Current status of Bunch (Q-) Train Extraction Studies Using Cs_2Te Photocathodes at PITZ

Outline

- **Problem descriptions**
  - ❑ Motivation (I@FLASH, II@PITZ)
  - ❑ Preliminary investigations at FLASH
- **Possible sources of problem**
- **Strategy of measurements**
- **First experimental results at PITZ**
  - ❑ Correlations of Q-train slope with laser & RF
  - ❑ Emission analysis w.r.t. Q-train slope
- **Summary & Next steps**

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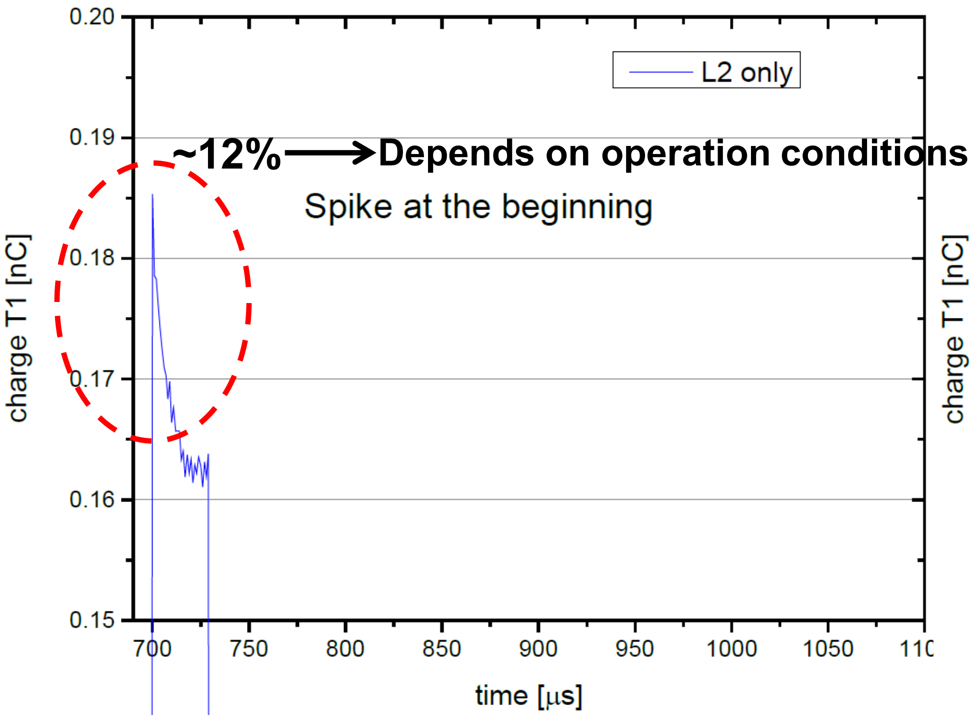
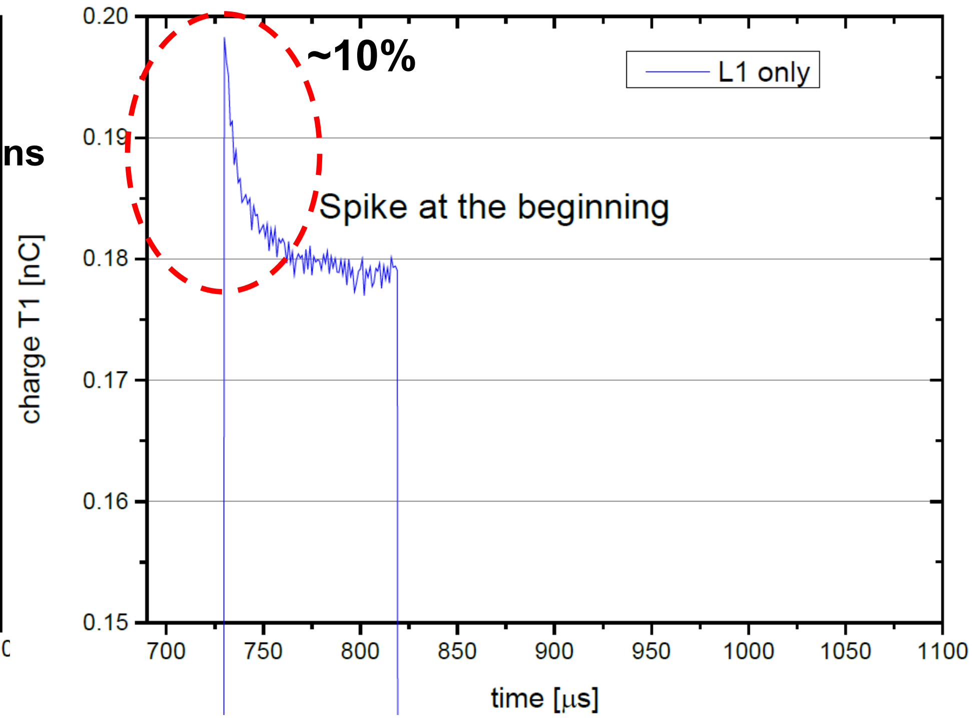
PPS, PITZ, DESY Zeuthen
Control Room, 20.10.2016

Problem description: Motivation I

- Observations at FLASH* using a "fresh" cathode
  - ❑ Large spike observed in bunch train extraction for FLASH laser 1 (L1) and 2 (L2) on fresh cathode -> not tolerable by users
  - ❑ Preliminary investigations done at FLASH -> no conclusion yet

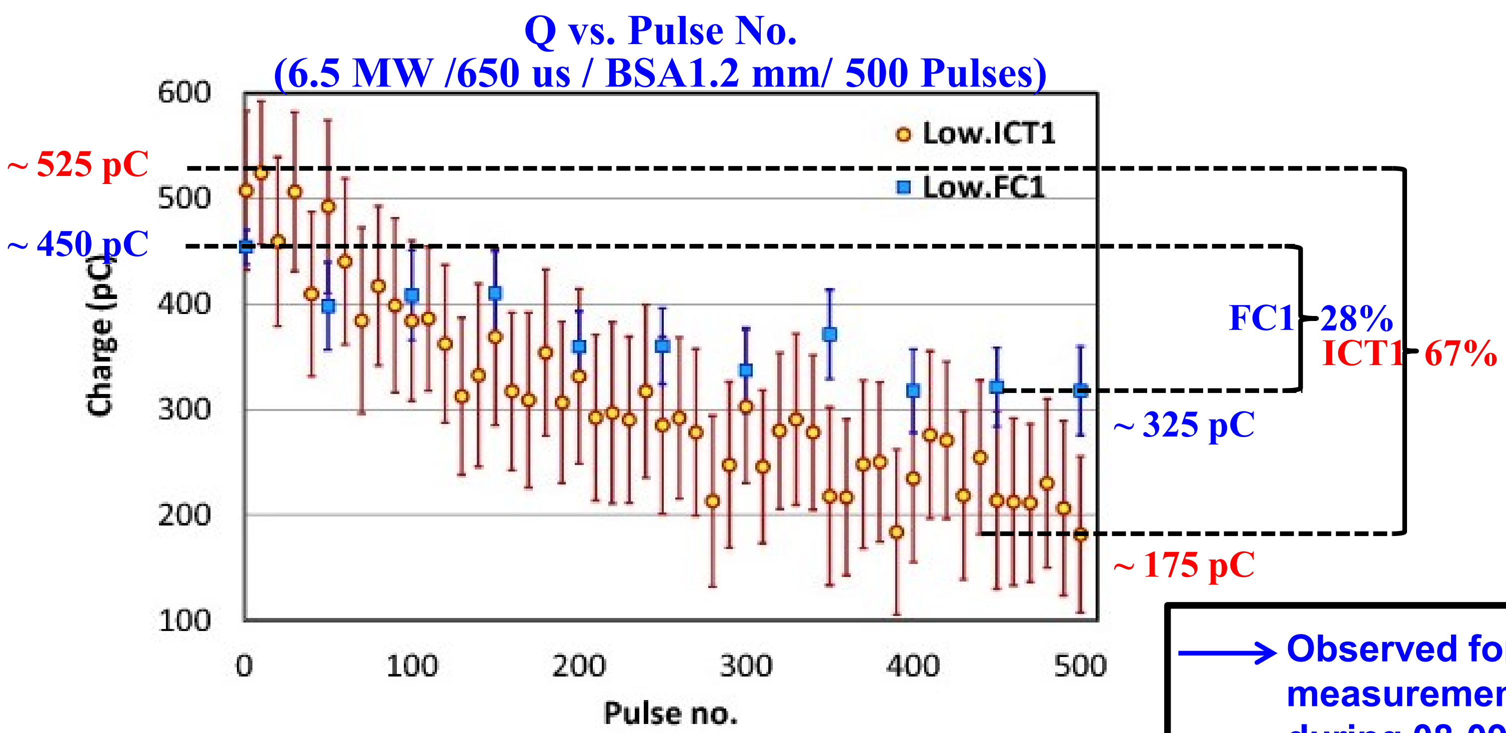




*S. Schreiber et al., Proceedings of FEL2015, Daejeon, Korea, 2015

Problem description: Motivation II

> **Previous measurements at PITZ using a "worn" cathode**



→ Observed for all following measurements at PITZ during 08-09, 2016

→ Observations @FLASH and @PITZ: **charge profile along bunch train not flat!**

Other parameters:

Charge measured at Low. ICT1 and FC1

MMMG at -128^0

LT = 29.8%

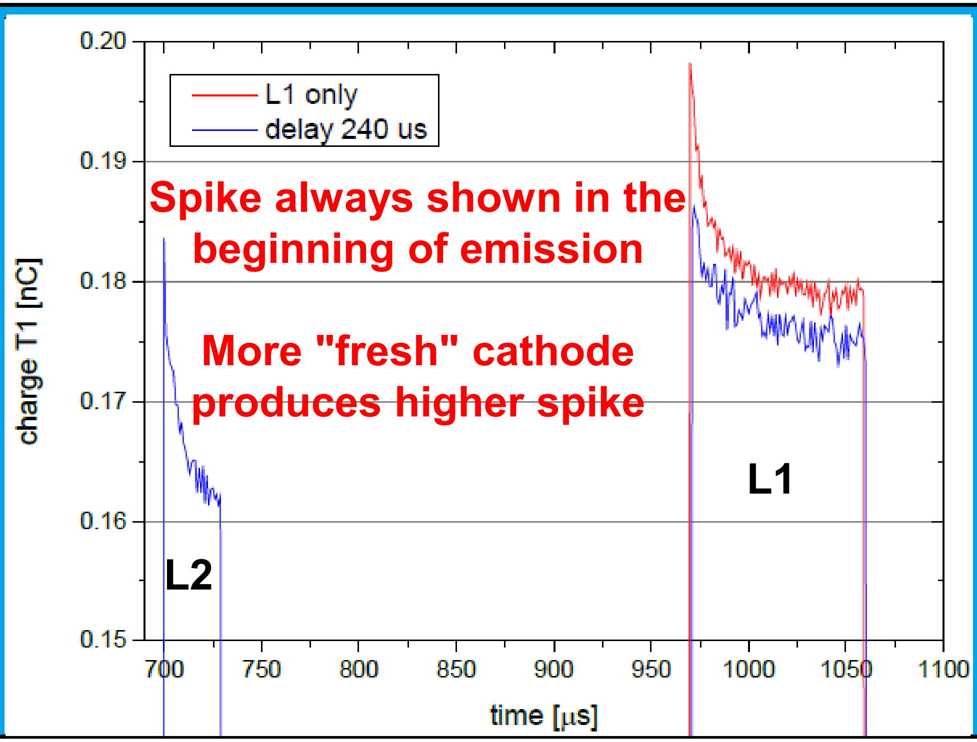
Observations:

1. Charge decreasing along Q-train
2. Effect stronger for LOW. ICT1(see X.Li's talk)

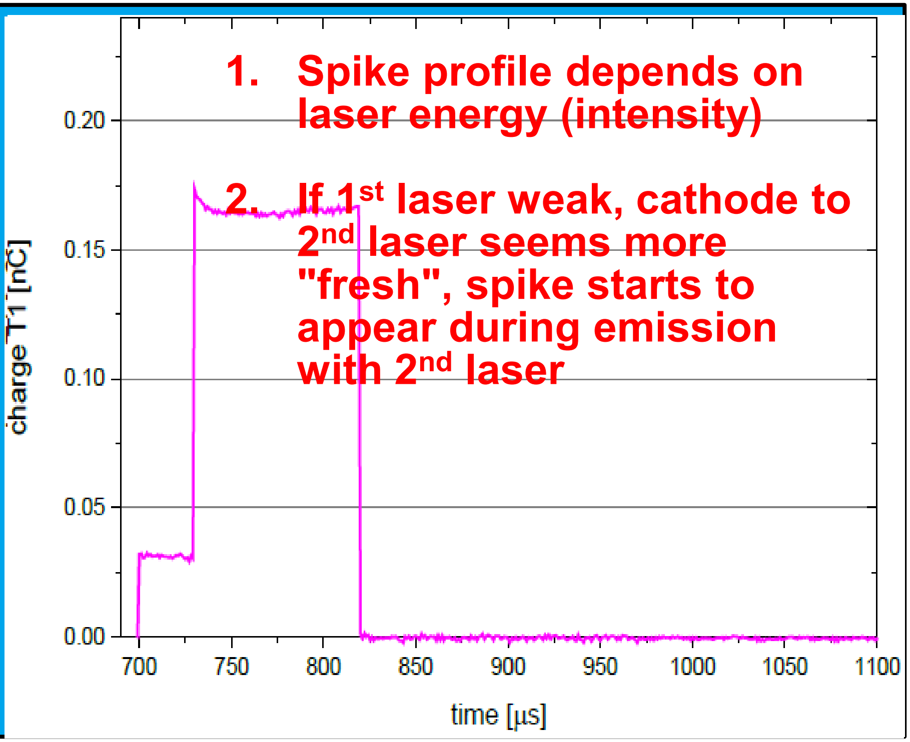
Problem description: Investigations at FLASH* (1)

- ❑ **Bunch train slope observed for all charge measurement devices**
- ❑ **Flatness of two laser profiles both checked**
- ❑ **Investigations of slope dependencies on laser intensity and RF powers**

Animation 1

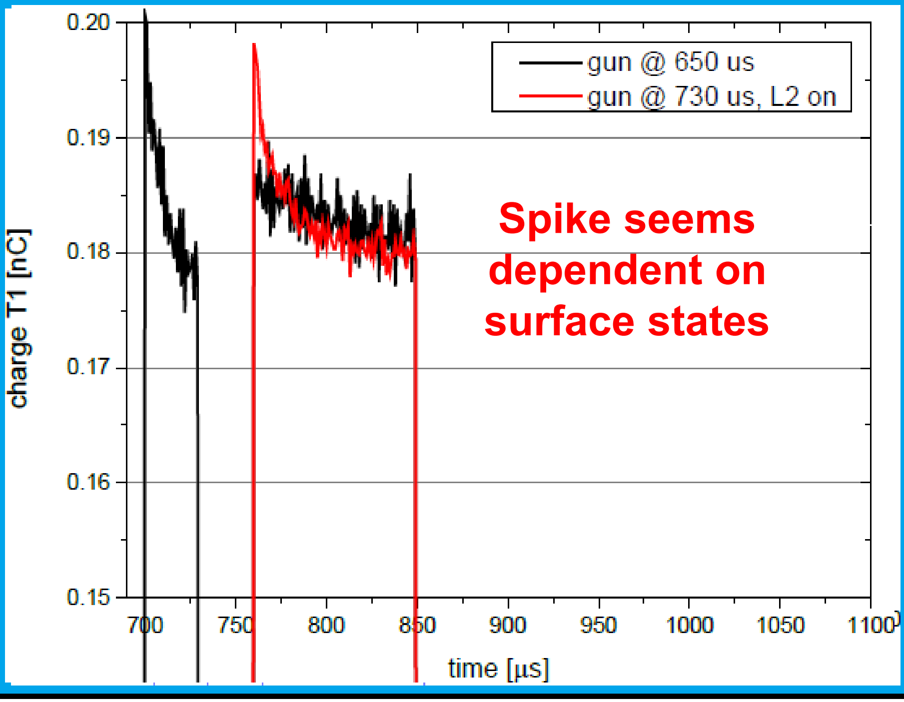


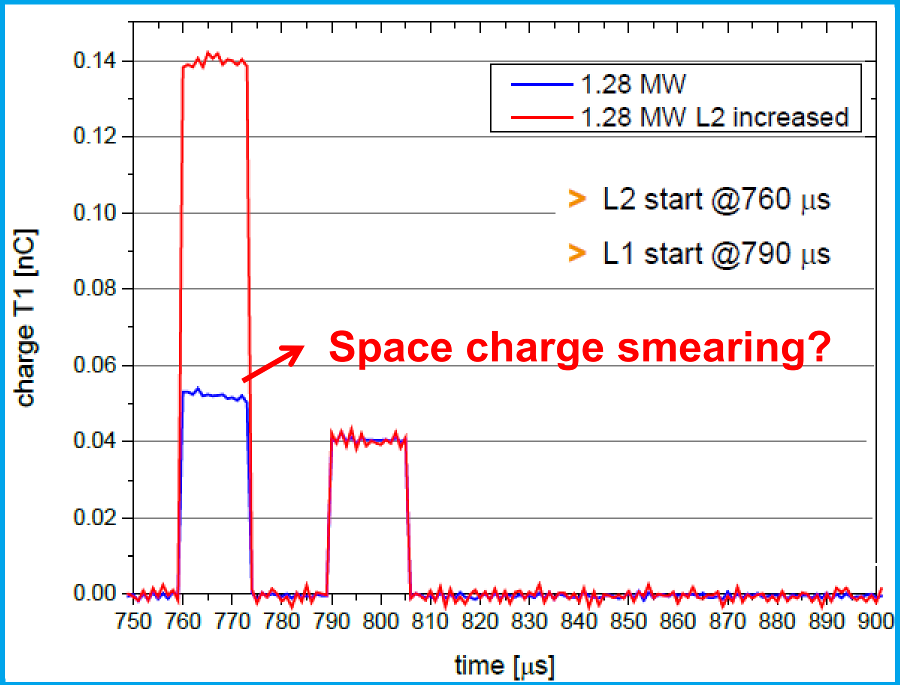
Animation 2



Problem description: Investigations at FLASH* (2)

Animation 3 | **Spike dependencies on RF** | **Animation 4**





Message from FLASH:

1> Spike always shown in the beginning of emission
2> Spike depends on laser intensity and RF
3> Spike gets smaller and slope gets less steep as cathode operation time rises

Possible sources of problem

- **Issues of charge measurement devices**
- **Issues of driving laser**, e.g., thermal lensing, flatness of intensity profile.
- **Issues of RF gun** (amplitude & phase) **stability**
- **Space charge effects,** e.g., shielding, coupling to QE, smearing, etc.
- **Photoemission physics,** e.g., recombination, band bending, etc.

Current strategy of PITZ measurements

- **Cross-check with various charge measurement devices and/or methods**
  - ❑ Scope measurements with LOW. ICT1, FC1 and FC2
  - ❑ Measurements using LOW.ICT1@ADC

Cross-checking charge measurements

- **Laser intensity profile check at PMT@LaserTrolley**
- **Check RF gun amplitude and phase @ μTCA**

Correlations with bunch train slope

- **Systematic multi-parametric measurements for Q-trains**

For micropulses on the train

- ❑ Charge measurements
- ❑ Attenuator scan
- ❑ Charge phase scan
- ❑ Laser intensity profile scan
- ❑ Gun amplitude and phase profiles scan

BSA \ P_{gun}	6.5 MW	3.375 MW	1.5 MW
0.6 mm			
1.2 mm			
2.4 mm			

For emission analysis

Correlations of laser intensity*, gun amplitude and phase** with bunch train*** slope (LOW.ICT1 @ ADC)

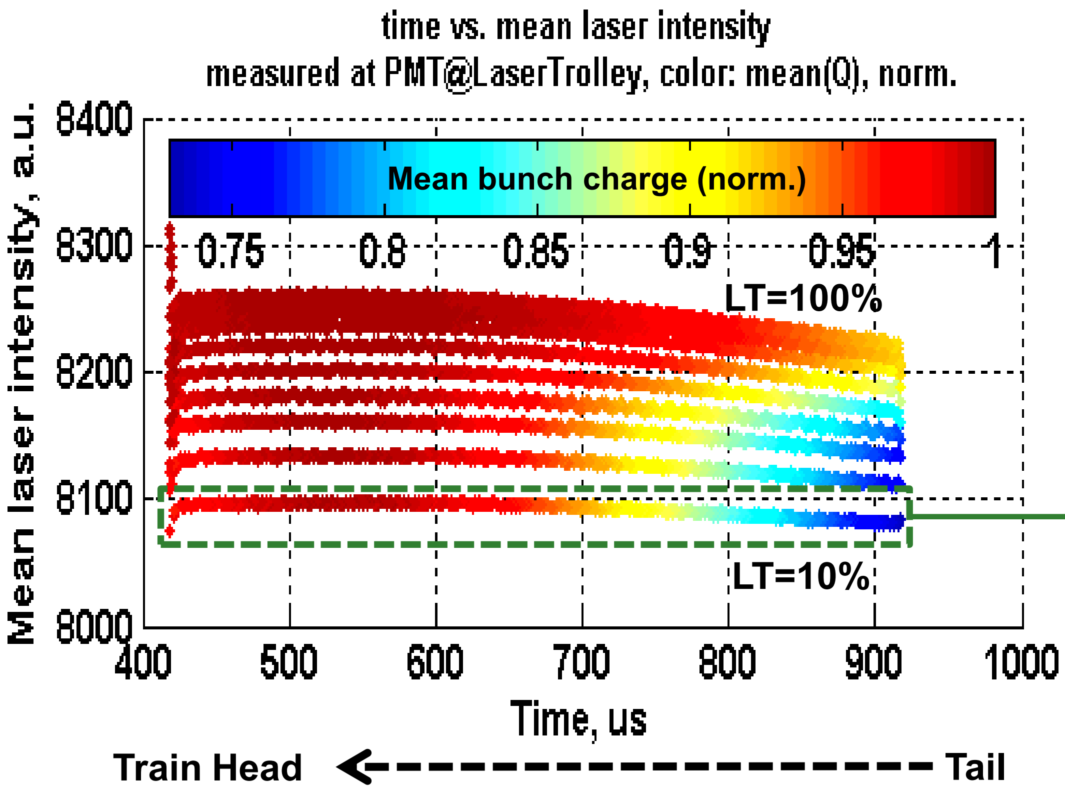
* Laser intensity: data taken from PMT@LaserTrolley

** Gun amplitude and phase: data taken from μTCA

*** Bunch train: measured from LOW.ICT1@ADC

Laser intensity (PMT@LaserTrolley) along bunch trains

❖ **6.5 MW in the gun @MMMG Phase, BSA=1.2mm**



$$\Delta Q = \frac{Q_{fst} - Q_{last}}{Q_{fst}} \times 100$$

Q_{fst}: charge of first pulse

Q_{last}: charge of last pulse

$$\Delta I = \frac{I_{fst} - I_{last}}{I_{max} - I_{baseline}} \times 100$$

I_{fst}: laser intensity of first pulse

I_{last}: laser intensity of last pulse

I_{max}: maxi. laser intensity

$I_{baseline}$: baseline laser intensity

For LT=10% case,

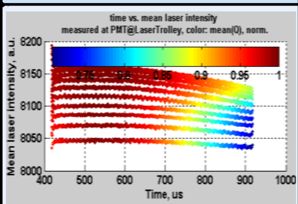
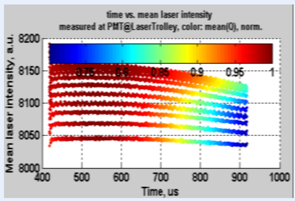
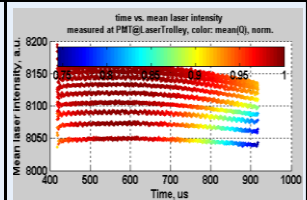
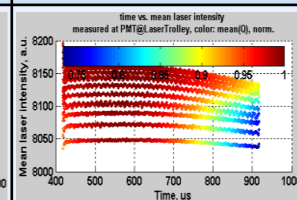
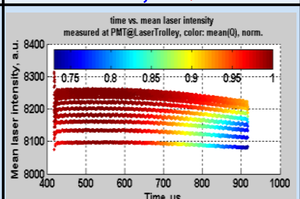
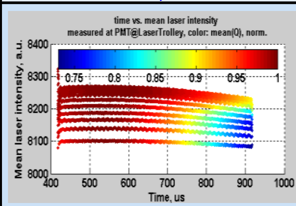
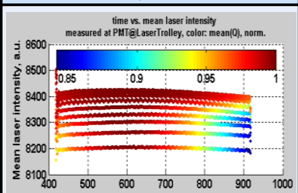
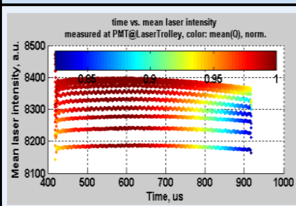
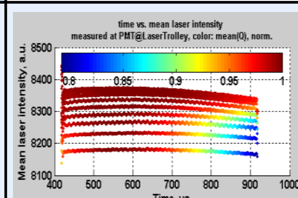
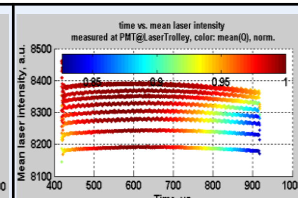
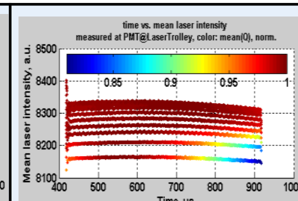
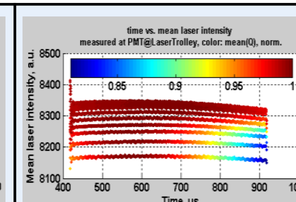
$$\Delta I \approx \frac{8094 - 8080}{8099 - 7997} \times 100 \approx 13.7\%$$

$\Delta Q \approx 25\%$

NB: color code stands for bunch charge normalized respectively by the maxi. charge for each laser transmission coefficient

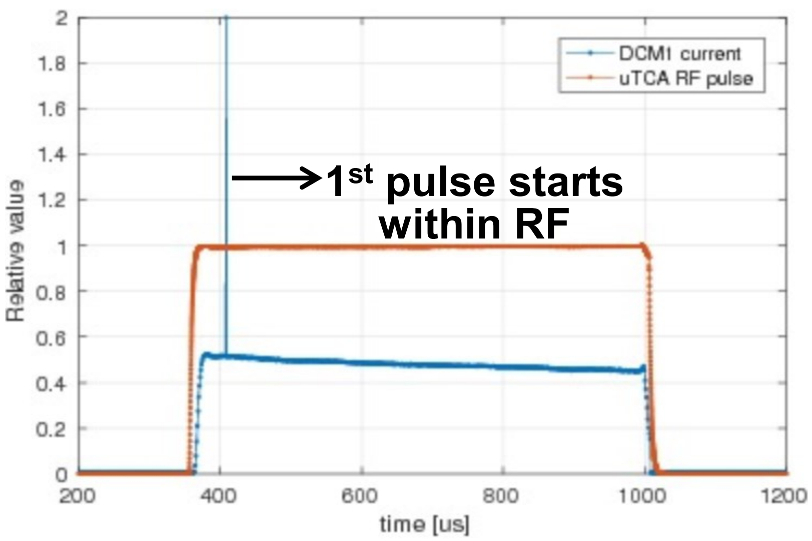
Correlation of laser intensity with bunch train slopes

❖ **Variation of gun power levels and BSA sizes**

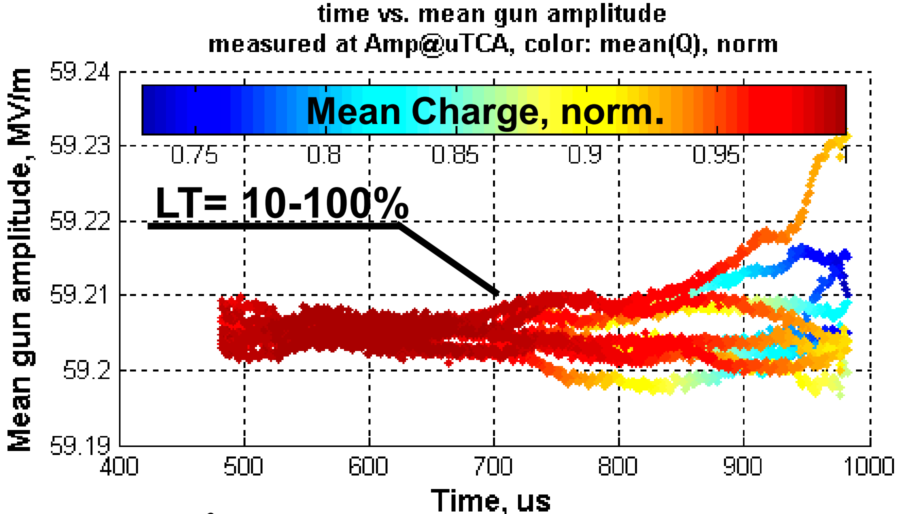
P_{gun} / BSA	~6.5 MW		~3.375 MW		~1.5 MW	
	@ MMMG Phase	@ MaxQ Phase	@ MMMG Phase	@ MaxQ Phase	@ MMMG Phase	@ MaxQ Phase
0.6 mm	 LT=10% $\Delta I \approx 15.4\%$, $\Delta Q \approx 25.6\%$	 LT=10% $\Delta I \approx 17.6\%$, $\Delta Q \approx 26\%$	 LT=10% $\Delta I \approx 10.9\%$, $\Delta Q \approx 18.2\%$	 LT=10% $\Delta I \approx 11.3\%$, $\Delta Q \approx 19.5\%$		
1.2 mm	 LT=10% $\Delta I \approx 13.7\%$, $\Delta Q \approx 25\%$	 LT=10% $\Delta I \approx 14\%$, $\Delta Q \approx 25\%$				
2.4 mm	 LT=10% $\Delta I \approx 4.7\%$, $\Delta Q \approx 10.7\%$	 LT=10% $\Delta I \approx 5.2\%$, $\Delta Q \approx 12.2\%$	 LT=10% $\Delta I \approx 5.8\%$, $\Delta Q \approx 14.7\%$	 LT=10% $\Delta I \approx 7.6\%$, $\Delta Q \approx 9.9\%$	 LT=10% $\Delta I \approx 8.8\%$, $\Delta Q \approx 14.6\%$	 LT=10% $\Delta I \approx 10.7\%$, $\Delta Q \approx 13.6\%$

Gun field amplitude stability (Amp@μTCA) along bunch trains

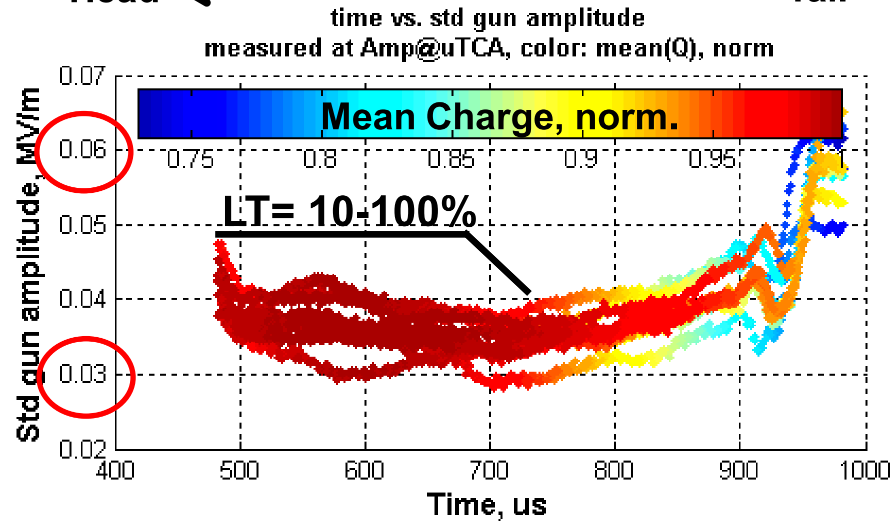
- **Script: first pulse finder for uTCA using DCM (I. Isaev)**



- **6.5 MW in the gun @MMMG Phase, BSA=1.2mm**



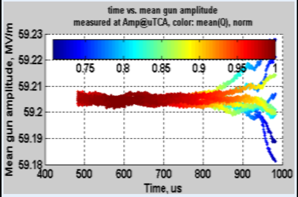
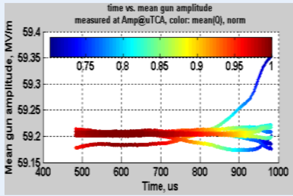
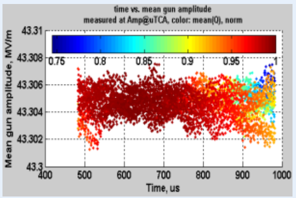
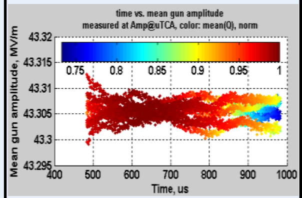
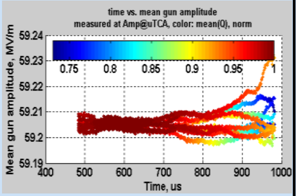
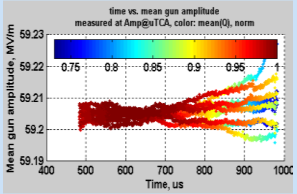
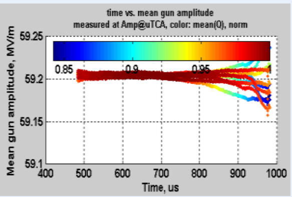
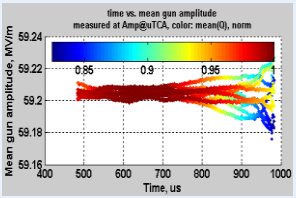
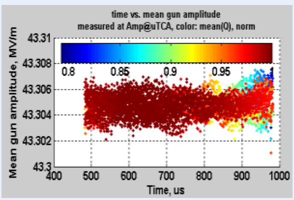
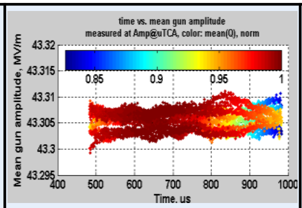
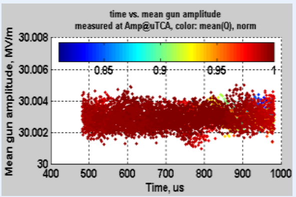
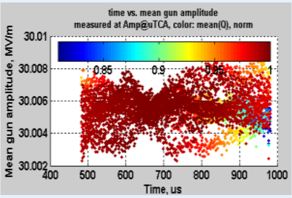
Head ← - - - - - - - - - - - Tail



E.g., if E -> [59.195-0.06, 59.23+0.06] (max.range) then ΔE_{max} ~ 0.3%

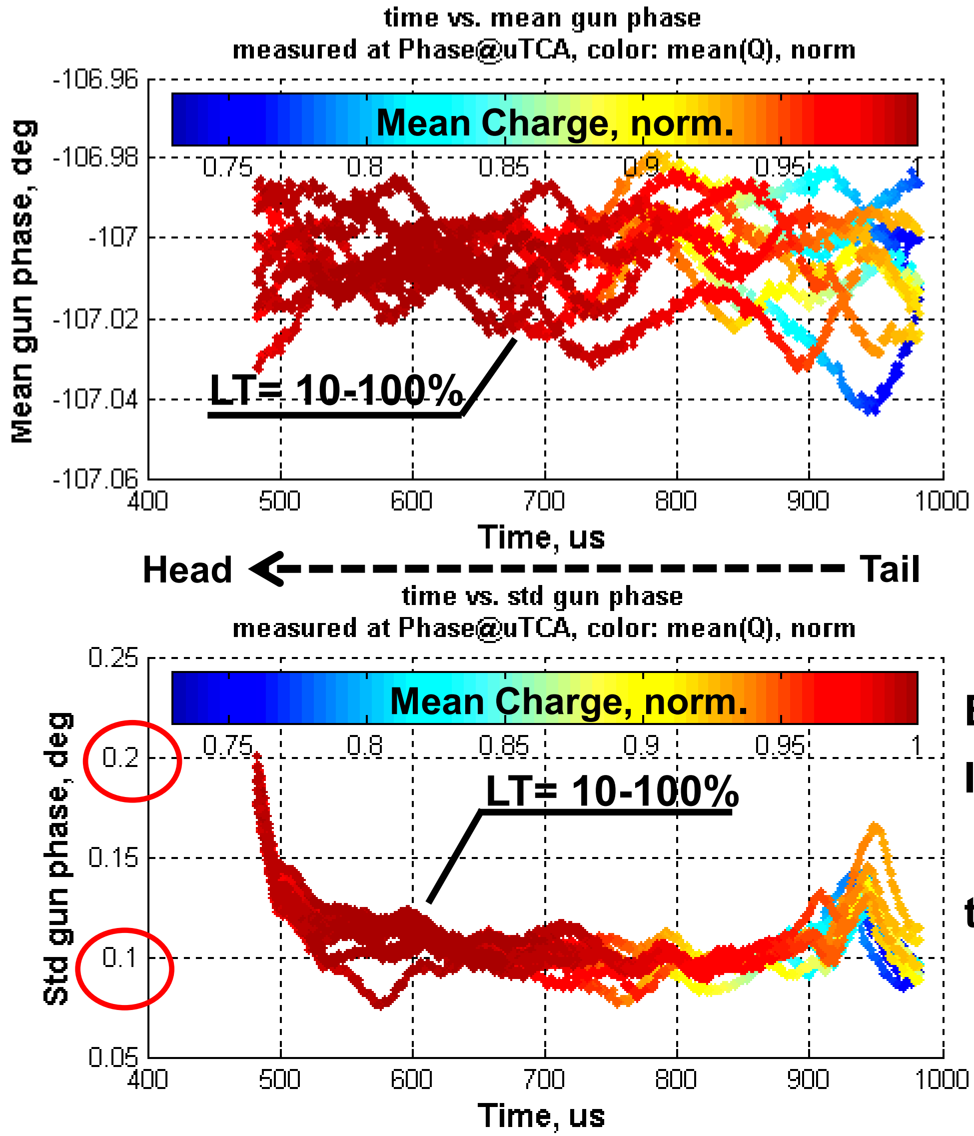
Correlation of gun field amplitude with bunch train slopes

❖ **Variation of gun power levels and BSA sizes**

P_{gun} / BSA	~6.5 MW		~3.375 MW		~1.5 MW	
	@ MMMG Phase	@ MaxQ Phase	@ MMMG Phase	@ MaxQ Phase	@ MMMG Phase	@ MaxQ Phase
0.6 mm						
1.2 mm						
2.4 mm						

Gun phase stability (Phase @ μTCA) along bunch trains

❖ **6.5 MW in the gun @MMMG Phase, BSA=1.2mm**



E.g.,

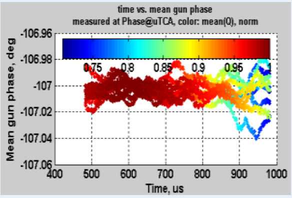
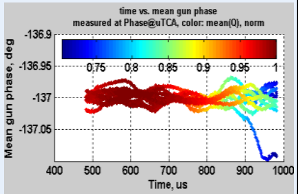
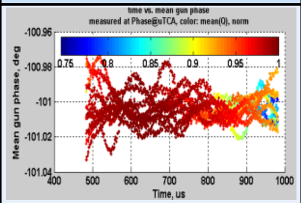
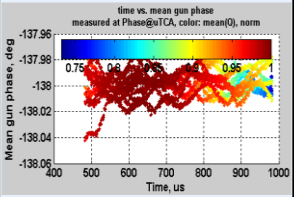
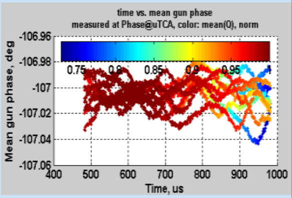
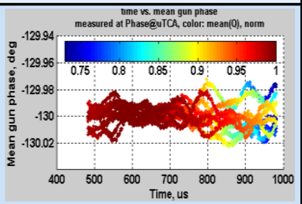
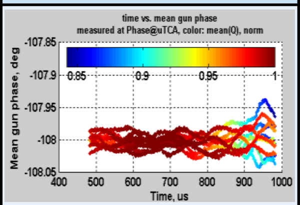
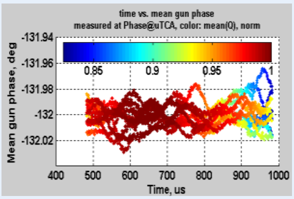
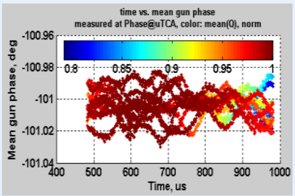
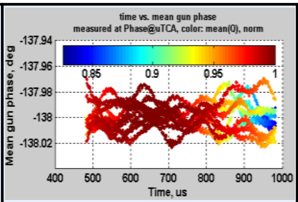
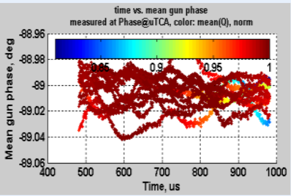
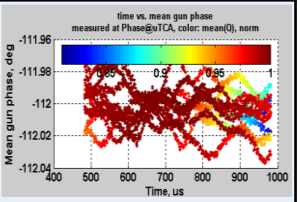
If ϕ -> [-107.04-0.2,

-106.98+0.2] (max.range)

then $\Delta\phi_{max}$~ 0.4%

Correlation of gun phase with bunch train slopes

❖ **Variation of gun power levels and BSA sizes**

P_{gun} / BSA	~6.5 MW		~3.375 MW		~1.5 MW	
	@ MMMG Phase	@ MaxQ Phase	@ MMMG Phase	@ MaxQ Phase	@ MMMG Phase	@ MaxQ Phase
0.6 mm						
1.2 mm						
2.4 mm						

Intermediate summary (1)

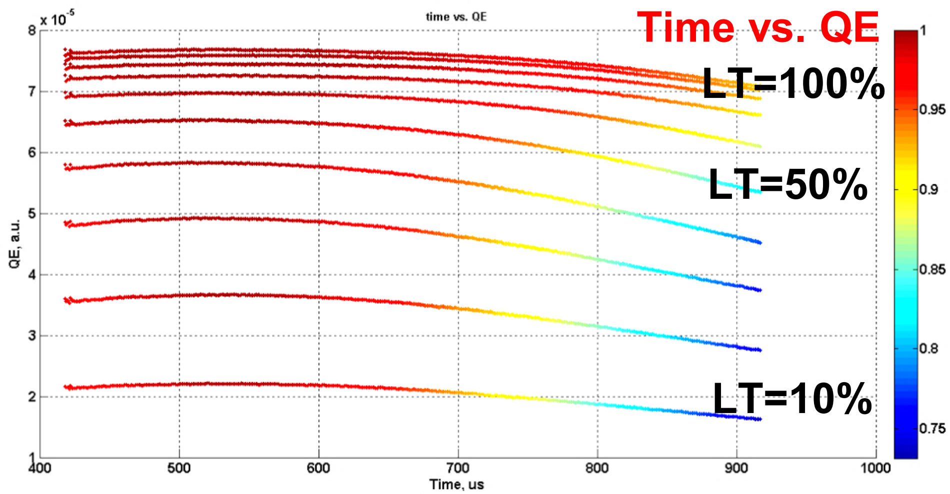
> **Flatness checked** for profiles of laser intensity, gun amplitude and phase

> **Observations** further confirmed **at 3 gun power levels** (6.5/3.375/1.5MW), **3 BSA sizes** (0.6/1.2/2.4mm), **2 gun phases** (MMMG/Max.Q) and **LT scan** for each case (10~100%)

> **Some correlations of laser flatness with bunch train slope found -> accuracy of PMT needs to be further checked** (500-pulse bunch train slope: tail2head ΔQ_{max}~25%)

> **"QE" drops along bunch trains** ⟶

$$QE = \frac{mean\ charge\ (ICT1@ADC)}{laser\ intensity\ (PMT)}$$



6.5MW @ MMMG phase, BSA1p2mm

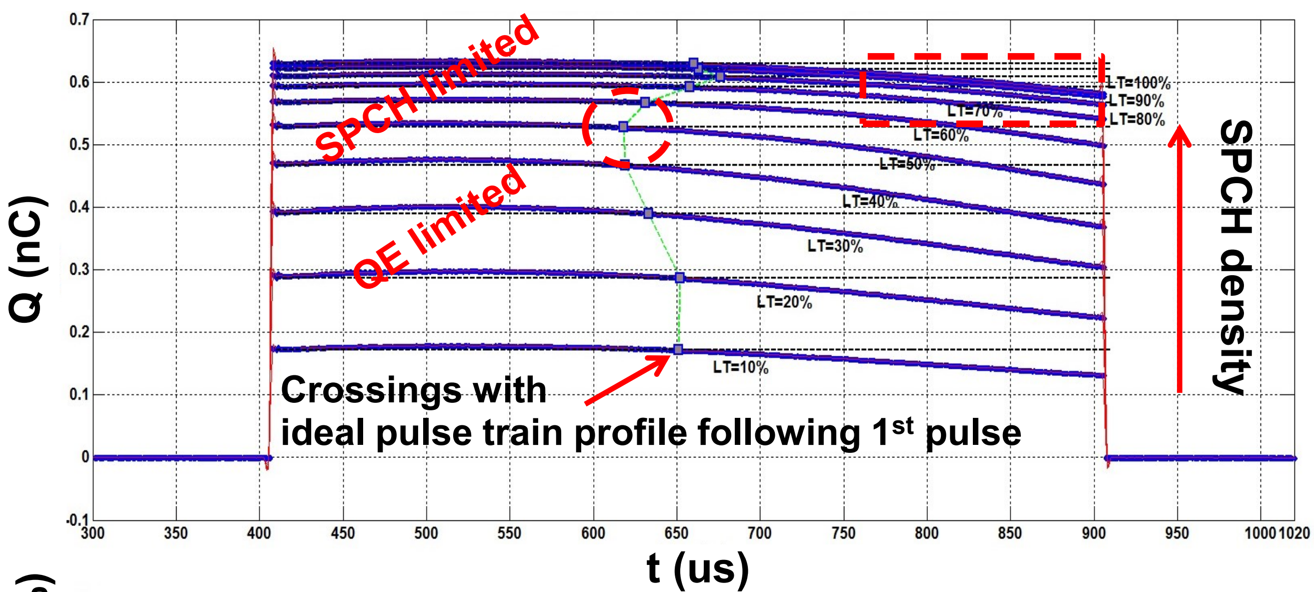
To be checked:

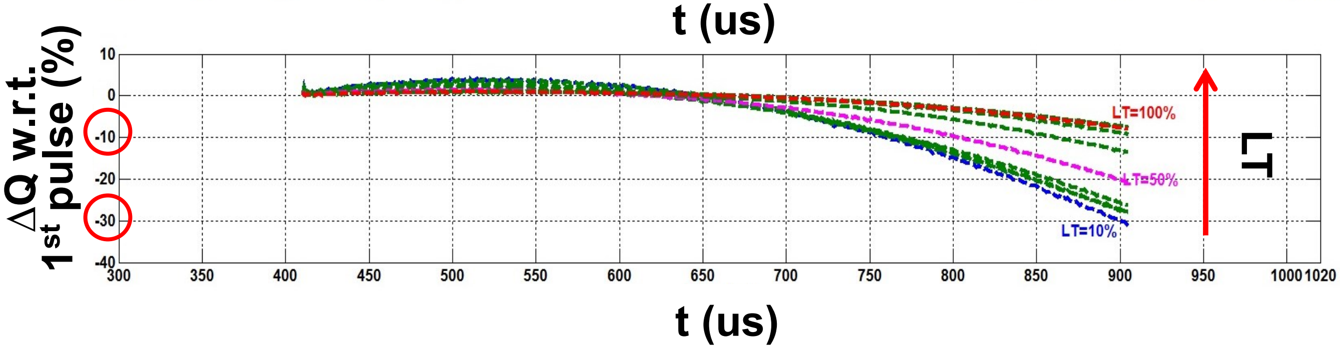
- **If PMT@LaserTrolley showing correct results?**
- **If no correlations indeed, how the slope depends on laser/RF parameters?**

Parametric analysis of bunch train slopes (LOW.ICT1@ADC)

Attenuator (LT) scan of 500-pulse bunch train: 6.5 MW in the gun @ MMMG, BSA=1.2 mm

6.5 MW @ MMMG Phase, BSA =1.2 mm





$$\Delta Q = \frac{Q_{fst} - Q_{last}}{Q_{fst}} \times 100$$

1. Slope observed for all cases (LTs) even at space charge (SPCH) limitation
2. As SPCH density ↑ (LT ↑), train slope becomes more flat

→ SPCH limitation drops or QE drops or mixed

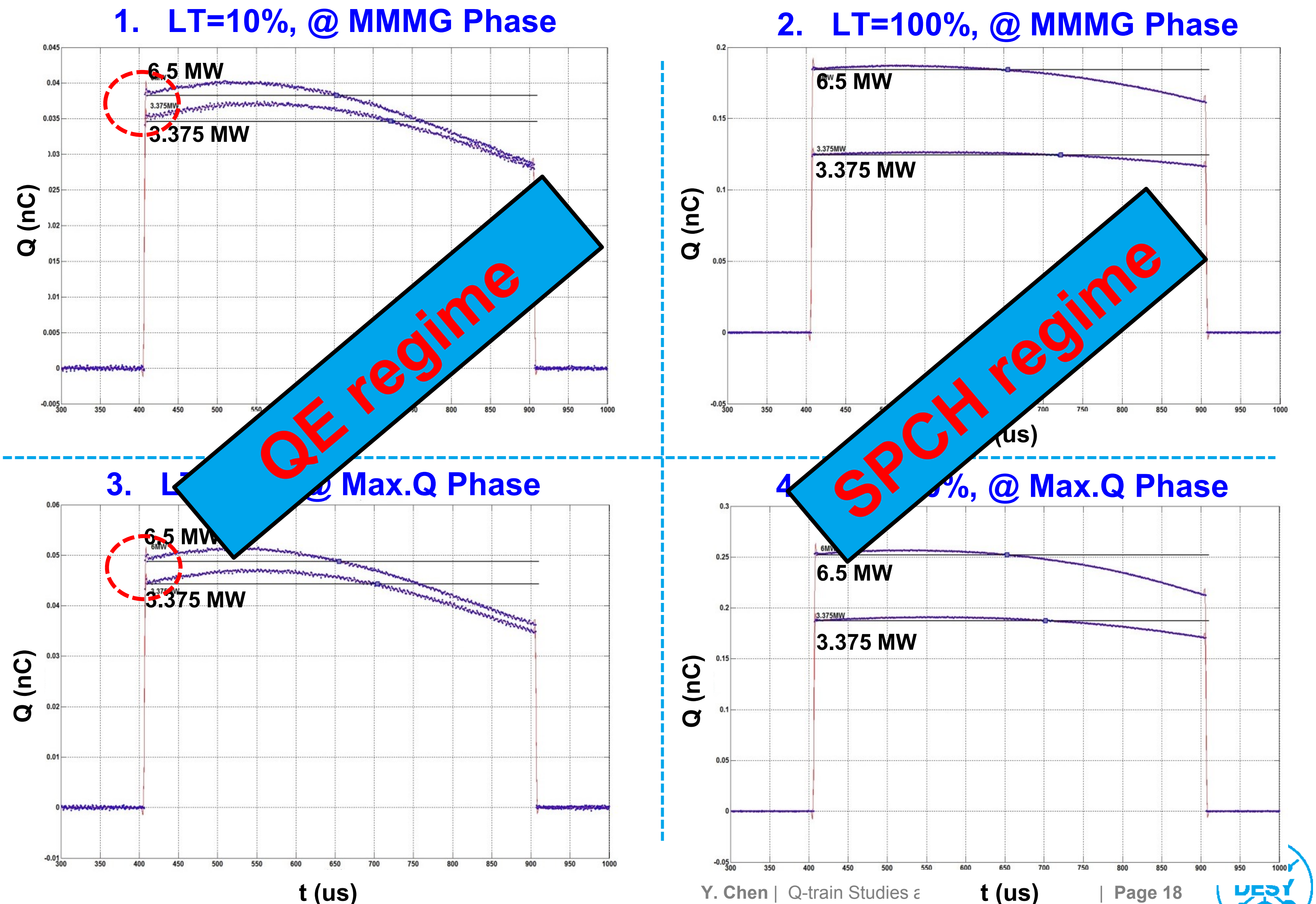
+

3. Q first ↑, then ↓ along the train
4. Crossings with ideal pulse train showing a turning point in the "transition" area

→ SPCH not only smearing out the slope but may also plays in the process of QE dropping

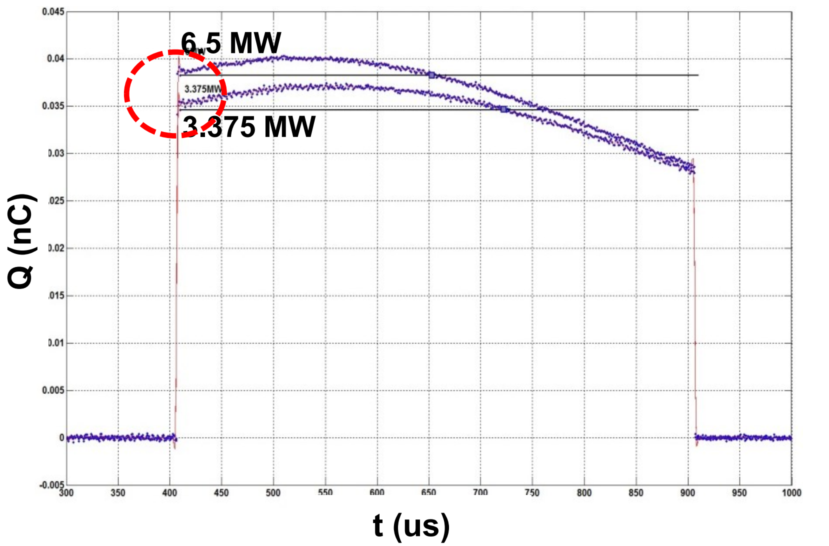
Consistent findings for other RF power levels, BSA sizes and gun phases (see backups)

Summary of BSA=0.6 mm cases for different RF power levels @ 4 working points

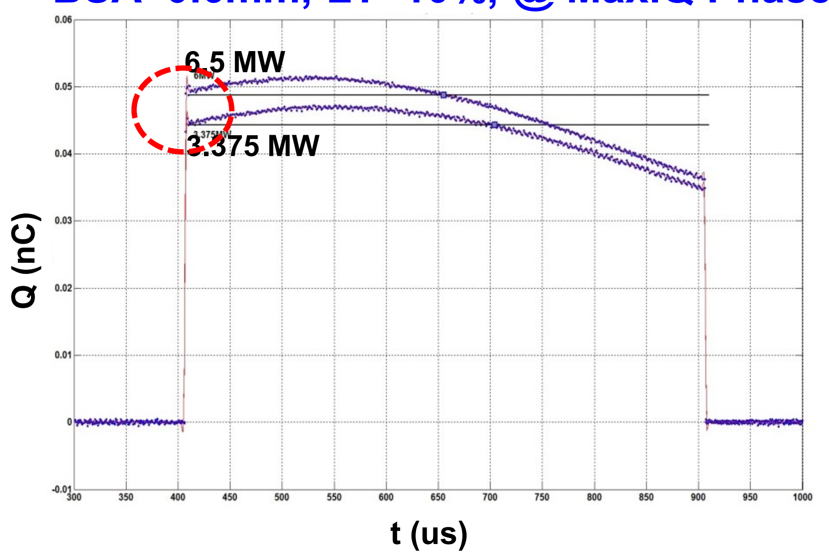


Summary of BSA=0.6 mm cases for different RF power levels @ 4 working points: charge production in QE regime

BSA=0.6mm, LT=10%, @ MMMG Phase



BSA=0.6mm, LT=10%, @ Max.Q Phase



- Produced total charge depends on RF powers when applying same but relatively low laser intensity in QE regime
  - SPCH effect? LT=10% -> far below SPCH limit
  - Laser drifts? -> 2 subsequent measurements within 1 hour, seems not
  - BSA size uncertainty? -> checked, ok
  - Solenoid focusing?
  - Cathode temperature?

- Schottky effect? (~59.20 MV/m vs. ~43.3 MV/m)

$$\Delta\phi_{schottkey}[eV] = \alpha\sqrt{\mathrm{E}[\frac{V}{m}]}$$

$$\alpha = e\sqrt{\frac{e}{4\pi\varepsilon_0}} = 3.7947\times10^{-5}[e\sqrt{Vm}]$$

$$QE \sim (h\nu[eV] - \phi_0[eV] + \Delta\phi[eV])^m$$

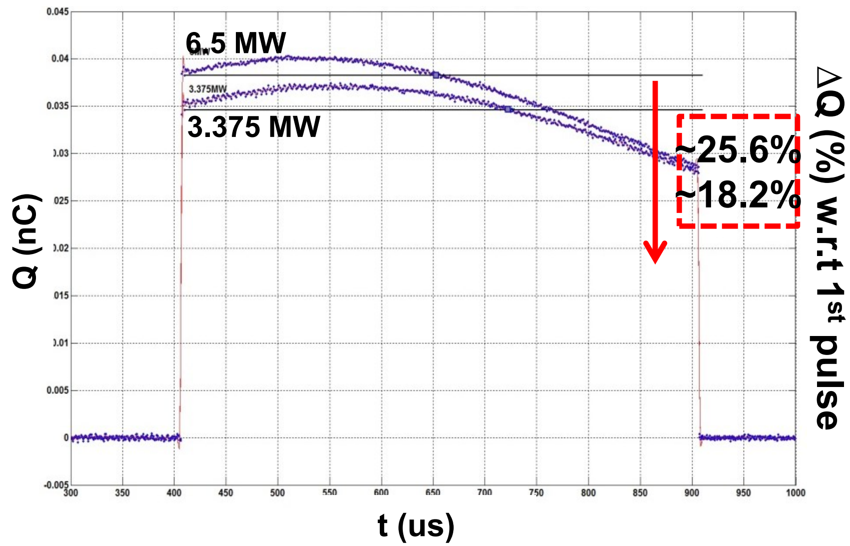
Q_{6MW}/Q_{3MW} = 0.038 / 0.034 (nC) ≈ 1.117 (at MMMG phase)

Comparable Schottky factor ≈ 1.11 (m≈4) for semiconductor

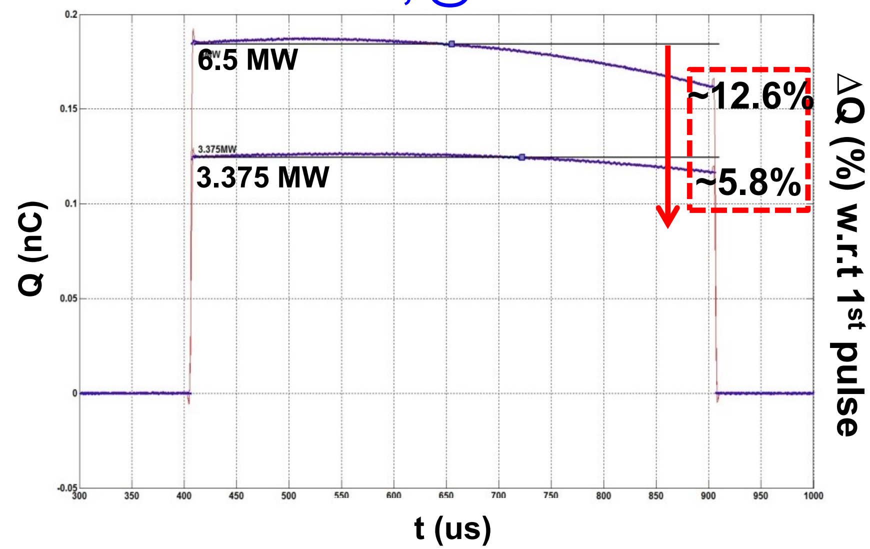
NB: no space-charge fields considered

Summary of BSA=0.6 mm cases for 2 RF power levels @ 4 working points

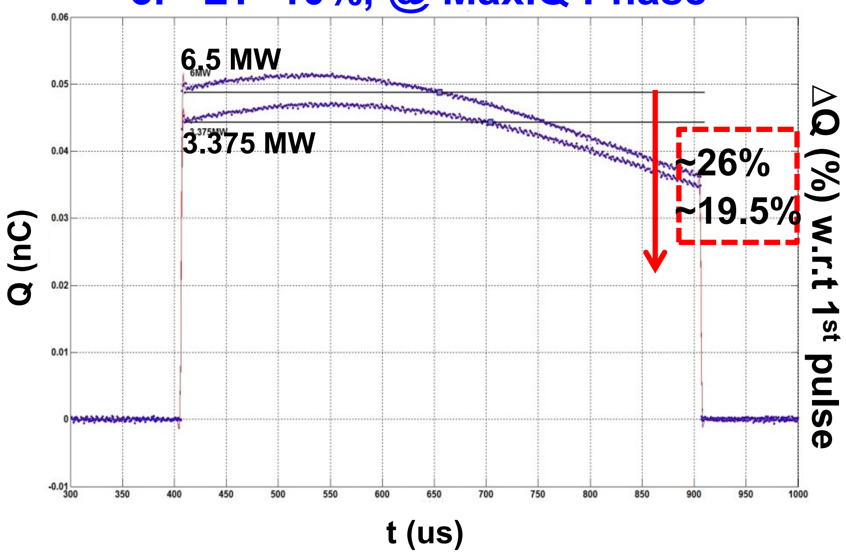
1. LT=10%, @ MMMG Phase



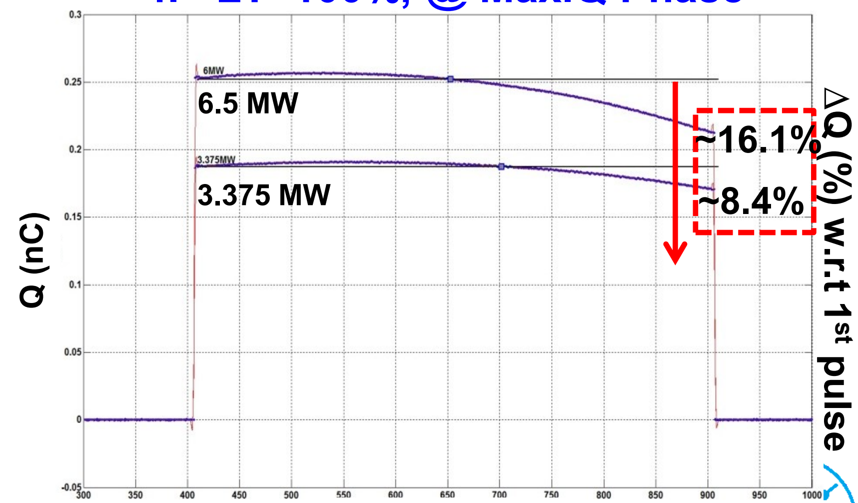
2. LT=100%, @ MMMG Phase



3. LT=10%, @ Max.Q Phase

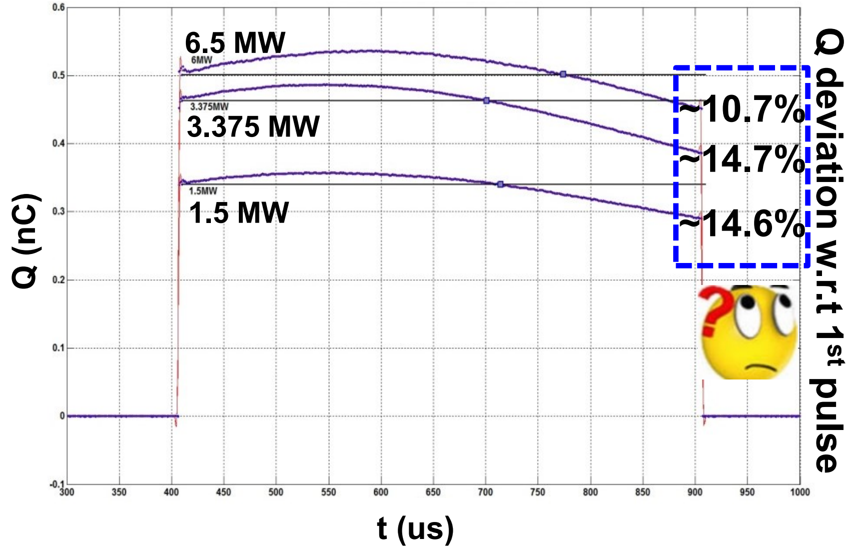


4. LT=100%, @ Max.Q Phase

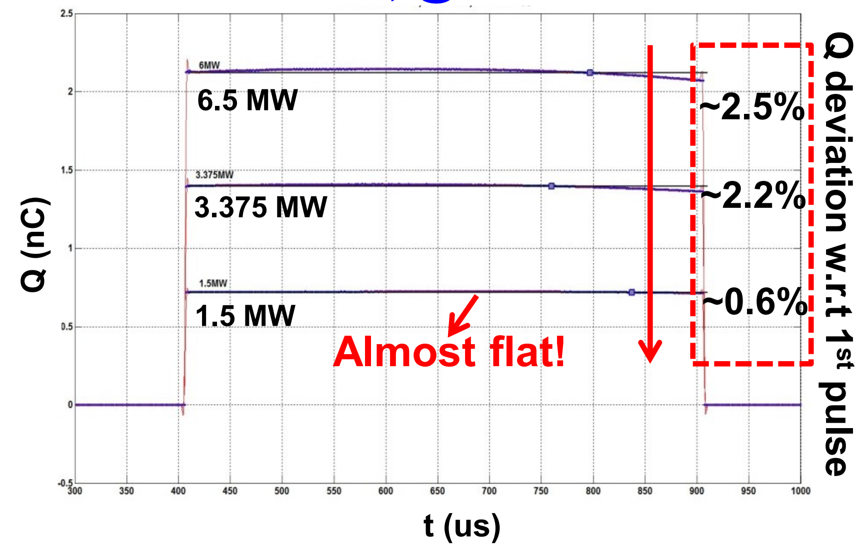


Summary of BSA=2.4 mm cases for 3 RF power levels @ 4 working points

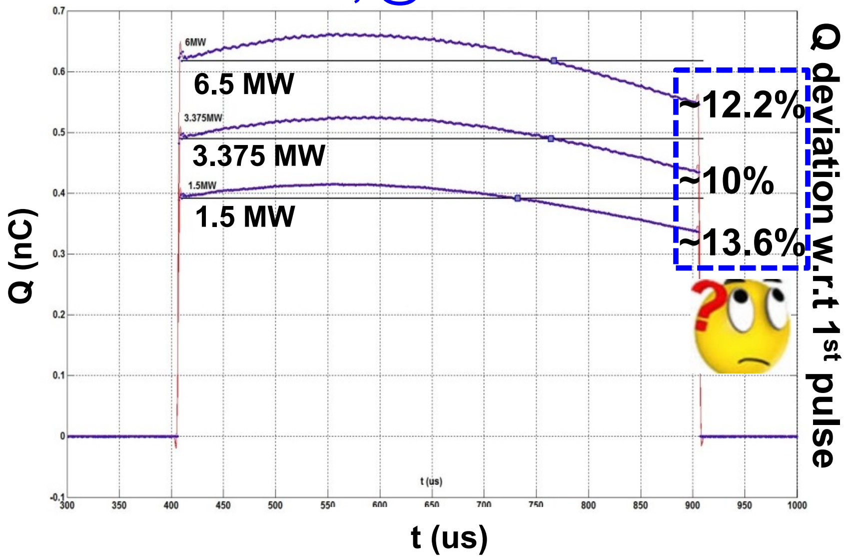
> LT=10%, @ MMMG Phase



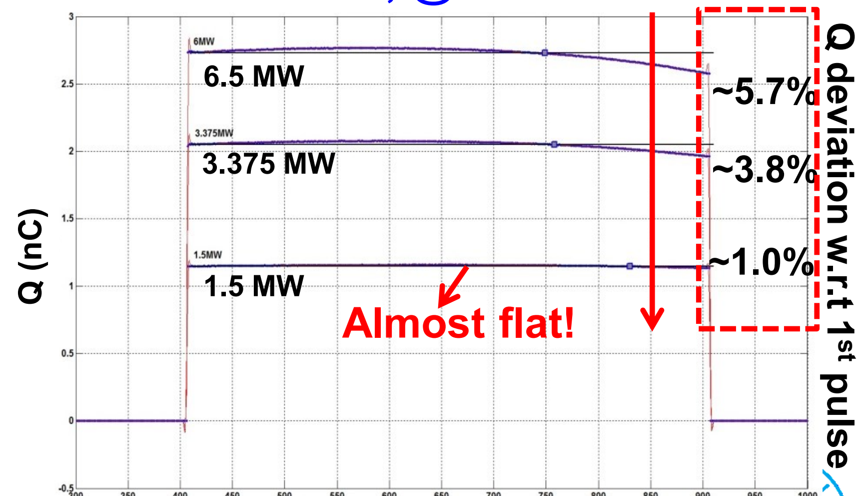
> LT=100%, @ MMMG Phase



> LT=10%, @ Max.Q Phase



> LT=100%, @ Max.Q Phase



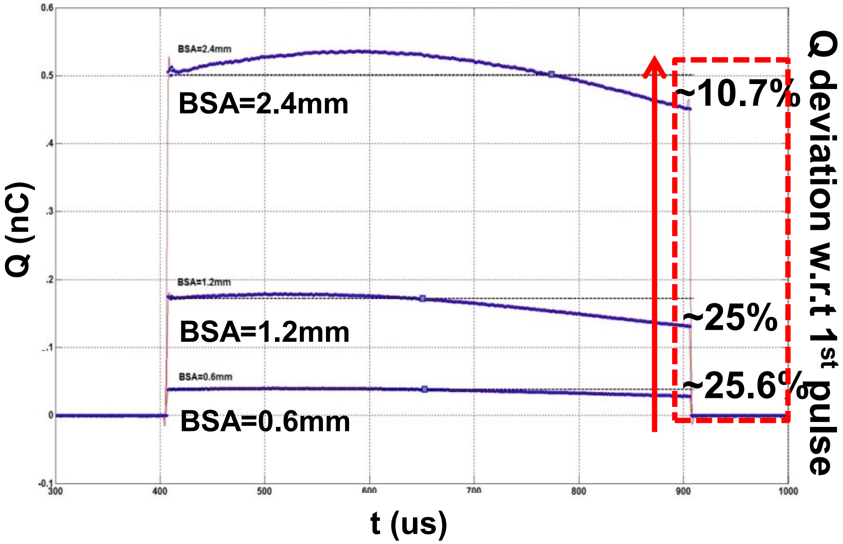
Intermediate summary (2)

- 1. Q-train slope affected by laser energy (intensity): LT ↑ -> Slope ↓
  - Problem originates in QE regime already
  - SPCH (partially) smearing out the slope

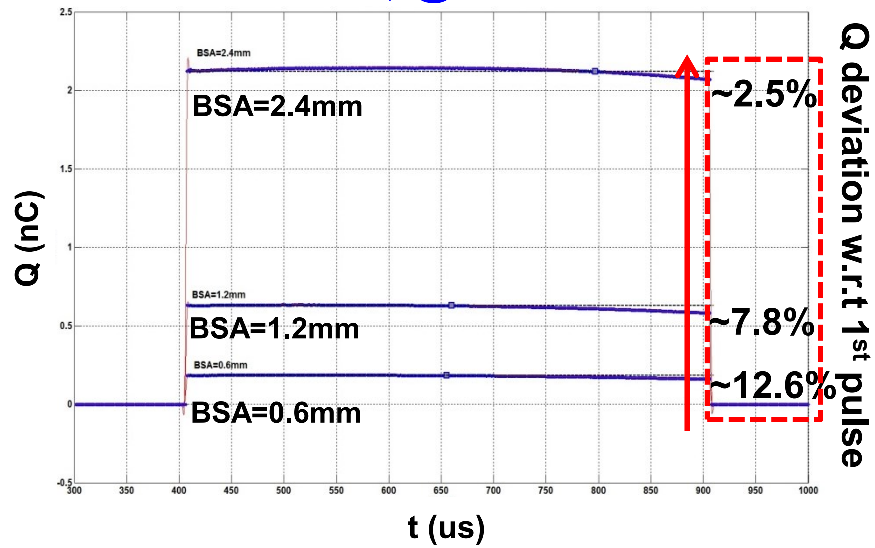
- 2. Q-train slope depends on RF power levels: P_{gun} ↓ -> Slope ↓ (for most cases)
  - Schottky effect plays
  - Larger slope @ Max.Q phase than MMMG: charge density ↑-> slope ↑
  - Lower RF power + higher LT rendering smaller bunch train slope

Summary of 6.5 MW cases for 3 BSA sizes @ 4 working points

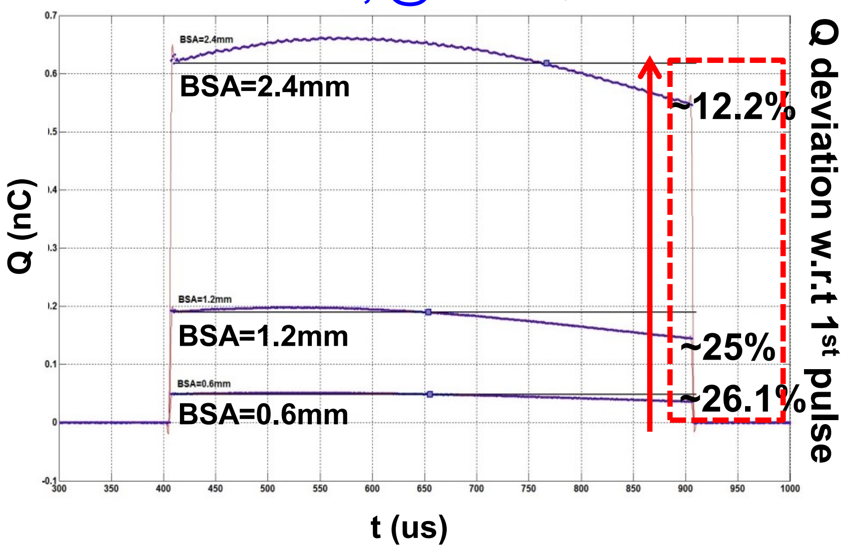
1. LT=10%, @ MMMG Phase



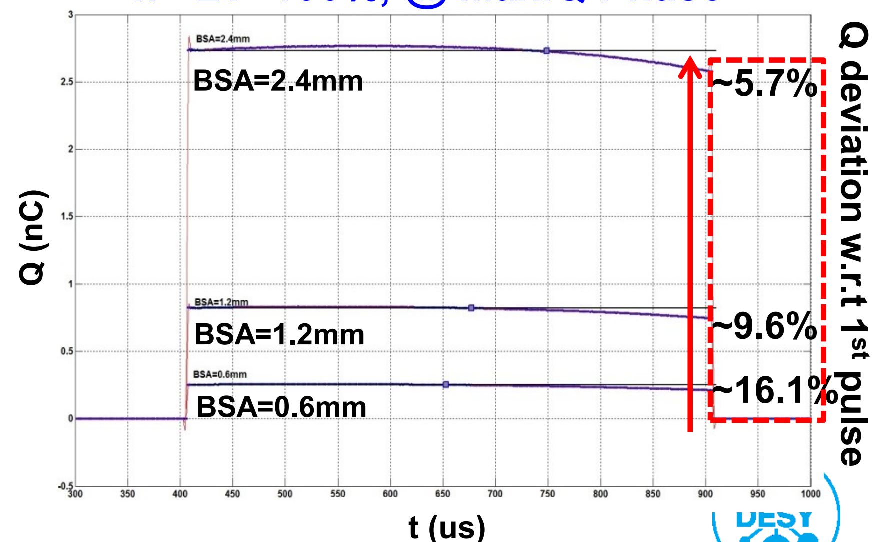
2. LT=100%, @ MMMG Phase



3. LT=10%, @ Max.Q Phase

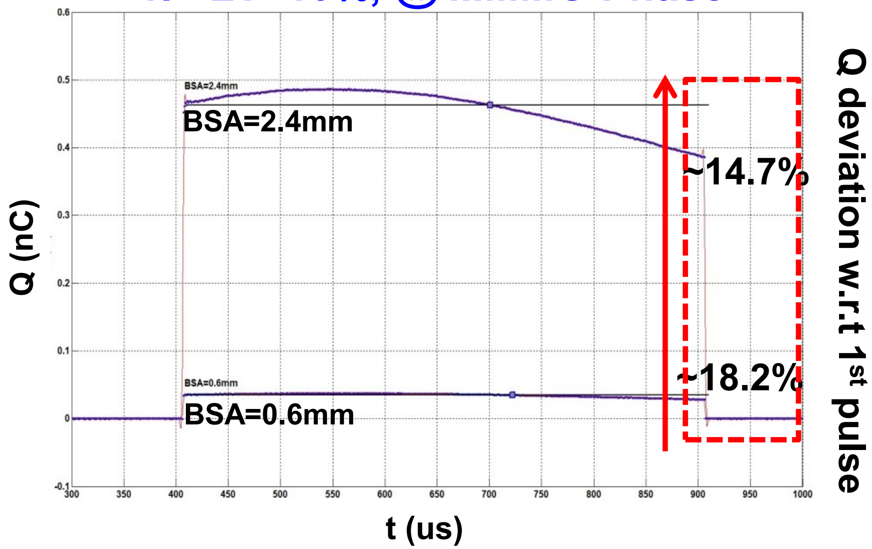


4. LT=100%, @ Max.Q Phase

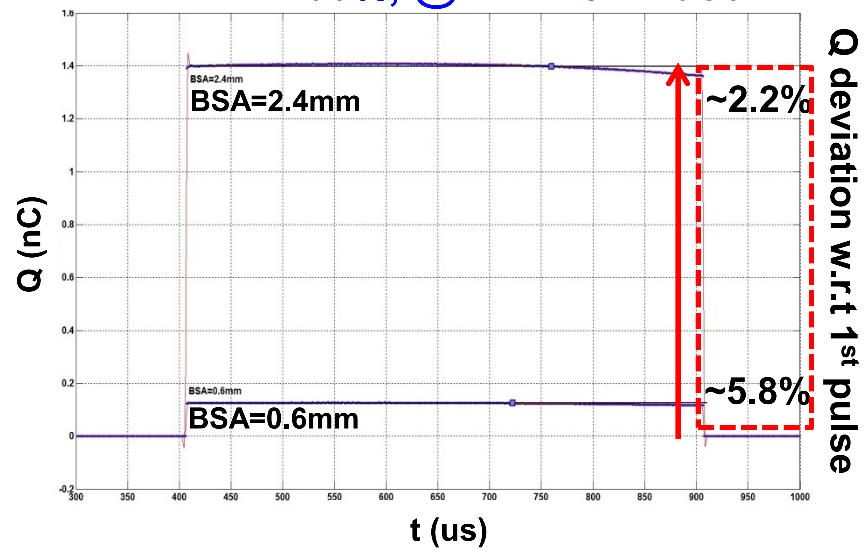


Summary of 3.375 MW cases for 3 BSA sizes @ 4 working points

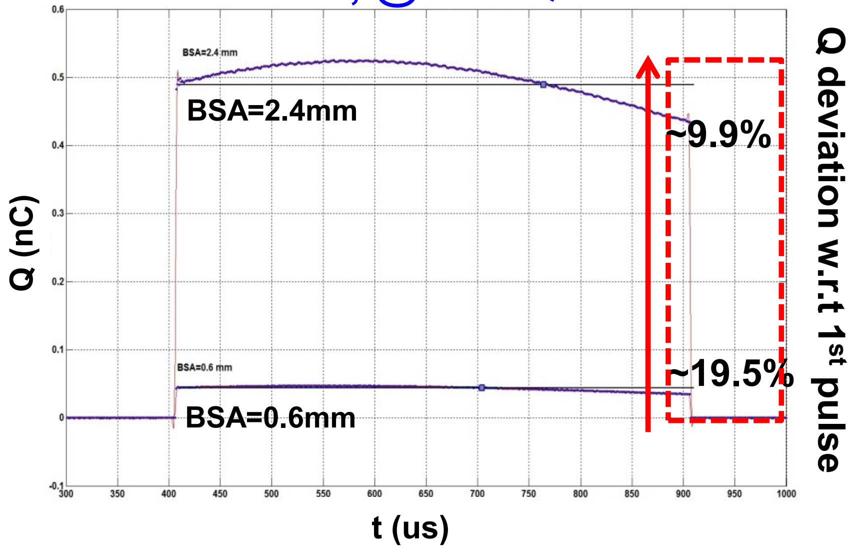
1. LT=10%, @ MMMG Phase



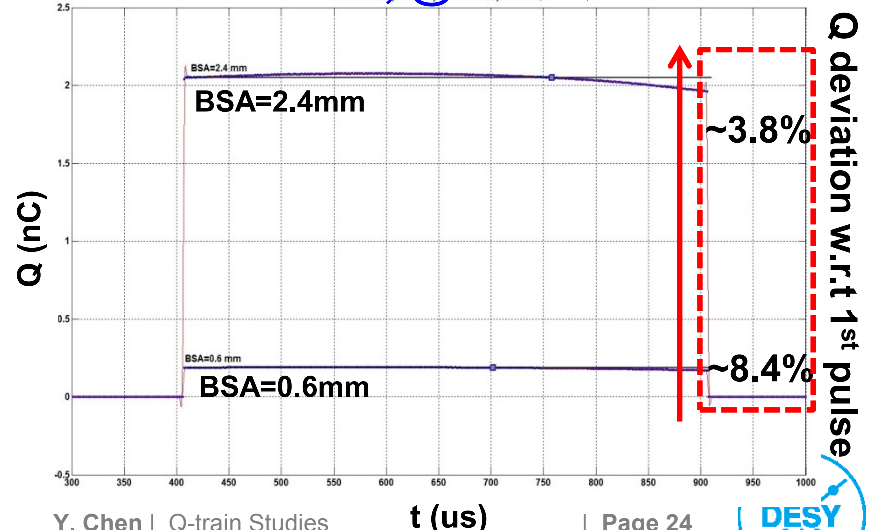
2. LT=100%, @ MMMG Phase



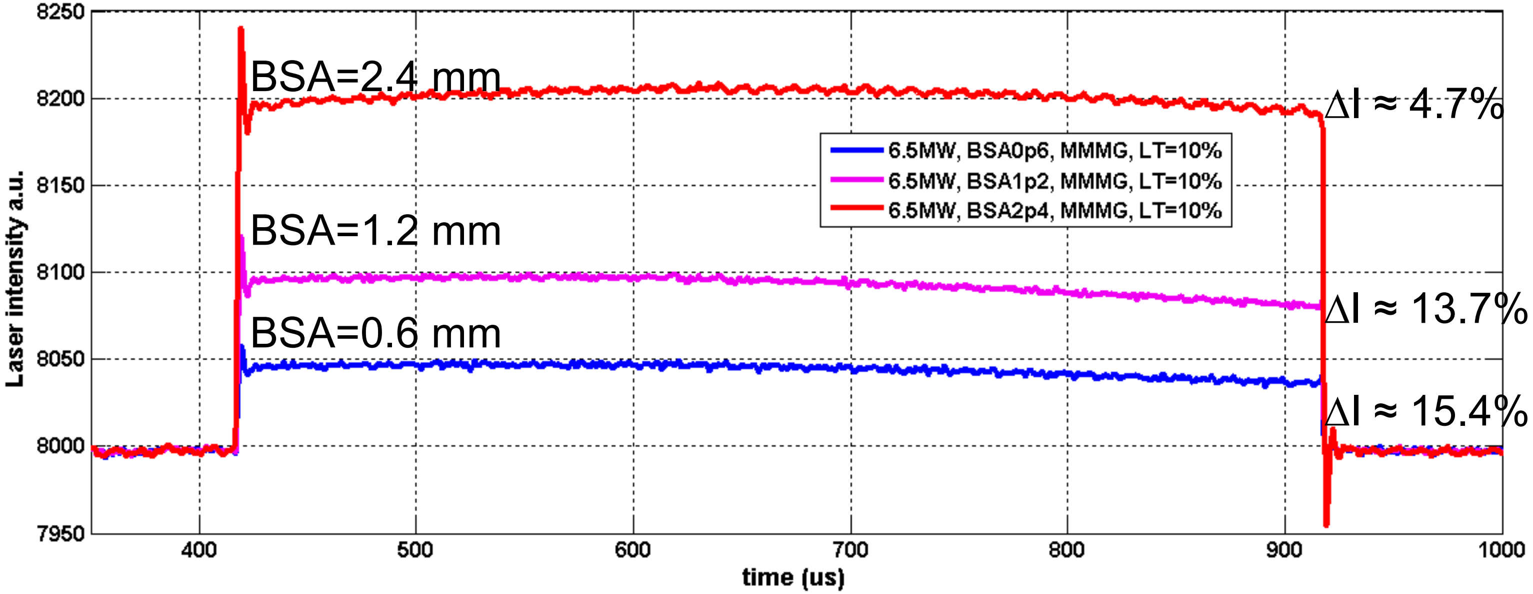
3. LT=10%, @ Max.Q Phase

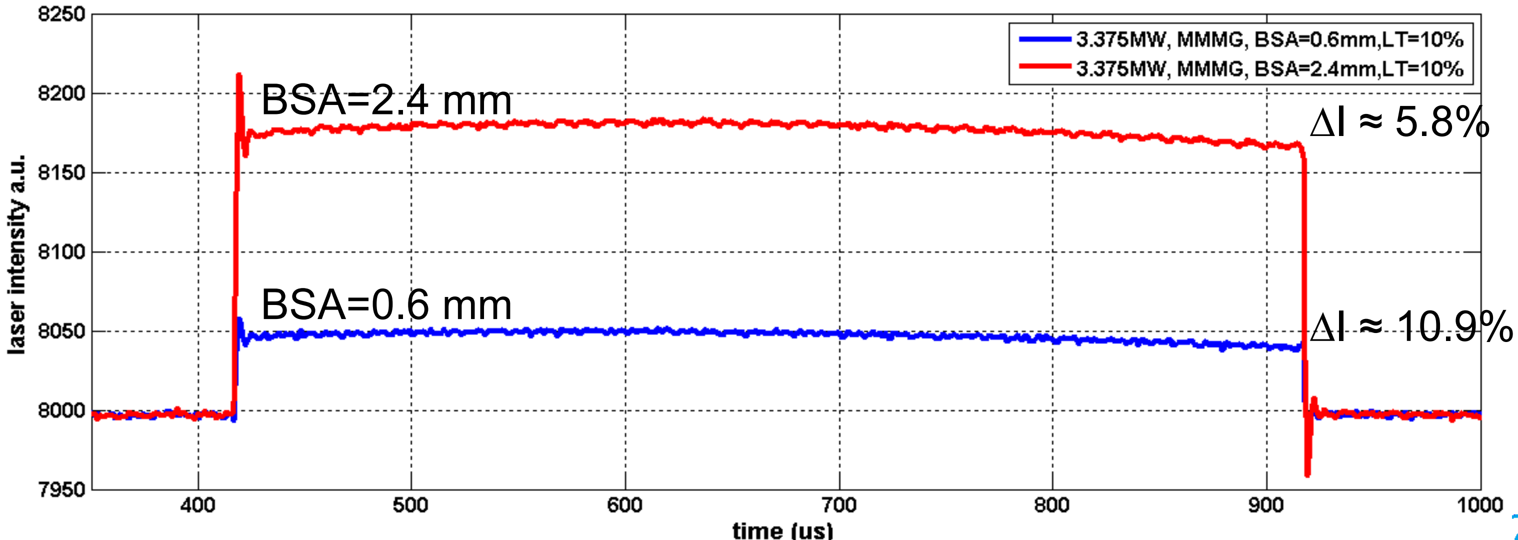


4. LT=100%, @ Max.Q Phase



Laser intensity at LT=10% for various BSA sizes

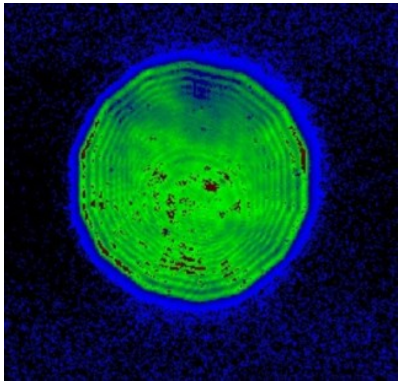




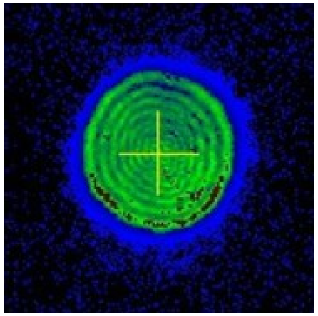
Intermediate summary (3)

- **Larger BSA sizes showing smaller slopes for all cases**
  - Seems systematic laser intensity behavior, **BSA size↑ -> slope↓**
  - Laser energy measurement needed for intensity evaluation
  - Seems consistent with the flatness of cathode laser intensity

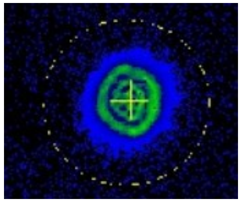
Laser at VC2



BSA = 2.4 mm

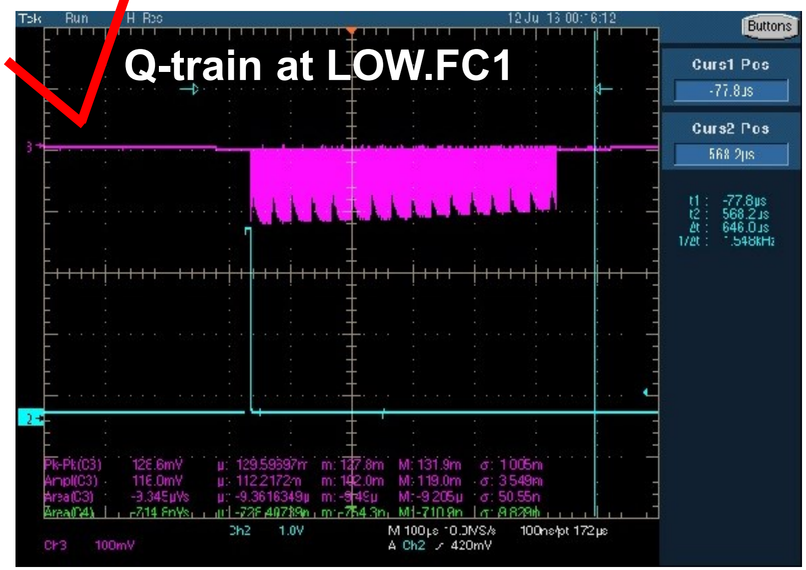


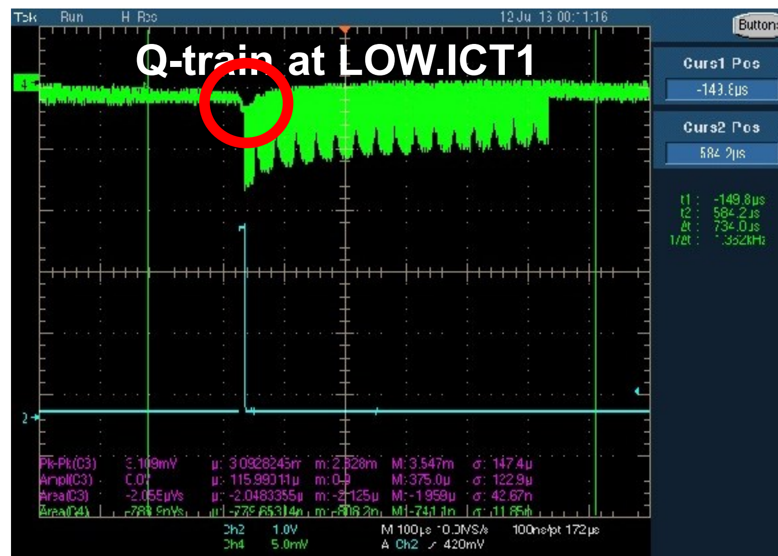
BSA = 1.2 mm



BSA = 0.6 mm

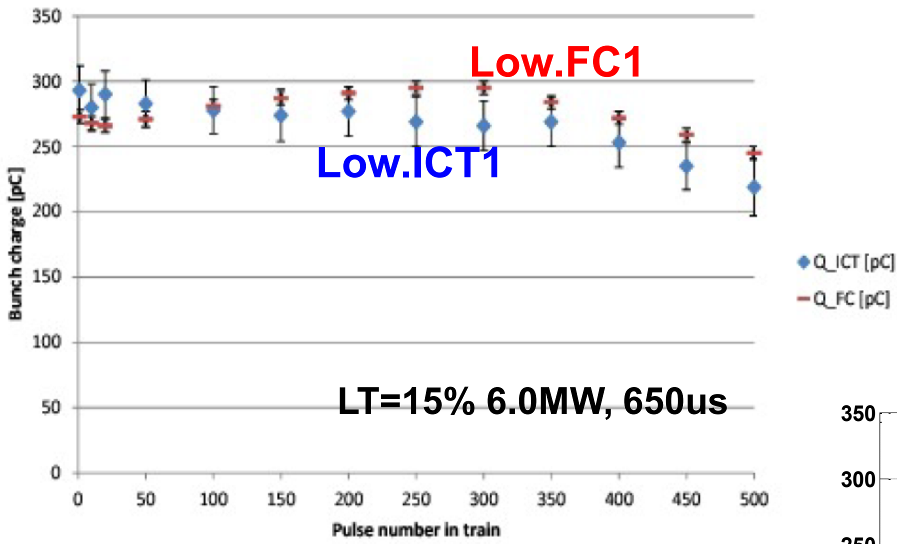
Parametric analysis of bunch train slopes (Scope measurements)





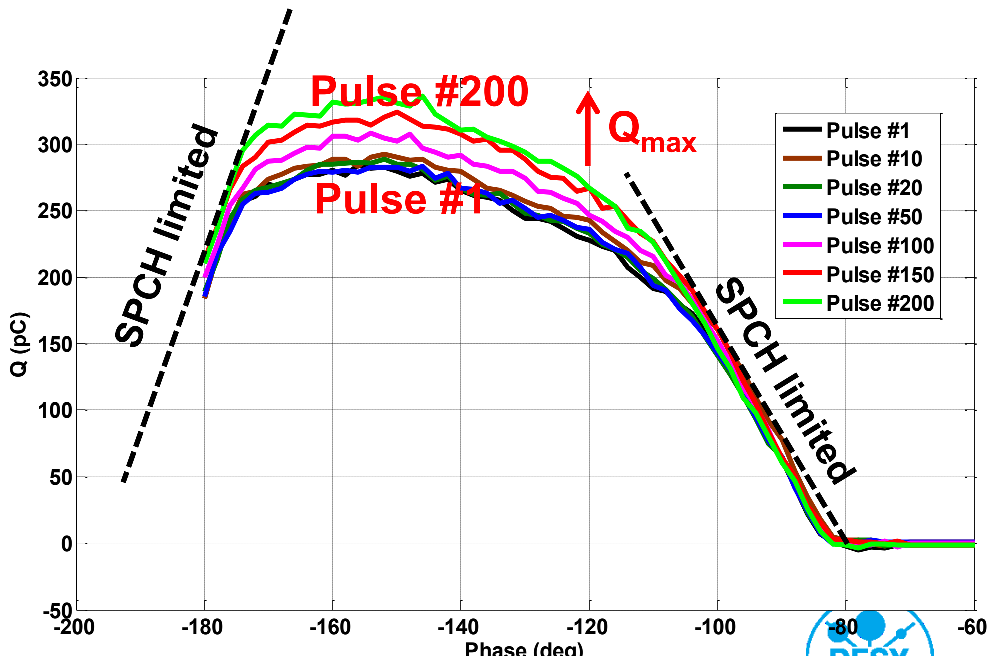
Charge along bunch trains / phase scans / LT scans (1)

- Measurements on 15.08.2016, using LOW. ICT1 and FC1 (6MW, 650us)



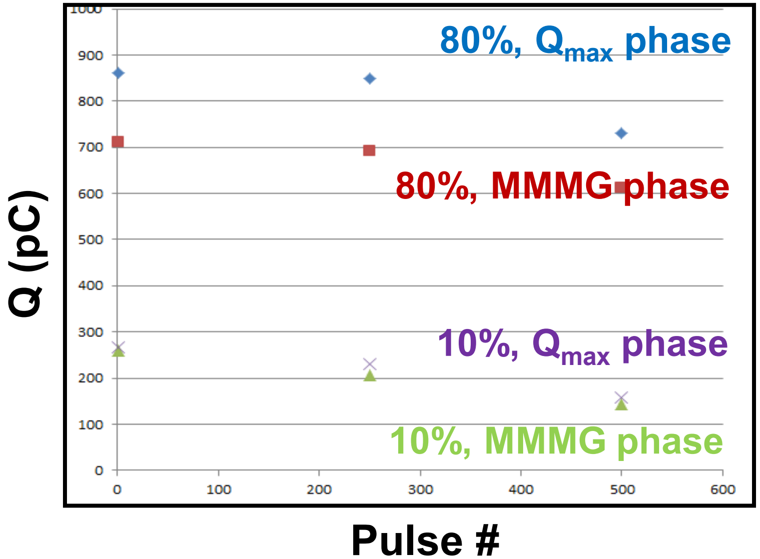
→ Q first ↑, then ↓ (Low.FC1)

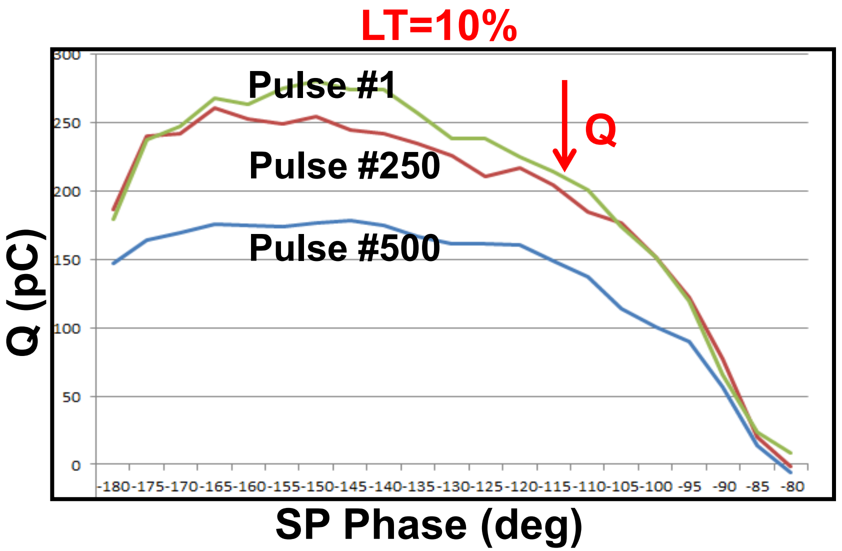
→ Consistent with ADC measurements

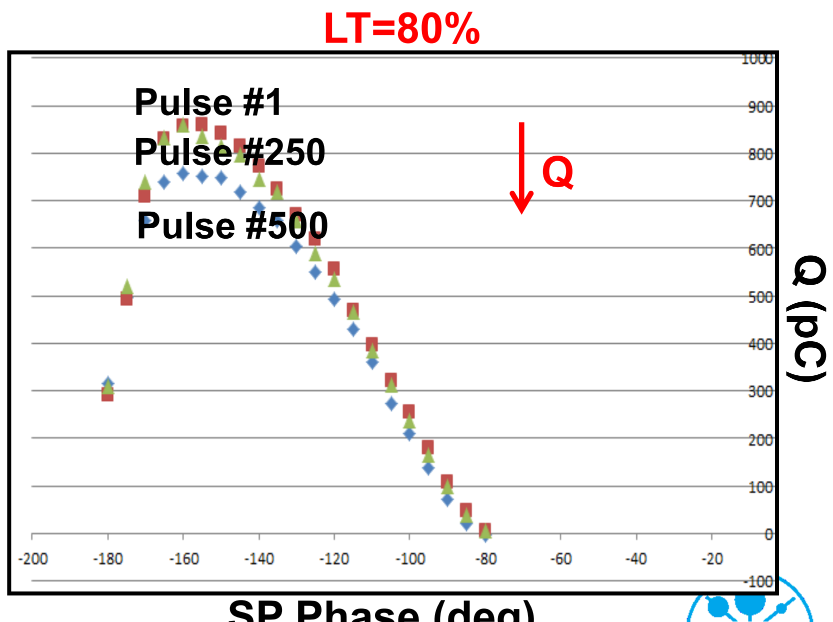


Charge along bunch trains / phase scans / LT scans (2)

- Measurements on 21-22.08.2016 using FC2 (6.5MW, 650us)

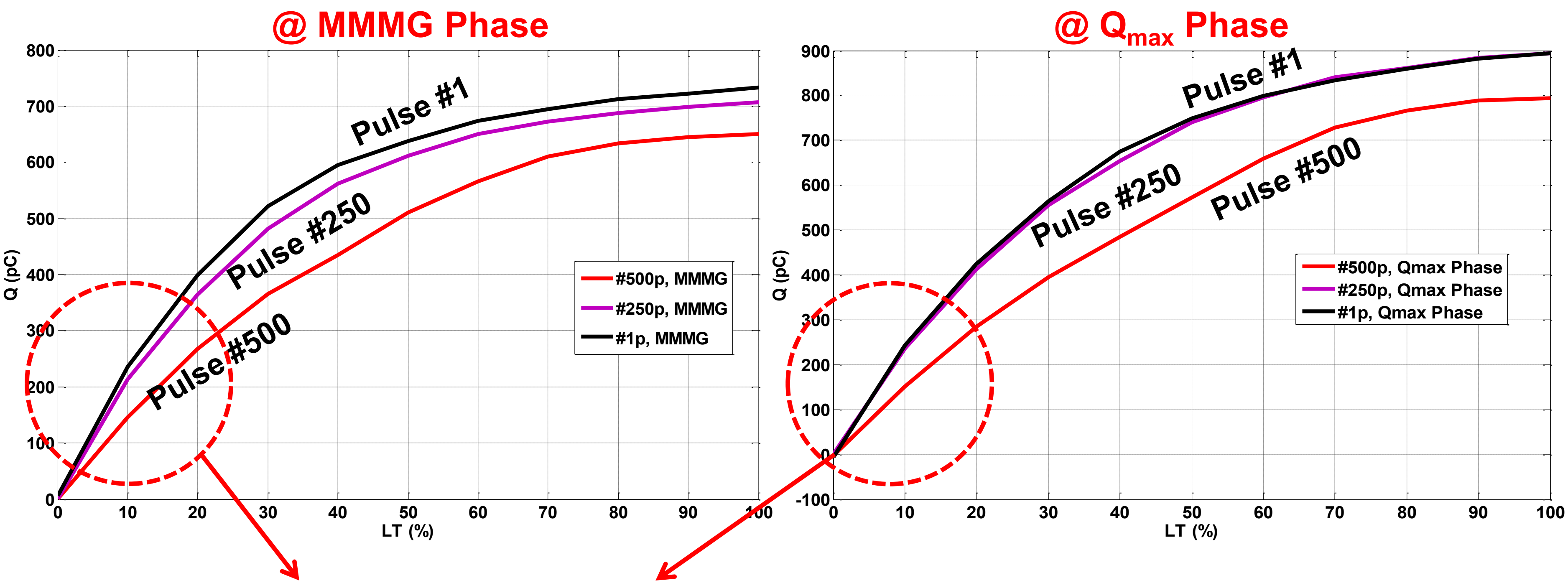






Charge along bunch trains / phase scans / LT scans (3)

- Measurements on 21-22.08.2016 using FC2 (6.5MW, 650us)



Total bunch charge production already differs in QE regime

Intermediate summary (4)

- **Scope measurements of Q-train slope**
  - Charge first slightly increases, then decreases dramatically
  - Behavior consistent with ADC measurements
- **Attenuator scans for each micro-pulse showing the discrepancy in charge extraction orignates in QE regime already**

Summary

- **A slope of Q-train profile observed for all measurements using a worn cathode during 08-09,2016 (charge first slightly increases, then decreases dramatically by up to ~25%)**
  - For all measurement devices or methods
  - For various RF power levels and BSA sizes
  - For various driving laser intensities
- **Some correlations of cathode laser flatness with Q-train slope found (PMT accuracy needs to be further checked)**
- **First parametric dependencies of the Q-train slope analyzed**
  - Slope↓ as laser intensity ↑ (BSA fixed, Pgun fixed, LT↑)
  - Slope↓ as Pgun↓ (BSA fixed, LT fixed)
  - Slope↓ as BSA ↑ (Pgun fixed, LT fixed)
- **Space charge effect plays -> smearing out spike at Q-train head**
- **Slope originates in QE (linear) regime already**
  - **QE varies along Q-train**
  - Schottky effect plays

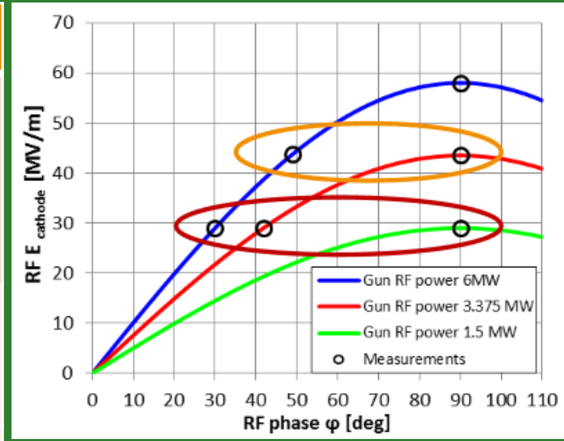
Next steps (proposals) (1)

- **Pulse train monitor (PTM) measurements (@ADC) + following experiments:**

Experiment #1: Offline measurements to further check cathode laser flatness using photodiode or QD diode (already on schedule)

Experiment #2: Construct PTM measurements at different power levels using same fields at the moment of emission (10 set points)

Pgun	Phase w.r.t. Phi0	BSA=1.8mm	BSA=0.8mm
6 MW	90 deg	PTM	PTM
	49 deg		
	30 deg		
3.375 MW	90 deg	PTM	PTM
	42 deg		
1.5 MW	90 deg	PTM	PTM



Next steps (proposals) (2)

➢ **Pulse train monitor (PTM) measurements (@ ADC) + following experiments:**

Experiment #3: Further cathode time response measurements (Q vs. time)

a) Fix BSA size
b) Set points for two cases in linear (QE-) regime
c) Extract 4nC and 0.1nC, respectively by changing LT (compared to previous measurements P17, charge ratio larger->effect on time response more prominent)

Experiment #4: Move e-bunch(es) within / out of RF pulse (due to laser electronics, the timing shift may be limited to maxi. ~17 us as discussed with laser experts)

a) Use single bunch or bunch trains
b) Move e-bunch(es) within RF pulse
c) Move part of a 50-pulse bunch train out of RF pulse (e.g., 20 pulses out, 30 pulses within)
d) Compare with the case of 30-pulse bunch train within RF using 1st pulse timing same as the timing for 30th pulse in c)

Experiment #5: QE measurements for Q-train (?)

a) Laser ('absolute') energy measurements -> QE along Q-train
b) Laser beam transverse distribution at VC2
c) Laser intensity evaluation

Next steps (proposals) (3)

➢ **Pulse train monitor (PTM) measurements (@ADC) + following experiments:**

Experiment #6: Laser beam size evaluation along Q-train (?)

Experiment #7: Fresh cathode vs. Worn cathode (near future)

a) **PTM measurements for the worn cathode (in operation)**
b) **Cathode exchange**
c) **PTM measurements for the fresh cathode**
d) **Comparisons between a) and c)**