Cryomodule String Test: TTF/FLASH 9mA Experiment

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Nick Walker (DESY)

GDE PAC Review May 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)

The (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)
  - Michael Davidsaver - DAQ applications programming
  - Jinhao Ruan - laser setup
- **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)
- **SACLAY**
  - Abdallah Hamdi - TPS installation / commissioning

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

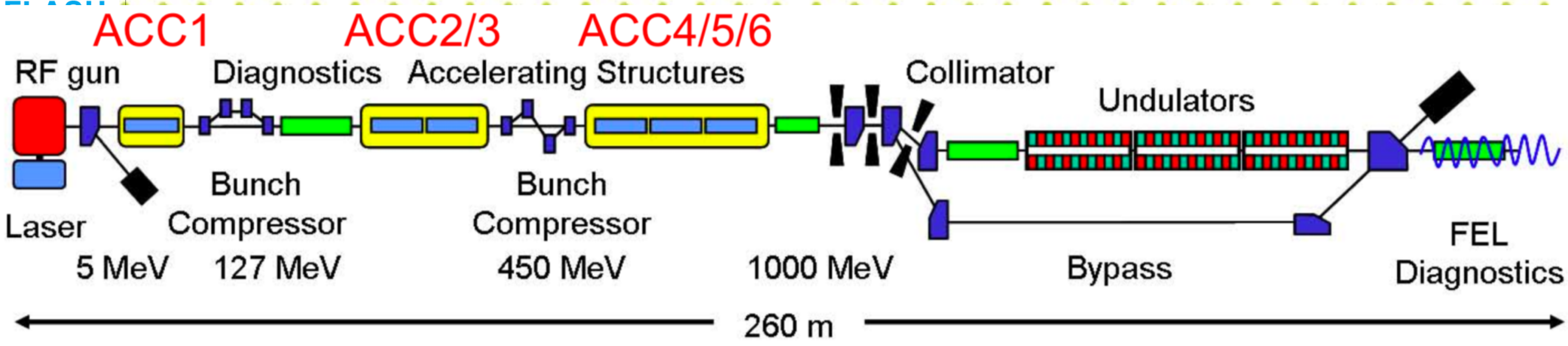
RF/LLRF collaborators:
DESY, KEK, FNAL, SLAC

Initiated by the ILC/GDE, co-led by DESY and GDE

A DESY programme with international participation

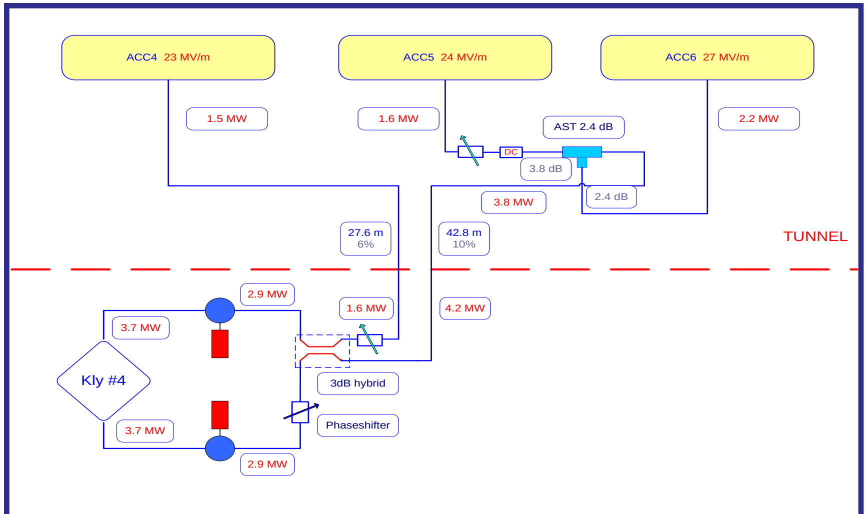
TTF/FLASH facility overview

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

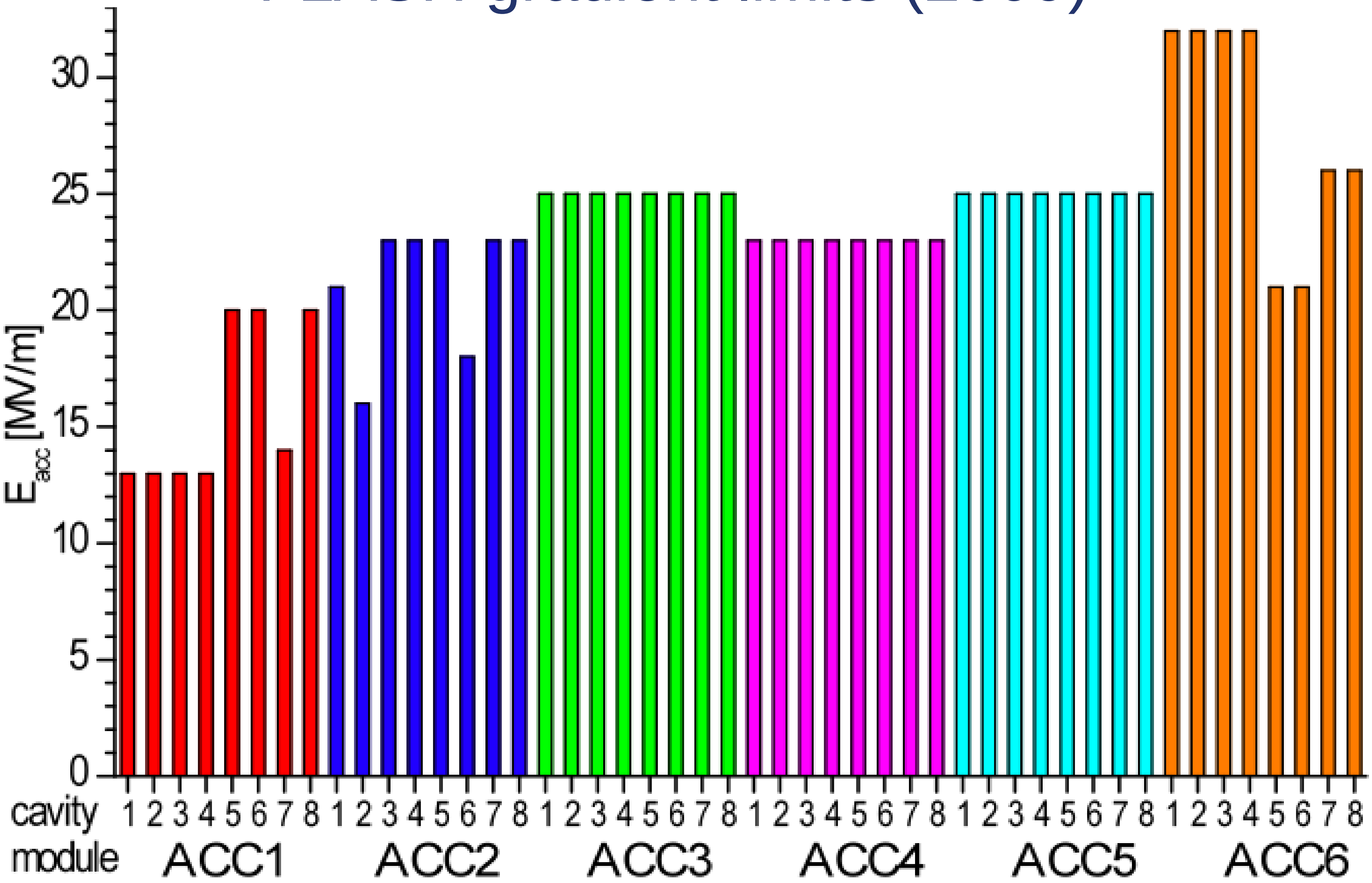


ACC456 HLRF layout

Synergies

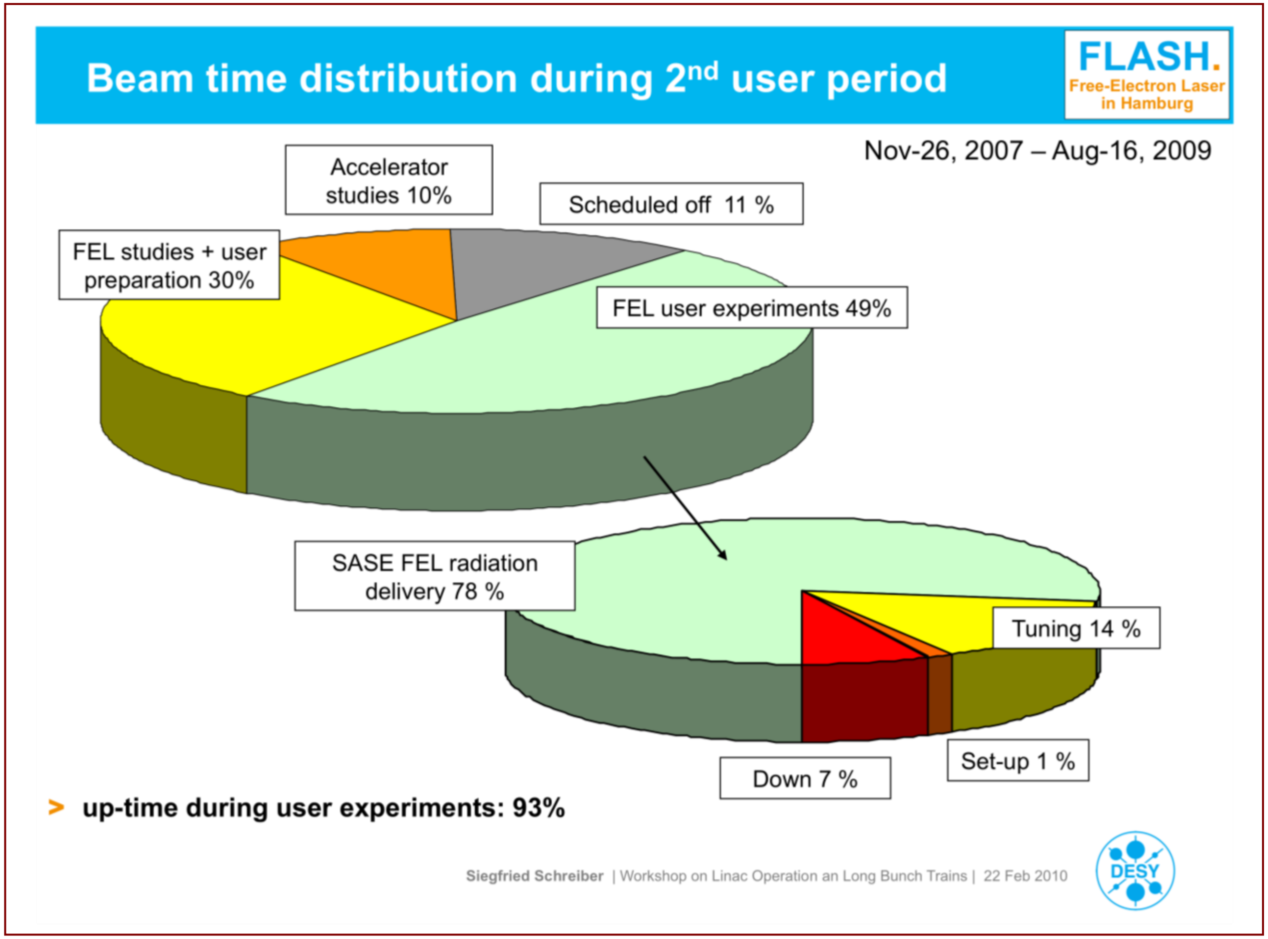
- FLASH FEL operations with long bunch trains
- XFEL design/development, future operations

FLASH gradient limits (2009)



FLASH is an operating user facility

Only 10% of the beam time is available for accelerator studies



There is stong competition for the limited accelerator study time

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

High power long bunch-train operation

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

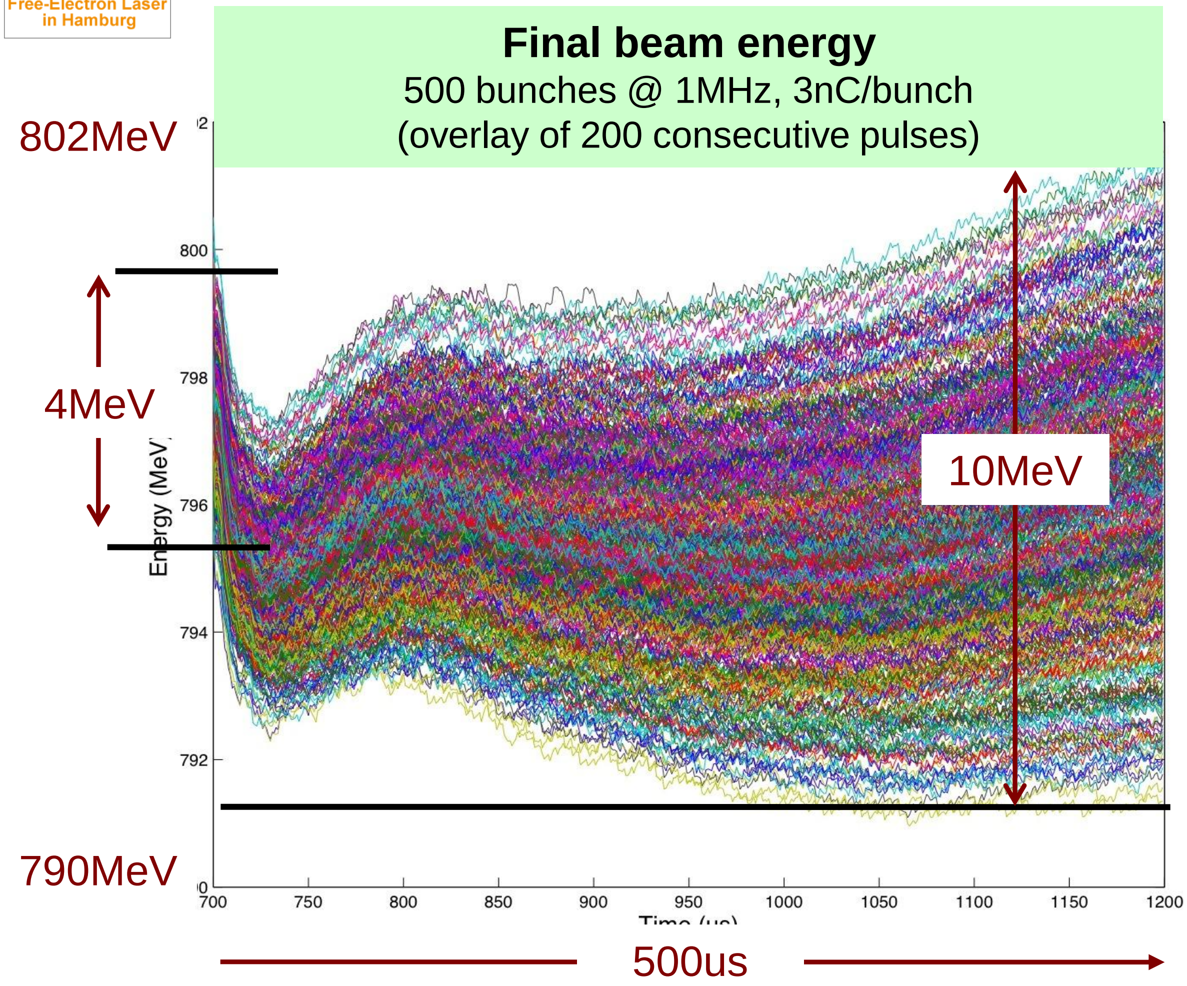
High average beam power
Exception handling…

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

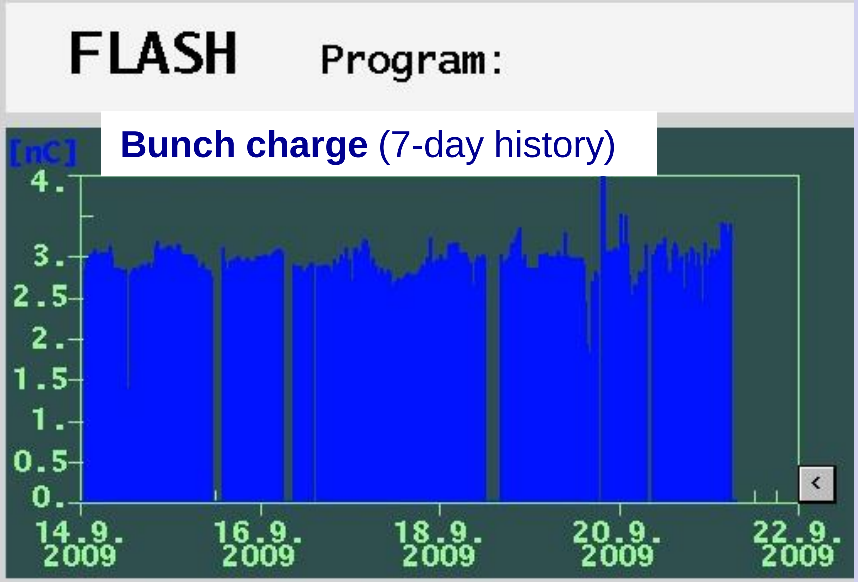
High power long bunch-train operation
(Accomplished during 2 weeks of studies in Sept 2009)

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)

Major accomplishments
…but operationally very challenging

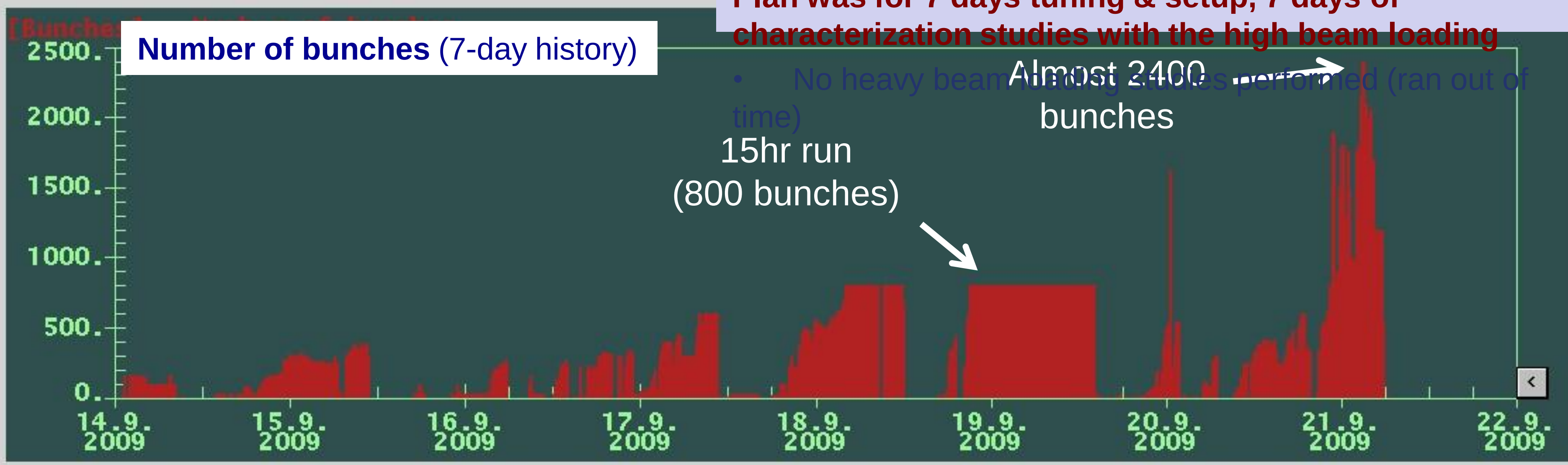


Reaching 3nC long bunch-trains was slower and more painful than in Sept 2008

- 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"*

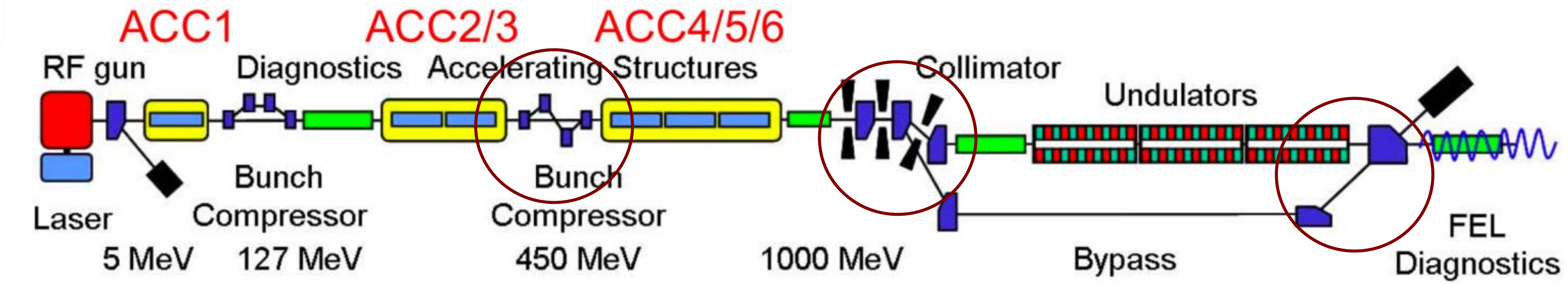
Plan was for 7 days tuning & setup, 7 days of characterization studies with the high beam loading

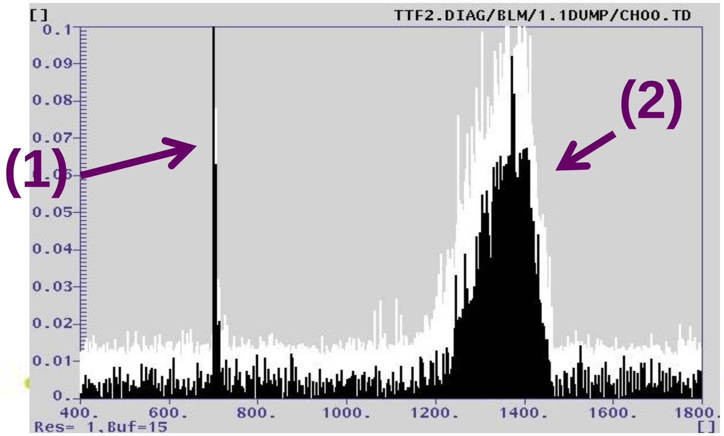
- No heavy beam loading studies performed (ran out of time)



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…





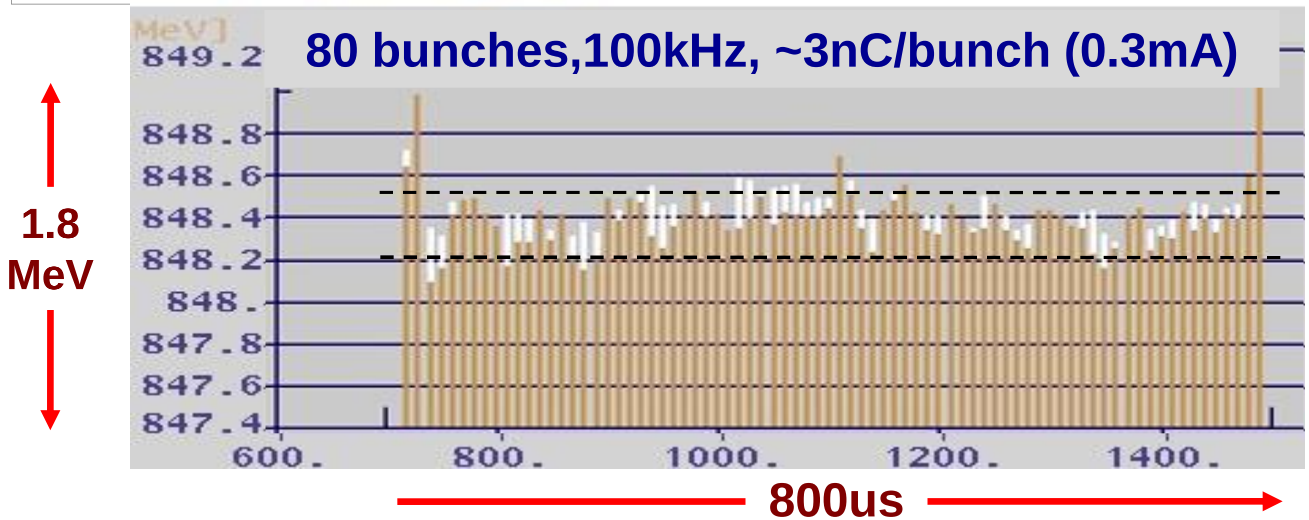
BLMs pick up gun dark current from gun

(1) Beam loss signal from bunch

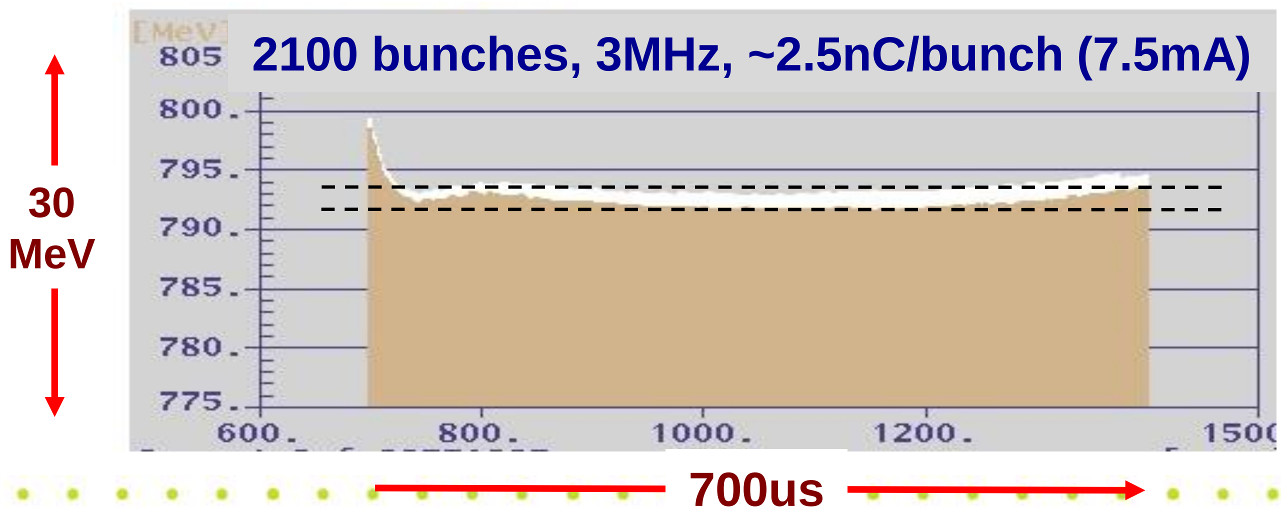
(2) Gun dark current loss signature at the end of the RF flat-top

Characterization of operational limits… (just starting)

Energy deviation along bunch train (examples)



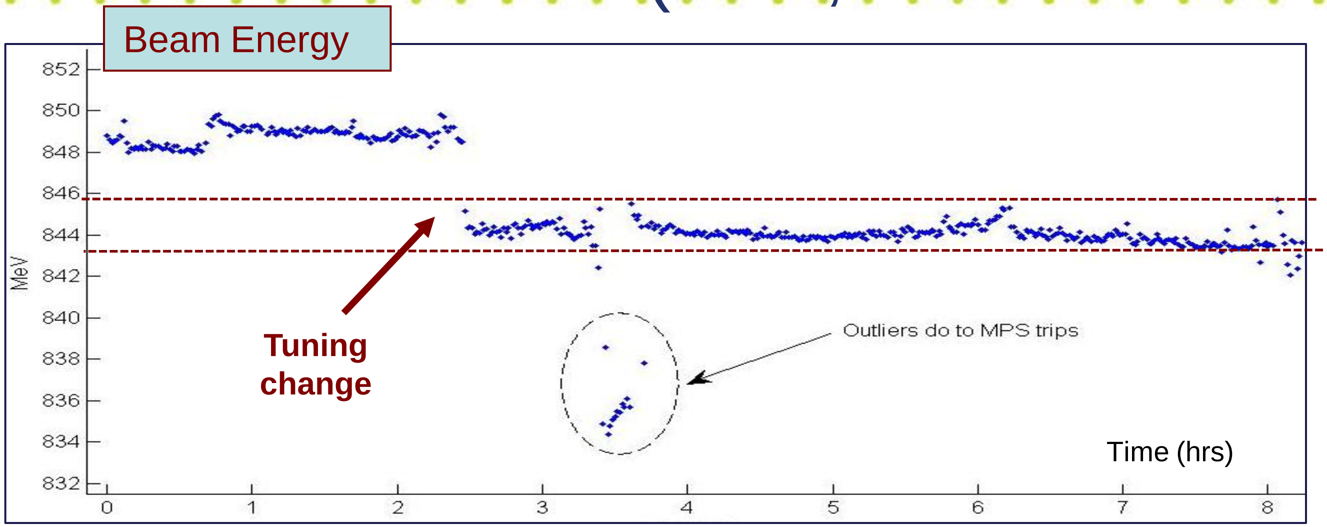
Along pulse: 0.035% p-p



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

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

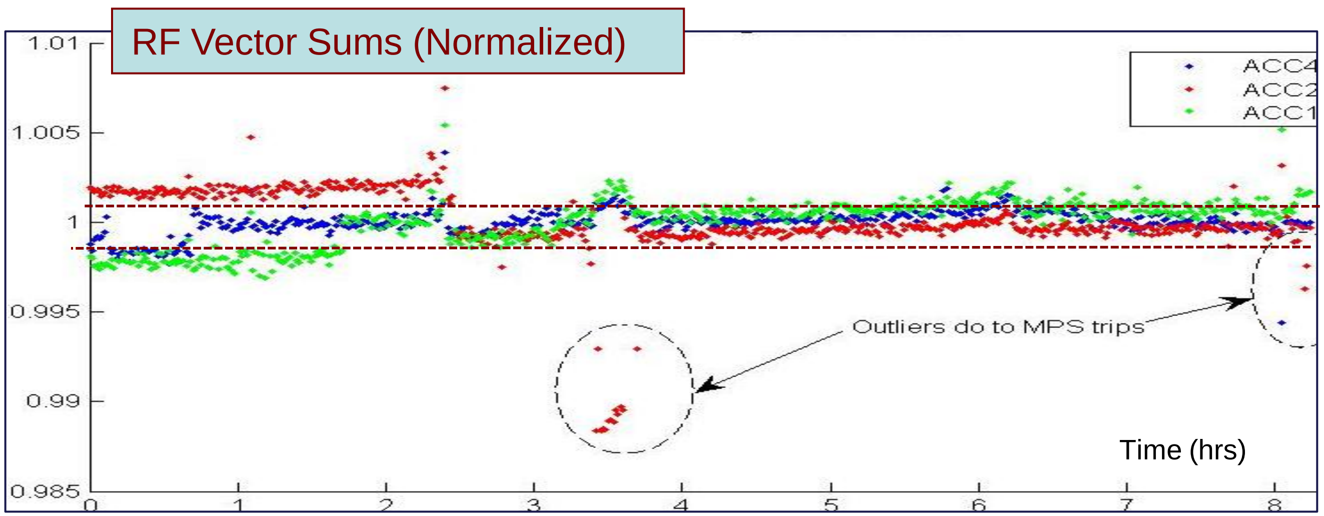
844 MeV



2MeV (0.25%)

(Spec: +/-0.1%)

Nominal

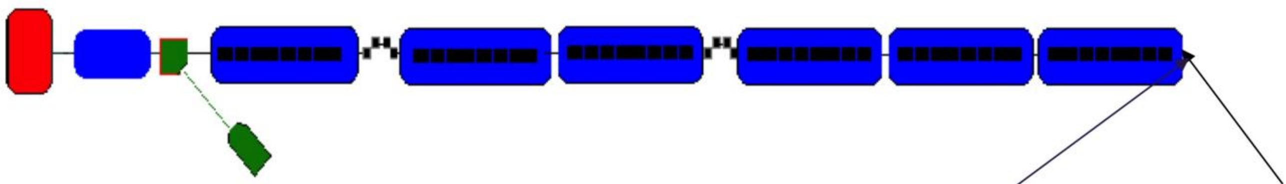


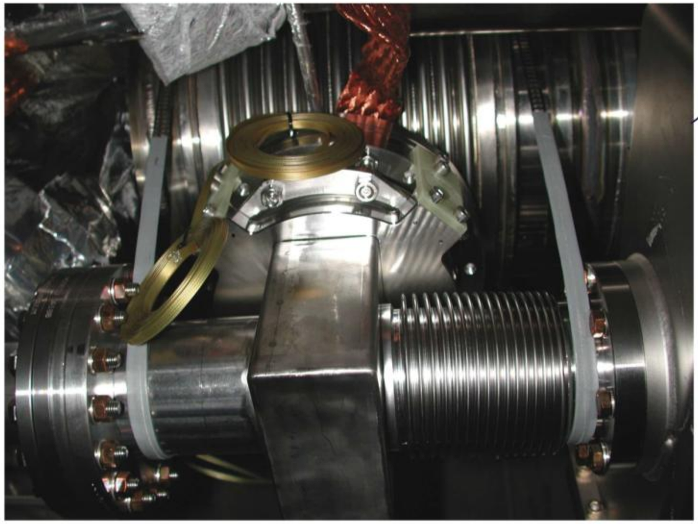
0.2%

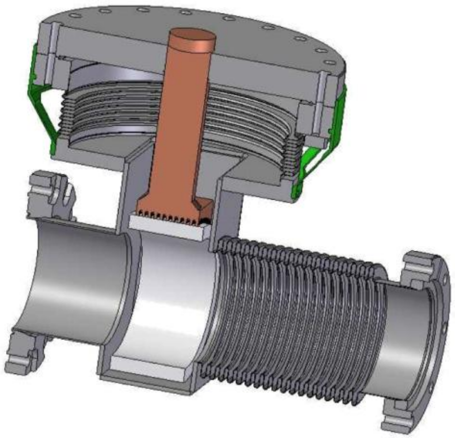
8 hrs

HOM absorber test setup at FLASH

2 Beam Tests in September 2008 and 2009

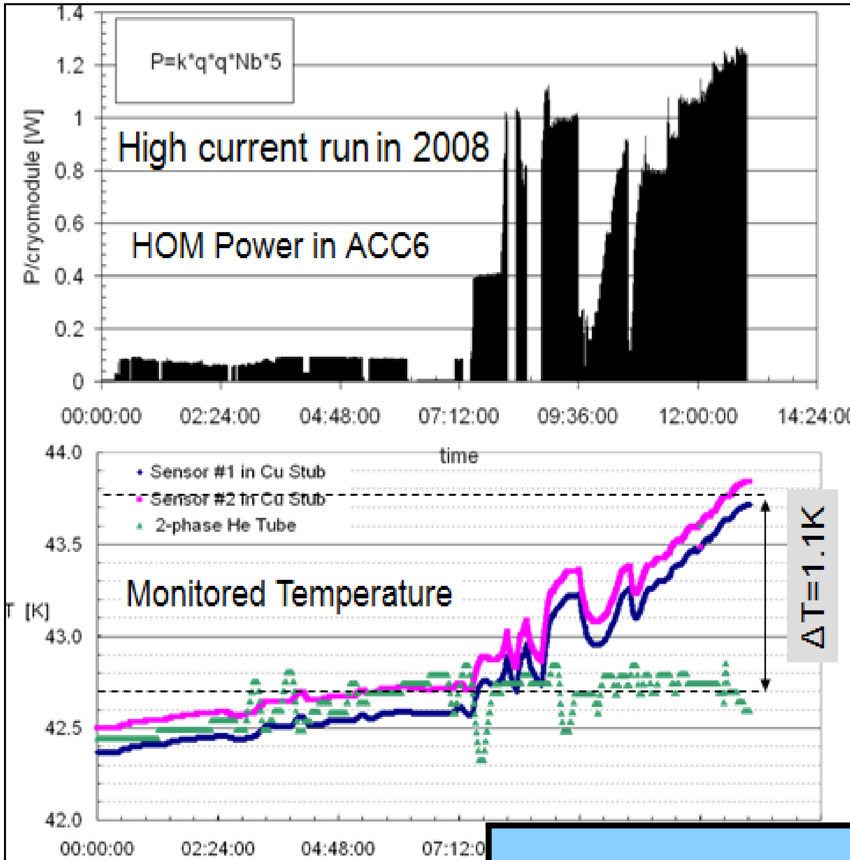


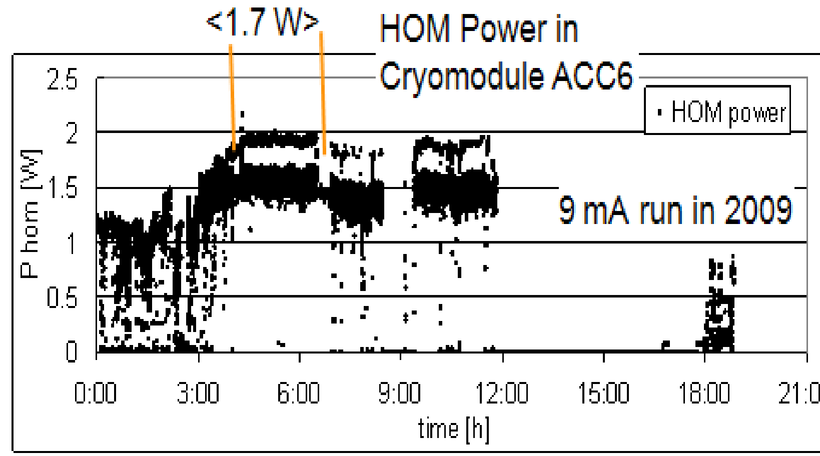


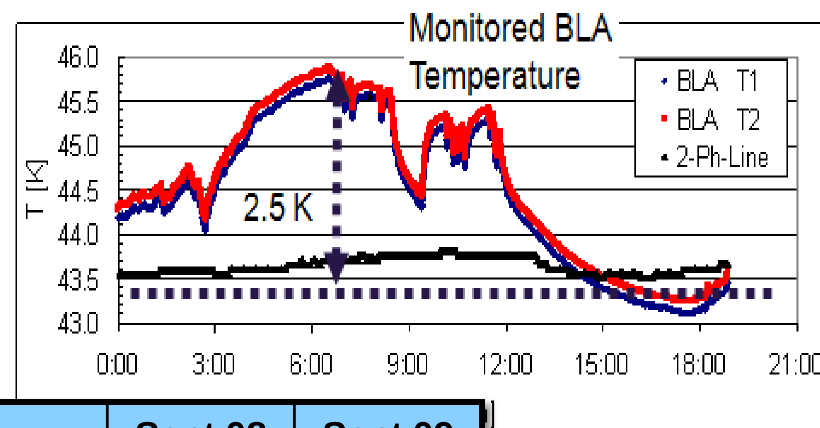


Computer modeling for the location of BLA (*M. Dohlus*): 15% of the HOM power should be absorbed in the BLA.

Results from HOM absorber study





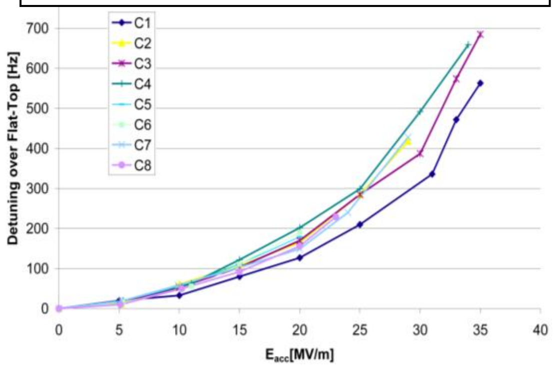


	Sept 08	Sept 09
Computed Absorbed Power [W]	0.180	0.255
Measured Absorbed Power [W]	0.143	0.325

J. Sekutowicz

FLASH cavity gradient limits:
Factors limiting maximum achievable operating gradients

Lorenz-force detuning vs gradient (1mS flat-top)



Maximum usable gradient

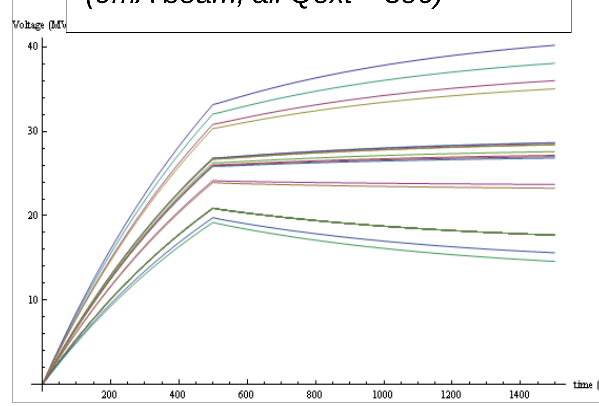
Quench limits

Gradient overheads
- RF Distribution System setup
- Margin for reliable operation (~2MV/m?)
- **Gradient tilts**

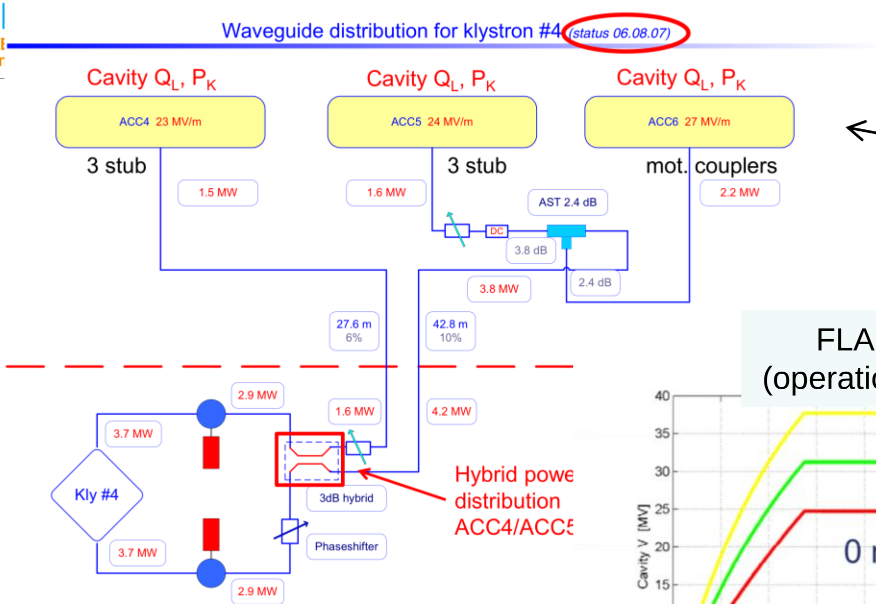
Qext / Pk schemes

RF power
- Overcome cavity detuning
  - **Lorentz-force detuning**
  - Microphonics
  - Static tuning errors
- Margin from klystron saturation to maintain minimum gain
- Cavity circulator power limit: 390kW
- Klystron power limit: 5-7MW

Gradient tilts over 1ms flat-top
(9mA beam, all Qext = 3e6)

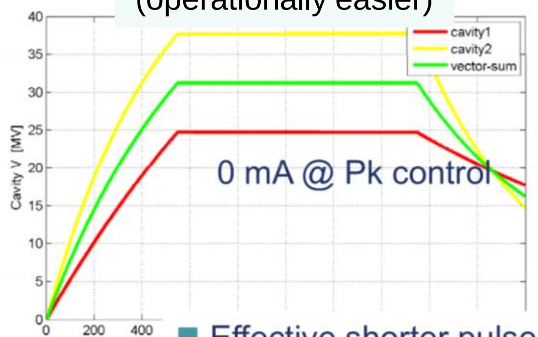


Cavity gradient tilts: RF distribution setups

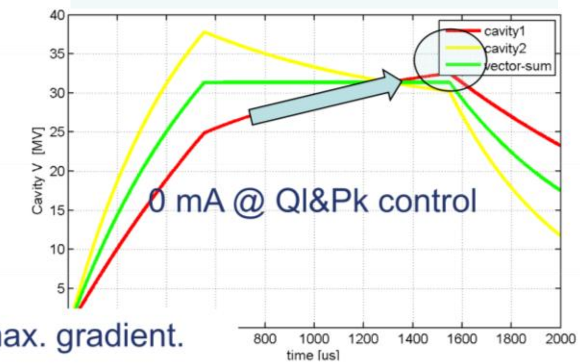


Cavity Q_L & P_K are set up for flat gradients at a particular beam current

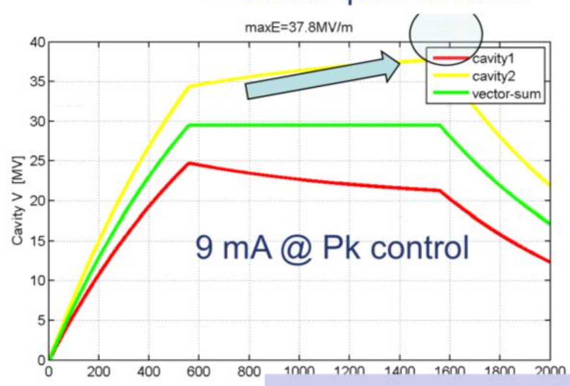
FLASH setup
(operationally easier)

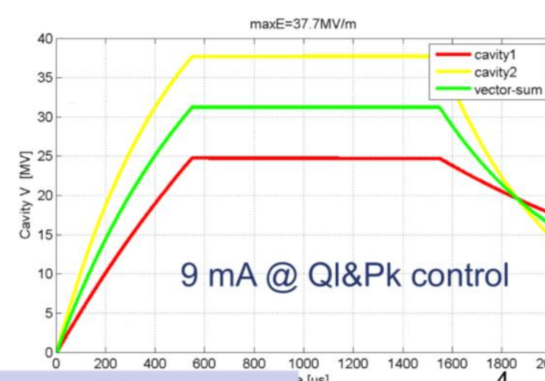


ILC Reference Design
(higher average gradient)



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

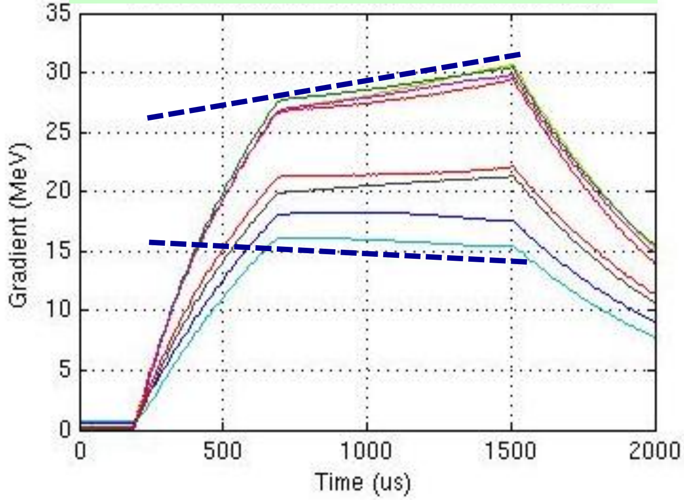




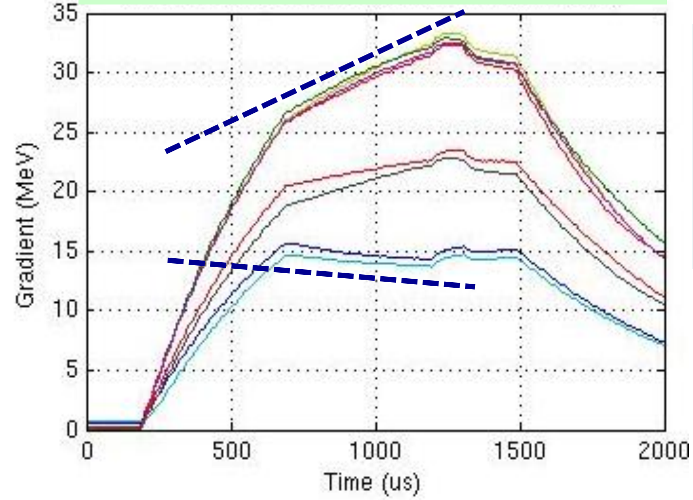
Simulation for 38 MV/m & 25 MV/m cavities

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

ACC6 gradients (3mA, 800 us)



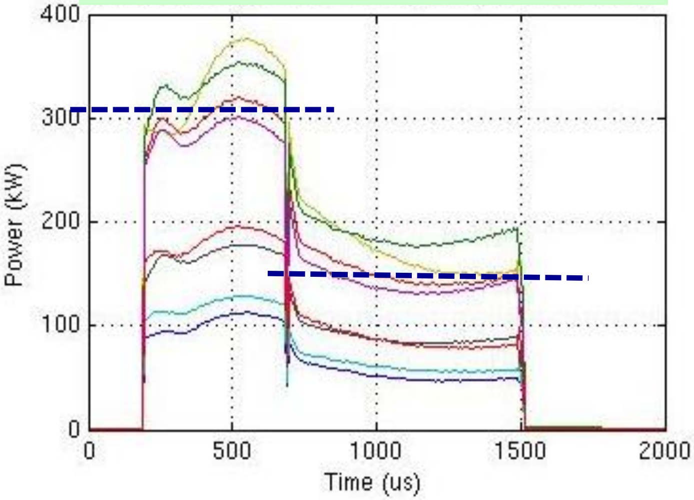
ACC6 gradients (7.5mA, 550 us)



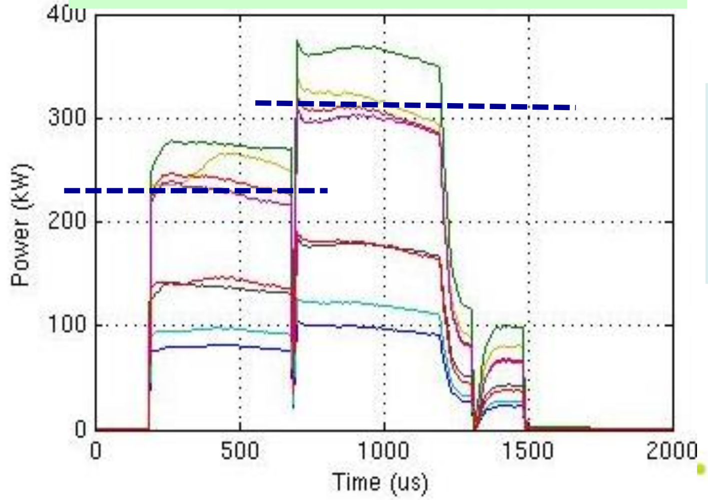
Gradient tilts are a consequence of using a single RF source to power cavities running at different gradients

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

"no-beam" study - 8/27/2009

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

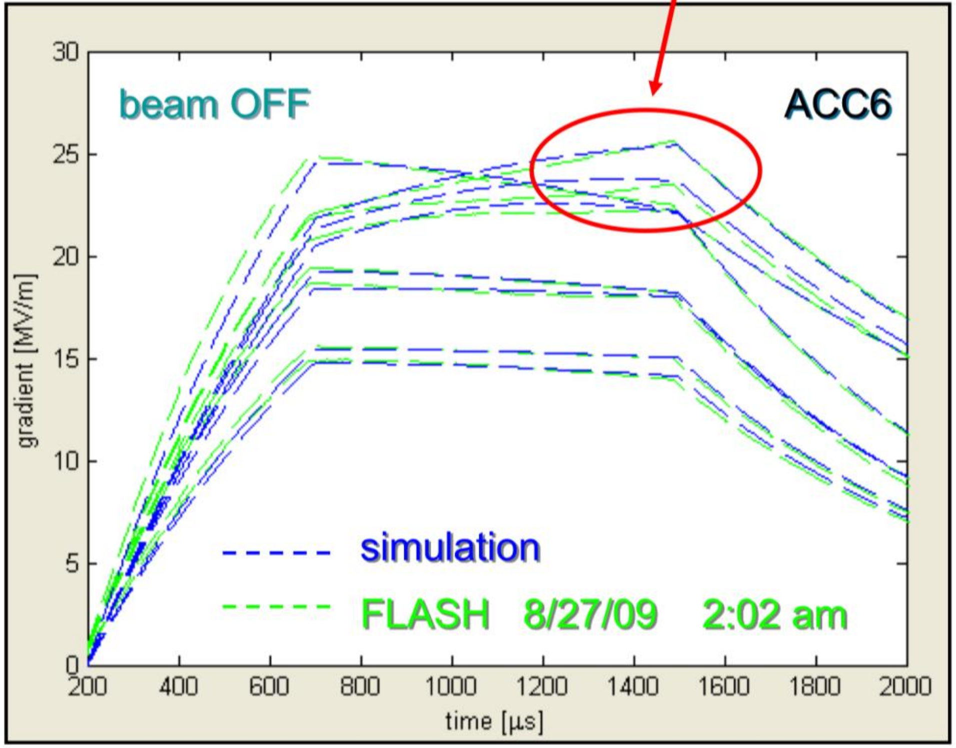
Verification of simulated cavity gradients vs. experimental data without beam

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

cavities with adjusted coupler values



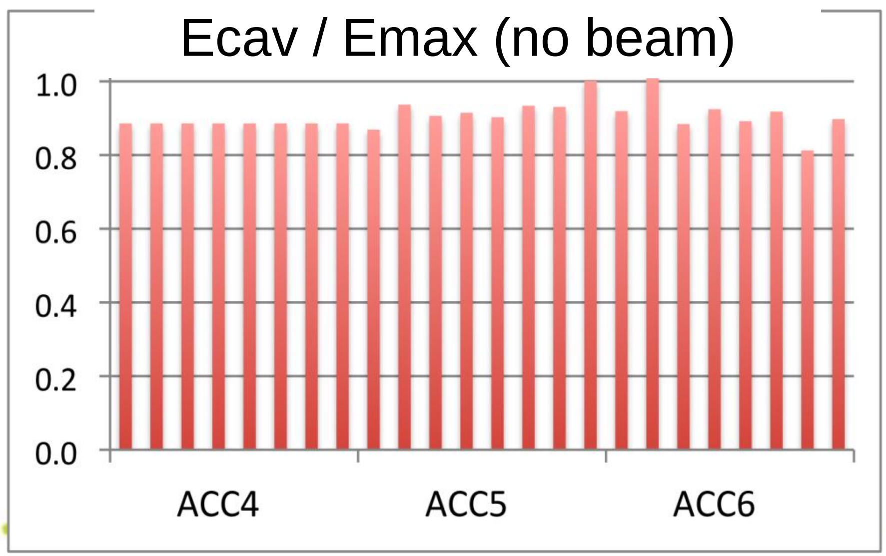
tilt up without beam → flat with beam

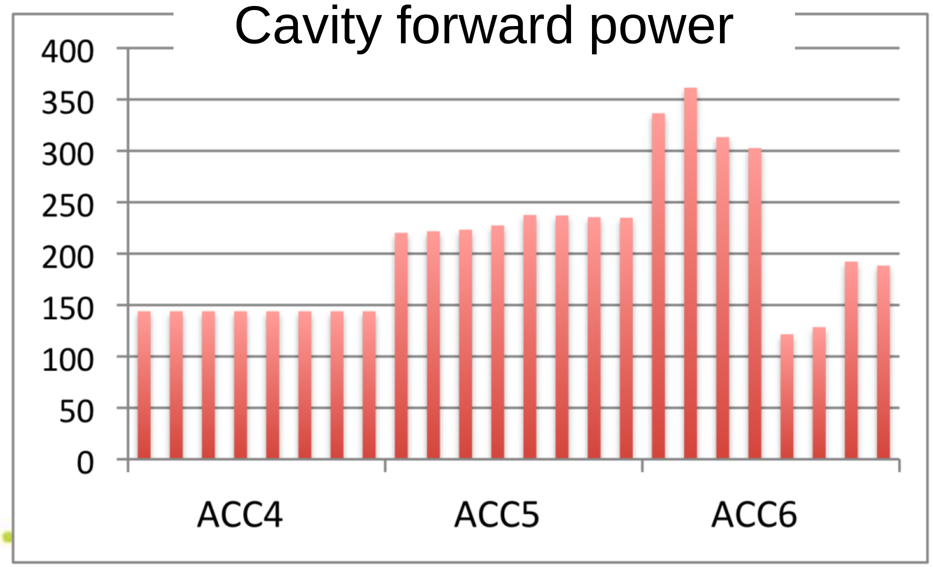
Estimating maximum operating gradients

Previous estimations of Ecav / Emax
(FLASH configuration in 2009)

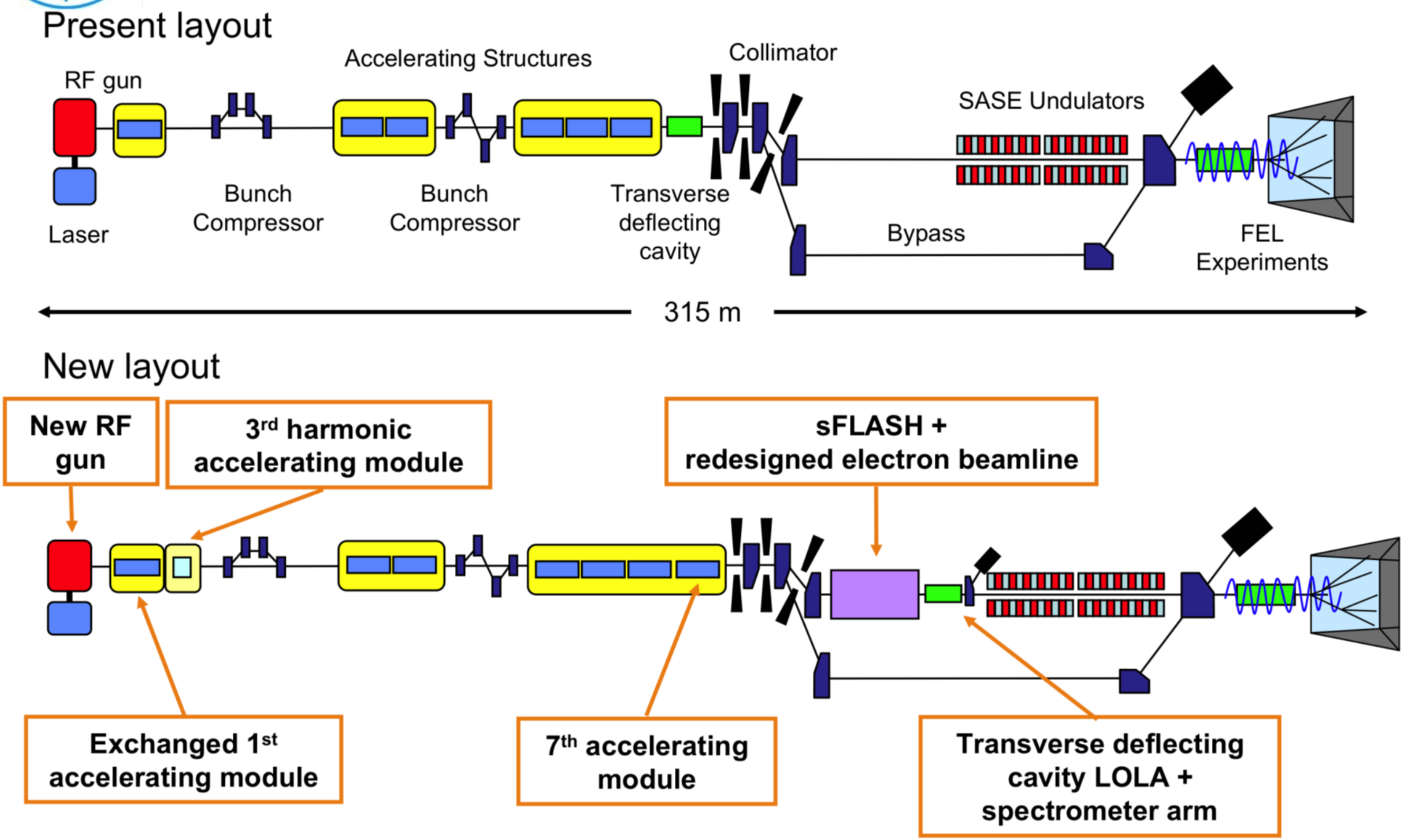
- If cavities are filled to point where first cavity quenches,
  - **Average gradient ACC4/5/6** **~24MV/m**
  - **Average gradient ACC6 C1-C4** **~30.8MV/m**
  - **Klystron power** **6.4MW**
  - **ACC6 C2 forward power** **360kW**

Limit: 5-7MW
Limit: 390kW

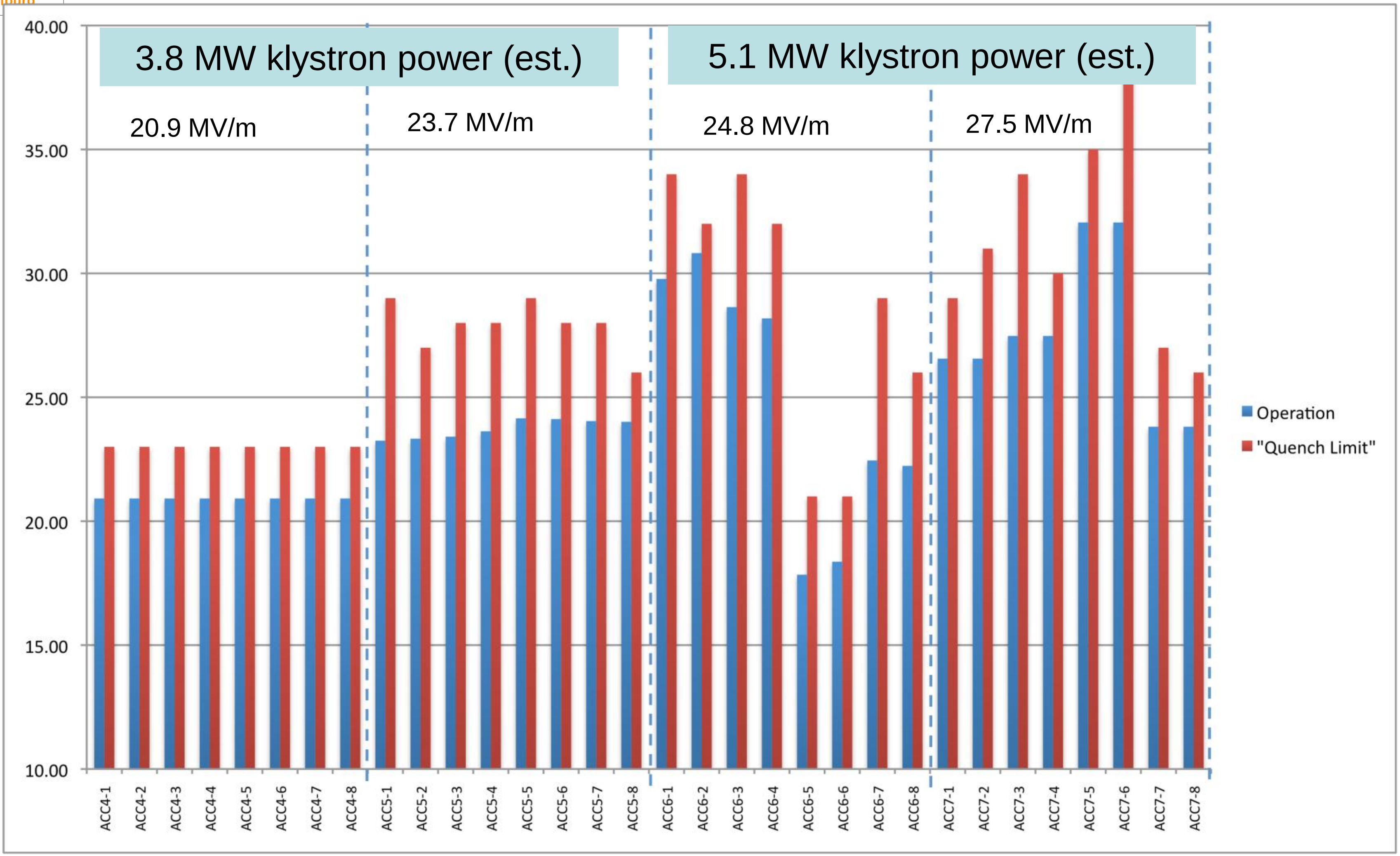




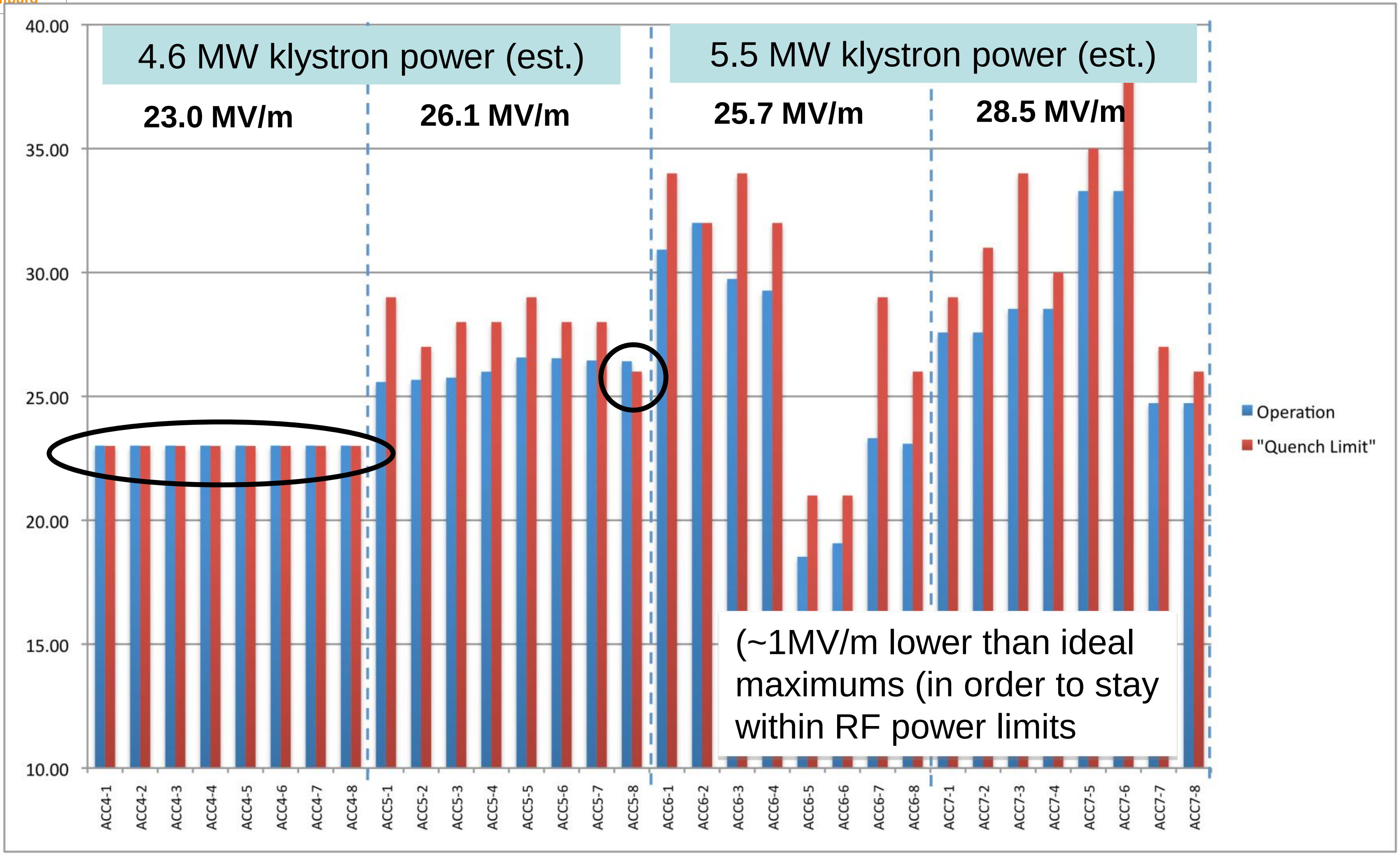
FLASH Upgrade 2009/10



Nominal operating gradients for ACC4-6

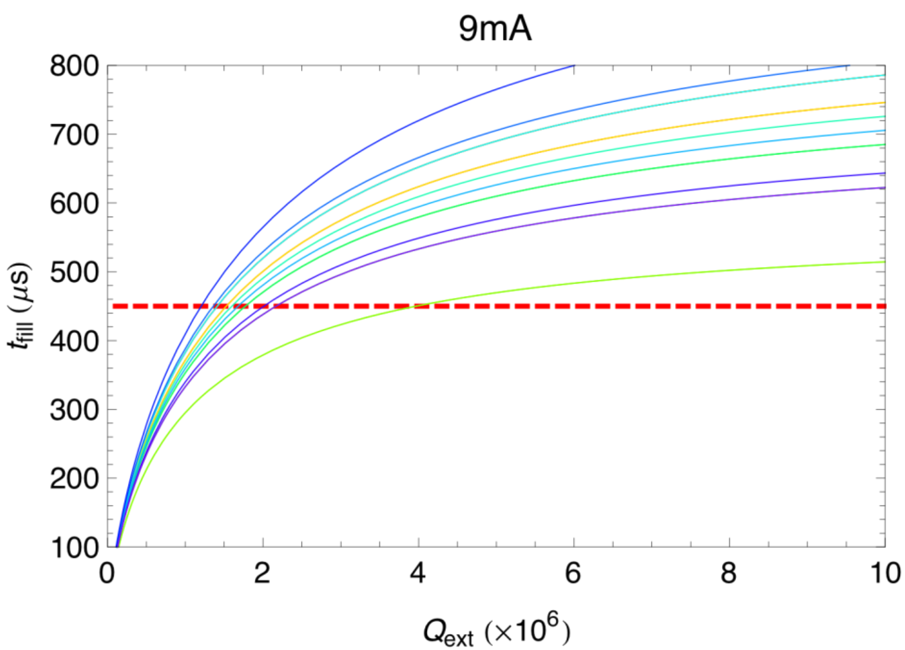


Theoretical maximum gradients
(2010 configuration, no operating margins)



RF distribution configuration for flat gradients without beam

Calculated Q and P settings for 9mA 'flat maximum gradients' (work in progress)



	P_{fwd} (kW)	Q_x	G (MV/m)
ACC6-1	350.16	1.4083×10^6	34.
ACC6-2	355.651	1.52609×10^6	32.
ACC6-3	331.421	1.4083×10^6	34.
ACC6-4	314.386	1.52609×10^6	32.
ACC6-5	192.16	3.96584×10^6	21.
ACC6-6	196.04	3.96584×10^6	21.
ACC6-7	225.673	1.77079×10^6	29.
ACC6-8	217.125	2.16533×10^6	26.
ACC7-1	255.852	1.77079×10^6	29.
ACC7-2	262.886	1.59672×10^6	31.
ACC7-3	286.284	1.4083×10^6	34.
ACC7-4	270.767	1.67749×10^6	30.
ACC7-5	360.241	1.35863×10^6	35.
ACC7-6	381.128	1.20249×10^6	39.
ACC7-7	219.789	2.00928×10^6	27.
ACC7-8	218.058	2.16533×10^6	26.

Sets cavities to reported quench limits. We choose 450 μs fill time to the cavity forward powers below 390 kW.

Average gradient: 30.0 MV/m
ACC6 28.6 MV/m
ACC7 31.4 MV/m

Feasible…?
… be studied

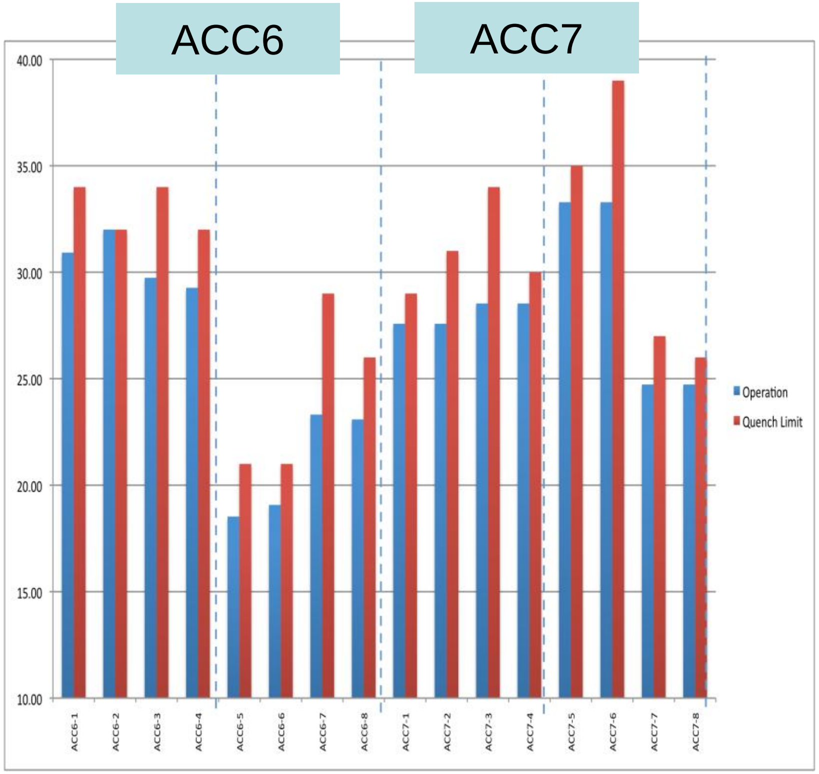
N. Walker

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 spec

Opportunity to study:

- **Gradient overhead and RF power overhead near ILC gradients**
- **RF distribution setup schemes with cavity powers close to ILC spec**
- **Lorentz-force detuning + piezo compensation near ILC gradients**

Broadly, we gain information about operating cavities with full beam loading, eg

- **Piezo compensation of LFD**
- **Running cavities close to quench**
- **Vector Sum field regulation**

Planning…

9mA study topics

- LLRF
  - **Long-term energy stability**
  - **Performance regulations at high gradient and high current**
  - **LLRF control studies related to SB2009 HLRF schemes***
- Gradient overhead studies (ACC67)
  - **Optimization of Pk/Qext, prove concept for at least 3mA**
  - **Microphonics and LFD, can be done w/o beam**
- Gradient flatness studies*
- Klystron power overhead studies
  - **Need high current, at 3mA need retune Qext**
- ILC Bunch compressor stability studies
  - **2 RF units ACC45 & ACC67 to demonstrate 0.25 deg phase stability**
- HOM coupler studies with different bunch lengths

*New study topics

GDE/PM re-evaluation of cavity field gradient

Results from 9mA studies at FLASH will provide essential real-world input to the gradient decision

A, Yamamoto, 10-02--23

- Important, optimum balance for 'Gradients'
- In Construction(in acceptance) and Accelerator Operation
  - **Cavity > Cryomodule > ILC Cromodule string**
    - For example: 1 > 0.95~xx > 0.9~xx
  - **Spread of Gradient**

Detailed were covered in SCRF presentation

  - **Operational Margin**
    - Cavity (itself) operational margin in terms of field/field-emission/cryogenics-load
    - LLRF tune-ability/operational margin or overhead
      - Expect S2 R&D: critical with FLASH (only by 2012)
- Much effort for re-evaluation required

More operations experience is needed

- Demonstrating long bunch-train operation with heavy beam loading was an important milestone… but marks only the start for 9mA studies

- Operational and technical improvements focused on improving long bunch train operation benefit all modes of operation
  - **Single bunch and long bunch-train operation**
  - **Delivering photons for FEL users and accelerator studies**

- Studies examples
  - **Build tuning and operations experience**
  - **Establishing and save/restore of machine working points**
  - **Stability and reproducibility of LLRF over long flat top with beam loading: feedback; adaptive feed-forward**
  - **Exception handling**
  - **Systematic procedures and automation for machine setup and tuning**

Planning issues

- Heavy beam loading is critical for answering key questions, but
  - **Can make useful progress at lower current, eg 1-3mA, 800us**
  - **Operational issues can be addressed at low current**

- FLASH is primarily an FEL user facility
  - **Only two short accelerator studies periods likely before 2012 (none in 2010)**
  - **FEL long bunch train studies are planned to start in July 2010**

- Need to be well prepared for the next 9mA studies shifts, eg
  - **2009 data analyized, modeling done, software tools developed,**
  - **Practical issues understood, eg RF limits, tuning ranges,…**

Wrap up

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 18TB of data from Sept 2009…

Summary

- The 9mA program at FLASH will provide essential input to several critical TDP decisions
- Significant progress has been made in a limited time, but additional beam studies are needed before 2012
- FLASH is an operating photon user facility and access is limited, but we have support from DESY Management and we anticipate getting additional beam time in 2011
- Long bunch-train FEL studies will start in July 2010
- The program would benefit from additional resources for data analysis, collaborating on FEL studies, and studies preparations

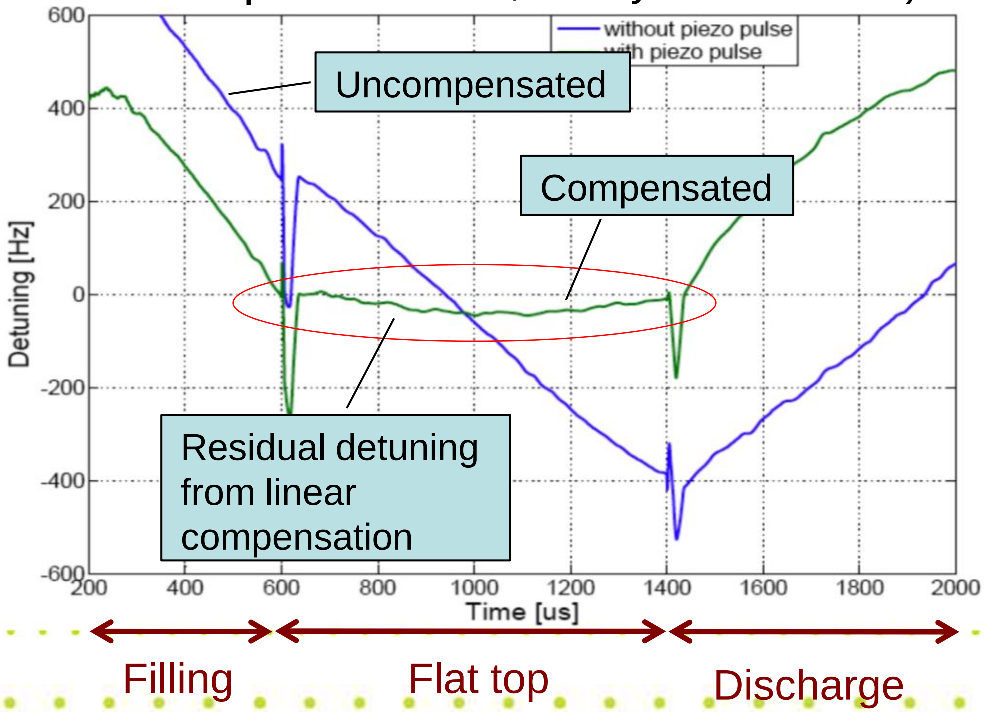
Thank you

Extras

Detuning compensation study using piezos

- Piezo tuners are installed and operational at ACC56
- Detuning compensation will be needed for 9mA test to reach high gradients with full beam loading

Example: Module 6, Cavity 3 at 35MV/m)

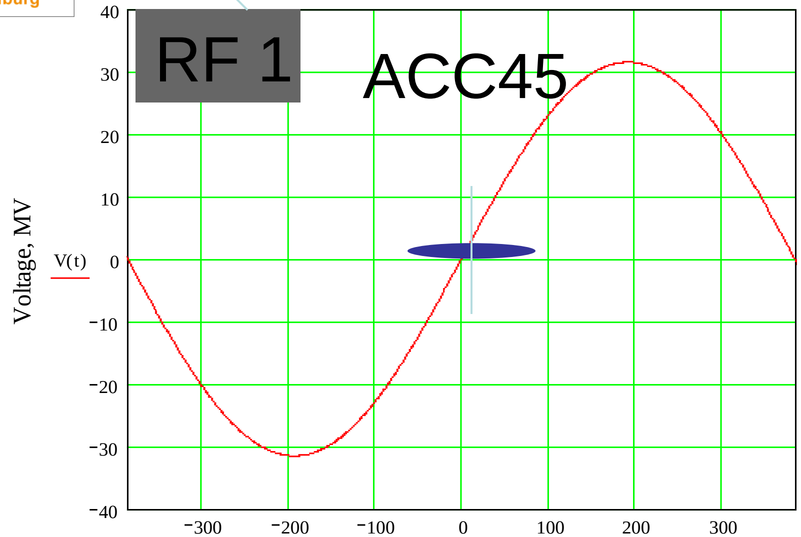


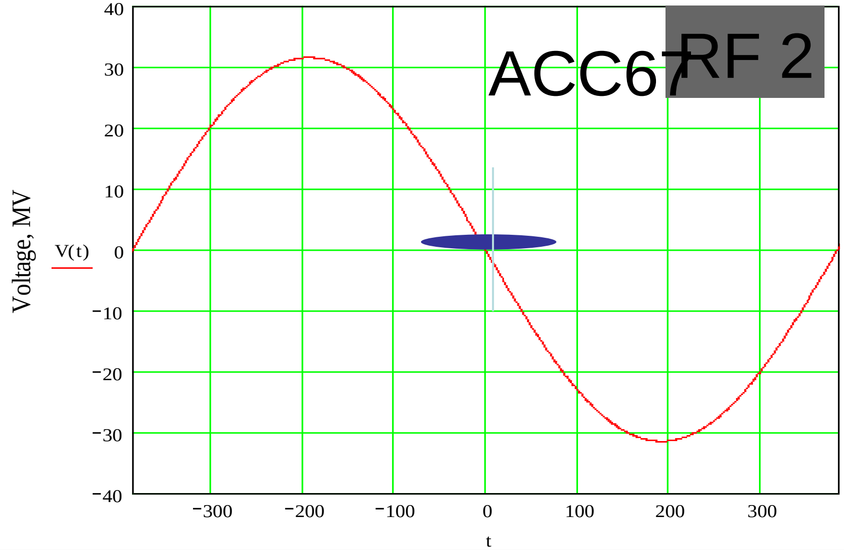
- Feed-forward compensation has been demonstrated on FLASH at up to 35MV/m but with low beam loading
- We plan to study operation and evaluate performance with full beam loading

K. Przygoda

Two RF systems

Two configuration is possible: One (ACC67)or Two (ACC45 and ACC67) RF stations





Schematic of the bunch jitter compensation.

Single ACC67 RF unit:

Energy resolution is OK for 0.25 deg

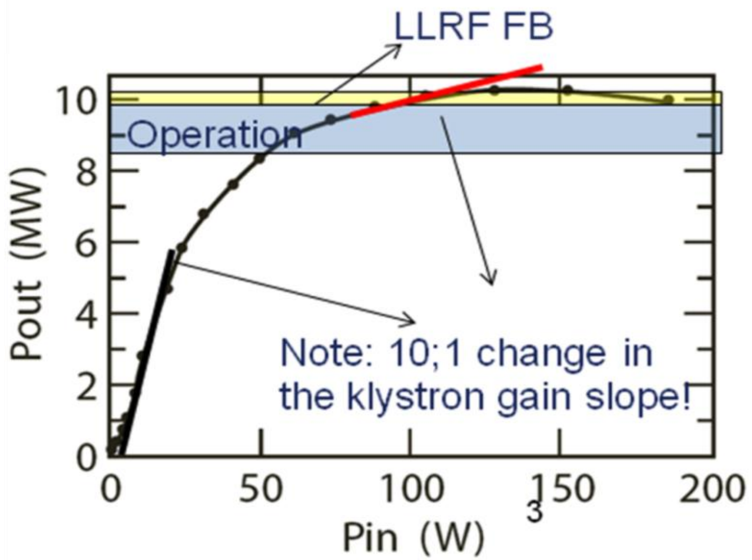
Large energy spread (~1%) if $\sigma > 1$mm

Two RF systems ACC45 and ACC67

- Low Energy ~ 500 MeV
- *Resolution is OK*
- *Bucnch length independent*

Operating near klystron saturation

- *goal: to operate near the klystron saturation.*
- ***The present operation point of the klystron is -5% from its saturation (the worst case*).***
- ***The llrf performance should be evaluated under the circumstance and compare with the case of -10% or more.***



* RF power budget cavity input 8.02 MW (33 MV/m * 1.038 m * 26 cav. * 9 mA)
a) reflection from waveguide system 1% (VSWR~1.2)
b) non-optimal coupling 2% (if over-coupling x1.3)
(We should also consider the rf-output reduction due to the rf reflection to klystron)
c) rf loss 8.54% (should be minimized!)
d) beam fluctuation 1% (should be compensated by fast feedforward)
e) modulator ripple 2.5% (pulse-to-pulse +/- 0.5%HV ripple)
f) cavity detuning 2% (*40 Hz peak* of Lorentz force and microphonics)
Remained rf power:
10 MW – 8.02 MW*(1.01 * 1.02 * 1.01* 1.025 * 1.02)/(1-0.0854)=0.47MW
LLRF feedback overhead
8.02* (1.01 * 1.02 * 1.01 * 1.025 * 1.02* X)/(1-0.0854)=10
X=1.049 (5%) *(2.5% in amplitude)*

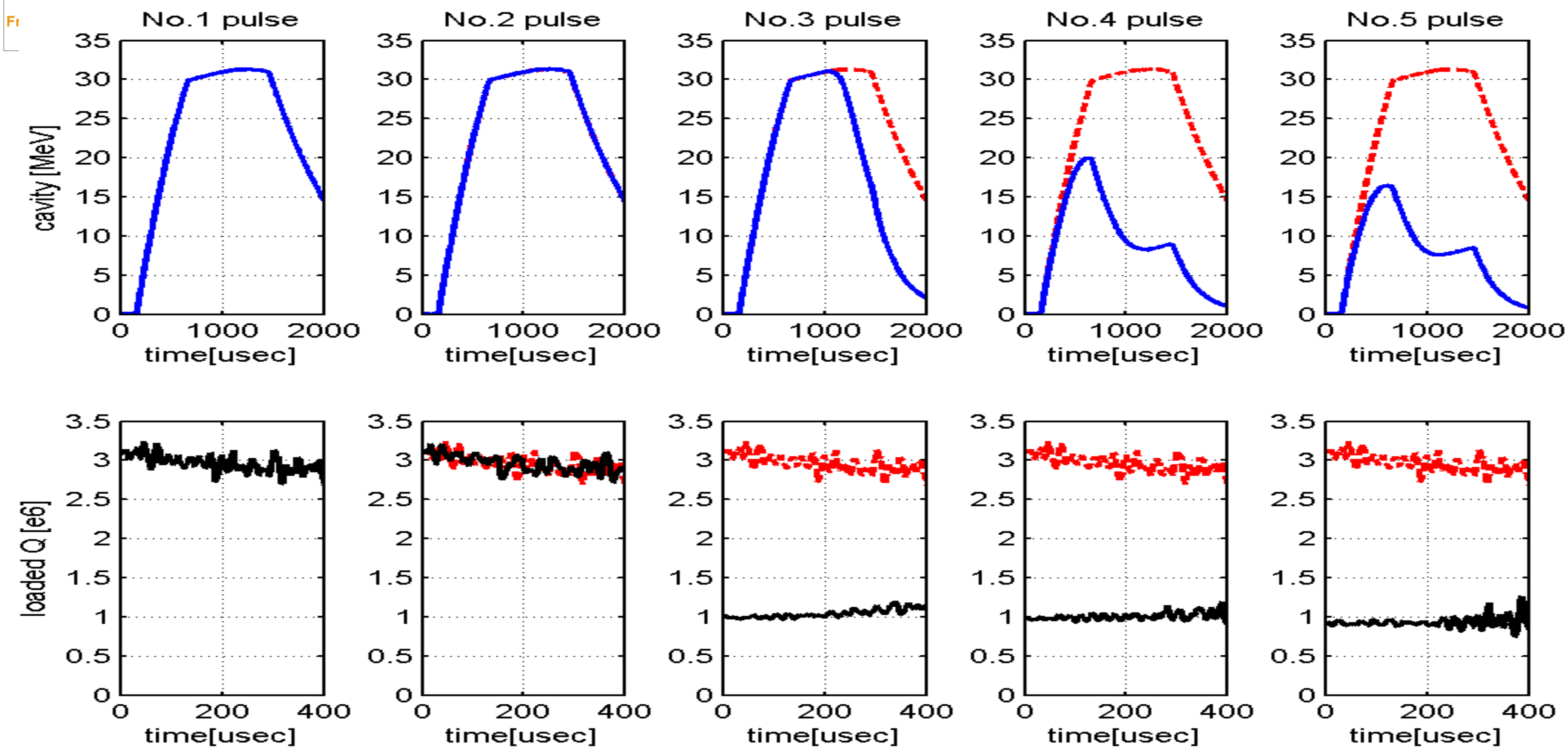
3

- ***proposed measurements:***

Field regulation under the rf operation near saturation (-5%, -10%, -20%)

S. Michizono

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.

FLASH milestone: lasing with 800 bunches

The Milestone

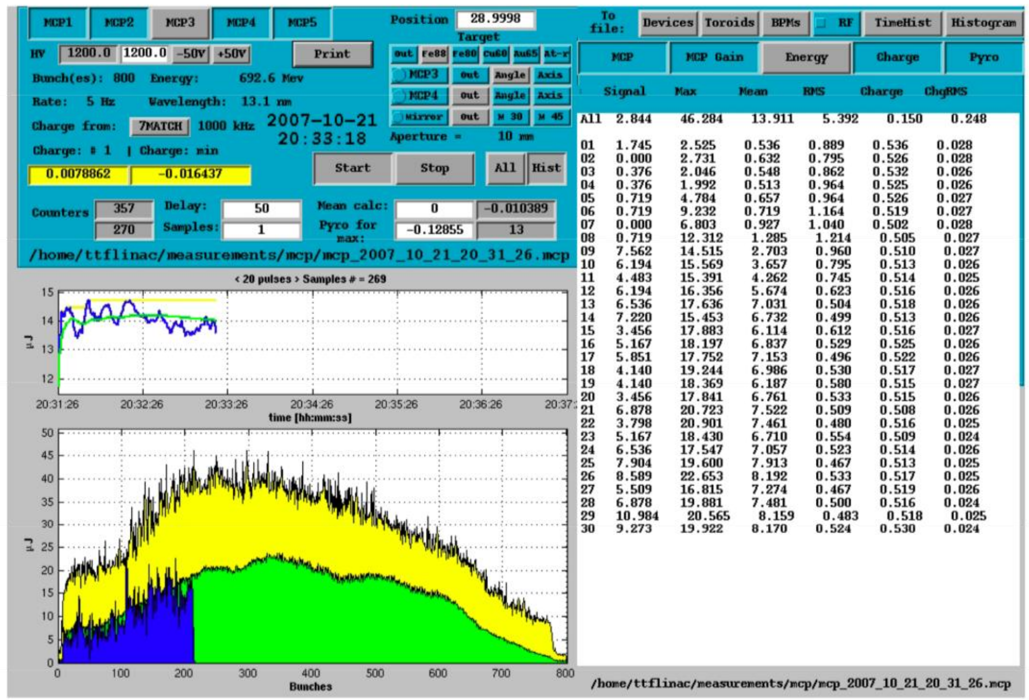
- Milestone: Lasing with 800 bunches, >10 μJ/pulse **achieved**

...without destroying the machine

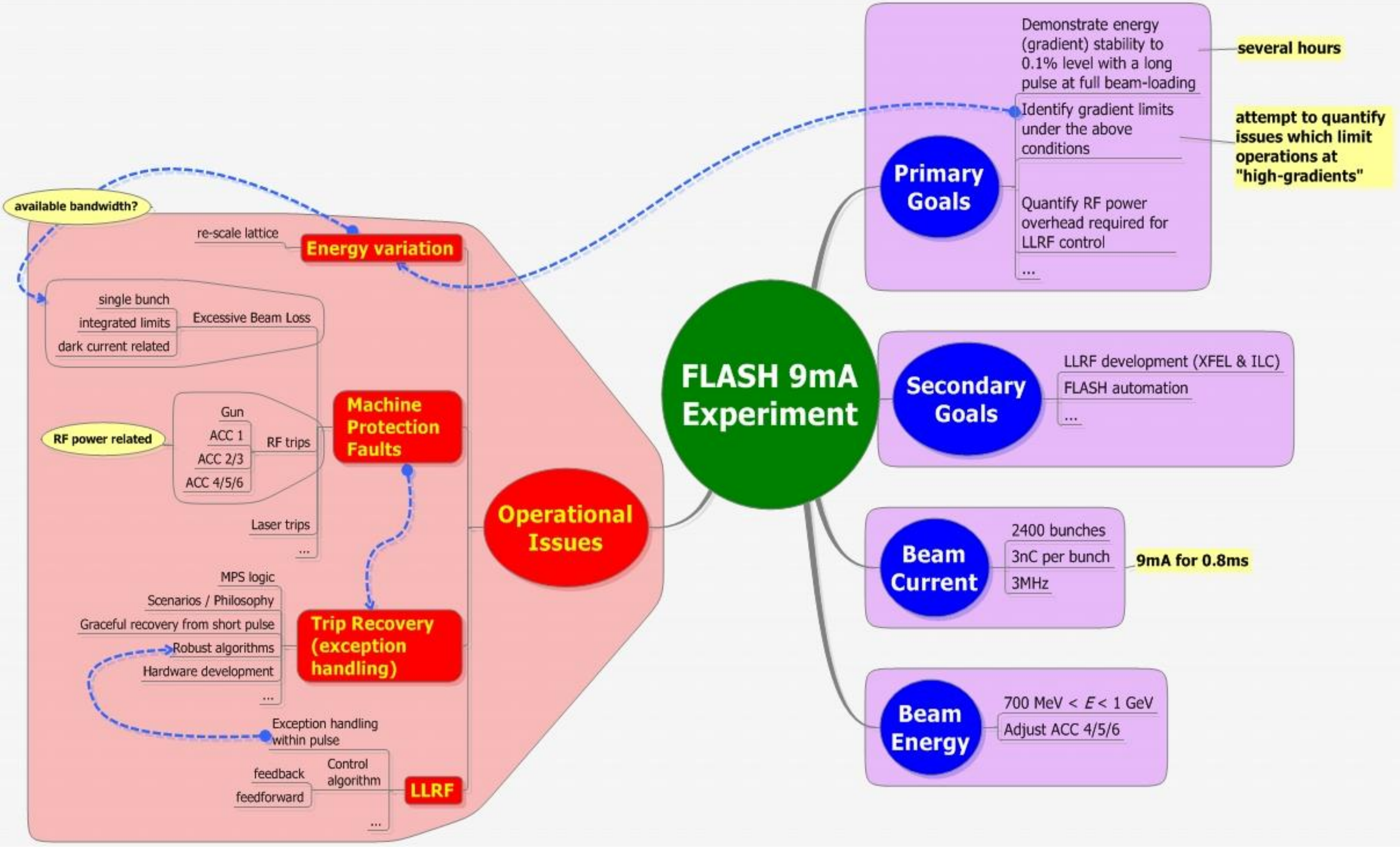
800 bunches at 685 MeV

electron beam: 2.7 kW

photon beam: 56 mW

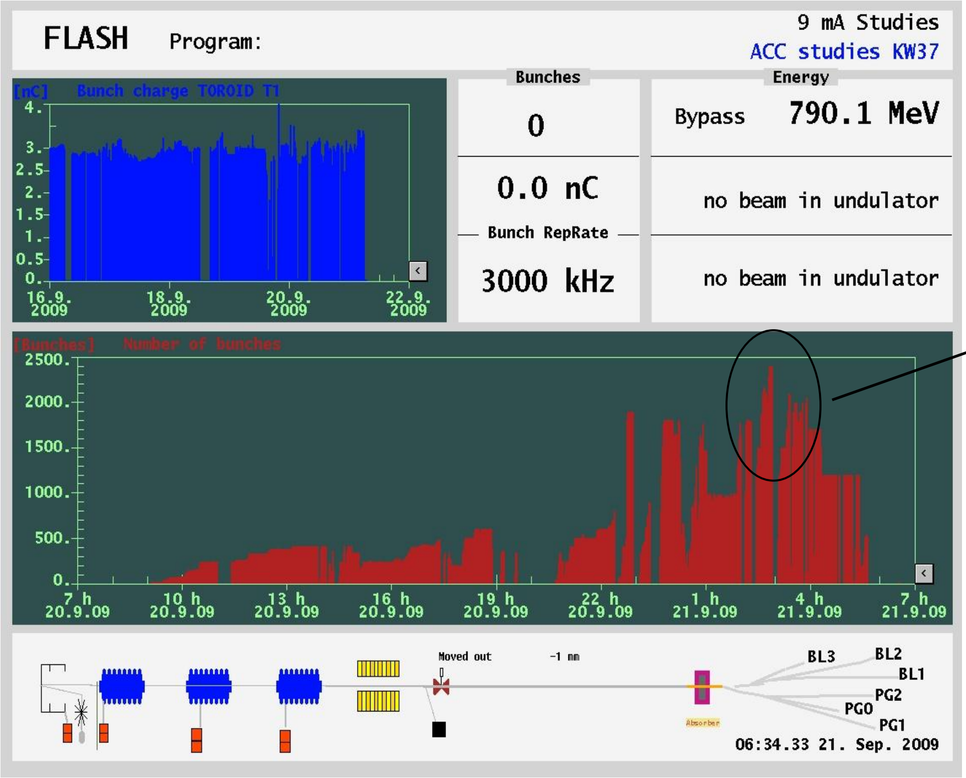


Achieving the goals…



Last 24hrs: ~2400 bunches, 9mA

Number of bunches and charge for Sept 20/21



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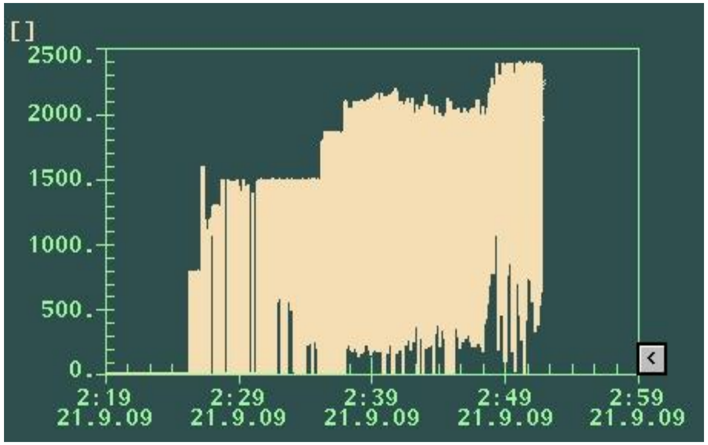

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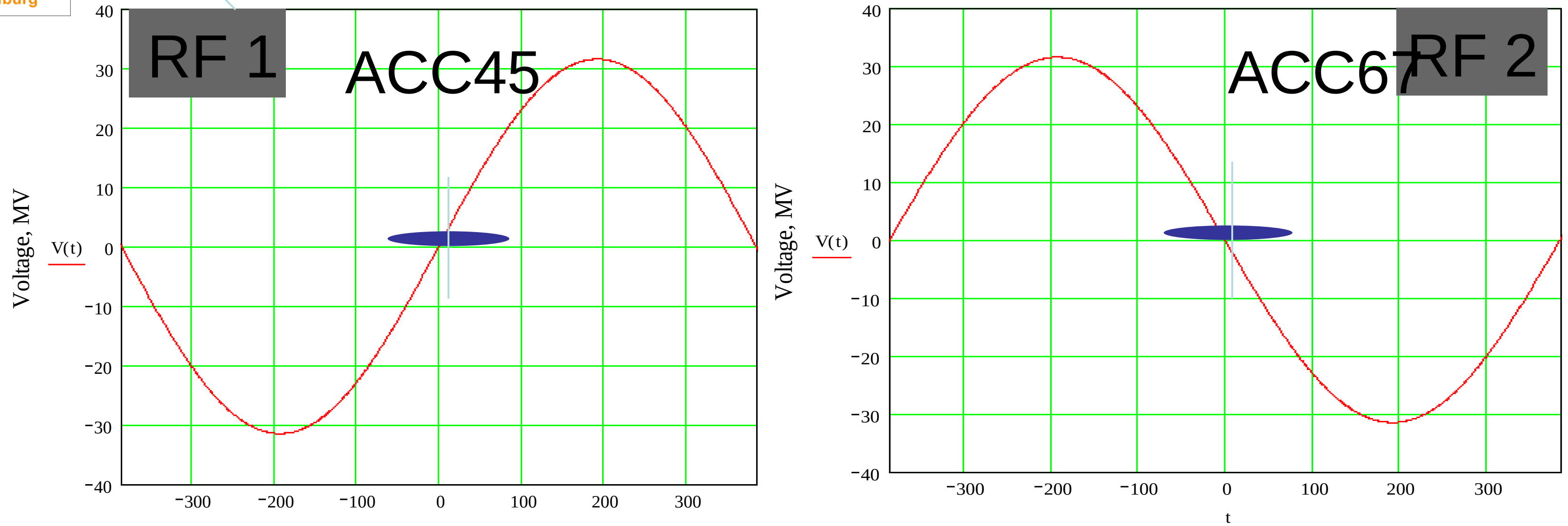

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