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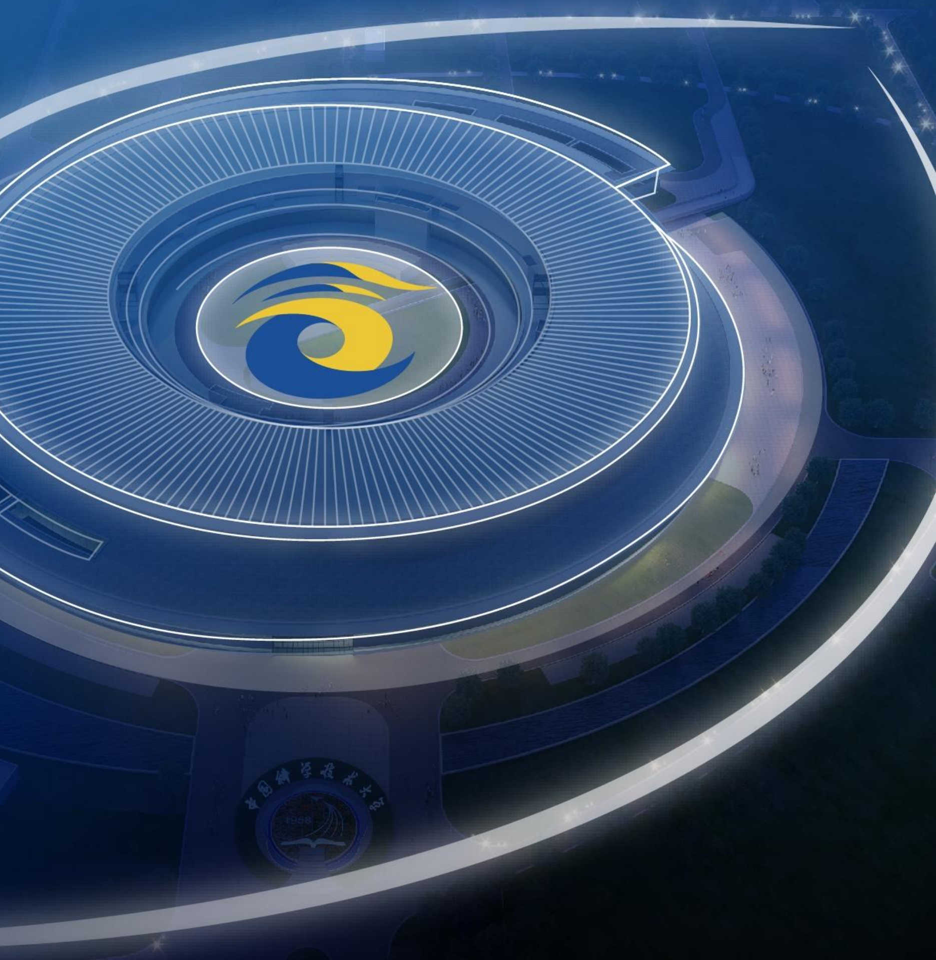
Nondestructive Beam Energy Spread Diagnostics for the Development of RF Phase Feedback in Linear Accelerators



Speaker: Qian Wang

Co-authors: Liuxu Zong, Letian Huang, Baogen Sun, Qing Luo

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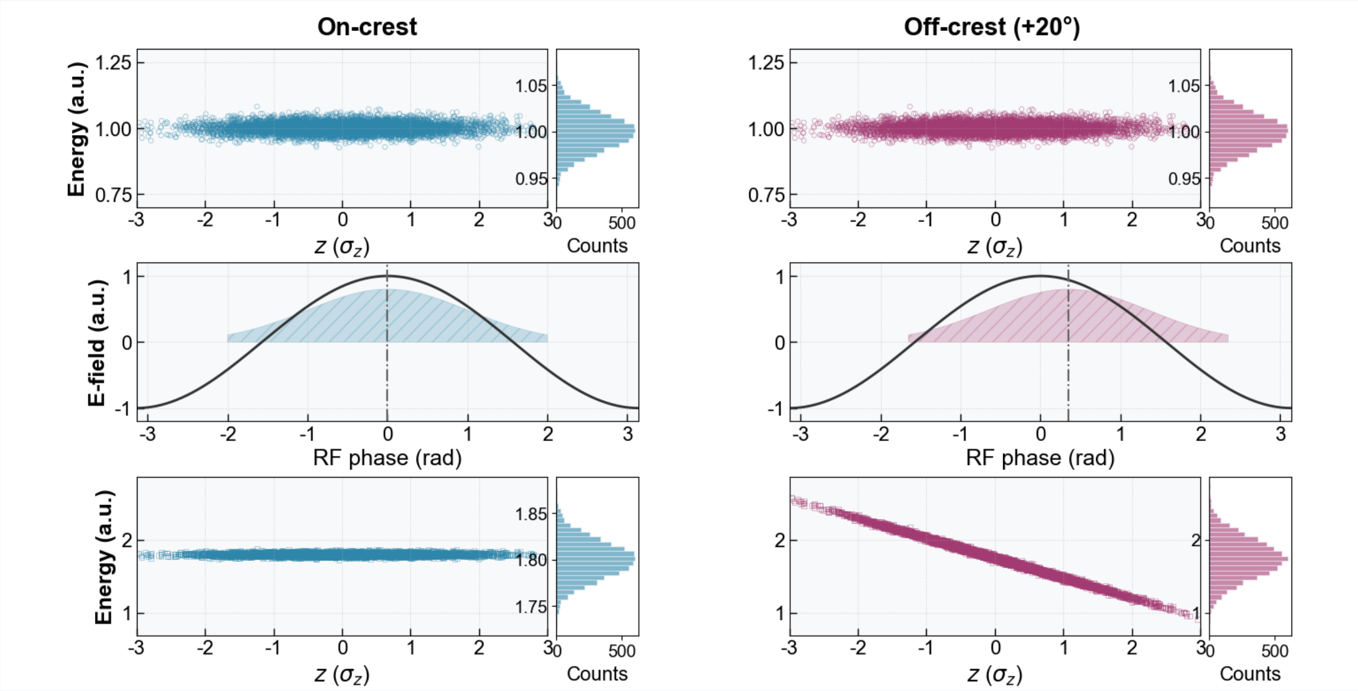
CONTENTS

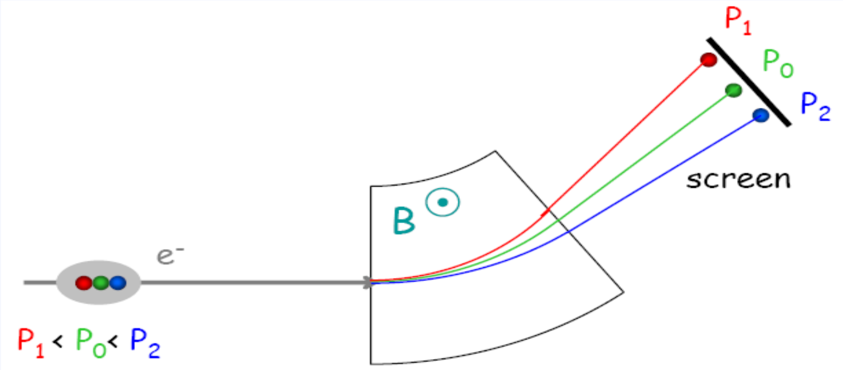
Why do we need nondestructive beam-based energy-spread monitoring?

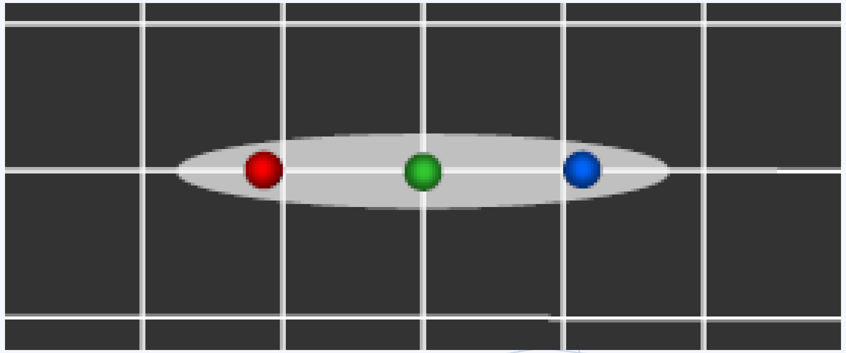
➢ RF phase VS energy spread



• A beam-based measurement of the energy spread provides a direct observable for RF phase monitoring and feedback.

➢ Conventional measurements

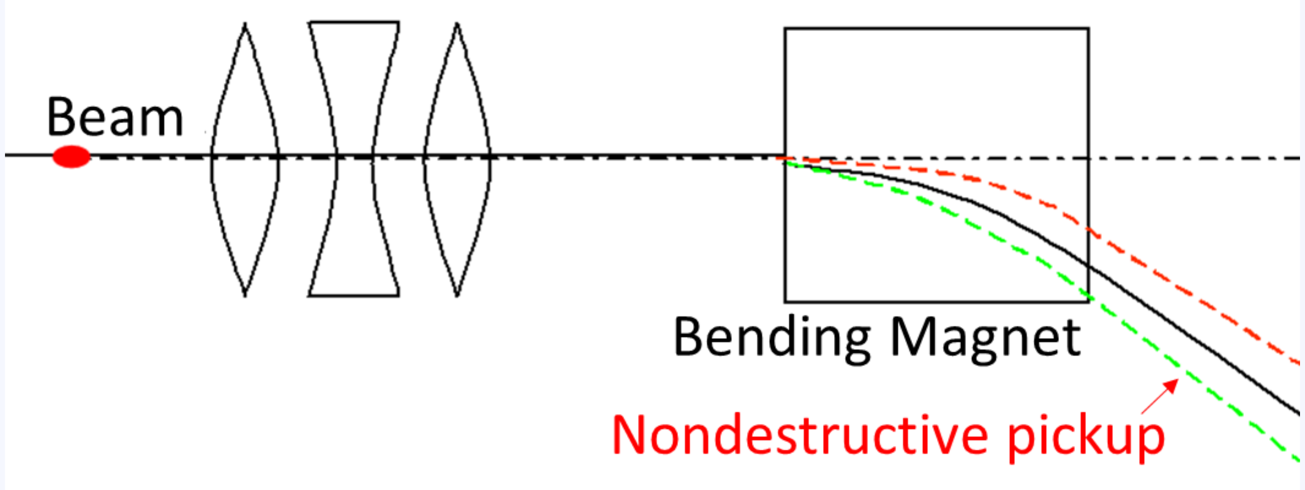




• Destructive

• Unsuitable for high-repetition-rate operation

Measure the energy spread without intercepting the beam



- Energy spread contributes to the transverse beam size

$$\sigma_y^2 = \varepsilon_y\beta_y + D_y^2\sigma_\delta^2 \qquad \sigma_x^2 - \sigma_y^2 = \varepsilon_x\beta_x - \varepsilon_y\beta_y - D_y^2\sigma_\delta^2 \qquad (D_x = 0)$$

σ_y: vertical beam size; ε_y: emittance; β_y: beta function; D_y: dispersion; σ_δ: relative energy spread

- Quadrupole moment contains the beam size term

$$Q_{\text{quad}} = x_0^2 - y_0^2 + \sigma_x^2 - \sigma_y^2$$

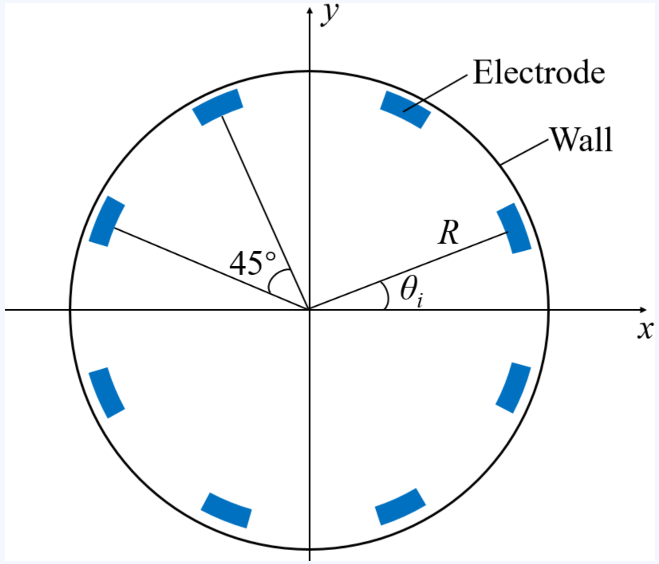
x_0, y_0: beam centroid position; σ_x : horizontal beam size

- The quadrupole moment can be obtained from the beam-induced RF signals of a nondestructive pickup

Eight-electrode approach

Nondestructive energy-spread measurement with eight electrodes

➢ Typical structure

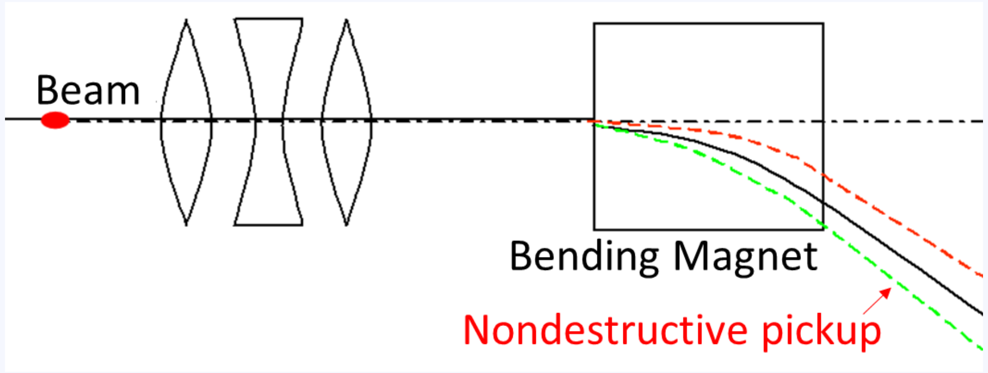


Eight uniformly distributed electrodes

$$Q_{\text{quad}} = \frac{\sum_{i=1}^{8} V_i \cos 2\theta_i}{\sum_{i=1}^{8} V_i}$$

- Quadrupole moment is extracted from the weighted sum of the eight electrode signals

➢ Challenges for high-repetition-rate FELs



- The beam pipe is relatively large downstream of the bending magnet, which reduces the beam-induced signal, especially the quadrupole signal.
- For high-repetition-rate FELs, we need bunch-by-bunch measurements at MHz repetition rates.

Optimized SBQM

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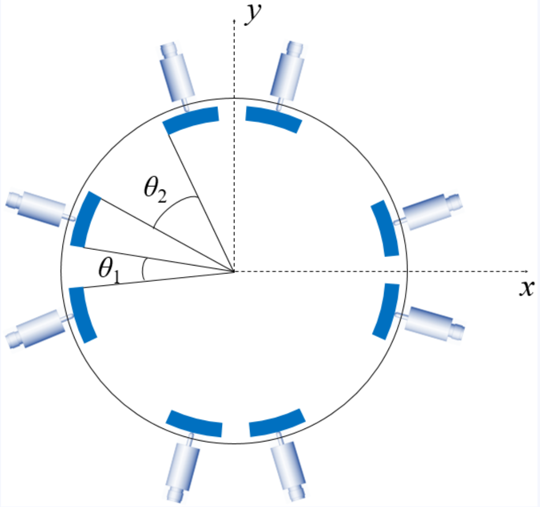
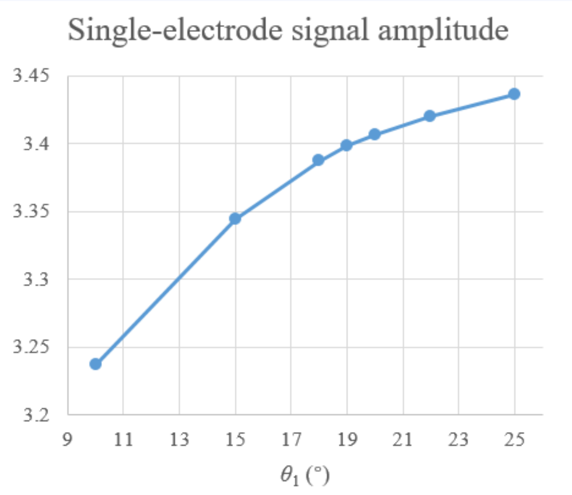
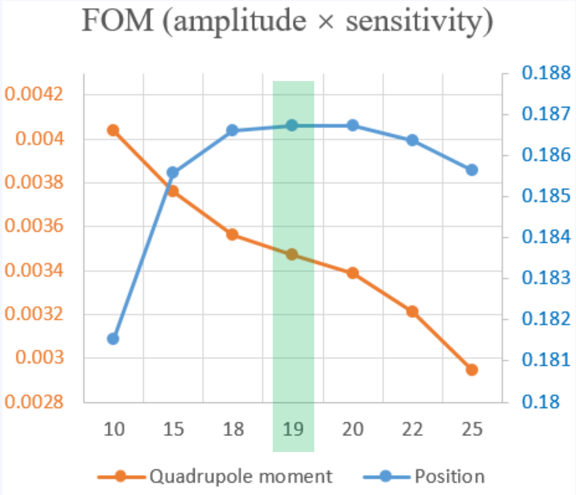
Non-uniform electrode spacing enhances quadrupole sensitivity

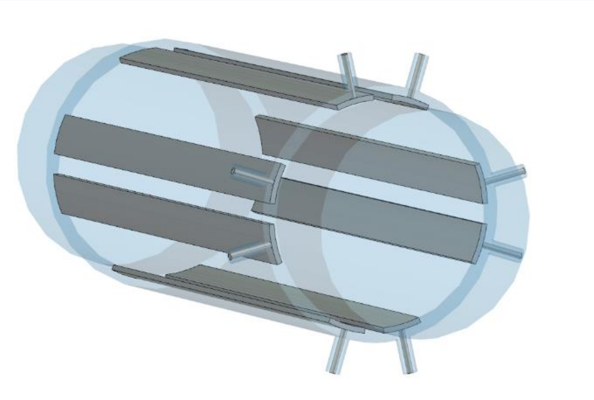
➤ Change electrode spacing: keep the 90-degree rotational symmetry, but make the electrode spacing non-uniform.



Simulation results

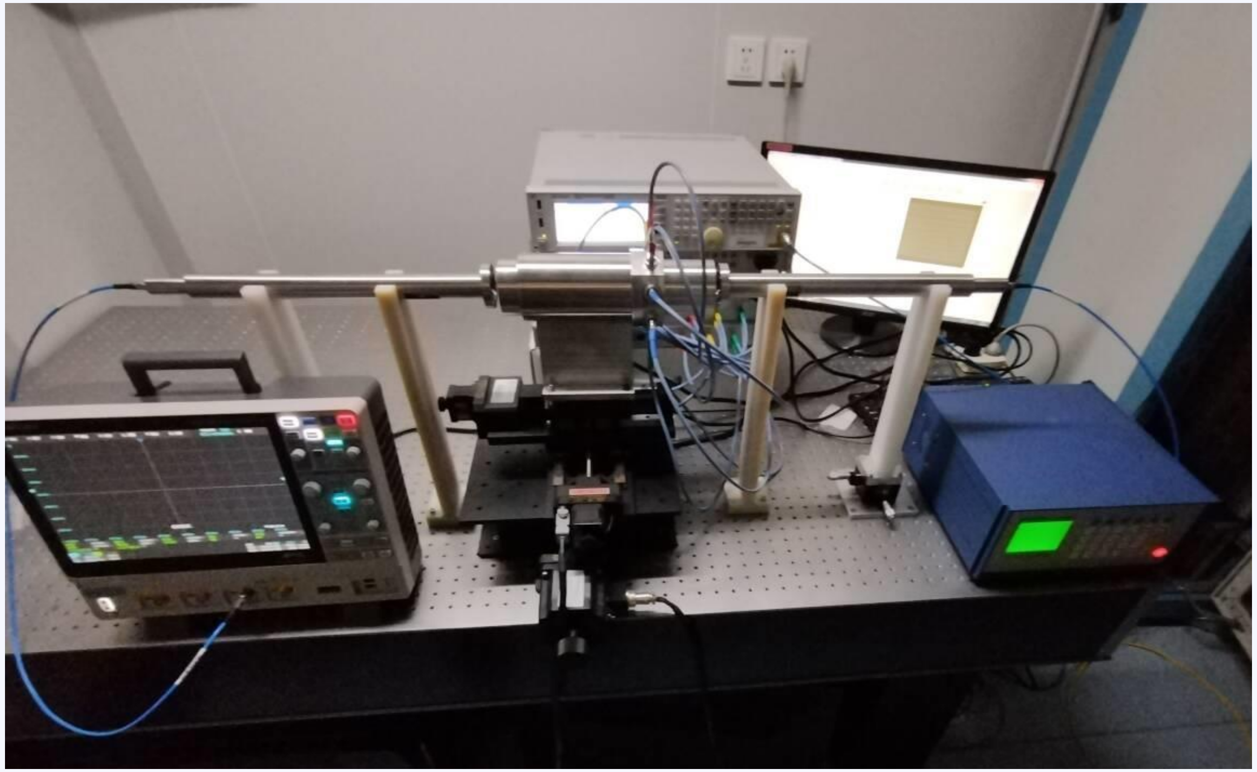






- θ_1 becomes smaller, the quadrupole sensitivity increases, and the signal from each electrode becomes smaller.
- For better measurement resolution, we need both high sensitivity and sufficient signal amplitude.

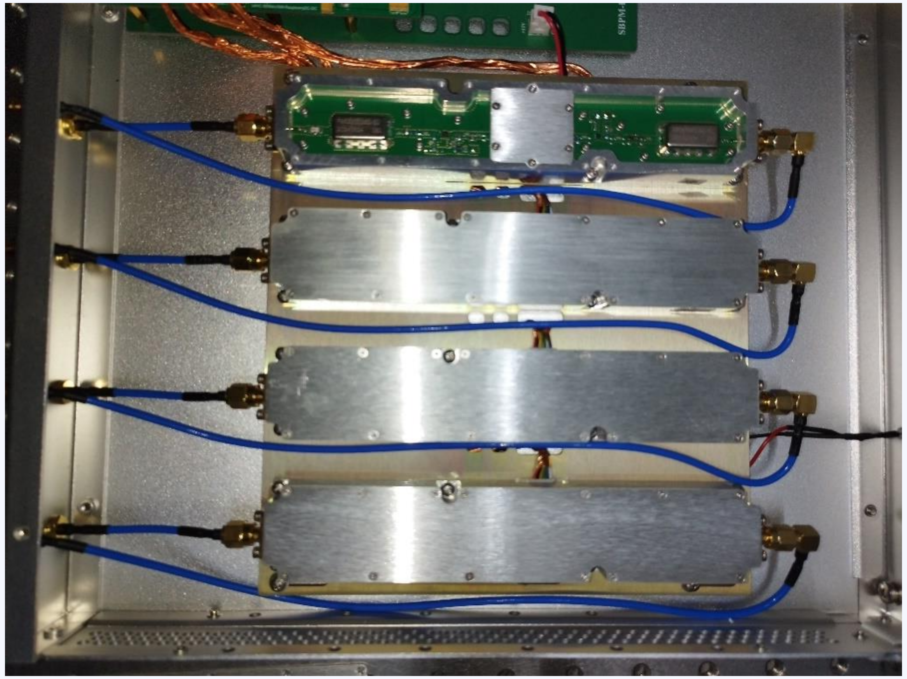
Offline wire-based calibration confirms the sensitivity improvement



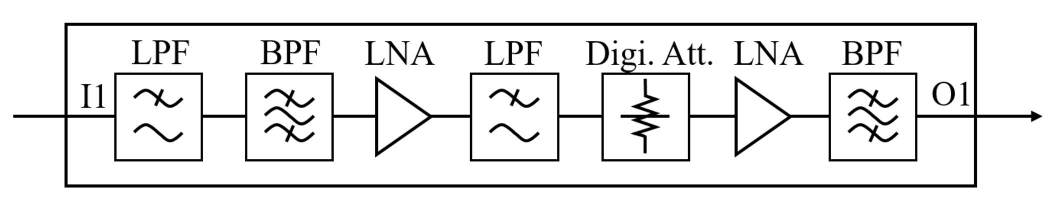
Measurand	Sensitivity	
	conventional pickup	optimized pickup
x position	0.0528 mm^{-1}	0.0554 mm^{-1}
y position	0.0524 mm^{-1}	0.0554 mm^{-1}
Quadrupole moment	0.937×10^{-3} mm^{-2}	1.025×10^{-3} mm^{-2}

- The optimized pickup shows higher position and quadrupole sensitivities than the conventional uniform pickup.
- The non-uniform electrode arrangement is suitable for the large-aperture chamber.

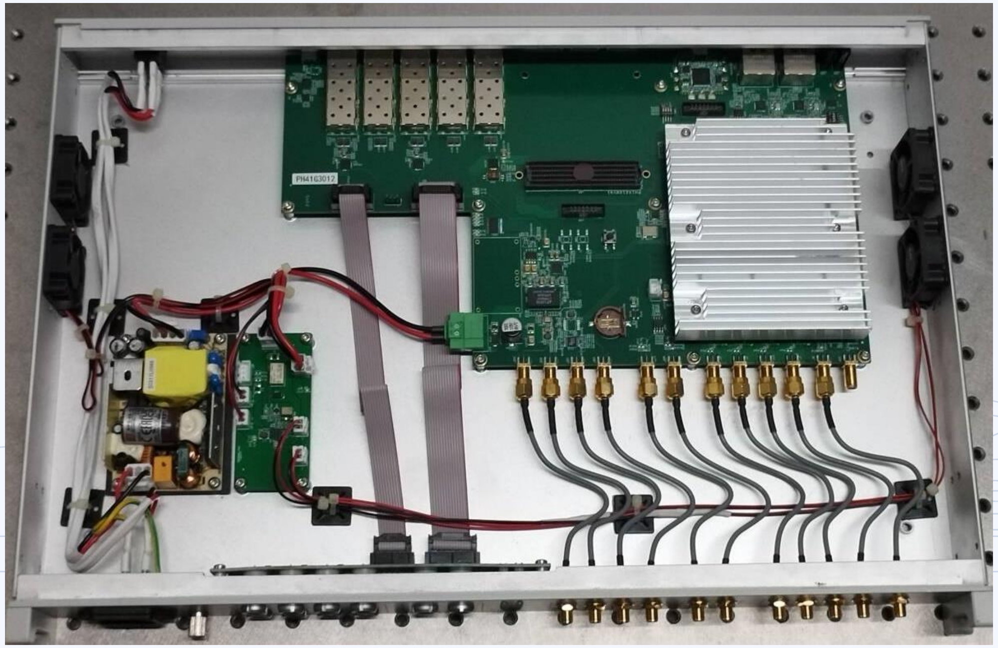
A complete SBQM system for MHz bunch-by-bunch measurements



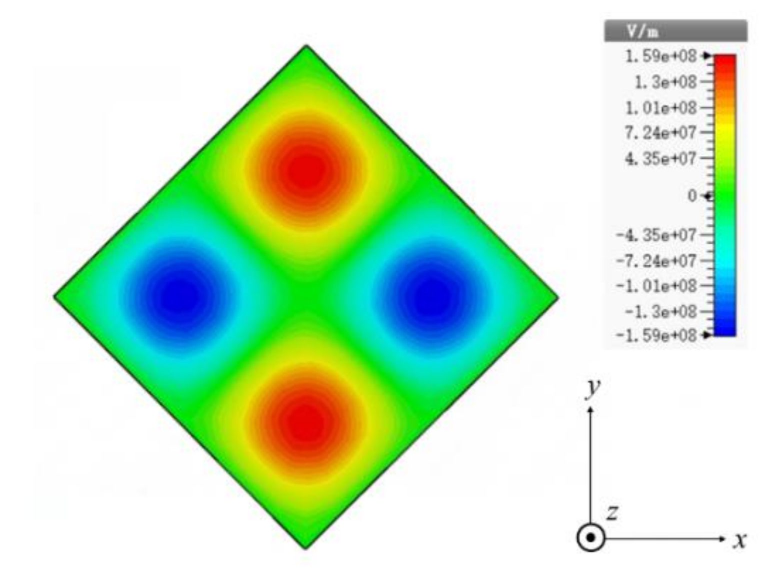
- The FPGA performs real-time extraction of the beam position and quadrupole moment for each bunch.
- The processed data are transmitted to the host computer through high-speed communication interfaces.

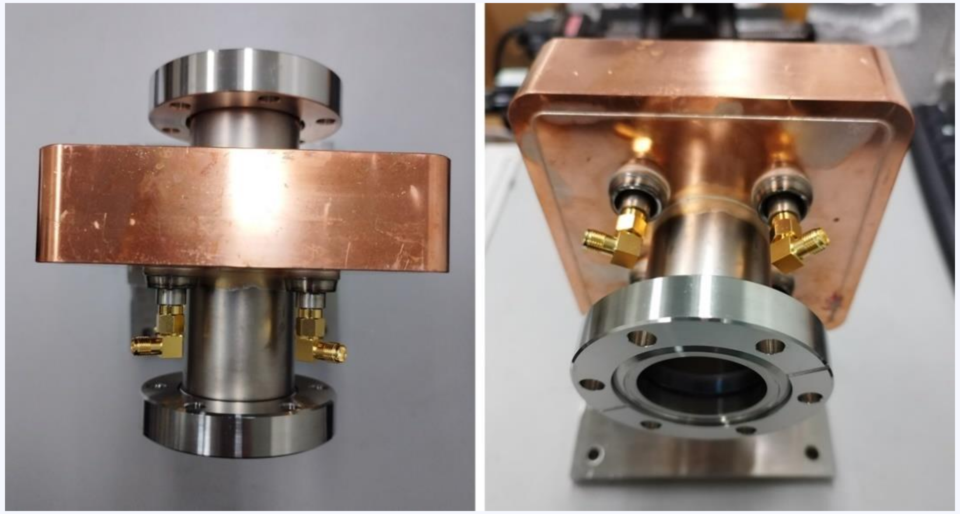


- The RF front end operates around 500 MHz, with a bandwidth of about 70 MHz.



A TM220 cavity for high-resolution quadrupole measurements





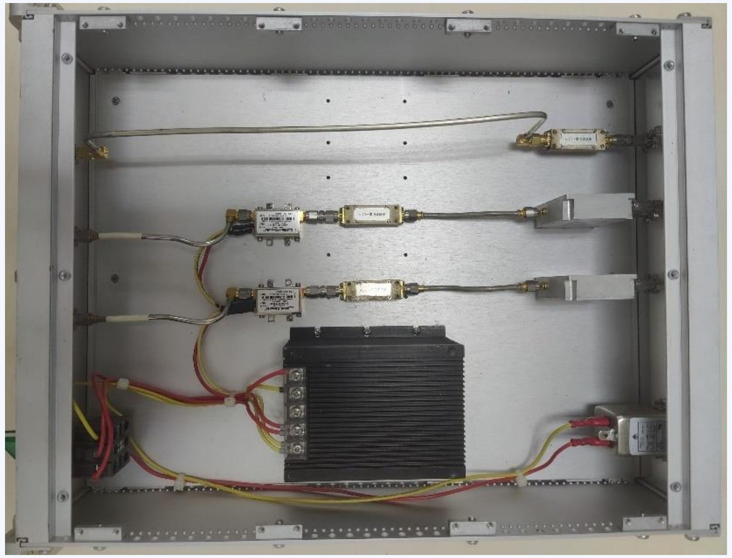
- With the diamond configuration:
  - The TM_{220} signal is proportional to the beam quadrupole moment

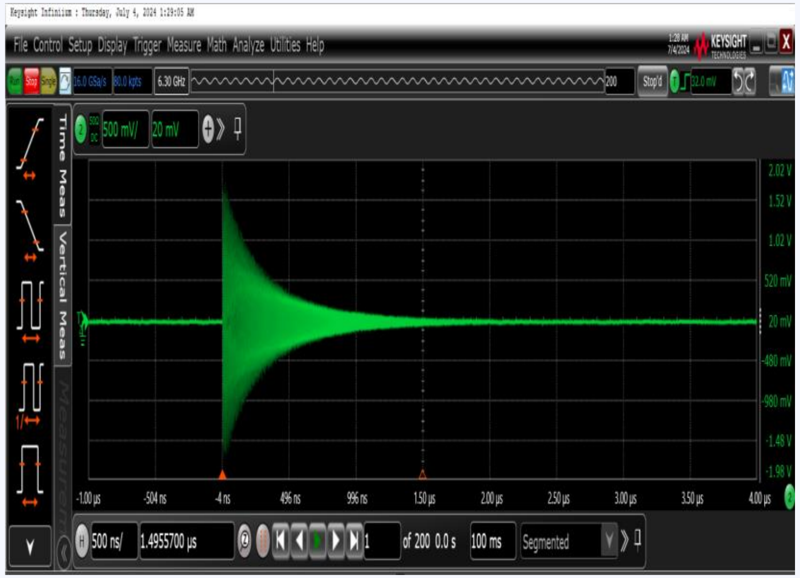
$$V_{\mathrm{TM220}} \propto q\left(x_0^2 - y_0^2 + \sigma_x^2 - \sigma_y^2\right)$$

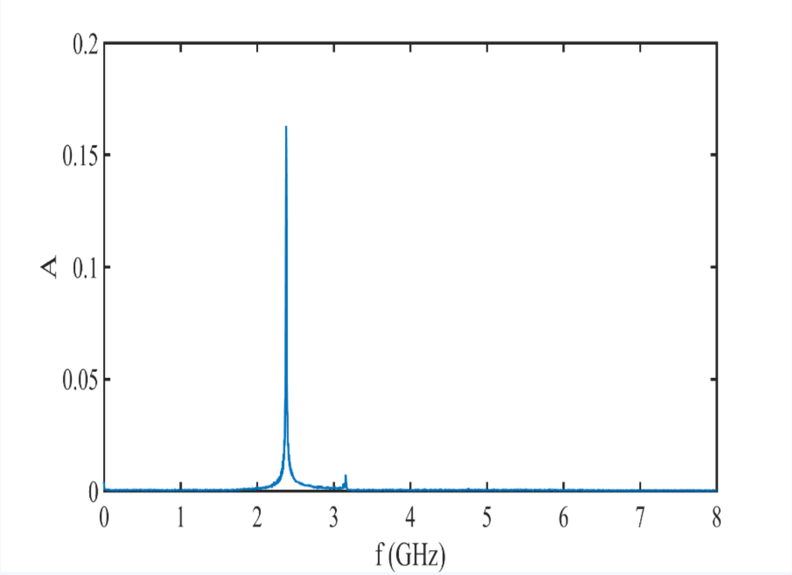
  - To remove bunch-charge fluctuations, the TM_{110} mode is used as a charge reference. Therefore, the ratio of the TM_{220} and TM_{110} amplitudes is used as the normalized quadrupole signal.
  - The cavity operates at 4.685 GHz, with a loaded Q of about 2600.

CBQM signal acquisition and processing

Cavity pickup → Low-noise preamplifier → Coaxial cables → High-speed oscilloscope → FFT amplitude extraction



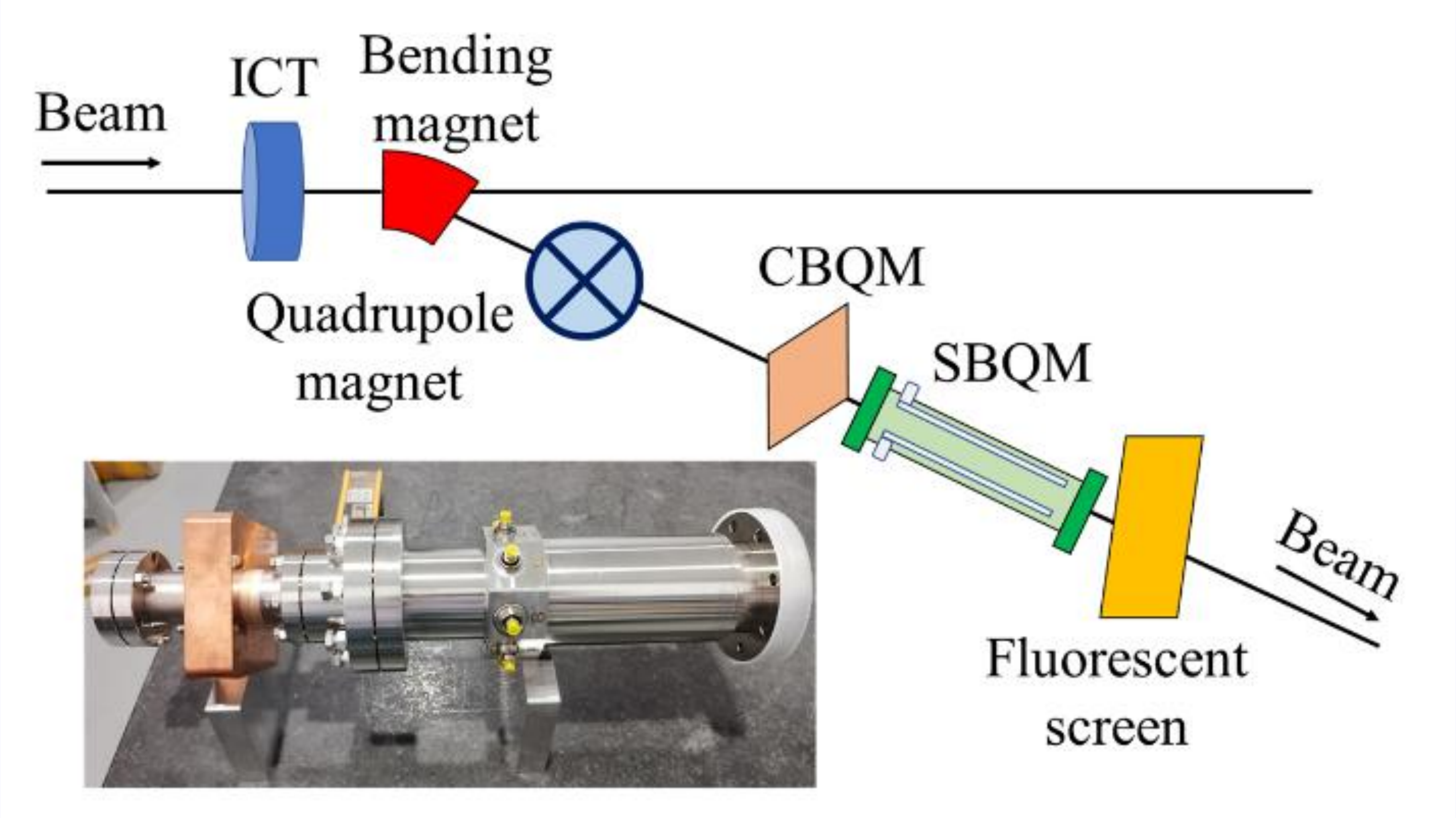




- The TM220 signal is first amplified by a low-noise preamplifier.
- A high-speed oscilloscope was used to acquire the time-domain waveforms.
- The amplitudes of the TM110 and TM220 signals are extracted using FFT.

Beam experiment

Beamline and beam conditions

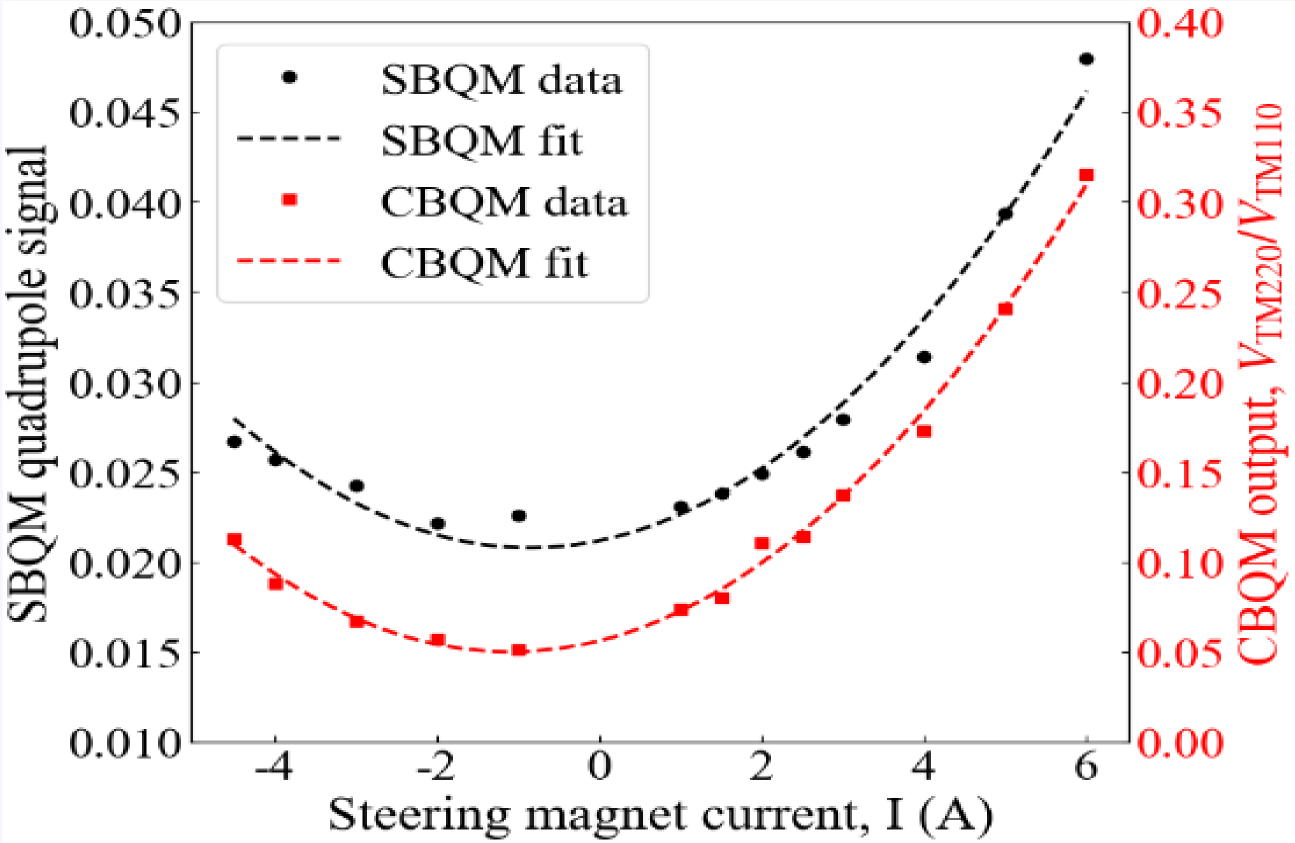


- Beam energy: 300 MeV
- Vertical dispersion: 0.57m
- Bunch charge: 350 - 400 pC
- ICT: provide the bunch-charge reference
- Fluorescent screen: provide beam position and profile measurements

Cavity-based approach

Beam response

➢ The beam position was changed by scanning an upstream steering magnet, while the signals from both monitors were recorded.



- The measured quadrupole signals from both monitors show the expected quadratic dependence on the beam position.
- Both monitors can reliably extract the beam quadrupole moment from the beam-induced signals.

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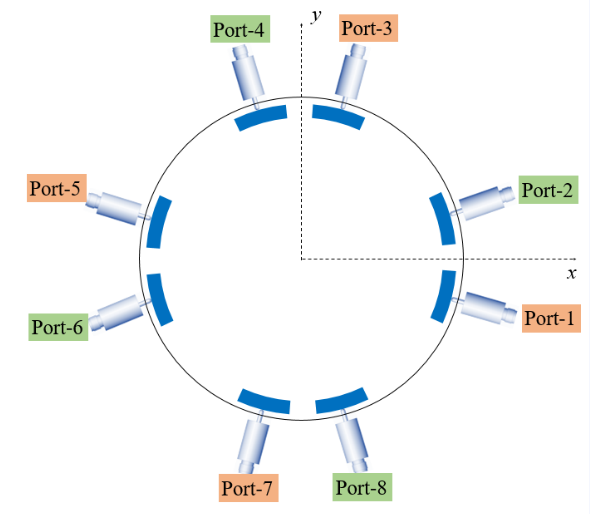
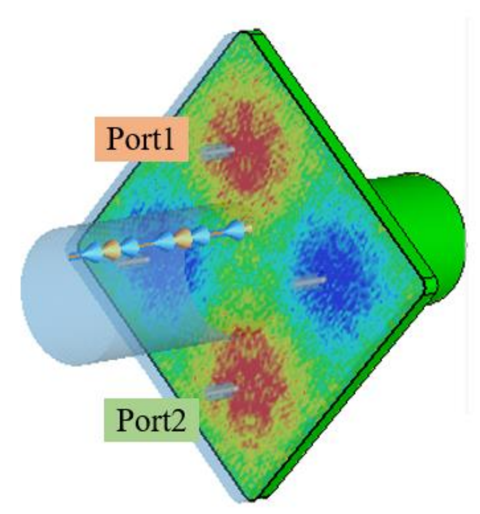
Measurement resolution and performance comparison

- By taking the difference between symmetric signals, the common beam fluctuations can be suppressed, allowing us to estimate the system noise.





$$\Delta_{SBQM} = (\text{Port1} + \text{Port2} + \text{Port3} + \text{Port4}) - (\text{Port5} + \text{Port6} + \text{Port7} + \text{Port8})$$

$$\Delta_{CBQM} = \text{Port1} - \text{Port2}$$

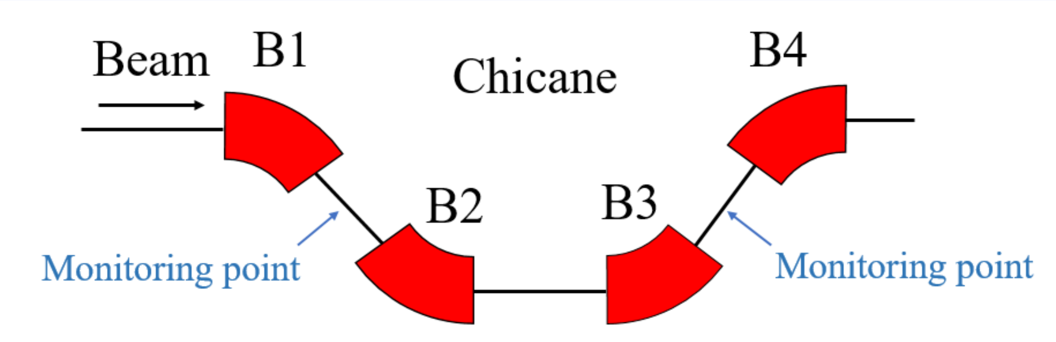
Parameter	SBQM	CBQM
Bunch charge	400 pC	350 pC
Quadrupole moment resolution	$< 0.16\ \text{mm}^2$	$< 0.034\ \text{mm}^2$
Position resolution	$< 5.6\ \mu\text{m}$	--

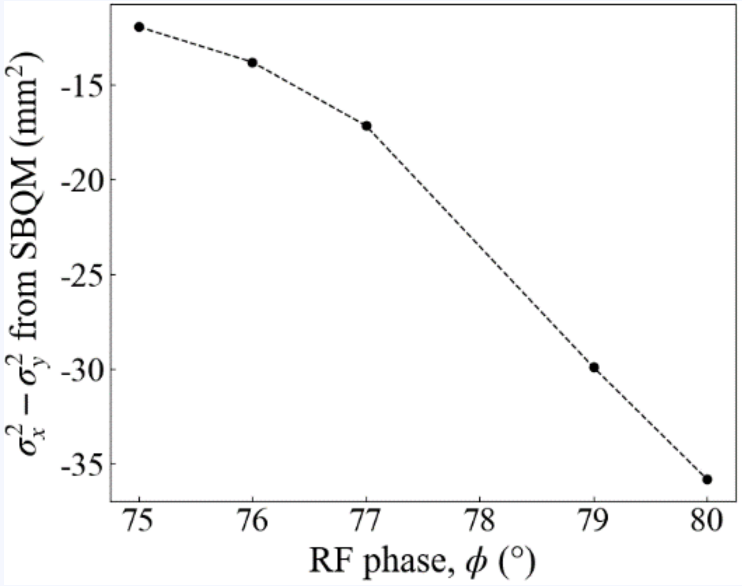
- The SBQM has a relatively simple architecture and can measure both beam position and quadrupole moment with the same pickup.
- The CBQM provides a much higher quadrupole measurement resolution because of its narrowband response. It requires more specialized electronics, and beam position correction currently relies on an external position measurement.

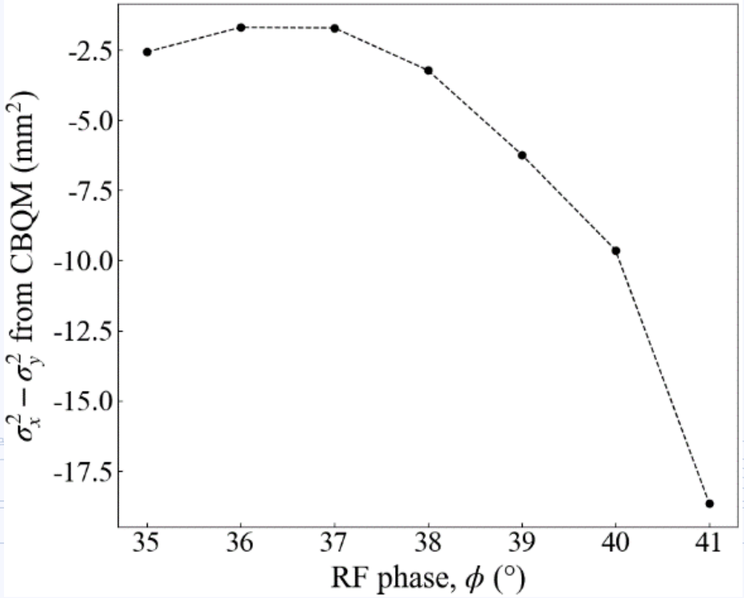
Beam experiment

RF phase response

- The RF phase of the accelerating cavity was scanned
  - A clear and repeatable trend was observed.
  - A phase variation of about 1° was distinguishable.
  - The potential for beam-based RF phase monitoring and future feedback was demonstrated.
  - Both monitors have a compact structure and can be installed in the chicane downstream of the accelerating cavities.







Summary

- Two nondestructive beam quadrupole-moment diagnostics were developed, including an optimized SBQM and a TM220 cavity-based monitor.
- The SBQM achieved a quadrupole-moment resolution better than 0.16 mm^2 and a position resolution of about 5.6 μm at 400 pC.
- The CBQM achieved a quadrupole-moment uncertainty of 0.034 mm^2 at 350 pC.
- RF phase variations of about 1° were distinguishable.
- These results provide an experimental basis for beam-based RF phase monitoring and future feedback in FELs.

Acknowledgments

Dalian Coherent Light Source (DCLS)for beam time.

THANKS!