Study and beam experiment on MERIT scheme

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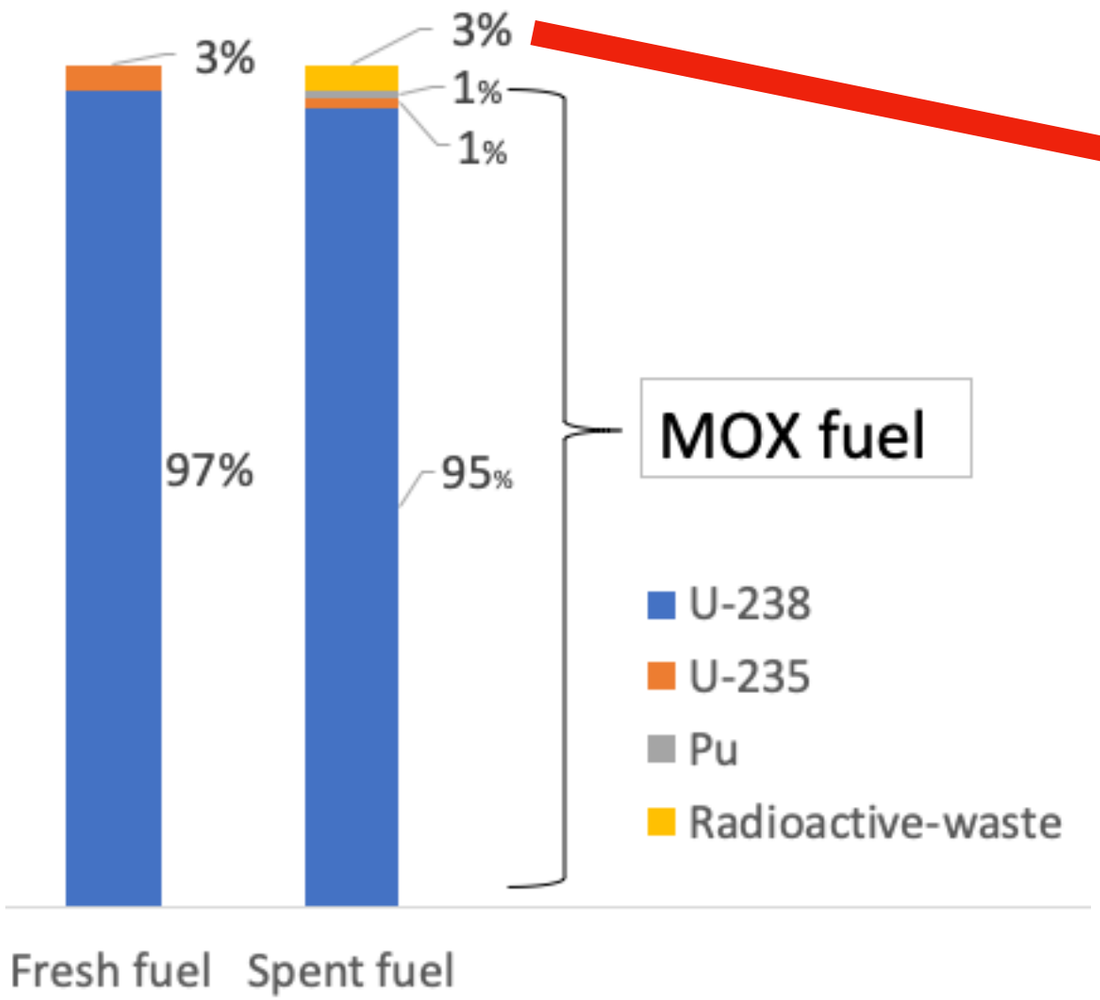
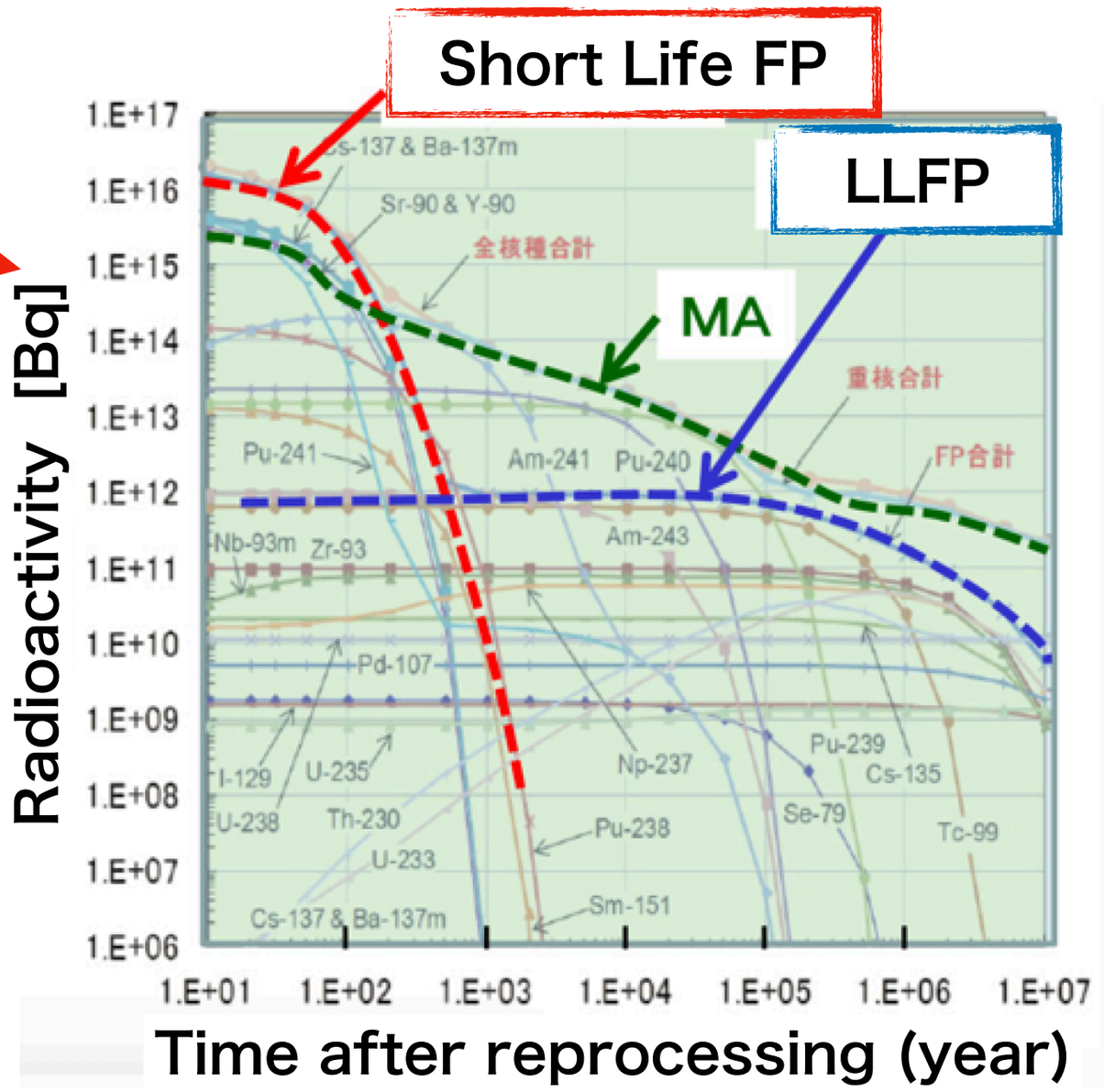
- Purpose
- MERIT Proof-of-principle ring (MERIT-PoP ring)
- Beam study and evaluation on MERIT scheme
- Summary

Radioactive waste from nuclear plants

Composition of fresh & spent fuel





※https://www.jst.go.jp/impact/program/08.html

○Disposal of MA & LLFP

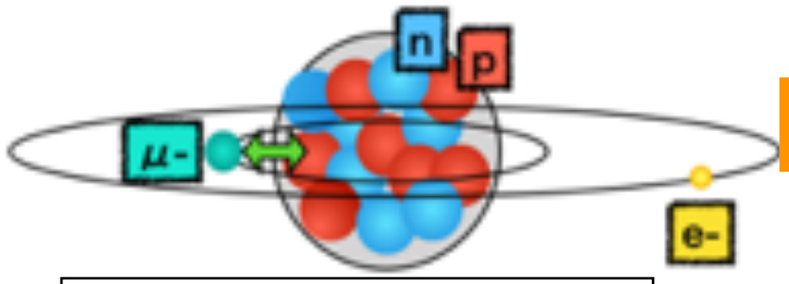
→ Radioactivity of spent fuel ~ 1000 year

○MA : Transmutation using ADS or FBR is useful solution

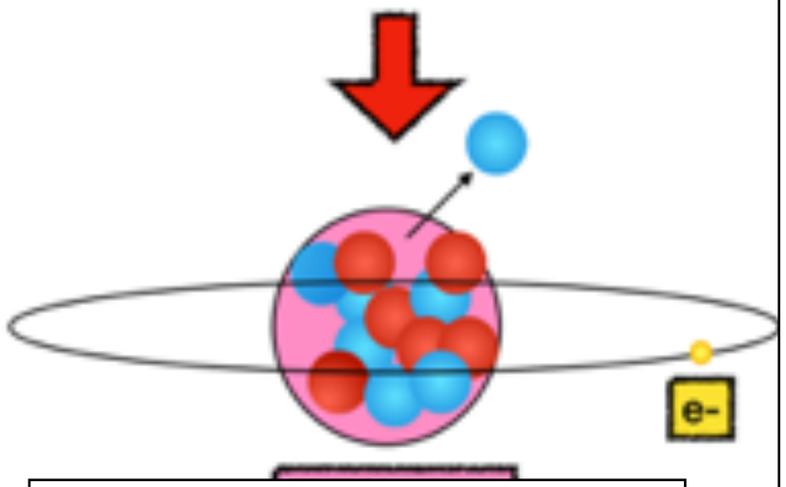
○LLFP : Transmutation using ADS or FBR is not practical

→ Requirements for effective transmutation scheme to reduce the LLFP

Negative muon transmutation



Atomic number Z



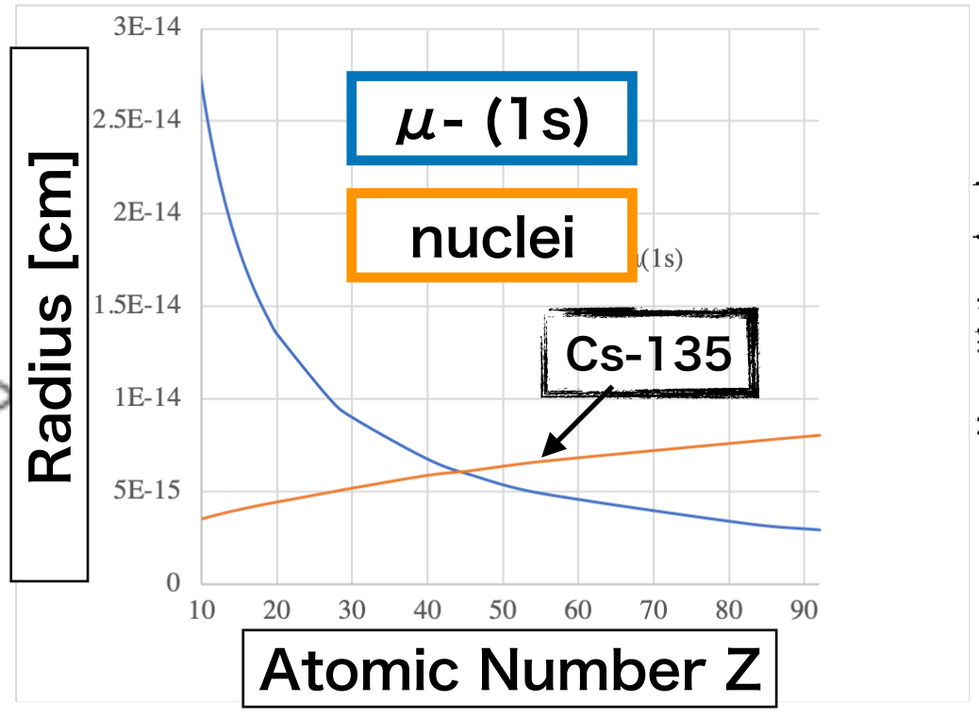
Atomic number Z-1

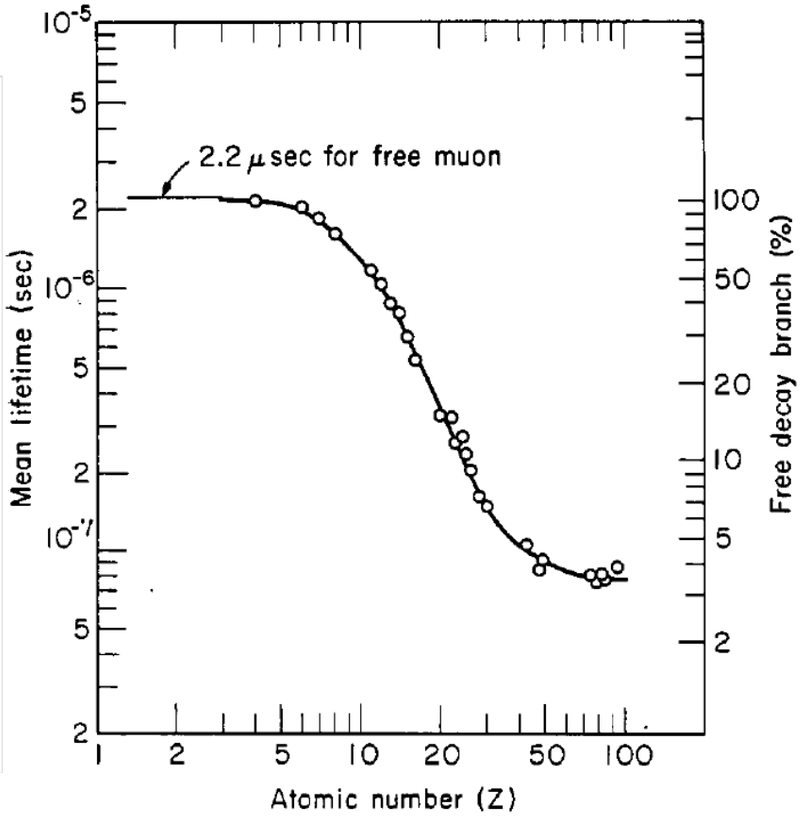
μ- (1s)

$$R_\mu(1s) \sim 270/Z \times 10^{-13}[cm]$$

nuclei

$$R_N \sim 1.2 \times (A)^{1/3} \times 10^{-13}[cm]$$





T.Yamazaki et al. Negative muon spin rotation. Phys.Scr., Vol. 11, pp. 133-139, 1975.

$$\mu^- + p \rightarrow n + \nu_\mu$$

Probability of transmutation > 95% (@Z>30)

Negative muon transmutation for LLFP

○Advantages of negative muon transmutation for LLFP

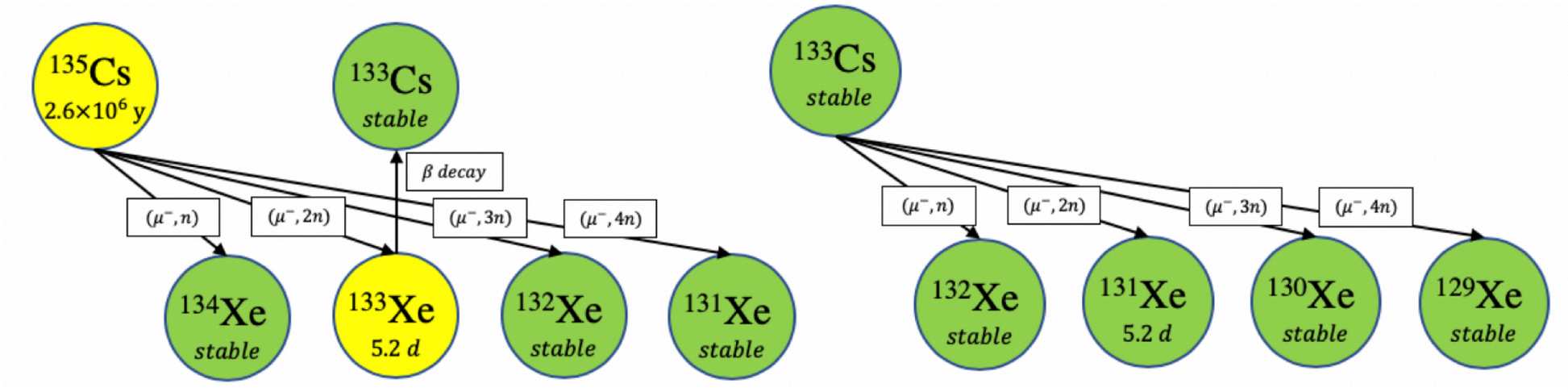
- Reduction of load of isotope separation
- Transmutation to stable nuclei

Example : Cs-135

$1.0\times10^{16}[\mu^-/s]$

$^{135}Cs(\tau_{1/2} = 2.6\times10^6$ y) → Xe (Stable)

(3% enriched ^{235}U fuel 1 ton) (processing year ~5 y)



High intensity & high efficiency negative muon production is indispensable

Issues of intense negative muon production

○Production of negative muon

$$p(> 300MeV) + n \rightarrow \pi^- + p + p$$

$\tau_{\pi^-} = 26[ns]$

$$\rightarrow \mu^- + \overline{\nu_\mu}$$

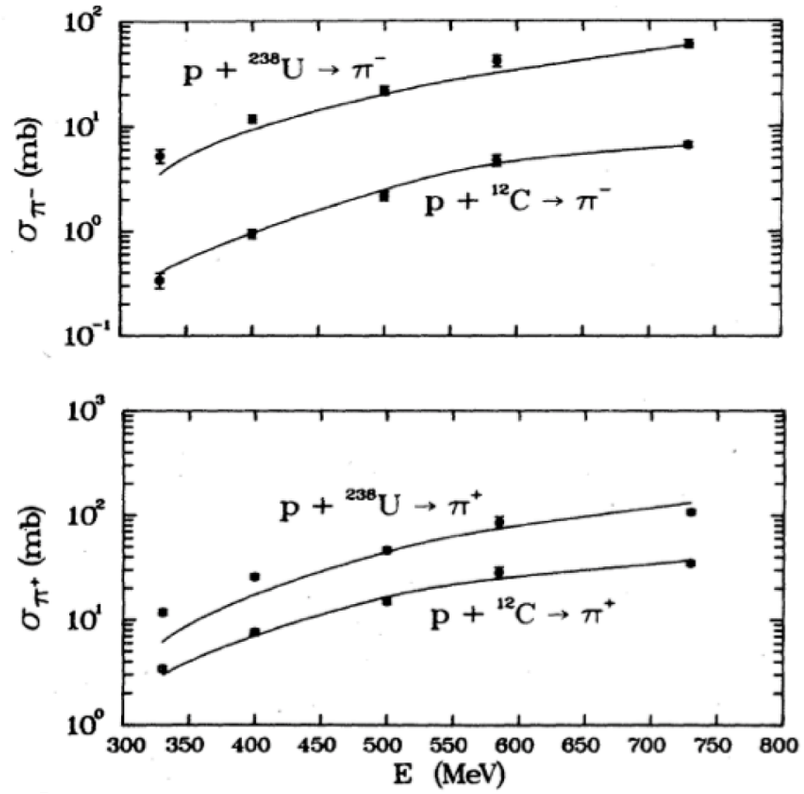
$\tau_{\mu^-} = 2.2[\mu s]$

○Thick target is necessary
for high intensity negative muon production

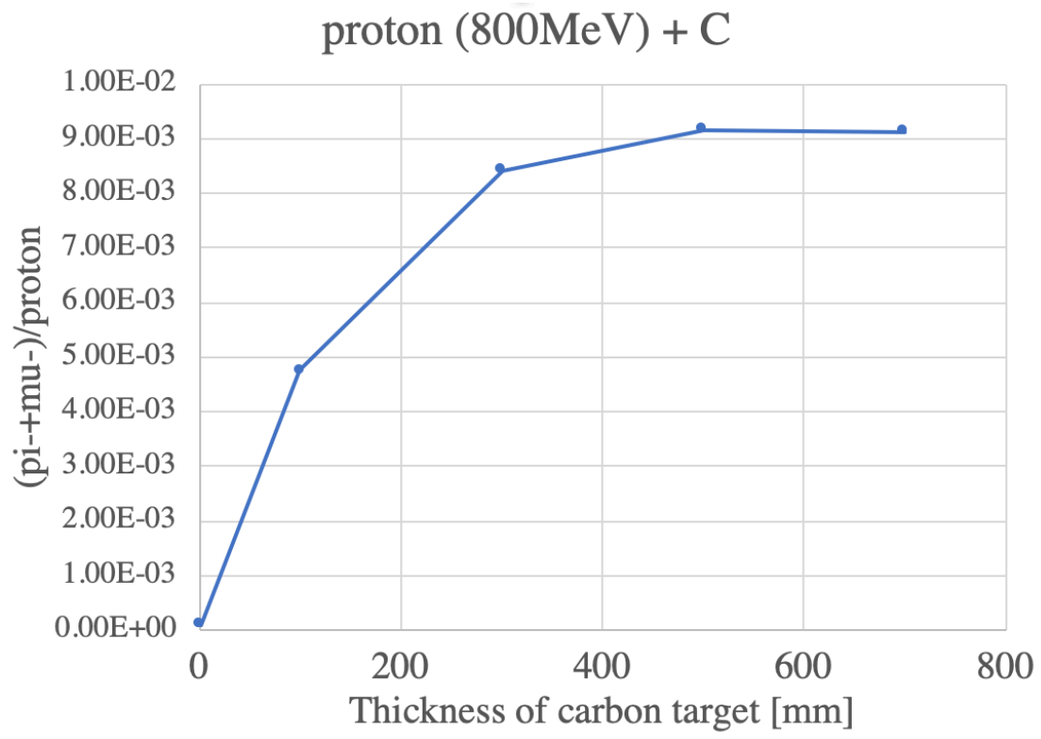
○Issues of negative pion production with thick target

→ Yield of negative pion is not much increased.

- Absorption of negative pion
- Range of negative pion
- Decrease of production cross section

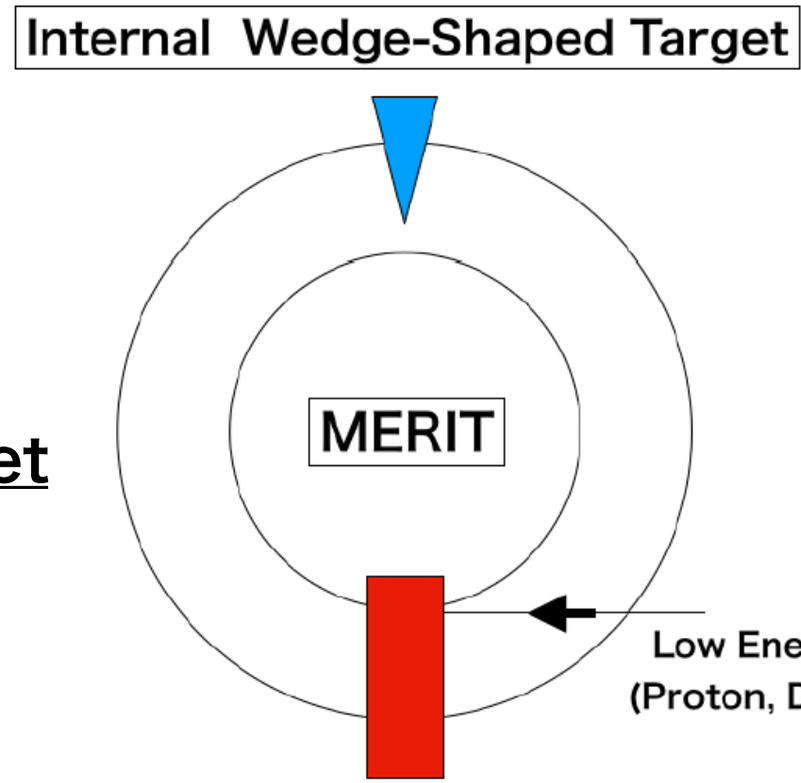


N.J.DiGiacomo et al. Inclusive pion production in 330, 400, and 500 MeV proton-neucleus collisions. Physical Review C, Vol. 31, No. 1, pp. 292-294, 1985.



MERIT scheme

MERIT : Multiplex Energy Recovery Internal Target



○Characteristics of MERIT scheme

<u>“Acceleration” and “Storage” using internal target</u>

○Advantages of MERIT scheme

□Negative pion production using <u>thin internal target</u>

- Reduction of loss of negative pion in target
- High production cross section

→high efficiency production

□Fixed RF (Semi-isochronous) acceleration

- CW beam operation
- Lower the injection energy

→High intensity production & reduction of load of injector

RF Cavity
Energy Recovery & Acceleration

Purpose

Proof of principle of MERIT scheme
“Acceleration” & “Storage” using internal target

Overview of this study

Development of MERIT-PoP ring
- Design of the ring
- Evaluation of field error and correction & injection matching
- Beam experiment for validation
- Betatron tune measurement

Study and beam experiment on MERIT scheme
- Semi-isochronous acceleration
- MERIT scheme with internal target

Design of MERIT-PoP ring

○MERIT-PoP ring was developed
by modification of existing ring “FFA-ERIT”

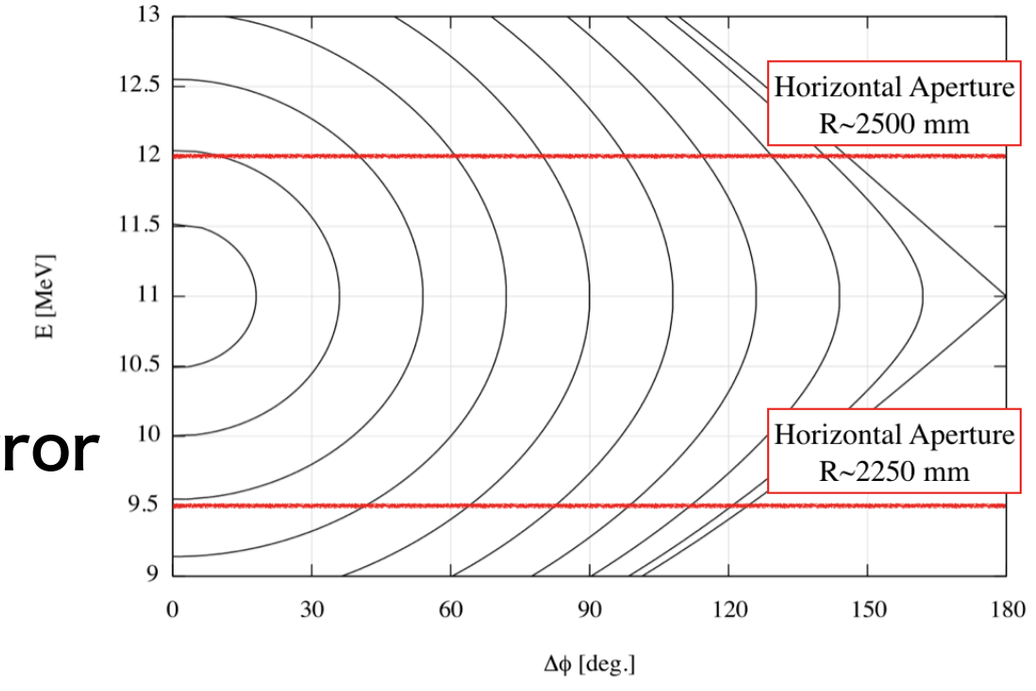
○Requirements for the MERIT-PoP ring
- Semi-isochronous acceleration (η_{slip}~0)
- Separation of circulation orbit
(Injection—>Target)

$$\eta_{slip} = \frac{1}{k+1} - \frac{1}{\gamma^2}$$

Particle	Proton
Number of Cells	8
Lattice	FDF-triplet
Field Index k	0.07
Energy Range [MeV]	9.5 – 12.0
Orbit Radius[mm]	2250 – 2500
Slippage Factor η_{slip}	-0.044
Tune H/V	1.03/1.25
Parameters of F/D Magnet	
Magnetic Field [T]	0.59/0.14 (at r = 2350 [mm])
Opening Angle of Magnet[deg.]	6.4/5.1
Minimum Half Pole Gap [mm]	84.0/85.2
Parameters of RF Cavity	
RF Voltage [kV]	75 – 225
Harmonic Number	6
RF Frequency [MHz]	18.12
Q Value	~ 7000

➡Field index k ~ 0.07 (η_{slip}~ -0.044)
→Acceleration range: 9.5 ~12.0 [MeV]
→Orbit separation: excursion~250[mm]

○Horizontal tune become close to integer
→Important to evaluate and correct field error

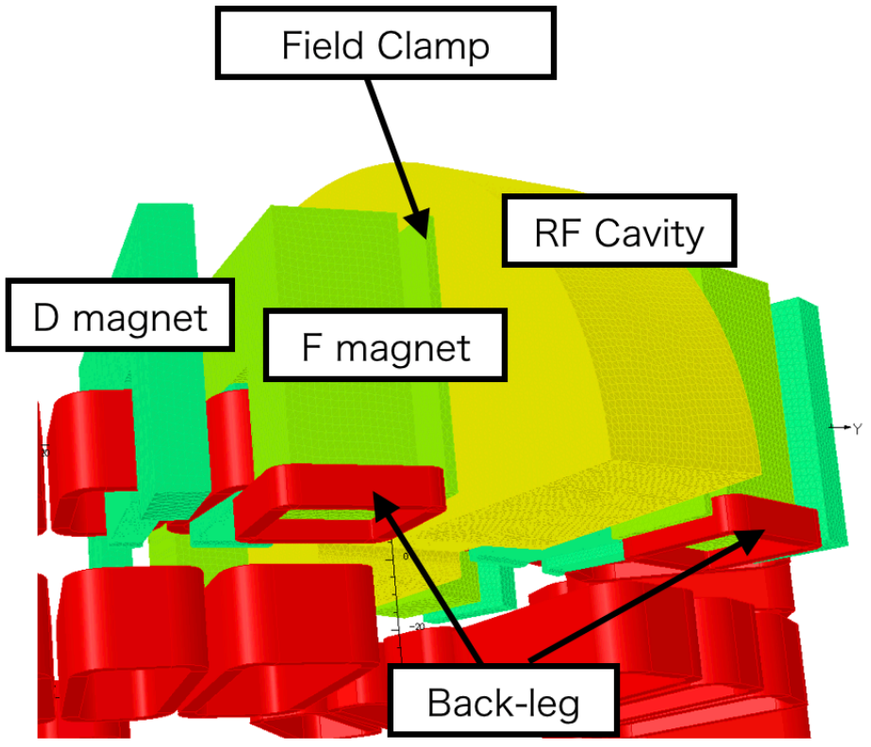


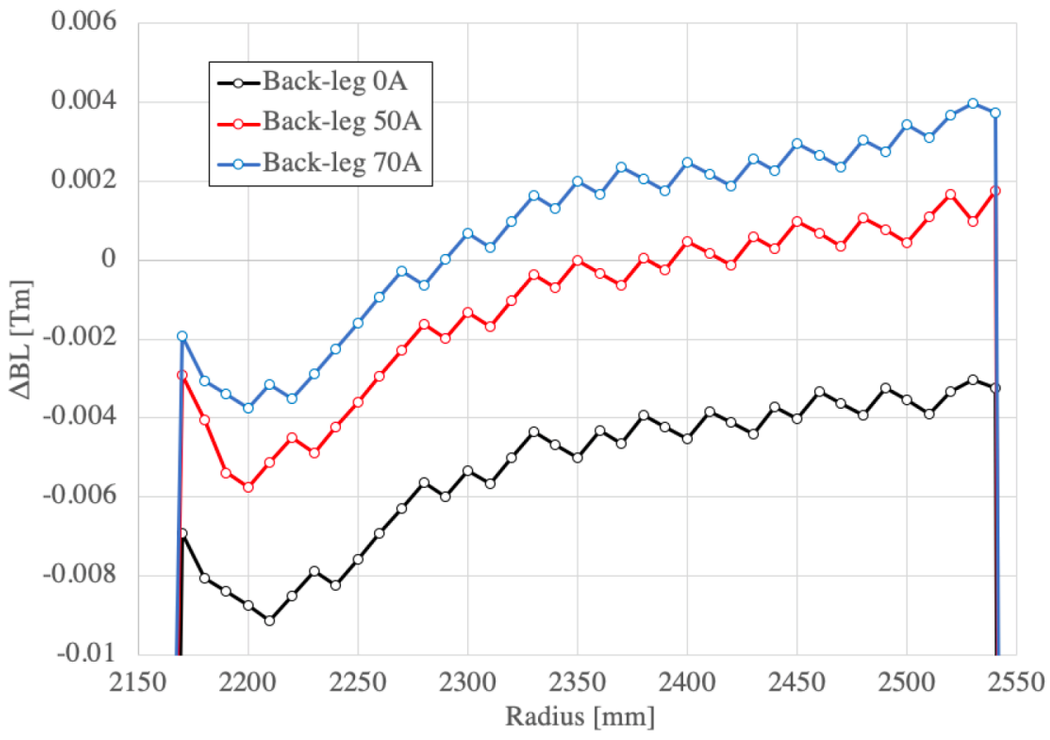
Field error correction

○Large horizontal aperture is essential for the beam experiment.
○COD decrease the horizontal aperture.
○Even if field error is small, induce large COD in MERIT-PoP ring

$$x(s) = \left[\frac{\sqrt{\beta(s)\beta(s_0)}}{2\sin(\pi\nu_H)} \frac{\delta(Bl)}{B\rho} \right] \cos(\pi\nu_H - |\psi(s) - \psi(s_0)|)$$

○Evaluation of field error @ RF section using OPERA3D/TOSCA
→Dipole field error : 10 [mrad] (~ COD amplitude ~ 70 [mm])
○Evaluation of correction using back-leg coil





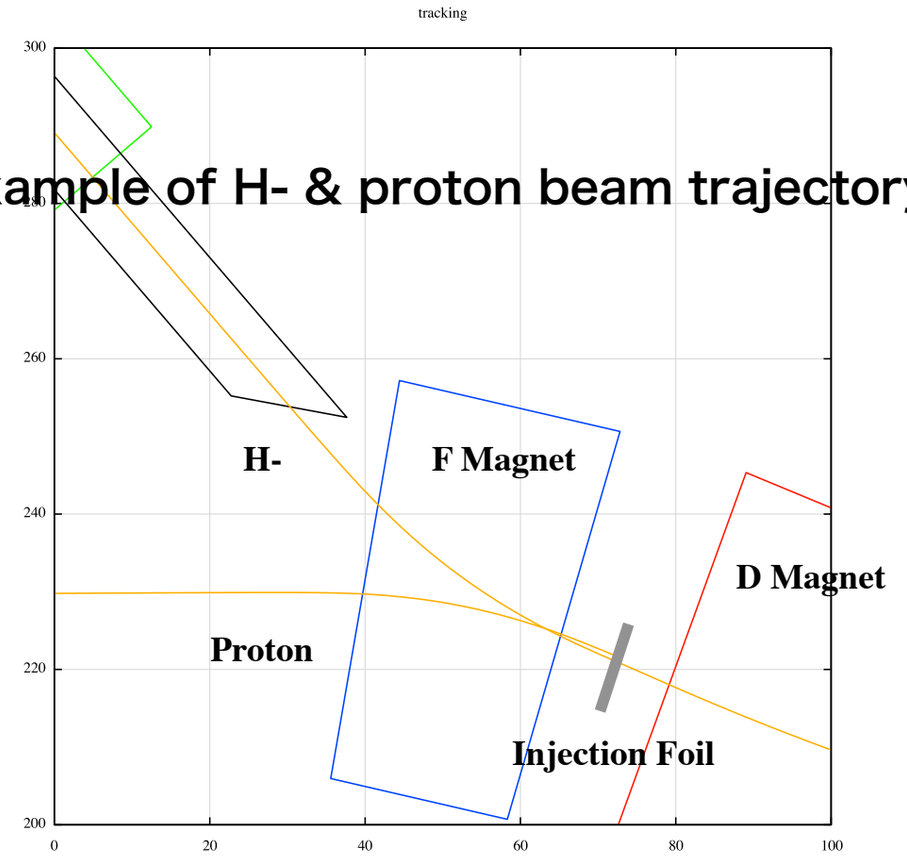
Correction scheme using back-leg is useful.

Injection matching

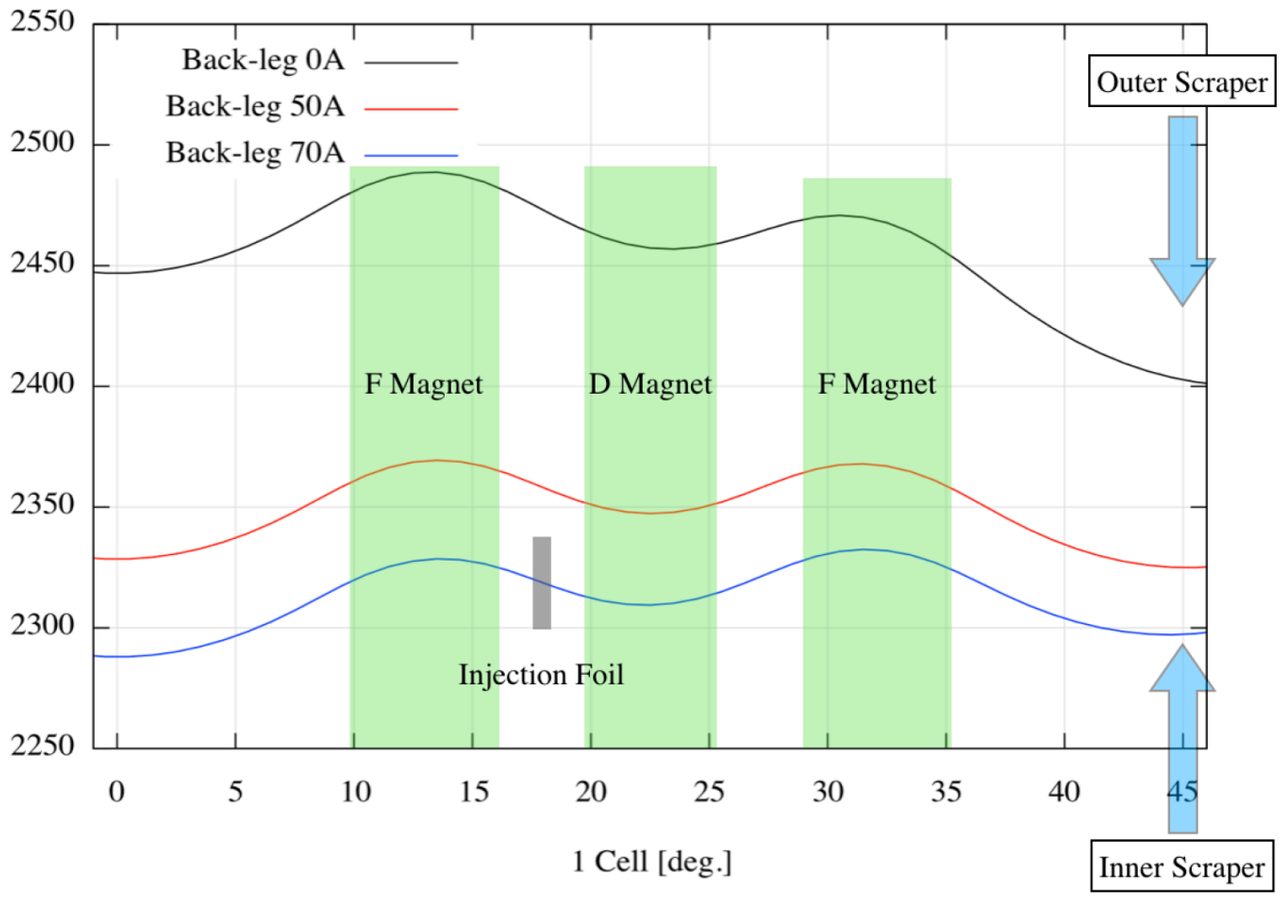
○Small initial beam size is also essential for the beam experiment.
→Injection matching is important.

○Evaluation of adjustment scheme using back-leg coil

example of H- & proton beam trajectory



Results of tracking

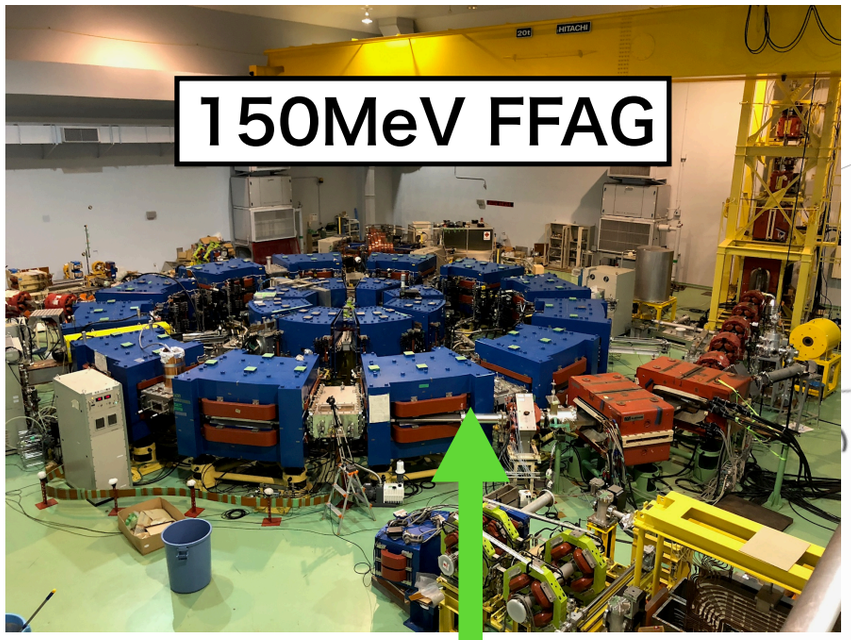


○Position matching is adequate @ back-leg 70 [A] (COD amplitude 20 [mm])

Adjustment scheme using back-leg coil is useful

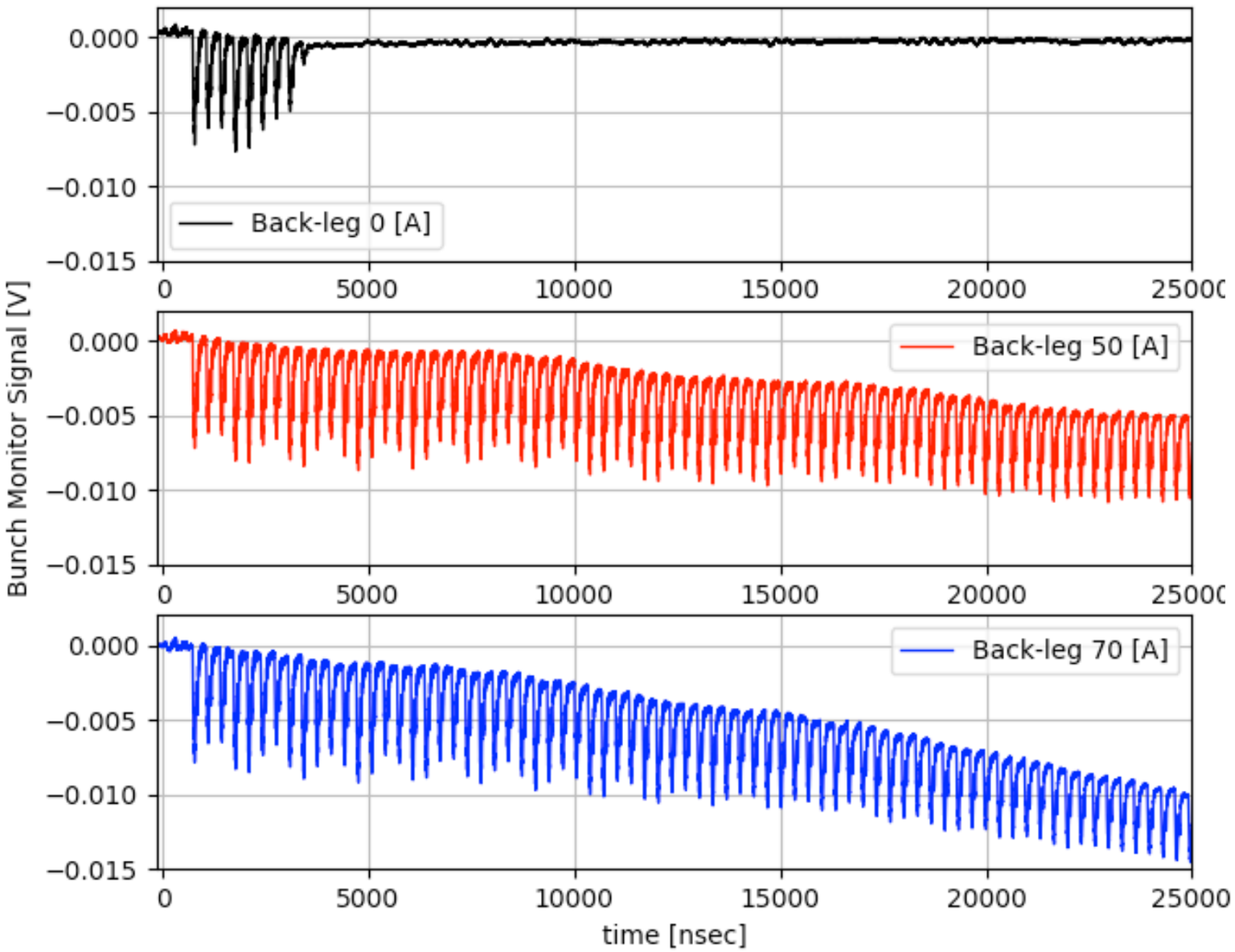
- Beam experiment for validation of field error correction & injection matching

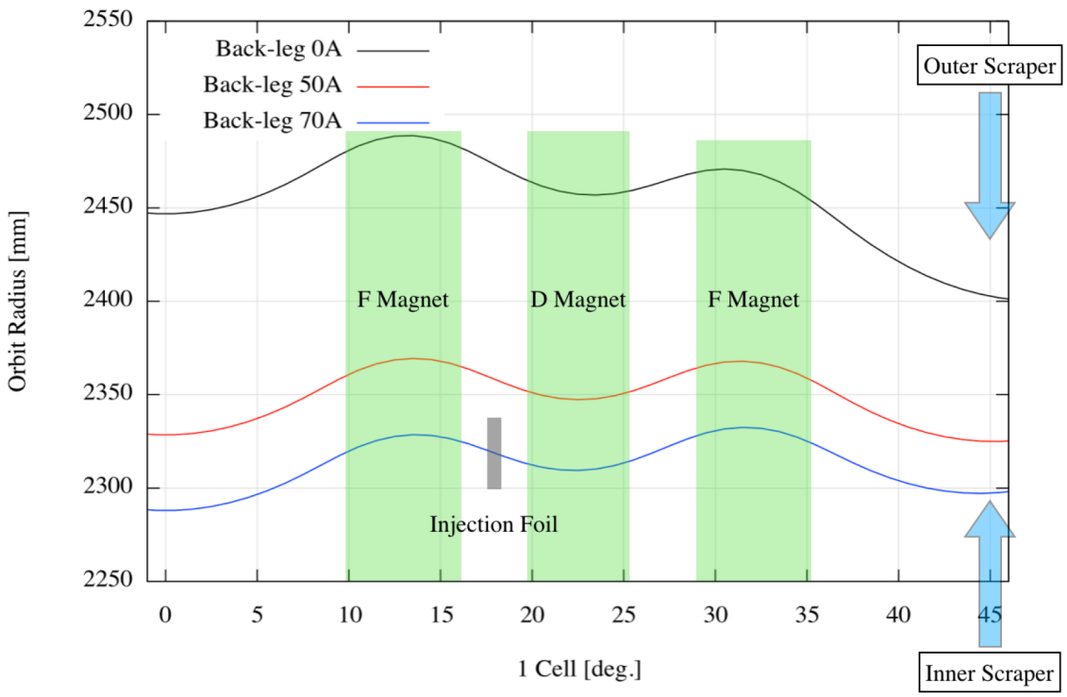
Apparatus of MERIT-PoP ring



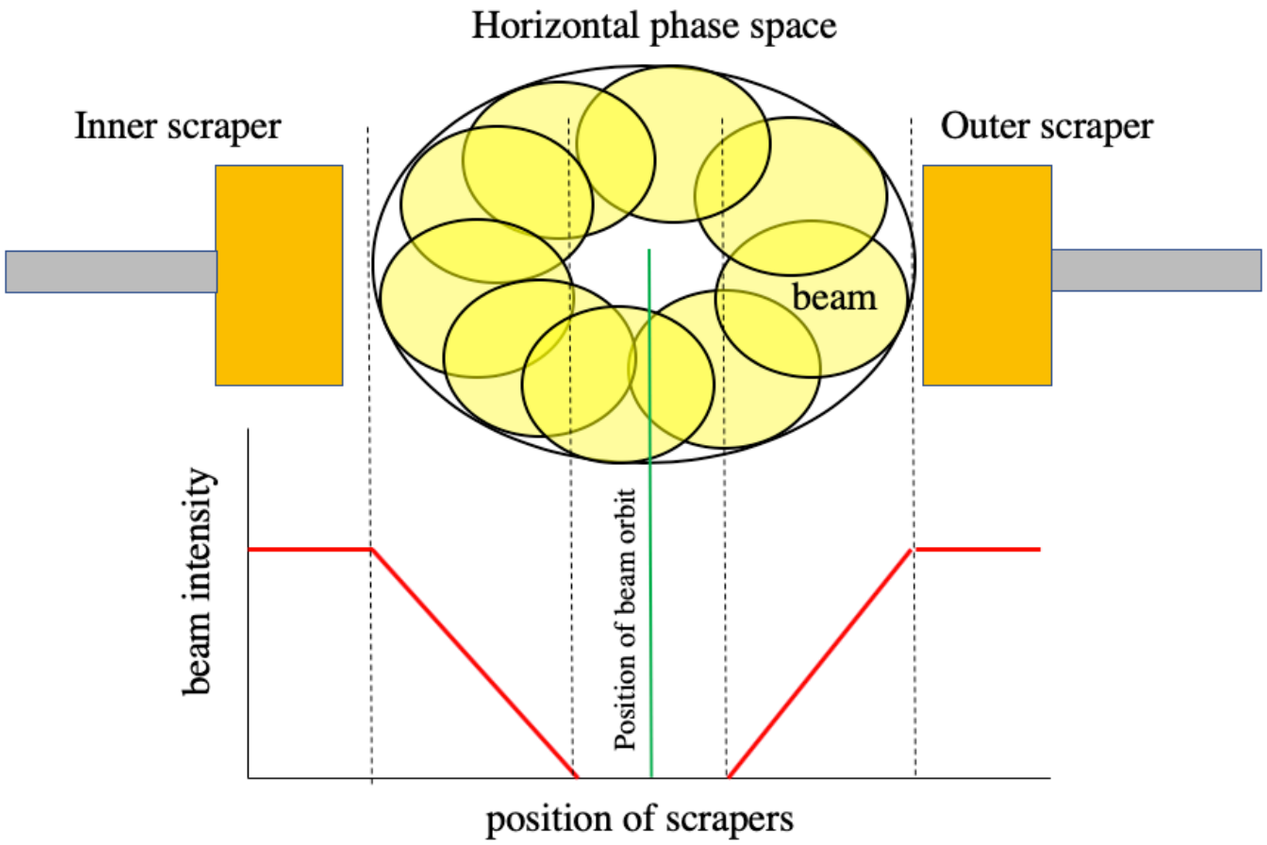
Beam experiment on field error correction & injection matching

Signals of bunch monitor

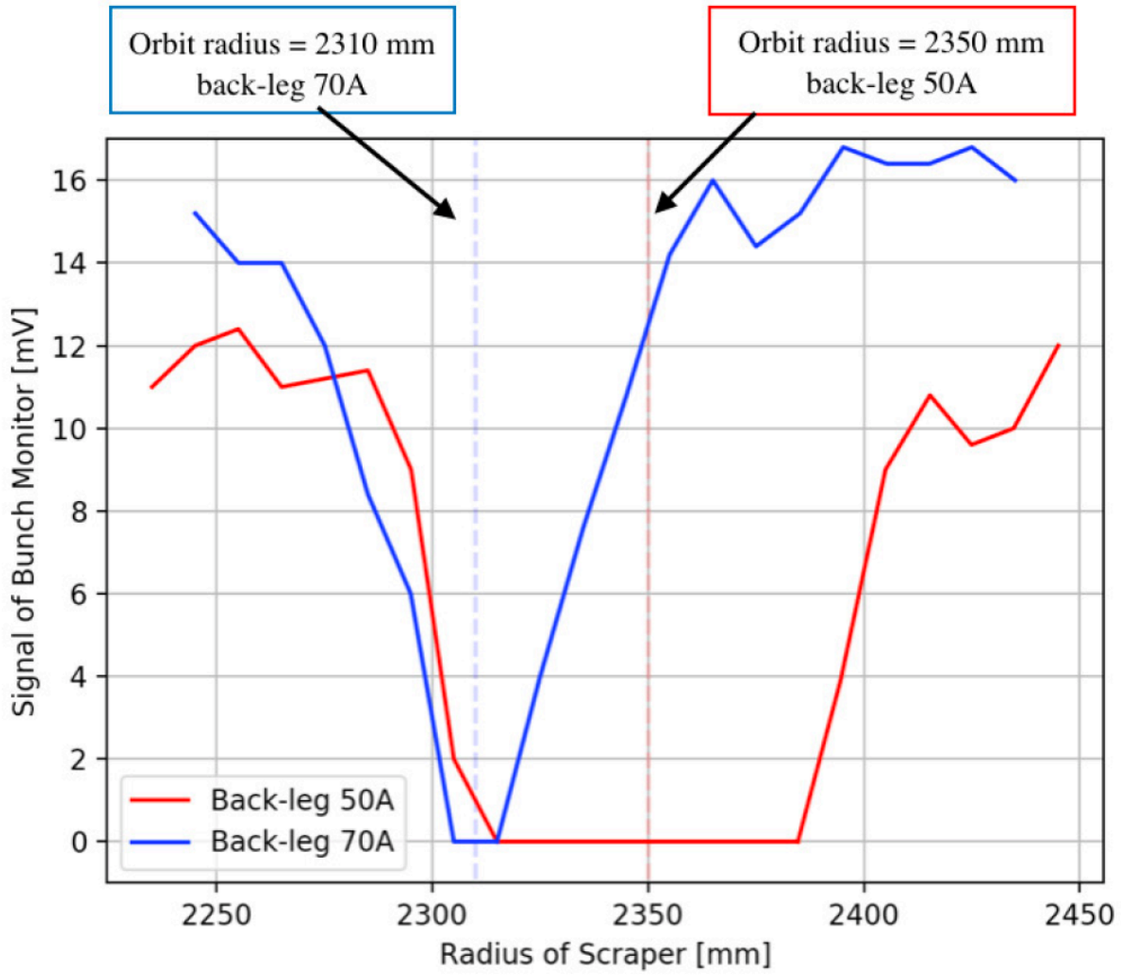




Beam experiment on field error correction & injection matching



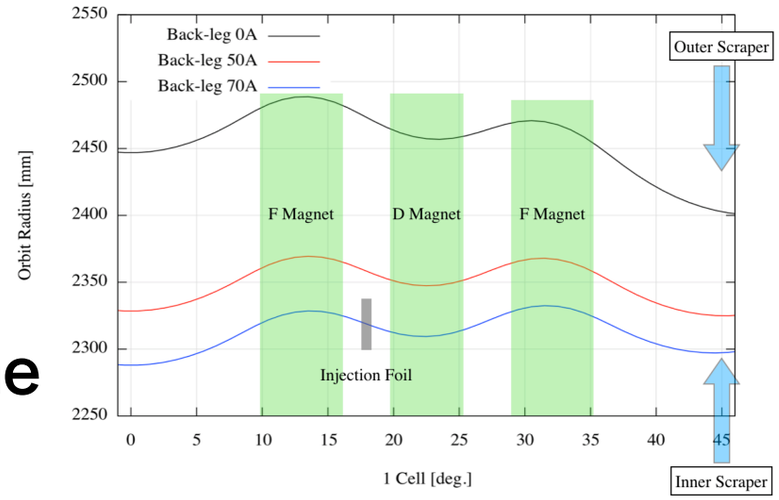
Orbit & beam size measurements



○Results of experiment

- Circulation more than 300 turns using back-leg
- Good injection condition @ back-leg 70[A]

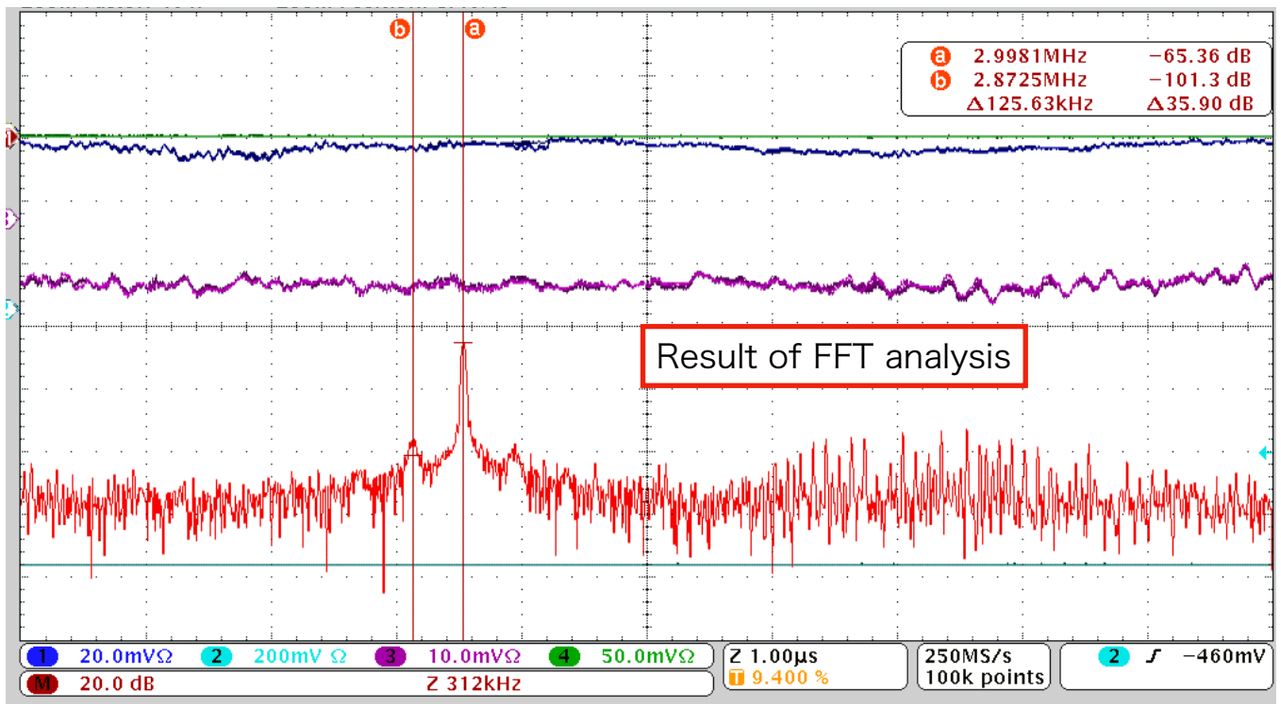
○Got ready to the beam experiment on MERIT scheme

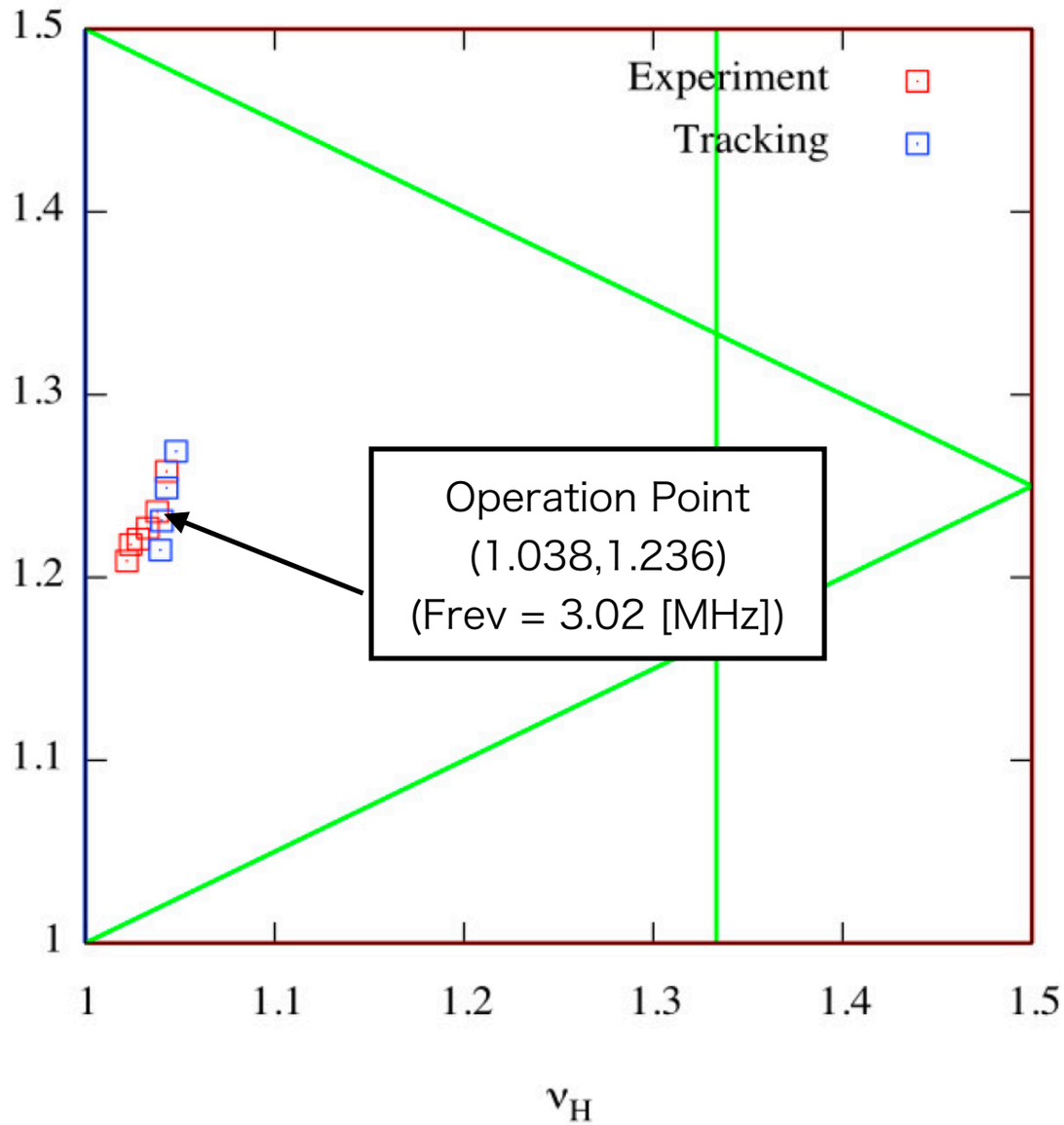


Tune measurement

Side band of horizontal betatron oscillation

Peak of revolution Frequency





- Tracking simulation & experimental study on MERIT scheme

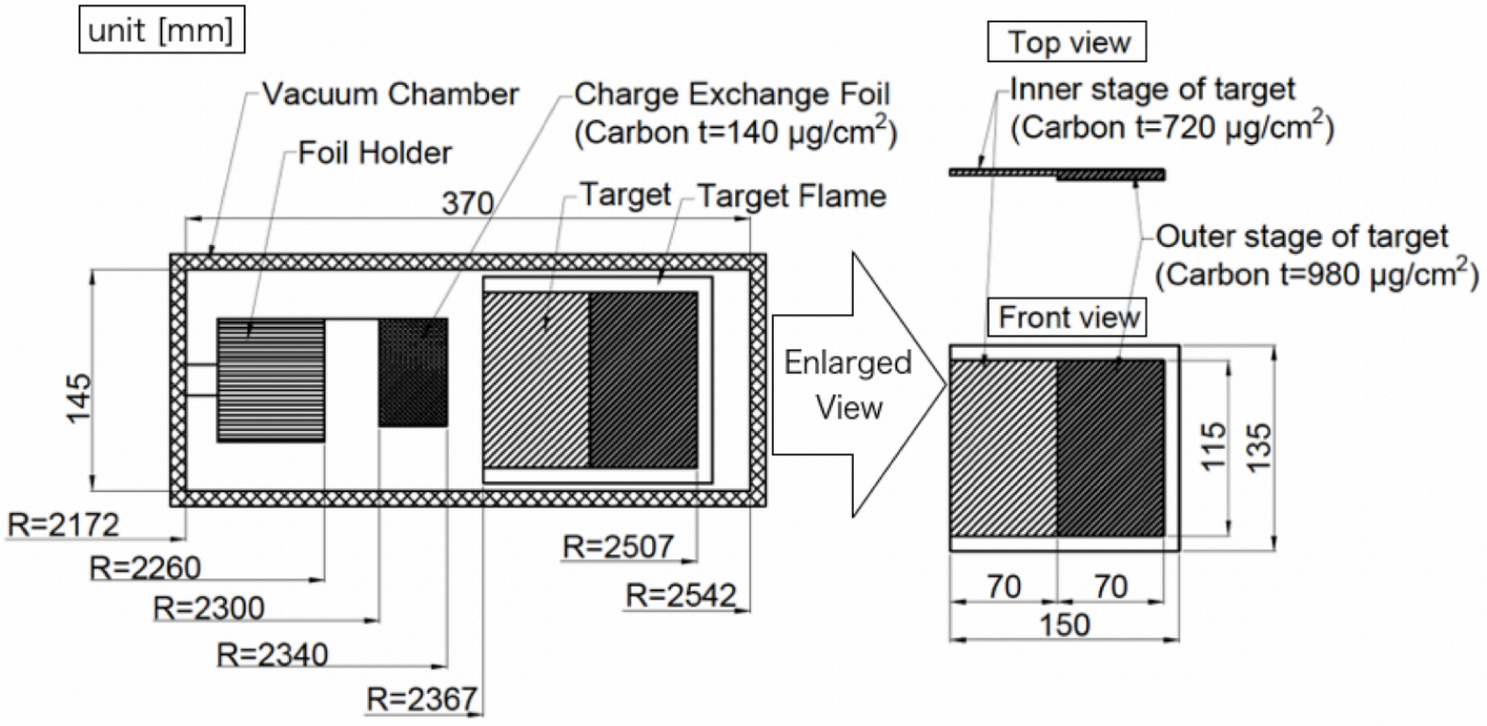
Internal target

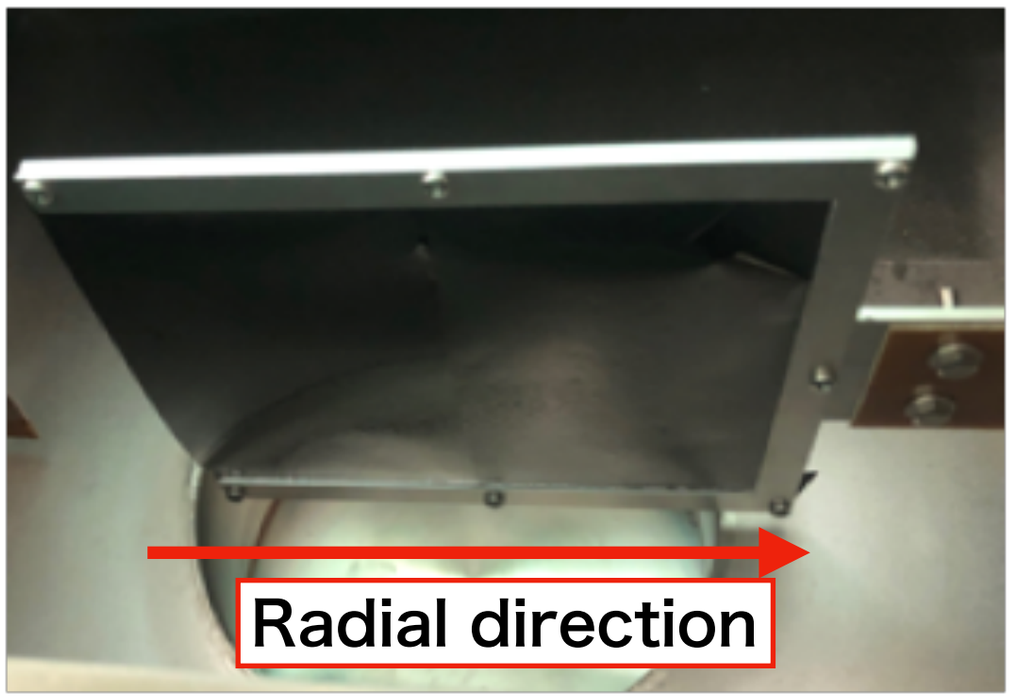
○Design of internal target

□Material : Carbon

□Two stage structure in radial direction

- 1st stage : t=720μg/cm^2, ΔE=27 keV, $\theta_{scatter}$=1.9 mrad
- 2nd stage : t=980μg/cm^2, ΔE=37 keV, $\theta_{scatter}$=2.2 mrad





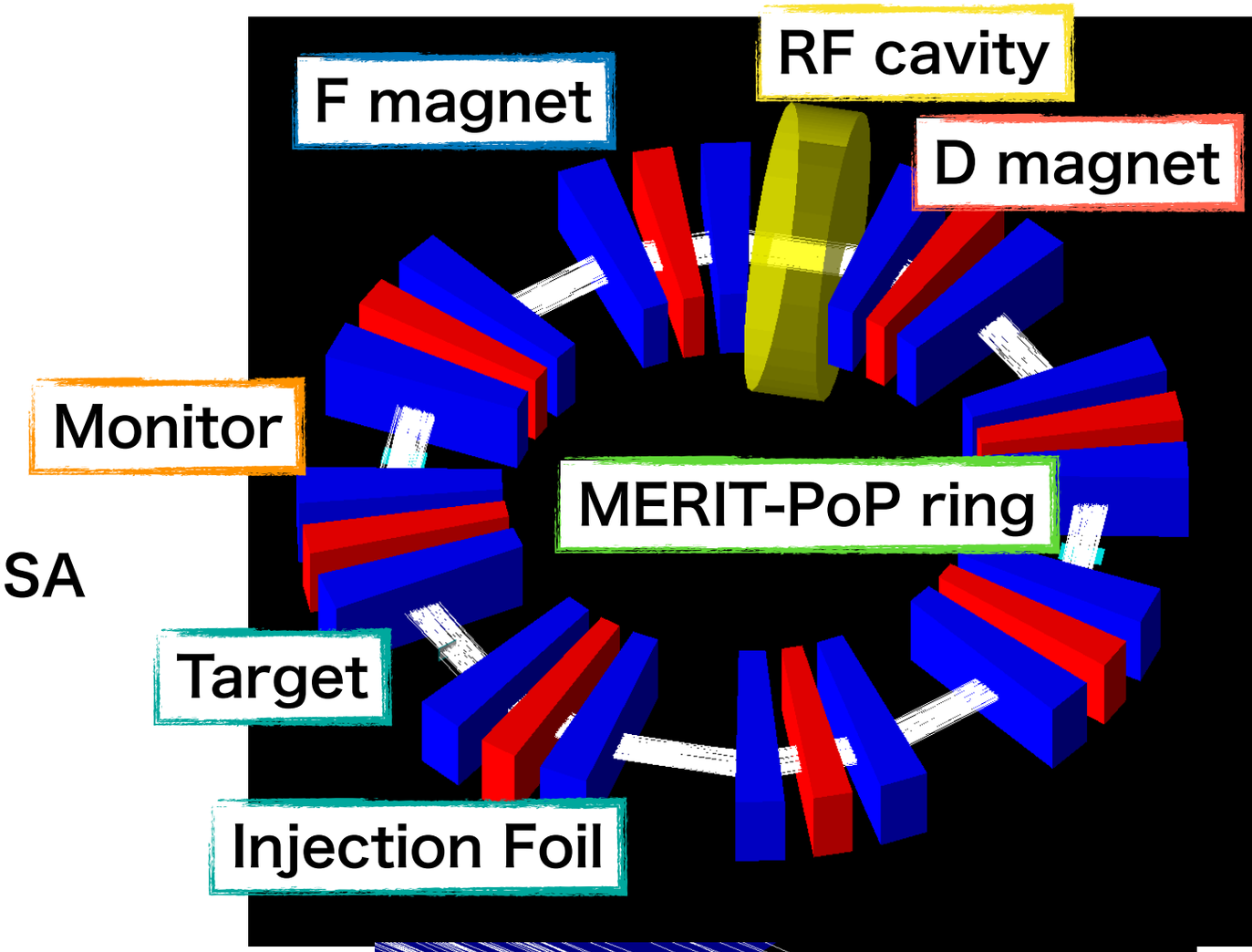
Tracking simulation for evaluation of semi-isochronous acceleration & acceleration and storage

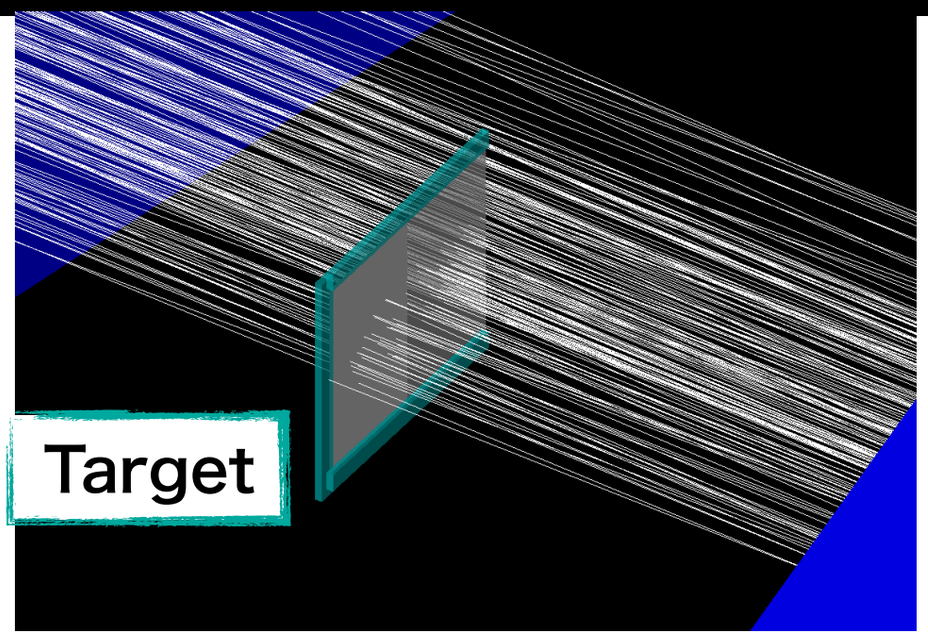
○About tracking simulation
- □Code: G4beamline
  Runge-Kutta + Geant4

○Field map of MERIT-PoP ring
- □3D field map of OPERA3D/TOSCSA

○Physical Aperture
- □Essential to evaluate beam loss
- □Developed code includes
  Vacuum chamber, foil holder, scraper, etc

○RF field
- □Numerical sin wave (V=V0sin(ωt))



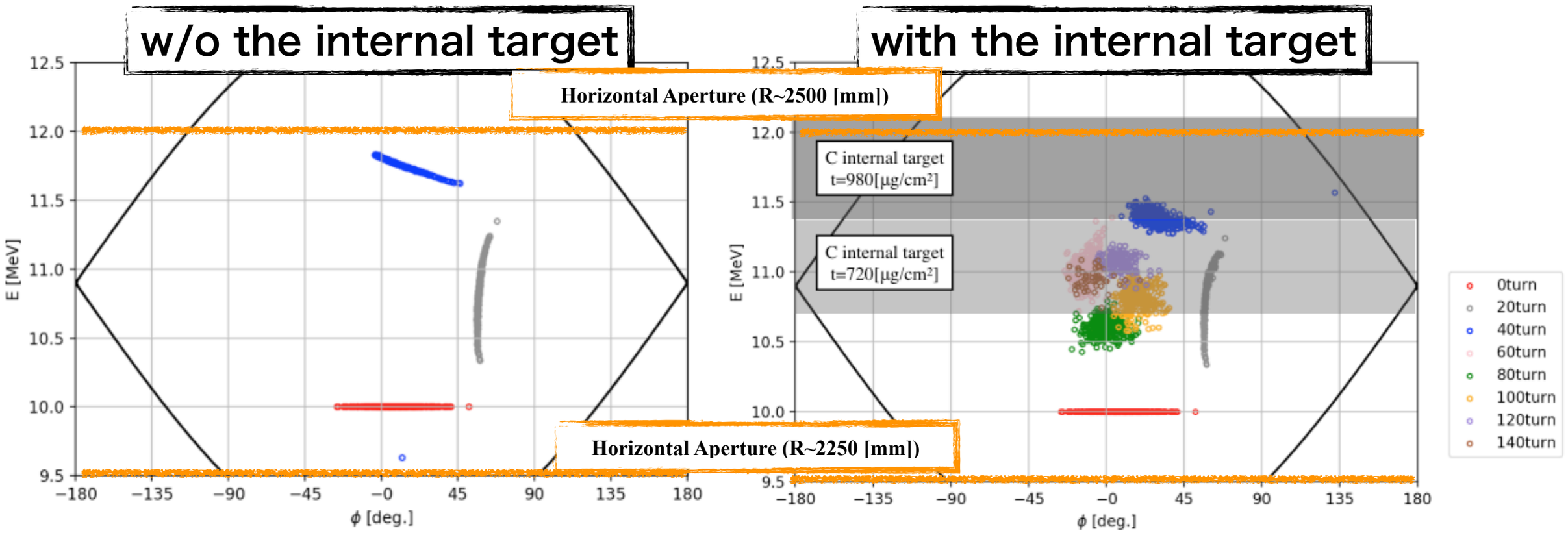


Evaluation on acceleration & storage in MERIT-PoP ring

○Tracking on acceleration & storage using G4BL

○Parameters of tracking simulation

- Initial proton E : 10.0 [MeV]
- RF voltage : 75 [kV]
- Frf : ~18.12 [MHz]
- with & w/o the internal target



○Beam start to hit the internal target from 20 turns.

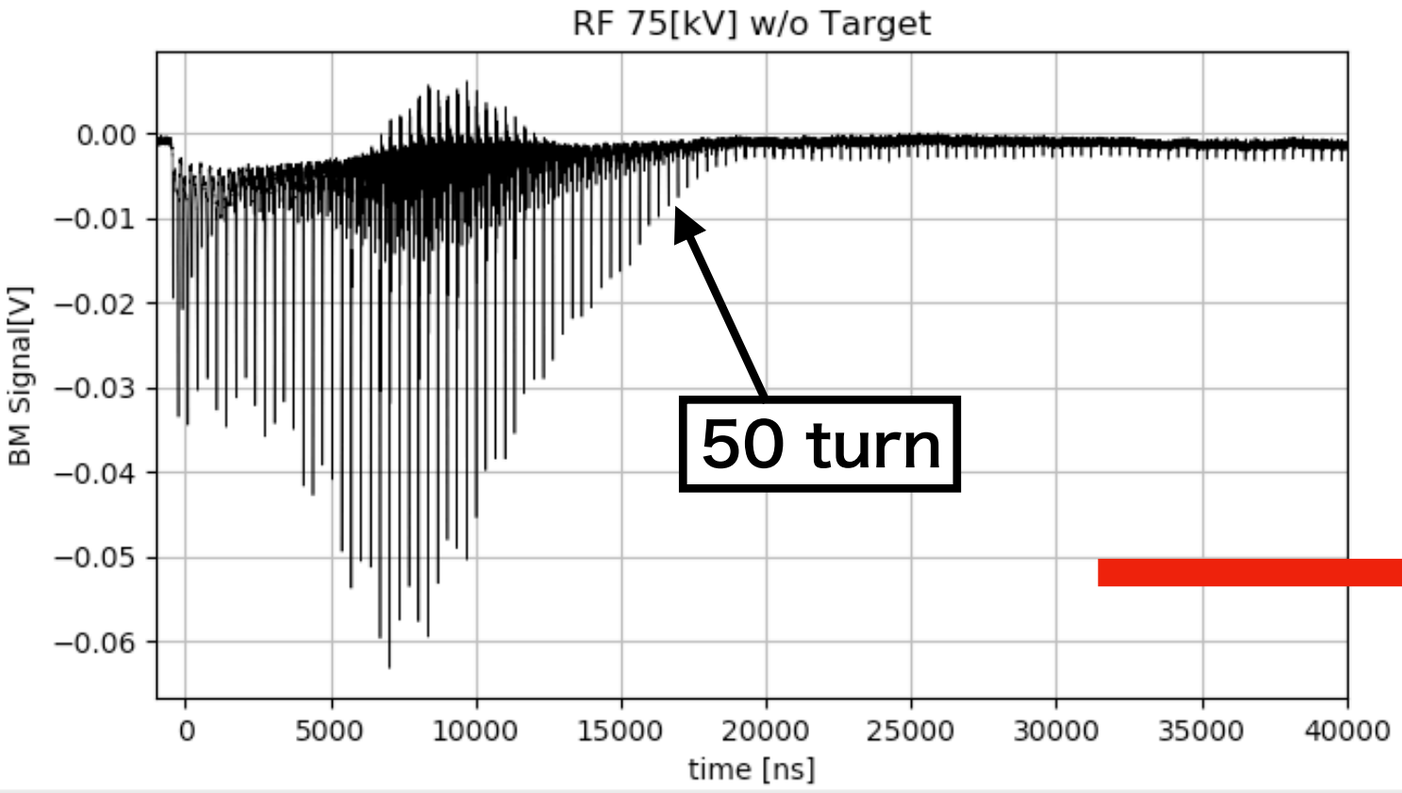
○Beam life is extended more than 100 turns by inserting the internal target.

○Beam loss is started from 100 turns because of emittance growth.

Beam experiment on semi-isochronous acceleration (w/o the internal target)

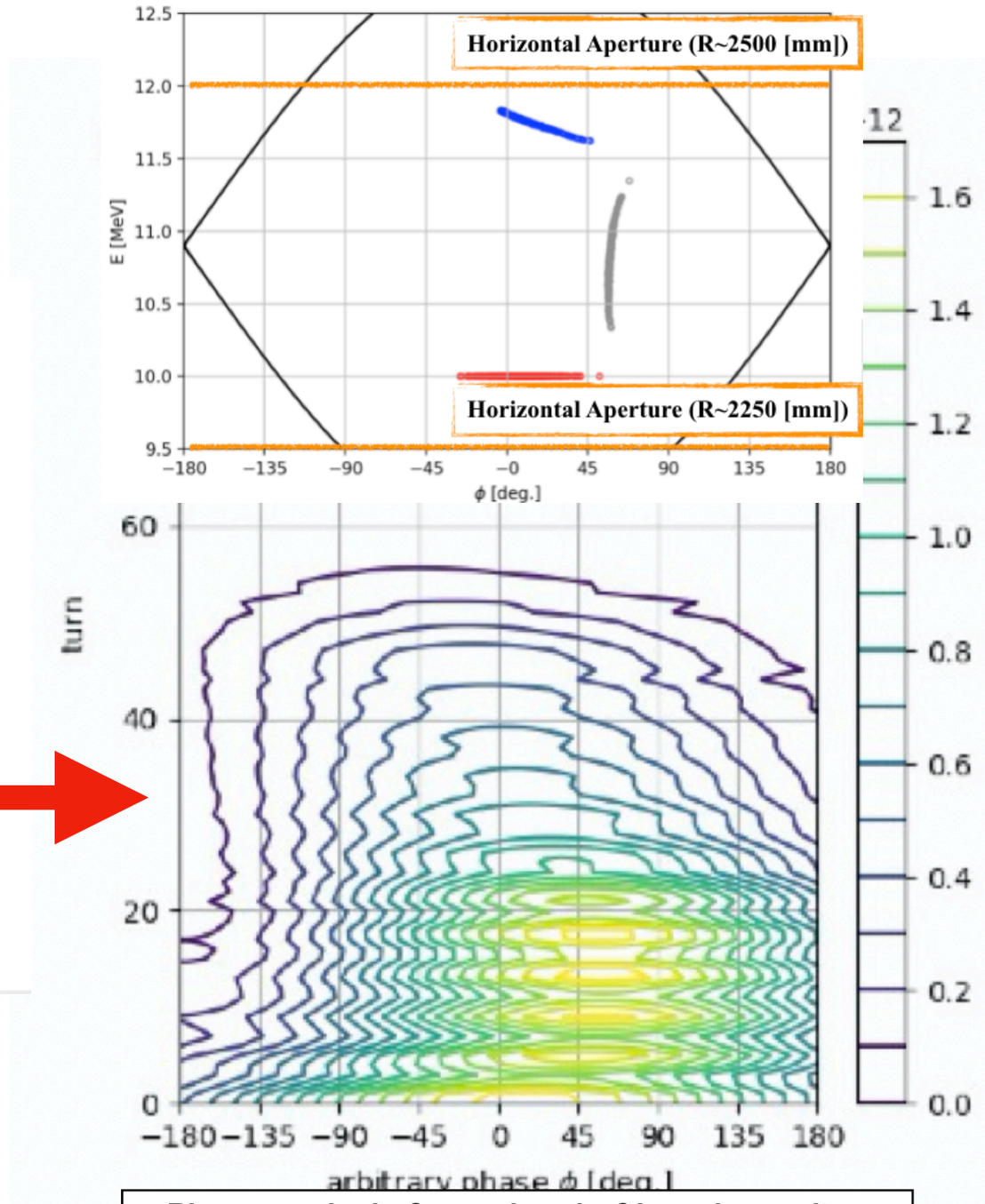
○Parameters of beam experiment

- Injection energy : ~10.0 [MeV]
- RF voltage : 75 [kV]
- Frf : 18.12 [MHz]



Signal of bunch monitor

Results on beam intensity from bunch monitor & G4BL tracking



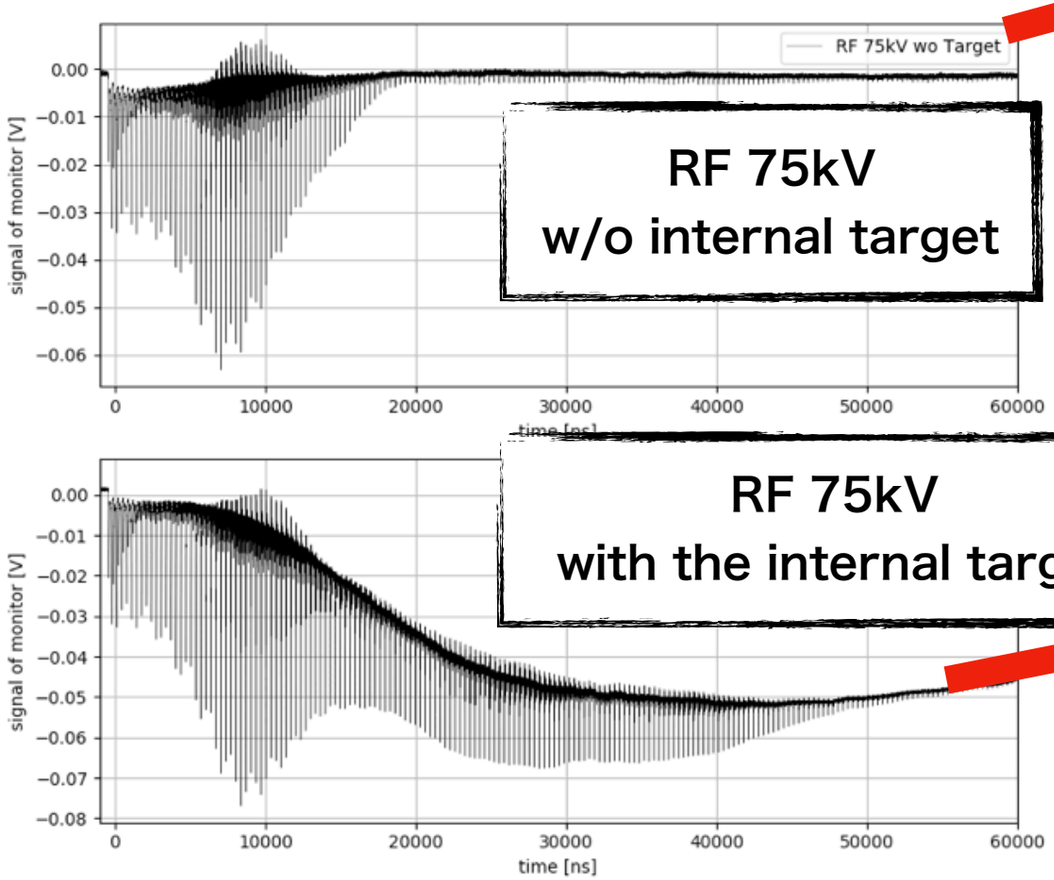
Phase analysis from signal of bunch monitor

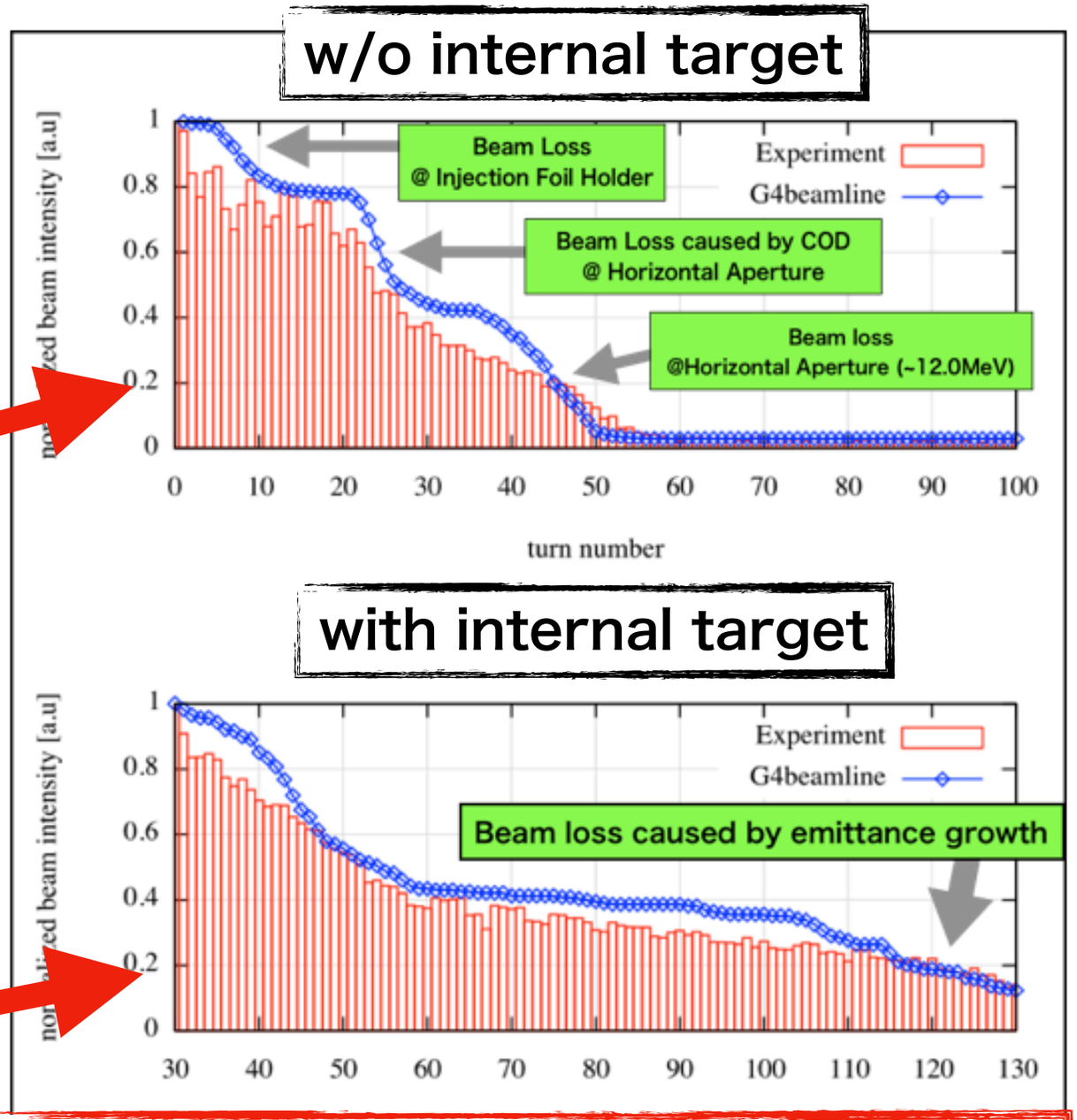
Experimentally confirmed semi-isochronous acceleration in MERIT-PoP ring

Beam experiment on acceleration & storage with the Internal target

○Parameters of beam experiment

- Injection energy : ~10.0 [MeV]
- RF voltage : 75 [kV]
- Frf : 18.12 [MHz]
- Target : R=2367~2507 [mm]





○More than 100 turns in case with the internal target

○Experimental results are in good agreements with G4BL

→Demonstrated the acceleration & storage experimentally

Summary

○Purpose

Proof of principle of MERIT scheme

“Acceleration” & “Storage” using internal target

○Development of MERIT-PoP ring

□Design of PoP-MERIT ring

□Field error correction & injection matching using back-leg

□Beam experiment for validation on correction & injection matching

□Betatron tune measurement

○Study and beam experiment on MERIT scheme

□Tracking simulation using G4BL

□Beam experiment

- Semi-isochronous acceleration

  ->Confirmed semi-isochronous acceleration in MERIT-PoP ring

- Acceleration & storage using the internal target

  ->Confirmed the effect of the internal target.

  ->Good agreement with calculation results.

→Demonstrated the acceleration & storage experimentally

Thank you for your attention