FLASH 9mA Experiment

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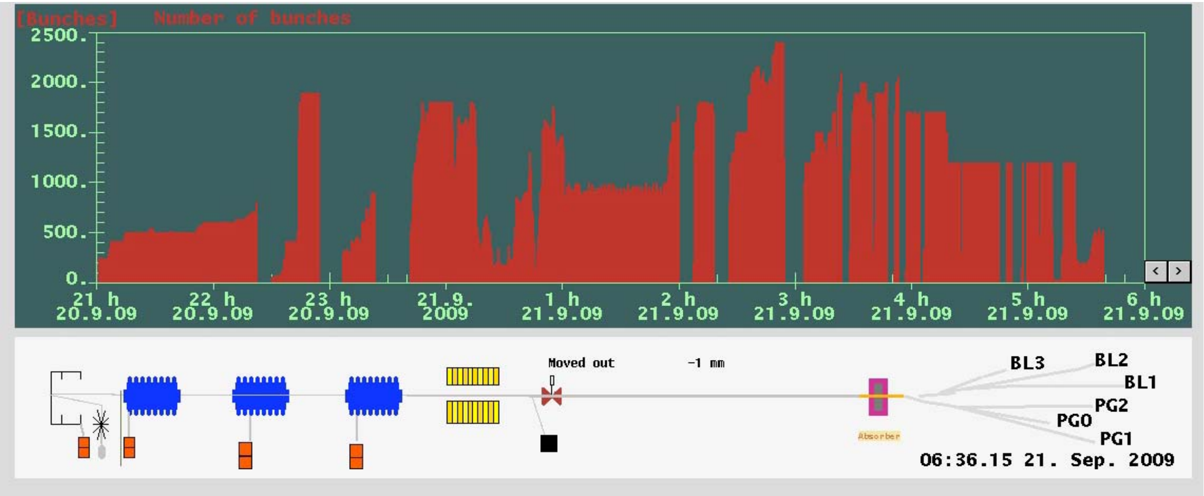
For the FLASH 9mA collaboration



Outline

- Goals
- Achievements
- Planning
- Highlights
- Operations items
- Data examples
- Thinking ahead…

String Test: goals from R&D Plan

Integration Tests

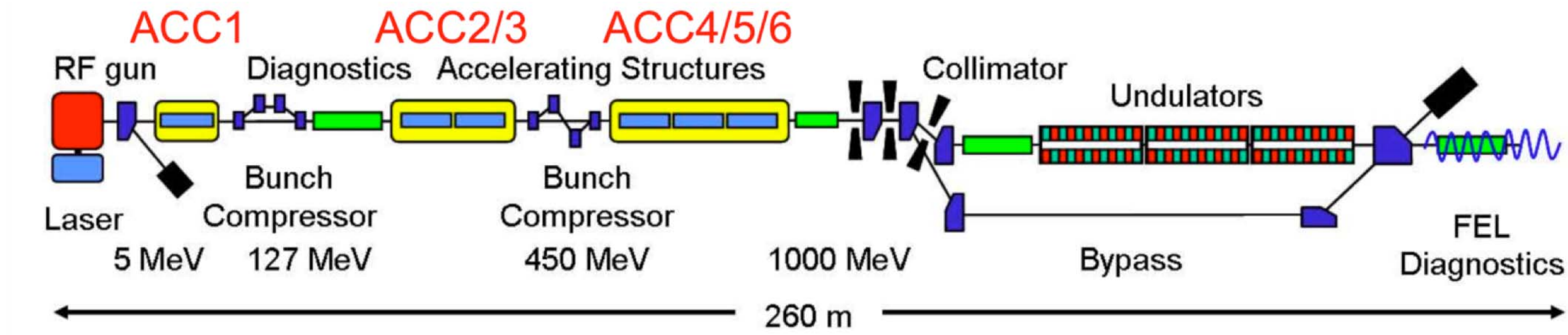
- **The highest priority goal is to demonstrate beam phase and energy stability at nominal current**

- Important because of their potential cost impact:
  - **demonstrate operation of a nominal section or RF-unit**
  - **determine the required power overhead**
  - **to measure dark current and x-ray emission**
  - **and to check for heating from higher order modes**

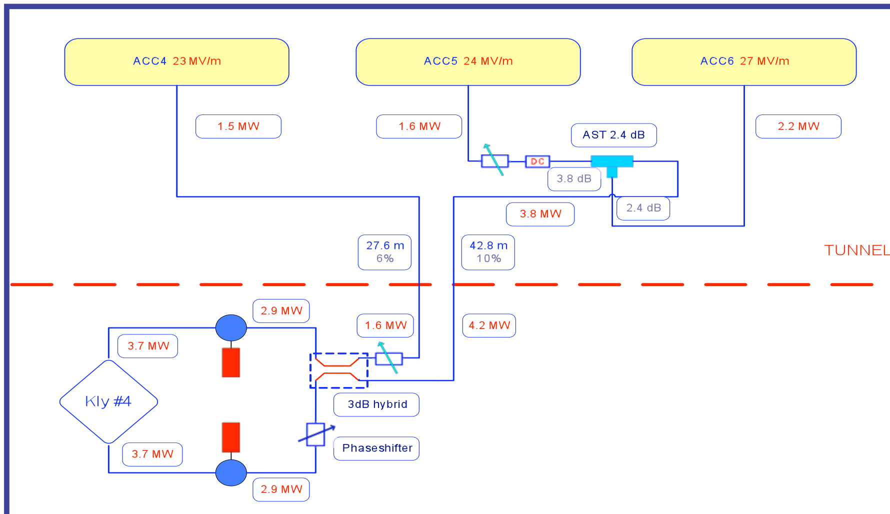
- Needed to understand linac subsystem performance:
  - **develop RF fault recognition and recovery procedures**
  - **evaluate cavity quench rates and coupler breakdowns**
  - **test component reliability**
  - **tunnel mock up to explore installation, maintenance, and repair**

TTF/FLASH 9mA Experiment

Full beam-loading long pulse operation → “S2”



		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

Prior achievements and goals set for the Sept 09 studies (ambitious!)

	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, ambitious 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)

TTF/FLASH 9mA Experiment

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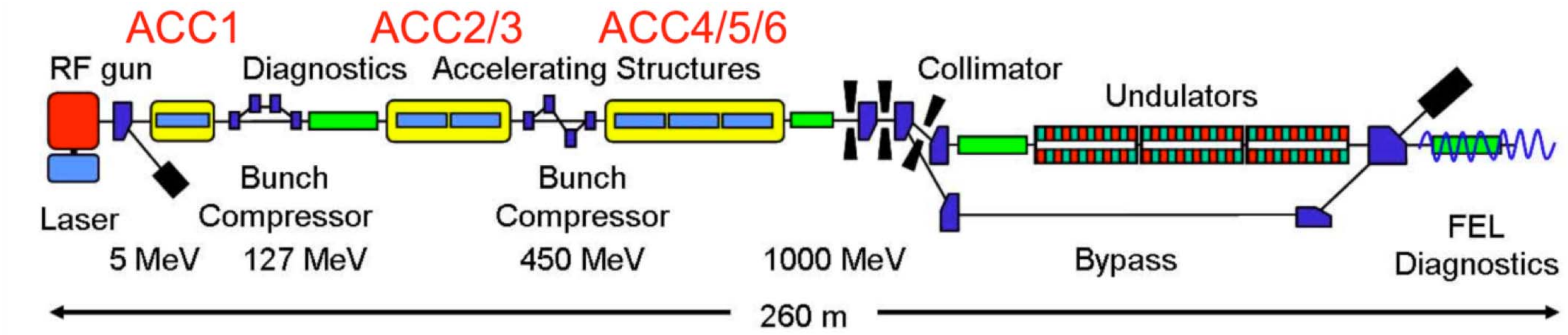

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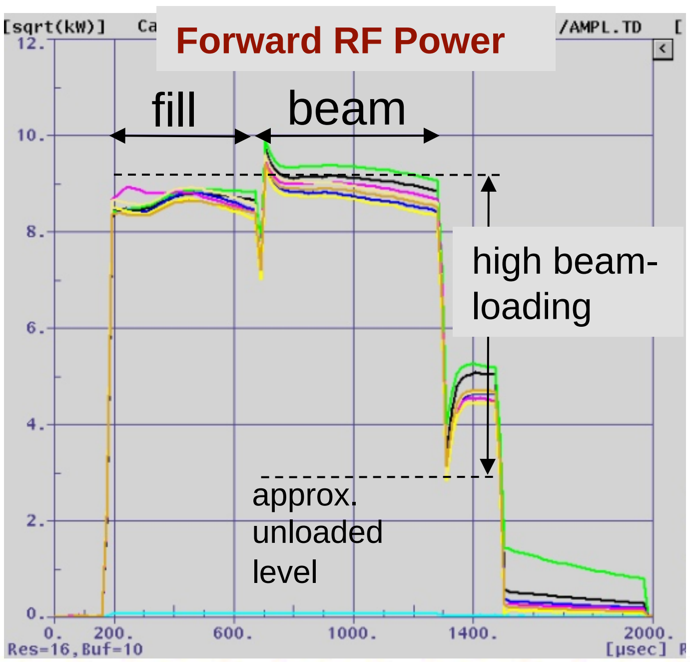
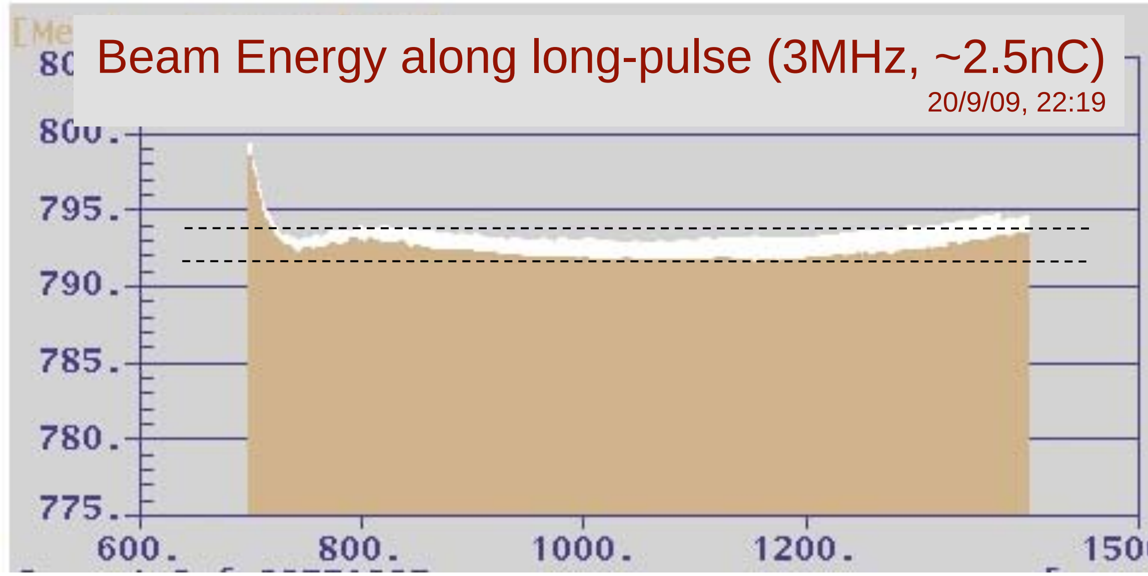
- Stable 800 bunches, 3 nC at 1MHz (800 μs pulse) for over 15 hours (uninterrupted)
- Several hours ~1600 bunches, ~2.5 nC at 3MHz (530 μs pulse)
- >2200 bunches @ 3nC (3MHz) for short periods

9mA Example Results

Much experience gained running with high beam-loading conditions

Approx. 15 TBytes of data to be analysed (beginning)





Along pulse: (after initial transient)	0.1% RMS (0.5% pk-to-pk)
Pulse-to-pulse (5Hz):	0.13% RMS

Integrated Systems Test
- Understanding trip and trip recovery (beam loss)
- RF parameter tuning
- RF system calibration

Extrapolation to XFEL/ILC

9mA Experiment Status

- Successfully completed 2-week dedicated experiment
  - **Total 5-week interruption to FLASH photon user programme when shutdown for dump-repair is included (thanks to DESY)**
- Commissioning of new hardware
  - **3MHz laser**
  - **Simcon-DSP LLRF system(s)**
  - **New instrumentation in dump line**
- Detailed data analysis now just beginning
  - **Will take some months of analysis**
- Stable operation with high beam-loading (high beam-powers) demonstrated, but
  - **Not all (original) 9mA goals were achieved**
  - **Routine operation of long bunch trains still requires work**
  - **Planning for next shifts (proposal) now underway**

Preparation and planning

Preparatory work

- Repair the dump, add new diagnostics to detect beam loss
- LLRF system upgrades at ACC456
  - **Upgrade hardware to latest generation (SimconDSP)**
  - **Algorithm improvements: beam loading compensation, feed-forward waveform generation, …**
- Optics work
  - **Improve alignment between model and measured lattice**
  - **Improve understanding of loss points and apertures**
  - **Refine the bypass lattice**
- Prepare gun and laser for operation with 3MHz bunch rate
- Studies planning!

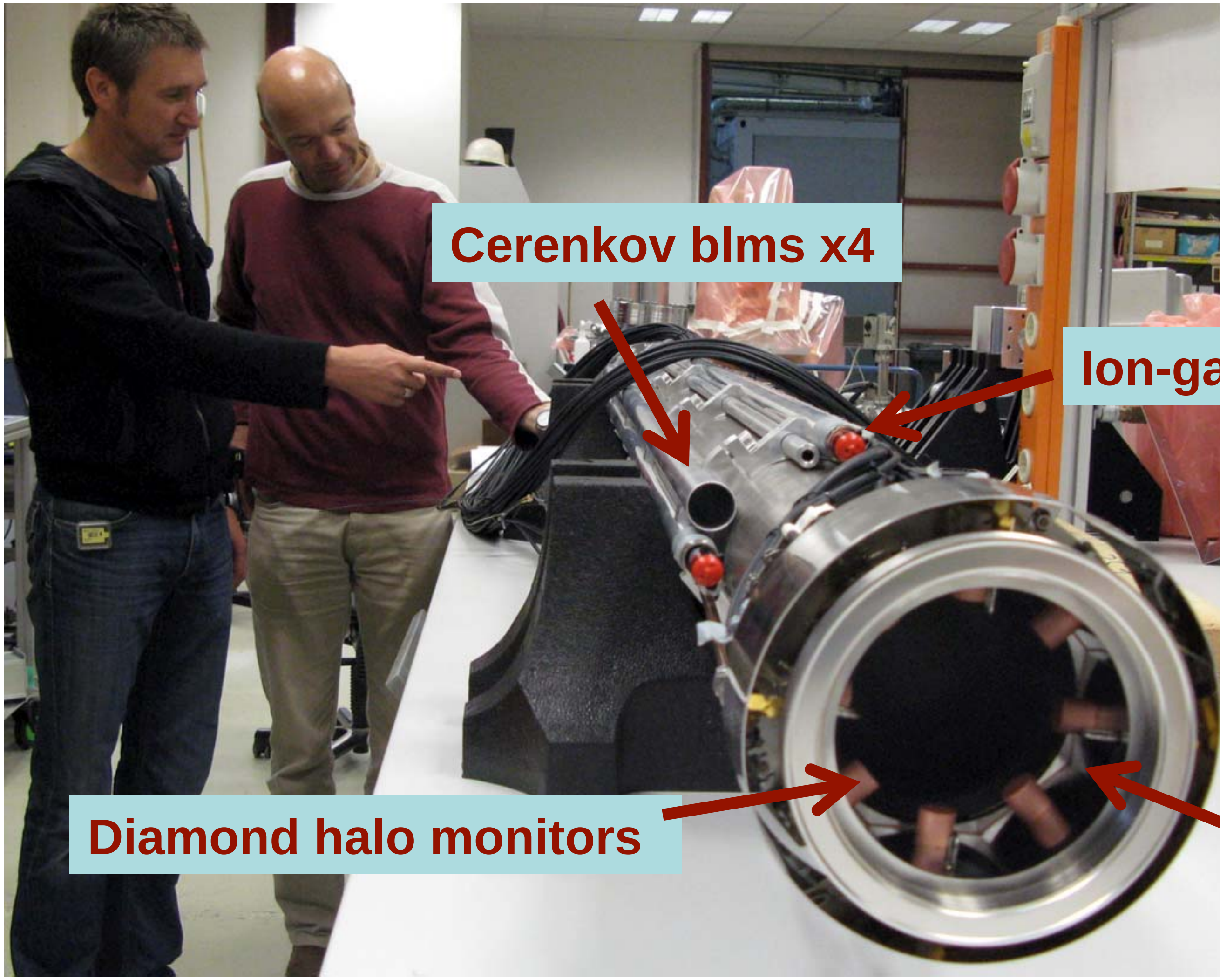
Time-line for 5-week studies period

- Weeks 34-35: Shutdown
  - **Install new dump line + diagnostics**
  - **Commission new RF system at ACC456**
  - **LLRF/RF tests during Week 35 (overnight)**

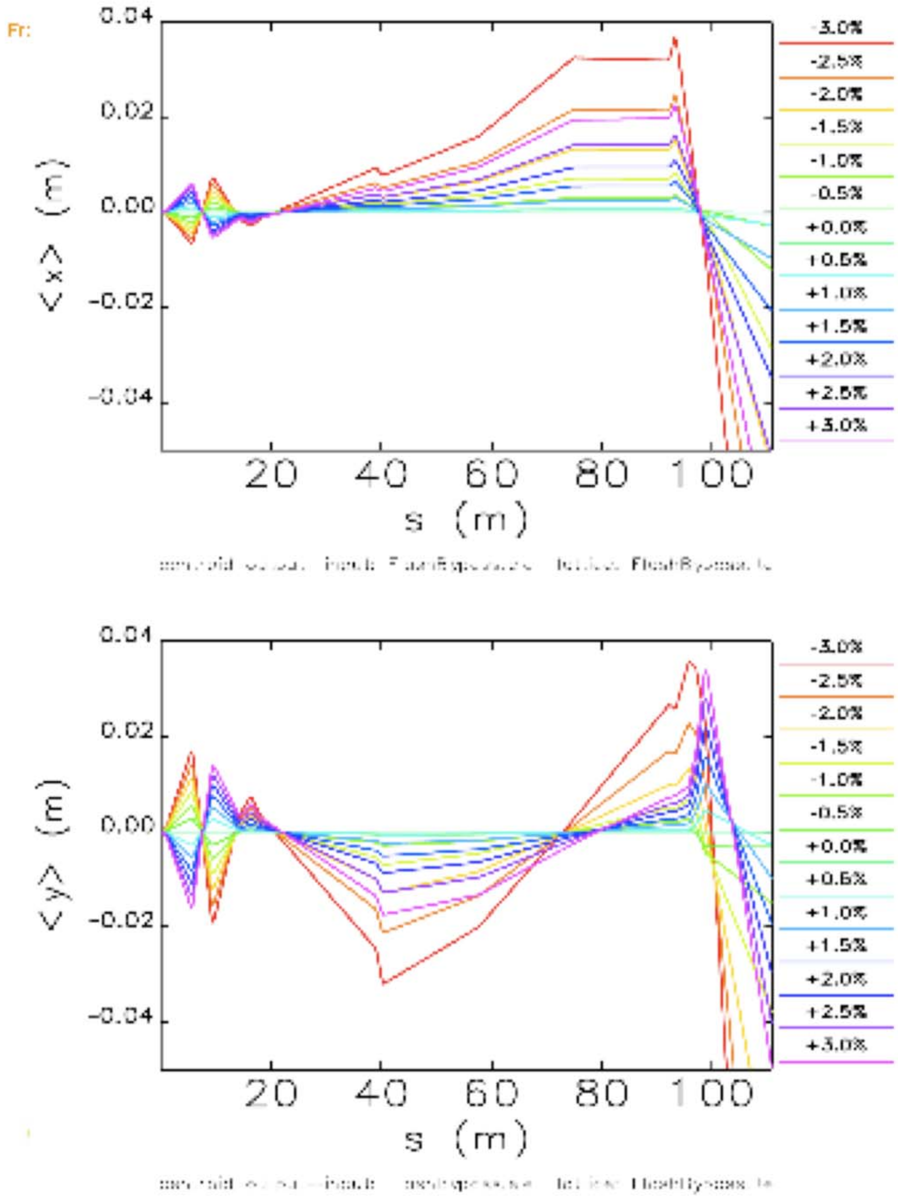
- Week 36: Machine start-up (earlier than planned)

- Weeks 37-38: Beam Studies

New dump-line + diagnostics



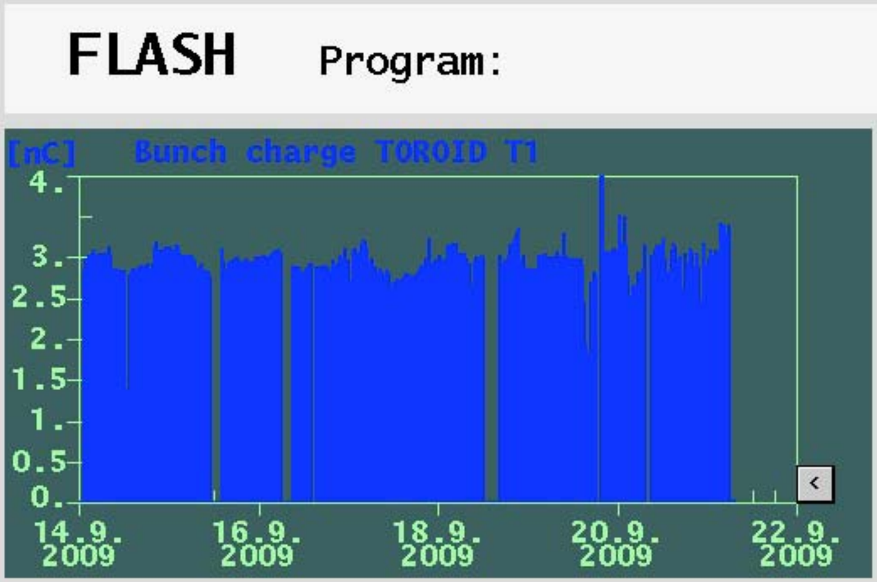
2nd order dispersion (Elegant simulation)



- Modeling bypass and dump only
  - input bunch has 3D Gaussian distribution and design parameters;
  - no physical aperture was taken into account
- Start to end (S2E) simulation
  - physical aperture of bypass and dump are included;
  - Astra was used to simulate RF gun and ACC1, so that more realistic bunch parameters are used
- In both case,
  - only theoretical optics;
  - up to 3rd order map are used

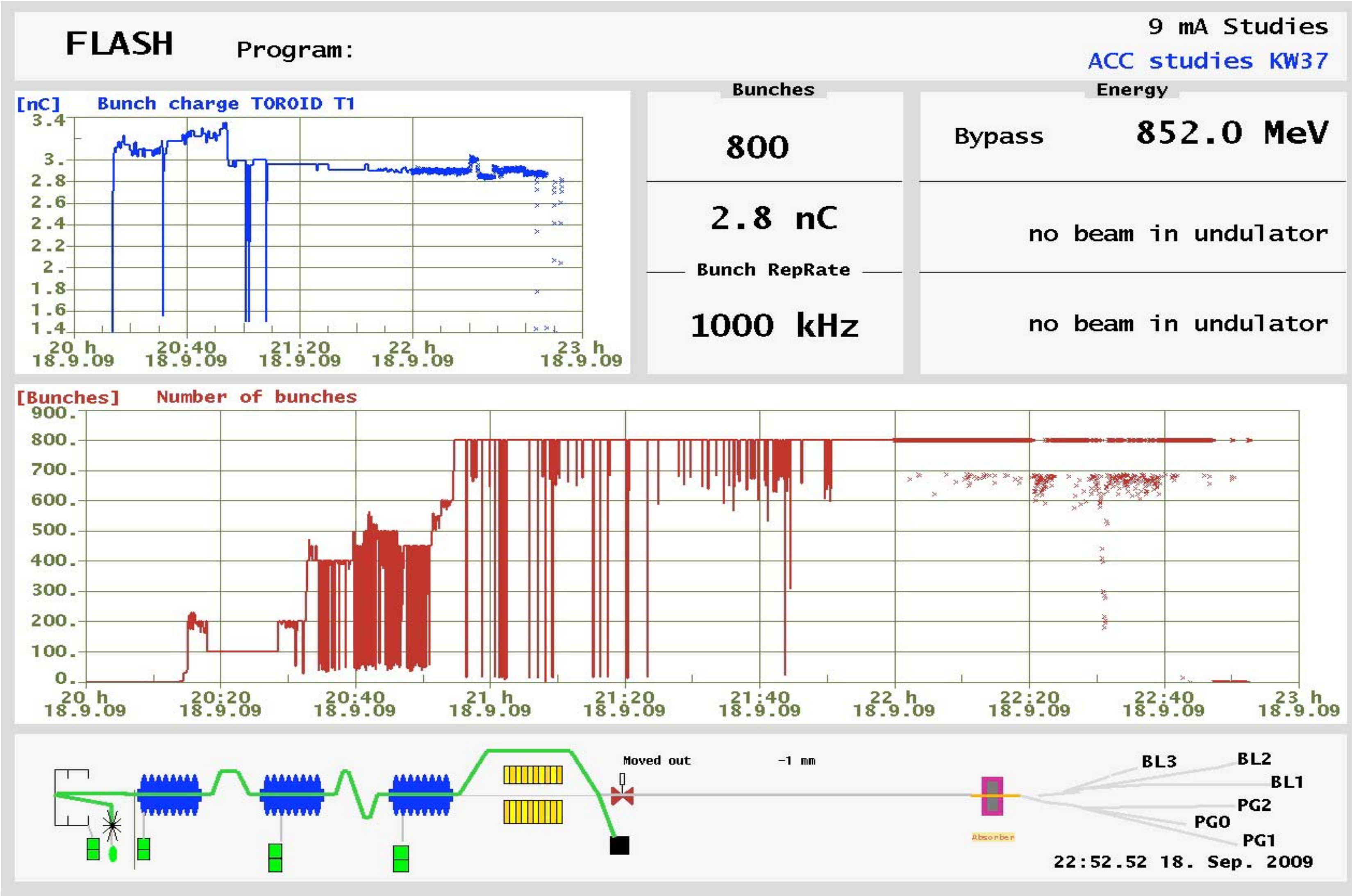
Highlights pictures

History of bunch charge and number of bunches during Week #2

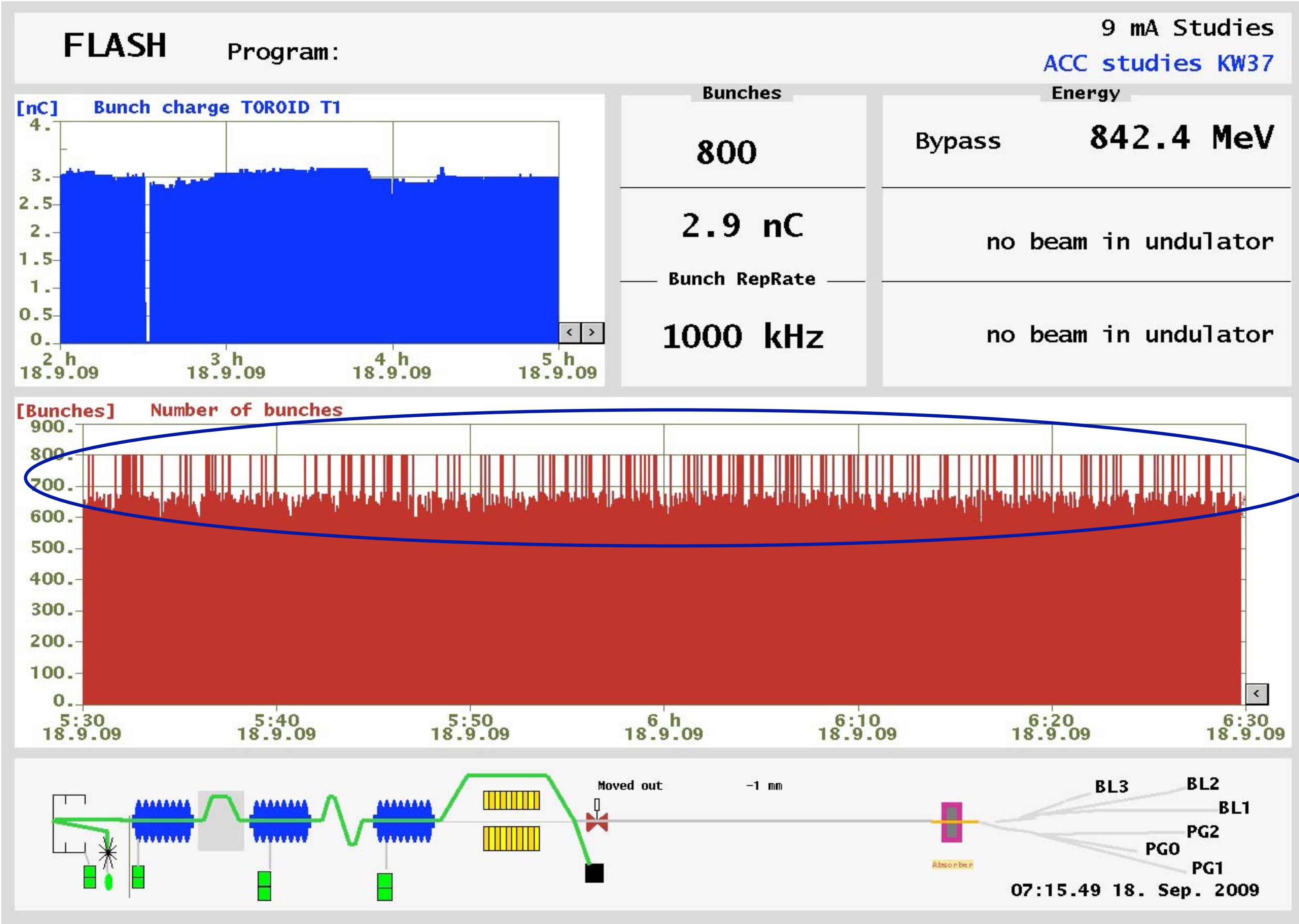


- Bunch charge was consistently between ~2.7nC and ~3nC
- Rapid progress increasing number of bunches during the last 3 days!

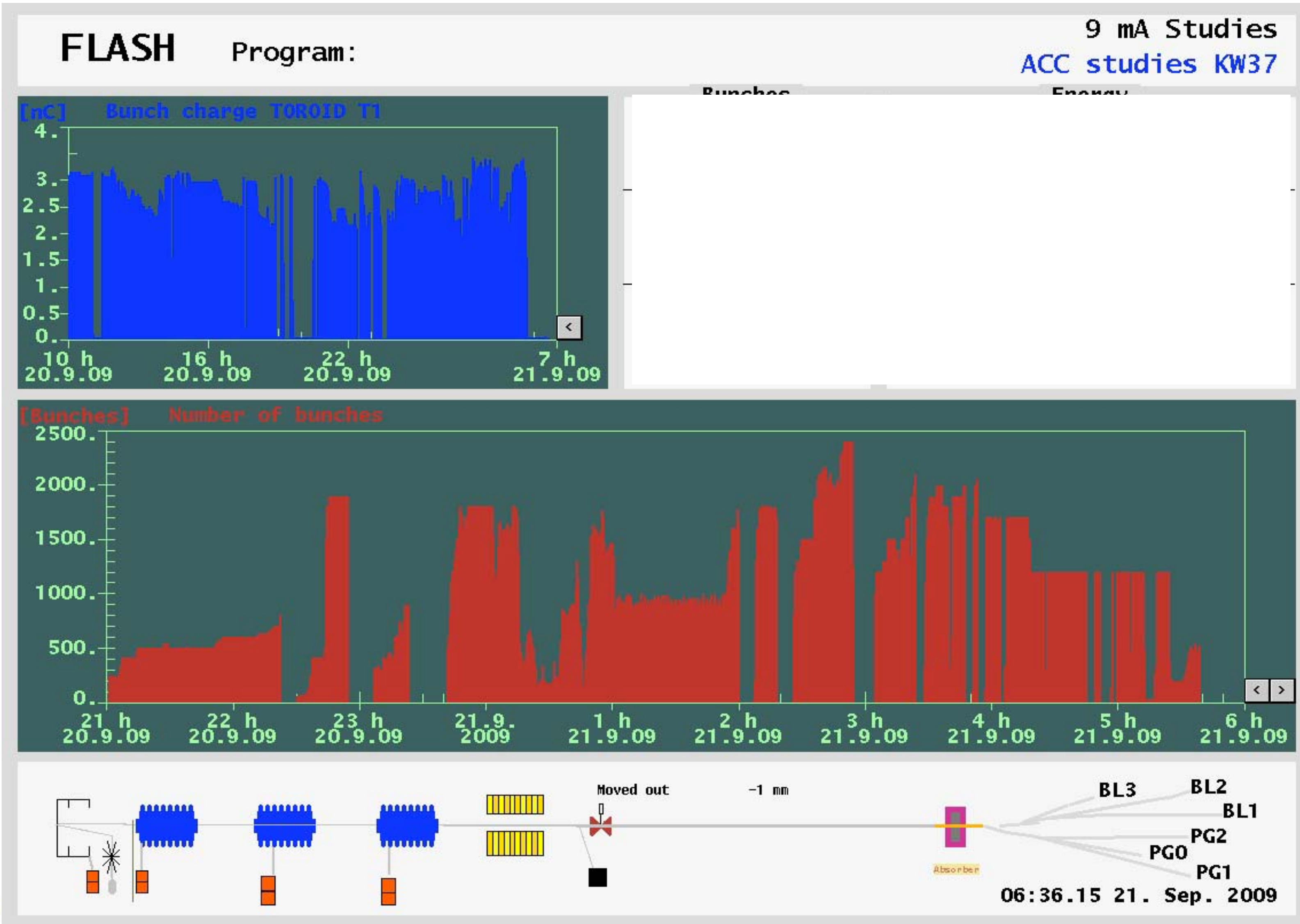
Rapid re-start after tunnel access
(0-800 bunches in 40 minutes)



A curious problem…
(nothing between 700 and 800 bunches)



Last shift… almost 2400 bunches



Operationally, it was hard!

Slow start ...

- Sept 3rd : beam to dump (3nC, 30 bunches)
- Sept 13: first time with more than 30 bunches
- *In Sept '08, we had long bunch trains within 24hrs*

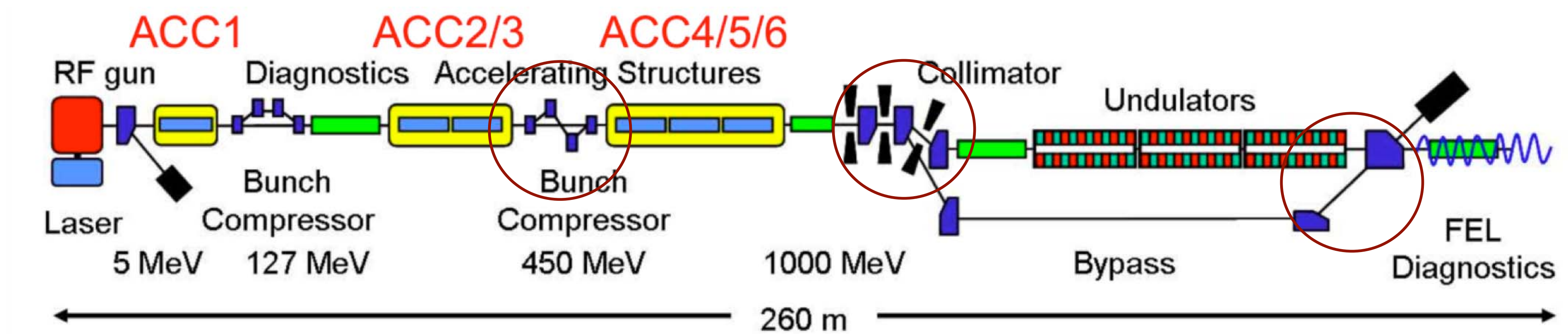
- So what was different…?

- 'Typical' operations problems coming out of a shutdown
- New LLRF system to debug at ACC456: hardware, firmware, doocs server, et al
- Then… we couldn't get the beam through the machine with sufficiently low loss (not entirely clear why)

Beam loss

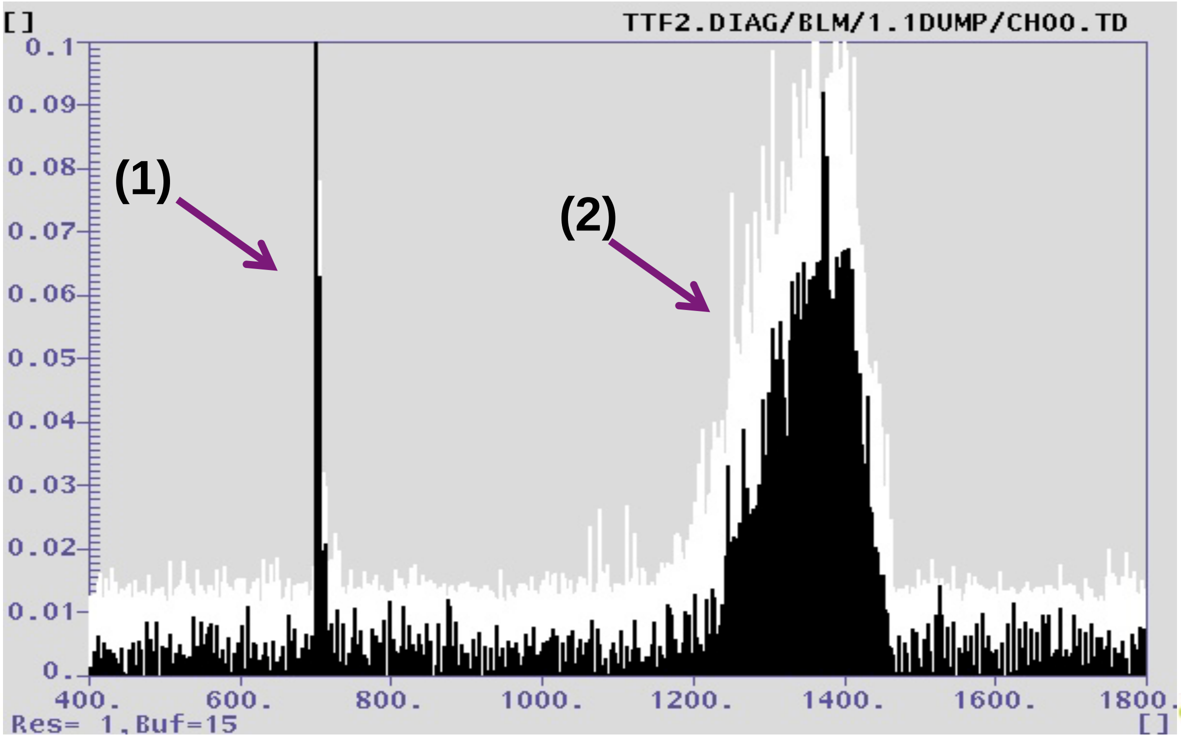
- Spent a lot of time fighting losses, mainly in three areas
  - **Bunch compressor BC3**
  - **First dipole of bypass line**
  - **Beam dump line**

- Losses speak to energy stability, orbit stability, energy / physical aperture, optics, dispersion,…



Beam losses

- Identified three contributors to the measured losses
  - **Bunch trains (1)**
  - **Dark current from the rf gun**
  - **Phantom bunches from leakage in laser switch (2)**



Machine tuning and MPS

- MPS allows two operating modes:
  - **Short-pulse mode (up to 30 bunches)**
    - Beam loss monitors and Toroid Protection System are inactive
    - Get the full bunch-train even if losses are high
  - **Long-pulse mode(>30 bunches)**
    - Beam loss monitors and TPS are are active
      - Single-bunch loss, 30-bunch avg, integrated loss
    - Bunch-train terminated when any threshold is reached
- Short-pulse mode is very effective for tuning
  - **Correct orbit, energy, beam-loading comp. etc without tripping**
  - **‘Sample’ the full flat-top using 30 bunches at 40kHz**
- There is no ‘tuning’ mode for long bunch trains
  - **Especially difficult for beam loading compensation tuning**
  - **Thermal effects due to frequently terminated bunch trains**

Some other issues

- Three different measures of energy that didn't agree
  - **Energy server: uses orbit changes in bypass chicane**
  - **RF gradient Vector Sums**
  - **First dipole in bypass**
- Temperature sensitivity of LLRF down-converters
- With higher power beams
  - **Klystron trips (waveguide power limitations)**
  - **ACC1 coupler trips**
- Manual beam loading compensation worked well, but was tricky, especially with heavy beam loading (not surprisingly)
- Sometimes the machine was very stable, but other times not… (why..?)

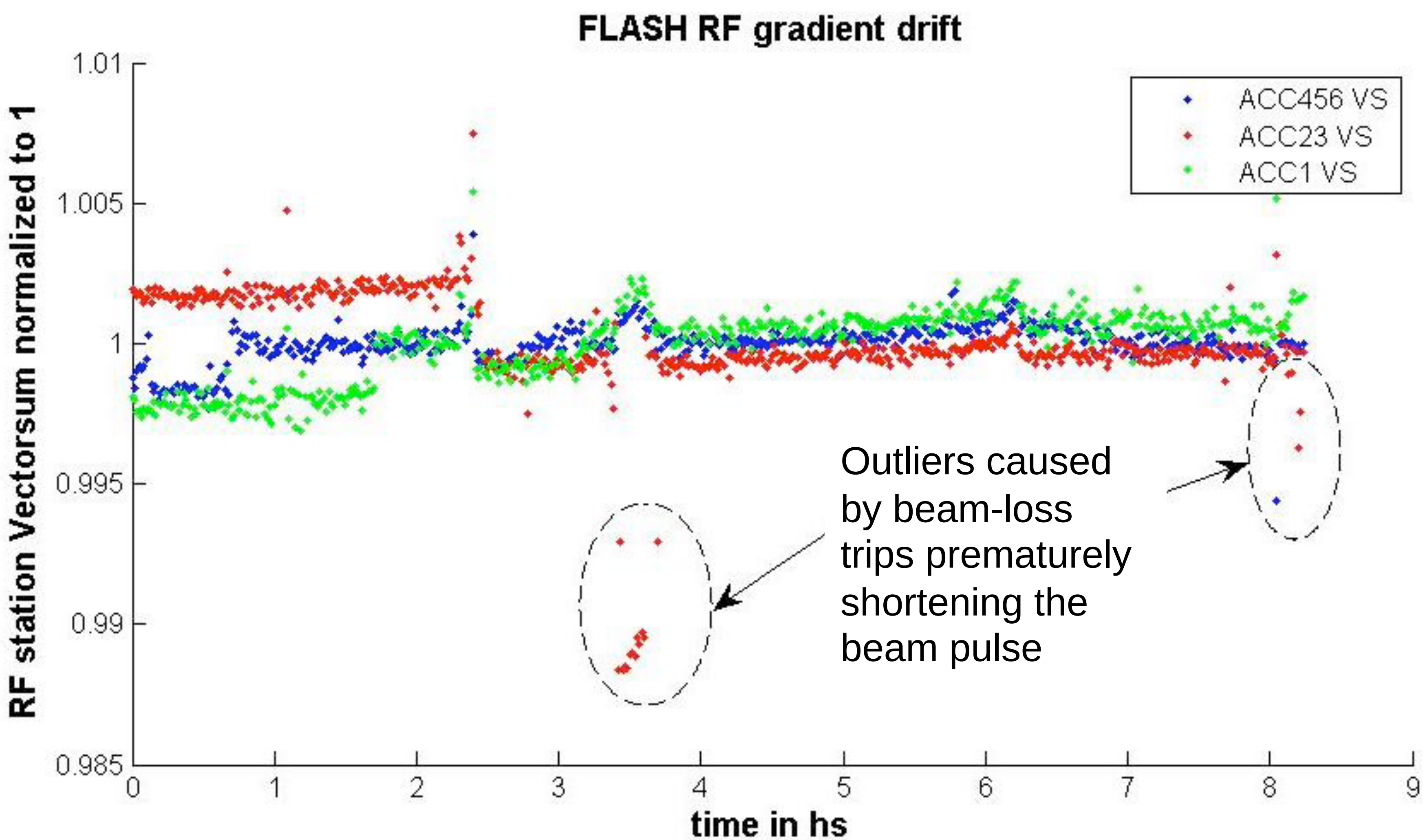
What worked well…

- FLASH!!
  - **Eg. 15hours uninterrupted with 800us, 3mA**
  - **Up to 9mA with 100’s us for several hours**

- LLRF systems were remarkably stable
- New dump-line diagnostics

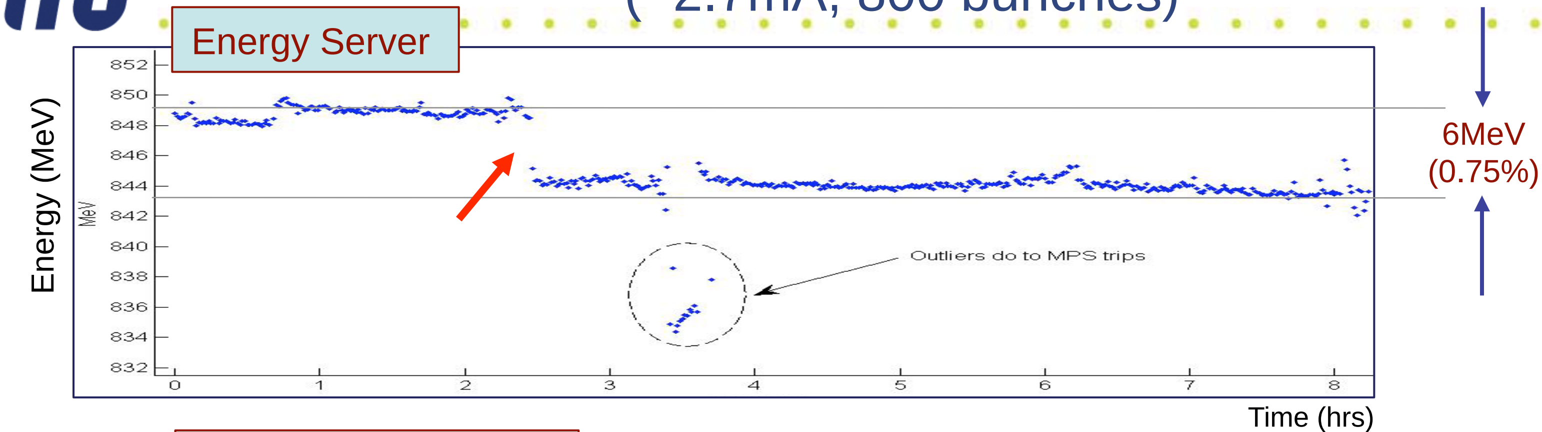
Example data: energy stability

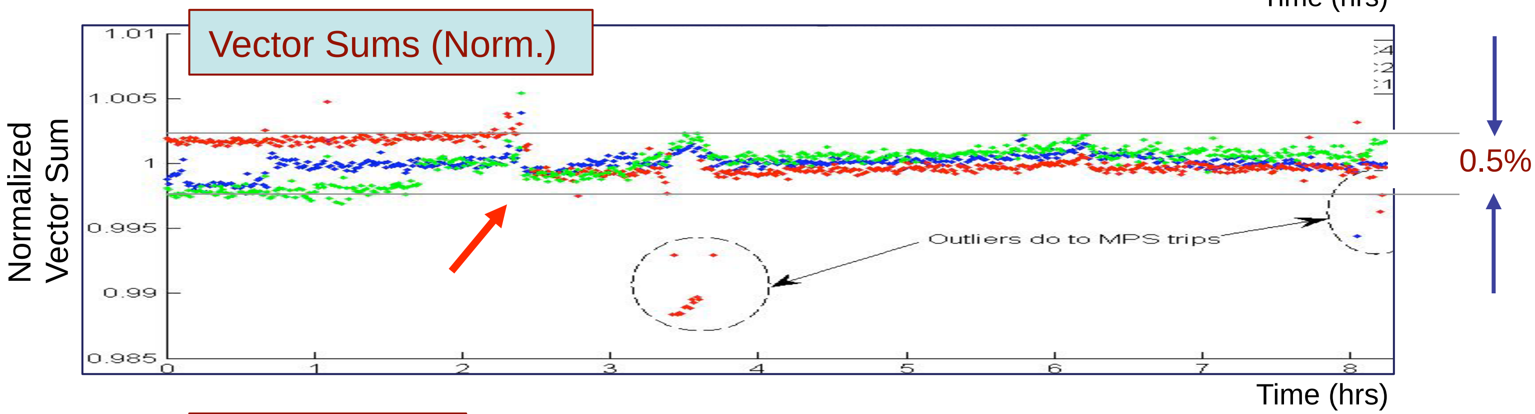
RF Gradient Long-Term Stability

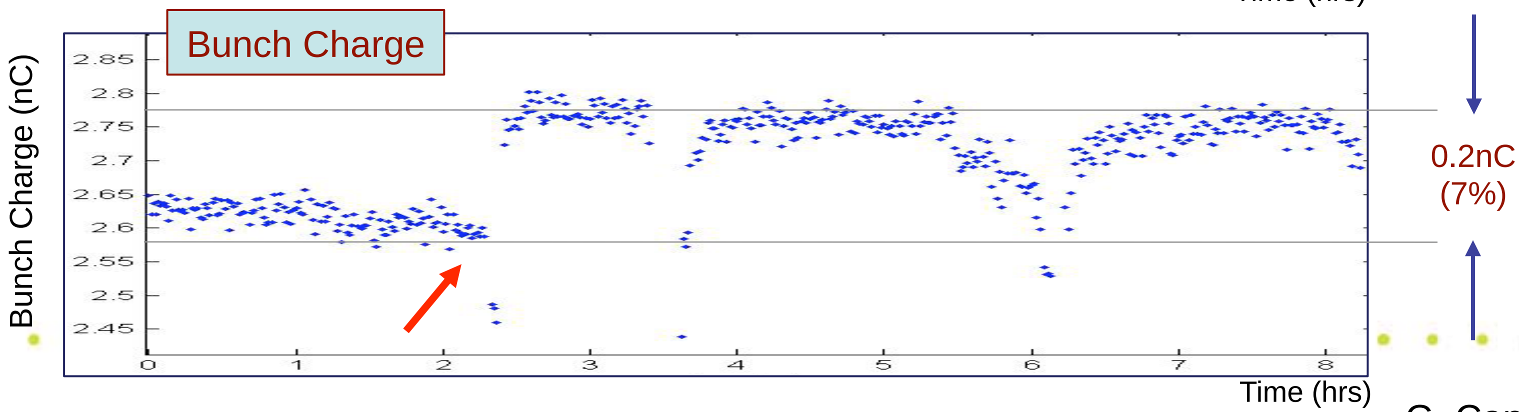


Example Result

Long-term drift over 8hrs
(~2.7mA, 800 bunches)

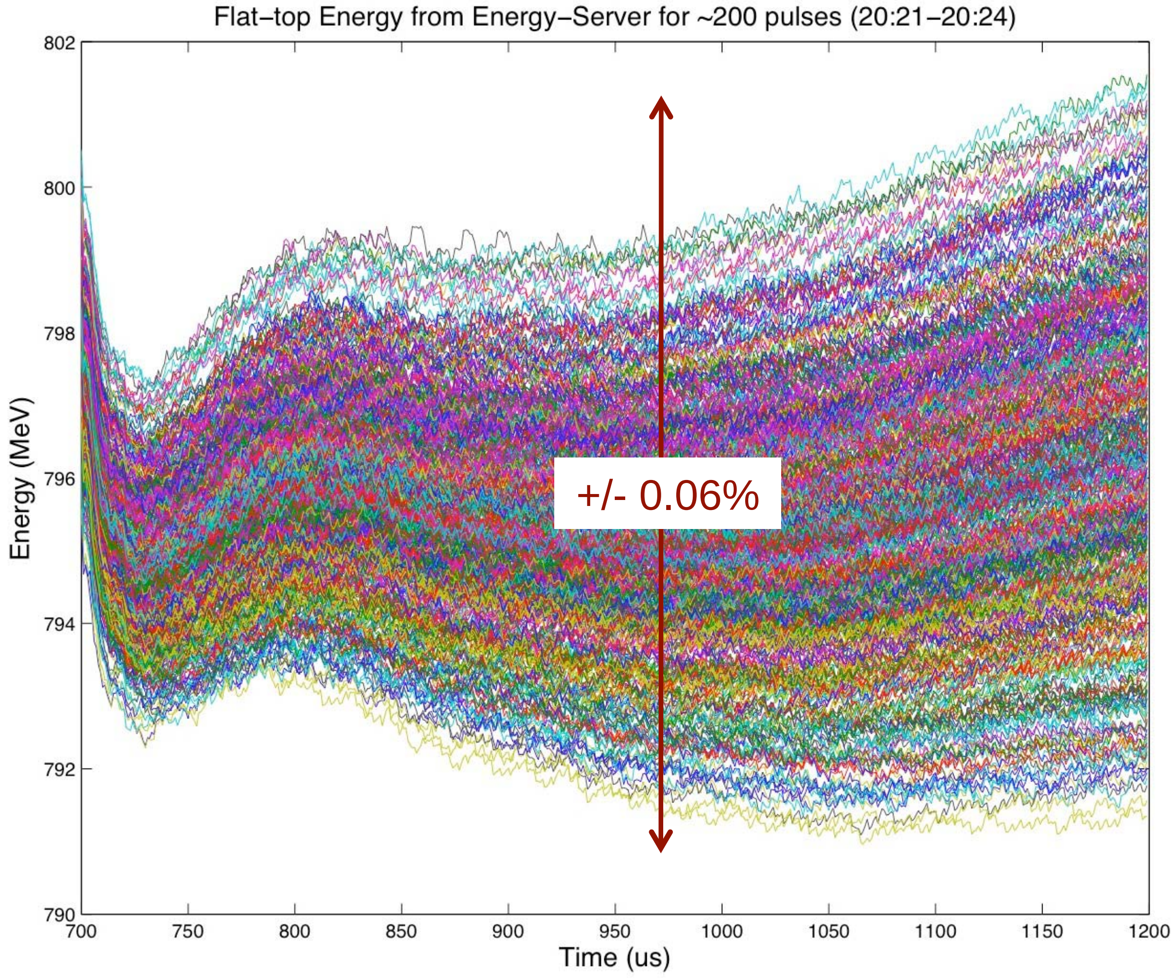






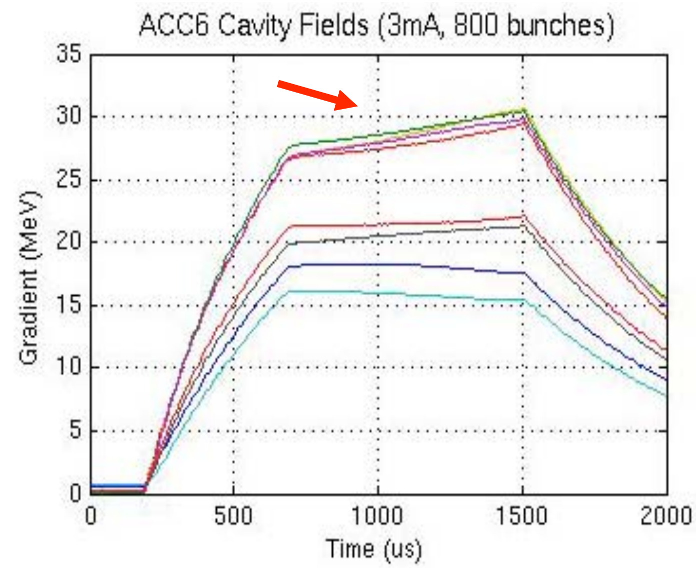
G. Cancelo

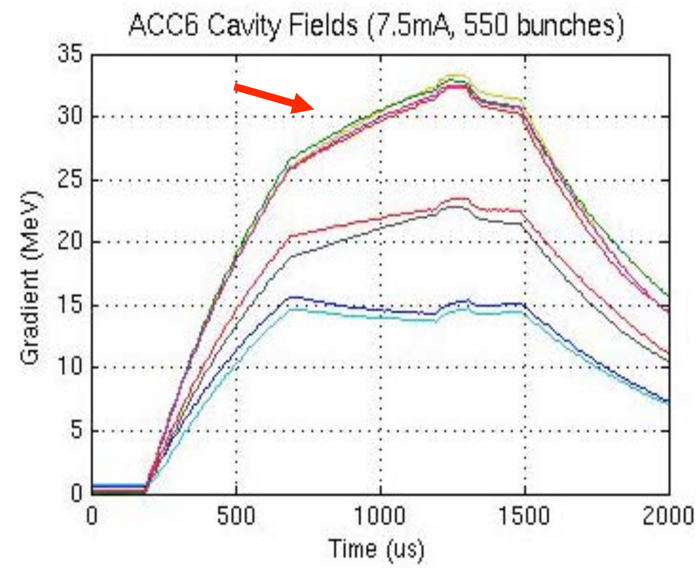
Pulse-to-Pulse energy jitter example (500us, ~3mA, 200 pulses)



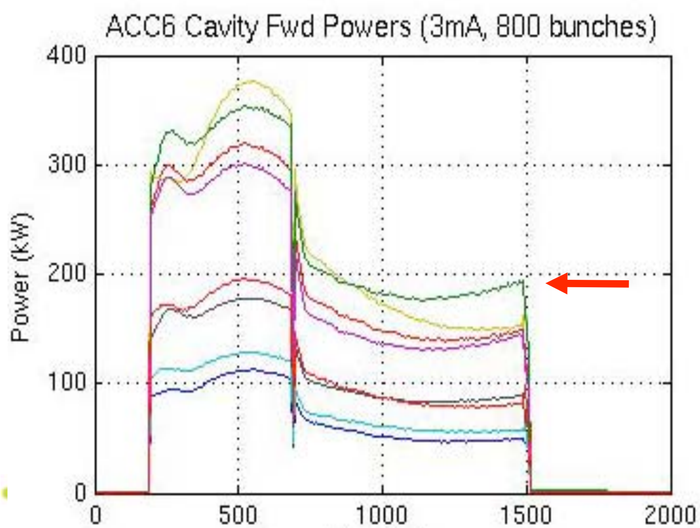
Example data: rf power vs current

Comparison of ACC6 cavity gradients and forward powers for 3mA and 7.5mA





Substantial increase in gradient 'tilts' with 7.5mA (would have quenched with 800us flat-top)



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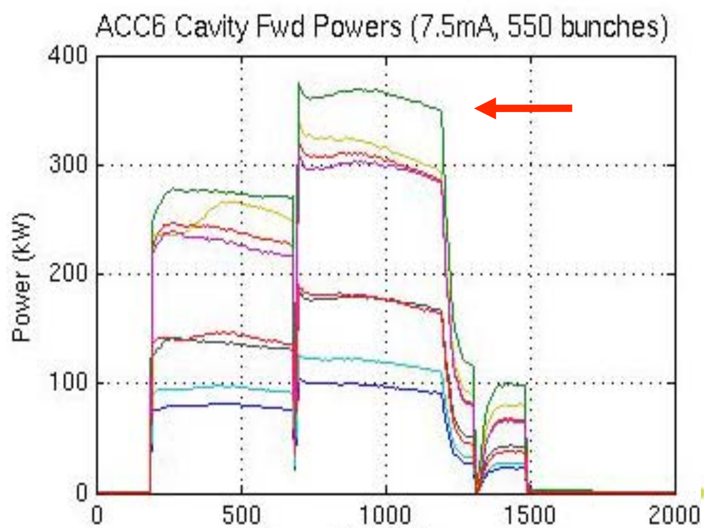

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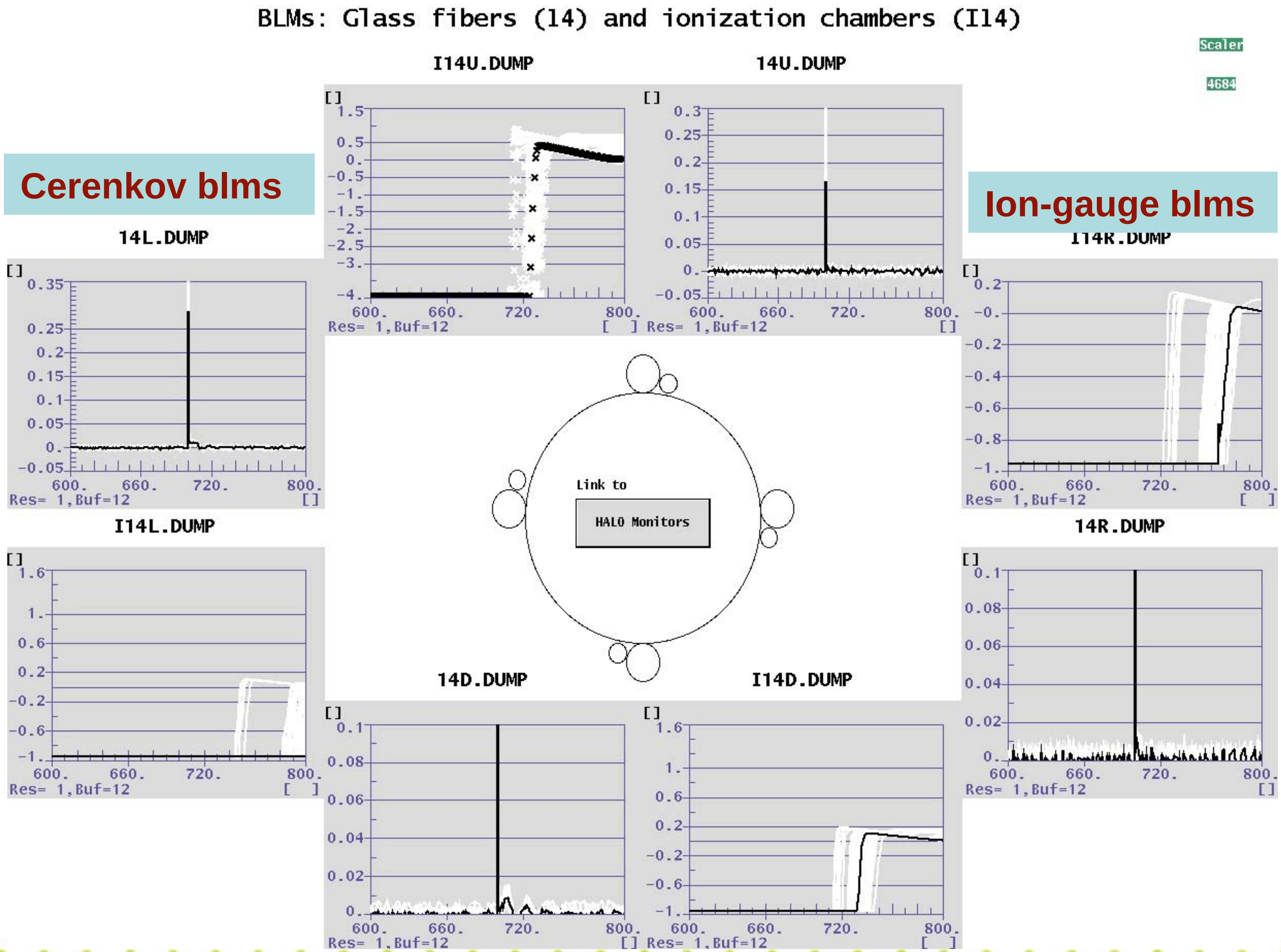
Power during flat-top is higher than the fill power for the 7.5mA case

Gradient had been lowered in 7.5mA case to reduce peak power and prevent klystron trips

Adaptive feed-forward was ON for the 3mA case

Example data: new dump line diagnostics

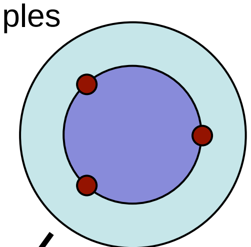
New dump-line instrumentation

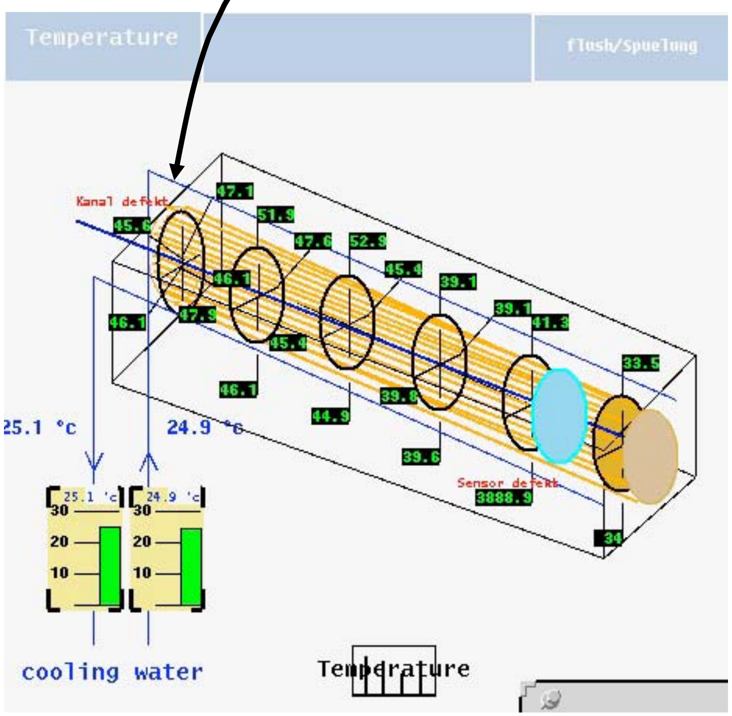


Example data: beam dump temperatures

Beam dump ‘thermocouple bpm’

Thermocouples
(First ring)





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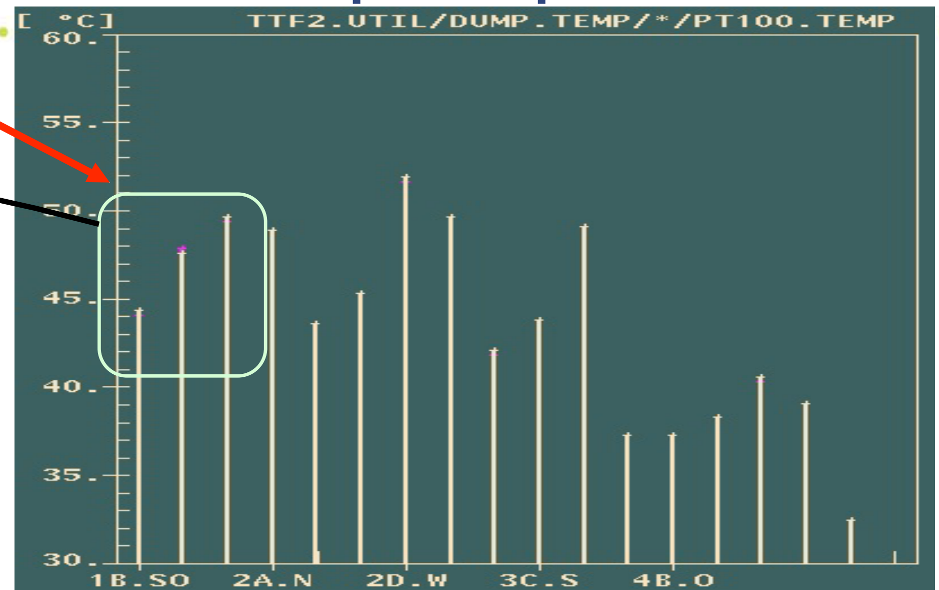

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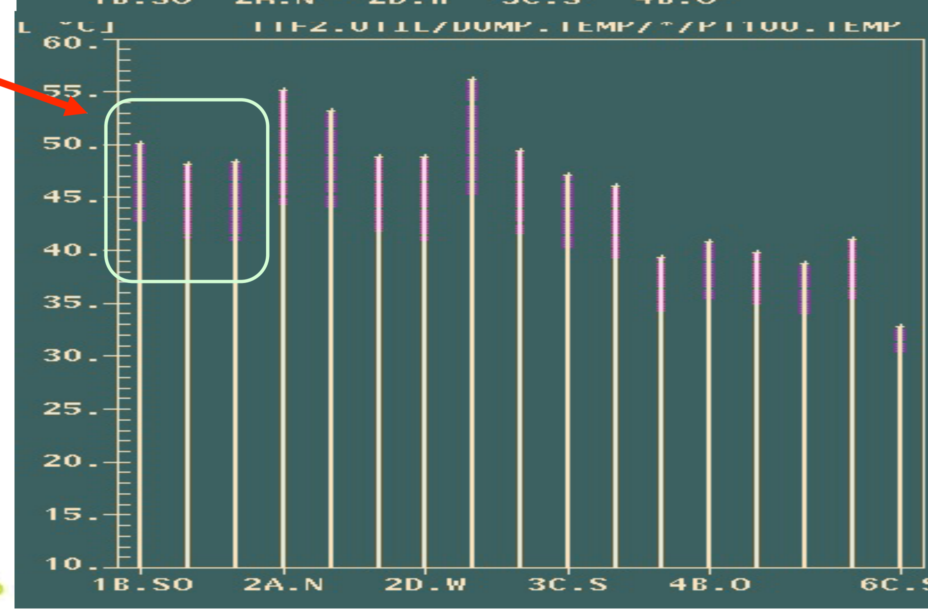
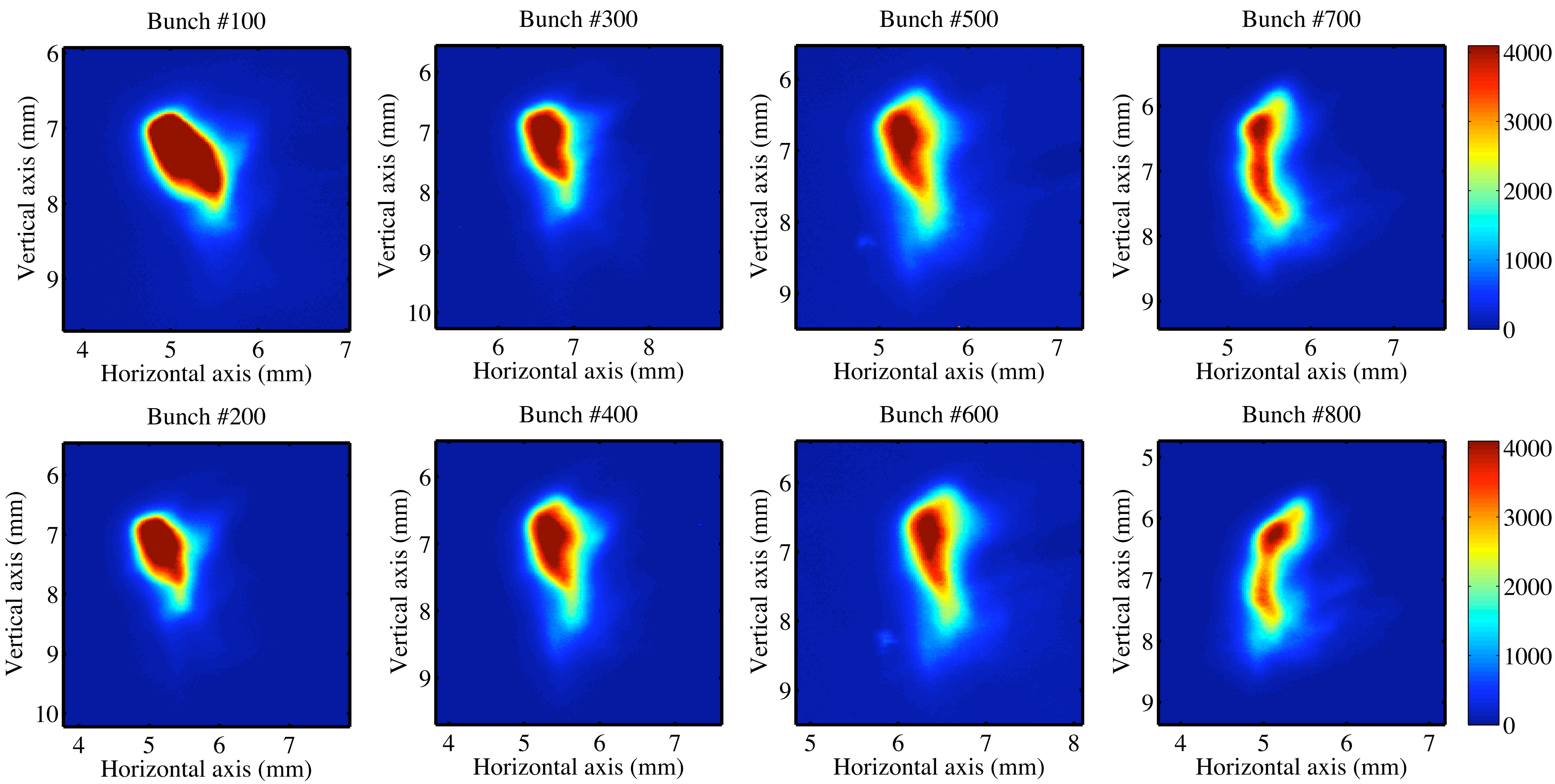


Example data: LOLA measurements during bunch train

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



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C. Behrens

DAQ data server

Some of the data available 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**
- 'Slow' data
  - **Beam dump thermocouples**
  - **Magnet currents**
  - **Cavity tuner positions**
  - **Vacuum**
- Event data
  - **Bunch rate, number of bunches**
  - **BIS and MPS interlocks**

Close to 20TB of data available for analysis

Looking ahead…

A few lessons learnt

- Adaptive feed-forward did not work well: more work is needed
- Exception handling: needs work
- Need a ‘tuning’ mode for long bunch trains…
- Re-evaluate thresholds for integrated beam loss alarms
- The DAQ is incredibly useful in the control room
- We don’t know the phases of the RF units relative to each other (to the master reference)

LLRF “Adaptive” feed-forward

- Purpose (promise)
  - **Refine the (rectangular) RF power feed-forward waveform to reduce the feedback system effort**
  - **Fine-tune the refined feed-forward waveform pulse-by-pulse (the adaptive part)**
    - Keep in step with drift, etc
    - Automatically tune LLRF beam loading compensation

- It did did not work despite much effort
  - **System must be more refined (stable) and robust**
  - **Exception handling is paramount**
    - Dealing with deliberate changes in the number of bunches
    - Dealing with bunch trains that are fore-shortened by MPS
  - **Definitely needed for machine automation (XFEL, ILC)**

For next time… (examples)

- Complete the study goals, eg operation at gradient limits, HLRF overhead studies,…
- Work towards demonstrating routine operation with heavy beam loading and long pulses
  - **Repeatable predictable performance**
  - **Machine tuning without always needing the experts**
  - **Run FLASH ‘as if it were the ILC or XFEL’ (automation)**

Closing slide

- **Stable operation of FLASH with high beam-loading has been demonstrated, …**but
  - **Not all (original) 9mA goals were achieved**
  - **Routine operation of long bunch trains still requires work**
  - **Planning for next shifts (proposal) now underway**
- Detailed data analysis is just beginning…