RF control and beam acceleration under XFEL conditions

Studies of XFEL-type Beam Acceleration at FLASH

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DESY, 24.5.2015

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Talk Outline

- Motivation for the study
  - 9mA study runs
  - Shift studies at FLASH (RF settings   XFEL ≠ FLASH)

- Shift outcome
  - Achievements from RUN1, RUN2, RUN3 and XFEL follow up study
  - Data analysis

- Conclusions
  - Side effects (good and bad)
  - Tradeoff
  - Optimal Q_L ?

A bit of history…


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9 mA revisited

Machine experts run DESY's FLASH accelerator under ILC parameters

The last two weeks were two of the most important (and intense) weeks for accelerator specialists working on the ILC. After a long period of preparation and a series of first tests, they have just finished a period of successfully running the superconducting linear accelerator FLASH at DESY under ILC-like conditions to demonstrate that a long train of electron bunches with high charge can be produced in and travel through the accelerator – and stay there, too. After the ILC-like run, which ended on Monday after long day and night shifts in the control room, FLASH will receive a major upgrade to improve capabilities and performance for the users of the laser light generated by FLASH.

The ILC team came with high goals and high demands. "We pushed many operational limits for FLASH," says co-coordinator John Carwardine from Argonne National Lab, "and we encountered some difficulties – but that meant we learned crucial lessons." The cavities are supposed to be pushed to the limit of their power to accelerate beams with a current of nine milliamps and 800-microsecond beam pulses. By the end of last week, the beam ran stably with a full 800-microsecond pulse for over ten hours, which meant that the team could commission a new laser that would get them up to their ultimate goal of operating FLASH at 9 milliamperes (mA). In the end they managed several hours of operation at 9mA with short trains (300-500 microseconds) and 2400 bunches at 800 microseconds at 6mA for short periods.

A year ago, almost to the day, was the last time the team ran preliminary high-power studies. They made rapid progress towards to final goal – showing that beam phase and energy can be stable, one of the highest-priority goals in the ILC R&D plan – until the studies were cut short by a vacuum event in the beam dump line. Preparations for these latest studies included installing a modified beam dump line that had been fitted with several new diagnostics systems to measure the position of the beam in the dump line and to detect beam losses. One such system, developed at DESY in Zeuthen, uses diamond and sapphire blades to measure beam halo. This is one of a number of improvements that have been made to FLASH for the longest run under ILC-like beam conditions so far. The low-level radiofrequency system (LLRF) was also upgraded and a new laser installed in order to produce three million bunches per second – three times more than last year.

Concentrated faces in DESY's main control room.

➡ *FLASH seminar:*
"ILC 9mA tests at FLASH"
02.07.2012

> DESY
- Nick Walker
- Siegfried Schreiber
- Bart Faartz
- Katja Honkavaara
- Holger Schlarb
- Valeri Ayvazyan
- Mariusz Grecki
- Wojciech Jalmuzna
- Wojciech Cichalewski
- Tim Wilksen
- Olaf Hensler
- Christian Schmidt
- Julien Branlard
-
- … and many others

> ANL
- Ned Arnold
- John Carwardine

> FNAL
- Brian Chase
- Gustavo Cancelo
- Warren Schappert
- Yuriy Pischalnikov

> KEK
- Shinichiro Michizono
- Toshihiro Matsumoto

> SLAC
- Chris Adolphsen
- Shilun Pei

Short History of the “9mA run”, for the ILC

> **2007**

- Pushing towards long bunch trains and high beam currents

> **2009**

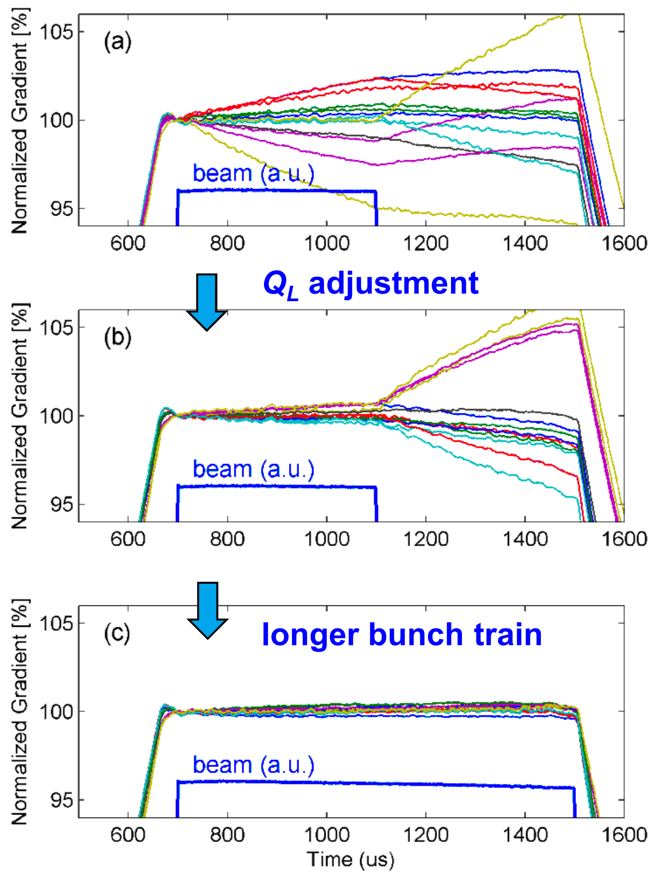
- 9mA beam operation
- Near quench operation
- Beam loading induced gradient tilts

> **2011**

- First attempt at compensating gradient tilts using Q_L

> **2012**

- Ql studies
- Quench studies
- Power overhead studies



John Carwardine's slides: Check-list of TD Phase accomplishments

> Long bunch trains, heavy beam loading demonstration

- 6mA / 800us demonstrated (TDR Baseline)
- 9mA / 800us marginally achieved (luminosity upgrade)

> Vector Sum control of RF unit

- Operation of RF units comprising 16 and 24 cavities
- Intra- and inter-pulse stability better than 0.02%

> Operating gradients

- Operation up to average of 29MV/m (24MV/m to 33MV/m)
- Lorentz-force detuning compensation on all cavities simultaneously

> Pk/Ql control for optimizing gradient profiles

- Demonstrated flat gradient solutions to +/-0.3%
- ILC baseline has more knobs (power ratios), so easier

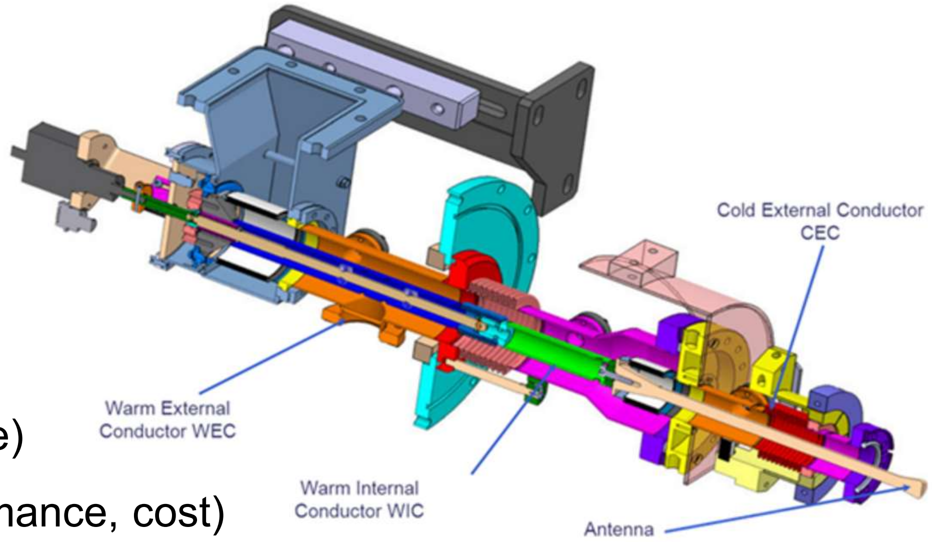
> Operation close to quench

- Operation of several cavities close to quench (5-10%) at 4.5mA, 800us
- Quench detection / prevention and rapid recovery after quench

John Carwardine GDE PAC: May 2012

"What's Q_L and why is it 3e6 at FLASH and 4.6e6 at XFEL ?"

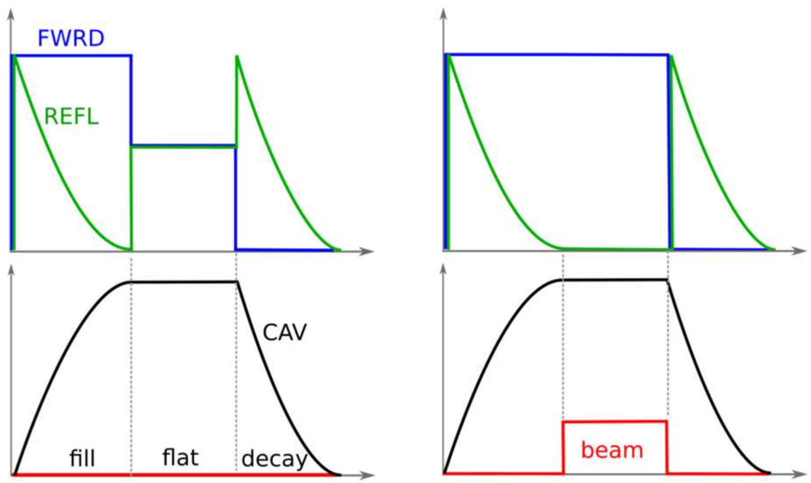
- Controls the input power coupling to the cavity
- Higher Q_L → smaller bandwidth
  - Q_L = 3.0e6 BW = 433 Hz   FLASH
  - Q_L = 4.6e6 BW = 283 Hz   XFEL



- Q_L impacts:
  - Power budget (cost)
  - Sensitivity to microphonics (performance)
  - Power overhead for FB controls (performance, cost)
- How to choose Q_L ?
  - Match for nominal beam at nominal gradient

Facility	I_{BEAM}	Q_L	T_{FILL}
FLASH	9.0 mA	3.0e6	500 us
XFEL	4.5 mA*	4.6e6	750 us

* I_{BEAM}(nominal)= 1.35 mA



"XFEL-like" studies at FLASH

- Investigate the impact of setting $Q_L = 4.6 \times 10^6$ instead of 3×10^6
  - Impact on the cavity modes (i.e. $8\pi/9$, $7\pi/9$)
  - Impact on the RF control stability (i.e. dA/A, dPhi)
  - Impact on the multi-beamline control (FLASH1 / FLASH2)
  - Impact on the power budget

- What is the "best" Q_L to operate the XFEL ?
  - Given the time constraints (modulator and klystron)
  - Given the moderate beam loading (XFEL $I_{nom.} = 1.35$ mA)
  - Simulation vs. experiment

“XFEL-like” studies at FLASH

> **RUN1**: 2015.07.02 (afternoon and night shifts)

- The goal of this study is to **demonstrate the XFEL stability requirements** (0.01 % in amplitude and 0.01 deg in phase), for XFEL nominal beam current (1–1.5 mA), and at an average accelerating gradient of 23.6 MV/m, using XFEL RF control parameters (Q_L = 4.6e6).

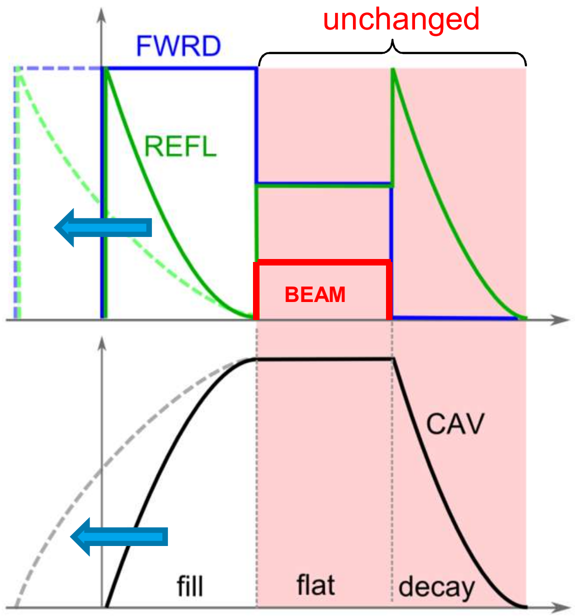
> **RUN2**: 2015.11.16 (morning, afternoon and night shifts)

- In this phase we would like to continue the studies already performed in July of this year, with the final goal of **demonstrating multibeam operation** with long pulses. Furthermore we would like to explore the option of **pushing the beam currents higher** in order to see stronger beam loading.

> **RUN3**: 2016.01.28 (morning, afternoon and night shifts)

- The goal of this study is to investigate in details the **impact of changing Q_L and the fill time on the LLRF controller stability and the overall power budget**. The impact of changing Q_L **on the beam loading** will also be investigated.

"XFEL-like" studies at FLASH



> LLRF setup

- LLRF setup (changing Q_L, changing timing, connecting piezos: tunnel access)
- Piezos: always need to bring back up system because not running routinely at FLASH
- Only showed that we would be able to run with piezo but actually didn't take measurement WITH piezos

> Machine setup

- High machine setup times (3 MHz x 5 Hz versus 1 MHz x 10 Hz)
- Complications due to shifting to 3MHz
  → we stayed with same machine/laser rep rate in the last run (we "gave up" high current)

> Beam setup

- Transmission to 1 nC, problems above 1 nC

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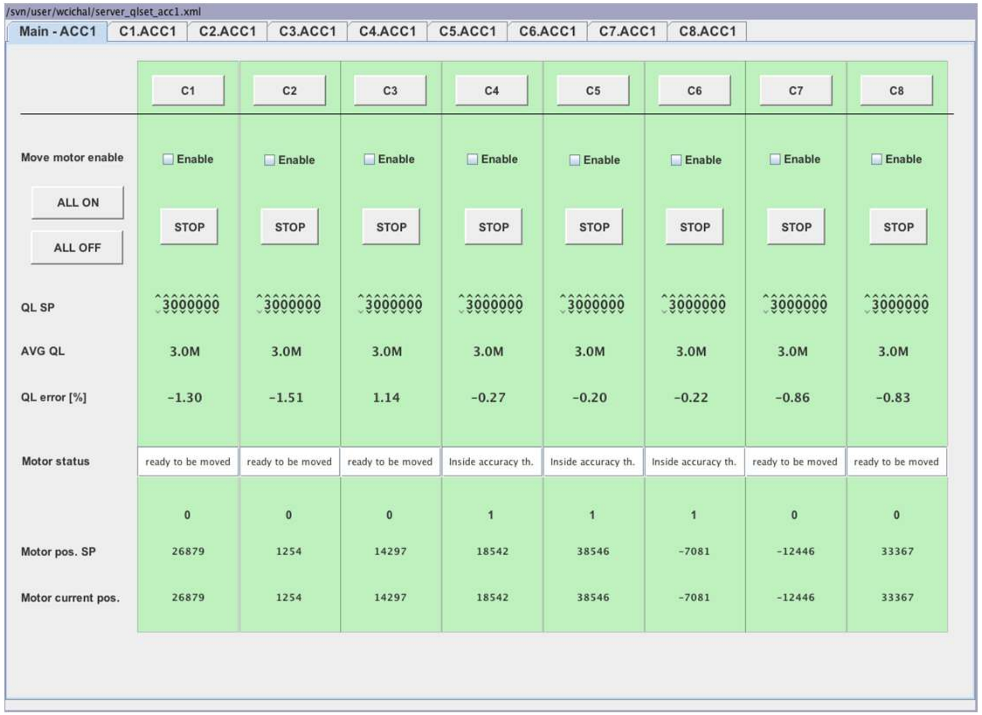
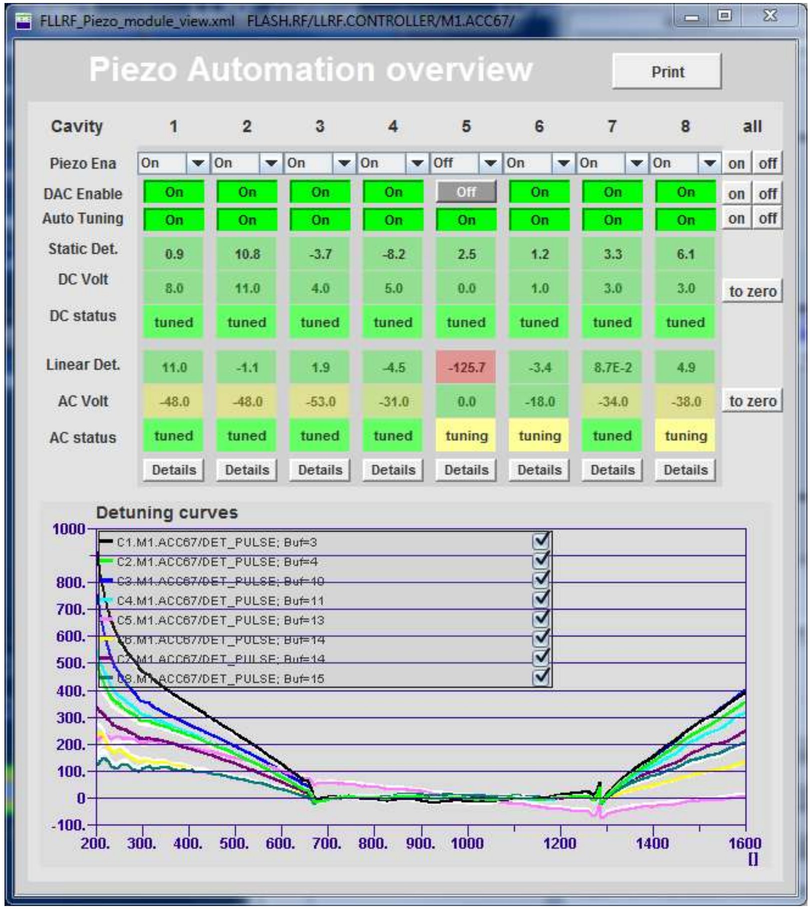
RUN1 achievements

- Commissioning of the automatic Q_L adjustment software

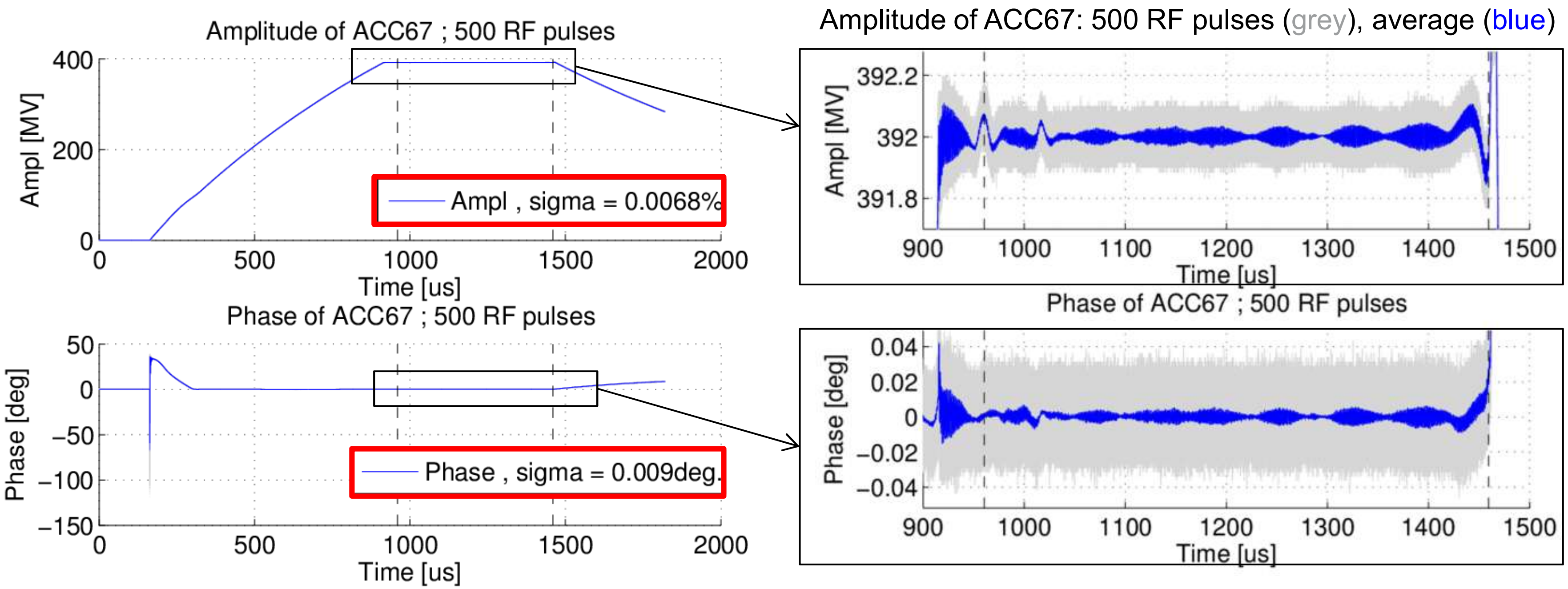


- Recommissioning of the piezo control and automation



RUN1 achievements

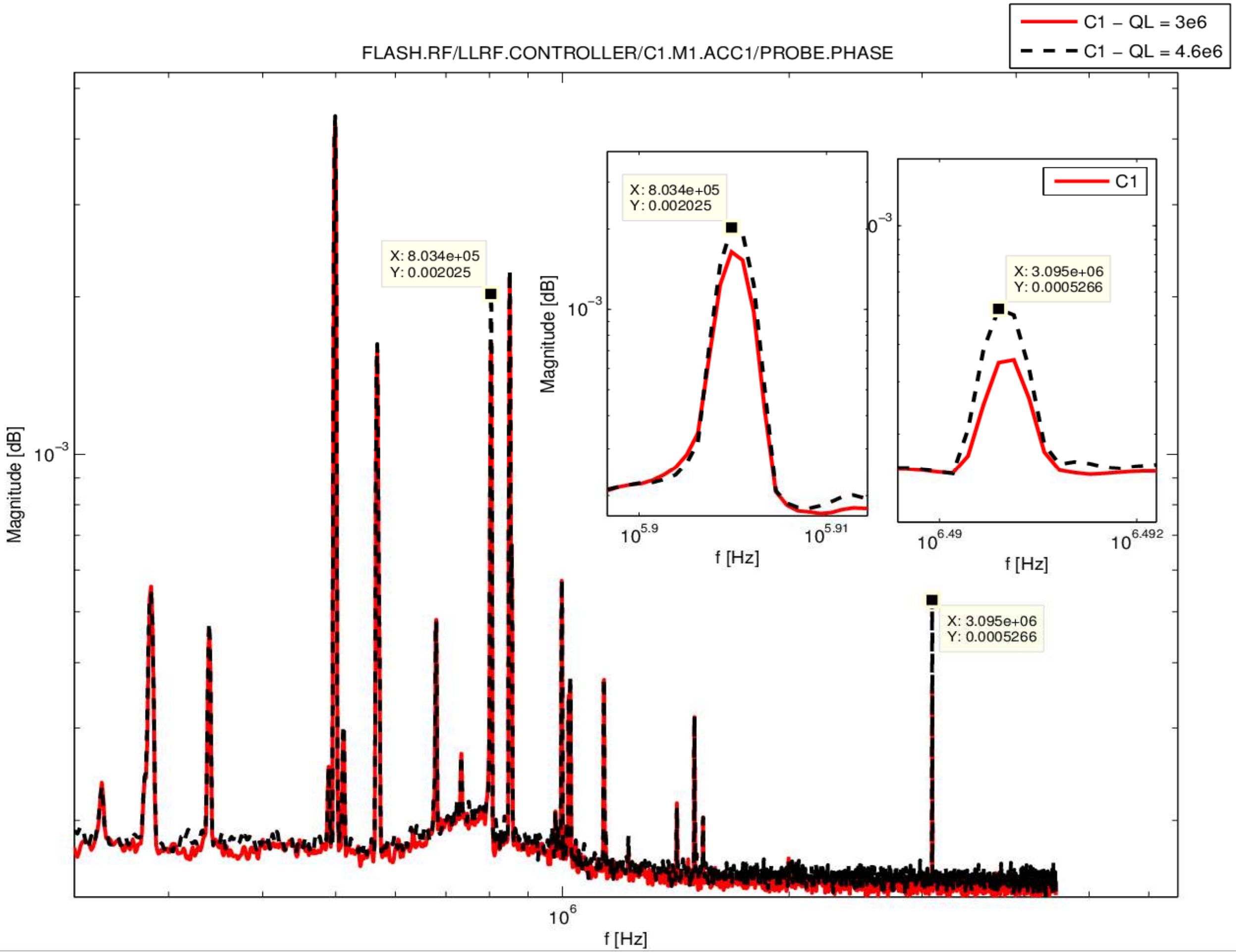
- Demonstration of XFEL stability requirements
  - with XFEL RF parameters
  - with low beam current



XFEL specs:	dA/A = 0.01%
	dPhi = 0.01deg

RUN1 achievements

- Impact of changing Q_L on the single cavity modes

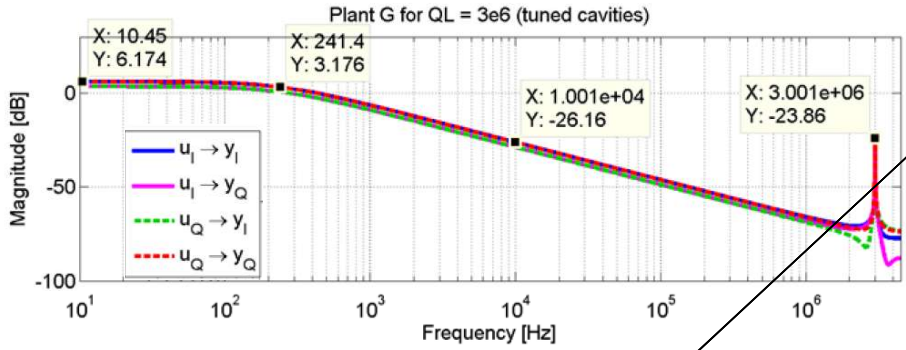


Note: ADC have been replaced since → many less spikes

RUN2 achievements

> System identification with the new RF parameters (Q_L change)

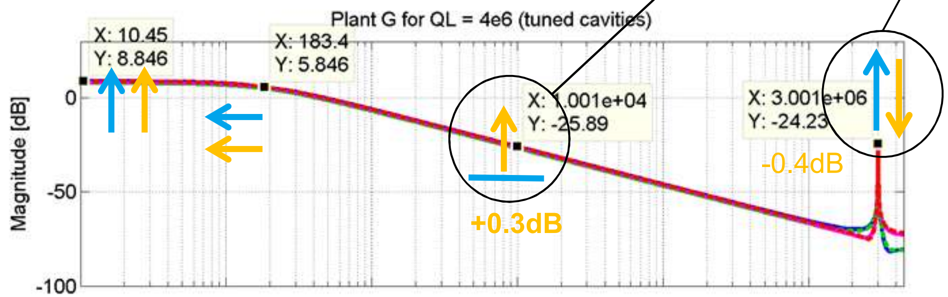
Q_L = 3e6

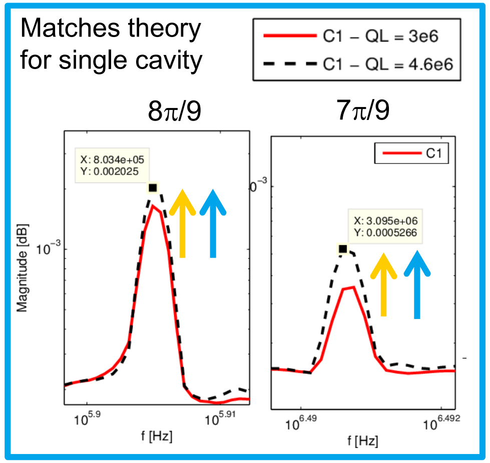


@10kHz: OVC changes A/P driving signal

@7π/9 mode: spread of 7π/9 modes for VS?

Q_L = 4e6



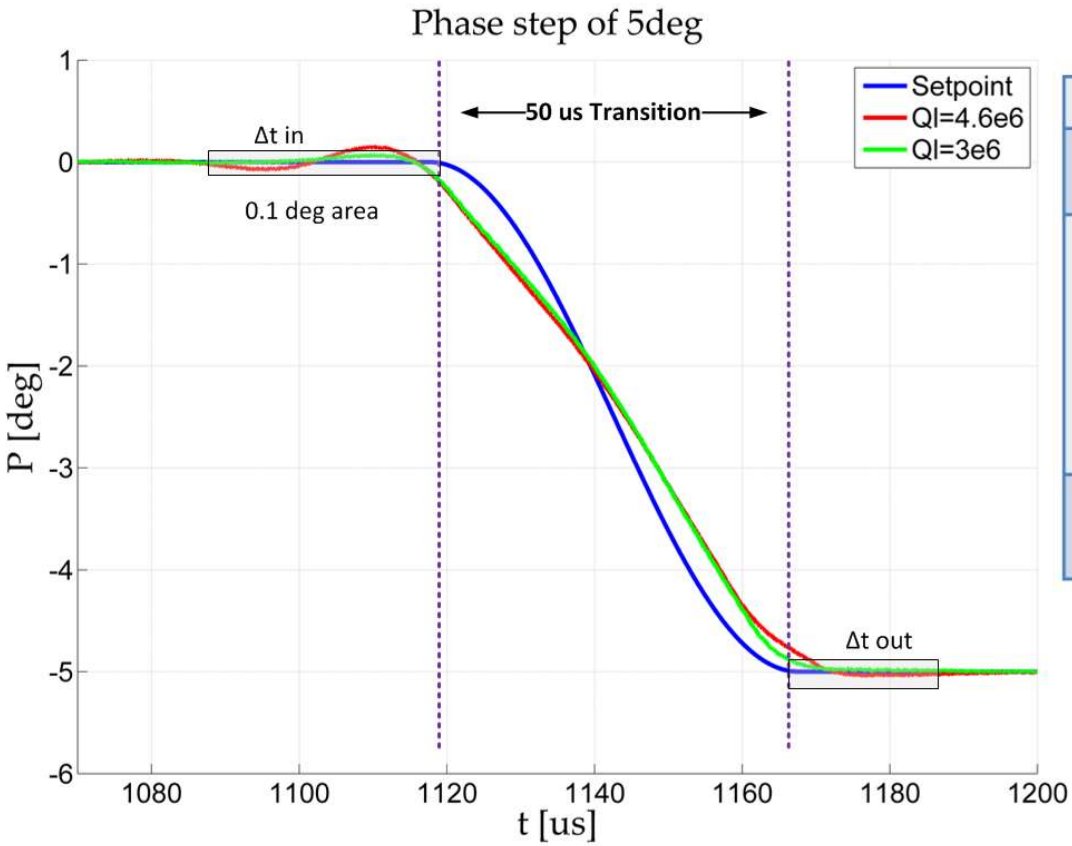


expected and **observed** model changes

Only minor system changes → MIMO controller adjustment is not necessary for ACC67
Depends on the RF system (location of passband modes in VS)

RUN2 achievements

- Full beam transmission though FLASH I (1200 bunches) and FLASH II (30 bunches), 0.4 nC on-crest
- Impact of changing Q_L on FLASH I - FLASH II transients



	Step change		Amplitude		Phase	
QL	ΔA [MV]	ΔP [deg]	Δt in [us]	Δt out [us]	Δt in [us]	Δt out [us]
4.6e6	5	0	12	13	0	0
	10	0	12	16	0	0
	0	2.5	28	25	22	26
	0	5	33	13	27	43
	10	5	57	53	47	33
3e6	10	5	17	8	25	23
	10	0	11	5	0	0

XFEL specs: 50 usec transition time

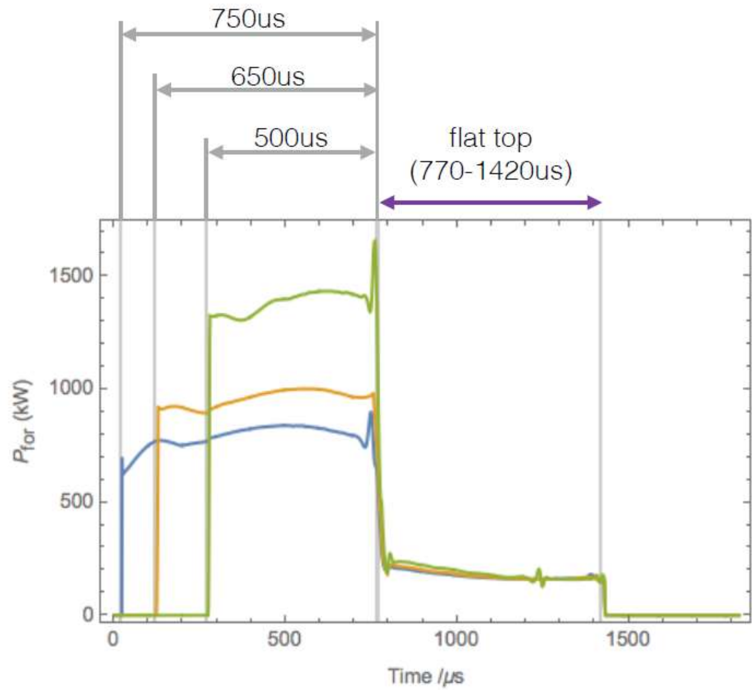
RUN3 achievements and follow up at XFEL A1.I1

> Q_L and fill time parameter study

Q_L \ T_{FILL}	500 usec	650 usec	750 usec
2.0e6	✓	✓	✓
3.0e6	✓	✓	✓
4.0e6	✓	✓	✓
4.5e6		✓	✓
4.6e6	✓	✓	✓

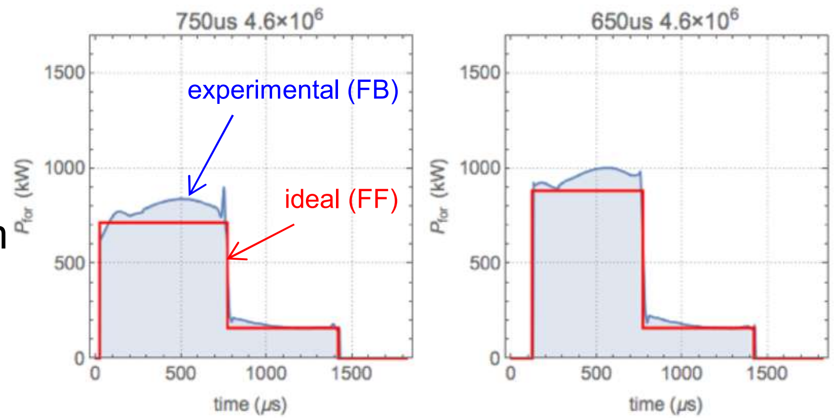
2 data sets

⇨ beam ON (1nC) & beam OFF



> For each data point, measure:

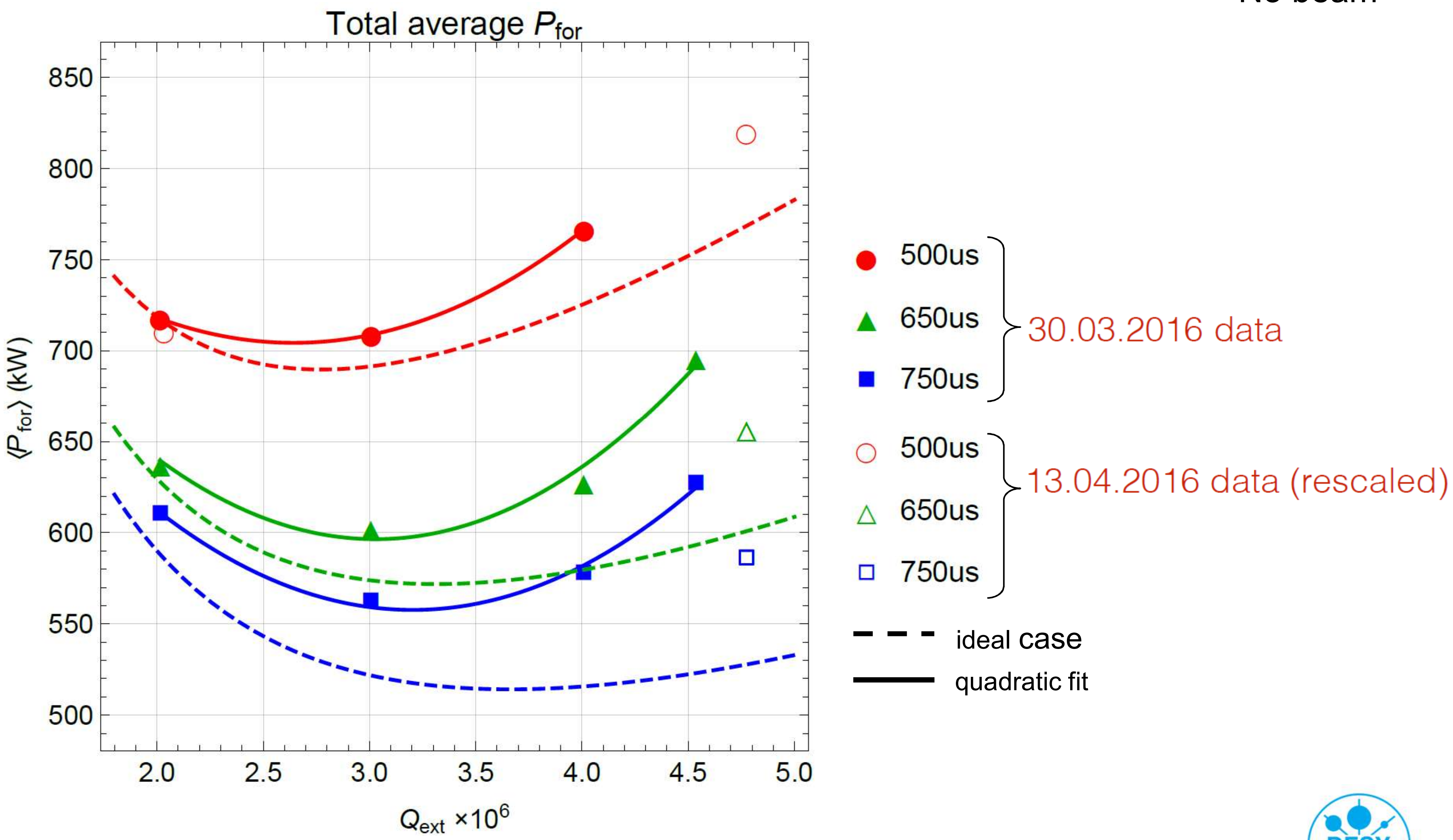
- controller performance with and without beam
- total power usage (i.e. fill time + flat top) in closed-loop operation



RUN3 achievements and follow up at XFEL A1.I1

> Q_L and fill time on power budget

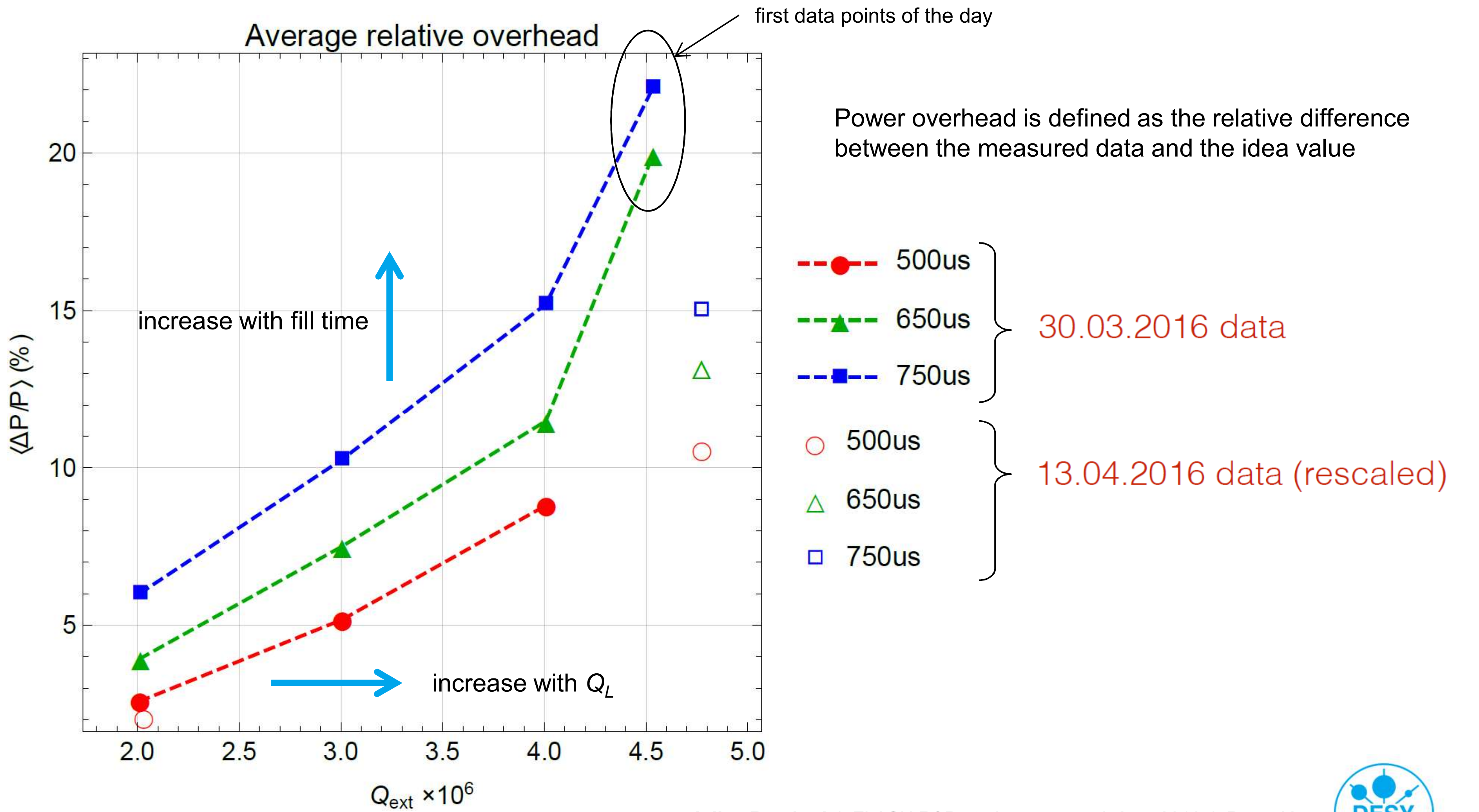
No beam



RUN3 achievements and follow up at XFEL A1.I1

> Q_L and fill time on power budget (continued)

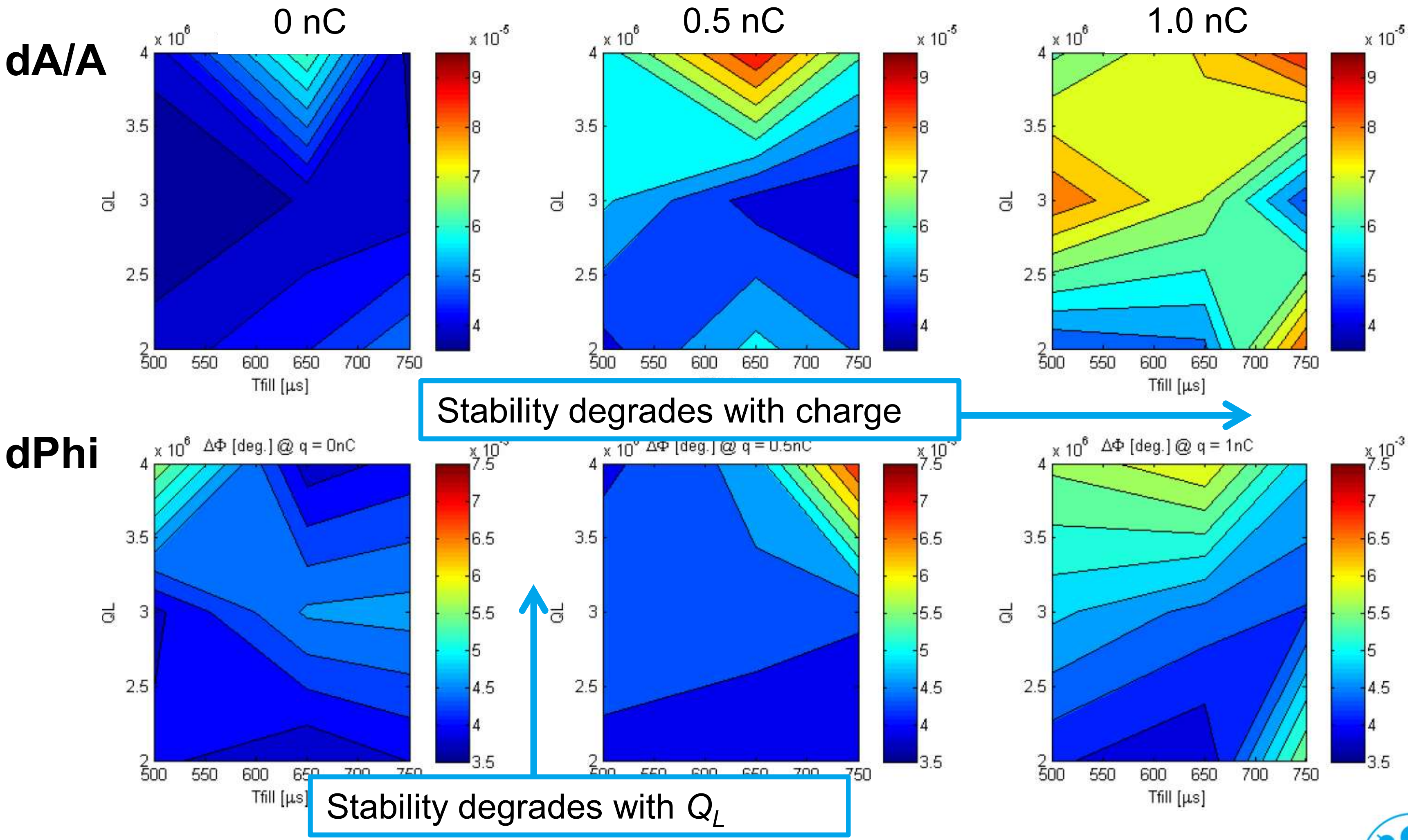
No beam



Power overhead is defined as the relative difference between the measured data and the idea value

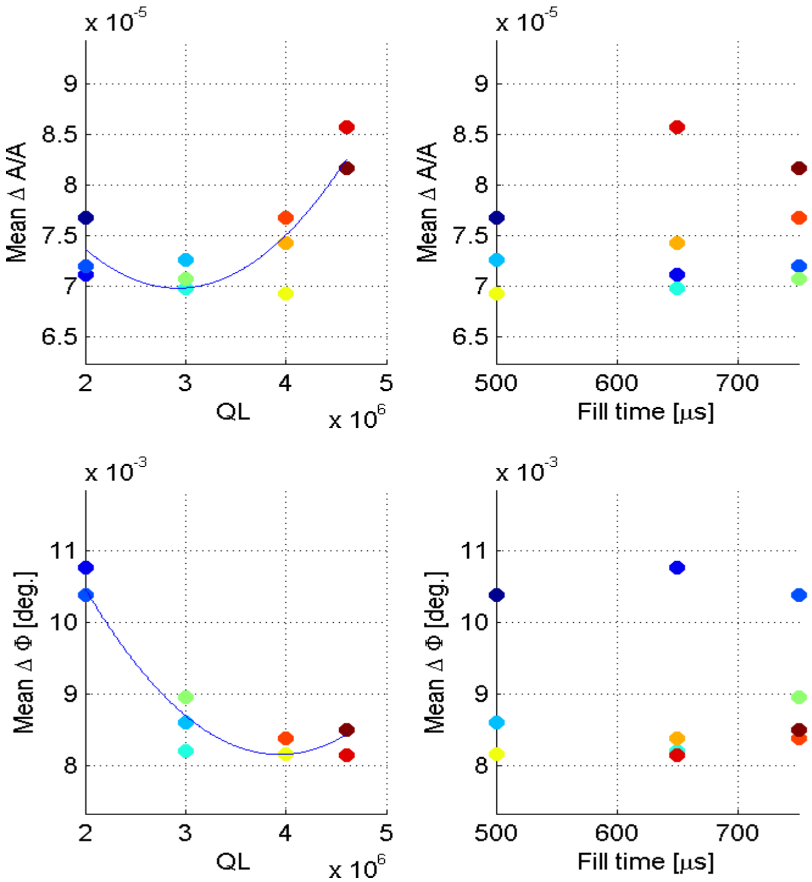
RUN3 achievements and follow up at XFEL A1.I1

- Q_L and fill time on stability

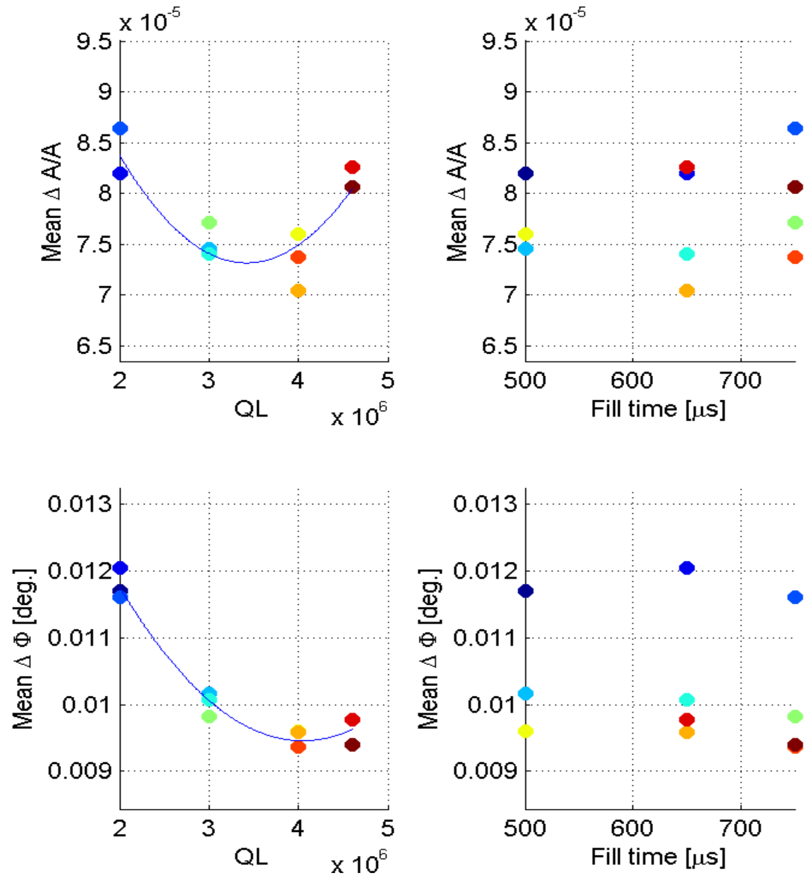


RUN3 achievements and follow up at XFEL A1.I1

- Q_L and fill time on stability (continued)



0 nC



0.5 nC

Colors only denote different measurement points

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Side effects

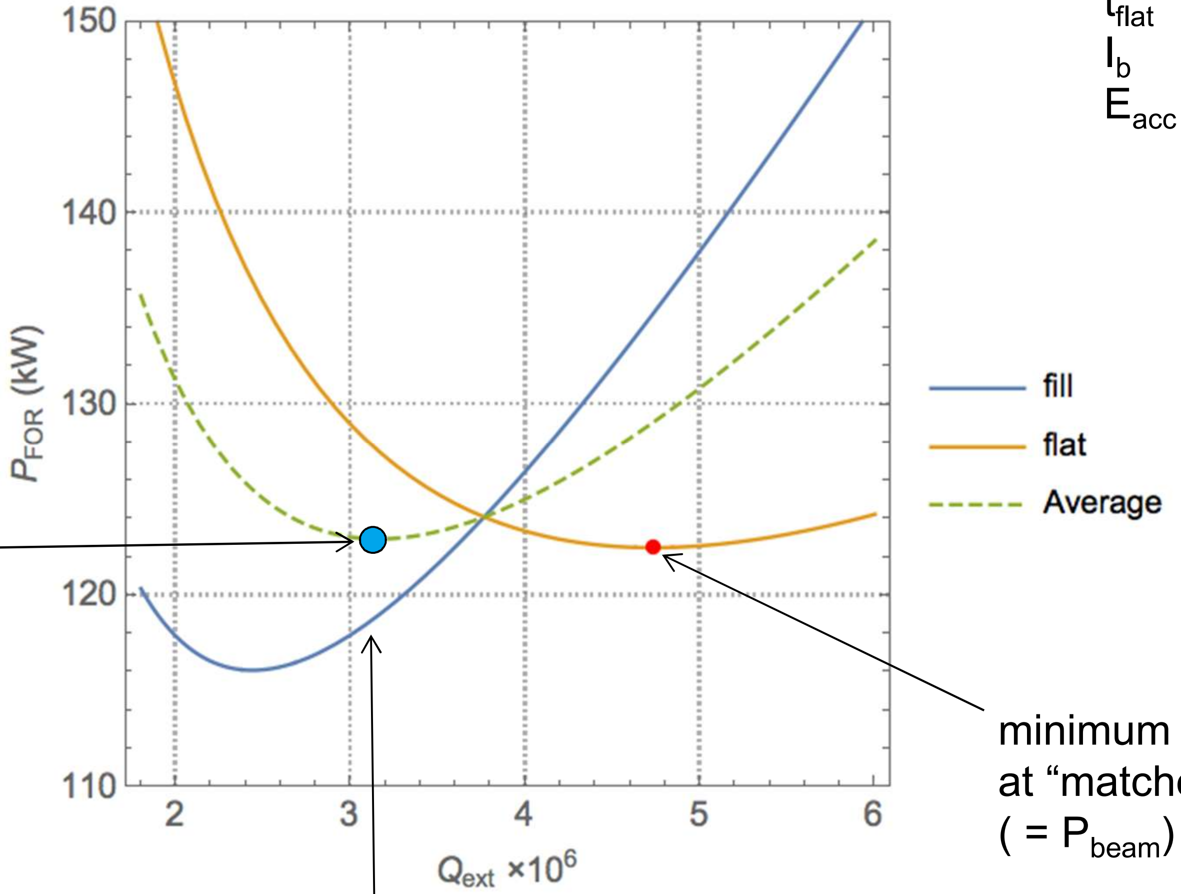
- C8.ACC7 field emission → dark current activation
  - What caused it?
  - What's happening (follow-up shifts)?

⇨ Lessons learnt for the XFEL ?

- Piezo recommissioning
- LLRF system improvements
  - BLC, LFF
  - Optimal SP Q_L
- "What is indeed the best Q_L ?"
  - Refocus of the shift goals

Fill versus Flat-Top Forward Power (trade off)

t_{fill} = 750 μs
t_{flat} = 650 μs
I_b = 5 mA
E_{acc} = 23.6 MV/m



minimum average power at lower Q_{ext}

minimum flat-top power at “matched” Q_{ext} (= P_{beam})

P_{FOR} during fill time reduced

Conclusions

- There is nothing magic about 4.6e6
  - The choice of 4.6e6 was based on full beam loading, valid for CW, but fails for pulse system, because one needs to take fill time take into account
  - lower bandwidth → more sensitive to detuning & microphonics → also requires more power for FB control
- Piezo operation will help!
- We would be better off at lower Q_L
  - ☺ better stability (larger bandwidth)
  - ☺ reduced power overhead for controls (follows from above)
  - ☺ reduced average forward power
  - ☺ reduced power during fill (which tends to be the peak operationally)
  - ☹ higher forward and reflected power during the flat-top
- There is actually flexibility
  - one could operate the machine at a different Q_L

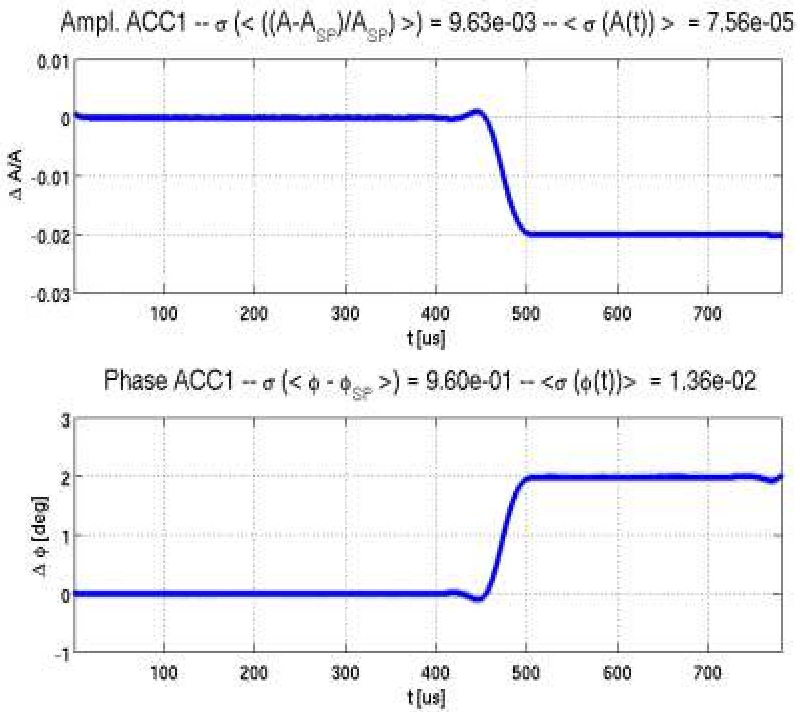
Thank you for your attention!

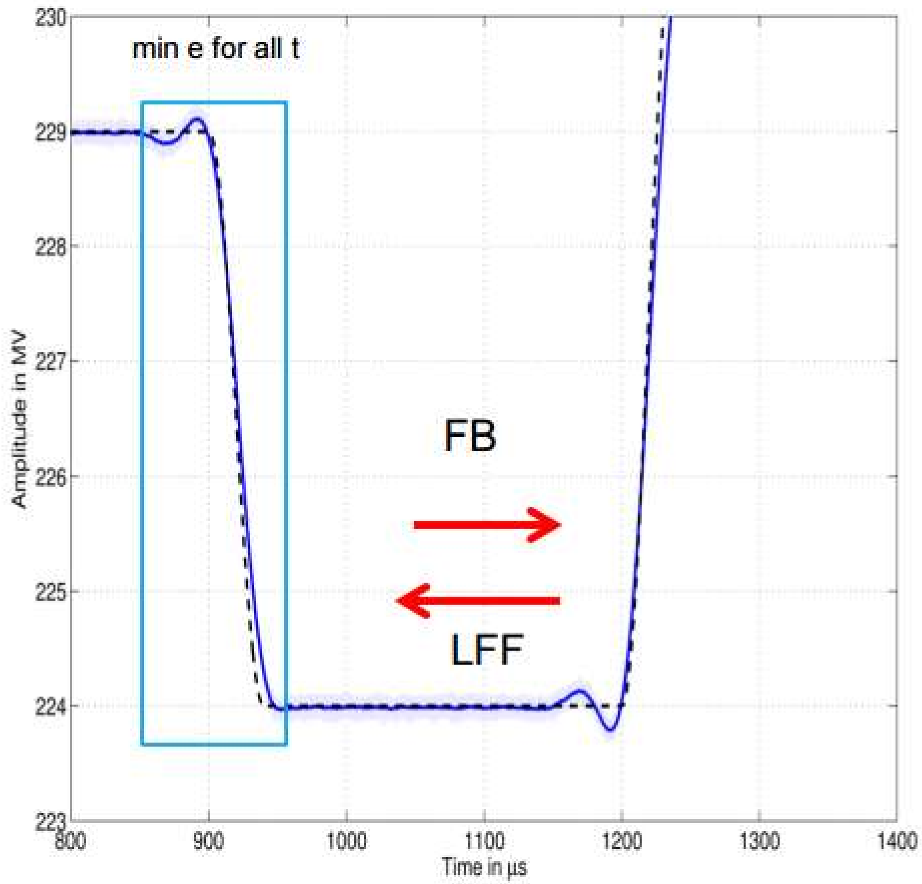
Photo: Dirk Noelle

BACKUP SLIDES

FLASH I – FLASH II transition

- Vector-sum amplitude and phase stability fulfills given requirements



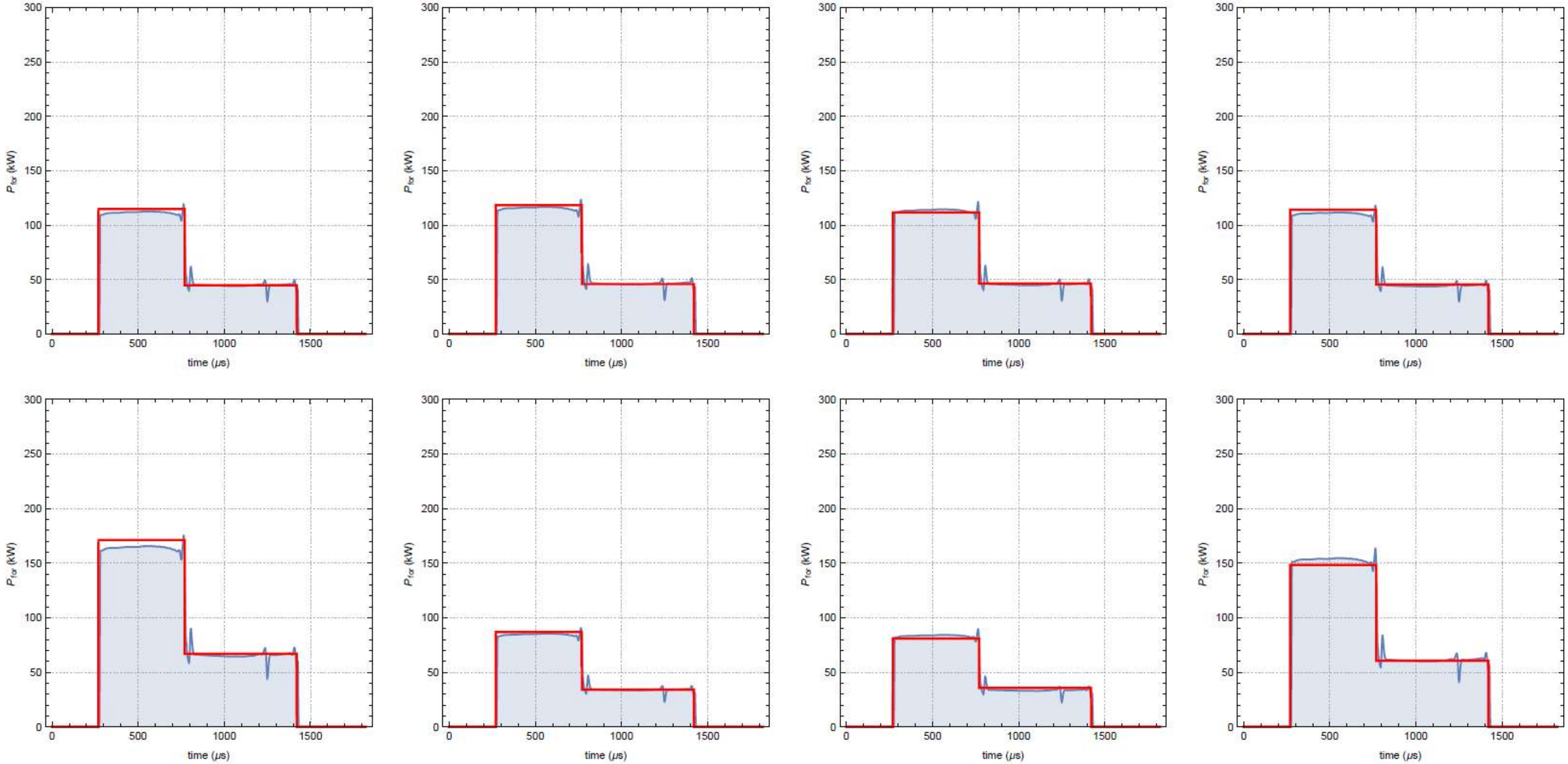


- Kicker given minimum transition time can be achieved
- Smooth transition steps to avoid broadband excitation

Courtesy: Valeri Ayvazyan: LLRF 2015, Shanghai

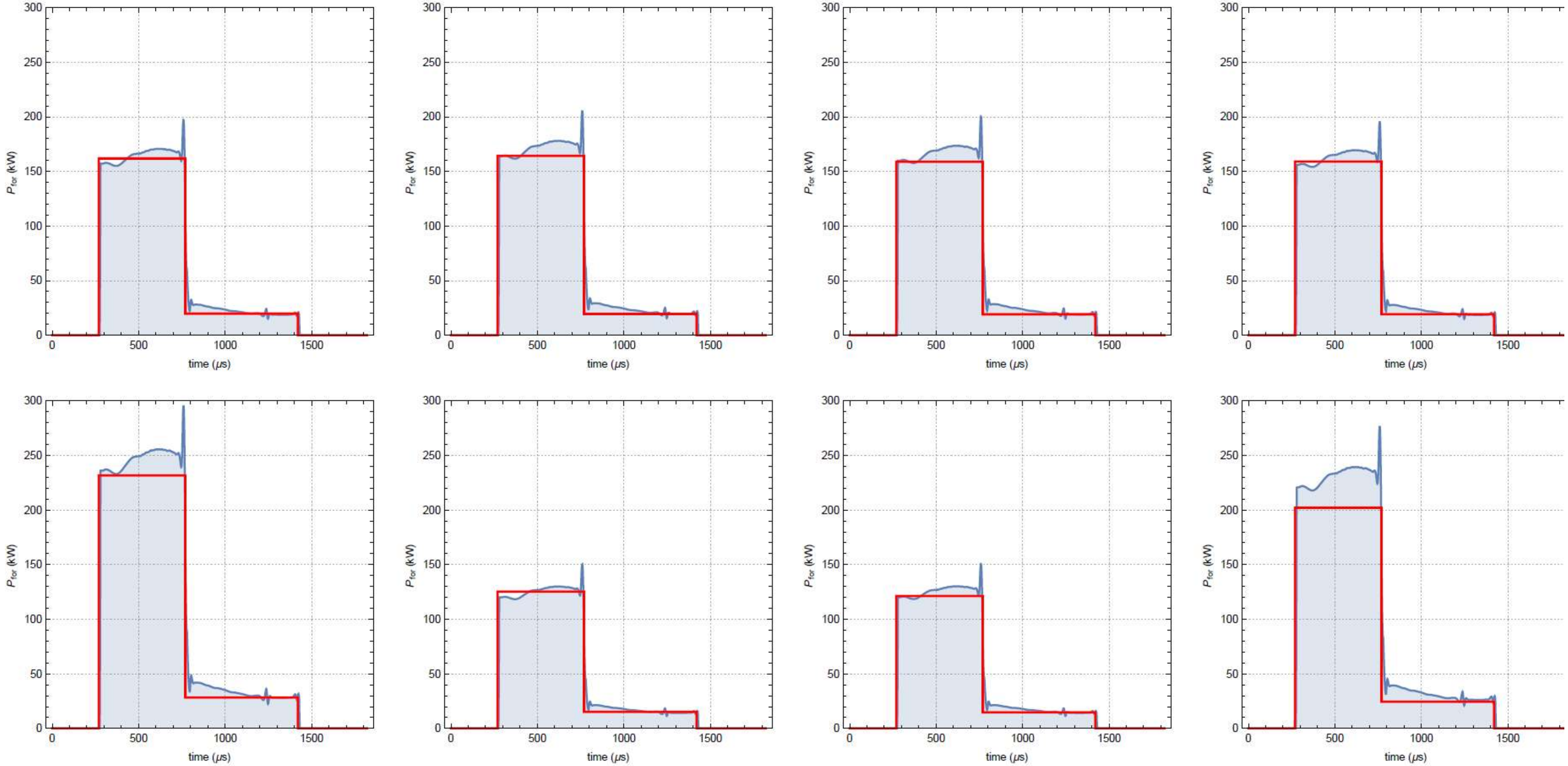
Forward power waveforms

- T_{FILL} = 500 usec $\quad\quad$ Q_L = 2.0e6



Forward power waveforms

> T_{FILL} = 500 usec Q_L = 4.6e6



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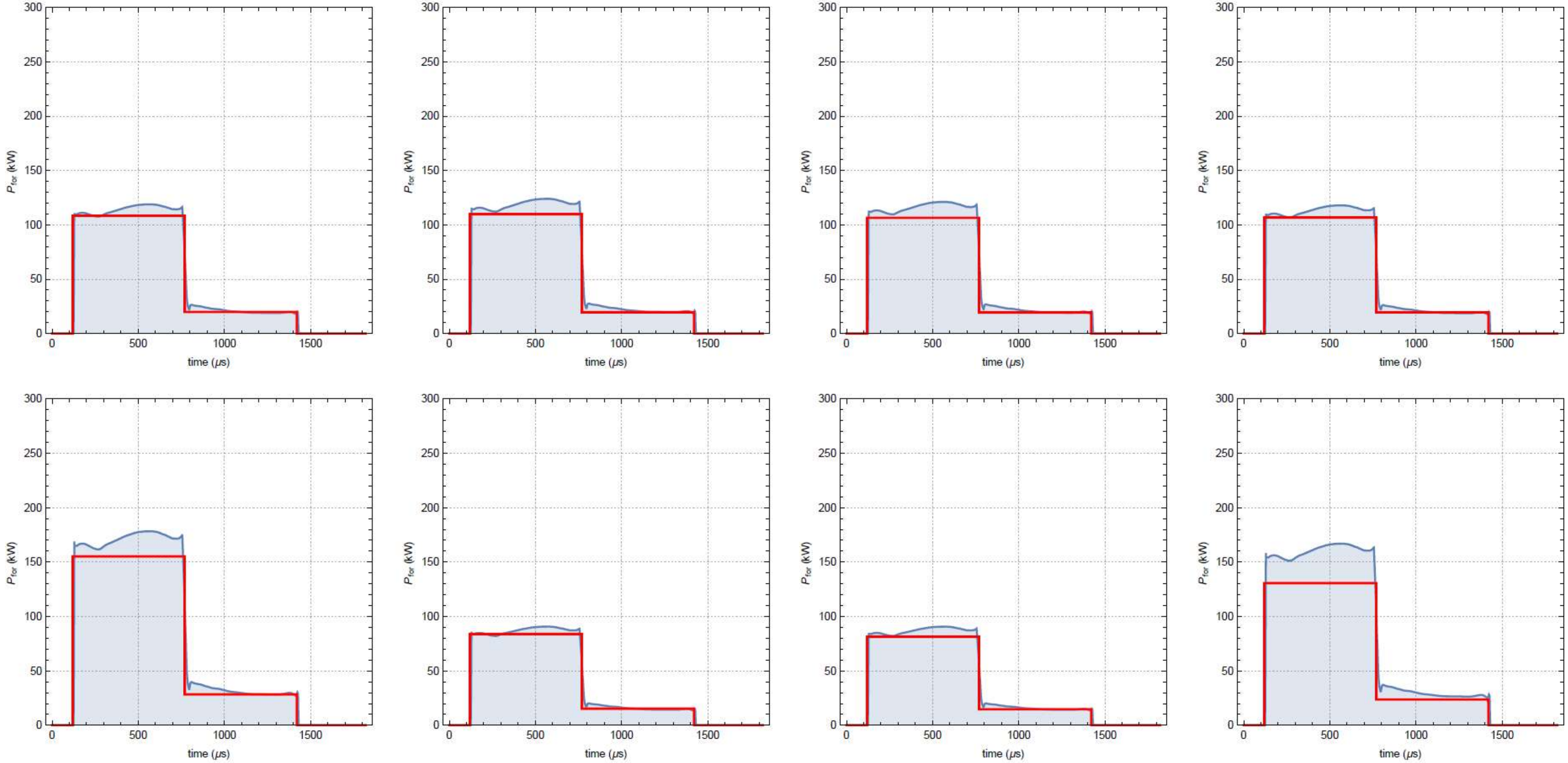
Forward power waveforms

- T_{FILL} = 650 usec $\quad$ Q_L = 4.6e6



Forward power waveforms

- T_{FILL} = 650 usec Q_L = 2.0e6