Cryomodule String Test: TTF/FLASH 9mA Experiment

John Carwardine (Argonne)
Nick Walker (DESY)

ART Program Review, 9-10 June, 2010

Outline

- Cryomodule String Test goals
- TTF/FLASH facility overview
- Progress, results
- Gradient limits for 9mA studies
- Planning the next studies
- Wrap-up

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***

FLASH is still the only facility where these tests can be performed

Specific objectives for the 9mA study

- Long bunch-train high beam loading (9mA) demonstration
  - 800μs pulse with 2400 bunches at 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

Demonstrate ILC-like beams

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

Studies requiring ILC-like beams

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

Operational challenge for FLASH
(well beyond typical beam parameters for photon users)

Americas

FLASH
Free-Electron Laser in Hamburg

An international 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 Golubeva	- optics calculations
– Vladimir Balandin	- 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
– Stefan Simrock	- LLRF (general)
– Kay Rehlich	- controls (DAQ)
– Kay Wittenburg	- diagnostics
– Dirk Noelle	- diagnostics (BPM)
– Nick Walker	- overall coordination
– Katya Honkavaara	- planning
– Mikhail Krasilnikov	- RF gun modelling

- **ANL**

– John Carwardine	- LLRF / overall coordination
– Xiaowei Dong	- Data analysis, optics modeling
– Ned Arnold	- DAQ and data analysis tools

- **FNAL**

– Brian Chase	- LLRF (experiment & data analysis)
– Gustavo Cancelo	- LLRF (experiment & data analysis)
– Julien Branlard	

- **KEK**

– Shinichiro Michizono	- LLRF (experiment & data analysis)
– Toshihiro Matsumoto	- LLRF (experiment & data analysis)

- **SLAC**

– Chris Adolphsen	- LLRF (experiment & data analysis)
– Tom Himel	- Planning & scope
– Shilun Pei	- LLRF (experiment & data analysis)

~40 subscribers to ttf9mA mailing list (not all shown here)

RF/LLRF collaborators:
DESY, KEK, FNAL, SLAC

Initiated by the ILC/GDE, co-led by DESY and GDE
A DESY program with international participation

9mA program resources & responsibilities

- **A DESY program with international participation**

- DESY
  - **Machine study time on an operating user facility FLASH**
  - **System implementation and upgrades (hardware, firmware, software)**
  - **Machine experts and operations personnel**
  - **New beam dump line and beam loss diagnostics**

- International (LLRF Focus): Argonne, Fermilab, KEK, SLAC

ART participation

- Focus on RF/LLRF, Global Systems WBS1.8 (~3FTEs total)
  - **Argonne (J. Carwardine, N. Arnold, X. Dong)**
  - **Fermilab (B. Chase, G. Cancelo, J. Branlard, N. Solyak)**
  - **SLAC (S. Pei, C. Adolphsen)**

- Beam loading studies planning and preparation (Fermilab)
- On-site participation in FLASH studies shifts (Argonne, Fermilab)

- Analysis of studies data
  - **LLRF performance, energy stability, microphonics... (Fermilab)**
  - **Cavity jitter, rf power overhead (SLAC)**

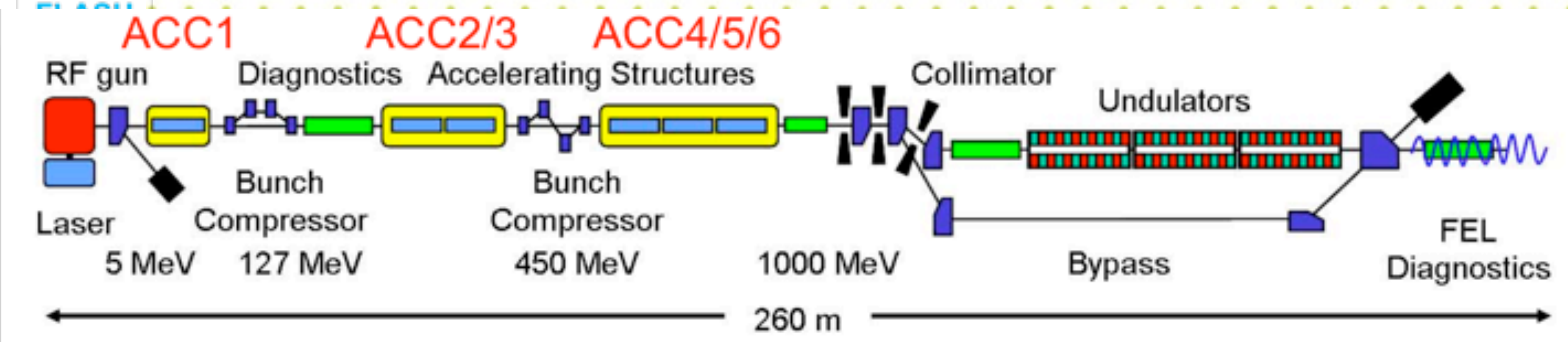
- Modeling & simulation
  - **RF power distribution cavity setup schemes (Fermilab)**
  - **End-to-end simulations, beam loss analysis (Argonne)**

- DAQ data archiver support and data analysis tools (Argonne)

TTF/FLASH facility overview

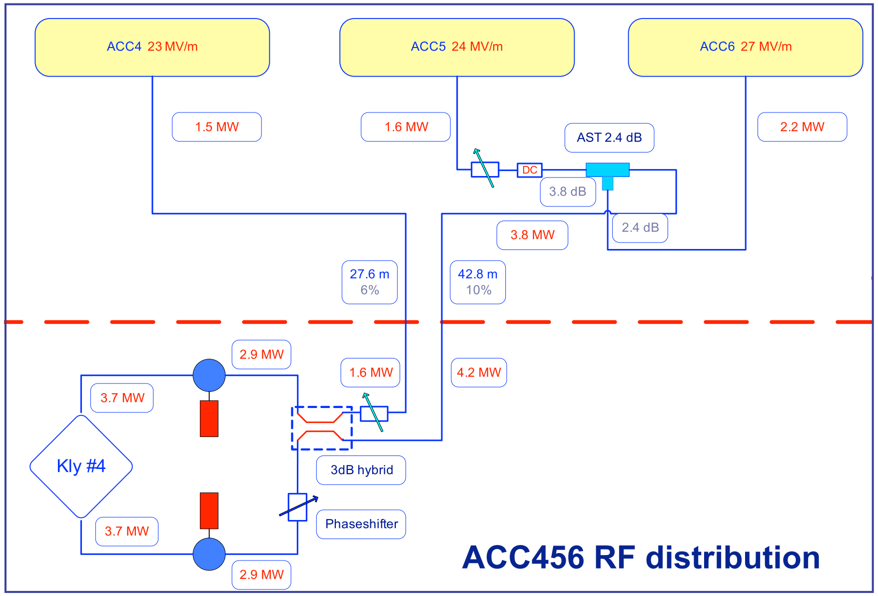
Americas

FLASH accelerator layout (2009)



Comparison of machine parameters

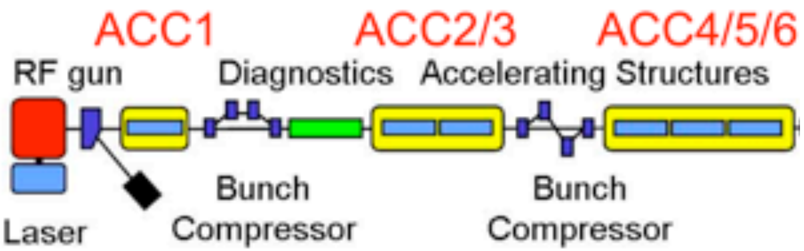
		XFEL	ILC	FLASH design	9mA studies
Bunch charge	nC	1	3.2	1	3
# bunches		3250	2625	7200*	2400
Pulse length	µs	650	970	800	800
Current	mA	5	9	9	9

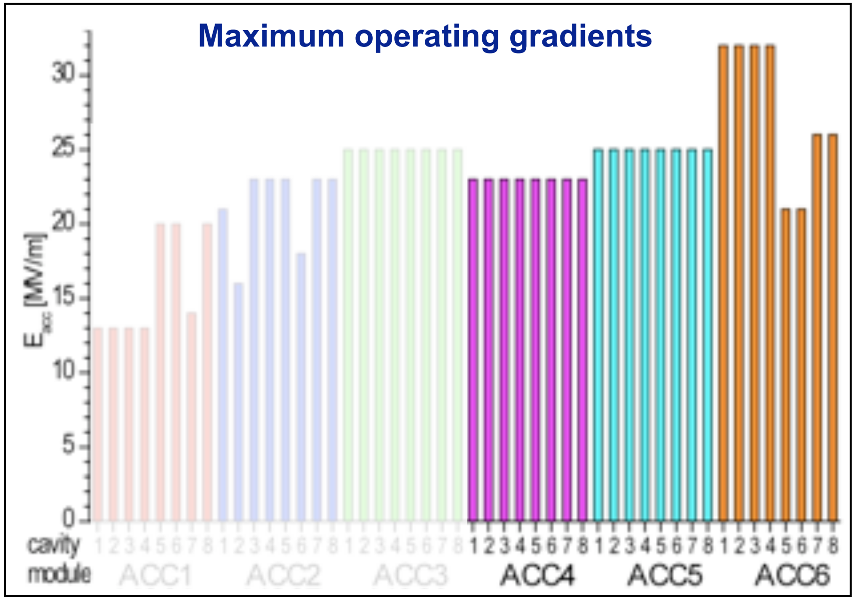


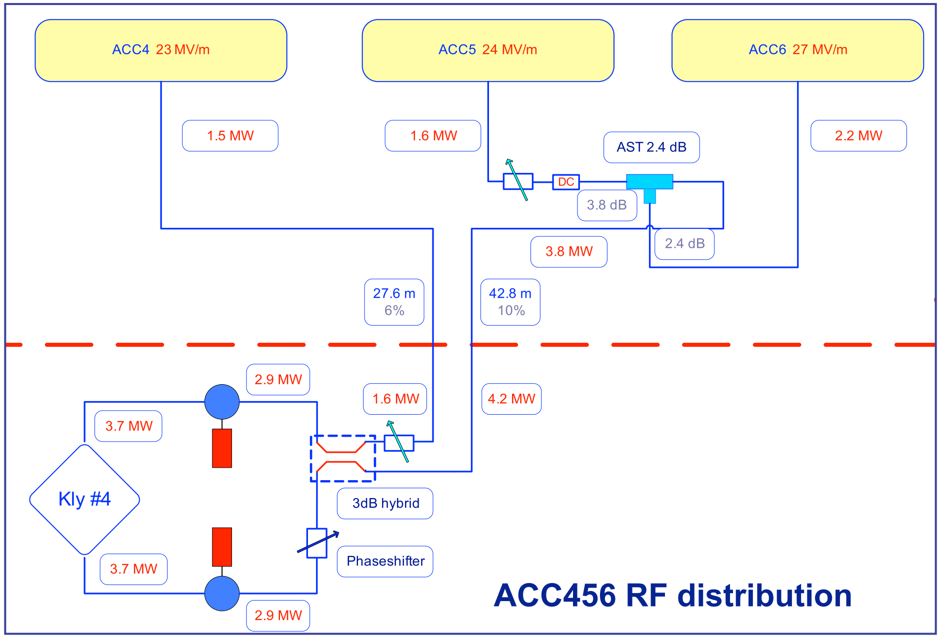
Synergies with 9mA program

- FLASH FEL operations with long bunch trains
- XFEL design/development, future operations
- Important operations experience for NML & STF

Cavity field vector sum control

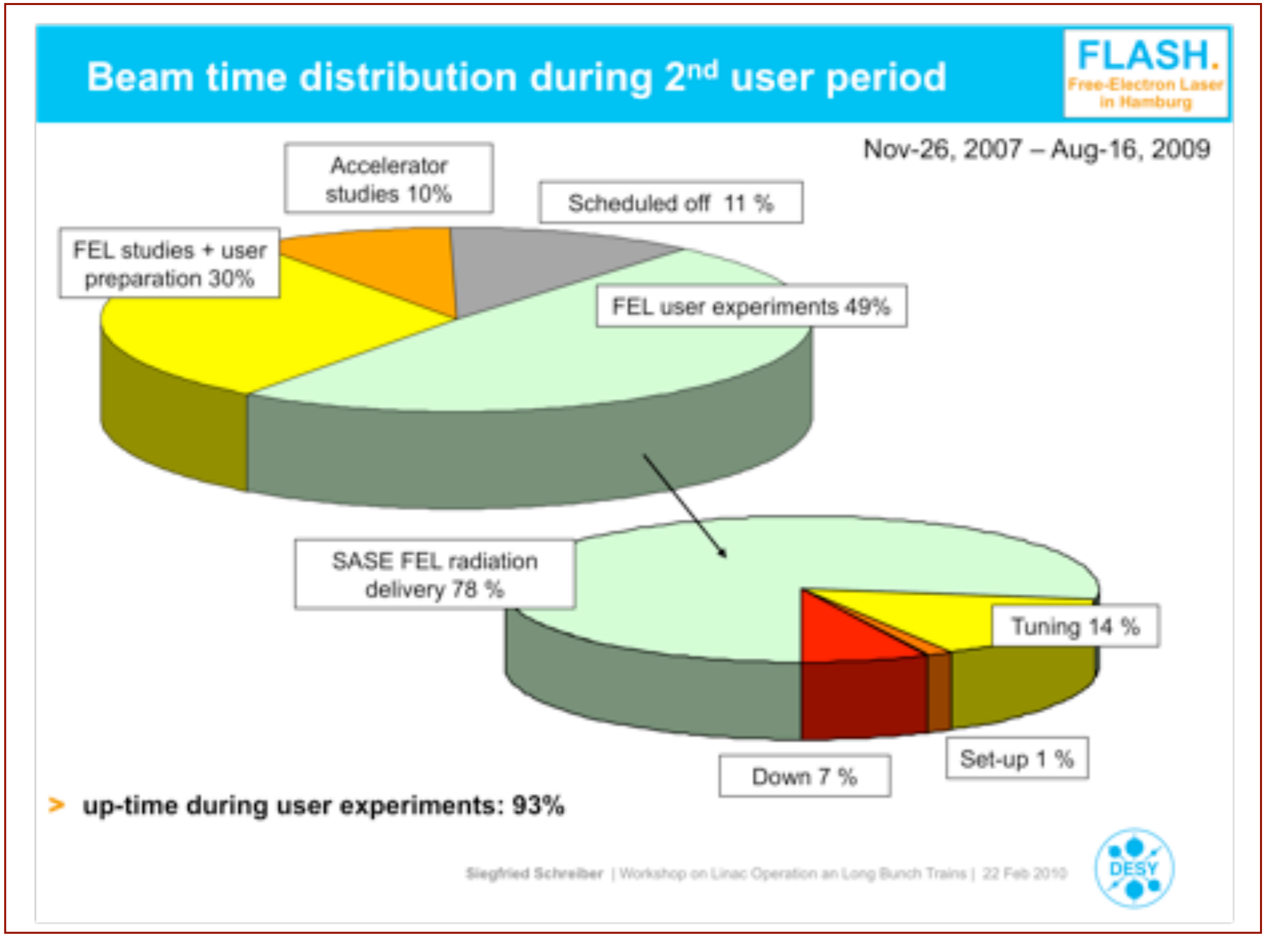






- A single klystron provides rf power to 24 cavities
- LLRF regulates the phase & amplitude of the vector sum of 24 cavity fields ("total energy gain")
- A critical issue: operating with a spread of gradients

FLASH is an operating user facility



There is stong competition for the limited accelerator study time

Long bunch-train high power operation

History of 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	
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

5 weeks (Aug 09 – Sept 09)

- Long bunch trains are a fundamental advantage of the TESLA SCRF technology
- Proof of principle has been long established
- '9mA' studies are focused on **operational limits** (pushed by ILC requirements)
- Total 9mA beam studies time to date: ~3 weeks

Long bunch trains vs single bunch

- **All the challenges with setting up and running the machine are magnified when running long bunch trains**
- Requires consistent bunch properties over the bunch train

  - **Final energy**
  - **Peak current / slice emittance**
  - **Electron bunch trajectory**

High power (9mA) studies
Minimize beam loss trips
= DeltaE/E, bunch trajectory

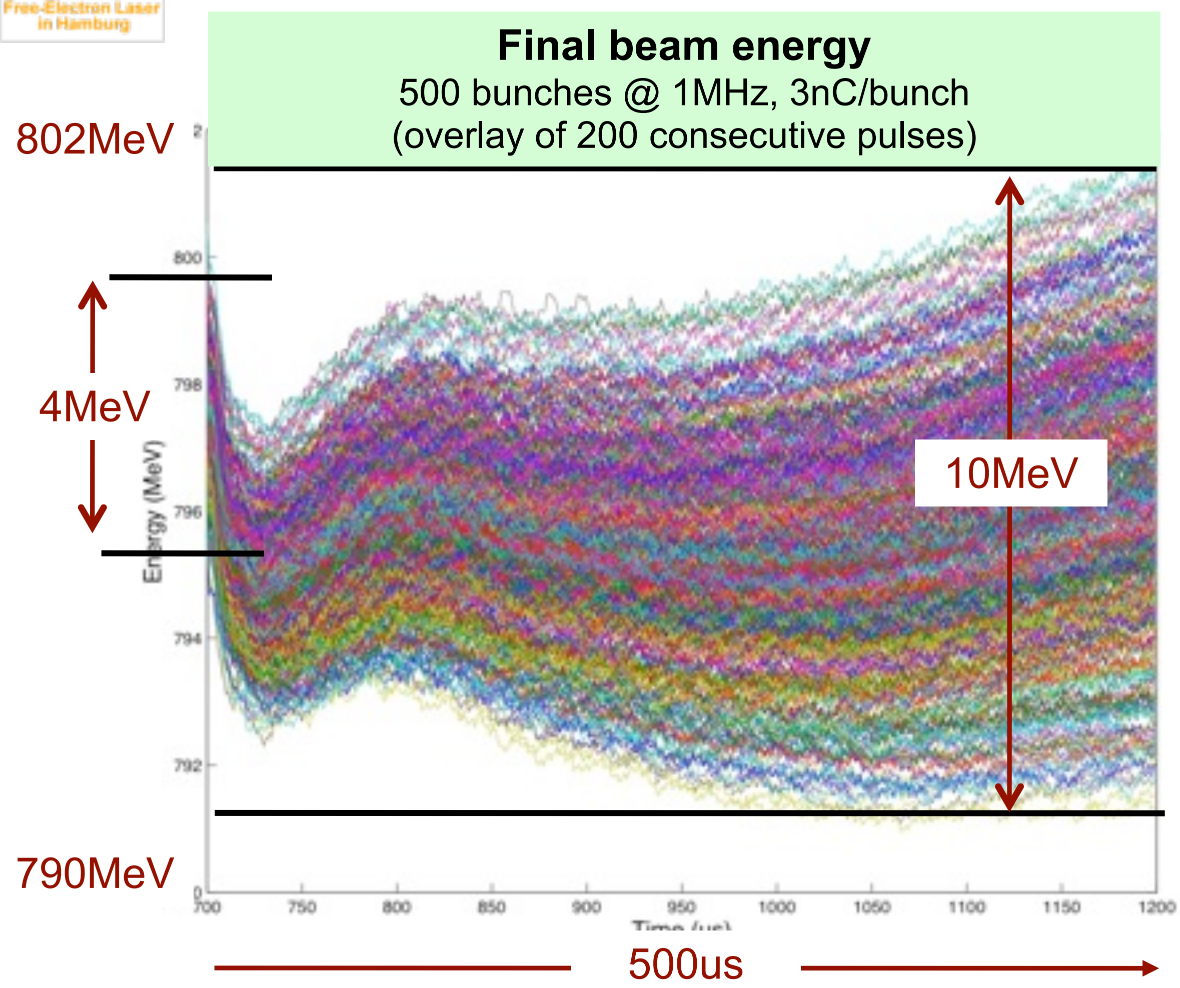
High average beam power
Exception handling…

Transient effects..
Beam loading
Lorentz-force detuning
Microphonics
Pulse-heating

Photon science
DeltaE/E: < 0.1%
Pointing accuracy: < 10's urad
Arrival time deltaT/T: 10's fs
Stable lasing conditions

Energy profile example (Sept 09):

Transient beam loading, Lorentz-force detuning,…



Jitter (first bunch): 4MeV

Jitter (all bunches): 10MeV

Energy spread within bunch-train: 5MeV

Americas

FLASH

High power long bunch-train operation

(Accomplished during 2 weeks of studies in Sept 2009)

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

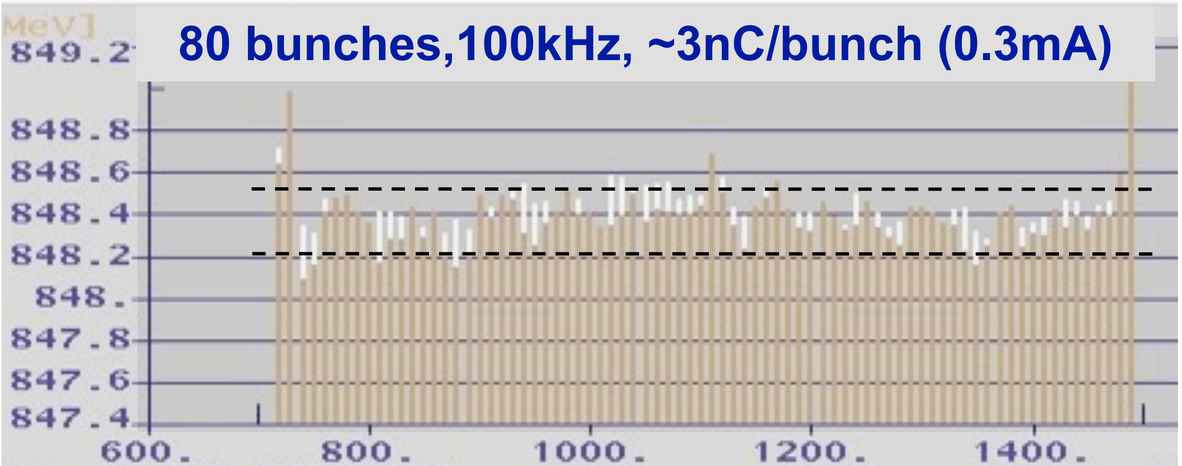
- Energy deviations within long bunch trains: <0.5% p-p (7mA beam)
- Energy jittter pulse-pulse with long bunch trains: ~0.13% rms (7mA)

Energy deviation along bunch train (examples)

Americas

FLASH Free-Electron Laser in Hamburg

1.8 MeV

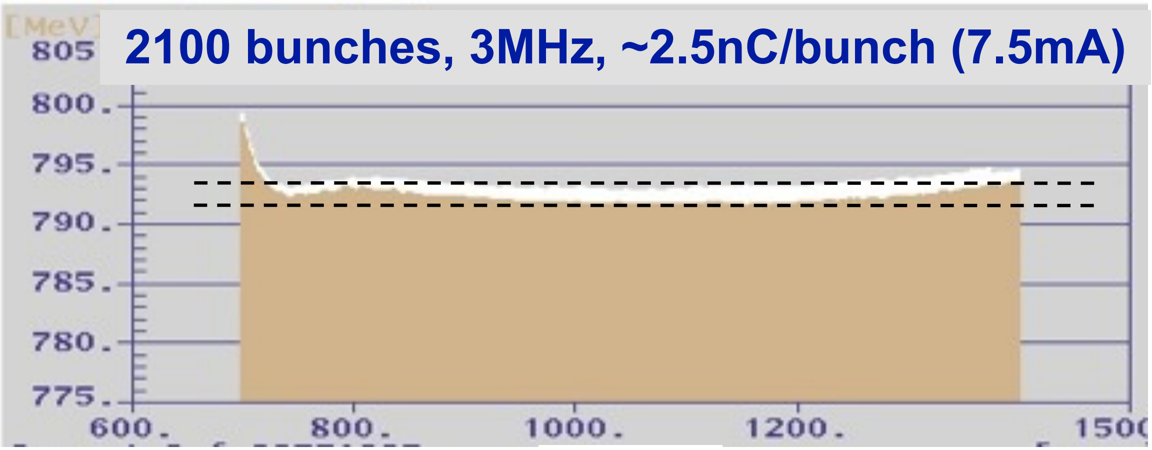


800us

Along pulse: 0.035% p-p

(Spec: +/-0.1%)

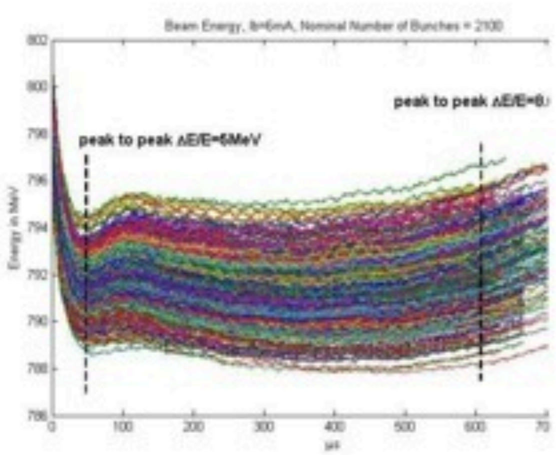
30 MeV



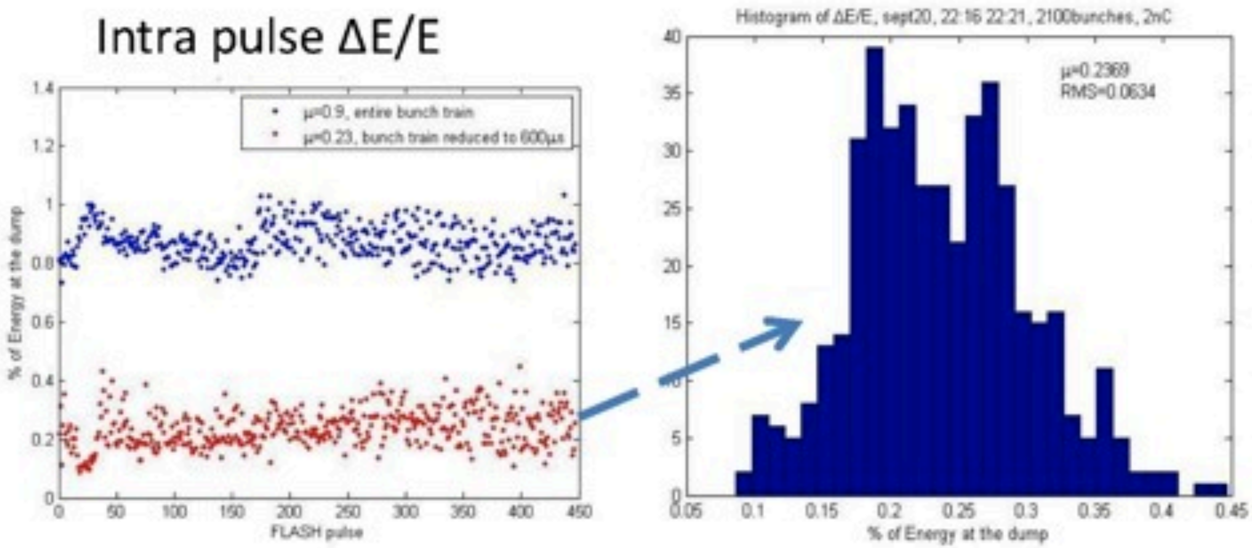
700us

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

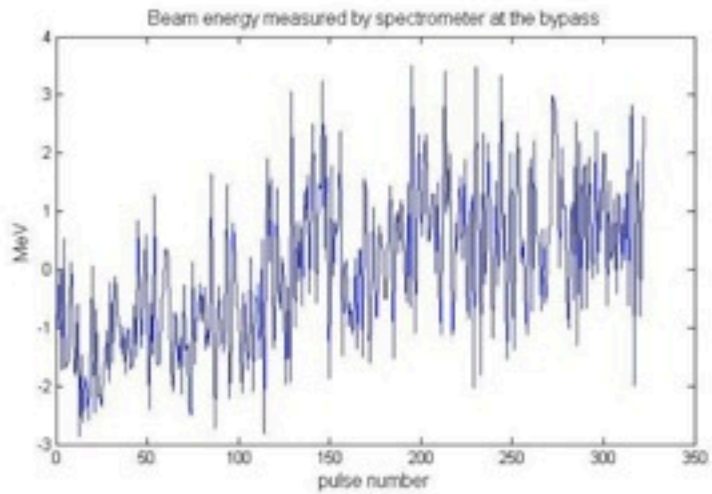
Energy stability - Sept.20, 22:16 22:17, 6mA, 2100bunches

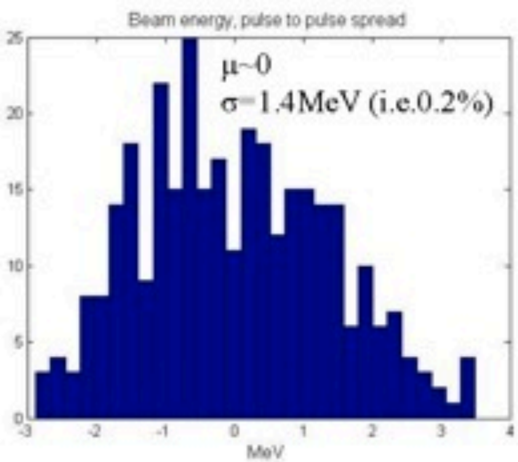


Intra pulse ΔE/E



Pulse to pulse ΔE/E

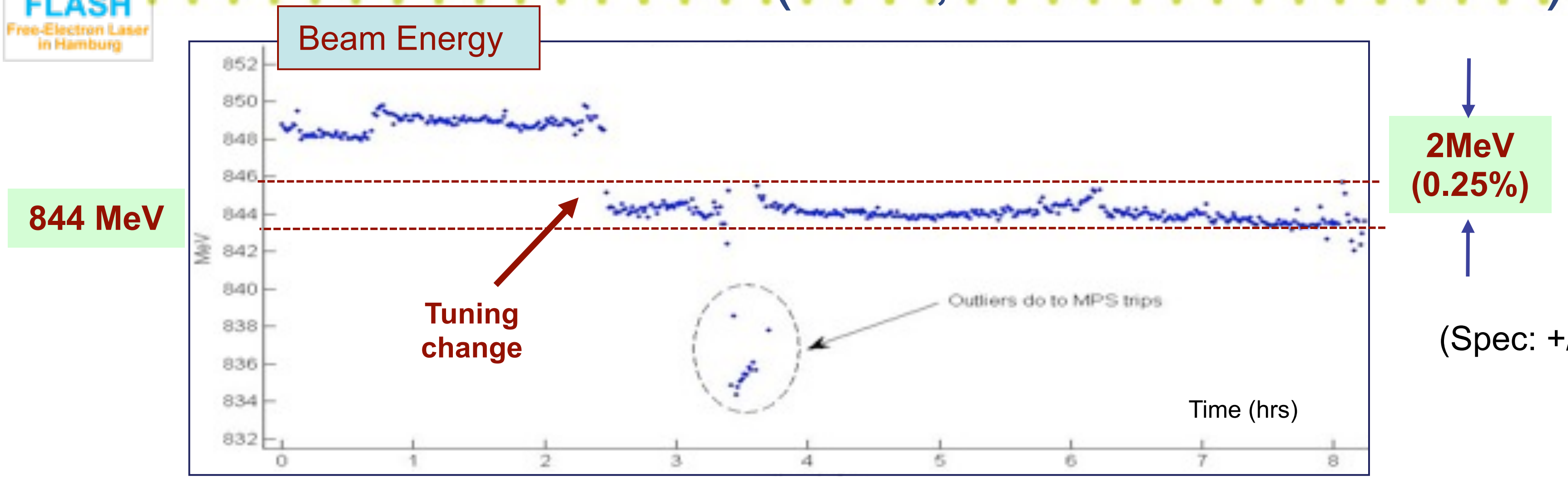




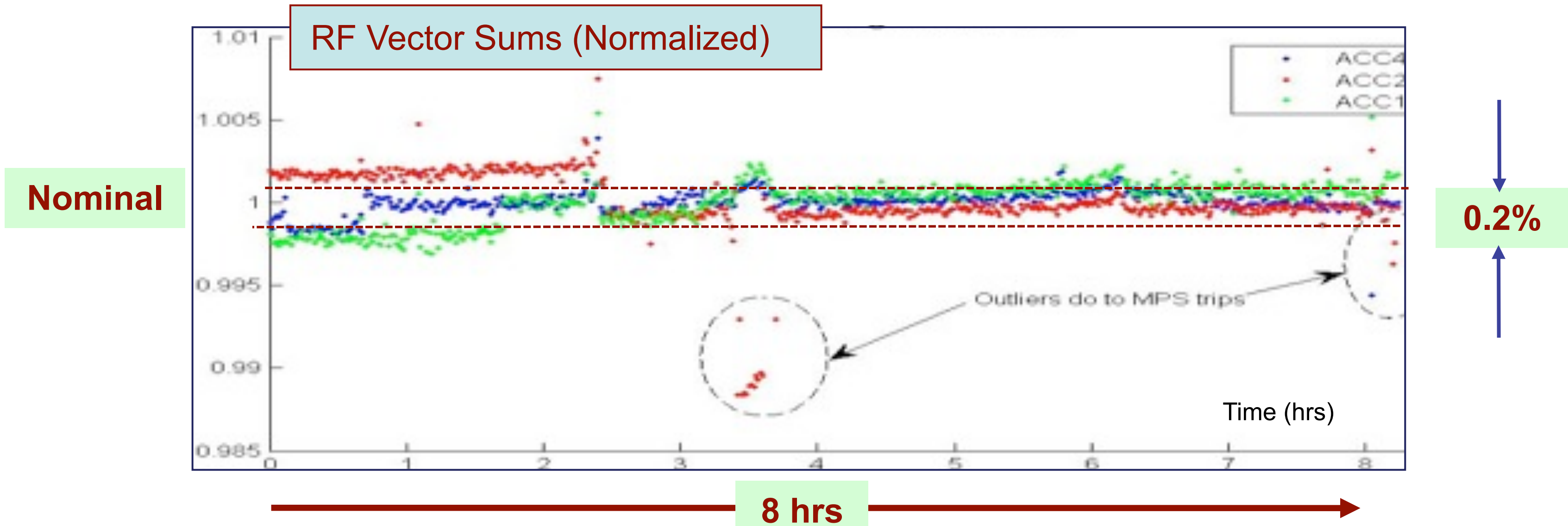
- RMS don't mean much. We need to look at peak to peak values.
- High frequency energy jumps of up to few MeV.

G. Cancelo

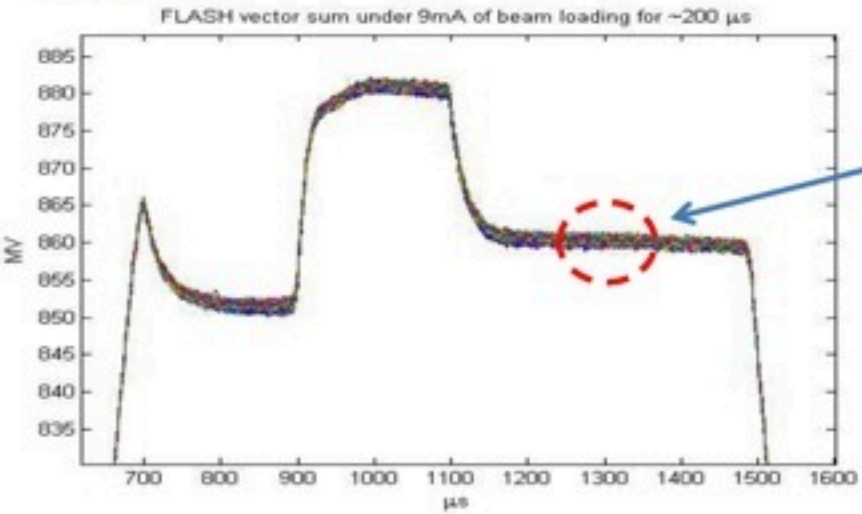
Energy stability over 8hrs (3mA, 800us bunch trains)



(Spec: +/-0.1%)

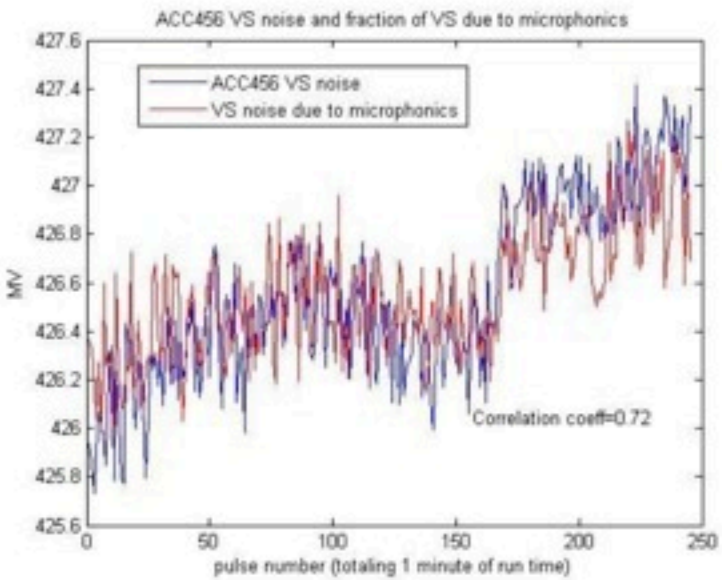


Disturbances: Microphonic detuning



Correlation of microphonic detuning at a point where the beam is off.
Method used: calculate microphonic detuning and fit the data using the equation

$$V_{cav}\big|_{t\to\infty} = \frac{I_g R_L}{1+\left(\Delta\omega/\omega_{12}\right)^2}$$

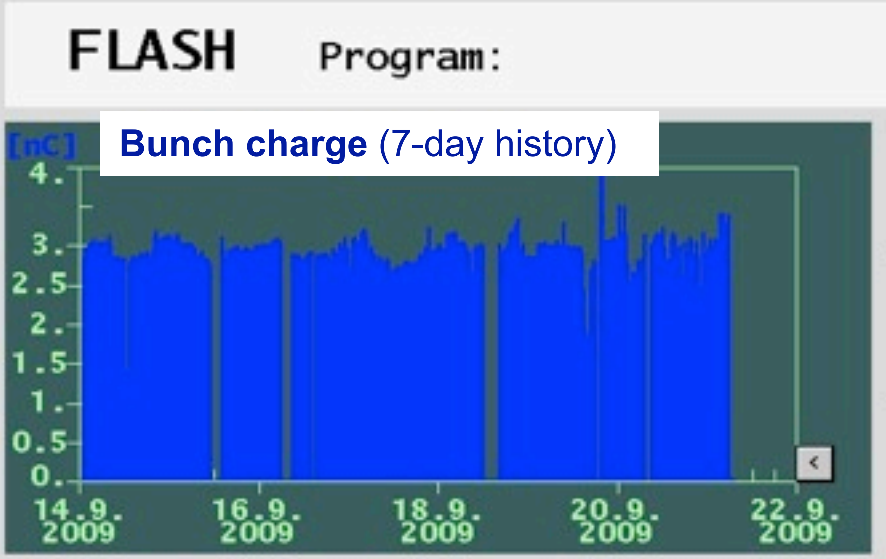


- Over70% of the VS noise can be explained in terms of microphonics.
- There is also a low frequency component. What is it?

Dataset: Sept. 16:03 16:04, 700bunches, 3nC/bunch, 3MHz.

G. Cancelo

Major accomplishments
…but operationally very challenging

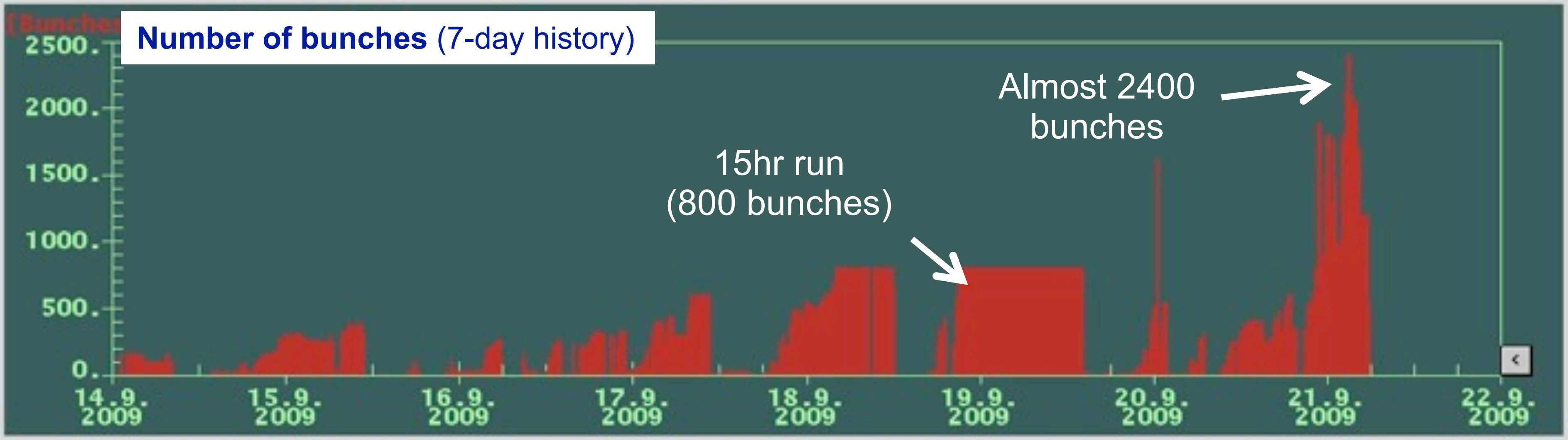


Reaching 3nC long bunch-trains was slower and more painful than in Sept 2008

- 10 days to reach 500 bunches (vs 3 shifts in 2008)
- Commissioning and debugging new systems
- Machine setup & tuning issues: fighting beam loss trips
- **But then… very stable with 800 bunches /1MHz (3mA)**
- During the last 3 days, made rapid progress towards 9mA / 2400 bunches (*but was not stable)*
- *"Could have done more if we had had more time"*

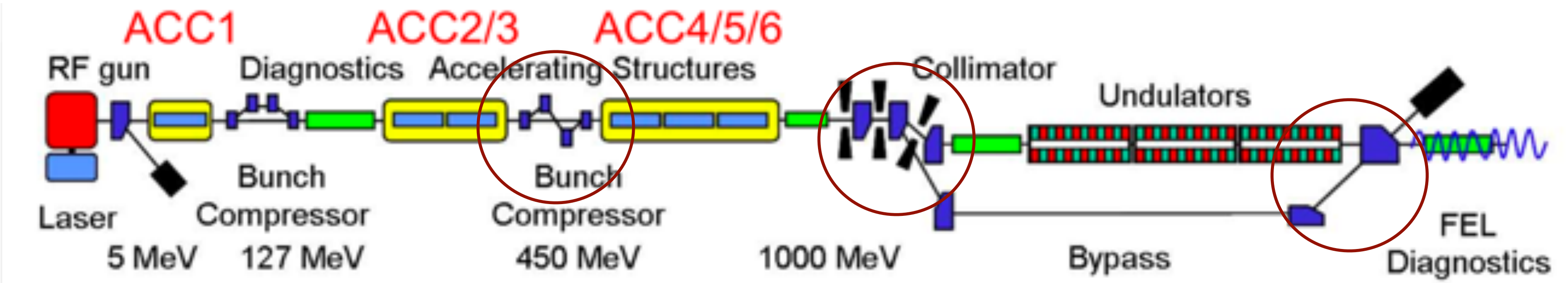
Plan was for 7 days tuning & setup, 7 days of characterization studies with the high beam loading, but

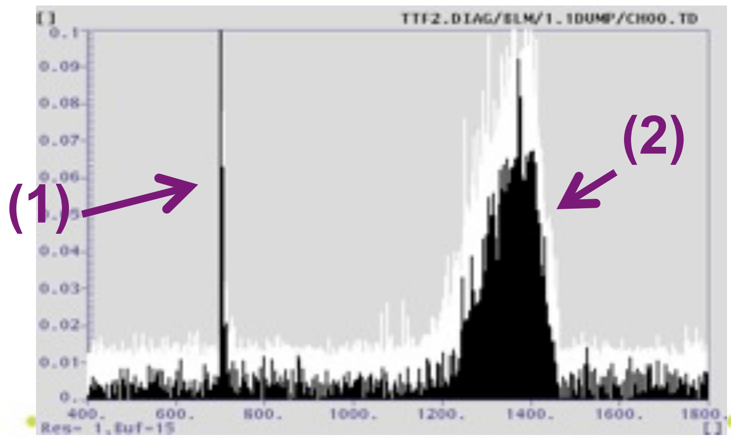
- No high beam loading studies performed (ran out of time)



Main operations issue: 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…





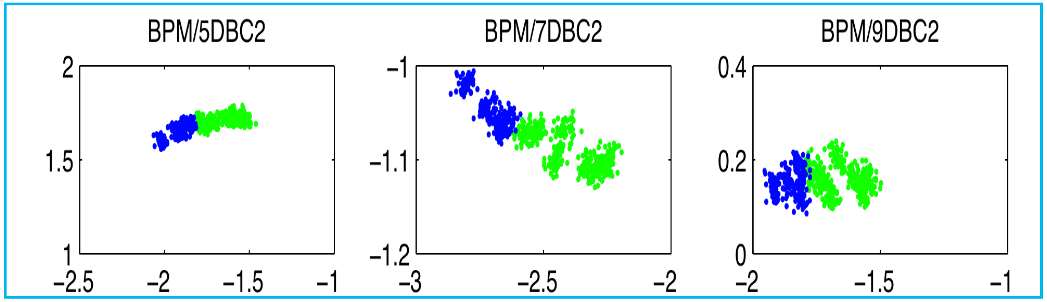
BLMs pick up gun dark current from gun

(1) Beam loss signal from bunch

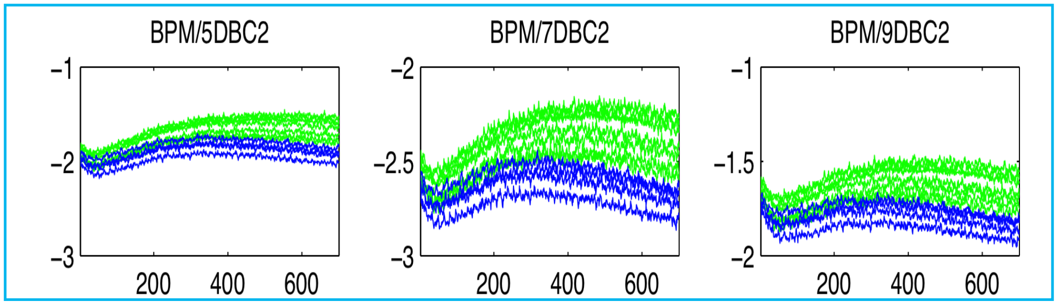
(2) Gun dark current loss signature at the end of the RF flat-top

Beam loss analysis example: orbit changes over bunch train for ‘good’ and ‘bad’ pulses (~7.5mA, 2100)bunches)

X-Y position (mm) of last few bunches in each pulse



Evolution of horizontal position (mm) over bunch train (us)



Blue = pulses terminated by blm integrated alarms
Green = ‘good’ pulses

The correlation between beam position and ‘good’ or ‘bad’ pulses is clear in this case

More analysis and ‘detective work’ is needed to quantify the limiting apertures and correlate with beam losses

Need to compare with other operating points (eg 3mA)

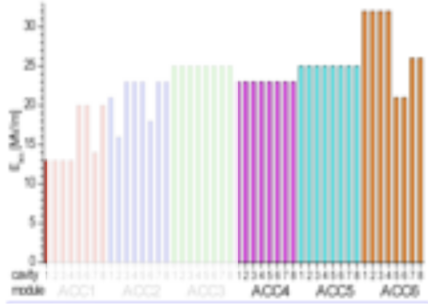
Note that this is one snapshot from one operating point

Characterization of operational limits…
(just starting)

Characterization of maximum usable gradients

'Ideal' maximum operating gradients

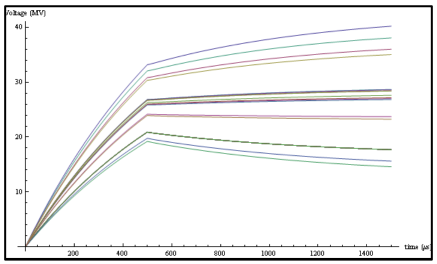
(Minus some margin: 1-2MeV/m?)



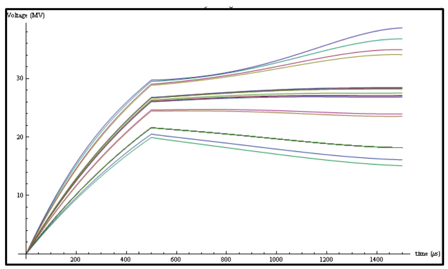
Gradient slopes on individual cavities due to beam loading

Cost penalties from operating with a spread of gradients

Lorentz-force detuning (gradient dependent)



Cavity voltages (constant VS) (9mA beam, all Qext=3e6, w/o LFD



Cavity voltages (constant VS) (9mA beam, all Qext=3e6, w/ LFD

RF distribution setup schemes (Pfwd, Qext)

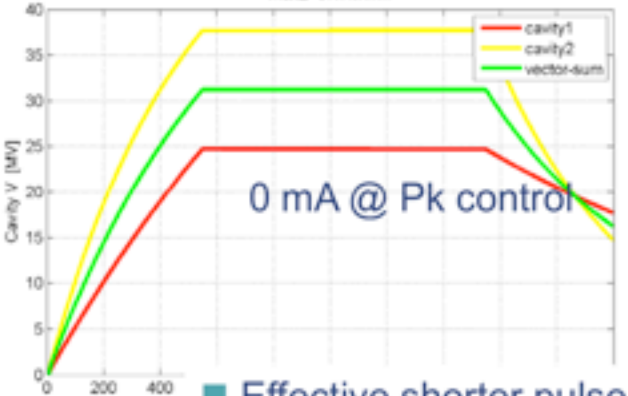
Mitigation schemes to be studied (key component of 9mA program)

Fast compensation using piezo tuners

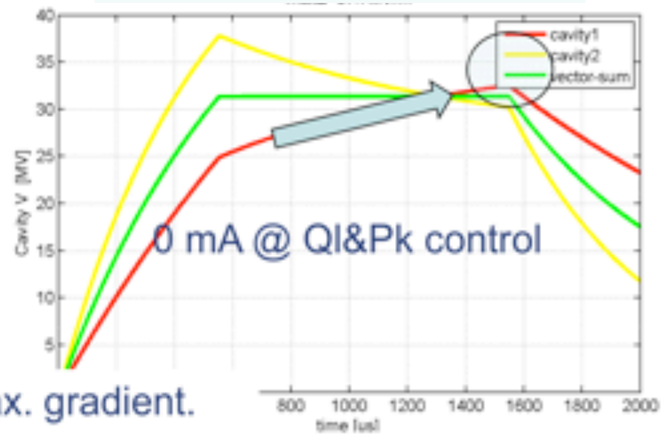
Cavity gradient tilts: RF distribution schemes

Americas

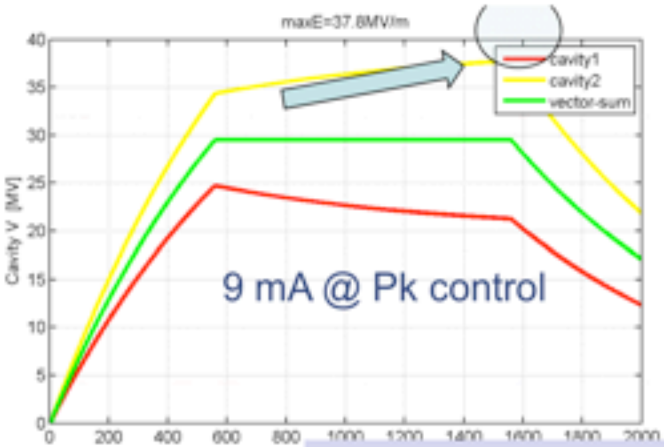
FLASH standard setup

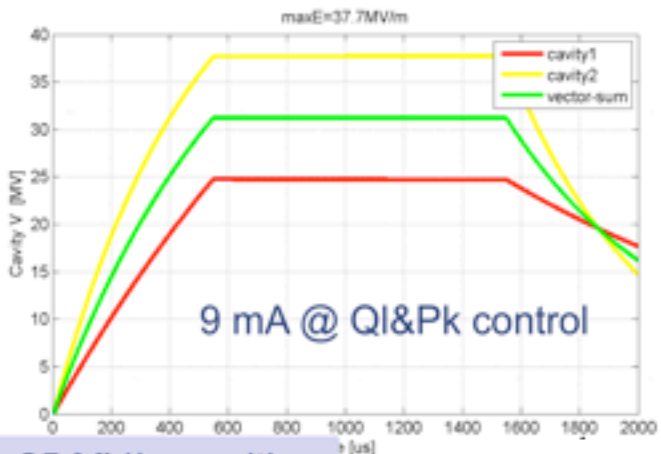


ILC Reference Design



- Effective shorter pulse at max. gradient.
- Same quench limit?





Simulation for 38 MV/m & 25 MV/m cavities

S. Michizono

For each cavity, P_K and Q_{ext} determine the operating gradient and matched beam current

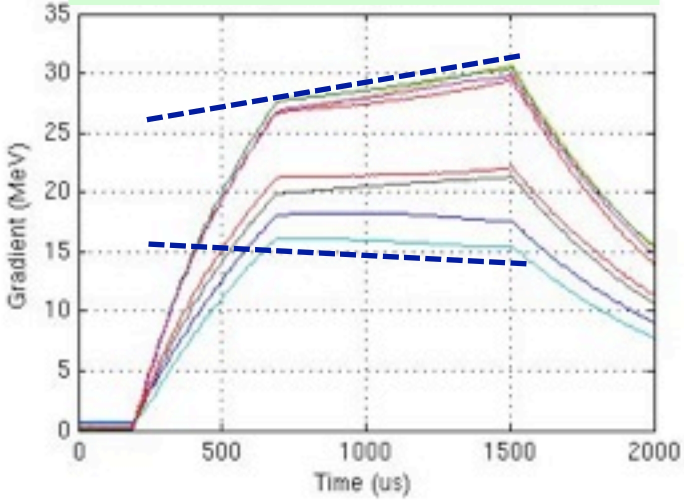
Cavity charges up if actual beam current is less than the matched current

Matched beam current with constant Pk:

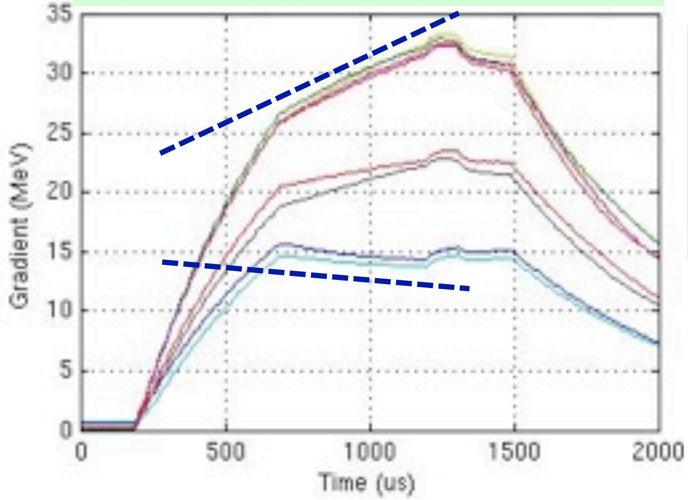
$$I_{matched} = \frac{V_k}{\left(\frac{r}{Q}\right) Q_{ext}}$$

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

ACC6 gradients (3mA, 800 us)



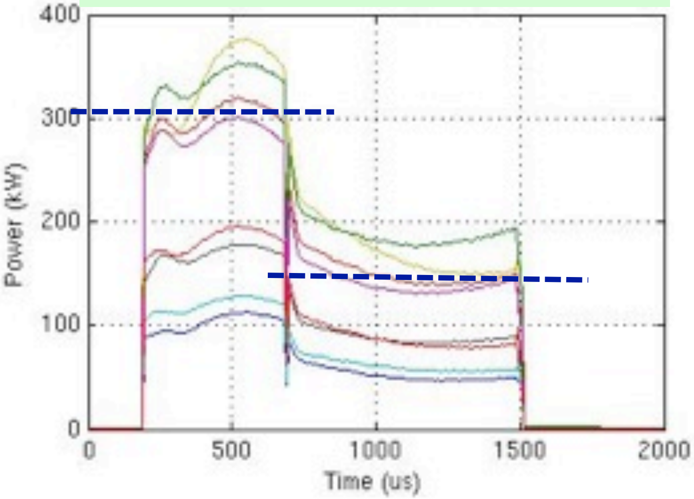
ACC6 gradients (7.5mA, 550 us)



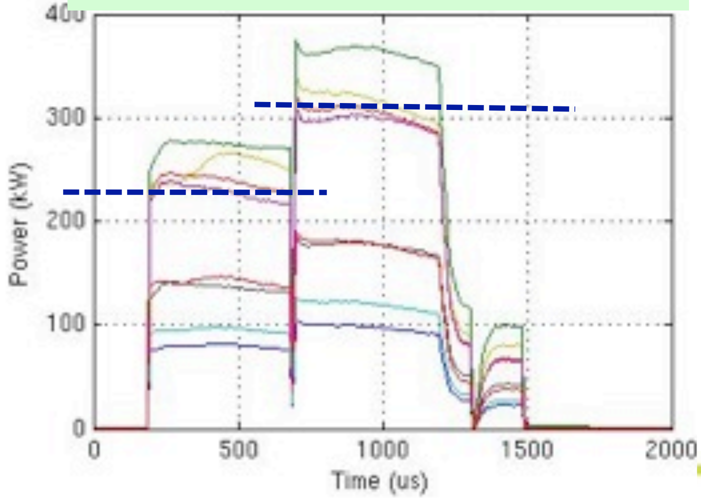
Gradient tilts are a consequence of using a single RF source to power cavities running at different gradients

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

Preliminary studies of alternate schemes for setting cavity Q_L and P_K

Example 1: FLASH 9mA test at DESY

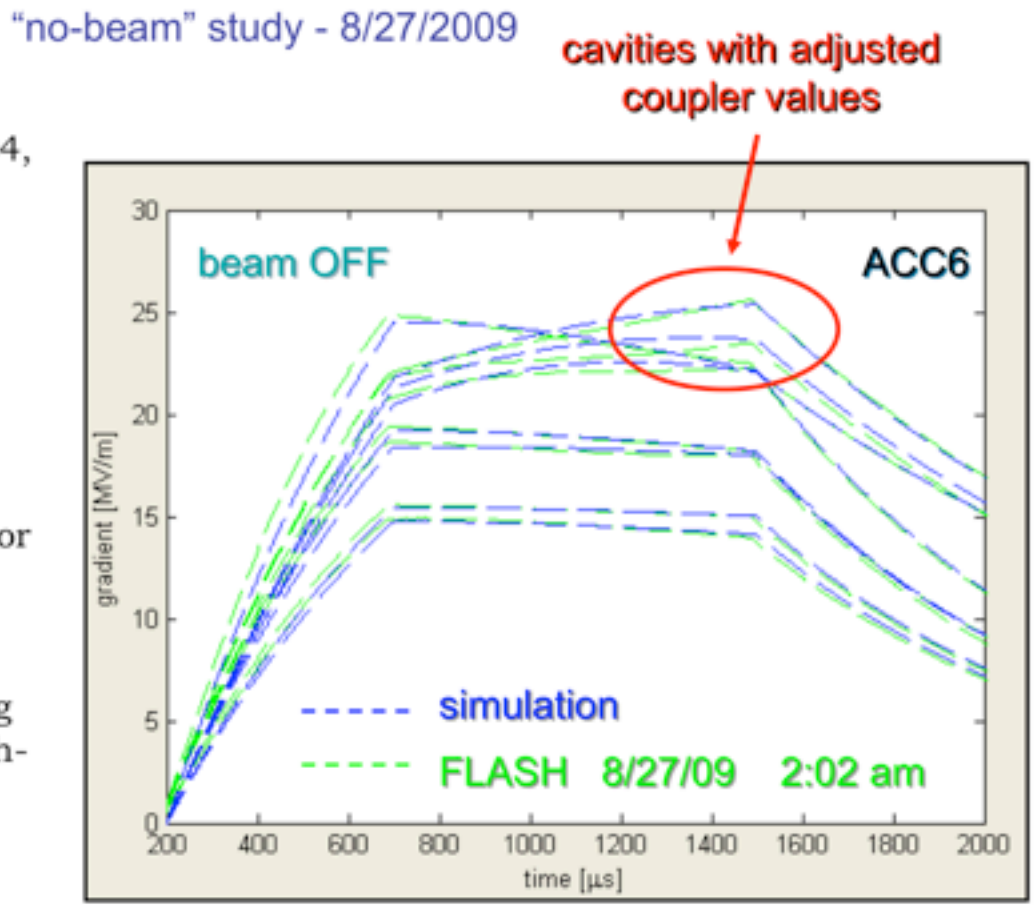
Simulator mimics power distribution & coupling for ACC4, 5 and 6

Verification of simulated cavity gradients vs. experimental data without beam

Using simulator, predict behavior with 9 mA beam current

Using simulator, propose tuning scheme to avoid quench of "high-gradient" cavities

Implement scheme and verify cavity tilts



tilt up without beam → flat with beam [21]

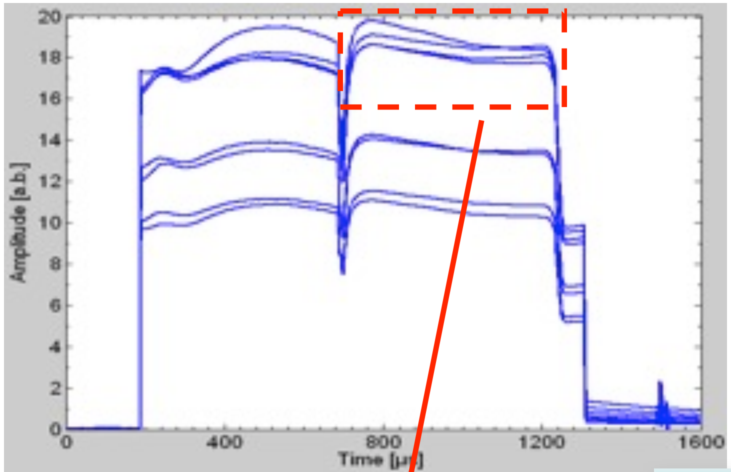
J. Branlard

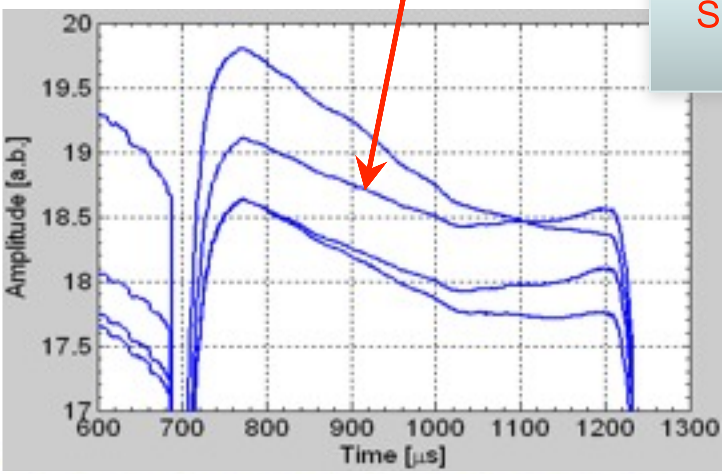
Piezo tuner compensation of Lorentz-force detuning (RF power overhead study)

Americas

FLASH Free-Electron Laser in Hamburg

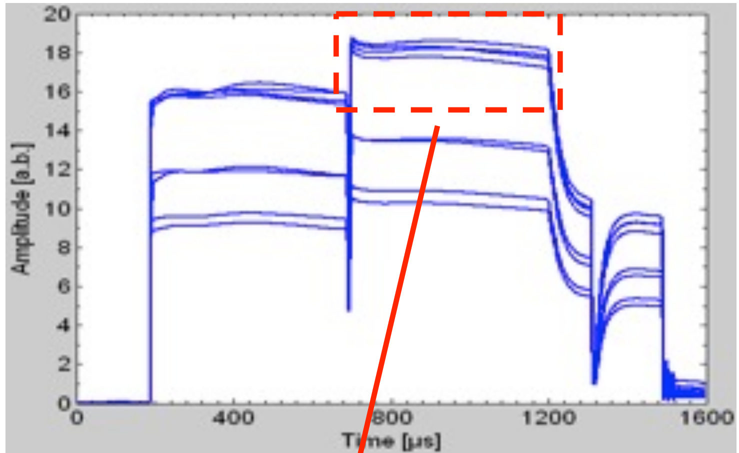
Cavities in ACC6 with piezo off
3MHz/3nC beam with 1600 bunches

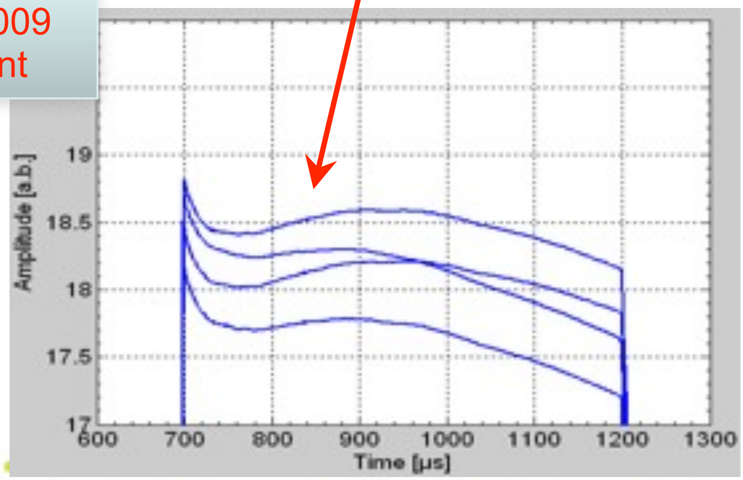




September 2009 Measurement

Cavities in ACC6 with Piezo on
3MHz/3nC beam with 1500 bunches





DAQ environment

- The FLASH 9mA program has been a primary impetus for enhancing the DAQ Data Analysis environment for 9mA studies
  - Tools developed for improved data analysis are now used by others
  - Many data analysis questions have led to changes/enhancements in the DAQ implementation and use

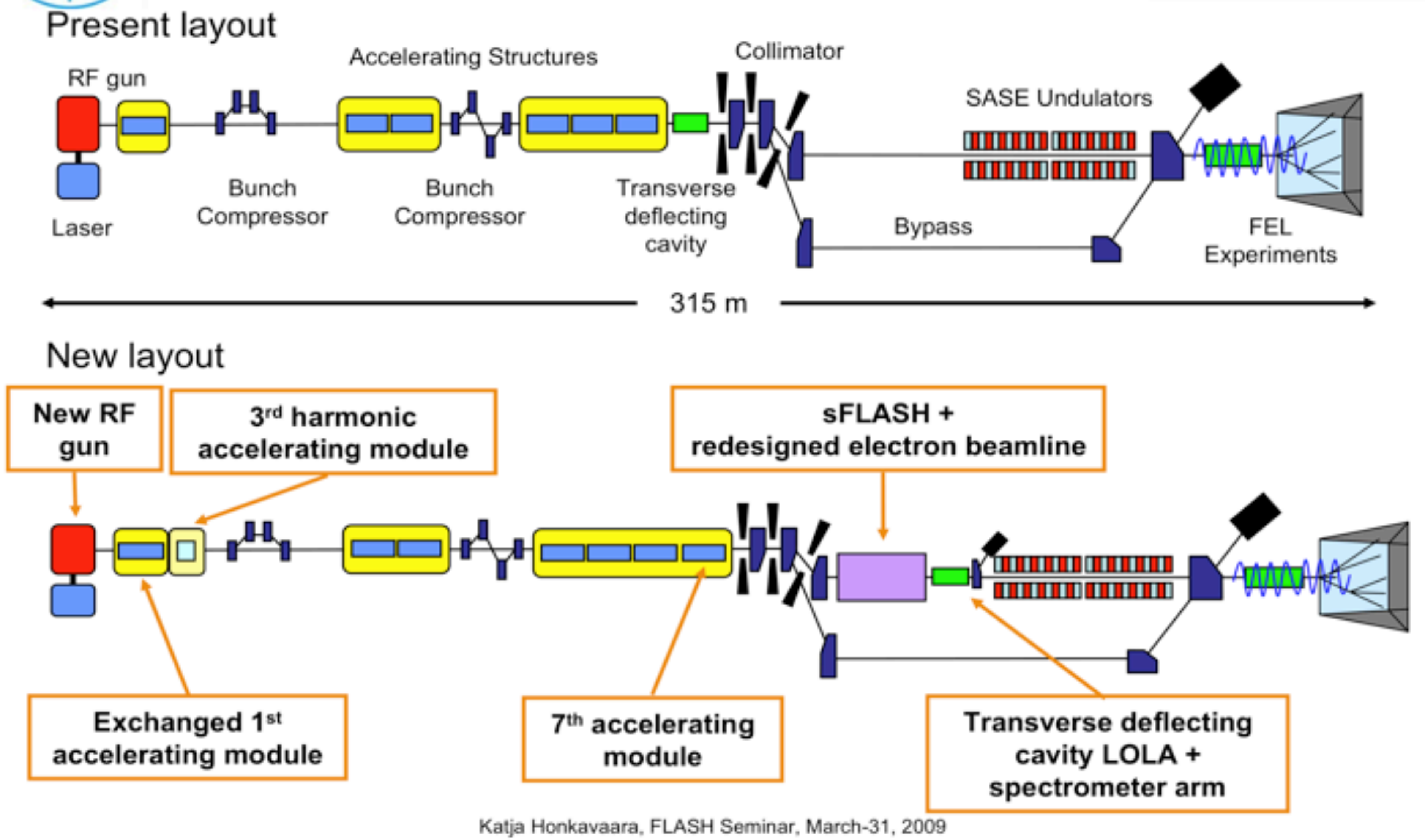
- Argonne currently has the responsibility for …
  - The Matlab interface to the DAQ archives (originally supported by FNAL)
  - Enhancing the channel database to better track and document the channel names and descriptions being archived in the DAQ
    - Used by system engineers to make sure all relevant data is included
    - Used by staff doing data analysis to understand what data is available
  - Development of a “DAQ Data Browser”, intended to facilitate the analysis of the most common use cases

- These contributions benefit ILC 9mA studies, FLASH, and XFEL

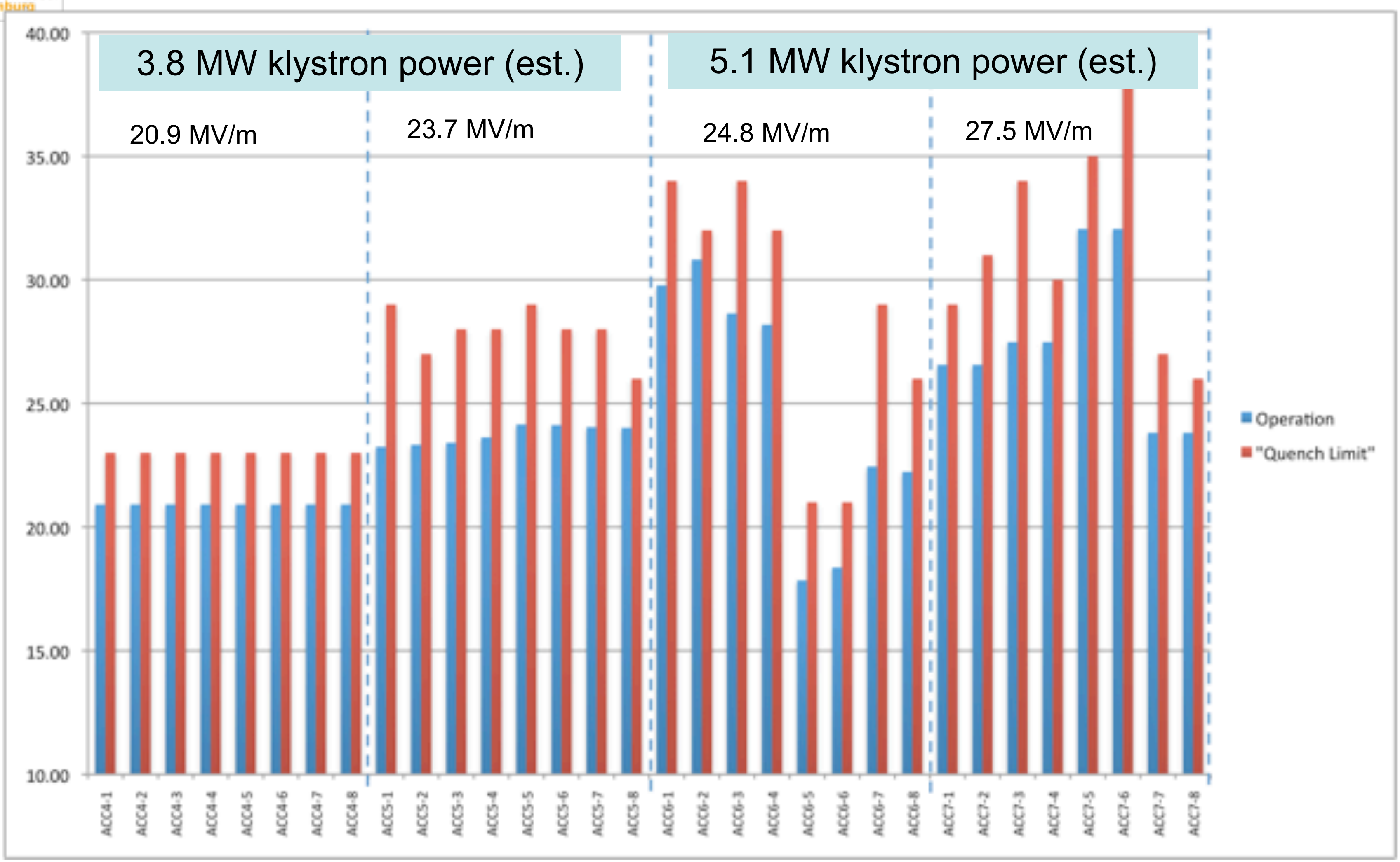
N. Arnold

Can the 9mA program be extrapolated to ILC gradients?

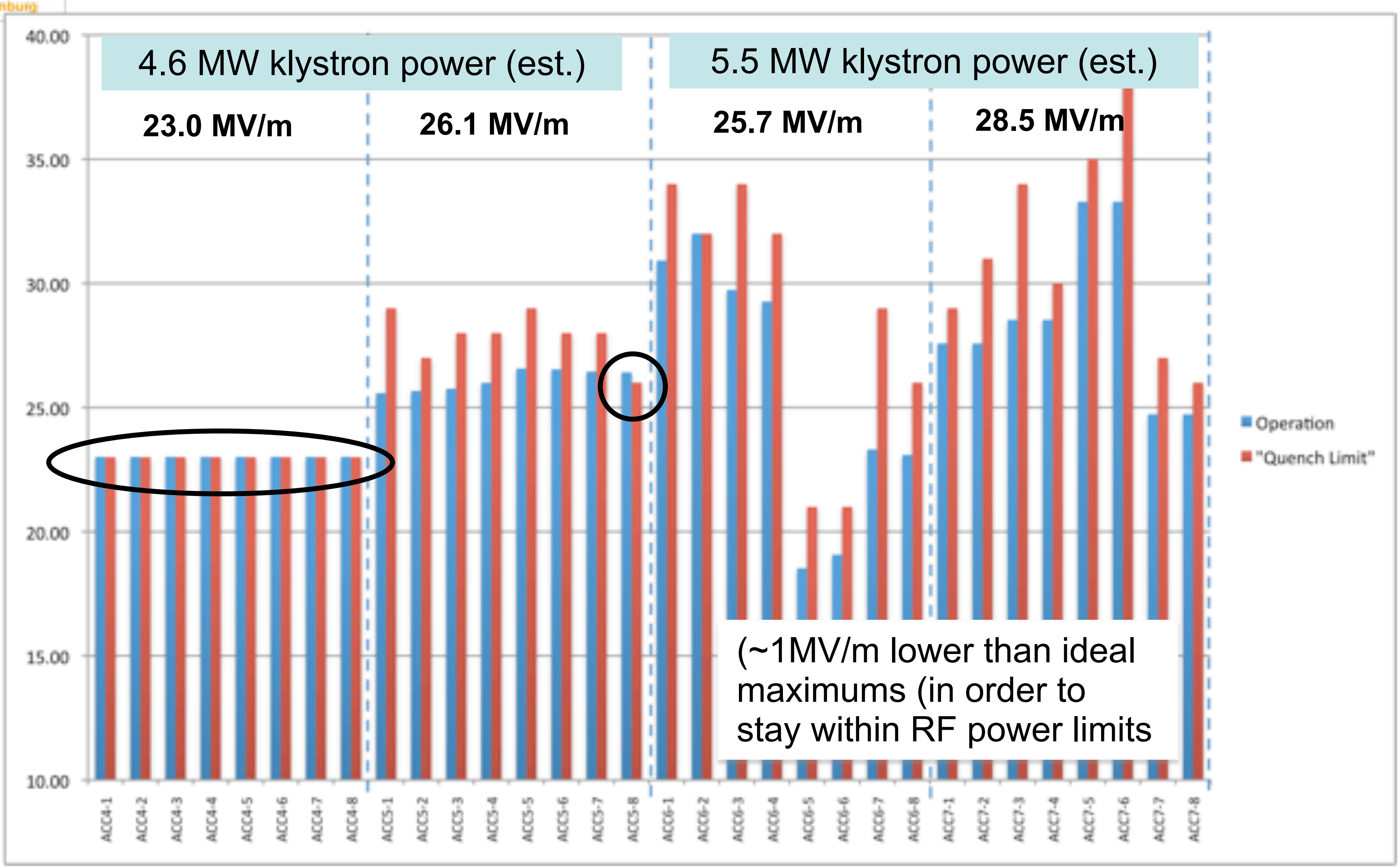
FLASH Upgrade 2009/10



Nominal operating gradients for ACC4-6



Theoretical maximum gradients
(2010 configuration, no operating margins)

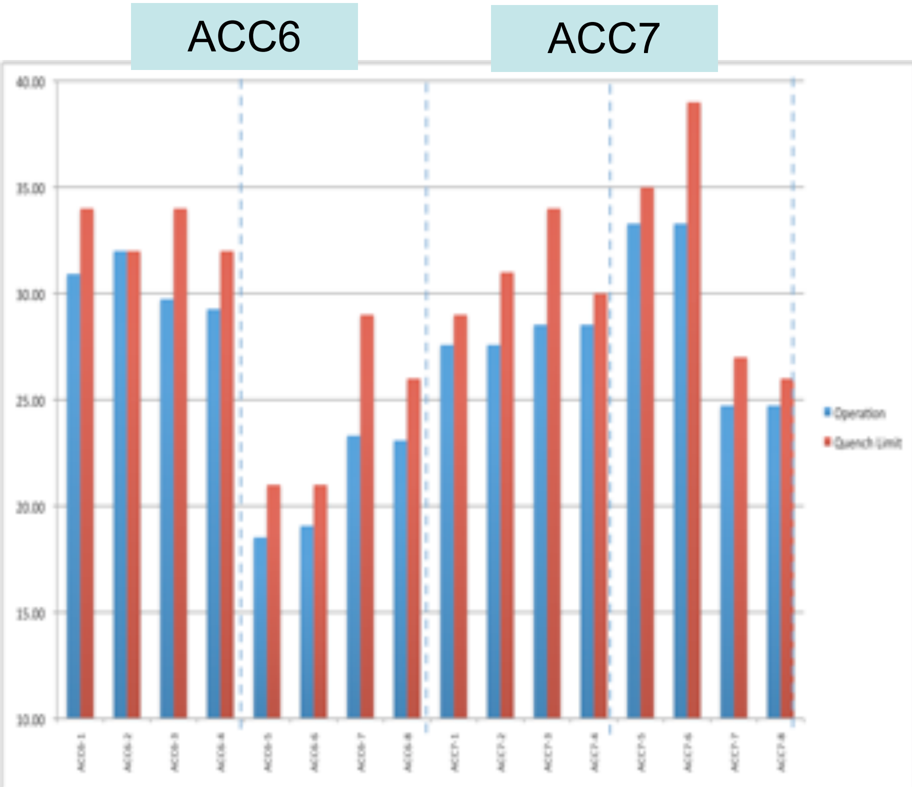


Comparison of gradient-related operational issues (2010)

	RDR	ACC6 / ACC7 (Pk only)	ACC6 / ACC7 (Pk and Qext)
Nominal maximum operating gradient over all cavities in RF unit	31.5MV/m	25.7 / 28.5	28.6 / 31.4
Spread in nominal maximum operating gradients	31.5MV/m +/-0	18-32 / 25-33	21-34 / 26-39
Number of cavities operating at 31.5MV/m or above	26 of 26 (all at exactly 31.5)	4	7
Cavity quench limits	All: >33MV/m	21-34 / 26-39	21-34 / 26-39
LFD compensation with piezos	All cavities	All cavities	All cavities
Operate cavities close to quench?	Yes	Yes	Yes

Operating margins not included (key study topic)

Extrapolating FLASH to ILC gradients



ACC7 cavity quench limits and gradient spread are approaching ILC nominal values. Allows realistic characterization studies of:

- **Gradient overhead and RF power overhead requirements and trade-study**
- **RF distribution setup schemes with cavity powers close to ILC spec and realistic spread in operating gradients**
- **Lorentz-force detuning + piezo compensation near ILC gradients**
- **Vector sum control of cavity fields**

Next…

Remaining 9mA study topics

Demonstrating long bunch-train operation with heavy beam loading was a major milestone… but marks only the start of 9mA studies

- LLRF regulation with long bunch trains and heavy beam loading
- Gradient and rf power overhead studies (ACC67)
  - **Optimization of Pk/Qext, prove concept**
  - **Piezo tuner compensation of LFD, microphonics**
  - **Trade-studies of cavity field regulation vs overhead**
- HOM coupler studies with different bunch length
- New 9mA study topics in support of ILC R&D and SB2009
  - **ILC Bunch Compressor stability studies**
  - **LLRF studies related to Klystron Cluster Scheme**
  - **Cavity 'Gradient flatness' studies (beam dynamics issue)**

Americas

FLASH
Free-Electron Laser in Hamburg

Revisiting ILC operations gradient: Input from FLASH 9mA program

SCRF: Status and Proposal

- In SB2009, ILC operational field gradient left unchanged
  - **CF&S study enables to stay at 31 km in ML tunnel length**
- R&D Goal for SCRF cavity gradient
  - **Keep: 35 MV/m (at Q0 = 8E9) with the production yield of 90 %,**
  - **Allow: Spread of cavity gradient effective to be taken into account**
    - to seek for the best cost effective cavity production and use,
- System Design to establish ILC operational gradient
  - **Necessary adequate balance/redundancy between the 'R&D gradient-milestone' and the 'ILC operational gradient**
    - G_{Cavity} > $G_{Cryomodule}$ > $G_{ILC\text{-}operation}$
    - <35 MV/m> : <33 MV/m> : <31.5 MV/m>
- Industrialization to be prepared
  - **Lab's collaboration and effort with regional varieties/features,**
  - **Industrialization model to be discussed and studied**
    - A satellite meeting for the 'ILC cavity Industrialization at IPAC, May 23, 2010.

A, Yamamoto, 10-05-13 ILC-PAC: SCRF Report 54

9mA studies for overhead characterization using ~ +/-20% gradient spread

9mA "operation at the limits" characterization of gradient and rf power

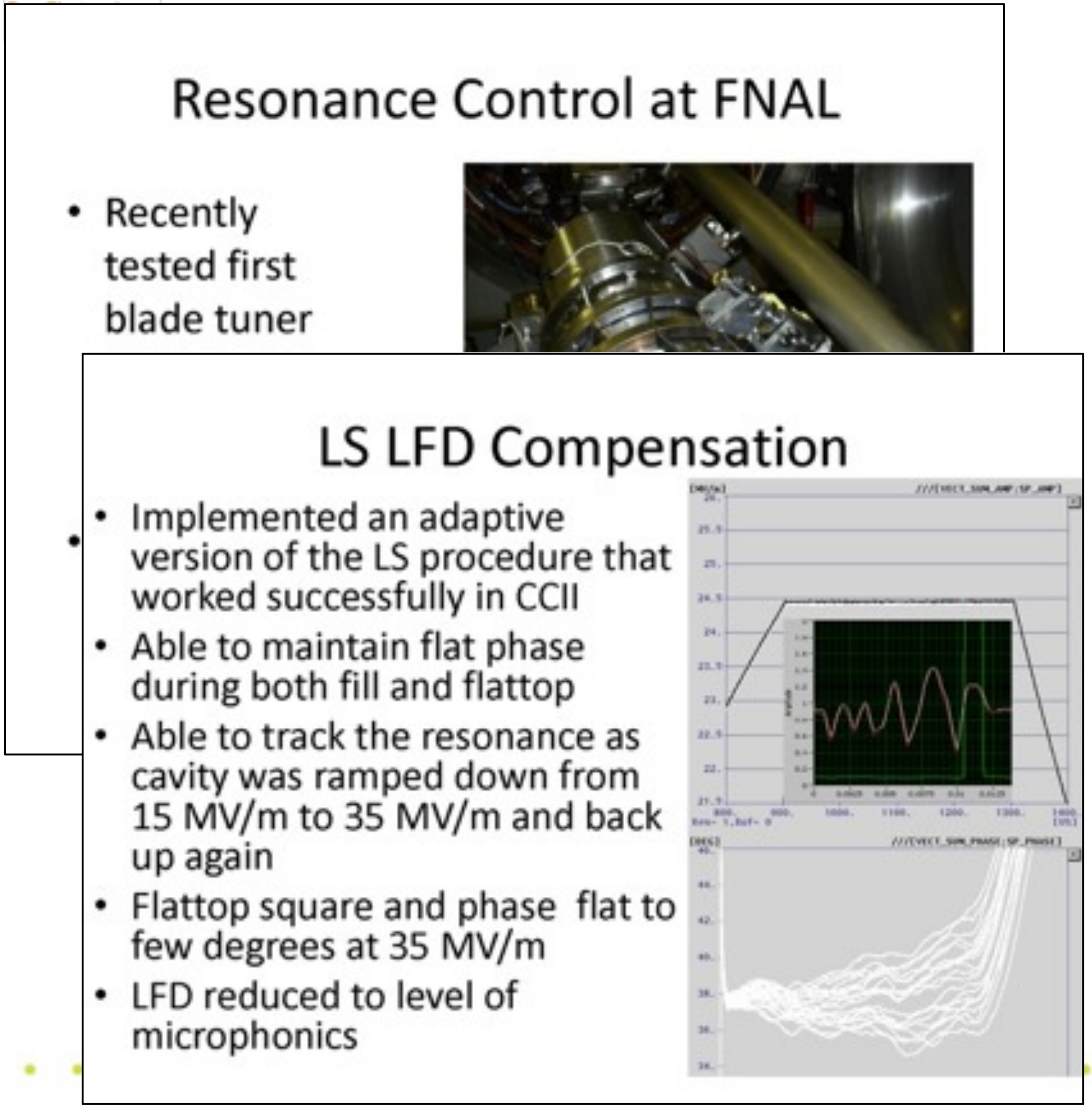
Preparing the next 9mA studies shifts

- Heavy beam loading is critical for answering key questions ...but
  - **Only two accelerator studies periods scheduled before 2012**
  - **(One week of 9mA studies anticipated for January 2011)**

- Must be well prepared to utilize the study time available
  - **2009 data analyzed, modeling done, software tools developed,**
  - **Practical issues understood, eg RF limits, tuning ranges,…**

- More operations experience is needed with long bunch trains
  - **Establish 'golden working points' + machine save/restore**
  - **Systematic procedures and automation for setup and tuning**
  - **Optimization for 3nC bunch operation**
  - **Stability and reproducibility over long flat top with beam loading**
    - LLRF in general, rf gun + laser system.
  - **Exception handling**

Lorentz-force detuning compensation



W. Schappert

- DESY is leading piezo tuner studies in support of 9mA program
- A least-squares procedure developed at Fermilab has yielded encouraging results at HTS (but single cavity, no beam loading)
- Appealing: collaboration between Fermilab and DESY in support of 9mA program

Proposal for ILC bunch compressor studies at FLASH

Americas

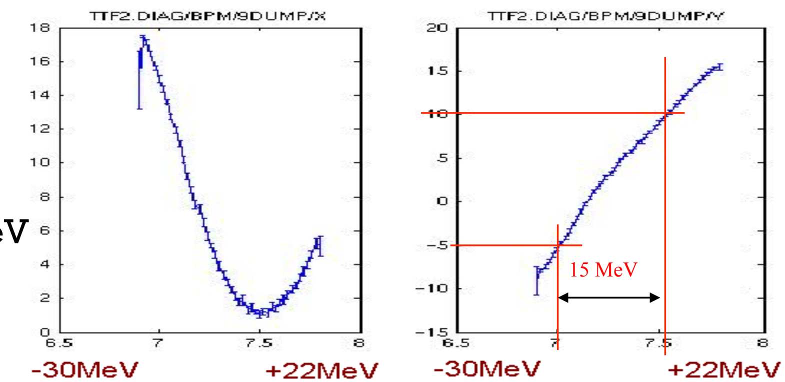
FLASH Free-Electron Laser in Hamburg

- FLASH provide good opportunity to test required stability requirement for the RF amplitude and phase stability: 0.25° and 0.5% rms at 1.3 GHz
- Beam off-crest, close to zero-crossing (new regime for LLRF)

Some estimations of effect:

Typ. result @ 720 MeV:

- Resolution < 0.5 MeV
  jitter: *ΔE/E <0.05%*,
- linear response 15-20 MeV
  spread *ΔE/E ~ 2%*,
  (optics accept ~1-2% ?)



Single ACC67 RF unit:

- Input Energy ~ 900 MeV
- ACC67 Voltage ~430 MeV
- Bunch length = 0.6 mm (1 deg)
- Phase jitter = 0.25 deg

→ Jitter: ΔE~1.8 *MeV* → *ΔE/E ~0.2%* (x4)
→ spread : ΔE~*7MeV* →*ΔE/E ~1%* *(x2 ?)*

Two RF systems ACC45 and ACC67

- Input Energy ~ 540 MeV
- ACC Voltage ~ 370 MeV
- Bunch length = 1 mm ← independent
- Phase jitter = 0.25 deg

→ Jitter: ΔE~3*MeV*→ *E/E ~0.6%* (x20)
→ Spread : ΔE~3*MeV*→*ΔE/E ~0.3 %* *(:6)*

Effect of phase jitter is measurable, but Two RF systems much better choice

N.Solyak, FNAL — FLASH Long bunch-train workshop, DESY, Feb22-24, 2010 — 12

N. Solyak

Wrap up

Program achievements to date

- **Long-pulse high beam loading (9mA) demonstration**
  - Reliable steady-state operation with 800us pulses and 3mA
  - Significant progress towards full spec: 9mA/600us, 6mA/800us
  - Energy stability with fully beam loading: <0.5% p-p
- Characterize operational limits
  - HOM studies with high beam power
  - **The 'real' studies to characterize gradient overhead and RF power overhead require additional beam time**
- Operation close to limits
  - Important operations experience from Sept 2009 studies
  - Machine tuning and setup is very challenging
  - Valuable experience can be gained from long-pulse FEL studies for photon users – we must participate

Data analysis - critical

We need to capitalize on operations data from Sept 2009

- Critical information about how the machine behaved – so we can more readily repeat the beam conditions
- Important preliminary information on 9mA specific 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

Issue: limited resources for analyzing >10TB of data from Sept 2009…

ART team: expected activities

- Analysis of Sept 2009 studies data (there's a long list)
- Modeling and preparation for upcoming 9mA studies (Jan 2011)
  - **RF power distribution (Pk/Qext) schemes**
  - **Gradient and RF power overhead characterization**
  - **'Gradient flatness' issue**
  - **Piezo tuner studies for LFD compensation**
  - **LLRF control & operations issues for Klystron Cluster HLRF scheme**
- DAQ enhancements and data analysis tools
- Participate in FEL long bunch-train studies in July and Nov '10
- Post January studies: analyze data, prepare for 9mA studies in late 2011
- Appealing would be strengthening collaborations with DESY, eg on LLRF operations and R&D

Summary

- The 9mA program at FLASH will provide critical input for the ILC/TDP and provides invaluable operations experience for NML and STF
- Long bunch-train operation with heavy beam loading has been demonstrated: now must begin the 9mA characterization studies
- Even with the strong support from DESY Management, there are few studies opportunities before 2012 - we must capitalize
- FLASH will remain the only facility capable of supporting the 9mA studies until beyond 2012 ...until NML and STF are commissioned
- Upcoming: second workshop on linac operations with long bunch-trains (Oct 4-7 at DESY)

Thank you