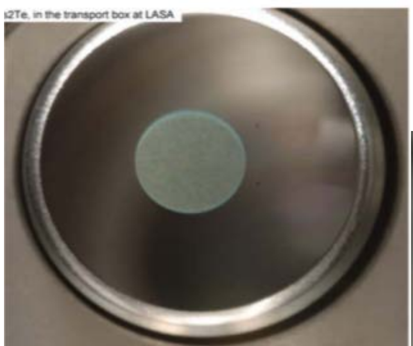
RF-Gun and Cathode Studies

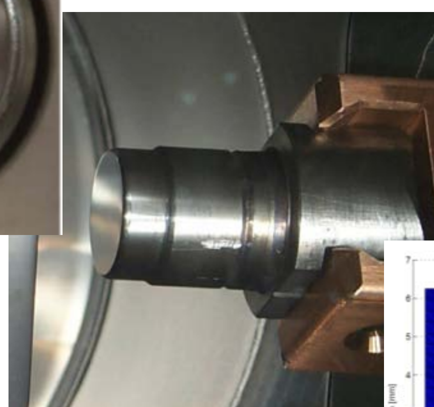
FLASH.
Free-Electron Laser in Hamburg

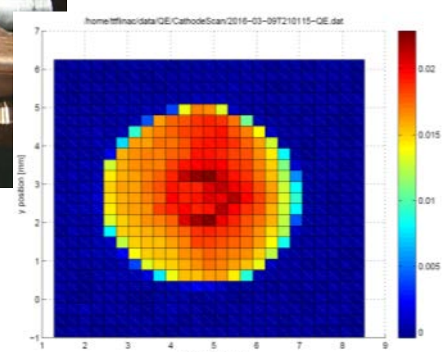
FLASH: the first soft X-ray FEL operating two undulator beamlines simultaneously

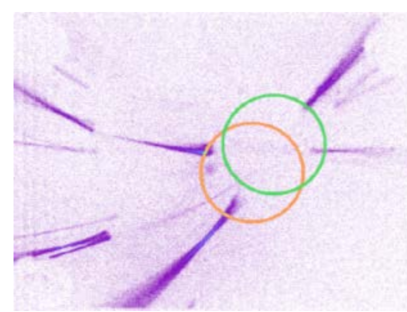
Siegfried Schreiber,
Sven Lederer, DESY

FEL Seminar
DESY, Mar 15, 2016









HELMHOLTZ GEMEINSCHAFT

DESY

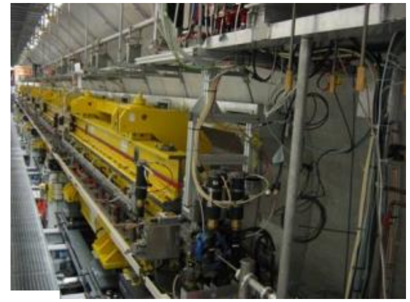
FLASH Layout

FLASH. Free-Electron Laser in Hamburg

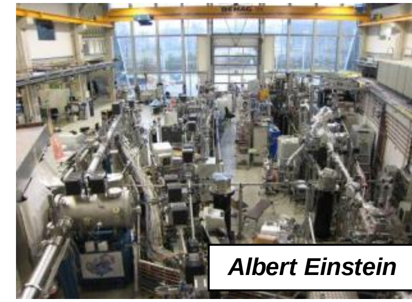
> 3rd harmonic sc module 3.9 GHz

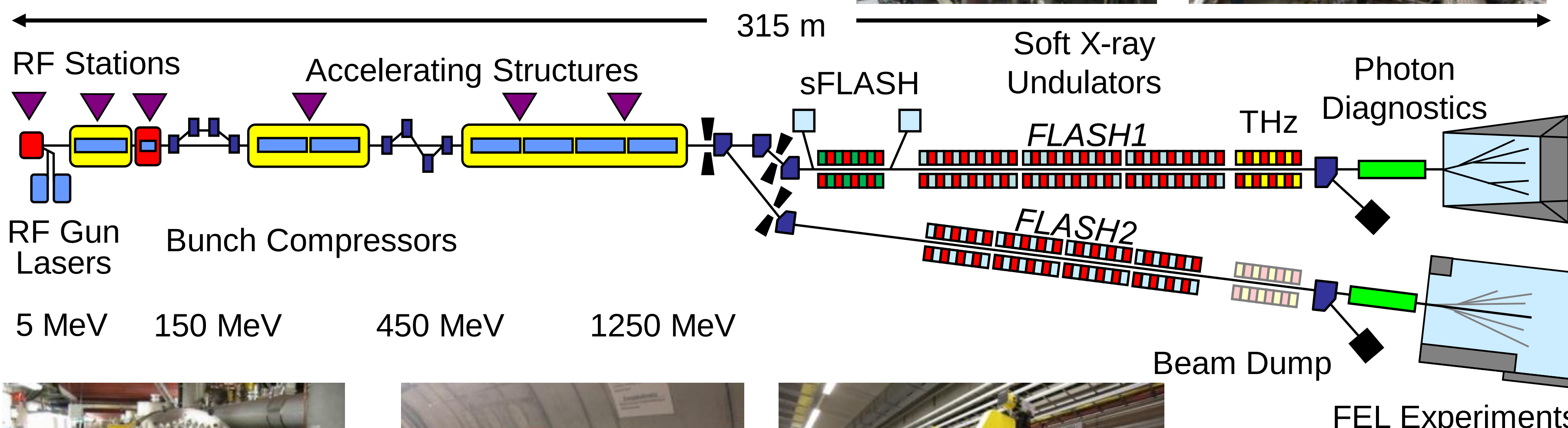
> TESLA type superconducting accelerating modules 1.3 GHz

> FLASH1 fixed gap undulators



> FLASH1 Experimental Hall





- Normal conducting 1.3 GHz RF gun
- Ce_2Te cathode
- Two Nd:YLF based ps photocathode lasers

> Extraction to FLASH2

> FLASH2 variable gap undulators

> FLASH2 Experimental Hall

FLASH Layout

FLASH.
Free-Electron Laser in Hamburg

> 3rd harmonic sc module 3.9 GHz

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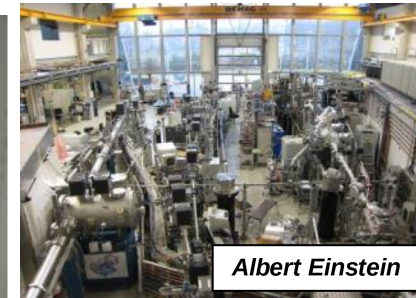
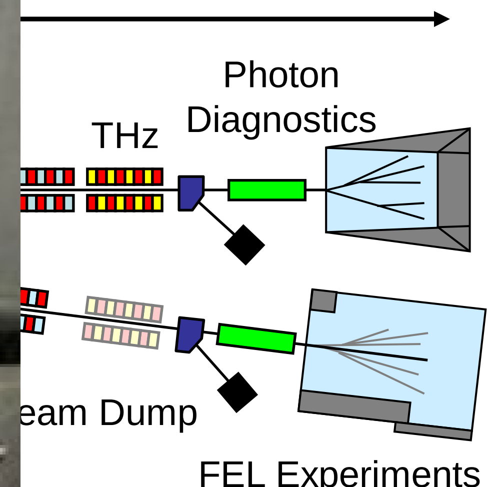




> Normal conducting 1.3 GHz RF gun
> Ce_2Te cathode
> Two Nd:YLF based ps photocathode lasers

> Extraction to FLASH2

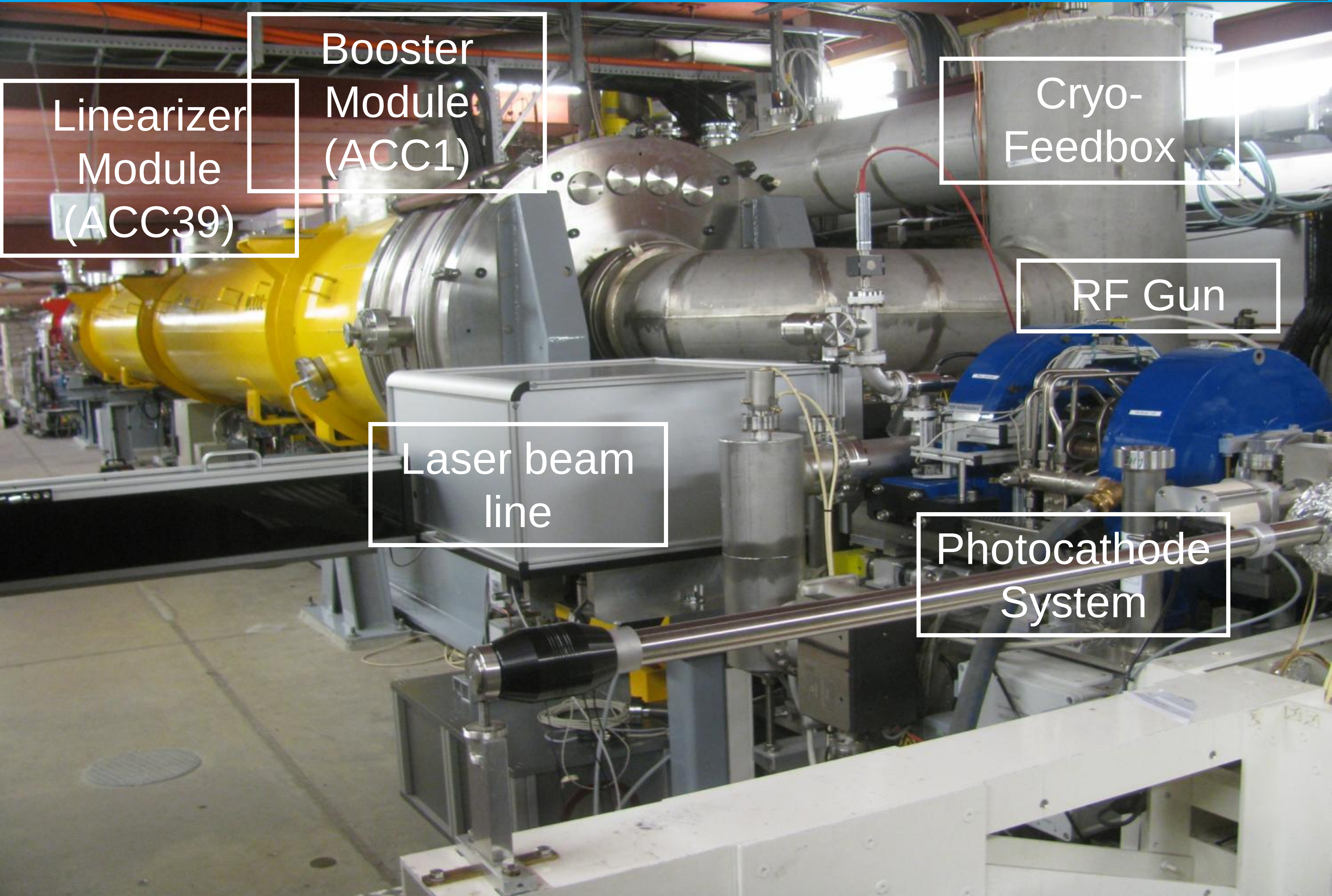
> FLASH2 variable gap undulators

> FLASH2 Experimental Hall

RF Gun

Electron Source

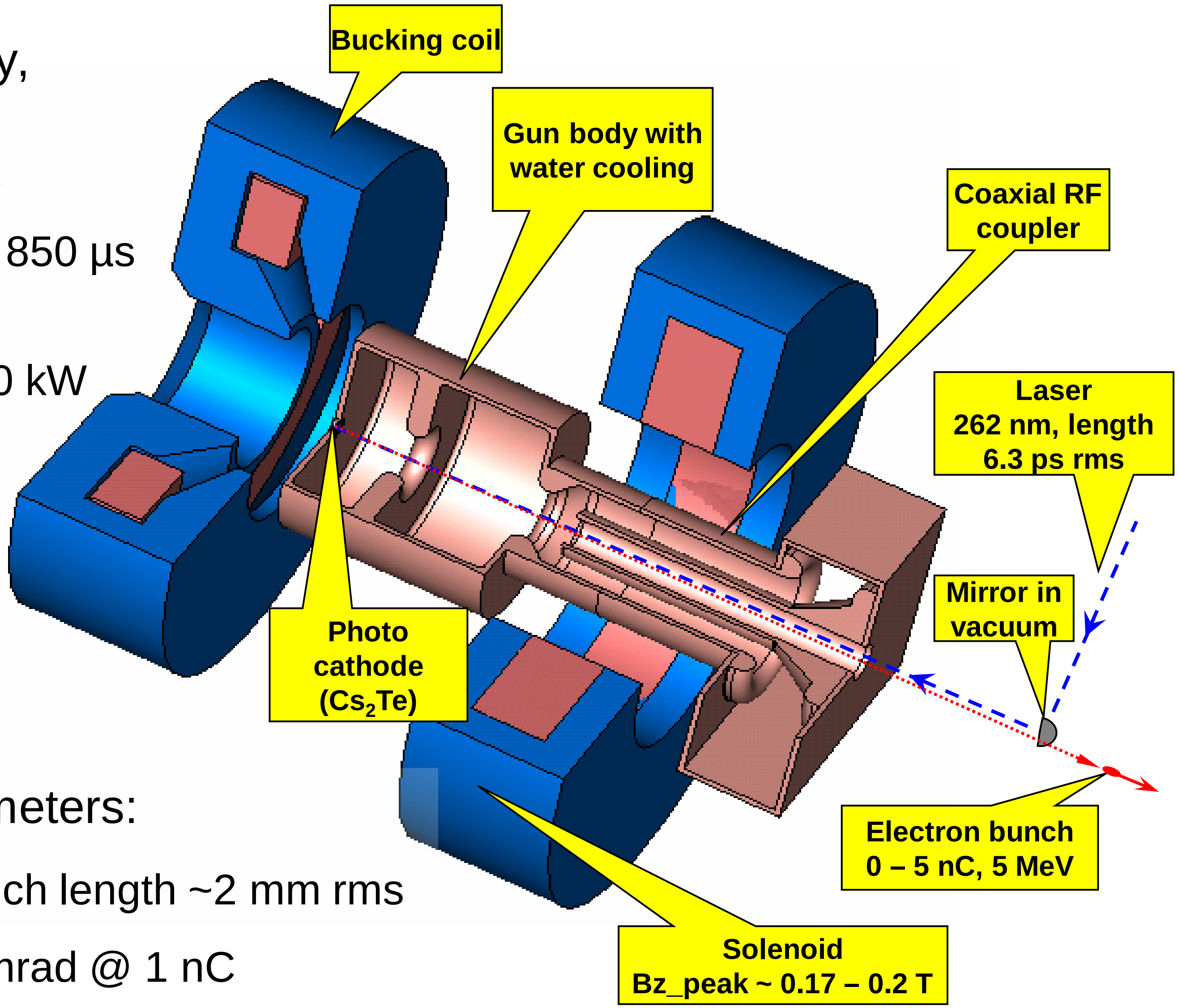
FLASH.
Free-Electron Laser in Hamburg



RF Gun (duty cycle 1:100)

> 1.3 GHz copper cavity, 1 ½ cell

- RF peak power 5 MW
  RF pulse length up to 850 µs
  rep.rate 10 Hz
- Av. RF power up to 50 kW
- Cs_2Te photocathode
- UV burst-mode laser



> Electron beam parameters:

- Charge 0…5 nC, bunch length ~2 mm rms
- Emittance <1.5 mm mrad @ 1 nC
- Trains of thousands of bunches/sec

RF Guns operated at FLASH since 2004

FLASH. Free-Electron Laser in Hamburg

Gun 2

2004 Gun2: 5 Hz, 3.5 MW, 350 µs, 5 kW, 680 GJ
Window: G29

2009 **Gun2 breakdown**

Gun 4.2

1/2010 Gun4.2: 10 Hz, 3.9 MW, 400 µs, 15 kW, 1200 GJ
Window: Gxx

6/2010 Window break down; → G67

9/2011 Window break down; → G29

5/2012 **Gun4.2 breakdown**

Gun 4.1

6/2012 Gun4.1: 10 Hz, 4 MW, 550 µs, 21 kW, 930 GJ
Window: G29

Gun 3.1

3/2013 **Gun3.1: 10 Hz, 5 MW, 550 µs, 27 kW, 1900 GJ(*)**
Window: Thales 5

4/2014 Window leak; → G64

Integrated RF-power

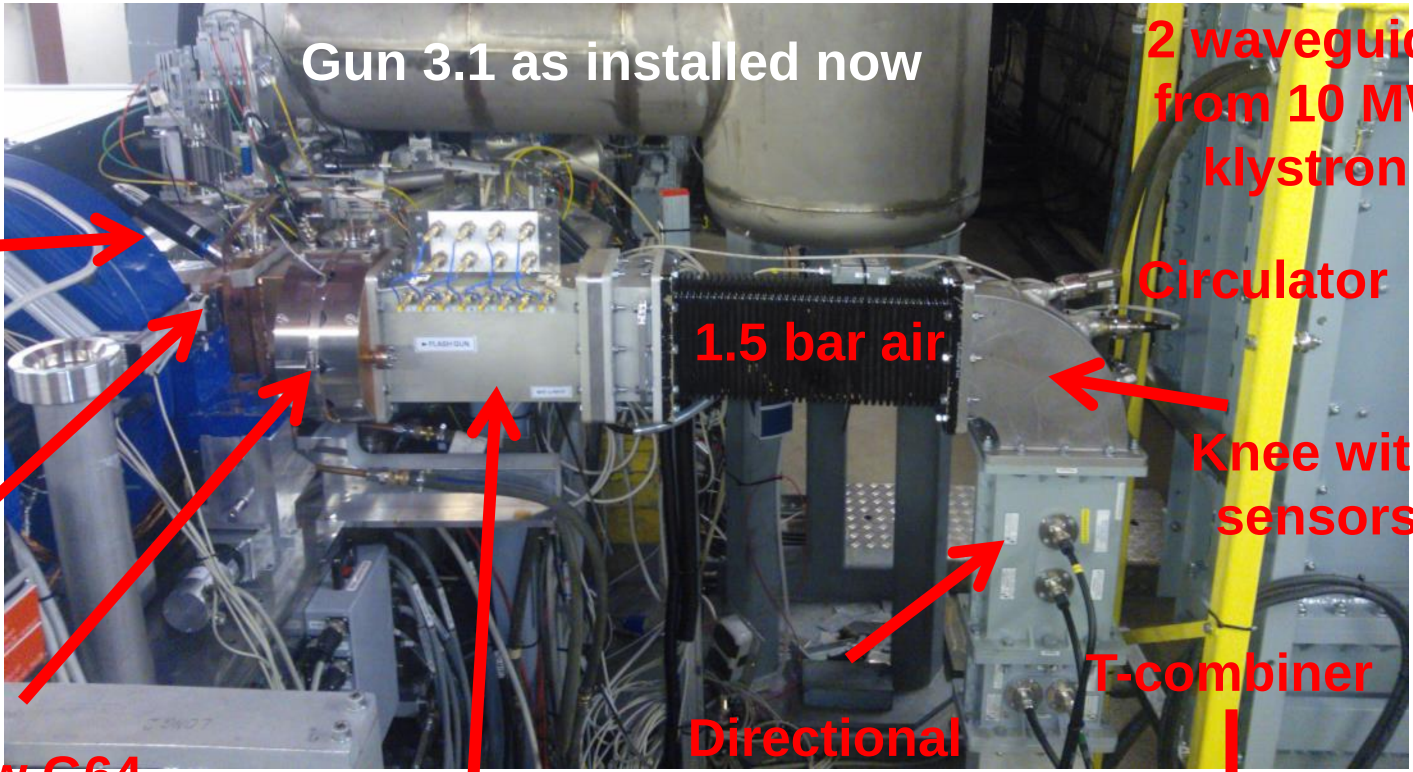
(*) until 15-Mar-2016

No breakdown events since 8-Jun-2014

RF gun controlled by a MTCA.4 based LLRF system since Jan 2015

Present coupler arrangement with 8-port pick-up

- To better understand the interference between forward and reflected wave during the RF pulse, we installed a waveguide piece with 8 pick-up's close to the RF-window
- Data from the 8-port agree with simulations: good understanding of coupler



Gun3.1 with DESY-type window G64

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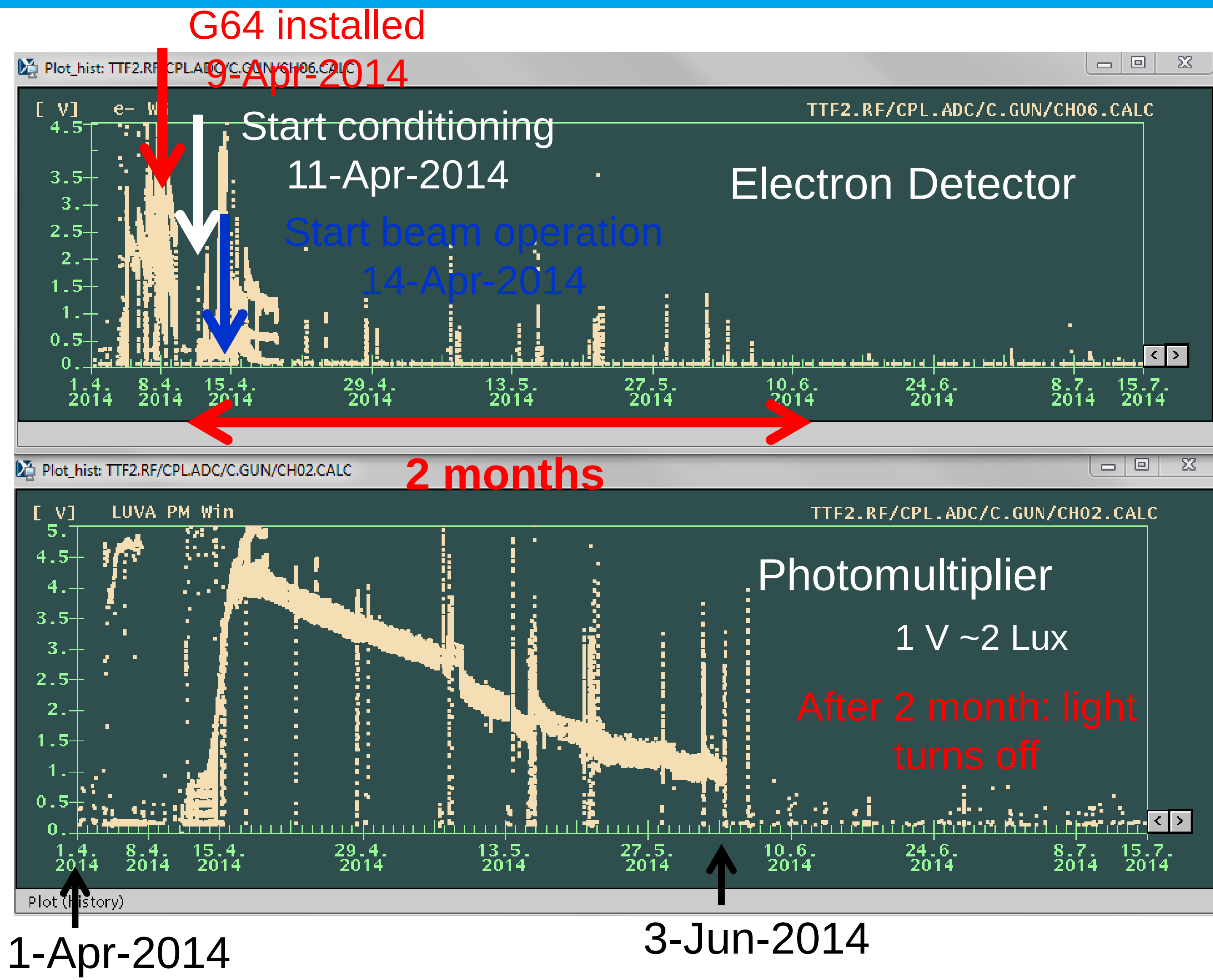

Gun Vacuum since Exchange of Window

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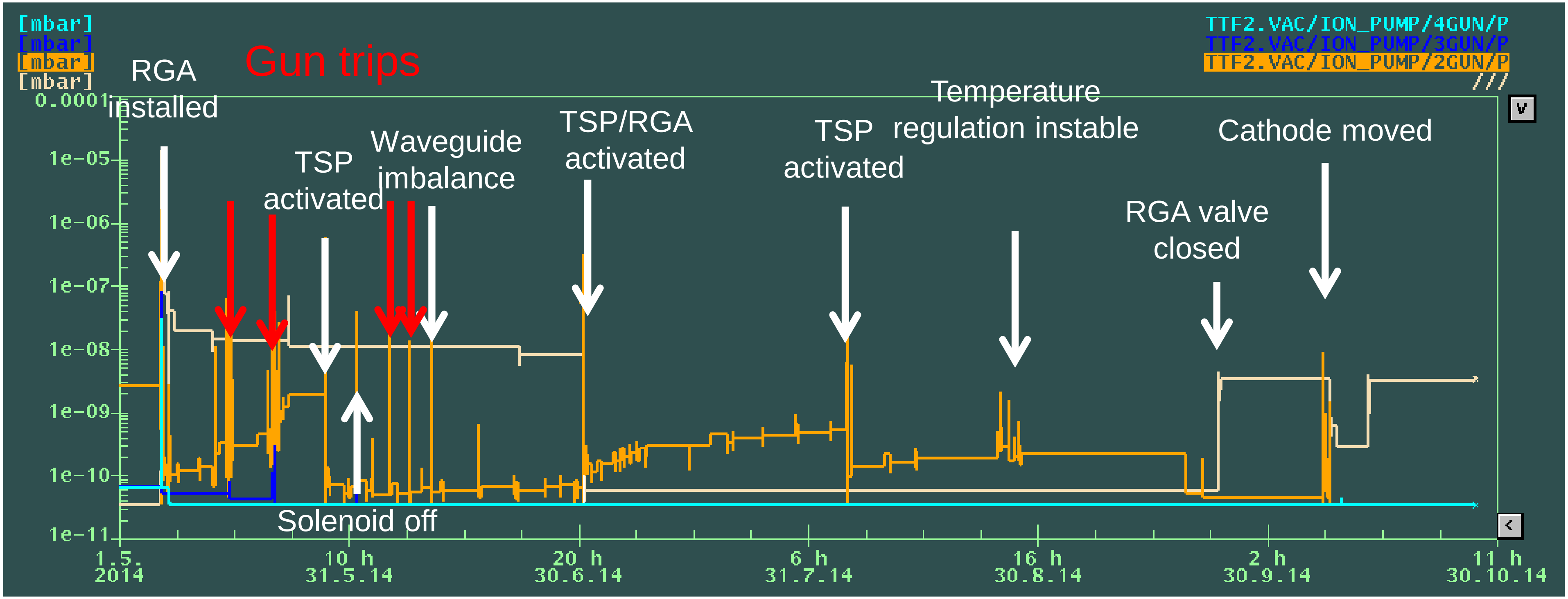
> Residual gas analyzer (RGA) installed: normal signature

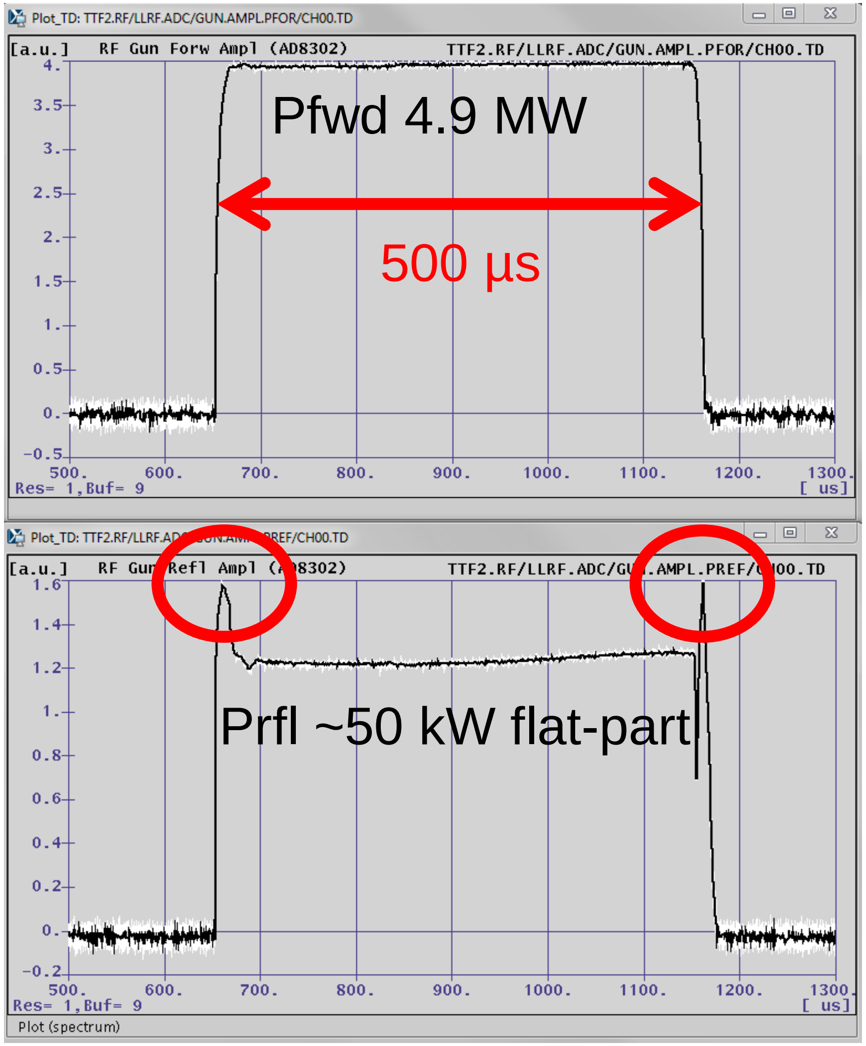
> Pressure decreases constantly, a few activations of the titanium sublimation pump (TSP) required

> Only 4 breakdowns observed, no breakdown event since then



RF Gun forward/reflected power

- Forward power is “smoothed” at start and end



Reflected power 300 kW peak within 20 µs

w/o smoothing 2.6 MW peak within ~2.5 µs

(released energy is the same in both cases)

RF Gun Temperature Stability

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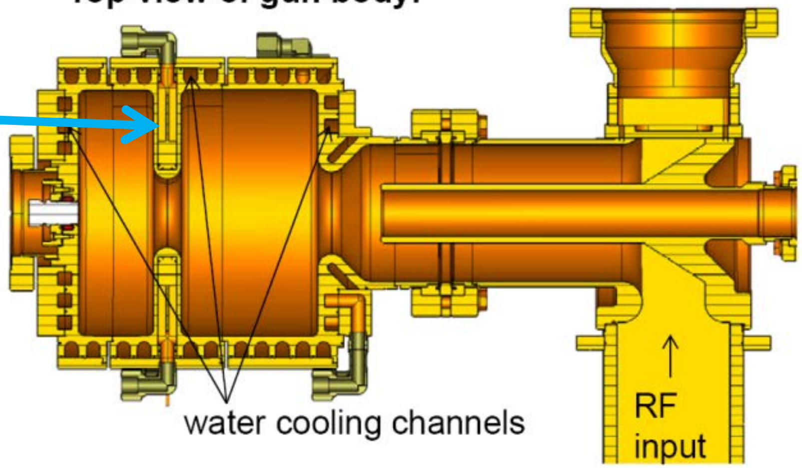
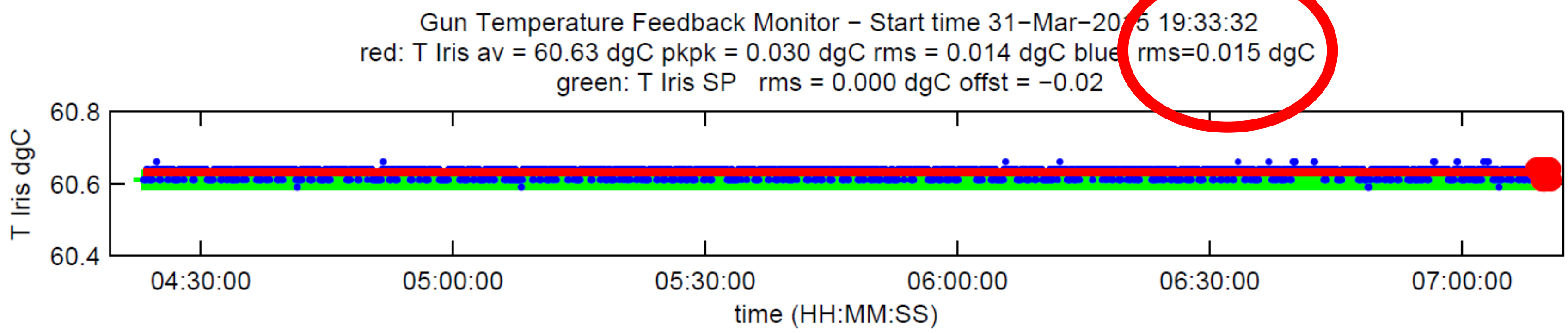
Free-Electron Laser in Hamburg

- Gun is tuned 1.3 GHz with its temperature
  - sensor in the iris separating full/half cell
- Temperature stability: dT = 0.015 dgC rms
  - Corresponds to df = 315 Hz or ~0.1 dg in RF phase
  - Quite a bit of work was going into tuning the feedback parameters of the gun water system



A large effort has been made to improve this by system modelling and pulse width modulation → Seminar by S. Pfeiffer



(1 bit jump = 0.02 K → better ADC resolution required)

Example for sensitivity of water temperature

RF Gun water circuit pressure change

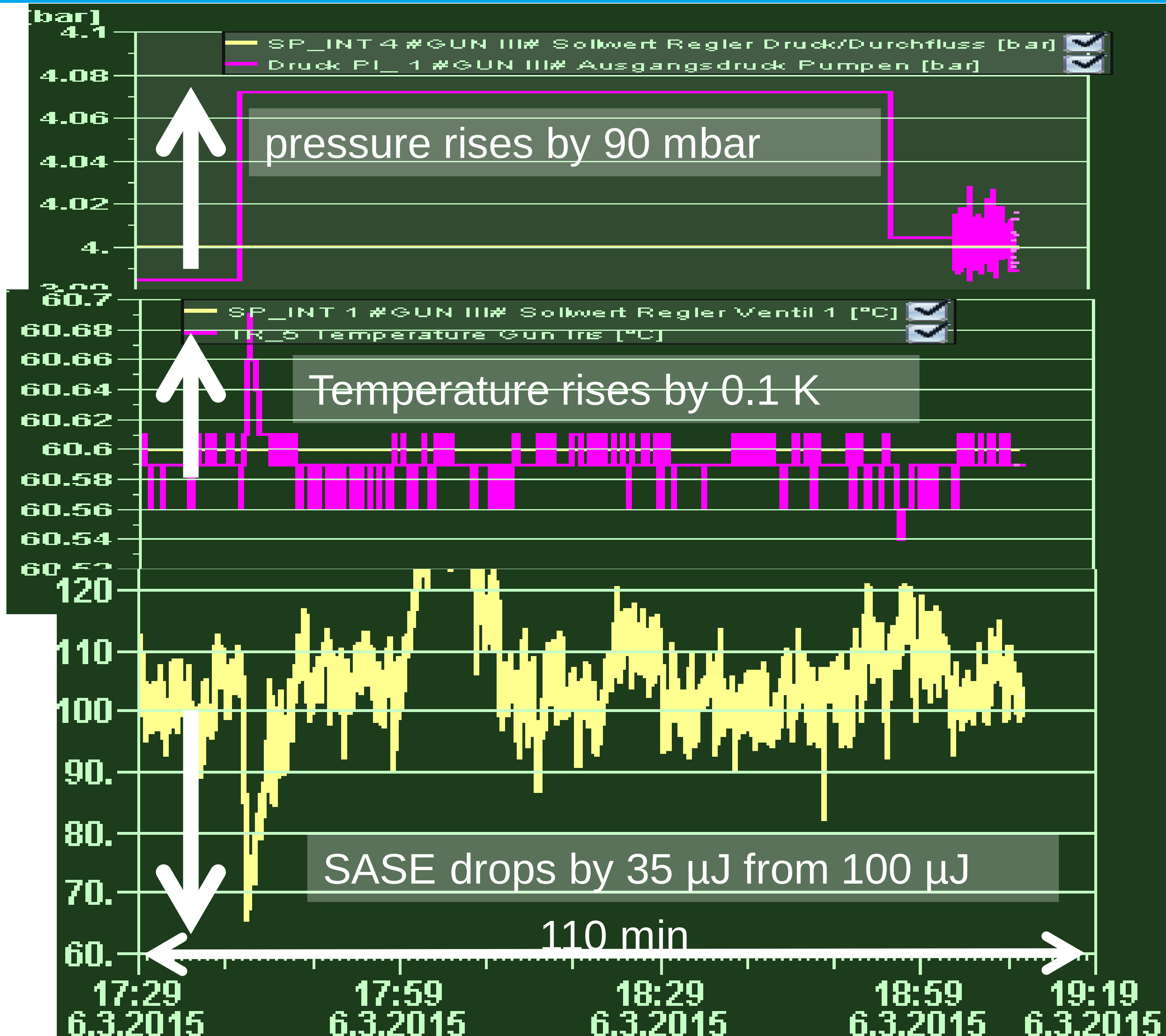
dP = 0.1 bar

↓

dT = 0.1 K

↓

dE/E (SASE) = -30%



RF Gun Low Level RF

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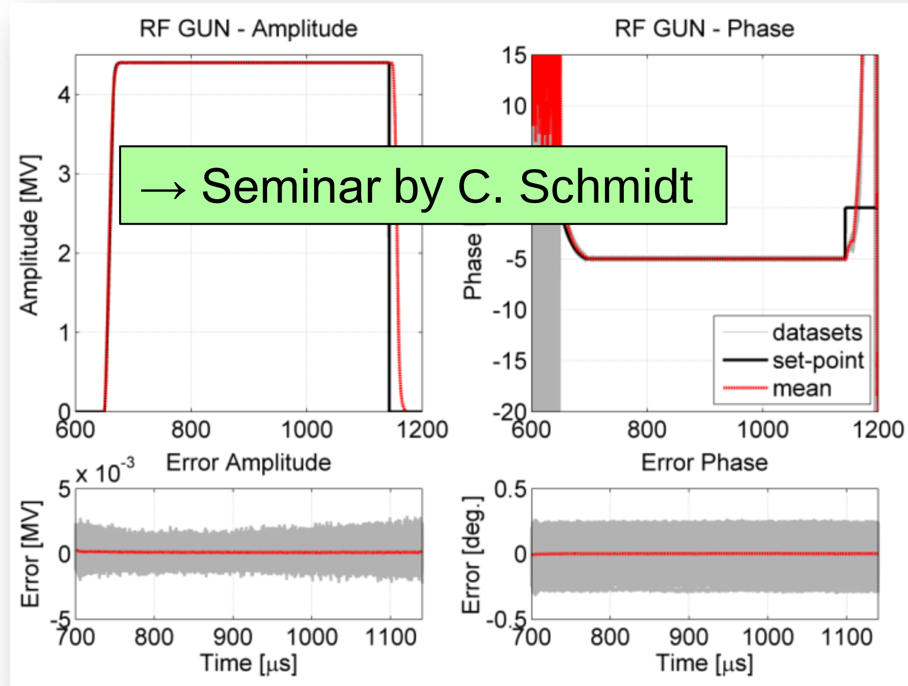
Free-Electron Laser in Hamburg

- Since Jan. 2015, LLRF is based on MTCA.4 standard
- System identification performed
  - Model found and controller designed
  - large loop latency compared to system bandwidth ~1.4 µs
- Runs smooth and stable
- Includes learning feedforward



Feedback gain currently **not** sufficient to achieve a phase stability of dφ < 0.01 dg

Regulation performance (rms)	Intra pulse (flattop)	Pulse to pulse (960 consecutive pulses)
Amplitude dA/A (%)	0.008	0.008 OK
Phase dφ (dg)	0.007	**0.076**

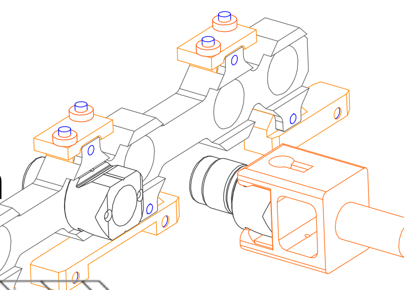
- Features additional protection mechanisms:
  - amplitude limiter, fast switch off

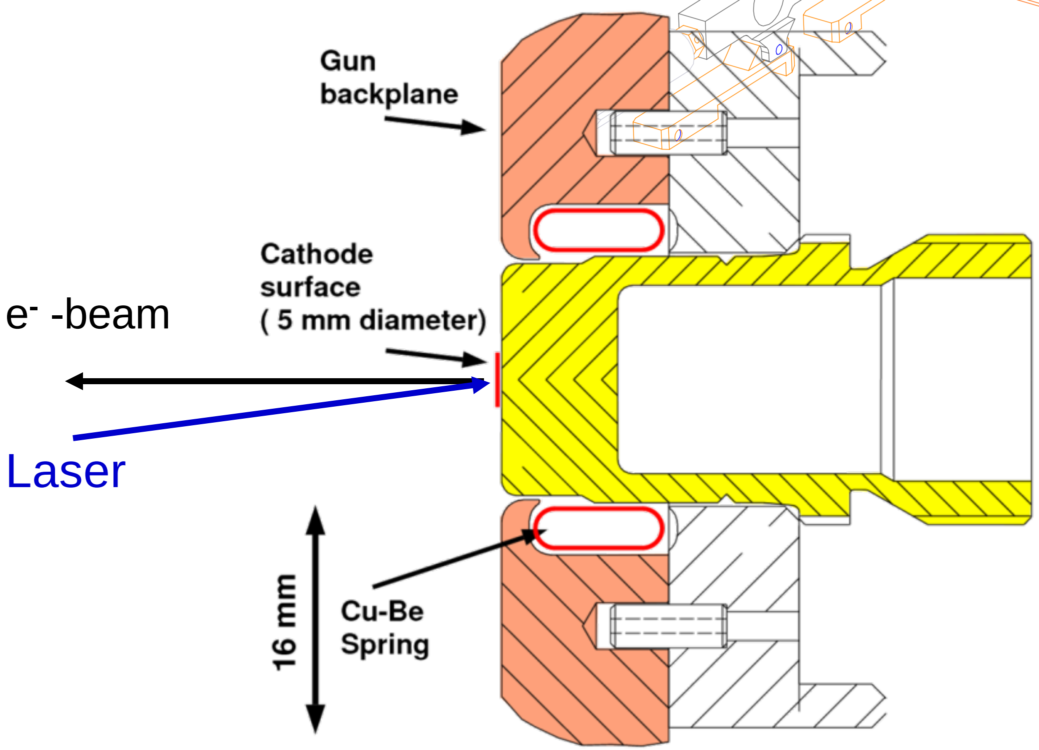
Goal: < 0.01% in amplitude and < 0.01 dg (rms) in phase

Cathode

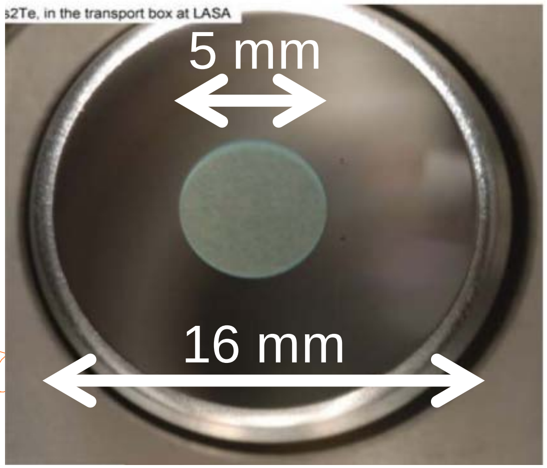
Cs_2Te Cathodes

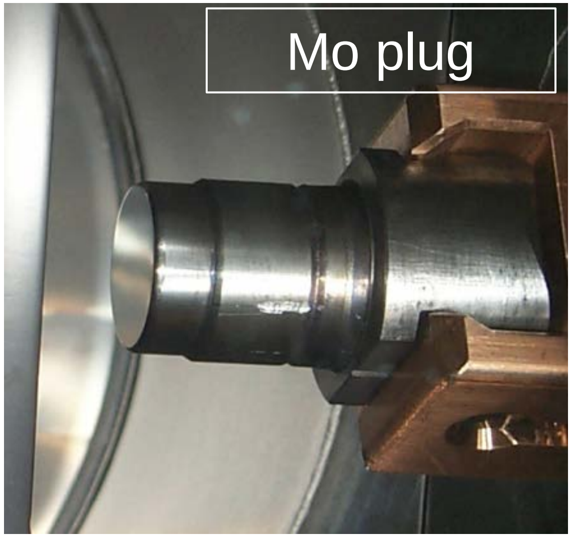
- High quantum efficiency 5 … 10 %
- Excellent lifetime > 1 year at FLASH
- Preparation systems at LASA, Milano and DESY, Hamburg
  - UHV transport boxes
- Requires UV laser 275 … 250 nm





Thin film of Cs_2Te on Mo plug





From Production to the Gun – keeping UHV all time

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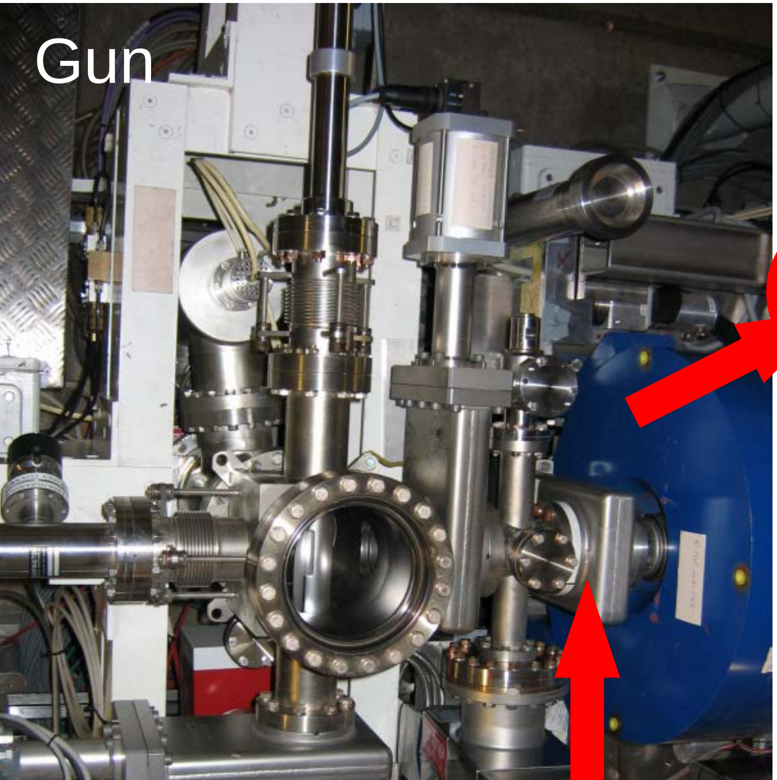
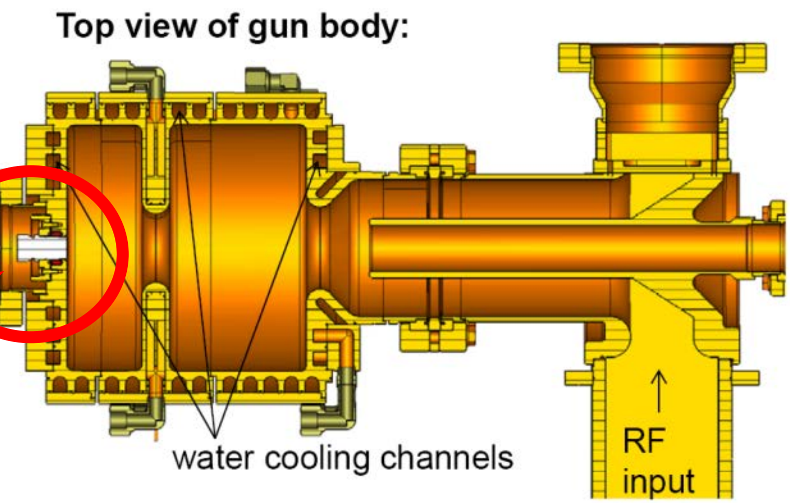
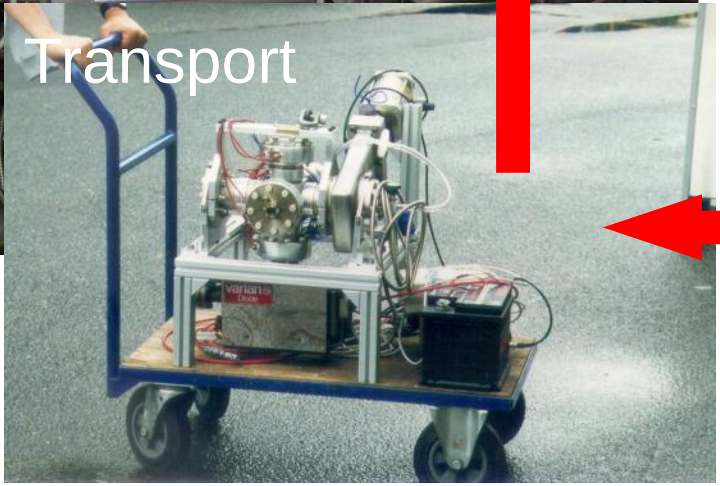
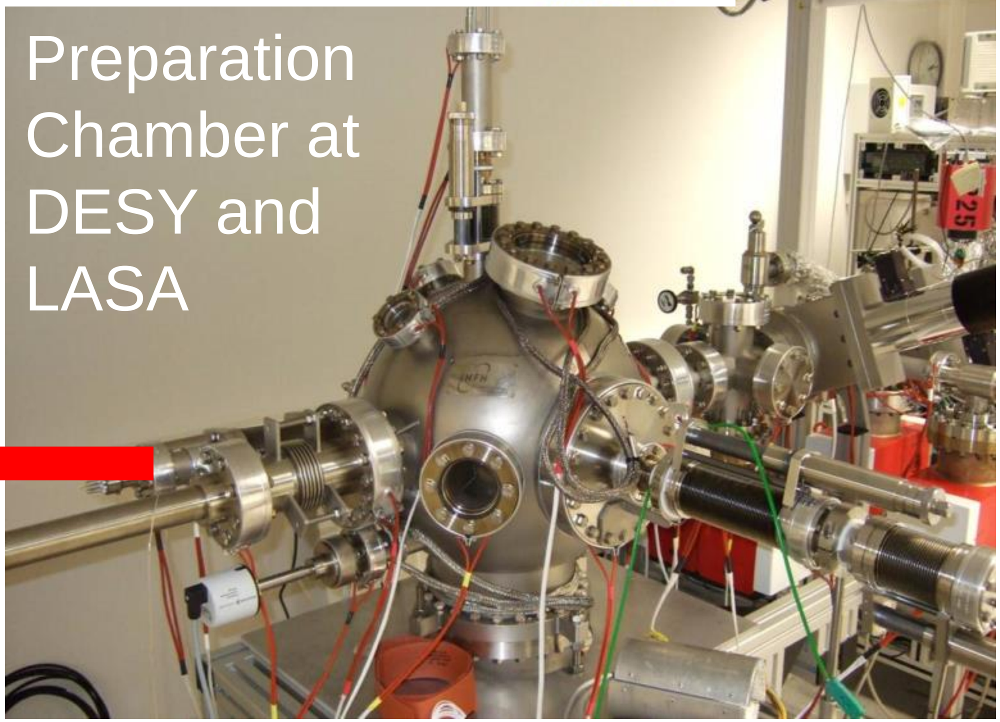
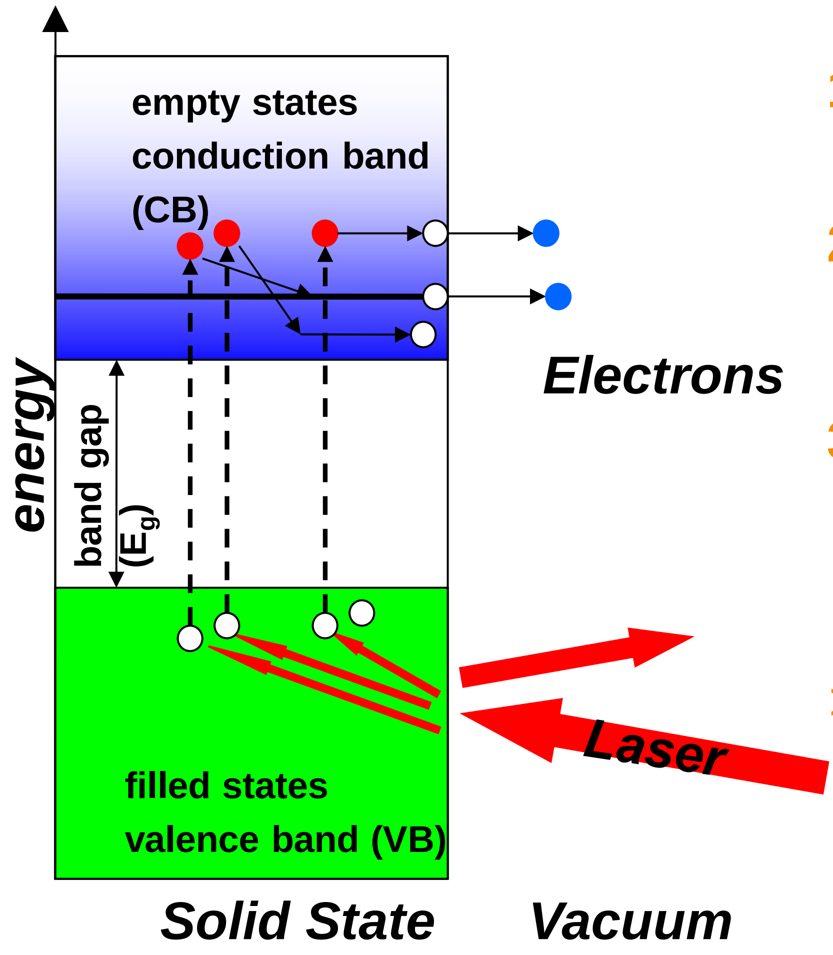








Emission Process



Three step model:

1. **Excitation from VB to CB**
   - Laser energy $h\nu > E_g$
2. **Electron transport to surface**
   - as long as $h\nu < 2\ E_g$ only electron phonon scattering
3. **Emission**
   - To be emitted, the electron has to overcome the potential barrier at the surface, here electron affinity E_A

> Theoretical values:

- $E_g = 3.3$ eV
- $E_A = 0.2$ eV

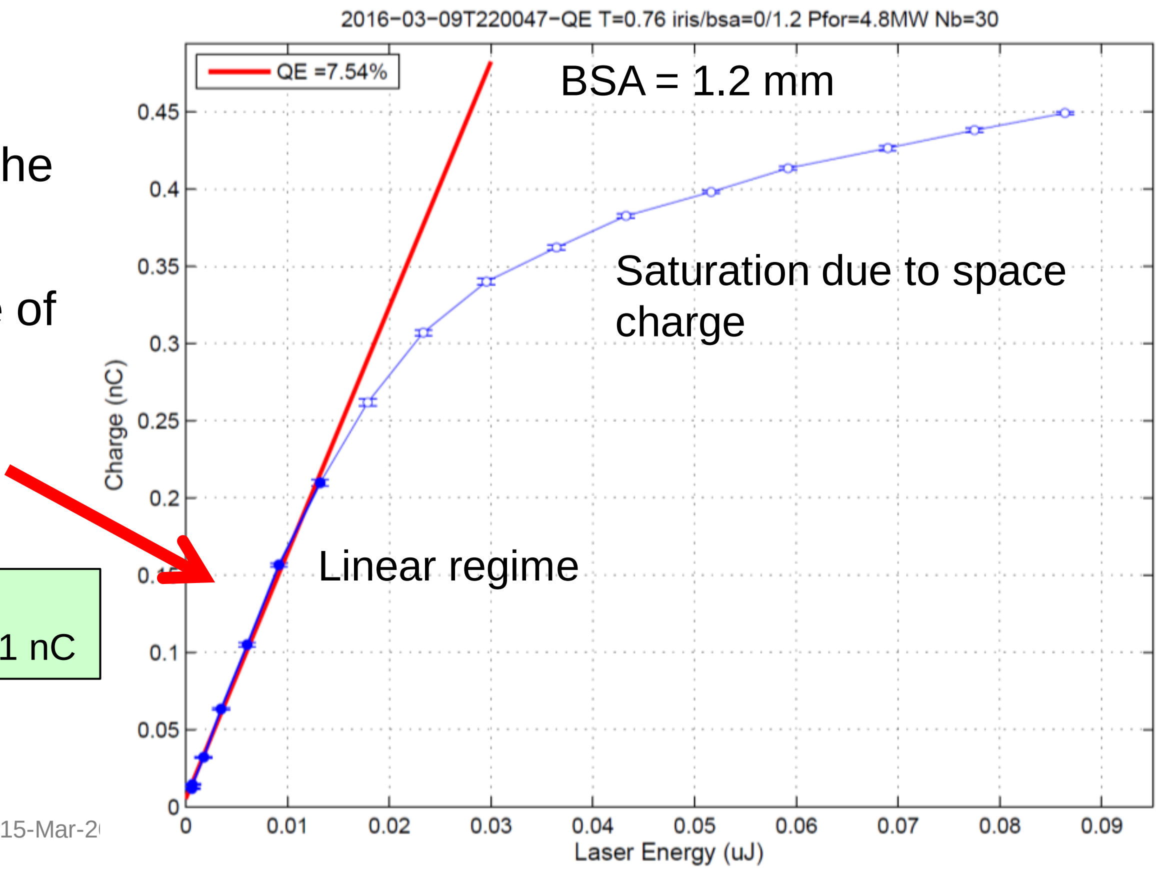
Powel et al., Phys. Rev. B ***8*** *(1973), 3987*

Quantum Efficiency (QE) measurement

FLASH. Free-Electron Laser in Hamburg

- RF Gun at nominal parameters (4.8 MW), phase 38º off zero crossing
- Laser pulse energy measured with an absolutely calibrated joulemeter (Molectron J-5/9, reflective coating, 17.82 mV/µJ)
- Beamline transmission (68%) measured and corrected for
- Laser wavelength 262 nm
- Charge is measured with the 3GUN toroid T1
- QE is defined as the slope of laser energy vs charge, obtained by a linear fit

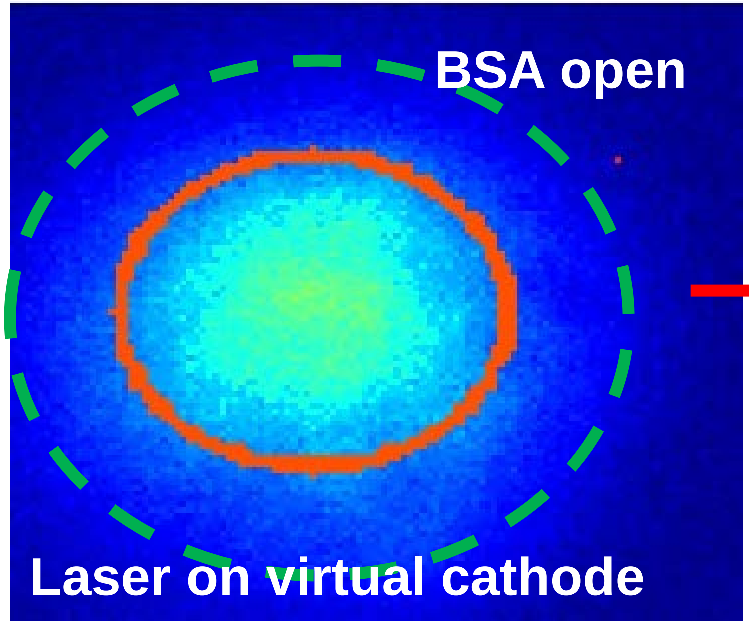
QE = 5% →
Laser pulse energy = 0.1 µJ for 1 nC

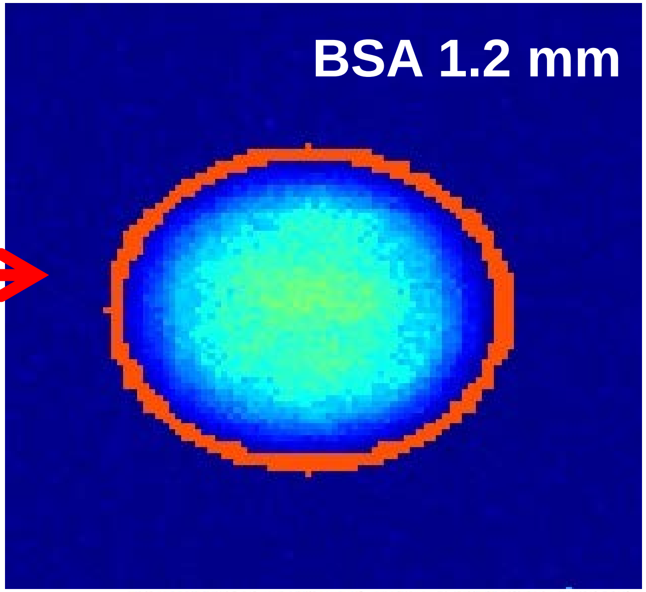


BSA = Beam Shaping Aperture

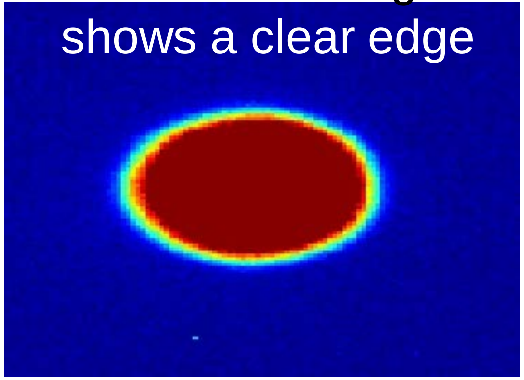
FLASH.
Free-Electron Laser in Hamburg

> The laser overfills the BSA → BSA is imaged onto the cathode

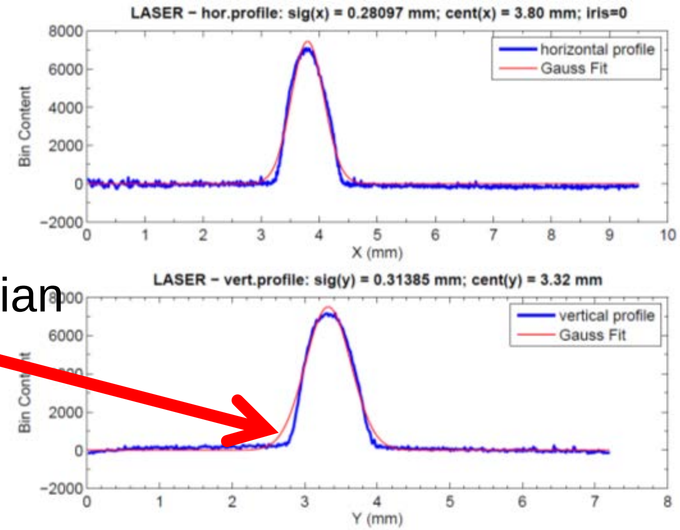




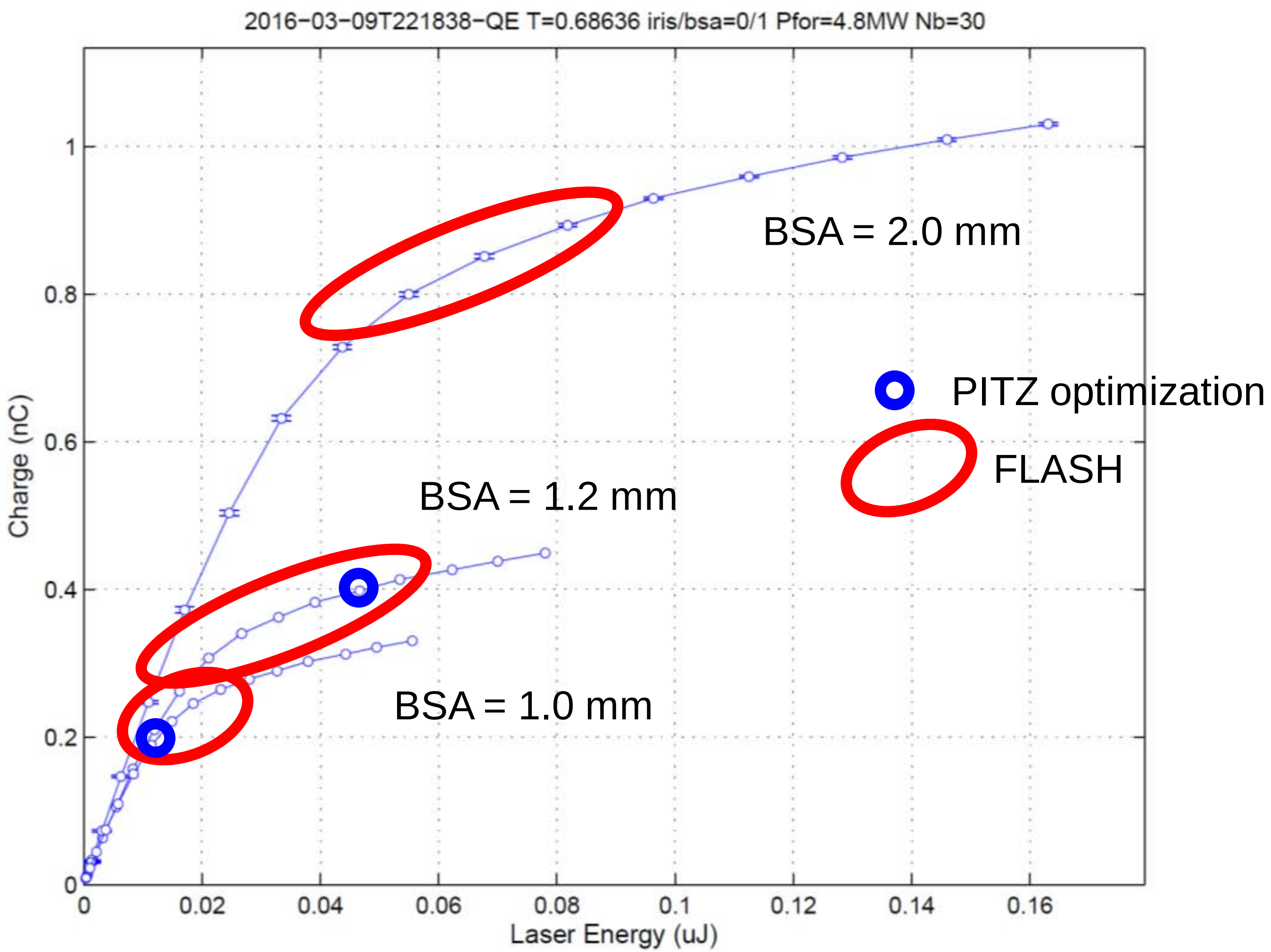
Saturated image
shows a clear edge



Projection of a
truncated Gaussian



Typical Working Points



Optimized Laser Spot Size vs Charge

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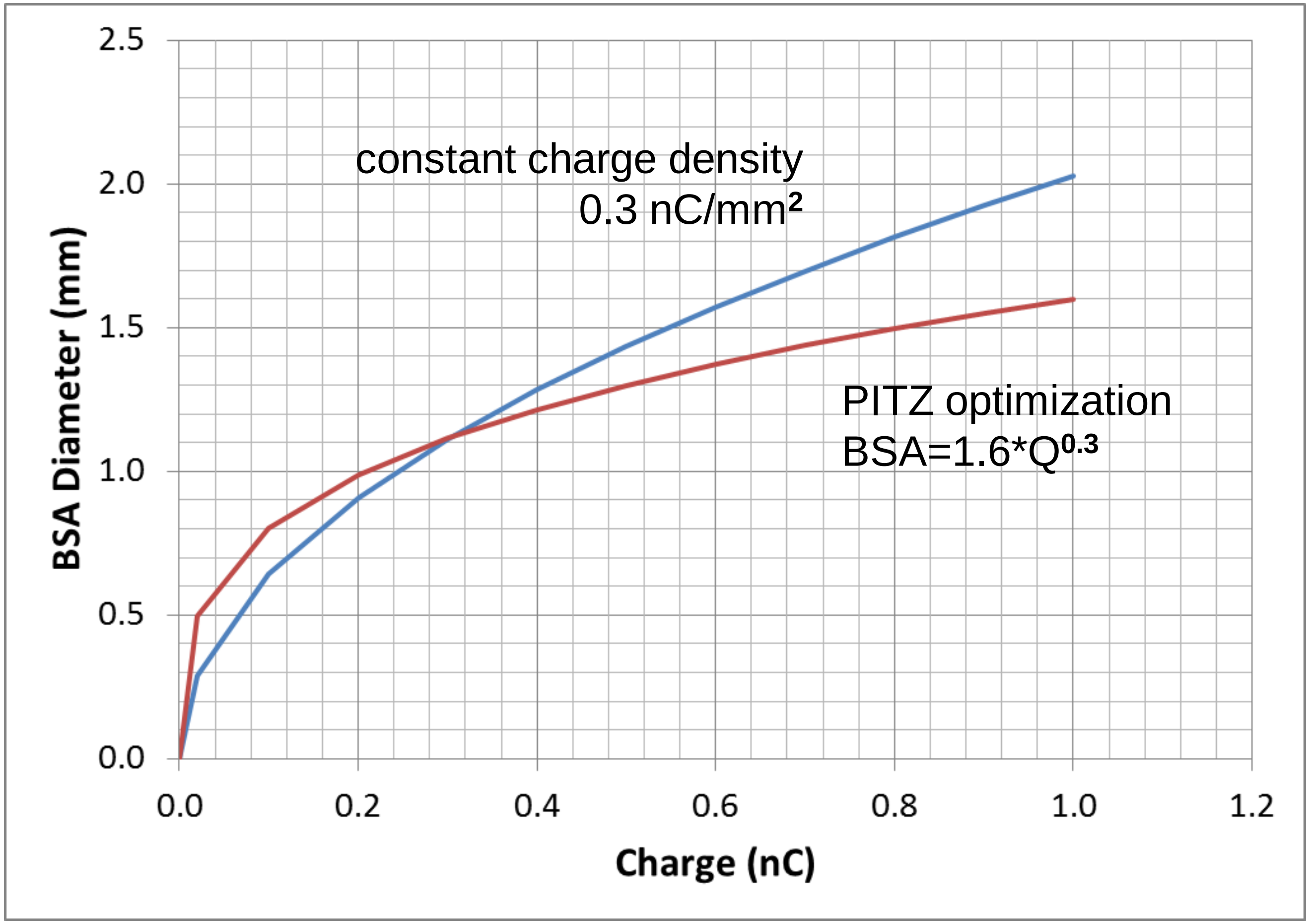
- > 1st approximation: keep charge density on cathode constant
- > Change laser spot size (BSA) rather then laser energy

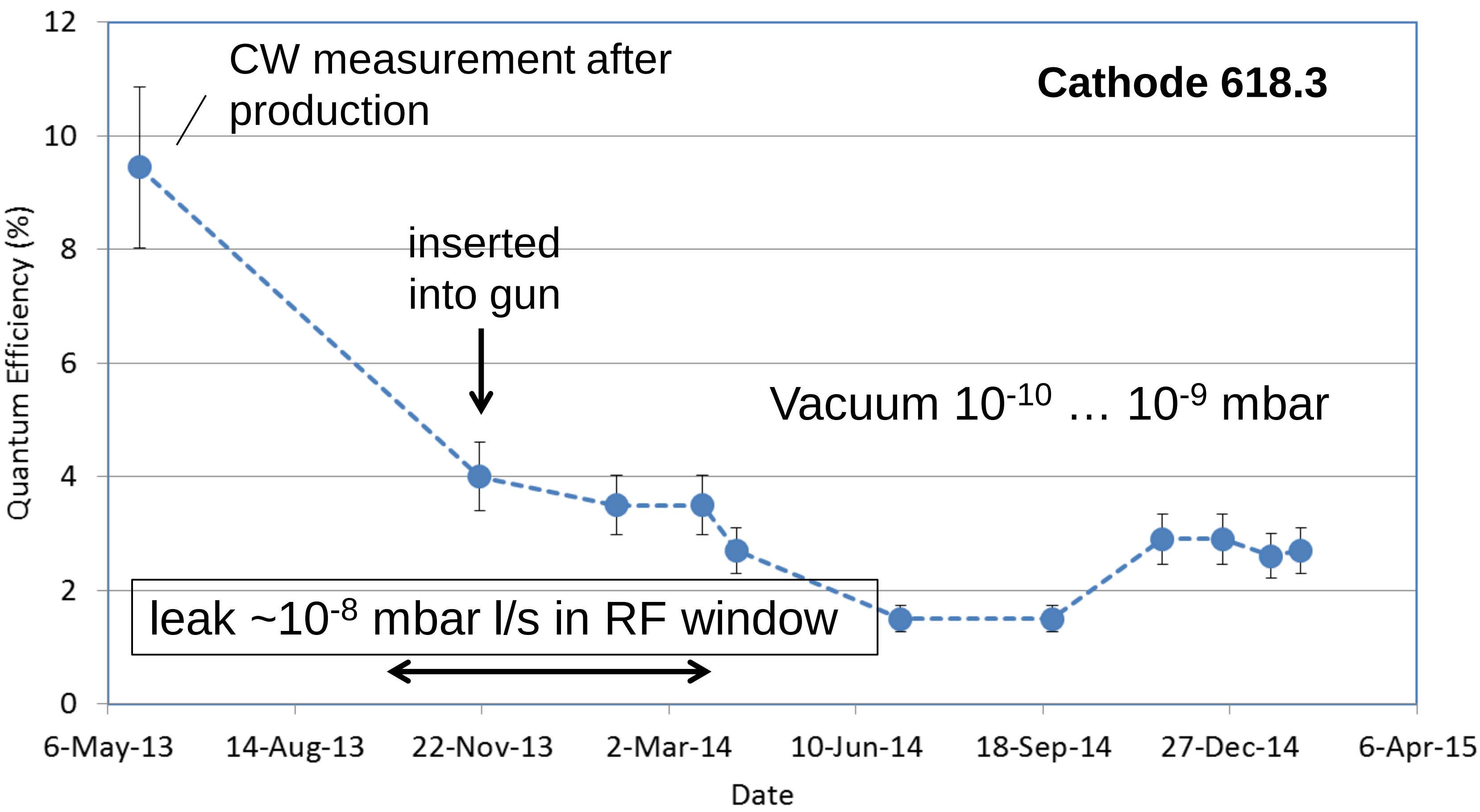


Cathode Lifetime: 618.3

FLASH. Free-Electron Laser in Hamburg

> Cathode 618.3: in use 21-Nov-2013 to 4-Feb-2015: 439 days in operation

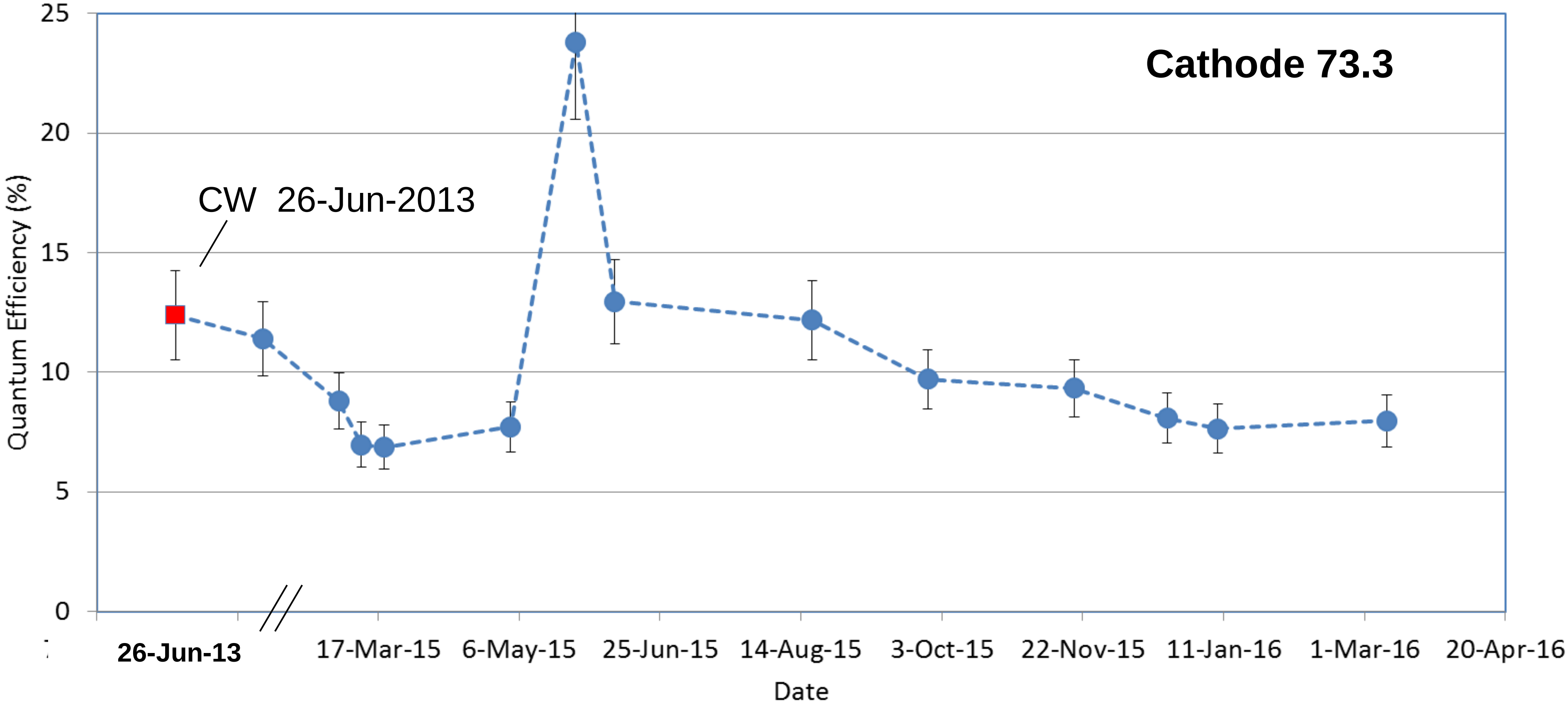
> Total charge extracted: 3.2 C



Cathode Lifetime: 73.3

FLASH.
Free-Electron Laser in Hamburg

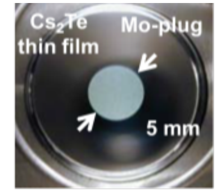
> Cathode 73.3: in use 4-Feb-2015 up to now: 400 days in operation
> Total charge extracted: 5 C

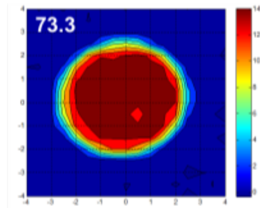


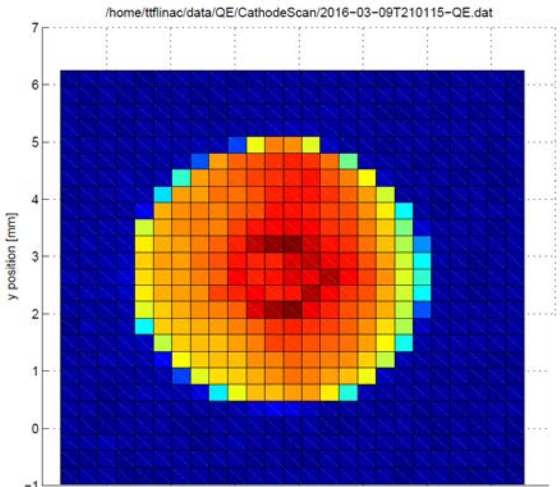
QE map evolution

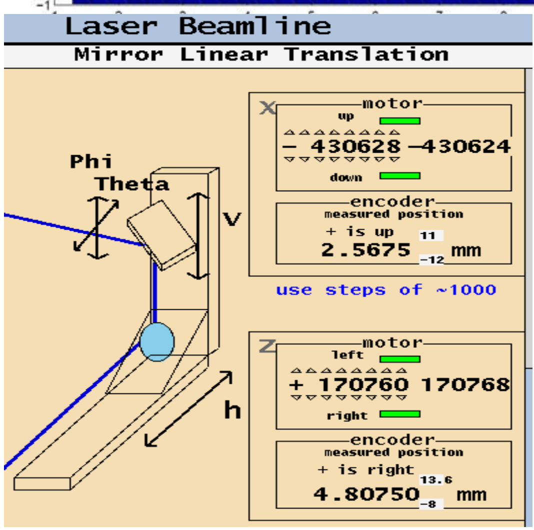
FLASH.
Free-Electron Laser in Hamburg

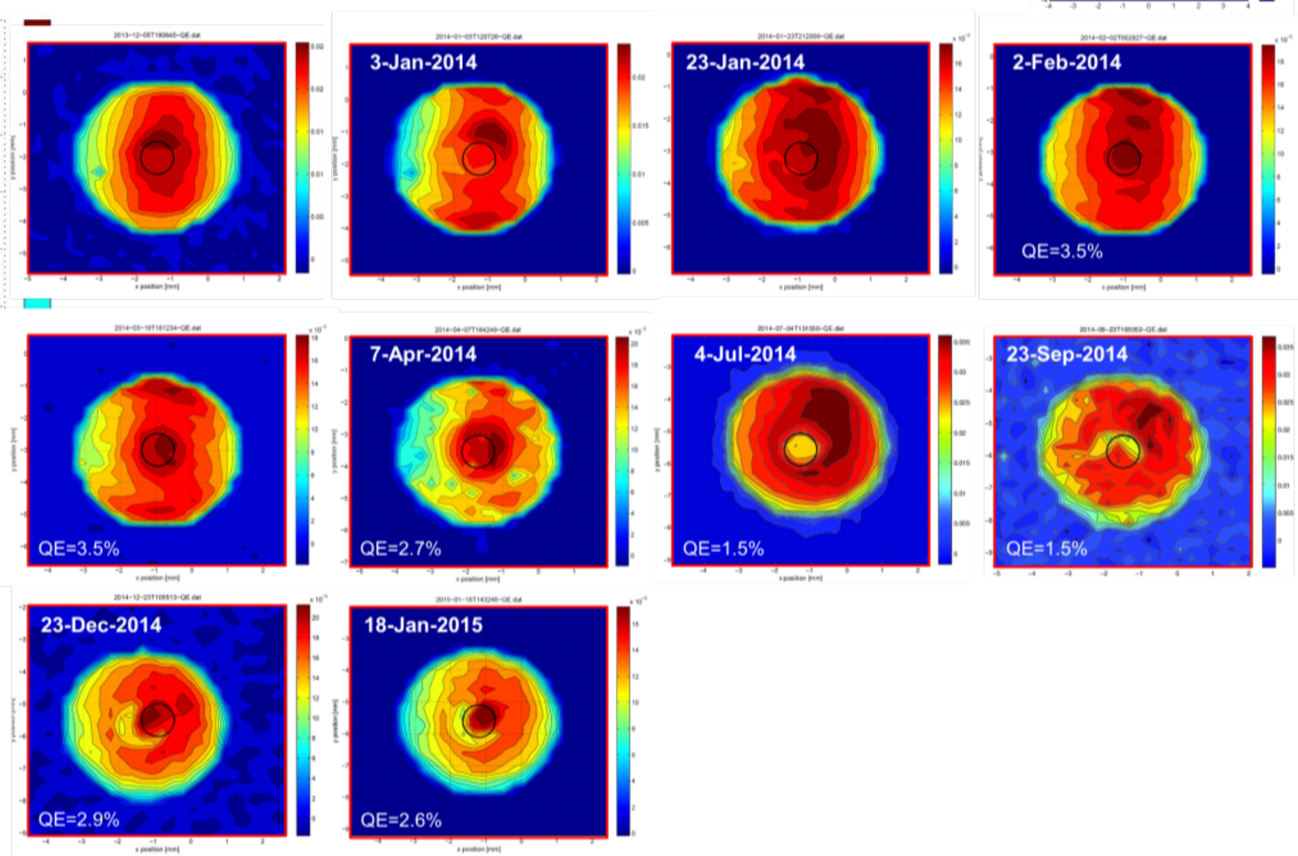
- Cathode 618.3
- QE map with laser spot size 100 µm diam., step size 85 µm







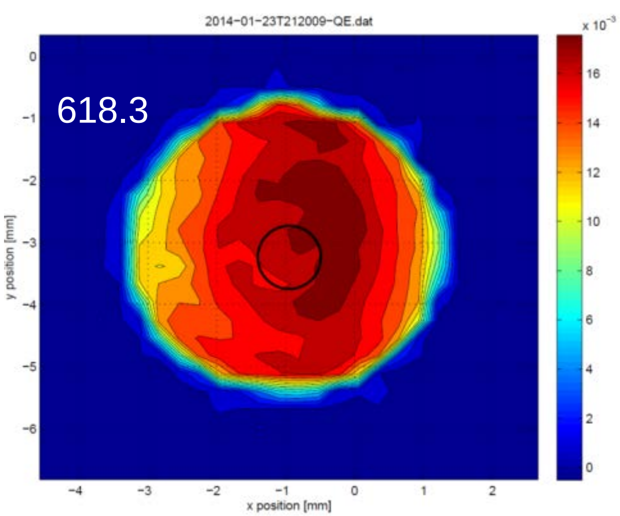




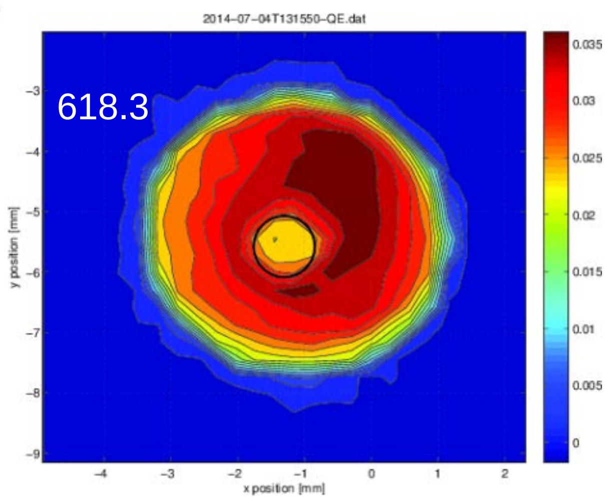
Note: the color code does not show absolute QE's, see scale

QE map Cathode 618.3

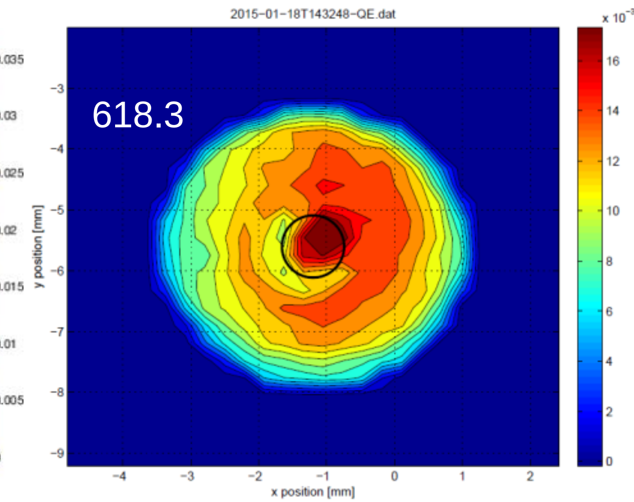
> Initial faster QE degradation where the laser hits
>
> Rest of cathode degrades slower - most likely related to the base vacuum
>
> Indication that QE recovered in the center (laser cleaning?)



23-Jan-2014



4-Jul-2014



18-Jan-2015

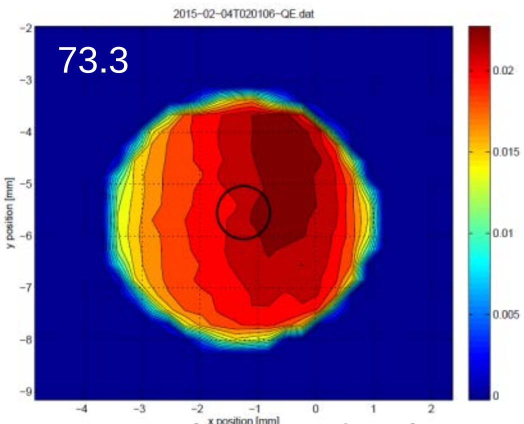
Center: QE=3.5% | QE=1.5% | QE=2.6%

QE map Cathode 73.3 at FLASH

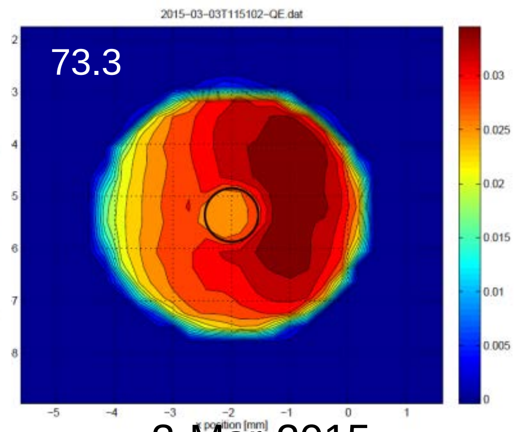
FLASH. Free-Electron Laser in Hamburg

> Cathode 73.3 inserted 4-Feb-2015, grown 26-Jun-2013, LASA

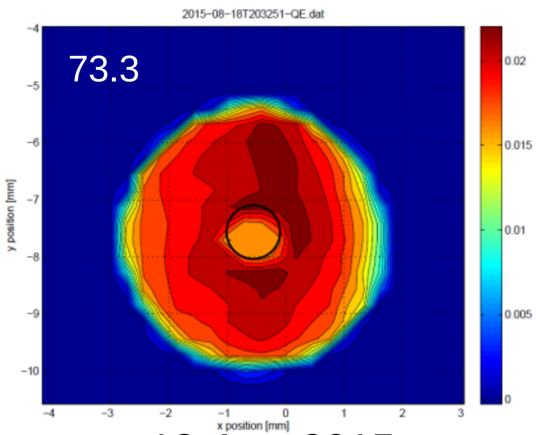
> Similar QE pattern as previous cathode 618.3 – but with differences



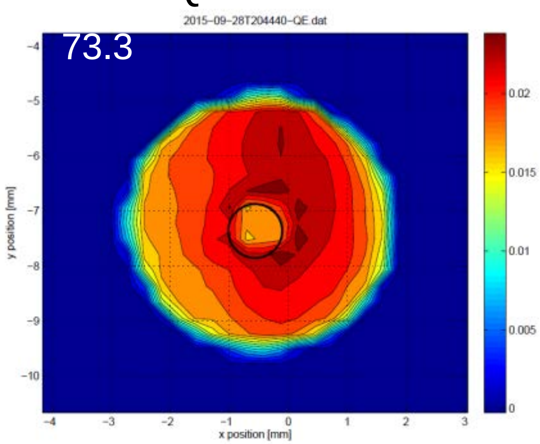
4-Feb-2015 fresh
QE=11.4 %



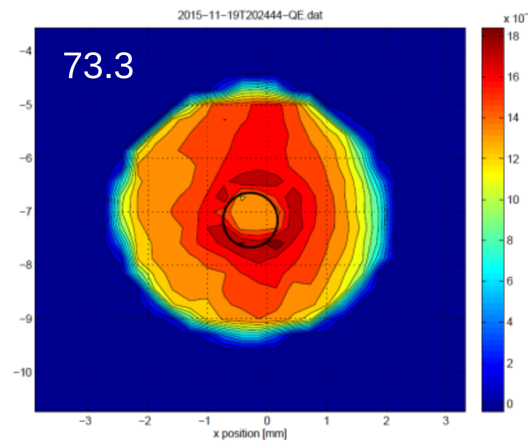
3-Mar-2015
QE=8.8 %



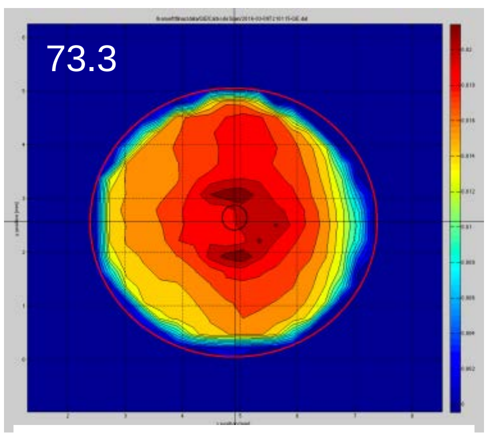
18-Aug-2015
QE=12.2 %



28-Sep-2015
QE=9.7 %



19-Nov-2015
QE=9.3 %



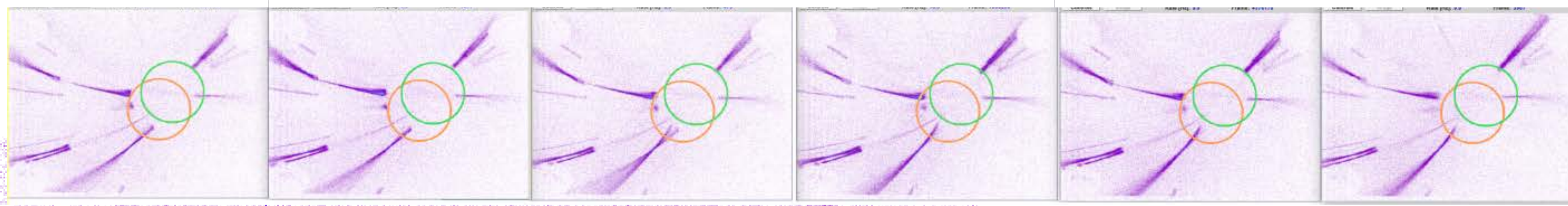
9-Mar-2016
QE=8.0 %

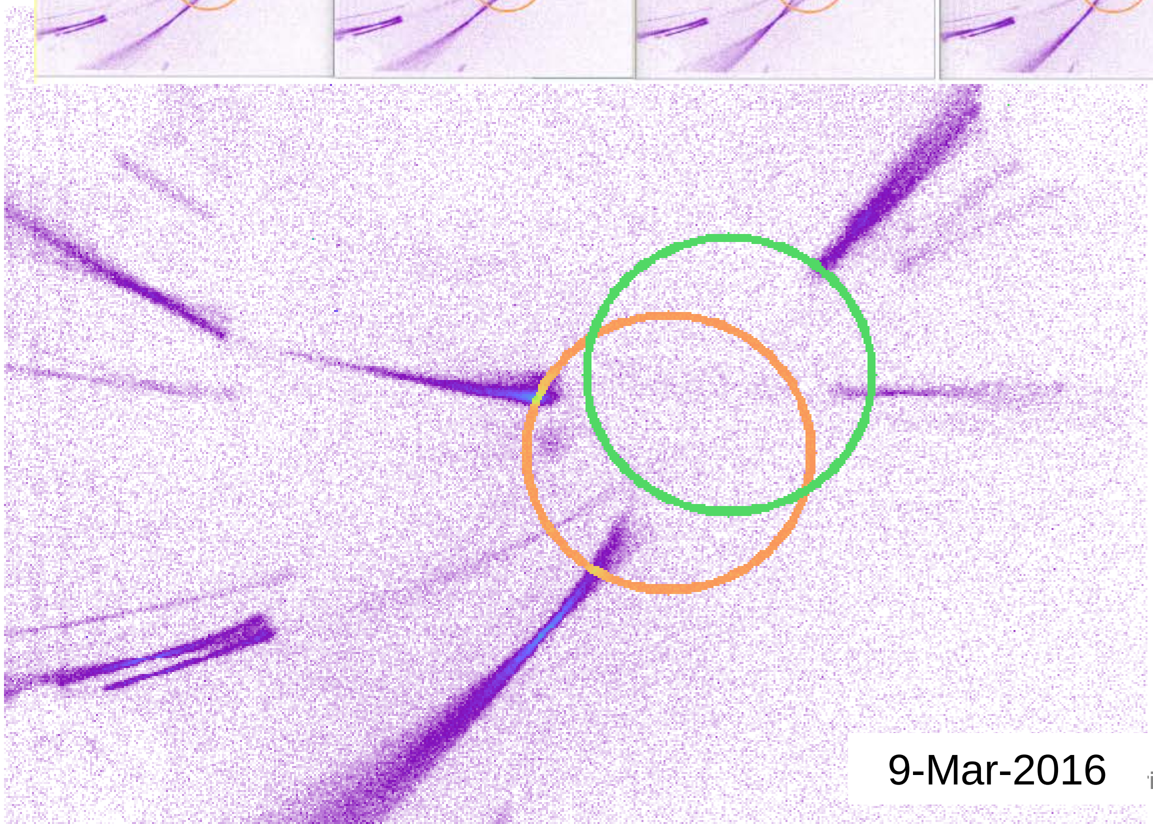
Darkcurrent with Cathode 73.3

FLASH. Free-Electron Laser in Hamburg

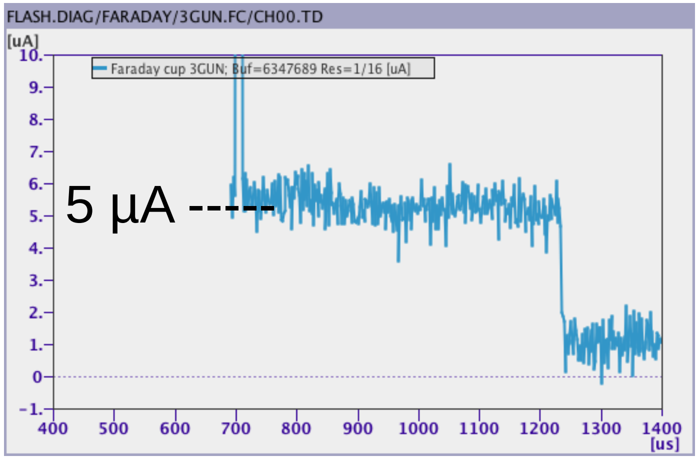
- Stable at 5 µA, stable pattern
- measured at 3GUN; 4.8 MW, 547 µs, Sol. 307.0 A; phase +4 dg

15-Jul-2015	18-Aug-2015	29-Sep-2015	11-Nov-2015	22-Dec-2015	7-Jan-2015





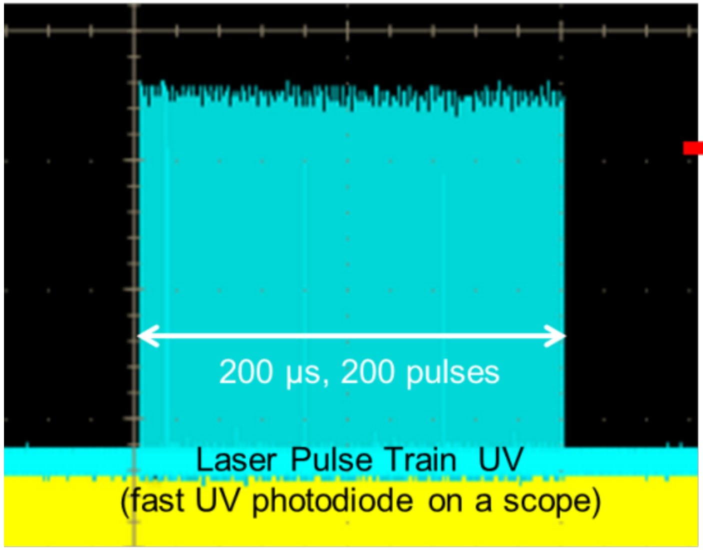
9-Mar-2016

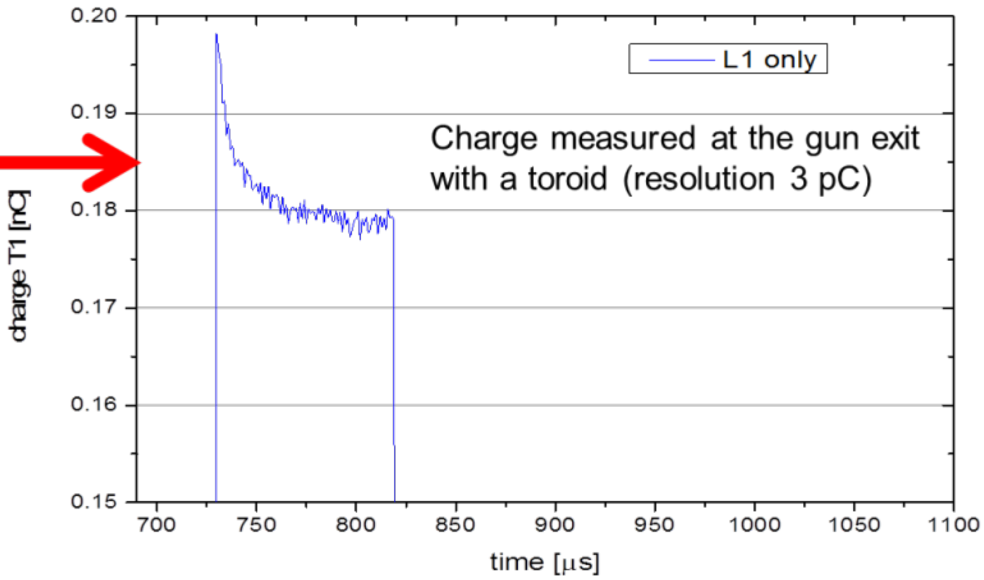


Emission issue of fresh cathode 73.3

FLASH. Free-Electron Laser in Hamburg

> Fresh in the gun 4-Feb-2015; QE=10%



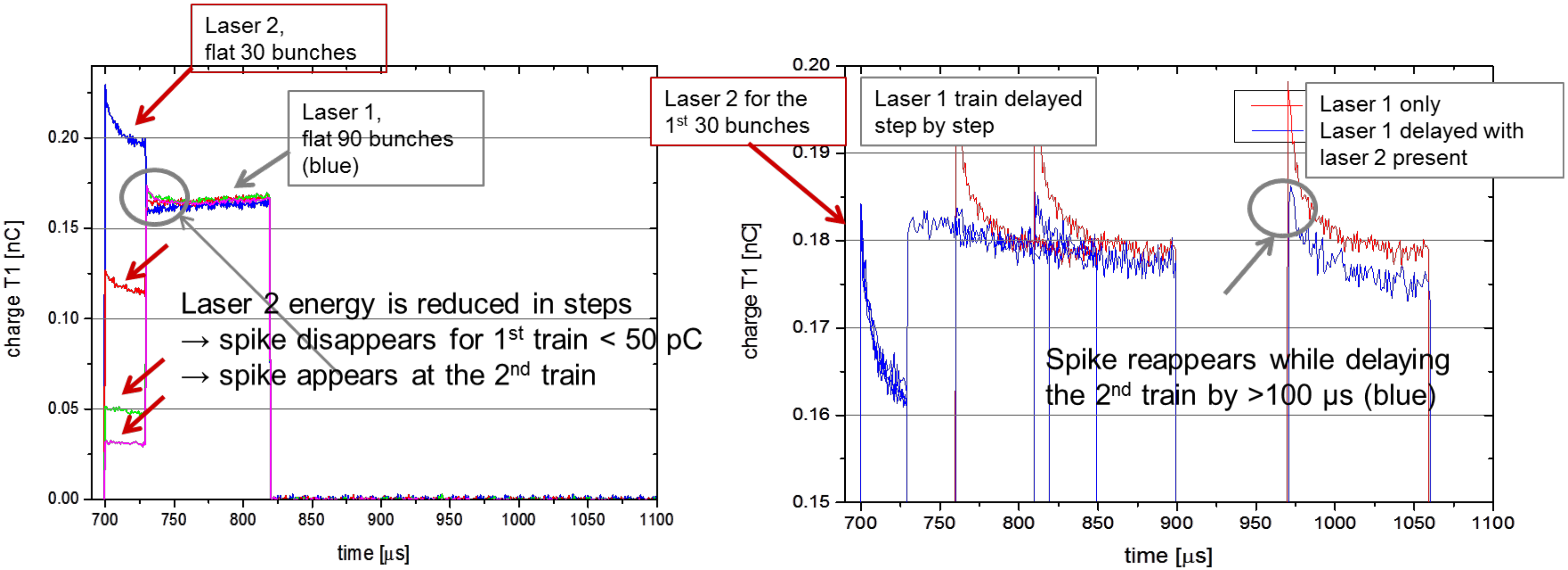


> A flat energy distribution of the laser pulse train produces a ‘spike’ at the head of the electron bunch train emitted from a fresh cathode – that’s not what one wants to have

Emission issue of fresh cathode 73.3

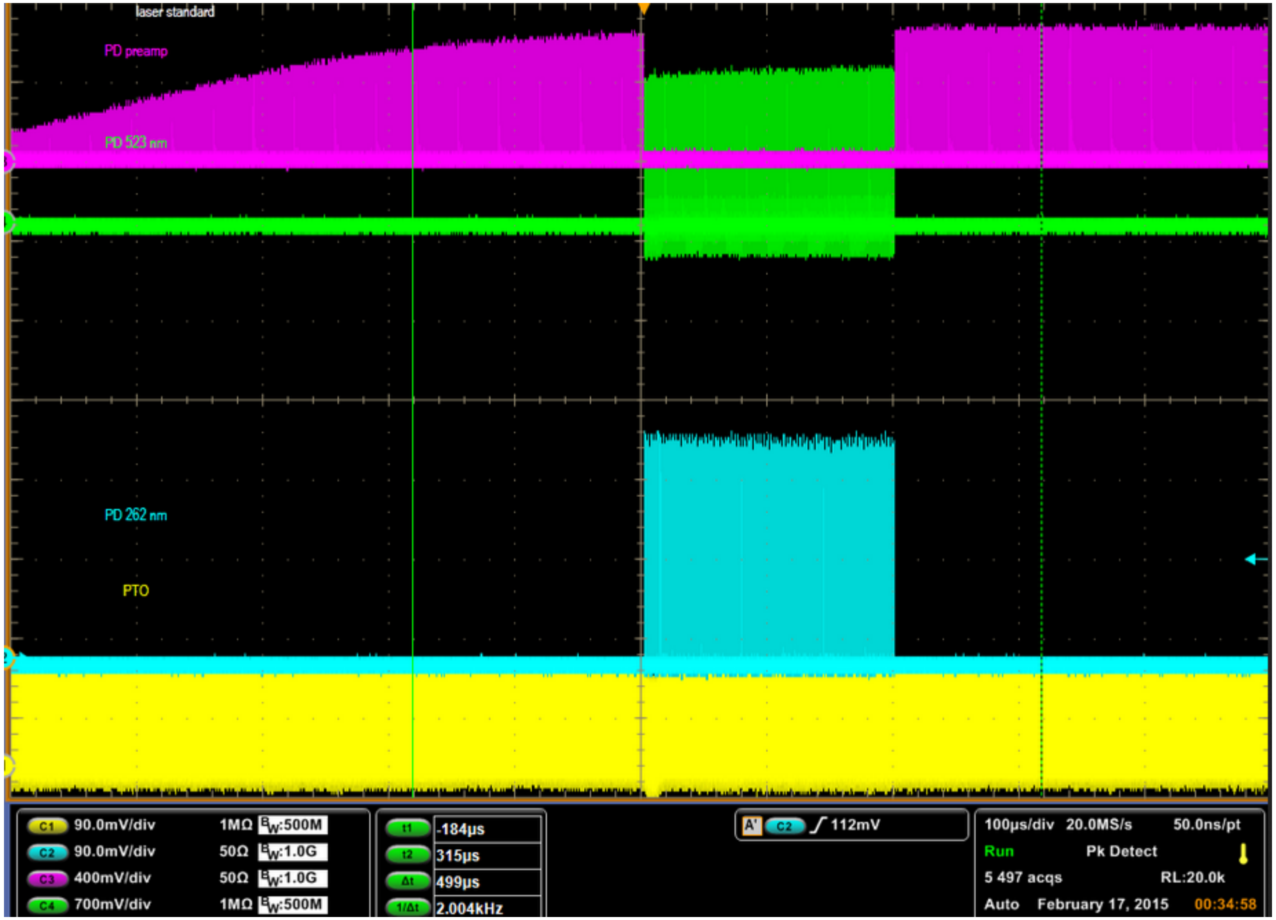
FLASH. Free-Electron Laser in Hamburg

- The spike is not produced by a spike in the laser train
- It originates from the cathode, for a field of >20 MV/m
- The decay time is ~10 µs, recovery time ~250 µs



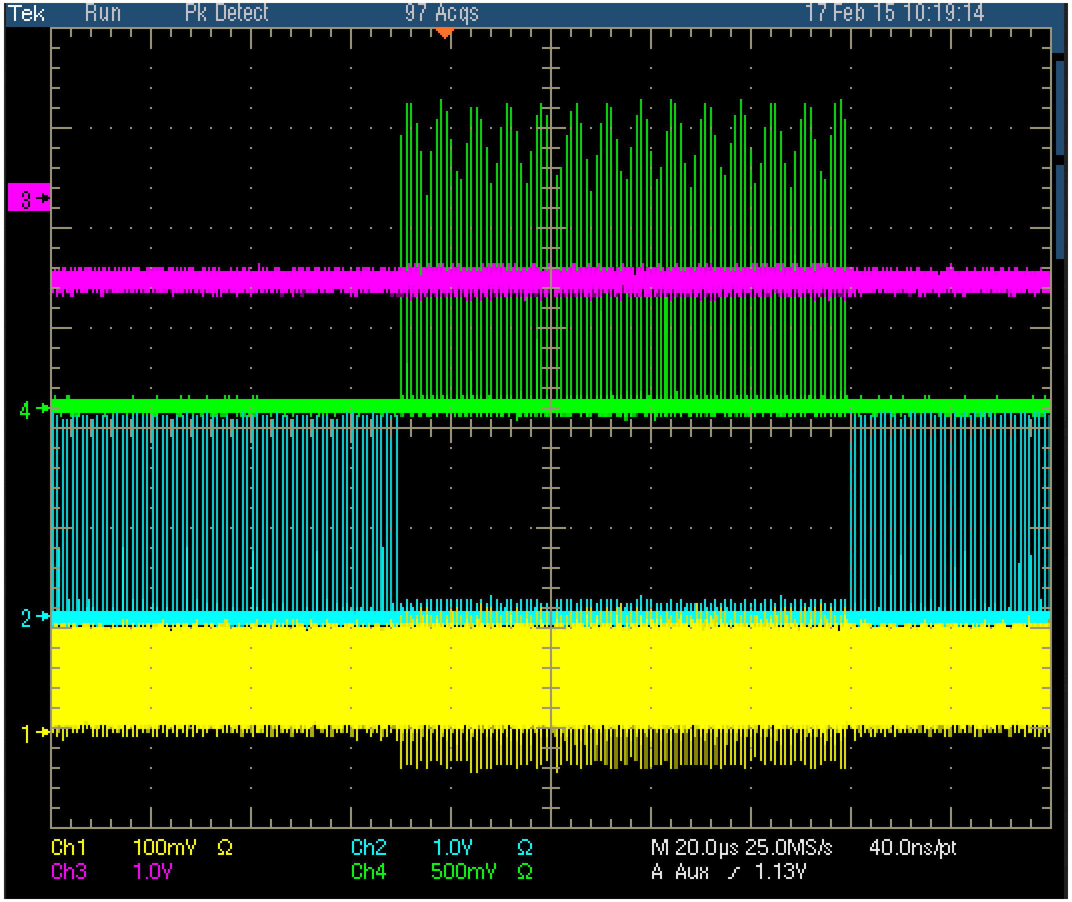
- Spike strength depends on laser energy density and accelerating field on cathode
- The decay time decreases slowly with time over weeks

Machine settings



Laser 2 on scope (UV-pulse train is blue)

Machine settings



Laser 1 on scope (UV-pulse train is green)

Only laser 2 (L2) on cathode

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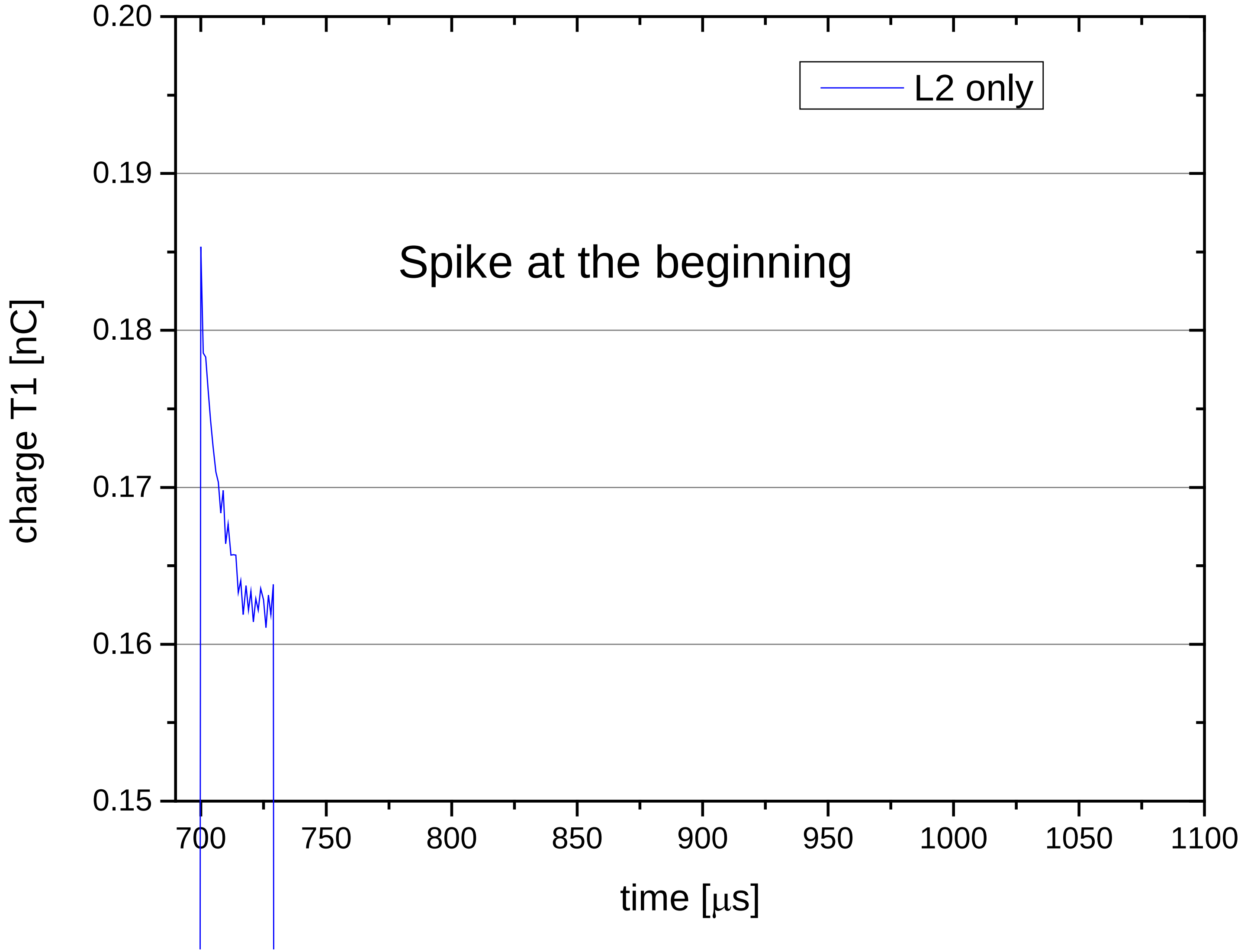
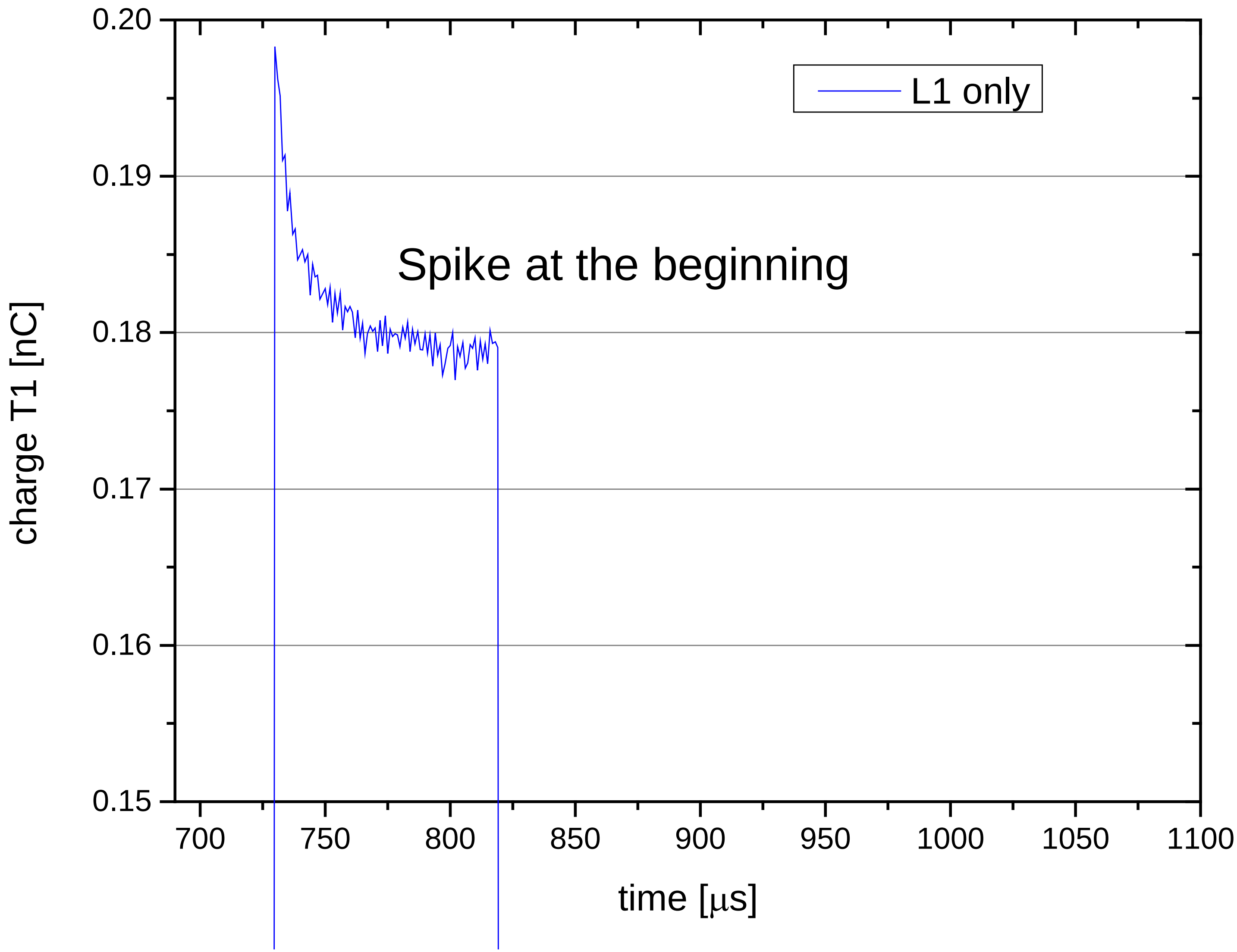
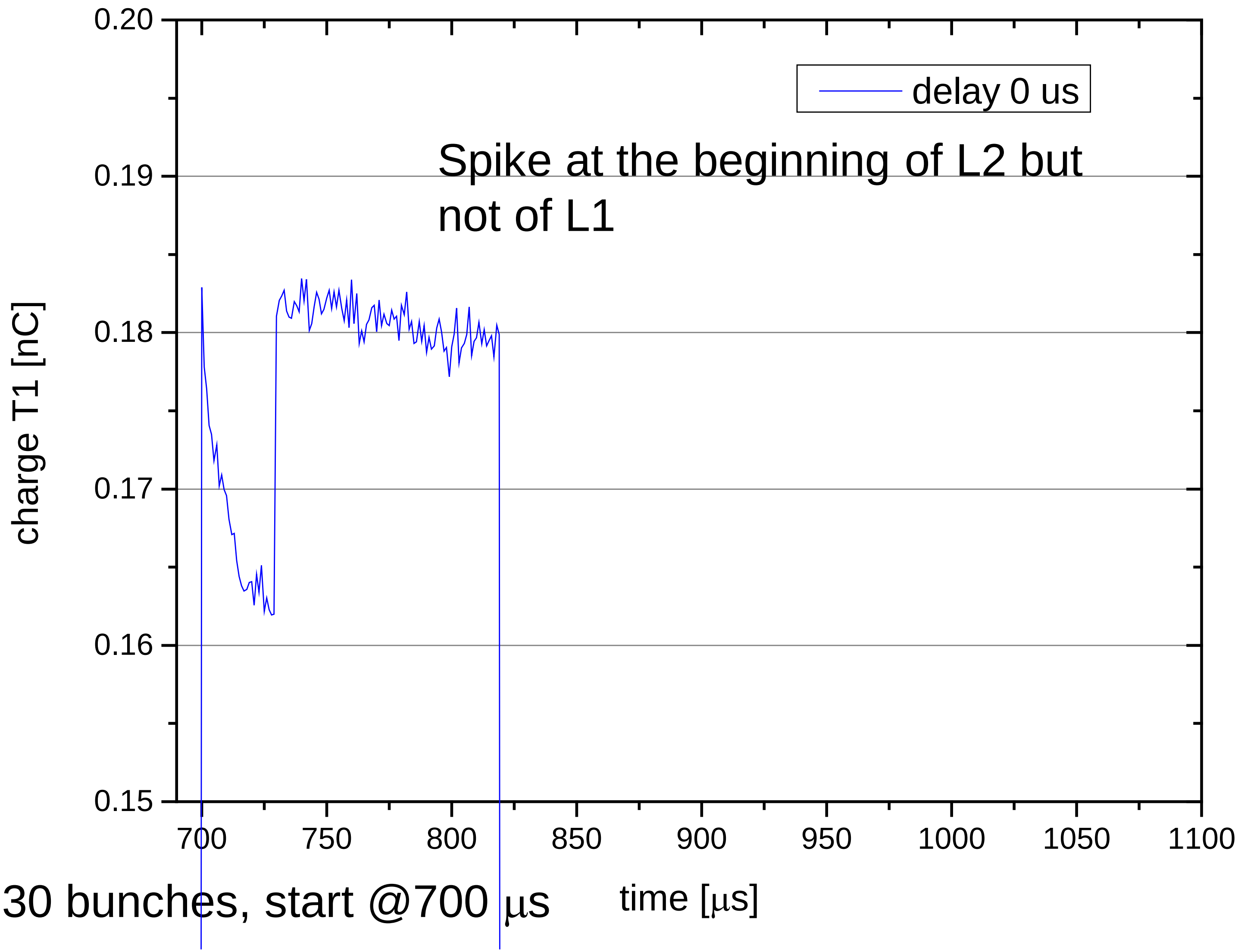
Free-Electron Laser in Hamburg



Only laser 1 (L1) on cathode



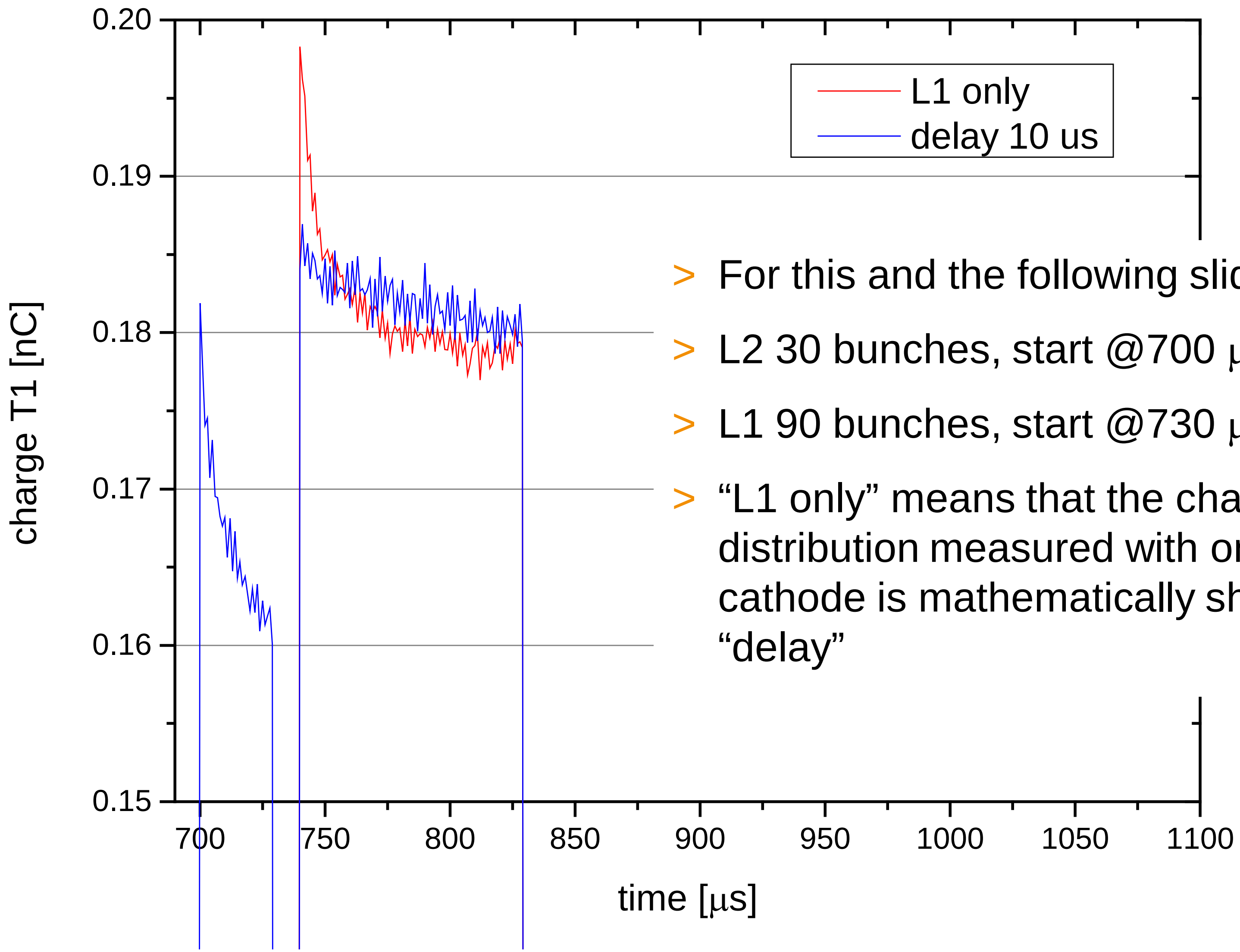
L2 and L1 on cathode



> L2 30 bunches, start @700 µs
> L1 90 bunches, start @730 µs

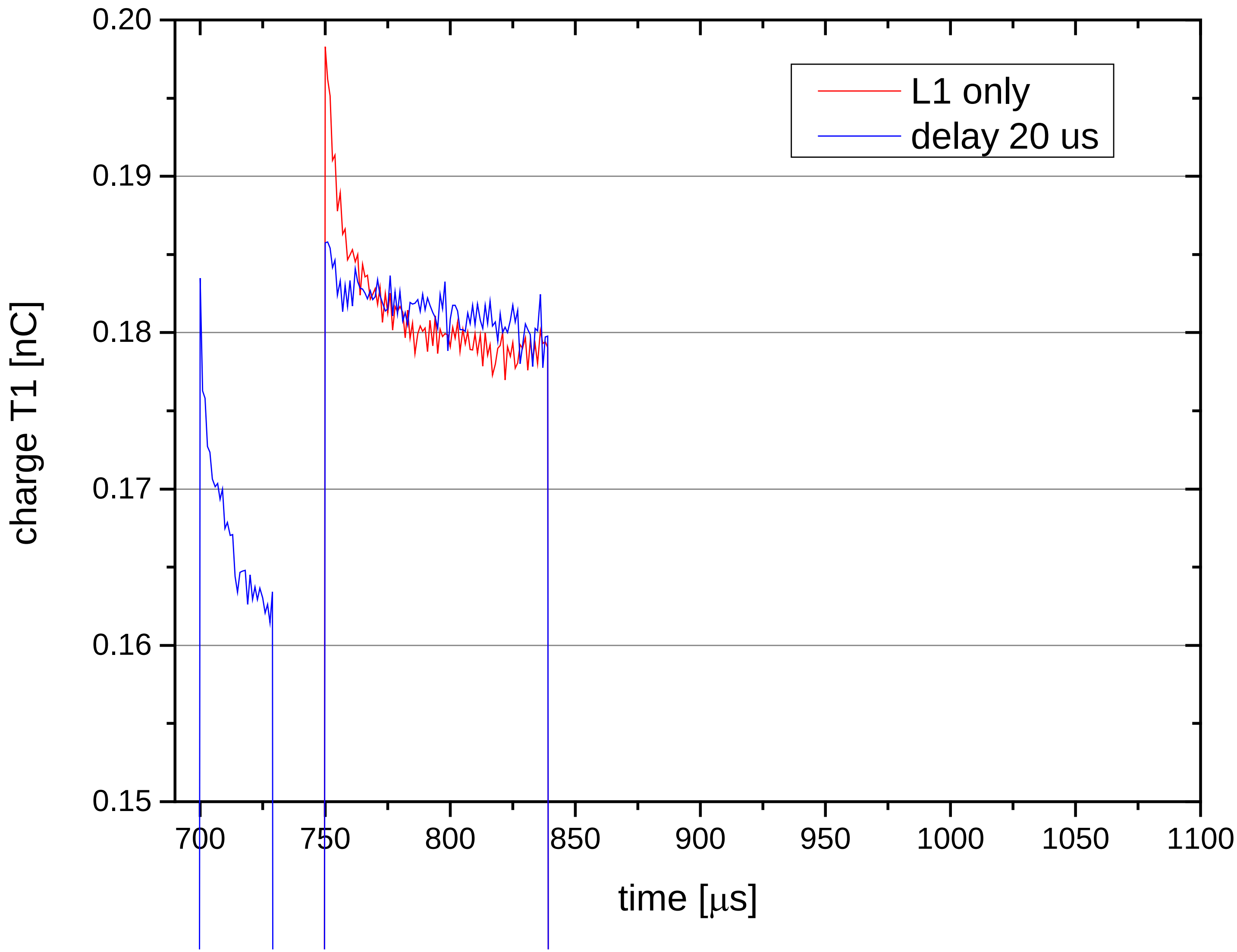
L2 and L1 on cathode

FLASH. Free-Electron Laser in Hamburg

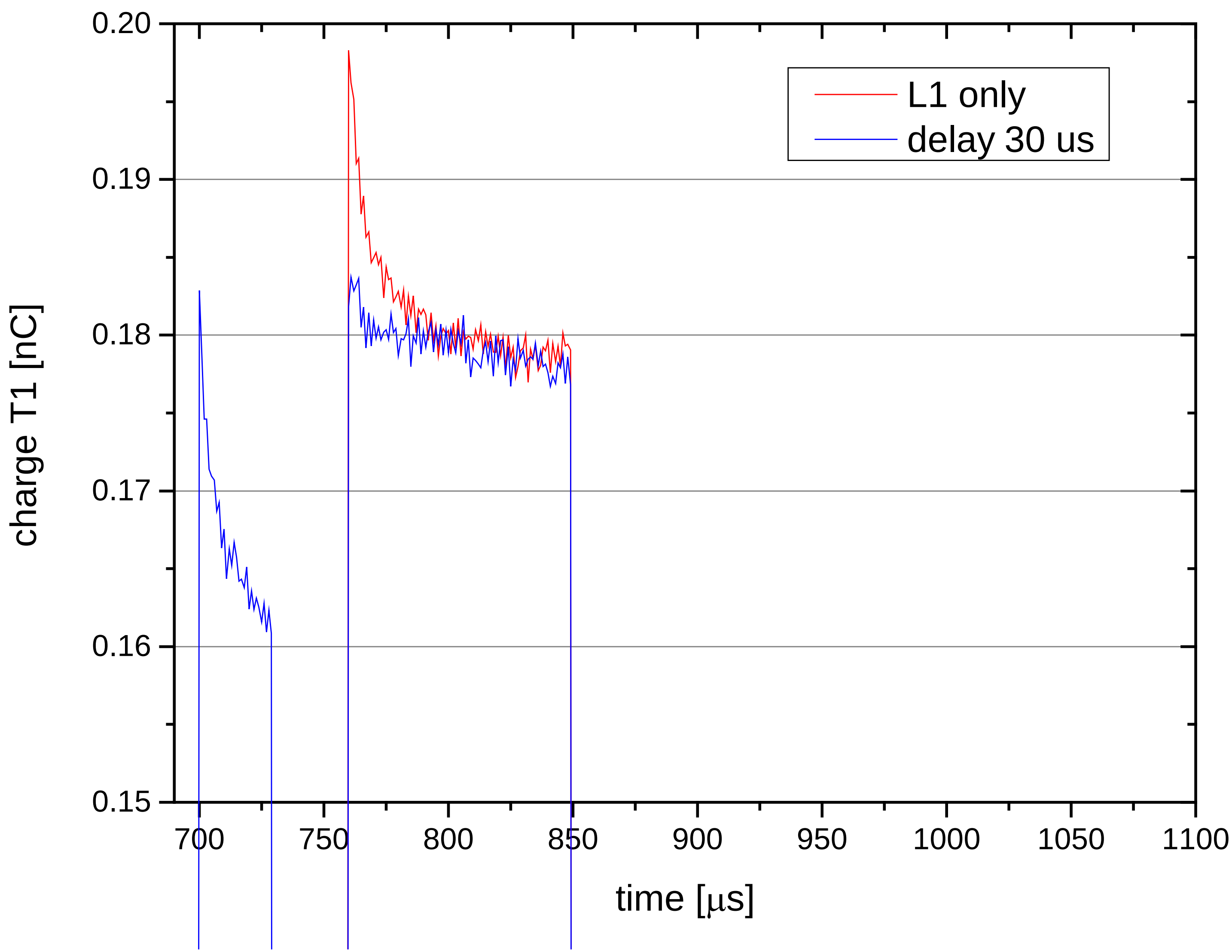


- For this and the following slides:
- L2 30 bunches, start @700 µs
- L1 90 bunches, start @730 µs + delay
- “L1 only” means that the charge distribution measured with only L1 on the cathode is mathematically shifted by “delay”

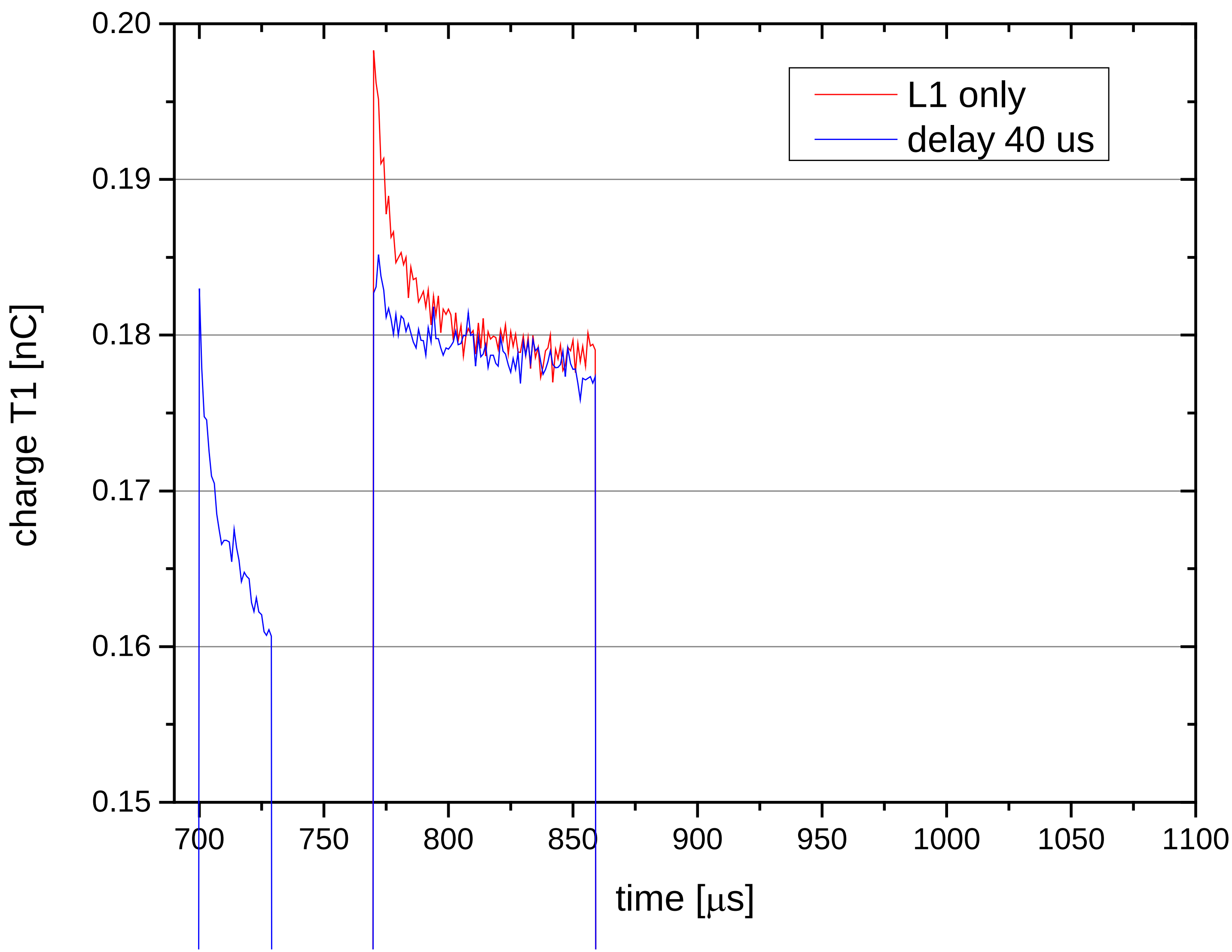
L2 and L1 on cathode



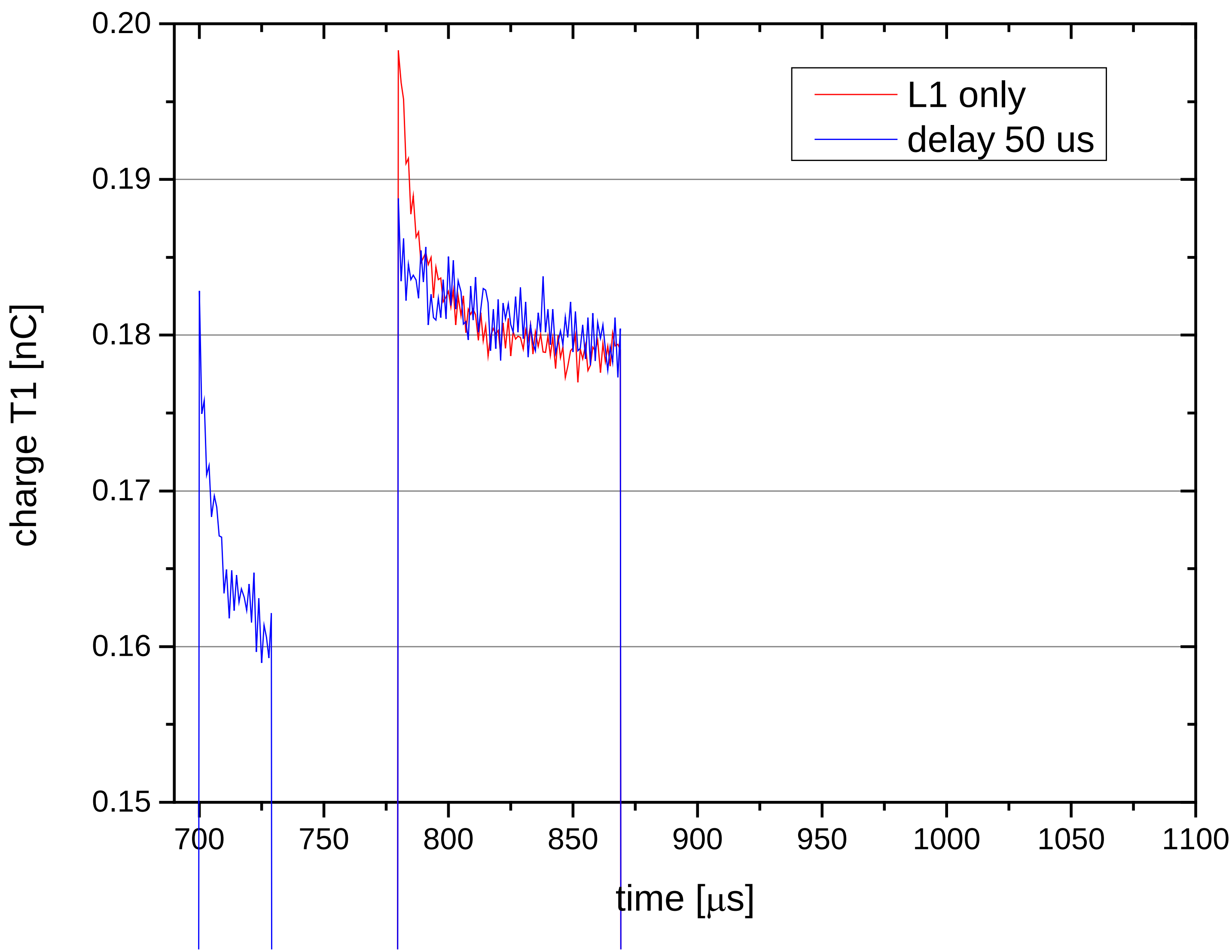
L2 and L1 on cathode



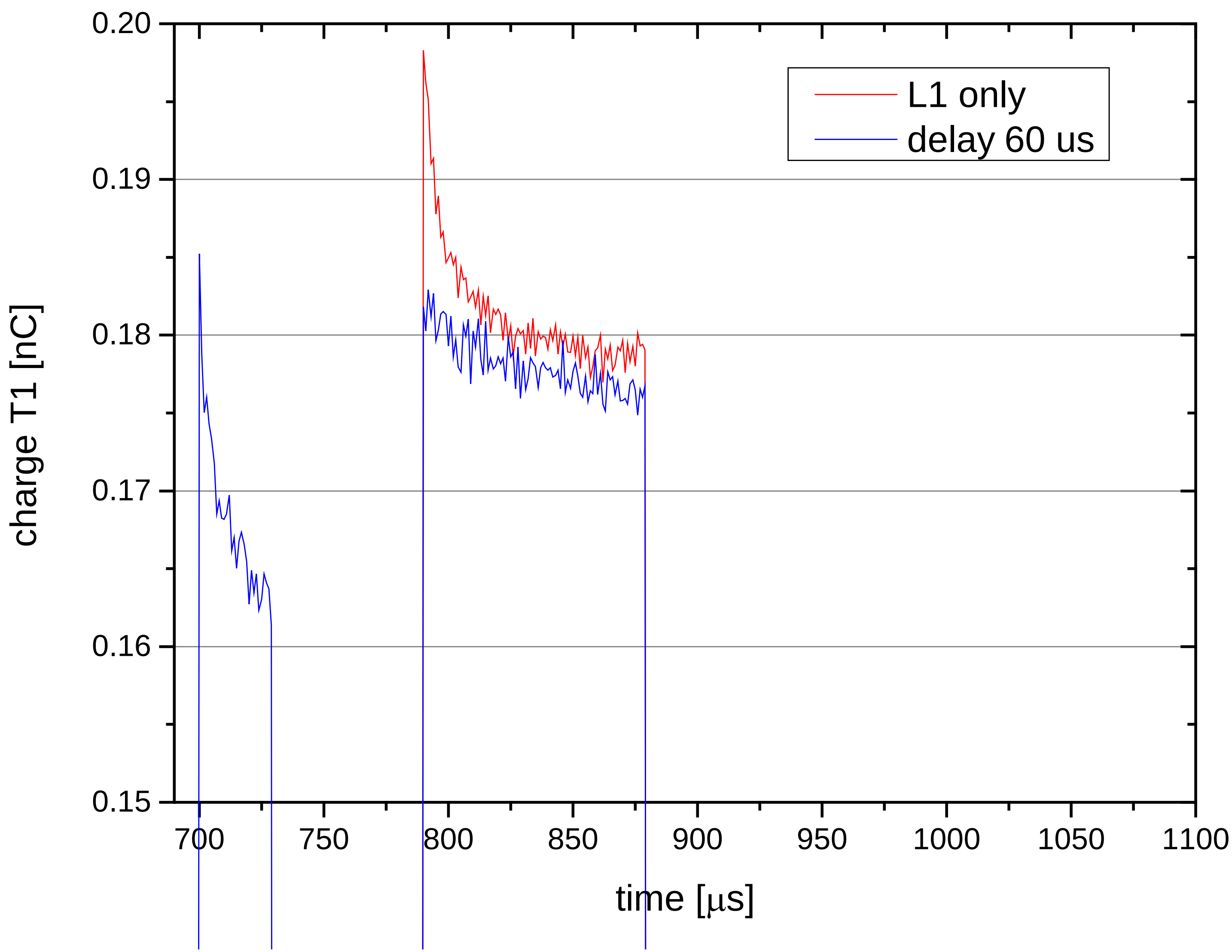
L2 and L1 on cathode



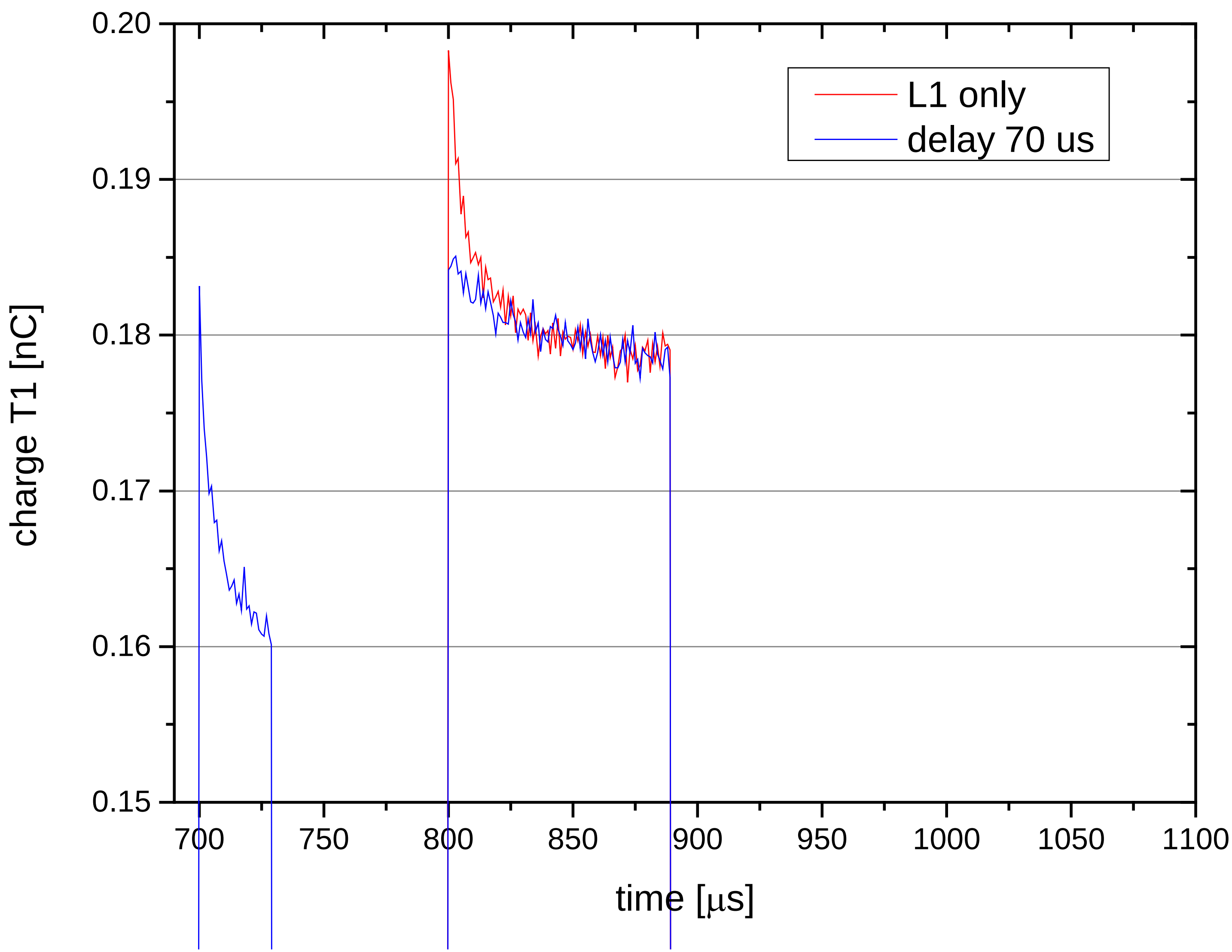
L2 and L1 on cathode



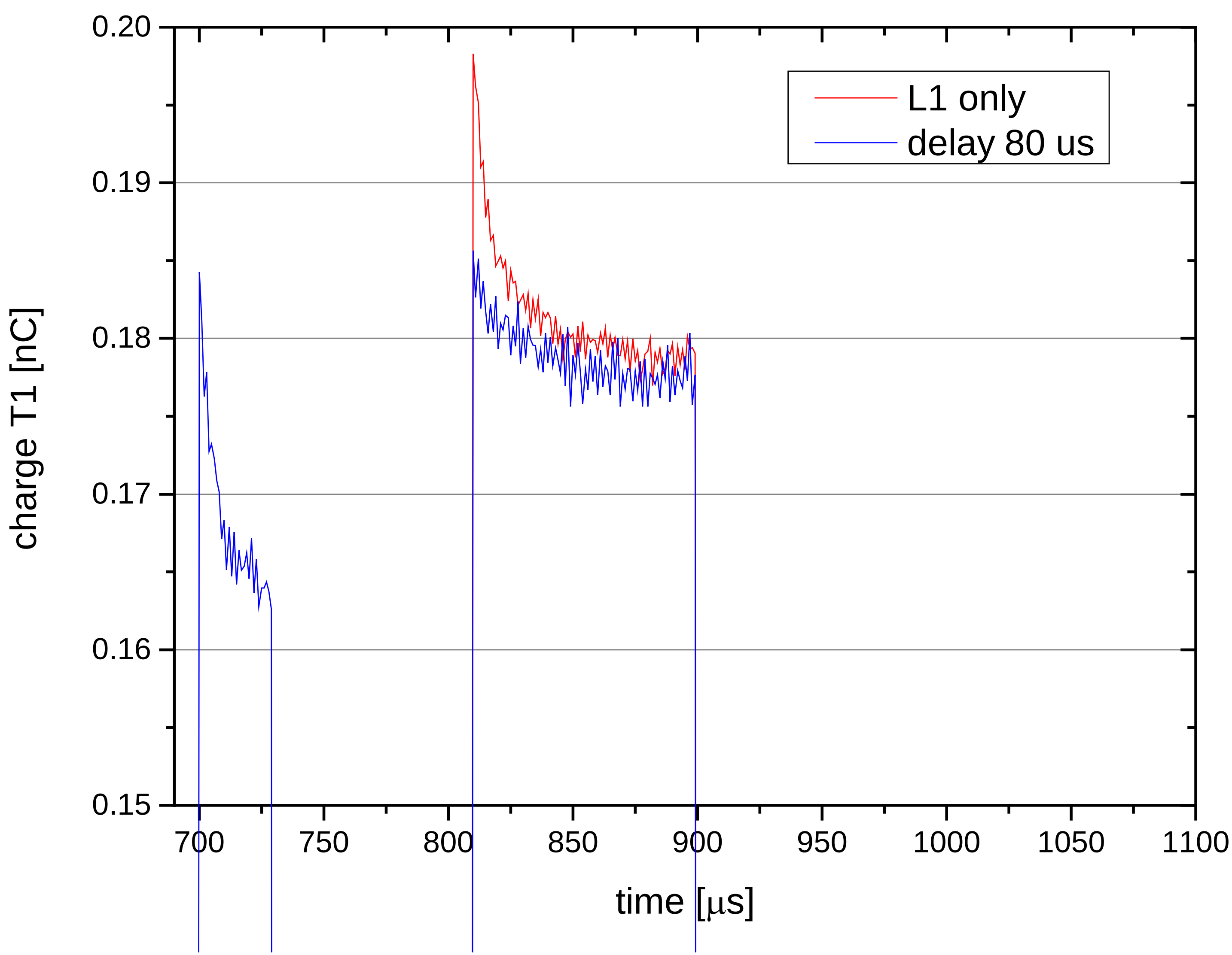
L2 and L1 on cathode



L2 and L1 on cathode

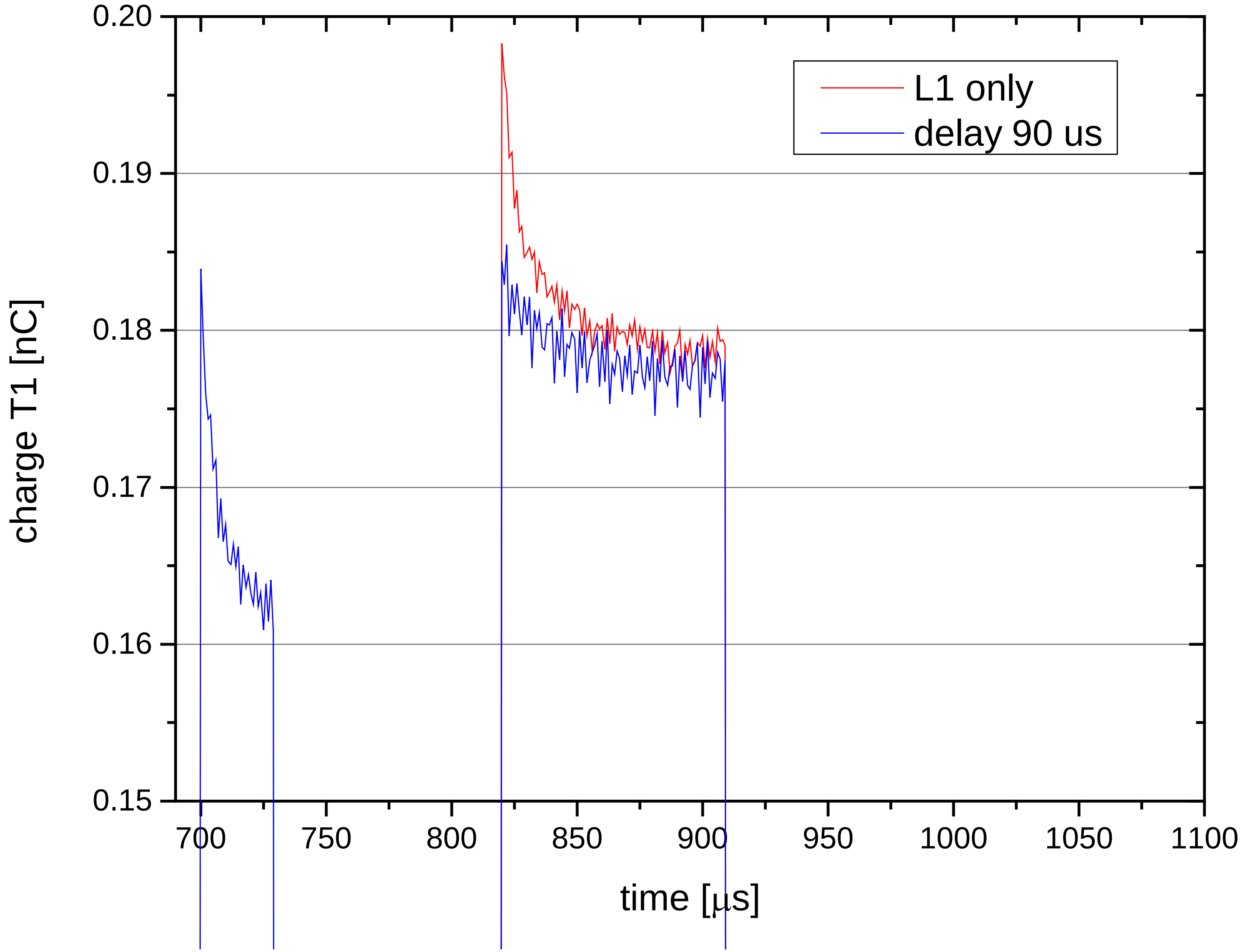


L2 and L1 on cathode

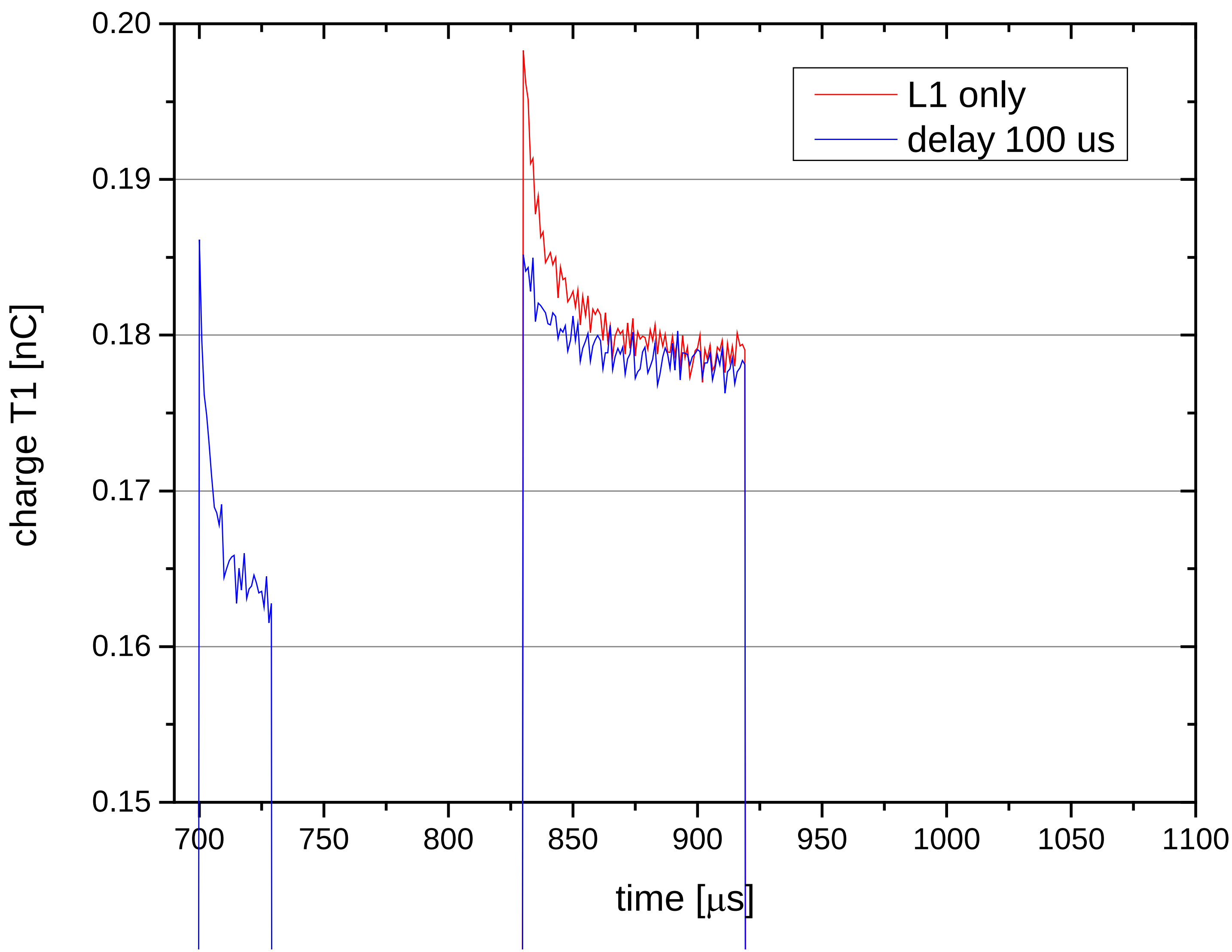


L2 and L1 on cathode

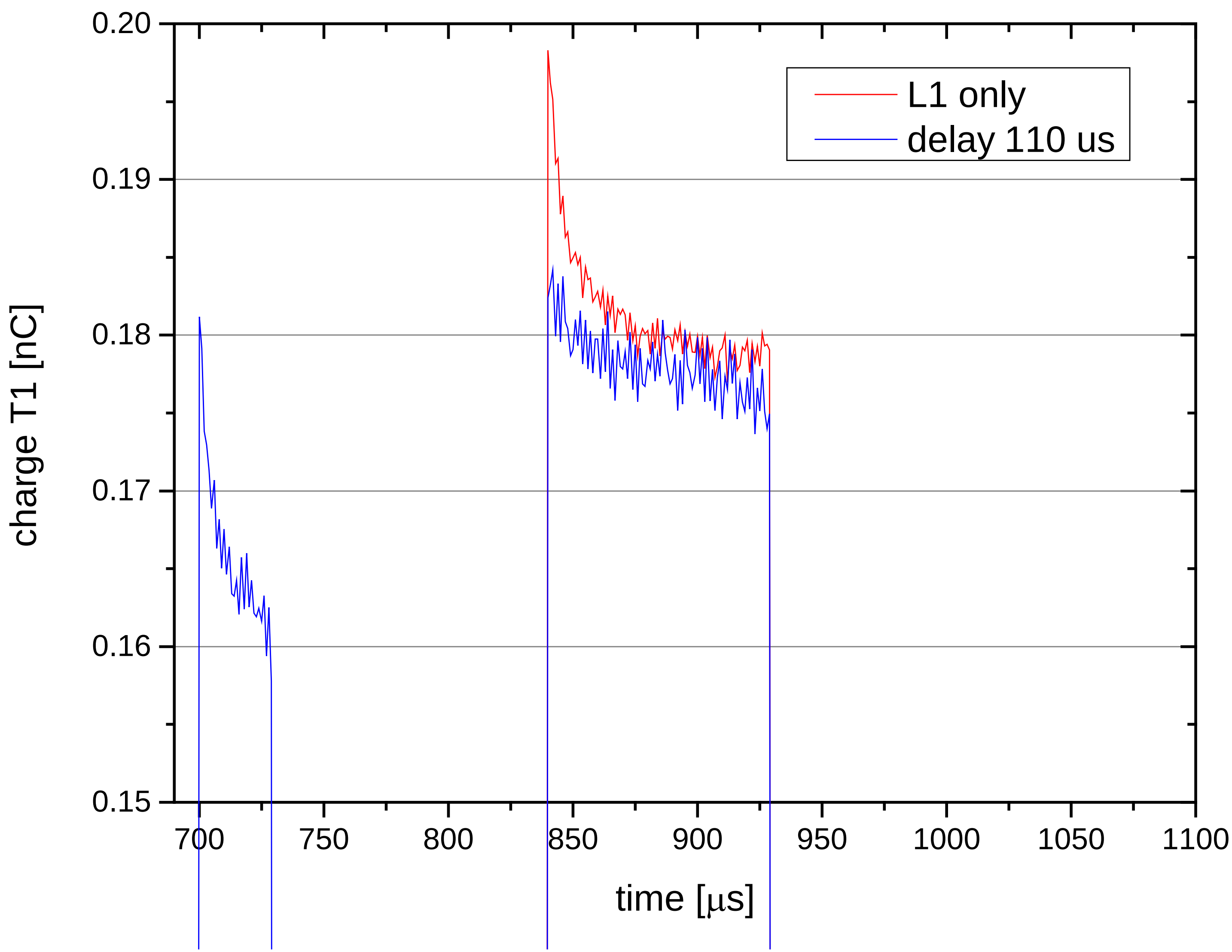
FLASH.
Free-Electron Laser in Hamburg



L2 and L1 on cathode



L2 and L1 on cathode



L2 and L1 on cathode

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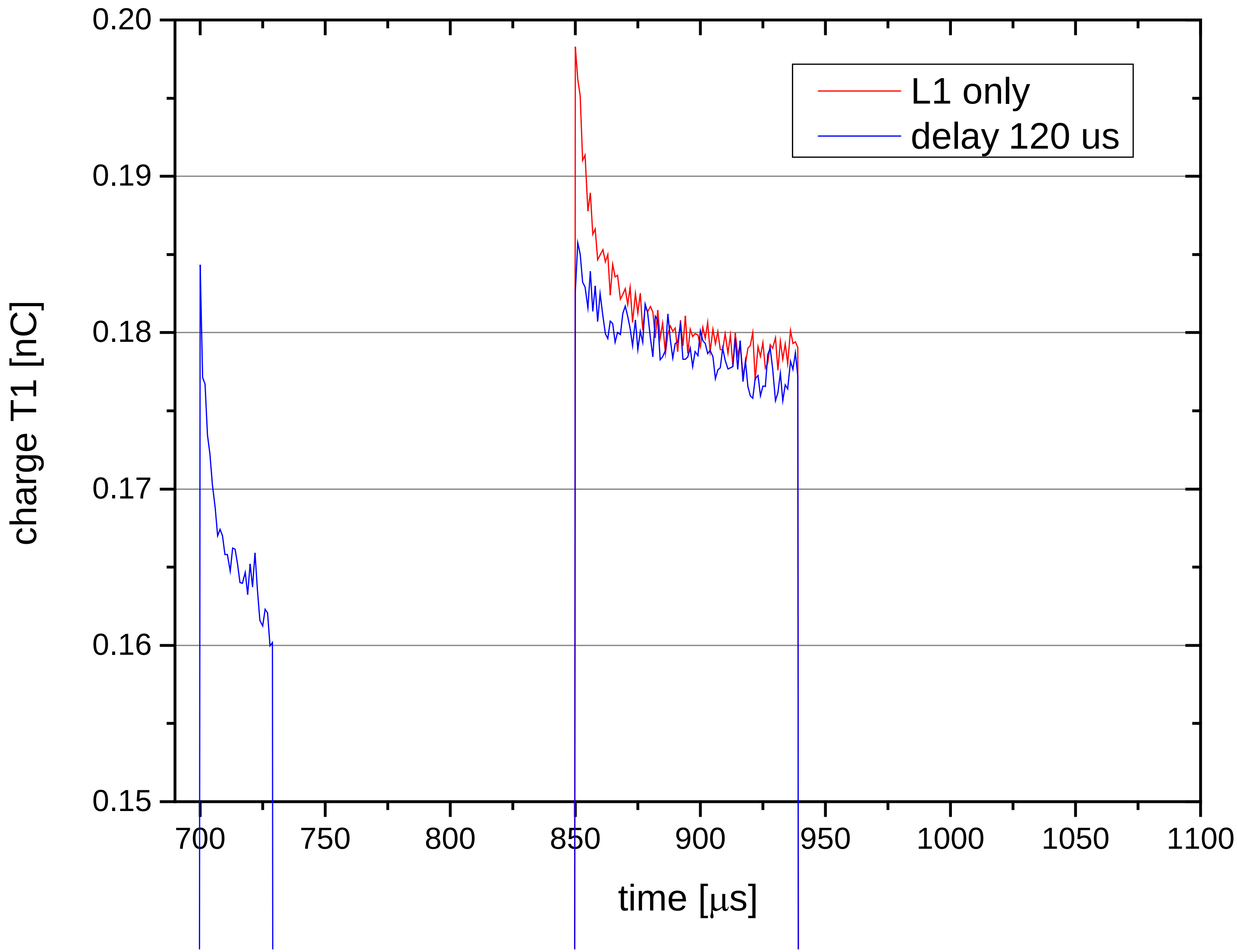
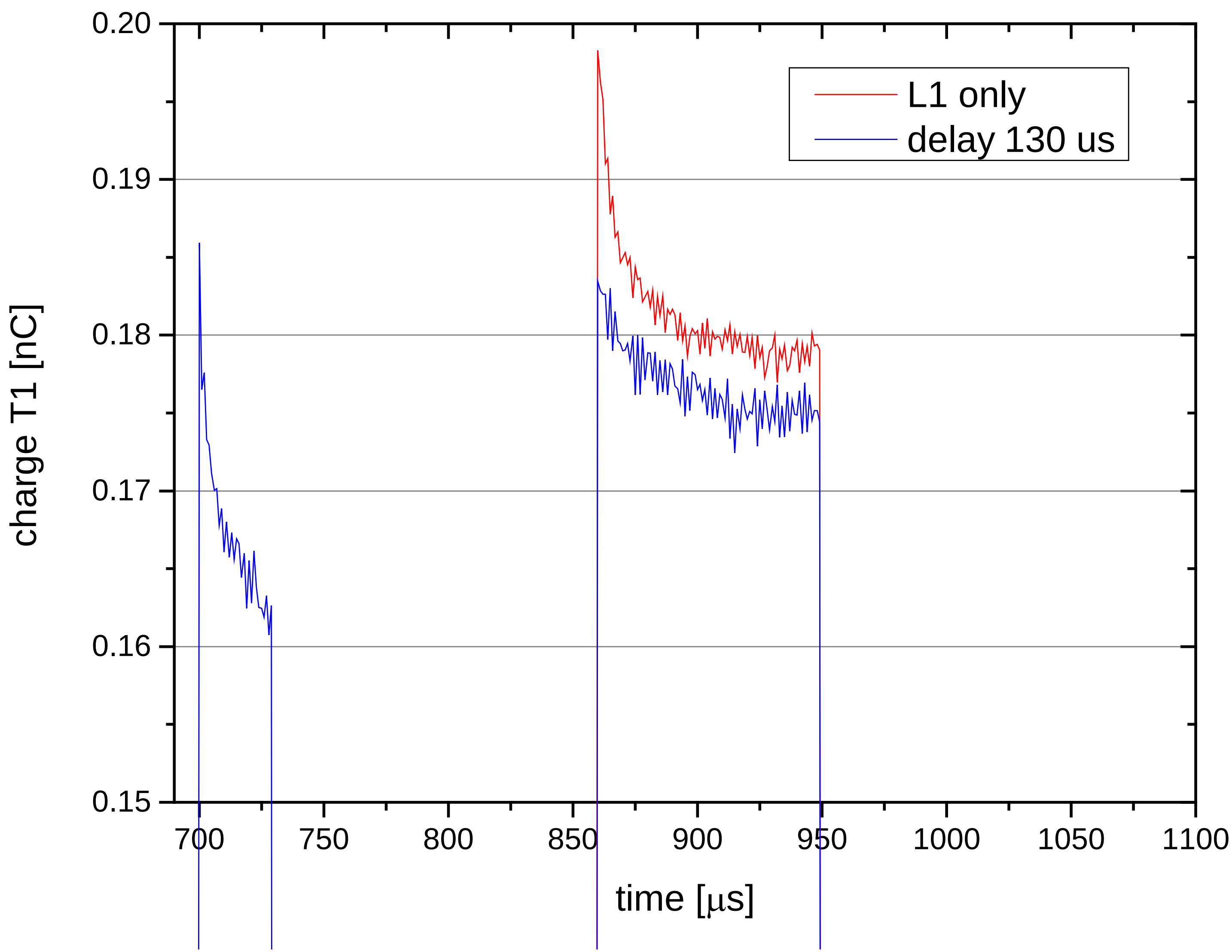
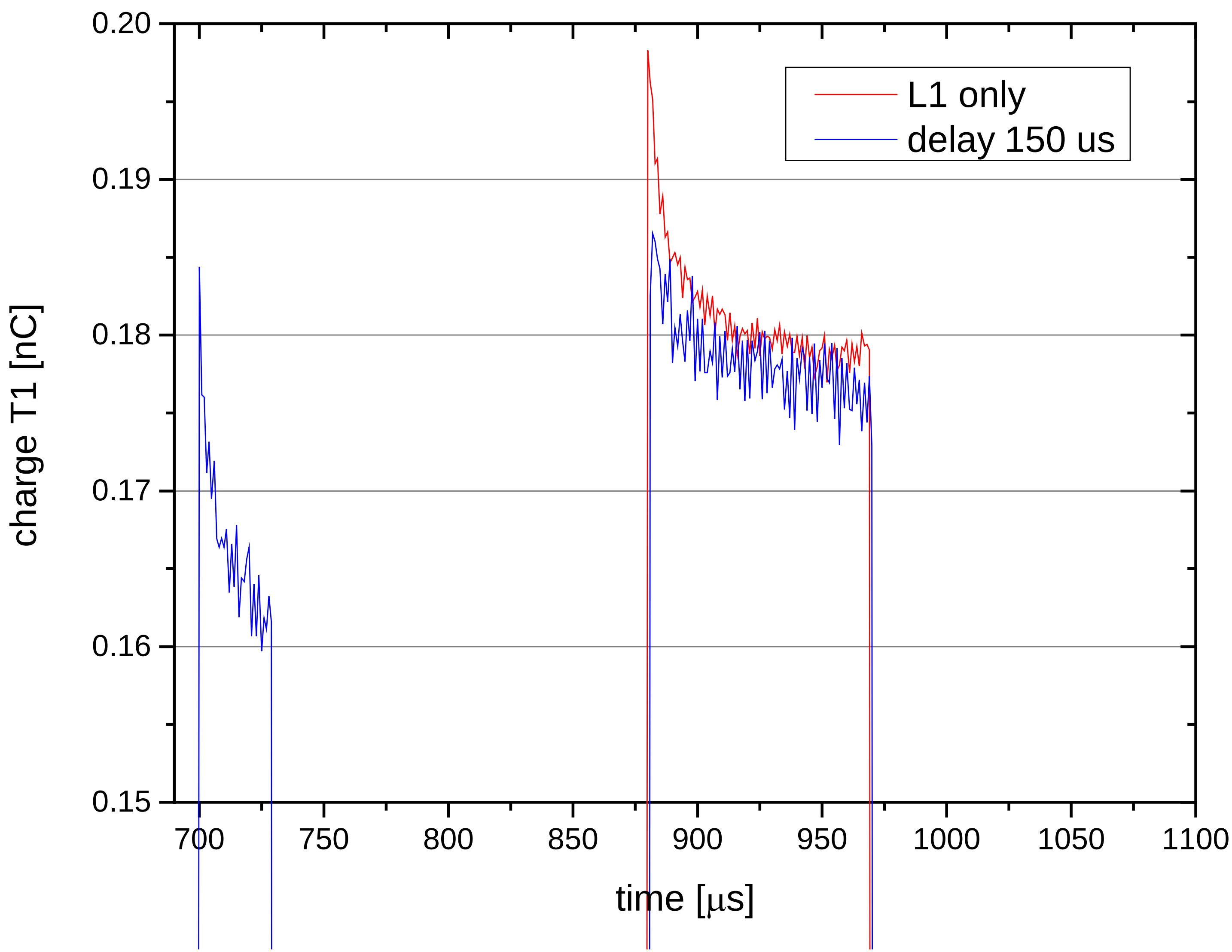
Free-Electron Laser in Hamburg



L2 and L1 on cathode

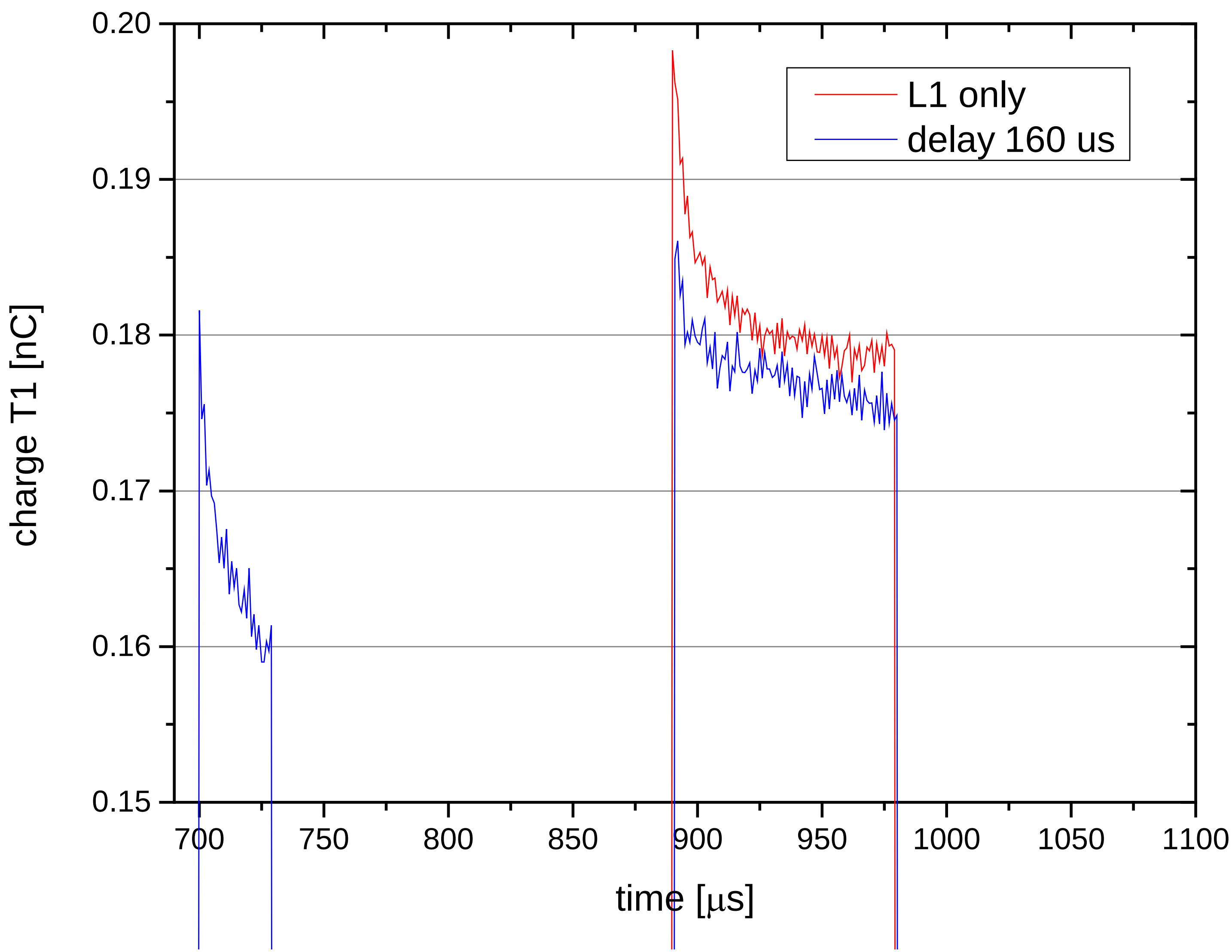


L2 and L1 on cathode

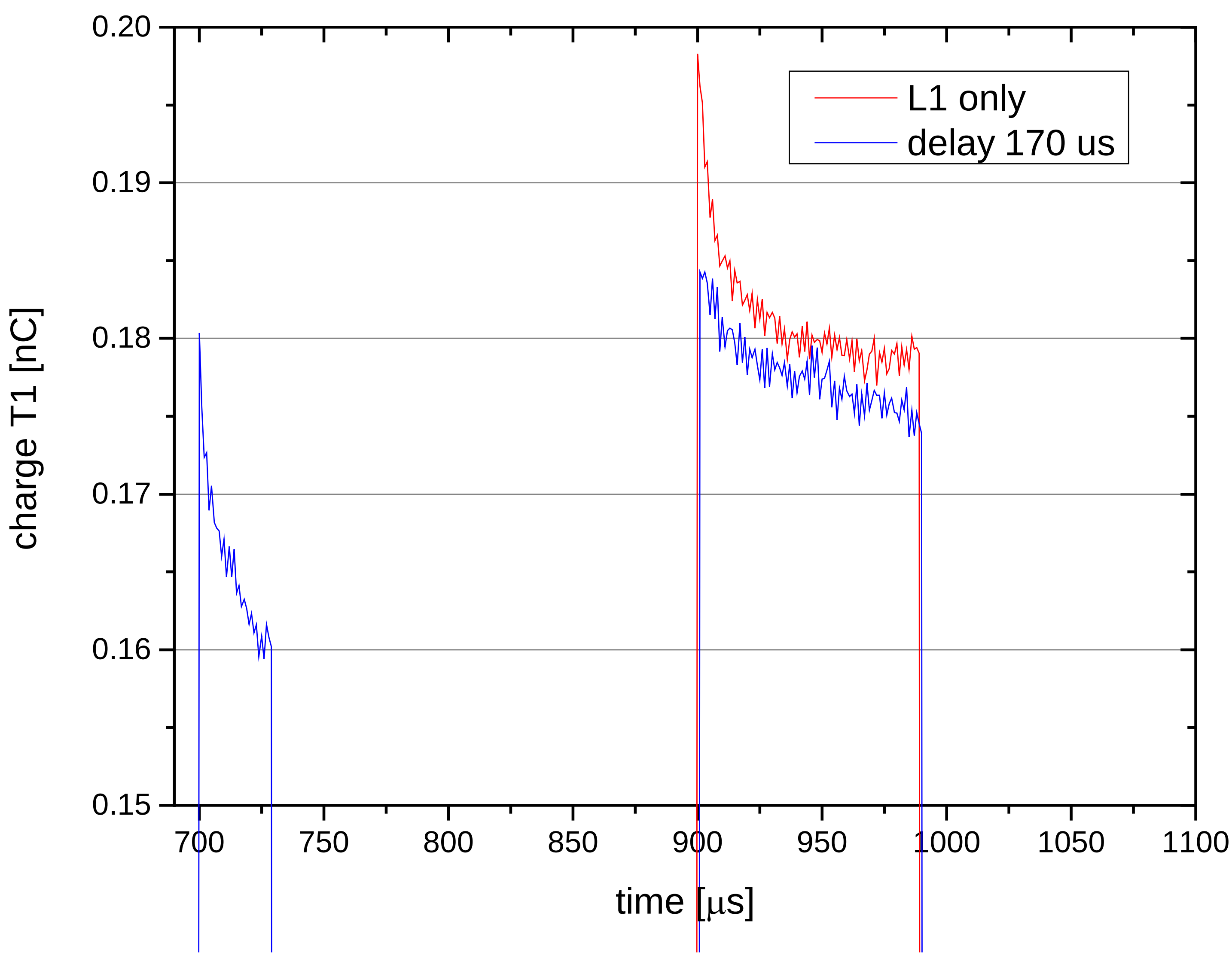


L2 and L1 on cathode

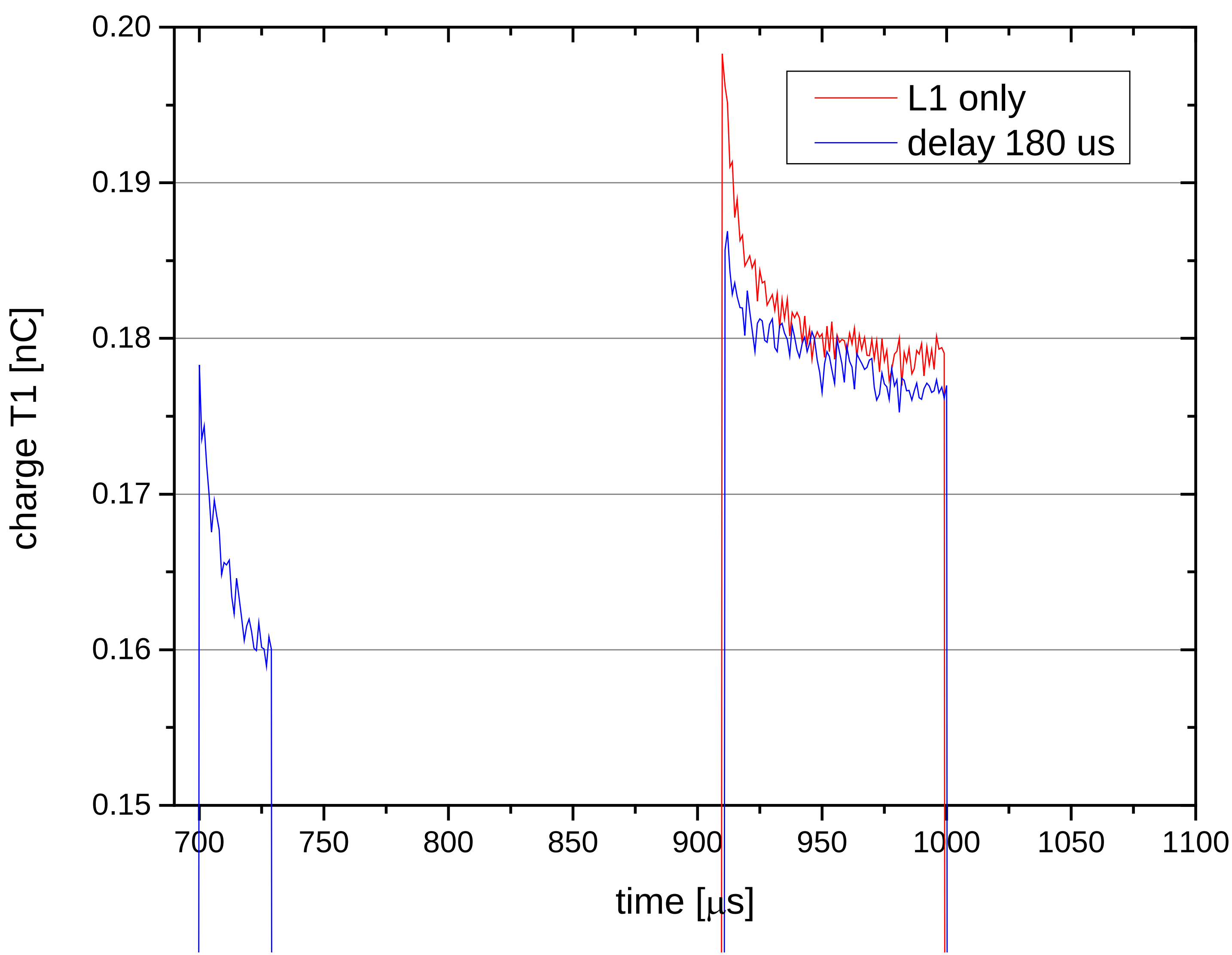
FLASH.
Free-Electron Laser in Hamburg



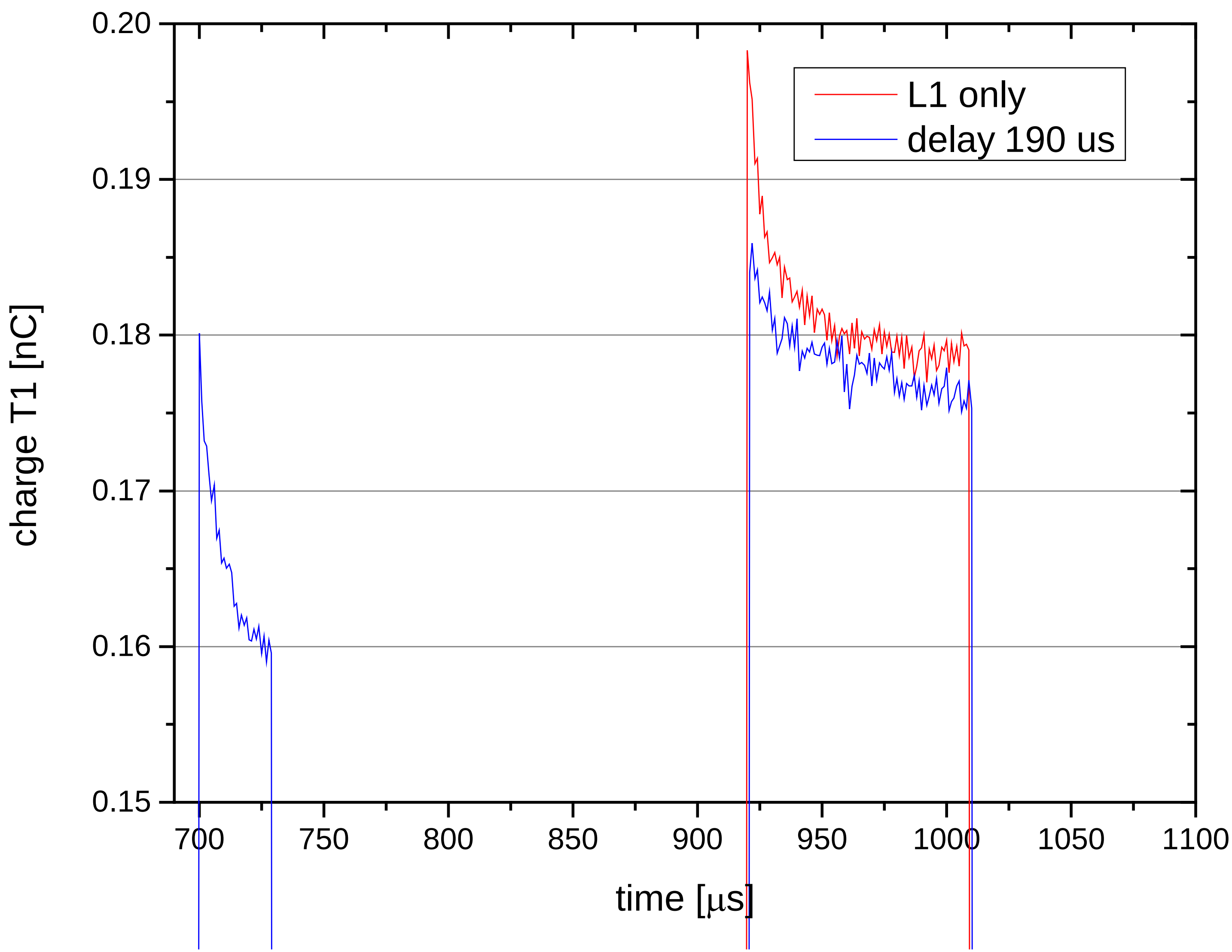
L2 and L1 on cathode



L2 and L1 on cathode

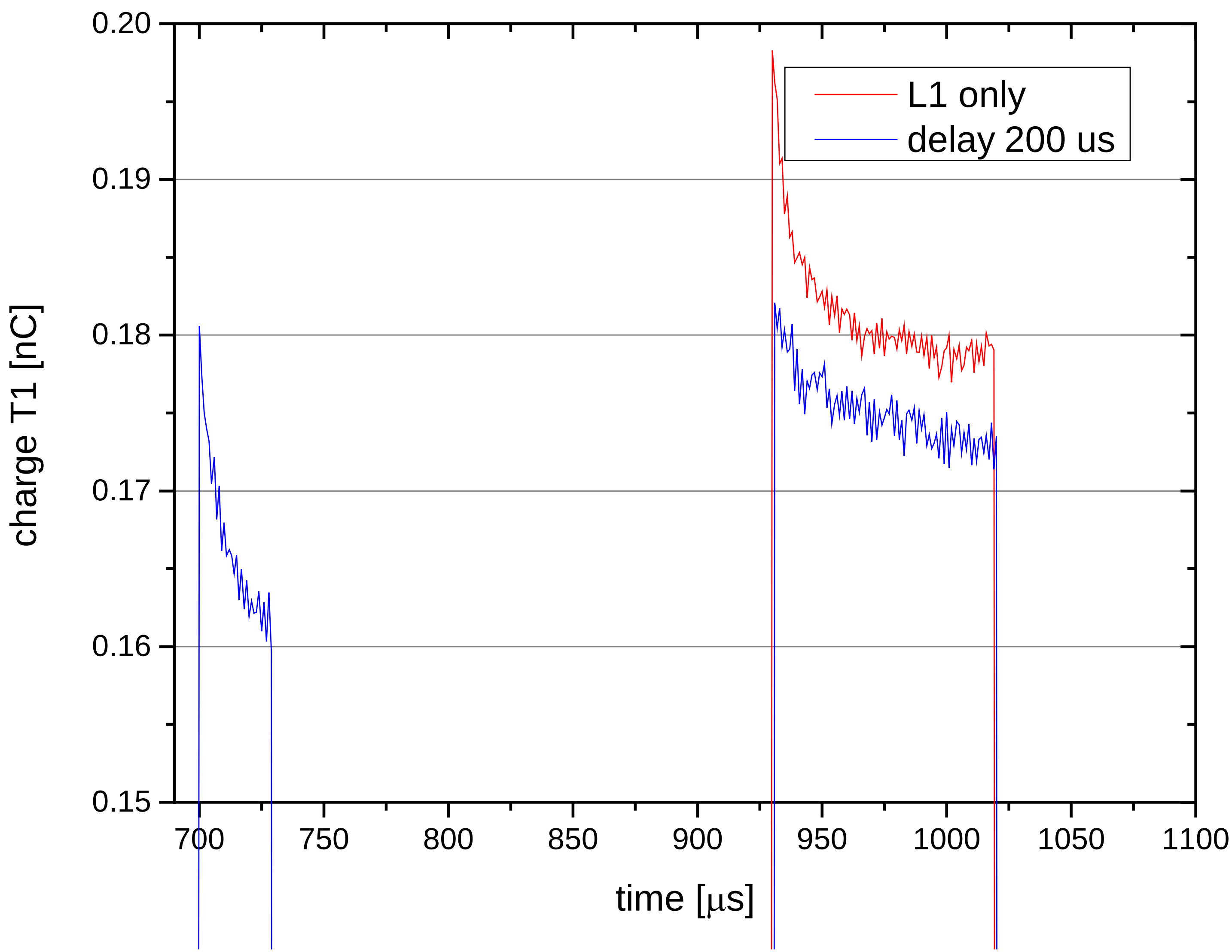


L2 and L1 on cathode

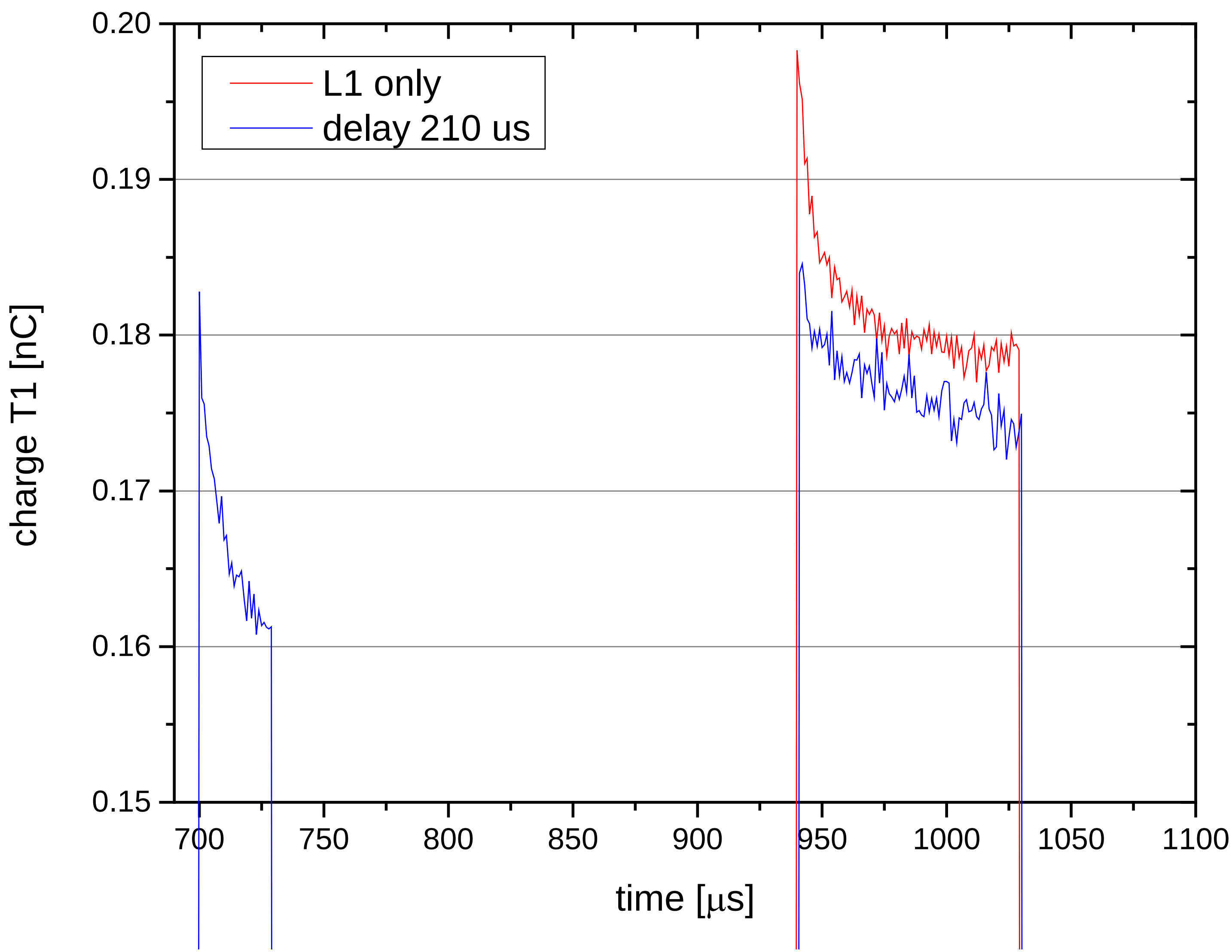


L2 and L1 on cathode

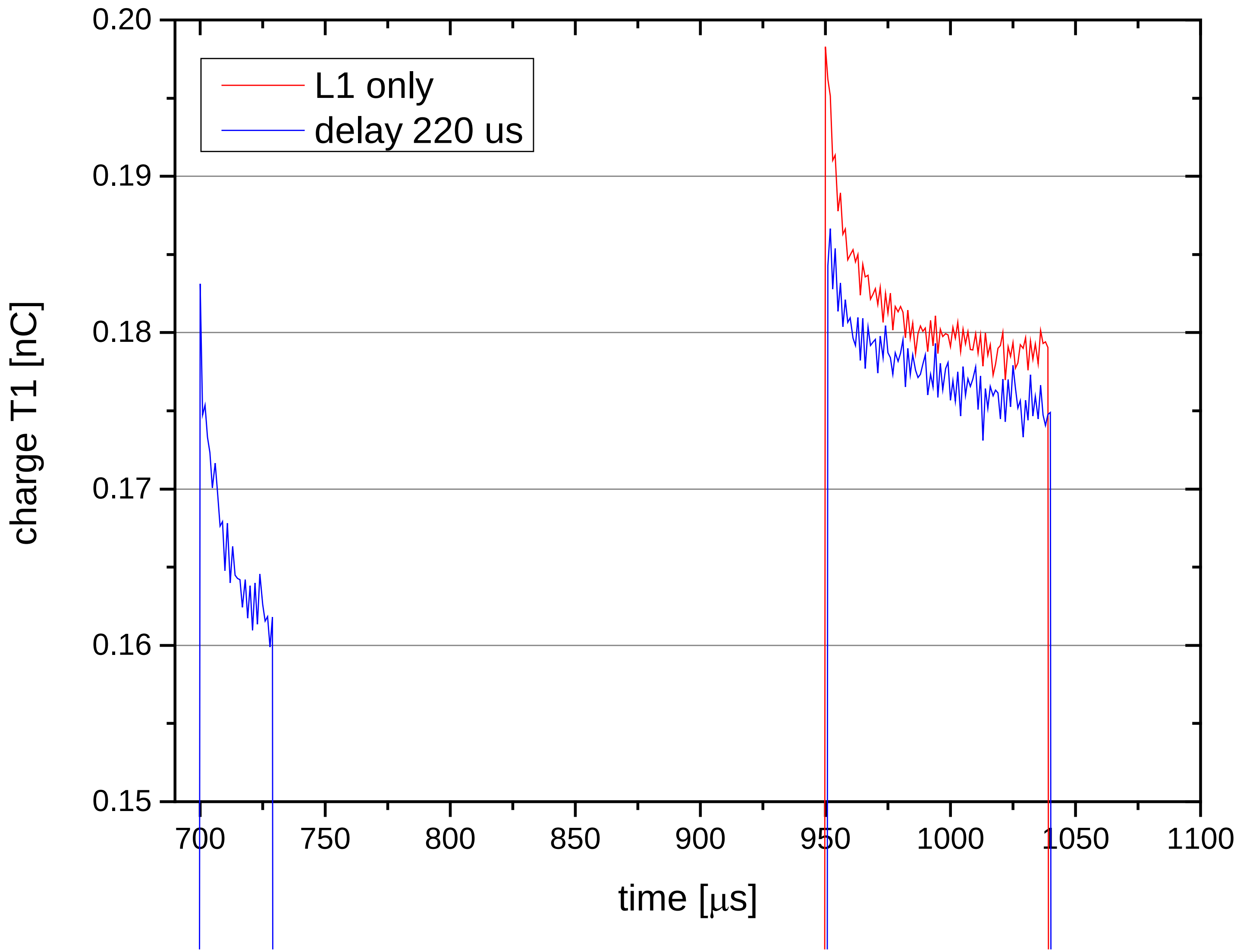
FLASH.
Free-Electron Laser in Hamburg



L2 and L1 on cathode

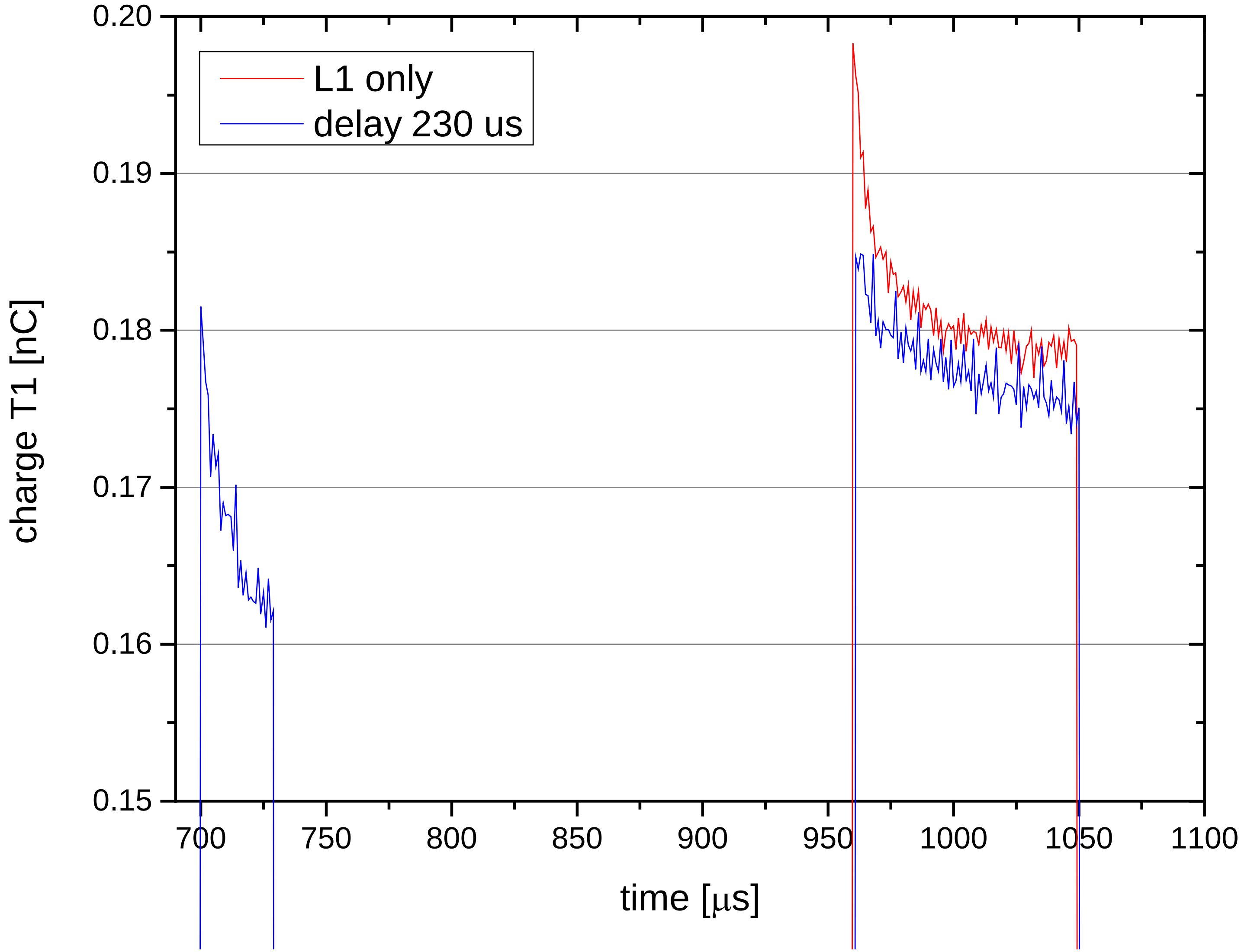


L2 and L1 on cathode



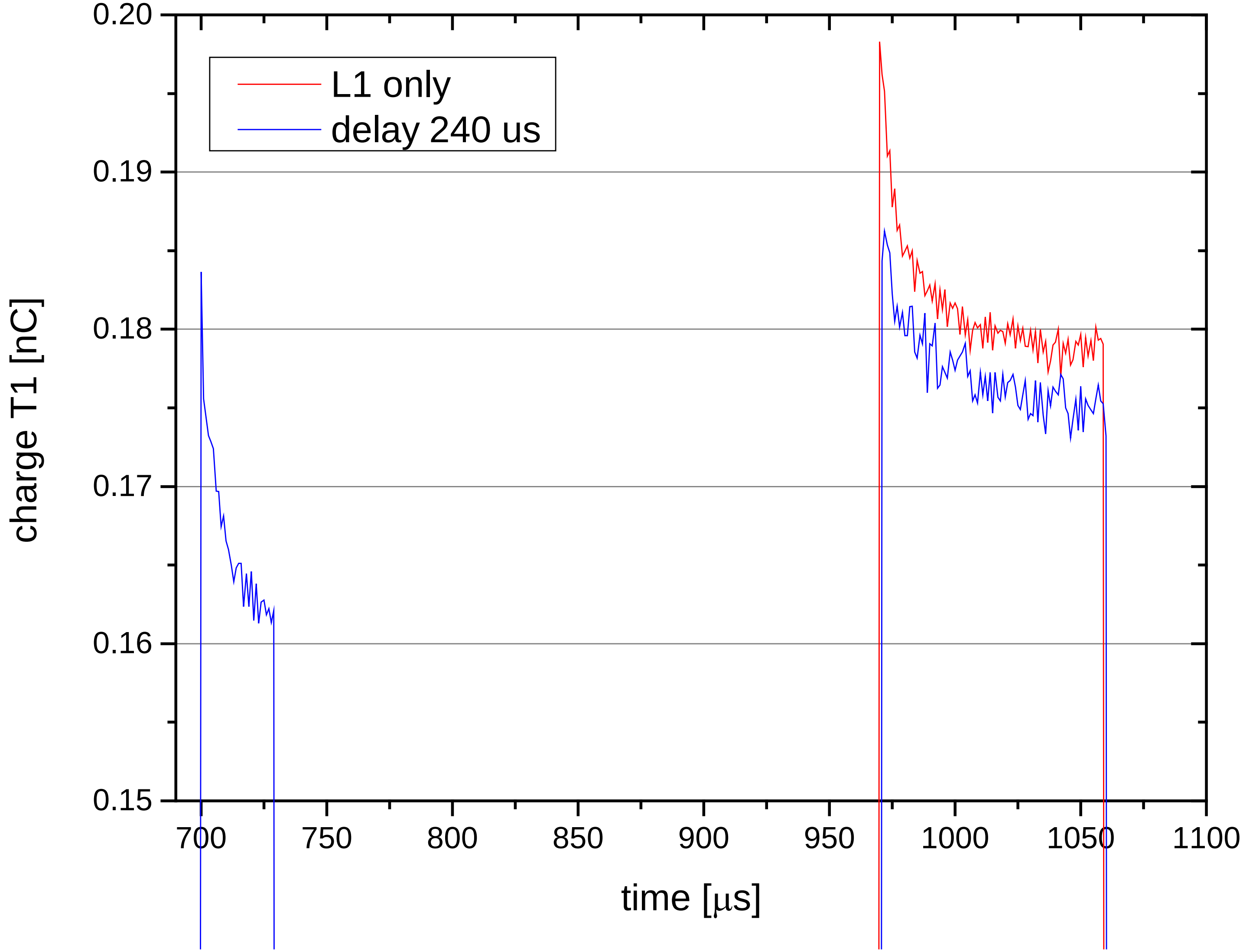
L2 and L1 on cathode

FLASH.
Free-Electron Laser in Hamburg



L2 and L1 on cathode

FLASH.
Free-Electron Laser in Hamburg



L2 and L1 on cathode, changing L2 intensity

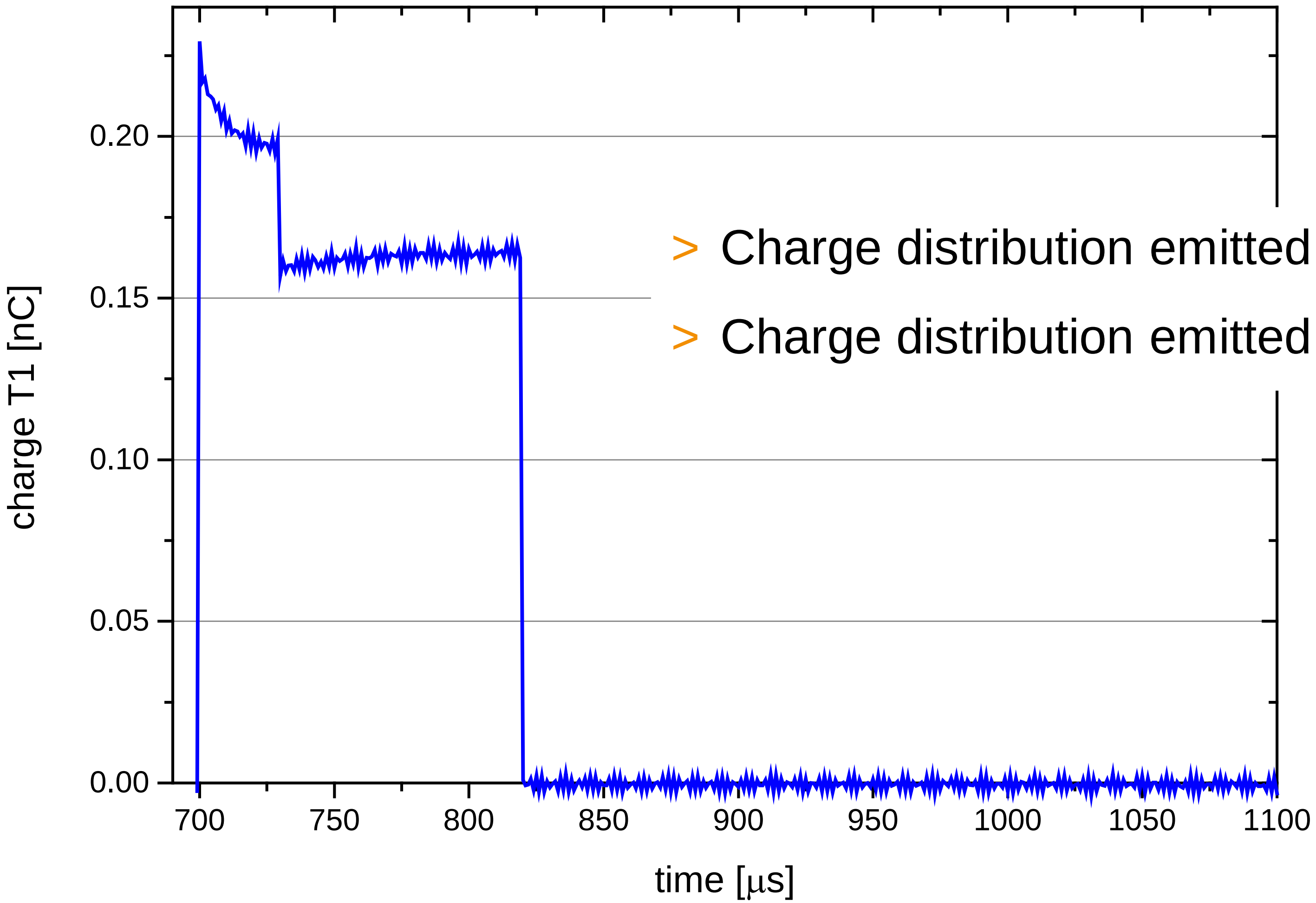
FLASH. Free-Electron Laser in Hamburg

> L2 30 bunches, start @700 μs

> L1 90 bunches, start @730 μs

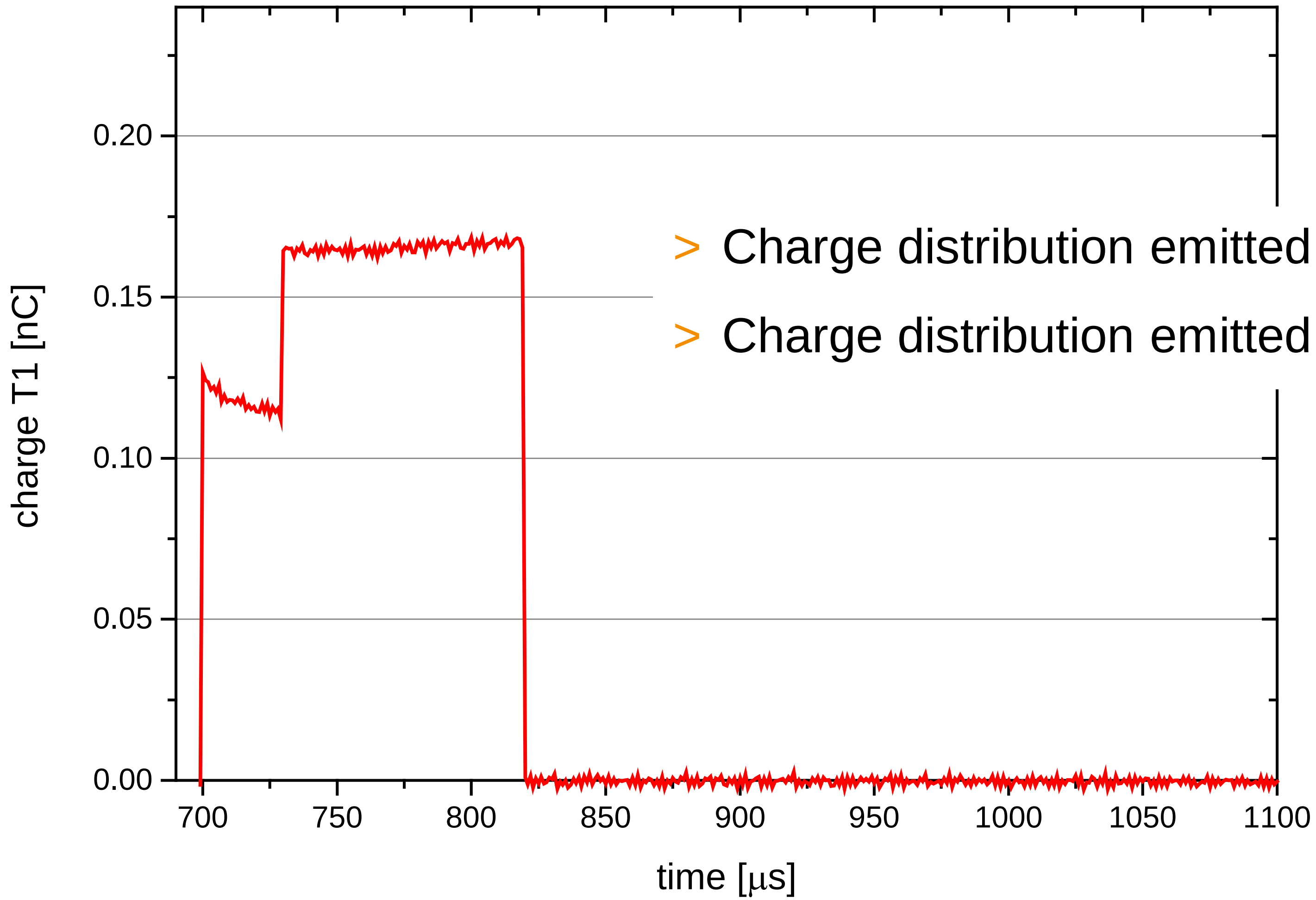
> For the following slides L1 was constant while the laser energy of L2 was be reduced.

L2 and L1 on cathode, changing L2 intensity



- > Charge distribution emitted by L2 spiky
- > Charge distribution emitted by L1 flat

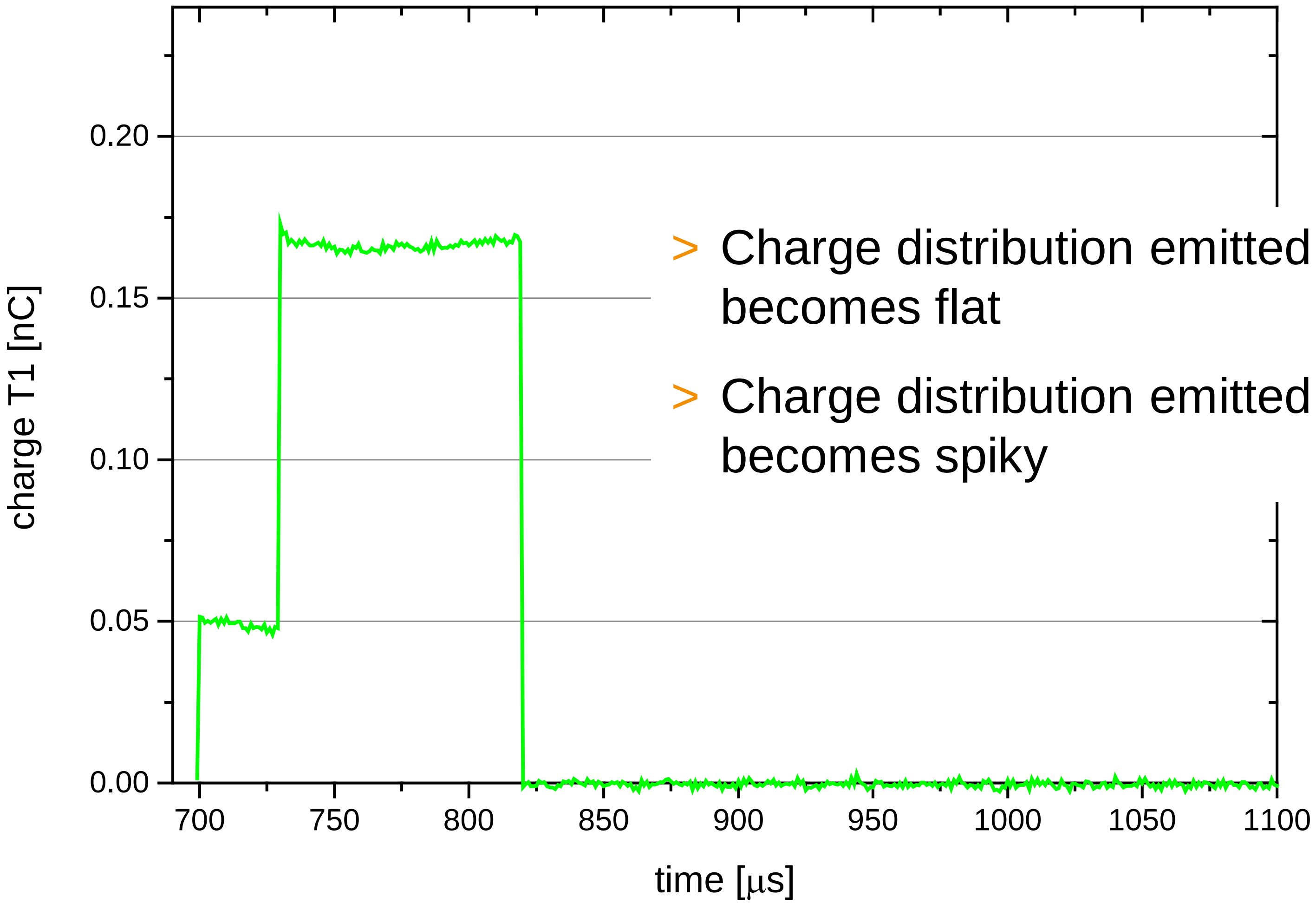
L2 and L1 on cathode, changing L2 intensity



- > Charge distribution emitted by L2 spiky
- > Charge distribution emitted by L1 flat

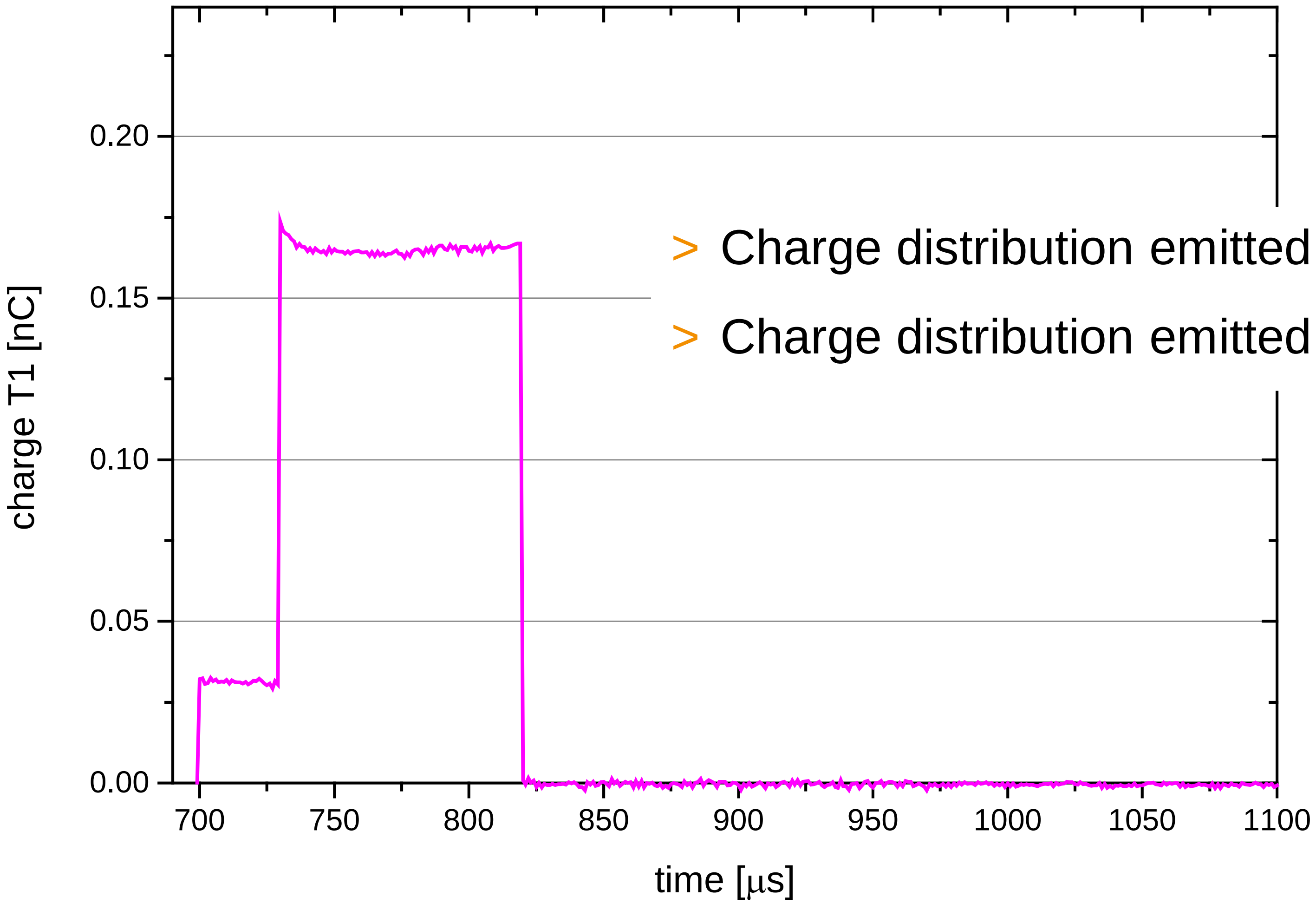
L2 and L1 on cathode, changing L2 intensity

FLASH. Free-Electron Laser in Hamburg



- Charge distribution emitted by L2 becomes flat
- Charge distribution emitted by L1 becomes spiky

L2 and L1 on cathode, changing L2 intensity



- Charge distribution emitted by L2 flat
- Charge distribution emitted by L1 spiky

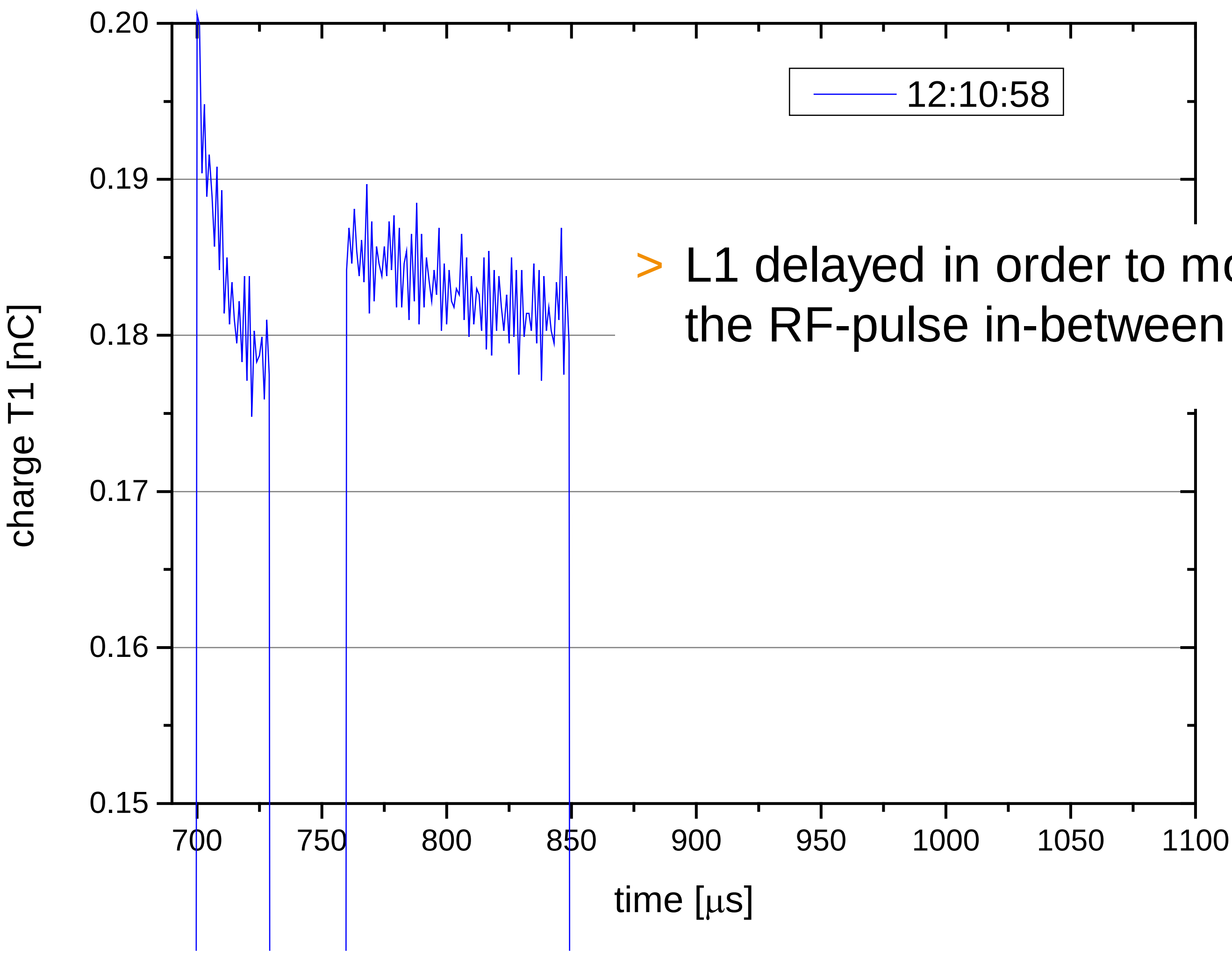
L2 and L1 on cathode, L2 before gun RF

FLASH. Free-Electron Laser in Hamburg

- In the following the RF-pulse of the gun was moved in order to see if just laser energy on the cathode is needed or both, electric field and laser energy.

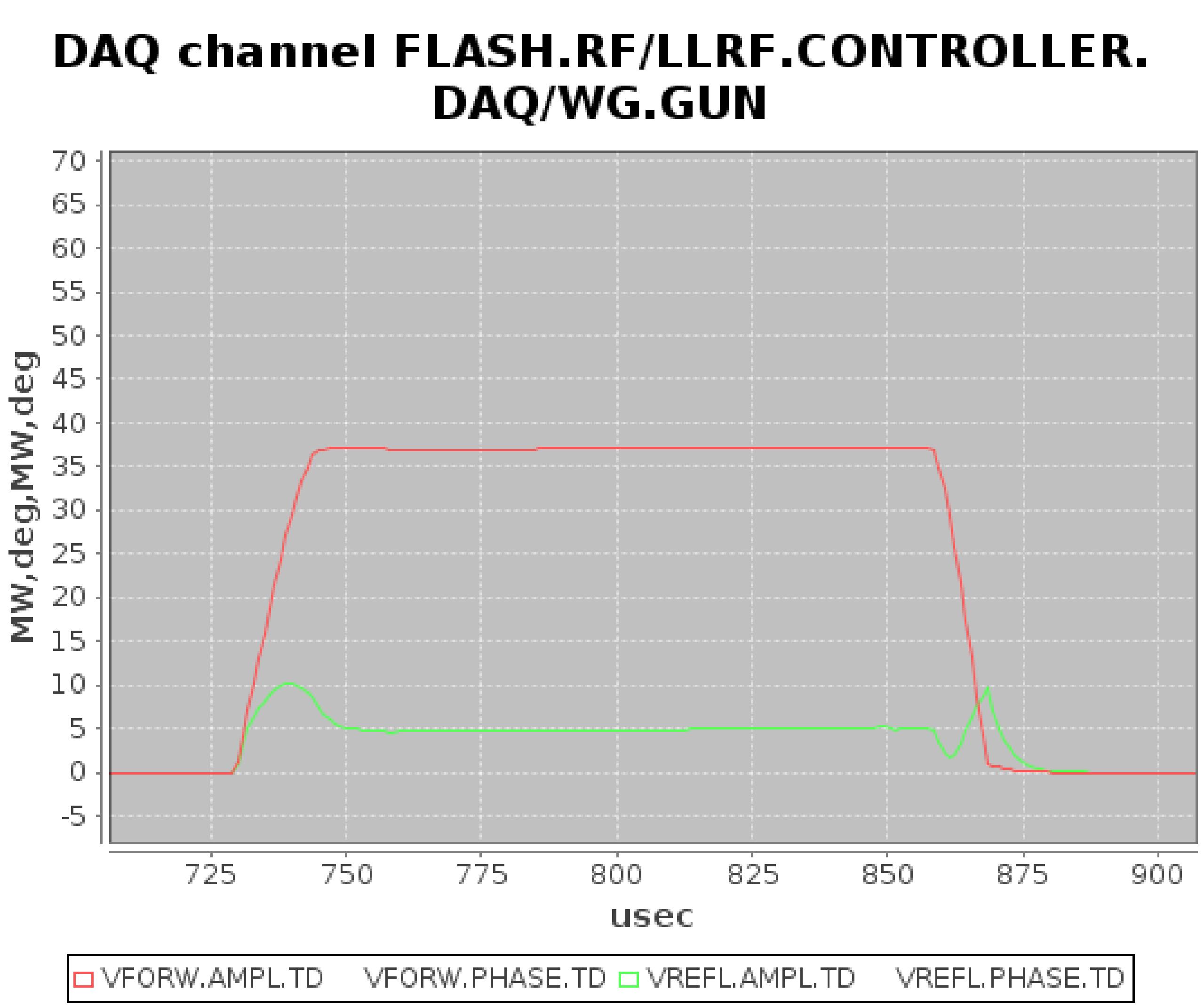
L2 and L1 on cathode, L2 before gun RF

FLASH. Free-Electron Laser in Hamburg

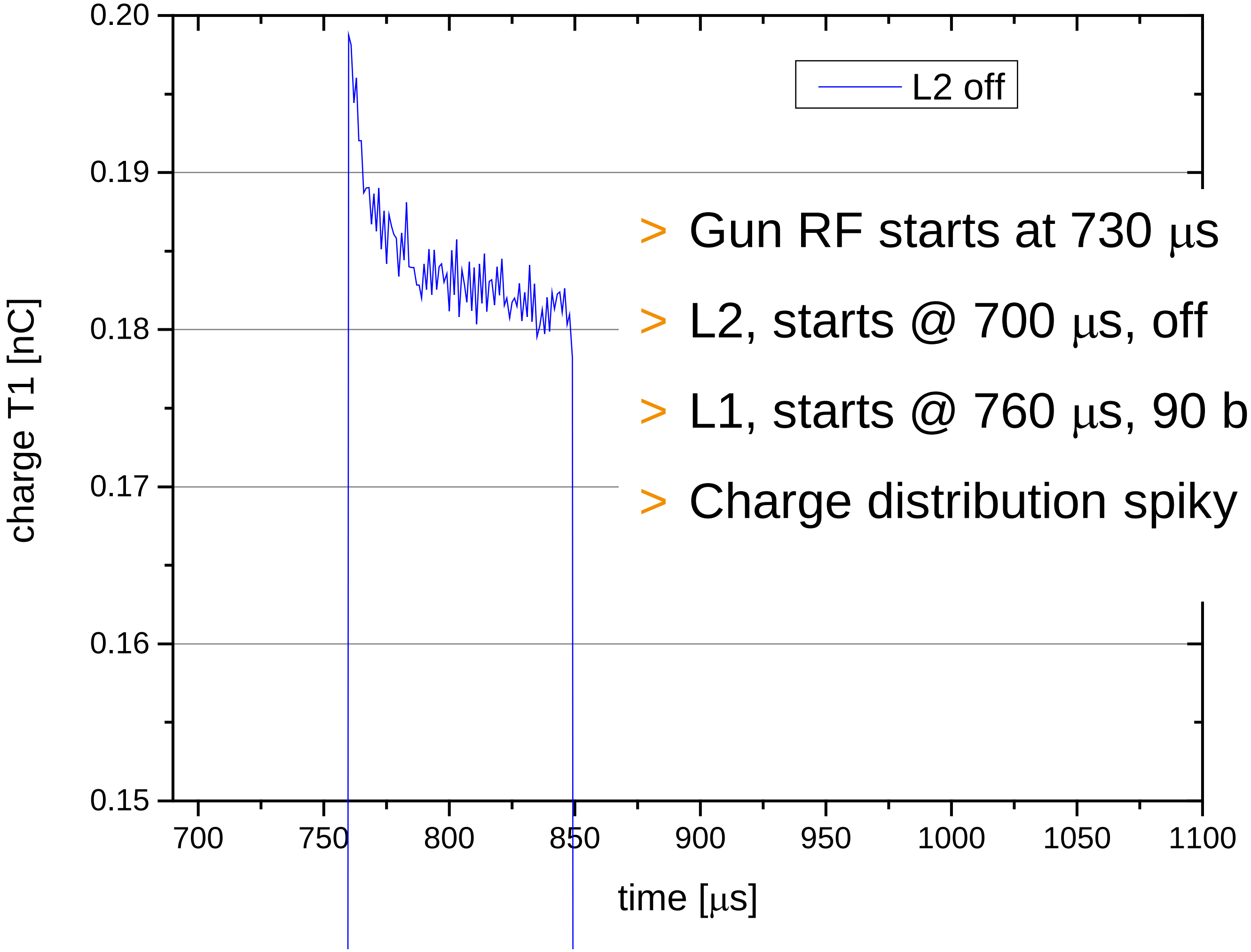


> L1 delayed in order to move the start of the RF-pulse in-between the two lasers

L2 and L1 on cathode, L2 before gun RF



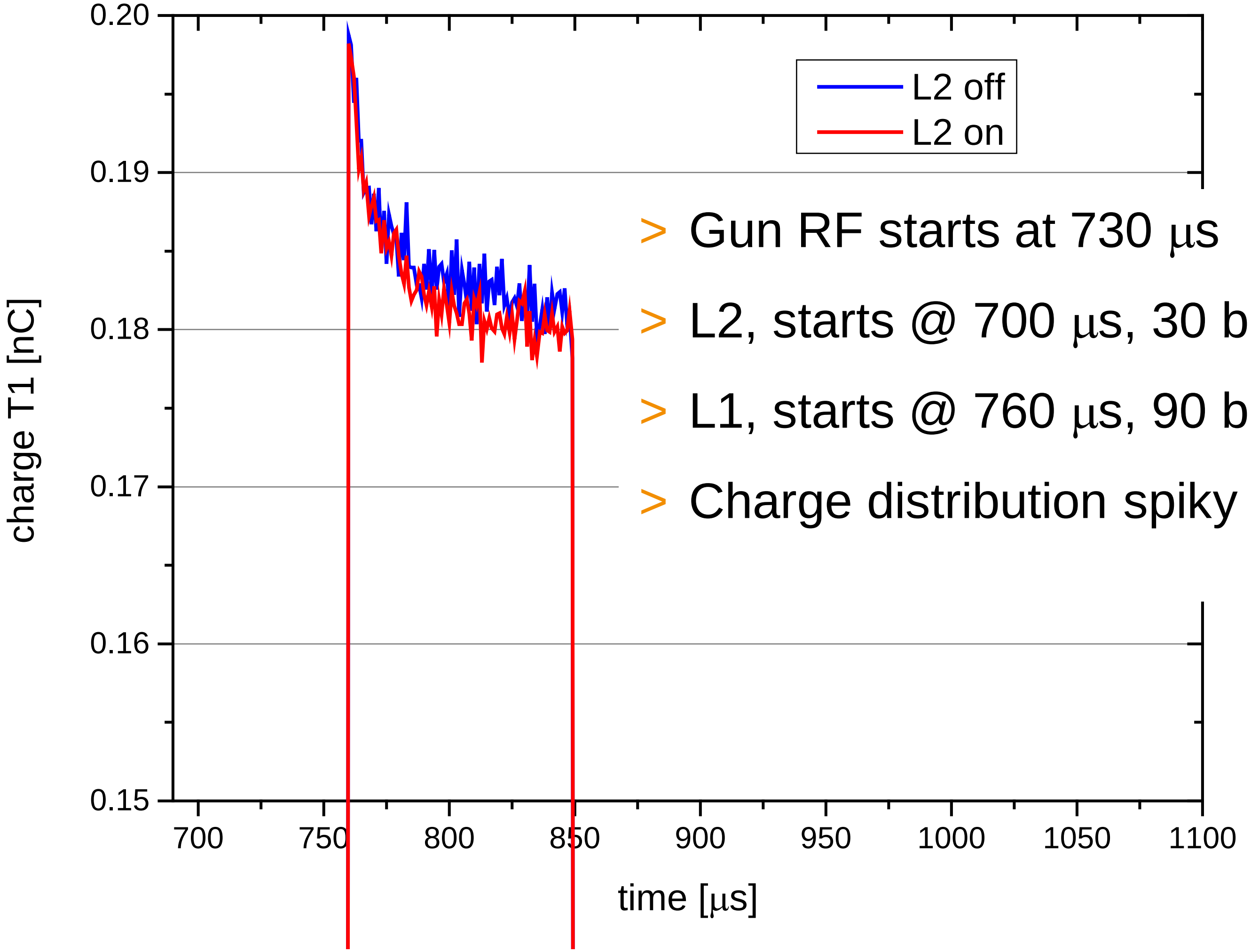
L2 and L1 on cathode, L2 before gun RF



- Gun RF starts at 730 μs
- L2, starts @ 700 μs, off
- L1, starts @ 760 μs, 90 bunches
- Charge distribution spiky

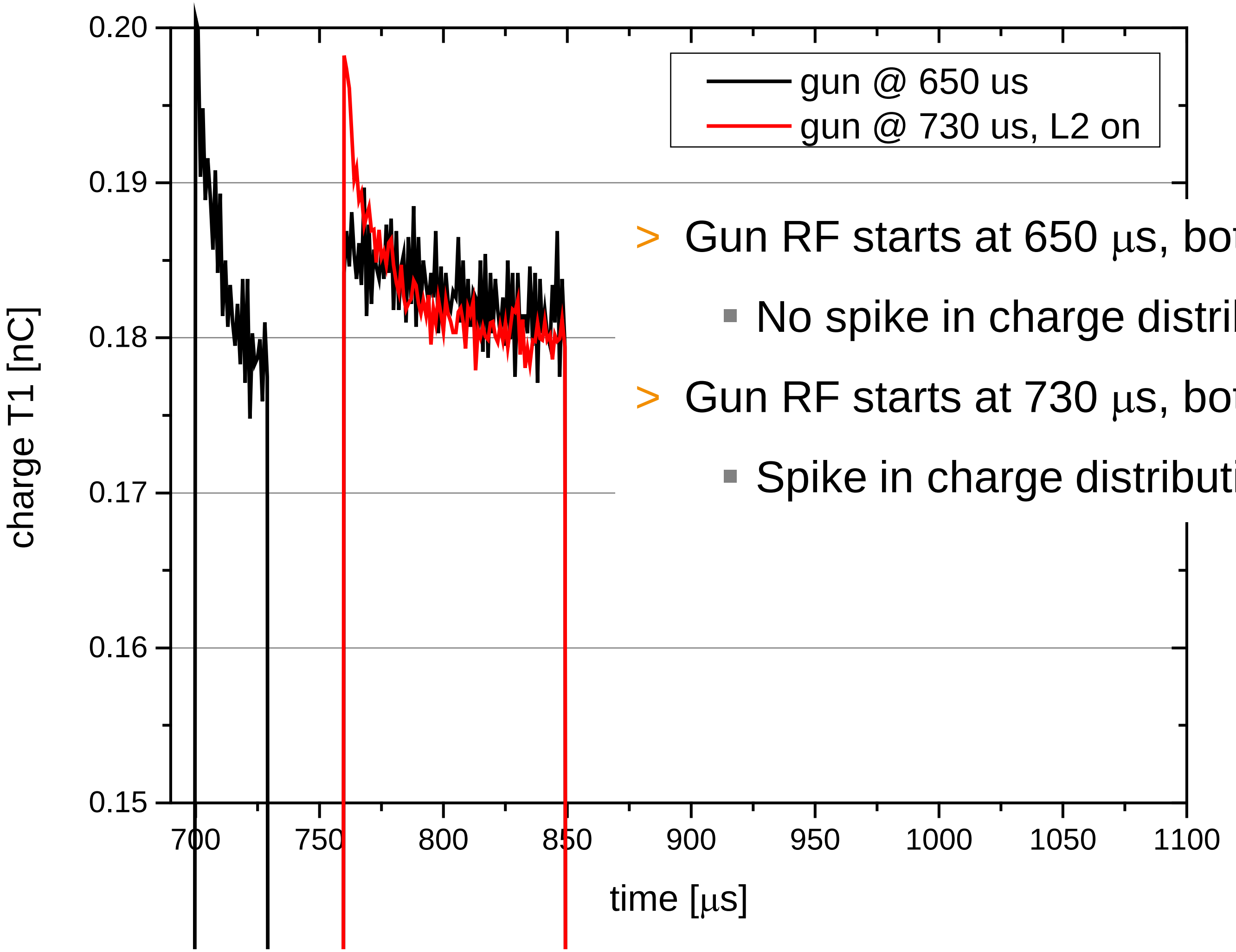
L2 and L1 on cathode, L2 before gun RF

FLASH.
Free-Electron Laser in Hamburg



- Gun RF starts at 730 μs
- L2, starts @ 700 μs, 30 bunches
- L1, starts @ 760 μs, 90 bunches
- Charge distribution spiky

L2 and L1 on cathode, L2 before gun RF



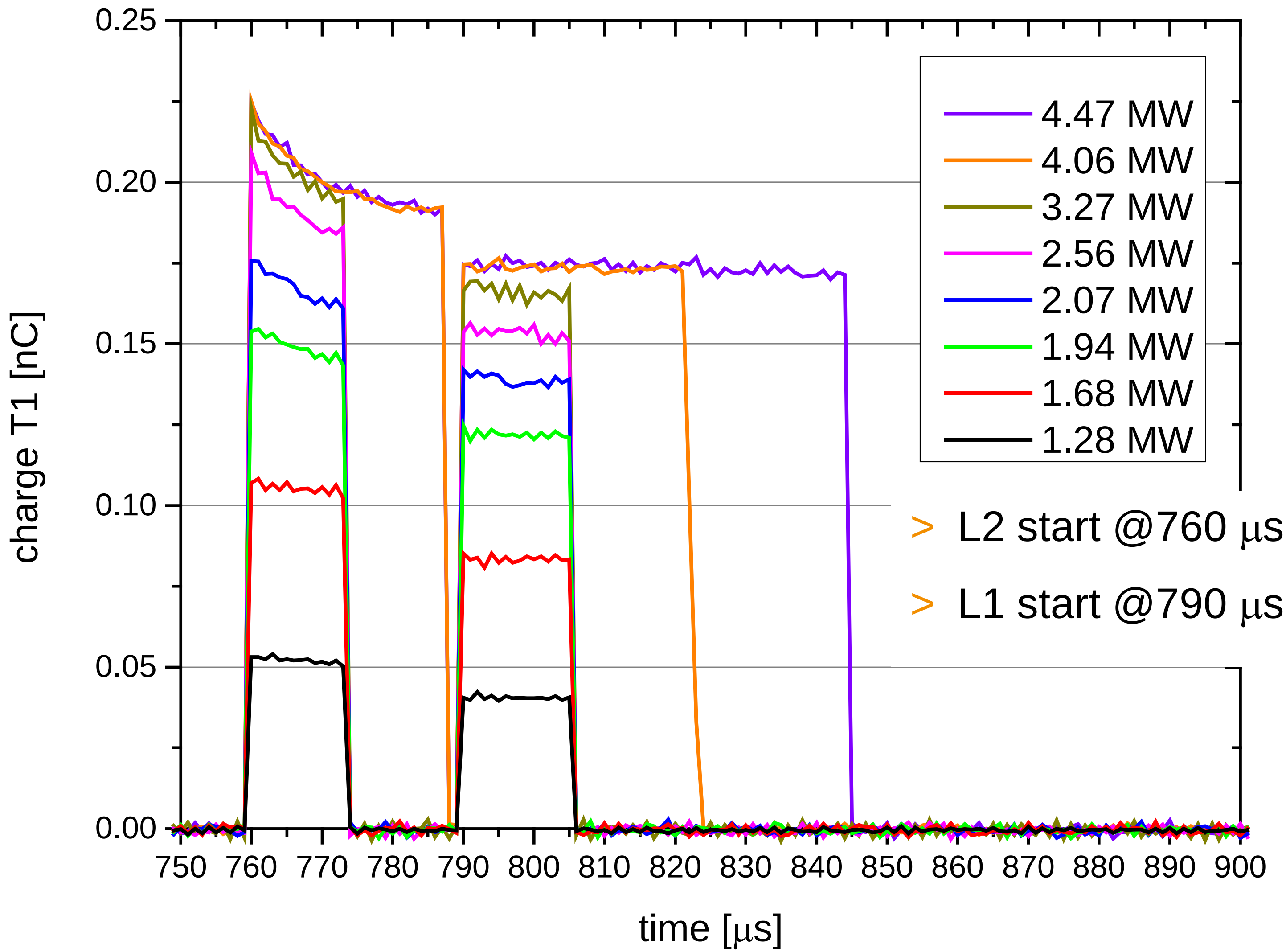
> Gun RF starts at 650 µs, both laser on:
  - No spike in charge distribution for L1

> Gun RF starts at 730 µs, both laser on:
  - Spike in charge distribution for L1

L2 and L1 on cathode, decreasing the power in the RF-gun keeping lasers constant

- Since the measurements before showed that field + laser on the cathode are needed for the effect, the field influence was further investigated.
- Therefore both lasers where moved in order to fit again into the gun RF-pulse and than the RF-power was decreased while keeping the lasers properties constant.

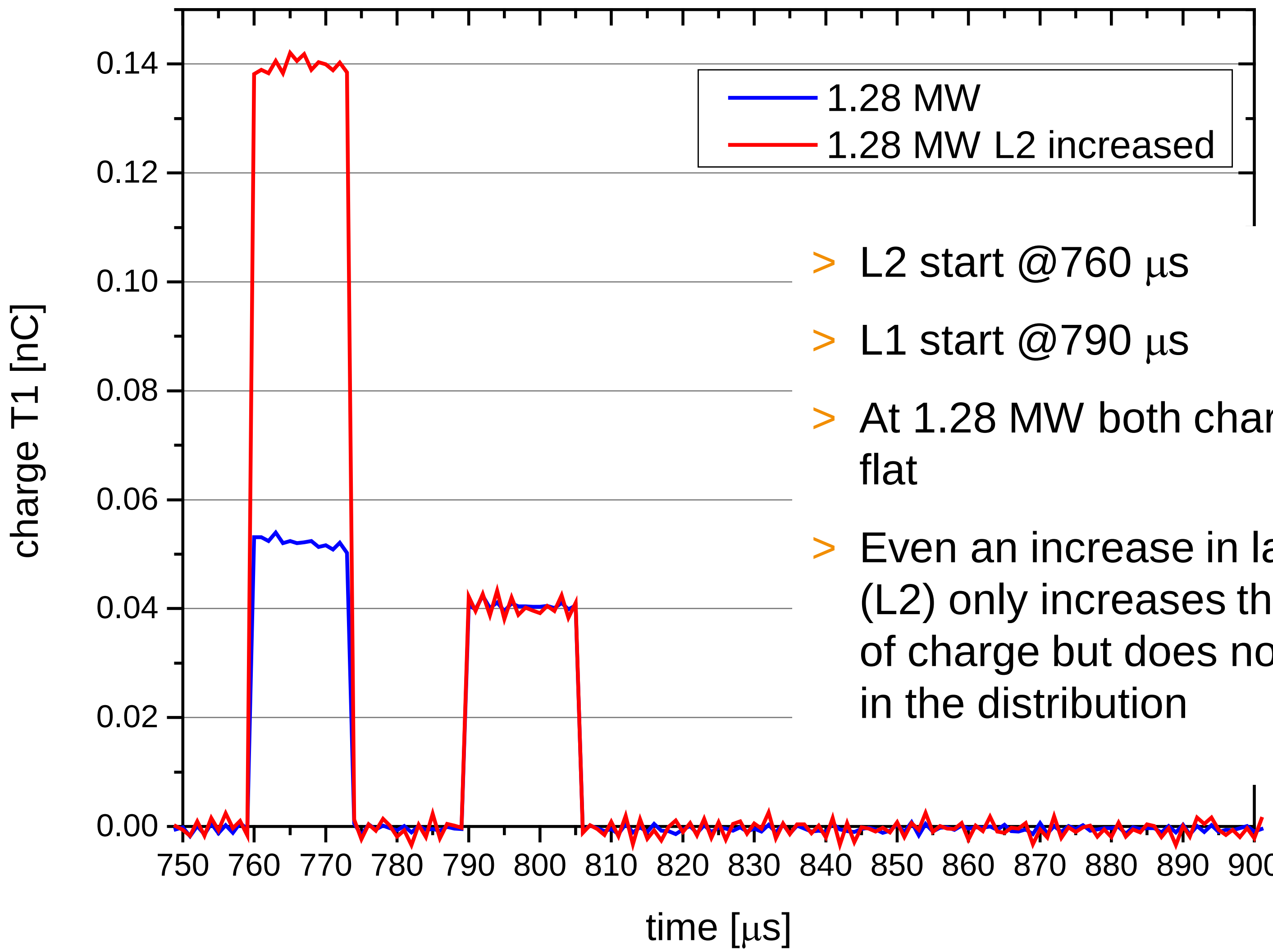
L2 and L1 on cathode, decreasing the power in the RF-gun keeping lasers constant



- Below 4 MW it was necessary to go into gun-mode, so number of pulses had to be decreased

L2 and L1 on cathode, low RF-power

FLASH.
Free-Electron Laser in Hamburg



- L2 start @760 µs
- L1 start @790 µs
- At 1.28 MW both charge profiles are flat
- Even an increase in laser energy (L2) only increases the total amount of charge but does not yield a spike in the distribution

Summary

FLASH.
Free-Electron Laser in Hamburg

> RF Gun runs stable with 5 MW, 550 us, 10 Hz
> Cathode lifetime excellent, now 400 days with a QE of 7%
> QE map: QE changes where the laser hits the cathode compared to the other parts
> Emission issue: puzzling, we need a solid scientific model