Commissioning of bunch lengthening through an active harmonic cavity in HEPS

Haisheng Xu

on behalf of HEPS commissioning team

Oct. 24, 2025

ESLS RF & HarmonLIP Workshops 2025

Acknowledgements

- We appreciate Dr. Gabriele Benedetti and Pol Solans for the kind discussions and invitation.

- Thank many colleagues in HEPS for helping prepare the slides:
  - RF system: Dr. Pei Zhang, Qunyao Wang
  - AP system: Dr. Yi Jiao, Dr. Na Wang , Dr. Zhe Duan, Dr. Tianmu Xin, Zihang Zhao, Liyan Qin …

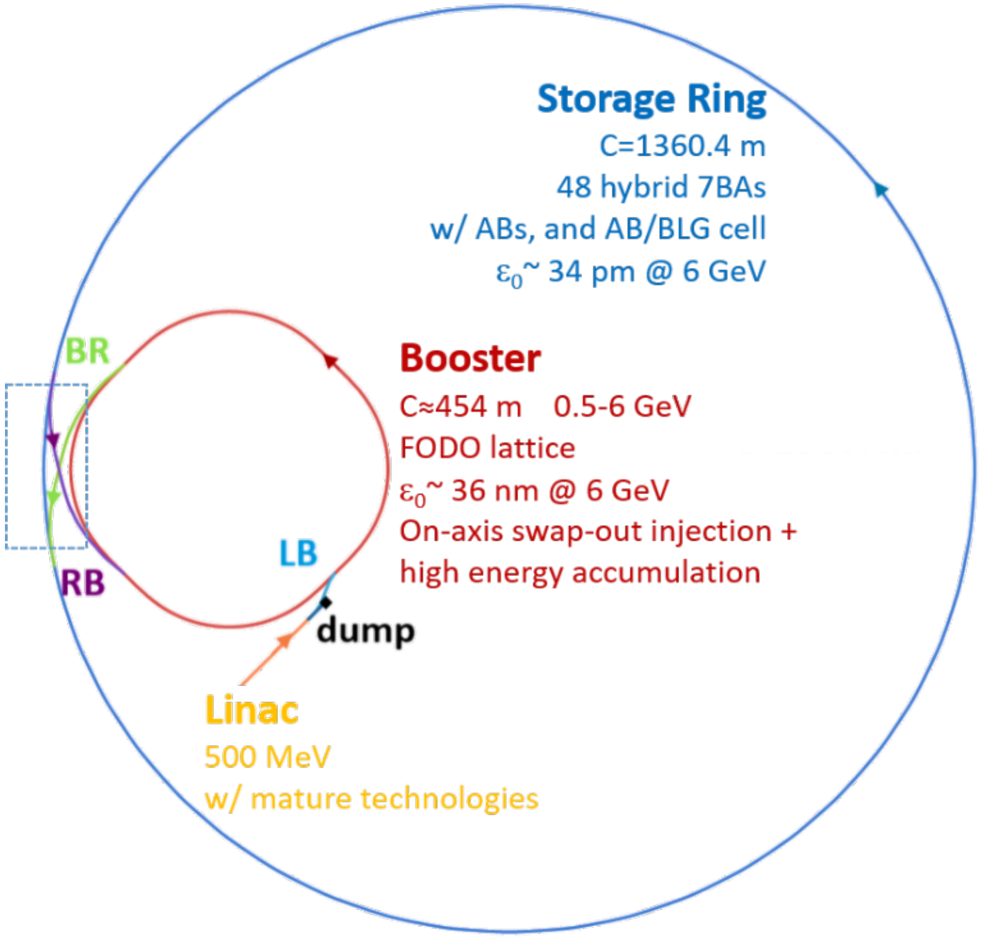
- Thank Dr. Tianlong He (USTC) for the fruitful discussions.

Outlines

- **Brief introduction**
- **Bunch lengthening commissioning of HEPS**
- **Summary & outlooks**

Brief Introduction of HEPS

Main Parameters of HEPS Accelerators



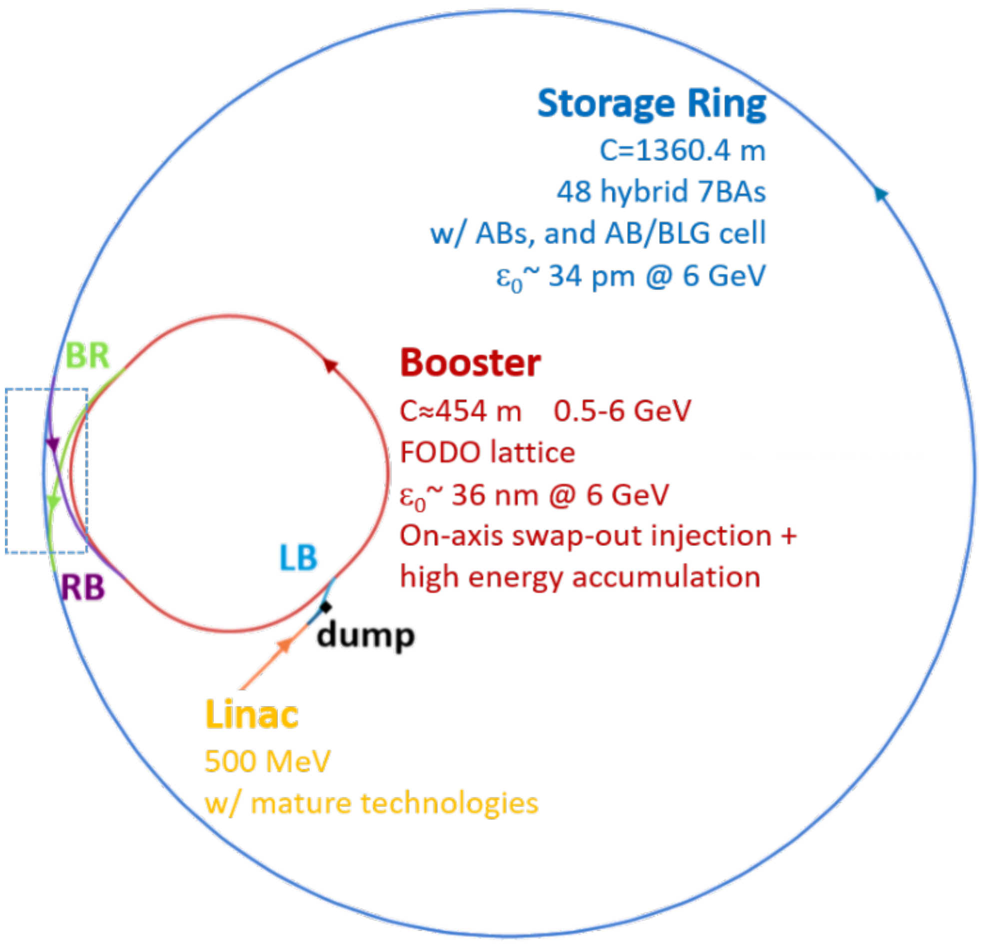
[1] Y. Jiao *et al.*, *J. Synchrotron Rad.* 25, 1611–1618 (2018).
[2] Y. Jiao, *RDTM* 4, 399 (2020).
[3] H. Xu *et al.*, *RDTM* 7, 279–287 (2023).

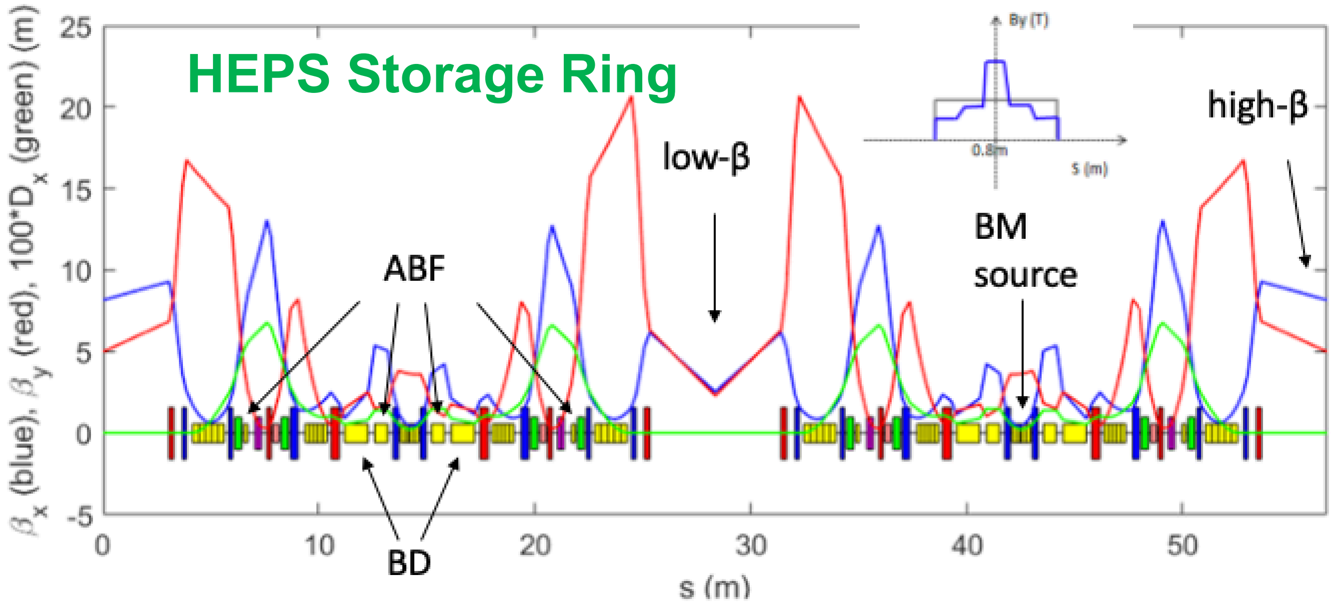
- **Accelerator complex**
  - Linac (500 MeV)
  - Booster (500 MeV to 6 GeV, 1 Hz)
  - Storage ring (6 GeV, top-up)

Parameter	Value	Unit
Beam energy	6	GeV
Circumference	1360.4	m
Lattice type	Hybrid 7BA	
Hori. Natural emittance	<60	pm·rad
Brightness	$>1\times10^{22}$	*
Beam current	200	mA
Injection mode	Top-up	-

*: phs/s/mm²/mrad²/0.1%BW

Main Parameters of HEPS Accelerators



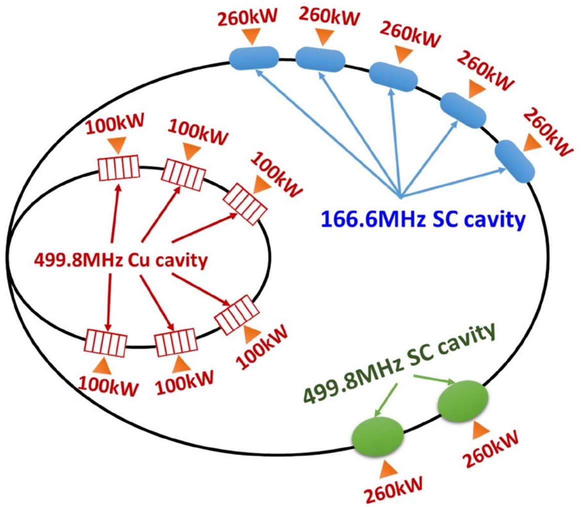


1700+ Magnets **19 IDs**

~1300 vacuum chambers

500+ BPMs **288 Girders**

5 166MHz SRF **2 500MHz SRF**



[1] Y. Jiao *et al.*, *J. Synchrotron Rad.* 25, 1611–1618 (2018).
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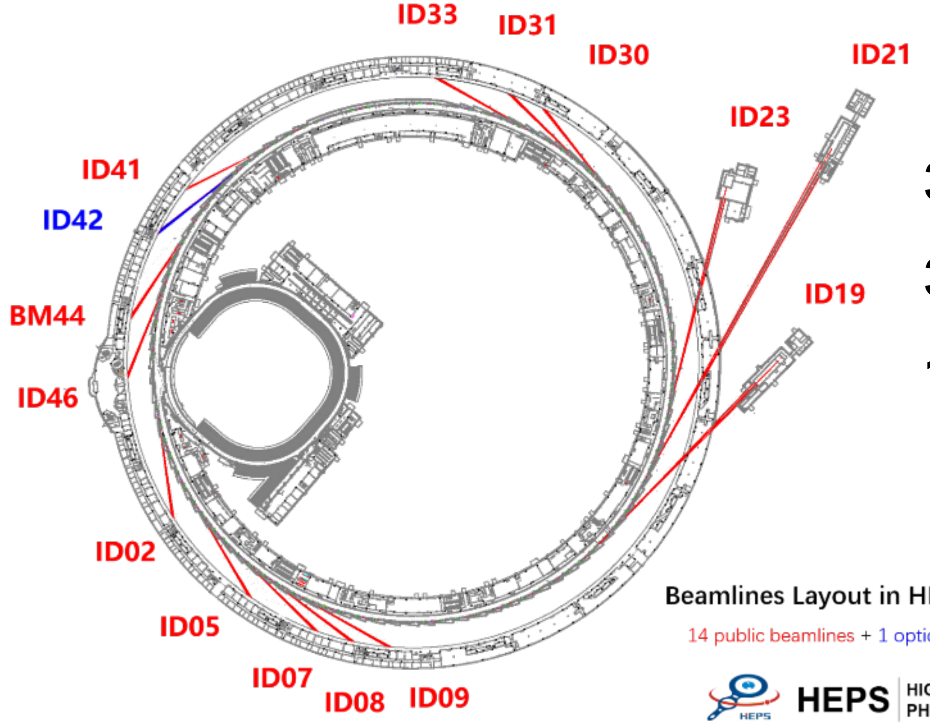
Main Parameters of HEPS Phase-I Beamlines

- Brightness of 5×10^{22} phs/s/mm²/mrad²/0.1%BW at the photon energy of 21 keV, can provide X-ray with energy up to 300 keV
- **14 user beamlines + 1 test BL** in Phase 1, HEPS can accommodate up to 90 BLs



Beamlines Layout in HEPS phase I

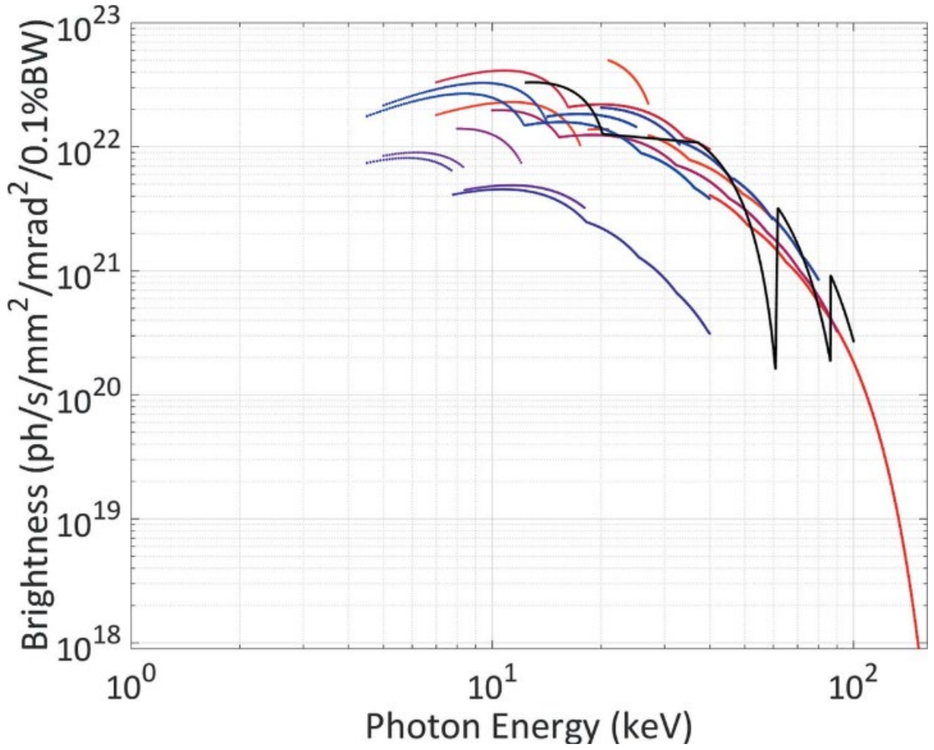
14 public beamlines + 1 optics test beamline

HEPS HIGH ENERGY PHOTON SOURCE

3 long BLs

350m longest

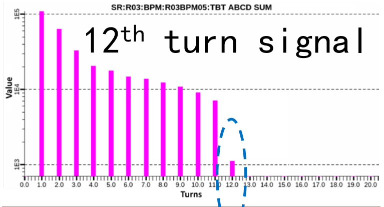
19 IDs 6 types



Y. Jiao *et al.*, *J. Synchrotron Rad.* 25, 1611–1618 (2018).

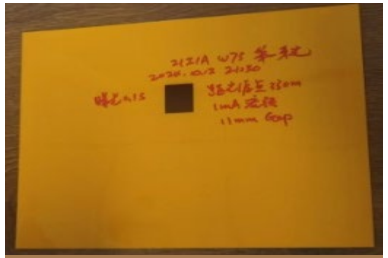
Milestones of HEPS SR commissioning

Commissioning commenced

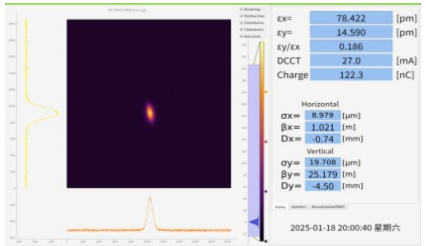


circulation > 10 turns

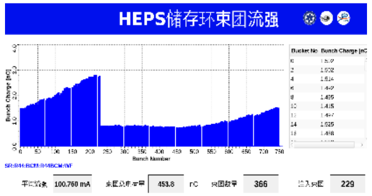
beam current reaches 12 mA



first light from ID



Emittance better than 100pm

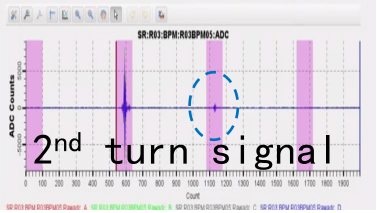


beam current reaches 100mA

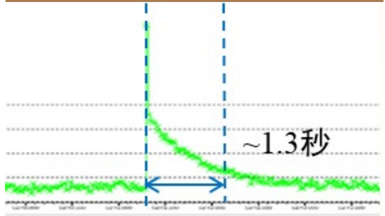
2024.07.23 — 2024.08.04 — 2024.09.22 — 2025.01.02 — 2025.03.18 — 2025.09.13

2024.07.23 — 2024.07.29 — 2024.08.18 — 2024.10.12 — 2025.01.12 — 2025.09.12

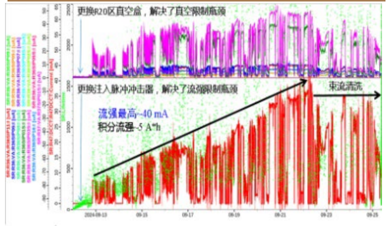
1st complete turn



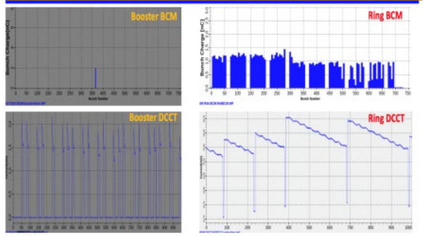
First stored beam



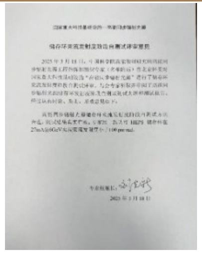
beam current reaches 40mA



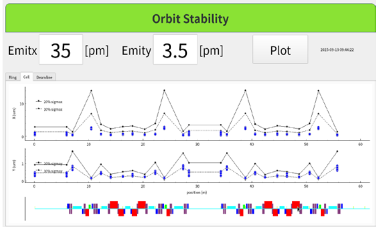
injection scheme demonstrated



emittance result passed review

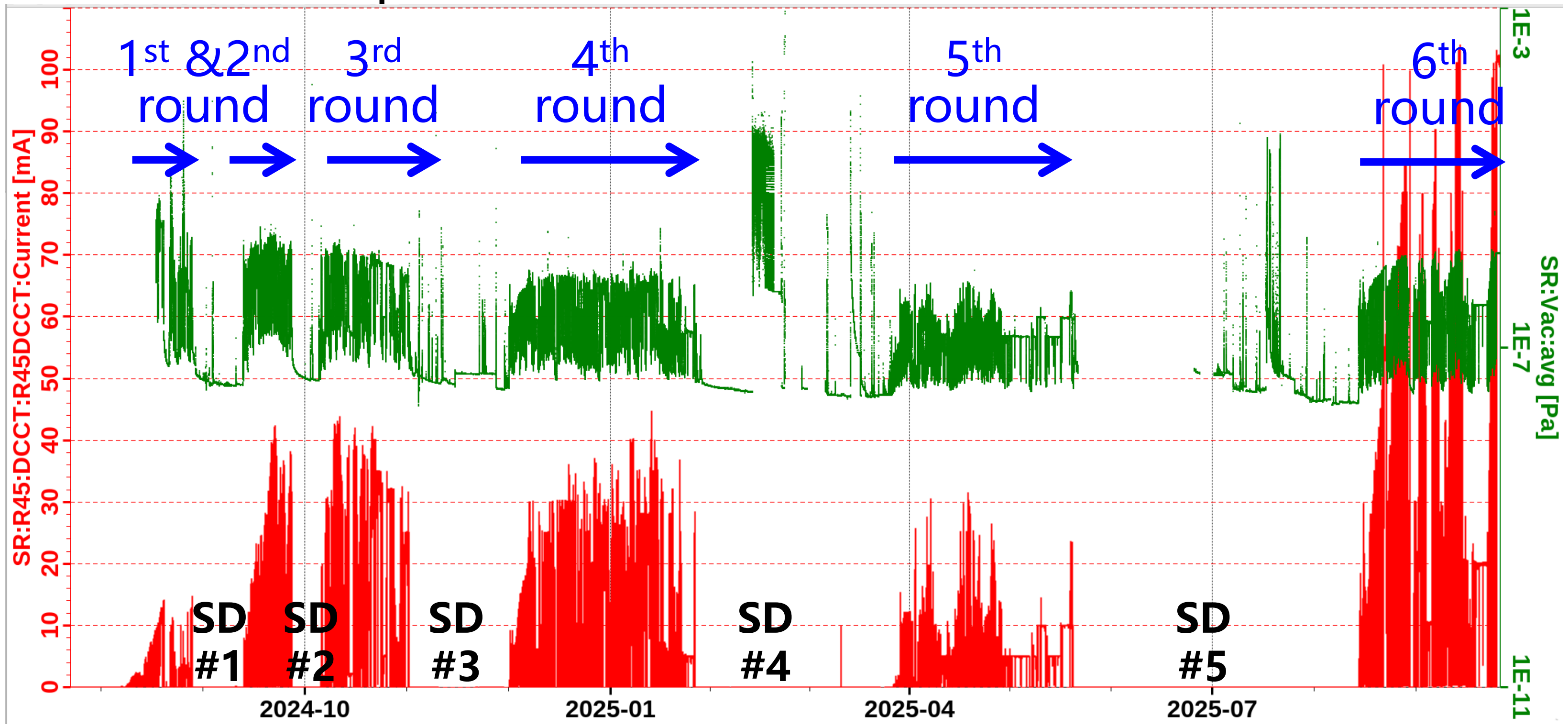


beam orbit stability better than 20%



Brief history of SR commissioning

- Not all hardware systems were ready at Day One
- The commissioning was paused a few times mainly for installation
- Staged commissioning
  - injection: slotted-pipe kicker -> stripline kicker
  - **RF: 500MHz RF -> 166 MHz RF + 500 MHz (3rd harmonic)**
  - ID: backup vacuum chamber -> In-air IDs -> In-vacuum IDs



1st round:
1, from first turn to 12 mA
2nd round:
1, ramp up current to ~40mA
3rd round:
1, first ID light, beamlines tuning
4th round:
1, optics corrections, < 100 pm emittance
2, demonstration of the injection scheme
3, beamlines tunings
5th round:
1, more optics corrections
2, beamlines tunings
6th round:
1, bunch lengthening
2, SR tunings for KPPs
3, beamlines tunings

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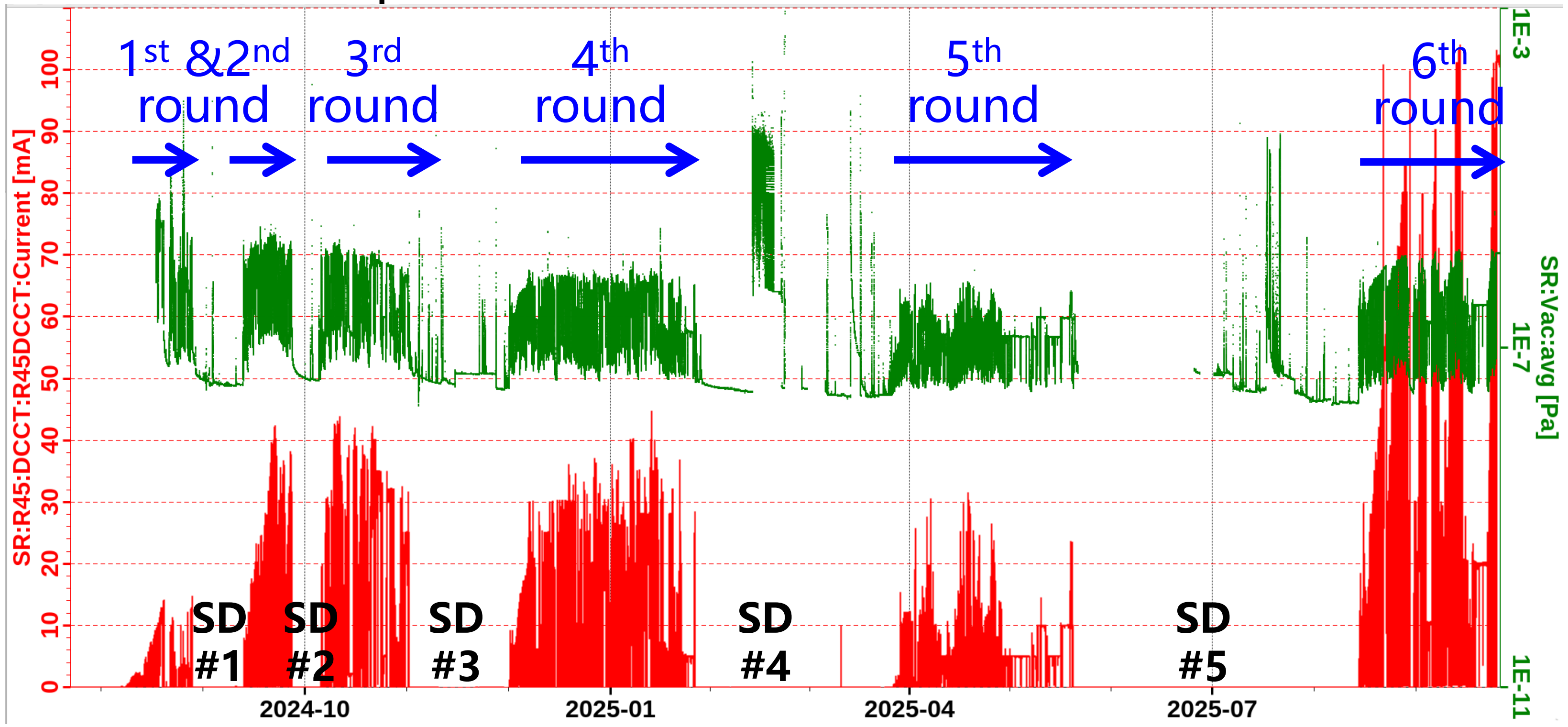


SD#1:
1, replace injection kickers & pulsers
2, replace R20VC14 vacuum chamber
SD#2:
1, replace vacuum chambers of ID21/42/46;
SD#3:
1, install ID09;
2, replace vacuum chambers of ID08 & ID30;
3, install 3 collimators;
4, replace 500MHz SCC;
SD#4:
1, install most IDs;
2, fine global alignment;
3, install beam dump kicker;
SD#5:
1, install 166MHz & 500MHz SCCs;
2, install 4th collimator;
3, fine alignment of booster;
4, install remaining IDs

Status of HEPS Storage Ring Commissioning

- Passed accelerator performance tests in Sep 26-29, now in full swing to reach beamlines KPPs

Parameter	Design	KPP#	Measurement	Unit
Beam energy	6	6	6.01	GeV
Beam current	200	100	100.5	mA
Natural emittance	34.8	100	56.8$	pm·rad
Beam stability	10%	20%	< 19.8%	fraction of rms beam size & divergence
Brightness	$>1\times10^{22}$	2×10^{21}	4.00×10^{21}	phs/s/mm^2/mrad^2/0.1 %BW
Capability of providing X-rays of 300 keV			349.57	keV

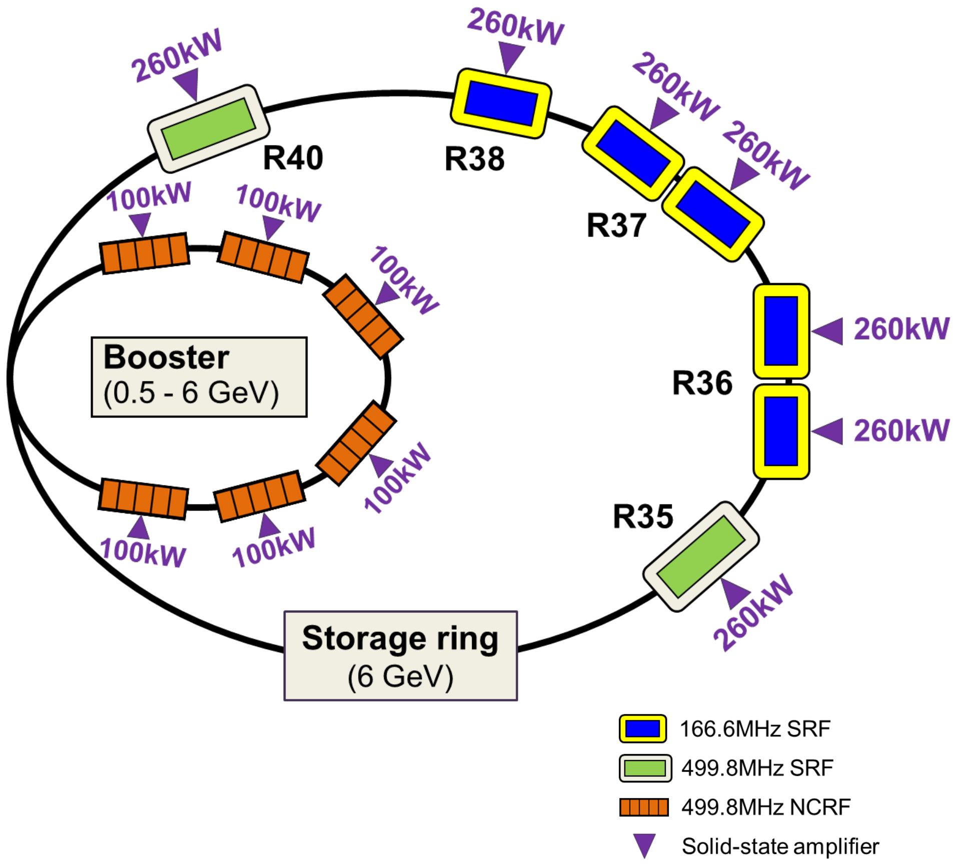
Key performance parameters for national acceptance test

$ Measured horizontal + vertical emittance @ 100 mA, with grating interferometry

HEPS RF system

Courtesy of Qunyao Wang

- **Cavities**
  - 5 sets of 166.6 MHz SRF cavity modules
  - 2 sets of 499.8 MHz SRF cavity modules
  - 6 sets of 499.8 MHz NCRF cavities
- **High-power RF**
  - 5 sets of 166.6 MHz 260 kW solid-state power amplifiers
  - 2 sets of 499.8 MHz 260 kW solid-state power amplifiers
  - 6 sets of 499.8 MHz 100 kW solid-state power amplifiers
- **RF controls**
  - 5 sets of 166.6 MHz RF control systems
  - 8 sets of 499.8 MHz RF control systems



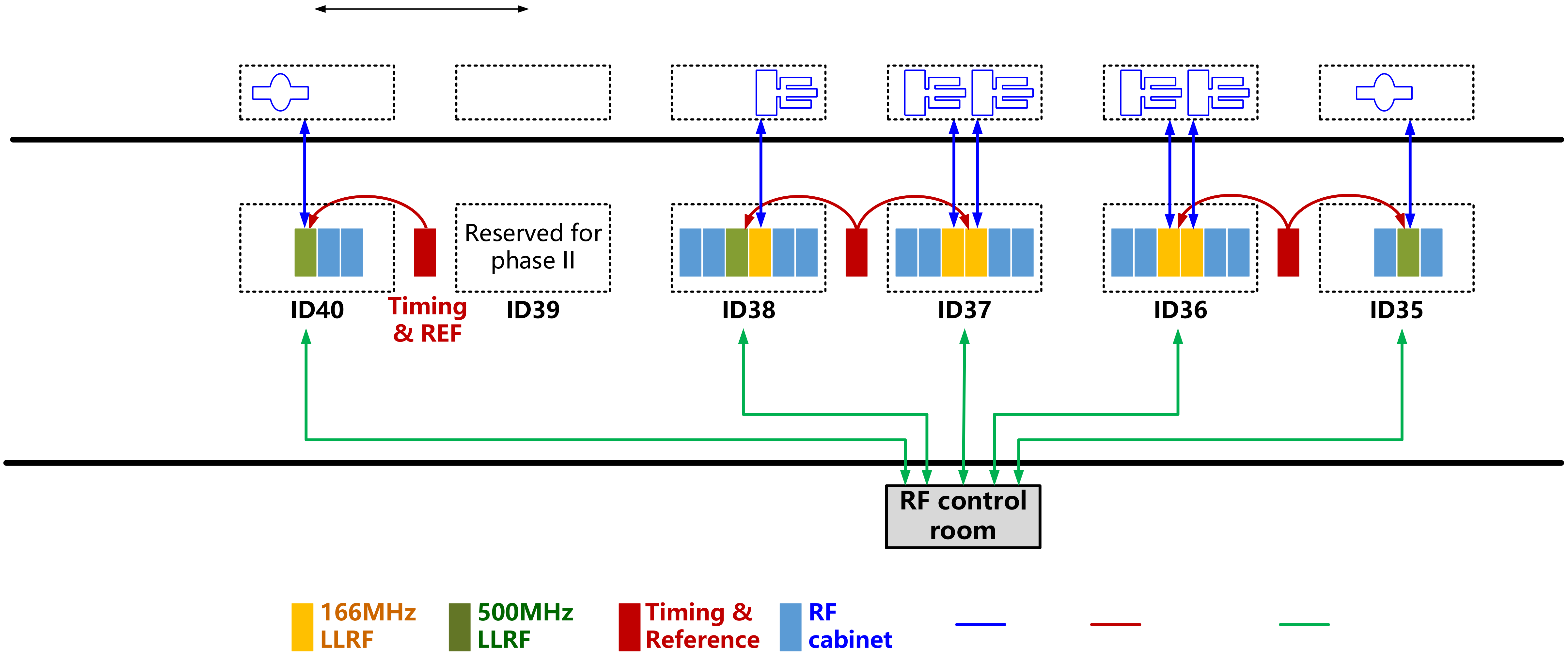
RF parameters

Courtesy of Qunyao Wang

	BS	SR (main)	SR (HC)	Unit
RF frequency	499.8	166.6	499.8	MHz
Total RF voltage	2 – 8	5.4	0.91	MV
Cavity technology	Normal-conducting	Superconducting	Superconducting	-
Cavity type	5-cell	β=1 quarter-wave	1-cell elliptical	-
Technology readiness	Mature product	In-house new dev.	In-house exp.	-
No. of cavities	6	5	2	-
RF voltage per cavity	1.35 (op.) 1.9 (design)	1.2 (op.) 1.5 (design)	0.91 (op.) 1.75 (design)	MV
RF power per cavity (max)	70 (61 cav + 9 beam)	170	105	kW
No. of transmitters	6	5	2	-
RF power per transmitter	100 (cw)	260 (cw)	260 (cw)	kW
Transmitter technology	SSA	SSA	SSA	-
LLRF control stability (pk-pk)	±1%, ±1°	±0.1%, ±0.1°	±0.1%, ±0.1°	-
LLRF technology	Digital LLRF (in-house development)			-

RF control layout (storage ring)

Courtesy of Qunyao Wang



F. Zhao et al., Interface description between SR-RF and TS division (Vol 1), HEPS-RF-ES-007, 2019. (In Chinese)

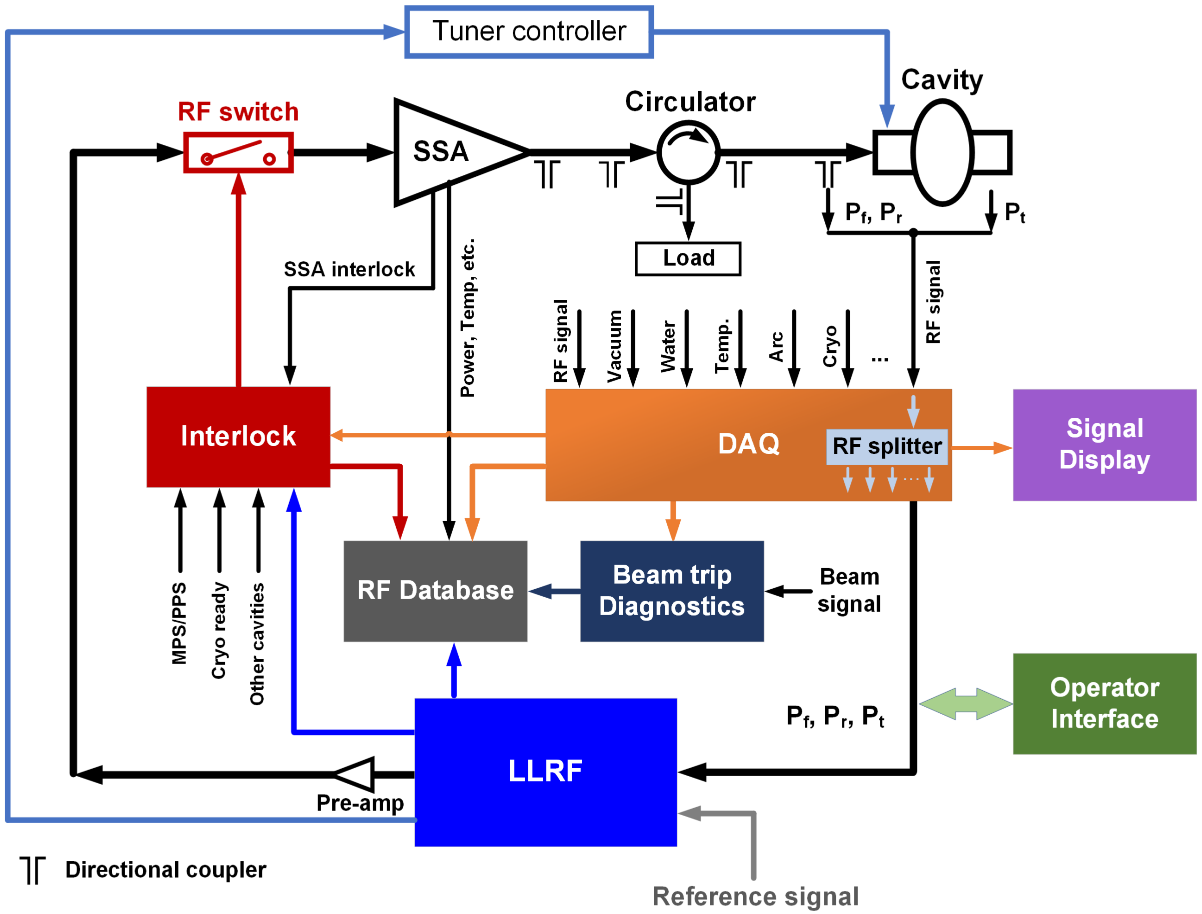
RF station

Courtesy of Qunyao Wang

Main constituents of each RF station: cavity, SSA, **LLRF**

Main components of LLRF

- **LLRF controller**
- **RF interlock**
- **DAQ**
- **RF database**
- **Beam trip Diagnostics**
- **Signal monitoring & display**
- **High-level interface (OPI)**



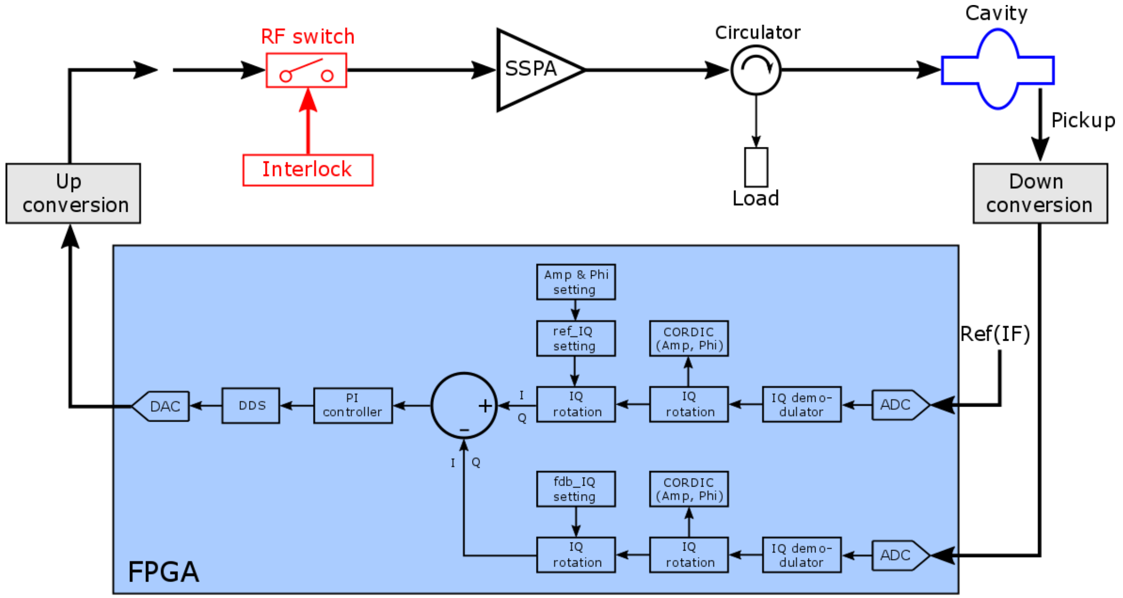
LLRF functions

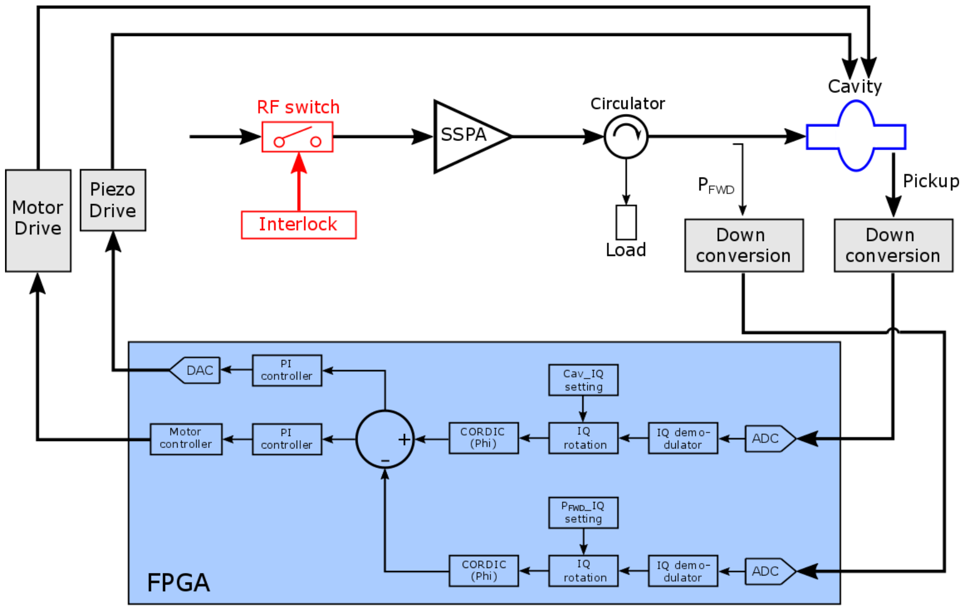
Courtesy of Qunyao Wang

Parameter	BS	SR-166	SR-500
Amplitude loop	Y	Y	Y
Phase loop	Y	Y	Y
Resonance loop	Motor	Motor & Piezo	Motor & Piezo
Field-flatness loop	Y	N	N
Ramping	Y	N	N
Refl. power interlock	Y	N	N
Phase-locked loop (PLL)	Y	N	N
Quench detection	N	Y	Y
GDR/SEL	GDR	GDR&SEL	GDR&SEL
Stability (pk-pk)	±1%， ±1°	±0.1%， ±0.1°	±0.1%， ±0.1°

Cavity field & resonance control: I/Q

Courtesy of Qunyao Wang





- **IQ vector control (field)**
  - Sample ref. & pickup signals
  - Non-IQ demodulate to IQ
  - IQ errors to PI controller
  - DDS output IF drive signal

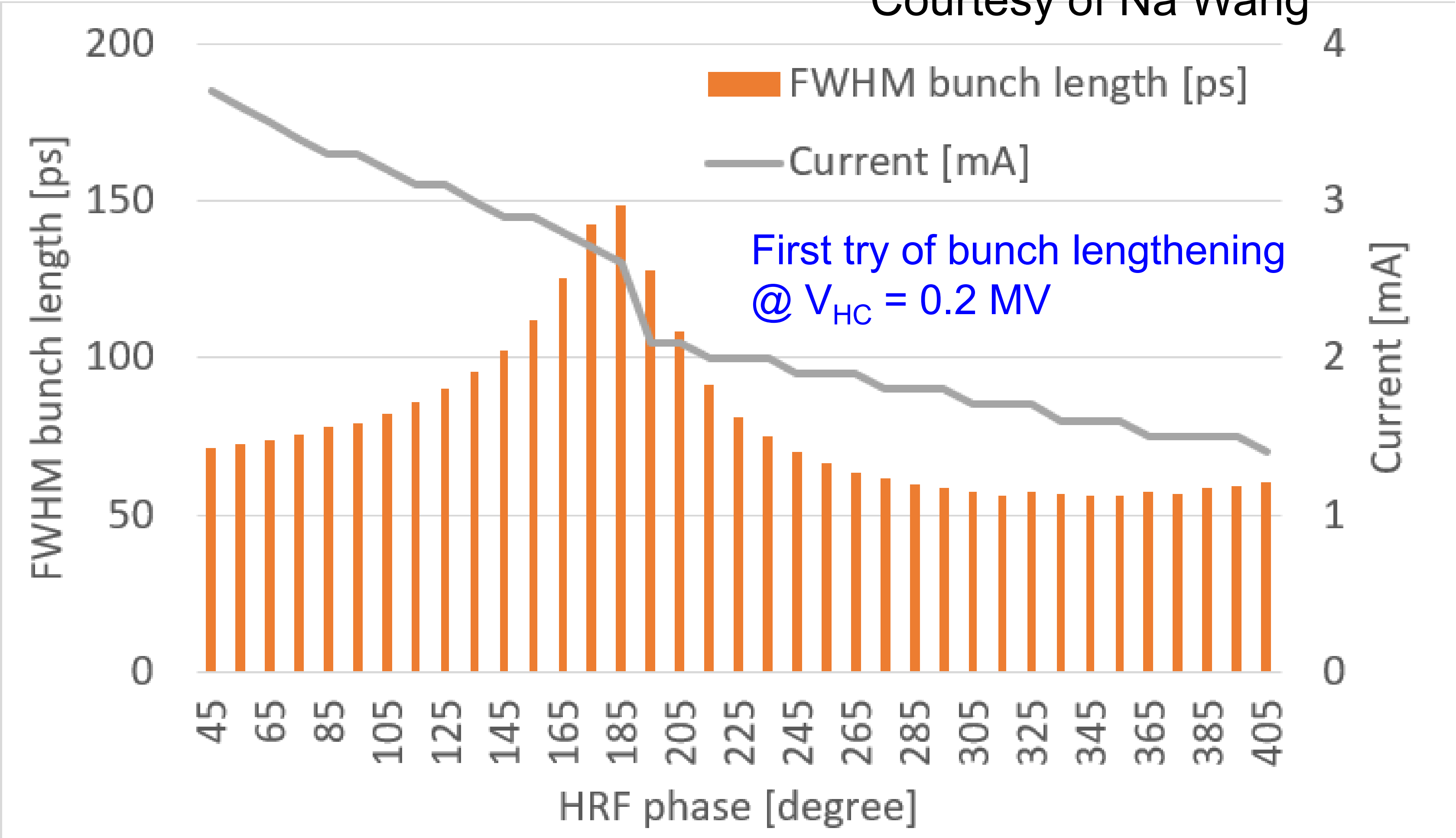
- **IQ vector control (resonance)**
  - Sample fwd. & pickup signals
  - Demodulate to IQ -> phase error
  - SC cavity tuner: Motor & Piezo
  - NC cavity tuner: Motor

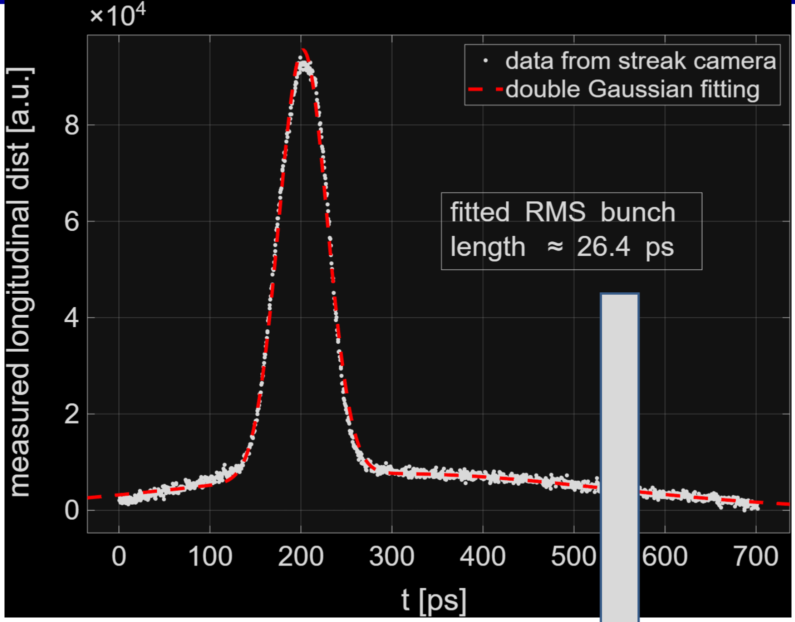
Bunch lengthening commissioning

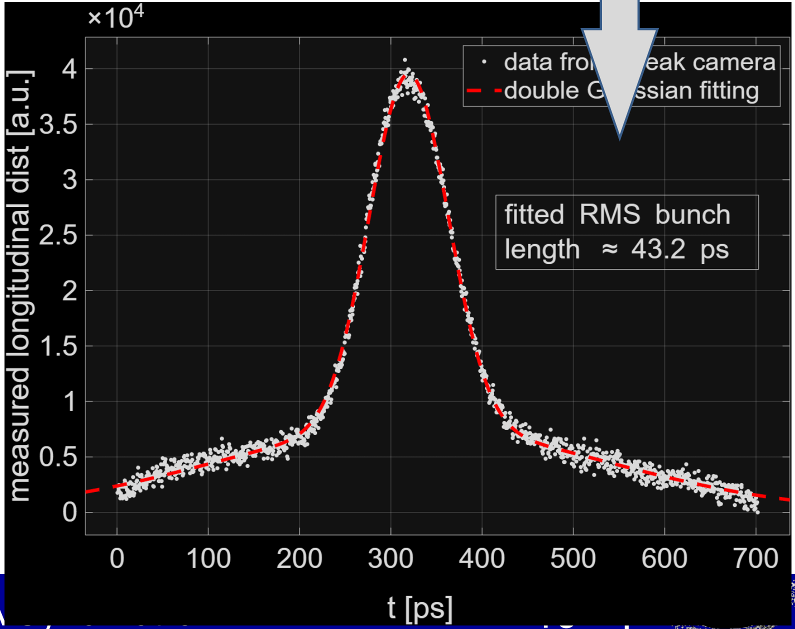
Near-ideal flat-top distribution achieved 'easily'

- **Aug. 14, the 1st attempt --- approximately 1.6 times lengthening**

Courtesy of Na Wang

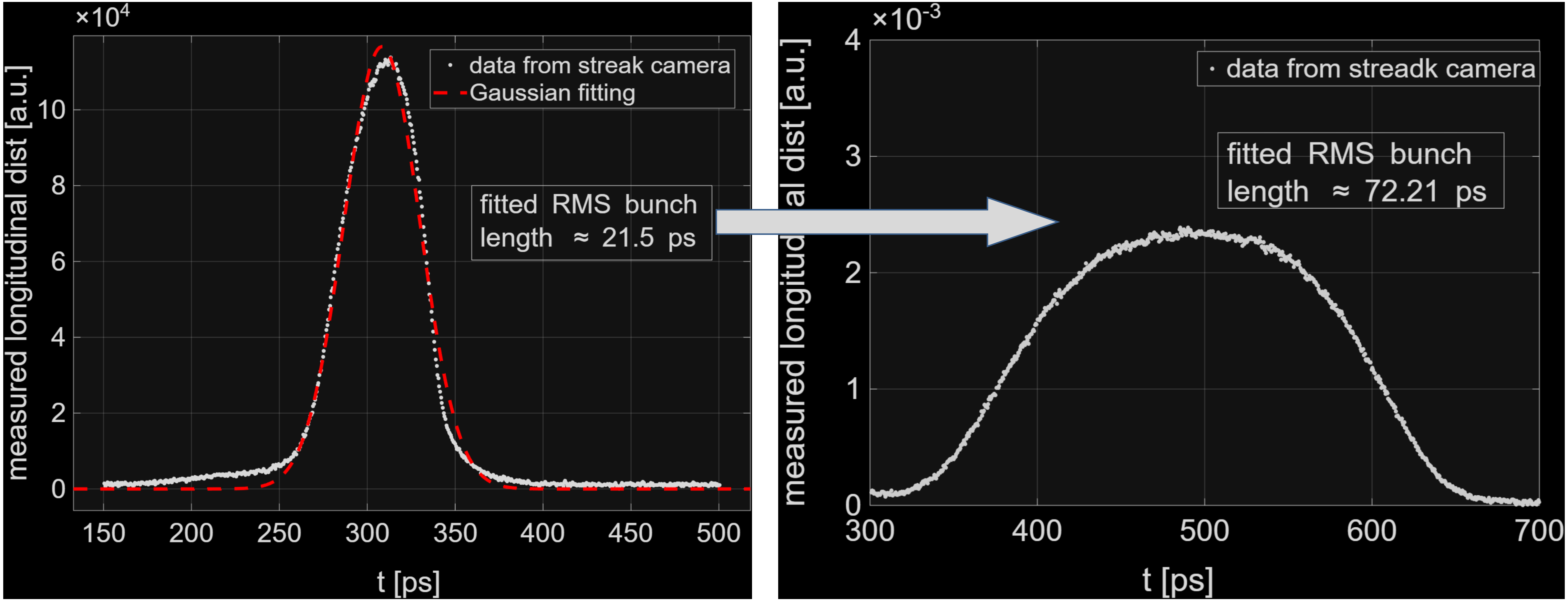






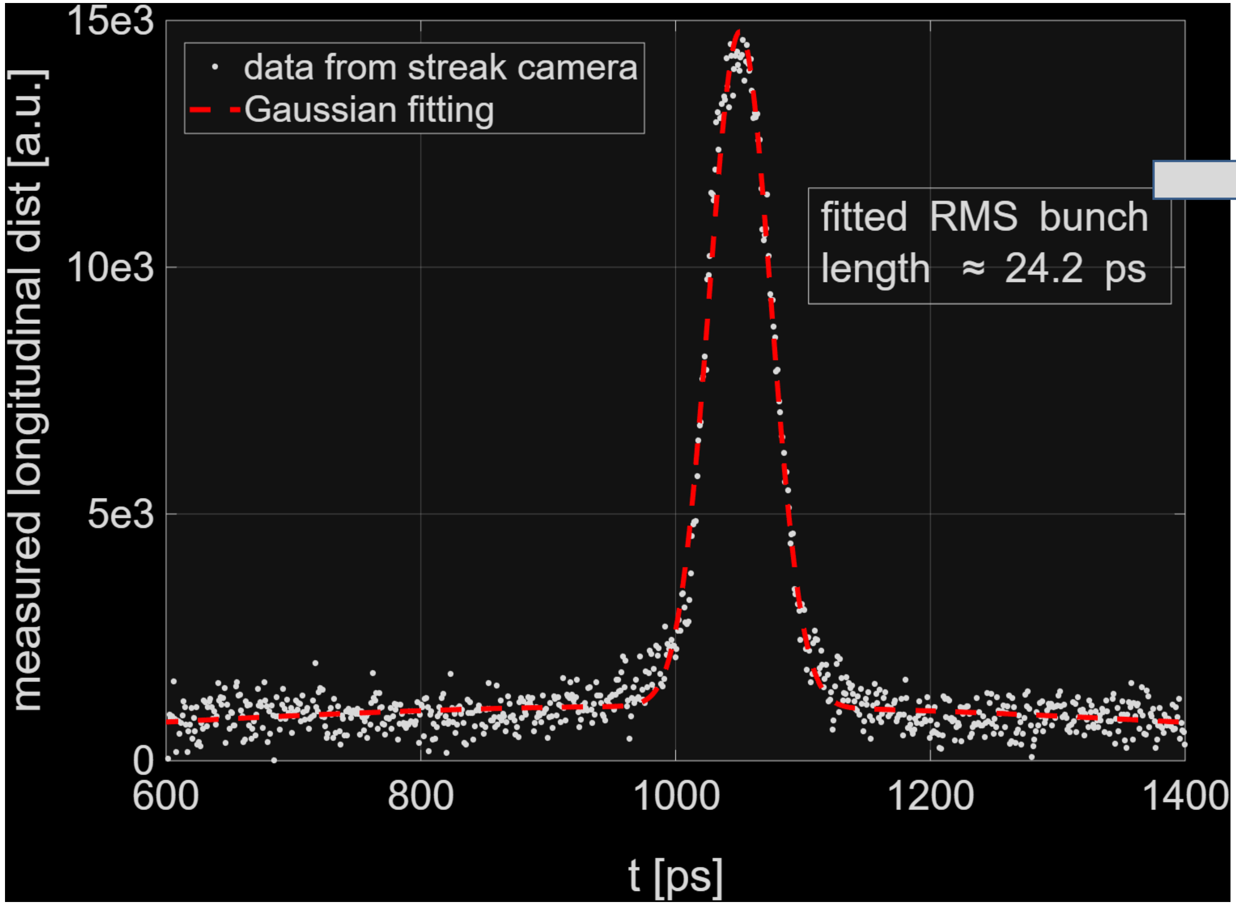
Near-ideal flat-top distribution achieved ‘easily’

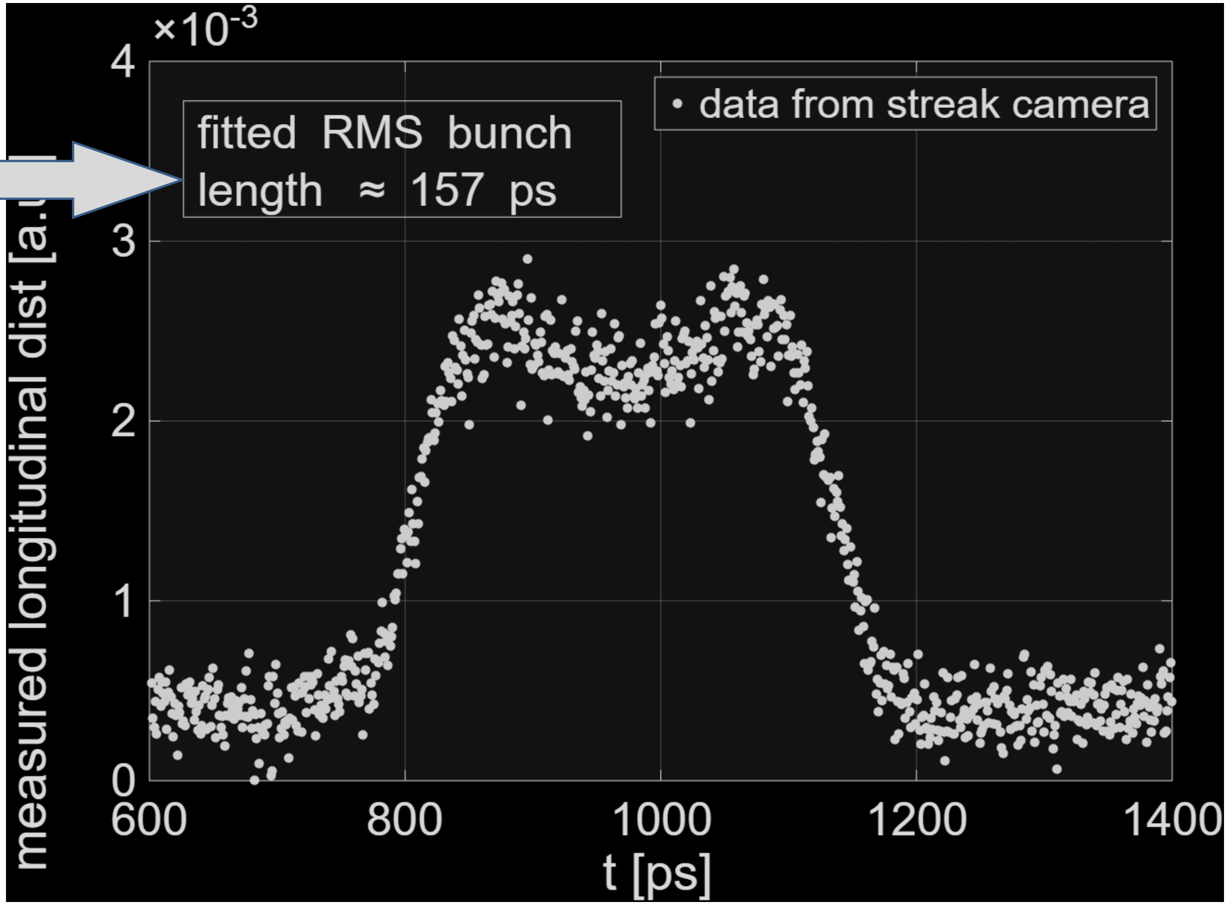
- **Aug. 18, the 2nd attempt --- approximately 3.4 times lengthening**



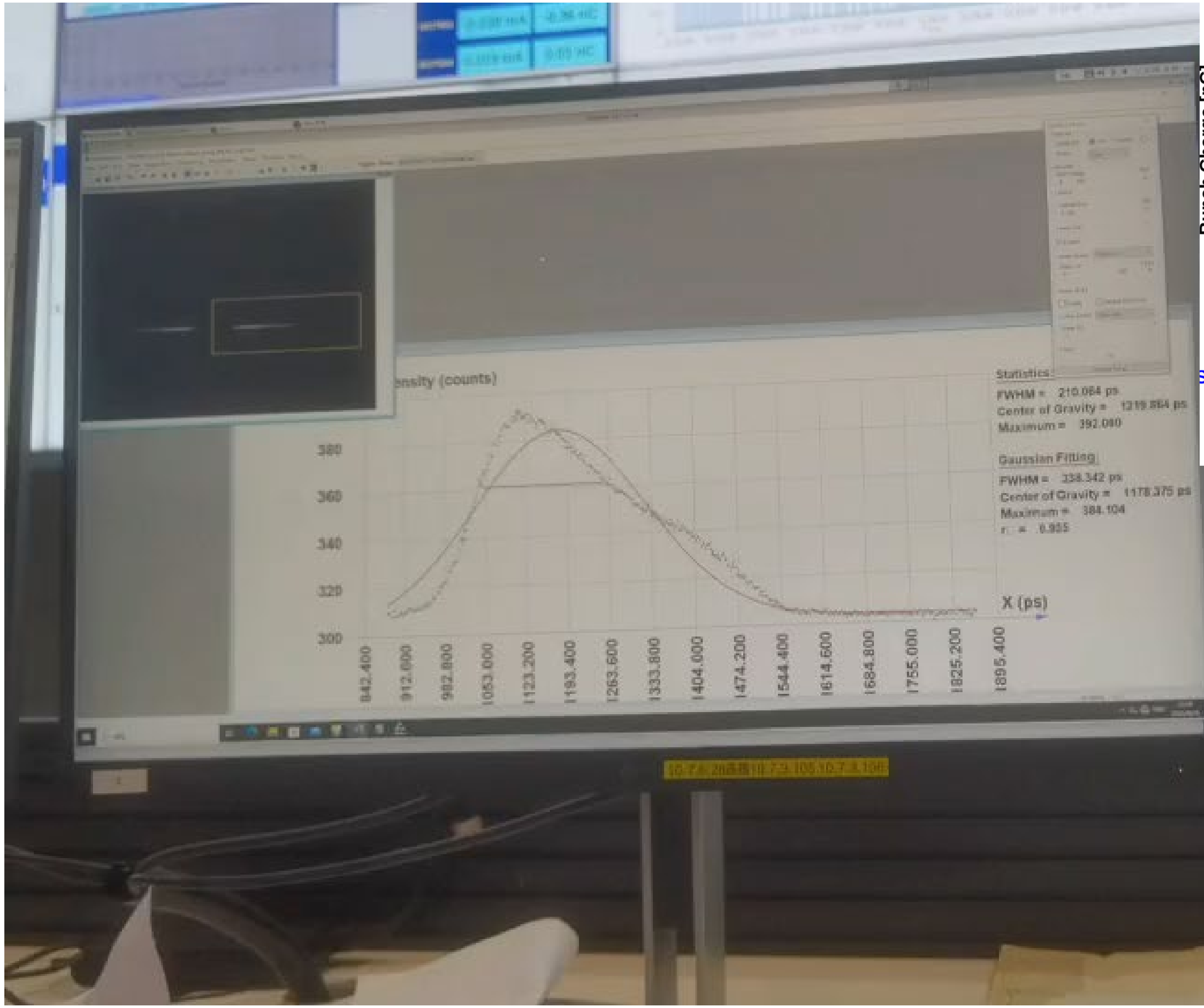
Near-ideal flat-top distribution achieved ‘easily’

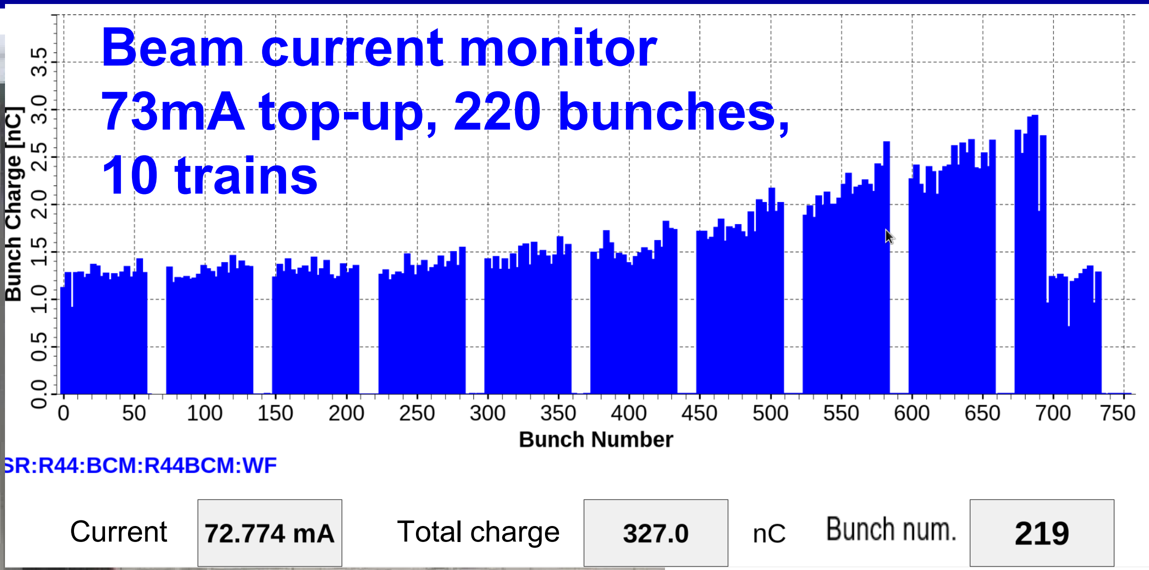
- **Sep. 09, the xx attempt --- approximately 6.5 times lengthening (overstretching)**



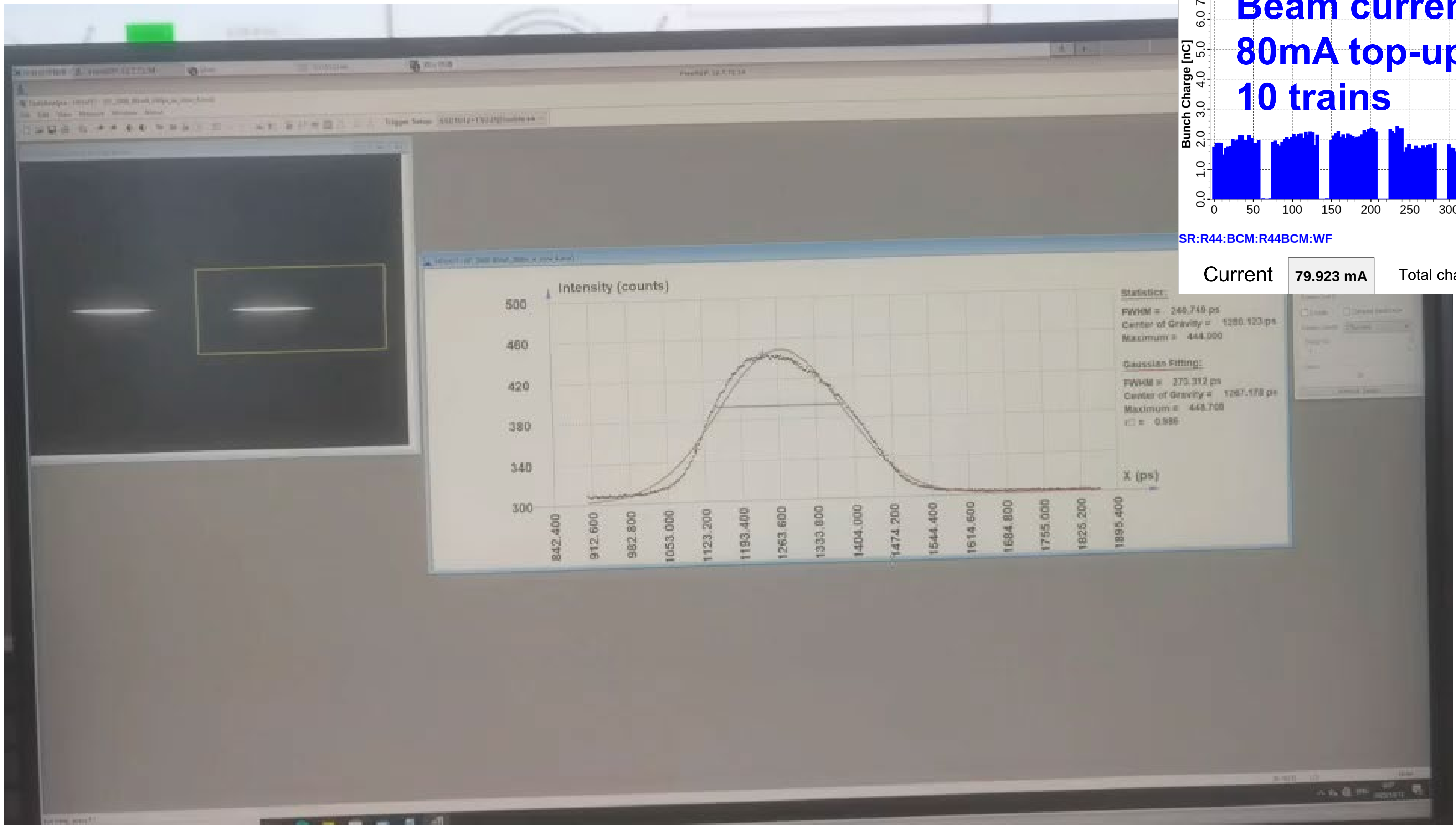


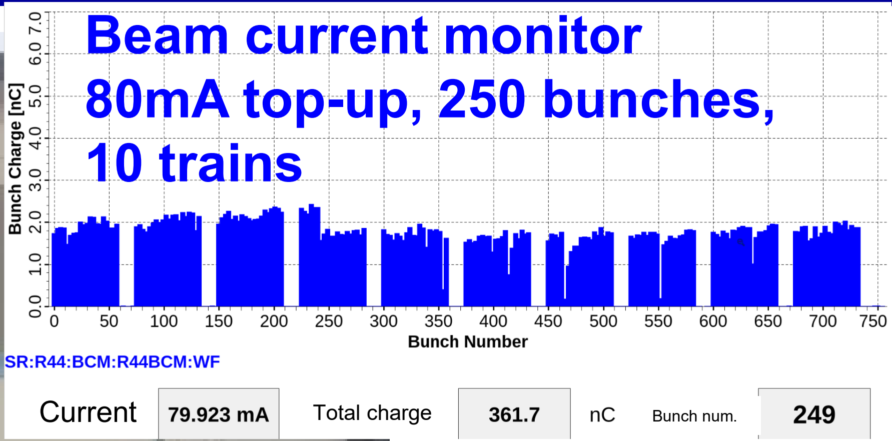
Very ‘slow’ oscillation of bunch distribution





Stable when staying ‘far away’ from the ideal lengthening



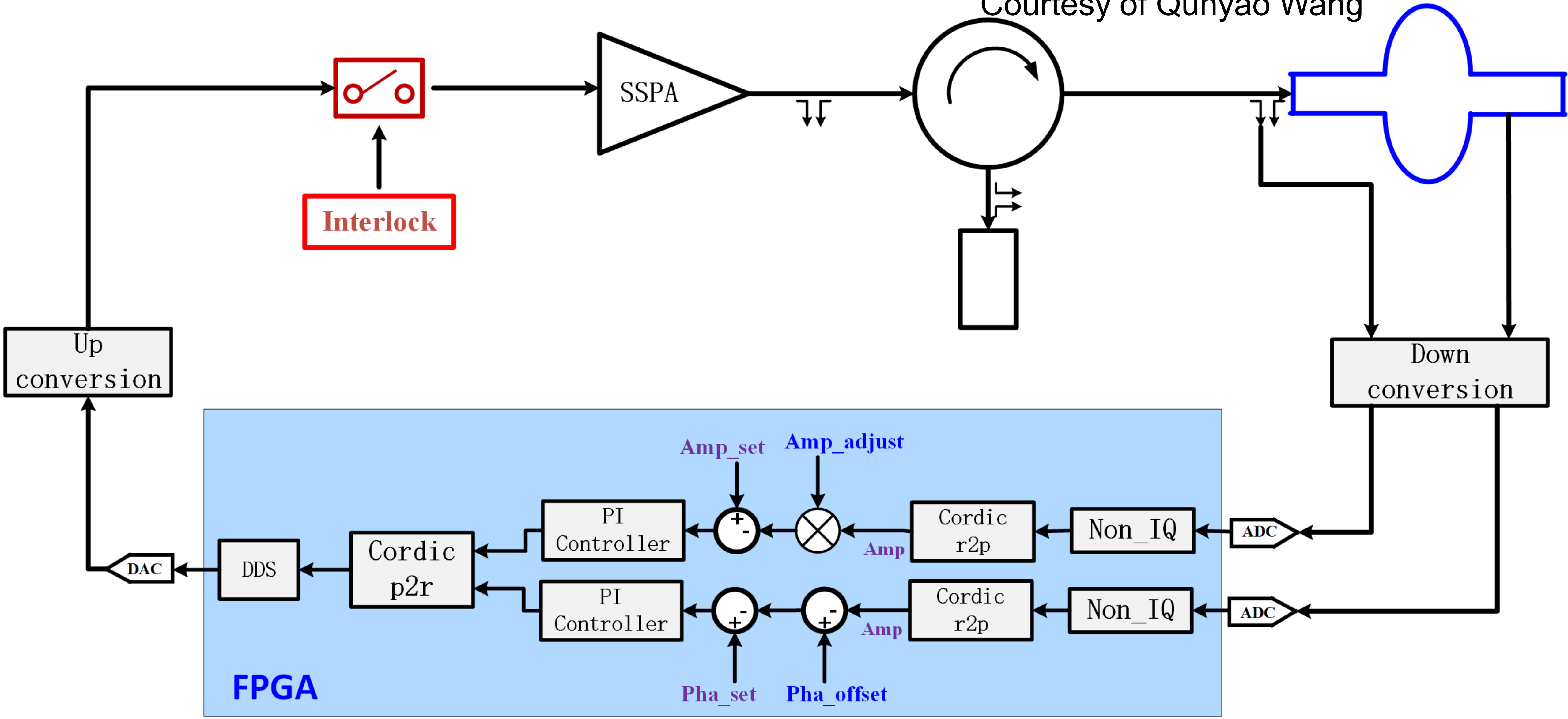


Try to understand and solve this problem

- **Establish a taskforce**
- **Assumptions and attempts (to-do list)**
  - **Tune away a bit from the ideal lengthening condition;**
  - **Use beam power feedback of the harmonic cavity;**
  - **A different LLRF control strategy of the harmonic cavity;**
  - **more simulations including impedance, RF modes, LLRF, etc.**
  - **……**
- **Difficulties**
  - **Not yet get dedicated beam time for accumulating more data;**
  - **Not yet get clear understanding and direction to go;**

A different LLRF control strategy of the harmonic cavity

Courtesy of Qunyao Wang



Ongoing simulations may be related

- **stability of RF voltage and phase when closed to the ideal lengthening condition**
  - Inspired by the previous computations of the equilibrium bunch lengths slightly deviate from the ideal lengthening condition.

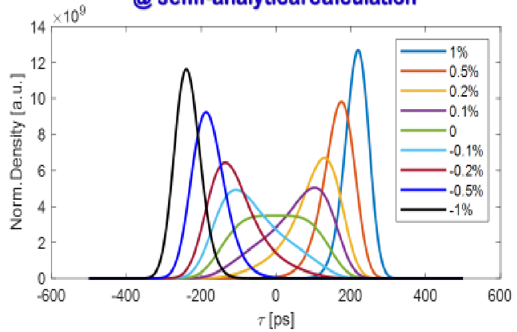
Breakdown of the Opt. Lengthening condition

Variation of the main cavity voltage

Variation of the energy loss (U0)

Courtesy of Tianlong He

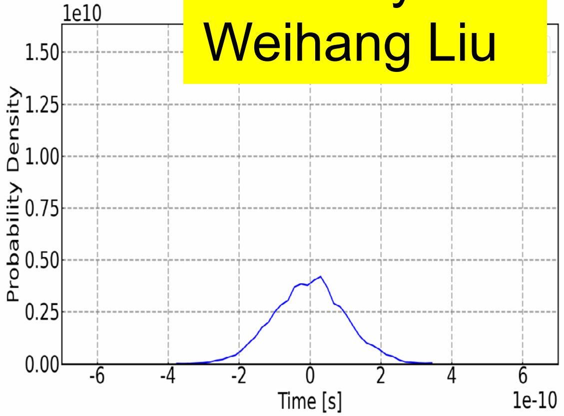
@ semi-analytical calculation



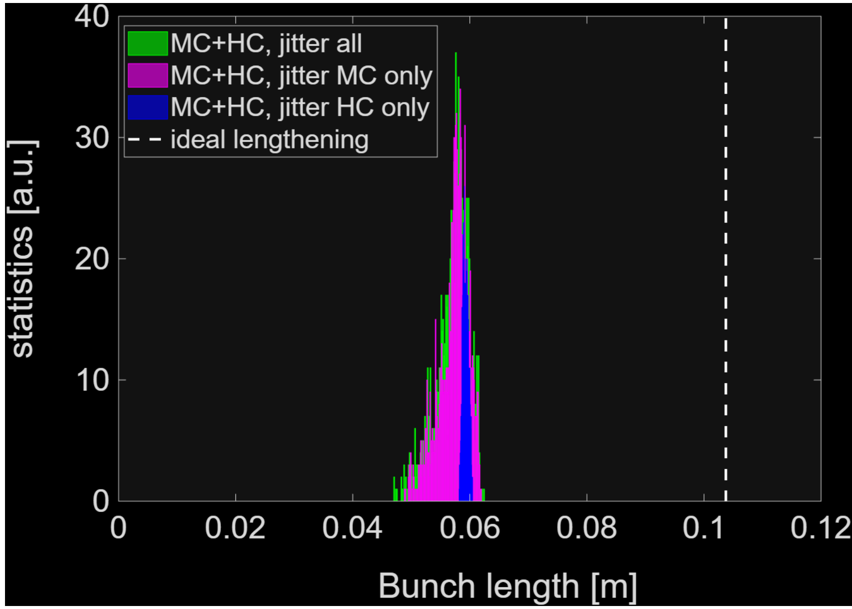
V_{rf} Variation	Rms bunch length
+1%	32.1 ps
+0.5%	43.2 ps
+0.2%	68.7 ps
+0.1%	83.9 ps
+0%	92.1 ps
-0.1%	85.0 ps
-0.2%	70.3 ps
-0.5%	45.5 ps
-1%	34.9 ps

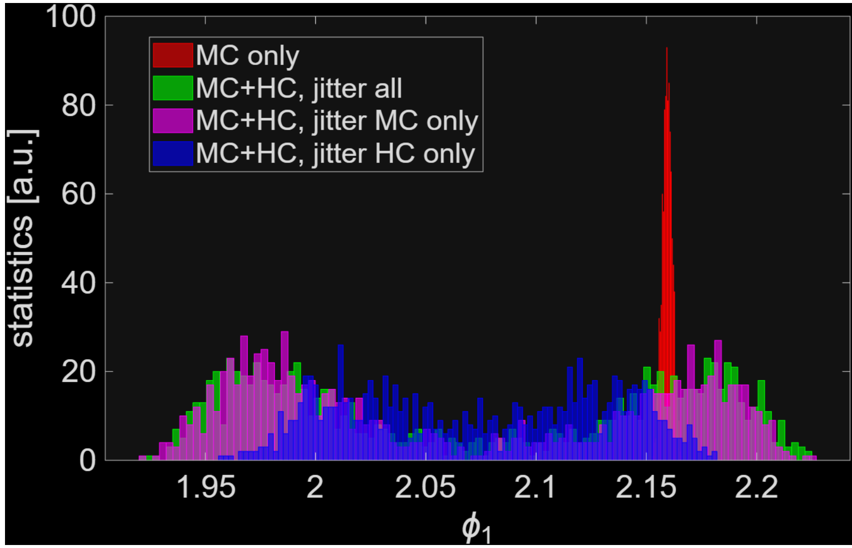
±0.2%主腔压幅值变化，会显著改变bunch profile (束长变化超过20 ps).

Courtesy of Weihang Liu



Cavity short-range impedance included





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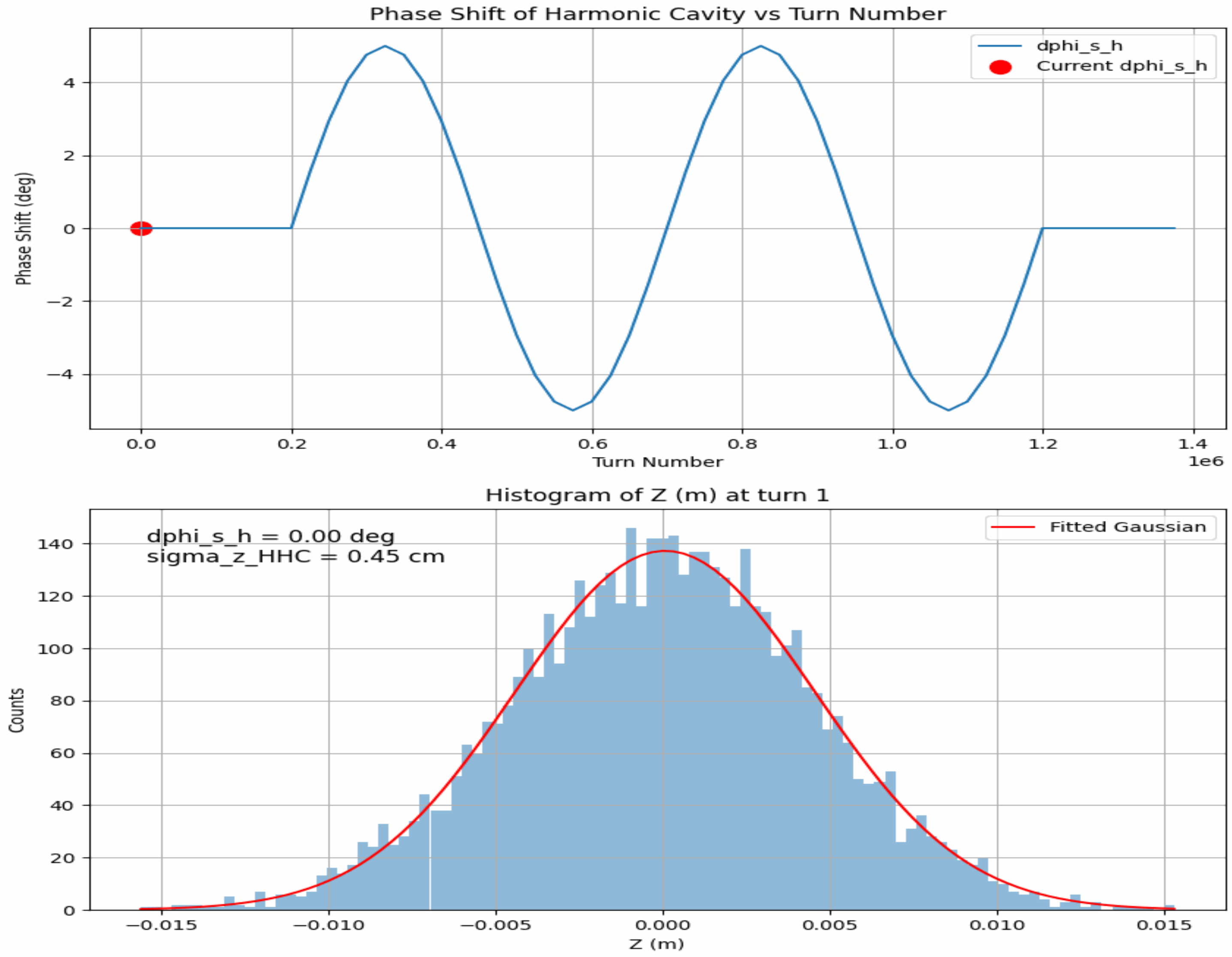


Courtesy of Tianmu Xin

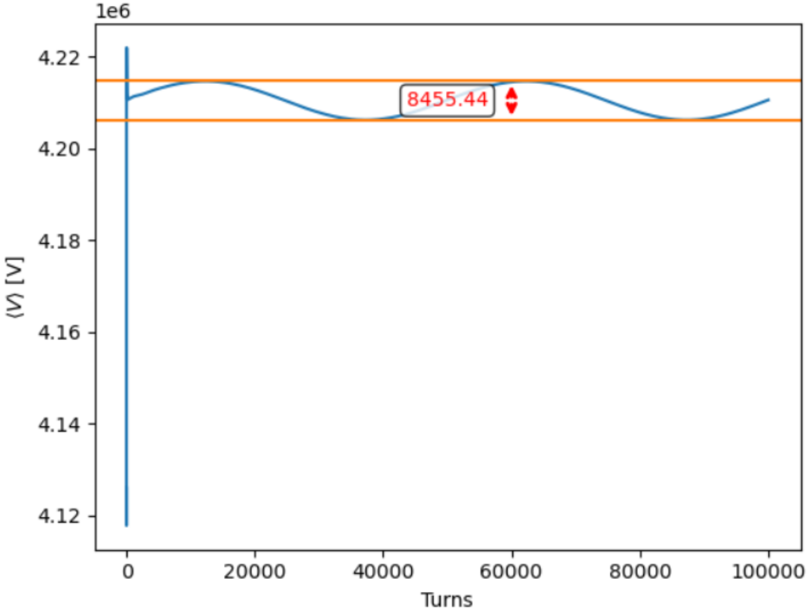
Tracking by APES code, Weibin Liu, et al., in Proceedings of IPAC’24, Nashville, TN.

Observations from computations

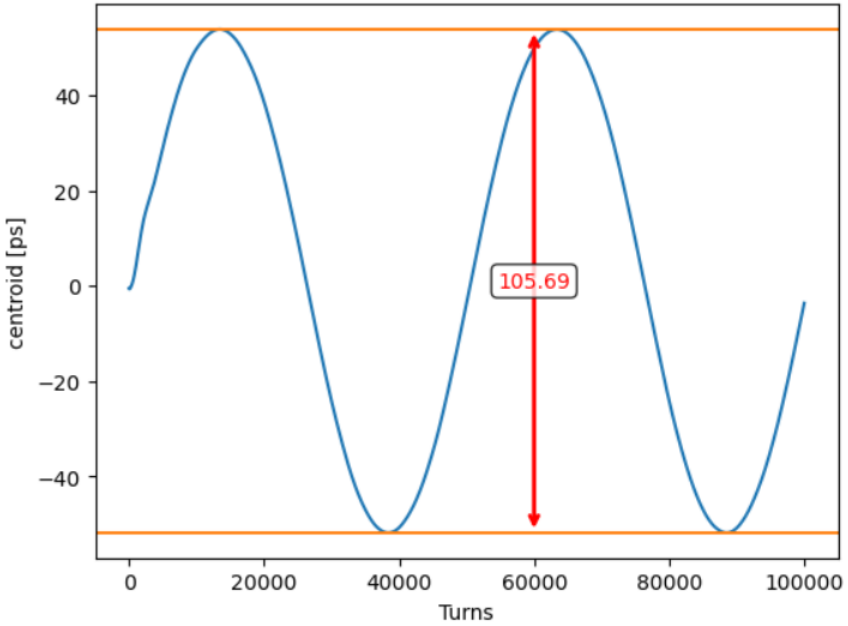
Liyan Qin &
Zihang Zhao &
Haisheng Xu

- **The deviation of main cavity (both voltage and phase) has larger impact comparing the harmonic cavity.**
  - **Set $\pm 0.1\%$(peak-to-peak) deviation to the voltage of main cavity**

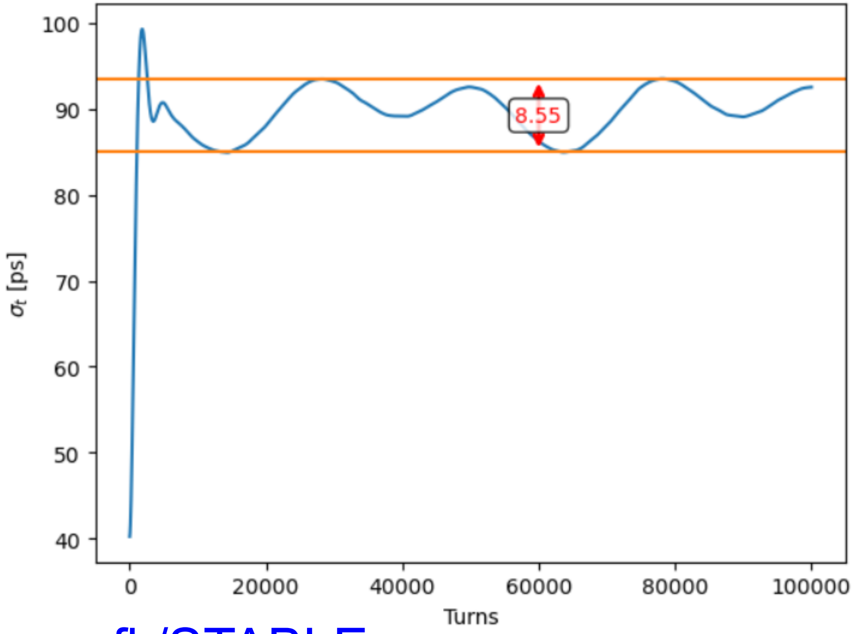
$\pm 0.1\%$(peak-to-peak) voltage deviation



106 ps (peak-to-peak) beam centroid shift

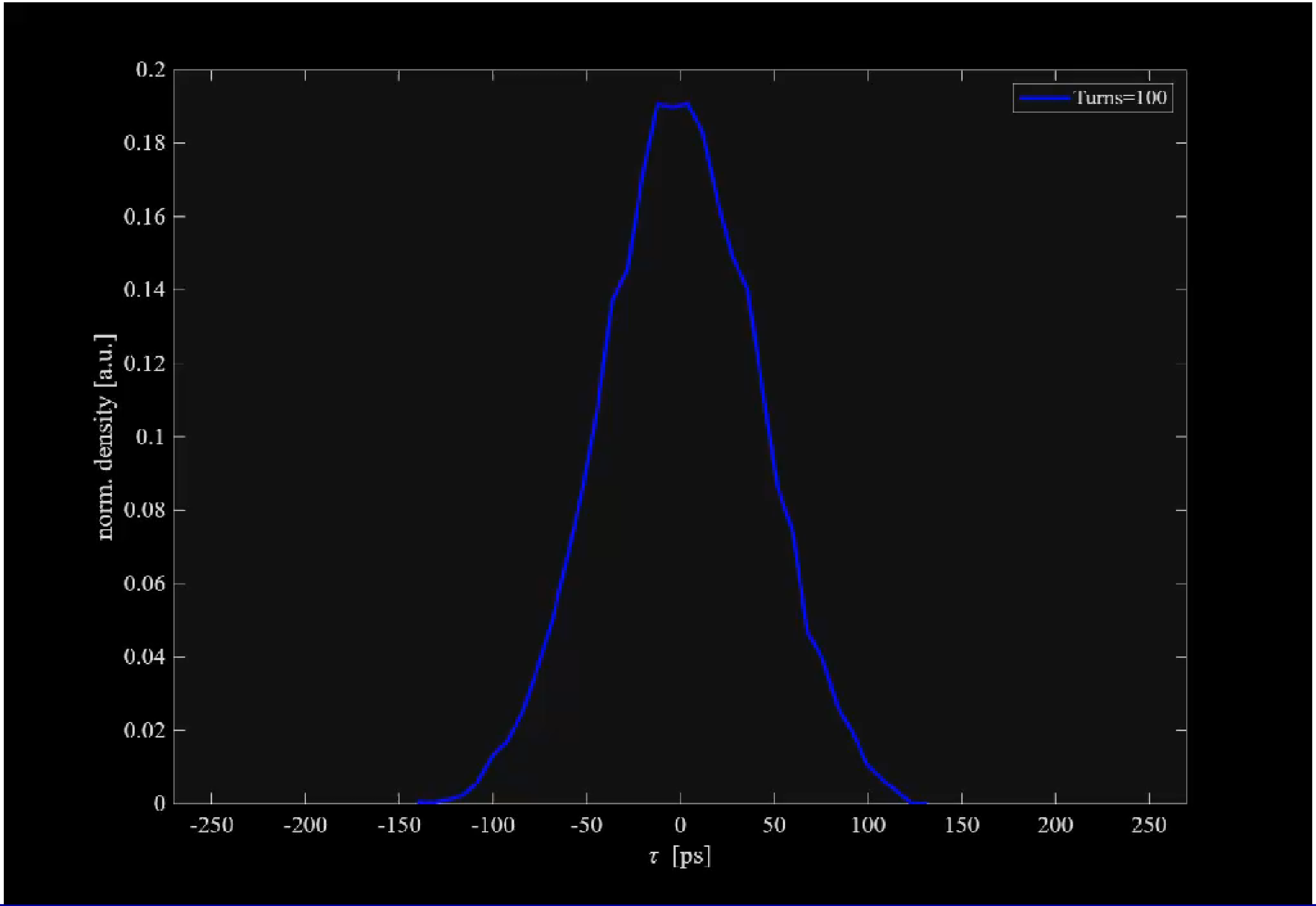


10% (peak-to-peak) bunch length deviation



Tracking by Tianlong He's STABLE code, https://github.com/hetianlong-afk/STABLE

Set ±0.1%(peak-to-peak) deviation to the voltage of main cavity



Liyan Qin & Zihang Zhao & Haisheng Xu

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  - **……**

Suggestions and comments are highly welcome!

Summary & Outlooks

Summary & outlooks

- **HEPS beam commissioning is still on going. All KPPs of the HEPS accelerators have passed the official test.**

  (100mA, ~57pm, etc.)
- **Beam longitudinal distribution has very slow oscillation.**
- **Studies ongoing to understand the reason.**
  - **stability of RF voltage and phase is one suspect.**
  - **……**
- **Beam experiments will be carried out soon.**

Thank you very much for your attention!