

## Beam Tests at FLASH



**John Carwardine (Argonne)**  
**April 29, 2009**

ART DOE/NSF Review April 2009: Beam Tests at FLASH (Carwardine)

Slide 1

## Outline

- **Brief overview of the FLASH facility**
- **9mA experiment overview**
- **Experiment results, data analysis**
- **Planning for August/September studies**
- **Looking ahead to FY10...**
- **US Resources for the 9mA program**
- **Wrap-up**

## Cryomodule String Test Goals

- The highest priority goal is to demonstrate beam phase and energy stability at nominal current
- Important goals 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
- Goals needed to understand linac subsystem performance:
  - develop RF fault recognition and recovery procedures
  - evaluate cavity quench rates and coupler breakdowns
  - test component reliability

### *System Integration Tests*

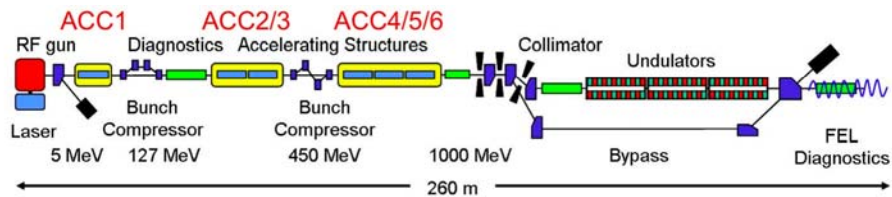
## Primary objectives of 9mA program

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

Primarily a  
LLRF  
experiment

# TTF/FLASH facility overview

## FLASH Accelerator Layout



Comparison of machine parameters

		XFEL	ILC	FLASH design	9mA studies	NML	Proj-X	HINS
Bunch charge	nC	1	3.2	1	3	3.2		
# bunches		3250	2625	7200	2400	2850		
Pulse length	$\mu$ s	650	970	800	800	950	1250	1000
Average current	mA	5	0	0	0	0	20	20

- **TTF/FLASH is used for different purposes**
  - VUV and soft X-ray FEL photon source
  - Test bench for accelerator R&D
- **Typical accelerator parameters for photon users:**
  - 2-30 bunches (up to 200),  $\leq 1\text{nC}$  per bunch, 1MHz bunch rate
  - 400MeV-1GeV
- **2008 machine time allocations**
  - FEL user operation: 161 days
  - FEL studies: 119 days
  - Accelerator studies: 49 days
- **The 9mA program has received 16 8hr shifts during the last three accelerator studies periods**

## The 9mA Experiment

## The (International) Team

### Americas

- **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 - LLLRF set-up and tuning
  - Mariusz Grecki - LLLRF set-up and tuning
  - Waldemar Koprek - LLLRF set-up and tuning (mostly gun)
  - Jacek Sekutowicz - HOM absorber measurements
  - Stefan Simrock - LLLRF (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 - LLLRF / overall coordination
  - Xiaowei Dong - data analysis, optics modeling
- **FNAL**
  - Brian Chase - LLLRF (experiment & data analysis)
  - Gustavo Cancelo - LLLRF (experiment & data analysis)
  - Michael Davidsaver - DAQ applications programming
  - Jinhao Ruan - laser setup
- **KEK**
  - Shinichiro Michizono - LLLRF (experiment & data analysis)
  - Toshihiro Matsumoto - LLLRF (experiment & data analysis)
- **SLAC**
  - Chris Adolphsen - LLLRF (experiment & data analysis)
  - Tom Himel - Planning & scope
  - Shilun Pei - LLLRF (experiment & data analysis)
- **SACLAY**
  - Abdallah Hamdi - TPS installation / commissioning

~40 subscribers to  
tff9mA mailing list  
(not all shown here)

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

## The 9mA experiment in context: Addressing R&D issues of several projects

- **ILC: GDE stated milestone for Technical Design Phase**
  - Primary motivation and driver for the experiment
  - Important for evaluating RF overhead and gradient control
- **XFEL: Close collaboration with world-wide LLRF groups**
  - Focus (potentially accelerate) development and planning
  - Critical design/dev't input from "operation at limits" experience
- **FLASH: Addresses many operational issues**
  - Focus / accelerate upgrades and enhancements
  - Better characterization of machine
  - Towards routine high-power long-pulse operation for users

## 9mA experiment chronology

- **First run (May 08)**
  - Hardware failures (power-out) effectively made shifts unusable
  - Poor machine setup made bypass optics/steering virtually impossible
- **Second run (September 08)**
  - Significant progress on all fronts
  - Careful set-up of injector (3nC, 1MHz) resulted in 'loss-free' transmission to dump (via by-pass)
  - Vacuum incident resulted in aborted programme
- **Third run (January 09)**
  - Beam loss studies
  - LLRF regulation, beam loading compensation algorithms
  - Run cavities at higher gradients
- **Upcoming fourth run (August/September 2009)**
  - 2 weeks of 24/7 dedicated 9mA studies

## Results to date compared with the 9mA 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

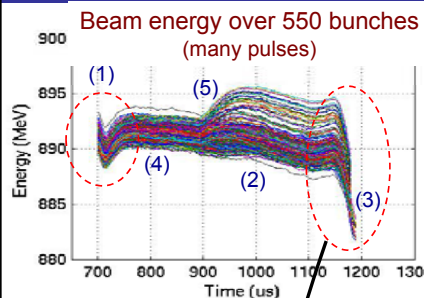
Also achieved...

## Examples of studies by US collaborators

- **Analysis of RF overhead, gradient, stability/jitter**
  - Shilun Pei, Chris Adolphsen (SLAC)
- **LLRF performance and improvements**
  - Gustavo Cancelo, Brian Chase (FNAL)
- **Analysis of beam loss, optics modeling**
  - Xiaowei Dong, John Carwardine (Argonne)
- **'Beta testing' of upgraded DAQ data archiver and tools**
  - Michael Davidsaver (FNAL)

US collaborators have participated in all the studies shifts

## Energy profile over long bunch trains (Sept 08 studies)



### Artifacts in energy profile

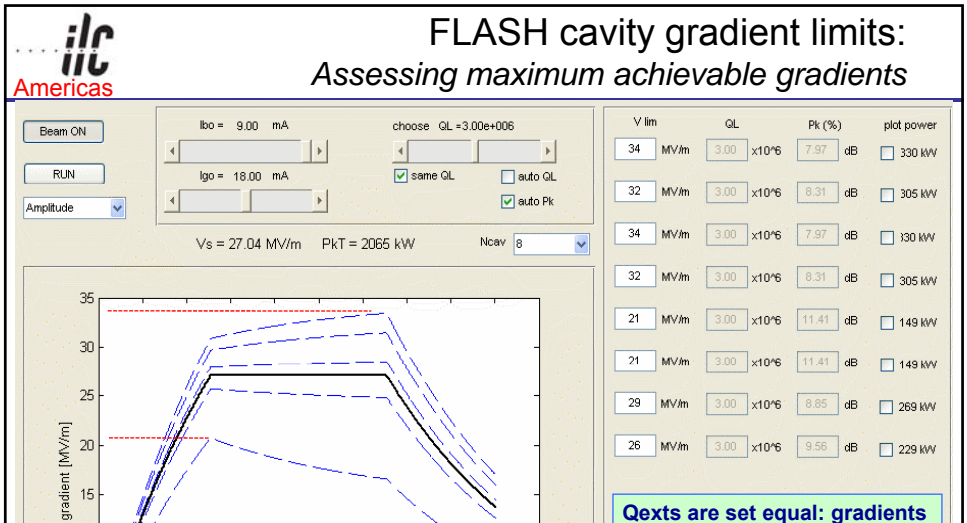
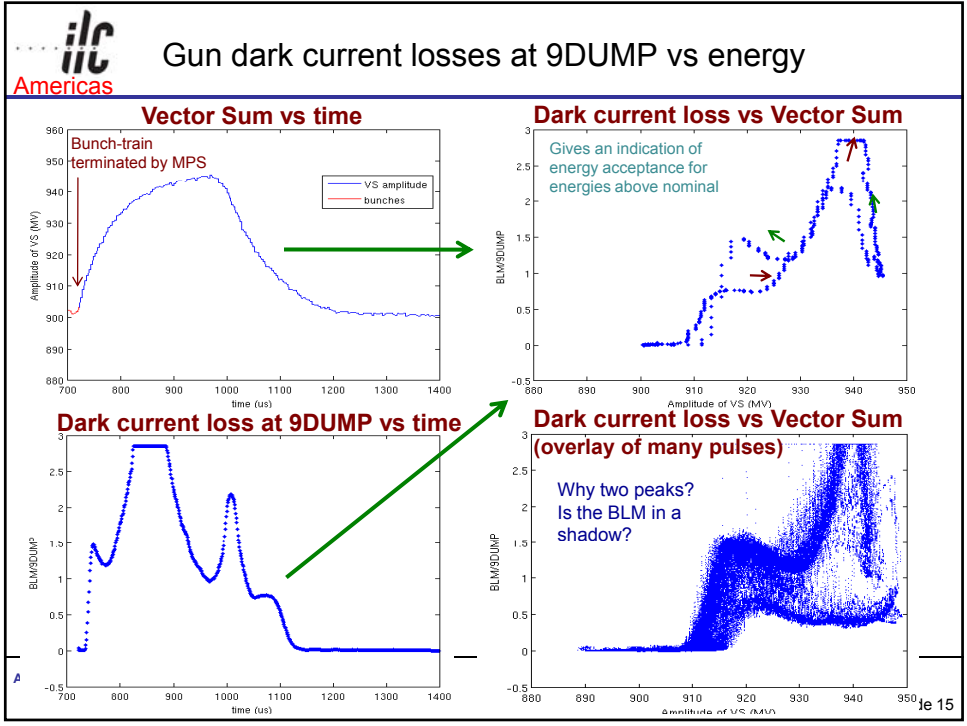
1. Beam turn-on transient (regulator)
2. Negative slope over flat top (Note: vector sum has a positive slope)
3. Droop at end of the flat top (beam loading compensation not set correctly)
4. Pulse-to-pulse jitter
5. Energy jumps if beam trips off early

Beam Loss Monitor at 10EXP for 200 vs time in pulse



### Planned regulation improvements...

- Increase feedback gain (only 20 now)
- Upgrade to latest generation LLRF





## Preparing for August/September 9mA studies

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- **Now to Aug 17:**
  - Deliver beam to users + fel studies
  - No machine studies scheduled
- **Aug 17-Sep 21: 5 weeks of dedicated machine time**
  - Tunnel access to repair dump vacuum line (3 weeks)
  - Two weeks of 24/7 dedicated 9mA beam studies
- **Sept 21: FLASH shutdown begins**

## Important operational experience...

- **So far, the main challenges have been operational issues**
  - **Controlling peak + integrated beam loss**
  - **LLRF system performance and tuning**
- **We need a better model of the bypass line optics**
- **A well-tuned and well-matched gun & injector is essential**
- **LLRF systems require expert attention when increasing beam current or pulse length**
  - **Tuning beam loading compensation**
  - **Reduce energy spread over long bunch trains: transients at start and end of pulse; slope over flat-top**

## Preparatory work prior to August

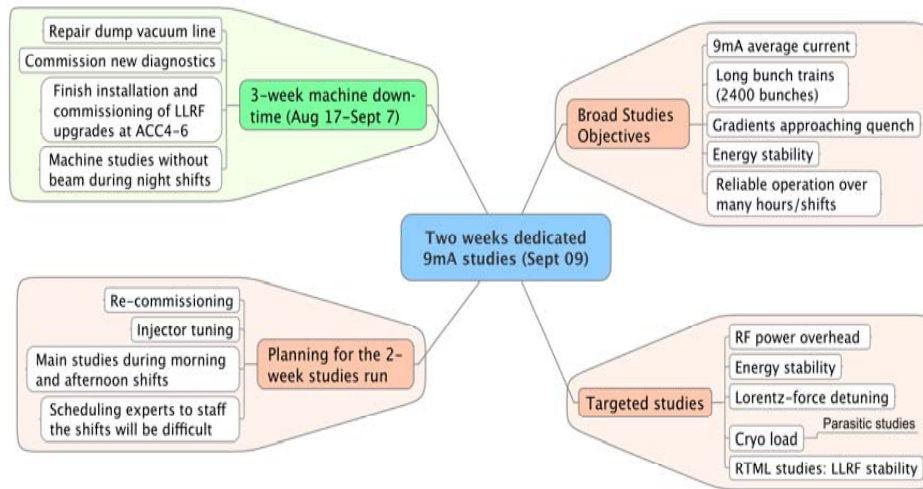
- **LLRF system upgrades at ACC456 (ACC23)**
  - **Upgrade hardware to latest generation (SimconDSP)**
  - **Upgrade rf signal down-converters for higher IF**
  - **Algorithm improvements: beam loading compensation, feed-forward waveform generation, ...**
  - **LLRF system modeling, study planning**
- **Optics work**
  - **Improve alignment between model and measured lattice**
  - **Improve understanding of loss points and apertures**
  - **Refine the bypass lattice**

DESY

DESY  
FNAL  
KEK

DESY  
ANL

## Aug/Sept 2009 studies planning



## US role FY09/Q3-Q4

- **Main task is to prepare for 2 weeks of studies in September**
- **Participate in LLRF system characterization & upgrades**
- **Participate in planning / preparation of the studies**
- **Continue data analysis and optics simulations, co-develop studies plans for tuning for low beam loss**
- **Participate and lead LLRF and accelerator studies shifts**

## Looking ahead...

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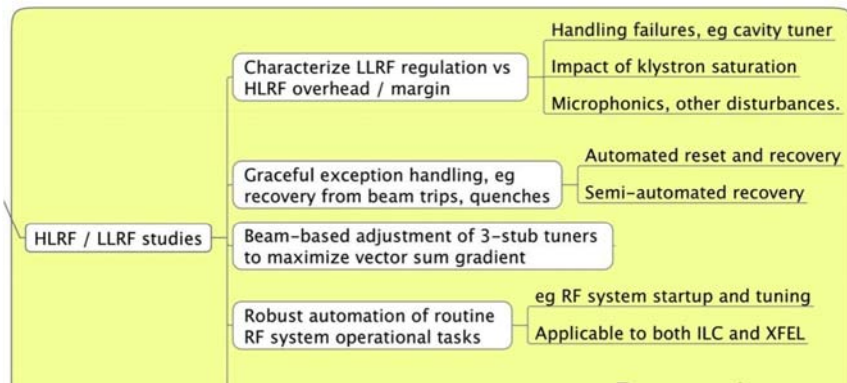
## FLASH long-range schedule

- **Shutdown for FLASH upgrade: Sept 21 – March 09**
- **Re-commission + machine & FEL studies: ~ 3months**
- **Restart operation for photon users: Summer 09**
- **User operation continues until end 2011**
- **Shutdown for FLASH-II upgrade: early 2012**

## Possible future studies at FLASH

- **If the machine can be operated reliably with high beam power, then the 9mA program could continue.**
  - **Continue with the major 9mA program topic area**
  - **Add: priority 2 an 3 items not covered earlier**
  - **Add: new ILC-related studies, eg RTML studies**
  - **Add: studies of mutual interest to ILC and XFEL**
  
- **Add studies of mutual interest with NML, Project-X, HINS,...**
  - **Opportunity to develop and test LLRF hardware, firmware, algorithms, operational issues,...**

## Potential RF System Integration studies



## Wrapping up...

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## US Resources for 9mA program

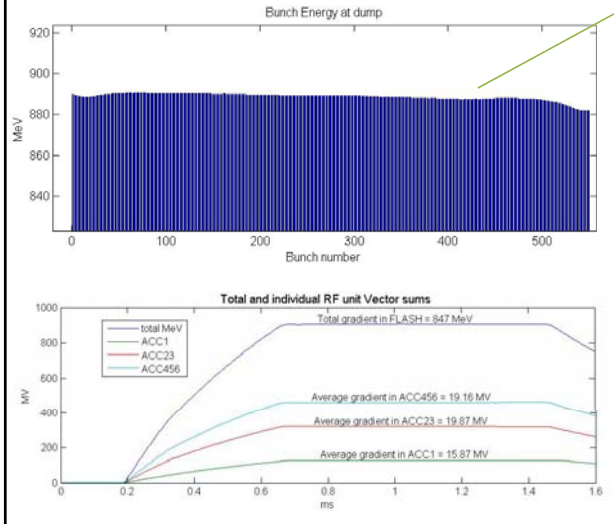
- **FY09 resources for LLRF (9mA study is one activity):**
    - **LLRF modeling & analysis at APS: 1 FTE**
    - **LLRF development at FNAL: 0.92 FTE**
  - **Additional 9mA program support has come from**
    - **GDE project management office (Carwardine)**
    - **HLRF Technical Area Group (Adolphsen, Pei)**
  - **The budget allows us to participate in machine studies, perform some data analysis, co-lead the program with N. Walker (DESY)**
- **LLRF resources are insufficient to make substantial technical**

## Summary

- **TTF/FLASH is the only facility that can address the GDE goal of running beam through a cryomodule string by 2012**
- **A relatively small US team is making important contributions on HLRF/LLRF, machine physics studies/modeling, analysis of key operational data**
- **The team is gaining important experience in SCRF linac 'operation at the limits'**
- **Continued US participation with the 9mA program is important to the GDE global collaboration and it will benefit new and ongoing SCRF projects in the US**

Backups

## High Beam-Loading Long Pulse Operation (Sept 08)



10 MeV over 550 bunches (~1%)  
(~4 MeV over 1<sup>st</sup> 500)

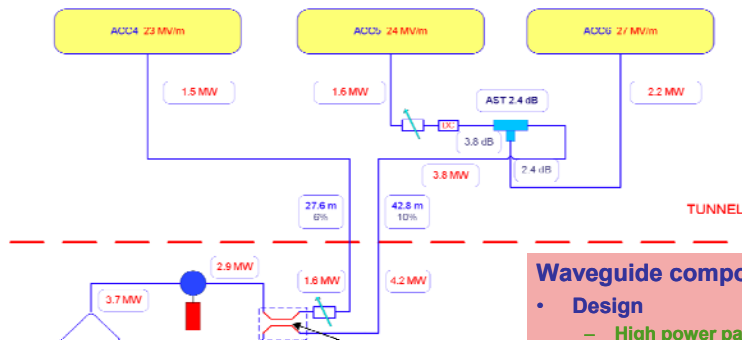
- **450 bunches achieved with stable operation**
  - Few hours of archived data
  - Currently under analysis
  - (vacuum OK)
- **Long bunch trains with ~2.5 nC per bunch:**
  - 550 bunches at 1MHz
  - 300 bunches at 500KHz
  - 890 MeV linac energy
- **All modules (RF) running with 800us flat-top and 1GeV total gradient**
- **Increase from 450 to 550 bunches eventually caused vacuum incident**
  - The "straw that broke the camels back!"

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## ACC4-6 RF Power Distribution

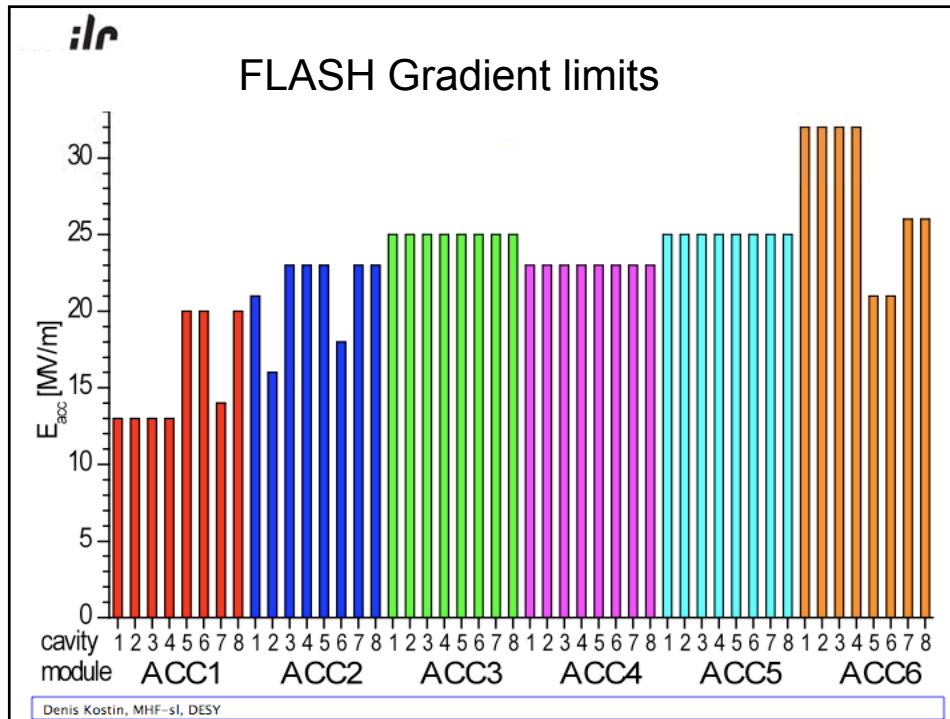
Waveguide distribution for klystron #4 (status 06.08.07)



### Waveguide component limits

- **Design**
  - High power part: 5MW max



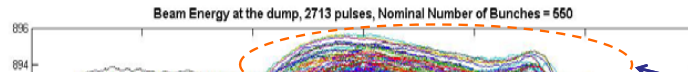


## Accelerating Modules

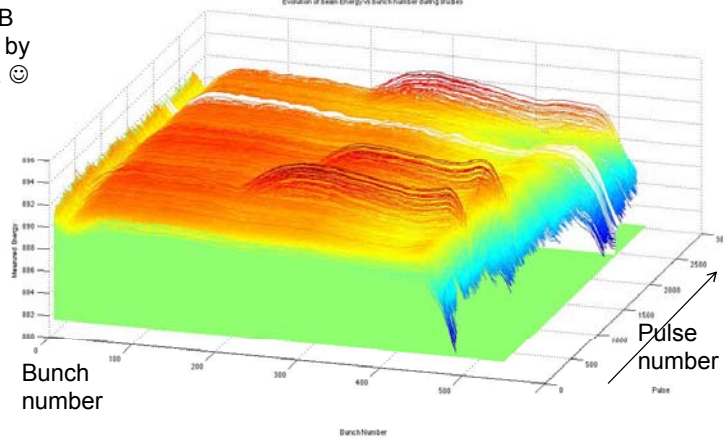
Six accelerating modules were installed into the TTF tunnel as a part of the FLASH Linac  
 Each module has 8 superconducting cavities and RF power input couplers

position	module	type	assembled	coupler type	cold window	warm window
ACC1	2*	II	Jan. 2004	FNAL/TTF III	Conical/Cyl.	Planar/Cyl
ACC2	1*		Mar. 2000	FNAL/TTF II	Conical/Cyl.	Planar
ACC3	7		Dec. 2006	TTF III	Cylindrical	Cylindrical
ACC4	4	III	Jul. 2001	TTF II	Cylindrical	Plane, WG
ACC5	5		Jun. 2007	TTF III	Cylindrical	Cylindrical
ACC6	6		May. 2006	TTF III	Cylindrical	Cylindrical

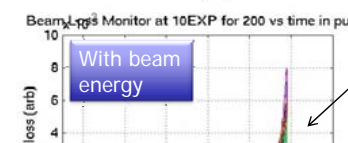
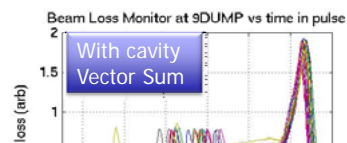
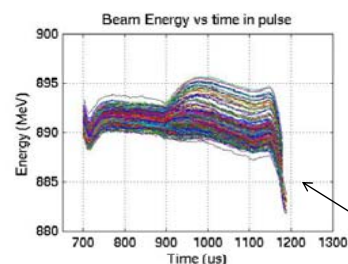
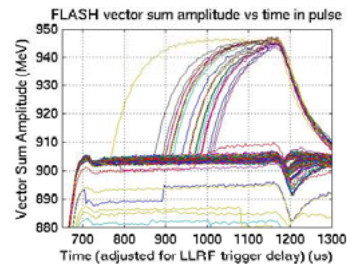
## Beam energy at the dump



MATLAB  
artwork by  
John C. ☺



## Correlation of beam loss with cavity vector sum and beam energy

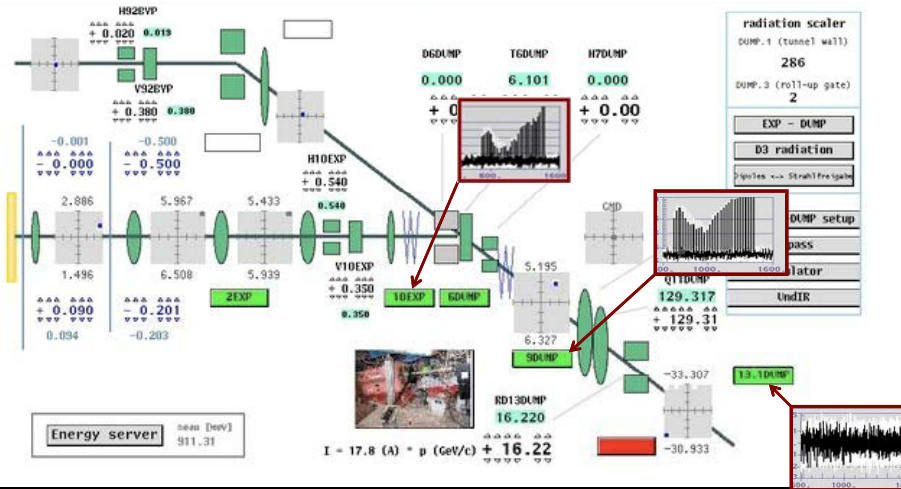


Beam not centered in the energy aperture?



## Beam losses signatures in dump region during tuning

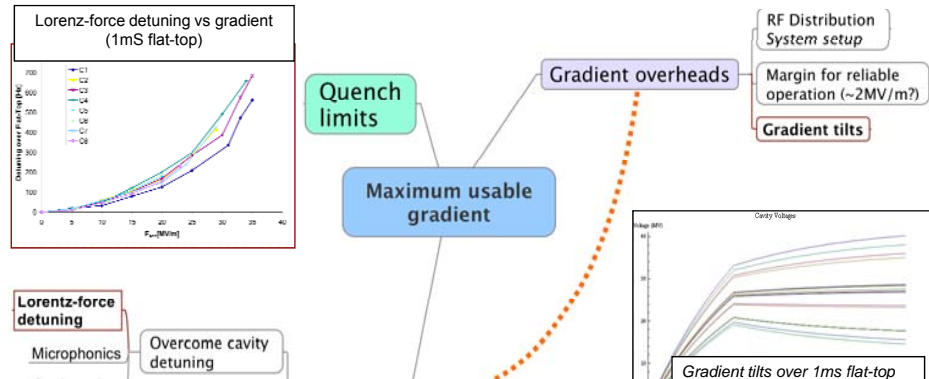
(30 bunches @ 50KHz)



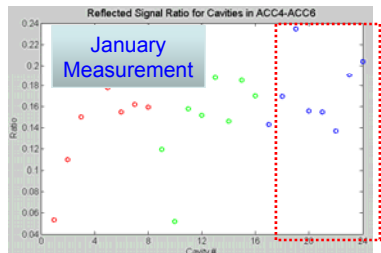
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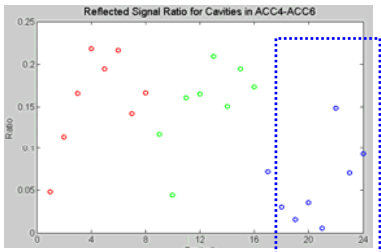
## FLASH cavity gradient limits: Assessing maximum achievable gradients



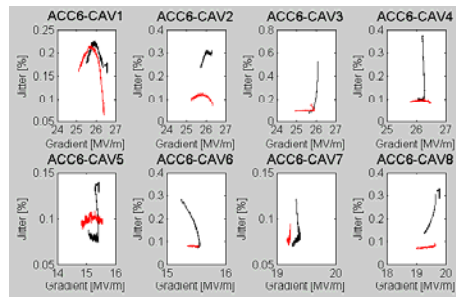
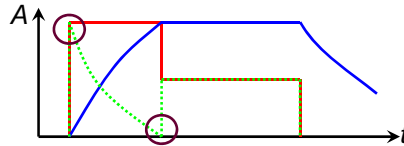
## Reflected Ratio for Piezo On/Off



Piezo Off with Nominal Initial Detuning



Piezo On with Nominal Initial Detuning

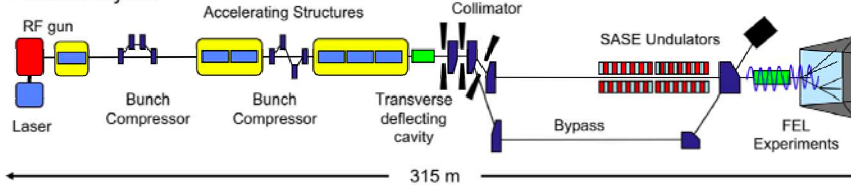


Red → Nominal Initial Detuning with Piezo Off.  
Black → Nominal Initial Detuning with Piezo On.

Piezo works well to reduce the reflection ratio (hopefully will minimize the rf power overhead) but adds some jitter as expected.

## FLASH Upgrade 2009/2010

Present layout



New layout

