Beam Diagnostics for Advanced Light Source

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Short Explanation of Course Materials

- **Particle accelerators come in various types. The beam diagnostic techniques discussed in this course focus on the diagnosis of high-energy bunched electron beam. Diagnosing heavy ions and low-energy electrons presents its own specific challenges; while the underlying principles are similar, practical details differ. Therefore, the experience or case studies presented in this course cannot be directly applied. Compared to high-energy electron accelerators, signals from low-beta accelerator beams exhibit lower intensity and narrower bandwidth.**

- **The content will primarily focus on the introduction and discussion of experimental methods and results, including only a small number of relevant formulas. For those interested in more details regarding specific issues, it is necessary to consult the relevant references and textbooks.**

- **The courseware incorporates extensive research findings from numerous domestic and international research groups, primarily sourced from journals such as PRAB, NIMA, IEEE TNS and NST, as well as proceedings of international conferences including IPAC, IBIC, BIW, EPAC and CERN CAS. Given the broad range of sources, it's possible that citations may not be fully comprehensive; we kindly ask for your understanding should any omissions occur.**

- **Many research teams have contributed to advancements in beam diagnostic technologies, resulting in hundreds of publicly published papers to date. For studies employing similar technical approaches, this lecture notes will not list every individual contribution exhaustively. Instead, we selectively feature the most representative works as illustrative case studies.**

- **During the preparation of these materials, we drew upon the research achievements of multiple colleagues and PhD candidates from both the Hefei Light Source and the Shanghai Synchrotron Radiation Facility (SSRF). Their substantial support during the collection and organization of references is deeply appreciated, and we extend our sincere gratitude to them here.**

Outline

- Overview of beam diagnostics
- Typical beam diagnostics
  - Beam intensity
  - Transverse position
  - Transverse distribution
  - Longitudinal parameters
- Beam diagnostics challenges for advanced light source
- Bunch by bunch beam diagnostics technology
- Outlook and summary

Beam Diagnostics Overview

What is Beam Instrumentation / Beam Diagnostics ?

- Obtain optical and electrical signals carrying beam information through the interaction between the sensor and the particle beam

- The output optical and electrical signals from the probe are processed to extract
  - spatial distribution characteristics of the particle beam (such as transverse cross-section dimensions, longitudinal bunch length, trajectory, emittance, etc.),
  - electrical parameters (including bunch charge, average current intensity, etc.),
  - and time-varying properties (like beam lifetime, bunch instability, etc.).

- Based on the measured beam parameters, accelerator characteristic parameters are derived: tune, response matrix, Beta function, dispersion function, coupling coefficient, chromaticity, etc..

What is Beam Instrumentation / Beam Diagnostics ?

Beam observer, beam (accelerator) data deliverer

- Accelerator builder: gauge for machine acceptance test
- Accelerator operator: commissioning & operation toolkits
- Accelerator physicist: machine study toolkits

An accelerator is just as good as its diagnostics

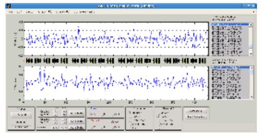
Beam Diagnostics for Accelerators, H.Koziol, CERN

不以规矩，不成方圆

《孟子·离娄上》

What is Beam Instrumentation / Beam Diagnostics ?

Beam diagnostics
- Behavioral Benchmarks
- Not essential for survival
- But crucial in determining system performance



Physics
(Brain)
Define the basic logic

Control
(nervous system)
Link all other systems together
Exchange information

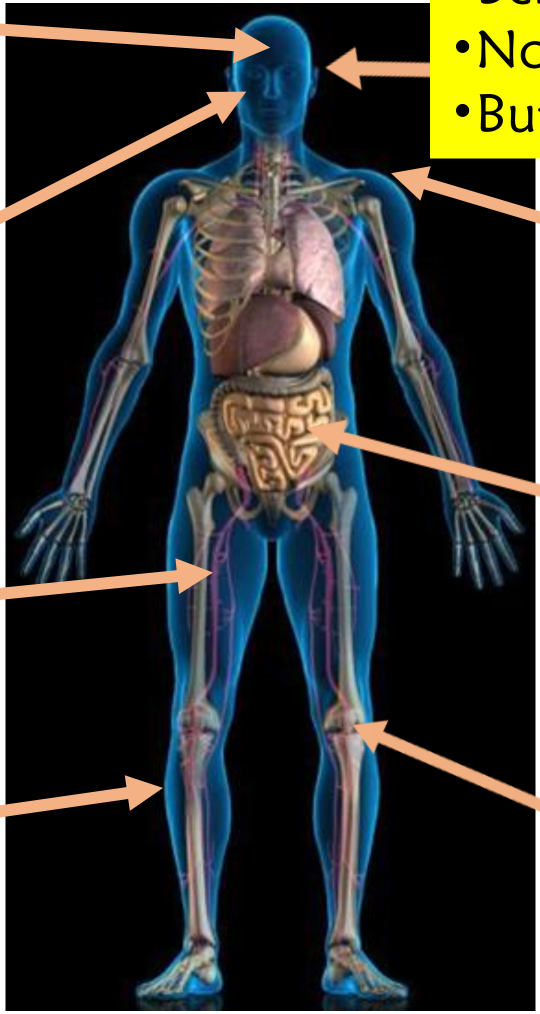
RF
(circulatory system)
Deliver energy to the beam

Vacuum
(skin)
Maintain the survival environment for the beam

Magnet
(Muscle)
Maintain beam path

Power supply
(digestive system)
Electrical power conversion

Mechanical support
(skeleton)
Frame, keep everything positioned precisely



Typical diagnostic devices and beam properties measured

PROPERTY MEASURED →	Intensity I , Q	transverse: Position	transverse: Size/shape	transverse: Emittance	longit.: Size/shape	longit.: Emittance	Q-value + ΔQ	Energy + ΔE	Polarization	Effect on beam: N	Effect on beam: –	Effect on beam: +	Effect on beam: D
Beam transformers	●				●	●				x			
Wall-current monitors	●	●			●	●				x			
Pick-ups	●	●	(●)		●	●				x			
Faraday cup	●												x
Secondary emission monitors	●	●	●	●				•			x	x	
Wire scanners		●	●	●				•			x		
Wire chamber		●	●								x	x	
Ionization chamber	●										x	x	
Beam loss monitors		•	•	•			•			x			
Gas curtain/jet		●	●	●							x		
Residual gas monitors		●	●	●						x			
Scintillator screens		●	●								x	x	x
Scrapers, targets		●	●	●									x
Schottky scan	●			●		•	●	●		x			
Synchrotron radiation		●	●		●	●				x			
LASER-Compton scattering			●	●					●	x			
Q-measurement							●			x	x		
Emittance measurement				●							x	x	x
Measurement of energy								●		x	x	x	x
Polarimeter									●	x			x

Effect on beam : N none
– slight, negligible
+ perturbing
D destructive

Beam diagnostics for accelerator, *H. Koziol*, CERN, Geneva, Switzerland

Longitudinal position is missing !

What kind of beam information do we need ?

Engineers: Meet any needs of accelerator operation and physical research.

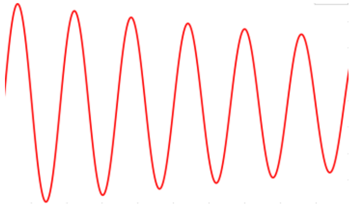
Charge, Current, Lifetime, Orbit, Size, Bunch Length, Energy, etc.

Scientists: A complete beam measurement should determine the distribution of particle groups (bunches) in four-dimensional space (three dimensions of real space x/y/z + energy E) and the their changes over time.

In practical, full dimension measurement is not feasible to achieve. Deliver lower dimension projection results to user:

- Charge/Current/Lifetime: Total number of particles in the bunch/First derivative with respect to time/Second derivative with respect to time.
- Bunch Position: The centroid of the bunch on a specific coordinate axis after one-dimensional projection in real space (xyz).
- Bunch Length: One-dimensional projection of the bunch along the direction of motion (z) in real space.
- Transverse profile: Two-dimensional projection of the bunch on the normal plane (xy) along the direction of motion in real space.
- Energy Spectrum/Energy: One-dimensional projection of the bunch on the energy axis (E)/The centroid of this projection.

What are we doing and how can we do it ?



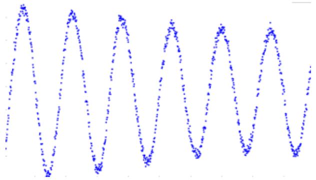
Electron Bunch in real world

- Charge/ Energy
- 3D position
- 3D distribution

EM coupling

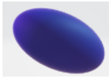
$$\delta_{CBPM} = std\left(\frac{U_1}{U_3} - \frac{U_2}{U_3}\right) \cdot k$$

Result evaluation

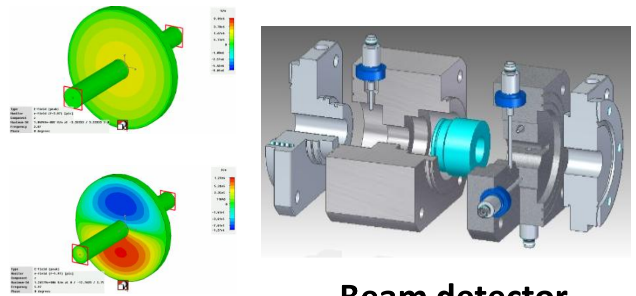


Electron bunch in digital space

- Meas. charge/Energy
- Meas. 3D positions
- Meas. 3D distributions



Bunch parameters

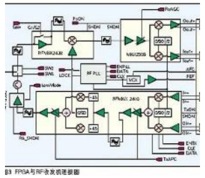


Beam detector

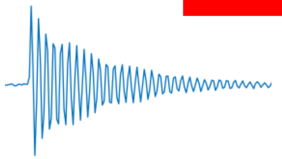
- ➢ **Establishing a perfect mapping of beams in the measurement space**
- ➢ **Multi-stage cascading achieves this mapping (relay race)**
- ➢ **Different stages are related by multiplication**
- ➢ **The performance of the system is not defined by a single stage**

$$k \cdot \frac{\sqrt[n]{\sum x_i^{\,n}}}{N} = \frac{\sqrt[n]{(k\cdot x_1)^n + (k\cdot x_2)^n + \ldots + (k\cdot x_N)^n}}{N}$$

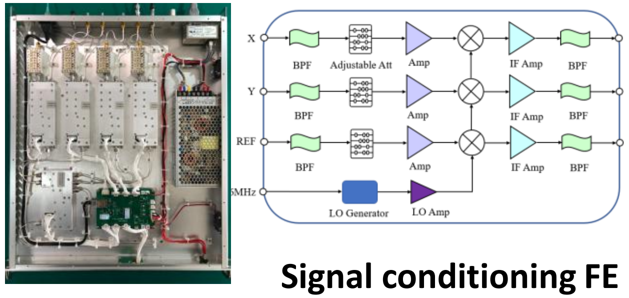
$$R = 1.56 \cdot \frac{\sqrt{(G_{RFFE}\cdot NF \cdot N_{RF})^2 + (N_{ADC})^2}}{G_{RFFE}\cdot A_{RF}} \cdot \sqrt{\frac{T_s}{\tau}}$$



Beam Information Extraction Algorithm



Raw broad band beam signal



Signal conditioning FE

IF analogue signal

Digital signal processer

Digital signal

How to do a beam diagnostics system design

Engineer way（Beam instrumentation）

One's self-positioning shapes the final results

- Find a solution that meets the requirements.
- Know how to build the system.
- Can directly refer to others' completed designs.
- Can be a world-class work (excellent students).
- No way to achieve a leading position globally.

知其然

SSRF BI system	Detector	Signal conditioning	Signal processor	Information Extraction Algorithm	System Evaluation Method
BPM	KEK/Soleil	DLS/Soleil	DLS/Soleil	DLS	APS
DCCT	SPEAR3	SPEAR3	**SSRF**	**SSRF**	**SSRF**
Interferometer	KEK	KEK	KEK	KEK	**SSRF**
MBFB	Spring-8	Spring-8	Spring-8	Spring-8	**SSRF**
Xray pinhole	ESRF	**SSRF**	**SSRF**	**SSRF**	**SSRF**
BCM	KEK	SLS	SLS	**SSRF**	**SSRF**

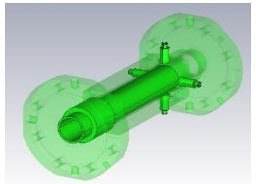
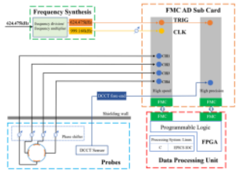
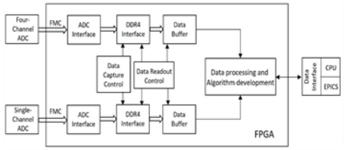
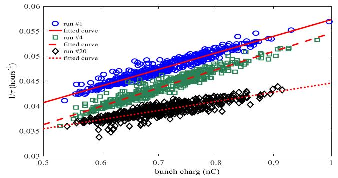
How to do a beam diagnostics system design

Scientist way（Beam diagnostics）

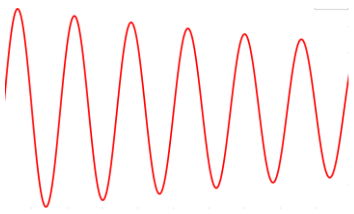
One's self-positioning shapes the final results

知其所以然

- **Find the optimal solution/the best solution for your own facility.**
- **Understand the basic logic why system built in this way.**
- **Requires analyzing and designing from first principles yourself.**
- **Potential to achieve a leading position globally.**

HALF/SSRF BCM system	Detector	Signal conditioning	Signal processor	Information Extraction Algorithm	Application
Target	Fast enough No Trans. Pos dep	BW vs SNR Small crosstalk	Slow and Fast DAQ combined	No bunch phase and length dep	Bunch lifetime Bunch Q loss Other applications
Related courses	Electromagnetism	Analog circuit	Electronics Eng.	Signals and systems	Accelerator physics
Key technology	CST/CAD Precision machining	Analog PCB design and fabrication	Analog and digital PCB design	FPGA coding	High level coding
Result			 		

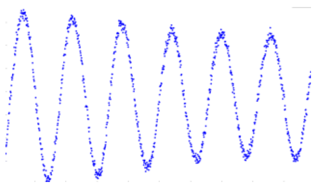
How to do a beam diagnostics system design



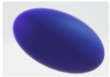
Electron Bunch in real world
- Charge/ Energy
- 3D position
- 3D distribution

$$\delta_{CBPM} = std(\frac{U_1}{U_3} - \frac{U_2}{U_3}) \cdot k$$

Result evaluation

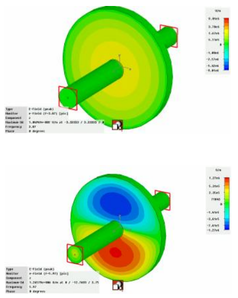


Electron bunch in digital space
- Meas. charge/Energy
- Meas. 3D positions
- Meas. 3D distributions



Bunch parameters

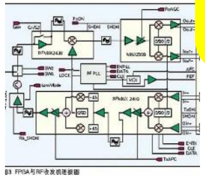
EM coupling



Sensitivity
Charge range
Band width
SNR

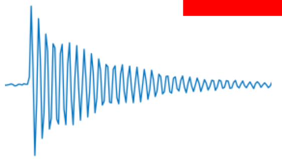
Beam detector

- No free launch
- No best solution for each module
- Expensive solution is not always right one
- Best solution defined by your boundary condition



Real-time processing
Best SNR
Low latency

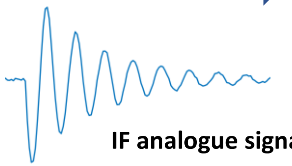
Beam Information Extraction Algorithm



Raw broad band beam signal

Linearity
Noise figure
Band width

Signal conditioning FE



IF analogue signal

Sampling rate
ENOB
Band width

Digital signal processer

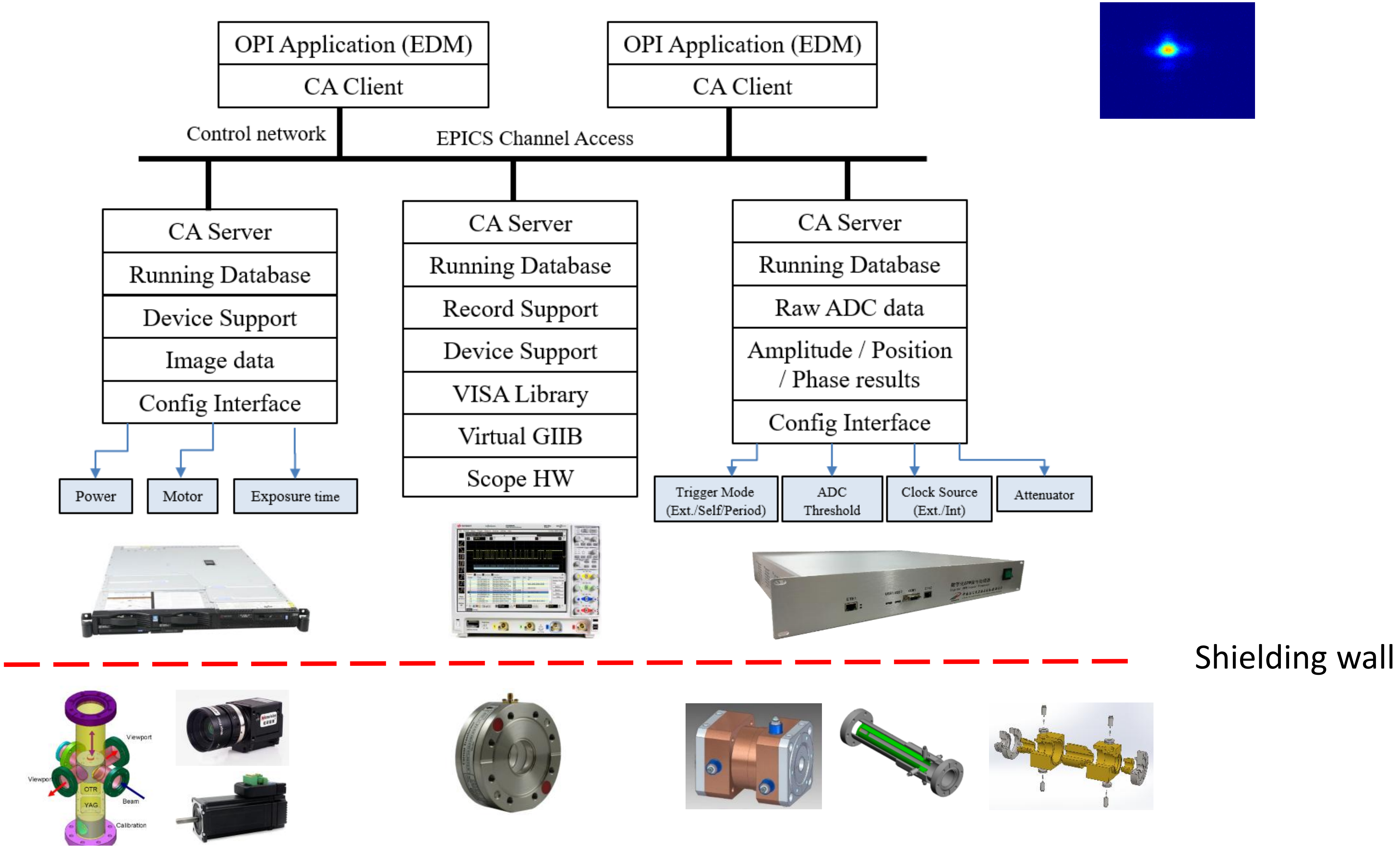
Digital signal

A typical beam diagnostics system: SXFEL

User interface
High level application

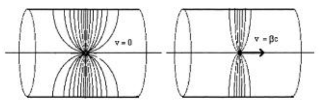
Data acquisition
Signal processing
Control

Beam signal pick up
Signal conditioning



Profile ICT CBPM、SBPM、BAM

What kind of beam signals we can use ?



Same longitudinal distribution
Dependent to beam trans. position
$\propto$ charge

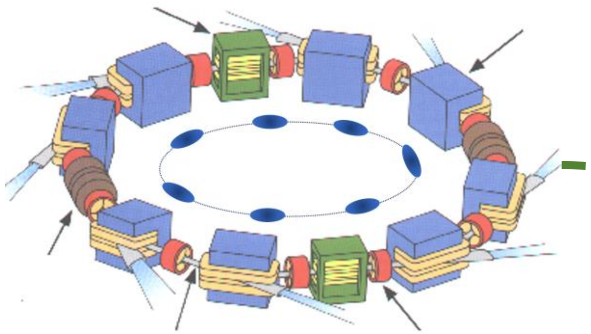
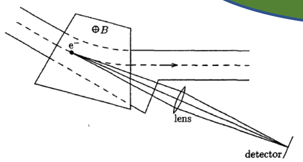


Image charge

- Wall current monitor
- Button pickup
- Stripline pickup
- Current transformer
- Cavity pickup
- EO sampling

Radiation



Light pulse faithfully
replicates the beam bunch

- Synchrotron Radiation
- Smith-Purcell Radiation
- Optical Diffraction

Interception

- Faraday cup
- OTR screen
- Compton scattering
- Fluorescent screen
- Wire scanner
- Cherenkov Radiation

Signal conditioning

Optical Signal

Attenuator

Splitter

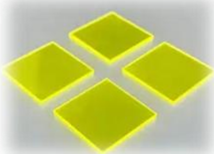
Grating

Focusing lens

Filter

Polarizer

Nonlinear Crystal



YAG screen

OE convertor

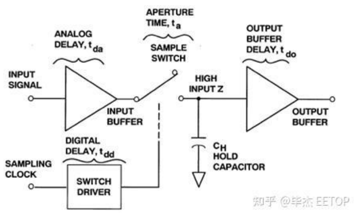
Electrical Signal

Filter

Amplifier

Mixer

RF Detector



S & H circuit

Attenuator

Splitter

Frequency Doubler

Phase shifter

DAQ solution




Commercial DAQ & Instruments





FPGA Development Toolkits

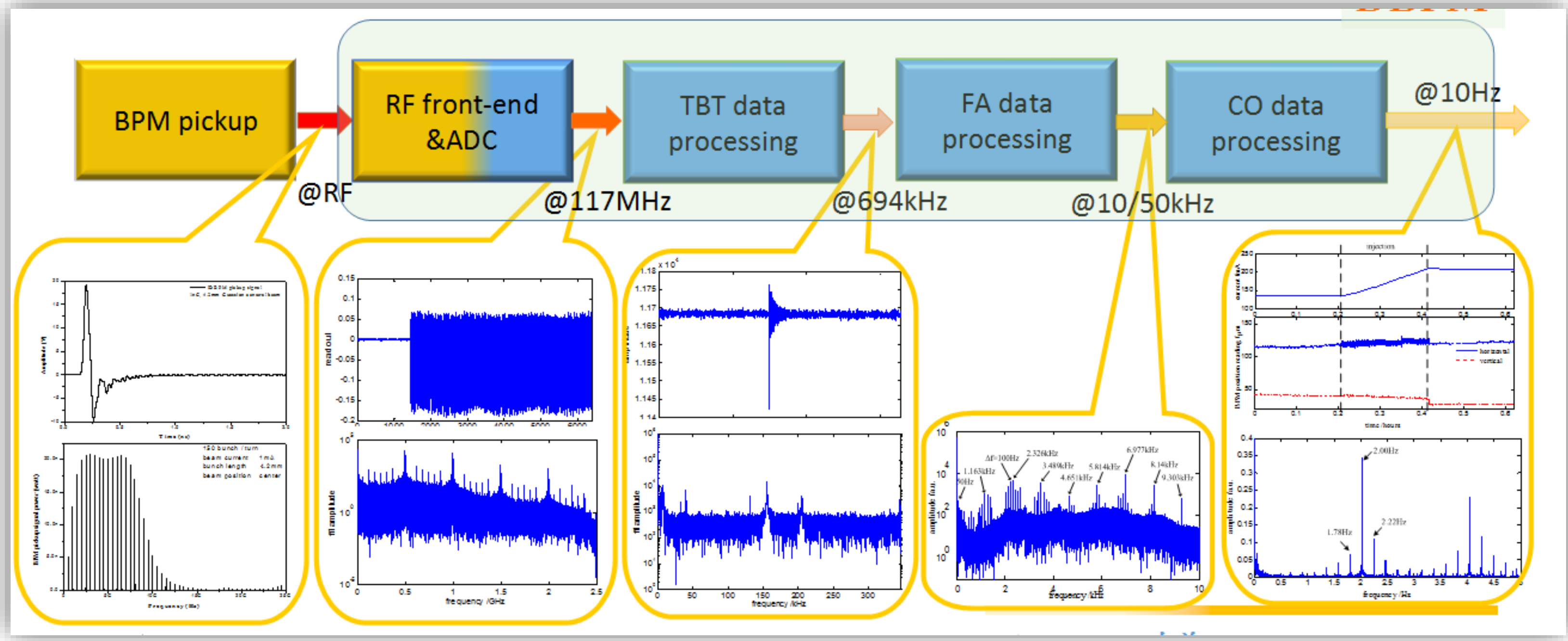


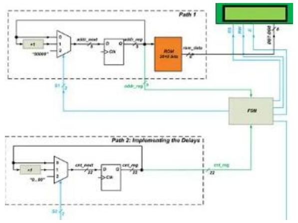
Commercial Dedicated Instruments


Custom Designed Beam Signal Processor

Signal processing method

Typical DAQ and digital signal processing of DBPM





Raw signal parameters extraction

- Digital Filtering
- IQ demodulation
- Integration
- FFT, amplitude and phase extraction
- Decimation, intepolation
- ……
- ML

Beam information calculation

- Delta/Sum calculation (beam position)
- Correlation
- Curve fitting (size or length)
- Lookup Table
- ……
- ML

Beam diagnostics technology evolution

LINAC (Free Electron Laser)

		Transverse position	Transverse distribution	longitudinal position	longitudinal distribution	Charge	Energy Spectrum
Before 2000	Macro bunch						
2010	Micro bunch				NA		NA
	Each particle	Final goal: The energy of each charged particle and the evolution of its three-dimensional position in real space over time					
2010	BYB		Not good				NA
2005	TBT		Not good				NA
Before 2000	Average						
		Transverse position	Transverse distribution	longitudinal position	longitudinal distribution	Charge	Energy Spectrum

Storage Ring (Synchrotron light source)

Operation

Machine study Coherent behavior

Machine study Incoherent behavior

Configuration and optimization

Machine commissioning stage

Small charge → **high sensitivity**
Uncorrected Lattice → **large dynamic range**
Tuning tools → **qualitative measurement, large measurement errors acceptable**

Facility acceptance test stage

Optimize accelerator performance → **high resolution**
Determine machine parameters → **Accuracy**
Continuous measurement not required → **destructive method acceptable**

Operation stage

Online monitors → **minimal interference for beam / non-interceptive**
Good enough to identify abnormal condition → **high resolution**
Easy to use → **reliability/repeatability/stability**

Beam data source for the various feedback or feedforward loops in the machine

High data rate, high bandwidth
Low latency

Typical Beam Diagnostics:
beam intensity and lifetime

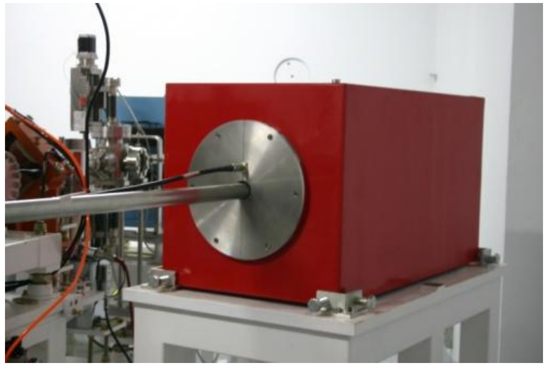
Typical diagnostics devices for beam intensity

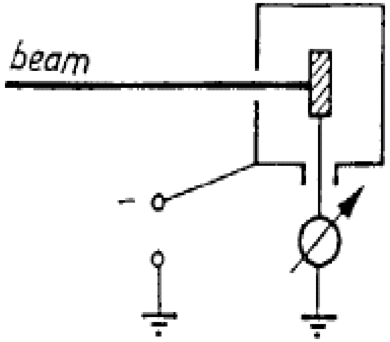
	Beam sensor	DAQ solution	resolution	Remarks 1	Remarks 2
Destructive	Faraday Cup	Q meter / Scope	~ 1%	Absolute value	LINAC
Non-destructive	ICT	Scope / fast digitizer	1 ~ 2%	Absolute value	LINAC
	DCCT	DMM	2 uA (1E-6)	Absolute value	RING and LINAC
	Other CTs	Scope / fast digitizer	~ 1%	relative value	LINAC and RING
	Wall current monitor	Scope / fast digitizer	~ 1%	relative value	LINAC and RING
	BPM sum signal	Scope / fast digitizer	0.02% (multi-turns)	relative value	RING and LINAC
	Cavity (TM_{0X0})	RF-FE + fast digitizer	0.01%	relative value	LINAC
	SR + PD	Scope / fast digitizer	~ 1%	relative value	RING

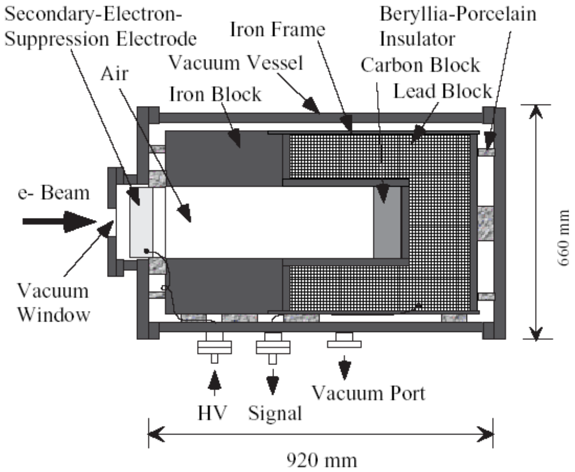
Faraday Cup

A Faraday cup is a device used to catch charged particles and measure their current, helping to determine the amount of electric charge carried by these particles. It works by collecting electrons or ions, which then generate a measurable electric current proportional to the number of particles striking the cup.

- **Primarily used for the absolute measurement of charge quantity in low-energy beams.**
- When the particle beam strikes the collector electrode, it dissipates all its energy, causing the charge to accumulate on the collector.
- By connecting an ammeter or electrometer across the collector electrode and the signal ground, the beam current or total charge can be measured.
- Given the relatively wide signal bandwidth, an oscilloscope is typically utilized as the data acquisition device.
- To mitigate signal distortion resulting from secondary electron emission, a negative bias voltage is conventionally applied to the shielded enclosure.



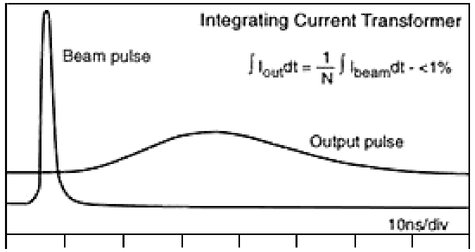


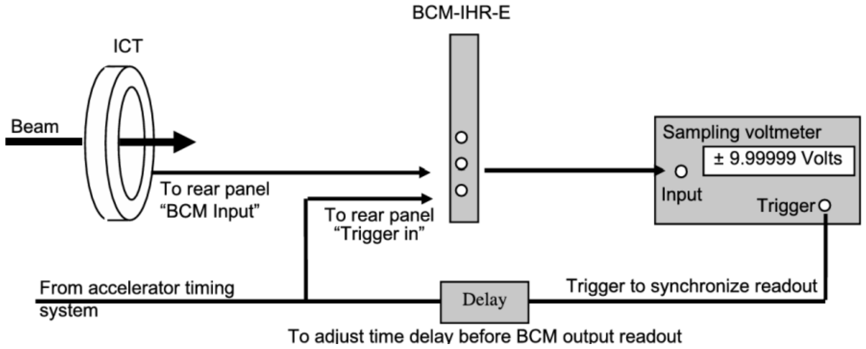


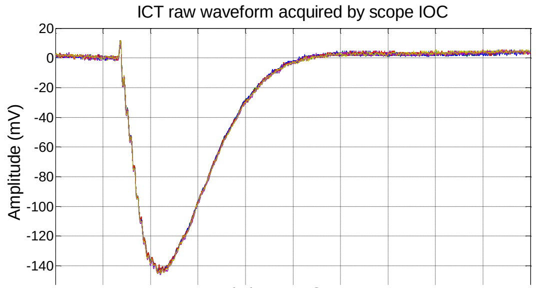
cross-sectional view of the FC of the KEKB injector linac (courtesy T. Suwada, 2003)

Integration Current Transformer (ICT)

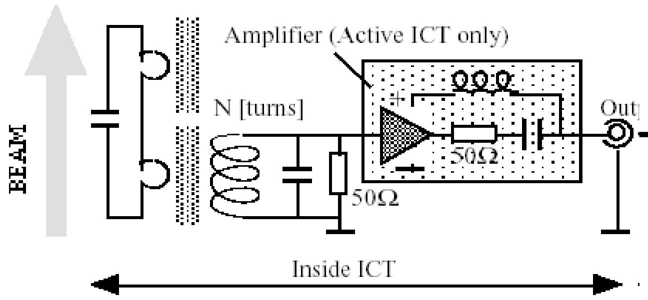
Suitable for absolute measurement of average beam current in storage rings and high-repetition-rate linacs (operating at tens of μA), serving as a reference calibration device for other measurement techniques.







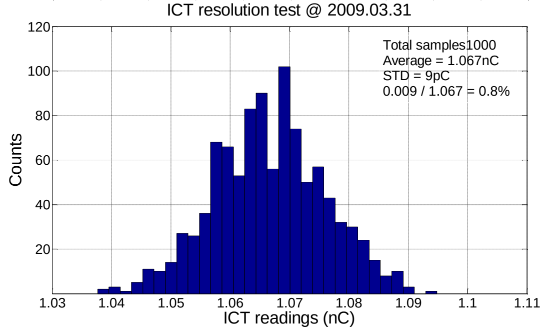
Bergoz ICT



Scope embedded IOC

Fast Scope

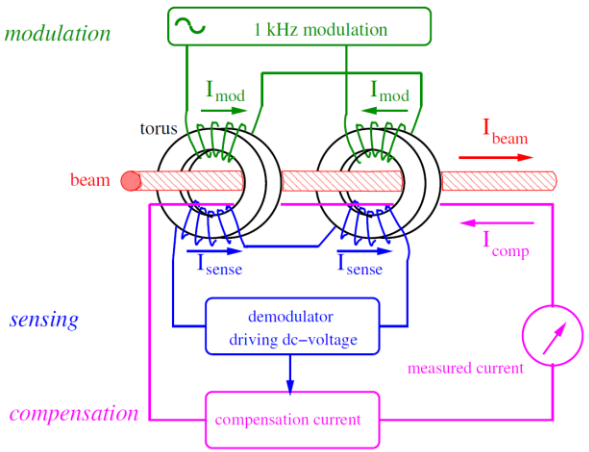
BW >= 200MHz



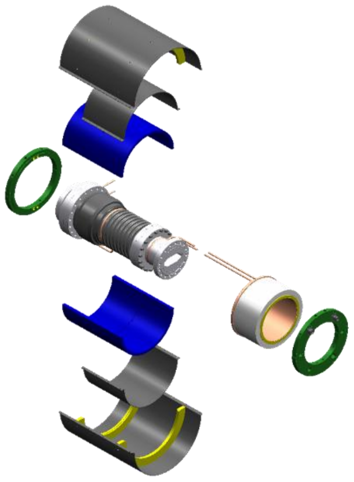
SSRF example: 1000 samples **RMS: 0.009/1.067nC = 0.8%** **P-P: 0.06/1.067 = 5%**

DC Current Transformer (DCCT)

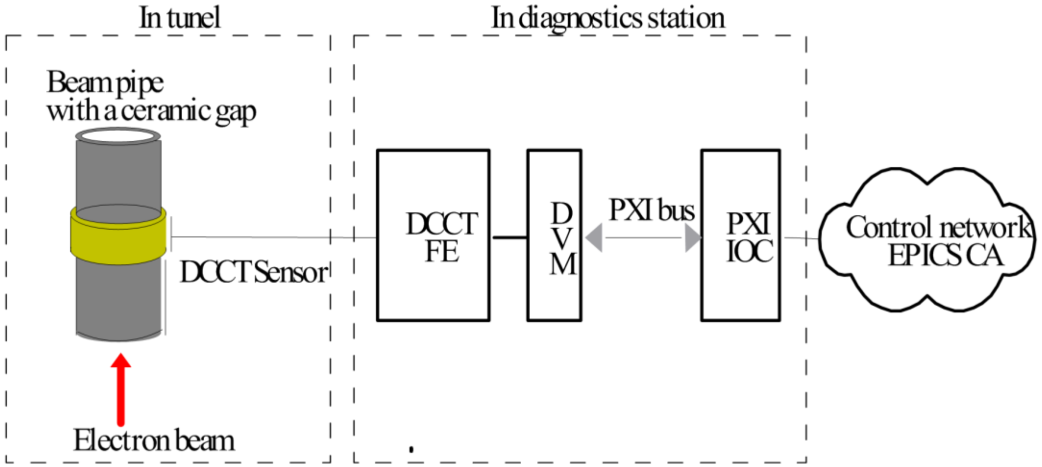
Suitable for absolute measurement of average beam current in storage rings and high-repetition-rate linac (operating at hundreds of μA), serving as a reference calibration device for other beam intensity measurement techniques.

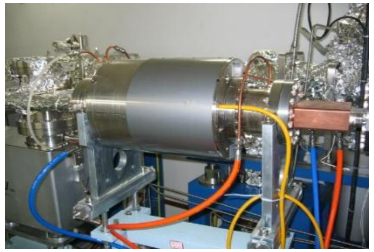


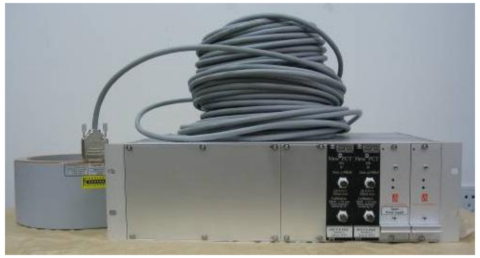
Beam Instrumentation and Diagnostics, Peter Forck, Proceedings of the General Introductory CAS course on Accelerator Physics & Technologies, 2019 and beyond



Shield design borrowed from SPEAR3





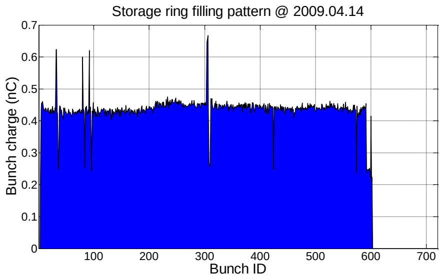


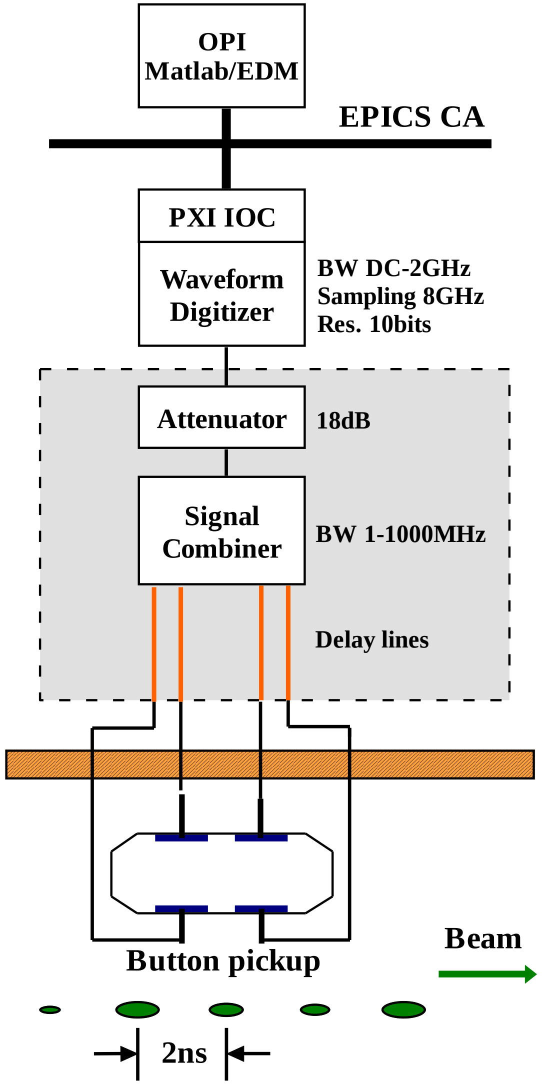
Bergoz NPCT175

NI 4070
DVM

NI 8187
PXI controller

Filling Pattern Monitor @ SSRF





Button pickup

Acquire beam signal, RF = 499.654MHz

Delay line

Compensate phase difference of signals form 4 buttons

Signal combiner

Filter out beam position independent intensity signal

Attenuator

Adjust signal level of FE output to ADC input range

Waveform digitizer

ADC @ BW 2GHz, sampling rate 8GHz, resolution 10bits

IOC

Rebuild waveform, calculate bunch charge

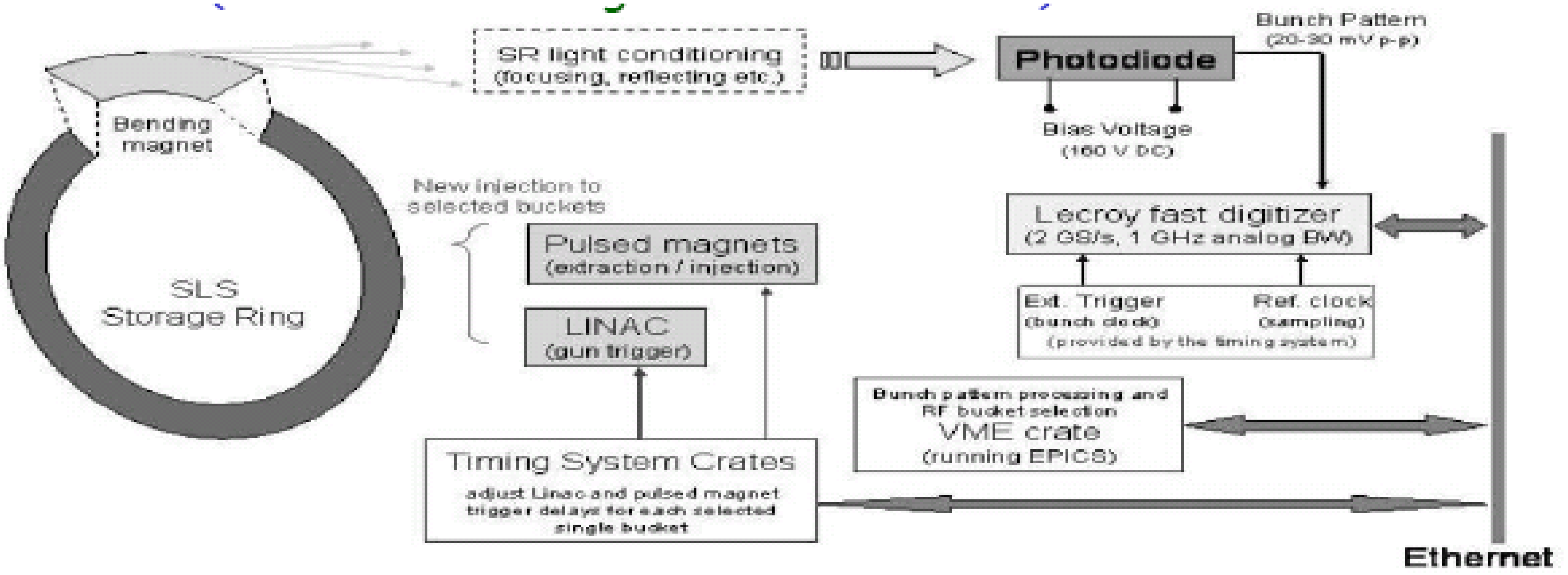
OPI

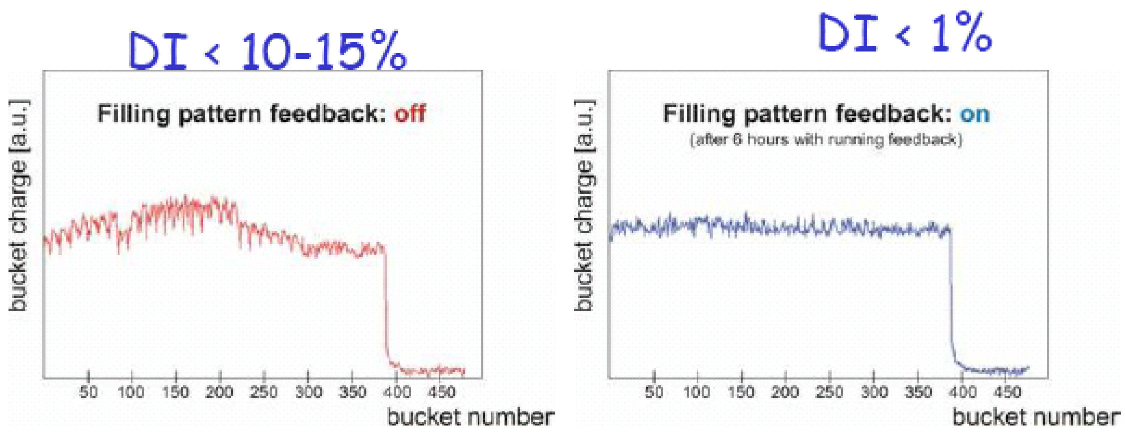
Provide human interface

$$V_b(t) = \frac{\pi a^2}{2\pi b}\frac{1}{\beta c}\cdot Z \cdot \frac{t-t_0}{\sigma^2} I(t) \cdot F(\delta,\theta)$$

Filling Pattern Monitor @ SLS

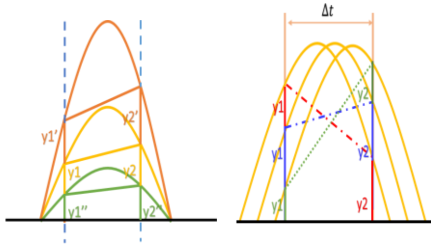
Standard SLS filling pattern:
- 390 buckets filled
- gap of 90 buckets



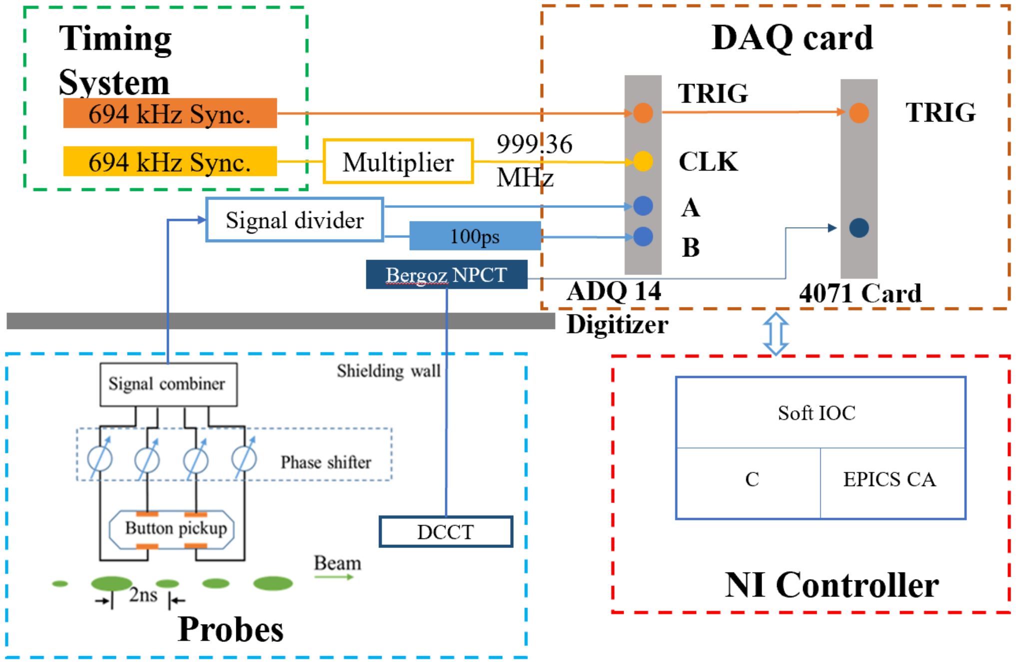


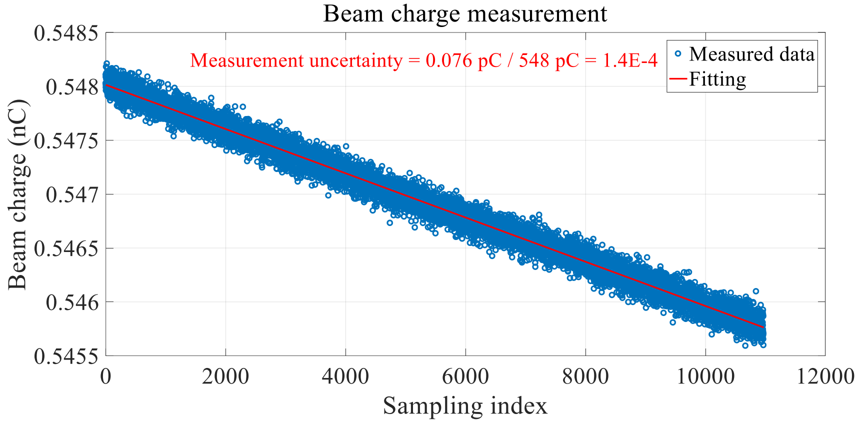
EPAC'04, Kalantari et al., SLS

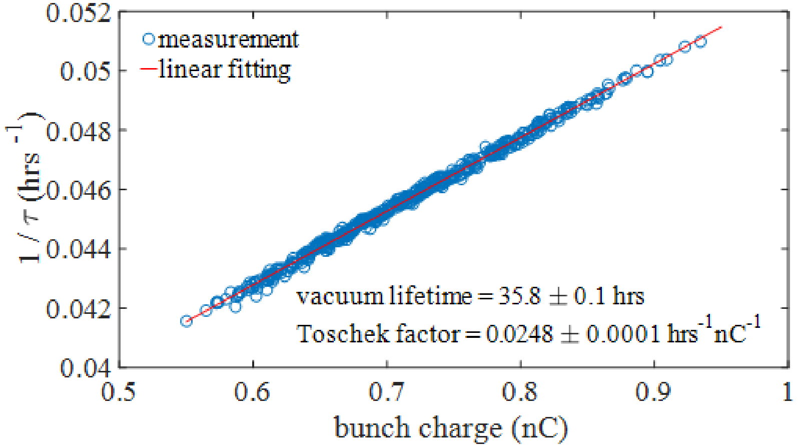
Bunch Charge and Lifetime Measurement @ SSRF



$$\frac{y_1}{y_{peak}} = f\left(\frac{y_1}{y_2}\right)$$



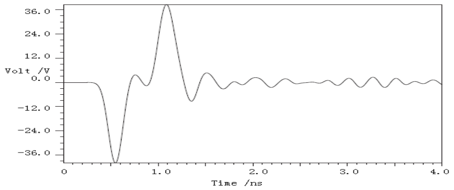
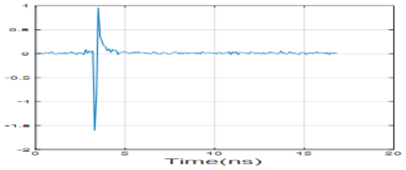
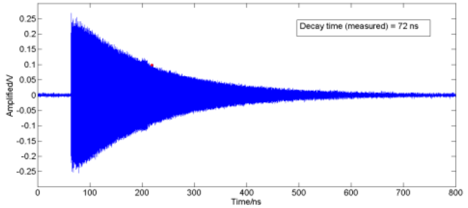
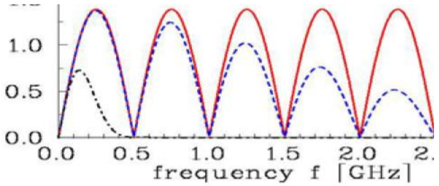
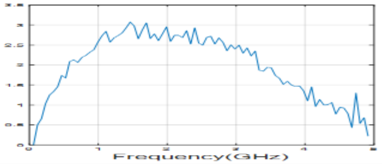
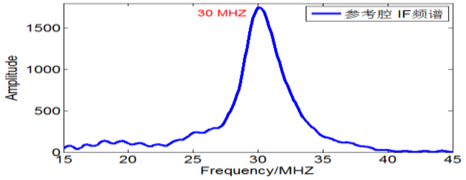
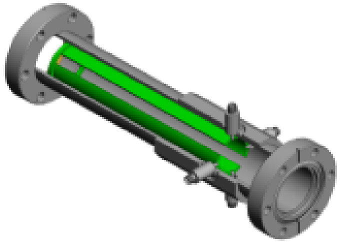
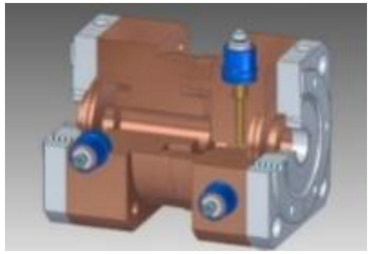
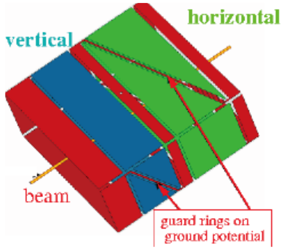




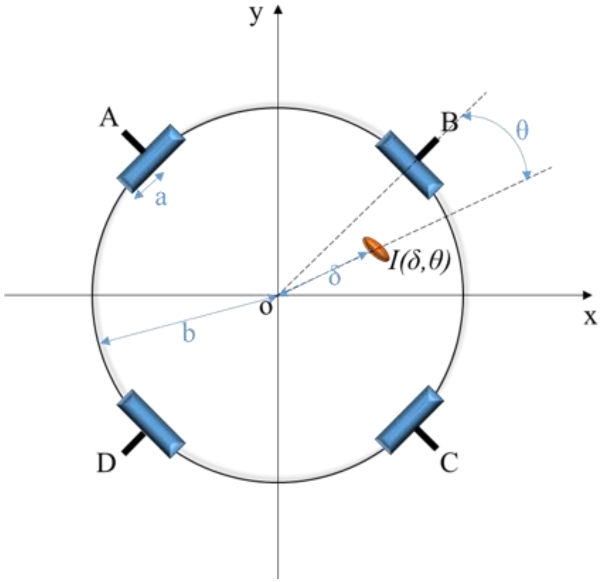
$$\frac{1}{\tau} = k_{Touschek} Q + \frac{1}{\tau_{vacuum}}$$

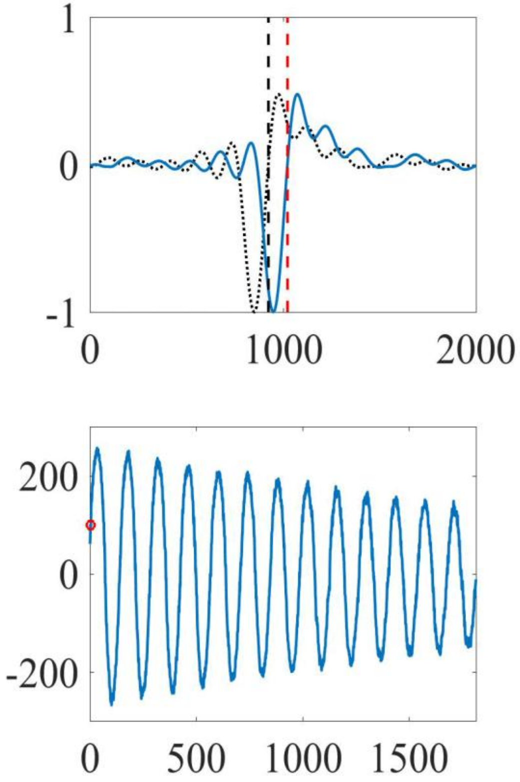
Typical Beam Diagnostics:
Beam Transverse Position

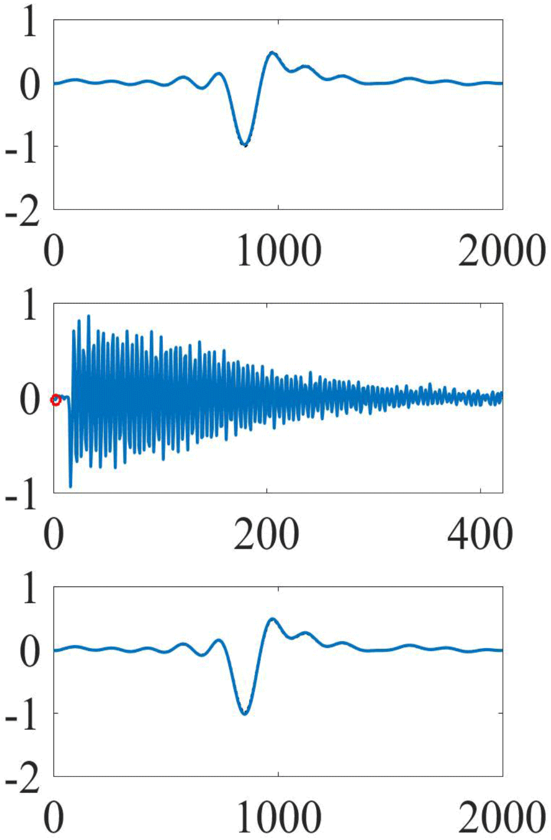
Typical diagnostics devices for beam position

Type	Stripline	Button	Cavity	Linear-cut
Advantage	High sensitivity Directional Coupling Small distortion	Small size Small beam impedance	High resolution High sensitivity High linearity	Very good linearity
Shortage	Large size Medium beam impedance	Small signal intensity Small linear region	Large beam impedance High cost	Complex structure Baseband processing
Application	LINAC Storage Ring	Storage Ring LINAC	LINAC (FEL)	Hadron machine
Time domain response				
Frequency domain response				
Detector structure				

Four Buttons / Striplines BPM System (principle)







$$U_{\Delta/\Sigma} = \frac{(Q_A + Q_D) - (Q_B + Q_C)}{(Q_A + Q_B + Q_C + Q_D)}, \quad V_{\Delta/\Sigma} = \frac{(Q_A + Q_B) - (Q_C + Q_D)}{(Q_A + Q_B + Q_C + Q_D)}$$

charge quantity **Longitudinal phase** **Transverse position**

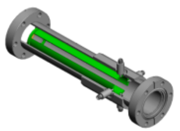
BPM pick-up signal (image current):
Charge, 3D position, bunch length

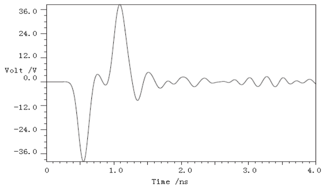
$$I(t) = \frac{Q}{\sqrt{2\pi}\sigma} exp[-\frac{(t-t_0)^2}{2\sigma^2}]$$

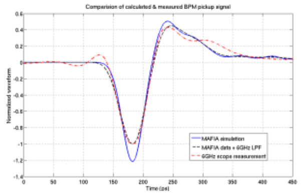
$$V_b(t) = \frac{\pi a^2}{2\pi b}\frac{1}{\beta c} \cdot Z \cdot \frac{t-t_0}{\sigma^2} I(t) \cdot F(\delta,\theta)$$

Bunch length

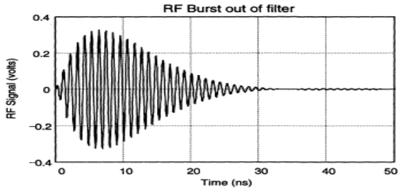
Button / Stripline BPM System

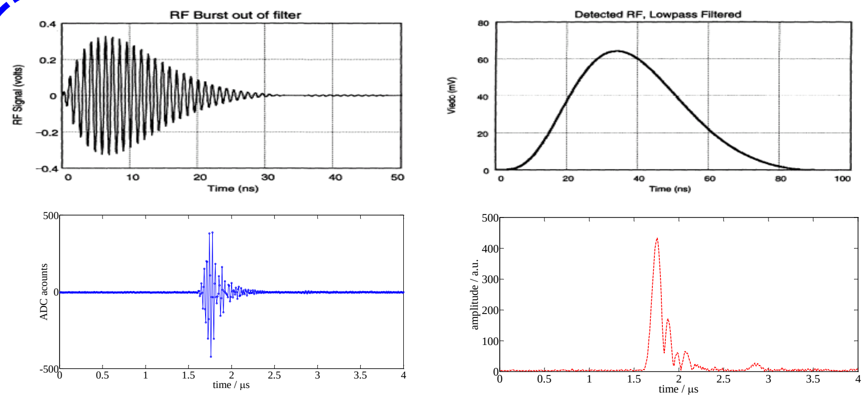


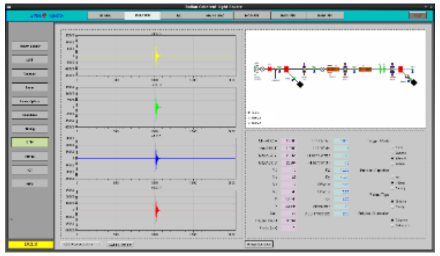




Band pass filter + over sampling + IQ demodulation



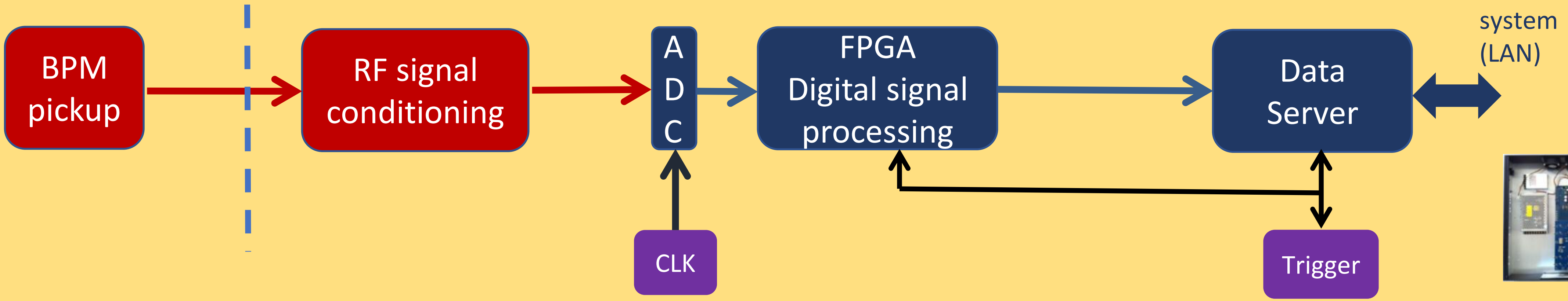




$$U_{\Delta/\Sigma} = \frac{(Q_A + Q_D) - (Q_B + Q_C)}{(Q_A + Q_B + Q_C + Q_D)}$$

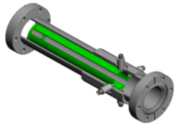
$$V_{\Delta/\Sigma} = \frac{(Q_A + Q_B) - (Q_C + Q_D)}{(Q_A + Q_B + Q_C + Q_D)}$$

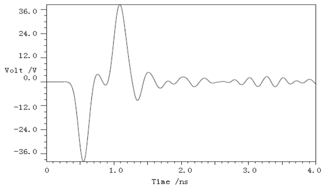
Band pass filter + under sampling + IQ demodulation

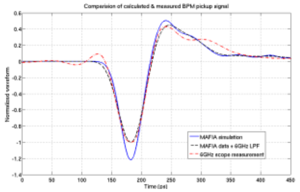


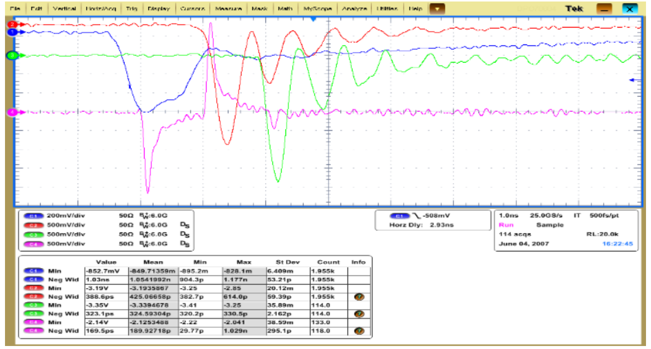
Button / Stripline BPM System

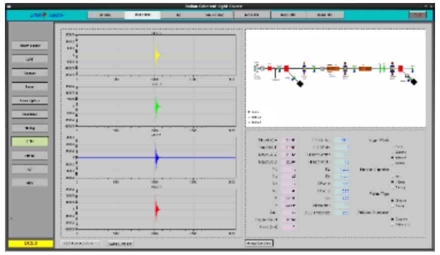
Or we can always use a **fast scope** or **high sampling rate ADC** to replace NB DAQ digitize beam signal in base band, which give us potential to do **bunch-by-bunch** measurement





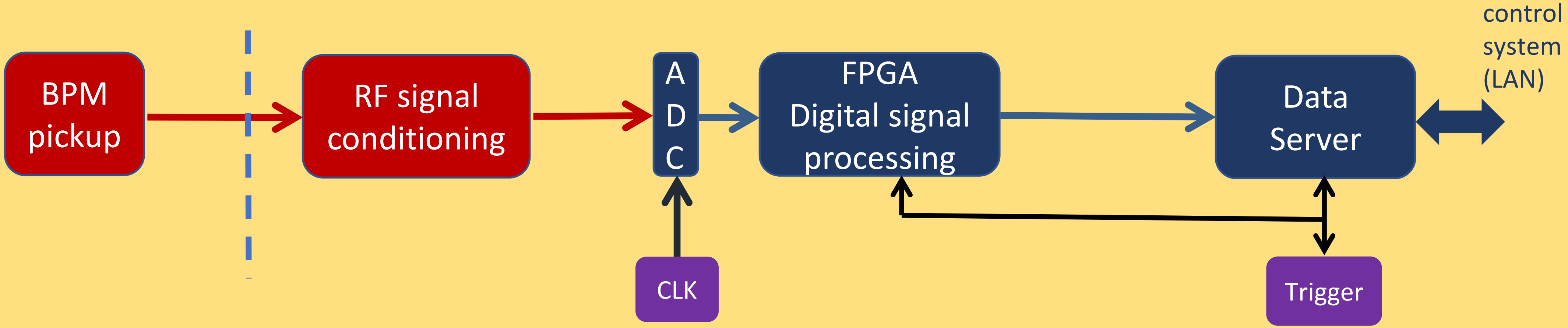




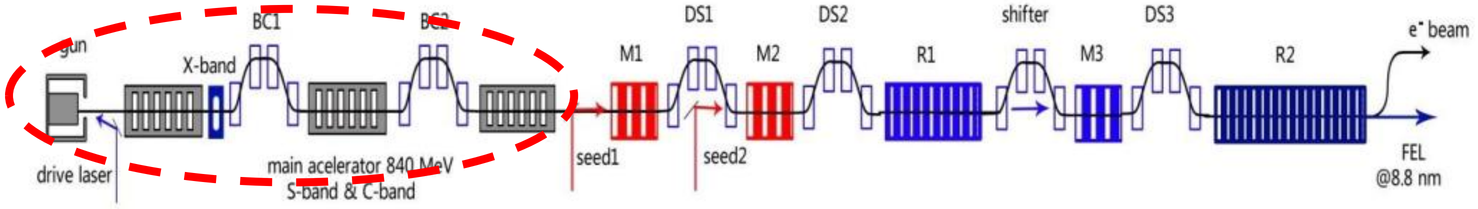


$$U_{\Delta/\Sigma} = \frac{(Q_A + Q_D) - (Q_B + Q_C)}{(Q_A + Q_B + Q_C + Q_D)}$$

$$V_{\Delta/\Sigma} = \frac{(Q_A + Q_B) - (Q_C + Q_D)}{(Q_A + Q_B + Q_C + Q_D)}$$

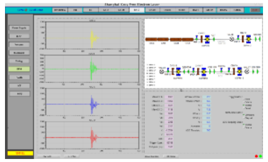


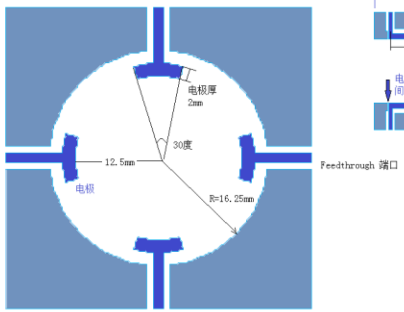
Stripline BPM system @ SXFEL



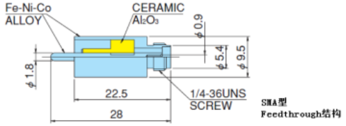
Designed by Y.X. Yuan

Control room

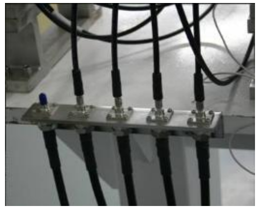


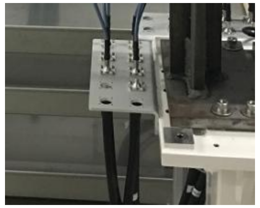


DBPM processor



Cable panel

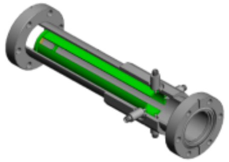


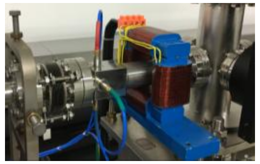


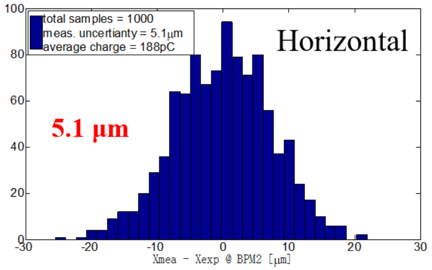
- Average beam charge: 188pC
- K = 5.24

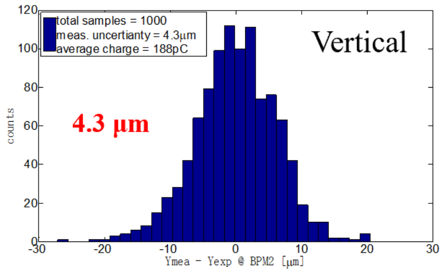
Shielding wall

Pickup assembly









Button BPM system @ SSRF

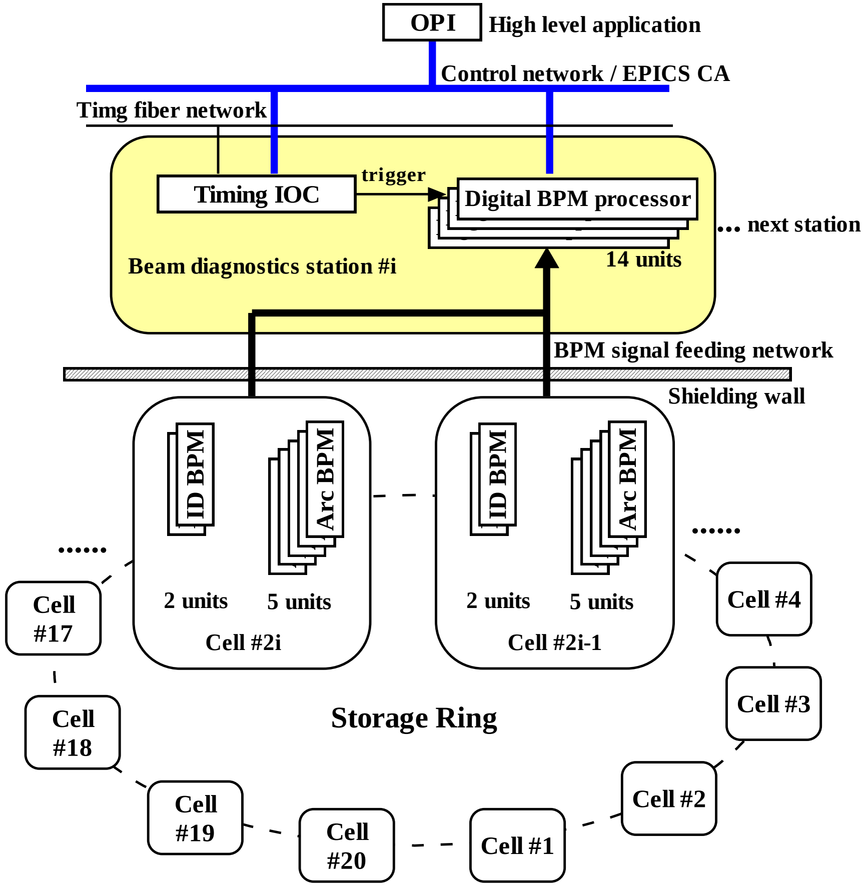
- Typical 3rd and 4th generation Synchrotron Light Source application
- Digital BPM processor (Libera) with BPF, under sampling and digital IQ demodulation
- Turn-by-Turn capability

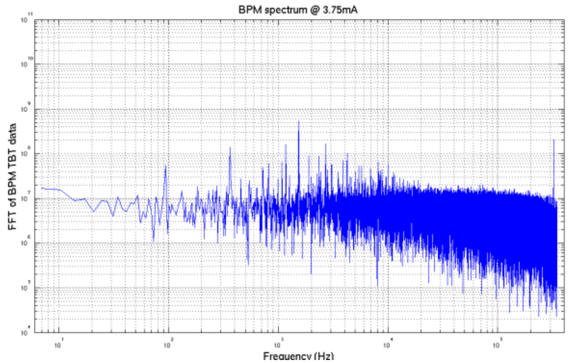
BPM processors
Libera

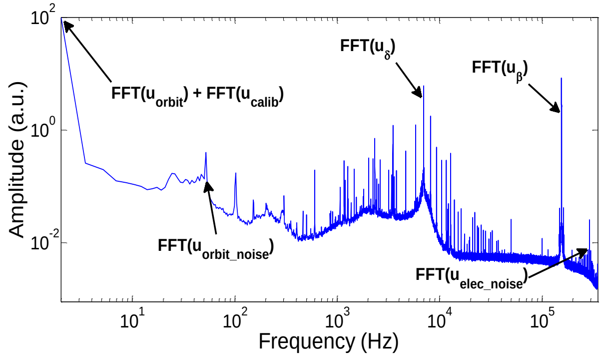
Cable panel
Cable tray

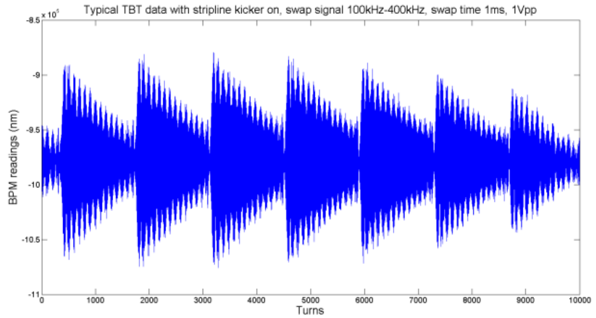
2 IDBPMs
& 5 ArcBPMs

Pickup assembly



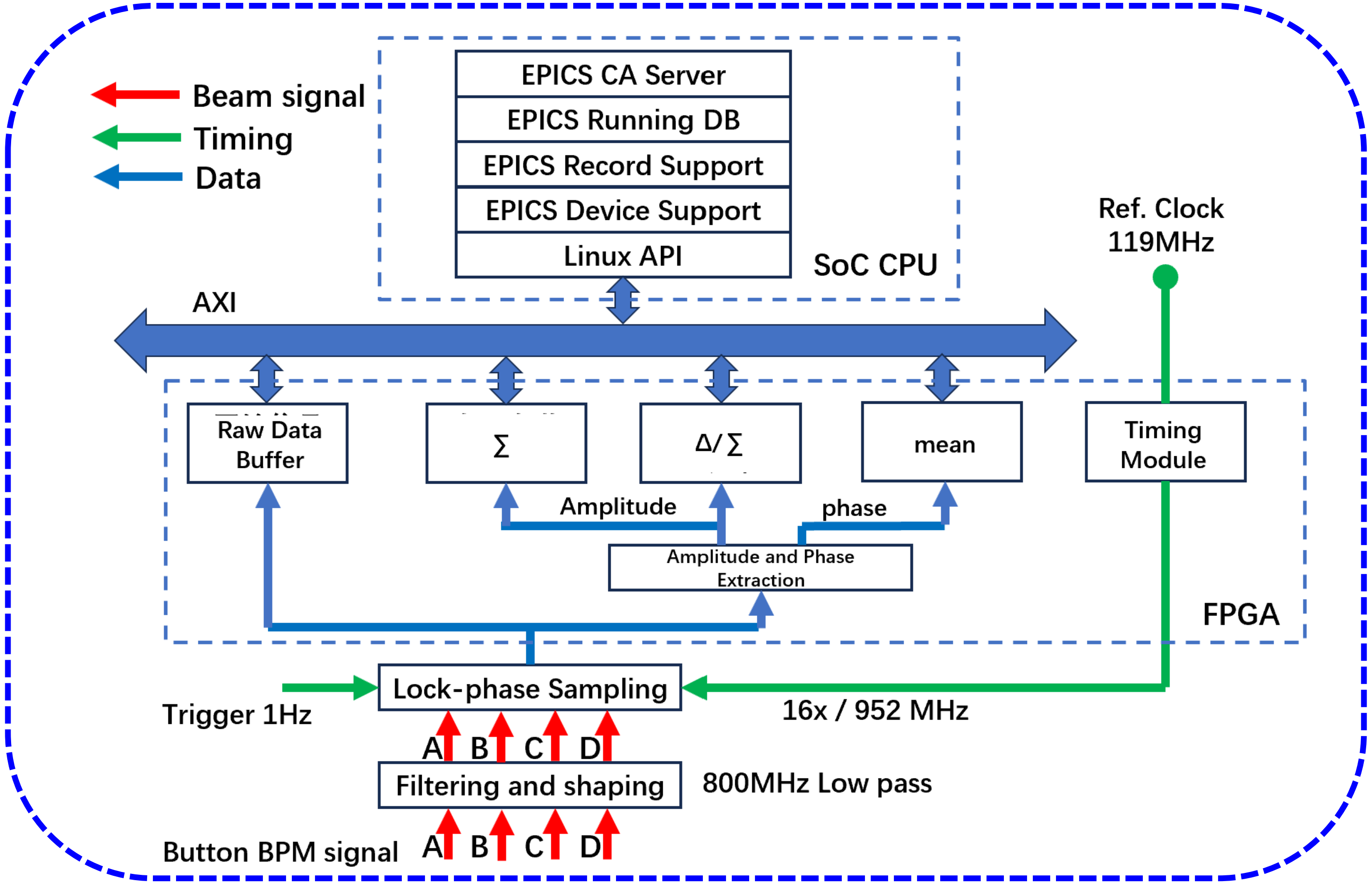


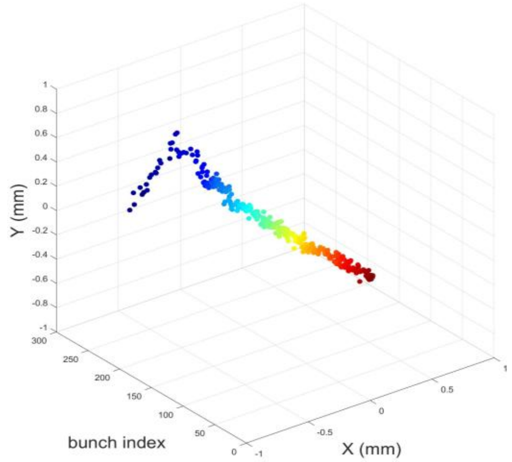


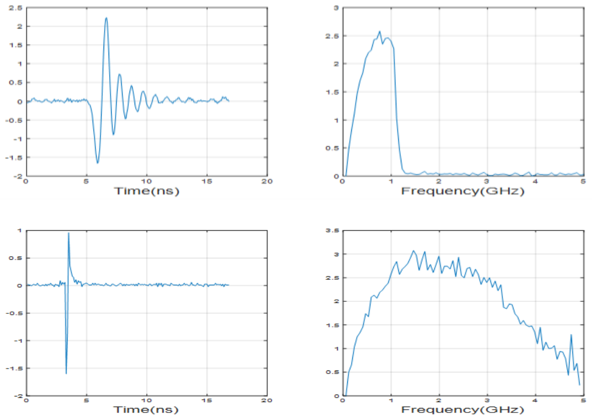


Button BPM system @ HF-IRFEL

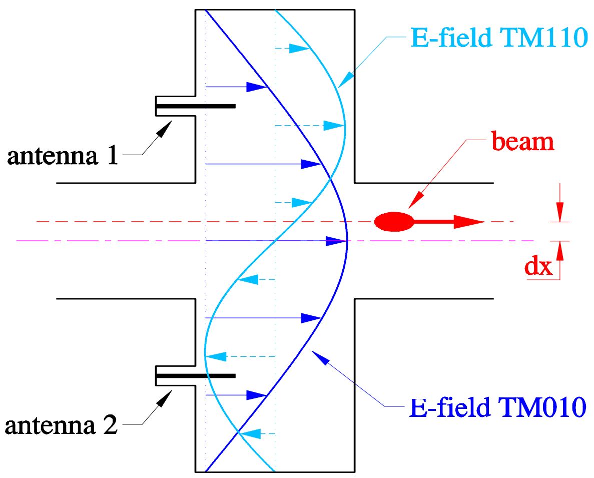
- Button pickup used for LINAC due to limited installation space
- Based band DAQ with very high sampling rate (16 X bunch interval)
- Bunch-by-bunch capability



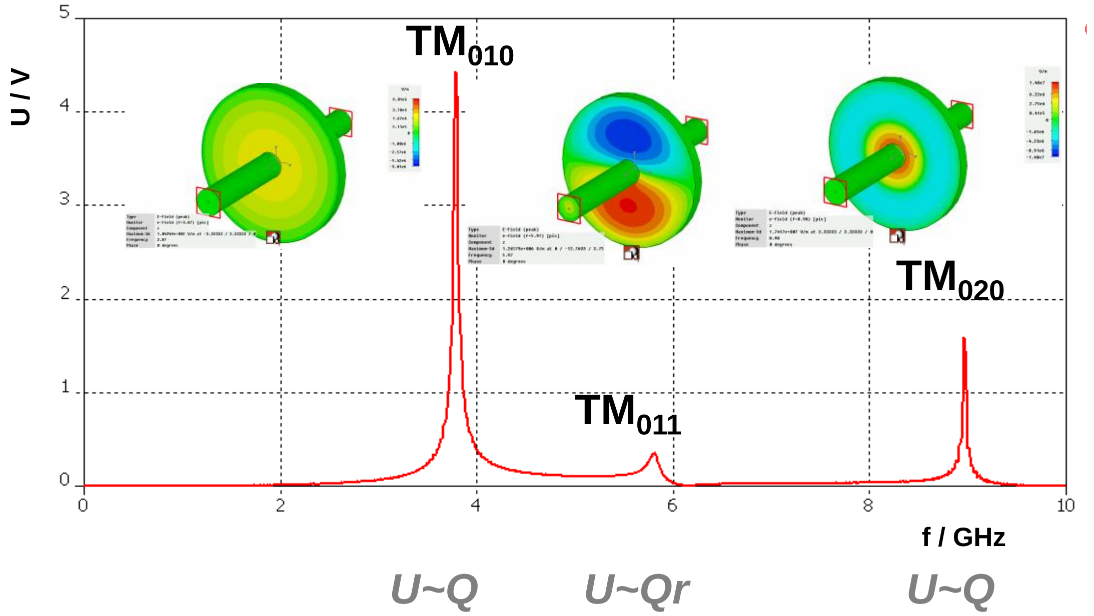




Cavity BPM system (principle)



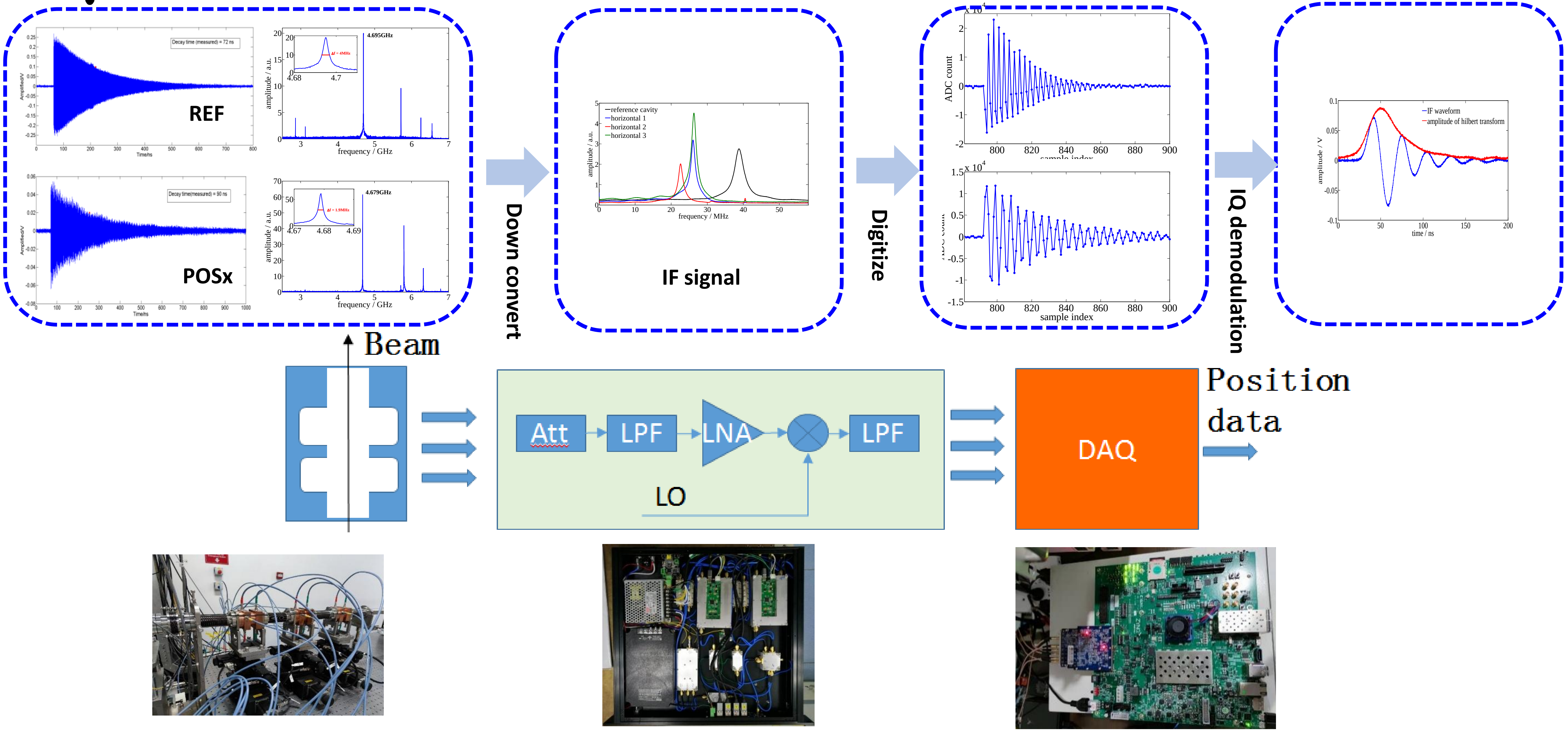
From D. Lipka, DESY, Hamburg



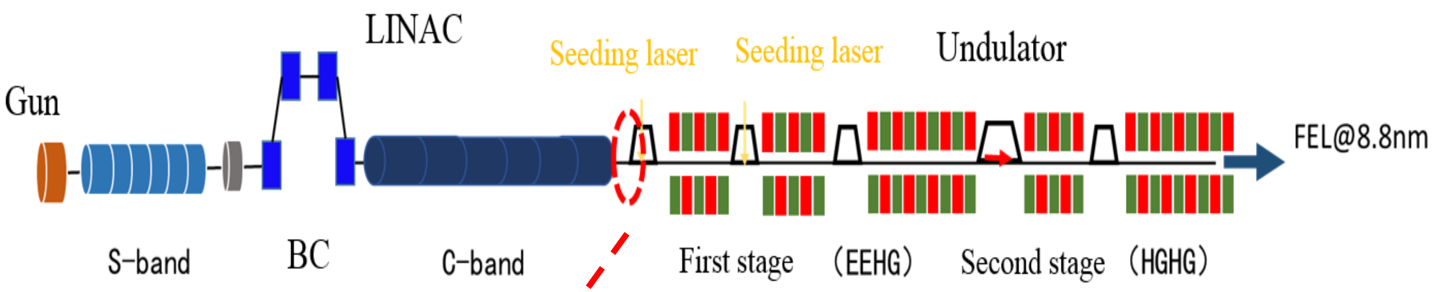
When the particle bunches pass through the resonant cavity, it excites multiple electromagnetic modes:

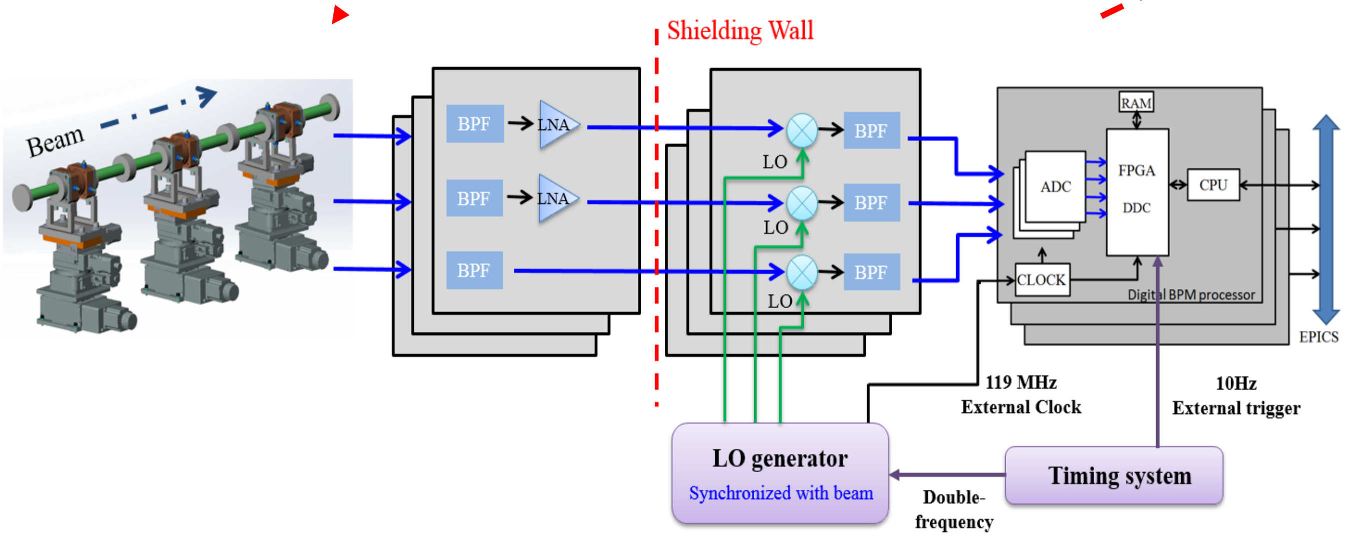
- **Fundamental Mode (TM_{010}):** Its electromagnetic field strength is **independent of the bunch position** but correlated with charge quantity and bunch length, making it suitable for normalization.
- **Dipole Mode (TM_{110}):** Exhibits axial asymmetry, with **electric field intensity proportional to the transverse position**. Variations in the TM_{110} signal strength enable derivation of the bunch position information.

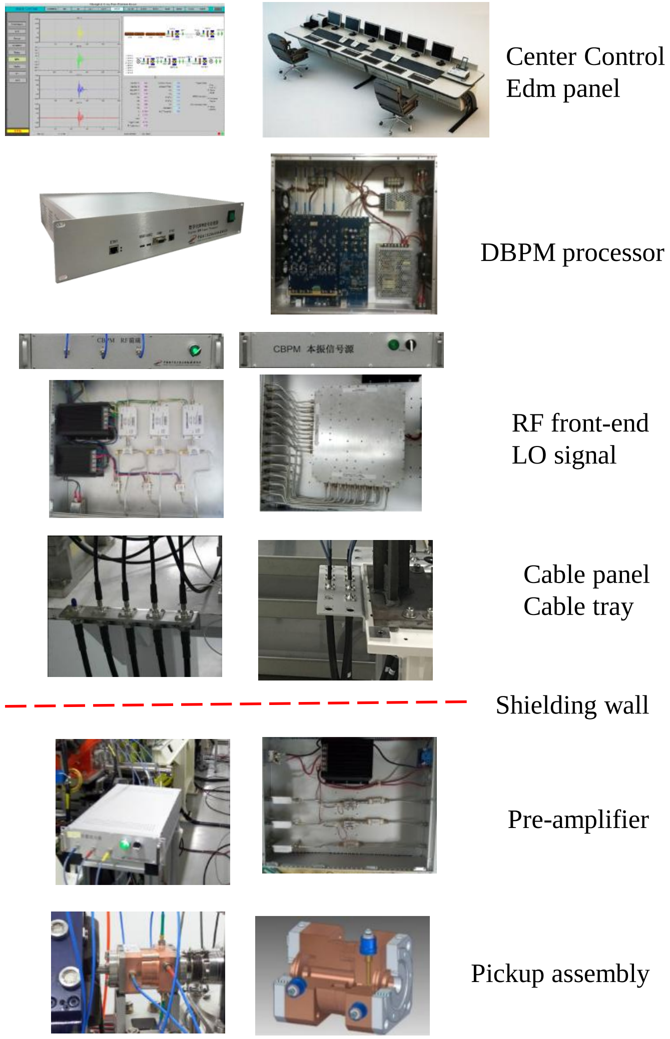
Cavity BPM system



Cavity BPM system @ SXFEL





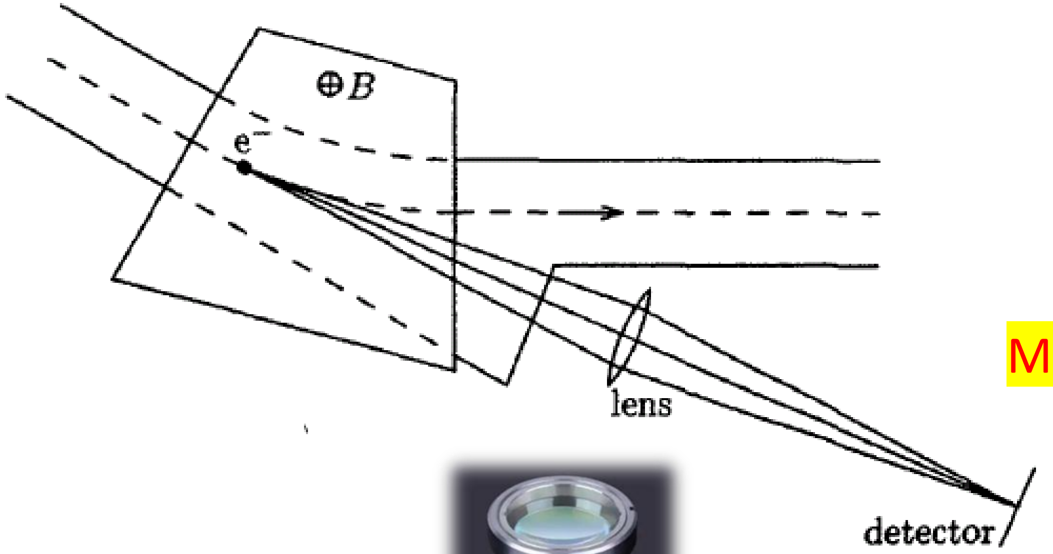


Typical Beam Diagnostics:
Transverse distribution (Beam Size)

Typical diagnostics devices for transverse distribution

	Beam sensor	DAQ solution	resolution	Remarks 1	Remarks 2
Destructive	Screen monitor （YAG / OTR）	Imaging lens + CCD	~ 20 um	Full distribution	LINAC
	Wire scanner	Wire mover + BLM	~ um	Average meas.	LINAC
	Scrapper + Q meter	Scra. Mover + DMM	~ um	Average meas.	LINAC
Non-destructive	SR visible light image	Imaging lens + CCD	~ 50 um	Full distribution	RING
	SR interferometer	Double slits + CCD	~ few um	Beam size	RING
	SR Xray pinhole camera	Pinhole + Xray CCD	~ 10 um	Beam size	RING
	SR Xray image	Zone plate + Xray CCD	~ um	Full distribution	RING
	SR Xray encoding	Mask + Xray CCD	~ 10 um	Beam size	RING
	SR Xray projection (Ver.)	Polarizer + CCD	~ few um	Beam size	RING

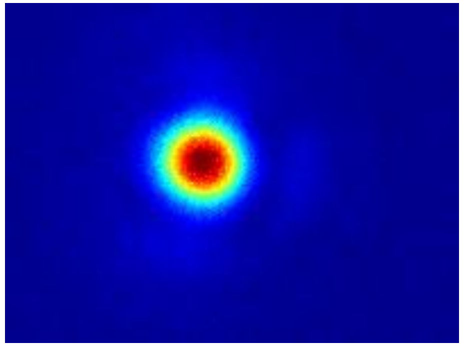
SR Visible light Image system (principle)



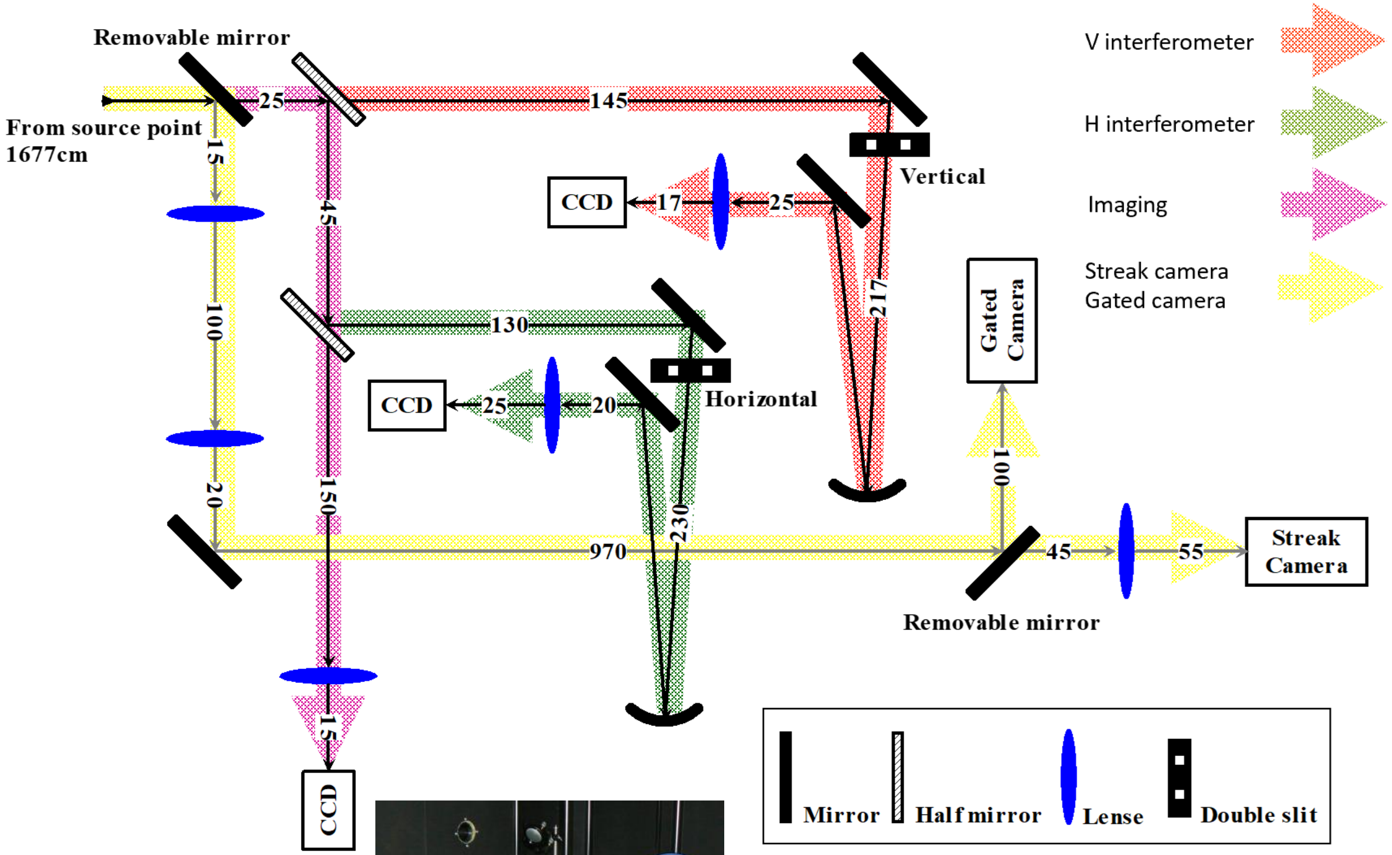
For SR Visible light focusing image, spatial resolution limited by

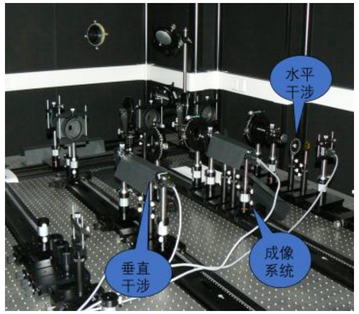
- **Diffraction Error (small opening angle)**
- Chromatic Imaging Error (multicolor light)
- Curved Trajectory Imaging Error
- Depth-of-Field (DoF) Imaging Error

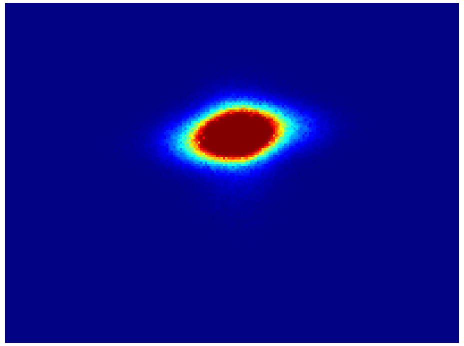
More precise (usually more complicated) technology required



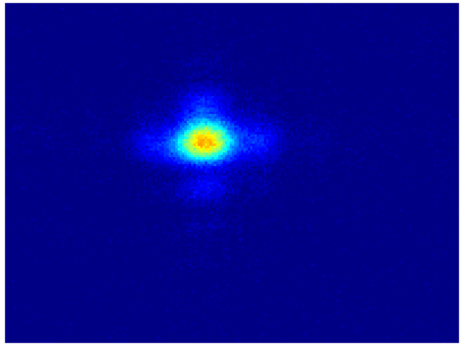
SR Visible light Image system @ SSRF



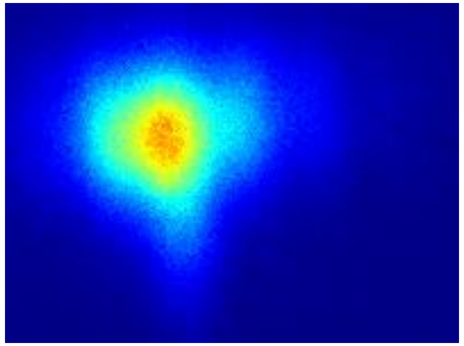




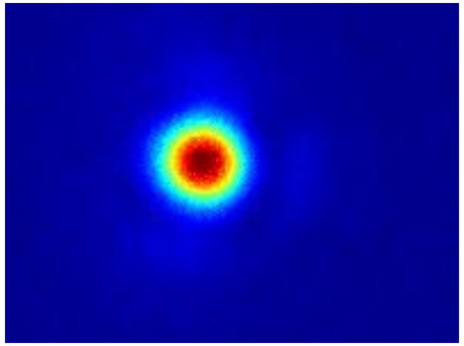
2008.01.03
80mA, no COD correction
copper cavity



2008.04.10
100mA, COD um level
copper cavity

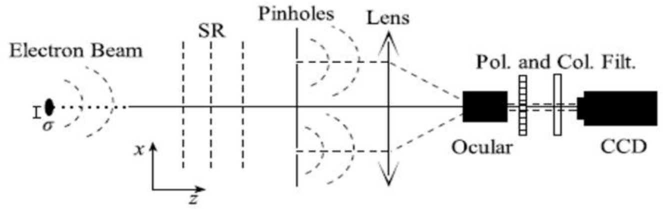


2008.10.01
150mA
SC cavity, noisy PS



2008.10.27
86mA
SC cavity, noisy PS fixed

SR Interferometer @ SSRF

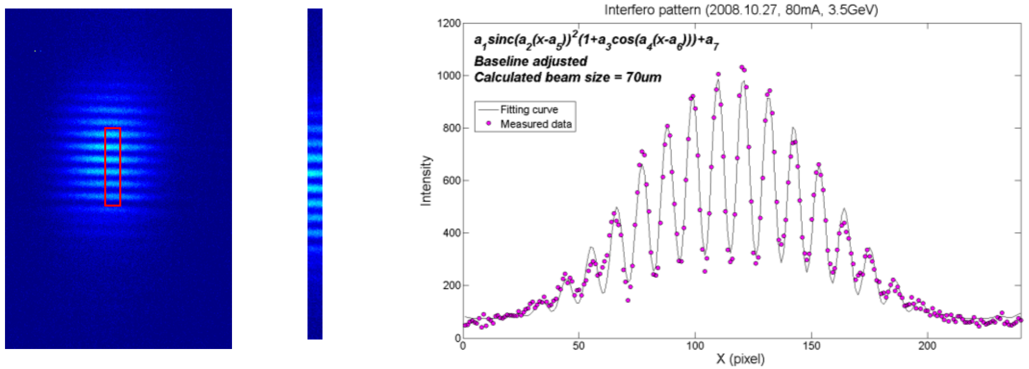


$$I = I_0 \left\{ \frac{J_1\left(\frac{2\pi a x}{\lambda f}\right)}{\left(\frac{2\pi a x}{\lambda f}\right)} \right\}^2 \times \left\{ 1 + V \cos\left(\frac{2\pi D x}{\lambda f}\right) \right\}$$

$$\sigma_x = \frac{\lambda L}{\pi D} \sqrt{\frac{1}{2} \ln \frac{1}{V}}$$

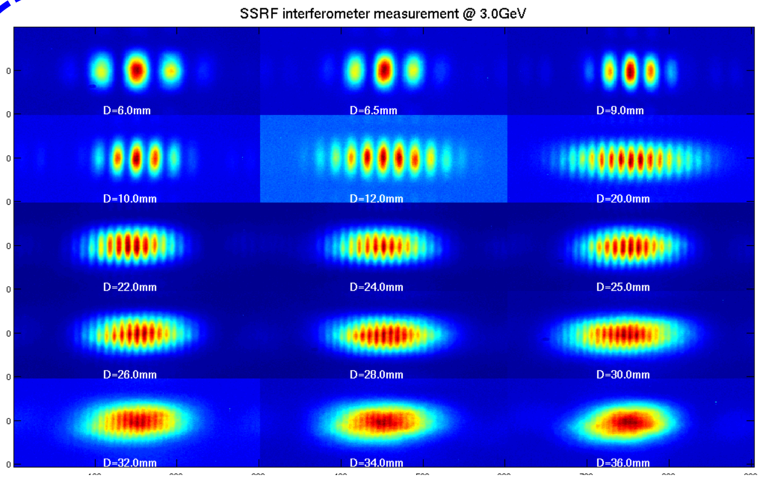
- I_0: Intensity
- a: Pinholes radius
- λ: SR wavelength
- f: Focal distance of the optical system
- D: Pinholes distance
- V: Visibility
- L: Distance from the source

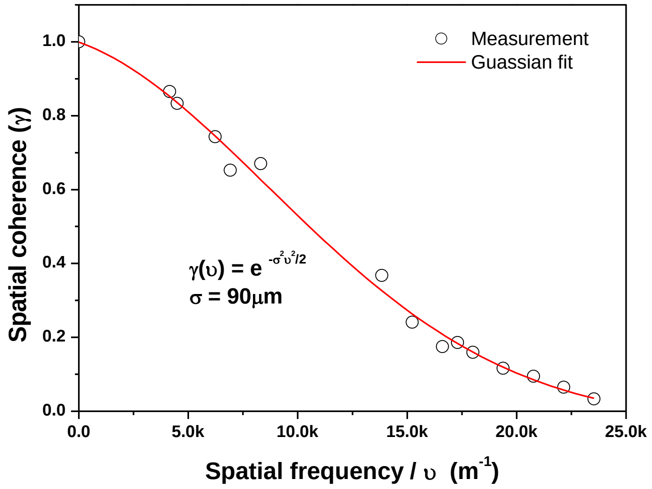
Working principle

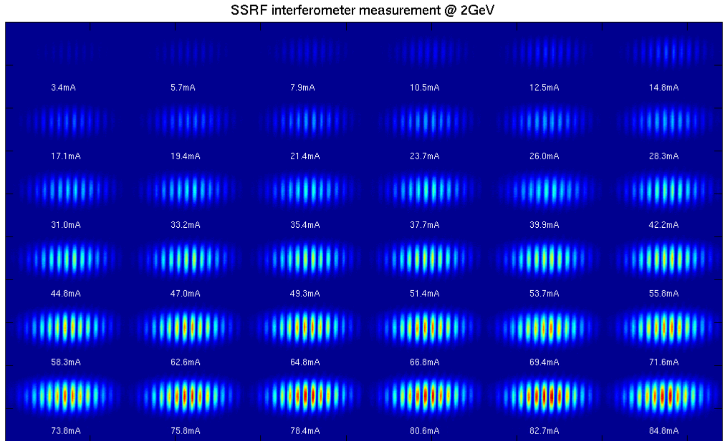


$$I(y_1) = I_0 [\sin c(\frac{2\pi a}{\lambda R_1} y_1)]^2 \cdot [1 + |\gamma(\nu)| \cos(\frac{2\pi D}{\lambda R_1} y_1 + \varphi)]$$

Typical interference image & signal processing

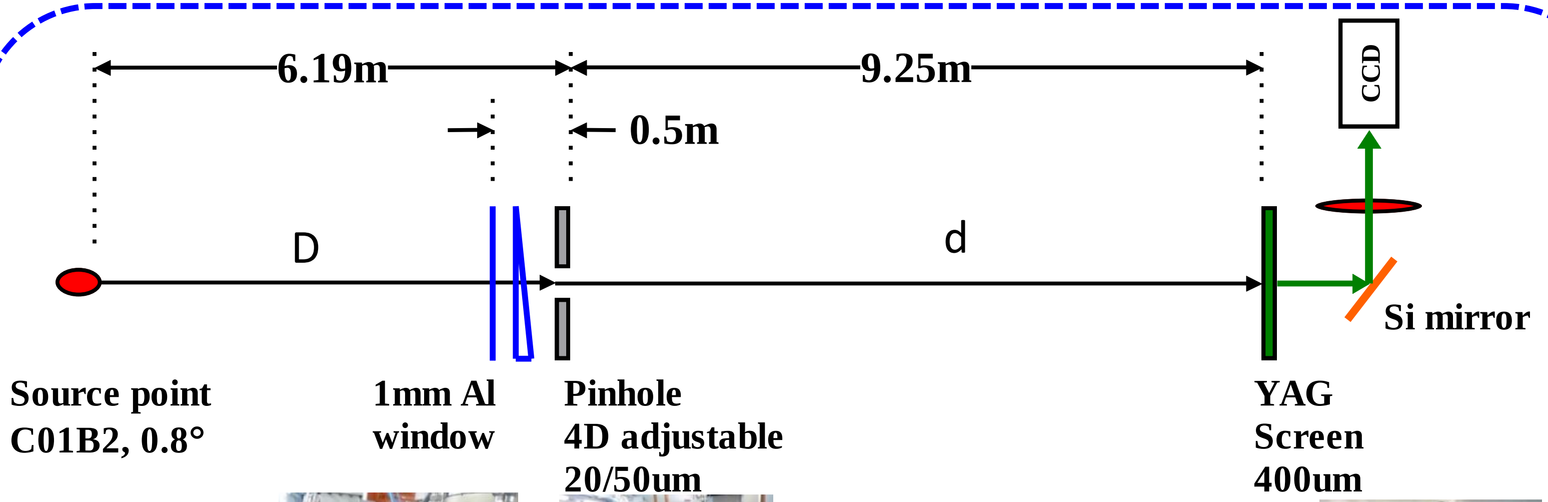






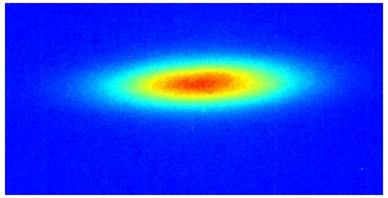
Application: (left) precise measurement; (right) beam size with different current

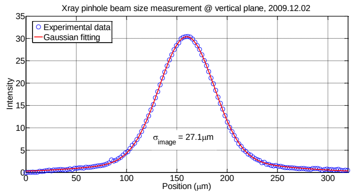
Xray Pinhole Camera @ SSRF

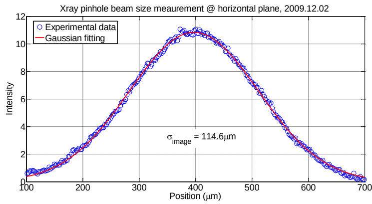


CCD: pixel size 4.65um

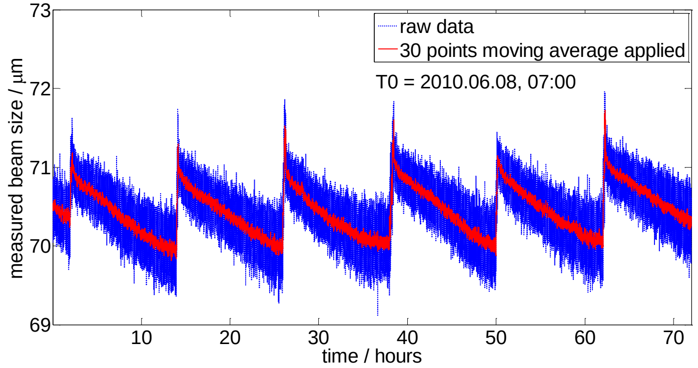
Lens: magnification 2

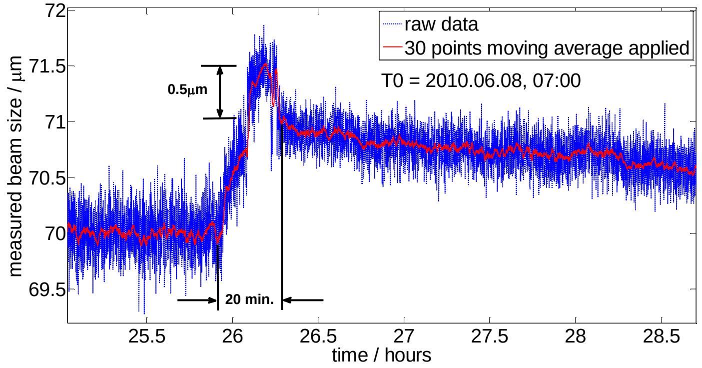


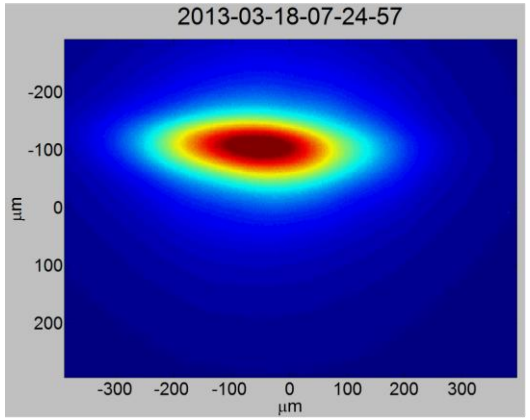




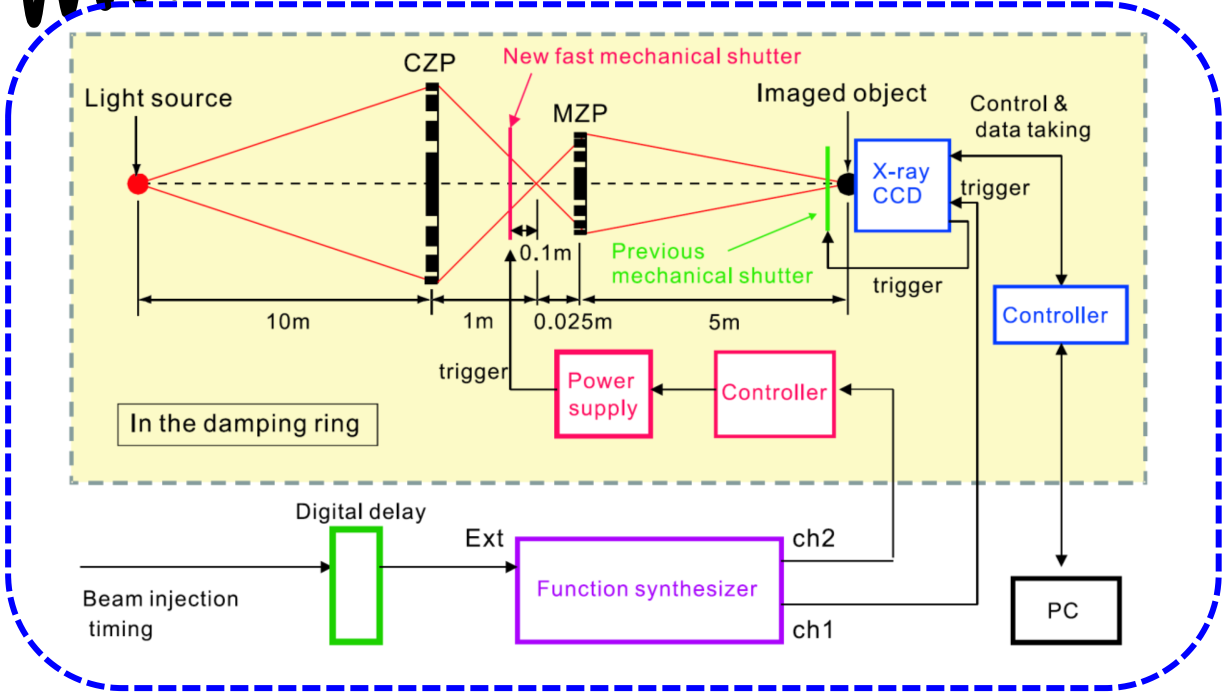
$$\sigma_{beam} = \sqrt{\sigma_{image}^2 - \sigma_{pinhole}^2 - \sigma_{screen}^2 / 1.49}$$

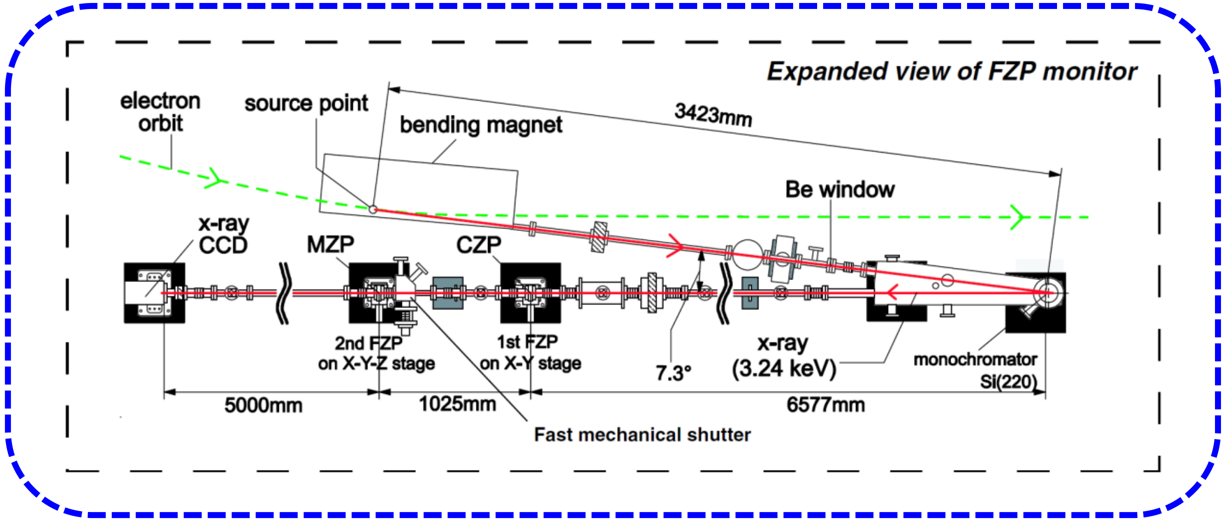


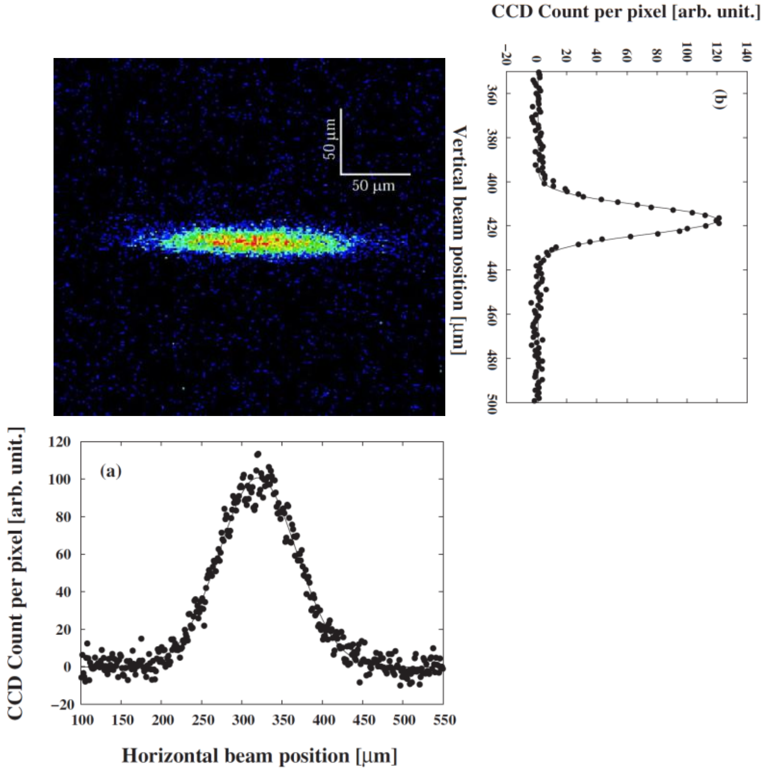


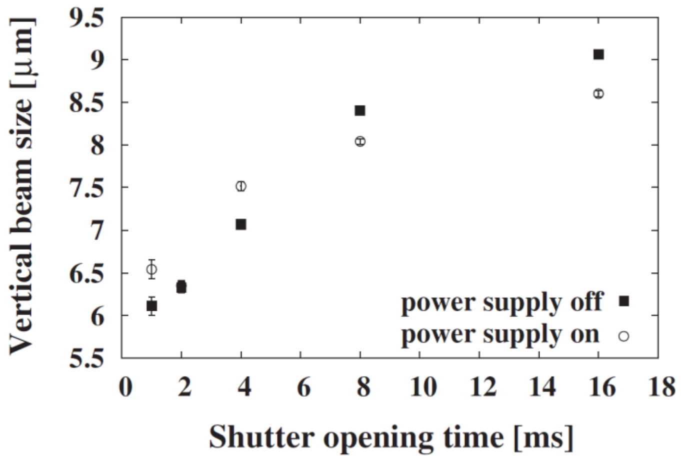


Xray focusing image system @ KEK



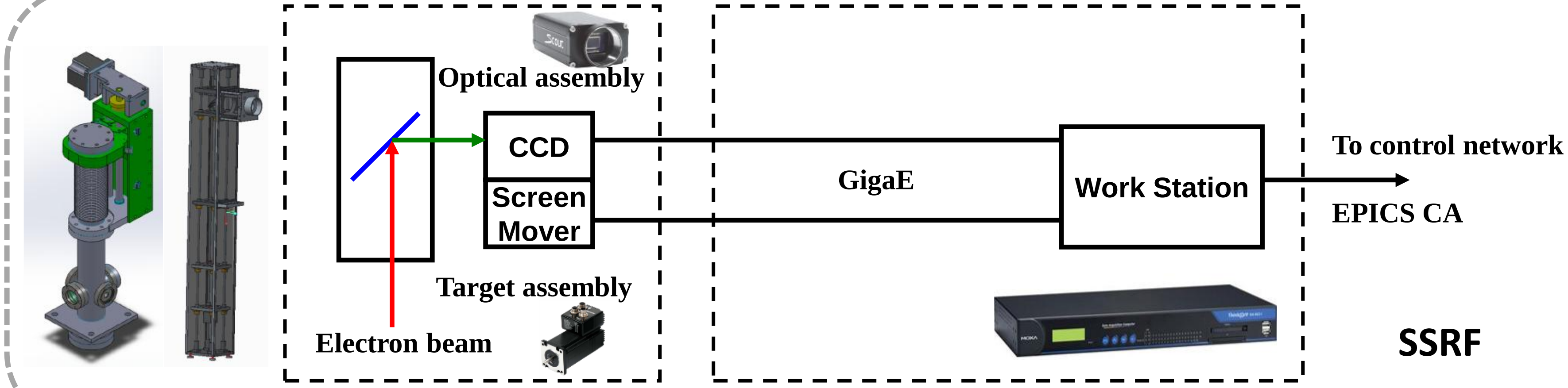


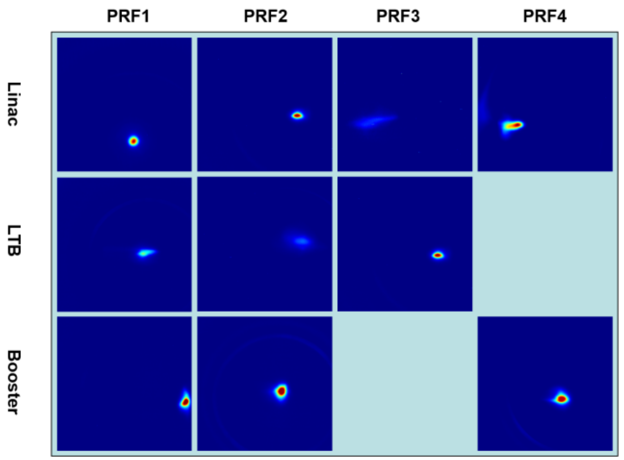




Improvement of Fresnel zone plate beam-profile monitor and application to ultralow emittance beam profile measurements, Hiroshi Sakai, etc., PRAB 10 (2007)

Screen Monitor (YAG/OTR)





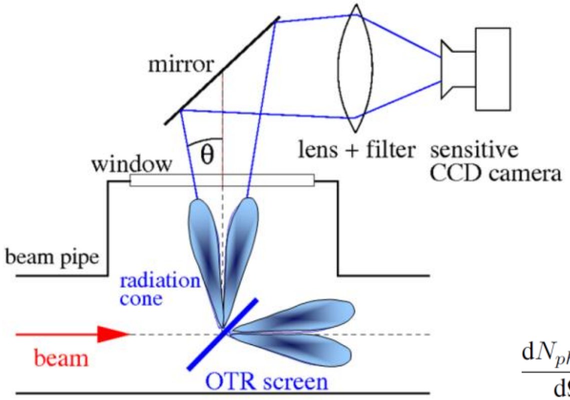
Fluorescent screen

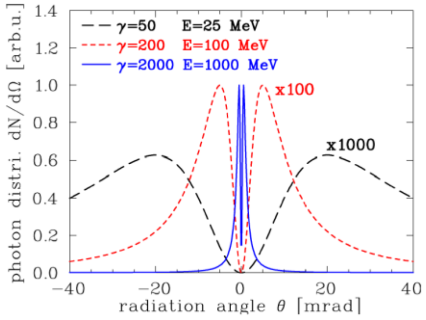
Good for almost all energy region, lower resolution

Abbreviation	Type	Material	Activator	max. emission	decay time
Quartz	glass	SiO_2	non	470 nm	< 10 ns
Alumina	ceramics	Al_2O_3	non	380 nm	~ 10 ns
Chromox	ceramics	Al_2O_3	Cr	700 nm	~ 10 ms
YAG	crystal	$Y_3Al_5O_{12}$	Ce	550 nm	200 ns
LuAG	crystal	$Lu_3Al_5O_{12}$	Ce	535 nm	70 ns
Cesium-Iodide	crystal	CsI	Tl	550 nm	1 μs
P11	powder	ZnS	Ag	450 nm	3 ms
P43	powder	Gd_2O_2S	Tb	545 nm	1 ms
P46	powder	$Y_3Al_5O_{12}$	Ce	530 nm	300 ns
P47	powder	$Y_2Si_5O_5$	Ce & Tb	400 nm	100 ns

OTR screen

High resolution, only for high energy, low photon number

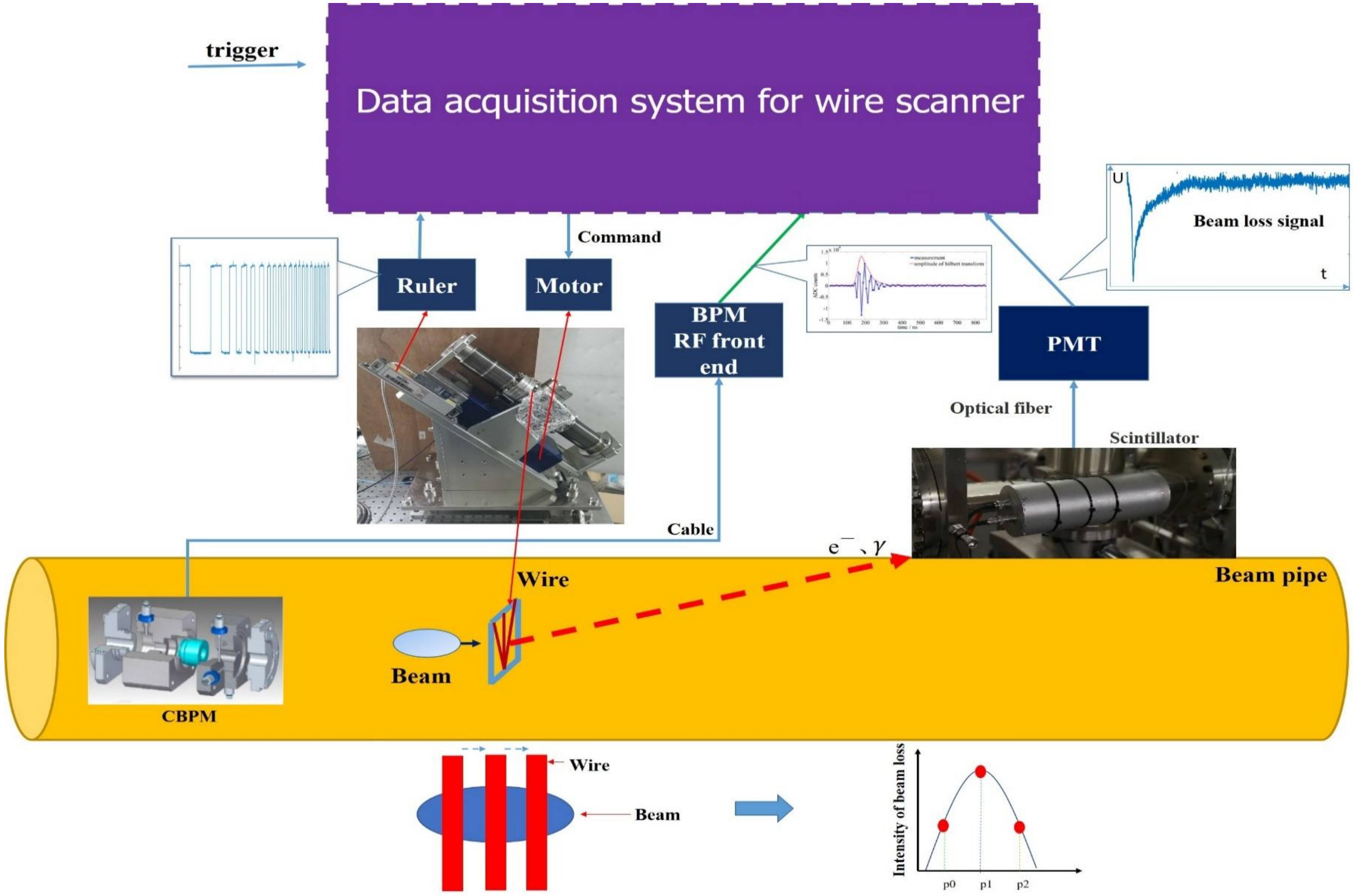


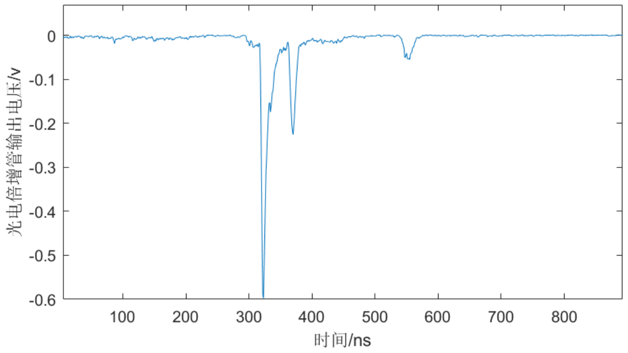


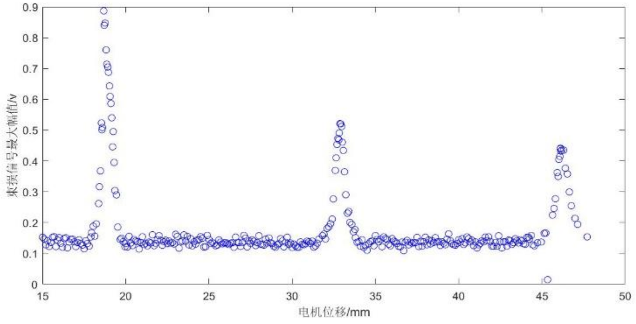
$$\frac{dN_{photon}}{d\Omega} = N_{beam} \cdot \frac{2e^2\beta^2}{\pi\hbar c} \cdot \log\left(\frac{\lambda_{begin}}{\lambda_{end}}\right) \cdot \frac{\theta^2}{\left(\gamma^{-2}+\theta^2\right)^2}$$

Beam Instrumentation and Diagnostics, Peter Forck, Proceedings of the General Introductory CAS course on Accelerator Physics & Technologies, 2019

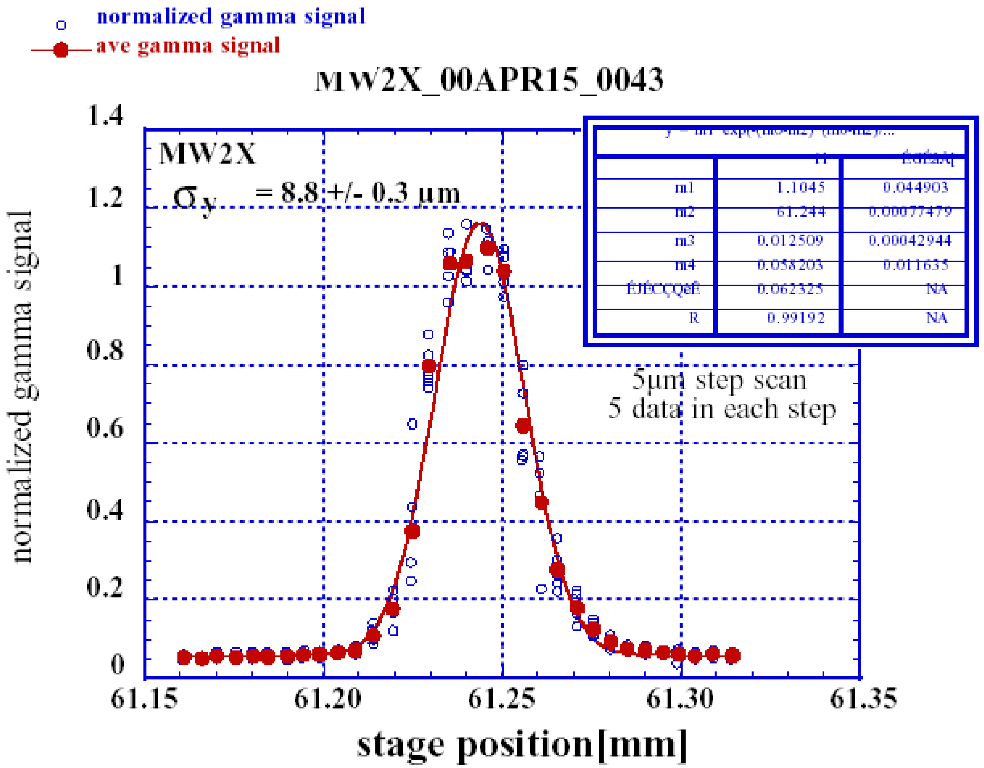
Wire Scanner @ SHINE (prototype)







Wire Scanner @ KEK



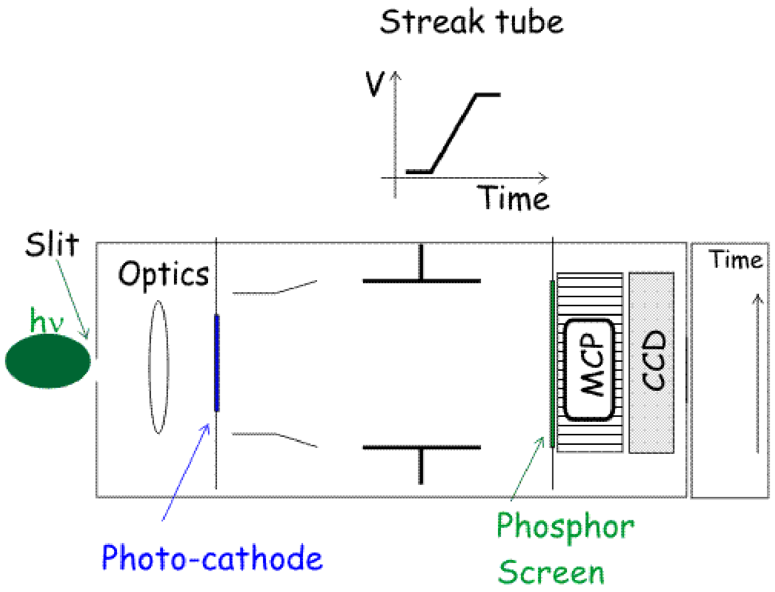
(left) wire scanner chamber installed in the ATF (KEK) extraction line and (right) example wire scan (courtesy H. Hayano, 2003)

Typical Beam Diagnostics:
Longitudinal distribution (Bunch length / phase)

Typical diagnostics devices for longitudinal distribution

	Beam sensor	DAQ and DSP solution	resolution	Remarks 1	Remarks 2
Destructive	TDC + Screen	Imaging lens + CCD	~ few fs	Absolute value	
Non-destructive	Streak camera		200fs / 2 ps	Absolute value	
	Michelson inter.	PD/PMT + digitizer	~ sub ps	Absolute value	Average meas.
	Optical correlator	Mirror mover + digitizer	~ sub ps	Absolute value	Average meas.
	Single photon coun.		~ few ps	Absolute value	Average meas.
	EO sampling	CCD / optical spectrum	~ 50 fs	Absolute value	
	Broad band sensor	Scope / fast digitizer	~ sub ns	Absolute value	
	Broad band sensor	fast digitizer + FFT	~ ps	Relative value	
	CSR + THz sensor	fast digitizer	~ 50 fs	Relative value	
	Phase cavity	RF-FE + fast digitizer	~ 10 fs	Phase only	

Streak camera (time domain)



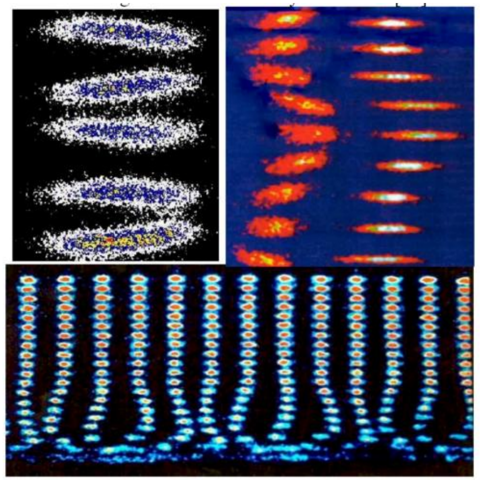


Fig.6a (left) : ESRF five turns of single bunch showing vertical Head-Tail instability,
Fig.6b (right) : LEP top & side views of bunch over 9 turns showing vertical Head-Tail effects, transverse motions and bunch length fluctuations,
Fig.6c (bottom) : APS horizontal coherent motions at trail of the 60ns filling pattern over 13 turns

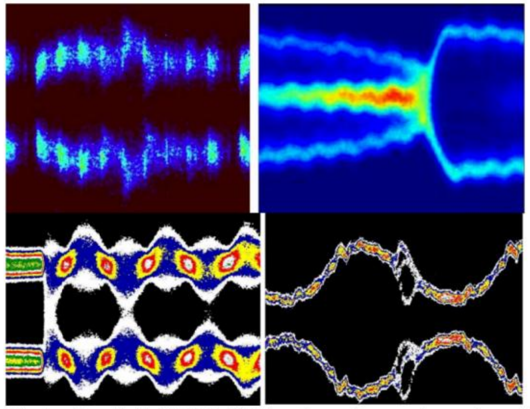


Fig.4a (top-left) PEP-2 HER: phase jumps in center of 1658 bunch train fill , fig.4b (top-right) Spear: full cycle of bunch filamenting with cavity tuning at Robinson instability, fig.4c (bottom-left) ESRF: longitudinal oscillations of the beam at injection into the Storage Ring, Fig.4d (bottom-right) : ESRF phase jumps with the beam undergoing RF Voltage modulation to obtain Landau damping

- Light pulses emitted by the electron bunch (SR, OTR, FEL, etc.) strike a **photocathode** to generate electron bunch pulses, whose longitudinal profile closely resembles the optical pulse distribution.
- As these electron bunch pulses pass a **transverse sweeping electric field**, differences in arrival time result in varying transverse deflection voltages experienced by the particles. This transforms the **longitudinal temporal distribution into a transverse spatial profile**.
- original optical pulse shape can be rebuilt by measuring the deflected electron bunch dimensions using a fluorescent target.

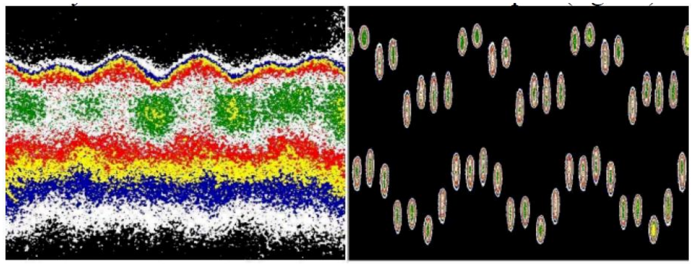


Fig.3a (left) : ESRF at low α : bunch length fluctuation
Fig. 3b (right) : ESRF HOMs causing longit. instabilities

K. Scheidt, ESRF, Proceedings of EPAC 2000, Vienna, Austria

Broad Band Sensor (Time domain)

CTF3 in CERN, DIPAC2003, A NEW WIDE BAND WALL CURRENT MONITOR，Bandwidth 10 GHz

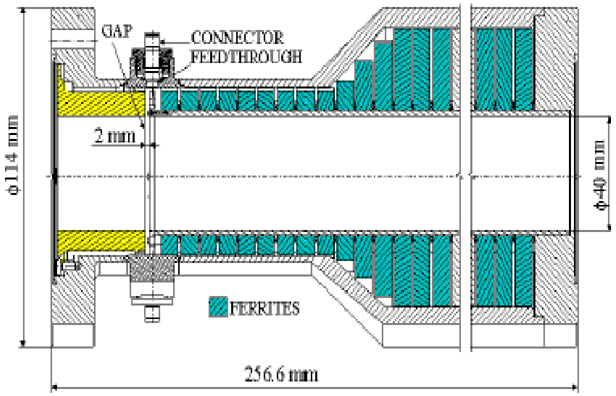
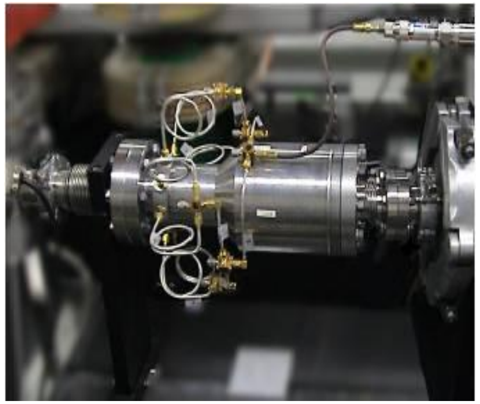


Figure 3: WCM general cross-section



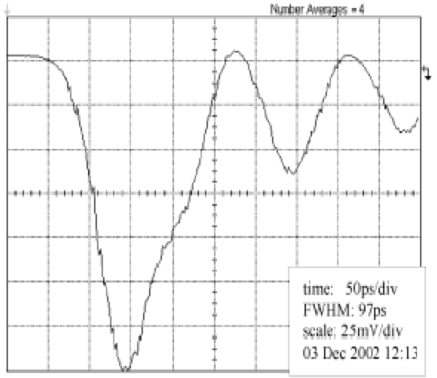
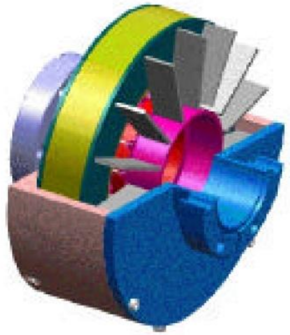


Figure 8: WCM signal on CTF2 beam

SLS in PSI, SLS LINAC AND TRANSFER LINE DIAGNOSTICS，Bandwidth 4-5 GHz



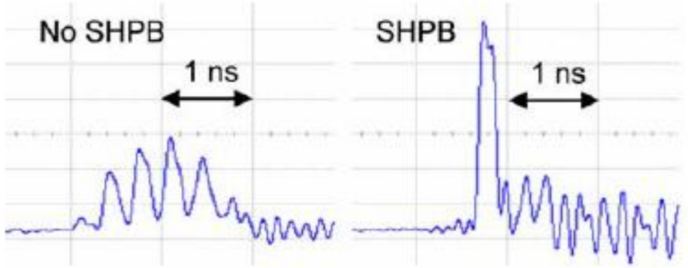


Figure 3: Beam at linac exit without (left) and with (right) SHPB recorded with wall current monitor.

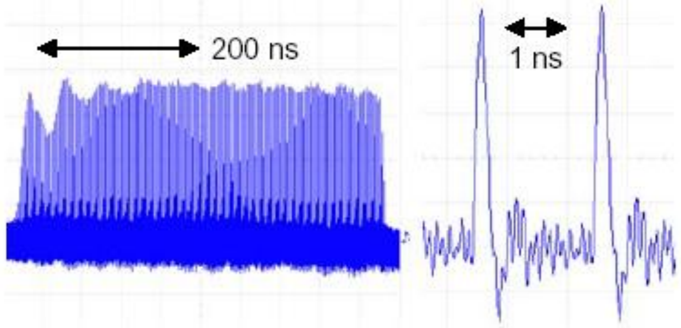
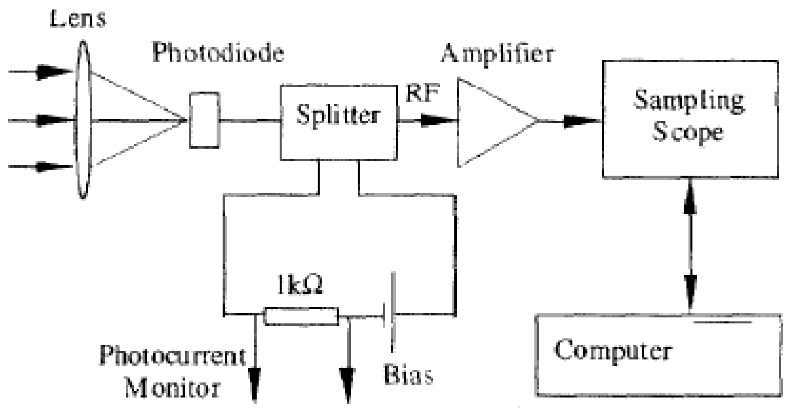
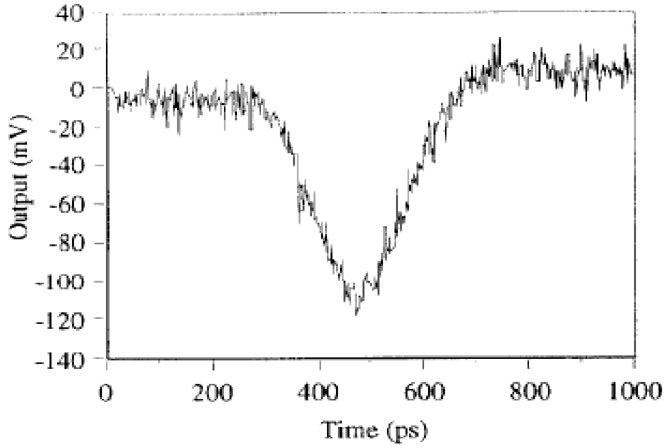


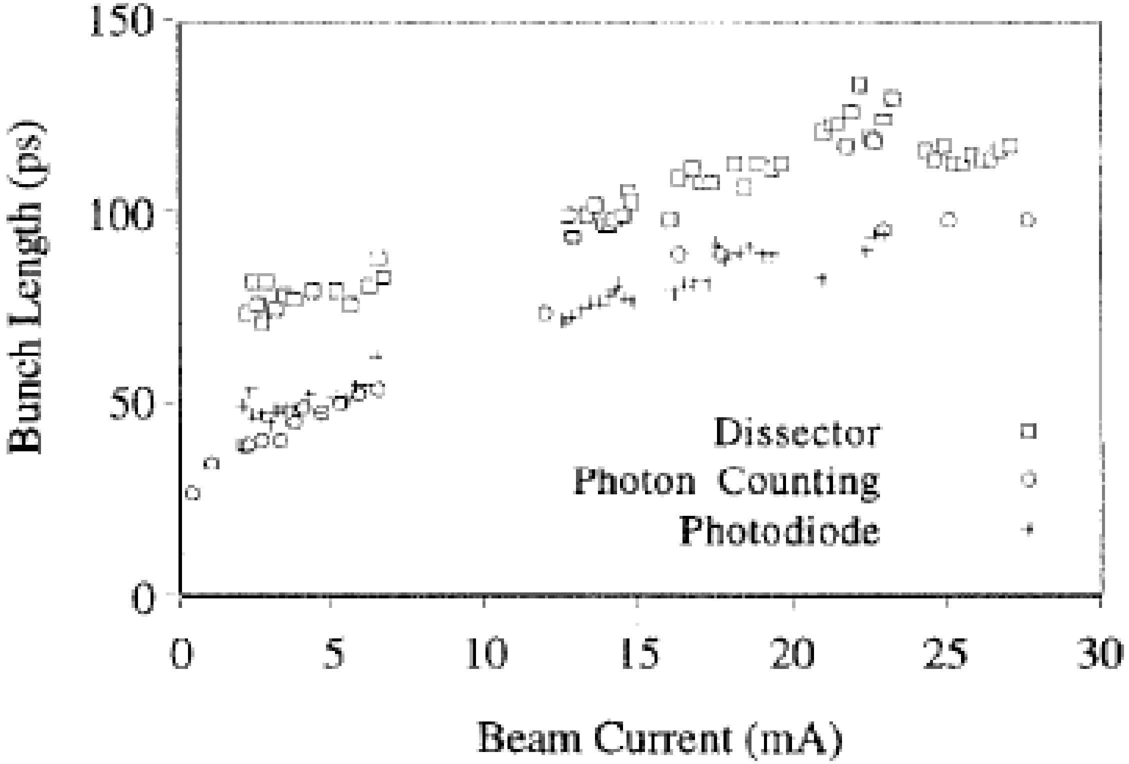
Figure 7: Multi bunch mode WCM2 trace: Entire pulse train (left) and detail (right).

Broad Band Sensor (Time domain)

The British SRS storage ring measured bunch length (~ 50 ps) with an 18GHz ultrafast photodiode, a wideband amplifier (0.1–18GHz, with a gain of 34dB), and a digital sampling oscilloscope TEK7854.







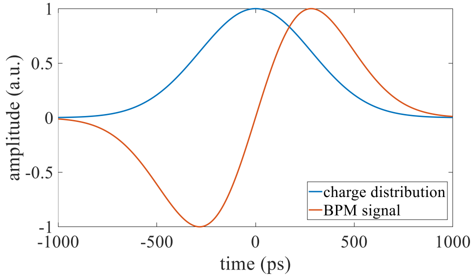
Broad Band Sensor (Frequency domain, HOTCAP)

Principle

charge quantity — Longitudinal phase

$$I(t) = \frac{Q}{\sqrt{2\pi}\sigma} exp[-\frac{(t-t_0)^2}{2\sigma^2}]$$

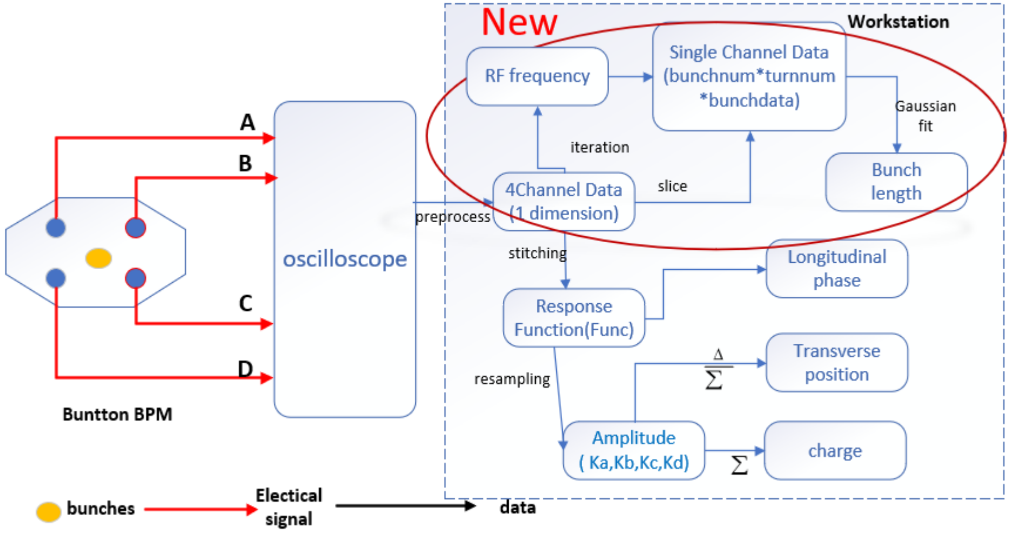
Bunch length



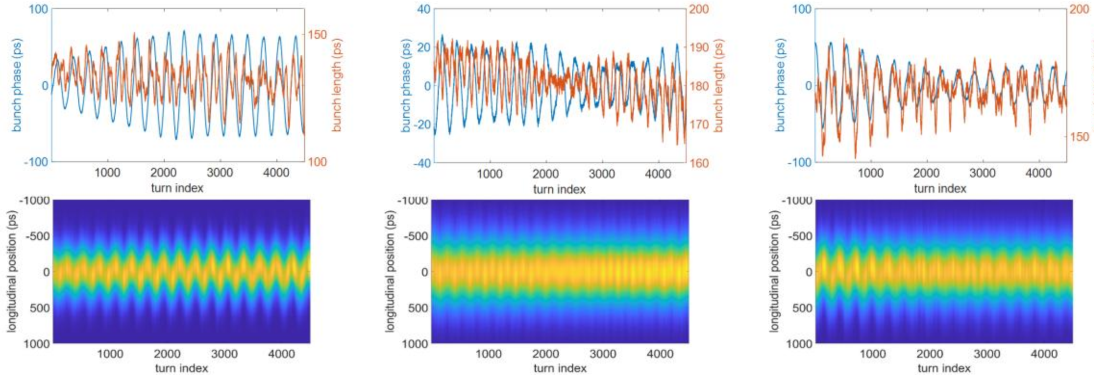
$$V(t) = I(t) * F_{Button}$$

$$V(f) = I(f) \cdot R_{Button}(f)$$

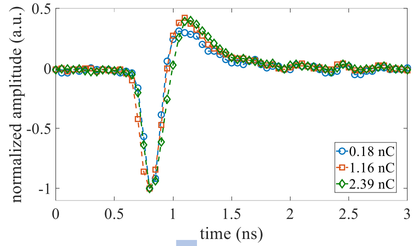
System architecture



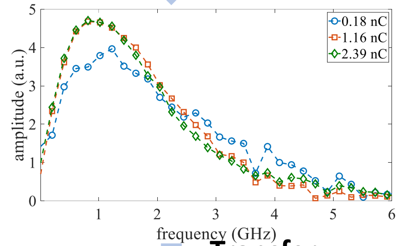
Application: HLS longitudinal instability observation



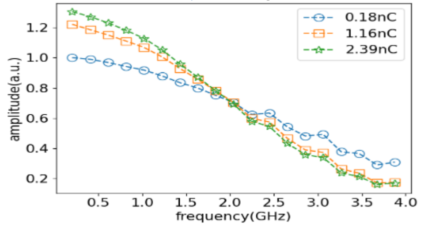
Data flow



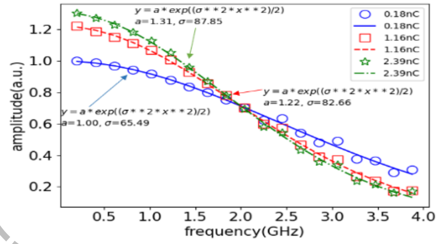
FFT



Transfer impedance com.



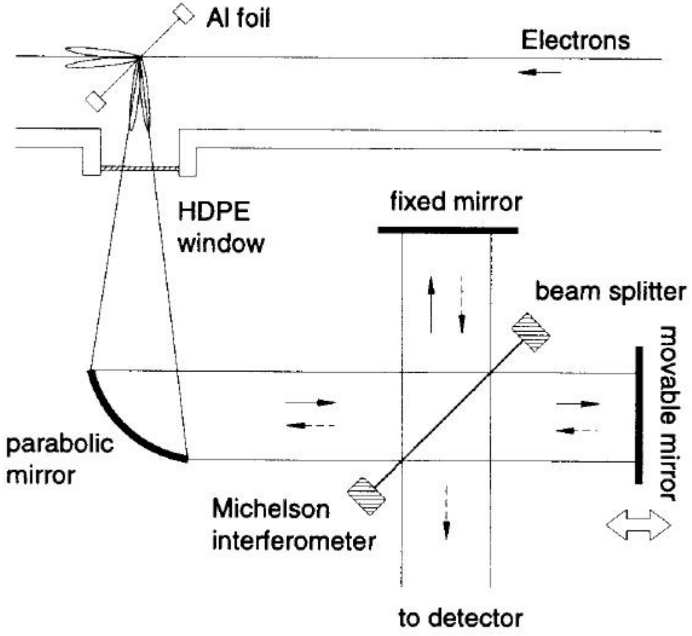
Gaussian fitting

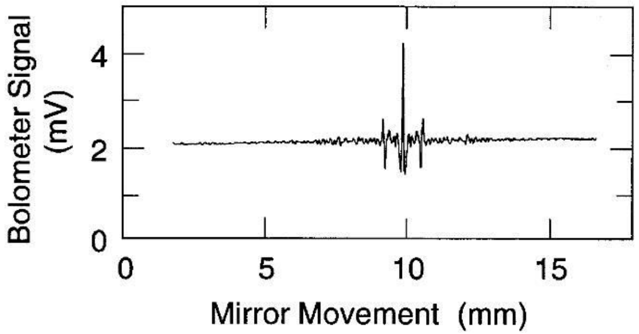


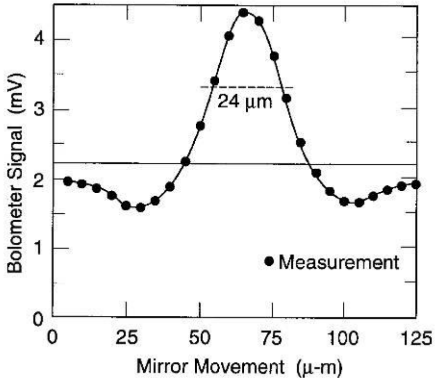
Hong-Shuang Wang, Yong-Bin Leng, etc., Bunch-length measurement at a bunch-by-bunch rate based on time–frequency domain joint analysis techniques and its application, NST, 24 May 2024

Optical Correlation (time domain)

- **Light pulses emitted by the particle bunch carry longitudinal distribution information.**
- **After splitting the light pulse into two beams traveling via distinct optical paths to the detector, adjusting the position of a movable mirror enables control over the optical path difference (OPD) between the two pulses.**
- **With small OPD (< bunch length), the two light pulse signals exhibit partial or complete amplitude superposition.**
- **With large OPD (> bunch length), the signals combine through linear intensity superposition.**
- **Bunch length will given by OPD vs. intensity curve.**





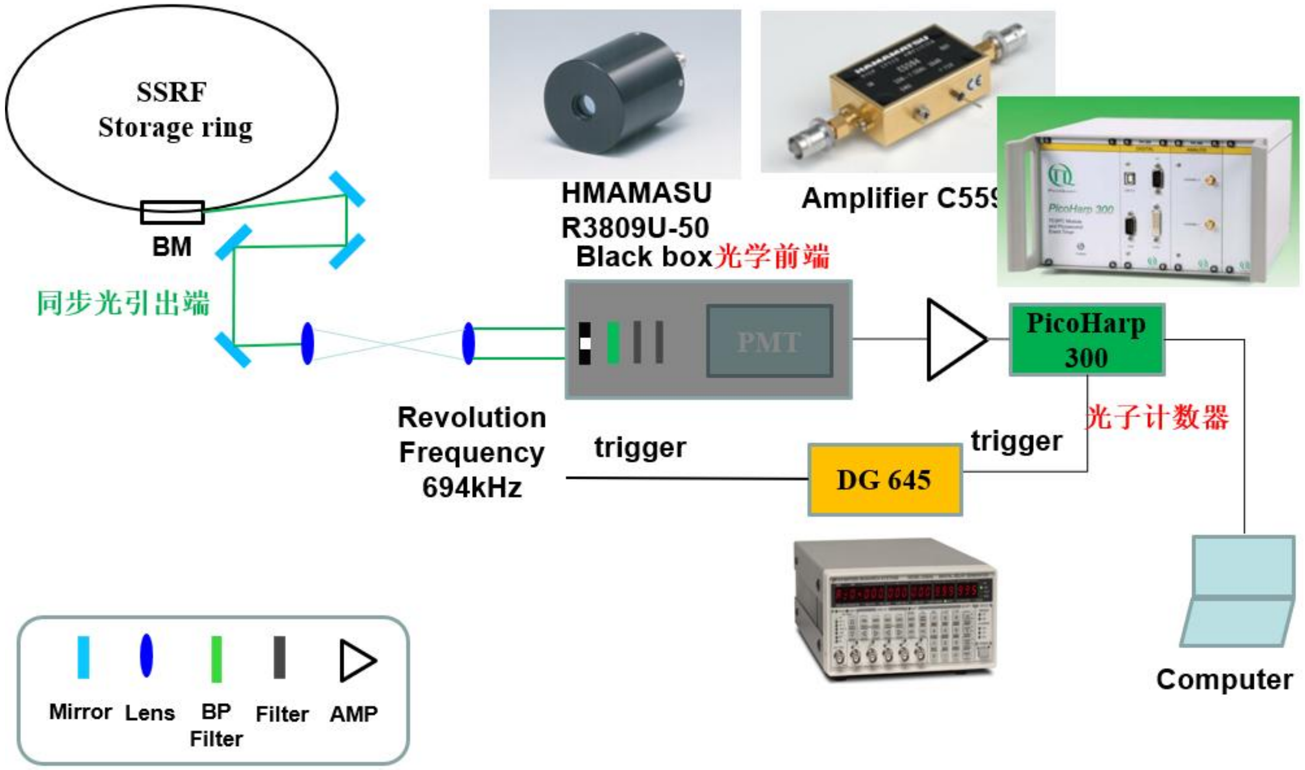


$$\left(\frac{2.35}{\sqrt{2}}\right)\sigma_z$$

examples: interferograms measured at the Stanford "sunshine facility" (courtesy H. Wiedemann, 2004)

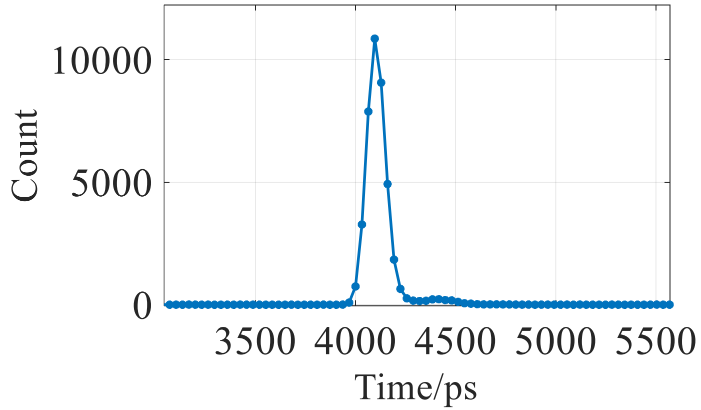
Single photon counting (time domain) @ SSRF

- While **optical pulse distribution defies direct resolution**, individual **photon arrival times are precisely resolved**.
- **Attenuate the photons emitted by the electron bunch to a level of fewer than one per turn.**
- **A time-to-digital converter (TDC) records each detected photon's arrival time with picosecond-level precision.**
- **By correlating photon detection events with the revolution frequency (radiofrequency, RF), longitudinal beam profiles can be reconstructed.**



Key components include:

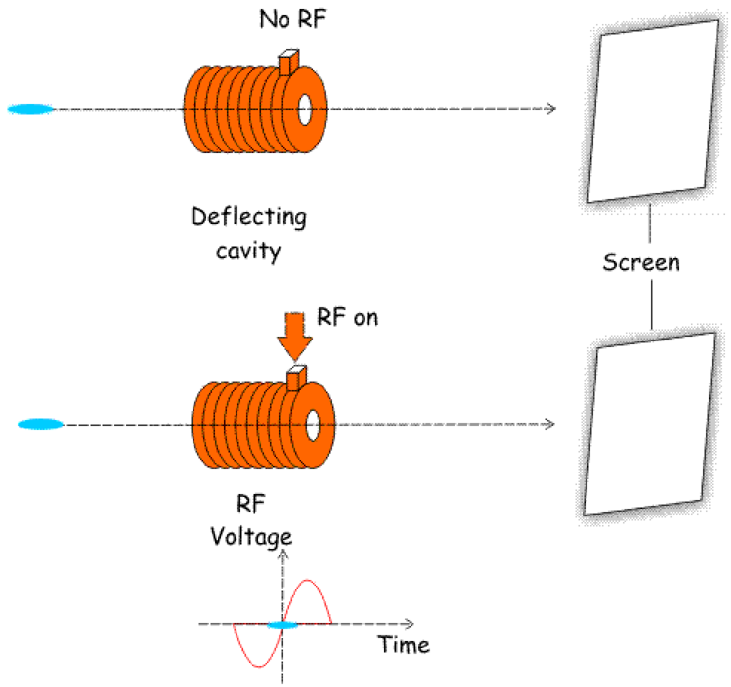
- ☑ Photomultiplier tube (PMT) as the photodetector
- ☑ Fast amplifier & leading-edge discriminator
- ☑ High-speed counter/TDC for timing registration
- ☑ RF synchronization system for bunch correlation

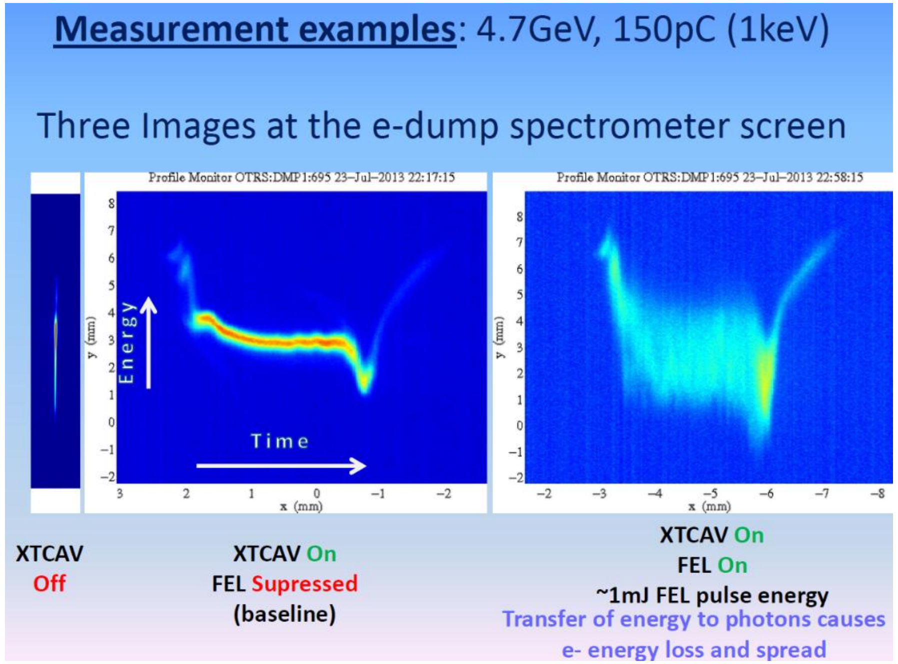


FWHW 65ps

Transverse Deflection Cavity (TDC)

- The measurement principle is similar with a streak camera.
- As the electron bunch passes through the TDC, individual electrons experience **varying magnitudes of transverse deflecting force based on their respective acceleration phase**.
- After a drift section, electrons subjected to stronger forces exhibit greater transverse displacement. In this way the **longitudinal distribution converts into a transverse profile**.
- The original longitudinal characteristics can be reconstructed with measured transverse profile.

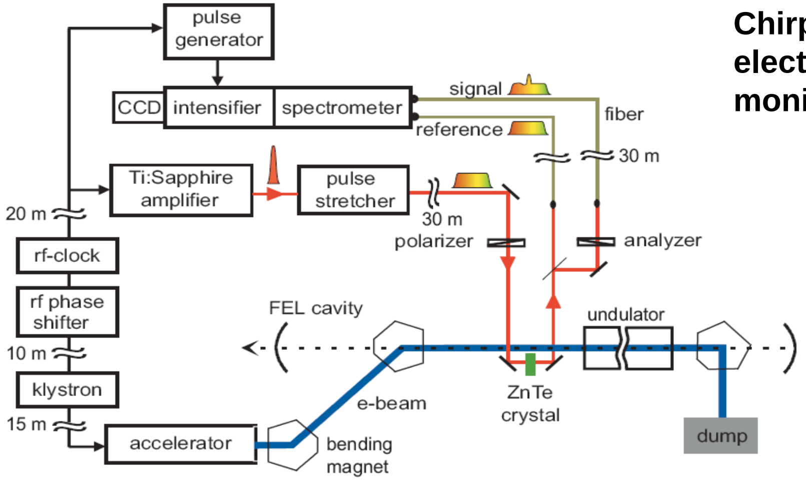




LCLS, Patrick Krejcik, IPAC2014

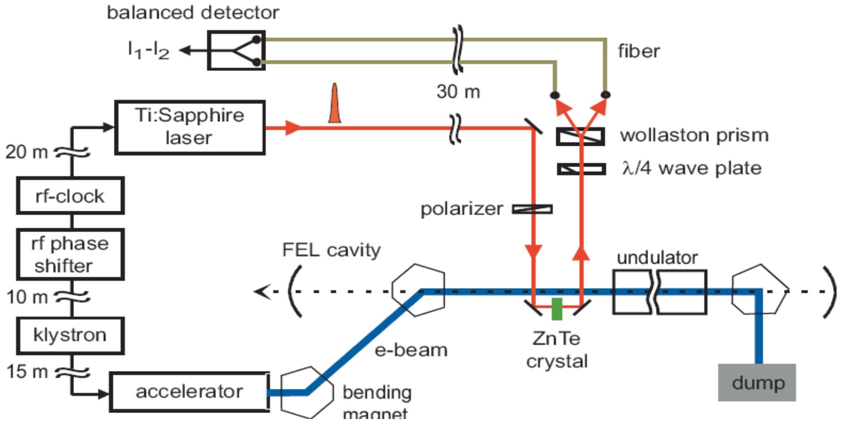
EO Sampling bunch length monitor

Delay scan



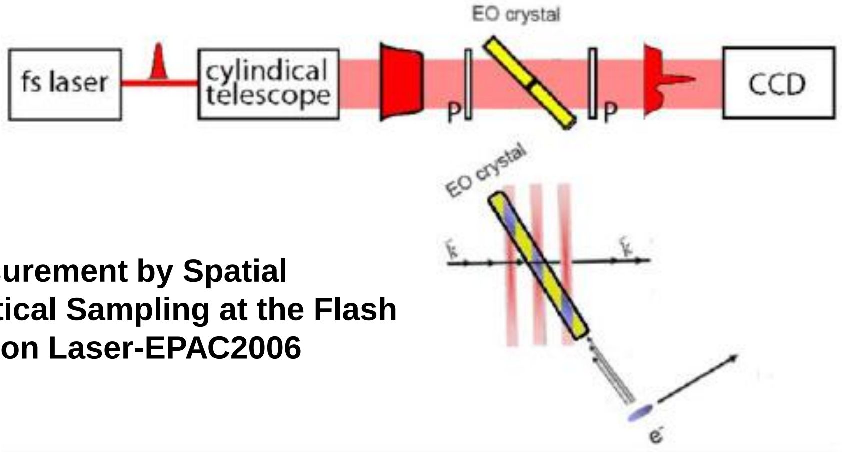
Chirped-laser based electron bunch length monitor-PAC2003

Spectral Decoding



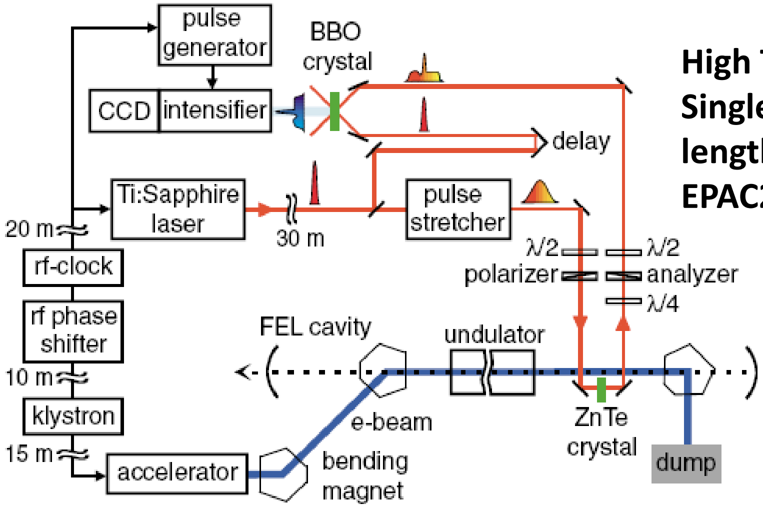
Electro-Optic Technique with Improved Time Resolution for Real-Time, Nondestructive, Single-Shot Measurements of Femtosecond Electron Bunch Profiles -PRL2004

Spatial Decoding



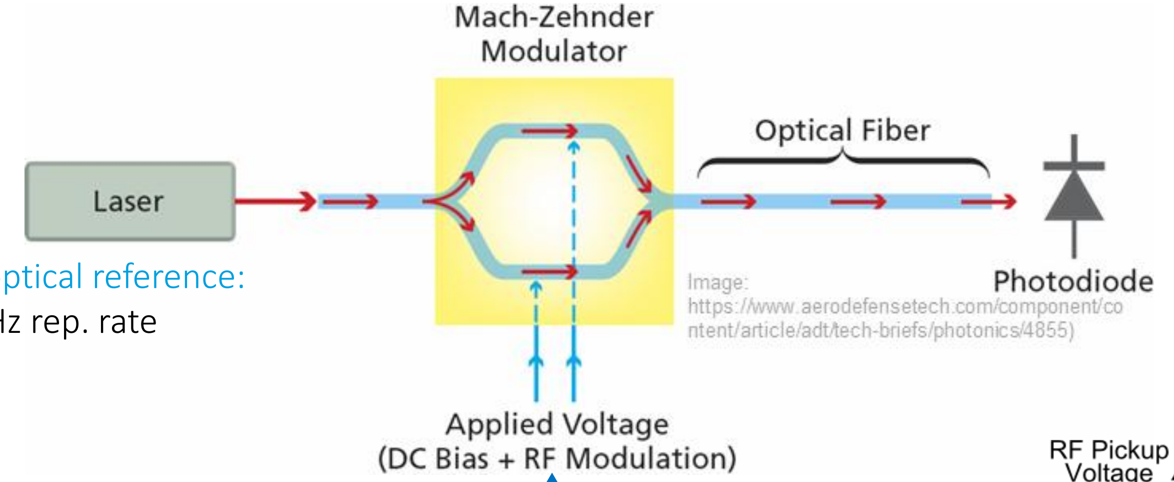
Jitter Measurement by Spatial Electro-optical Sampling at the Flash Free Electron Laser-EPAC2006

Time Decoding



High Temporal Resolution, Single-shot Electron Bunch-length Measurements-EPAC2004

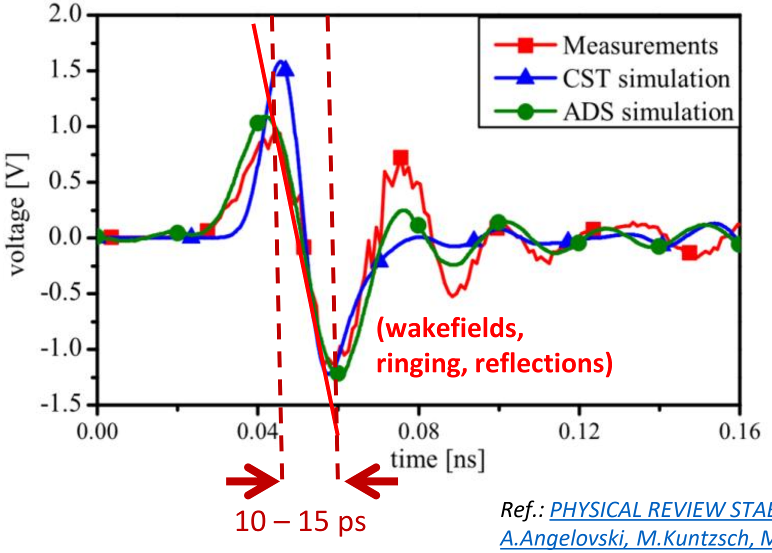
EO Sampling BAM



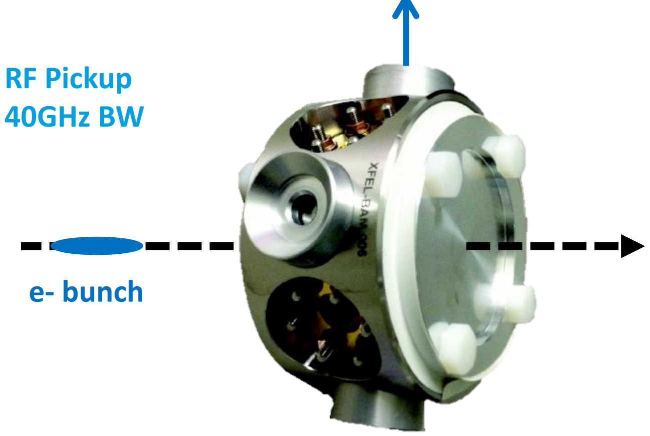
From optical reference:
216MHz rep. rate

RF Signal of 1 bunch

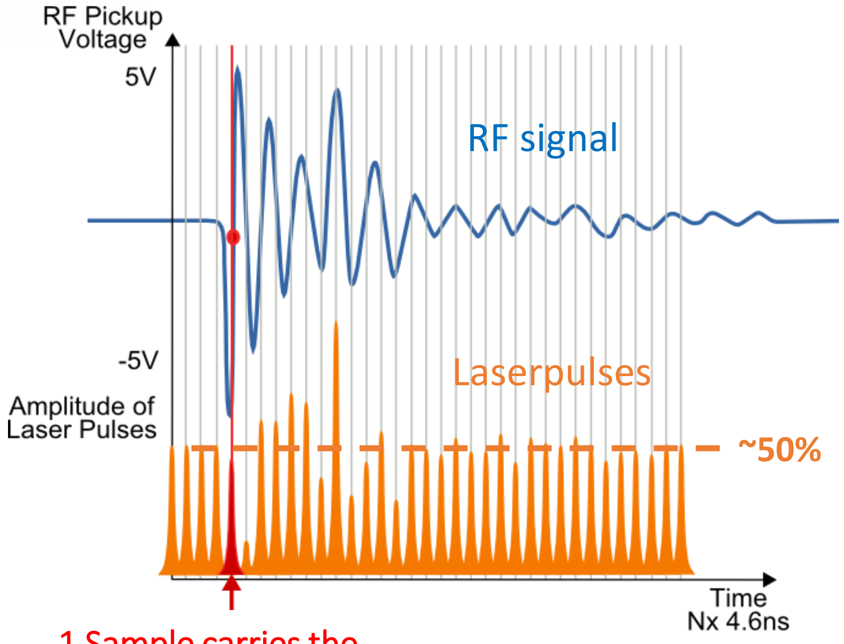
Slope: @20pC > 0.3 mV/fs



RF Pickup
40GHz BW



Encode $t_{arrival} \rightarrow A_{laser}$

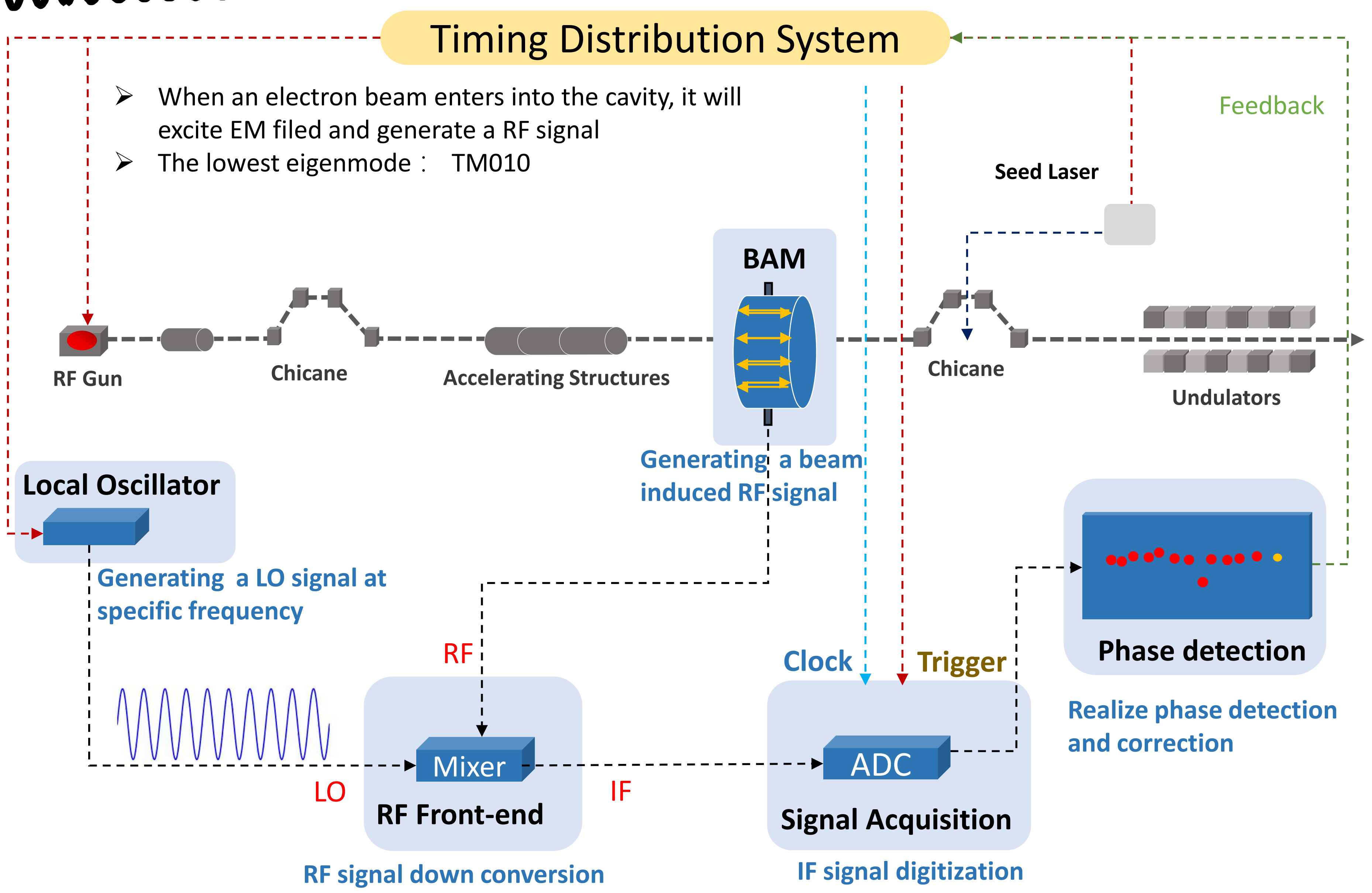


1 Sample carries the
Arrival time information.

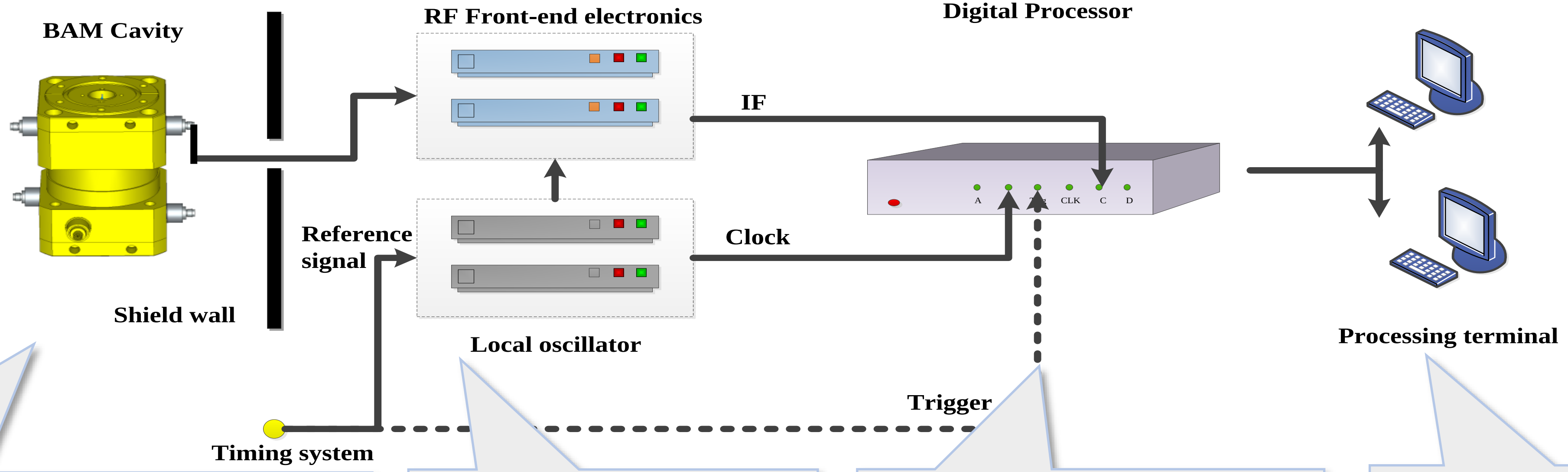
Ref.: PHYSICAL REVIEW STAB, 18, 012801 (2015)
A.Angelovski, M.Kuntzsch, M.K.Czwalinna, et al.

Phase cavity based BAM (Principle)

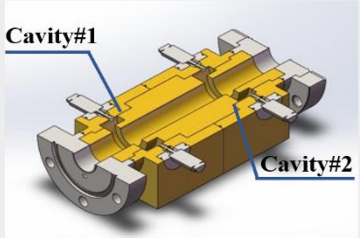
- When an electron beam enters into the cavity, it will excite EM filed and generate a RF signal
- The lowest eigenmode： TM010

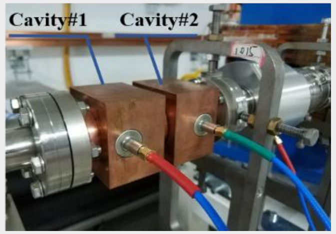


Phase cavity based BAM @ SXFEL



Beam arrival time monitor





Parameters	Cavity #1	Cavity #2
Frequency/ GHz	4.685	4.72
Q_L	4671	4716
R over Q/Ohm	107.2	107.9
Bandwidth /MHz	1.002	1.025
τ /ns	318	318

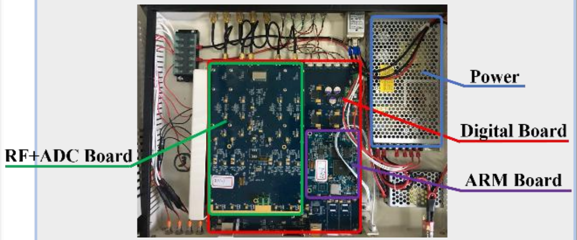
RFFE

LO

Front panel

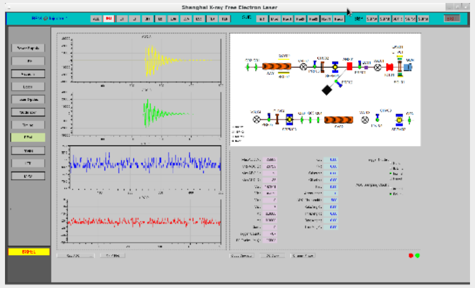
Back panel

DBPM



Para.	Value
Sampling rate	119 MHz
Number of bits	16
Channels	4

GUI

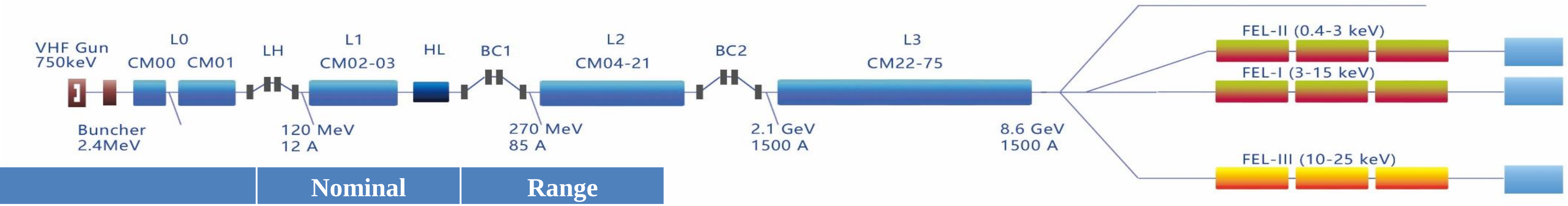


- Data acquire and publish;
- Real-time display ;
- Monitor and control

Beam Diagnostics Challenges for Advanced Light sources

Beam diagnostics demands for FEL

Shanghai HIgh repetitioN rate XFEL and Extreme light facility (SHINE)

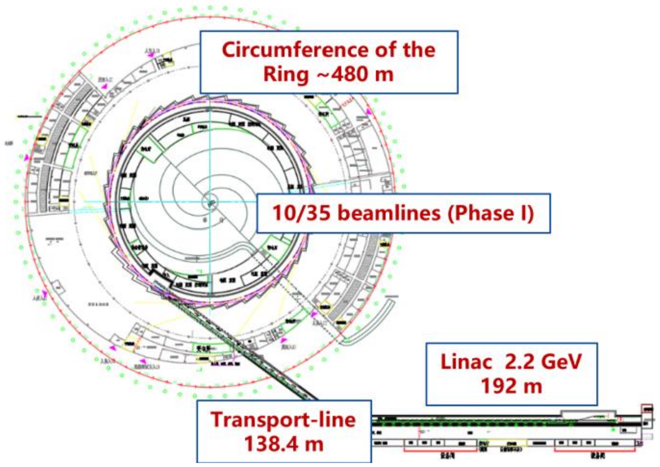


	Nominal	Range
Beam energy/GeV	8.0	4-8.6
Bunch charge/pC	100	10-300
Max rep-rate/MHz	1	up to 1
Beam power/MW	0.8	0 - 2.4
Photon energy/keV	0.4-25	0.4-25
Pulse length/fs	20-50	5-200
Peak brightness	5×10^{32}	1×10^{31}-1×10^{33}
Average brightness	5×10^{25}	1×10^{23}-1×10^{26}
Total facility length/km	3.1	3.1
Tunnel diameter/m	5.9	5.9
2K Cryogenic power/kW	12	12
RF Power/MW	2.28	3.6

Beam diagnostics and control tasks:

- Characterize electron bunch parameters and monitoring online
- Find and maintain the optimal beam trajectory (undulator section) for maximum lasing
- Maintain synchronization between electron bunch and seed laser pulse
- Stabilize the FEL output power using feedback or feedforward

Beam diagnostics demands for DLSR



	Design
Energy [GeV]	2.2
Current [mA]	350
Circumference [m]	479.86
Natural emittance [pm·rad]	86.3
Lattice	6BA
Straight section number	20L+20S
Straight section length [m]	L/5.3,S/2.2
Operation mode	top-off

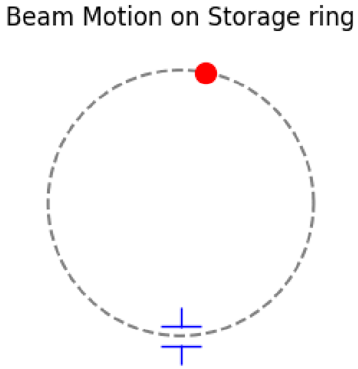
Hefei Advanced Light Facility (HALF)

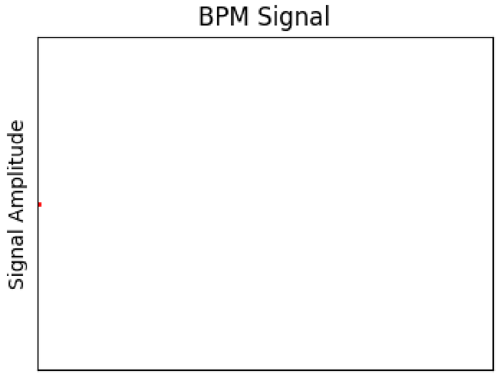
Beam diagnostics and control tasks:

- Characterize electron bunch parameters and monitoring online
- Find and maintain the golden orbit in the whole ring
- Keep the beam orbit drift and 3D size as small as possible using feedback or feedforward

Beam Signal Difference between Ring and Linac

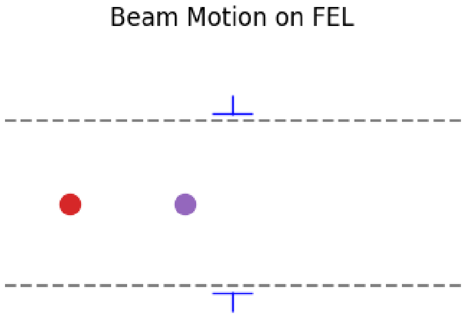
Same bunch passes through pickup many turns

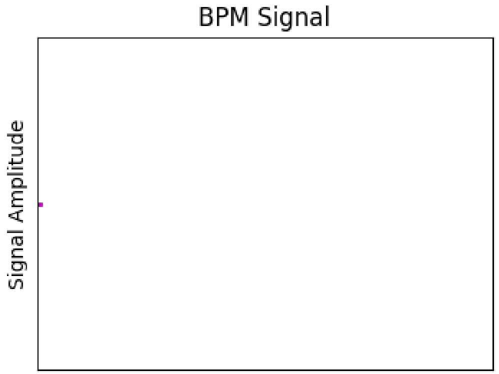




- Approximately strictly periodic signal, Averaging and correlation analysis.
- Short bunch spacing, broad band processing.
- Beam disruption is not permitted.

Many bunches pass through pickup once





- Non-periodic signal， every one is new single shot measurement
- long bunch spacing, narrow band processing.
- beam disruption is permitted under special circumstances.

Requirements and Challenges

		SHINE	HALF
Requirements	Charge	0.1% @ 100 pC	2 uA @ 350 mA **0.02% @ 700 pC**
	Transverse position	**100 nm**	**50 nm**
	Arrival time	**~ 10 fs**	~ sub ps
	Transverse size	~ 10 um	**~ few um**
	Bunch length	**~ 10 fs**	~ ps
	Orbit feedback	TBD	**BW 500Hz**
Challenges		Single shot measurement Small charge	Destructive diag not acceptable Small bunch spacing High Feedback BW
Advantages		Destructive diag acceptable Large bunch spacing (1 us) Narrow band sensor is OK	Multi turns averaging acceptable Diagnostics beamline Well developed FOFB technology

Diagnostics solution for SHINE and HALF

	SHINE	HALF
Charge	ICT & FC + high speed scope BPM pickup + DBPM processor Cavity sensor + DBPM processor DCCT?	ICT + high speed scope BPM pickup + HOTCAP (BYB) DCCT
Transverse position	BPM pickup + DBPM processor CBPM + DBPM processor	BPM pickup + DBPM processor (FOFB) BPM pickup + HOTCAP (BYB)
Arrival time	CBPM + DBPM processor EOS + digital processor	BPM pickup + HOTCAP (BYB)
Transverse size	Screen monitor (low rate) Wire scanner (multi shots) Visible SR monitor (interferometer?)	Xray zone plate imaging Xray pinhole camera Visible SR interferometer
Bunch length	CSR monitor (online) EOS + ICCD (online) Transverse cavity + screen (destructive)	Streak camera BPM pickup + HOTCAP (BYB)
Key components	**CBPM, digital signal processor, EOS**	**New DBPM, BYB tools (HOTCAP)**

Bunch by Bunch Diagnostics

Why bunch-by-bunch diagnostics

For accelerator physicists

- Compared with bunch train (turn-by-turn), single bunch (bunch-by-bunch) is more ‘like’ macro particle. Using bunch-by-bunch observations to check with the textbook or develop new theory is more reasonable.
- To understand and improve a specific machine well, more information required. Not just common behavior (SA and TBT data) but also individual behavior (BYB data).
- Powerful toolkits for collective effects, nonlinear dynamics study.

For machine operators

- Powerful toolkits to monitor, capture, and even predict instability events (beam loss).
- Powerful toolkits to optimize operation mode, such as filling pattern, tune, injection parameters, and so on.

For BI physicists or engineers

- Sampling and analyzing raw beam signal at BYB rate instead of filtered signal with ’under sampling rate’ is more reasonable.
- Bunch-by-bunch diagnostics will be a very important step toward ideal diagnostics.

For low emittance storage ring

- Low emittance, small vacuum pipe, and small gap IDs make collective effects much harder than normal ring. BYB tools required to help commissioning at the first stage and understand machine well during operation.
- High intensity and low lifetime require frequent injection and very low beam loss. Transient stages like injection and random beam loss need to be recorded and analyze to help improving machine performance.

What bunch-by-bunch observation do we need?

In the simplest case

Assume:

- Bunching beam
- Gaussian distribution in the three-dimensional space

Six spatial parameters **(x, y, z, σx, σy, σz)**	**+**	**Charge** **(Q)**	**=**	**an independent bunch**

6-dimensional **bunch-by-bunch diagnostic system**

Why focus on injection transient stage

- **Dedicated machine study**

  Change machine parameters, compare the measured value with the expected value

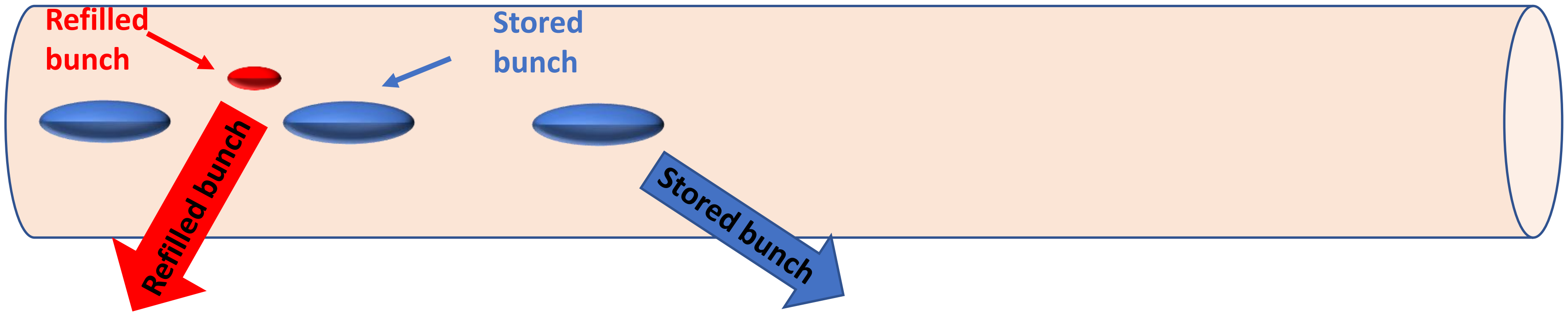
  (Ideal experiment for beam instability study, Require dedicated machine study time)

- **Monitor Injection transient stage**

  Retrieve dynamic information from stored bunches and refilled bunch behavior

  (frequently observe during the user run at SSRF)

- **Betatron Damping oscillation** ← **mismatch of kickers, also injector and storage ring**
- **Synchrotron Damping oscillation** ← **mismatch of injector and storage ring**



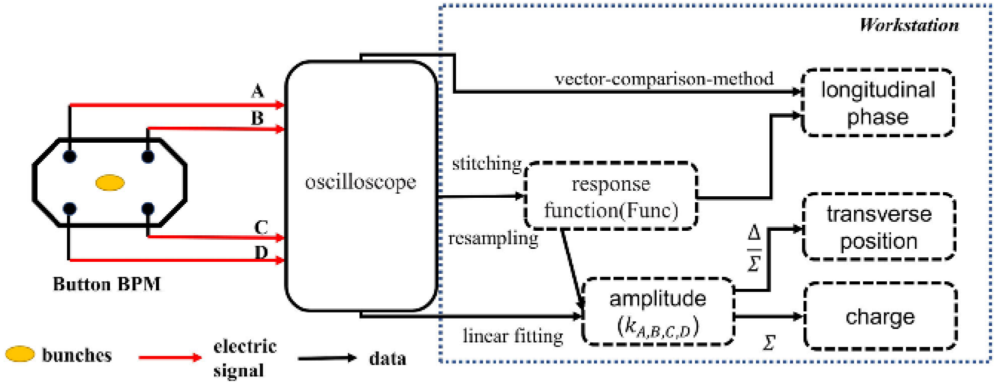
- ***Refilled charge / Qr***
- ***Betatron amplitude / A_r***
- ***Synchrotron amplitude / z_m***
- ***Synchrotron damping time / τ***
- ***Initial position in phase space / ϕ_0***

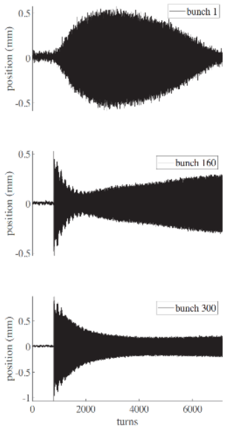
- ***Stored charge / Qs***
- ***Transverse tune / ν_x, ν_y***
- ***Betatron amplitude / A_s***
- ***Betatron damping time / Lx***

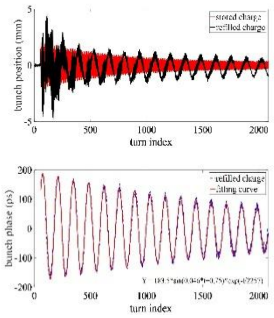
HOTCAP: 5D BYB measurement tools

HOTCAP originally developed from 2018 and released the first version in 2021, deliver 3D position + charge

Xingyi Xu, Yongbin Leng, etc.， Bunch-by-bunch three-dimensional position and charge measurement in a storage ring， PRAB 2021



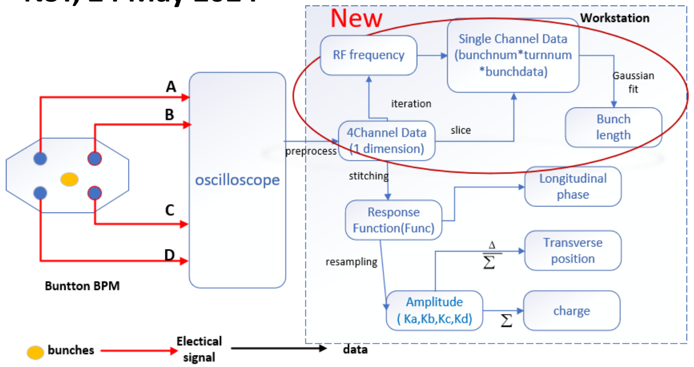


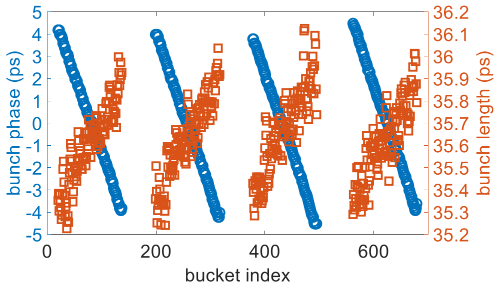


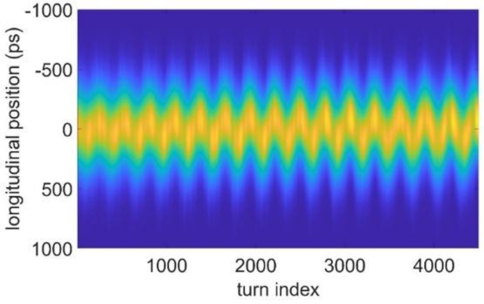
Upgraded

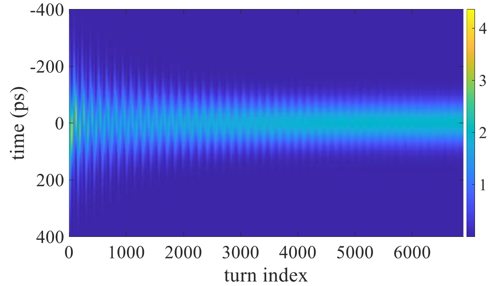
Upgrade to HOTCAP+ in 2024, deliver 3D position + charge + bunch length

Hong-Shuang Wang, Yong-Bin Leng, etc., Bunch-length measurement at a bunch-by-bunch rate based on time–frequency-domain joint analysis techniques and its application, NST, 24 May 2024







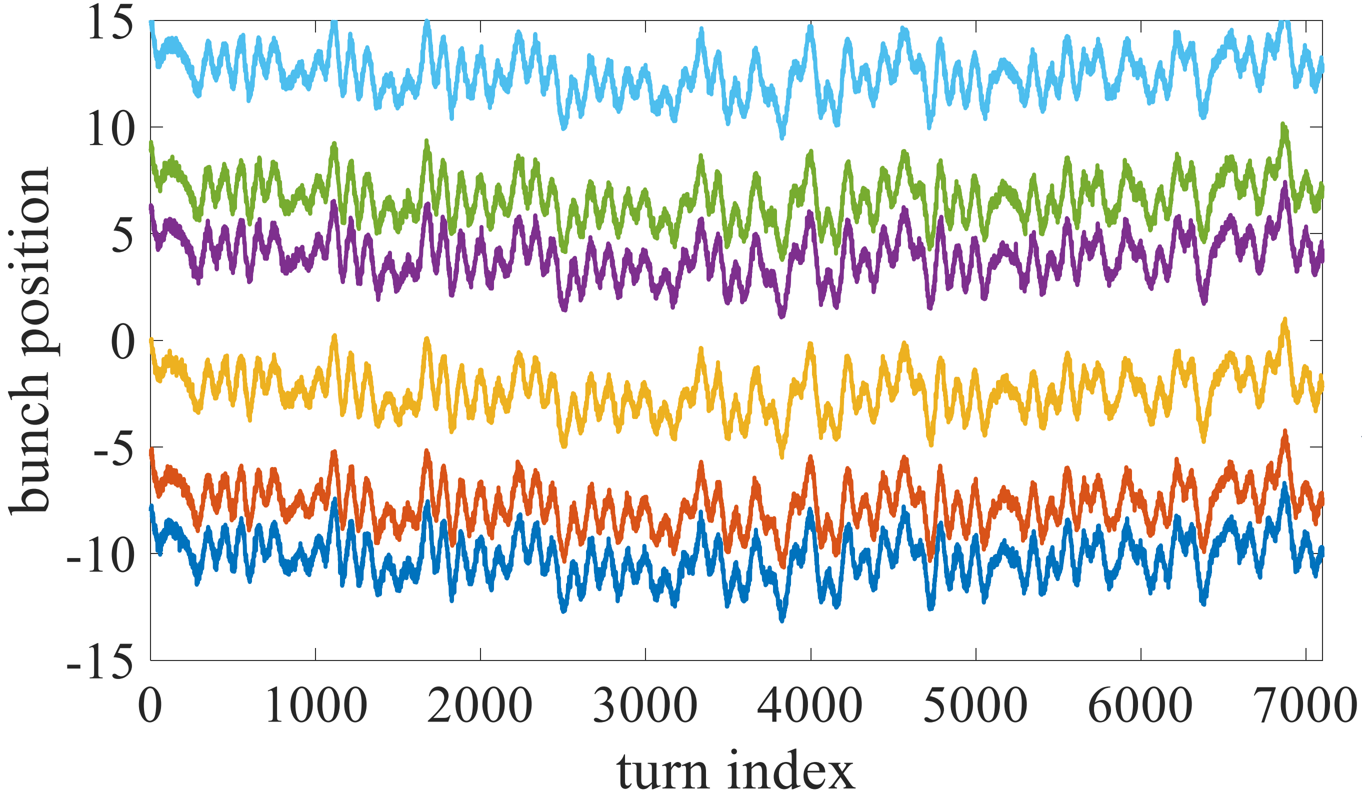


Typical measurement result: longitudinal position

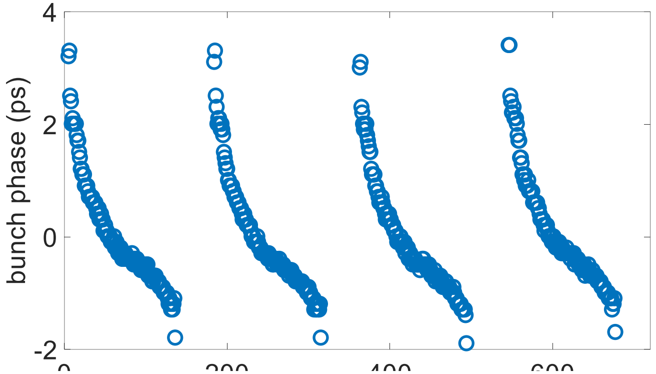
Charge (Q)、horizontal position (X)、vertical position (Y)、longitudinal position (phase)

Measurement result: 2D array (M X N) , M = bunch number, N = turn number

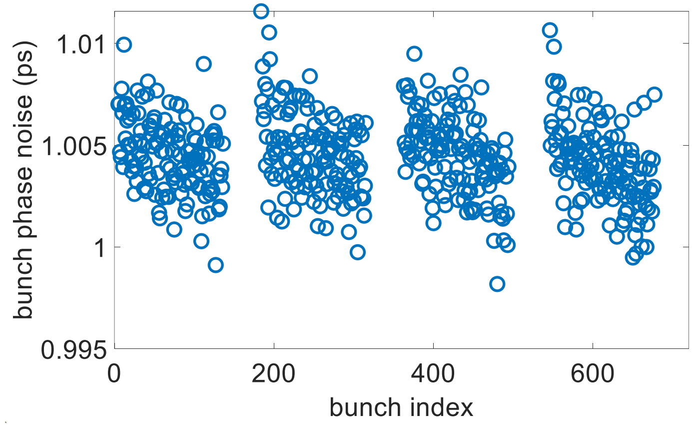
Example of longitudinal results:



Averaging each bunch

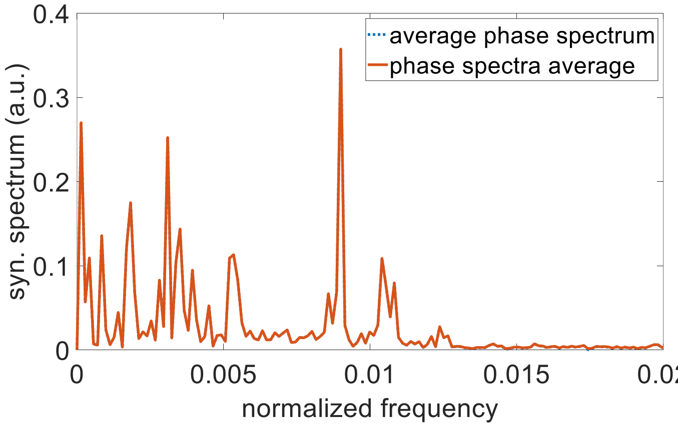


STD each bunch



Average of bunch FFT

FFT of bunch averaging



Typical measurement result: injection

$$z_d = z_m \sin(\omega t + \varphi_0) \cdot e^{-\frac{t}{\tau}}$$

Maximum oscillation amplitude (z_m)

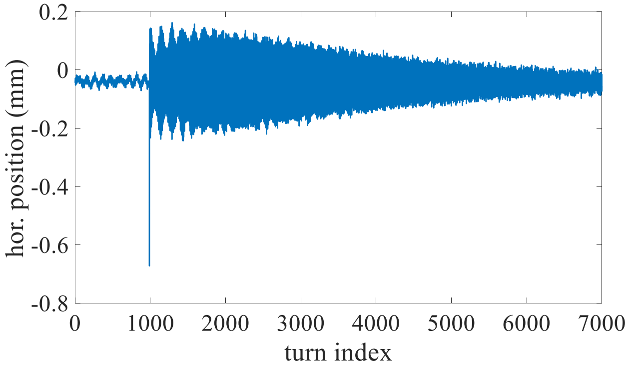
Initial phase (φ_0)

Damping time (τ)

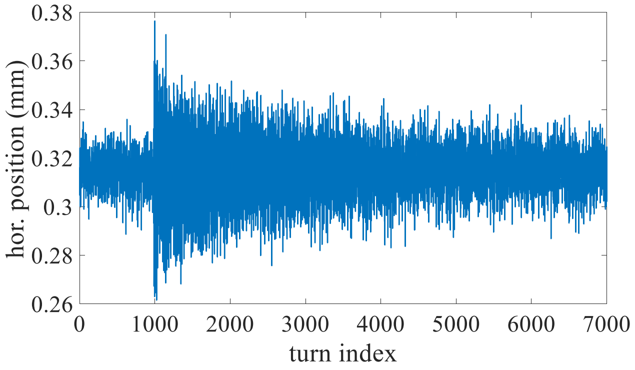
$$\alpha_s = \frac{1}{\tau}$$

$$\omega = \sqrt{\Omega^2 - \alpha_s^2}$$

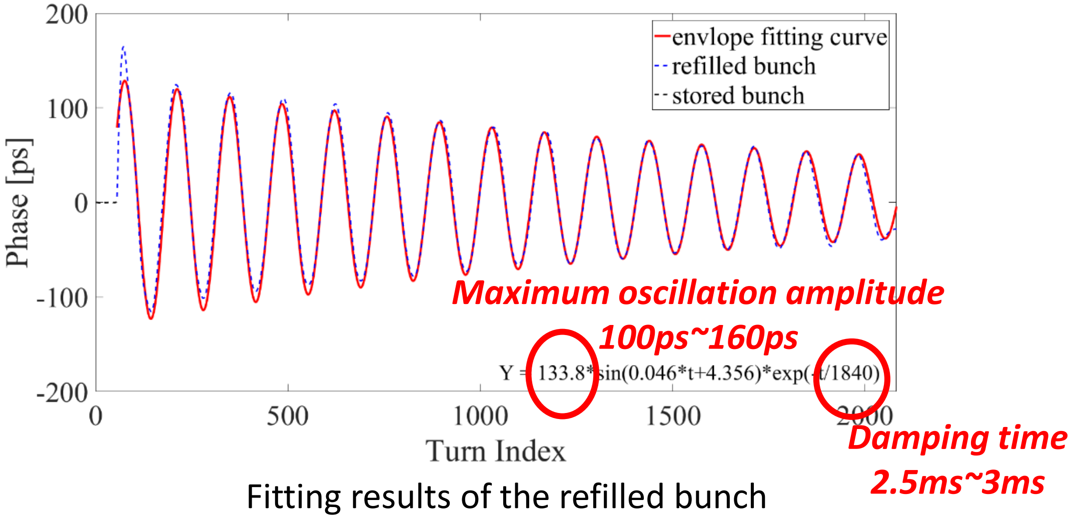
Synchrotron frequency (~0.0072) (Ω)



Horizontal Betatron oscillation of stored bunch



Vertical Betatron oscillation of stored bunch



Fitting results of the refilled bunch

Outlook & Summary

Outlook: optical technology

Beam detector

- EO sampling used in the FEL and ring: very fast response and time resolution. Good enough for slice sampling.
- Interferometer used in the ring: very high spatial resolution.
- More optical modulation techniques can be used to improve resolution and bandwidth.

Signal conditioning FE

- OE convertors used (PMT, PD, etc.) widely. Not good enough for slice measurement.
- Bandwidth and response time limited in this stage.
- Direct optical signal conditioning will prevent bandwidth loss.

Signal processor

- Electrical ADC and calculation circuit is the major bottleneck to limit system bandwidth.
- Optical calculation and ADC as potential to do continuous slice measurement.

Beam information extraction method

- Image processing techniques already applied in present BI system.
- More optical techniques can be used: such as computational Imaging

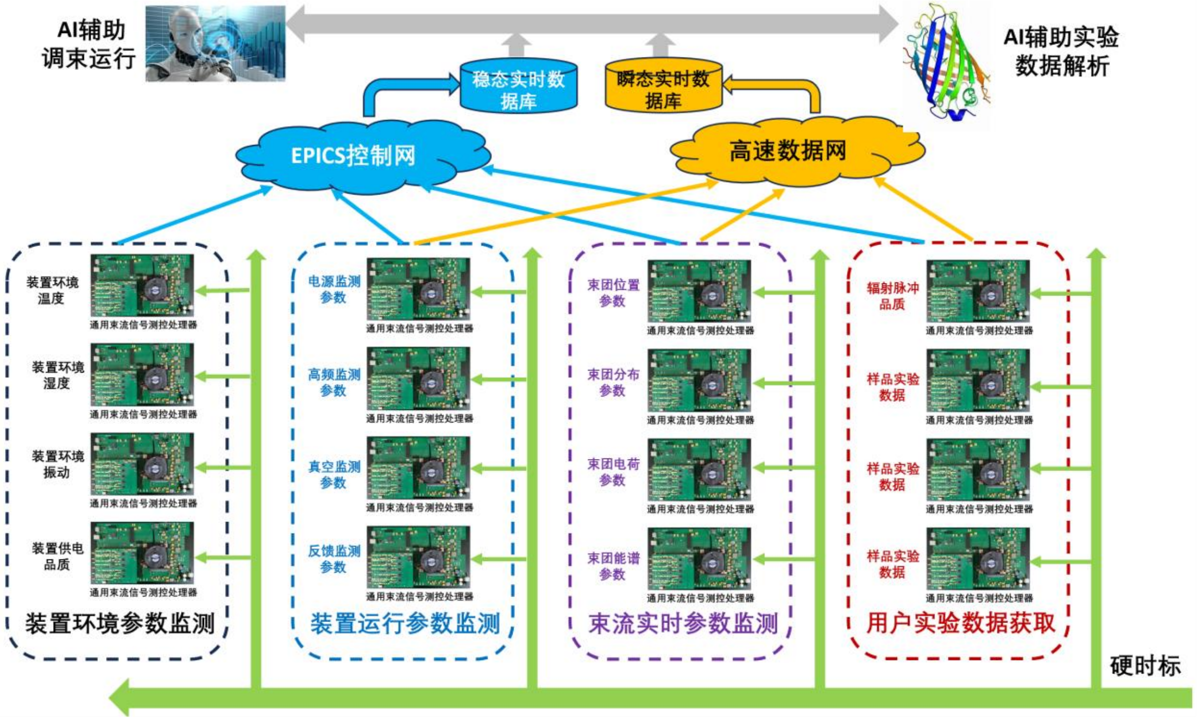
Outlook: Universal DAQ platform for AI application

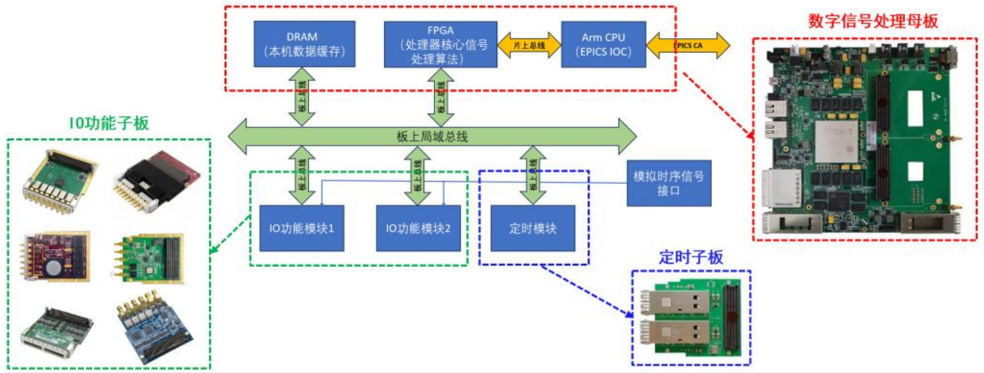
Problem:

- ➢ The data lacks unified standards and formats.
- ➢ The inconsistency of datasets being compromised due to bad synchronization.
- ➢ The data pool has sufficient breadth but insufficient depth.
- ➢ A significant amount of expert manpower is needed to clean and label the raw data.

Solution:

- ➢ Build a standardized large-scale scientific facility DAQ system based on a universal DAQ platform.
- ➢ A real-time dataset of the whole facility with guaranteed integrity and consistency.
- ➢ AI online accesses data from the standardized real-time data warehouse to complete tasks assisting facility operation and experimental data analysis.
- ➢ The application of the latest AI technology is ensured by data support.





Summary

- Both DLSR and FEL face some common beam diagnostic challenges, such as precise charge measurement, transverse position measurement, and transverse size measurement.

- Due to the different boundary conditions, they also face some unique challenges:
  - FEL: very high-resolution longitudinal parameter diagnostics and synchronization tools
  - DLSR: bunch by bunch multi-parameter measurement tools

- Engineers' self-positioning is insufficient to support the completion of world-leading large scientific facility construction. Everyone should be a ‘scientist’ in his own field.

- The beam diagnostics system should become one of the active promoters and biggest beneficiaries of AI technology applications. Building a facility global data warehouse based on a universal DAQ platform is a viable approach.

- With the help of the latest optical technology, it-time continuous measurement of slice it is hoped to achieve real-time continuous measurement of slice parameters within the bunch.

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NATIONAL SYNCHROTRON RADIATION LABORATORY

Hefei Advanced Light Facility

合肥先进光源——探索微观世界之眸

Thanks for your attention!

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