# Train Orbit Studies for XFEL

## Summary of first measurements at PITZ

## Outline

- **Motivation**
- **Review of previous simulations**
- **First experimental results**
- **Summary and Outlook**

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# Why train orbit studies?

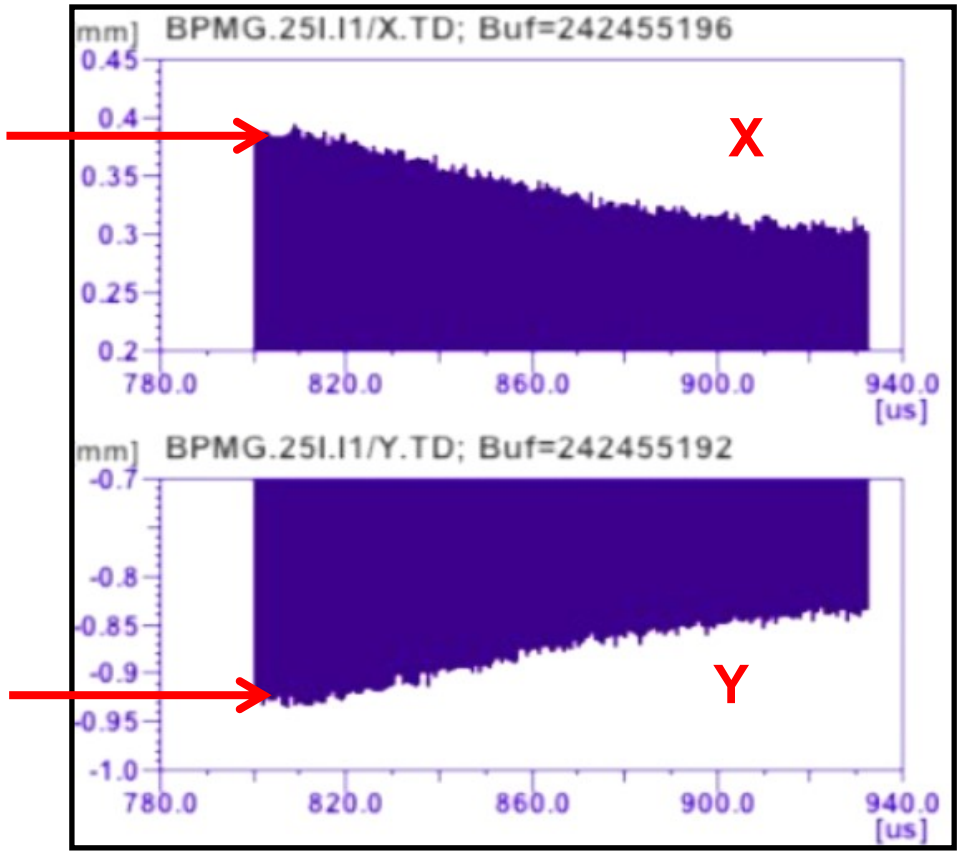
→ follow-up studies of XFEL operation issues

- **Orbits of bunches over the train**
  - **Issue:** different orbits for different bunches along the bunch train at XFEL
  - **PITZ task:** What is the cause? How to solve this?
    → **related to previous coupler kick studies?**

- **The offset showed dependencies on**
  - **Gun detuning** from -250 Hz to +6.7 kHz
  - Bunch **charge** between 100 to 300 pC
  - Gun **phase** over the RF pulse by 10 degree

  **But, the change over the bunch train remained the same**

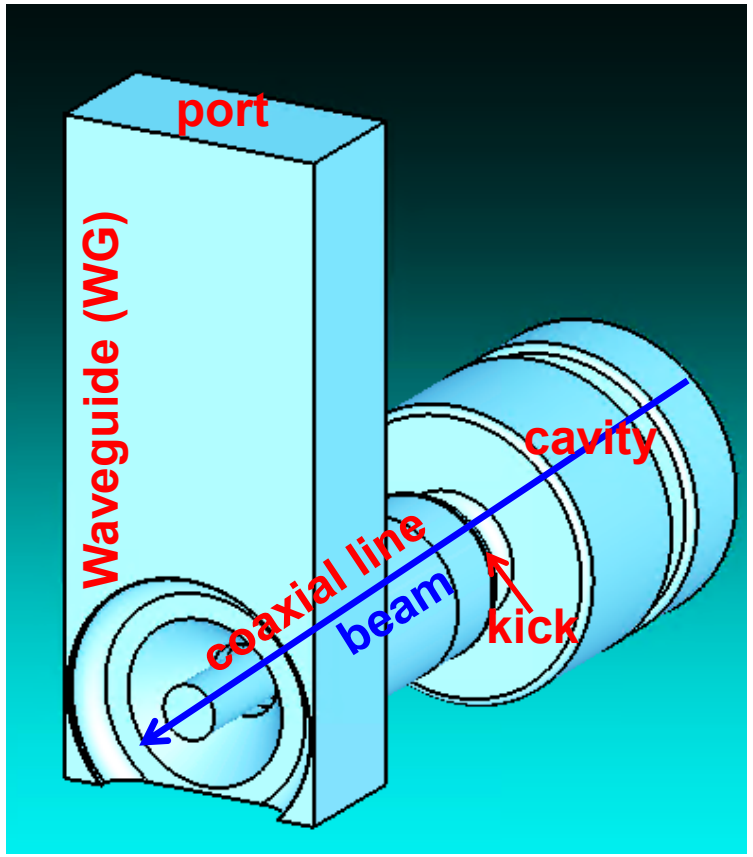
**Different orbits** observed
for different bunches along the train
(e.g. 160 bunches at 1.1 MHz)



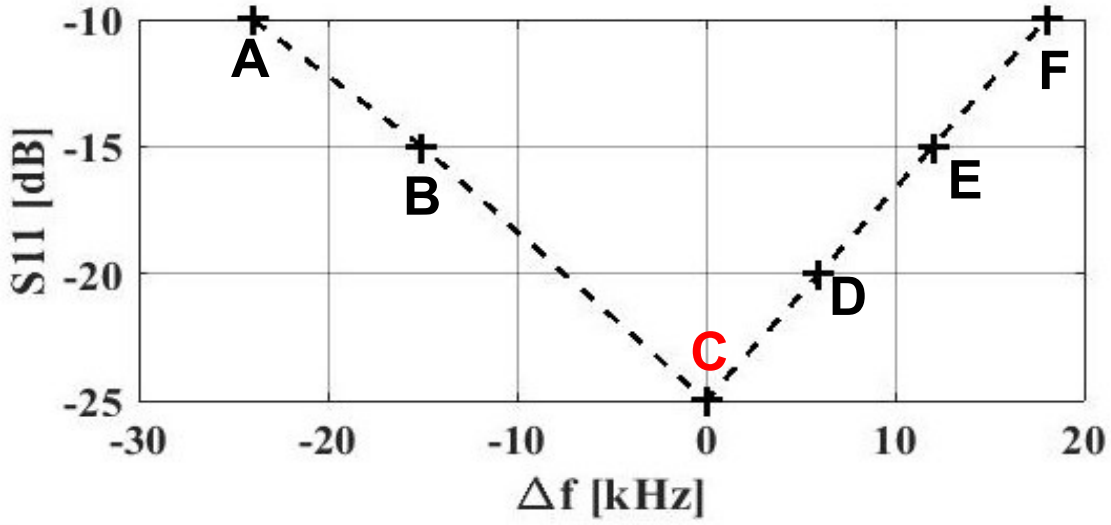
# Previous simulations

## simulation strategy

- **What has been done in simulations**




Define: detuning $\Delta f = f - f_0$  f : drive frequency  $f_0$: resonance

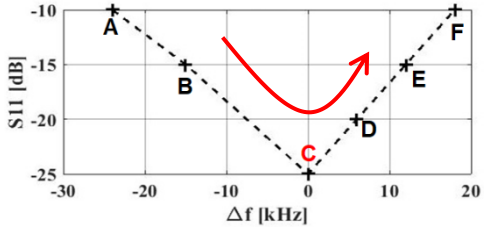


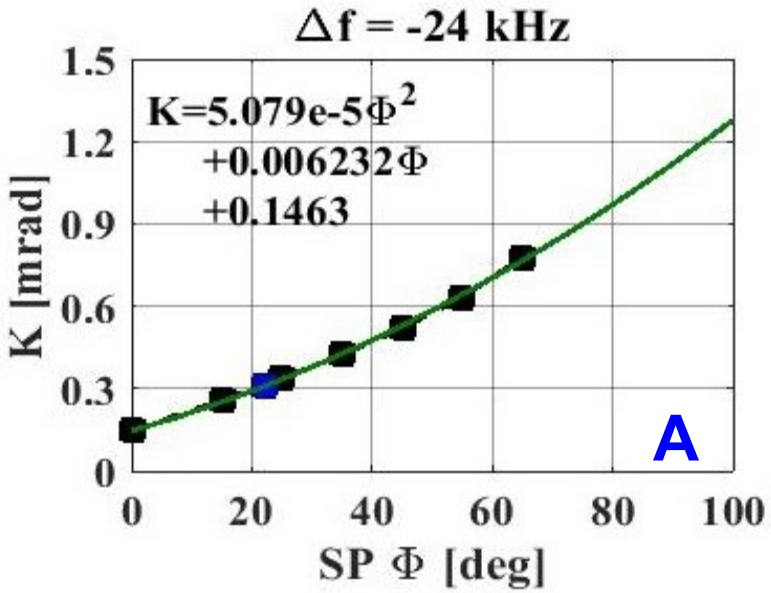

→ **Particle tracking simulations for Case A — Case F using obtained field maps (frequency detuning between -24 kHz and +18 kHz)**

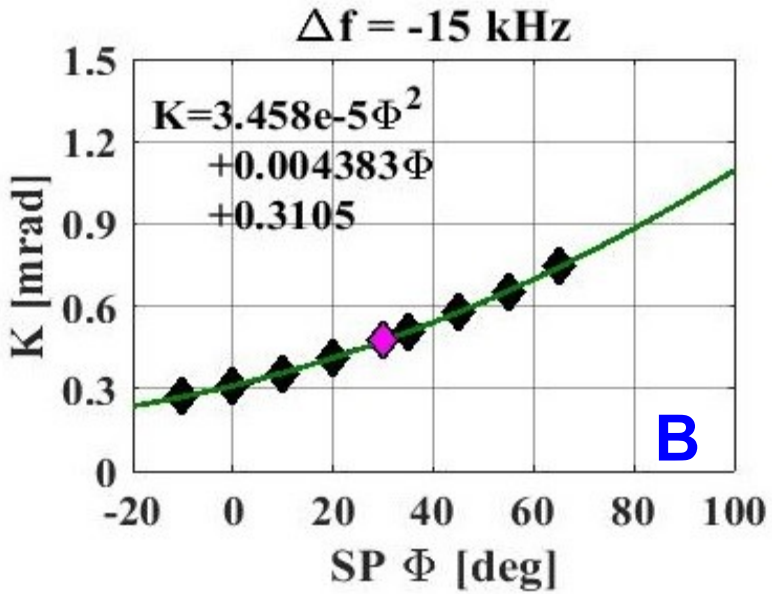
→**frequency** domain solver
→**mono-frequency** excitation method
→slightly tuning thickness of the gasket for optimum matching

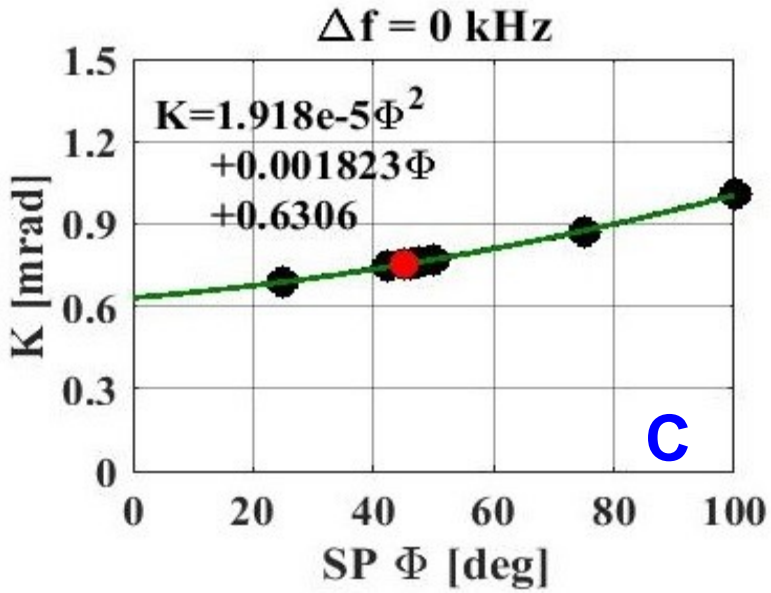
# Learned from simulations

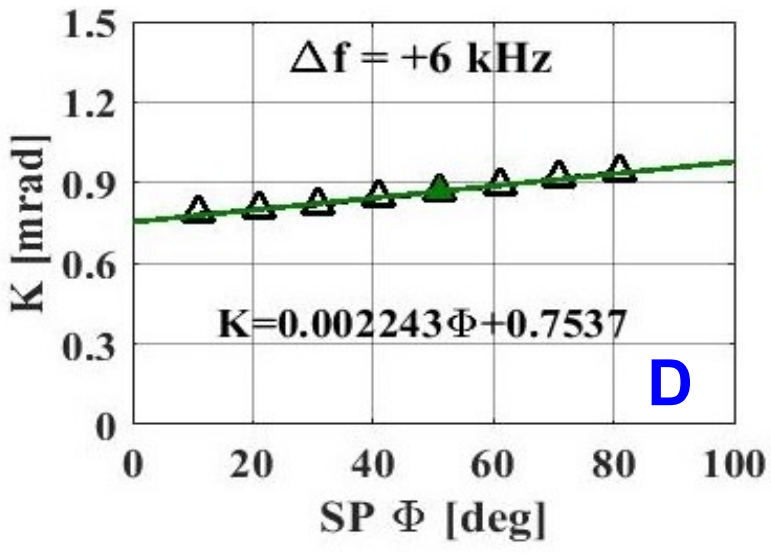
## simulation results

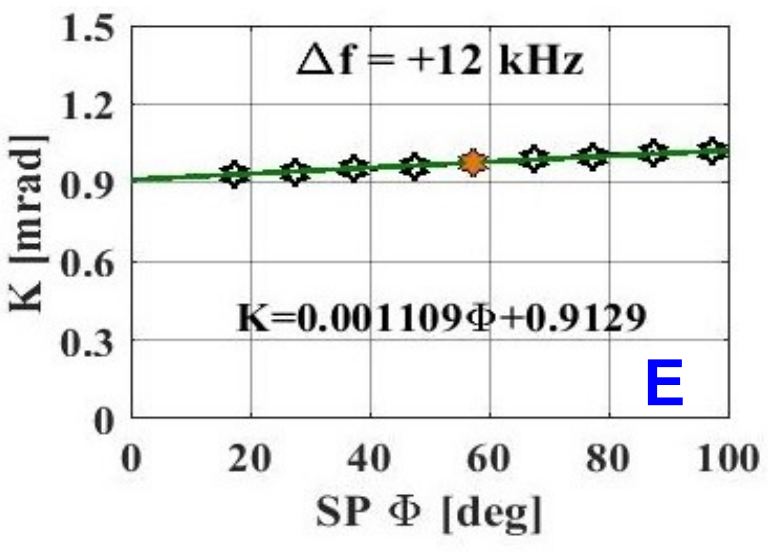


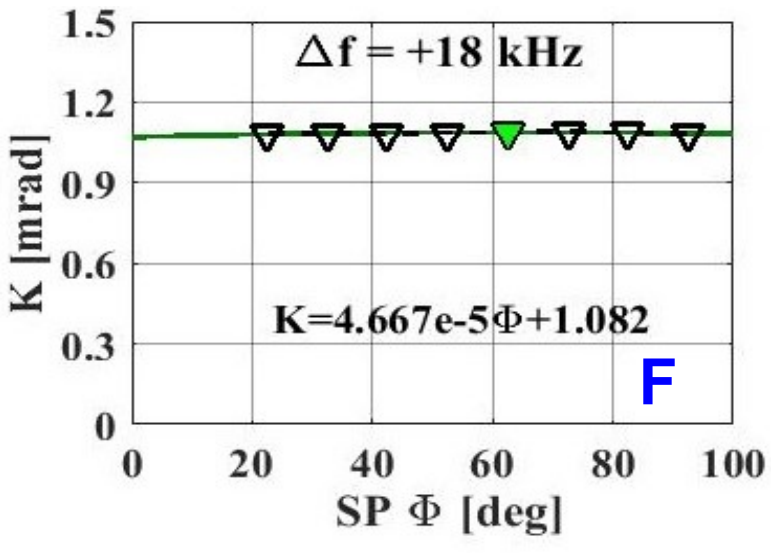



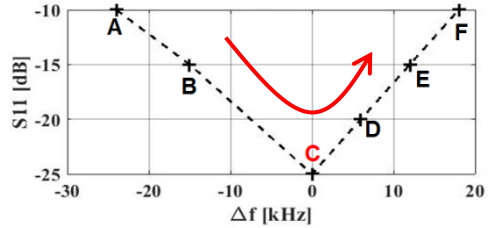



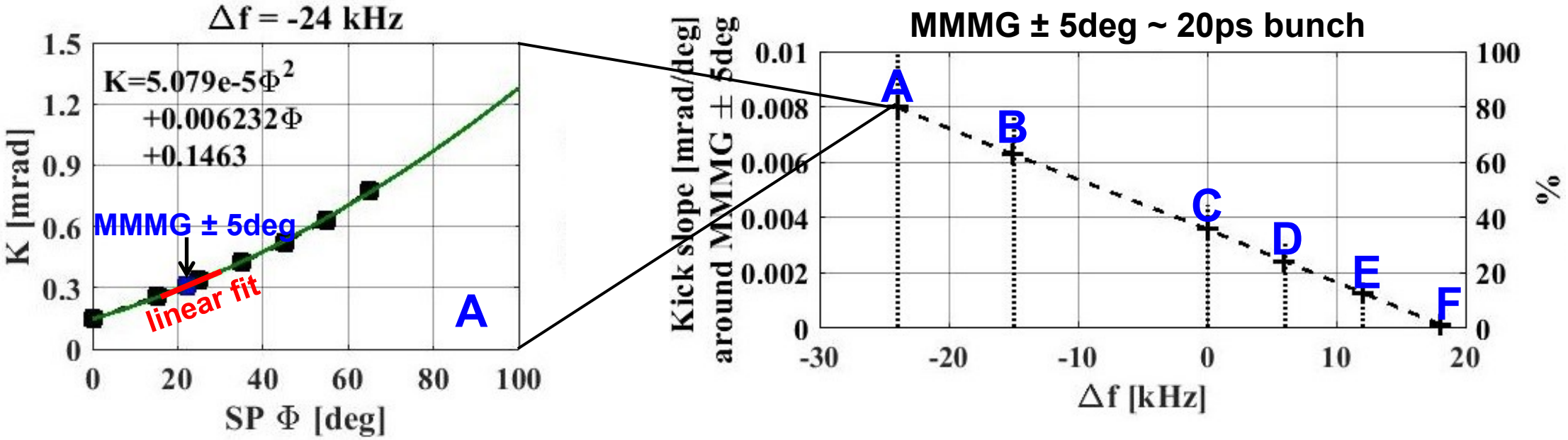



# Learned from simulations (cont'd)

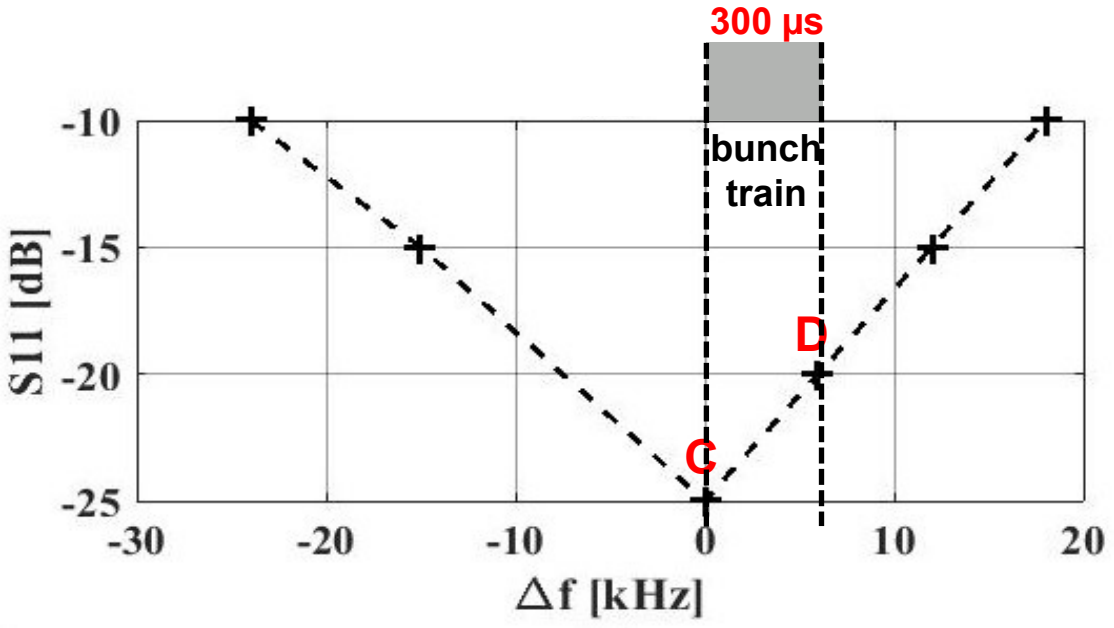
## simulation results (cont'd)

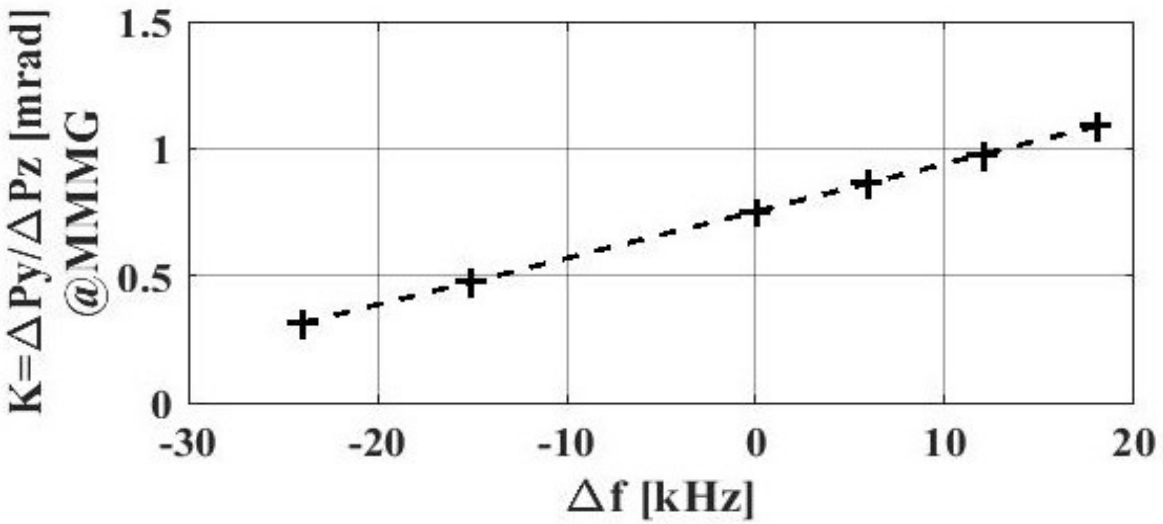


# Learned from simulations (cont'd)

## simulation results (cont'd)




→ In experiments, $\Delta S_{11}|_{\text{head-tail}} \approx 5$ dB
- → ~Comparable with the **bunch train between C and D**
- → C: Kick at MMMG: 0.7528 mrad
- → D: Kick at MMMG: 0.8647 mrad
- → $\Delta K|_{\text{head-tail}} \approx 0.112$ mrad
- → @BPM24 XFEL: $\Delta r \approx \Delta K|_{\text{head-tail}}(z1\text{-}zk) \approx 93$ μm
- → @BPM25 XFEL: $\Delta r \approx \Delta K|_{\text{head-tail}}(z2\text{-}zk) \approx 216$ μm → **fairly agrees with XFEL experiments**

→ the linearity may explain why **changing gun temperature at XFEL did not change the tendency of the orbit change** along the bunch train

# What to be first clarified in experiments

## based on simulations, i.e. goals of first experiments at PITZ

1. Evidence of kick **existence**
2. **Kick slope over gun phase** vs. frequency detuning (overheating → smaller slope)
3. Adjustments of gun phase for **kick growth over frequency detuning**
4. Evidence of kick existence for **bunches along the train**
5. **Momentum change** of bunches along the train vs. gun phase
6. Estimation of **beam loading** effect (vs. bunch charge)

# Experiments at PITZ

## measurement strategy

- **Single bunch operation**
  - frequency detuned (Δf) by adjusting gun water temperature (ΔT)
  - S11 characterized as ratio of  reflected power to forwarded power with cross-checking with Smith Chart readings
  - measure bunch position change (Δr)  at H1.S1 using both LYSO and YAG
  - measure Δr for variable gun phase (Φ) by adjusting gun water temperature (T)
  - measure Δr for variable T by adjusting Φ

**NB:**

- check if MMMG phase changes for different temperature SP
- if beam momentum slightly varies for different temperature SP, adjust gun SP to have the same momentum
- keep solenoid current for H1.S1 fixed

# Experiments at PITZ (cont'd)

## measurement strategy (cont'd)

- **Bunch train operation**
  - frequency detuned (Δf) by adjusting gun water temperature (ΔT)
  - S11 characterized as ratio of reflected power to forwarded power with cross-checking with Smith Chart readings
  - measure bunch position change (Δr) at H1.S1 using both LYSO
  - adjust H1.S1 camera timing to have the last bunch along the train (cross check with NoP±1)
  - measure for the selected bunch Δr for variable gun phase (Φ) by adjusting gun water temperature (T)
  - measure for the selected bunch Δr for variable T by adjusting Φ

**NB:**

- check if MMMG phase changes for different temperature SP
- if beam momentum slightly varies for different temperature SP, adjust gun SP to have the same momentum
- keep solenoid current for H1.S1 fixed
- adjust Disp1.Scr1 camera timing to have the last bunch along the train (cross check with NoP±1)
- measure for each selected bunch the beam momentum

# Measurement conditions

## single bunch operation and bunch train operation

### Parameters/conditions:

### RF:
Gun SP@ 60.5 (±0.5 when necessary for variable ΔT)
Gun phase under consideration: [MMMG-10  MMMG+10]
5.8 MW±, 200μs, FB on
Booster off

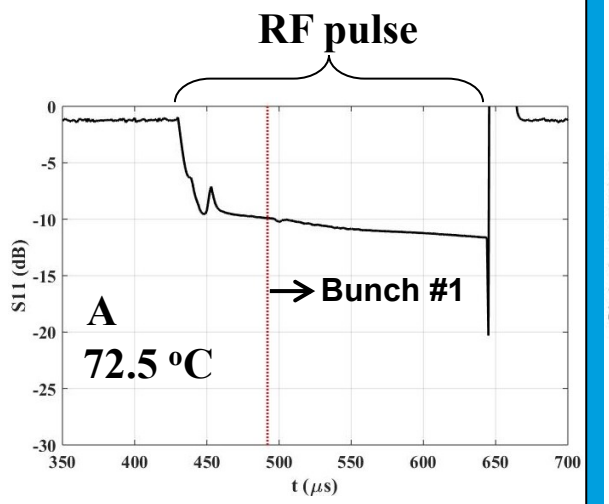
### Laser:
BSA = 1.0 mm
LT adjustable when necessary for 100, 200 and 500 pC
Up to 100 bunches
Pulse length

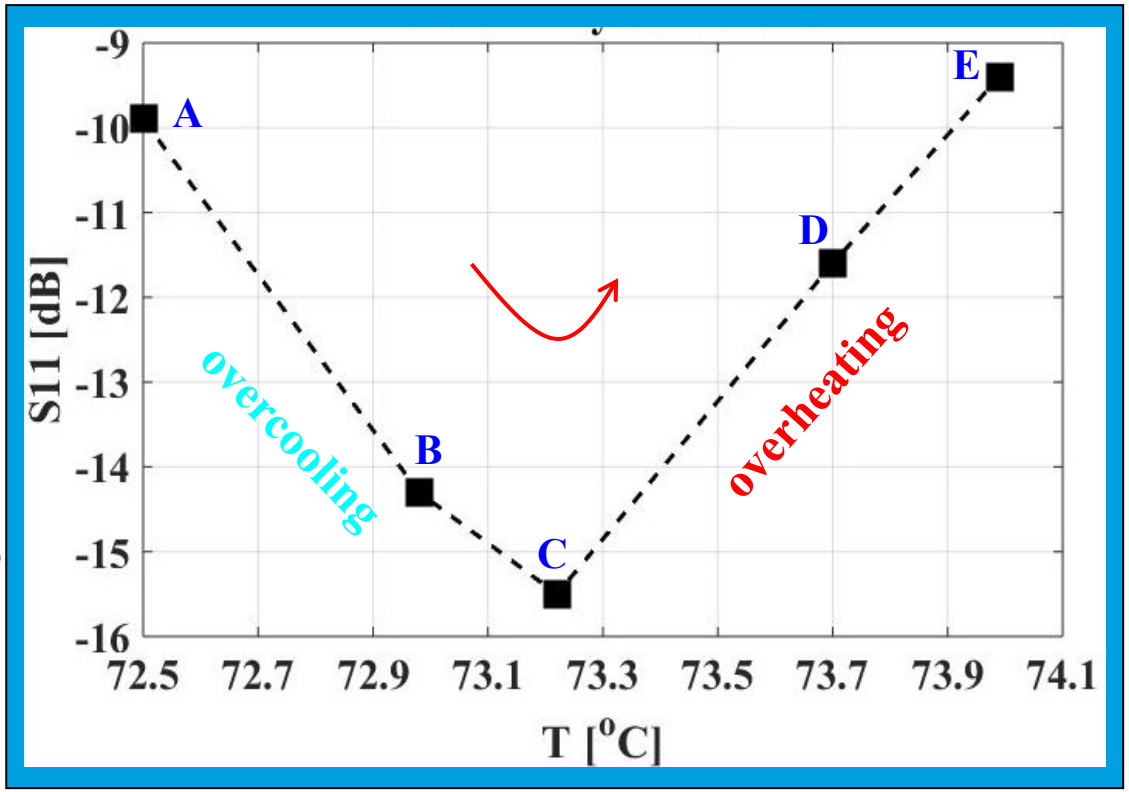
### Observation during 3 shifts:

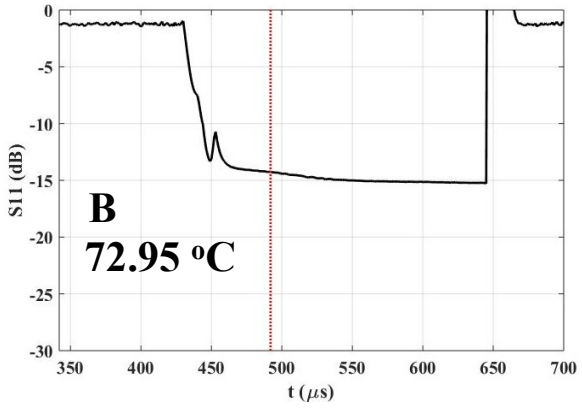
**Beam absolute position** at H1.S1 for same ΔT and Φ varies
**Beam momentum** varies for same RF settings (before measurement started)
-20190112N  Pz ~ 6.2**72** MeV/c at MMMG
-20190113N  Pz ~ 6.2**90** MeV/c at MMMG
-20190114N  Pz ~ 6.2**63** MeV/c at MMMG

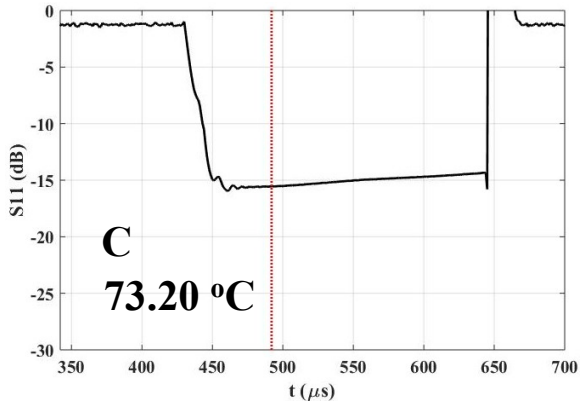
# S11 seen by Bunch #1

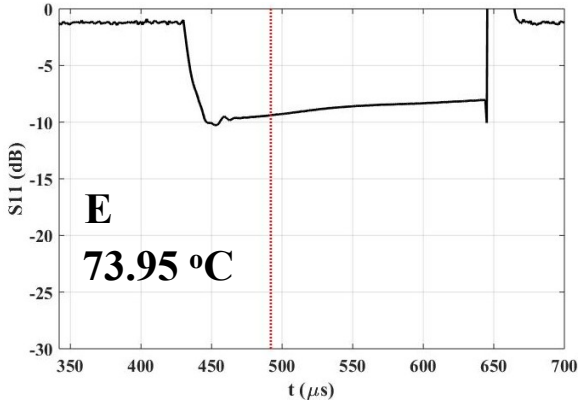
## single bunch operation

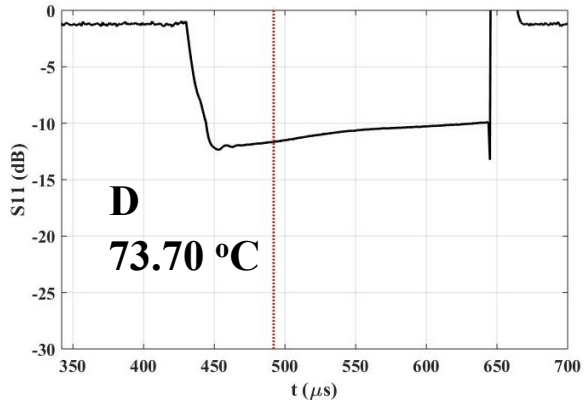


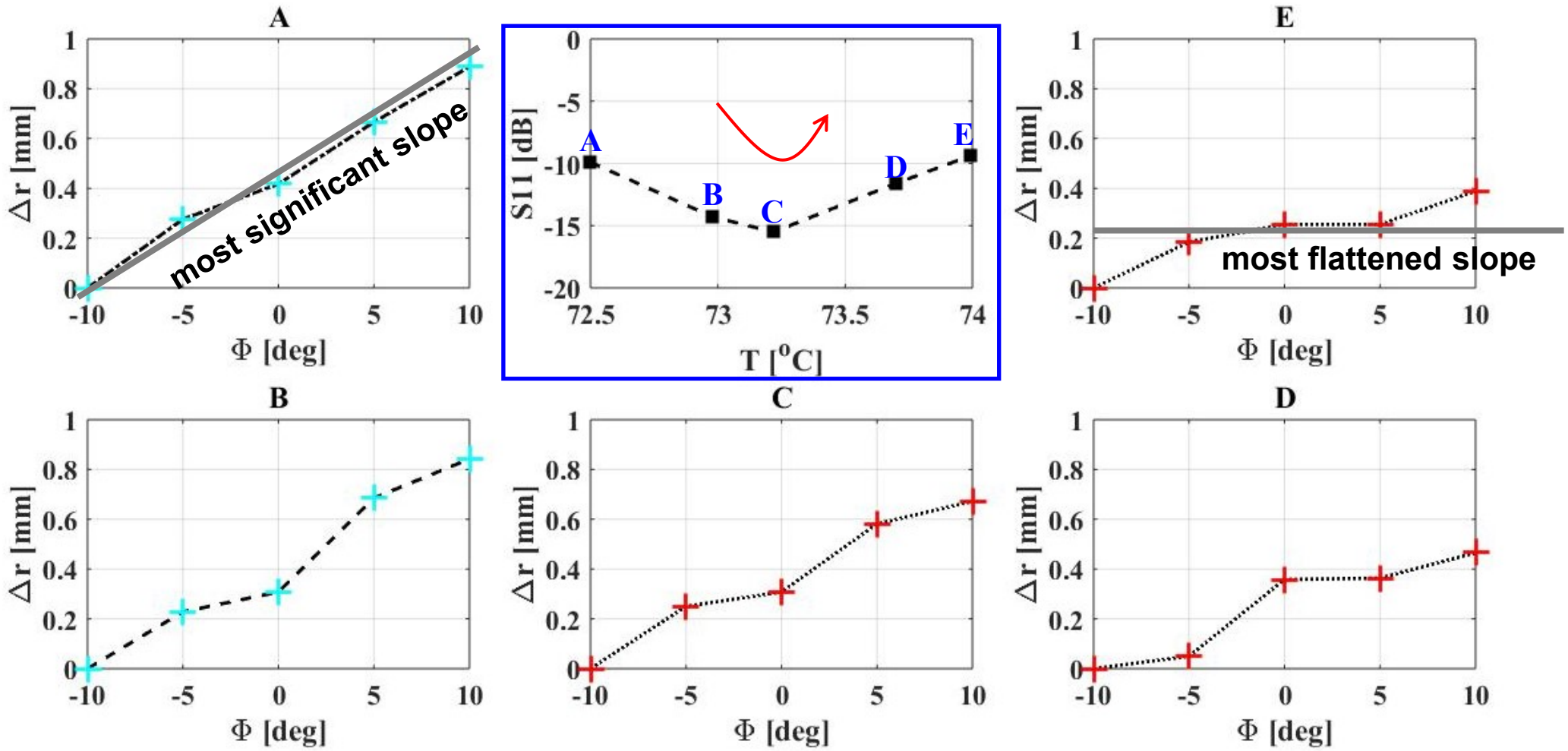



# Kick slope on gun phase w.r.t. frequency detuning

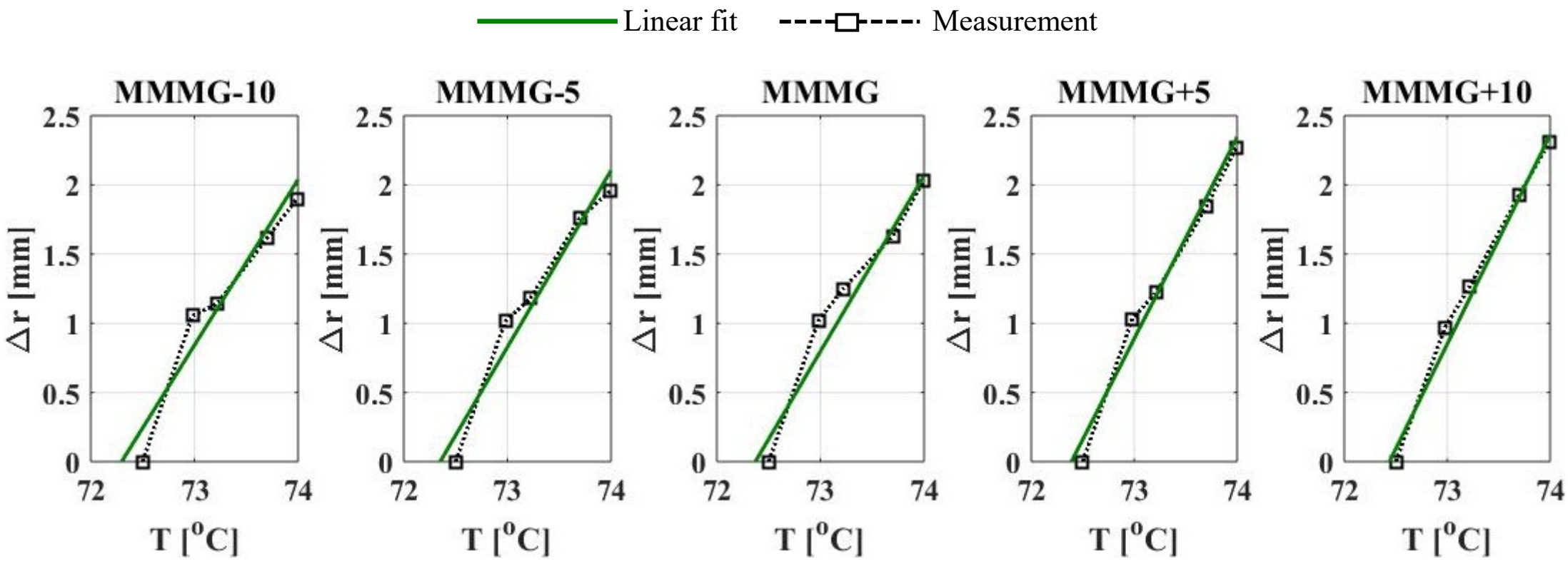
## single bunch operation, with LYSO at H1.S1




→ Overheating case gives most flattened kick slope on gun phase → consistent with simulations

# Kick slope on T w.r.t. gun phase tuning

## single bunch operation, with LYSO at H1.S1



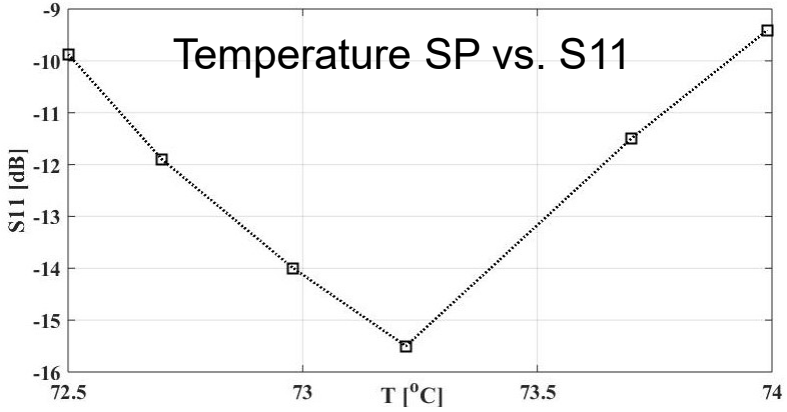

k ~ 1.197 | k ~ 1.276 | k~1.269 | k~1.456 | k~1.513

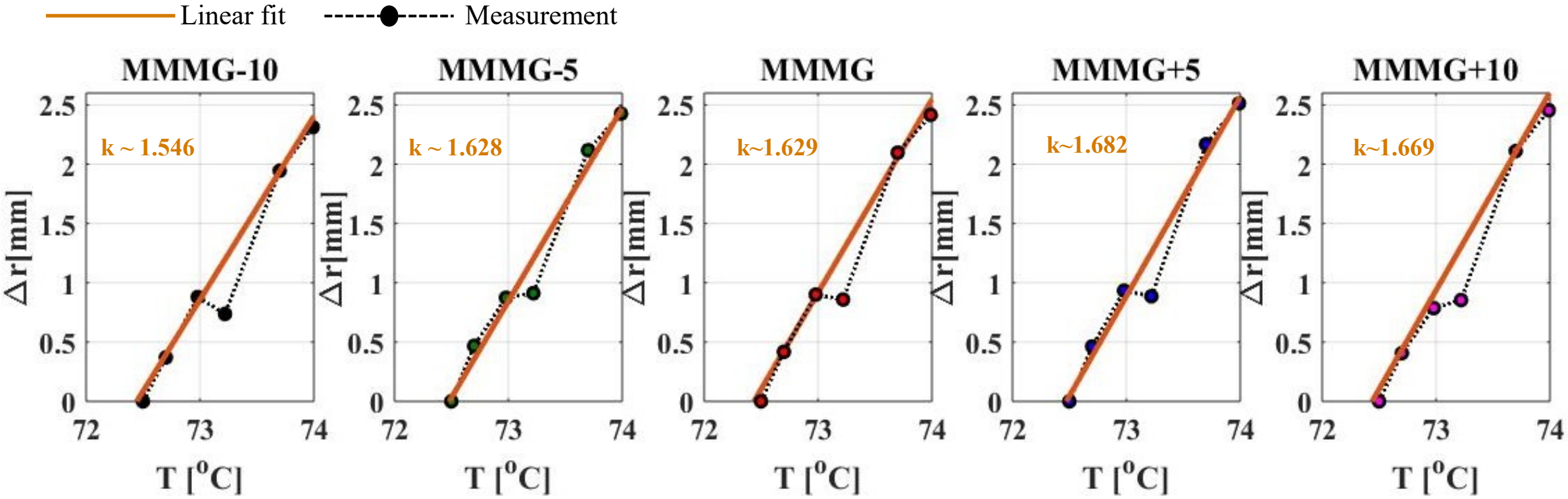
→ Adjusting gun phase cannot kill the kick

# Kick slope on T w.r.t. gun phase tuning

## single bunch operation, with YAG at H1.S1

- ΔT → frequency detuning, Δf
- Independent of gun phase the kick showing **~linear** behavior over Δf on both LYSO and YAG screens at H1.S1

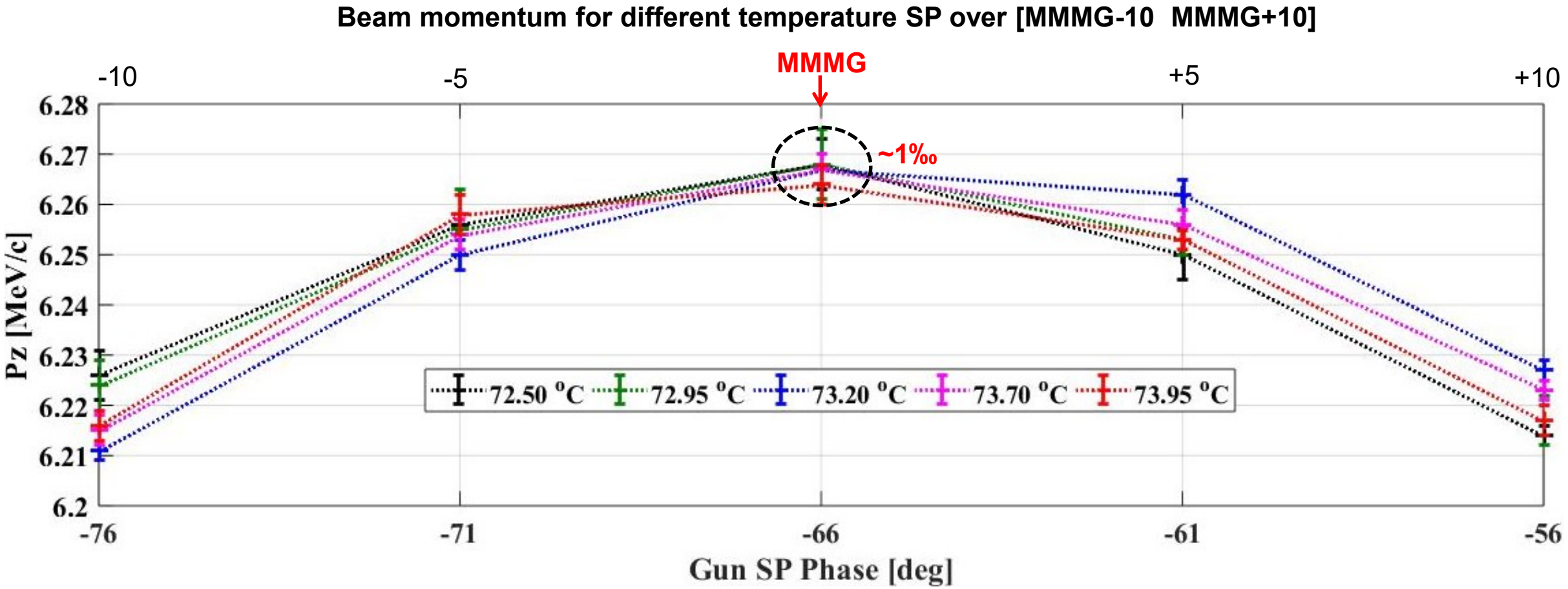


# Momentum check

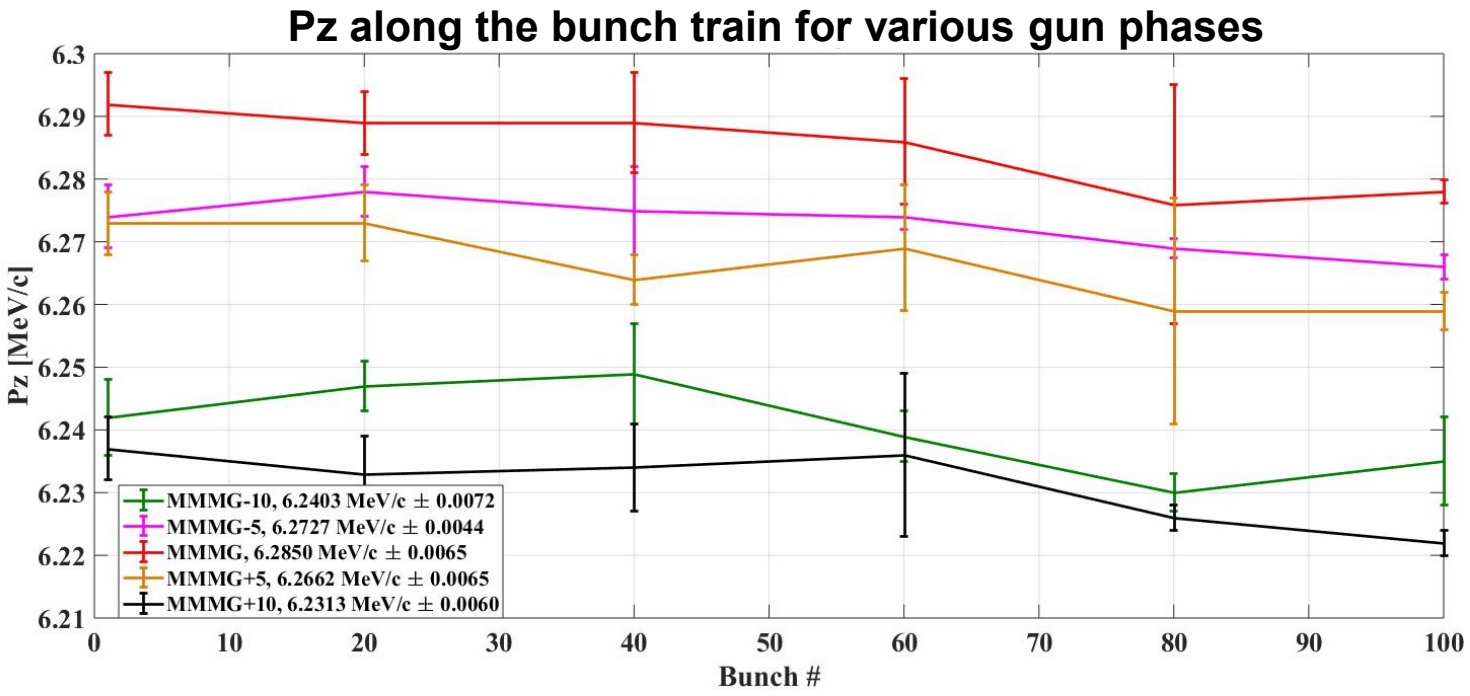
## single bunch operation at different temperature SP

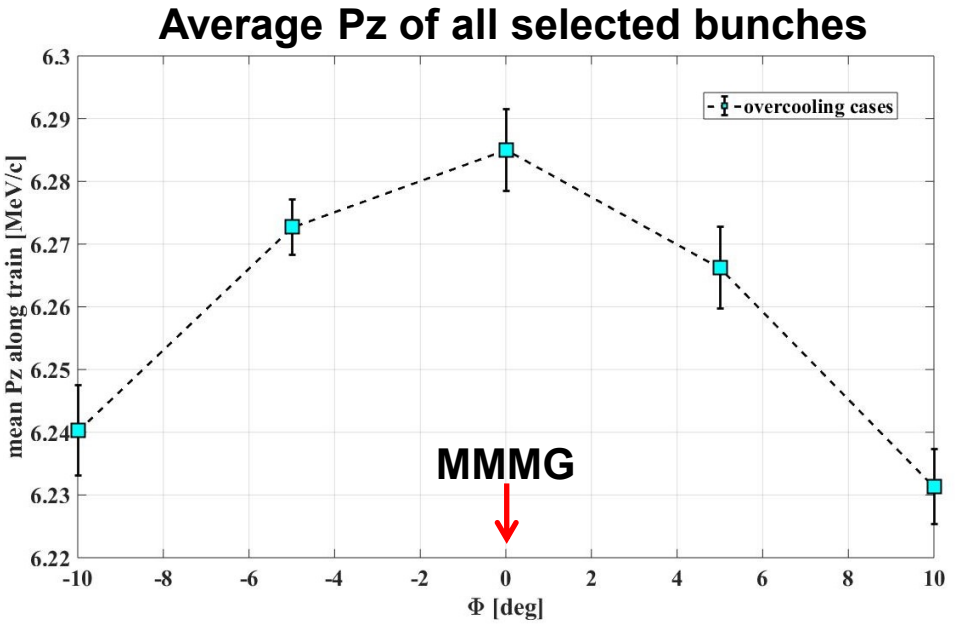
→ MMMG phase not changing for temperature SP range under consideration
→ Beam momentum slightly varies and leveled off by adjusting the Gun SP$^{\pm 0.5}$



# Bunch train operation

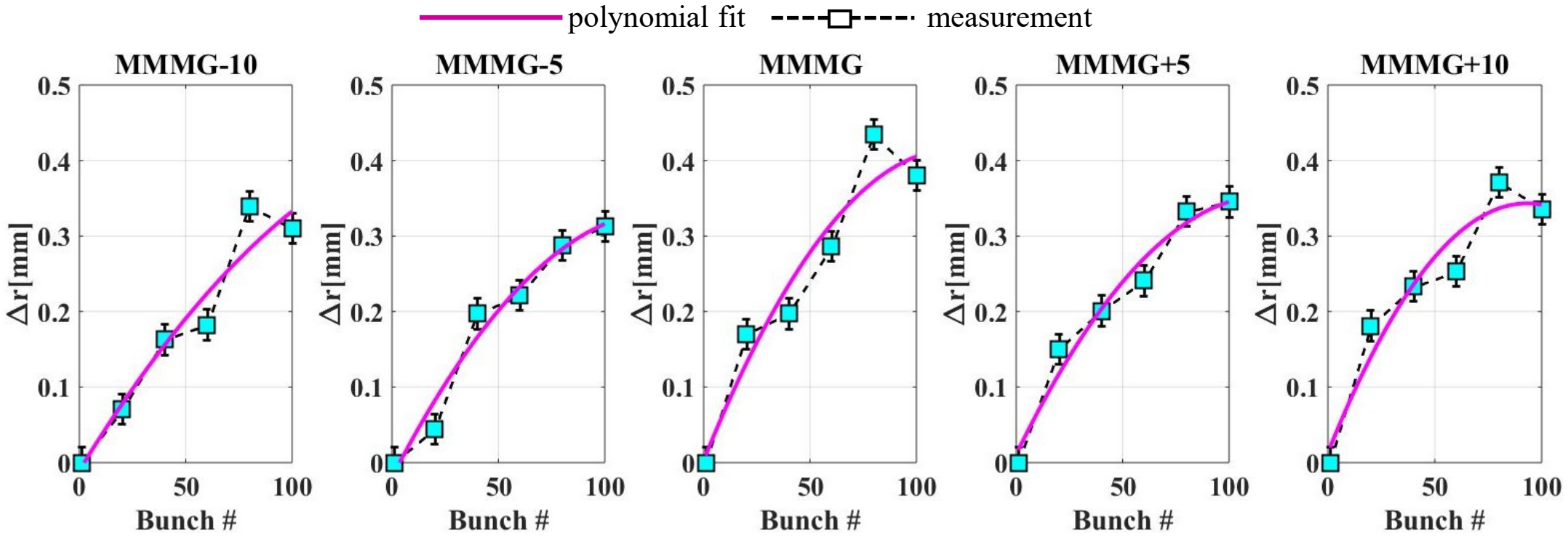
## Pz along bunch train for [MMMG-10  MMMG+10], "overcooling" case, train #2



# Bunch train operation (cont'd)

## Kick slope on T w.r.t. gun phase tuning, "overcooling" case

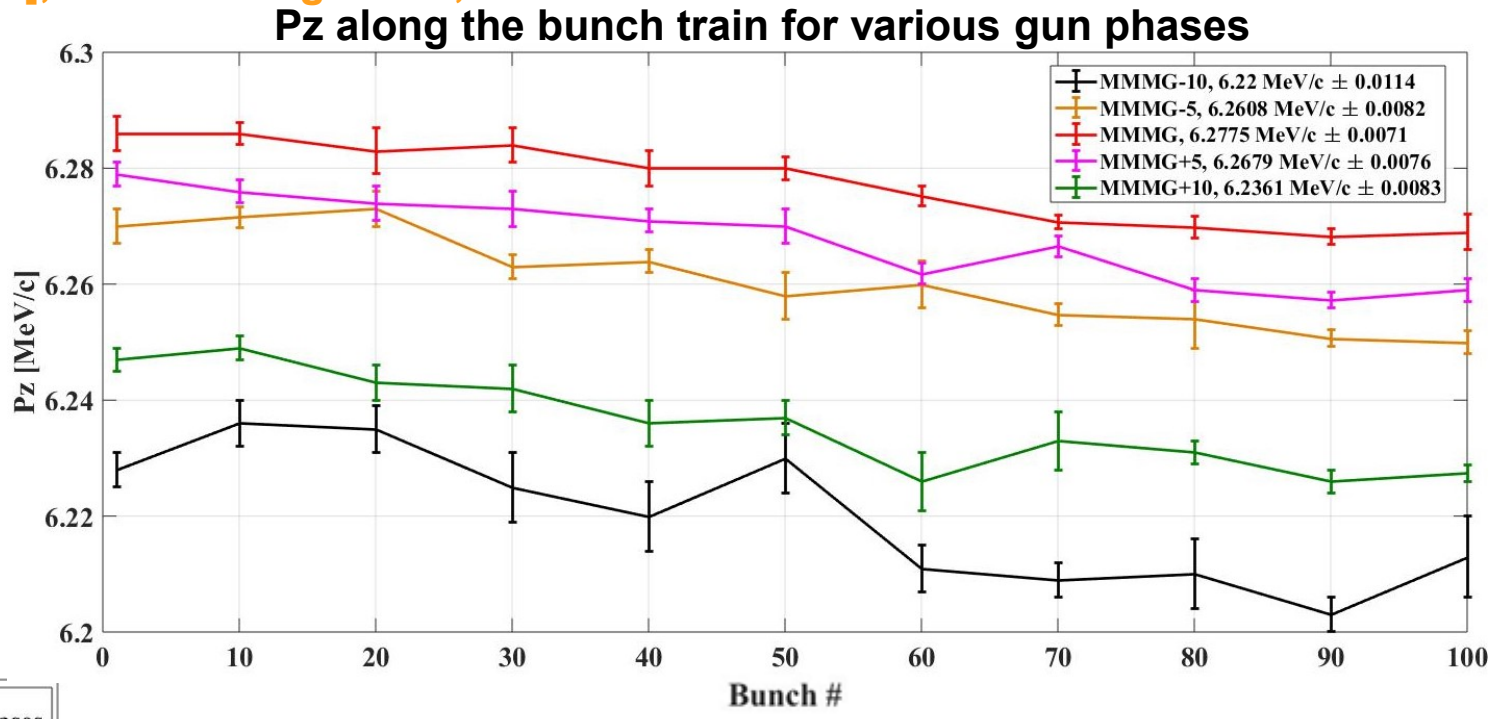


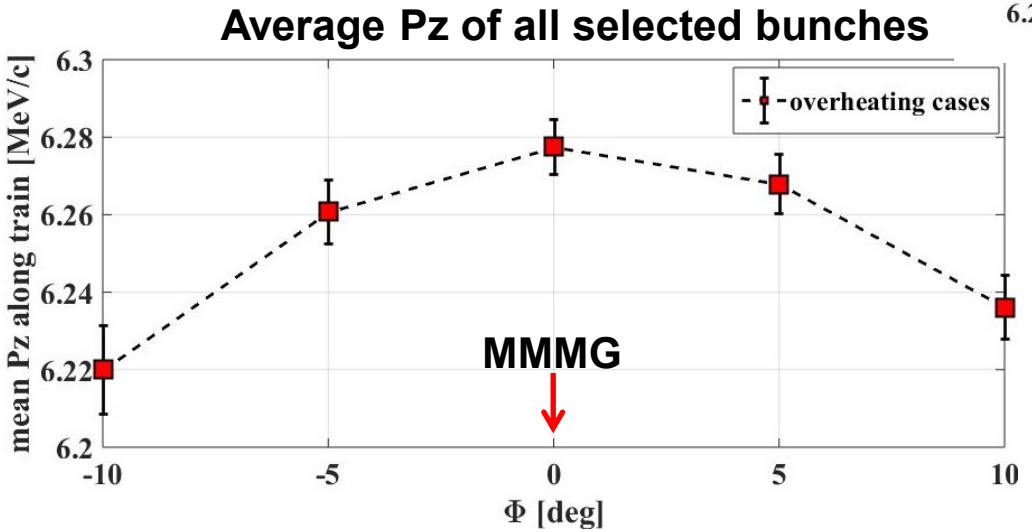

**Take Δr ~ 350 μm @ H1.S1**
**Then, ΔK~0.069 mrad**

| | | | |
|---|---|---|---|
| MMMG-10: | -1.186e-5 *bunch#$^2$ | +0.004616 *bunch# | - 0.01044 |
| MMMG-5: | -2.113e-5 *bunch#$^2$ | +0.005468 *bunch# | - 0.01942 |
| MMMG: | -2.974e-5 *bunch#$^2$ | +0.007000 *bunch# | +0.00267 |
| MMMG+5: | -2.439e-5 *bunch#$^2$ | +0.005781 *bunch# | +0.01106 |
| MMMG+10: | -3.793e-5 *bunch#$^2$ | +0.007079 *bunch# | +0.01301 |

# Bunch train operation (cont'd)

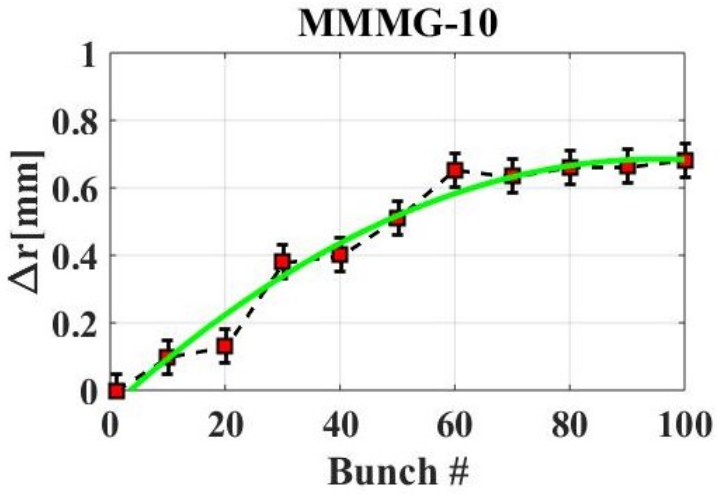
## Pz along bunch train for [MMMG-10  MMMG+10], "overheating" case, train #1

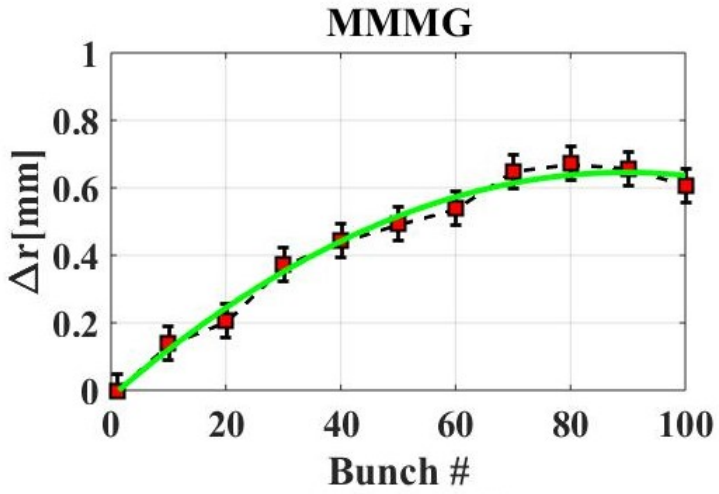


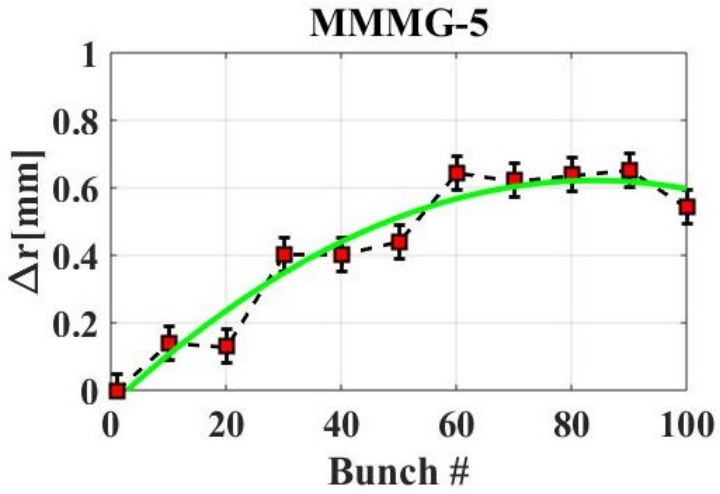



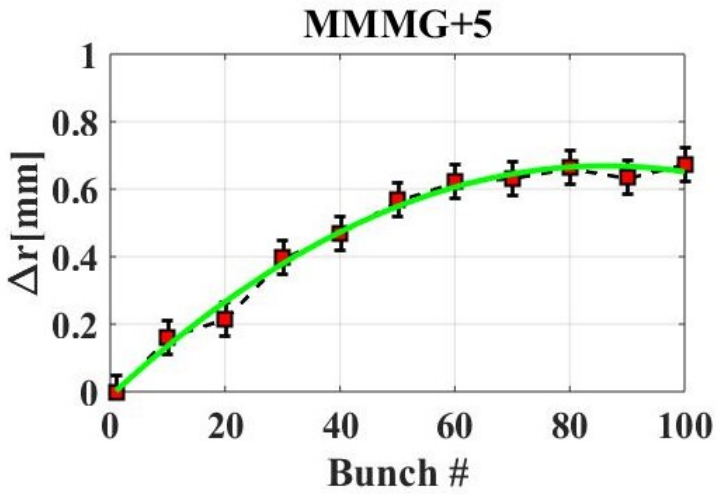
# Bunch train operation (cont'd)

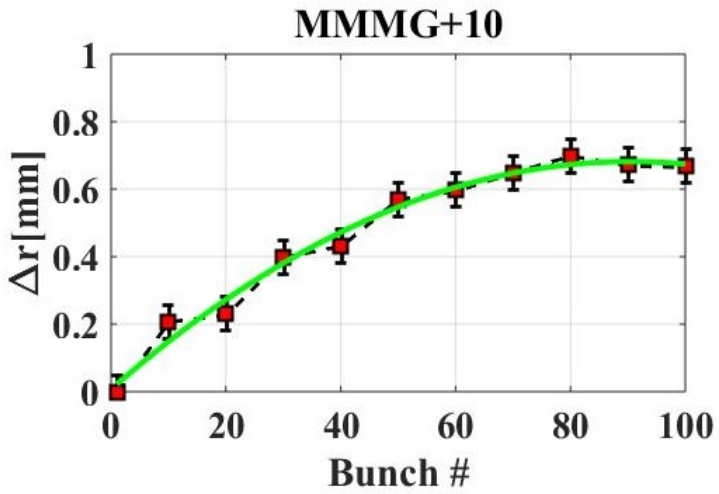
## Kick slope on T w.r.t. gun phase tuning, "overheating" case



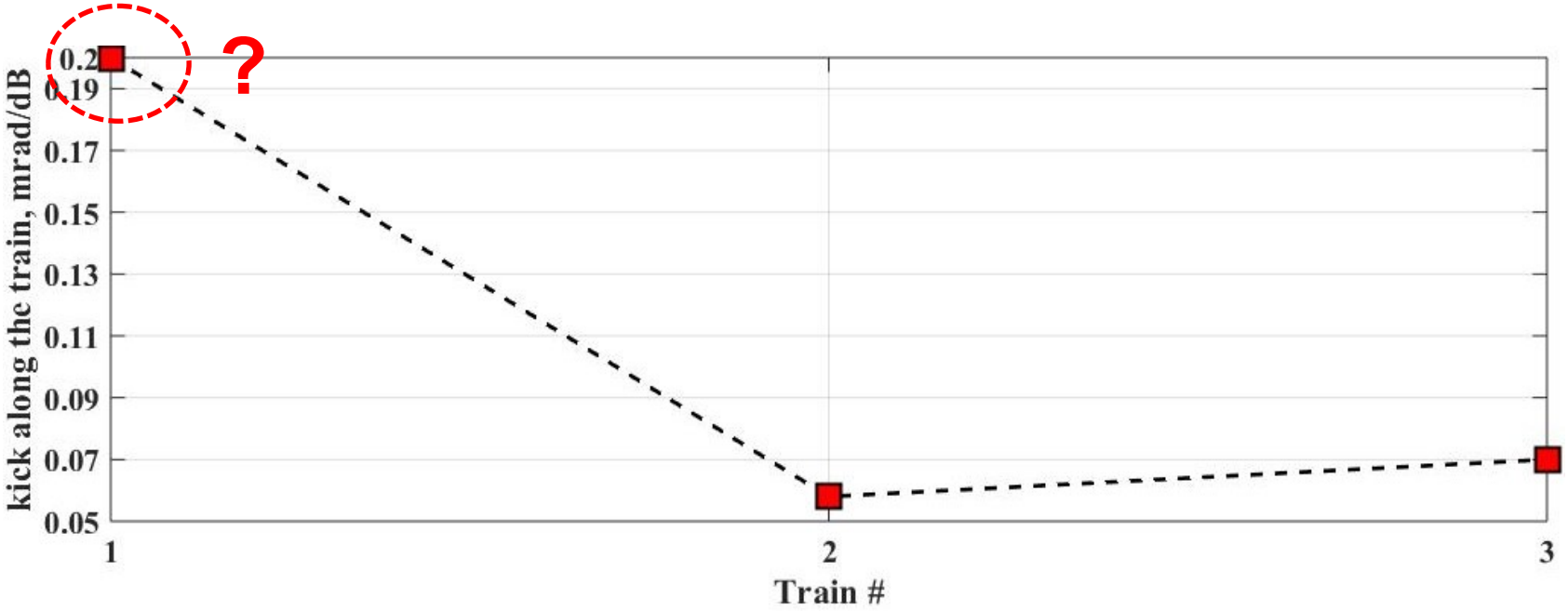

polynomial fit

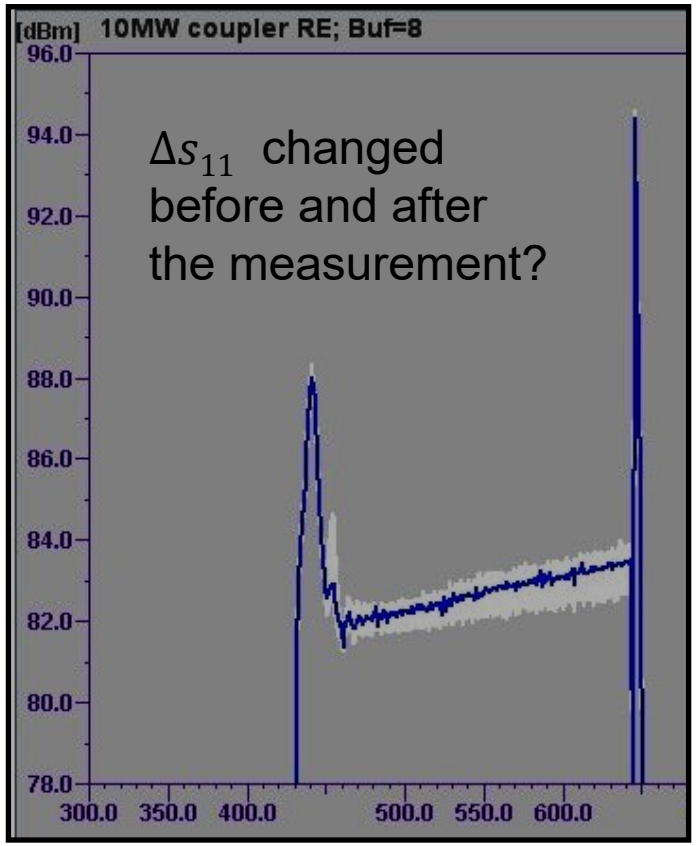
measurement

**MMMG-10:** -8.076e-5*#$^2$ +0.01544*# -0.05281
**MMMG:** -8.294e-5*#$^2$ +0.01486*# -0.02
**MMMG-5:** -9.446e-5*#$^2$ +0.01586*# -0.04402
**MMMG+5:** -9.187e-5*#$^2$ +0.01584*# -0.01375
**MMMG+10:** -8.260e-5*#$^2$ +0.01493*# +0.00716

**Take Δr ~ 650 µm @ H1.S1**
**Then, ΔK~0.127 mrad**

# Discussion



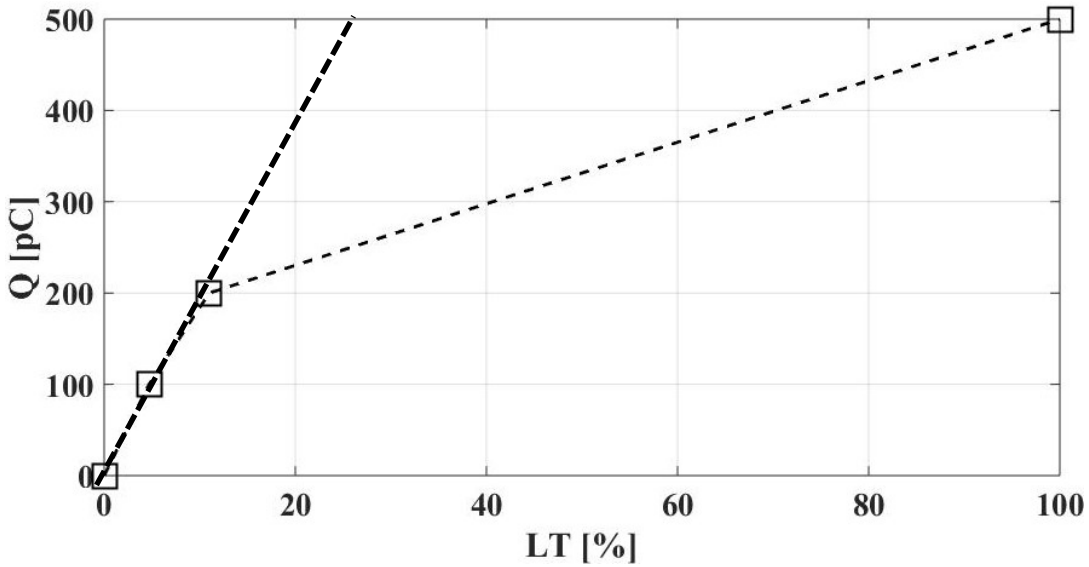




Kick along the train in mrad/dB defined as $\frac{\Delta r}{\Delta L} * \frac{1}{\Delta s_{11}}$

$\Delta s_{11}$ : train head to tail difference in S11
$\Delta r$ : bunch position change on screen (radial)
$\Delta L$ : drifting distance from kick location to observation screen

# Bunch train operation (cont'd)

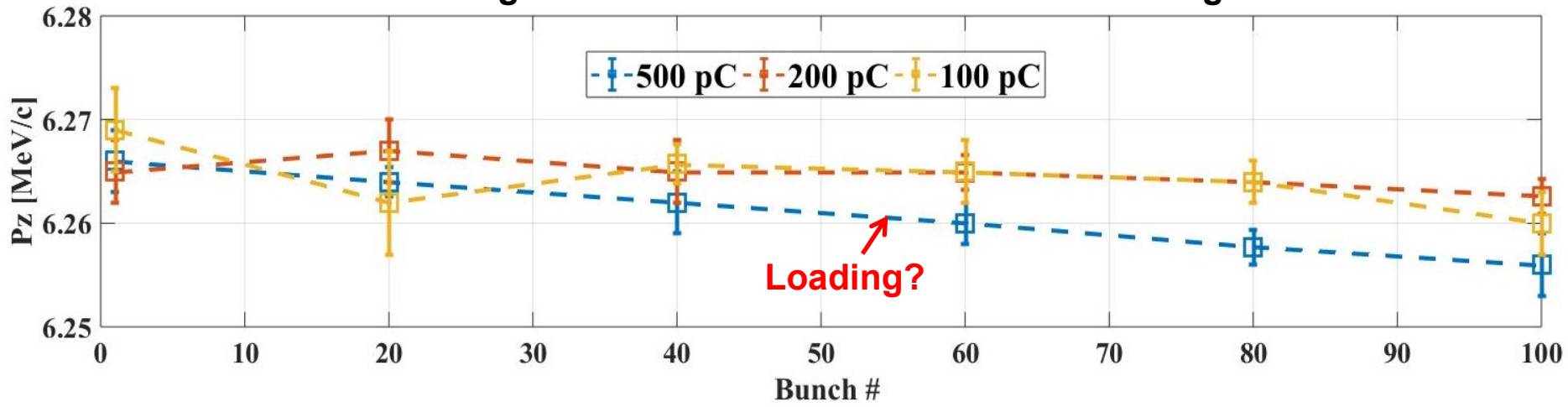
## vs. bunch charge




**Average Pz of all selected bunches**

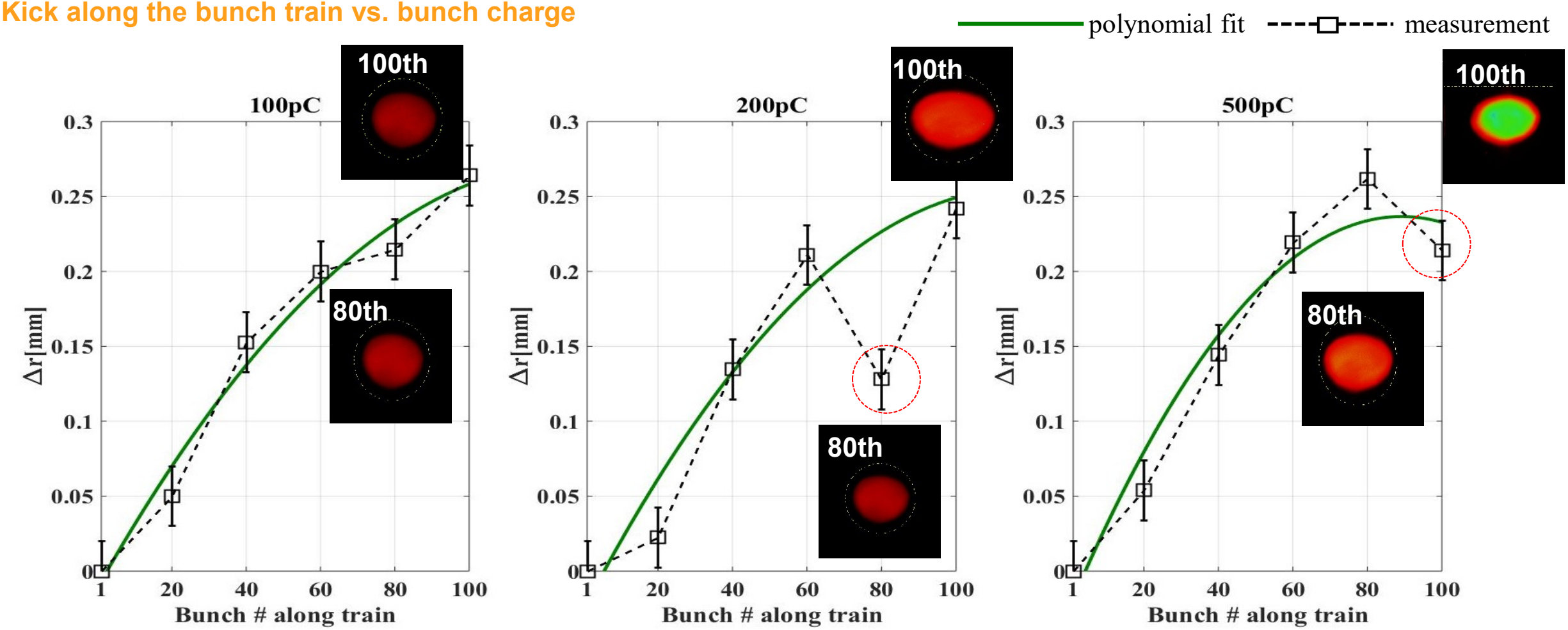
- 500pC: 6.2610 +/- 0.0038 MeV/c
- 200pC: 6.2648 +/- 0.0014 MeV/c
- 100pC: 6.2643 +/- 0.0031 MeV/c

**Pz along the bunch train for different bunch charges**



# Bunch train operation (cont'd)

## Kick along the bunch train vs. bunch charge




**100pC:** Δr[mm] = -1.694e-5 #$^2$ + 0.004386# -0.0110
**200pC:** Δr[mm] = -2.018e-5 #$^2$ + 0.004768# -0.0258
**500pC:** Δr[mm] = -3.284e-5 #$^2$ + 0.005856# -0.0245

**Take Δr ~ 250 μm @ H1.S1**
**Then, ΔK~0.05 mrad**

# Summary

1. **Bunch position change** (Δr) on H1.S1 (both YAG and LYSO) **observed** for both single bunch operation and  bunch train operation (individual bunches along the train)

2. Kick characteristics seem **consistent with previous findings**
   - **Δr vs. Φ** (gun phase) for different T (temperature)
   - **Δr vs. T** for different Φ

3. **Beam loading** effect observable (now up to 500pC)
   - seems **not significant** on the kick along the train

4. **Remaining issue:** one of three train orbit measurements showed inconsistent kick strength than others; reason unclear