First measurement of longitudinal profile of high-power and low-energy H^- beam by using bunch shape monitor with graphite target

- Introduction: Bunch-Shape Monitor (BSM)
- New target for the front-end BSM
- Beam tests of BSM using the graphite target
- Longitudinal measurement with BSM at front-end
- Summary

JAEA/J-PARC

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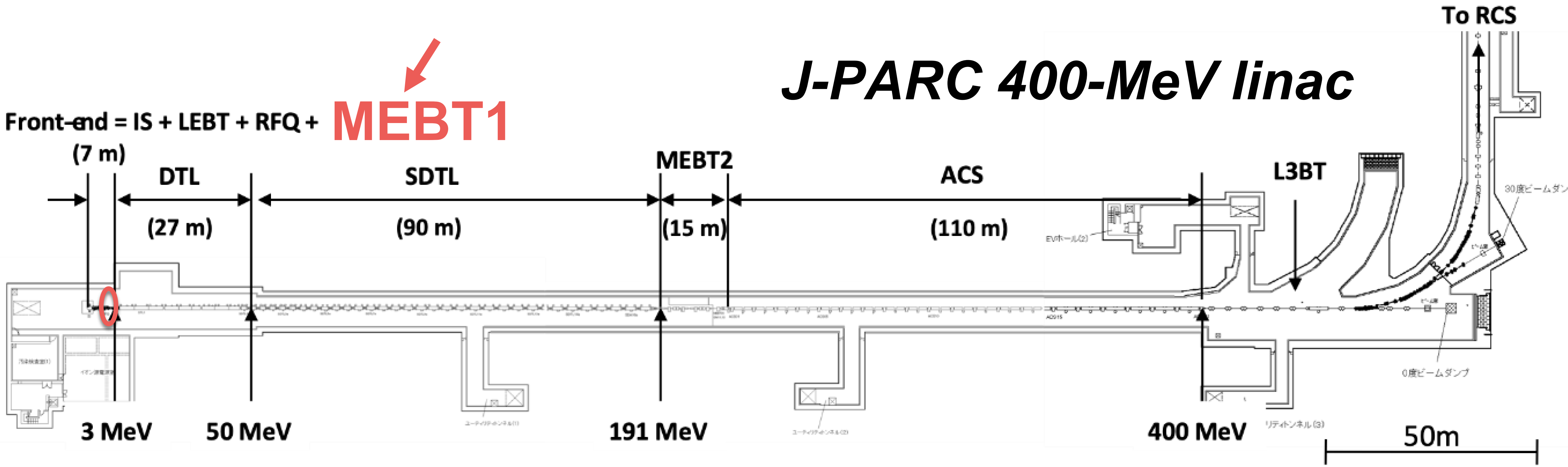
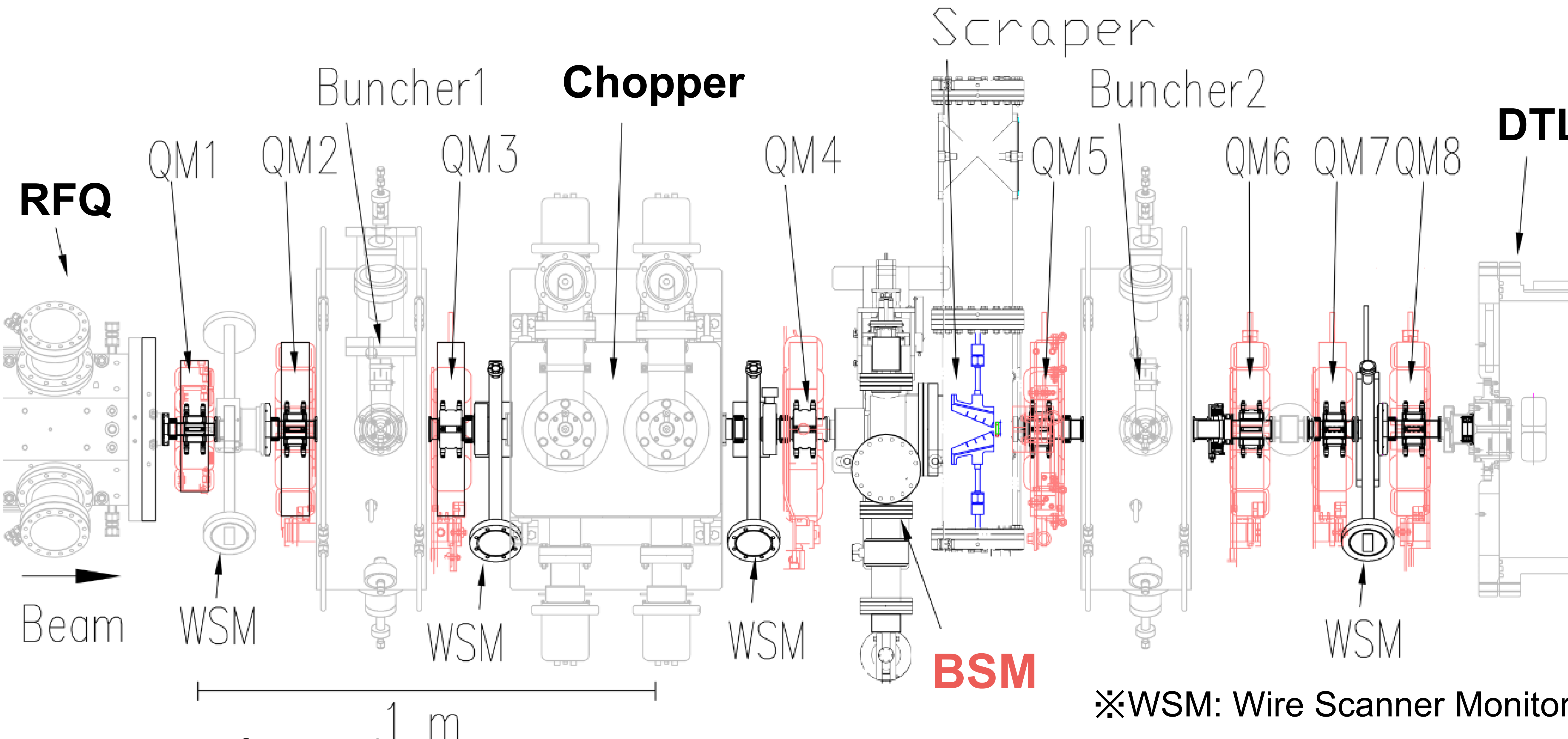
Ryo Kitamura on behalf of J-PARC linac

Introduction



- Japan Proton Accelerator Research Complex (J-PARC)
  - 400-MeV linac, 3-GeV Rapid-Cycle Synchrotron (RCS), and 30-GeV Main Ring (MR).
  - Linac accelerates the negative hydrogen ion (H^-) beam with a peak current of 50 mA.
- Beam studies at the front-end are being conducted to reduce the beam loss.
  - Important matching section : Medium-Energy Beam Transport1 (MEBT1)
- MEBT1 should be tuned to mitigate the emittance growth due to the space-charge effect.
  - Both the transverse and **longitudinal** matches are required for the high-power beam.
- **Motivation: understanding and improving longitudinal beam dynamics at MEBT1**

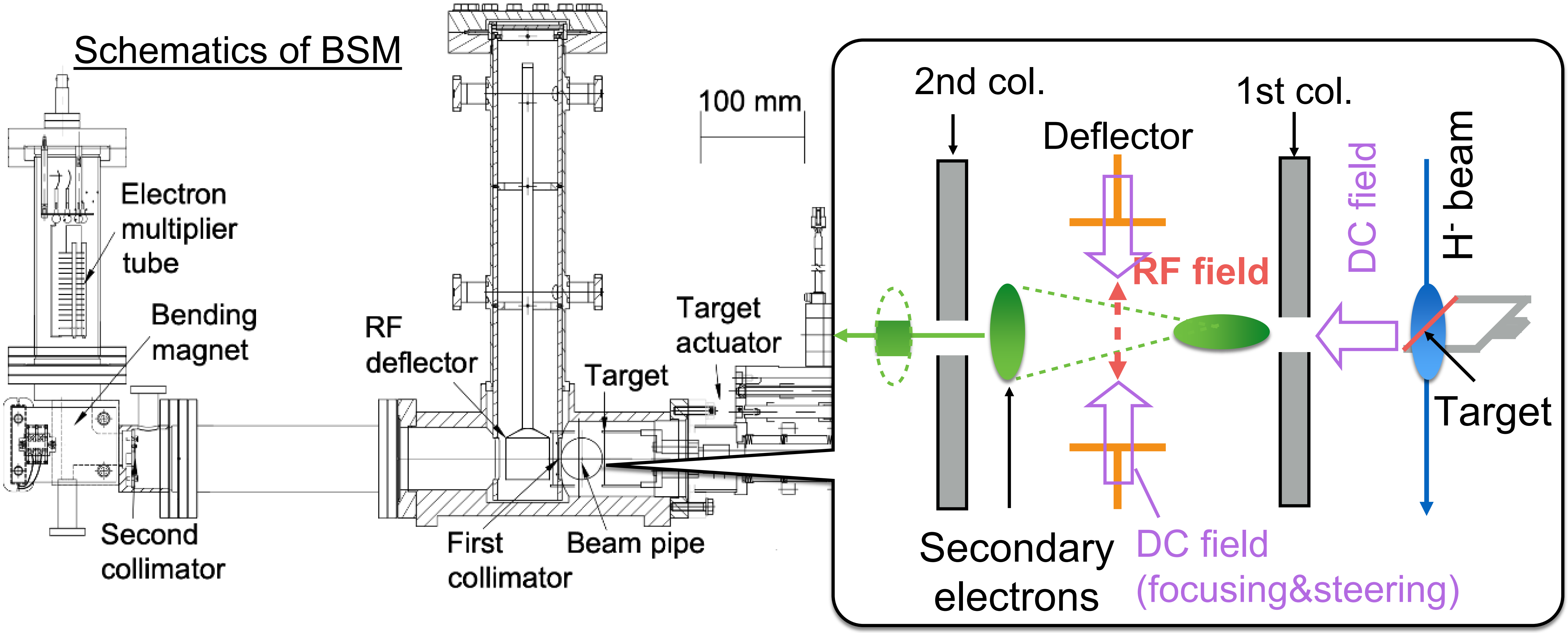
Structure of MEBT1



※WSM: Wire Scanner Monitor

- Functions of MEBT1 :
  - (1) Beam matching of the DTL → 8 quadrupoles and 2 bunchers
  - (2) Bunch structure for the RCS injection → RF chopper system
- Low-energy (3-MeV) H^- beam in the MEBT1 is strongly affected by the space-charge force.
- Compared with the transverse monitor (WSM), the longitudinal monitor was insufficient.
- **BSM was installed for the longitudinal beam tuning.**

Bunch-Shape Monitor (BSM)



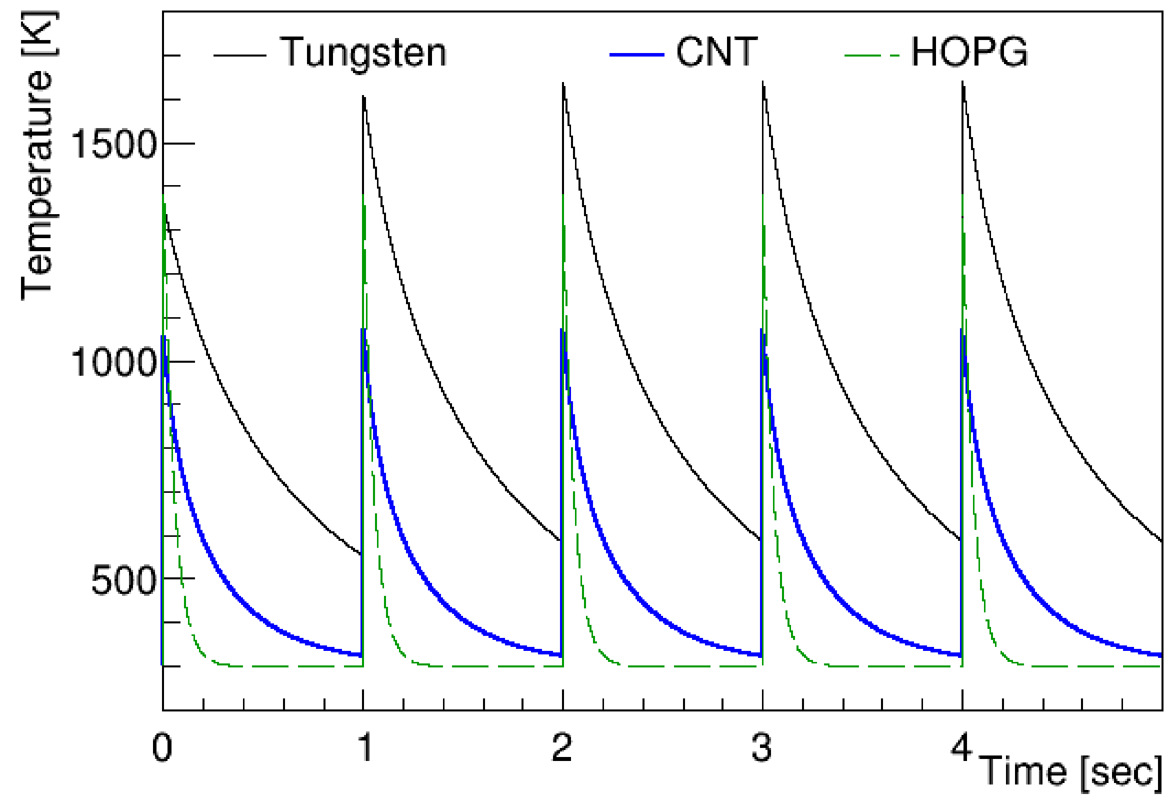
- BSM is a standard longitudinal beam profile monitor for the linac.
  - Secondary electrons are produced by the interaction between H^- beam and BSM target.
    - Note) ***Negative bias voltage*** was applied to the BSM target.
  - Electrons related to longitudinal profile of H^- beam are modulated by RF field in deflector.
- Problem of BSM in the MEBT1:
  - Heat loading derived from the high-power beam caused the target wire breaking.
- **New BSM target material for the MEBT1 was developed using the graphite material.**

Thermal estimation for BSM targets

Properties of target candidates

Material	Density (g/cm^3)	Thermal cond. (W/m・K)	Melt. point (K)
Tungsten	19.3	19.3	3700
CNT	**0.56**	90	3300
HOPG	2.22	**1700(in plain)** 7(face-to-face)	3300

Temperature calculation

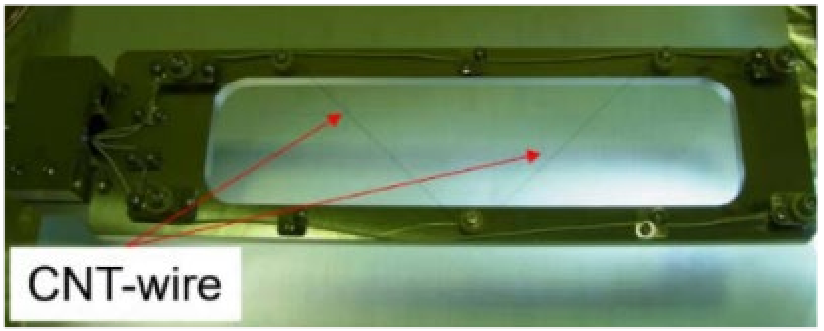


- There were **3** candidates for the BSM target to mitigate the **heat loading** from H^- beam.
  - (1) Tungsten: used as the standard target material for the BSM.
    - △ Wire breaking frequently occurred due to the heat loading.
  - (2) Carbon Nano Tube (CNT): used for the WSM to measure transverse profiles.
    - ◯ Its low density is suitable to mitigate the heat loading.
  - (3) **Graphite (Highly Oriented Pyrolytic Graphite: HOPG)**
    - Used for the beam scraper.
    - ◯ Its high thermal conductivity is suitable to mitigate the heat loading.

Which is better?

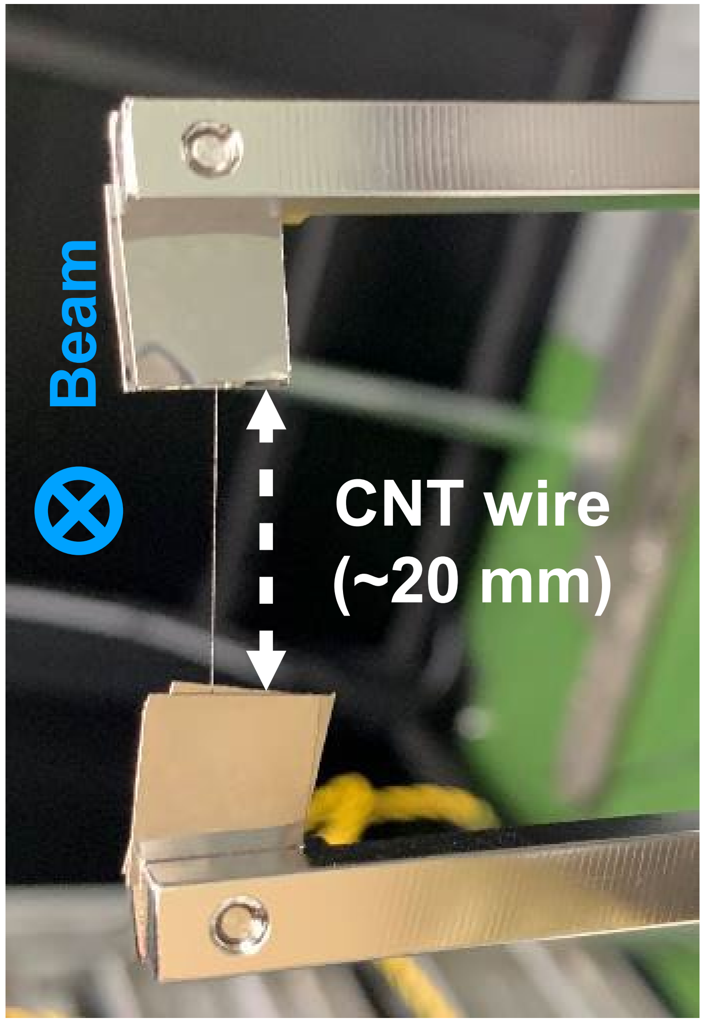
CNT target wire

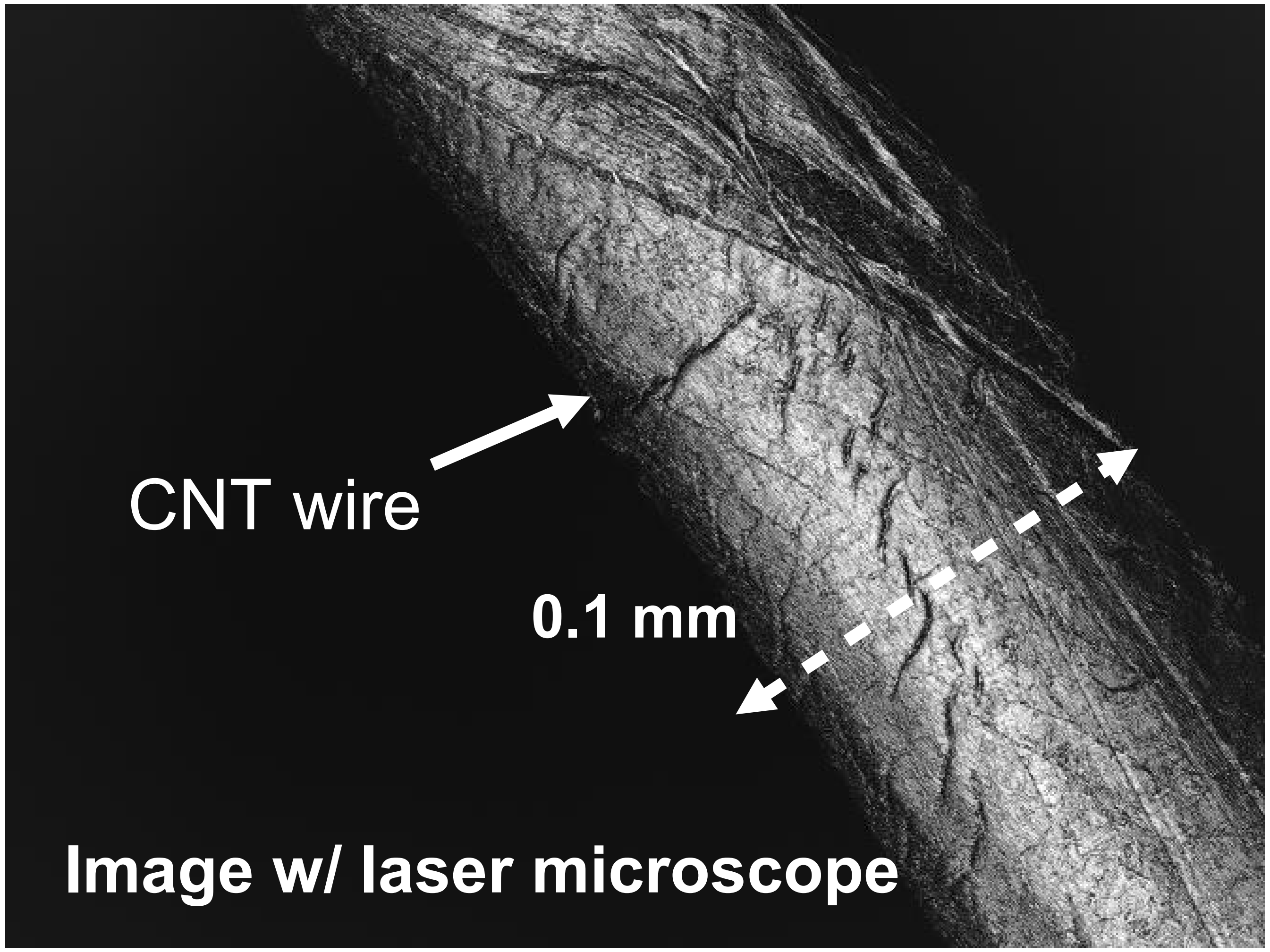
CNT wire mounted on WSM



Microelectronics reliability,
64 pp.484-488 (2016).

CNT wire on BSM target holder



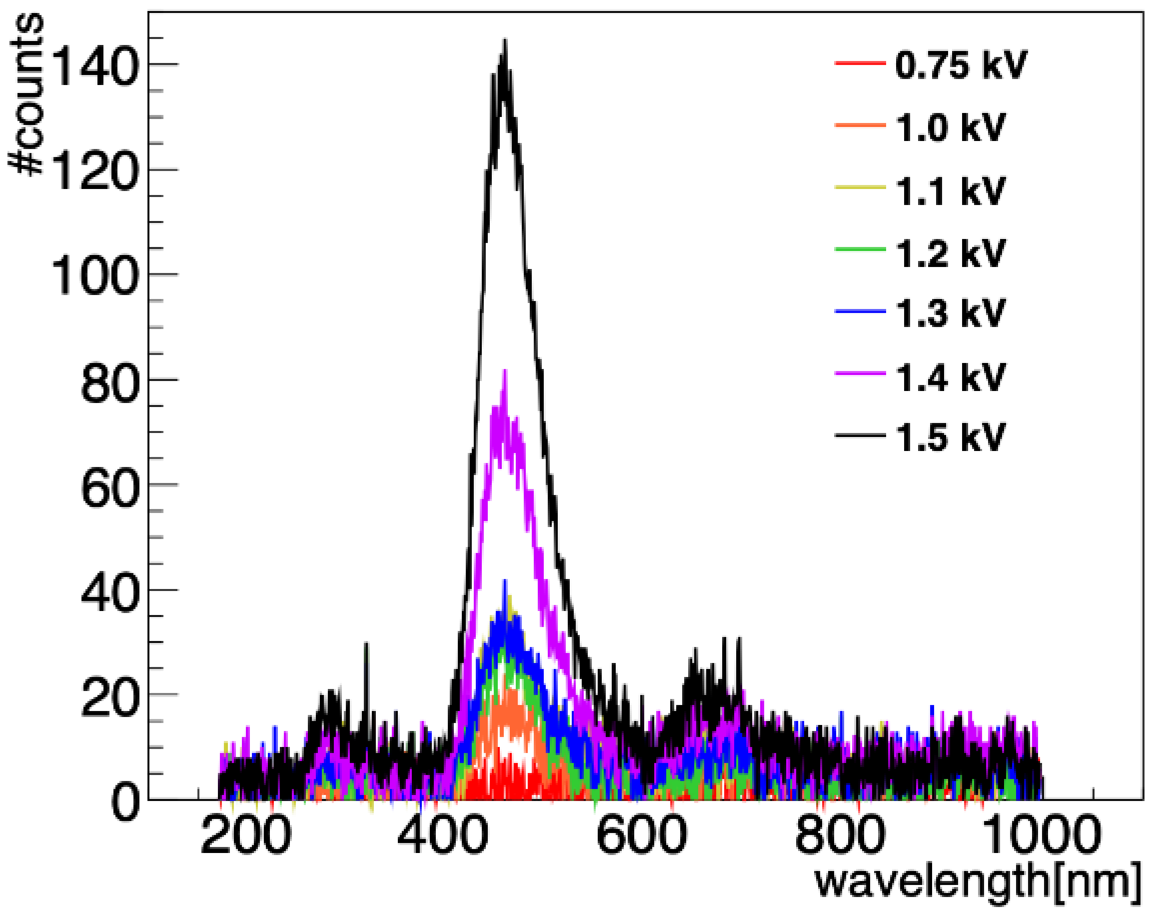


Proc. of IPAC2019 ,WEPGW033 (2019).

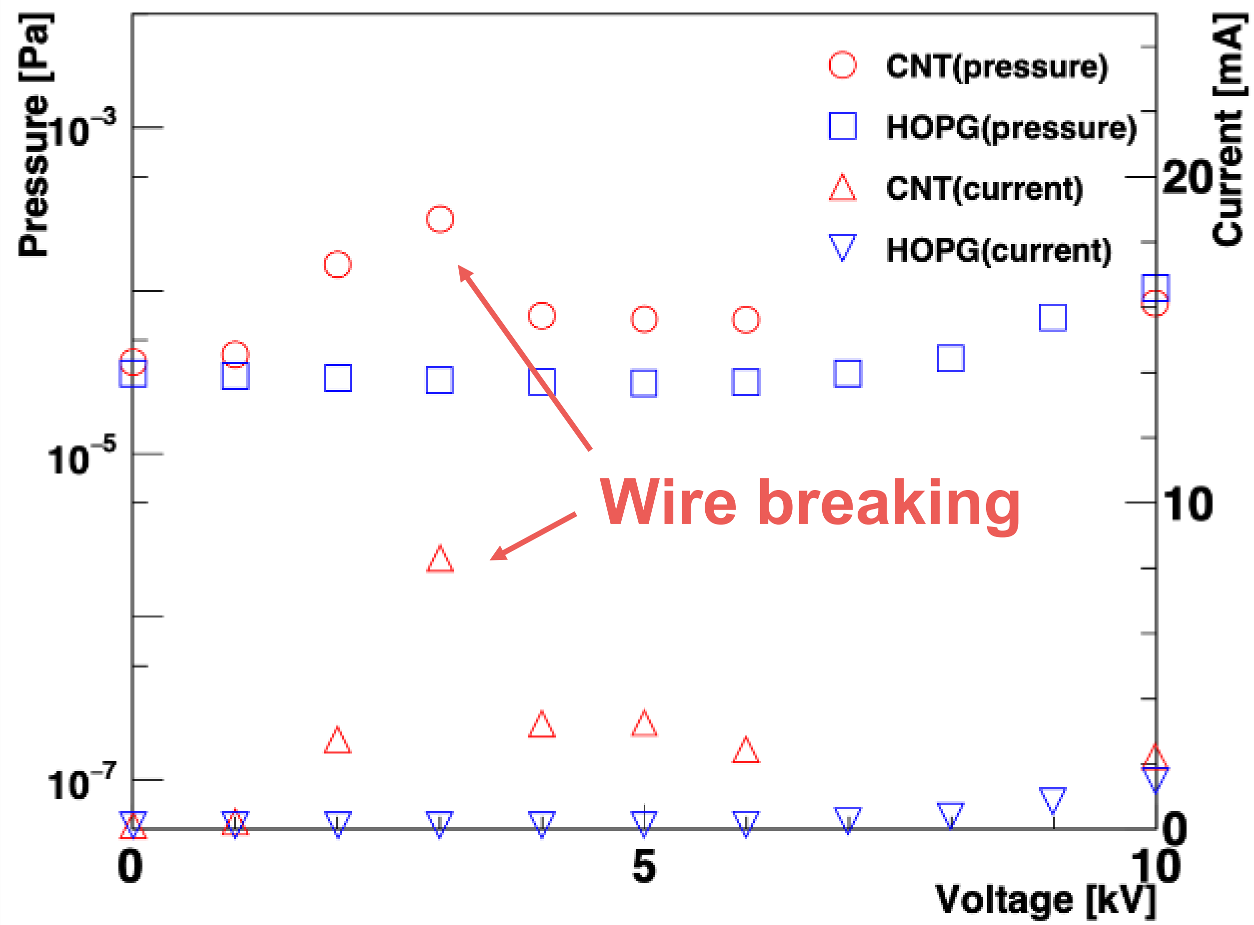
- CNT wire has been used for the stable target wire of the WSM in the MEBT1.
- It is easy to replace the CNT wire with the tungsten wire.
- Question**:** Can **the negative bias voltage** be applied to the CNT wire to extract secondary electrons as BSM?
- **Offline test of applying the bias voltage was conducted.**

Emission electrons from CNT wire

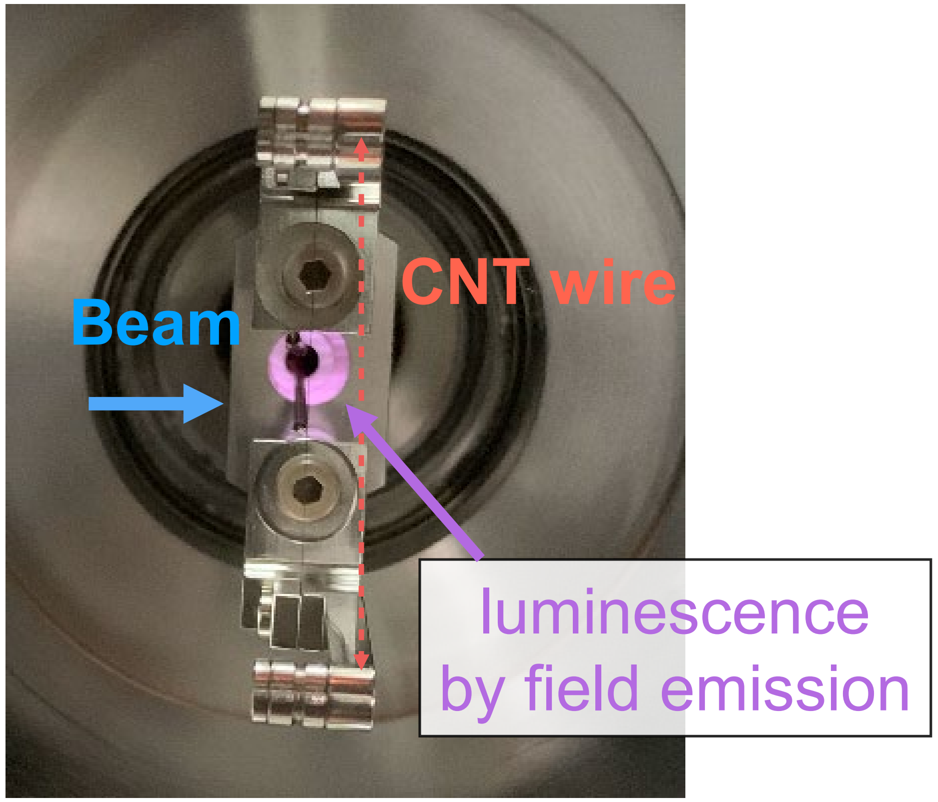
Spectroscopic measurement



Vacuum pressure-leak current



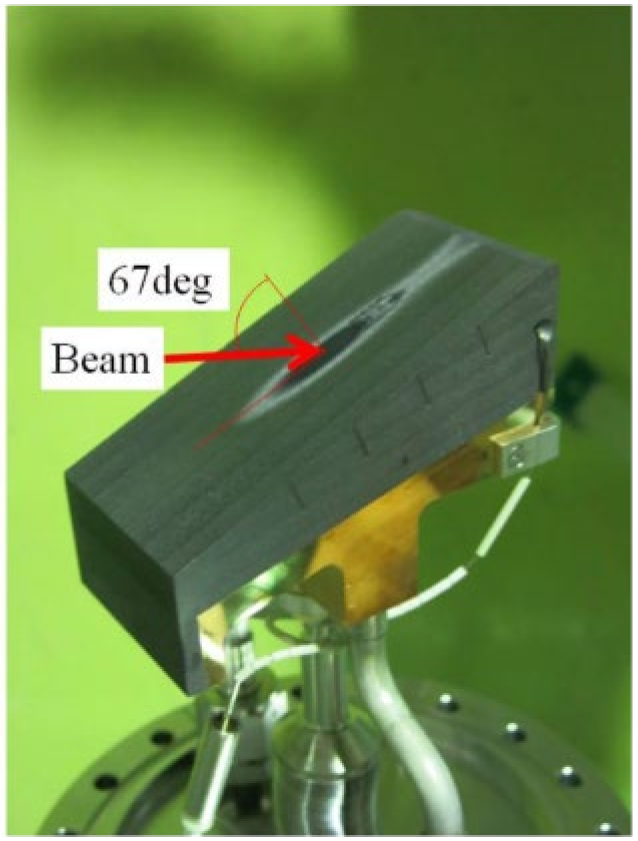
Proc. of IPAC2019 ,WEPGW033 (2019).
JPS Conf. Proc. 33, 011012 (2021).



- CNT is known as its electron emitter property.
- Result of the offline test:
  - Luminescence from insulator ceramics
  - Spectrum peak due to field emission was observed.
- Field emission from the CNT was serious for the BSM.

⇔ OTOH, successfully applying bias voltage to HOPG.

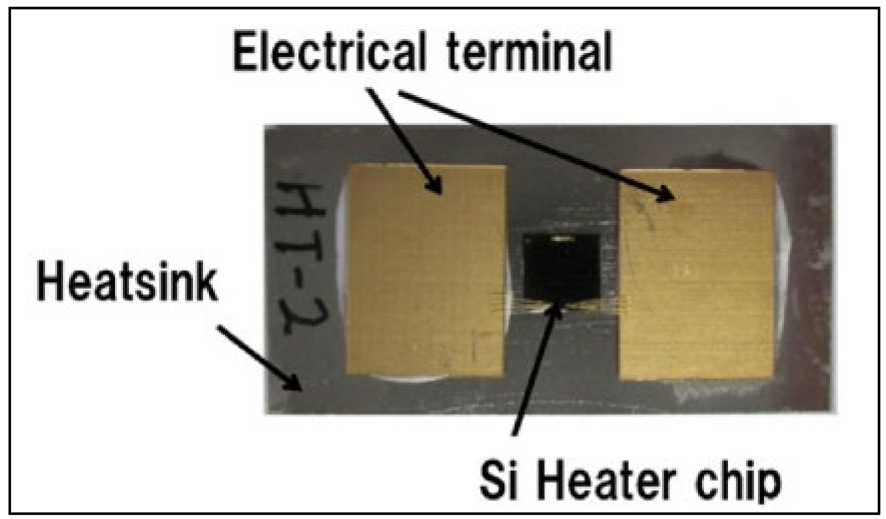
HOPG target



Proc. of PASJ2016, MOP005, pp.310-313 (2016).

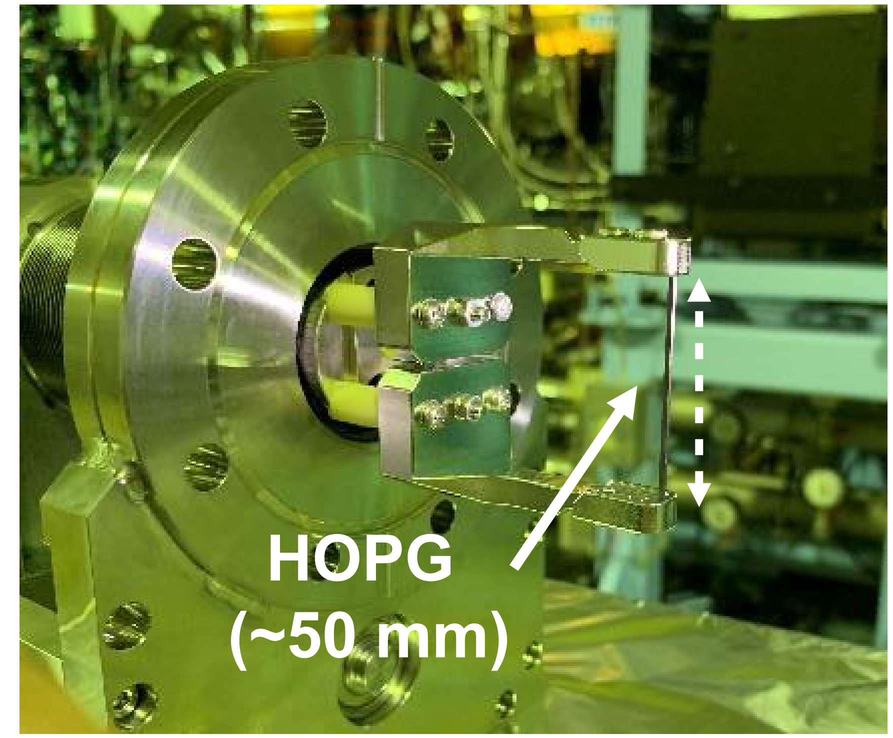
←J-PARC beam scraper (carbon composite)

↓ HOPG used as heatsink



Microelectronics reliability, **64** pp.484-488 (2016).

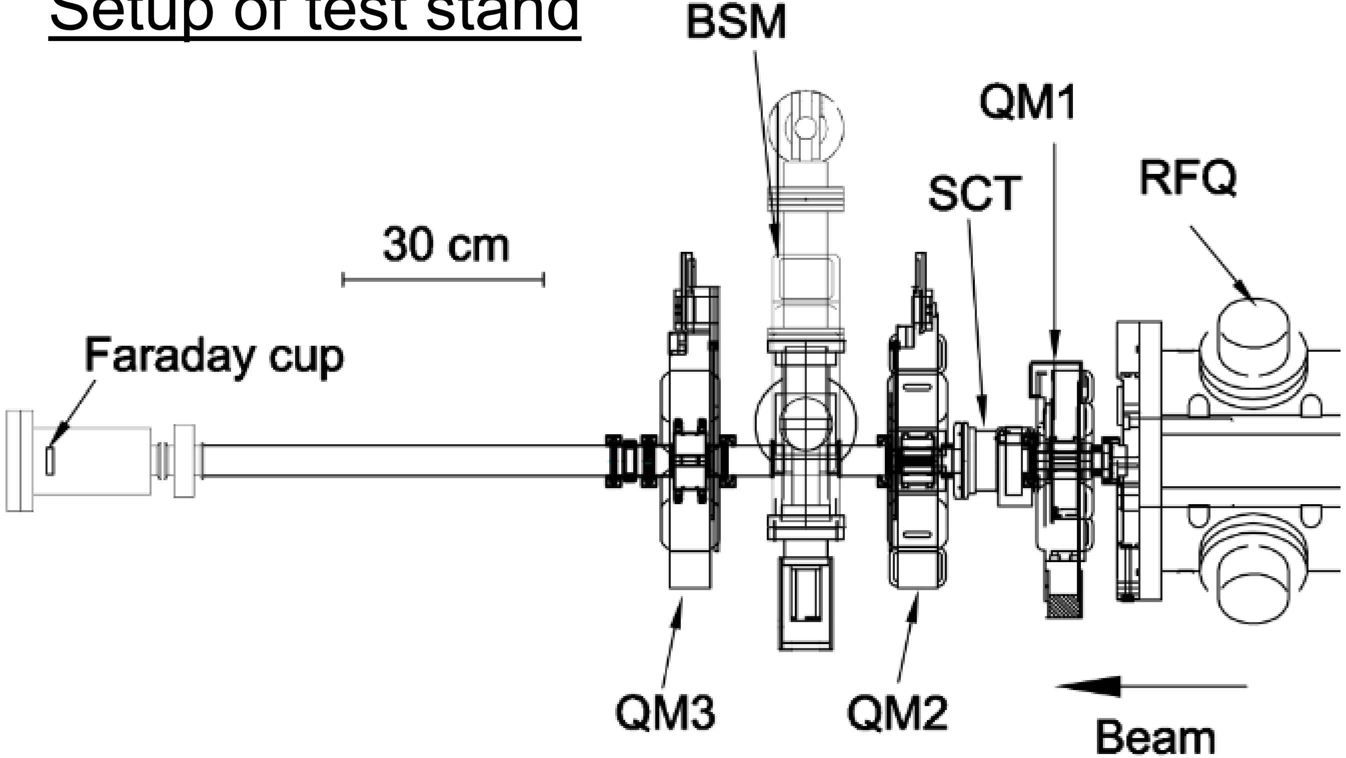
HOPG target for BSM

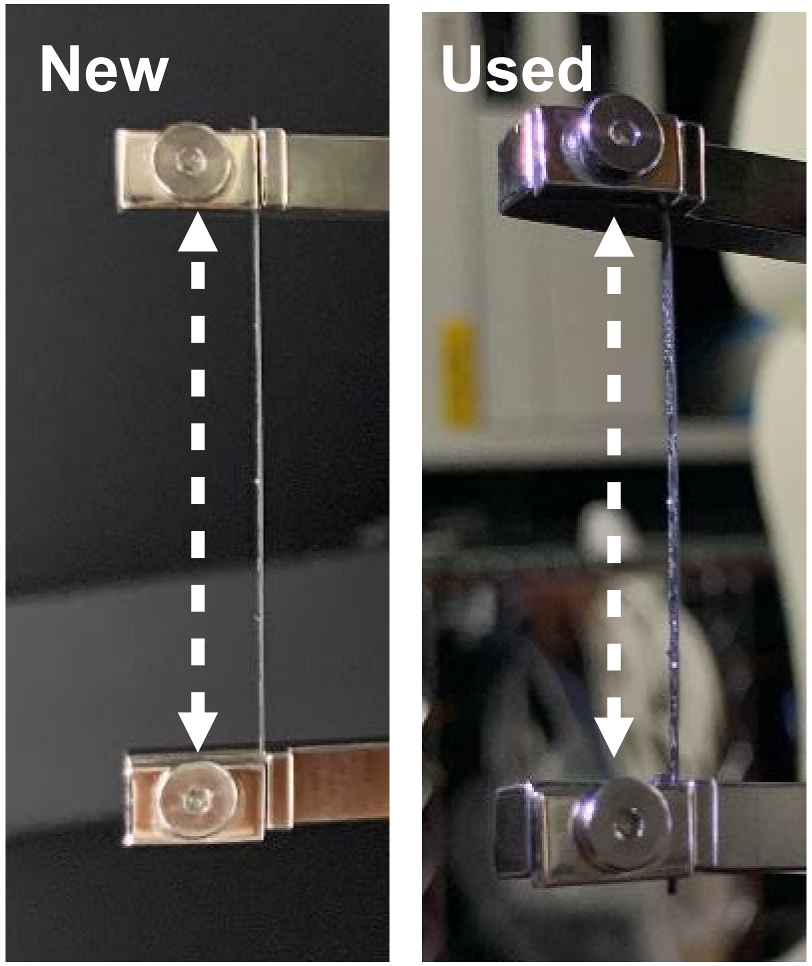


- HOPG was originally the candidate material for the beam scraper of the MEBT1.
  - Its high thermal conductivity was suitable to mitigate the heat loading.
  - **It was easy to apply the negative bias voltage from the result of the offline test.**
- Target size of the HOPG (~1 mm^2) is thicker than the CNT wire (~φ0.1 mm).
  - Question**:** Does the thick HOPG target affect the measurement of longitudinal profiles?
- **Beam test of the target-size effect for the BSM using the HOPG was conducted.**

Beam test at test stand

Setup of test stand





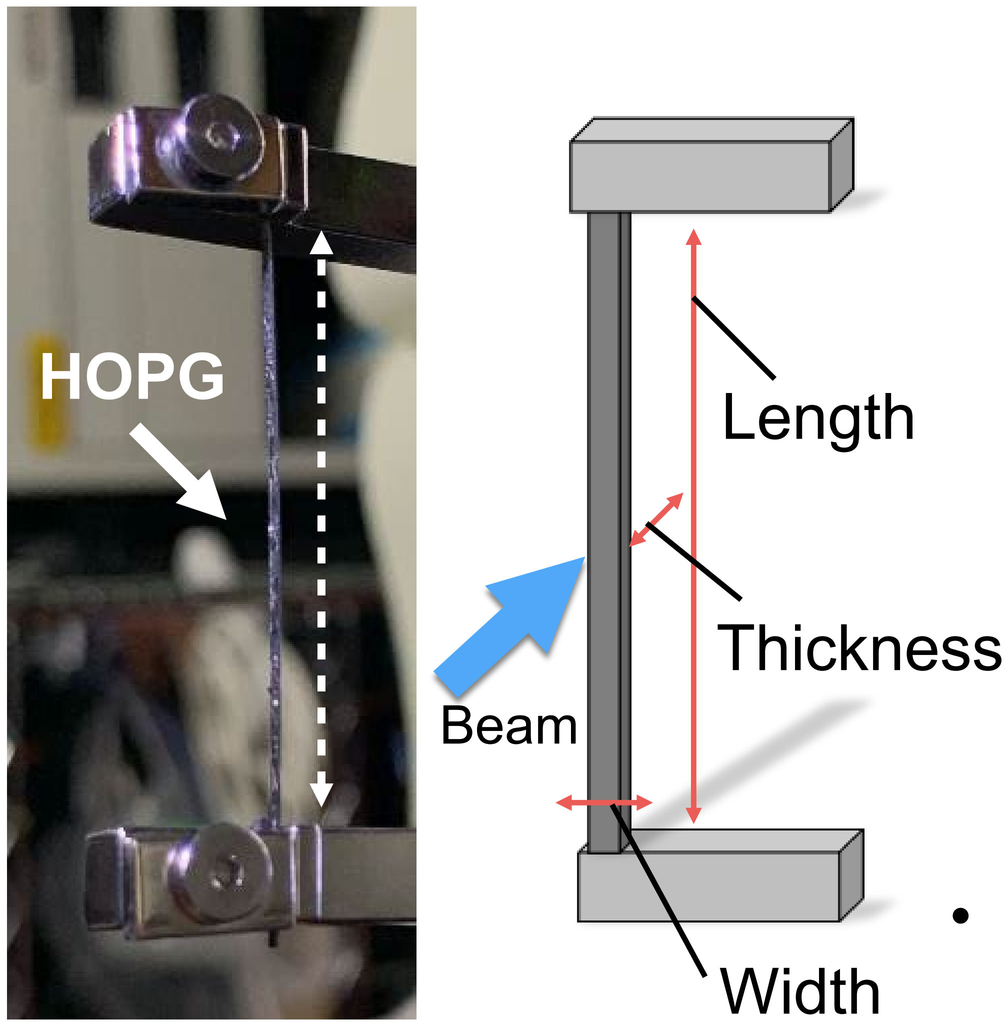
Beam condition

Peak current	~50 mA
Energy	3 MeV
Pulse length	50 μs
Repetition	1 Hz

- Test stand in the J-PARC linac building was used for the beam test of the HOPG-BSM.
- BSM was installed in diagnostic BL after the 3-MeV RFQ.
- Beam condition was the same as the MEBT1.
- Stability test of the target: ~6h/day irradiation for a month
- Visually no damage on the HOPG target.

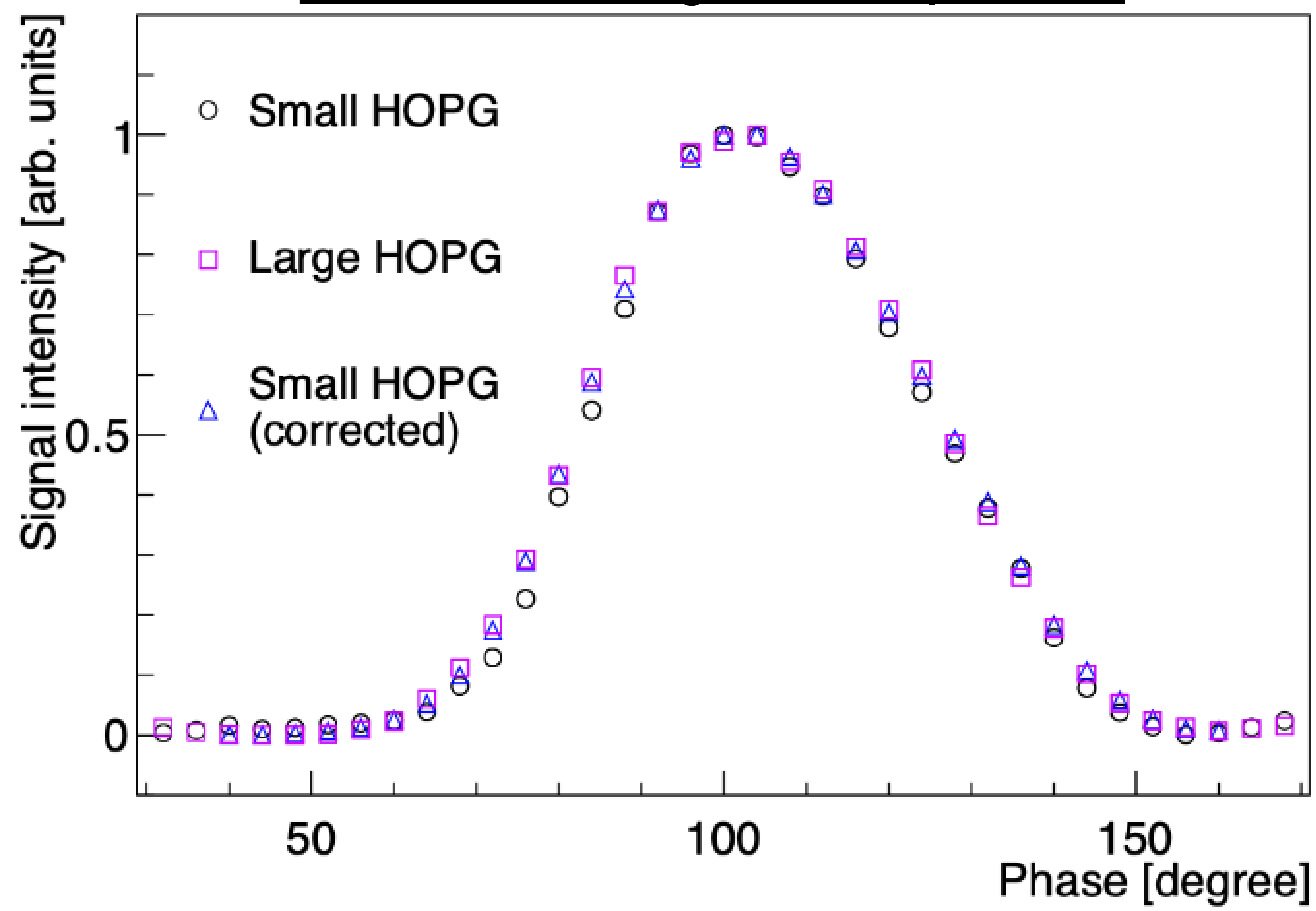
Study of target-size effect

HOPG targets for BSM



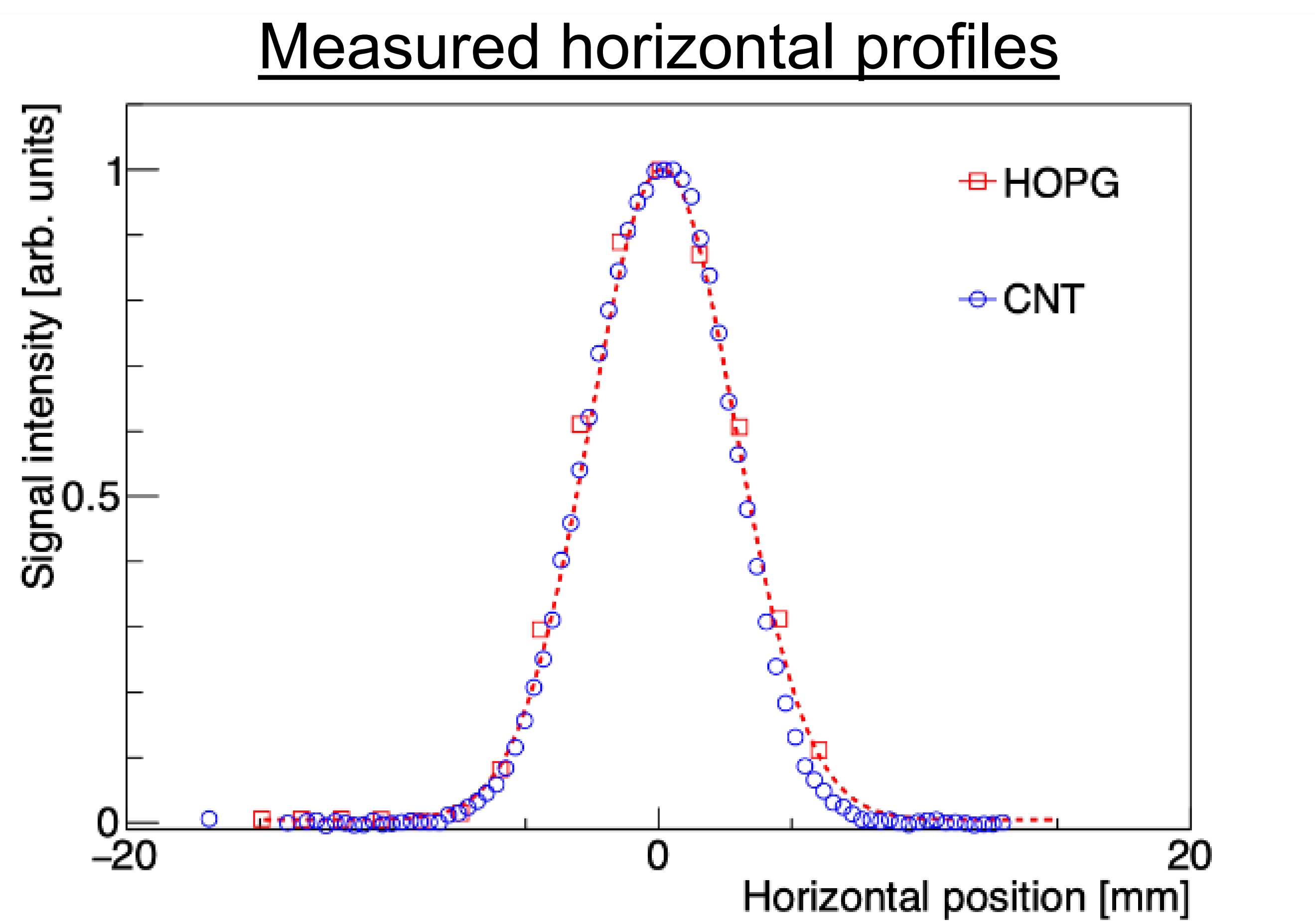
Type	Width [mm]	Thickness [mm]
Large	1.0	1.0
Small	0.2	

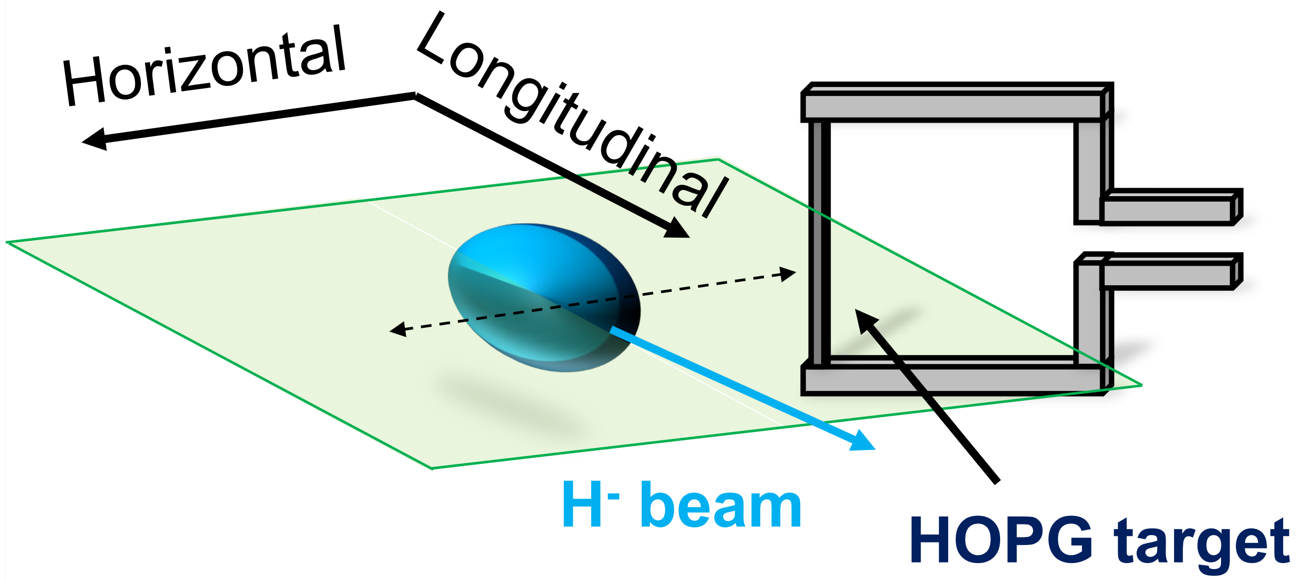
Measured longitudinal profiles



- Two types of HOPG targets were prepared.
  - Minimum size is limited by its cutting method.
- Target size affects the Time-of-Flight (ToF) of extracted secondary electrons.
  - Large target smears the measured longitudinal profile.
- ToF effect was estimated by the Geant4 simulation and corrected.
- **Target-size effect is confirmed by the ToF correction.**

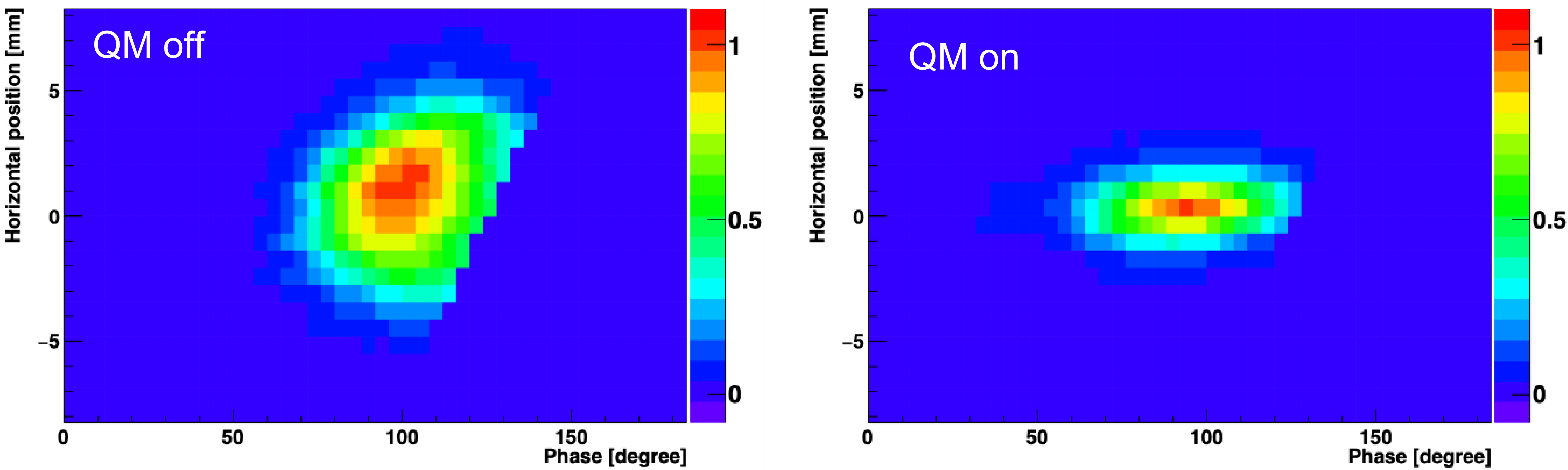
Tuning horizontal target position

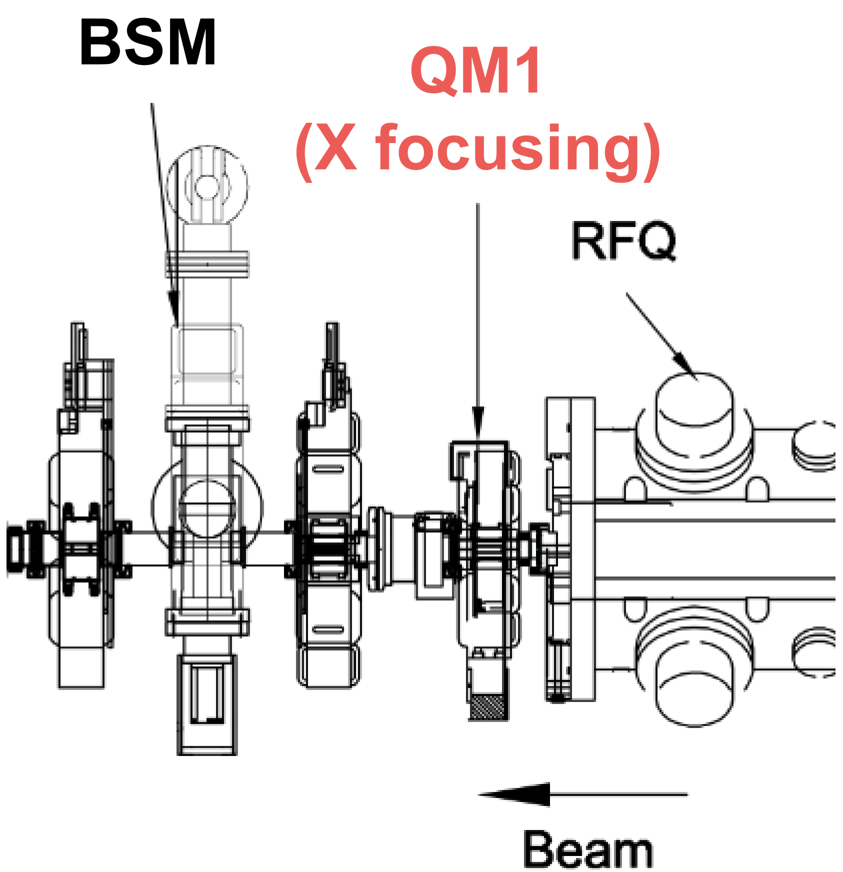




- HOPG target position was tuned to measure longitudinal profiles at the beam center.
- Horizontal profile was measured by detecting the current induced in the HOPG target, which is the same method as the WSM.
- Measured horizontal profiles with the BSM using the HOPG was consistent with the WSM result using the CNT wire.
- Idea: Can the dependence of longitudinal profiles be measured in terms of the horizontal direction?
- **Longitudinal and transverse profiles can be measured with the HOPG-BSM.**

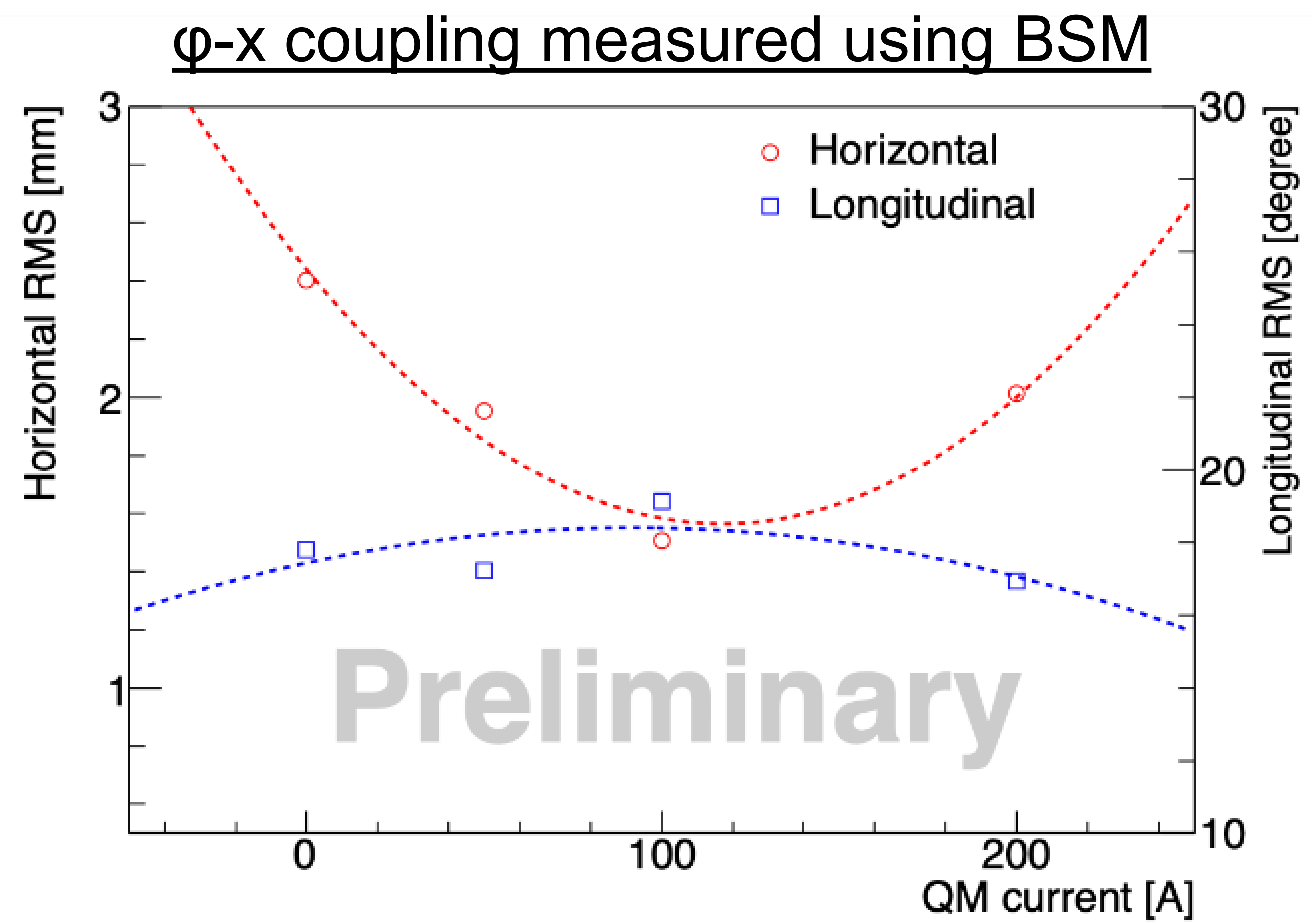
Longitudinal and transverse profiles

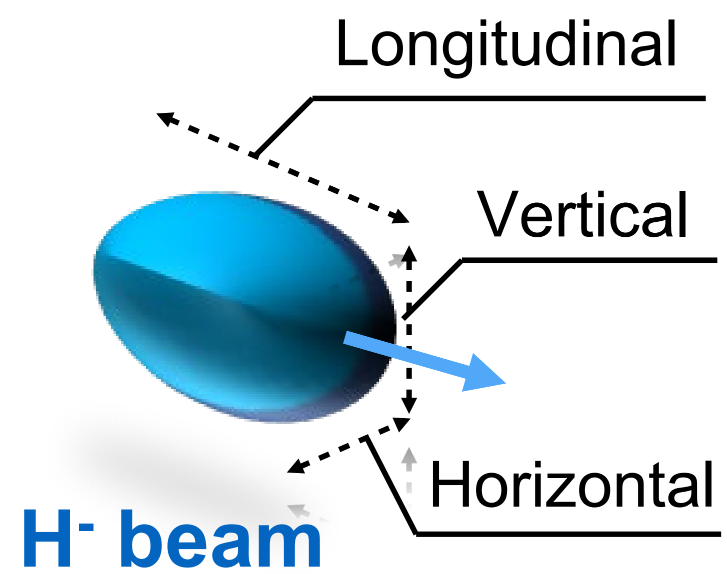




- Advantage of our new BSM using the HOPG target:
  - Measuring longitudinal profiles at any horizontal position.
- Longitudinal(φ) and horizontal(x) profiles were measured.
- Space-charge effect strongly affects profiles in MEBT1.
  - Expectation: longitudinal and transverse profiles are coupled under the space-charge effect.
- Quadrupole (X focusing) was tuned on.
- **Change of the 2D profile was successfully observed.**

φ-x coupling measurement

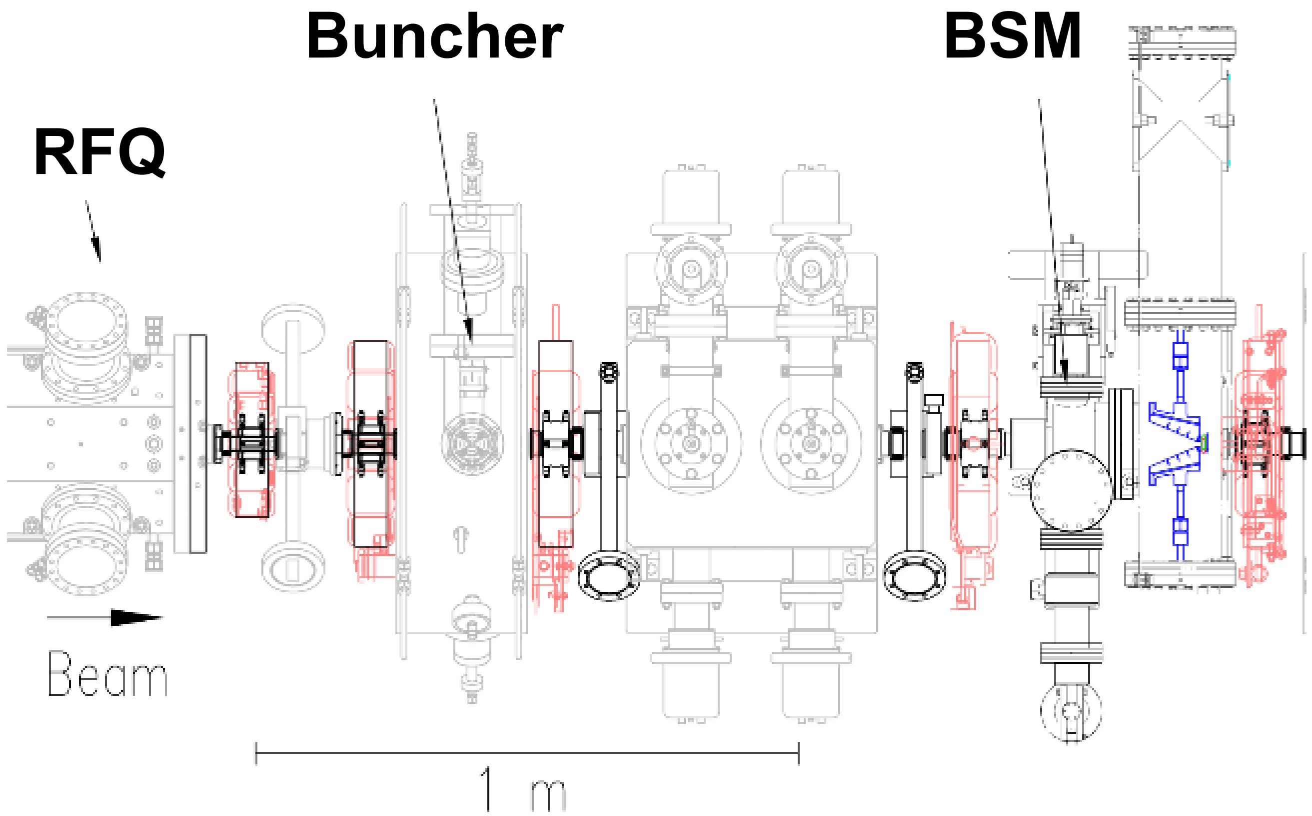




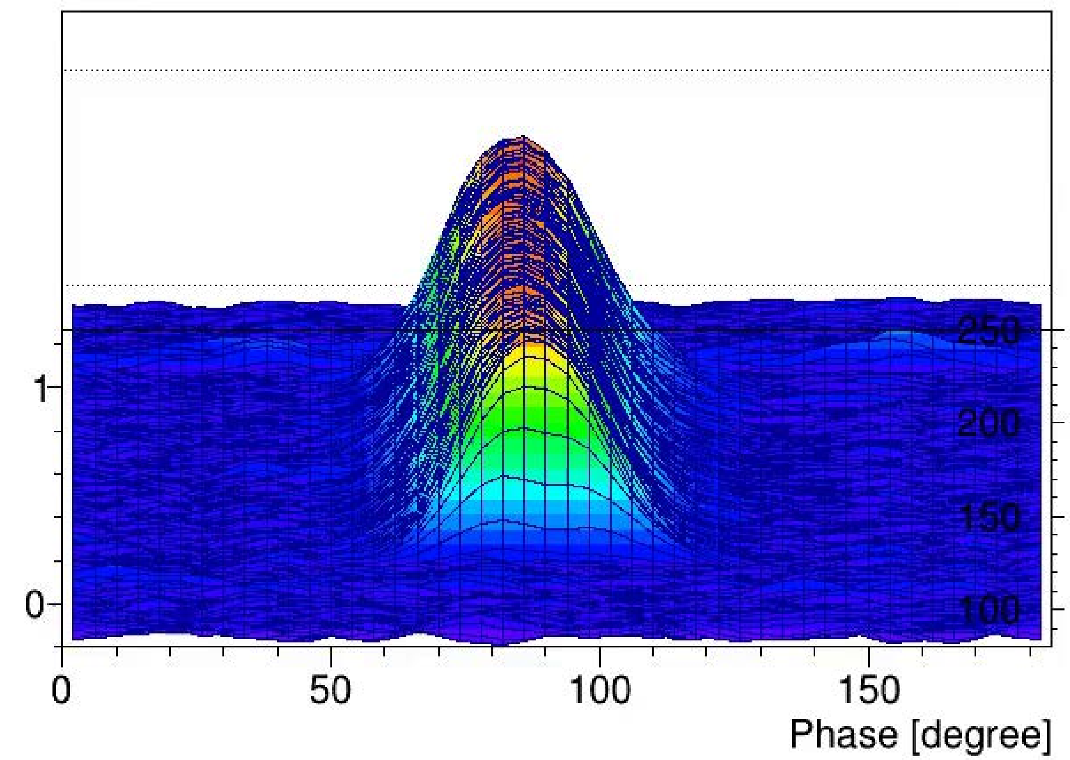
- Transverse (horizontal; x) focusing affects longitudinal profile through space-charge force.
- Dependence of φ(phase)-x(horizontal) profile was measured by scanning QM focusing.
- **Correlation between longitudinal and transverse profiles was observed.**
  - HOPG-BSM is the interesting instrument to study the space-charge effect.
  - Correlation between horizontal, vertical, and longitudinal profiles can be observed.
- **HOPG target is valuable to develop the frontier of the high-power beam.**

Longitudinal measurement at MEBT1

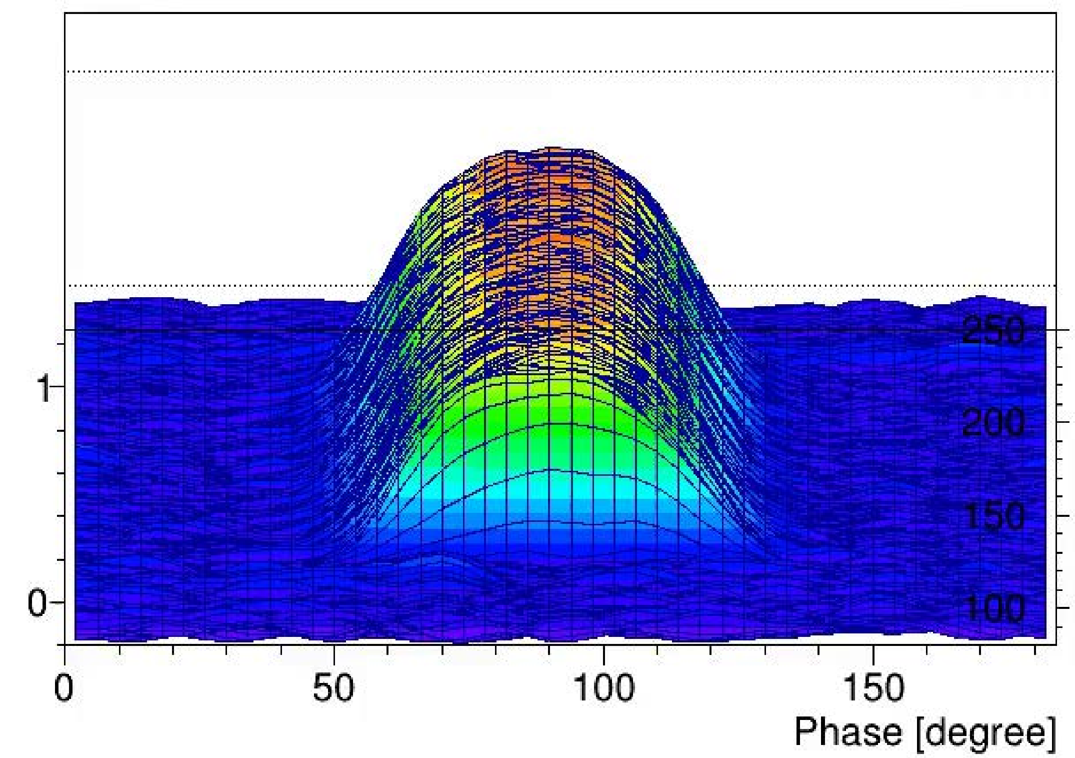
Setup of MEBT1 (upstream)



Waveform of BSM with strong focusing

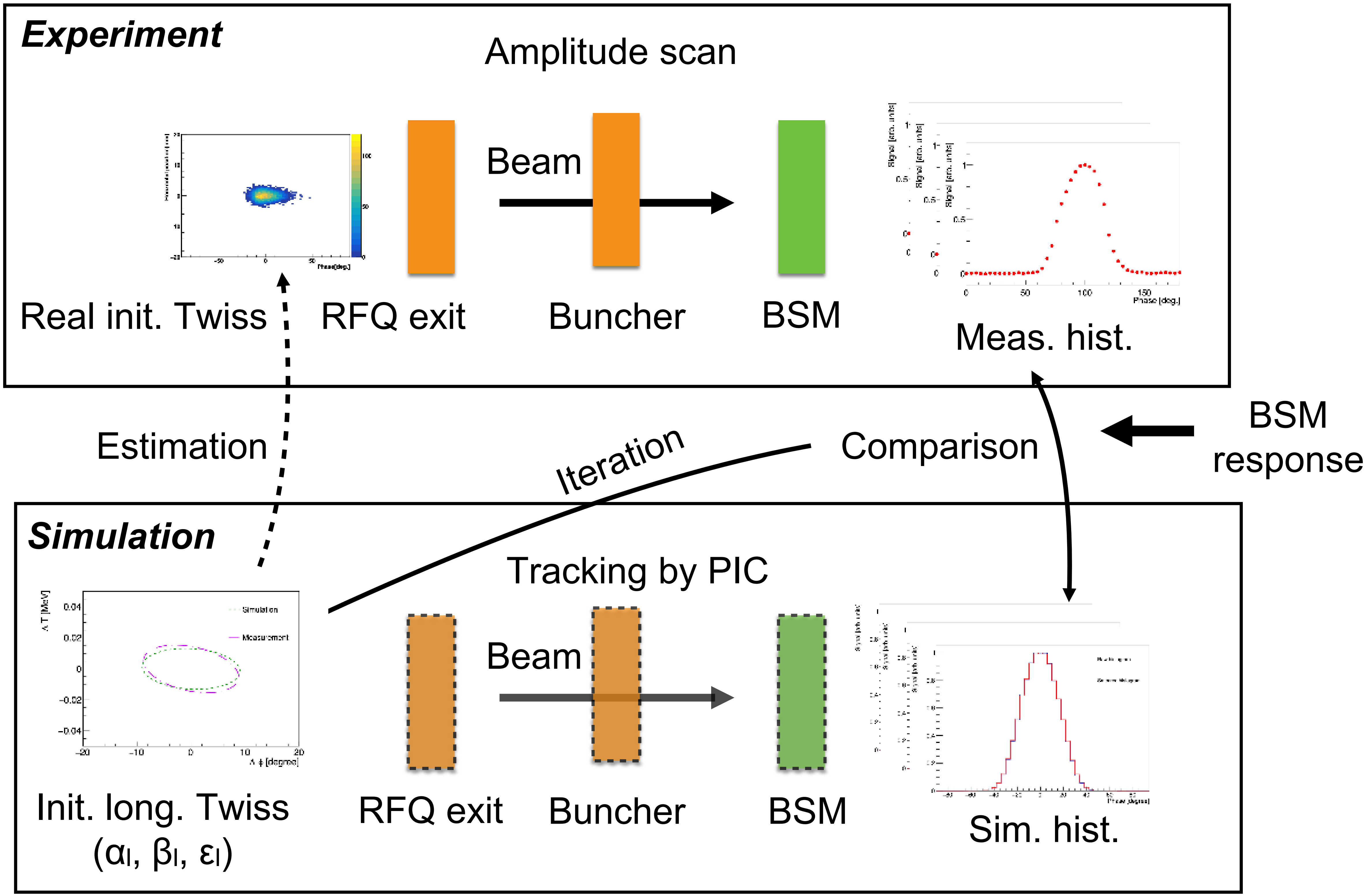


Waveform of BSM with weak focusing



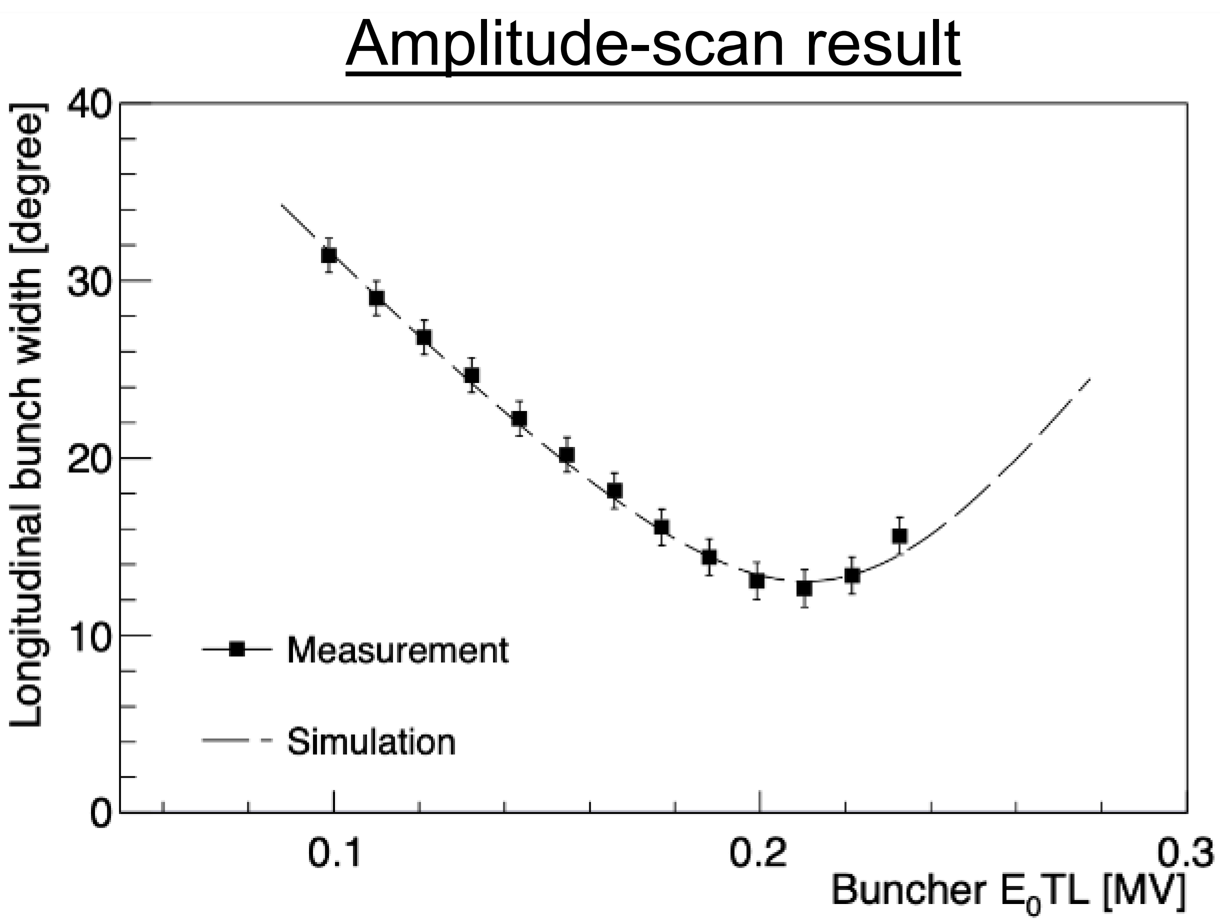
- Longitudinal beam parameters (Twiss and emittance) were measured using the BSM.
  - Amplitude scan method with buncher.
  - Required time ~ 1 hour/scan
- When the amplitude of the buncher was scanned, the dependence of longitudinal profiles was observed as expected.

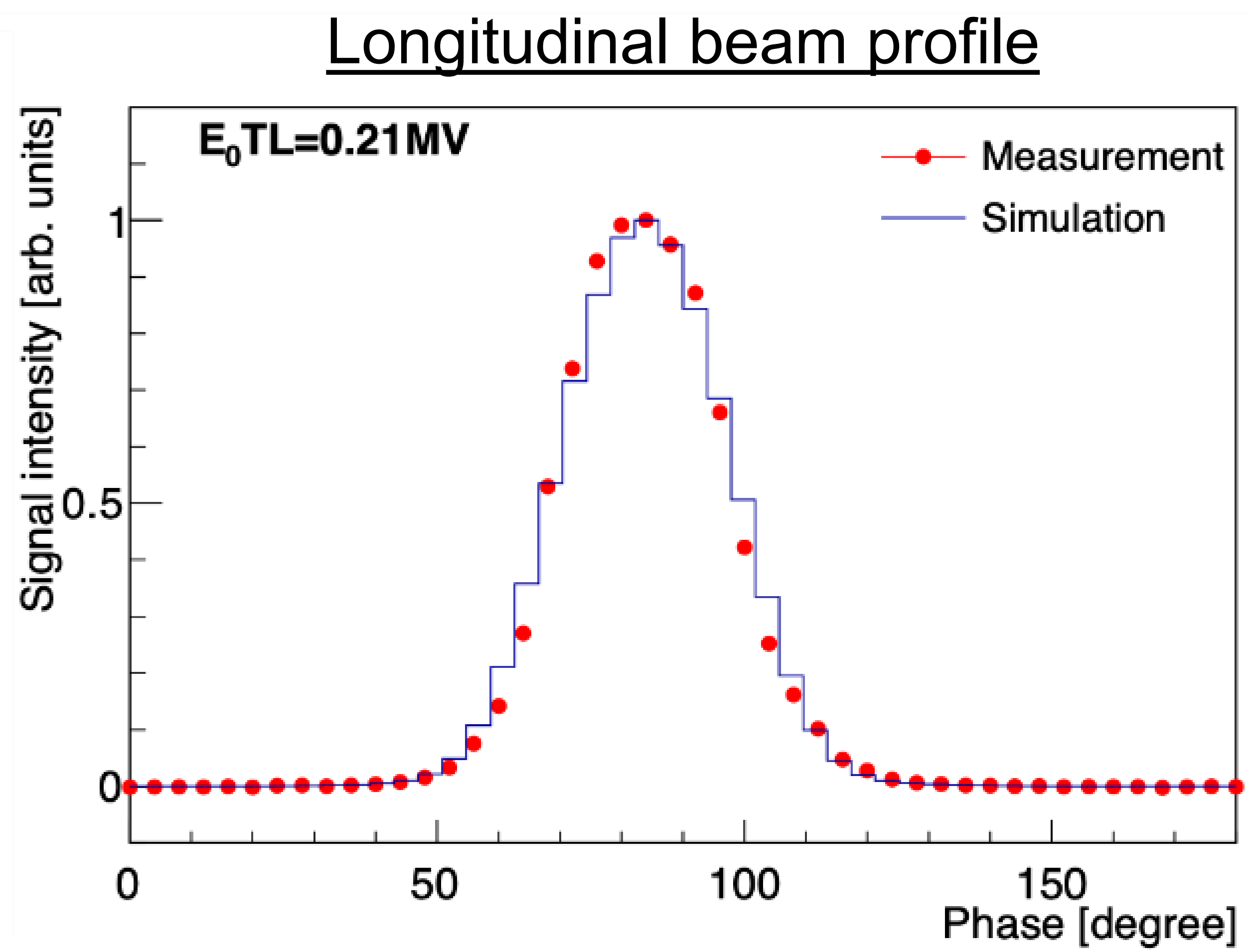
Procedure to evaluate longitudinal parameters



- Real initial parameters are estimated with 3D Particle-In-Cell code (IMPACT).

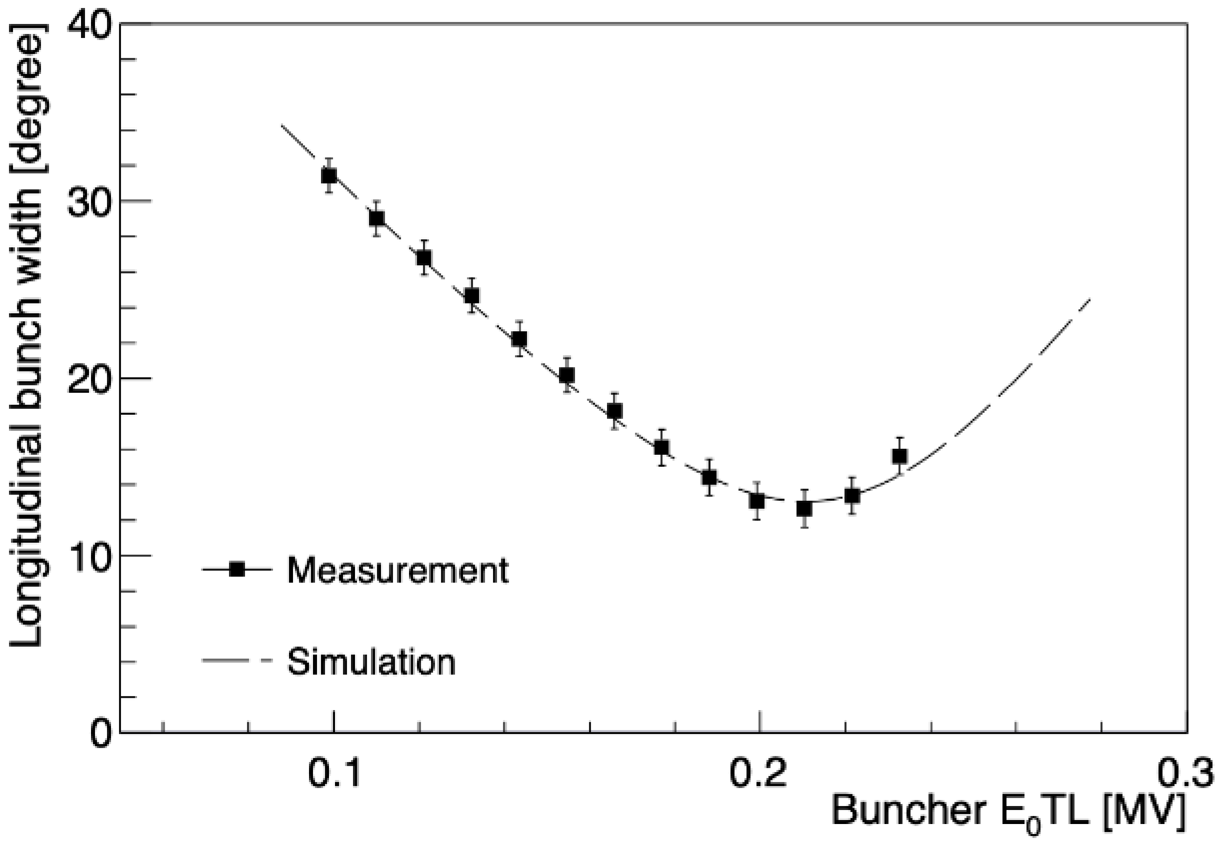
Fitting result using simulation

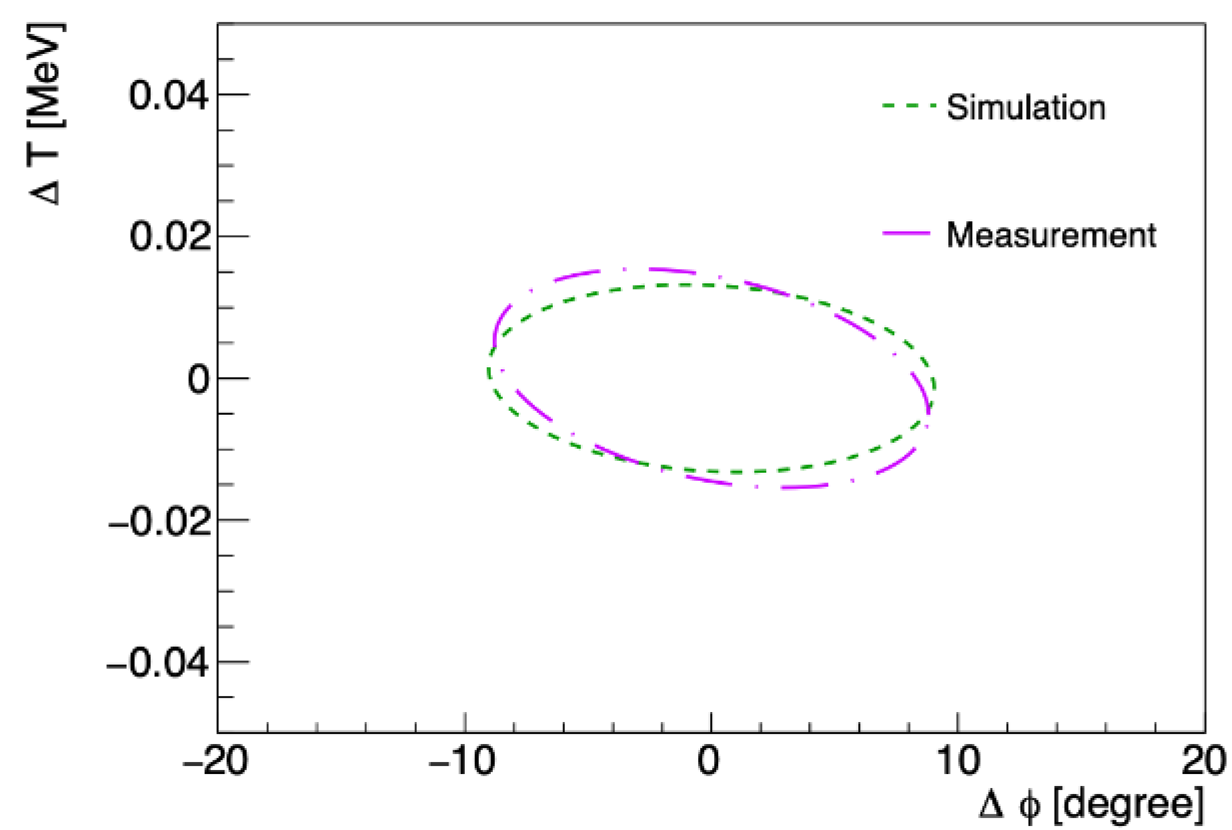




- Longitudinal profiles were measured with the BSM by scanning the buncher amplitude.
  - Fitting curve of the amplitude scan by IMPACT was consistent with the measurement.
  - Simulated longitudinal profiles were consistent with measurement.
  - **Estimated initial Twiss parameters reproduced the experimental result.**

Fitting result using simulation





- Longitudinal profiles were measured with the BSM by scanning the buncher amplitude.
  - Fitting curve of the amplitude scan by IMPACT was consistent with the measurement.
  - Simulated longitudinal profiles were consistent with measurement.
  - **Estimated initial Twiss parameters reproduced the experimental result.**
- Design Twiss parameters were calculated using the ion source and RFQ simulation.
  - **Measurement was consistent with design simulation for Twiss and emittance.**
- **Our BSM and MEBT1 system were well understood in the high-power operation.**

Summary

- New BSM has been developed to measure the high-power beam in MEBT1.
- Performance evaluation of the BSM using the HOPG target was conducted.
- First measurement of longitudinal beam profile was demonstrated using BSM. Measurement was consistent with the design simulation in the MEBT1.
- As further application, our new BSM is the attractive and powerful instrument to study the space-charge effect at the front-end.