Design and Initial Commissioning of Beam Diagnostics for the KEK Compact ERL

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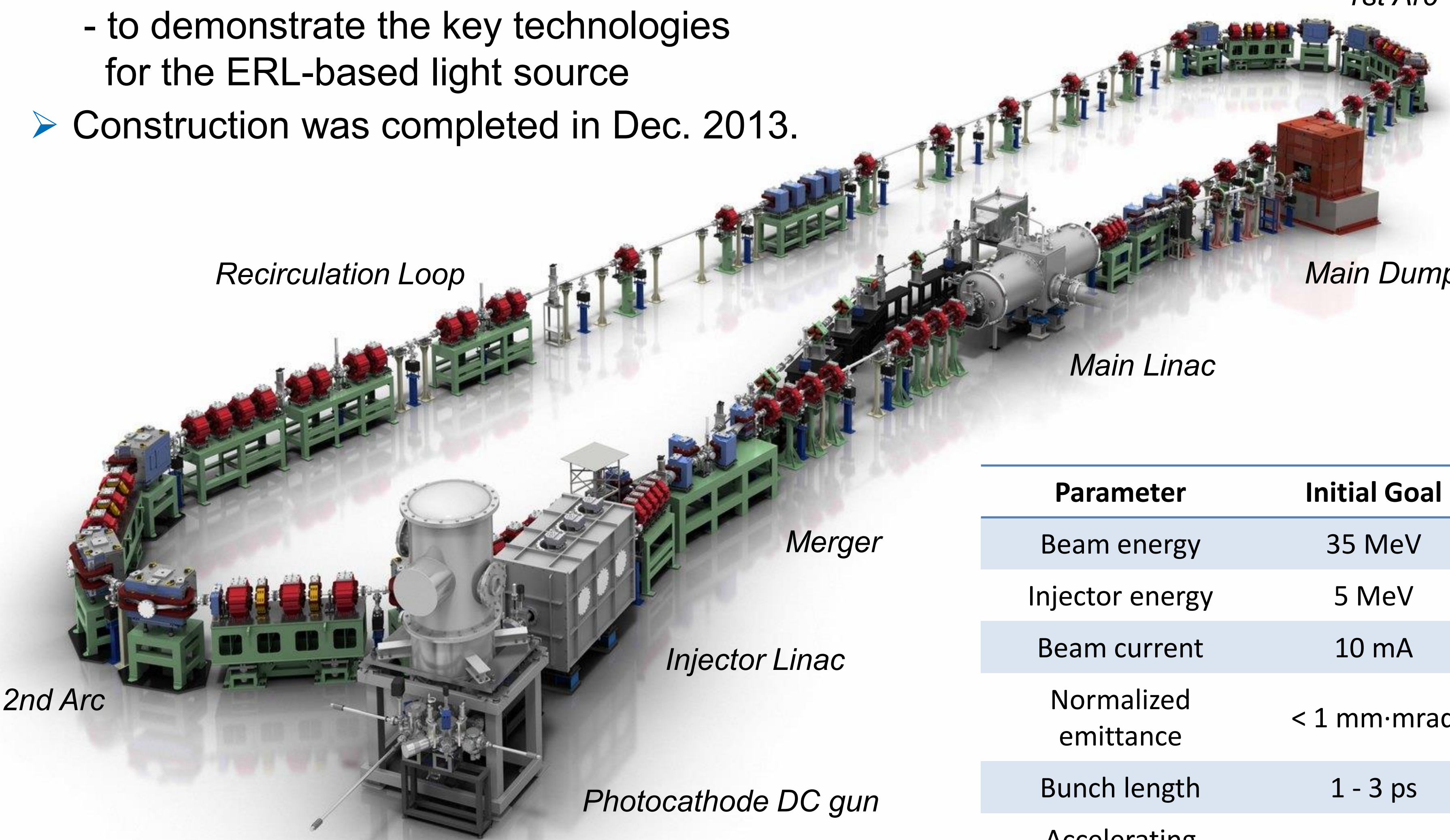
The Compact ERL (cERL) at KEK

- Purpose of the cERL
  - to demonstrate the key technologies for the ERL-based light source
- Construction was completed in Dec. 2013.



Parameter	Initial Goal
Beam energy	35 MeV
Injector energy	5 MeV
Beam current	10 mA
Normalized emittance	< 1 mm·mrad
Bunch length	1 - 3 ps
Accelerating Gradient	15 MV/m
RF frequency	1.3 GHz


Injector
Main Linac
Recirculation Loop

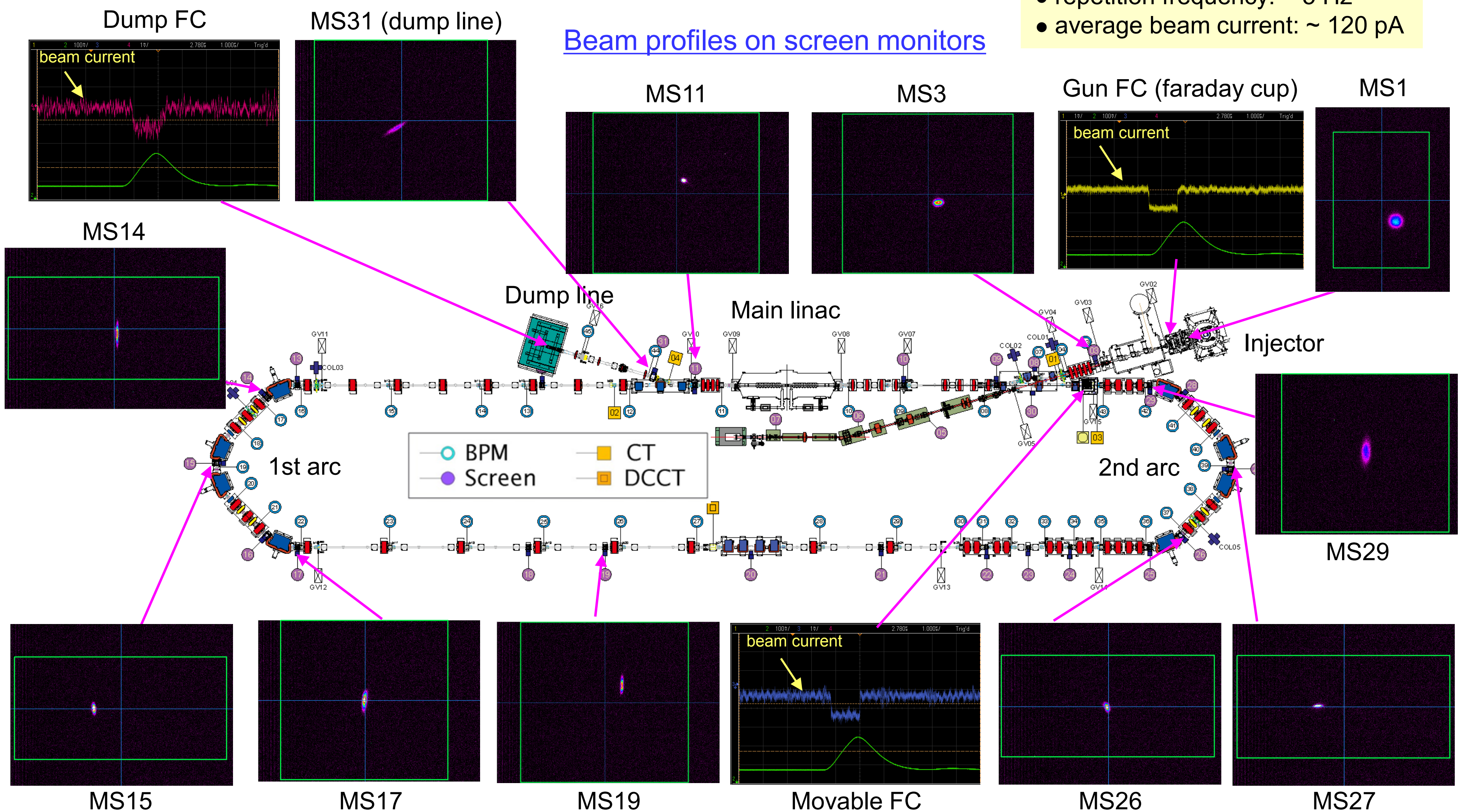
Commissioning Result with Low-current Beams

Beam energy (*E*)
- Injector: 2.9 MeV
- Recirculating loop: 19.9 MeV

Parameters
- Gun voltage: 390 kV   Buncher: V_c = 30.7 kV
- Injector cavities: E_{acc} = (3.2, 3.3, 3.1) MV/m
- Main-Linac cavities: Vc = (8.58, 8.59) MV

Beam pulses (macropulse)
- peak current: ~20 μA
- macropulse width: 1.2 μs
- repetition of bunches: 1.3 GHz
- repetition frequency: 5 Hz
- average beam current: ~ 120 pA

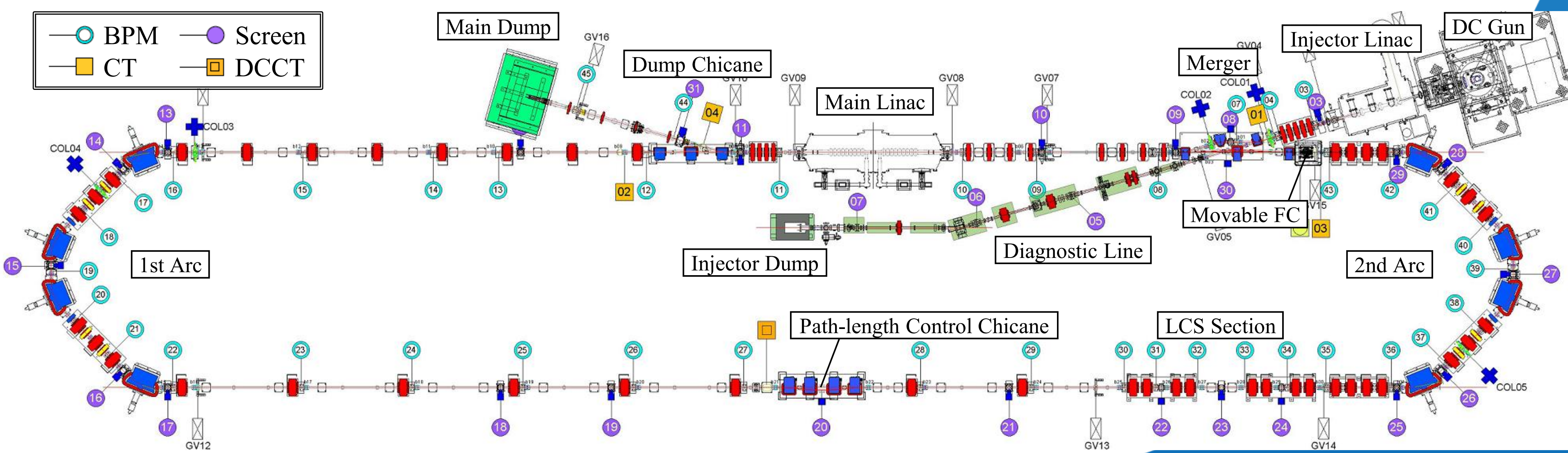
Beam profiles on screen monitors



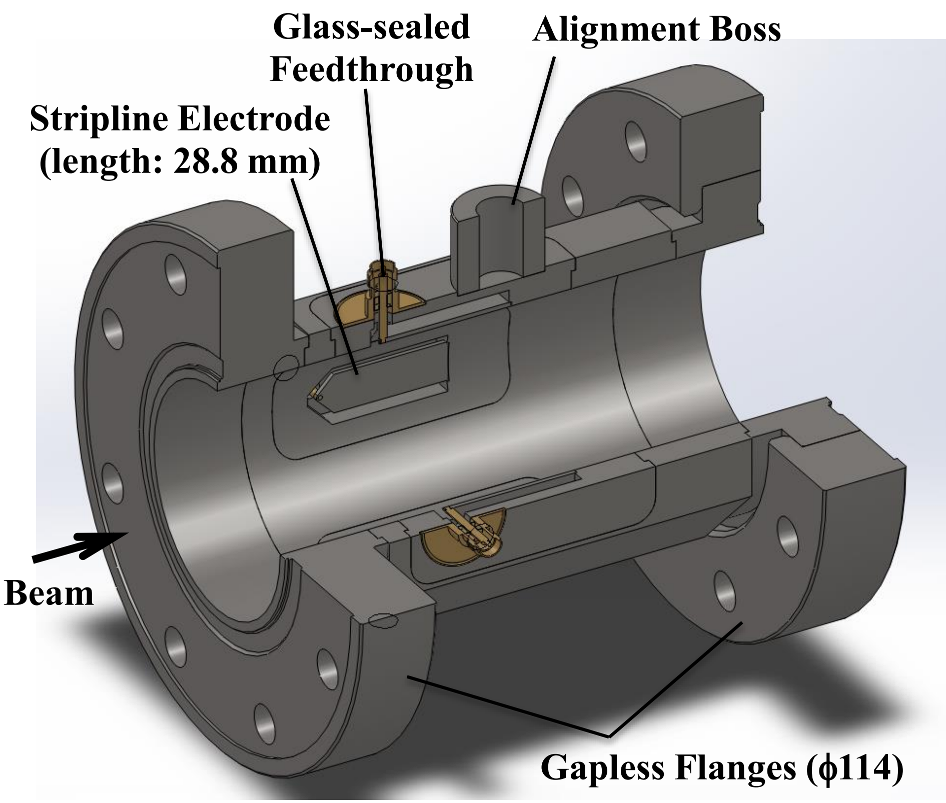
Beam Monitors for the cERL

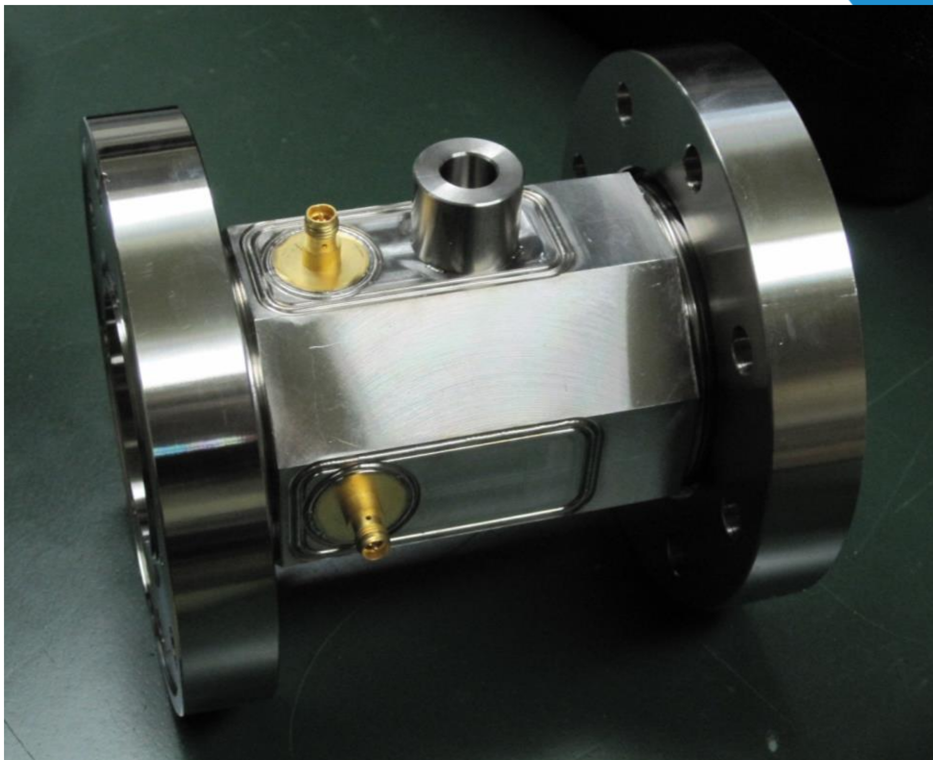
Monitor Type	Objective	#
BPM (Stripline/Button)	Position, Charge	45
SCM (Ce:YAG/OTR)	Position, Profile	30
BLM (Fiber&PMT)	Loss	4
CT	Charge	4
DCCT	Current	1
Movable FC	Charge	3

- ✓ CsI-scintillator-based BLMs, described later, are not listed here.
- ✓ A slit scanner and a deflecting cavity are installed along the diagnostic line.



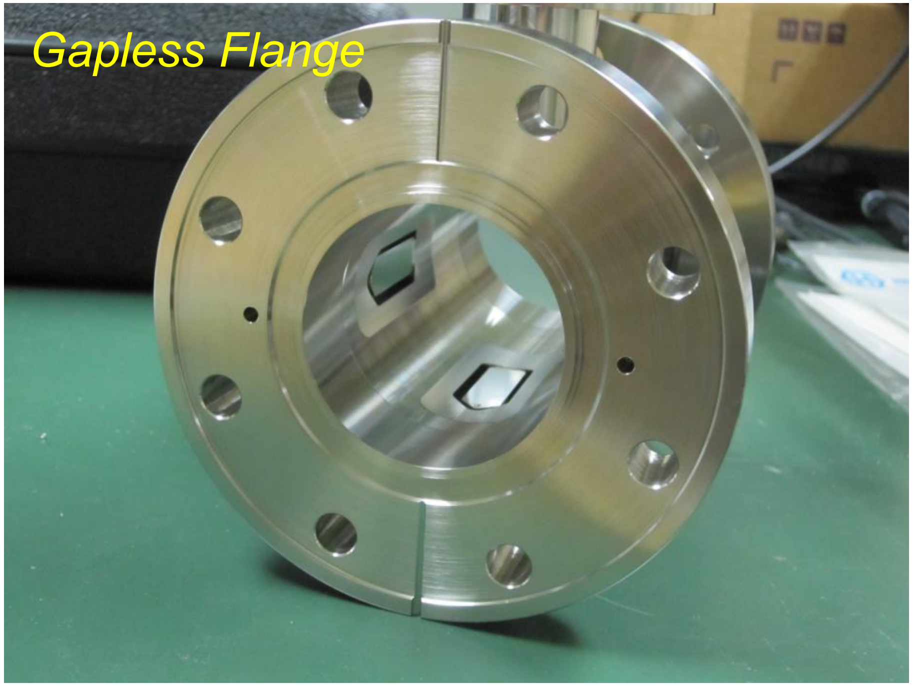
Design of the BPM Duct



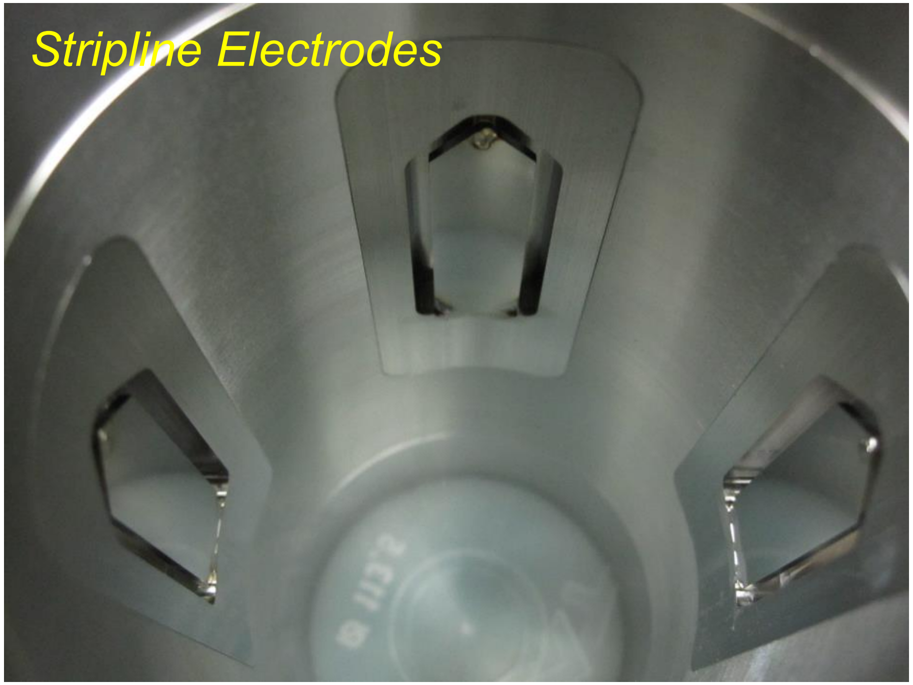


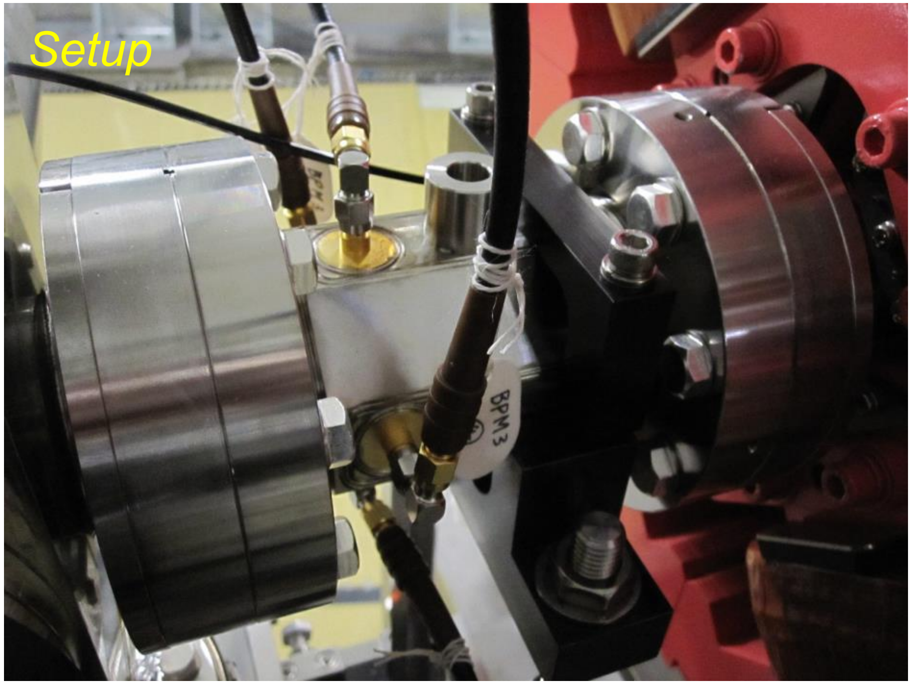
- Inner diameter: 50 mm
- Electrode length: 28.8 mm (to maximize sensitivity to 2.6 GHz)
- Electrode width: Opening angle 20°
- Characteristic impedance: 50 Ω
- Glass-sealed feedthrough (Kyocera, BHA glass, ε_r = 5.0)

- Gapless and stepless flanges
- Boss for precise alignment
- Longitudinal loss factor was evaluated by using GdfidL.
- For a 1-mm bunch-length beam,
  Loss factor: 59.1 mV/pC
  Power loss: 4.6 mW @10 mA

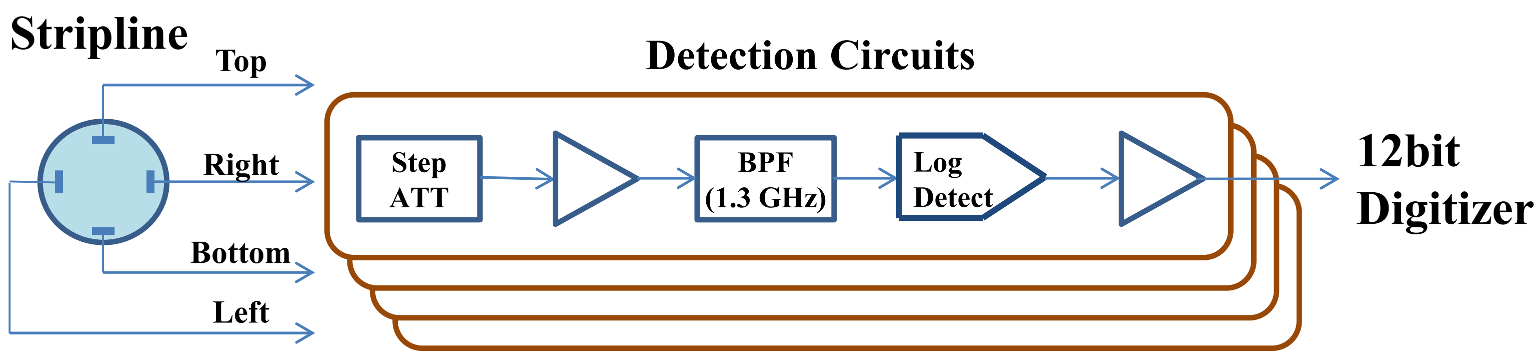

Gapless Flange


Glass-sealed Feedthrough


Stripline Electrodes


Setup
BPM3

Detection Circuit & Digitizer

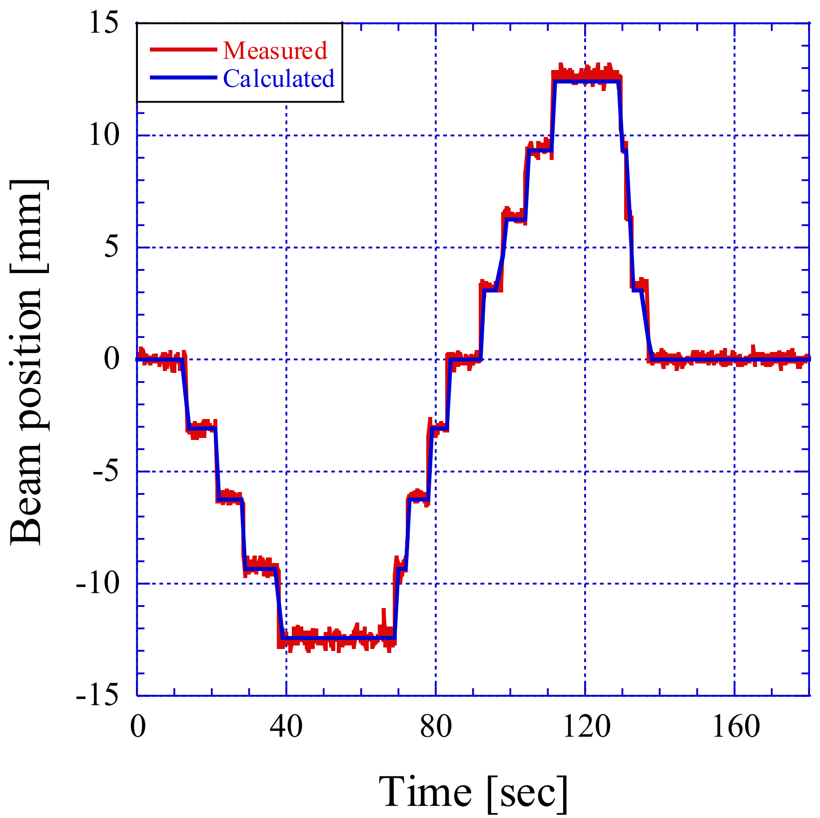


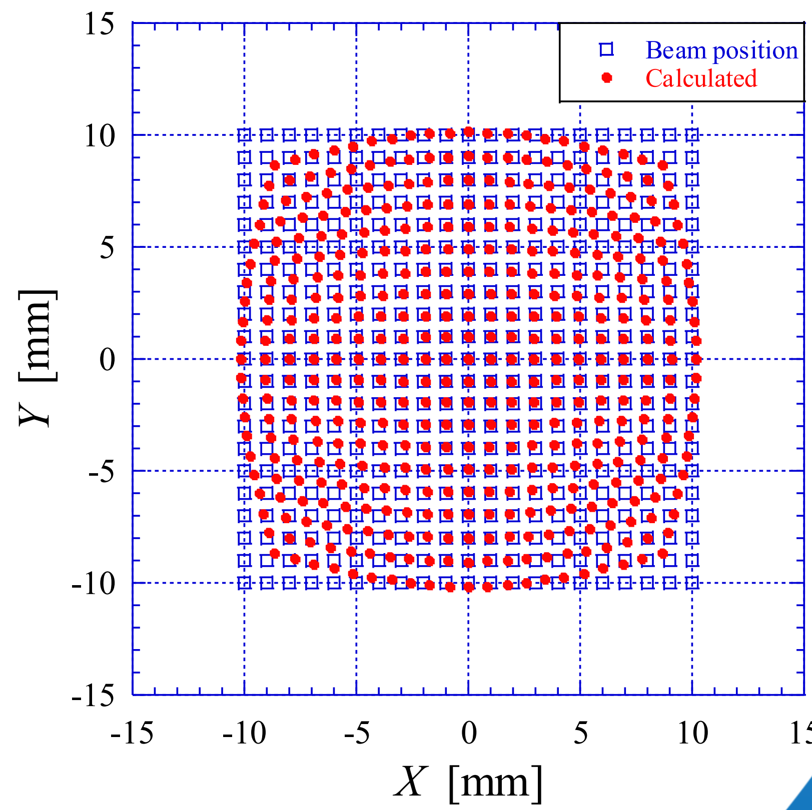
SL1000 with insulating input modules
(Yokogawa, 100 MS/s, 12 bit)

- Log detection circuit with a broad dynamic range
- Bandwidth: 10 MHz
- Center frequency: 1.3 GHz
  (due to the cut-off frequency of octagonal duct)
- Log-linearly response to the input of -90~-30 dBm
- Rise time for a pulse input: ~200 ns

- Commercial high-speed data acquisition unit
- Wide analog bandwidth, 12-bit resolution
- It can be utilized for other waveform analyses.
  (e.g., beam current monitoring with a Faraday cup)

BPM Calibration

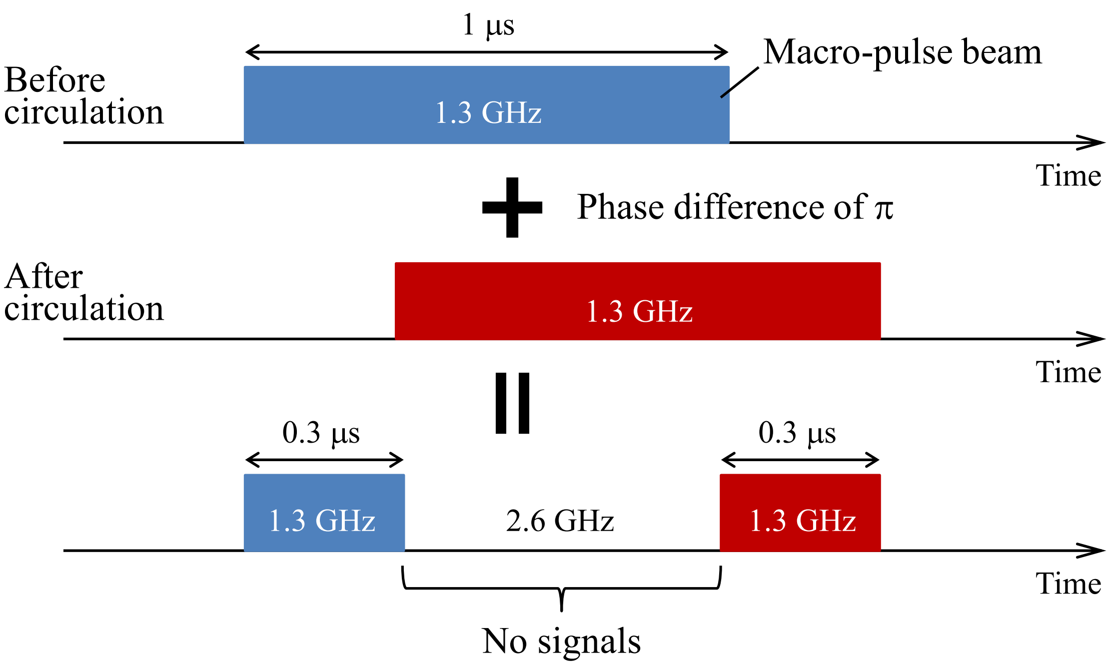


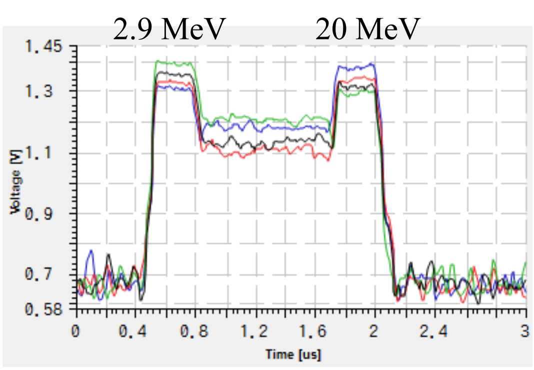


- Beam position was changed stepwise by using a upstream steering magnet.
- Red: beam positions measured by the BPM
  Blue: nominal positions obtained using a SCM
- Resolution (including beam position jitter): 150 μm

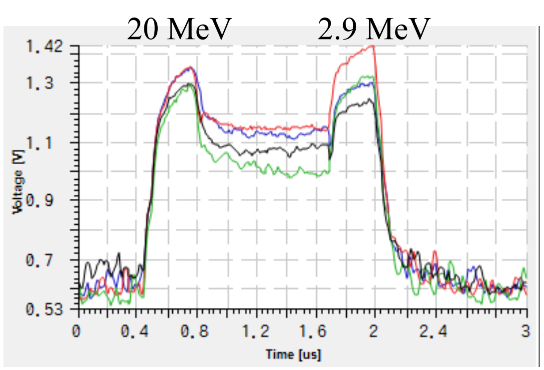
- BPM mapping results
- Calculated using CST PS
- Sensitivity curve obtained by fitting the 5th degree polynomial to this map was used.

2-color beams measurement





Upstream of Main Linac



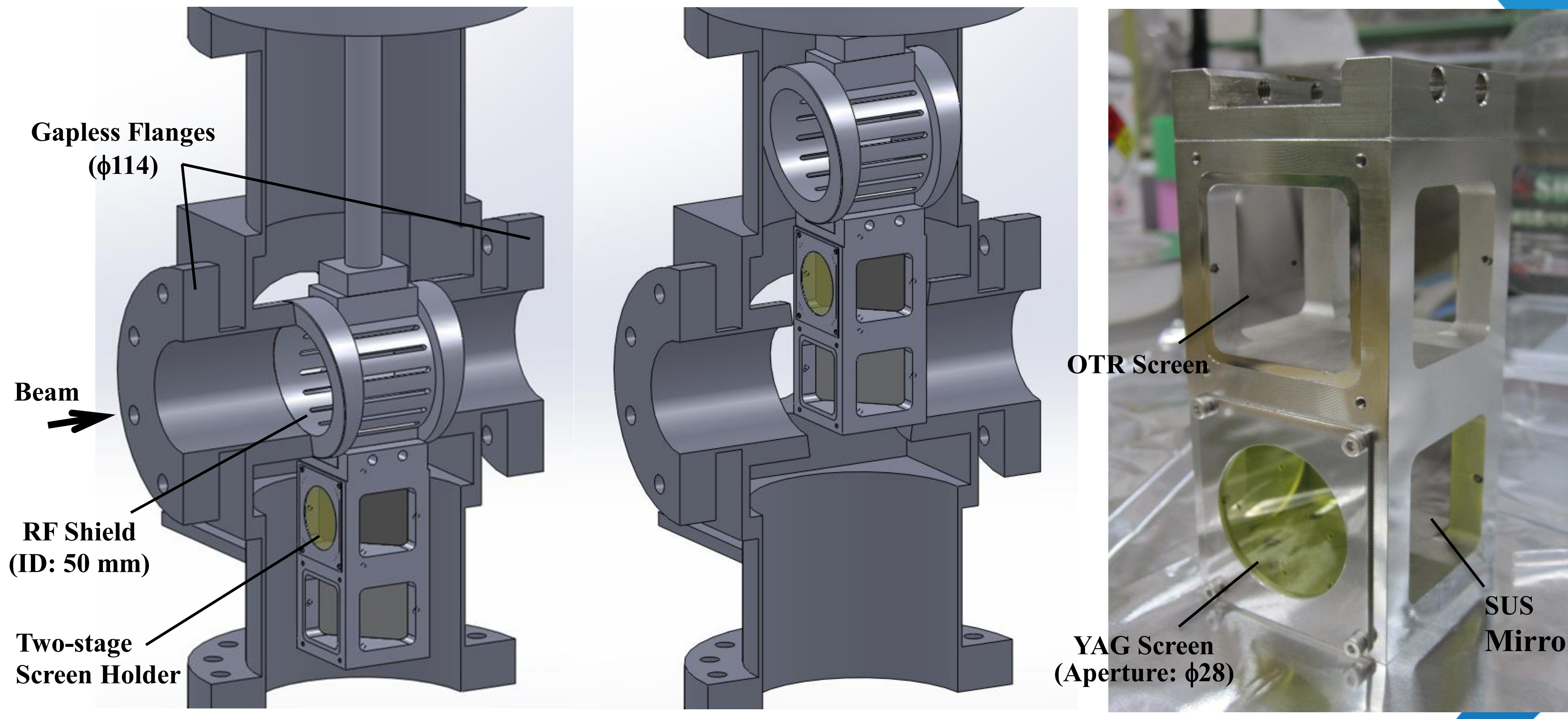
Downstream of Main Linac

- We devised a simple method to detect the positions of 2-color beams using a BPM.
- Post-circulation beam signals superimpose on pre-circulation beam signals with a constant delay corresponding to the circulation time. (~300 ns for the cERL)
- So, the head and tail parts of the detected signal contain only pre- and post-circulation beam signals, respectively.
- Ideally, there are no signals between these two parts because the 2.6 GHz signals is removed by the BPF in the detection circuit.

- Actually, finite signals appear !
- Reason: the phase difference of 180° shifts in proportion to the distance from the main linac because of the beam energy difference.
- In other words, this part can be used as a beam phase monitor.

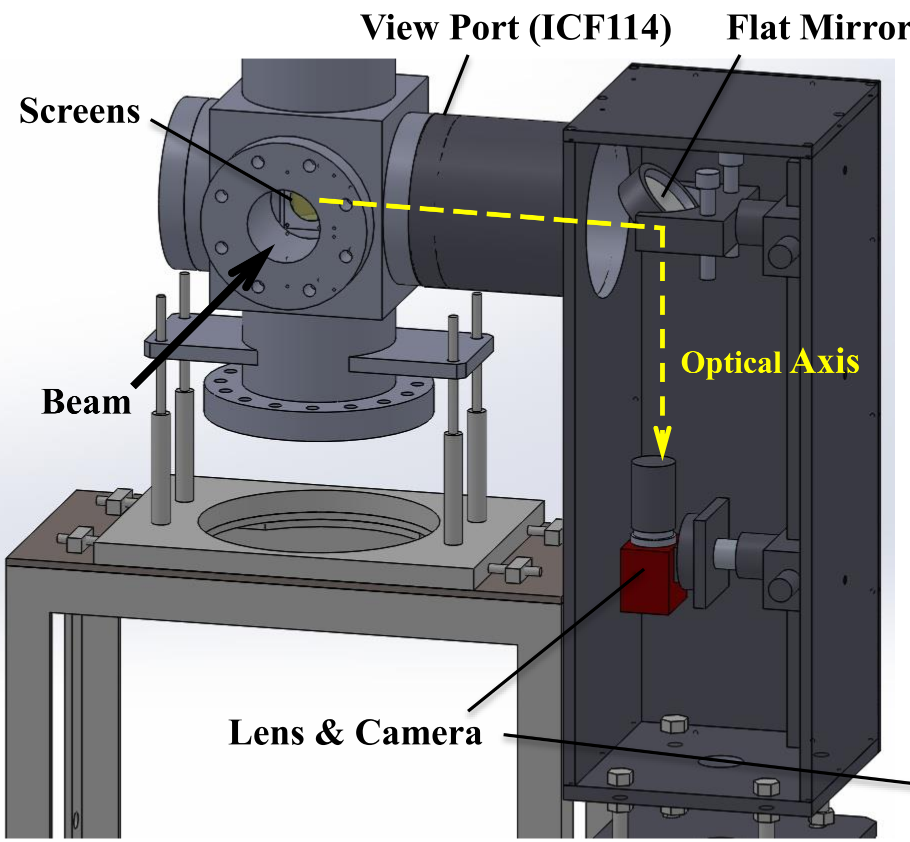
If a negligible blank area with no beam is added periodically, this method can be applied to the CW beams!

Design of the SCM Duct



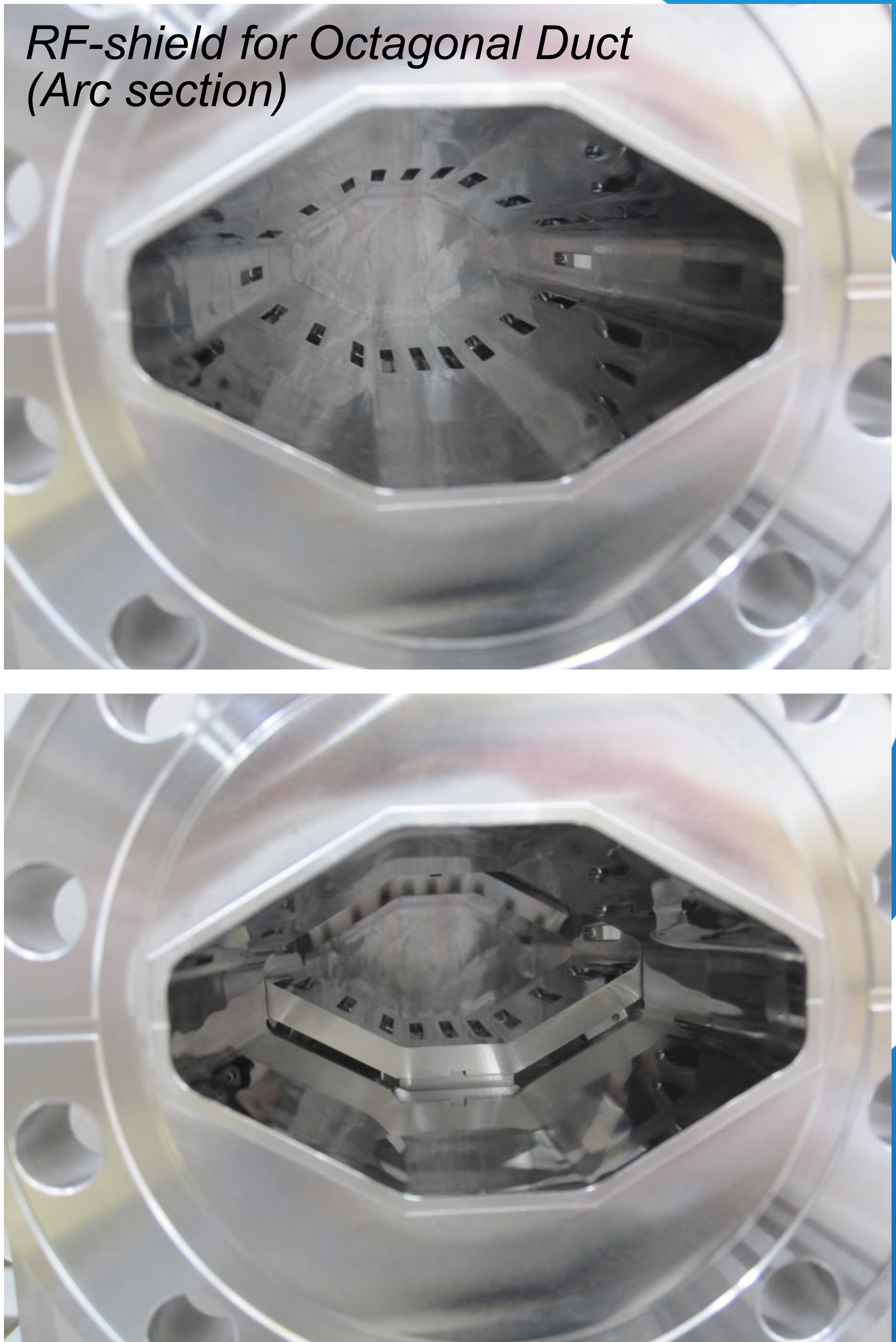
- Inner diameter: 50 mm, Screen's aperture: 28 mm
- Two-stage screen holder allows us to use two different screens according to the beam energy and intensity.
- Ce:YAG scintillator
  - Thickness: 100 μm
  - Beam incidence surface is coated with a 3-nm-thick aluminum. (to avoid damage due to charge-up)
- Alminum-coated silicon wafer (OTR radiator)
  - Coating / Wafer thickness: 40 nm / 70 μm (to flatten the radiation surface)
- These screens are concealed behind a cylindrical RF shield when not in use.
- Only with a physical contact through high-precision fitting
- Such an internal structure was designed on the basis of that employed at JLab and BNL.

Imaging Optics & CCD Camera

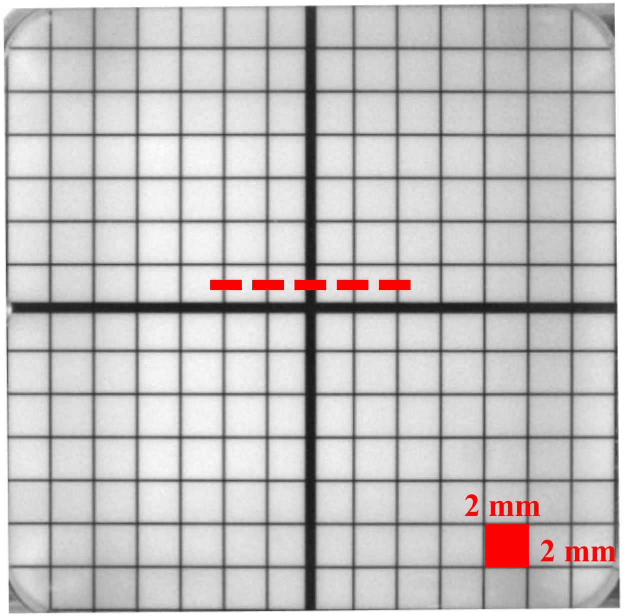


- The light is extracted in the direction perpendicular to the beam axis and then relayed via an optical window and a flat mirror to a CCD camera.
- GigE camera (AVT, 659x493, 12 bit, 90 fps)
  + Low-distortion lens with a diaphragm
- Flat mirror is useful for adjusting the optical axis and protecting the camera from radiation-induced damage.

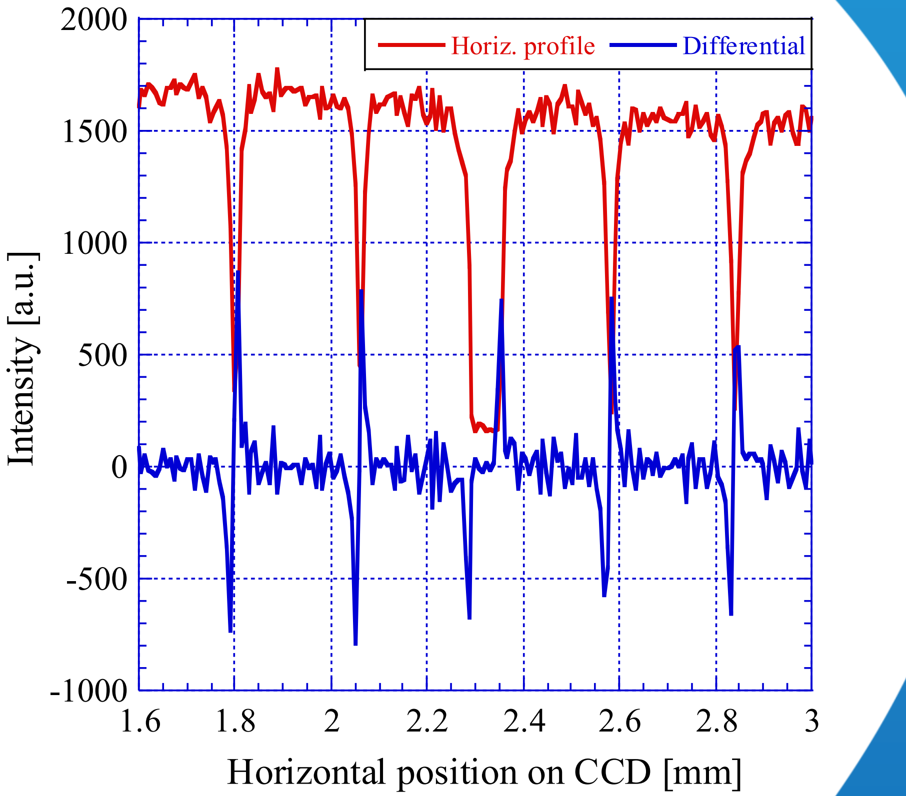

Setup


RF-shield for Octagonal Duct
(Arc section)

SCM Calibration



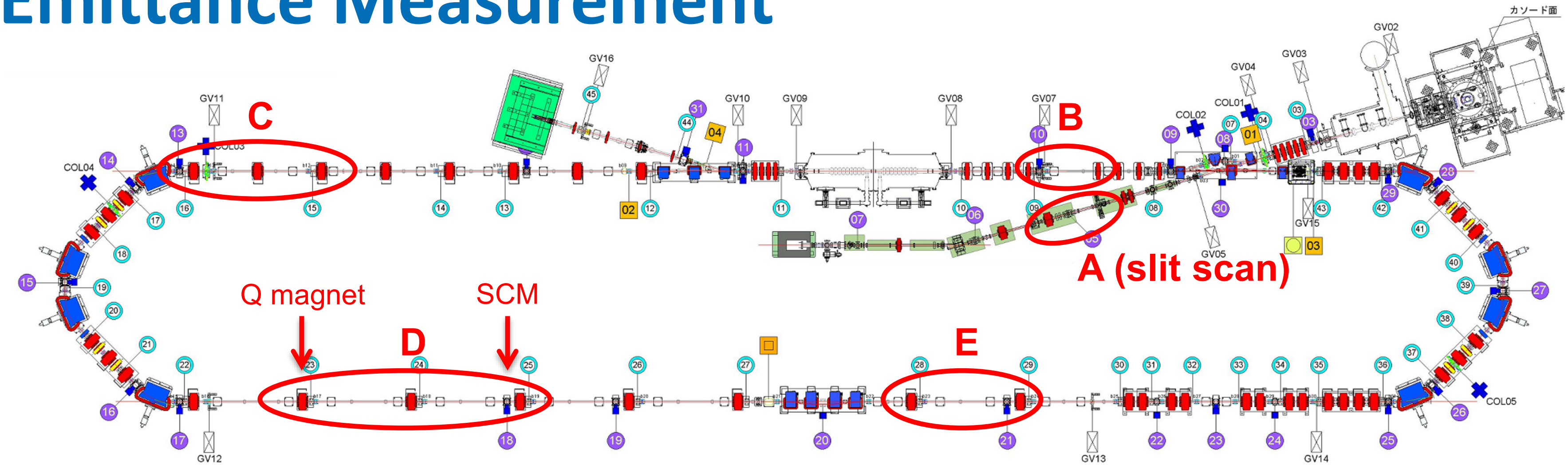
Focused image of a calibration pattern obtained using the imaging optics with a magnification that is actually used in the commissioning



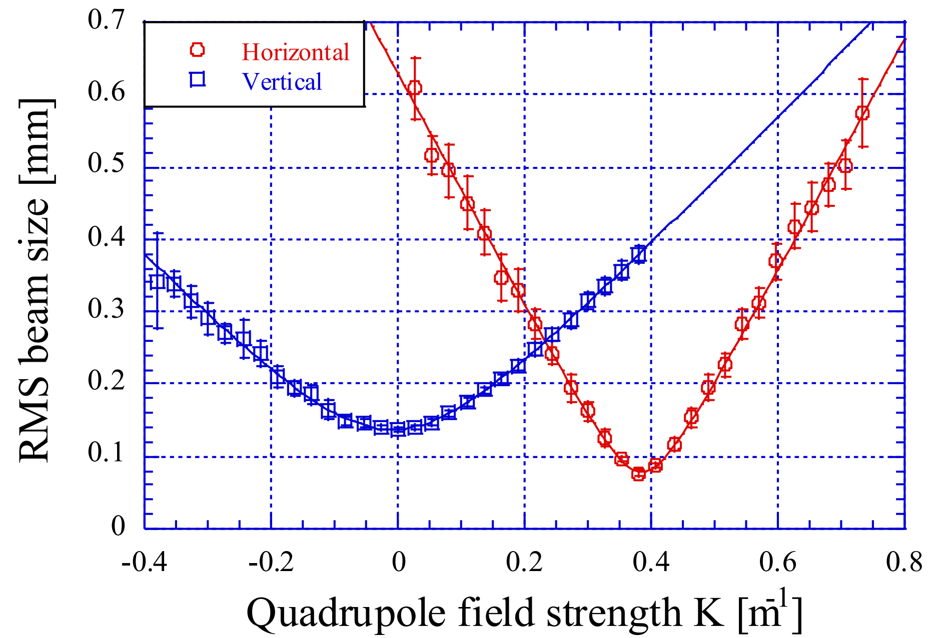
Horizontal profile on the dashed line and its position differential

- The spatial resolution of the YAG screen was estimated by accounting for the depth of field and multiple scattering of electrons in the crystal in addition to the edge width of this image.
- Spatial resolution
  - YAG screen: 62 μm
  - OTR screen: ~ 40 μm
- A difference between the two resolutions are caused by multiple scattering of electrons in the Ce:YAG crystal.

Emittance Measurement



- Normalized emittance was measured by employing the Q-scan method at four sections (B, C, D, E).
- Result for low bunch charge: 0.14 mm·mrad
- This is almost the same as the design value.
- Emittances measured at five sections were consistent with each other.
- For high bunch charge (7.7 pC/bunch), emittane is still larger than the target value, but it is decreacing steadily because of elaborate optics matching using SCMs.

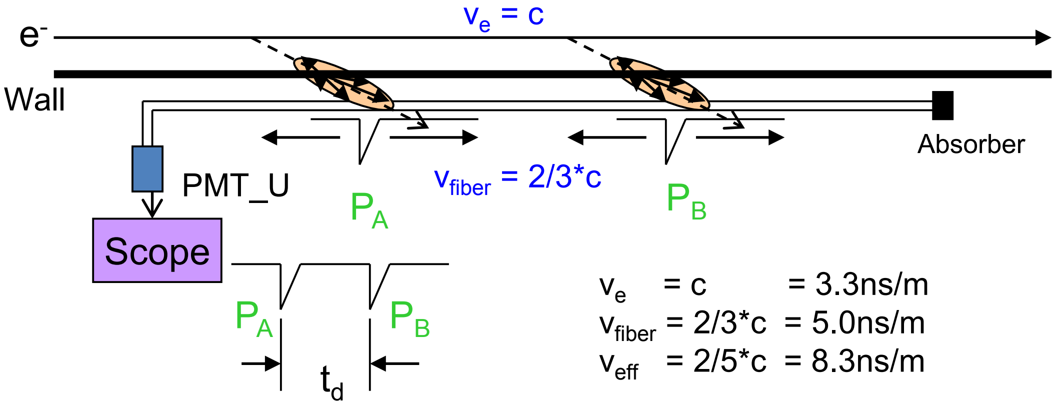


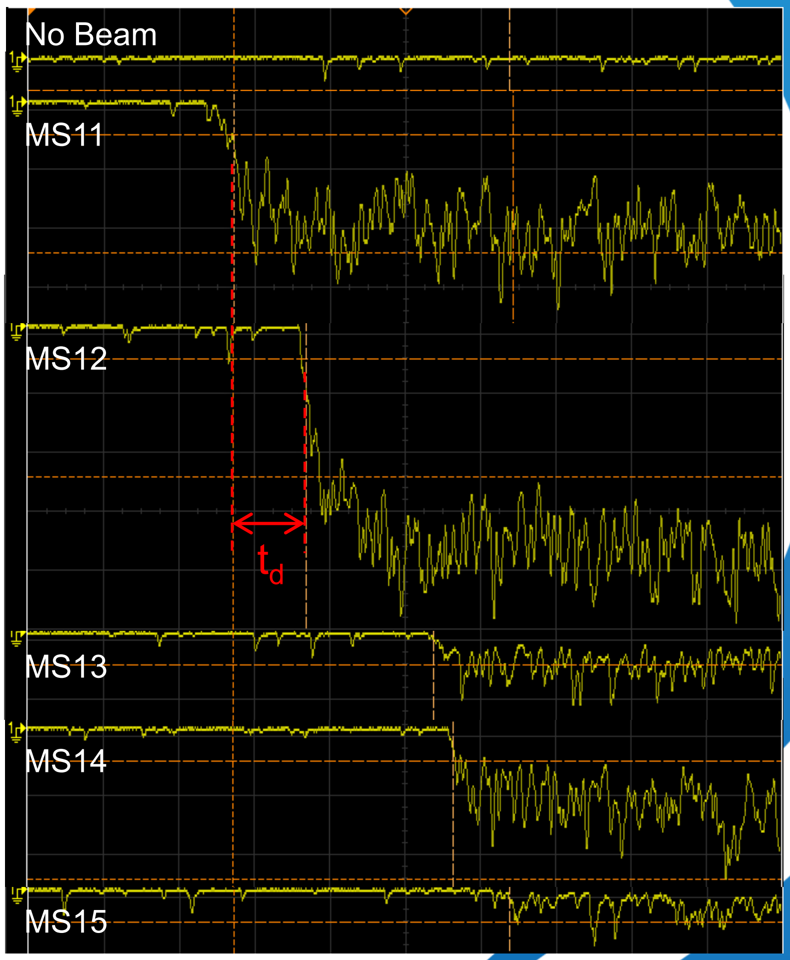
Example of the Q-scan result acquired at section D
(for a low bunch charge of ~20 fC/bunch)

Fast Beam Loss Monitors #1

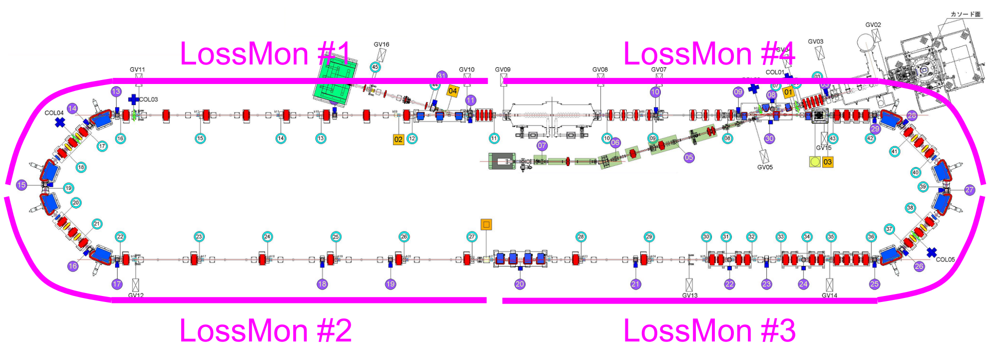
- Optical Fibers with PMTs
  - ✓ Glass fiber: Pure Silica (Core diameter: 600 μm)
  - ✓ PMT: Hamamatsu, H10721-110

- Principle





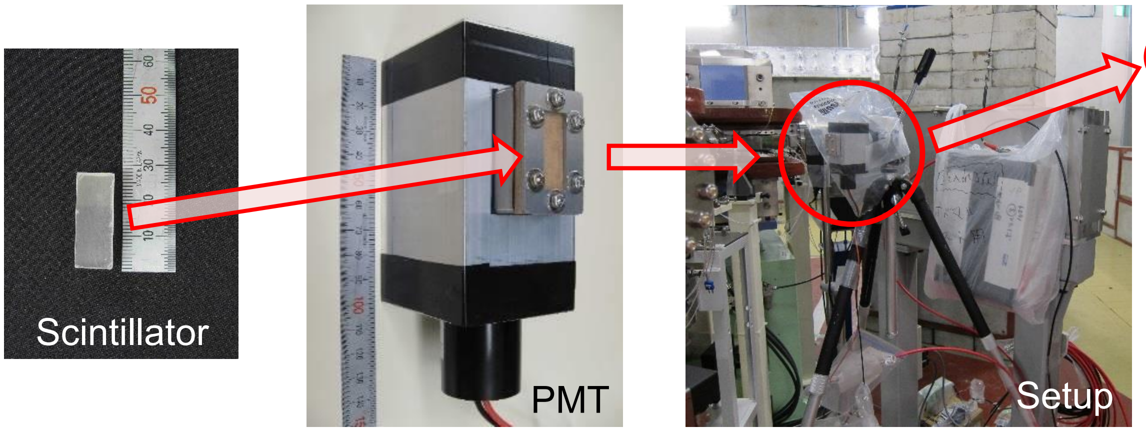
- Four sets of fiber loss monitors cover the entire cERL circumference.

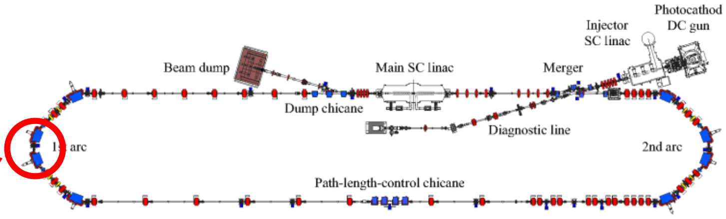


We can estimate the beam-loss point along the circumference by analyzing the time structure of the output signal.

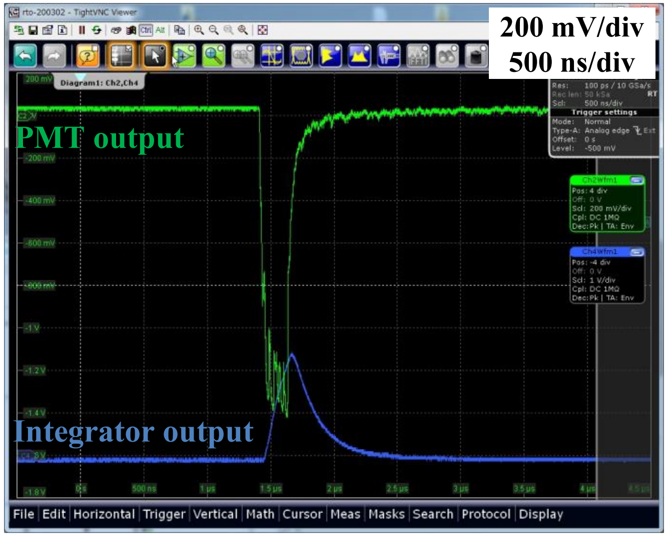
Fast Beam Loss Monitors #2

- CsI Scintillators with Large-cathode PMTs (under development)
  - ✓ Scintillator: Pure CsI crystal (10 mm×10 mm×25 mm)
  - ✓ PMT: Hamamatsu, H10721-110

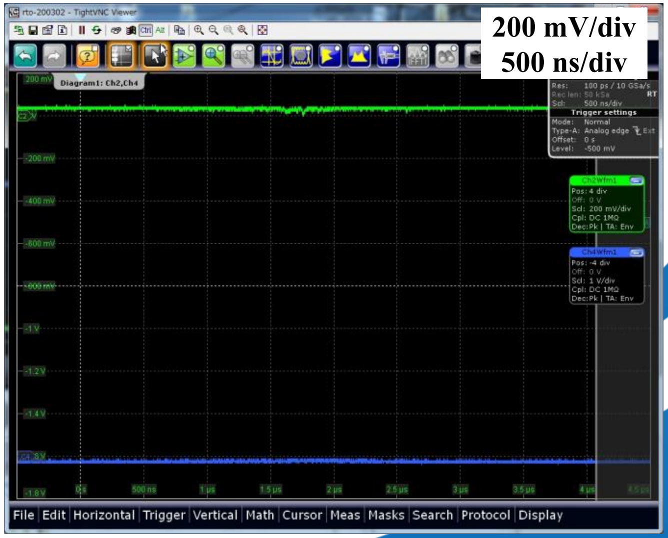




@center of the 1st arc
(around MS15)



Before optics matching



After optics matching

Summary and Future Plan

- For the main BPMs, we adopted the stripline type, the time response of which is improved by using a glass-sealed feedthrough.
- The SCMs are equipped with two types of screens and an RF shield for wake-field suppression.
- Optical fibers with PMTs, covering the entire cERL circumference, are used as the BLM. CsI scintillators with large-cathode PMTs are also prepared for detecting local beam loss.
- These standard monitors have greatly contributed to the efficient cERL commissioning.
- From the next year (Jan. 2015), we are planning to start the commissioning toward the experimental utilization of pulsed X-rays generated by LCS.
- By that time, we plan to add two button-type BPMs and a large-aperture SCM. In addition, we are also preparing for bunch-length measurement using CTR and a Michelson interferometer to confirm the effect of bunch compression with the first arc.

Acknowledgment

We would like to thank all members of the cERL commissioning team for their collaborative efforts during this work.

Thank you for your kind attention !

PEARL
Photon Factory

cERL Development Team

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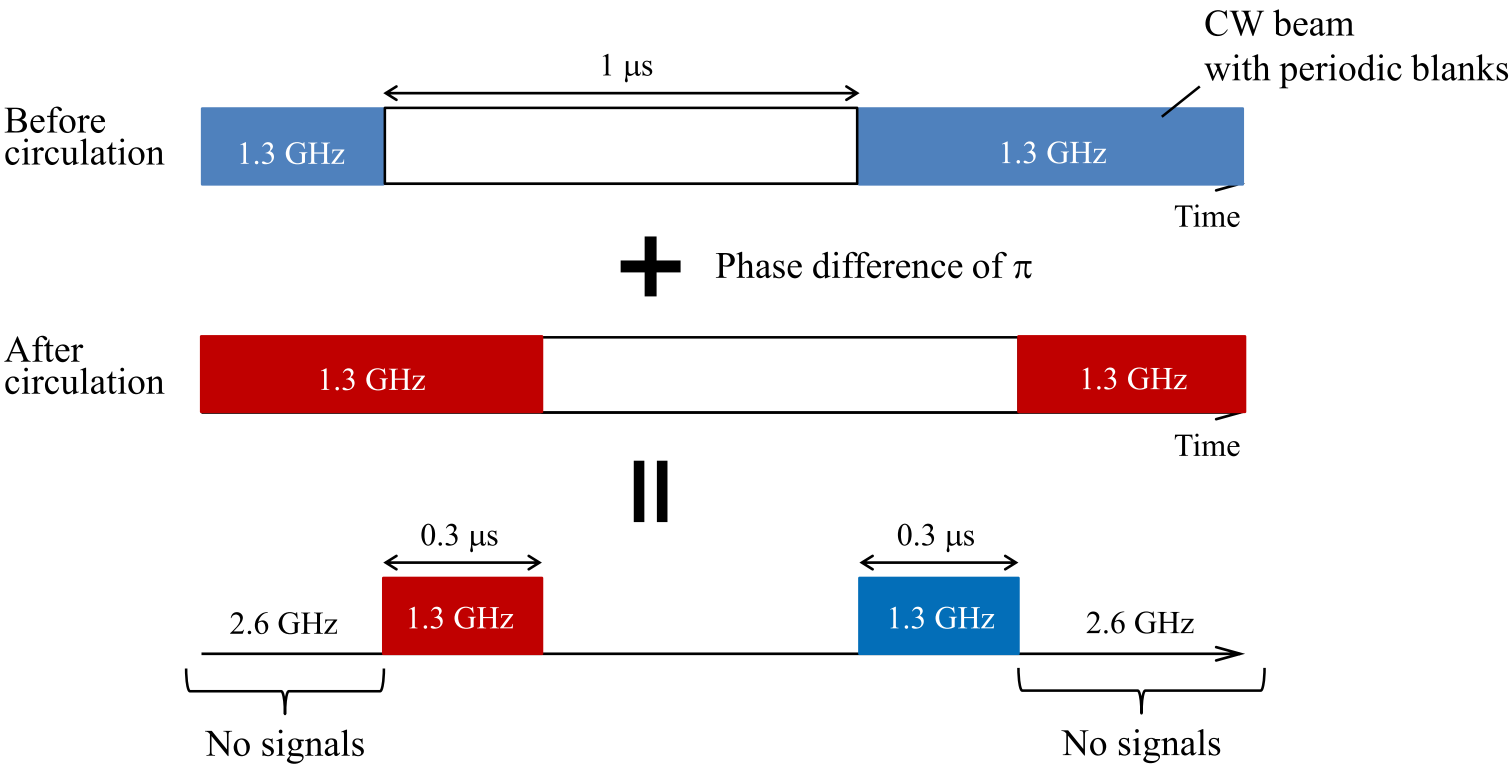
Backup Slides

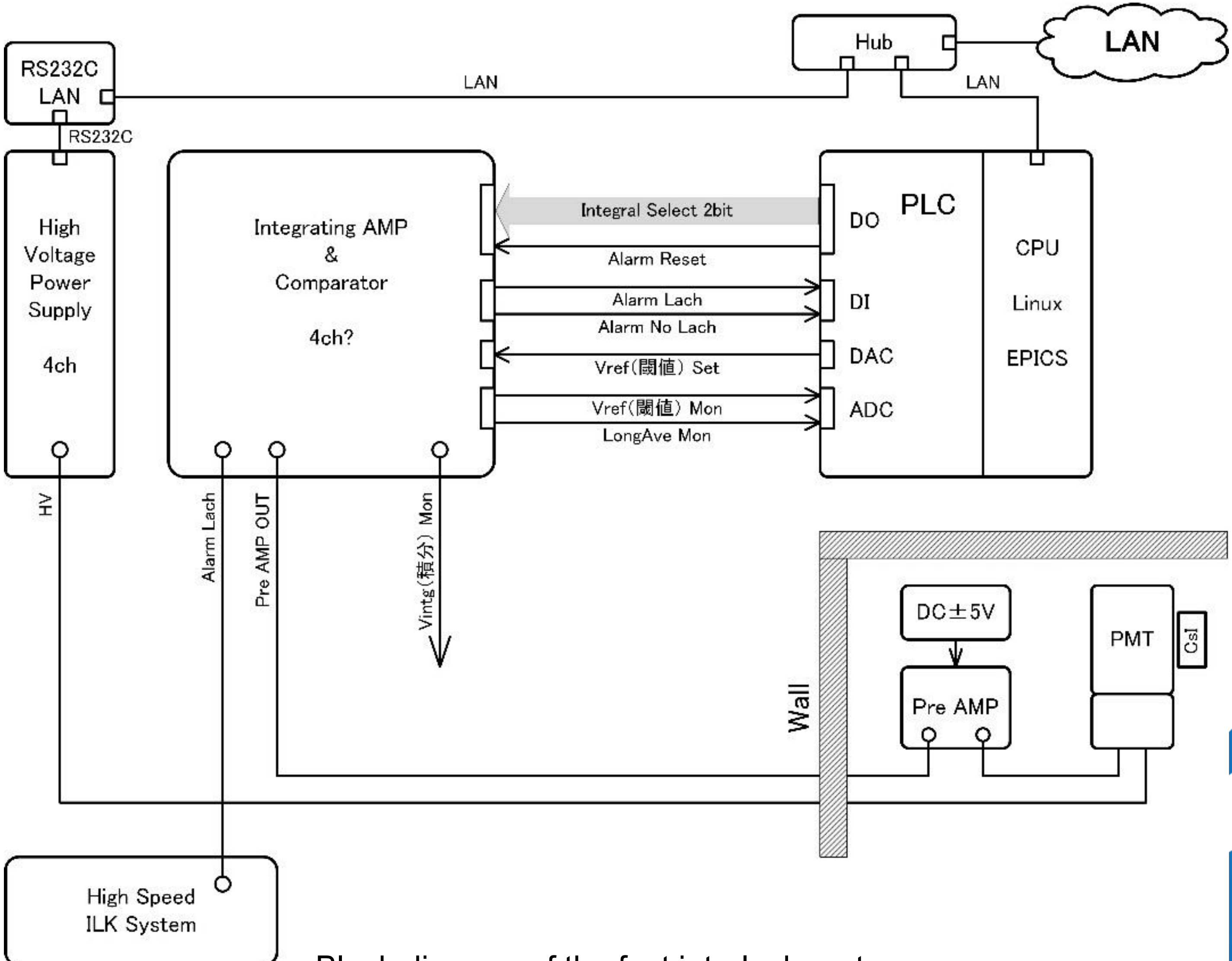
2-color beams measurement (for CW beams)



- Simple method to detect the positions of 2-color beams using a BPM can be applied to the CW beams in a negligible blank area with no beams is added periodically.
- In this case, the order of detected signals of pre- and post-circulation beams is interchanged with each other compared to the case of macro-pulse beams.

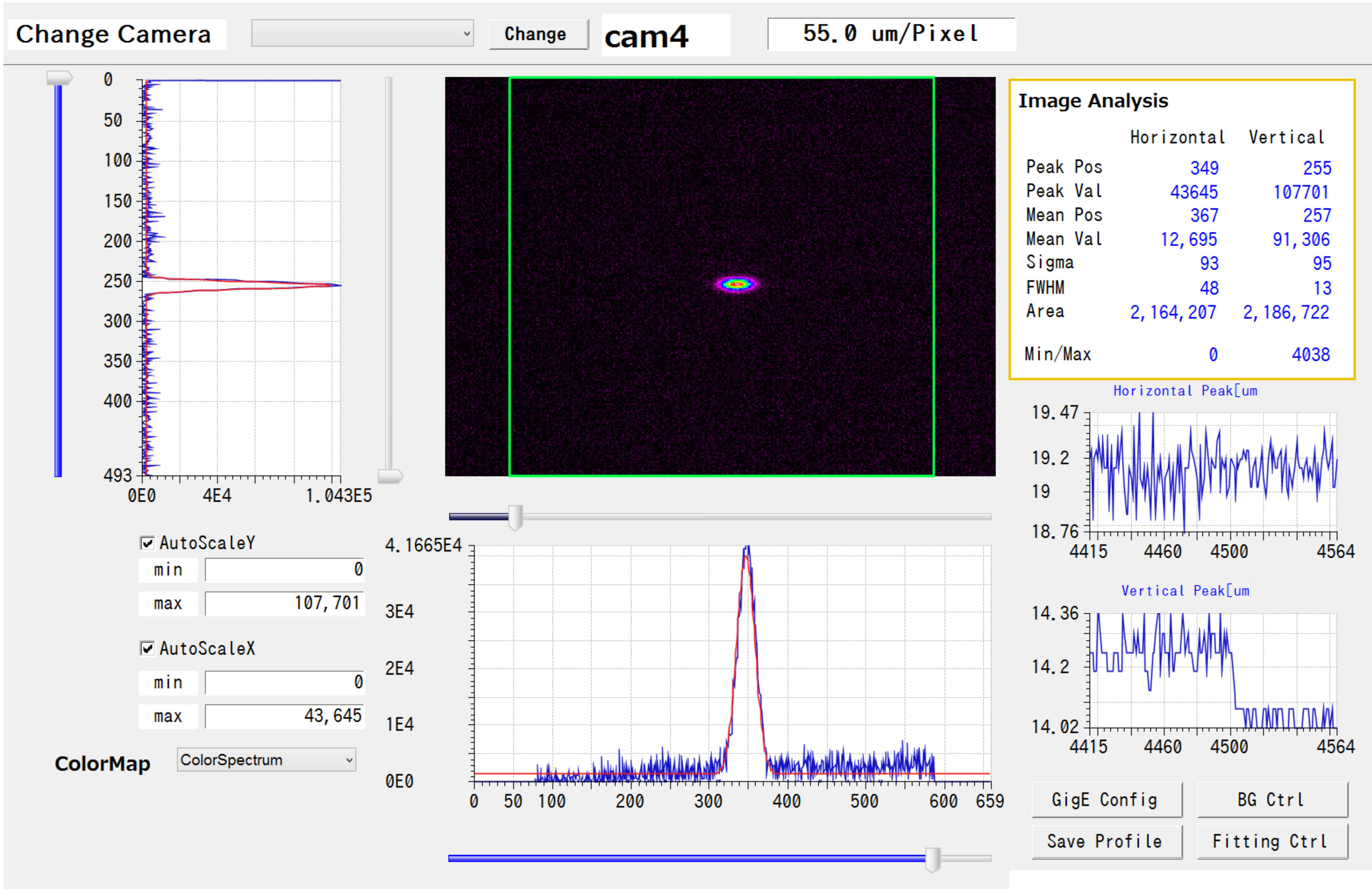
Fast Beam Loss Monitors #2

- CsI Scintillators with large-cathode PMTs (under development)



Block diagram of the fast interlock system

Control Panel of the GigE Camera for SCM



The cERL control system is constructed with EPICS and CSS.