Experimental observation of a frequency detuning dependent RF gun coupler kick

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- Updates on XFEL-related studies at PITZ
- Experiments of gun coupler kick
- Summary

Ye Chen
DESY-TUD Collaboration Meeting
13.06.2019, Darmstadt

Updates on XFEL-related studies at PITZ

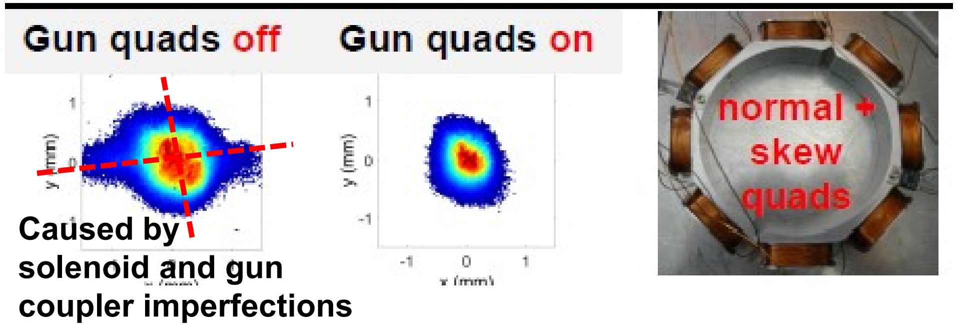
Motivation & (some) Topics

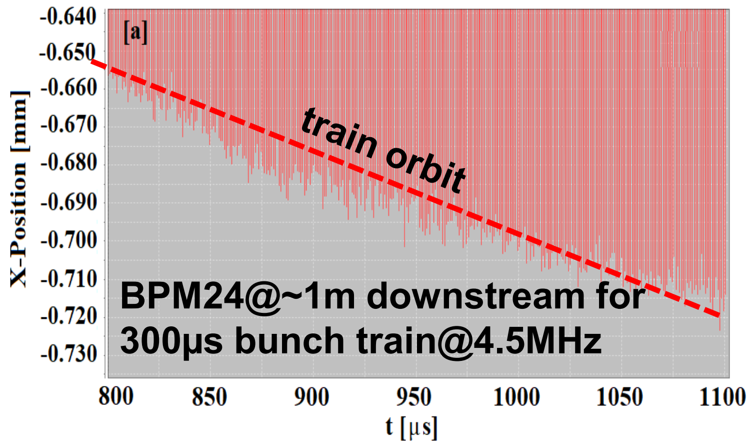
Motivation

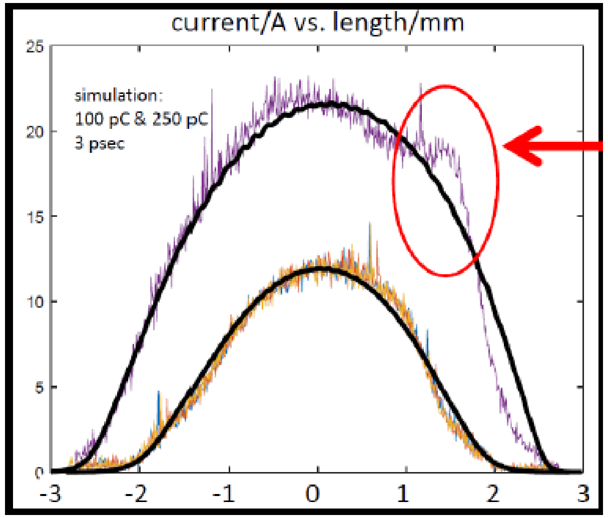
– Tackling XFEL operation issues at PITZ due to limited beam time for accelerator studies at XFEL

Topics

– Gun quads for beam asymmetry compensation
– Longitudinal bunch profile modification ("sub-structure")
– Orbit change of bunches along the train
– etc.

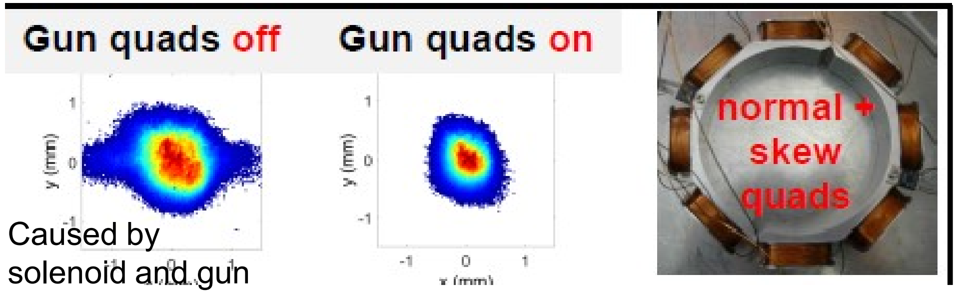






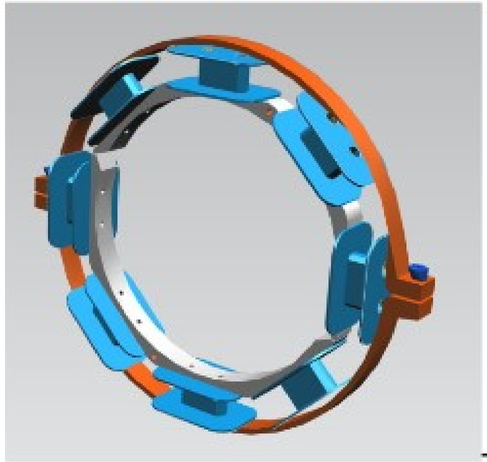
Current profile with sub-structure

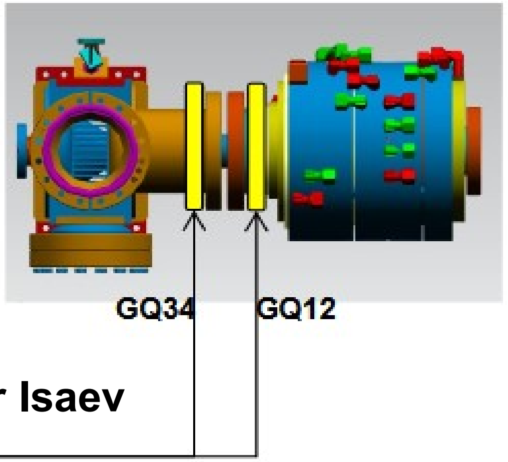
Gun quads for beam asymmetry compensation



Caused by solenoid and gun coupler imperfections

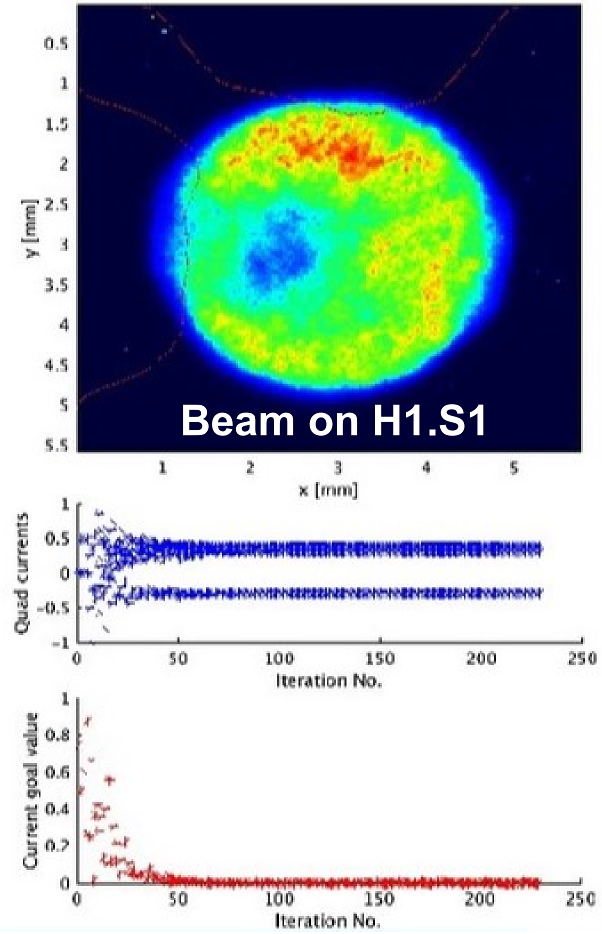
Design 3: GQ1,2,3,4





Igor Isaev

Gun Quad OptimiserMk2



- **New pair of gun quads installed** →additional degree of freedom for "round beam" optimization
- **Quads online tuning** with multi-parameter optimization algorithm (M. Krasilnikov, G. Loisch)
- **Test results obtained** in March-April 2019
  - **Beam profiles** on a set of downstream screens
  - **Emittance** w/ and w/o quads

Gun quads for beam asymmetry compensation

Result A

Same settings of gun quads for **beam profiles** on different screen locations

	w/o gun quads			w/ gun quads		
	X_rms	Y_rms	Roundn.	X_rms	Y_rms	Roundn.
Low.Scr1	1.61	1.58	0.06	1.60	1.62	0.04
Low.Scr3	1.00	0.92	0.18	0.94	0.95	0.07
High.Scr1	0.36	0.26	0.58	0.30	0.28	0.1
High.Scr3	0.48	0.46	0.12	0.44	0.43	0.11
High.Scr5	0.68	0.74	0.21	0.68	0.68	0.10

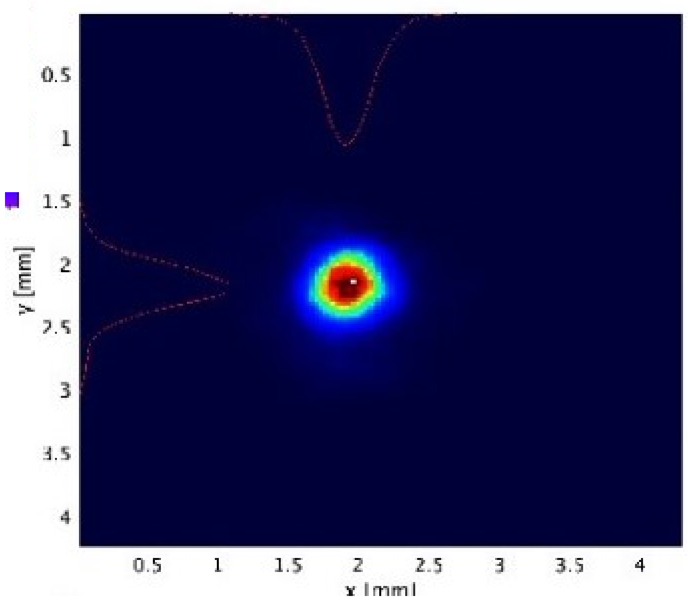
→Seems 4-quads configuration can deliver round beam simultaneously at multiple positions

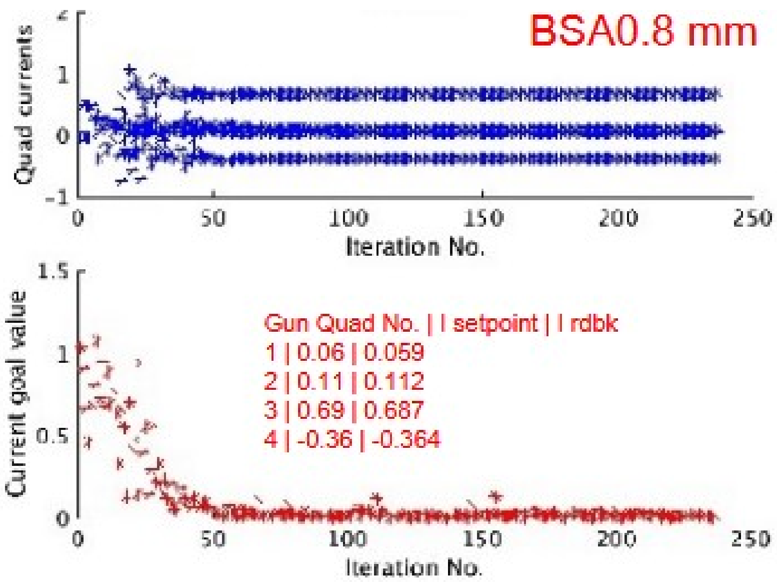
Gun quads for beam asymmetry compensation

Result B

Emittance measurement w/ and w/o gun quads

(250pC, flat-top 7ps, Gun 6.3 MeV/c, Booster exit 18.7 MeV/c)





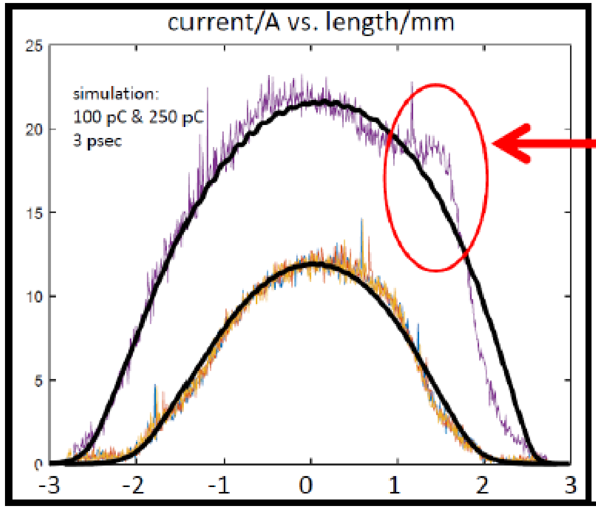
- BSA0.8mm, w/o gun quads
  - EmX = 0.650 +/- 0.020 um
    EmY = 1.030 +/- 0.012 um
    EmXY = 0.818 +/- 0.015 um
- BSA0.8mm, w/ gun quads
  - Xemt = 0.616 mm mrad
    Yemt = 0.650 mm mrad
    XYemt = 0.633 mm mrad

~22% reduction

→4-quads configuration (further) improving emittance

Longitudinal bunch profile modification ("sub-structure")

M. Krasilnikov, H. Qian



Simulations expect simple broadening of Gaussian distribution but measurements show wider **current profile with sub-structure**

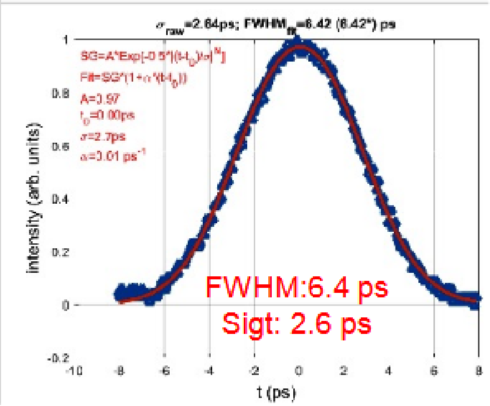
→ **observed at 130 MeV dogleg at XFEL**

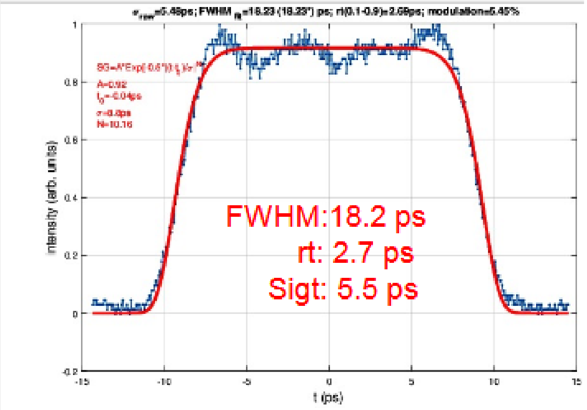
Measuring e-bunch profile by TDS vs.

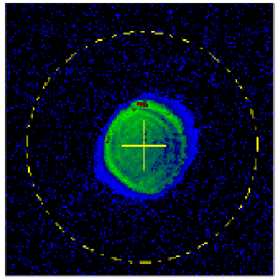
- BSA size
- Temporal laser pulse profile
- Temporal laser pulse length
- Bunch charge
- RF gun phase

OSS back into operation

→ improved cathode laser diagnostics

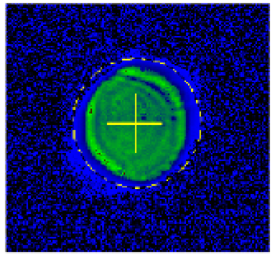






<x> = 0.063 mm
<y> = 0.035 mm

Xrms = 0.169 mm
Yrms = 0.189 mm



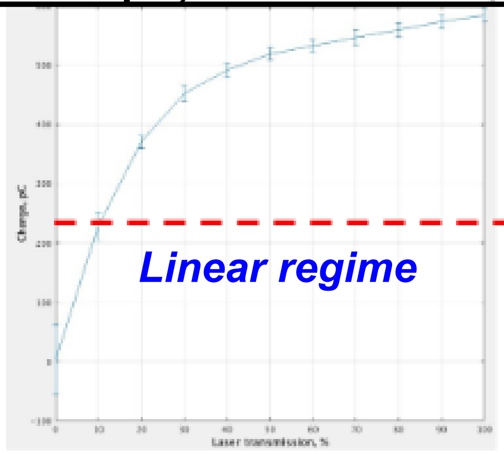
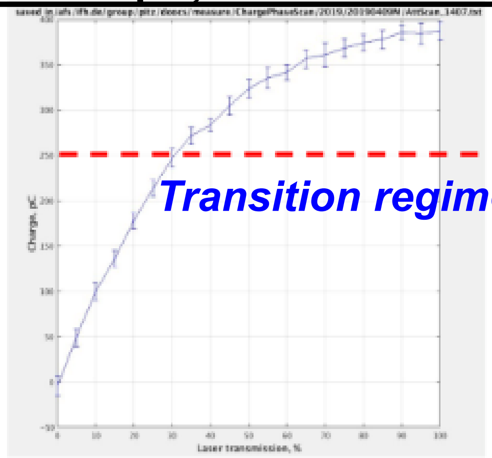
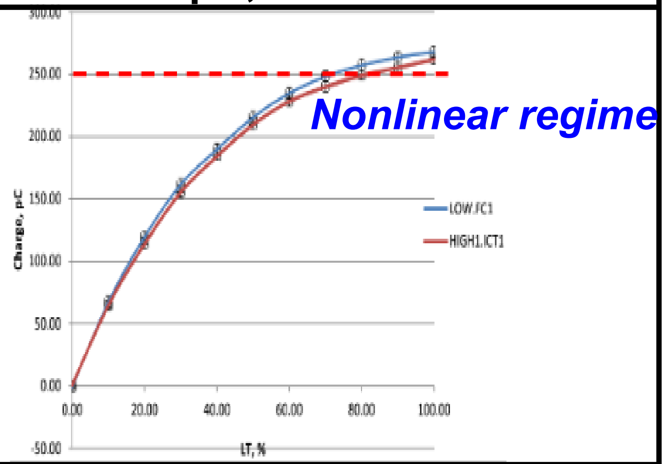
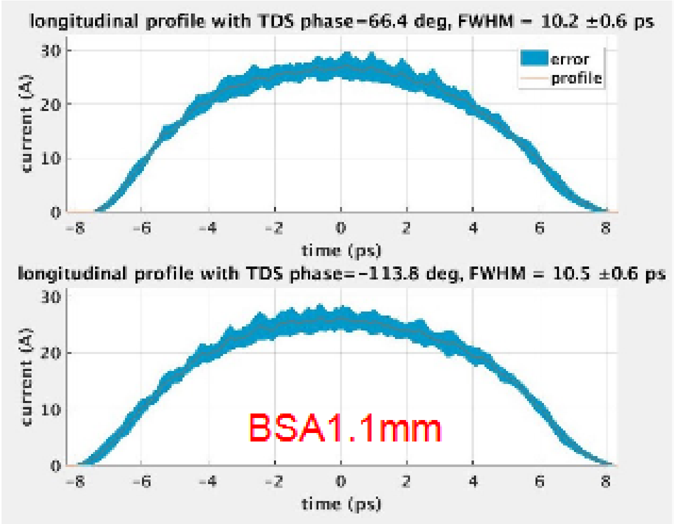
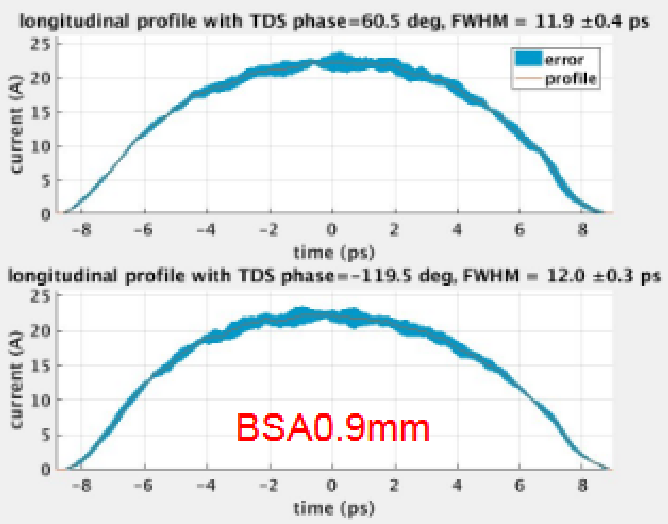
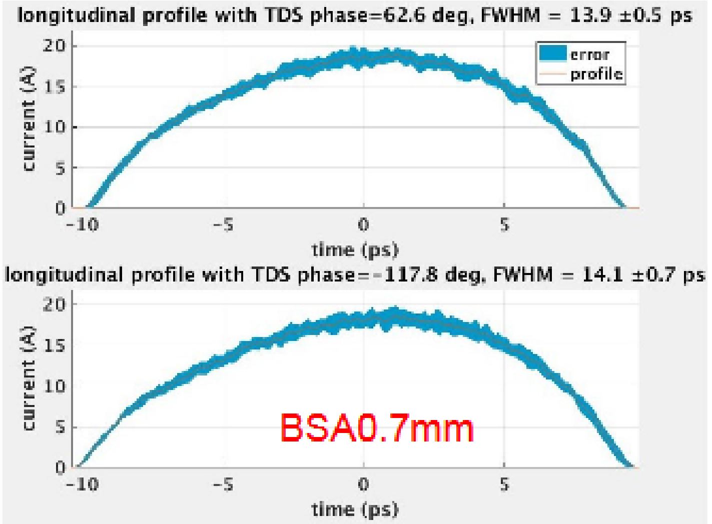
<x> = 0.106 mm
<y> = 0.022 mm

Xrms = 0.169 mm
Yrms = 0.183 mm

Longitudinal bunch profile modification ("sub-structure")

Result A

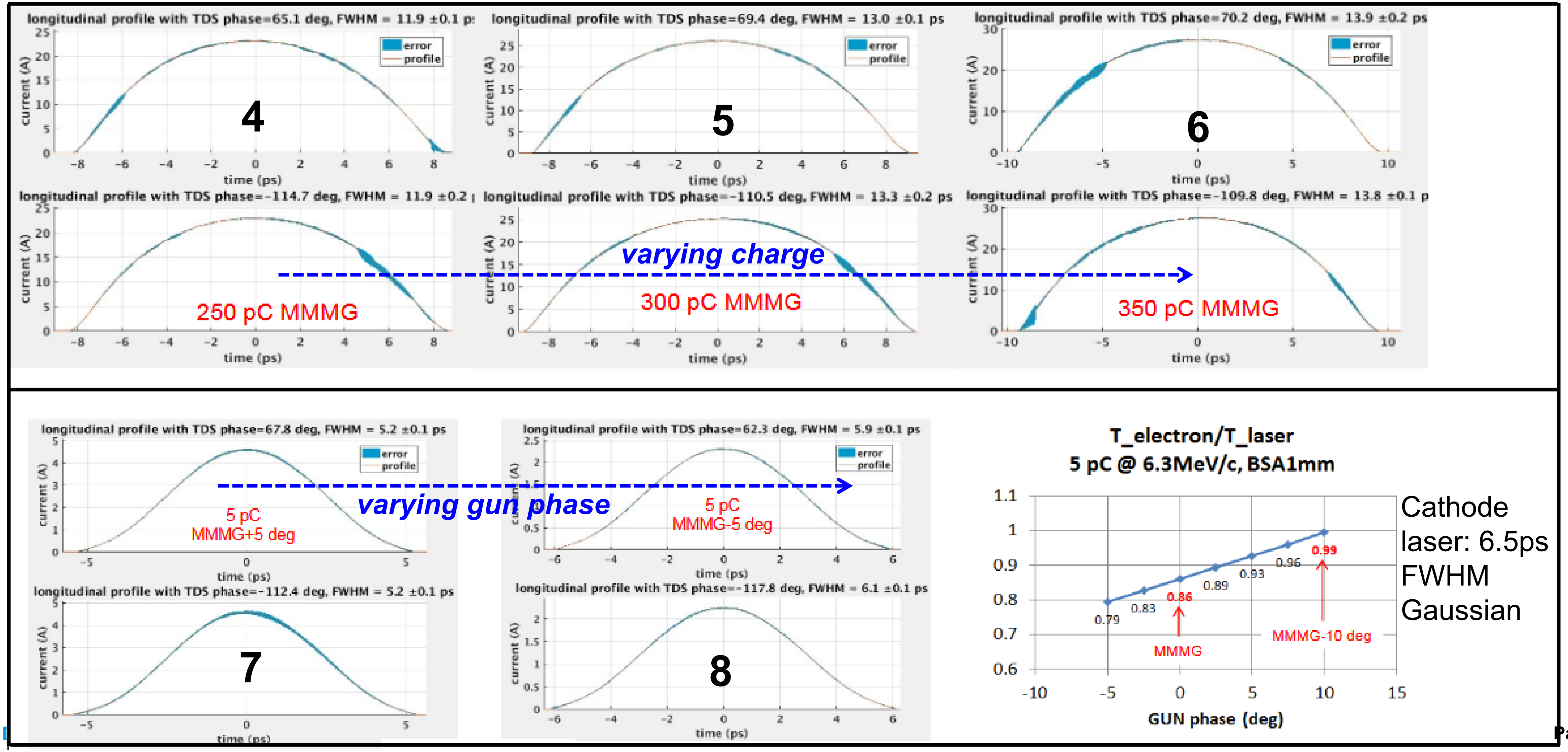
Experiments carried out in different emission regimes → no sub-structures observed

	250pC, BSA=1.1mm	250pC, BSA=0.9mm	250pC, BSA=0.7mm
Charge vs. laser intensity	 1	 2	 3
Measured e-bunch profile by TDS			

Longitudinal bunch profile modification ("sub-structure")

Result B

Bunch charge (space charge) and rf phase (rf compression) varied → no sub-structures observed



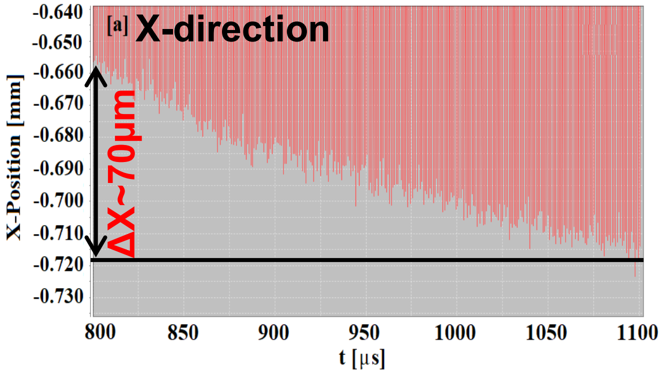
Cathode laser: 6.5ps FWHM Gaussian

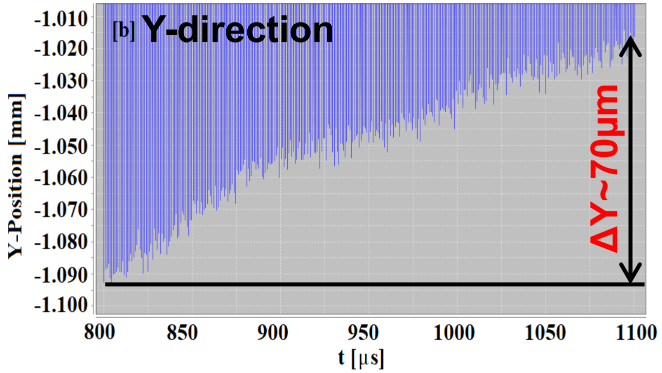
Experiments of gun coupler kick

XFEL Observation

- Orbit change of bunches along the train observed at XFEL

BPM24@~1m downstream for **300μs** bunch train@4.5MHz





BPM24@~1m: **Δr ~ 100 μm**

BPM25@~2.1m: **Δr ~ 231 μm**

The offset showing dependencies on

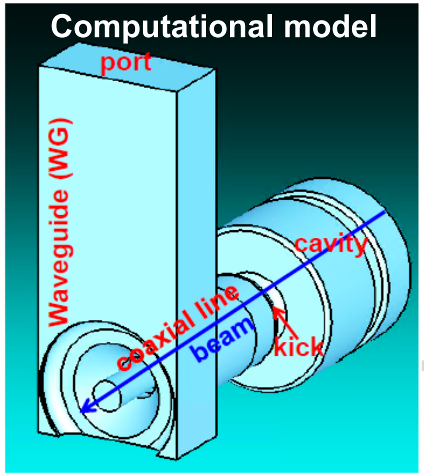
- Gun detuning from -250Hz to +6.7kHz
- Bunch charge 100-300 pC
- Gun phase over the RF phase by 10 deg
- Gun amplitude over the RF phase by 0.3MV/m

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

Courtesy: Frank Brinker

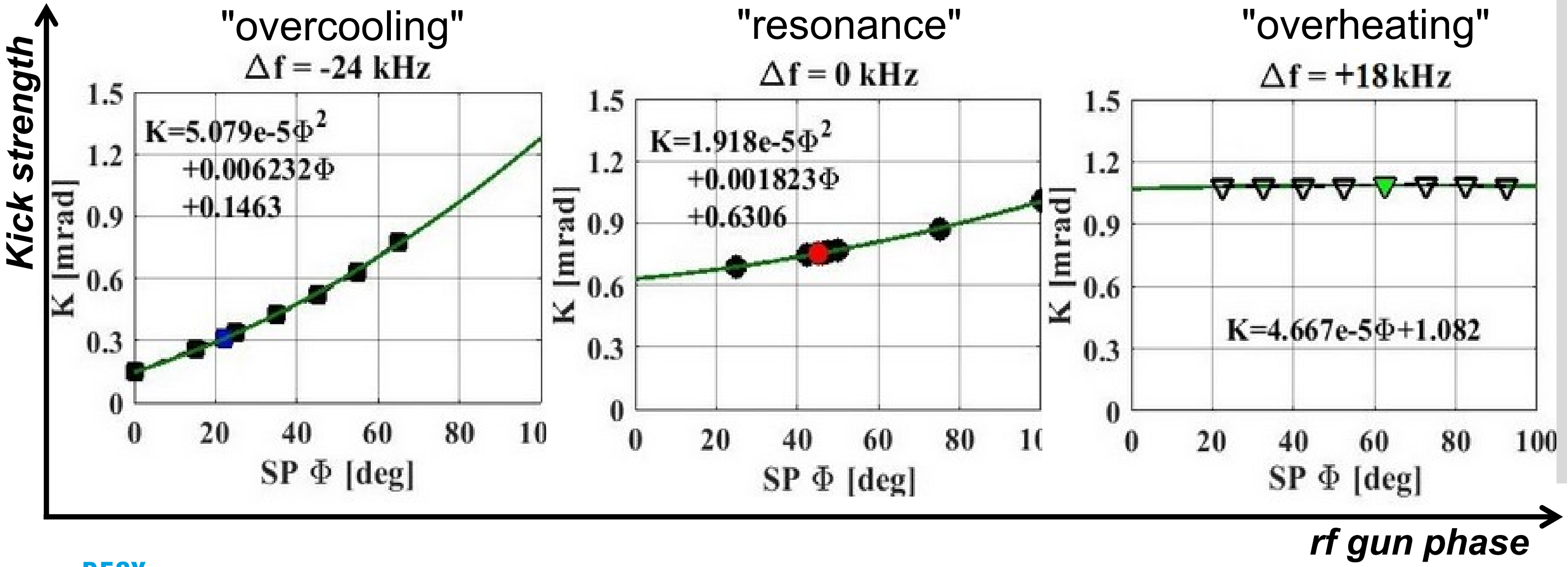
Kick behaviors in simulations

see 10.3204/PUBDB-2018-05590 for simulated results

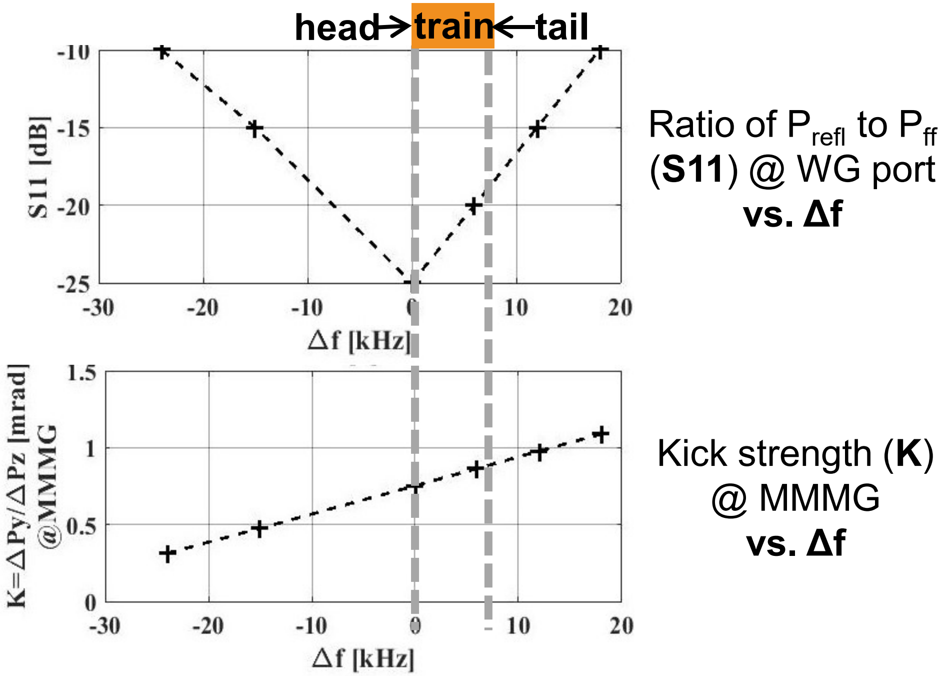


- **Part I:** Simulation of **coupler kick** [Y. Chen et al, WEP005, FEL'17]
  → Component: main **dipole** + small quadrupole
  → Strength: K**~0.65 mrad**@6.5MW
  → Integral kick region: 0.19~0.23 m **(end of coupler)**
  → Single bunch (20ps) tilting: $\Delta K_{head\text{-}tail}$**~0.05 mrad**
  → emittance growth

- **Part II:** Simulation of **transient kick slope on rf gun phase** vs. frequency detuning, Δf
  → Kick slope on phase varying vs. Δf



- **Part III:** Simulation of **frequency detuning dependency** of the kick



→ Kick strength depends on Δf
→ Bunches along train within rf pulse see different Δf
→ Kick varies along the train
→ Kick slope on Δf almost linear

Experiments of gun coupler kick

Based on simulation studies, what are to be verified in experiments:

- $dK/d\Phi$ varies vs. Δf
- $dK/d\Delta f$ (or dK/dT) ~ linear
- for a fixed $dK/d\Delta f$, $\Delta K_{head\text{-}tail}$ ~ constant for a given train

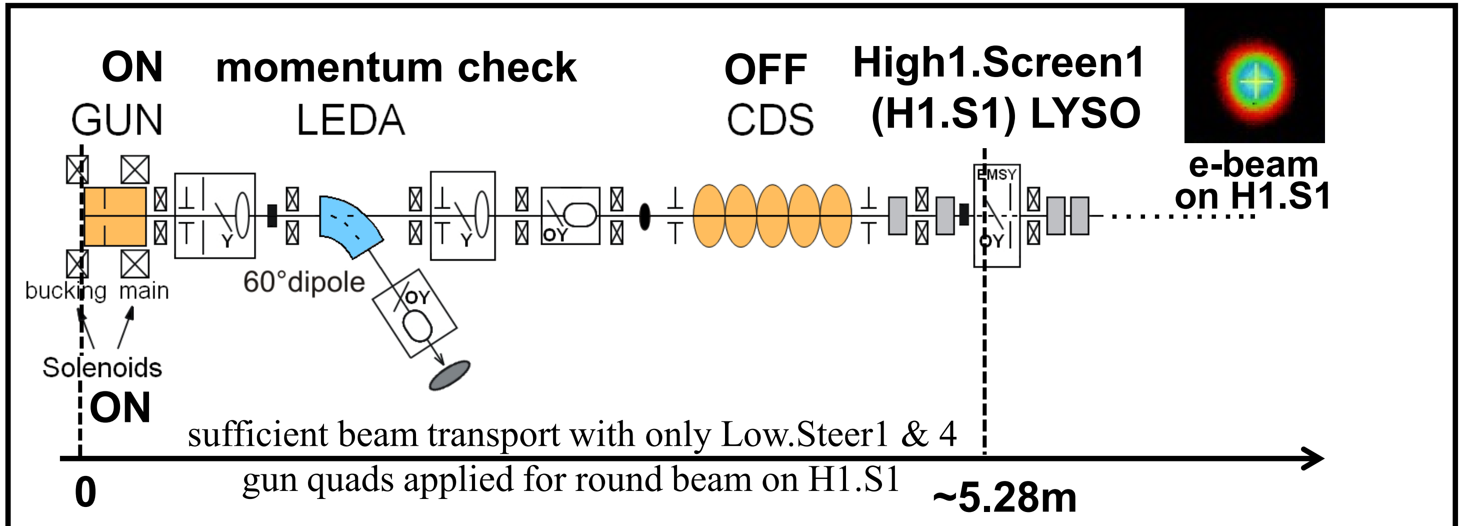
K: kick strength, Φ: rf gun phase

Δf: frequency detuning, T: gun cooling water temperature

Experiments of gun coupler kick

setup & procedures

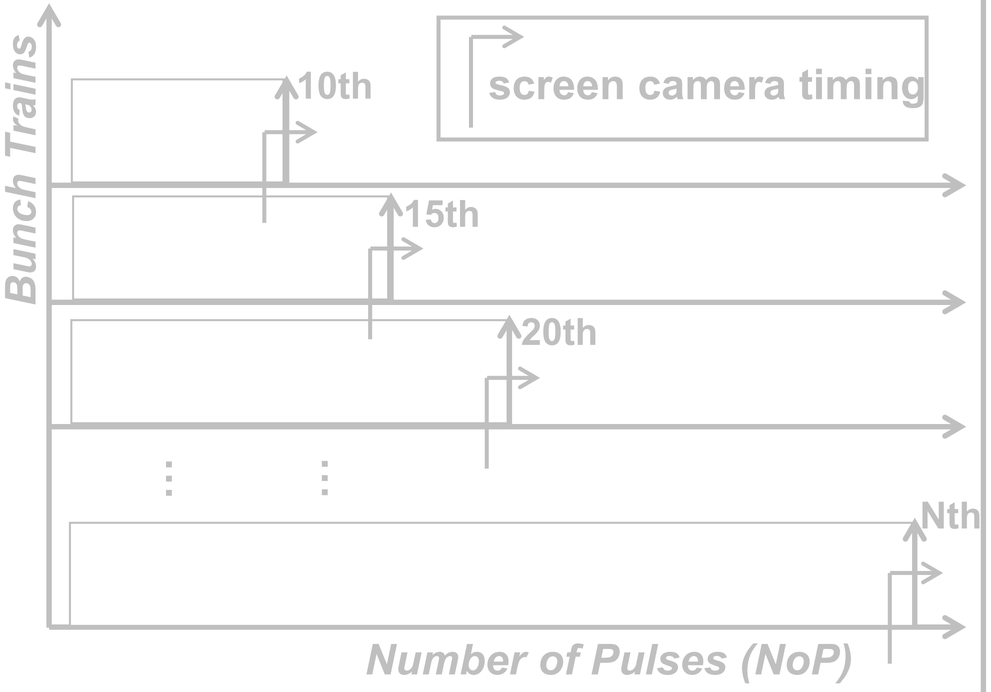
- Use e-beam for measuring transverse RF kick properties
- **Setup & procedures**



– frequency detuning adjusted by tuning gun cooling water temperature (**T**)
– measure the change of bunch position (**Δr**) and size (**Δσ**) on H1.S1 when **changing T (/Δf)** and **gun phase (Φ)**

[1] temperature set-point further characterized by S11
[2] keep solenoid current unchanged
[3] check if MMMG phase varies for different T (→ no change found)
[4] if beam momentum varies for different T, adjust gun SP to keep momentum unchanged (→ within ±0.5)

- **For bunch train mode:**



– **Select individual bunches** along the train **for measurements** by every time adjusting timing of the camera at the observation screen and NoP for the very last pulse of all sub-trains

[5] background taken: adjust timing→NoP-1→taking image while keeping shutter open
[6] if laser train not flat, tune laser intensity for having same bunch charge along the train

Experiments of gun coupler kick

setup & procedures

- Use e-beam for measuring transverse RF kick properties
- **Setup & procedures**

0 gun quads applied for round beam on H1.S1 ~5.28m

– frequency detuning adjusted by tuning gun cooling water temperature (T)
– measure the change of bunch position (**Δr**) and size (**Δσ**) on H1.S1 when **changing T (/Δf)** and **gun phase (Φ)**

[1] temperature set-point further characterized by S11
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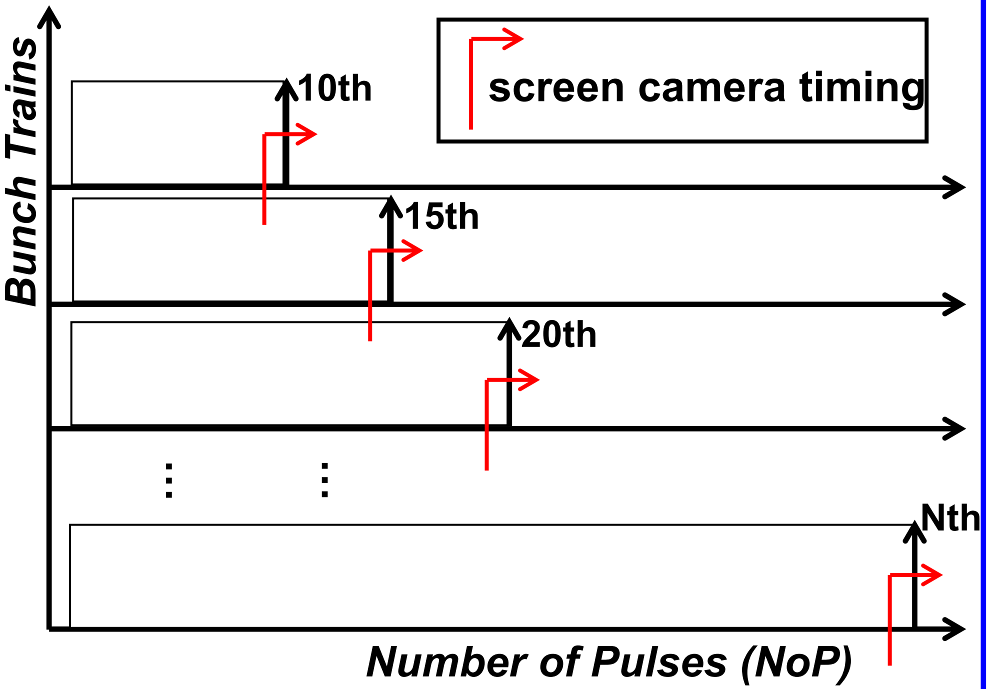

– **Select individual bunches** along the train **for measurements** by every time adjusting timing of the camera at the observation screen and NoP for the very last pulse of all sub-trains

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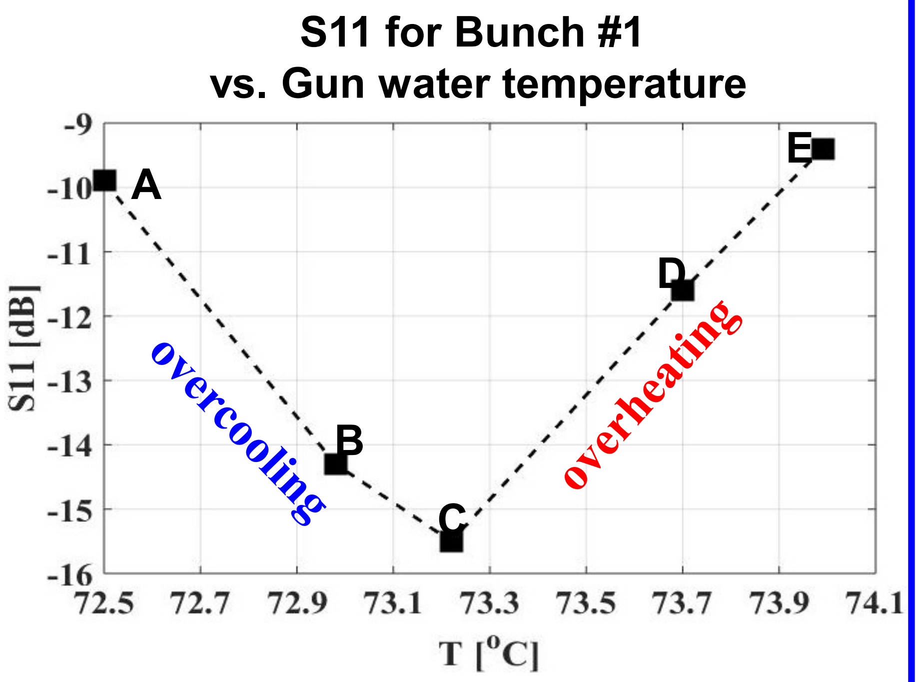
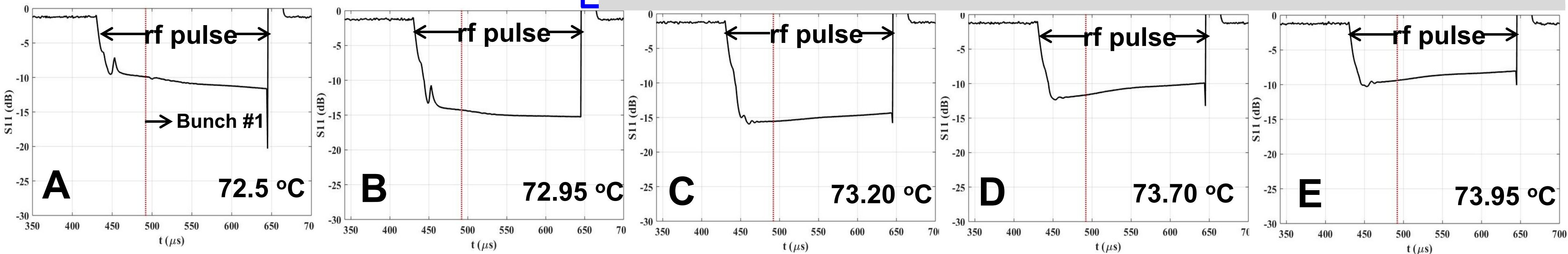
[6] if laser train not flat, tune laser intensity for having same bunch charge along the train

Experiments of gun coupler kick

Measured phase slope of the kick



Measured phase slope of the kick vs. Temperature

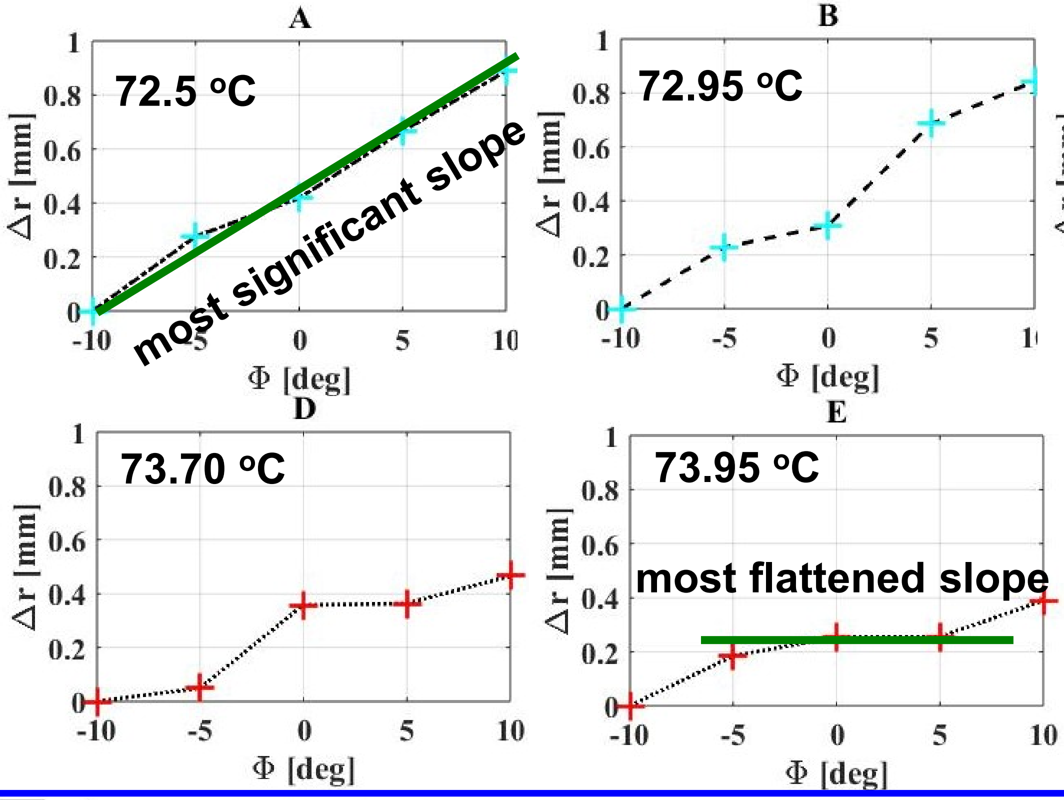


Experiments of gun coupler kick

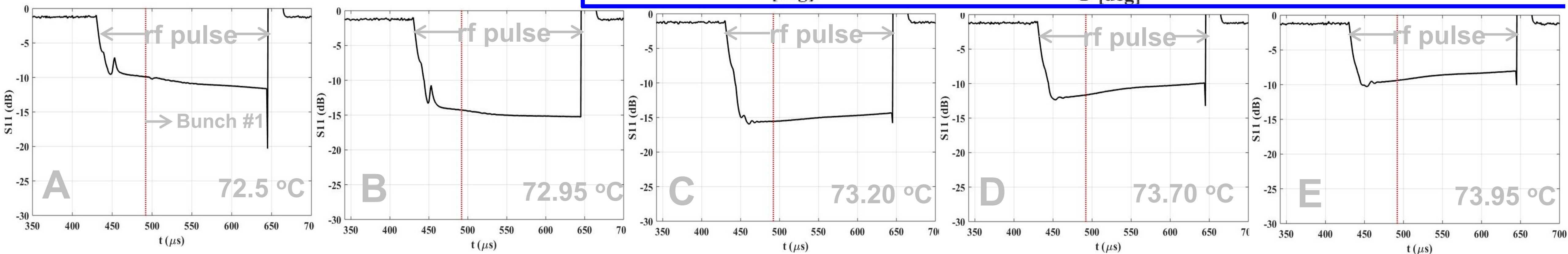
Measured phase slope of the kick

S11 for Bunch #1
vs. Gun water temperature

Measured phase slope of the kick vs. Temperature

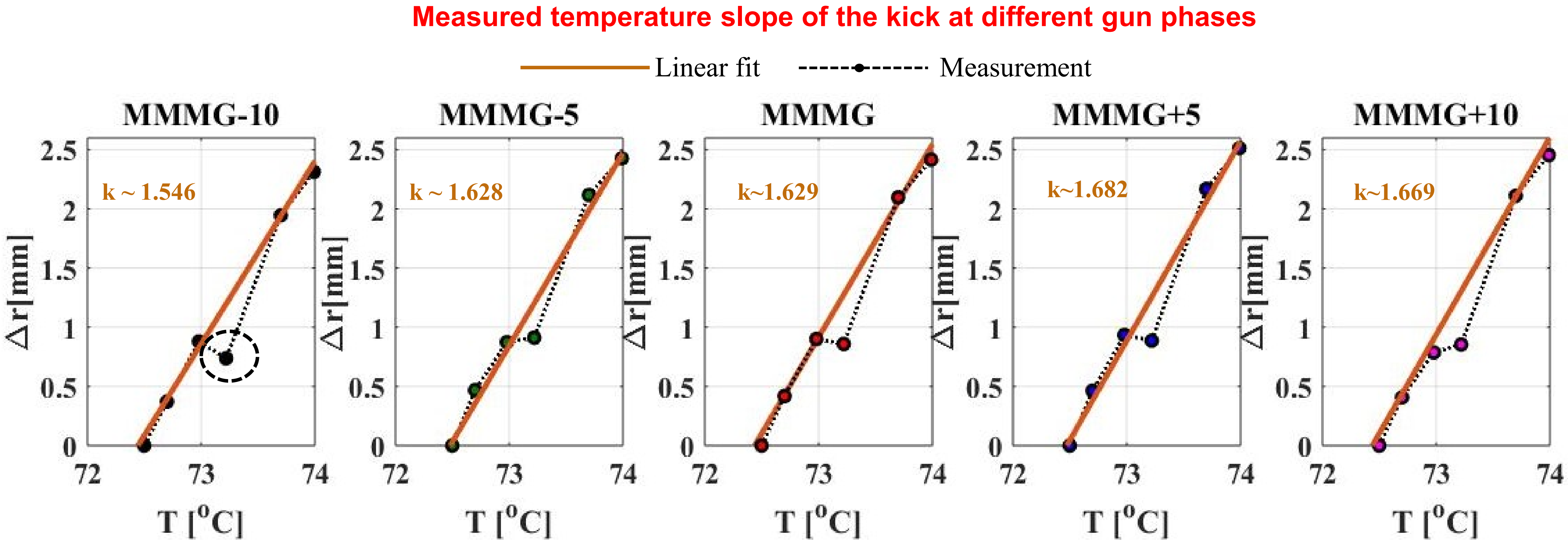


→ Overheated gun has smaller kick slope on rf phase



Experiments of gun coupler kick

Measured temperature / frequency detuning slope of the kick

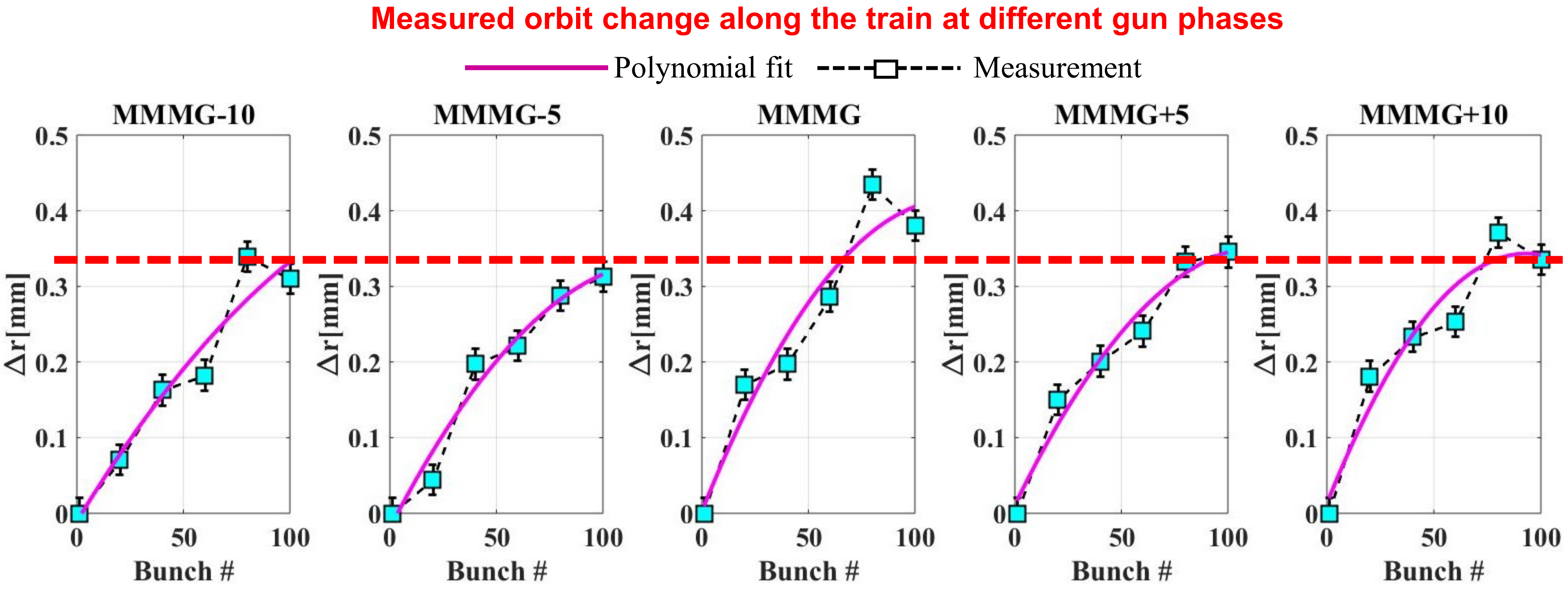


→ ~Linear slope of the kick on temperature / frequency detuning

→ Behavior checked at different gun phases

Experiments of gun coupler kick

Bunch train mode: orbit change



Take radial position change **Δr~320μm** @ downstream screen location **z~5.28m**,

→kick difference between train head and tail, **ΔK~0.063 mrad**

Experiments of gun coupler kick

Peak to Peak orbit change along the train

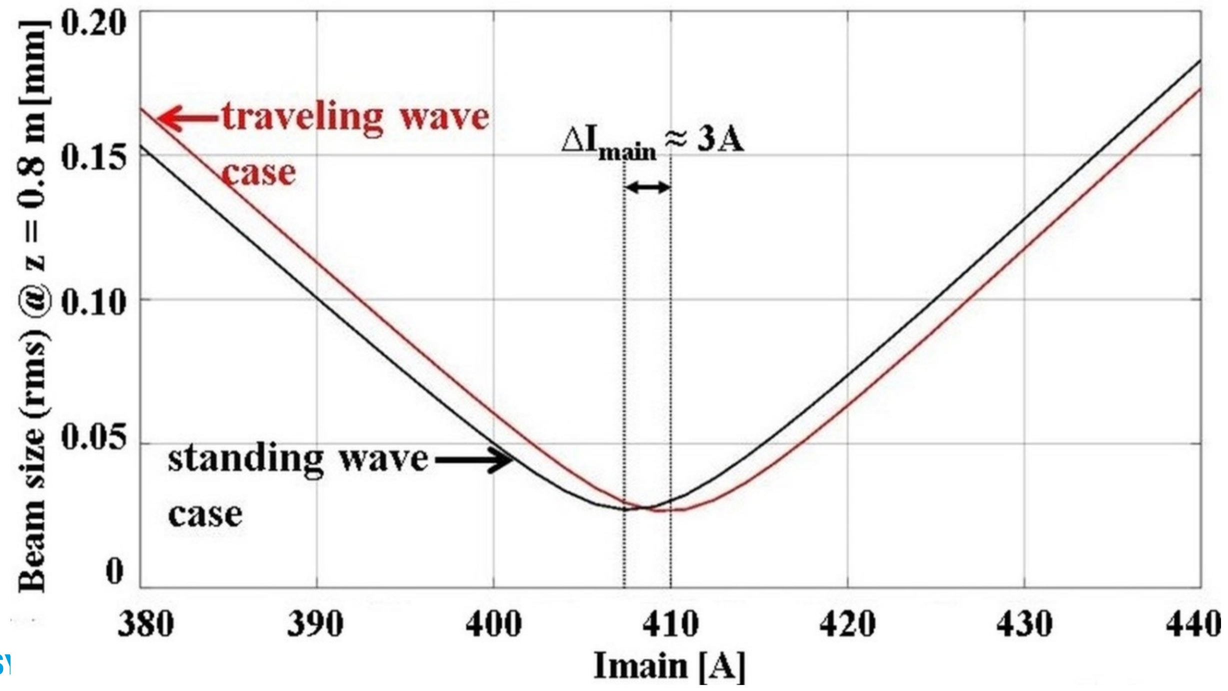
Observation Position	Head-Tail Orbit Change		
	EuXFEL Observation	PITZ Simulation	PITZ Experiment (scaled* to EuXFEL case)
z ≈ 1.0 m	~100 μm	93 μm	~151 μm
z ≈ 2.1 m	~231μm	216 μm	~359 μm

*Linearly scaling the kick with bunch train length

Measurements of additional focusing effect

- **Why "coupler focusing" study?**

  1. **Disturbed rf fields** by the end of coaxial coupler
     → Dipole kick
     → Focusing effect (?)
  2. Use **two field maps** to simulate downstream beam focusing
     → **standing wave** (Eigen mode) vs**. traveling wave** (frequency domain)
     → both normalized to deliver same beam momentum
     → **different solenoid currents needed for best focusing**



Measurements of additional focusing effect

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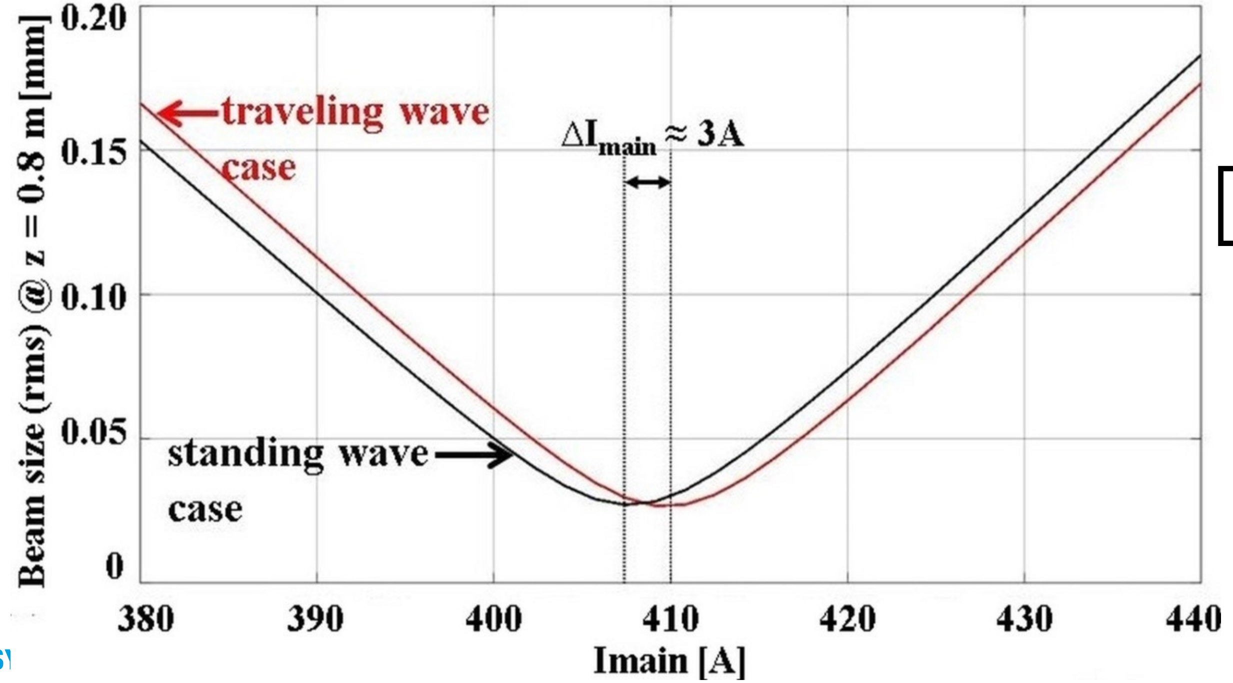
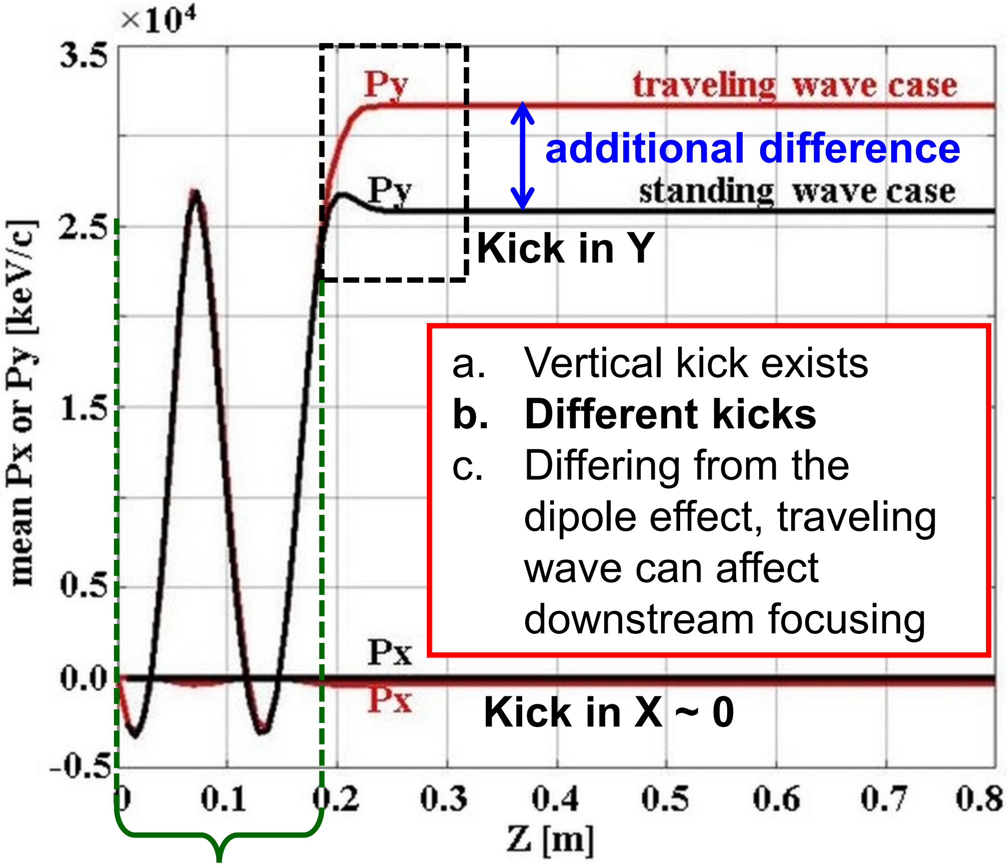


Tracking a bunch through two field maps

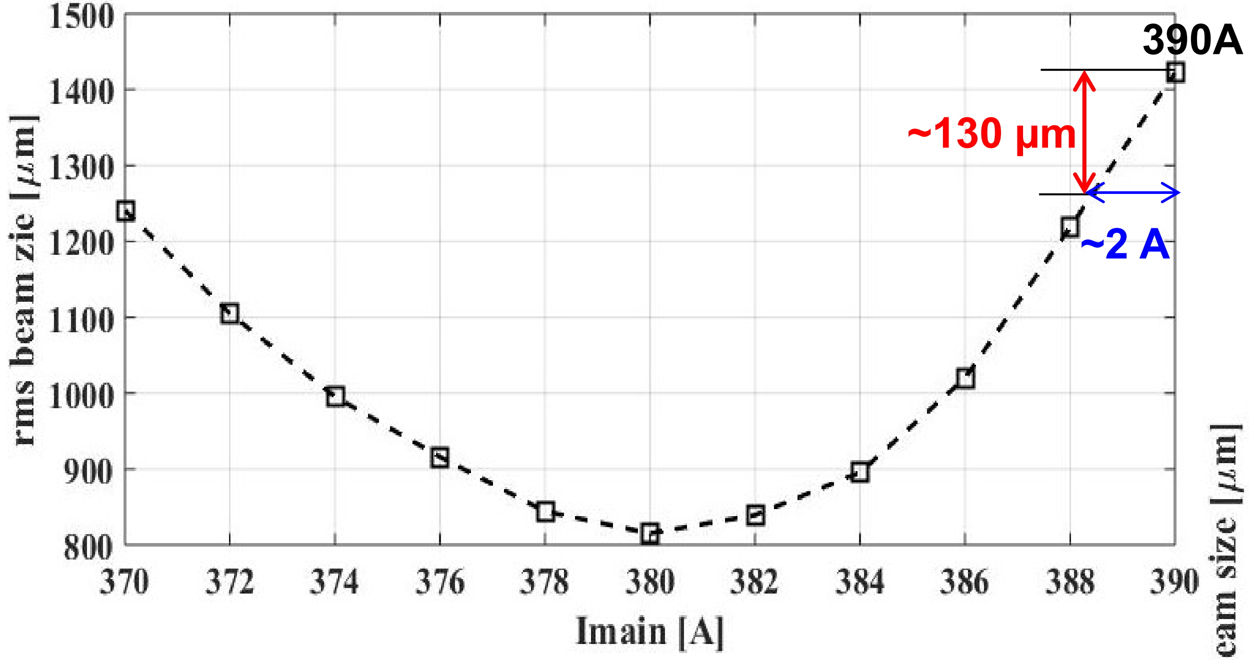


a. Vertical kick exists
b. Different kicks
c. Differing from the dipole effect, traveling wave can affect downstream focusing

Measurements of additional focusing effect

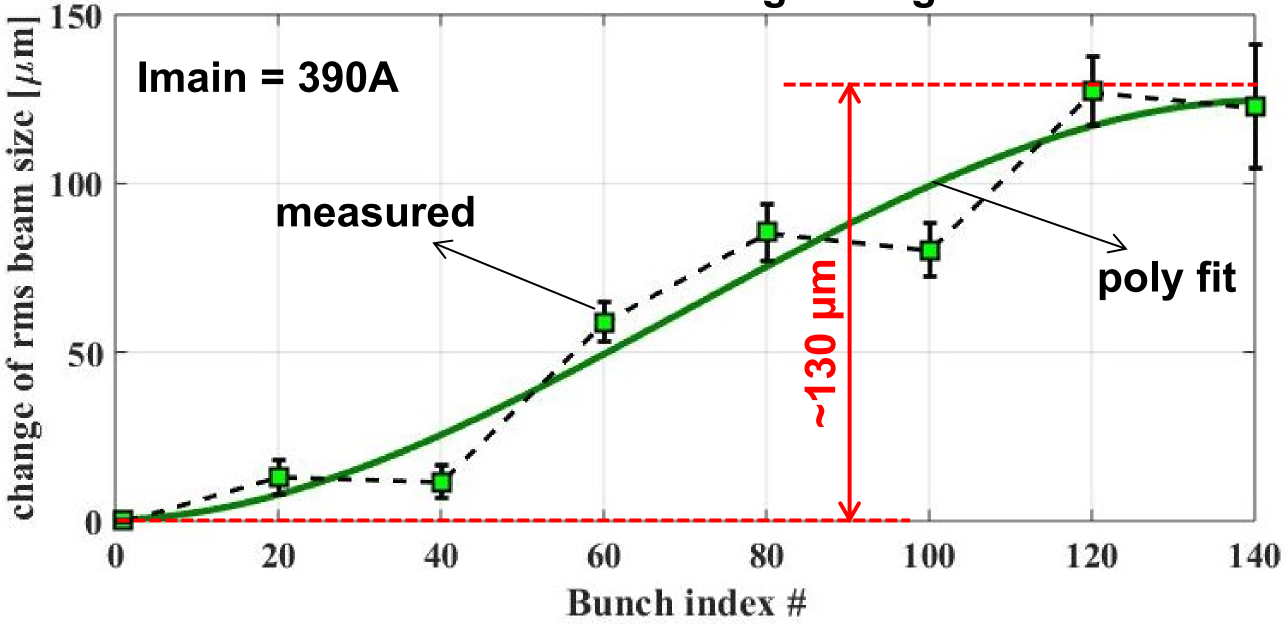
Bunch train mode

Measured rms beam size on H1.S1 vs. Main solenoid current



Conditions:
Gun SP = 65 @ MMMG phase, 200µs
Booster off
Gun Water Set-Point **~ 73.67°C**
100pC, BSA=0.8mm
Adjusted laser transmission for same charge along the train

Measured beam size change along the train



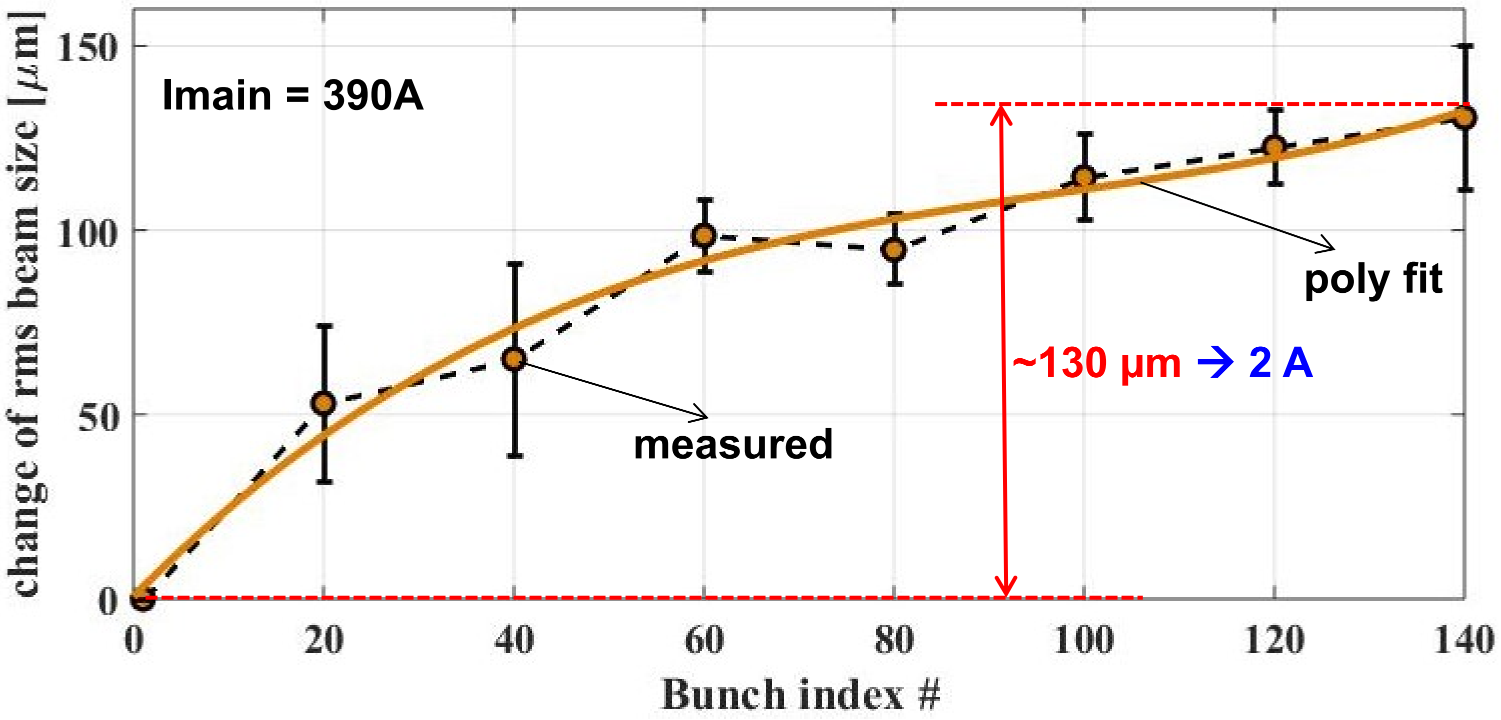
Measurements of additional focusing effect

Bunch train mode

Conditions:
Gun SP = 65 @ MMMG phase, 200µs, Booster off
Gun Water Set-Point **~ 73.30°C**
100pC, BSA=0.8mm
Adjusted laser transmission for same charge along the train

1. At same solenoid current, P2P change of the beam size almost same when changing the cooling water temperature of the gun
2. **Head-tail focusing difference ~ 2A**
3. Stronger effect for longer train
4. Stronger effect for stronger space charge density

Measured beam size change along the train



Summary

- **Two pairs of gun quads** installed allowing **"round beam" optimization** along beamline & **emittance reduction**

- **No sub-structure of e-bunch temporal profiles observed** in PITZ experiments so far when varying bunch charge, BSA size, temporal profile, RF gun phase, emission regime, etc.

- Experiments performed on **gun coupler effects** at PITZ and **measured kick behaviors consistent with simulations**
  - dK/dΦ varies vs. Δf
  - dK/dΔf (or dK/dT) ~ linear
  - for a fixed dK/dΔf, $\Delta K_{head\text{-}tail}$ ~ constant for a given train

- **"Coupler focusing** effect" **depends on frequency detuning within the rf pulse**
  - **2A** difference in solenoid focusing along 140μs bunch train
  - very likely **caused by "traveling wave effect"** (NOT caused by non-symmetrical geometry of the coupler)
  - can influence beam size, emittance, twiss parameters, etc.

Thank you for your attention!