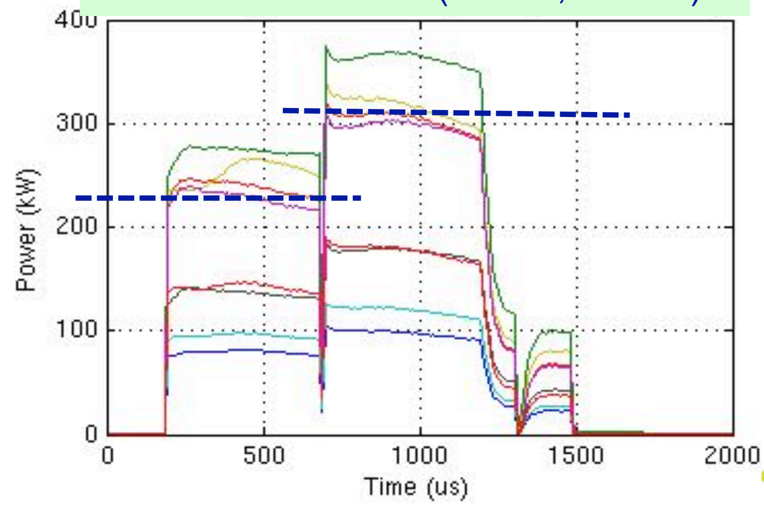
Gradient tilts are a consequence of using a single RF source to power cavities running at different gradients

At 7.5mA, ACC6 cavities #1 and #2 approached their quench limits at the end of the pulse

ACC6 Fwd Power (3mA, 800 us)

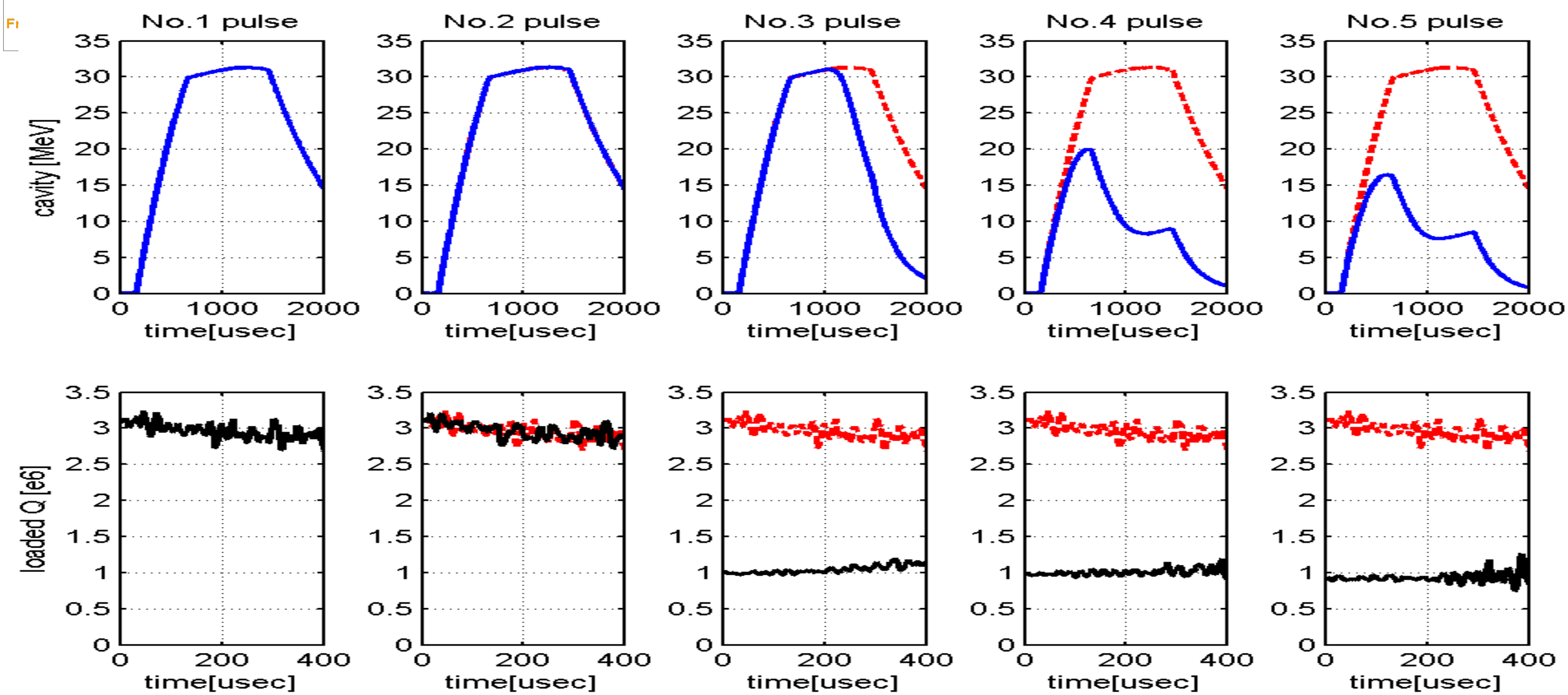


ACC6 Fwd Power (7.5mA, 550 us)



The RF power during flat-top is higher than the fill power for the 7.5mA case

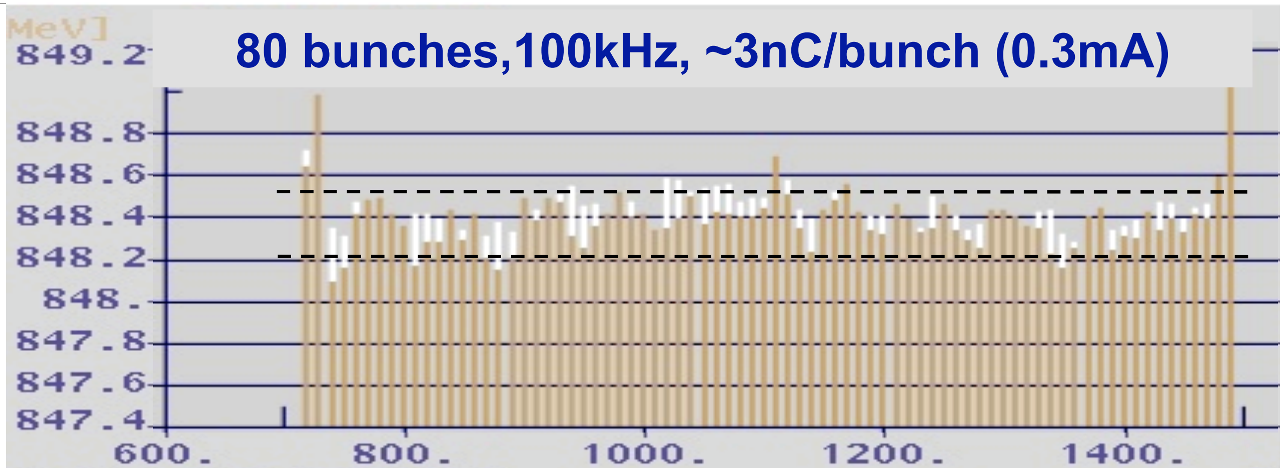
Quenches during 800us RF pulses, no beam



- 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.

Energy deviation along bunch train (examples)

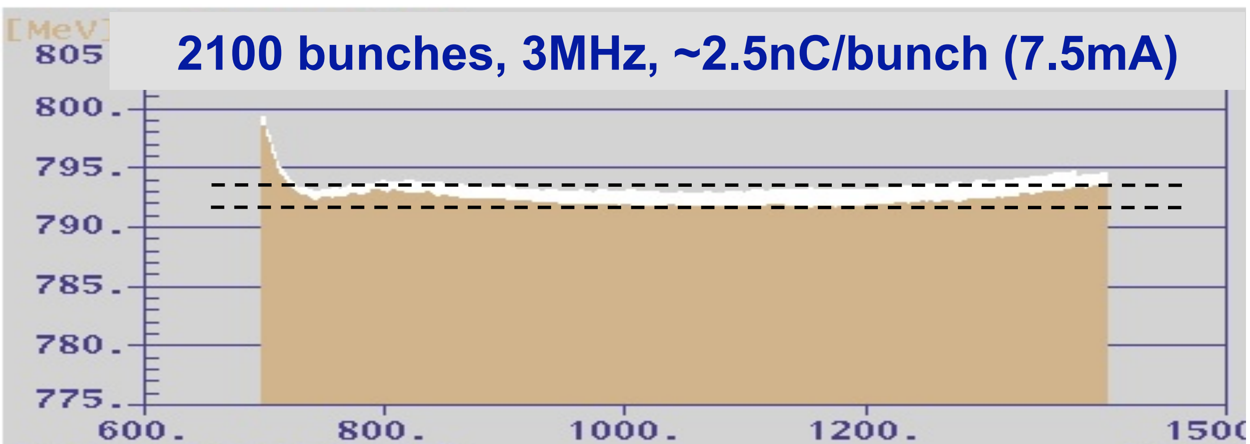
1.8 MeV



800us

Along pulse: 0.035% p-p

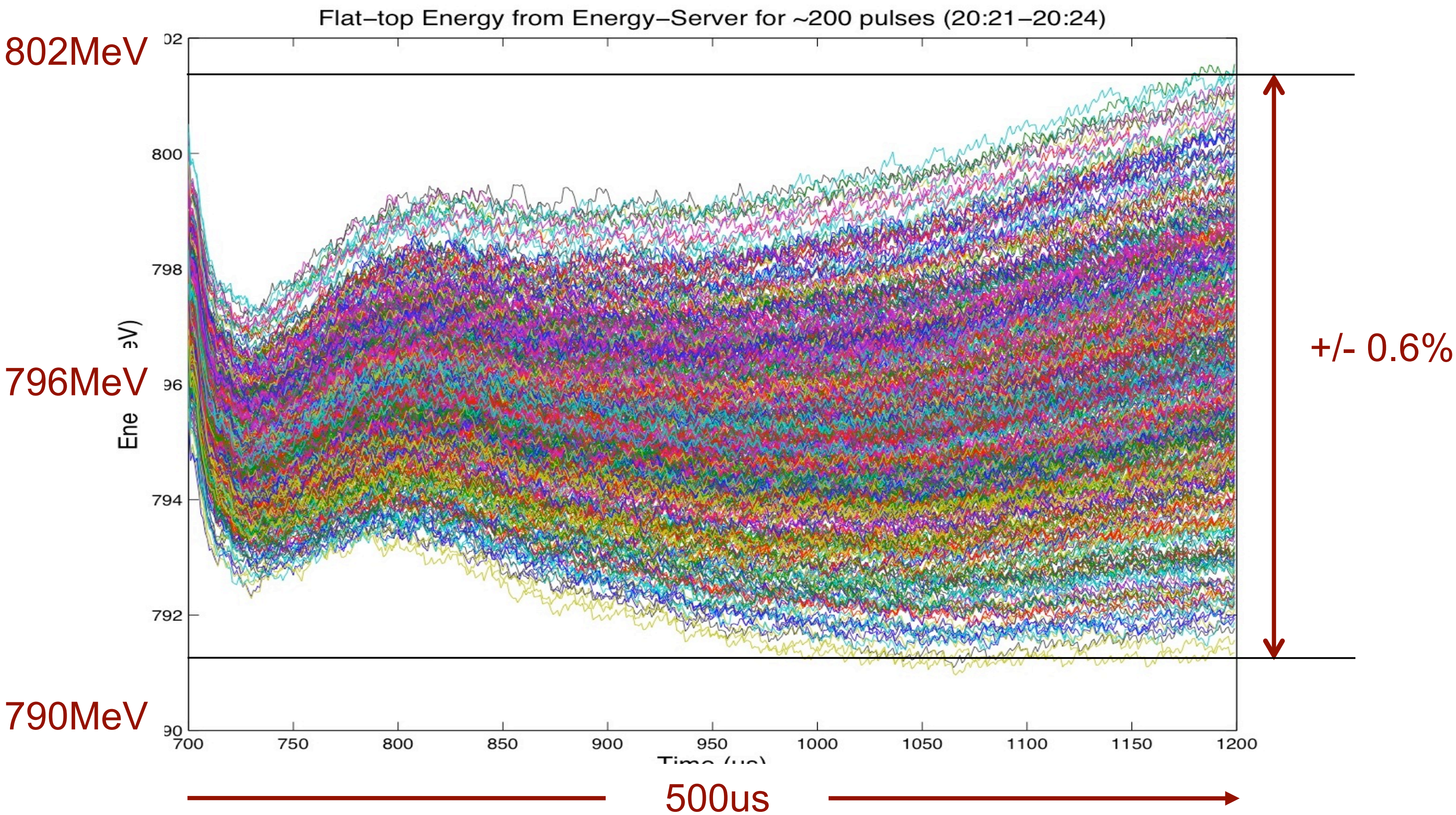
30 MeV



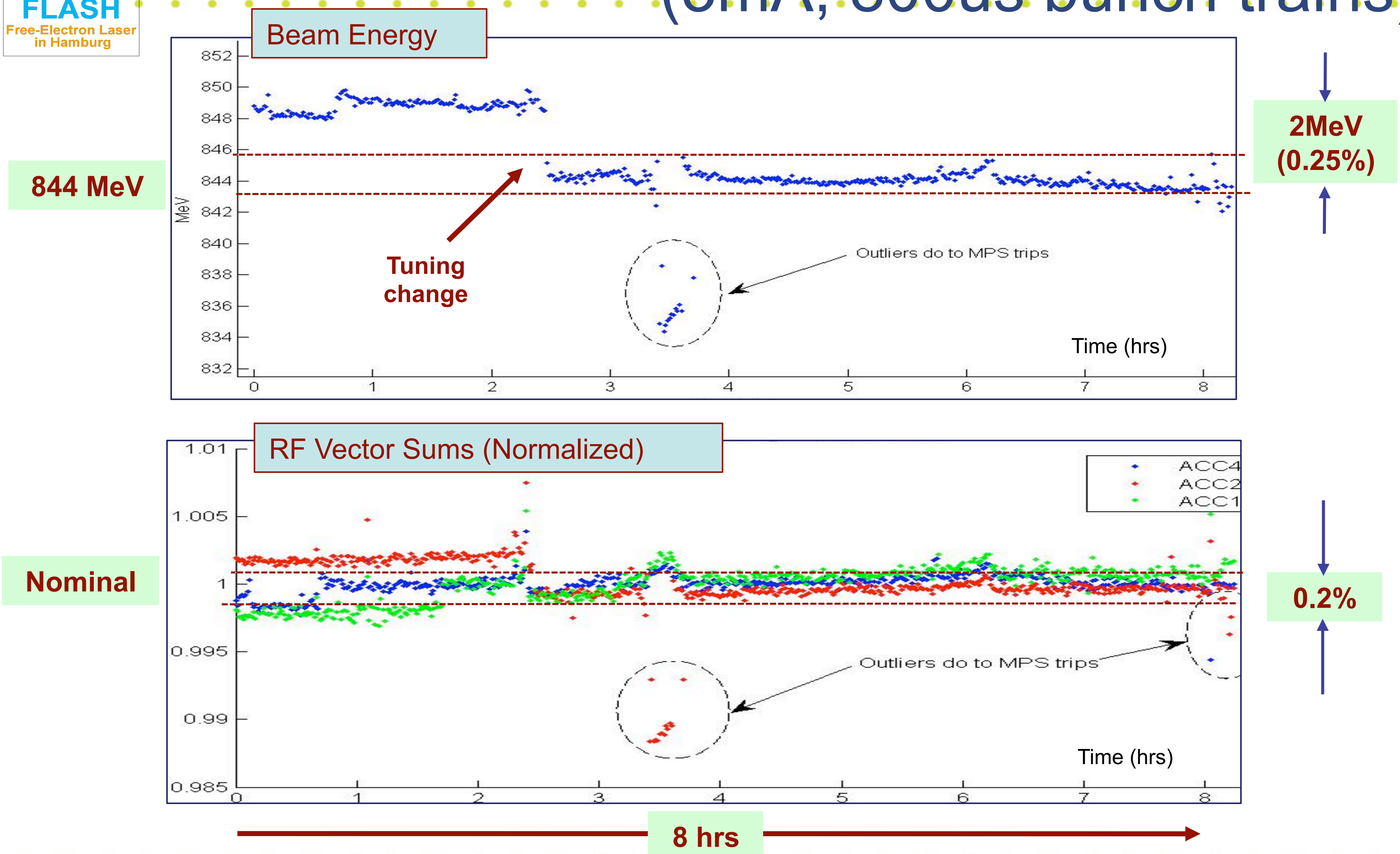
700us

Along pulse: 0.5% p-p
Pulse-pulse: 0.13% RMS

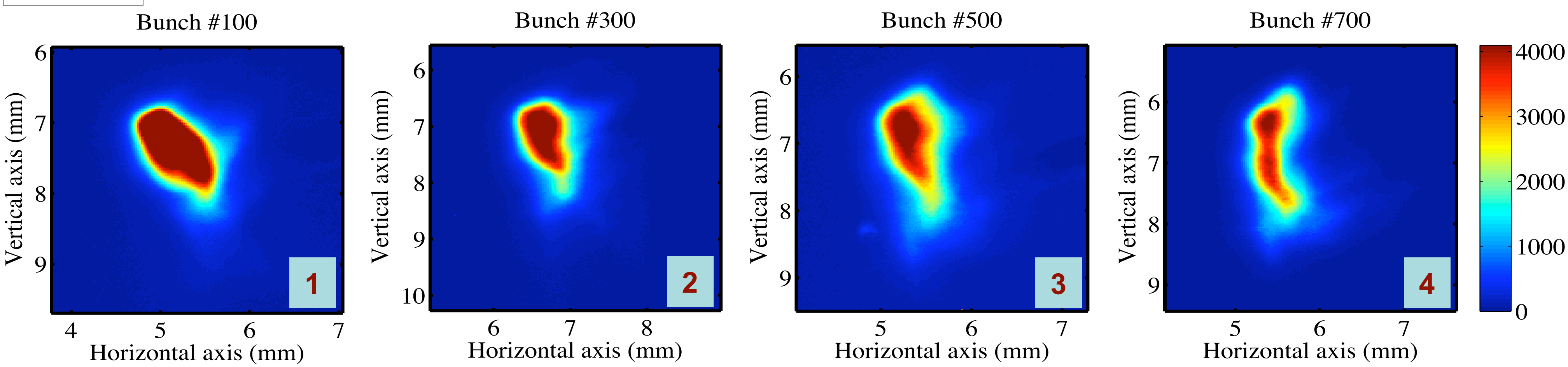
Example of pulse-to-pulse energy jitter (500us, ~3mA, 200 pulses overlaid)

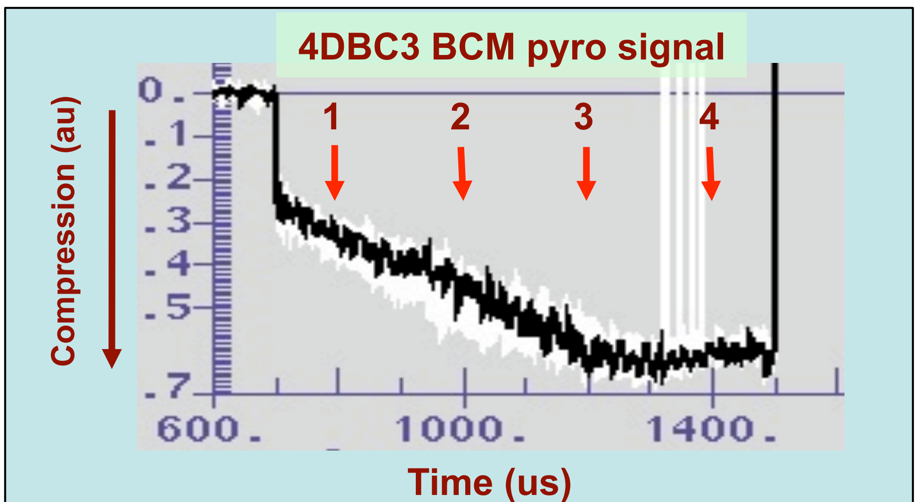


Energy stability over 8hrs (3mA, 800us bunch trains)



Transverse bunch distributions along bunch-train (800 bunches @ 1MHz, ~3nC/bunch)



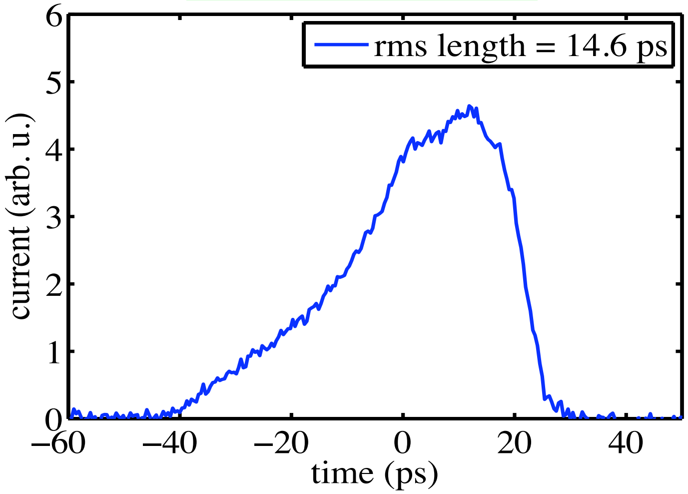


First bunch at 700us, last bunch at 1500us

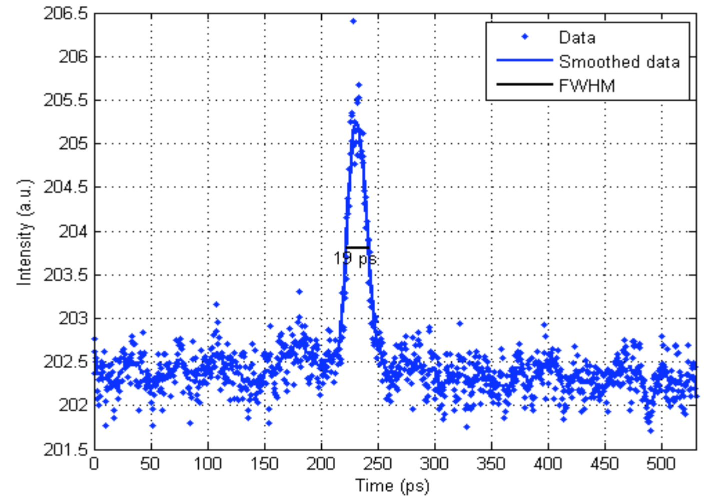
- Transverse bunch distributions clearly show changes in bunch size and shape over the long bunch train
- ACC1 phase and BCM signals appear correlated with the changes in bunch distributions
- **LOLA was only available diagnostic for single-bunch measurements with long bunch trains at full-energy**

Longitudinal bunch profile (3nC)

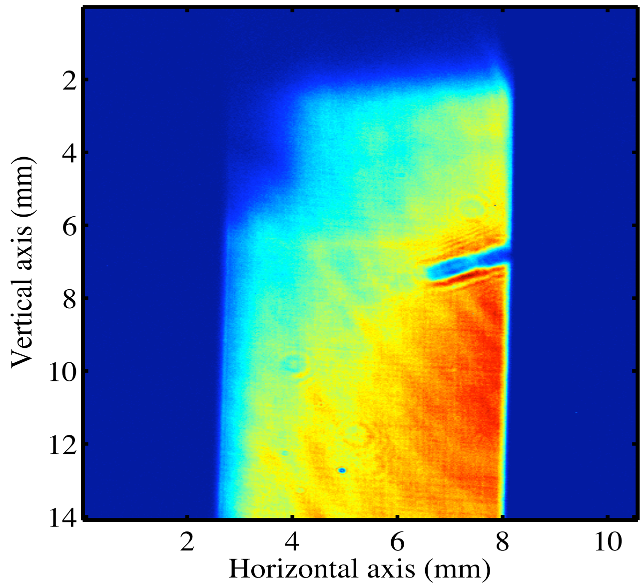
LOLA: 14.6ps

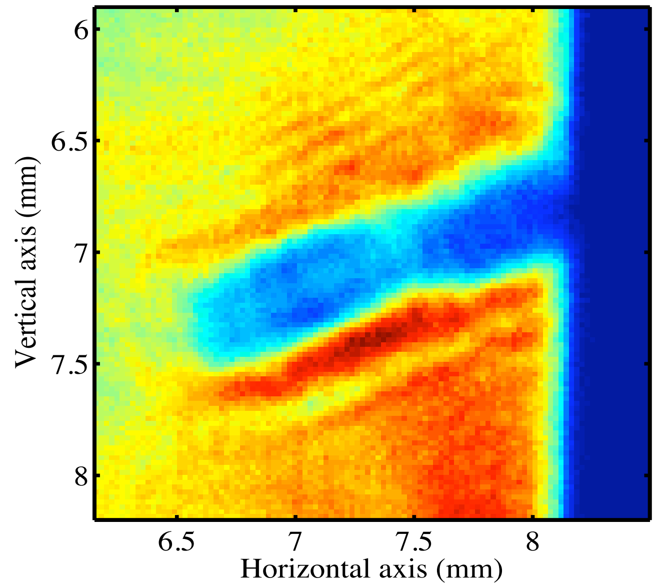


Streak Camera: 17ps



LOLA off-axis screen with 800 bunches
(no bunches kicked or streaked)





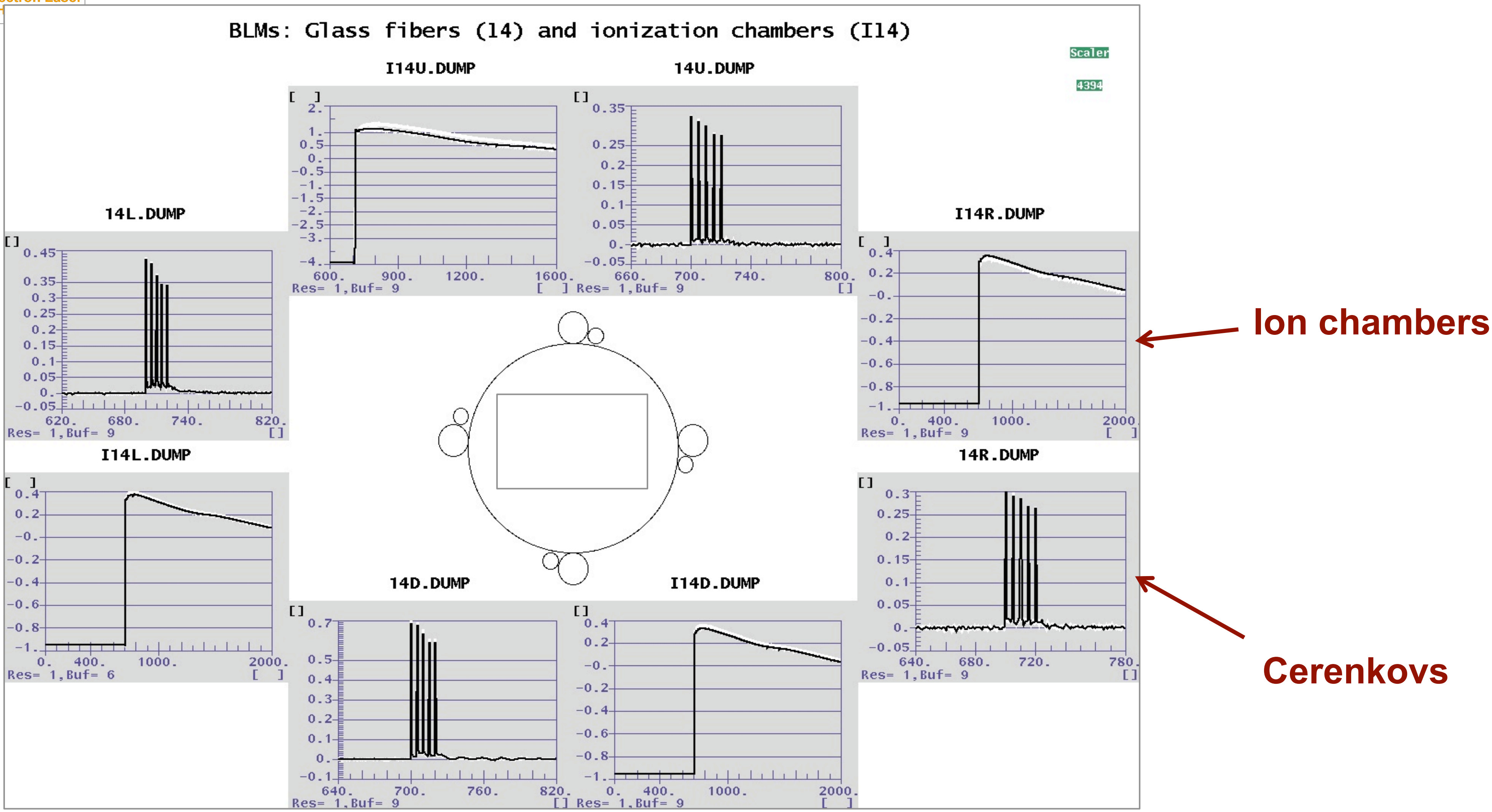
- LOLA screen flooded with light from bunch train
  - **Synchrotron radiation from upstream magnets…?**
- Cut on screen close to the orbit
  - **Damage caused by what…?**

Dump-line diagnostics

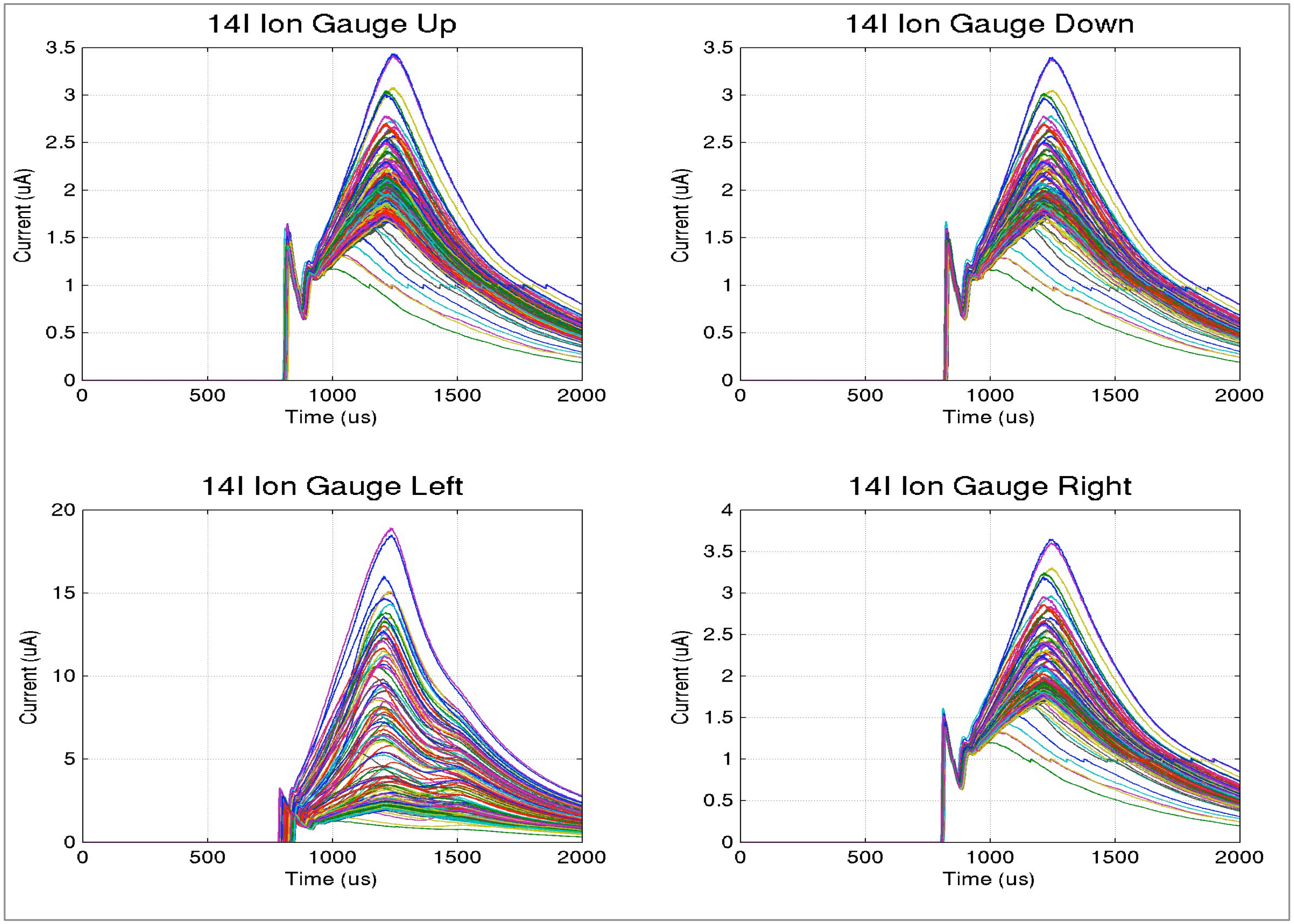
In-air bpm
Ion chamber blms
Cerenkov fiber blms
Halo monitors

Ion Chambers and Cerenkov fibers

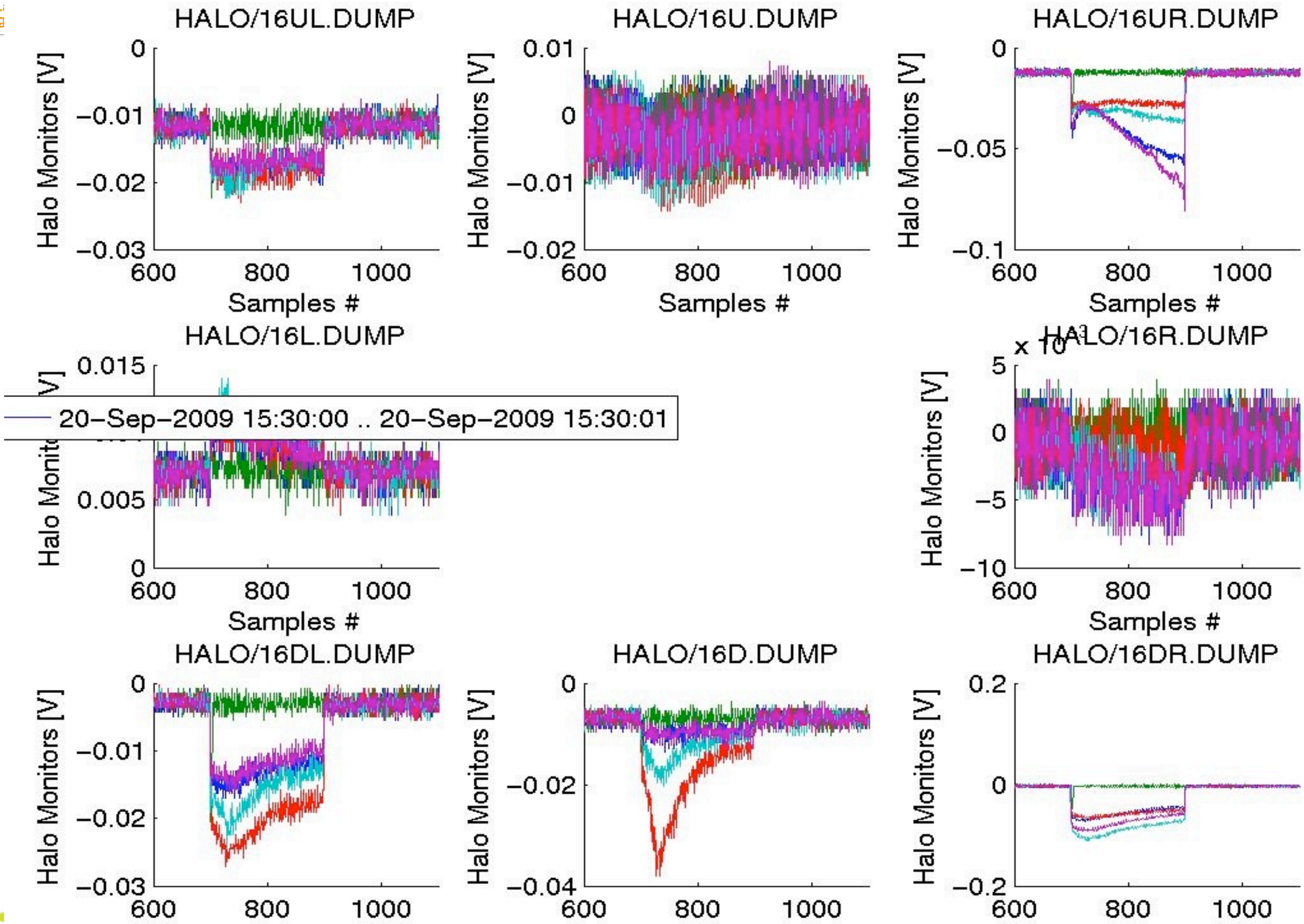
(5 bunches, 3nC/bunch, 250kHz)



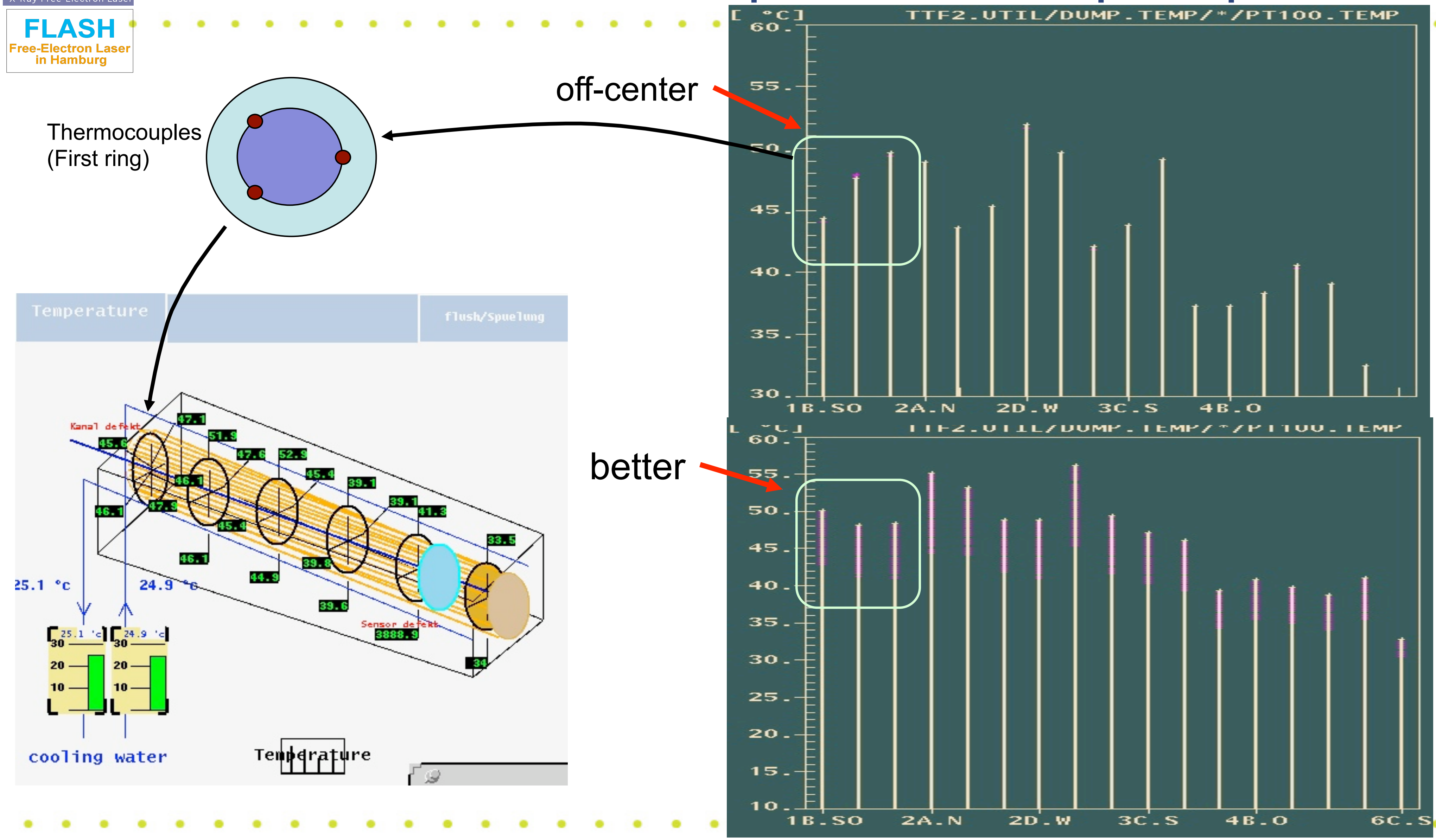
Ion chambers: many bunches at 3MHz
(~200 pulses overlaid)



Halo sensors



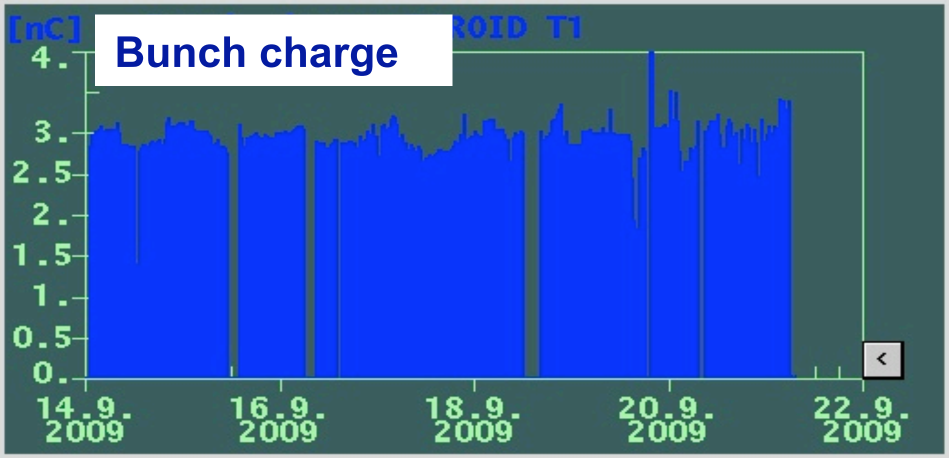
Beam dump ‘thermocouple bpm’



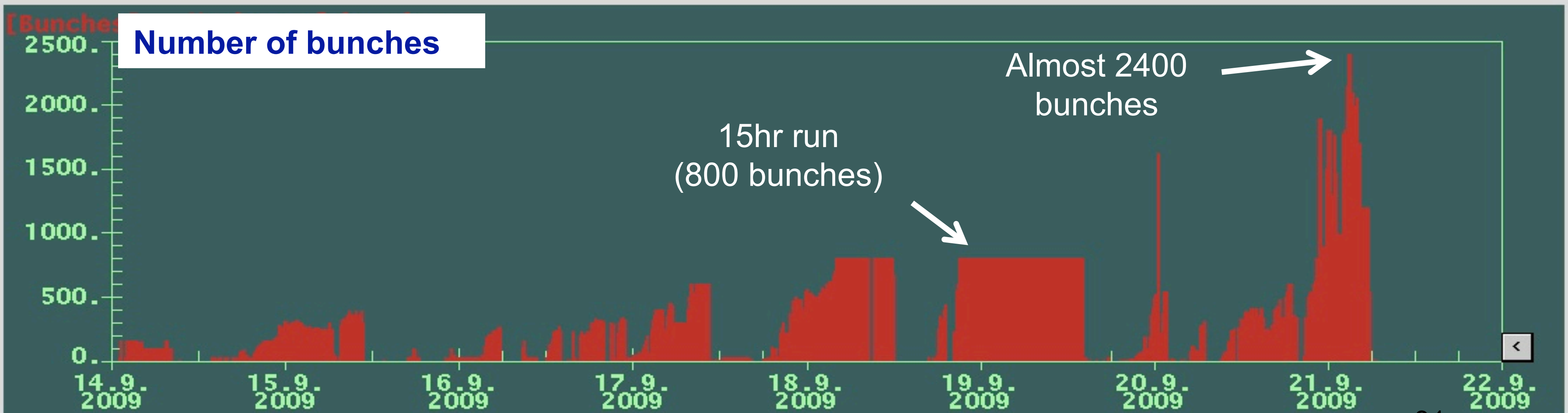
Operations experience

7-day history of number of bunches + bunch charge
(Second week of studies)

FLASH Program: 9 mA Studies
ACC studies KW37



- Bunch charge was consistently between ~2.7nC and ~3nC
- Rapid progress increasing number of bunches during the last 3 days!



Slow start...

- In Sept '08 we had more than 30 3nC bunches in 24hrs
- In Sept '09 it took 10 days to get to the same point

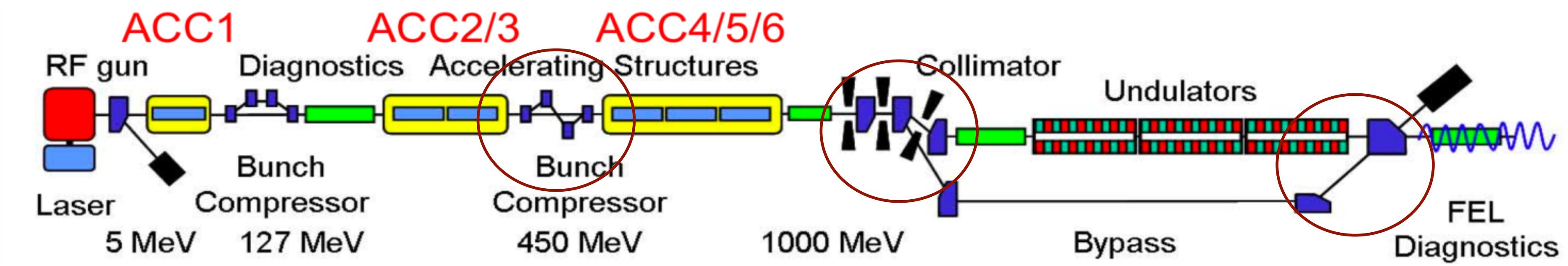
What was different this time…?

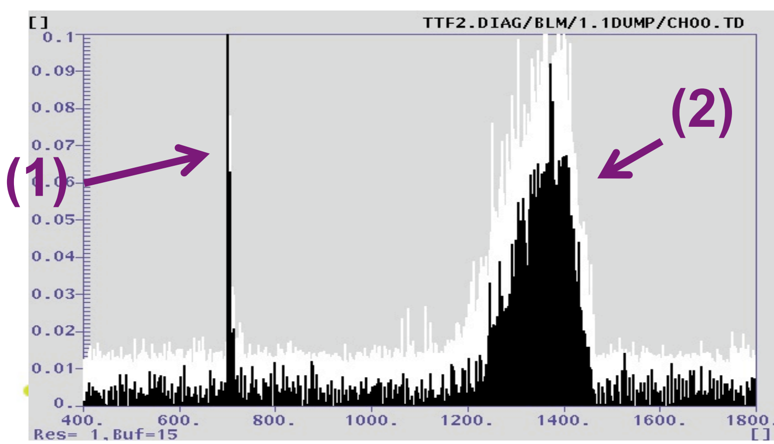
- Mostly: we couldn't get the beam through the machine with low enough losses to allow enabling of MPS long-pulse mode
- Typical problems when coming out of a shutdown
- Spend time debugging the new ACC456 LLRF system – problems that had not shown up during commissioning

- In the end, we only got a few days of high power operation instead of the ~10 days we had hoped for
  - **Unable to perform several important parts of the program**

Beam loss

- Spent a lot of time fighting beam loss alarms, mainly in three locations
  - **Bunch compressor BC3; first dipole of bypass line; dump line**
- Largely about trying to find good operating points…





BLMs pick up gun dark current from gun

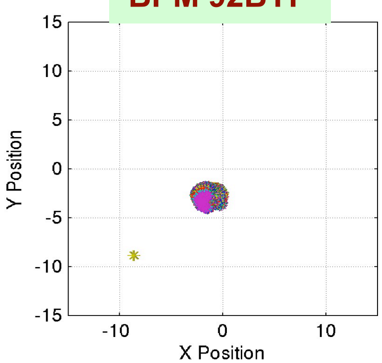
(1) Beam loss signal from bunch

(2) Gun dark current loss signature at the end of the RF flat-top

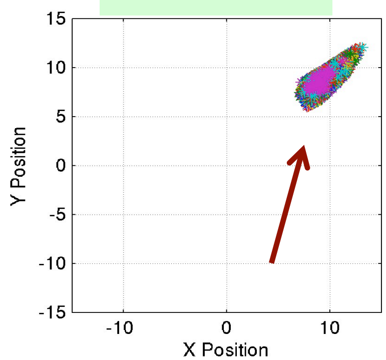
Orbit in dump-line example from last shift:

(~200 pulses, many bunches at 3MHz)

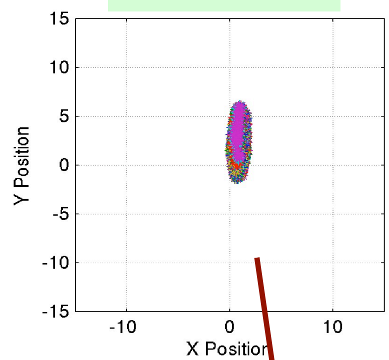
BPM 92BYP



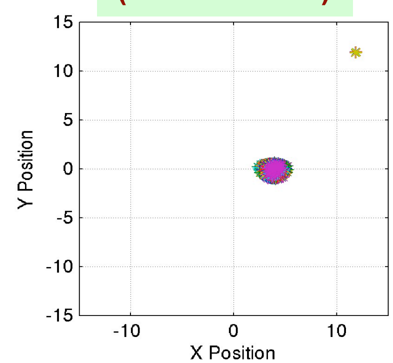
BPM 5DUMP



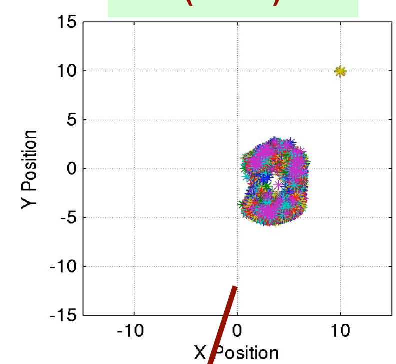
BPM 9DUMP



BPM 13DUMP (new location)



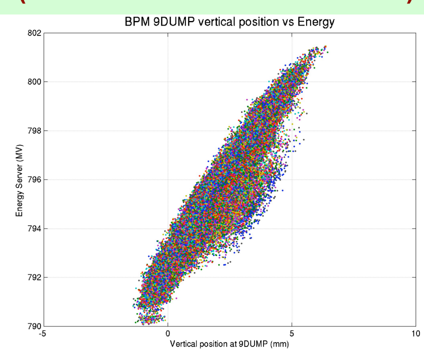
BPM 16DUMP (in-air)

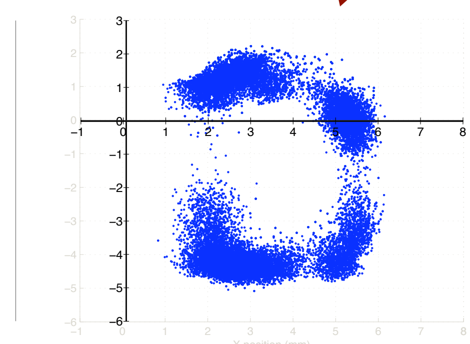


DAQ data analysis to study…

- *If this really is a good working point*
- *If we had the right energy…*
- *Why so far off axis at 5DUMP…*

Energy Sensitivity at 9DUMP (+/-3mm from +/-6MV / 800MV)





Overlay of many pulses shows rotation from 13ROT

Wealth of information in the FLASH DAQ…

- **Sample-synchronous pulse-by-pulse data (1MHz)**
  - All bpms, toroids, beam loss monitors, phase monitors
  - Energy Server, LLRF Vector Sums
  - Forward & reflected powers, Field Probes for every cavity
  - Coupler PMs and E- monitors
  - Some klystron waveforms
  - Some gun waveforms, some laser waveforms
  - One toroid and one BLM sampled at 81MHz

Working on the tools for accessing and analyzing data

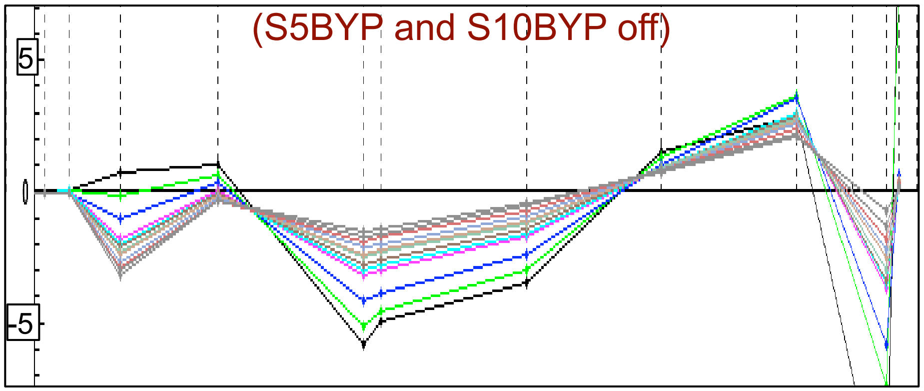
- **'Slow' data**
  - Beam dump thermocouples
  - Magnet currents
  - Cavity tuner positions
  - Vacuum

The data needs to be analyzed…

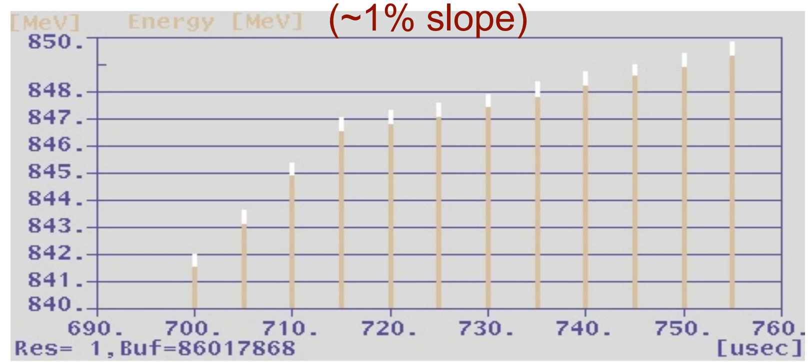
- **Event data**
  - Bunch rate, number of bunches
  - BIS and MPS interlocks

Energy spread as tuning aid…

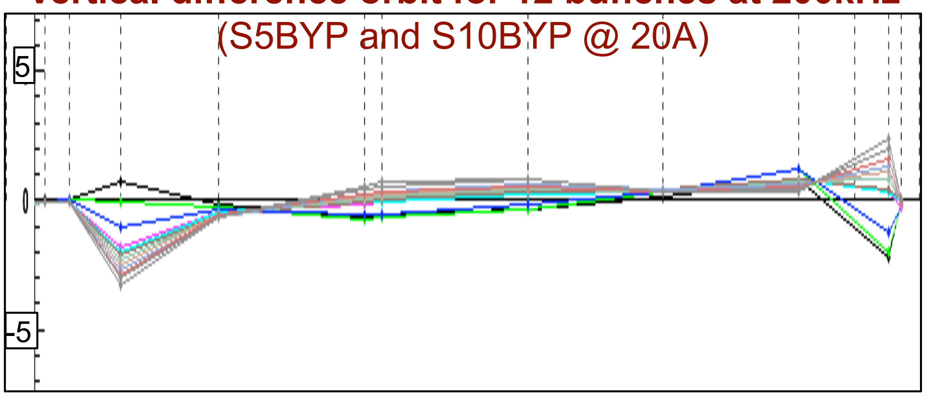
Vertical difference orbit for 12 bunches at 200kHz



Beam energy in bypass



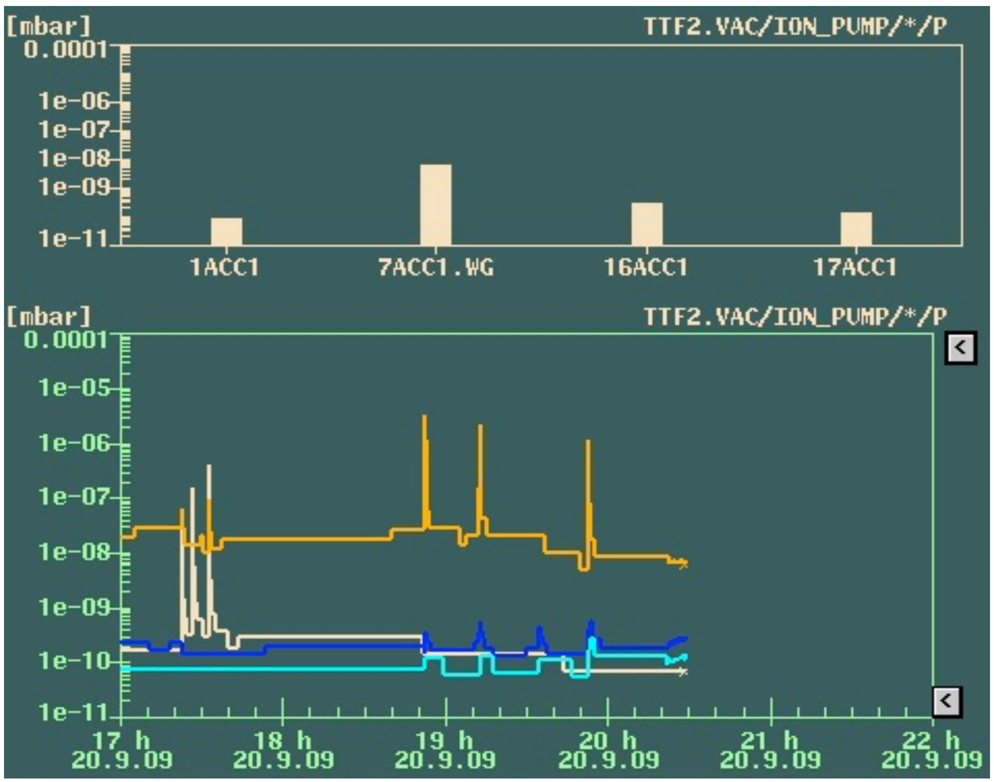
Vertical difference orbit for 12 bunches at 200kHz

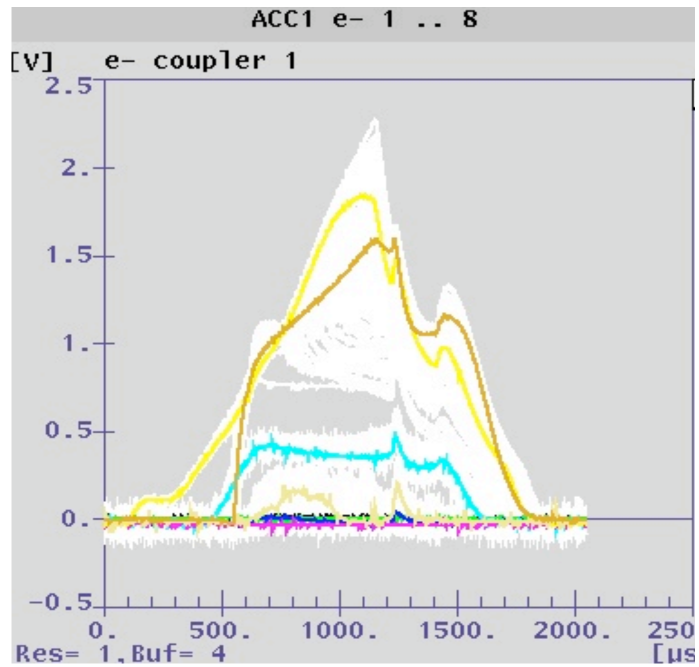


Energy slope along the bunch-train shows second-order dispersion on the orbits of the individual bunches

Coupler events

- Coupler e- trips were observed on ACC2 and on ACC1
  - **Most likely conditioning…?**





Some ‘Lessons Learnt’ topics

- Energy acceptance is narrower with long bunch trains and high current
- Exception Handling philosophy, eg MPS alarms, quenches,...
  - **Issues: thermal stability, learning systems,...**
- Beam loss management
  - **Overall philosophy, alarm thresholds, machine tuning mode**
- Beam-based feedback
  - **Injector stabilization over the bunch train (laser, gun, ACC1)**
- Calibrated readbacks of key parameters
  - **eg Beam energy!**

Data analysis - critical

- It is critical that we capitalize on the Sept studies …and before memories fade
  - **Better understanding of how the machine behaved – so we can more readily repeat the beam conditions**
  - **Show measurable and visible benefits from the studies**

Analysis examples

- Quantify the ‘good’ machine tuning conditions
- Stability of key parameters, sensitivity to jitter, drift, etc
- Optics, energy measurements,…
- Multi-bunch effects over long bunch trains
- System performance: diagnostics, LLRF, feedback, etc

For the next studies…

- Work towards demonstrating routine operation with heavy beam loading and long pulses
  - **Repeatable and predictable performance**
  - **Machine tuning without always needing the experts**
  - **Run FLASH ‘as if it were the ILC or XFEL’ (automation)**

- Study / develop beam-based feedback with long bunch trains and heavy beam loading

- Complete the main ILC study goals, eg operation at gradient limits, HLRF overhead studies,…

- *Not all studies need the high power beams*

Planning a workshop on the 9mA studies (22-23 February 2010)

- Discuss results and lessons from the Sept 9mA studies, consolidate what was learnt, and plan future studies
- Will address both ILC and XFEL/FLASH interests

Proposed topics / sessions

- FLASH operations and Technical System reports
- Results / data analysis
- Working Groups on major ‘lessons-learnt’ themes (conveners?)
- Planning for machine studies
  - **Continuation of 9mA studies: R&D for ILC, FLASH/XFEL**
  - **Operation of FLASH with long bunch trains**

Closing slide

- **Demonstrated that FLASH can operate reliably with long bunch trains and high current – without breaking the machine!**

- Studies using the high power beam are still to be done (proposed)
  - **Gradient overhead studies: RF power overhead studies**
  - **Other studies with the high power beam (eg RTML)**

- Much progress towards FLASH operation with long bunch trains
  - **Still work to be done before this could become routine**
  - **Automation, rapid tuning, repeatable operating conditions…**

- Detailed data analysis is just beginning…

- Workshop in February!

Thank you for your attention

The 9mA studies team...

DESY
- **Siegfried Schreiber**
- **Bart Faartz**
- **Nicoleta Baboi**
- **Martin Staack**
- **Florian Loehl**
- **Holger Schlarb**
- **Valeri Ayvazyan**
- **Mariusz Grecki**
- **Waldemar Koprek**
- **Stefan Simrock**
- **Kay Rehlich**
- **Wojciech Jalmuzna**
- Wojciech Cichalewski
- **Jaroslav Szewsinski**
- **Nick Walker**
- **Katja Honkavaara**
- **Christopher Behrens**
- **Michael Schmitz**
- **Tim Wilksen**
- **Olaf Hensler**
- **Raimund Kammering**
- **FLASH Operations Experts**
- ...**and many others**

ANL
- **Xiaowei Dong**
- **Ned. Arnold**
- John Carwardine

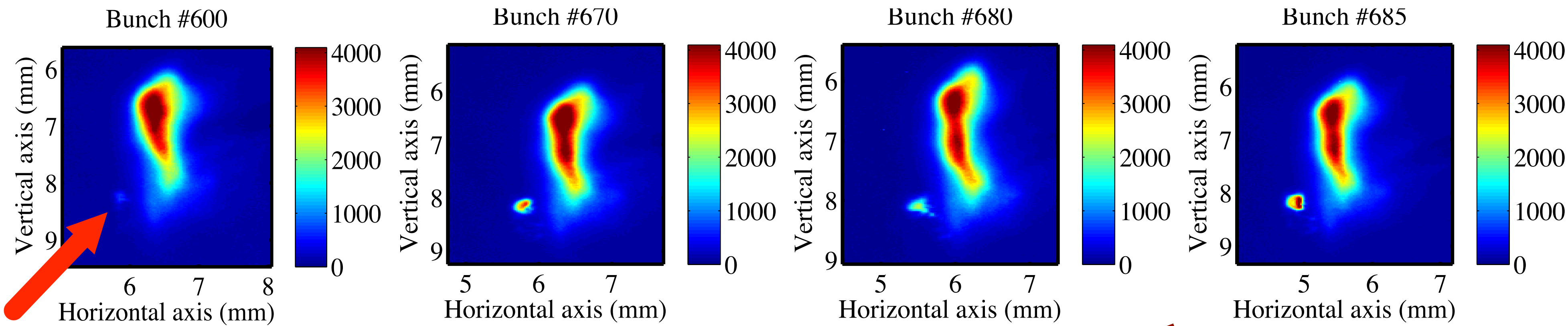
FNAL
- **Brian Chase**
- **Gustavo Cancelo**
- Julien Branlard

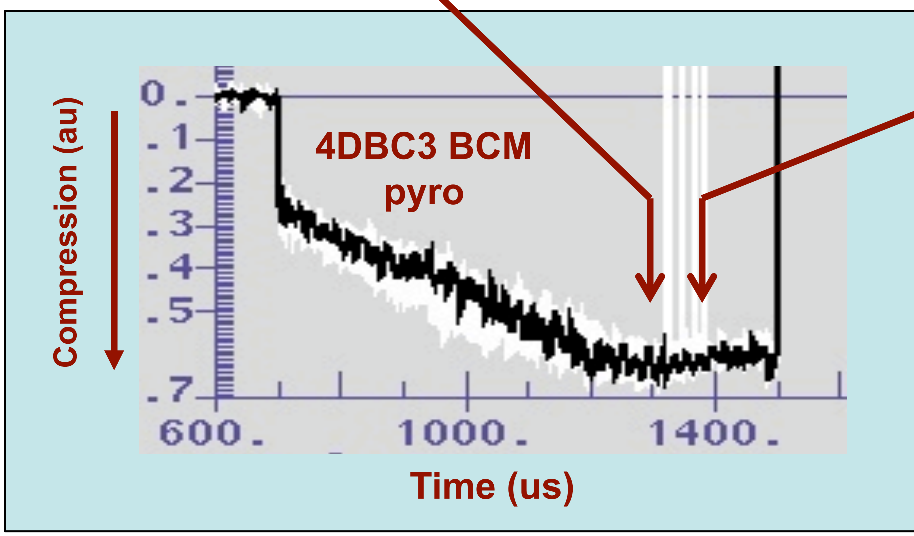
KEK
- **Shinichiro Michizono**
- **Toshihiro Matsumoto**

SLAC
- **Chris Adolphsen**
- **Shilun Pei**

Backups

What is this?
(800 bunches @ 1MHz, ~3nC/bunch)





- The spot is visible where the 4DBC3 pyro signal is strongest