Cavity-based bunch arrival monitor for Ultrafast Electron Diffraction beamlines

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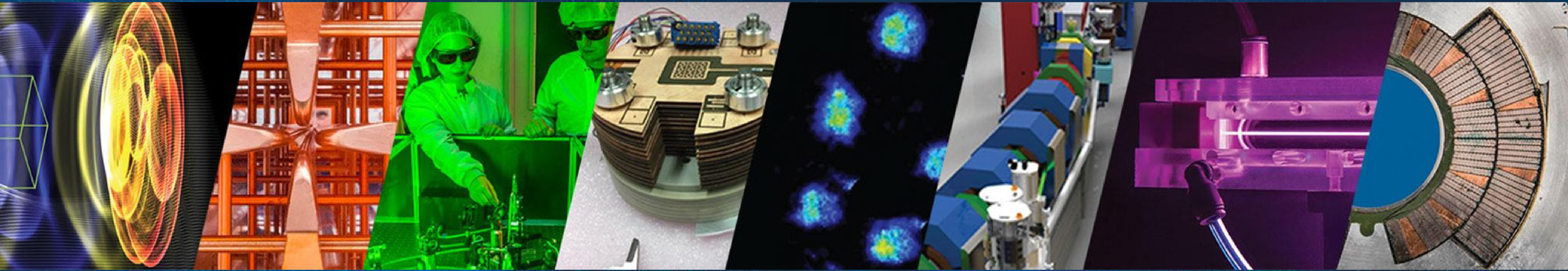

IBIC 2026

15[TH] INTERNATIONAL BEAM INSTRUMENTATION CONFERENCE

Whistler Conference Centre

August 30[th] to September 3[rd]

Whistler BC, Canada

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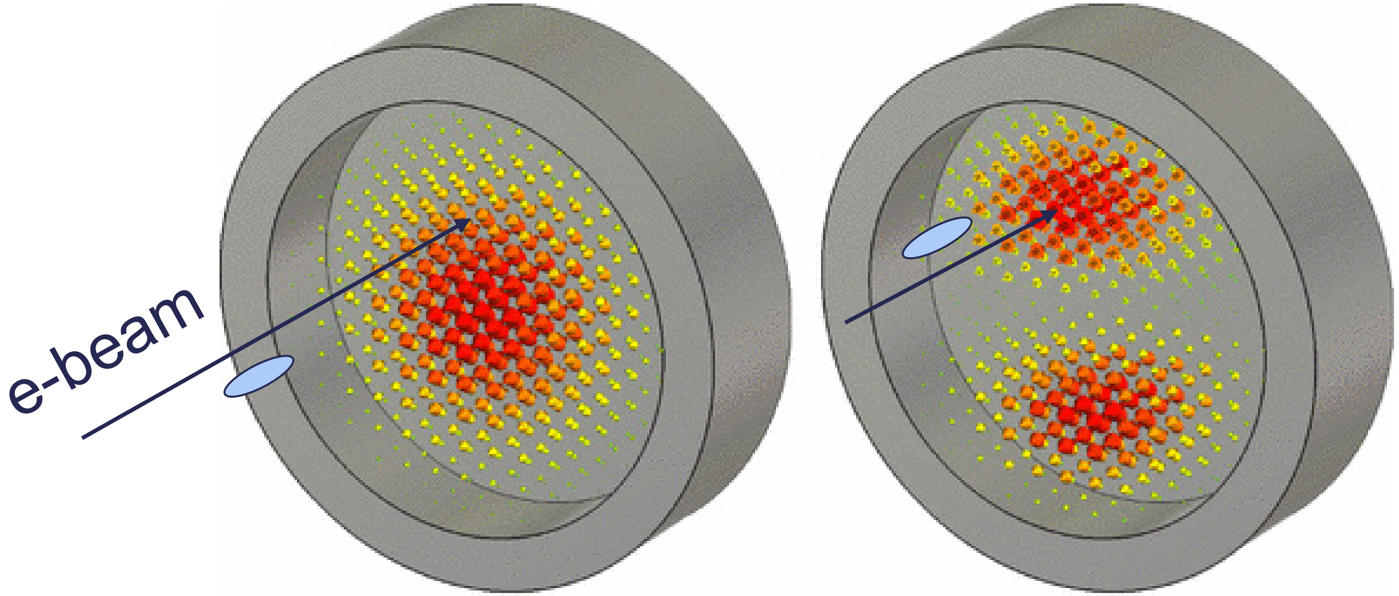
Outline

- **Background**:
  Cavity Based **B**eam **M**onitor (**a**rriving time (BAM) and beam **p**osition (BPM))
- **Experiment at UCLA-PEGASUS beamline**
- **Preliminary Results**: First Order Agreement on BAM and BPM
- **Discussion & Outlook**

Cavity Based e-Beam Monitors (CBM): Passive Wakefield Resonators

- The wakefield can be used for non-destructive beam diagnostic
- Cavity-based beam monitors, based on wake field excitation of TM 010 from the beam, offer a highly sensitive single-shot measurement for both charge and time of arrival
- e-Beam can excite different RF resonant modes e.g. TM 110 dipole in the cavity, depending on the excitation positions (and angles)

BAM: beam arrival monitor **BPM: beam position monitor**



(a)TM_{010}. (b)TM_{110}.

Credit: Thorsten R. Pusch, et. al.,
Phys. Rev. ST Accel. Beams **15**, 112801 (2012)

Cavity Beam Monitors: Established Performance and Operating Charge

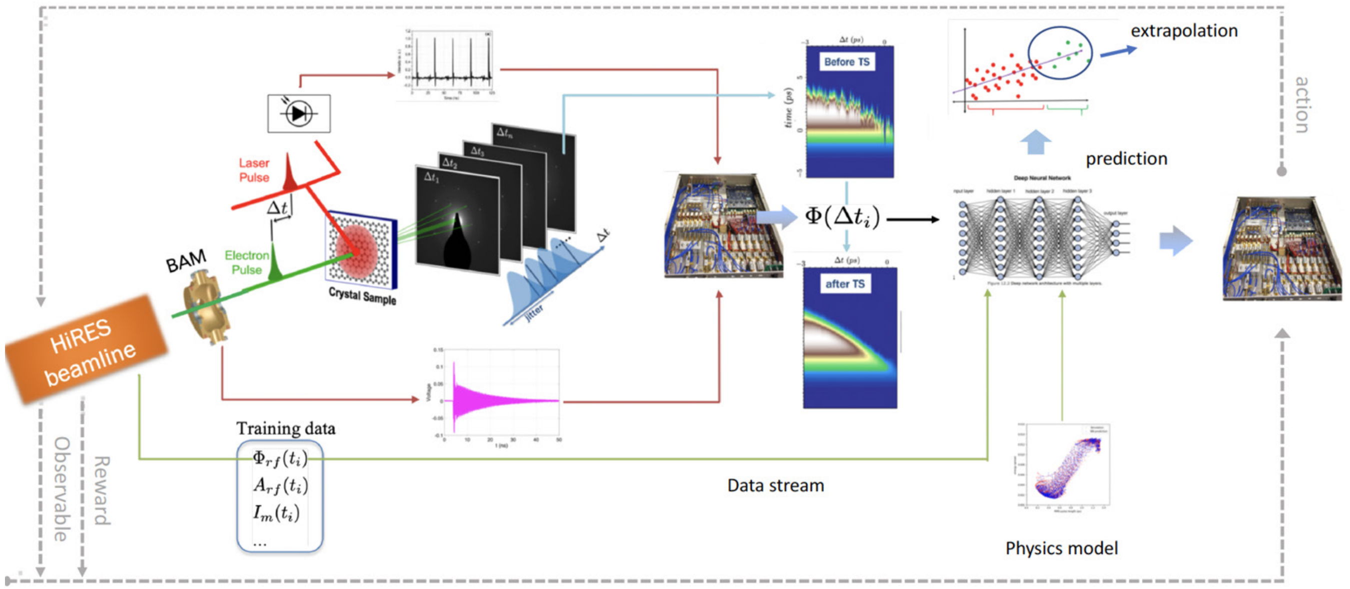
- Passive cavity resonators excited by the beam wakefield provide **non-destructive**, **single-shot**, **bunch-by-bunch** diagnostics, with decades of operational experience [1].
- **Monopole TM_{010} (BAM)**: amplitude $\propto$ bunch charge; phase relative to the RF reference gives arrival time.
- **Dipole TM_{110} (BPM):** amplitude $\propto$ charge × transverse offset; phase gives the sign of the offset.
- Demonstrated performance **spans tens-of-fs arrival time and nm- to sub-μm position resolution**, set by cavity *R/Q* and coupling, RF front-end noise, and reference-phase stability.

Facility / Ref.	Type	Operating charge	Reported performance
KEK ATF [2]	BPM	**1 nC**	few–10 nm position resolution
SPring-8 [3]	BPM	**300 pC**	200 nm position resolution
LCLS [4]	BPM	**200 pC**	200 nm position resolution
European XFEL [5]	BPM	**180 pC**	188 nm position resolution
Tsinghua [6]	BAM	**0.5 pC**	33.46 fs arrival-time resolution

All above were characterized at 0.5 pC or higher:
BAM timing at 0.5 pC, high-resolution BPM position at ~180 pC–1 nC.

[1] R. Lorenz, "Cavity beam position monitors," AIP Conf. Proc. 451*, 53–73 (1998).*
[2] D. R. Bett et al., Phys. Rev. Accel. Beams 25*, 022801 (2022).*
[3] H. Maesaka et al., Nucl. Instrum. Methods Phys. Res. A 696*, 66–74 (2012).*
[4] S. Smith et al., in Proc. 2009 Particle Accelerator Conf. (PAC'09), pp. 754–756 (2009).
[5] M. Stadler et al., in Proc. 1st Int. Beam Instrumentation Conf. (IBIC'12) (2012).
[6] C. Song et al., Phys. Rev. Accel. Beams 26*, 012803 (2023).*

Research Gap:toward High Spatiotemporal resolution for Sub-100 fC Beams



- Application of **MeV ultrafast electron diffraction (UED)** and **Single Event Effect (SEE)** sits in a different regime: operate **well below 100 fC**, where the cavity signal is orders of magnitude smaller while the noise floor is unchanged
- Combined BAM/BPM can be powerful tool for ML enhanced high-resolution timing and position controls for HiRES UED at LBL (PI: Dr. Dan Wang at BACI-LBL)

0.1 fC | 1 fC | 10 fC | 100 fC | 1 pC | 10 pC | 100 pC | 1 nC

UED / SEE regime

target of this work

Tsinghua

33 fs@ 0.5 pC

(BAM demo)

XFEL

LCLS

SPring-8

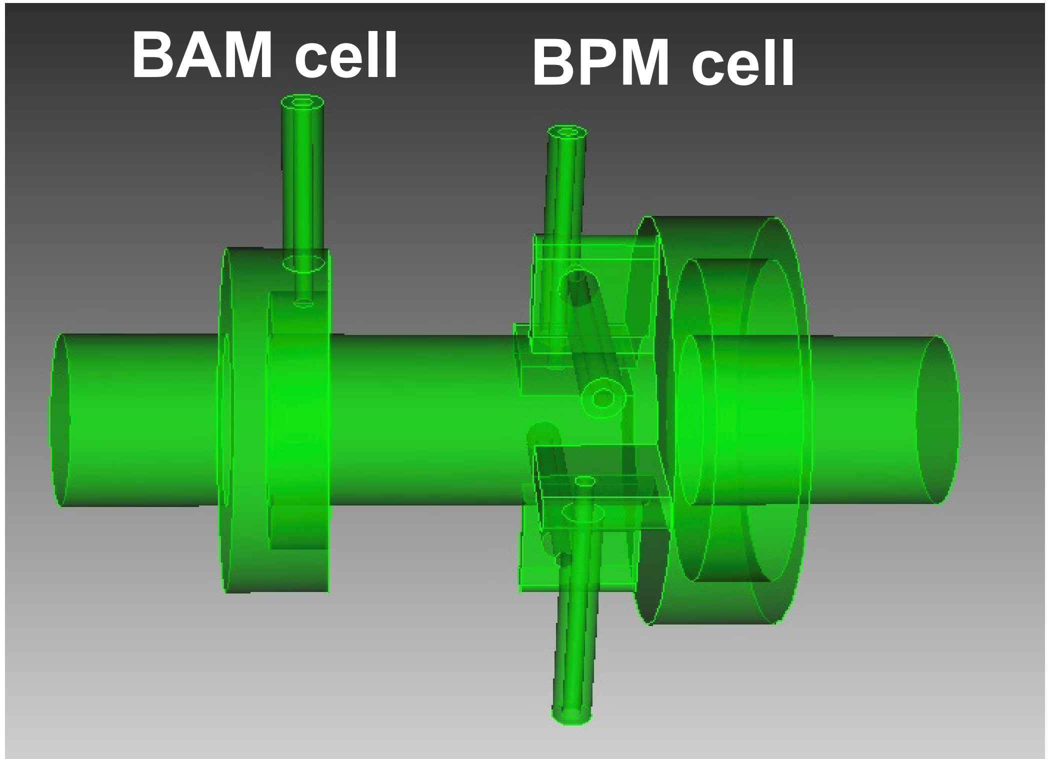
KEK ATF

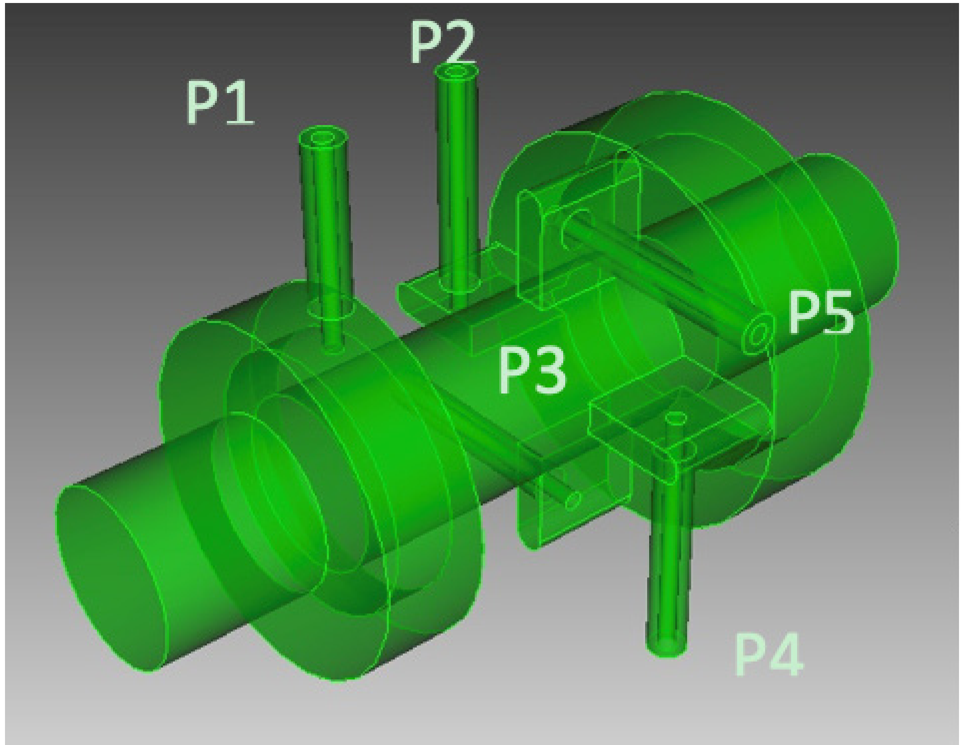
(BPM demos)

This work: implement **a two-cell BAM/BPM cavity** with **fC-level charge sensitivity**
Toward: high spatiotemporal resolution for **sub-100 fC** beams, with **simultaneous RFSoC acquisition.**

Two-cell BAM/BPM cavity design and simulation

- One structure with two cells — adopted as high-resolution diagnostic tool for HiRES beamline (Daniele Filippetto)
- **BAM Cell** has one output P1, coupling to TM010 mode for total charge, as longitudinal, beam arrival monitor
- **BPM Cell** has four outputs P2-P5, coupling to TM110 mode for beam position, as transverse, beam position monitors



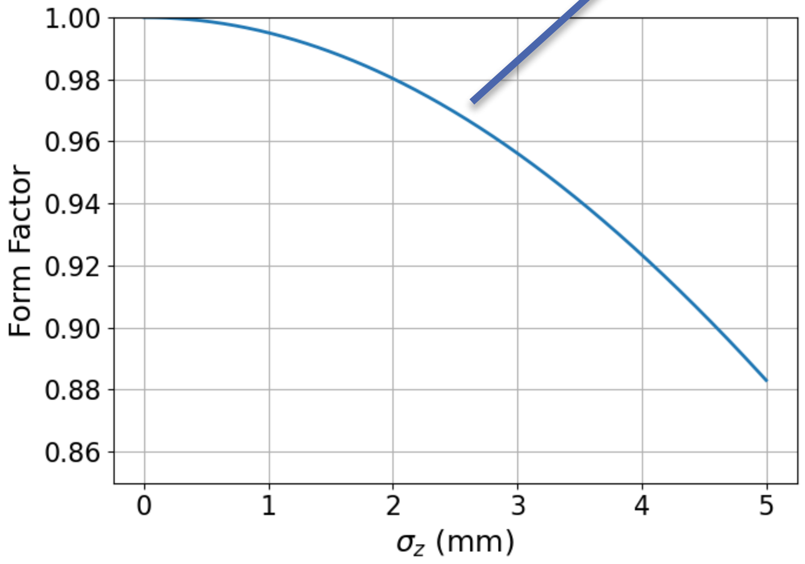


Designed and built by Tsinghua University
PhysRevAccelBeams.26.012803 (2023)

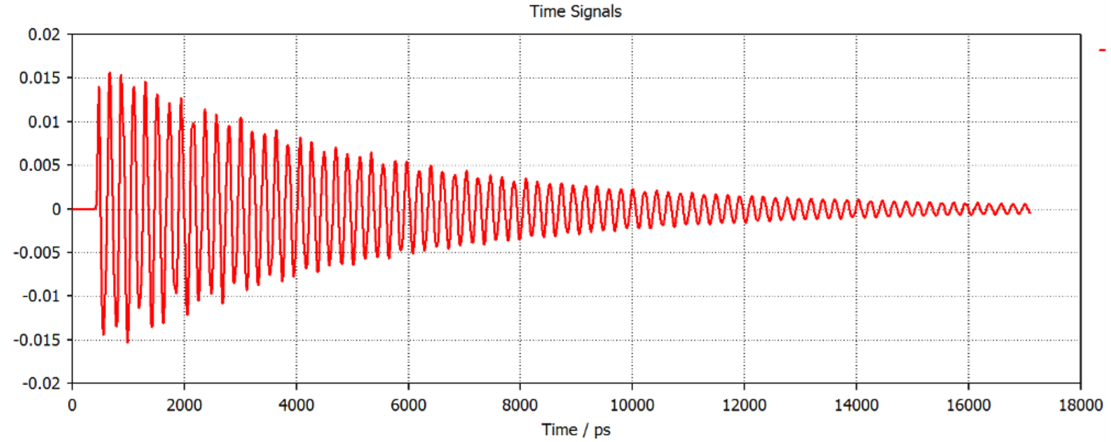
(PI: Dr. Tianhuan Luo at BACI-LBL)

Calculated BAM - beam longitudinal signal, charge-sensitivity

$$V_{peak} = \frac{\omega q}{2}\sqrt{\frac{Z}{Q_{ext}} R/Q}\, \exp\left(-\frac{\omega^2 \sigma_z^2}{2c^2}\right)$$



cst simulation:

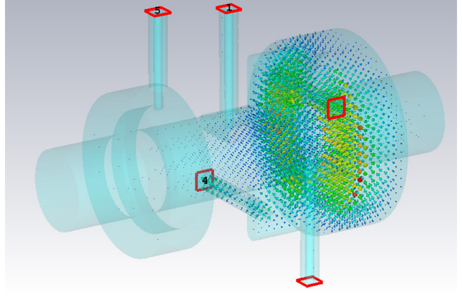


	CST simulation	RF test results
Omega = 2 pi* f	4.755 GHz	4.76 GHz
R/Q	53	53 (Use CST)
Z	50	50
Qext		369

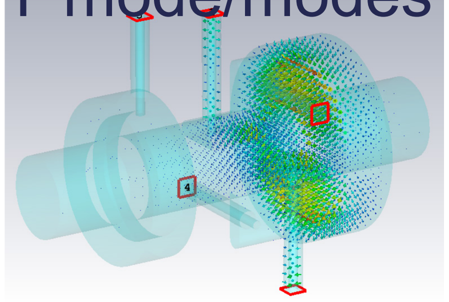
BAM Signal insensitive to micrometer bunch length, but proportional to beam bunch charge q, with a calculated sensitivity (40 mV/pC)

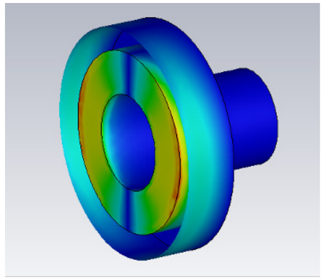
Simulated BPM - beam transverse signal, position-sensitivity

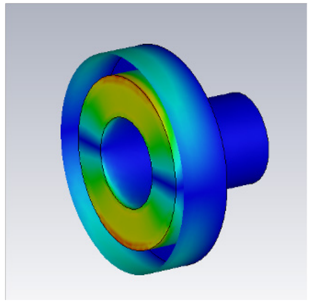
X mode/modes



Y mode/modes



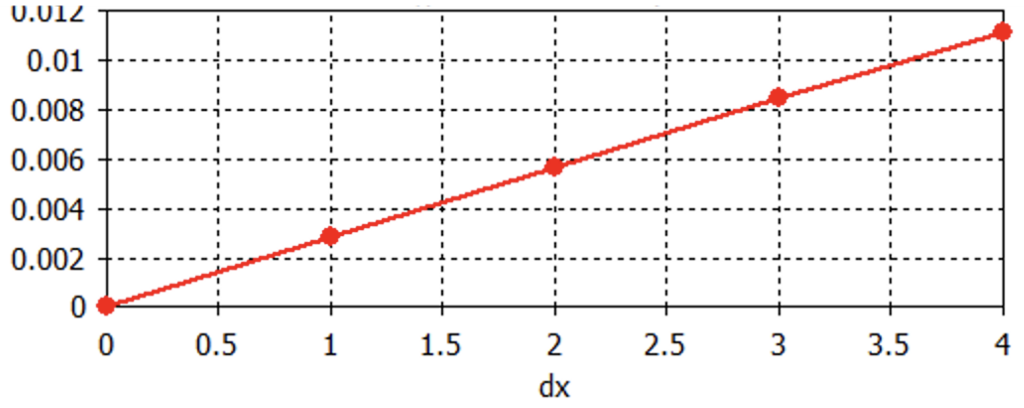




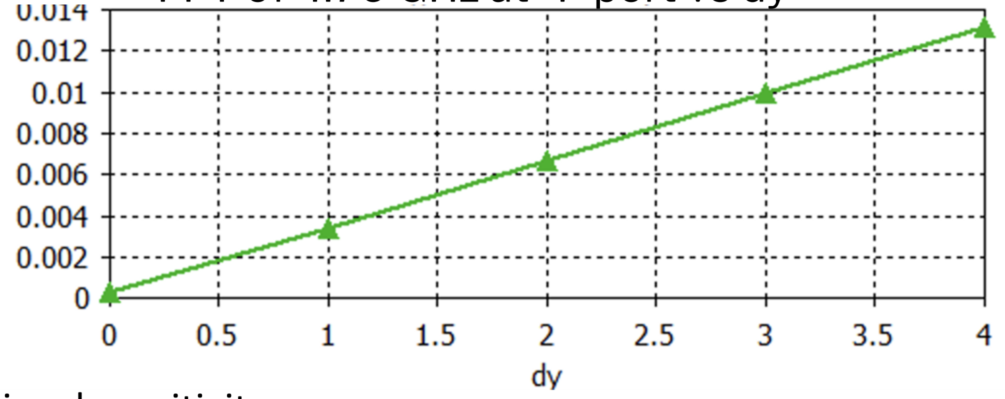
	TM010	TM110
F	3.5784 GHz	4.7629 GHz
R/Q	48	-
Qe / Ql	>1e9 (no coupling out)	101
Q0	3861	4435
Z	50	50
(q, sig_z)	(25 pC, 1um)	(25 pC, 1um)
Vout	No coupling out	~20 times smaller than port 5

Two orthogonal dipolar modes, amplitude proportional to charge & (x-offset / y-offset):

FFT of 4.76 GHz at X-port vs dx



FFT of 4.76 GHz at Y-port vs dy



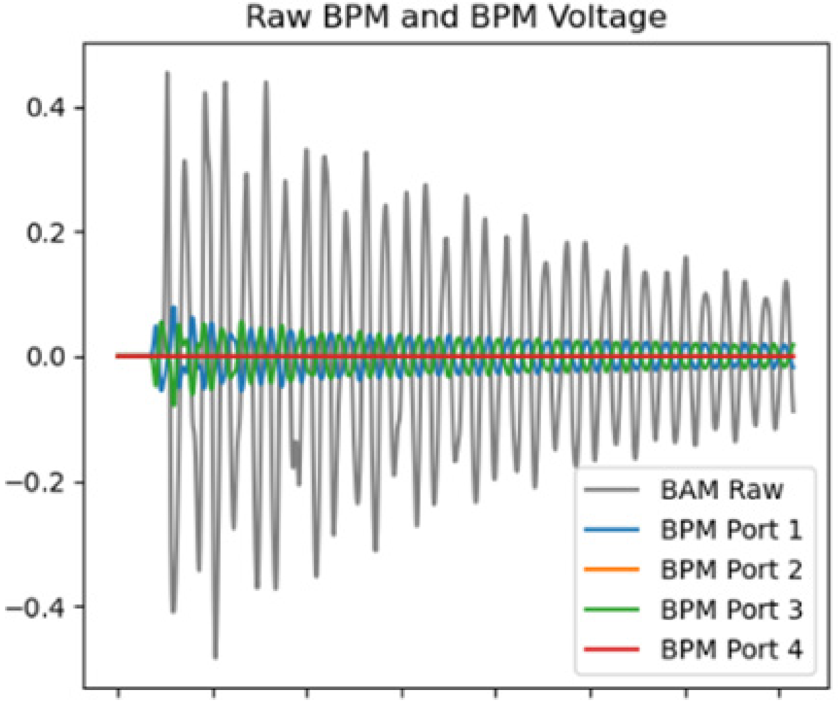
Signal sensitivity

~1.2 mV/ 1pC/ 1mm offset for X

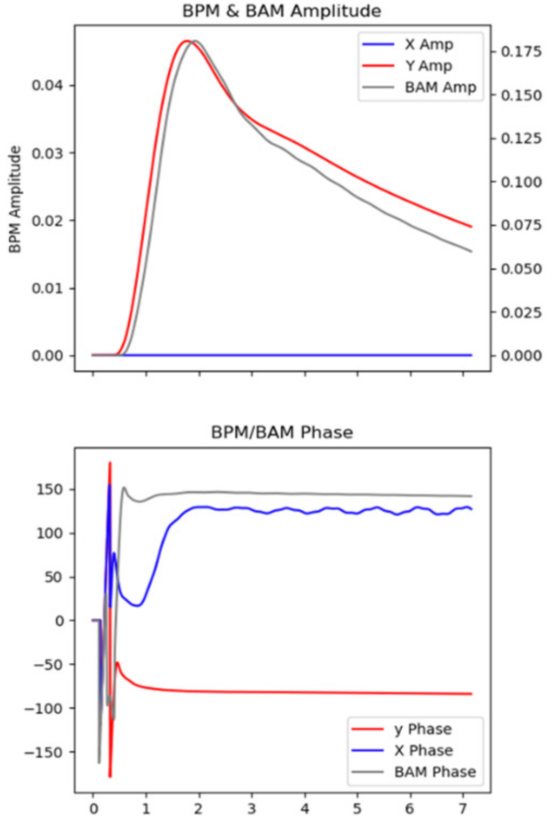
~ 2 mV/ 1 pC/1mm offset for Y

CST Prediction of BPM Amplitude and Phase Across the Electrical Center

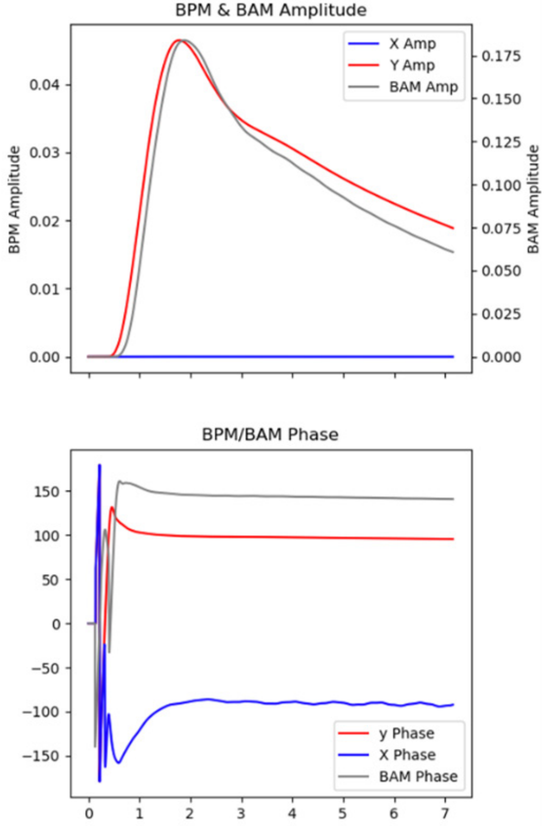
Example of CST simulation of BAM and BPM pickup signal at (0,2) mm



CST simulated DDC of beam at **(0,2) mm**

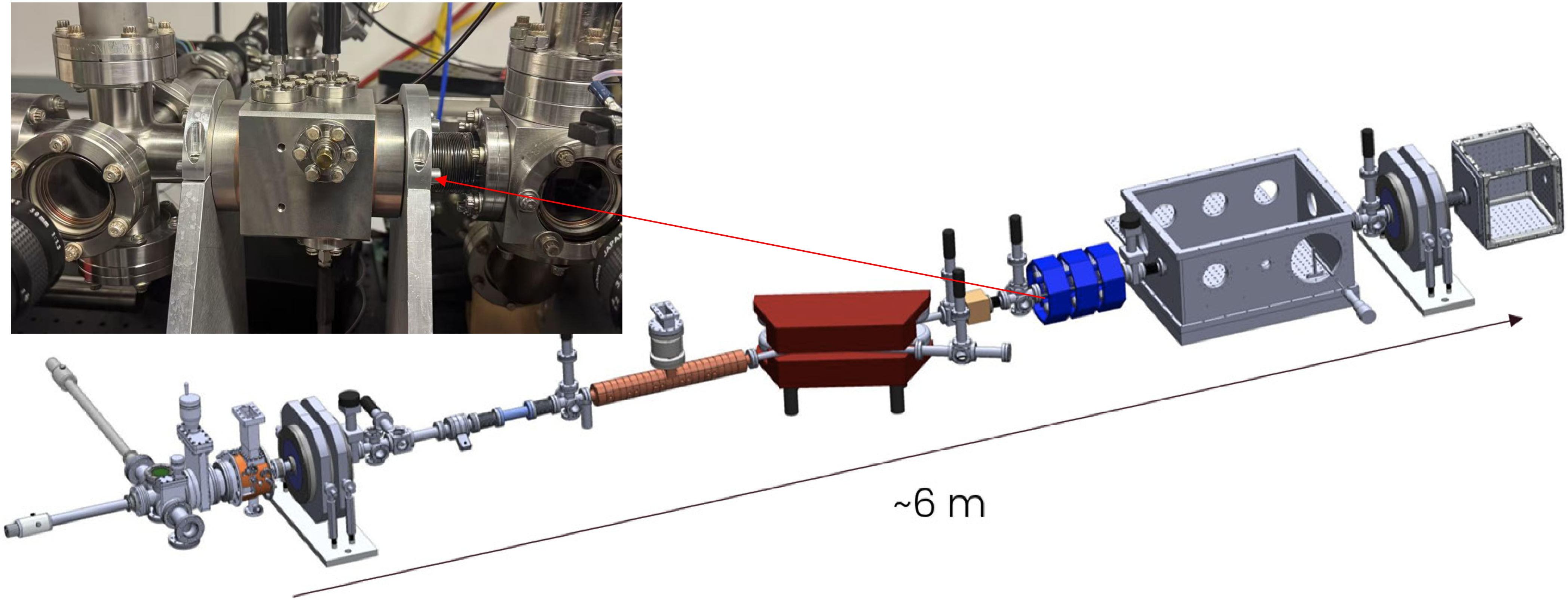


CST simulated DDC of beam at **(0,-2) mm**



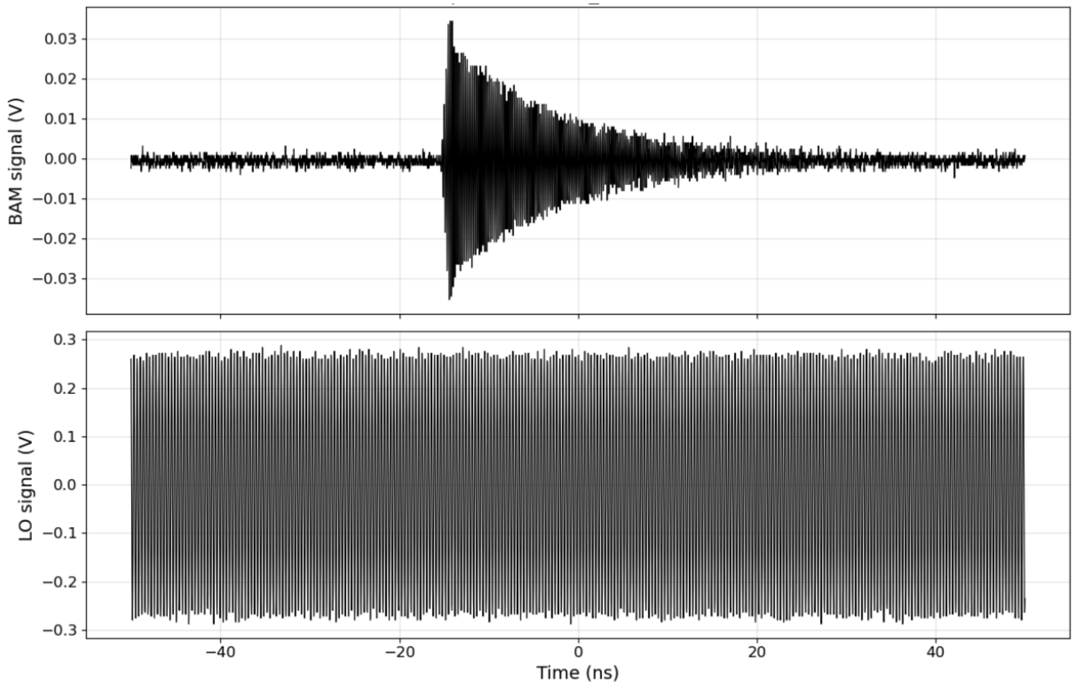
- CST simulations at **y=±2y mm** show **comparable Y-port amplitudes** and an **180 degree phase reversal** across the electrical center, which validates the expected **dipole-mode symmetry**.
- **BAM monopole mode** provides the **charge normalization** and **phase reference** for BPM dipole signals.
- The X-port response remains small because no horizontal offset is applied.

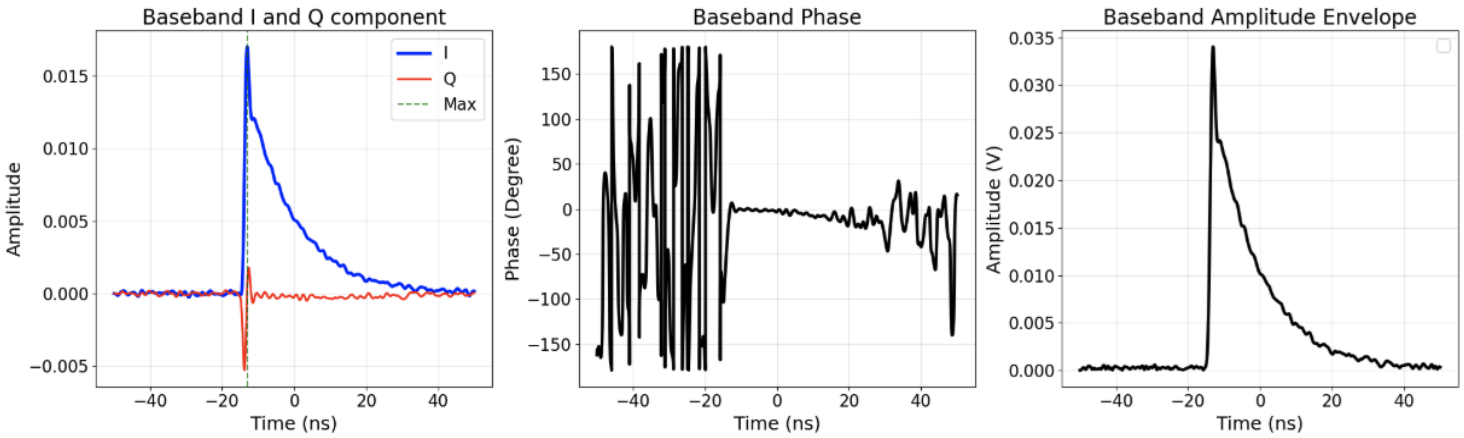
Experimental setup at UCLA-PEGASUS beamline



- 3-8 MeV electron test accelerator
- Photoinjector relying on RF acceleration
- Research on high-brightness beams, dynamics, and applications
- Versatile capabilities (ultrashort pulse widths, FELs, Compton Scattering, ultrasmall spot sizes)

Signal Acquisition and DDC Processing



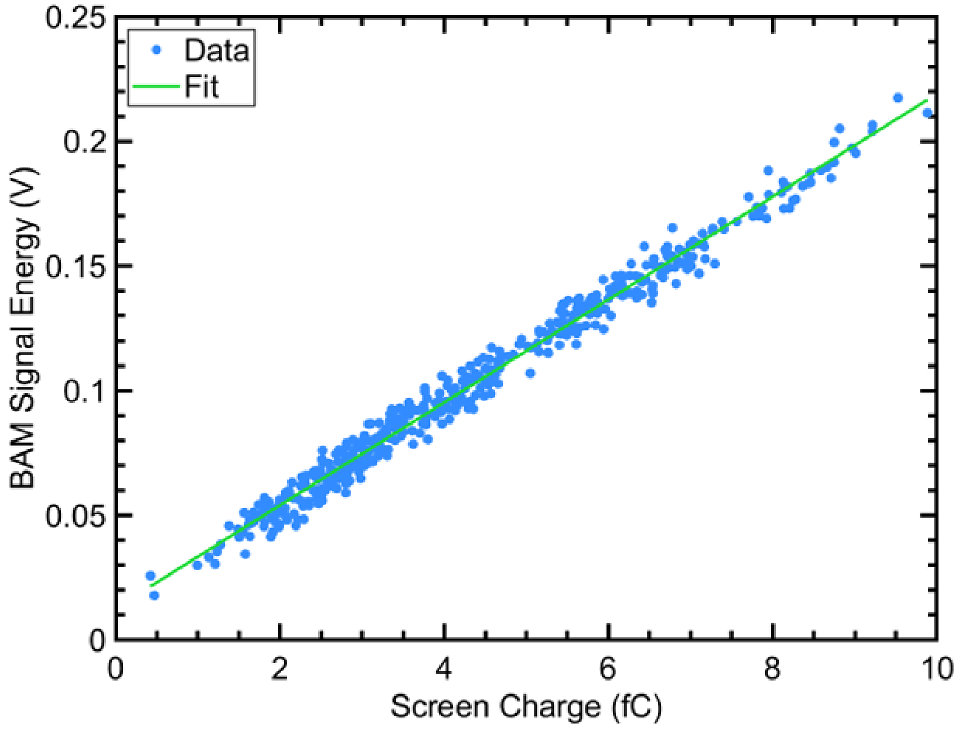


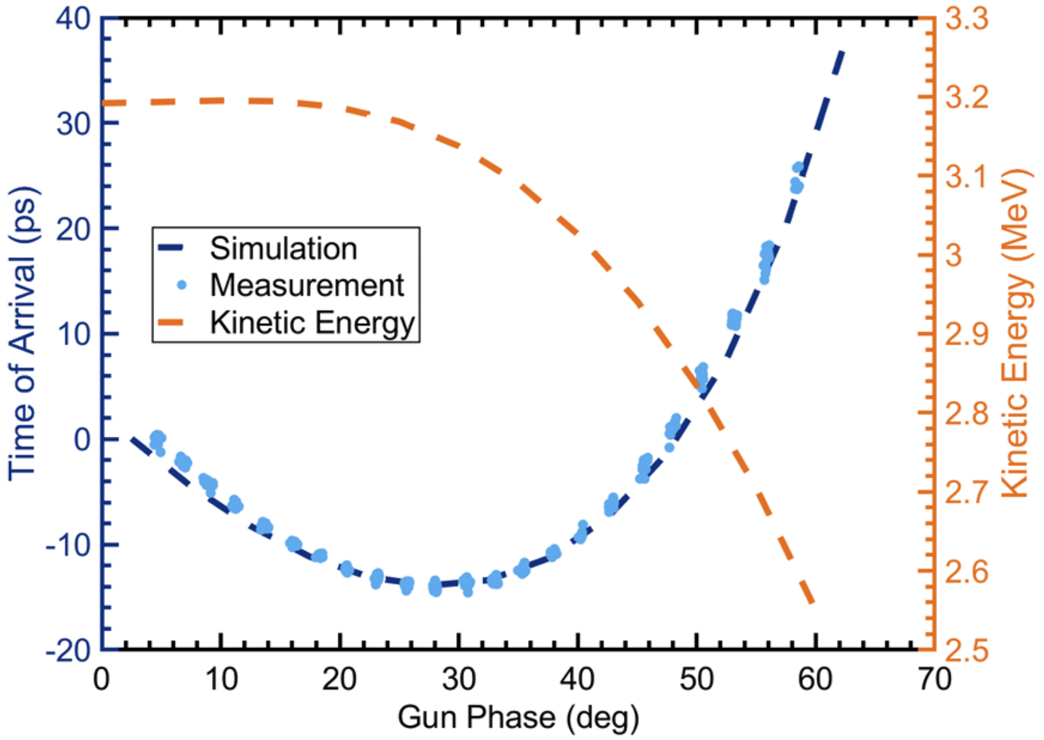
Raw **BAM signal at 4.76 GHz** and **LO signal at 2.856 GHz** is acquired on an 8 GHz (20 GSPS) oscilloscope

Digital Down-Conversion (DDC): performing DDC individually on each channel extracts clean amplitude and phase information from each signal, enabling precise timing measurements

Charge sensitivity of BAM cell and Time of Arrival Dynamics

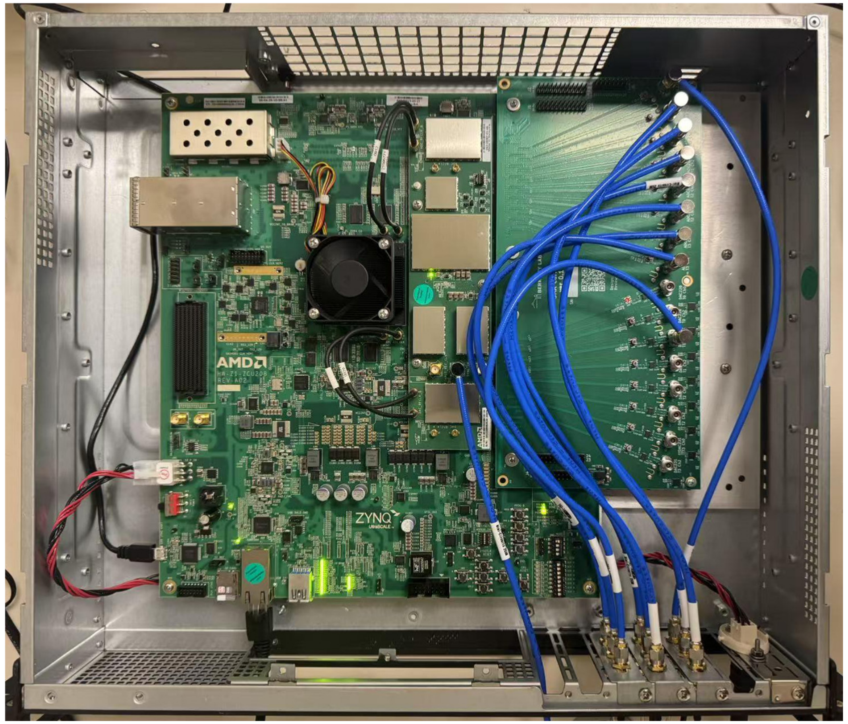
More details on the Cavity-Based Beam Charge and Arrival Time Monitor,
Welcome to our poster session: Poster TUP035 · Tuesday, September 1, 2026 · 4:20 PM · Ballroom C
Credit to and presented by: **Atharva Kulkarni (UCLA)**





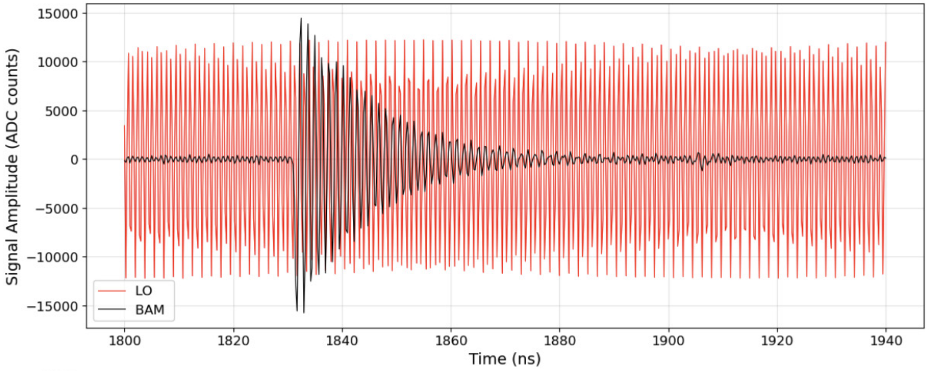
- Bunch charges as low as 0.5 fC were measured, charge resolution of 260 aC RMS,
- Gun phase scan yields per-shot time of arrival, which is well in line with simulation

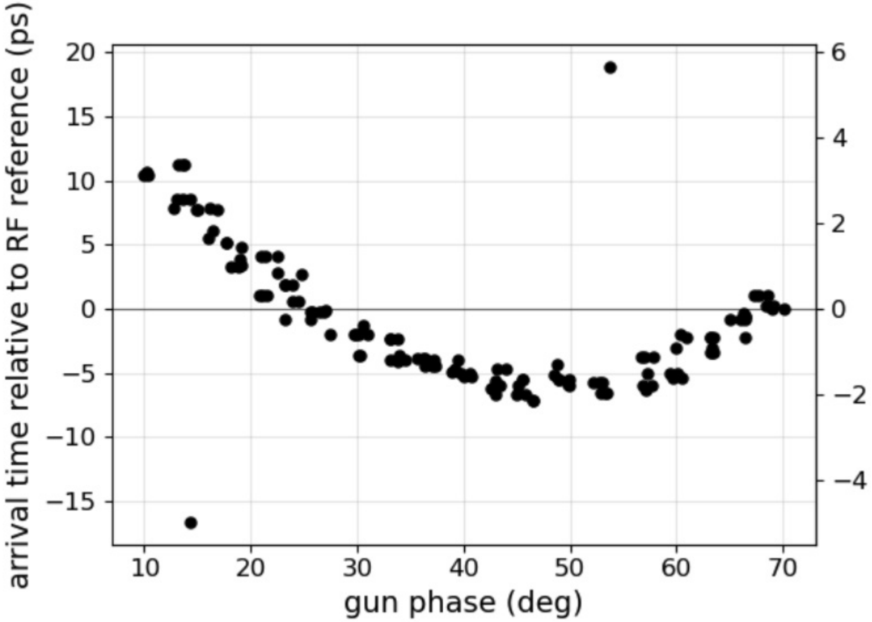
RFSoC instrumentation for digital processing of BAM/BPM RF signals



RFSoC for signal processing based on zcu208 architecture

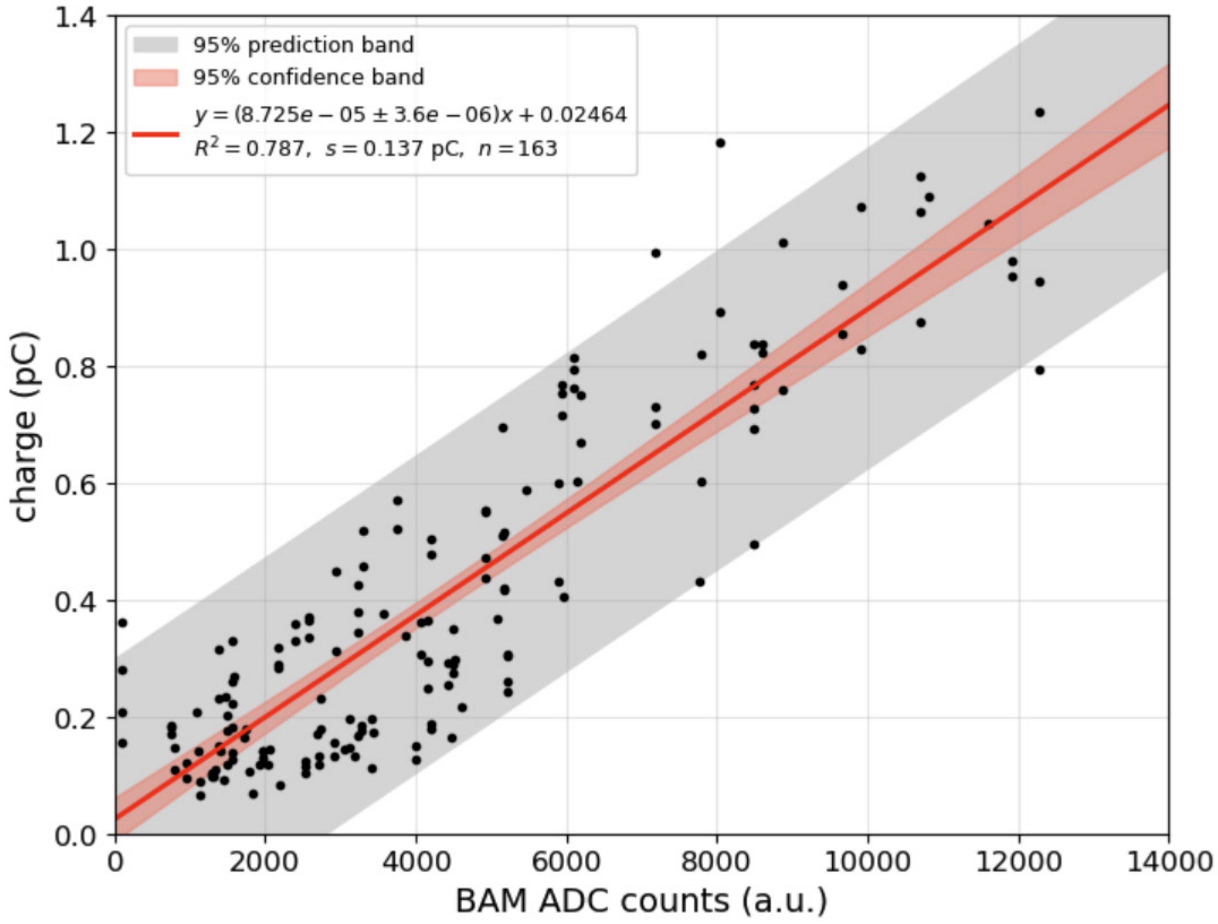
- Eight synchronized 14-bit, 5 GSPS ADC channels support simultaneous BAM/BPM acquisition.
- Direct RF bandpass sampling and digital down-conversion extract amplitude and phase without analog mixers.
- FPGA processing provides a path toward ML-adaptive beam control with low-latency, multi-channel beam diagnostics.





- Raw BAM and LO RF signals digitized directly by the RFSoC, showing the characteristic beam-induced amplitude modulation (envelope) used to extract bunch arrival time via DDC processing

RFSoC instrumentation for digital processing of BAM/BPM RF signals

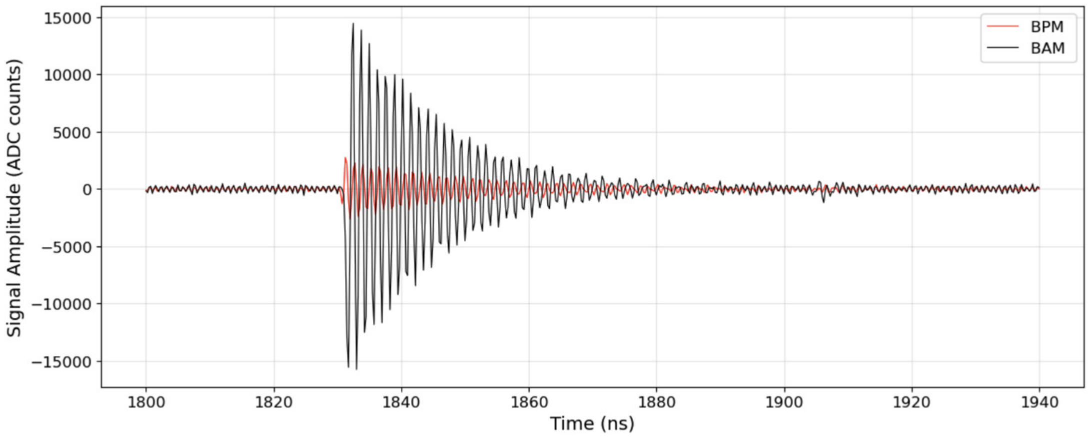


RFSoC-digitized BAM amplitude vs. independently measured bunch charge

- **RFSoC-digitized BAM amplitude increases with independently measured bunch charge over the tested range** (R^2 = 0.787, n=163), demonstrating charge-dependent signal acquisition.

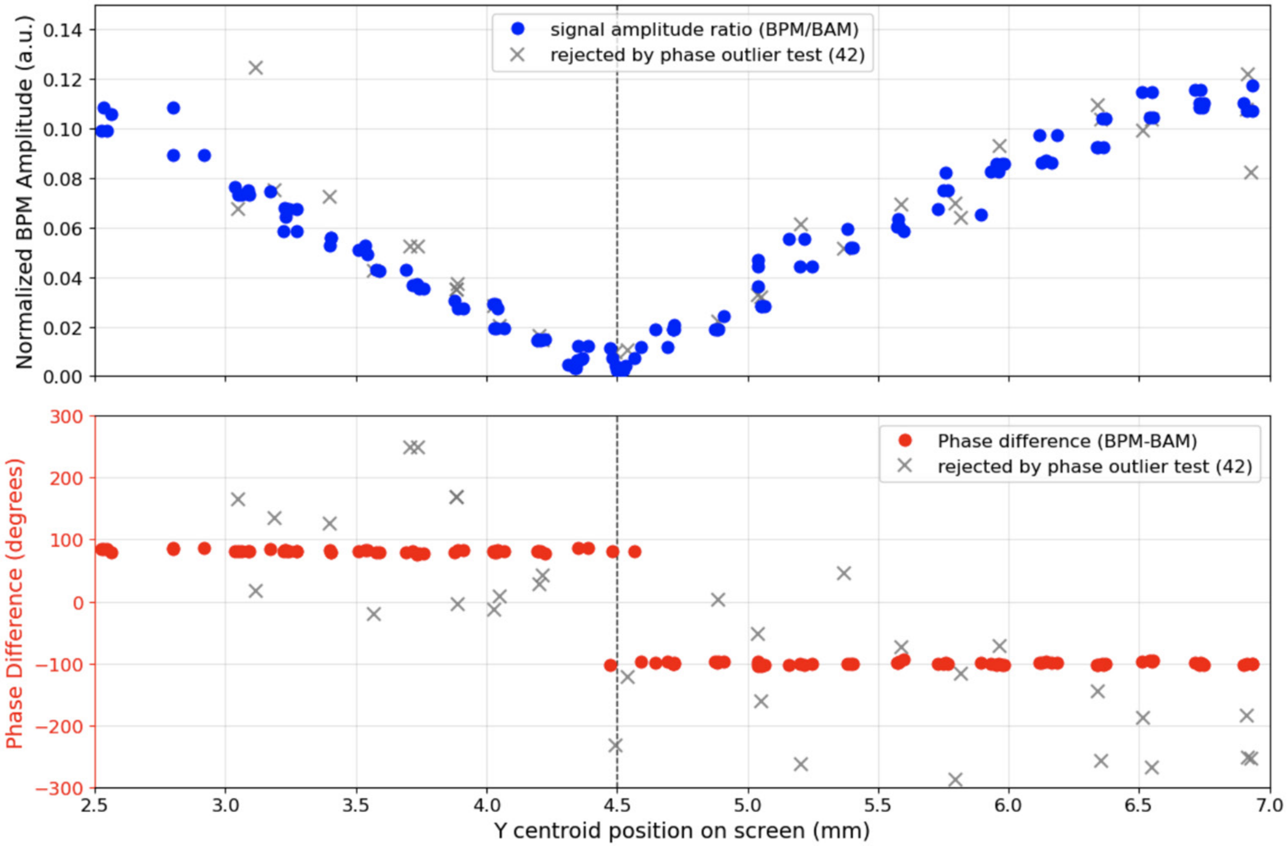
- **The 0.14 pC RMS fit residual represents the total scatter in this dataset** (not the RFSoC charge resolution. The RFSoC noise-equivalent charge will be quantified using beam-off noise and repeated fixed-charge measurements.)

RFSoC instrumentation for digital processing of BAM/BPM RF signals



- Simultaneous acquisition of BPM and BAM raw signals by the RFSoC during a vertical beam position scan

- BPM amplitude normalized by BAM amplitude removes shot-to-shot charge dependence, revealing a clear linear decrease in dipole-mode signal as the beam approaches the BPM's vertical center
- The BPM-to-BAM phase difference shows the expected ~180° flip when the beam crosses the vertical center, consistent with the dipole-mode field reversal predicted by BPM simulations.



Demonstration of simultaneous RFSoC-based BAM/BPM acquisition and DDC processing

Summary and Plan

Current Status:

- Demonstrated a cavity-based BAM/BPM system at the UCLA-PEGASUS beamline, with measured charge sensitivity (sub-pC/fC resolution) and arrival time response vs. gun phase in good agreement with CST simulations and analytical models
- Validated RFSoC-based digital down-conversion (DDC) for simultaneous BAM/BPM signal processing, showing clear charge-normalized position sensitivity and the expected 180° phase reversal across the beam center

Next Steps:

- Improve phase referencing and triggering (e.g., using the BAM signal as a BPM trigger) for future beamline tests
- Add uncertainty quantification to fit results, incorporating image centroid and beam angle errors
- Develop advanced DSP techniques to further improve timing and position resolution

Outlook:

- Extend toward an ML-enhanced cavity-based beam monitor (arrival time and position) for HTU/HiRES
- Enable high-resolution diagnostics and active feedback for beam stability, supporting advanced UED, FEL, and laser-plasma accelerator applications

Acknowledgement

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The BAM/BPM cavity was designed and fabricated by Tsinghua University, China.

Beam-based characterization and beam-dynamics studies were conducted at the UCLA–PEGASUS beamline in Prof. Pietro Musumeci's group.

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Thank you