Low-level RF Development for FLASH and ILC

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ASD Seminar, 7th January 2013

Outline

- Overview of FLASH facility
- High-level RF architecture
- Pulse-to-pulse and intra-pulse LLRF control
  - Cavity field regulation
  - Cavity resonance control using fast piezo tuners
- LLRF issues for ILC
  - Operation close to cavity quench
  - Klystron linearization
- Wrap-up

FLASH overview

Origins: high energy physics

- LCLS, FLASH, and EU-XFEL all have their origins in HEP (e-/e+ linear colliders)

- **LCLS (originally SLC – Stanford Linear Collider)**
  - Room-temperature X-band accelerating cavities (12GHz)
  - Short RF pulse (100ns), high gradients (100MV/m)
  - Pulse repetition rate: 120Hz, single bunch per pulse

- **European XFEL (derived from the TESLA design)**
  - Superconducting L-band cavities (1.3GHz)
  - Long RF pulse (1.6ms), lower gradients (25MV/m)
  - Pulse repetition rate: 10Hz, up to 3000 bunches in a 650us-long pulse

- **FLASH (TESLA test facility)**
  - Feasibility demonstration of superconducting technology for a linear collider

FLASH at DESY in Hamburg

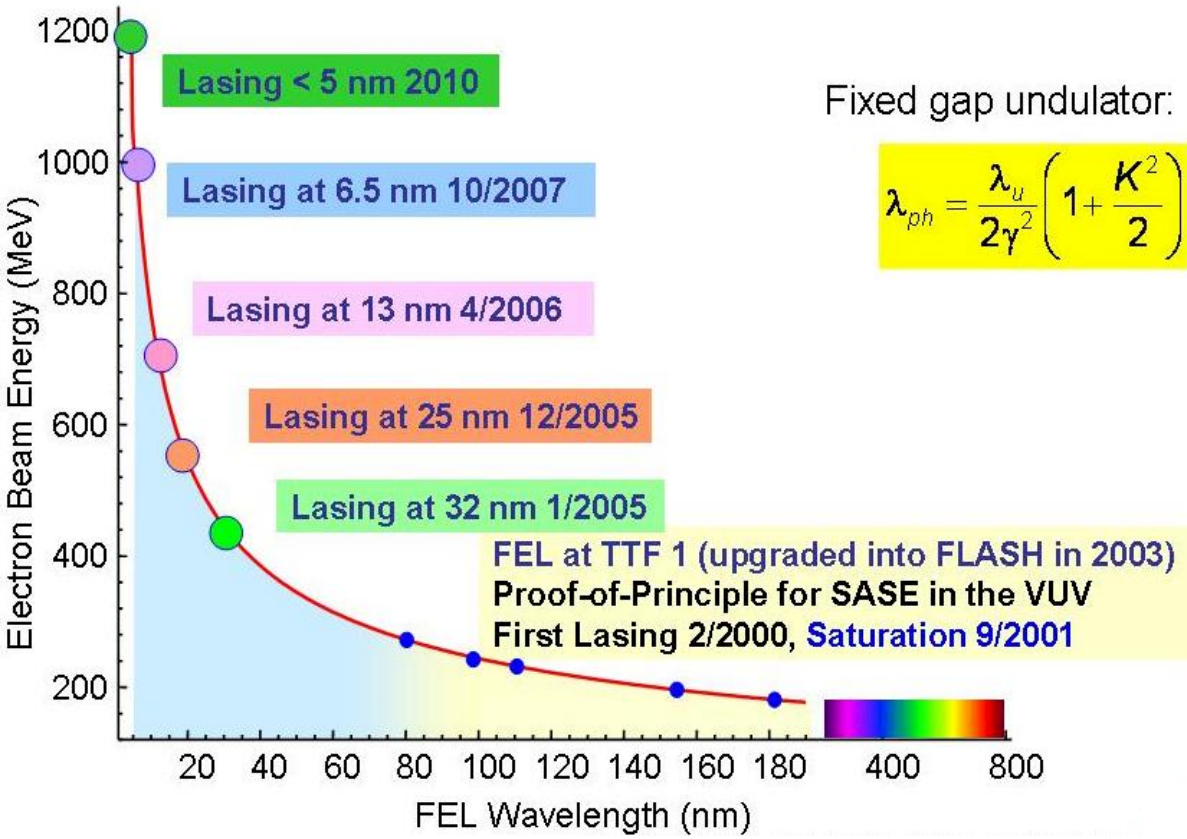
- Many upgrades from original TTF
  - Now capable of 1.25GeV
- Free-electron laser user facility since 2005

- Single-pass high-gain SASE FEL
- Photon wavelength range from vacuum ultraviolet to soft x-rays
- FLASH-II: second undulator line, seeded FEL

- FLASH is also a test bench for the European XFEL and the International Linear Collider (ILC)

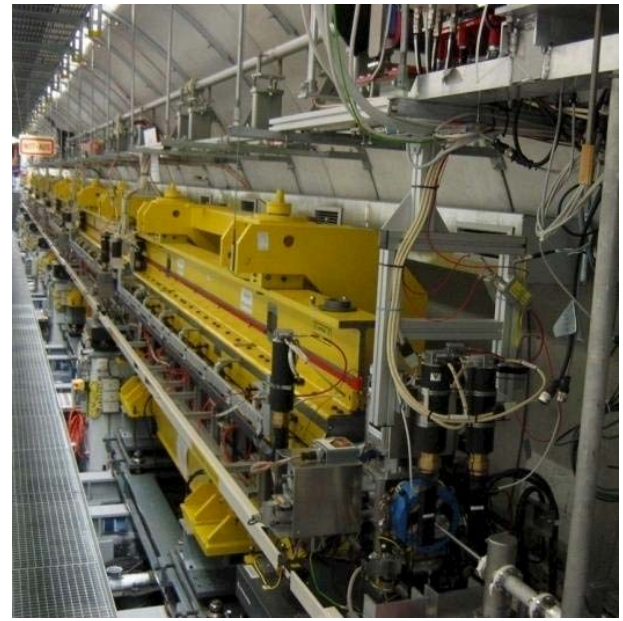
FLASH Undulators

- 6 undulator modules, total length 27 m
- Fixed gap of 12 mm
  - permanent NdFeB magnets
  - peak B = 0.48 T, K = 1.23, period of 27.3 mm



Fixed gap undulator:

$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$



Bunch trains offer the possibility of many measurements in a millisecond)

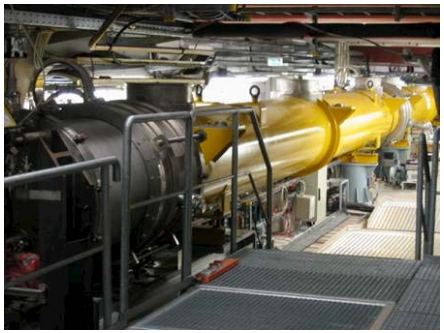
Many FLASH users want long bunch trains …but not if they lose reliability or single-bunch performance

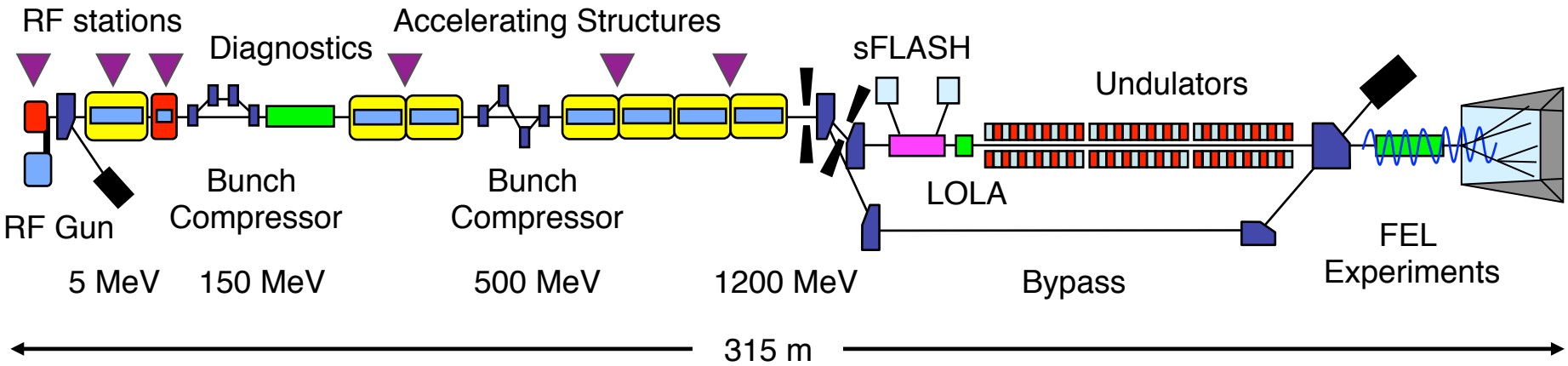
Courtesy: S. Schreiber

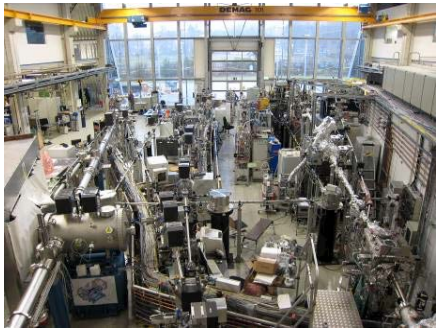
FLASH layout

Main linac building-block:

- 1.3GHz TESLA-type 9-cell cavities
- Groups of 8 cavities per cryomodule





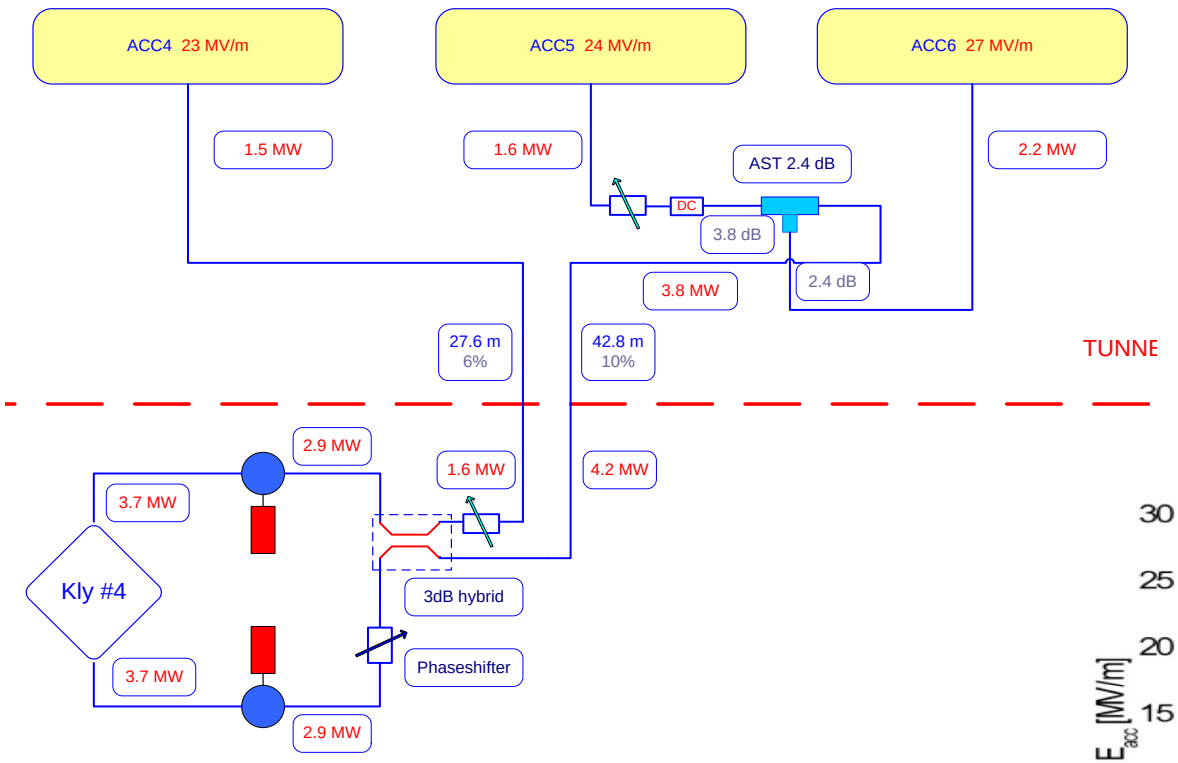


Courtesy: S. Schreiber

TESLA 9-cell cavity FLASH cryomodules

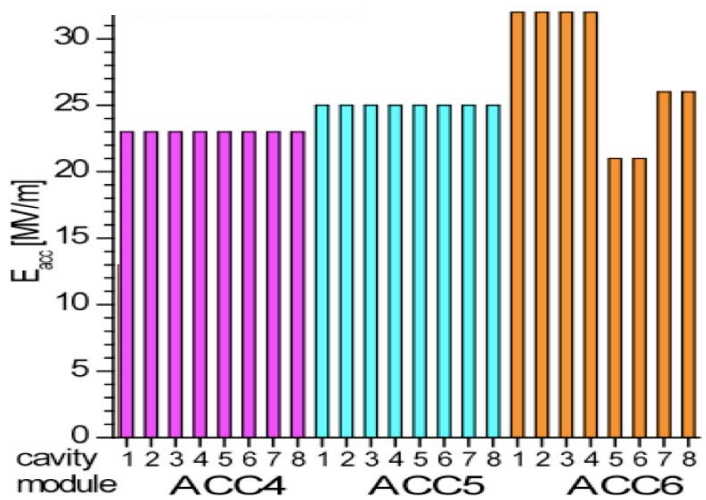
FLASH RF system layout

HLRF configuration: single klystron feeds many cavities



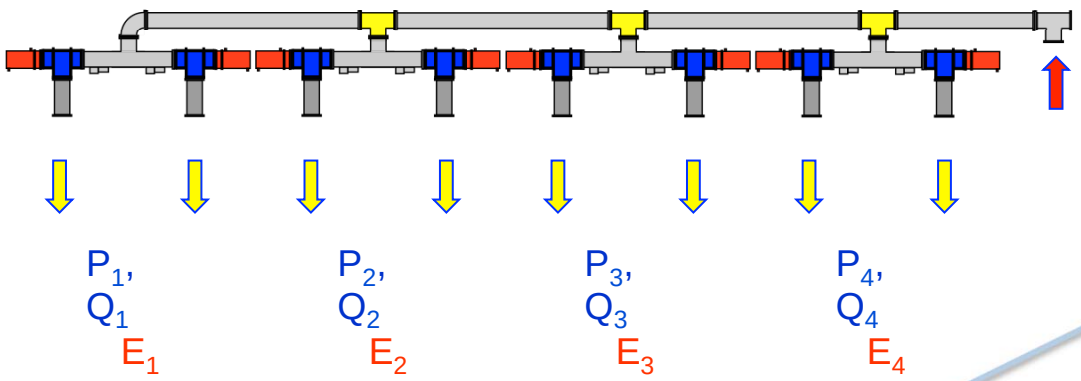
For each cavity:

- Power divider
- Phase shifter
- Input circulator
- Mechanical tuner + piezos

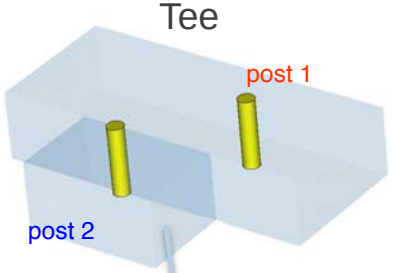


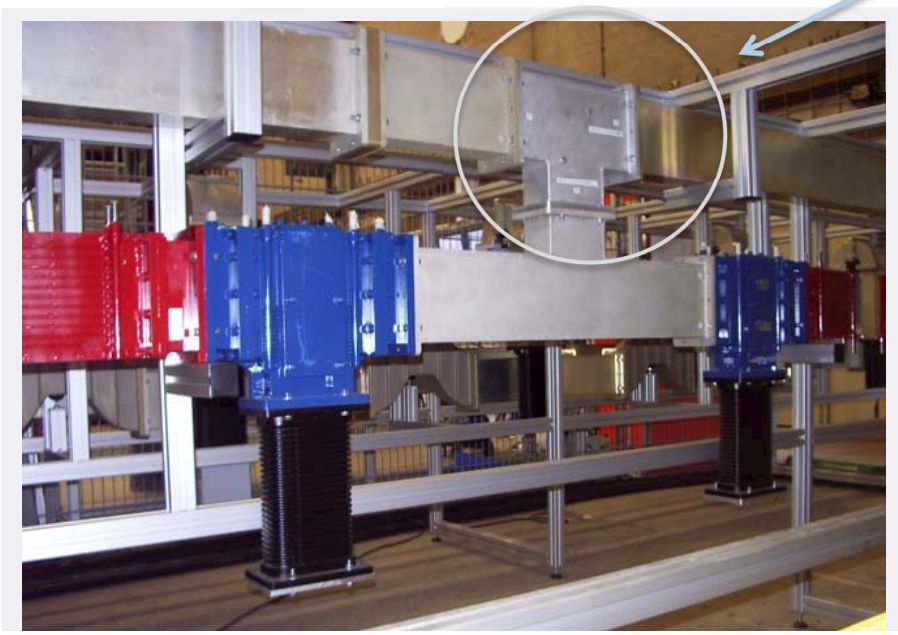
- One klystron means one knob for all 24 cavities.
- LLRF regulates the vector sum of the cavity fields

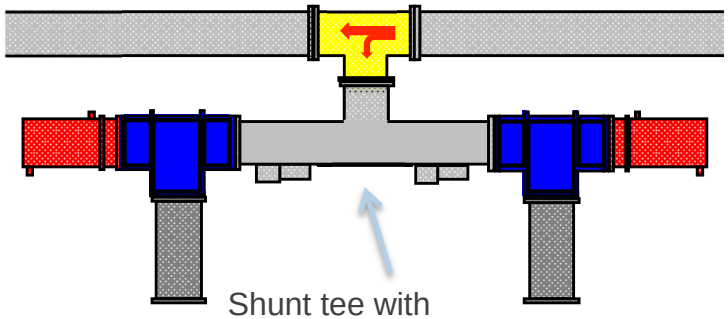
FLASH waveguide distribution system (ACC6)



Asymetric Shunt Tee







Shunt tee with integrated phase shifter

- Posts in AST are fixed in place during manufacture – locations are determined analytically from the desired power ratio.
- Measured ratio is typically within +/-0.1dB of the design value
- To change the power ratio, would have swap out the ASTs with a new set (requires 2-3 days tunnel access)

Single klystron for many cavities: Regulate vector-sum of cavity fields

Benefits of vector-sum control

- *Significant cost savings*
- More-direct regulation of what the beam sees (total energy gain)
- Effect of uncorrelated noise-sources is reduced by sqrt of number of cavities
- Lower maintenance
- Fewer units to be controlled

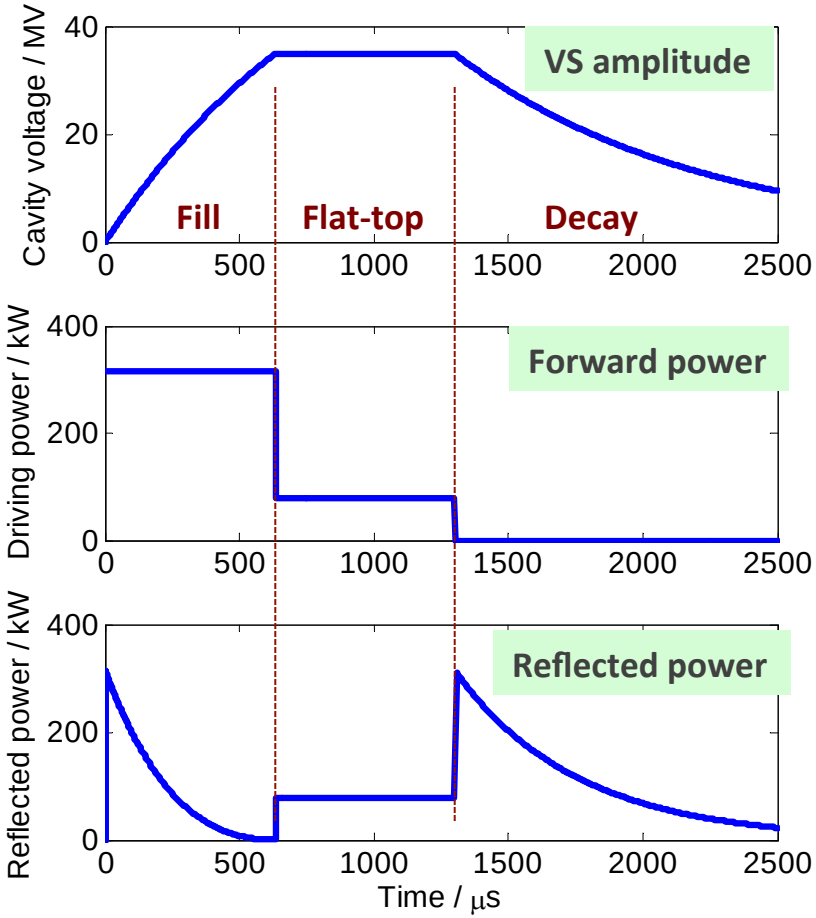
Disadvantages of vector-sum control

- Calibration of vector-sum is challenging
- No regulation of individual each cavity fields (if that's important)
- RF power distribution must be precise in order to get highest total energy gain
- By-passing of individual cavities is more difficult

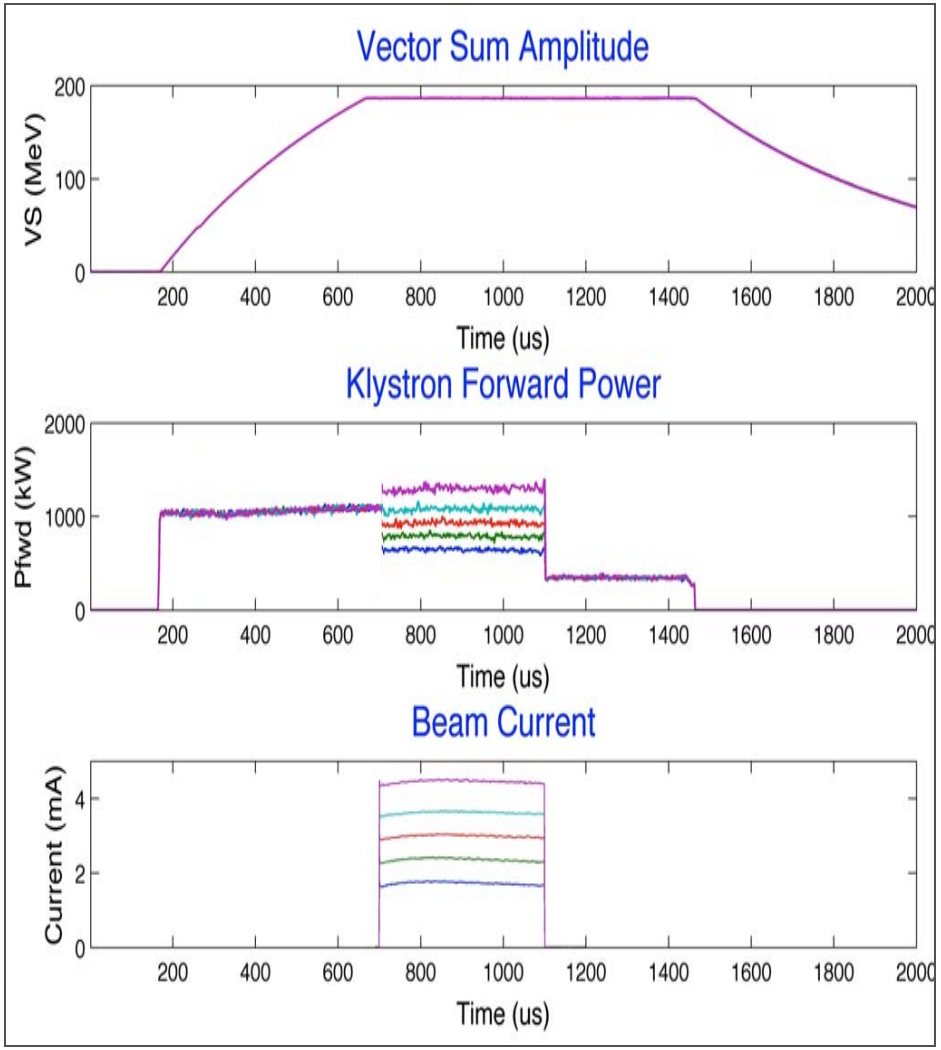
Pulse-to-pulse and intra-pulse LLRF control

RF pulse profile

No-beam waveforms

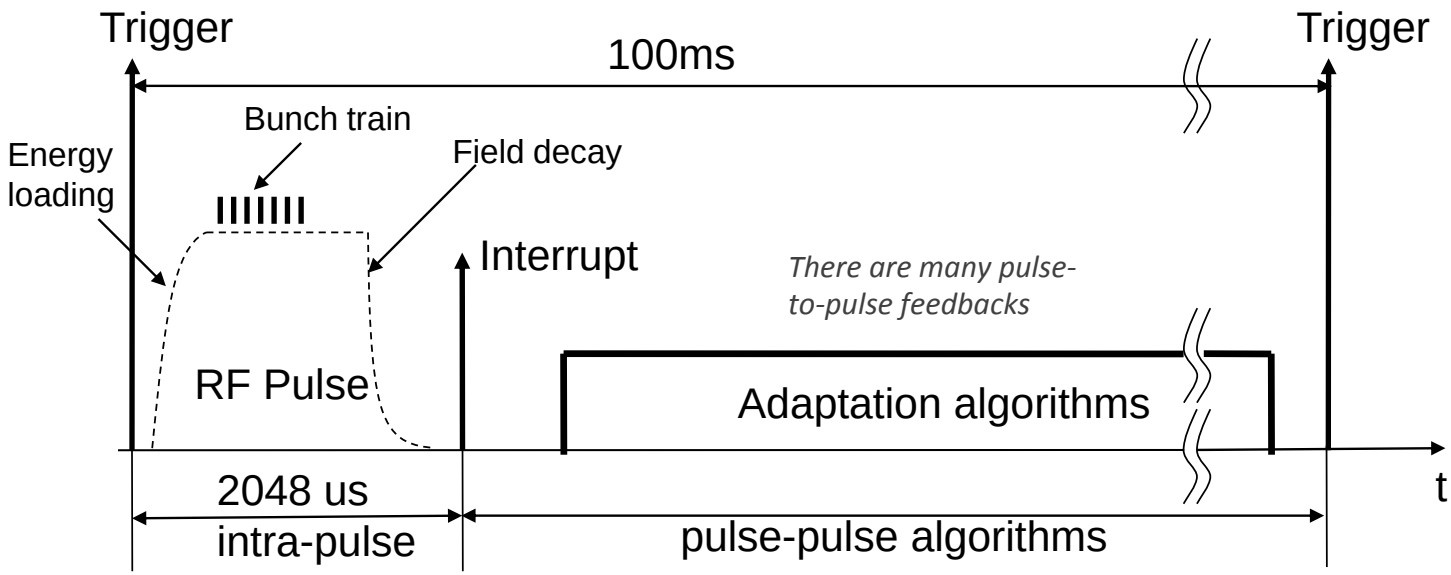


With beam-loading



Regulation following the transient from fill to flattop is the most significant LLRF challenge!

FLASH pulsed mode operation



LLRF control systems stabilize field in the cavities:

- Intra-pulse feedback
- Pulse-pulse feedback

Beam based feedback stabilize beam properties

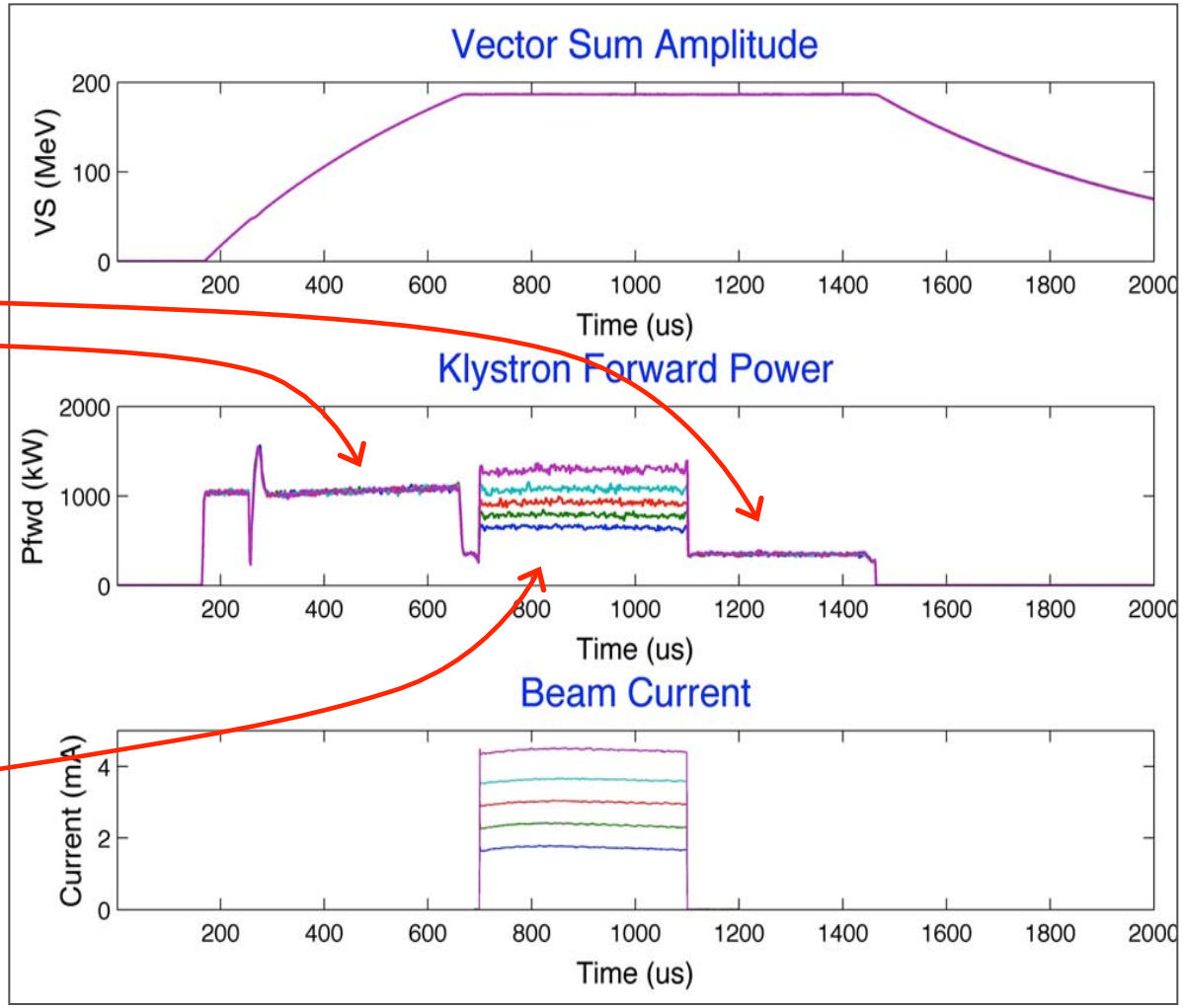
- Intra-train feedback
- Pulse-pulse feedback

Components of the RF Power feed-forward

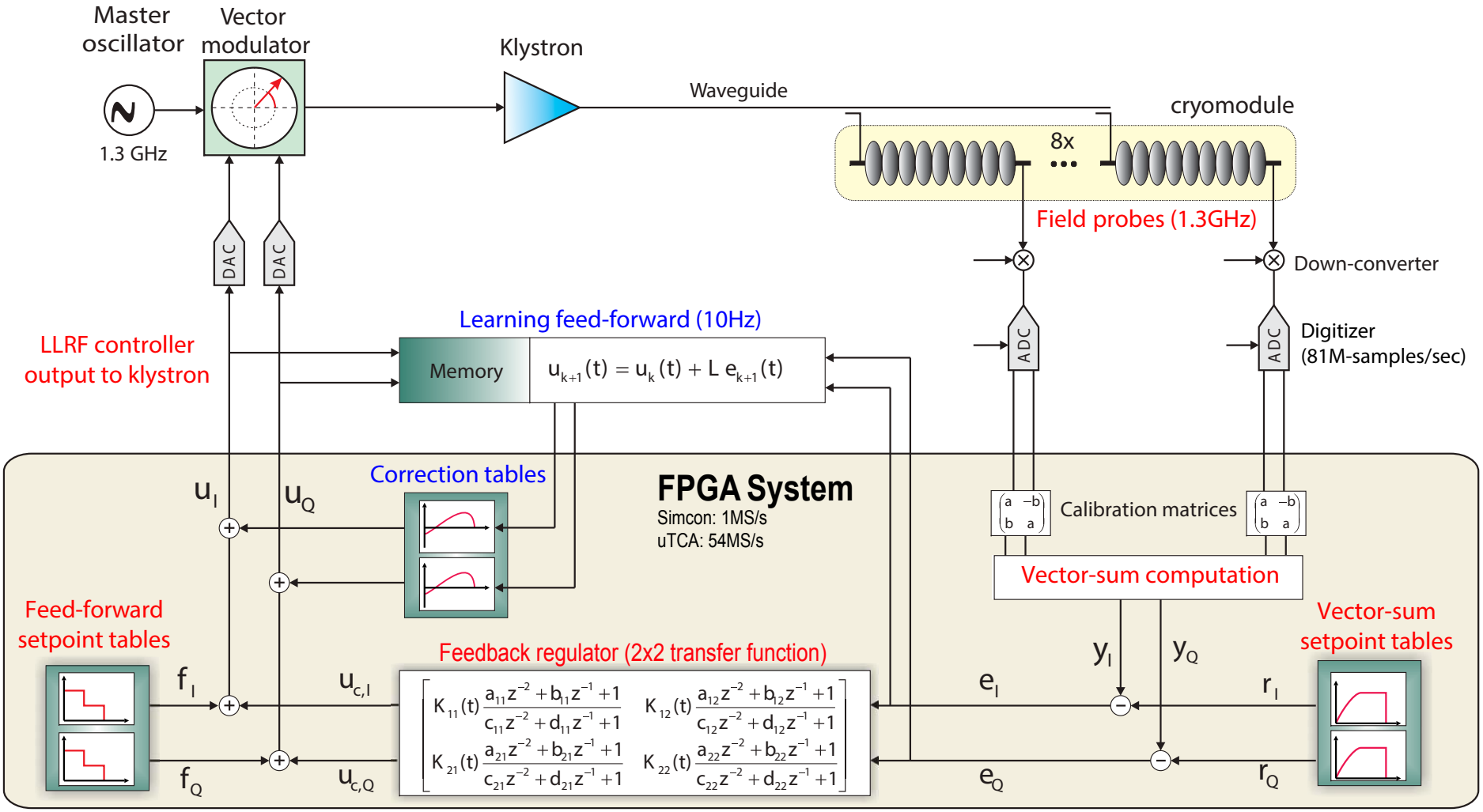
RF power for fill and flat-top are pre-computed from the required vector sum

Learning FF controller fine-tunes the RF power waveform to minimize repetitive errors in vector sum

Beam-loading compensation feed-forward is added during beam-on period (scaled by the bunch charge)



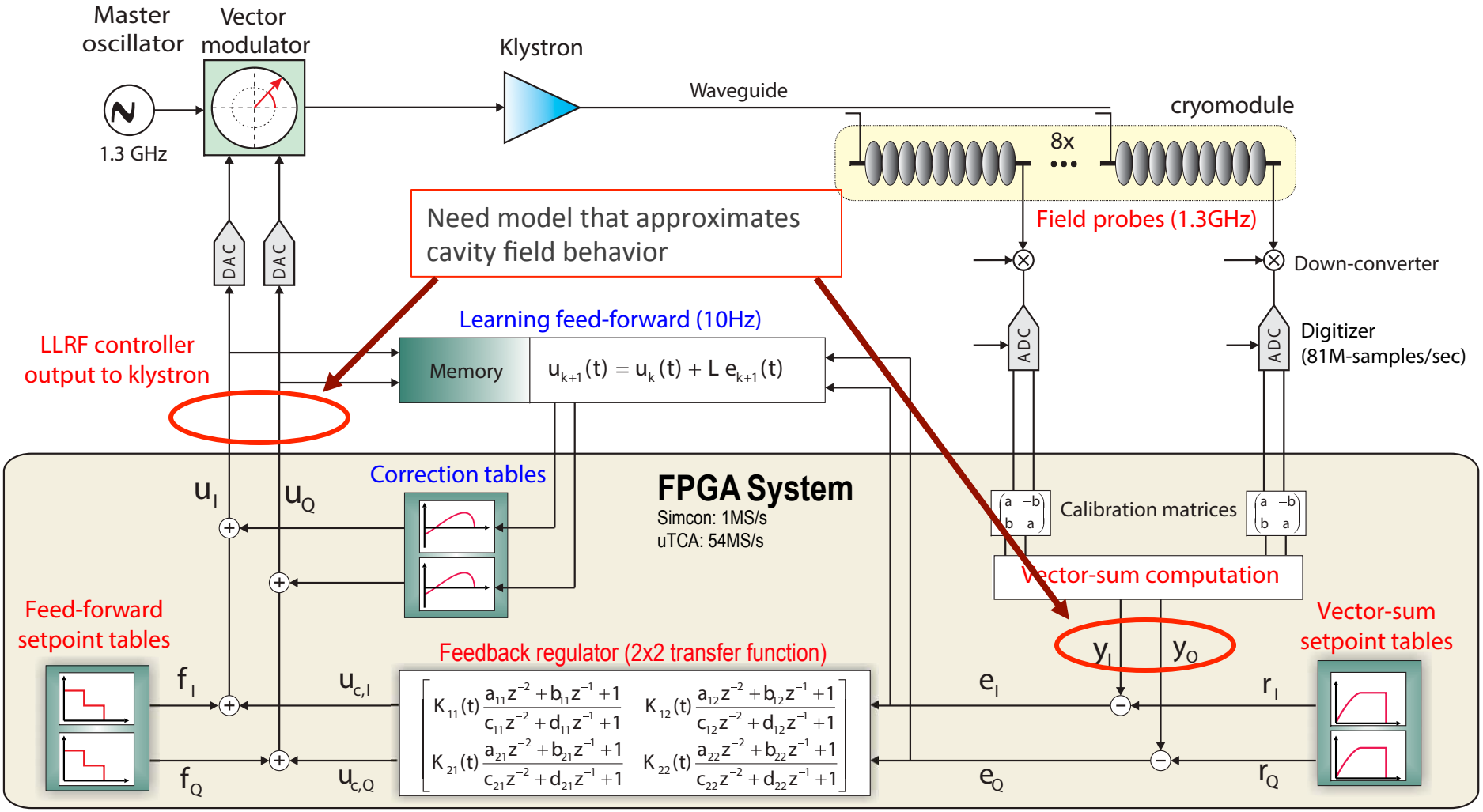
LLRF control schematic: MIMO controller



(Vector computations, performed in In-phase/quadrature space)

Courtesy: C. Schmidt

LLRF control schematic



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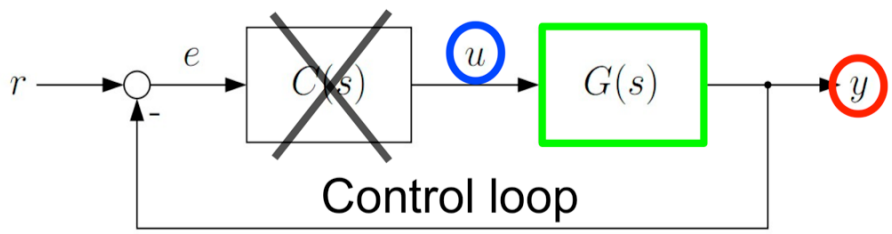
System Identification: grey box model

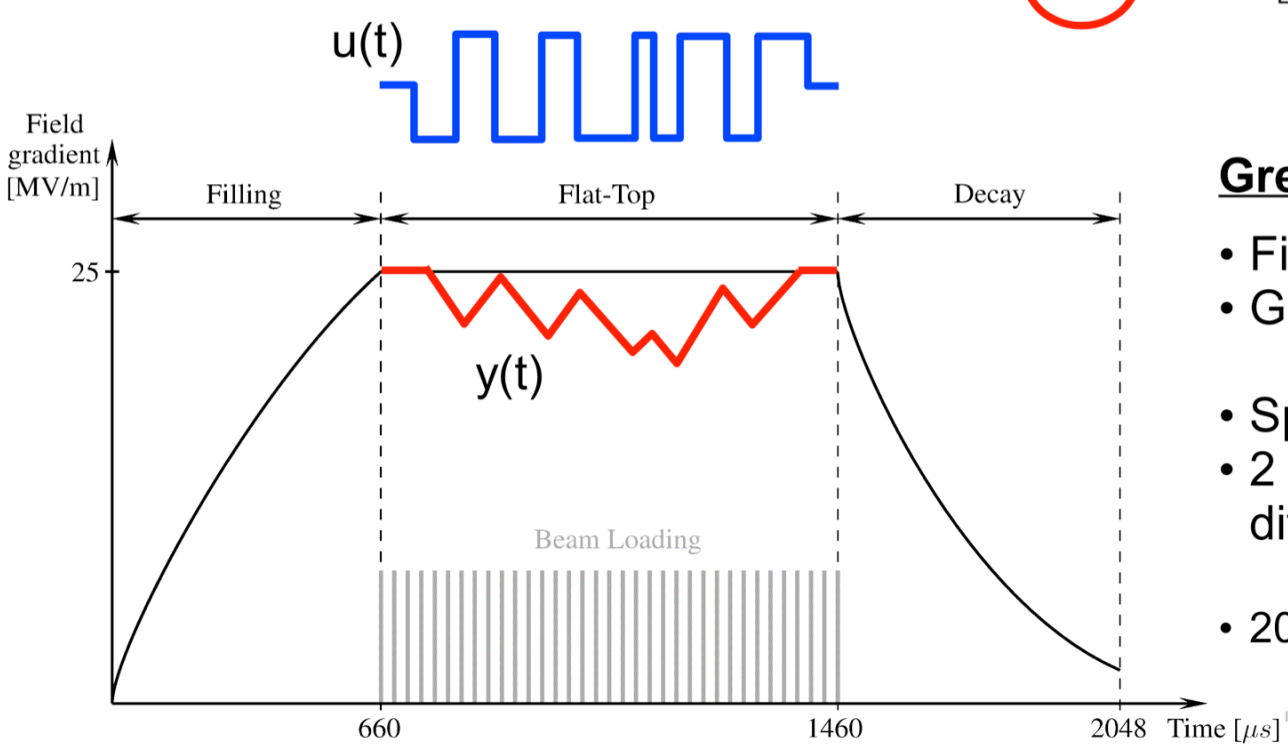
Pulsed mode
Limited excitation time – Flattop



- Bandwidth (1 real pole)
- Resonant modes (8/9 pi mode,...)
  (2 poles – complex conjugate pole pair)

$$x(k+1) = \begin{bmatrix} \Phi_r & 0 \\ 0 & \Phi_c \end{bmatrix} x(k) + \begin{bmatrix} \Gamma_r \\ \Gamma_c \end{bmatrix} u(k)$$

$$y(k) = \begin{bmatrix} C_r & C_c \end{bmatrix} x(k)$$



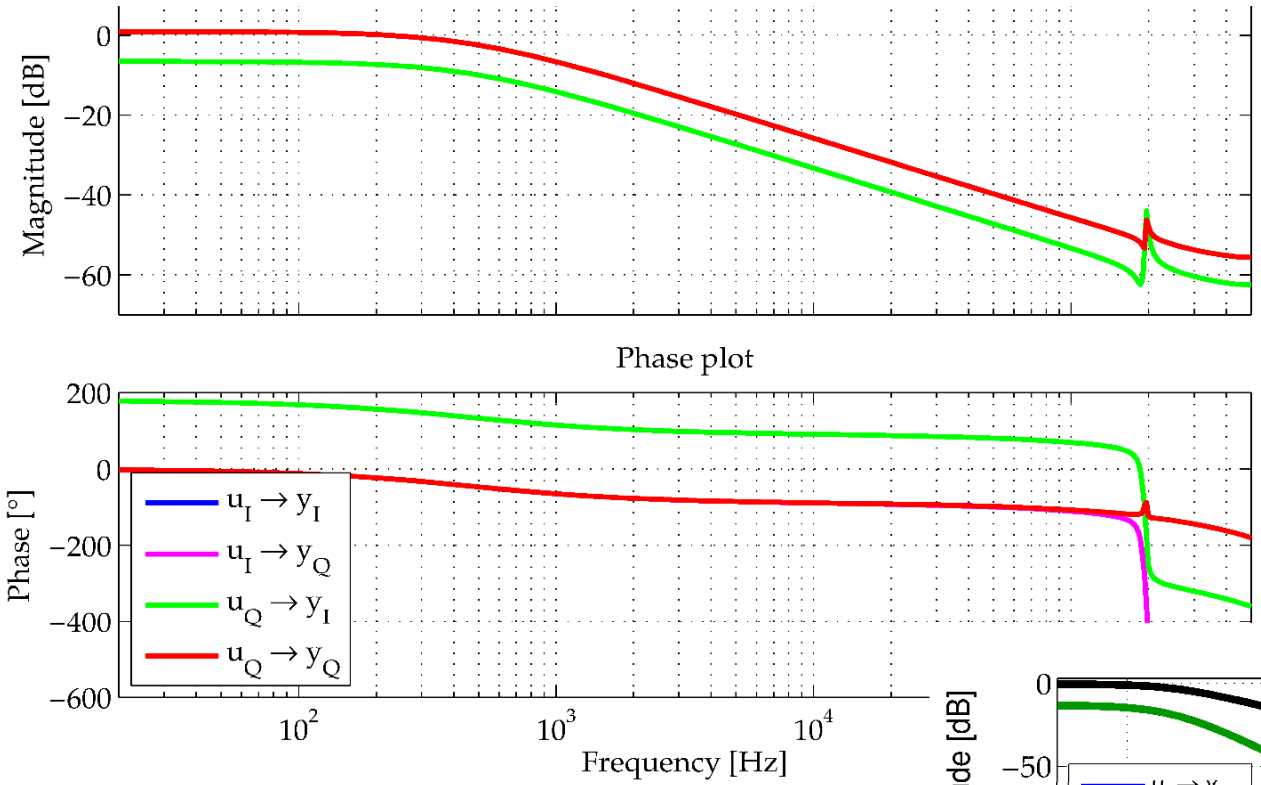
Grey box model:

- Fixed model structure
- Get physical insight

- Specific excitation signals
- 2 step identification for different frequency ranges

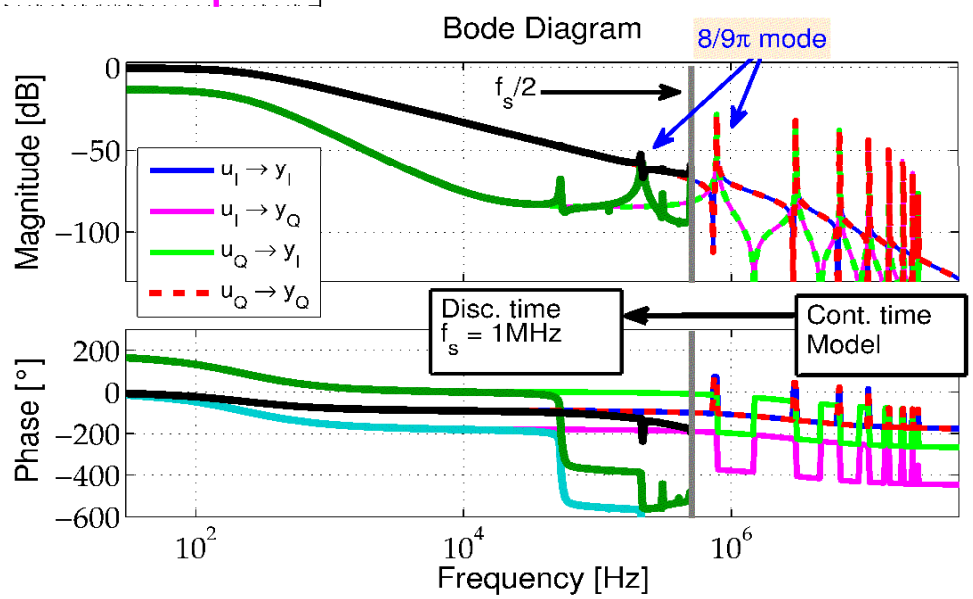
- 200Hz vs. 200kHz (800kHz)

System identification: bode plot

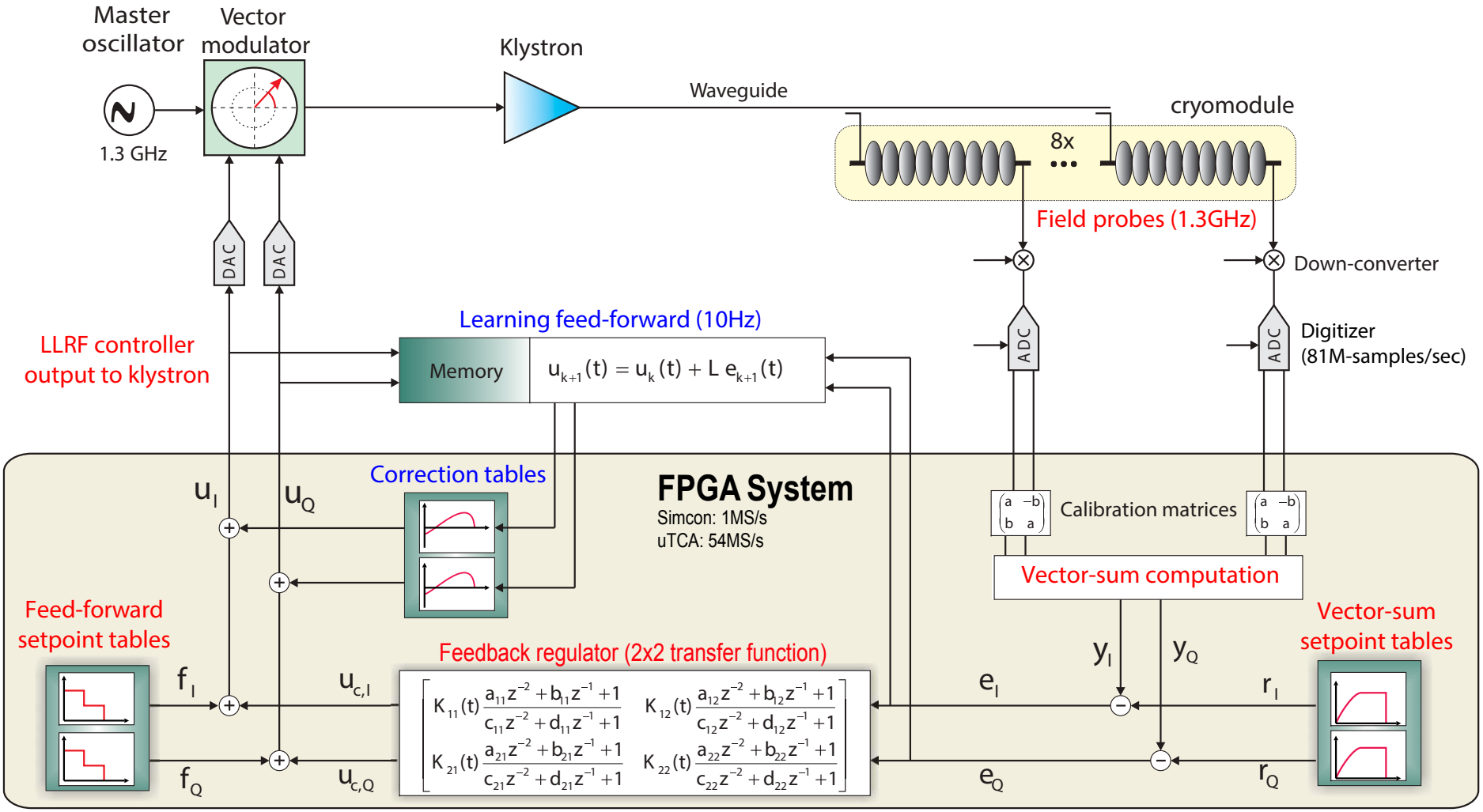


System Identification ACC1

Theory



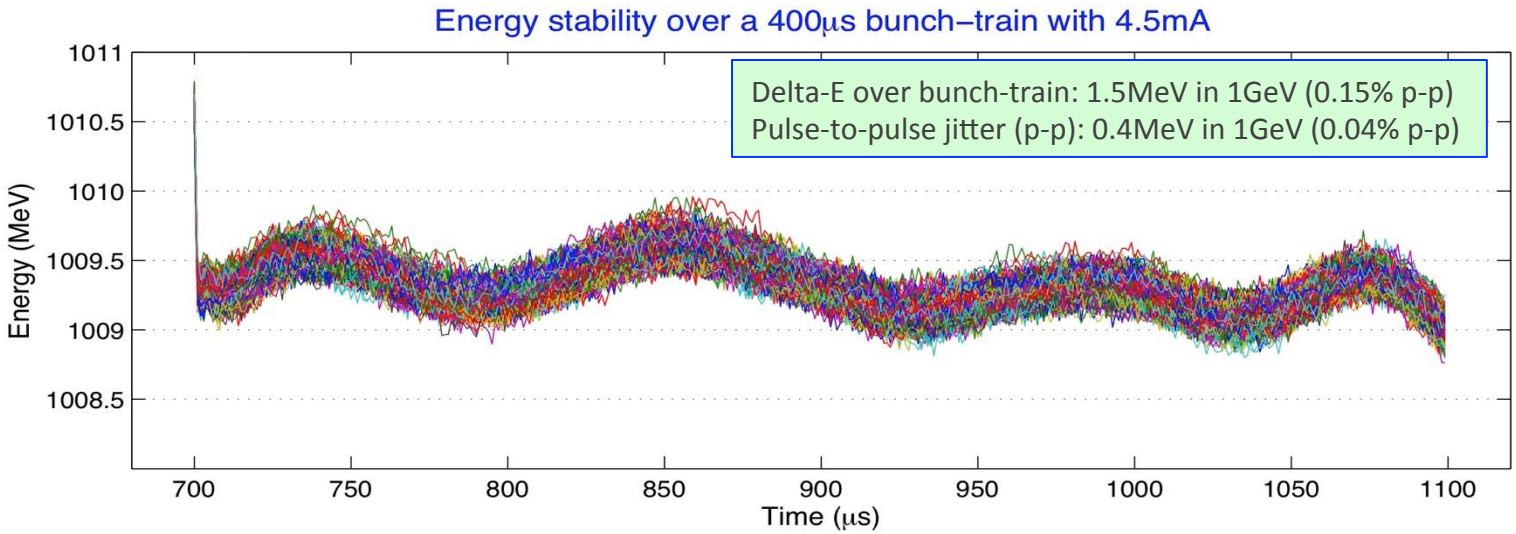
LLRF control schematic: MIMO controller

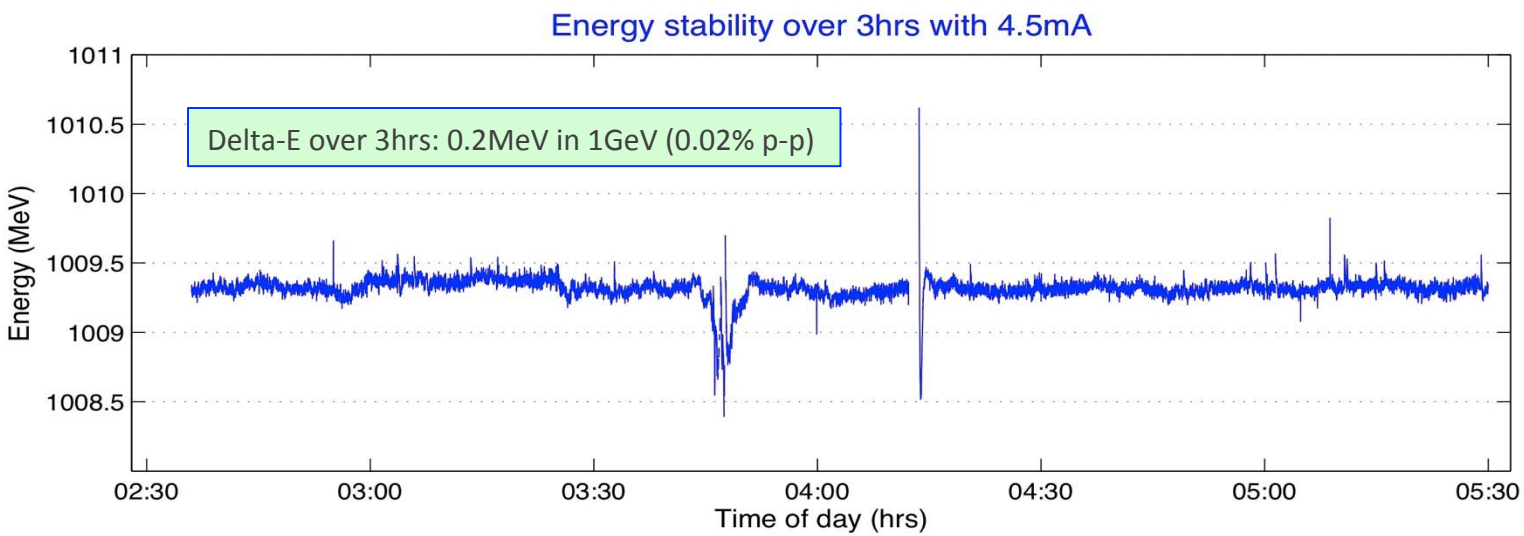


(Vector computations, performed in In-phase/quadrature space)

Courtesy: C. Schmidt

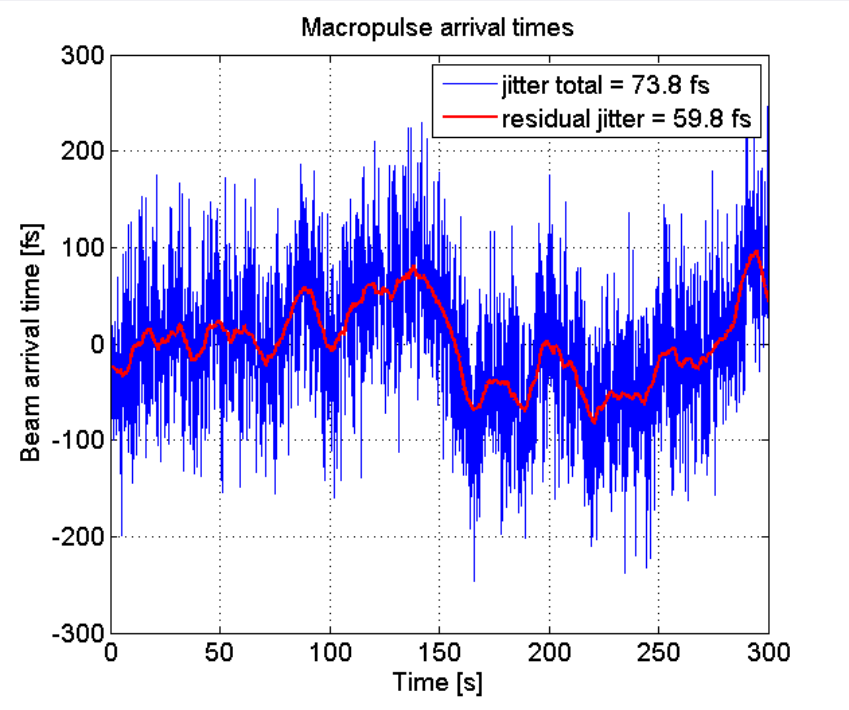
Achieved short-term and long-term energy stability (before inclusion of beam-based feedback)



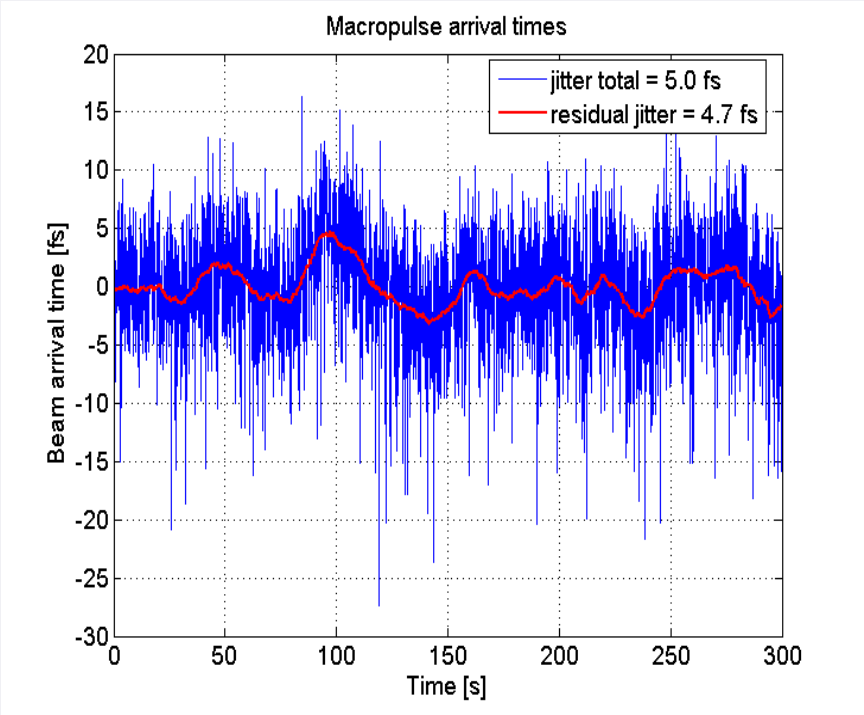


Improvements in pulse to pulse jitter from adding bunch arrival-time feedback to injector LLRF systems

No Beam Based Feedback
Learning Feed Forward ON
rms = 74 fs



With Beam Based Feedback
running in ACC1 and ACC39
rms = 5 fs



LLRF Regulation → $\Delta A_1 / A_1 \sim 10e\text{-}4$

$\Delta\varphi_1 < 0.03^{\circ}$

- rapid fluctuations averaged out
- resolution of BAM ~ 10 fs for single shot

FLASH LLRF system hardware

- **Digital FPGA-based controller**
  - -Third-generation currently installed ('SimconDSP')
  - -Gun/ACC23/ACC45/ACC67
  - - IF=250kHz, IQ-sampling scheme
  - - Sampling rate 81MHz (use averaging)

- **Upgraded for new 3.9GHz cavity**
  - -New RF down converter & LO generation with IF=54MHz, non IQ-sampling, LO = 3954MHz
  - - Sampling rate 81MHz

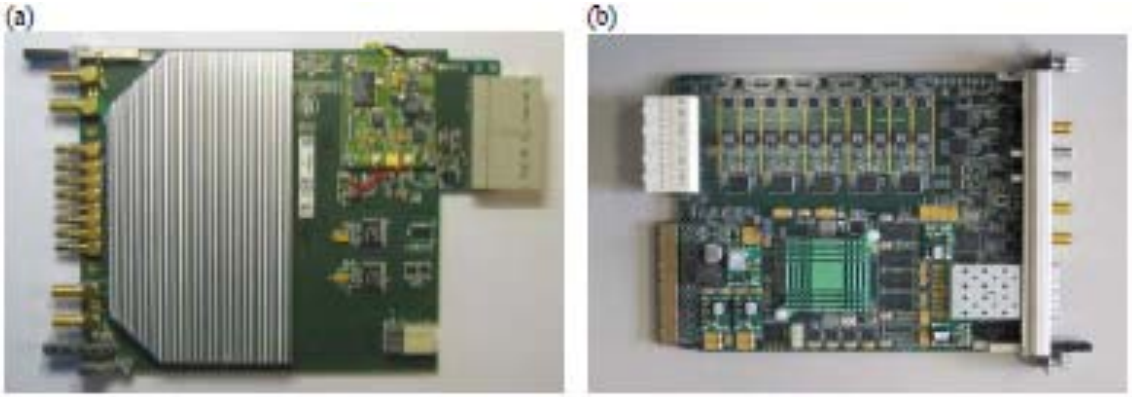
- **2013: uTCA-based system (XFEL prototype)**
  - -New RF down converter & LO generation with IF=54MHz, non IQ-sampling, LO = 3954MHz
  - - Sampling rate 81MHz
  - -Control loop operating at 9MHz

VME-based SimconDSP

10 Channel 14bit ADCs
81 MHz clock rate
8 DAC, 14 bits
2 Gigalinks
FPGA: XILINX Virtex II pro

Hardware changes: Layout of uTCA LLRF system

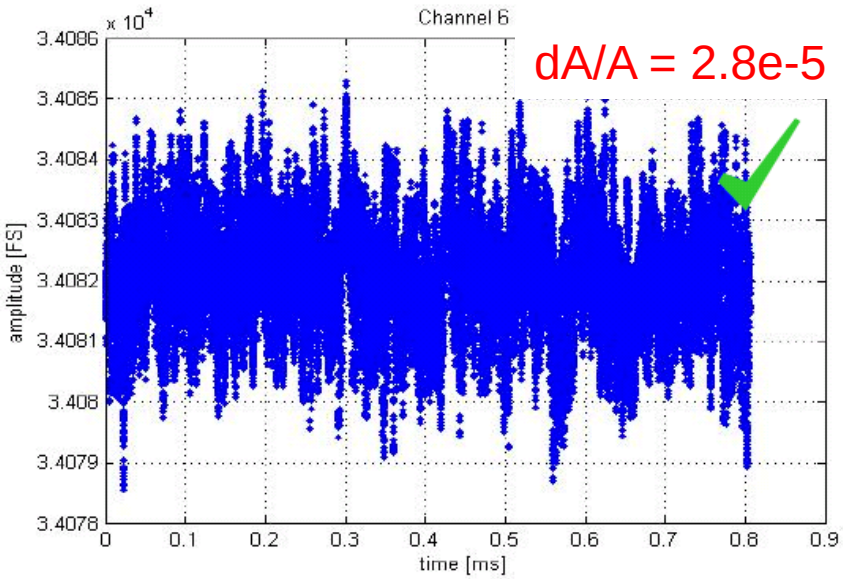
Laboratory test of DCW & ADCs successful:

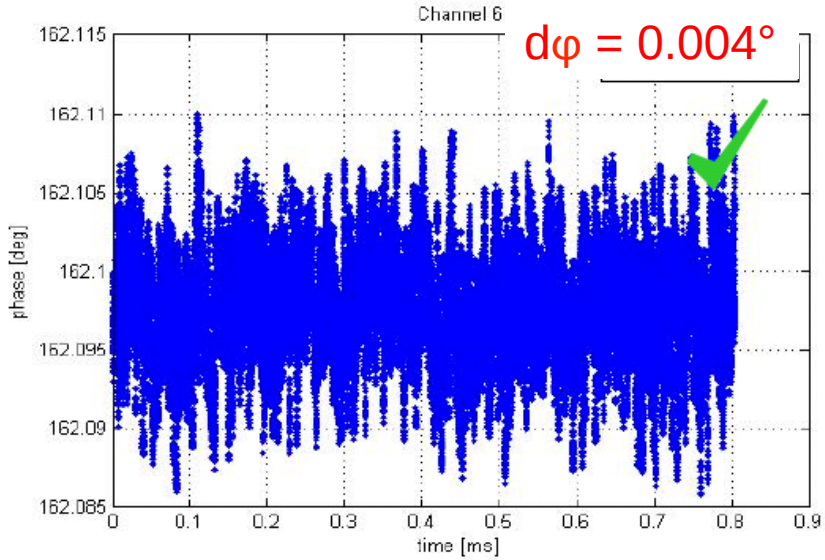


Single cavity approximately 5 times better resolution than current system

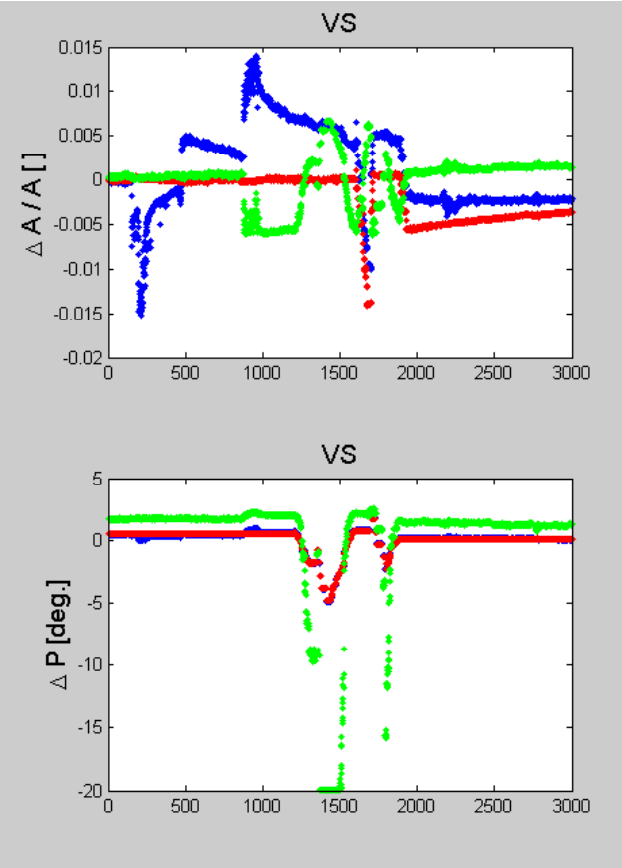
Tests at FLASH July 2011

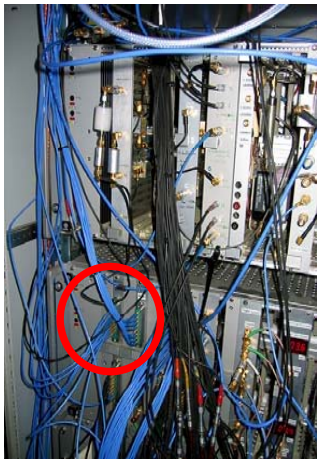
=> Talk from Frank Ludwig





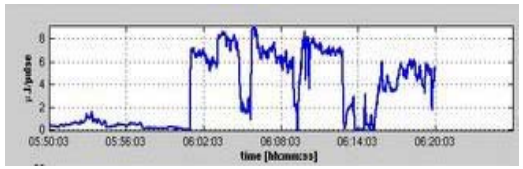
Cautionary tale: mechanical stability of RF cables





Cable test in the injector, approx. 2mm motion!!!
ACC1,DEV1 LFF ON, Gain=50, Pyro Feedback OFF
Action:
6:01h: shot 130 DEV Injector door open (probe cable touch inner door)
6:02h: shot 200 DEV Probe cable bunch (Attenuator to DWC 1300MHz)
6:03h: shot 300 DEV IF cable bunch (baseband DWC to ADC)
6:04h: shot 400 DEV RF MO signal to VM
6:04h: shot 450 DEV Injector door close
6:05h: shot 700 ACC1 Probe cable bunch DWC input (sensitive,cause interlocks)
6:05h: shot 1200 ACC1 phase readjustment
6:11h: shot 1700 (approx) ACC1 Probe cable bunch 1/2" top rack, attenuator partly not fixed!
6:13h: shot 2500 New MO Main bunch distribution (right panel, middle rack 2)

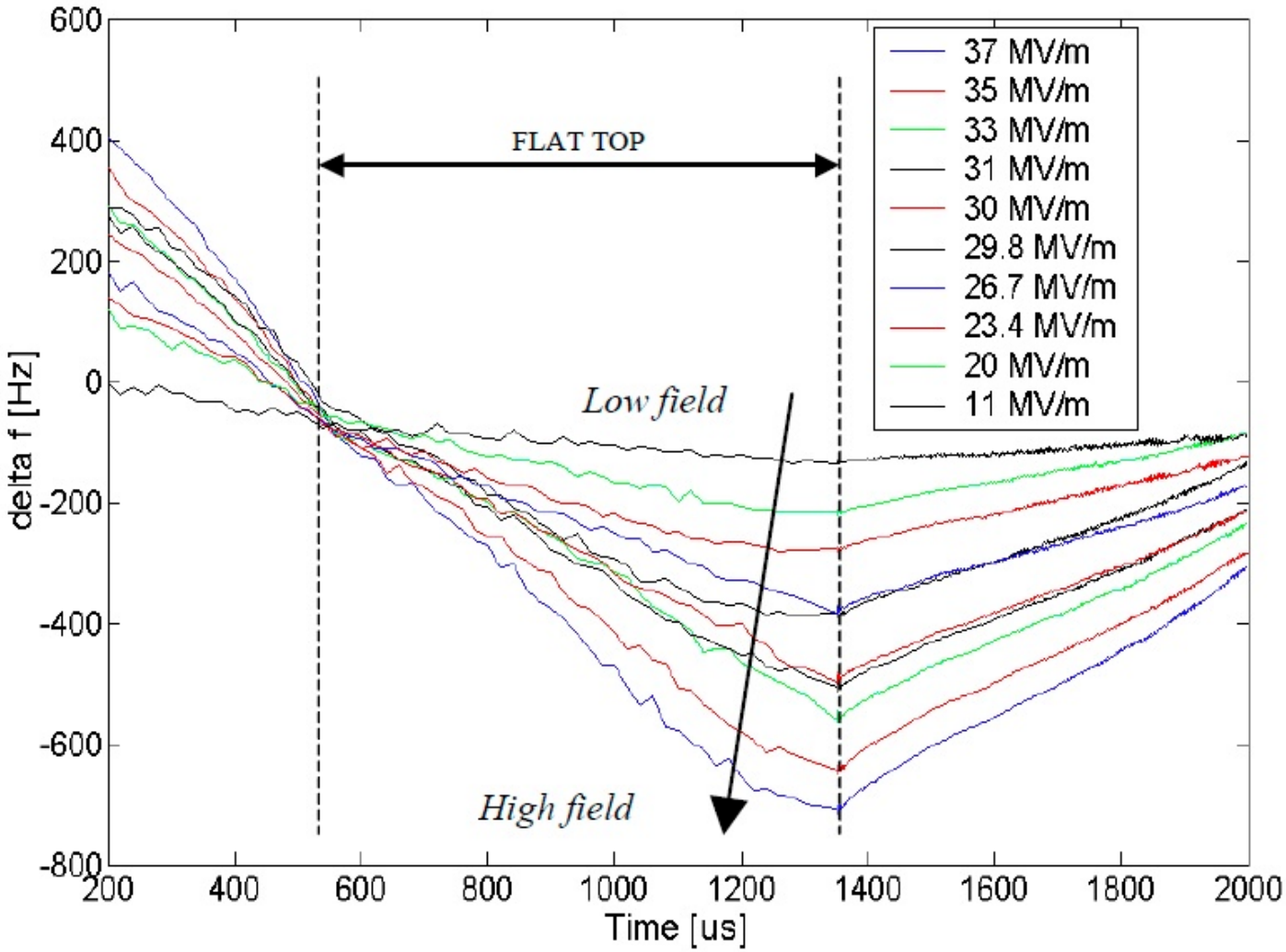
SASE:



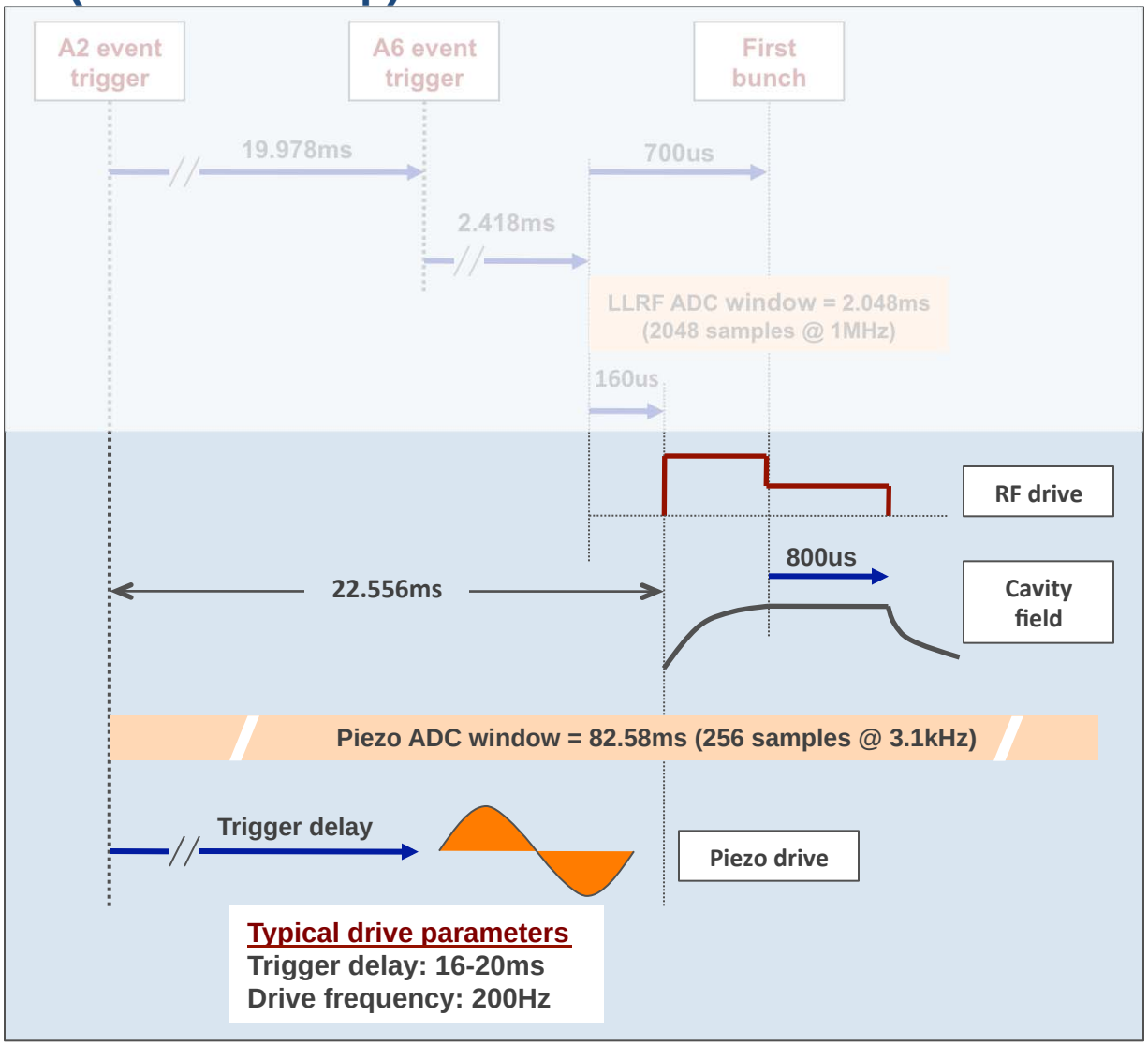
- Driftcalibration in phase and amplitude
- Short ACC1 ½“ type pickup cables
- Field detectors located at cavities
- N-Type connectors -> PCBs

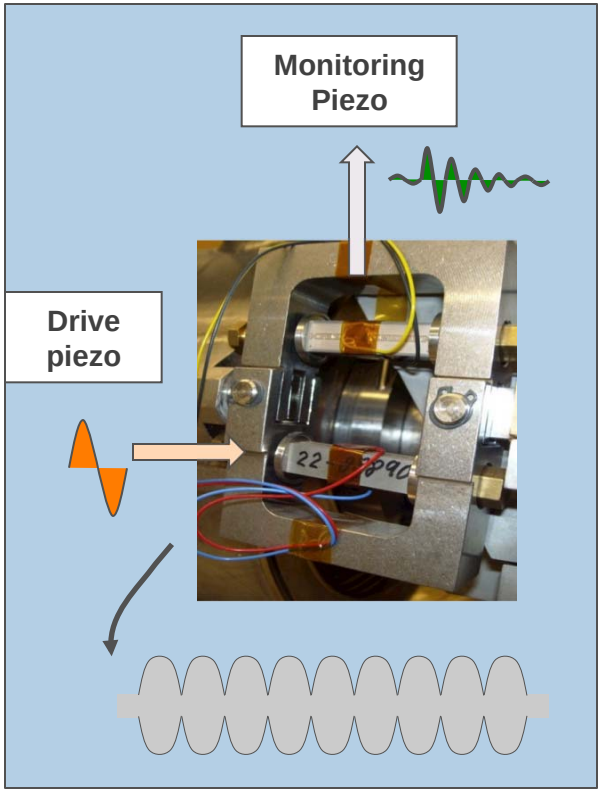
Cavity resonance control using piezo tuners

Lorentz-force detuning evolution over 2ms pulse



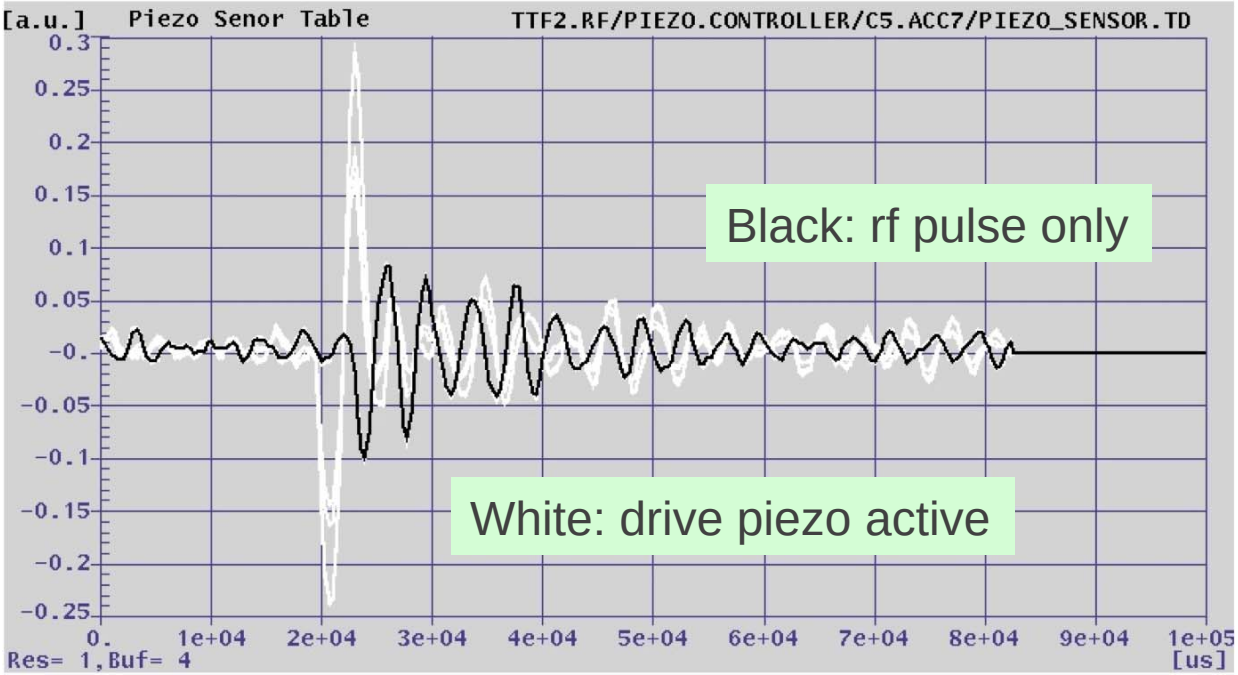
Compensation of LFD using fast piezo tuners by
(nominal setup)





Aim is to excite mechanical resonances to oppose RF-pulse induced Lorentz forces

Cavity mechanical motion from RF pulse and piezo drive (80ms timescale)

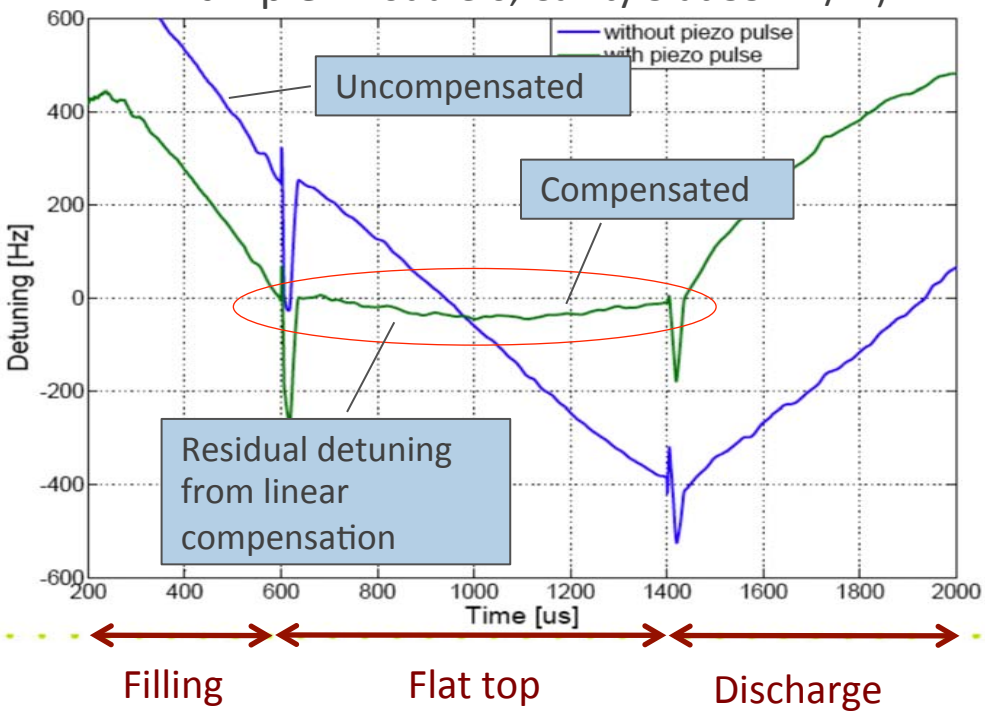


- The ping used for Lorentz-force detuning compensation is quite large compared with the ping from the cavity itself

Detuning compensation study using piezos

- Piezo tuners are installed and operational at ACC56
- Detuning compensation is essential for reaching high gradients

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



- Feed-forward compensation has been demonstrated on FLASH at up to 35MV/m and with heavy beam loading
- Pulse-to-pulse feedback is used for updating feed-forward waveforms and for stabilizing static detuning

Online calculation of detuning

Cavity field decay

Forward power to maintain cavity voltage

Forward power to compensate beam loading

$$\Delta f = \frac{1}{2\pi}\left(\frac{d}{dt}\varphi_c + 2\omega_{1/2}\frac{|V_{for}|}{|V_c|}\sin(\varphi_{for}-\varphi_c) + 2\omega_{1/2}\frac{|V_b|}{|V_c|}\sin(\varphi_b-\varphi_c)\right)$$

$\Delta f - detuning,$

$V_c, \varphi_c - field\ amplitude\ and\ phase,$

$\omega_{1/2} - cavity\ bandwidth$

$V_{for}, \varphi_{for} - forward\ power\ amplitude\ and\ phase$

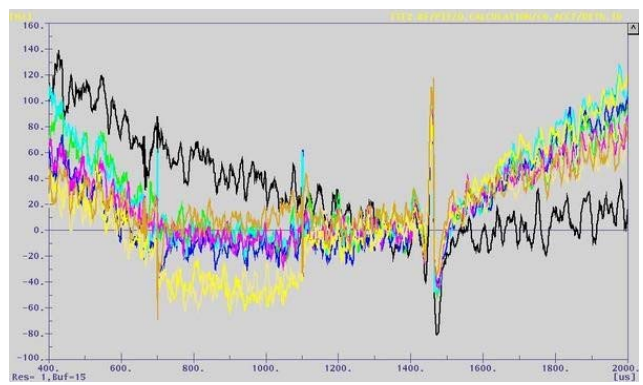
$V_b, \varphi_b - forward\ power\ amplitude\ and\ phase$

Achieving ~Hz accuracy is difficult (Pfwd calibration)

$$V_b = C_b I_b$$

$C_b - calibration\ factor$

$I_b - beam\ current\ (measured\ at\ toroid)$



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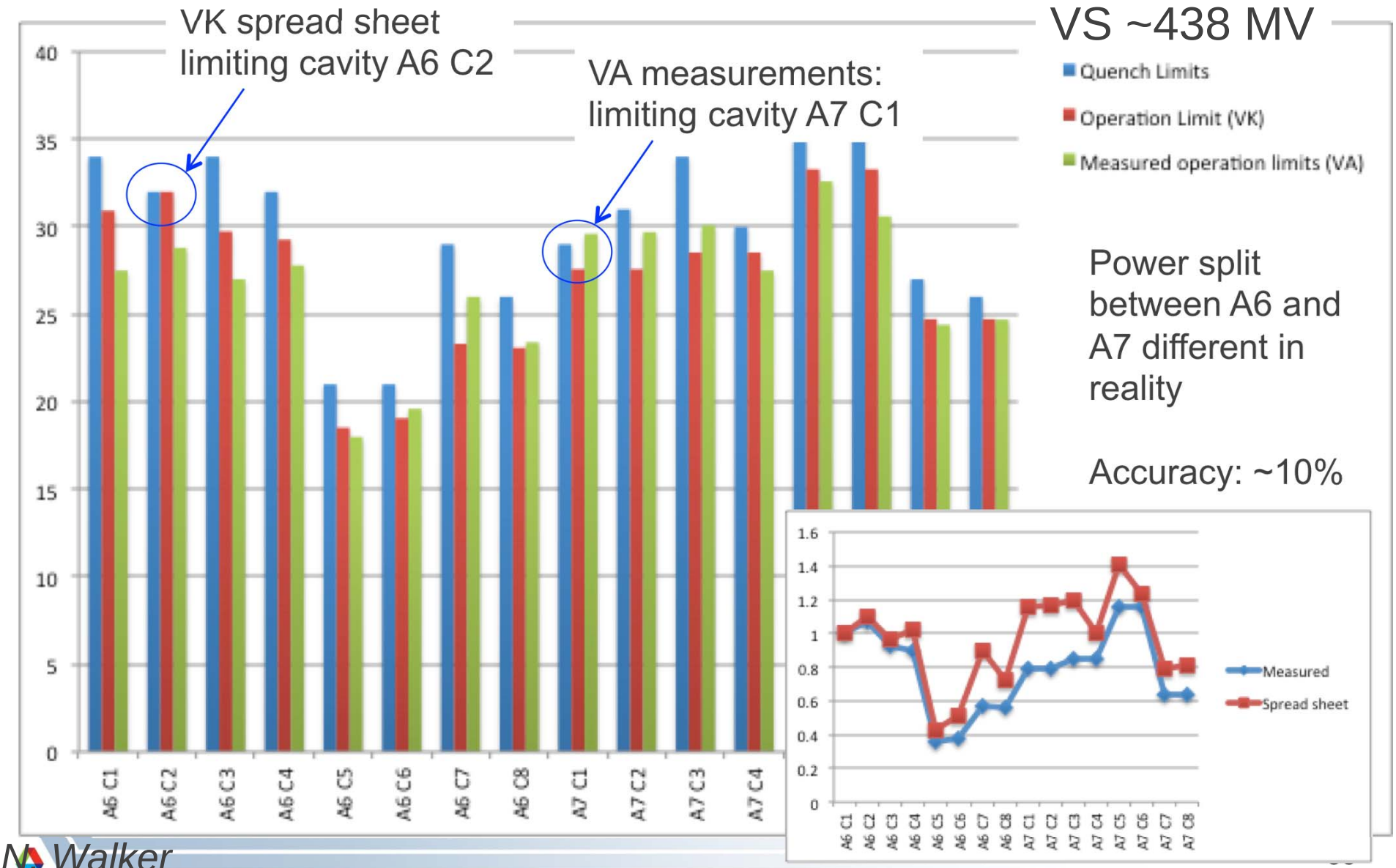
Gradient and power overhead studies for ILC

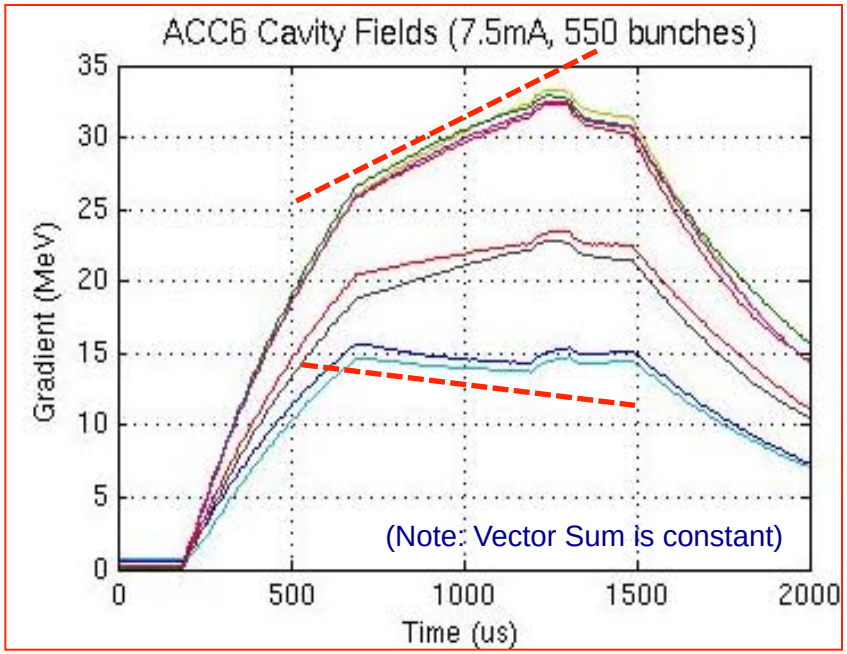
ILC-related beam studies at FLASH: priorities

- High beam current
  - From 4.5 mA to 6 mA
- Gradient study for near quench limit operation
  - ILC design parameters assume all cavities operate within 5% of quench
  - Minimize cavity gradient excursions over beam-on period
- Klystron output linearization
  - To operate the klystron near saturation, linearization would be essential for high gain feedback operation.
- RF operation near klystron saturation
  - The ILC design assumes 5% power overhead

Experimentally determined operational limits



Cavity gradient tilts from beam loading



A 'feature' of running cavities with a spread of gradients when the are all fed from same RF source

Steady-state cavity voltage

$$V = \sqrt{P_{for}\left(\frac{r}{Q}\right)Q_{ext}} - I_b\left(\frac{r}{Q}\right)Q_{ext}$$

Solution: adjust individual Pks and Qls so each cavity is 'matched' for the same beam current

***Ratios* of power required by each cavity are different between beam off and beam on**

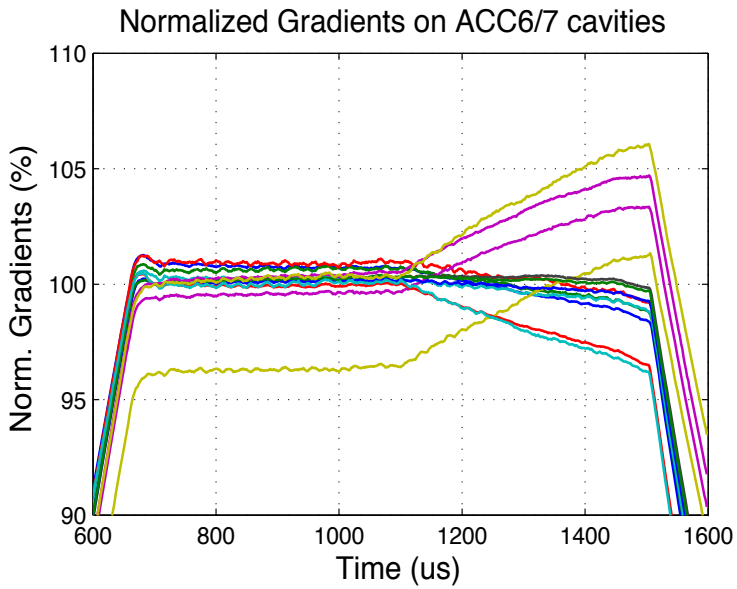
Klystron power increases linearly with beam current

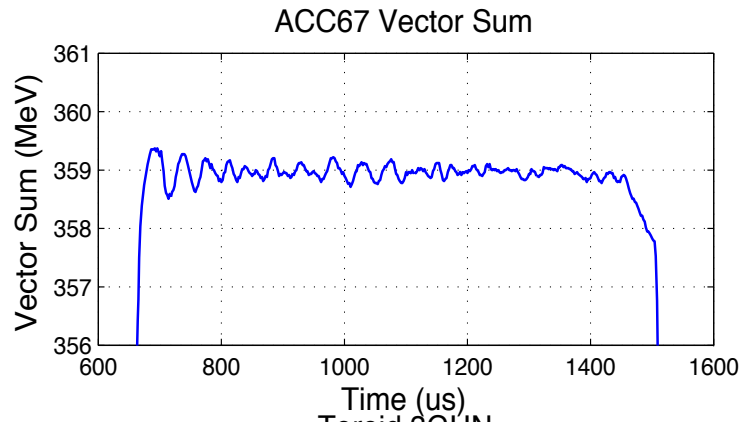
- Higher gradient cavities get too much extra power
- Lower gradient cavities get not enough extra power

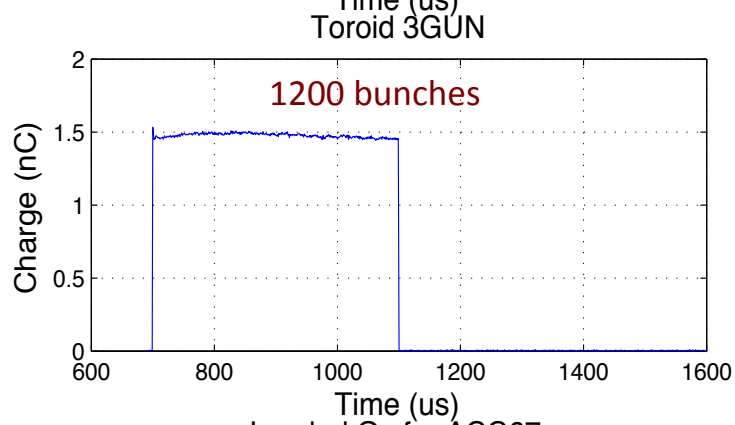
$$I_{matched} = \frac{V_k}{\left(\frac{r}{Q}\right)Q_{ext}}$$

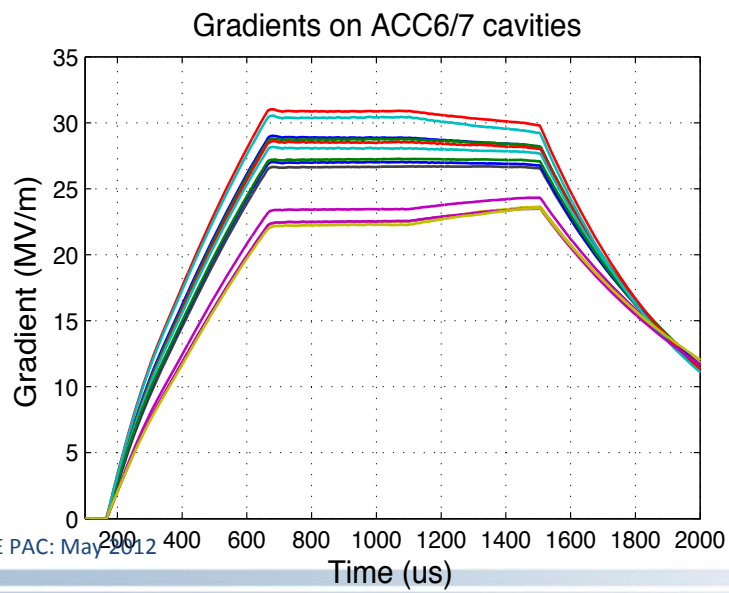
Must be solved uniquely for a given beam current and set of gradients

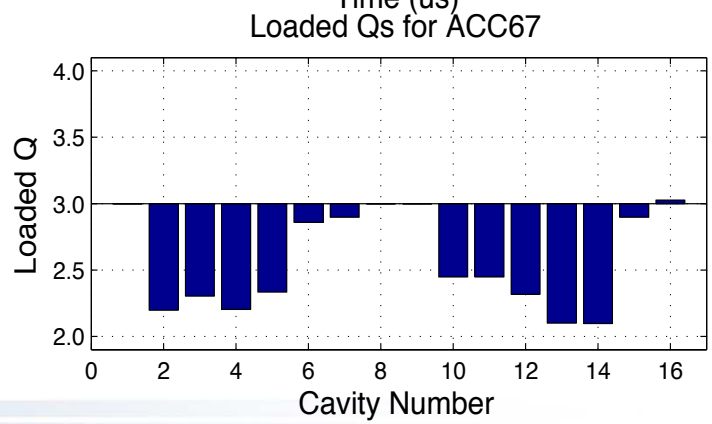
Ramp-up of the beam pulse length (400us)











Wrap-up

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- LLRF stability requirements are very difficult to achieve!
- There is a very active LLRF development program at DESY: FLASH FEL operation; ILC R&D; XFEL LLRF testing

- LLRF system achieves energy stability close to 1e-5 using a combination of
  - 'Slow' pulse-by-pulse control (of many parameters)
  - Learning feed-forward of RF profiles to compensate repetitive pulse-to-pulse effects
  - Intra-pulse feedback compensates residual unpredictable / random effects
  - Beam-based feedback for stabilization of bunch properties (factor five improvement)
  - Extensive (and increasing) use of automation

- ILC design criteria push the envelope in terms of LLRF control requirements: minimal gradient margin and minimal rf power overhead

- *Watch this space….*

Thank you for your attention