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Muon Cyclotron for Transmission Muon Microscope

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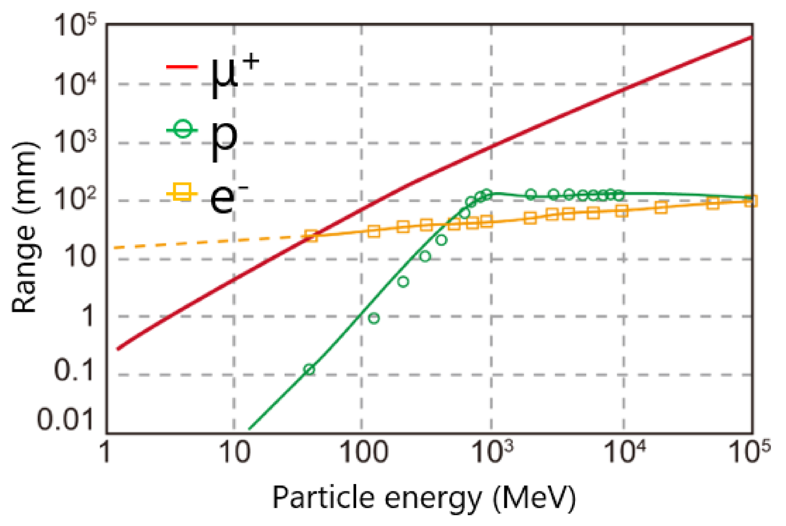
Transmission Muon Microscope

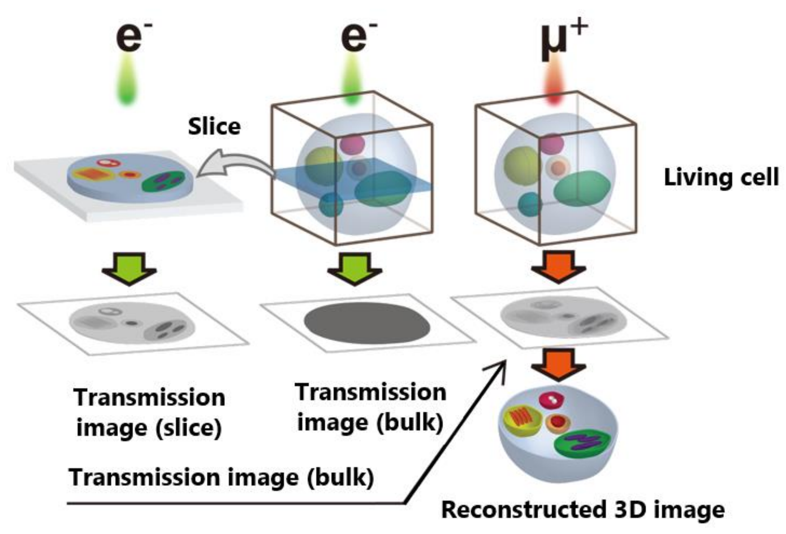
Muon ($\mu^{\pm}$)

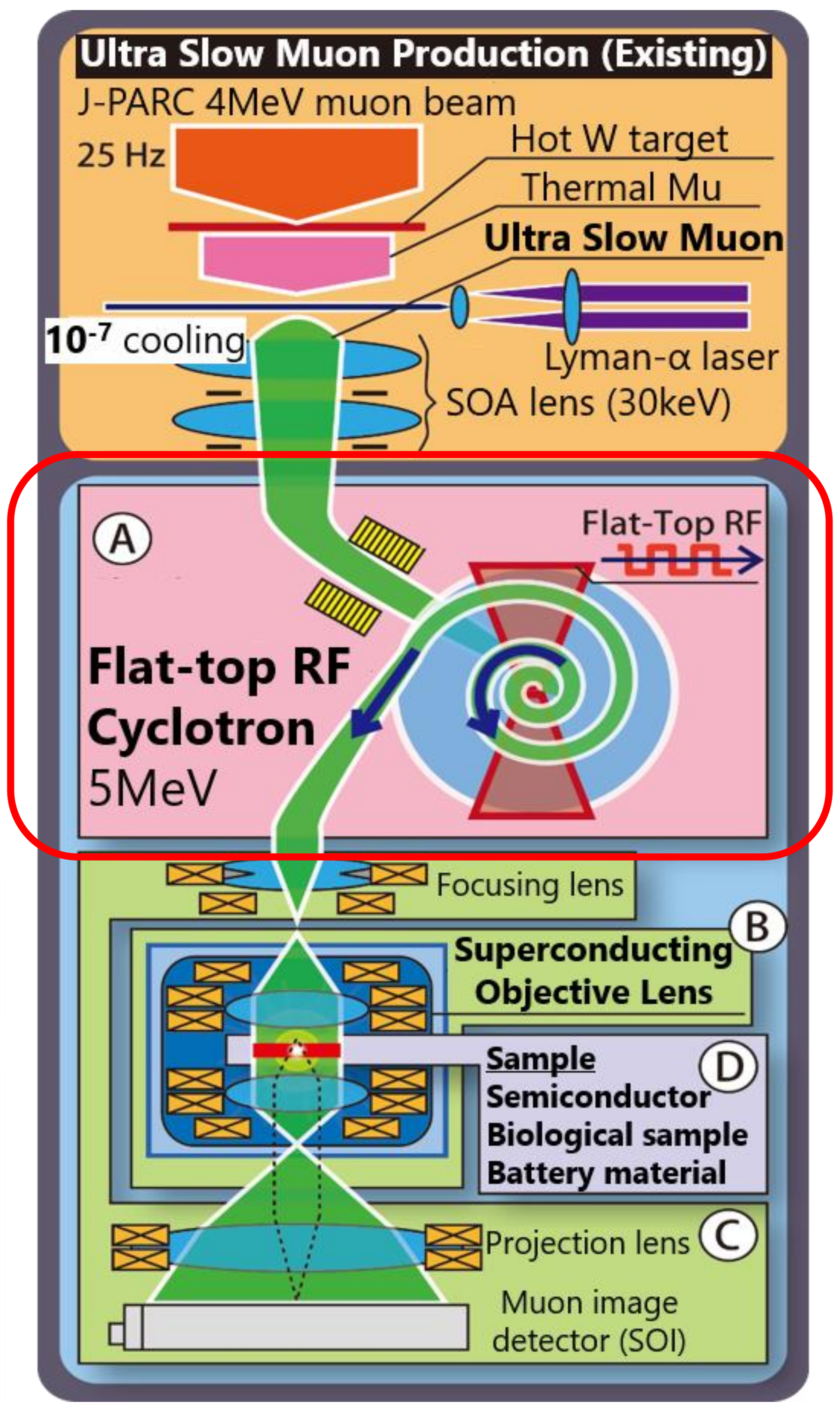
m_{μ} = 105.6 MeV/c^2, τ_{μ} = 2.2 μs

Penetrative power of muons increases as a function of its energy



5 MeV muons enables us to observe living cells (~10 μm) non-desctuctively!



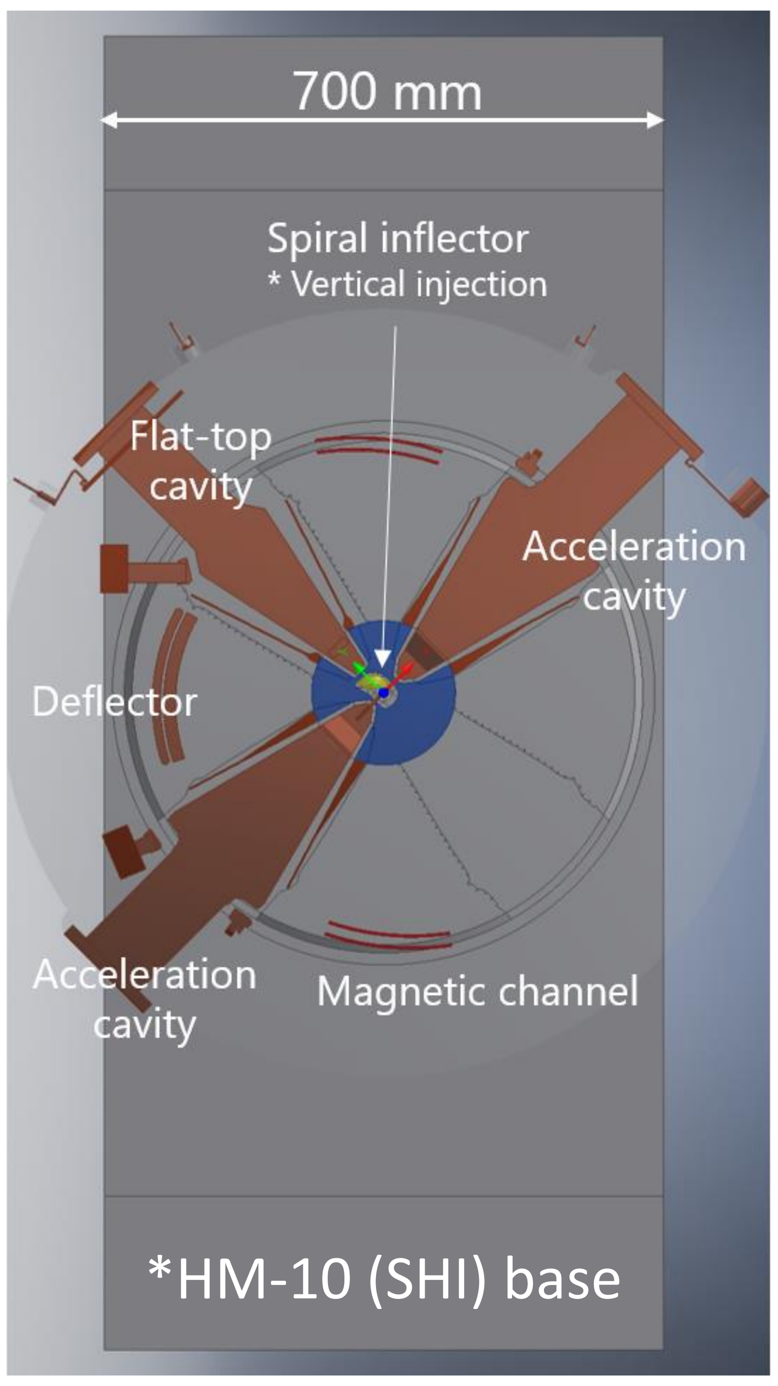


To make a muon microbeam, ultra-slow muon (0.2 eV) should be re-accelerated up to 5 MeV with energy spread ΔE/E = $O(10^{-5})$

Muon Cyclotron

1. Short lifetime (2.2 μs)
2. ΔE/E = $O(10^{-5})$
3. Low cost

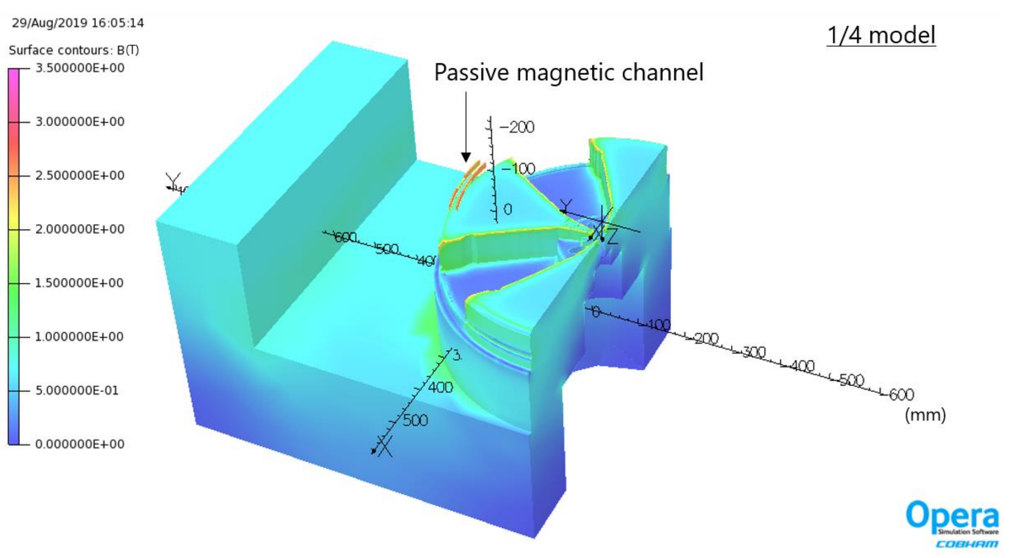
AVF cyclotron with a flat-top RF system

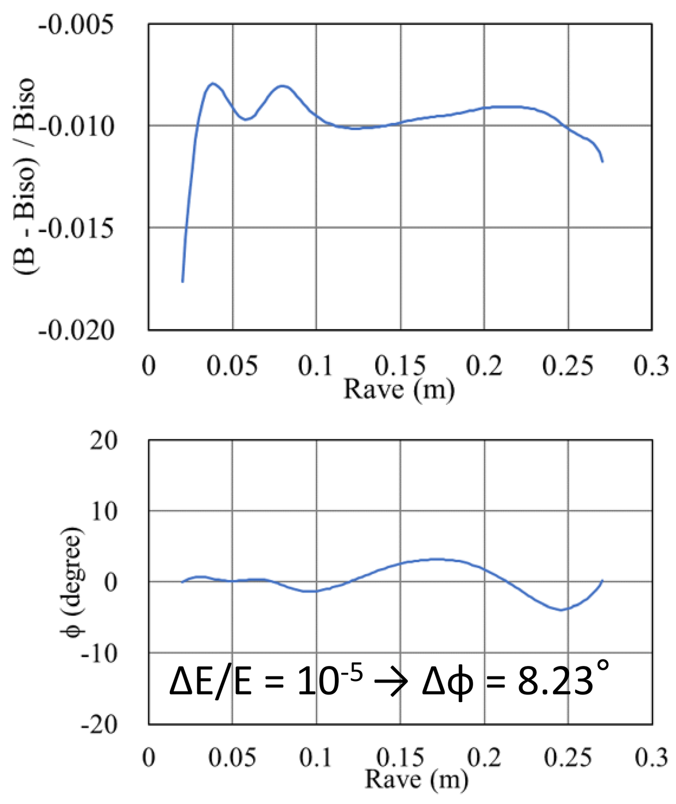


Injection	
Number of particles	10^4 /pulse
Repetition rate	25 Hz
Kinetic energy	30 keV
Pulse width	200 ps
Emittance (1σ)	1π mmmrad
Extraction	
Kinetic energy	5 MeV
Energy width (ΔE/E)	$O(10^{-5})$
Emittance (1σ)	0.1π mmmrad
Magnet	
Average field	0.4 T
Number of magnet sectors	4
Hill gap	54 mm
Valley gap	200 mm
Extraction radius	262 mm
Trim coils	None
RF	
Number of dees	2(main) / 1(flat-top)
Harmonic mode	2
RF frequency	108 MHz
Dee voltage	50 kV
Flat-top RF frequency	324 MHz
Flat-top dee voltage	10 kV
Injection	
Spiral inflector	±4.5 kV
Extraction	
Deflector	±7.5 kV/mm
Magnetic channel	Passive

3D EM Simulations

Magnetic field simulated using Opera-3D





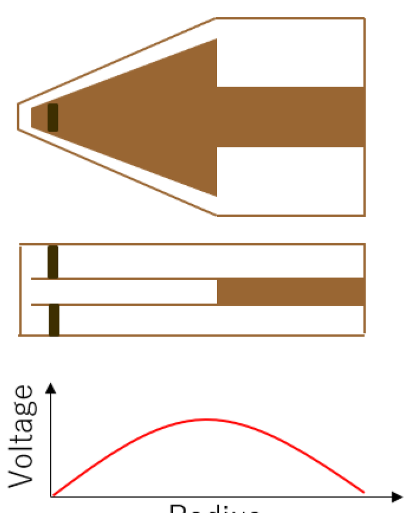
Isochronous condition is well satisfied even without passive shimming.

✓ ±3 mm in R > 90 mm is possible.

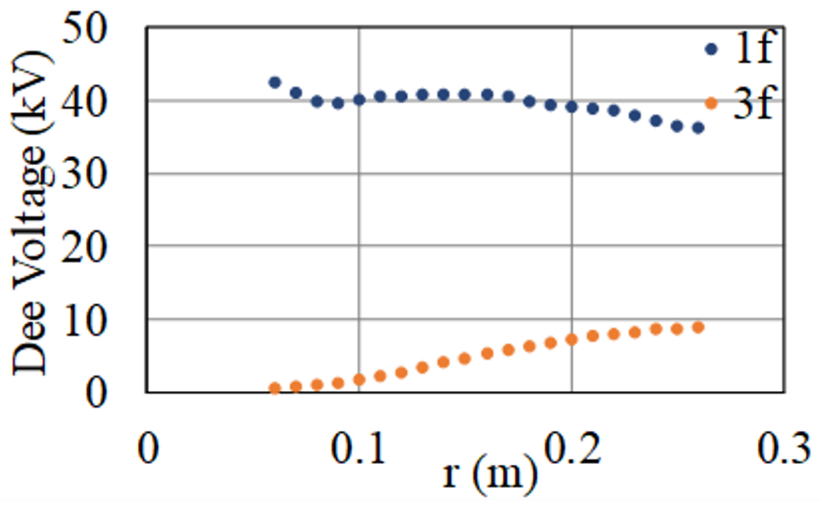
Flat-top (3f) cavity simulated using CST MWS

λ/2 resonator

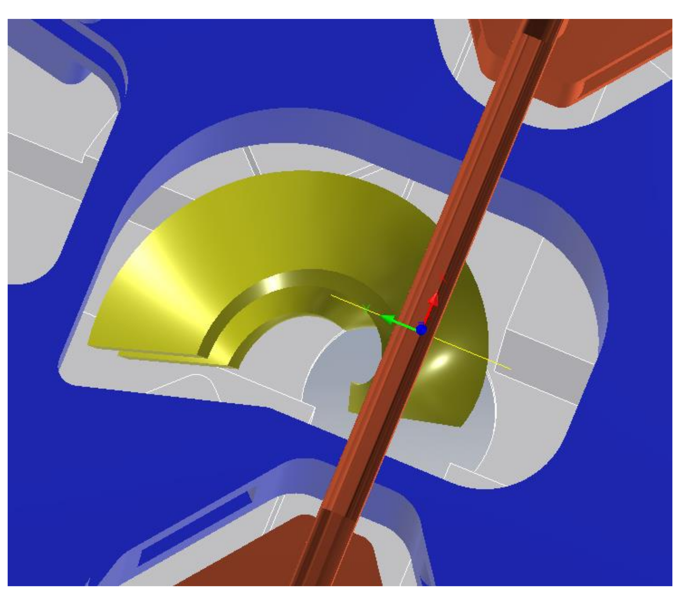
based on Y. Kumata's open patent.

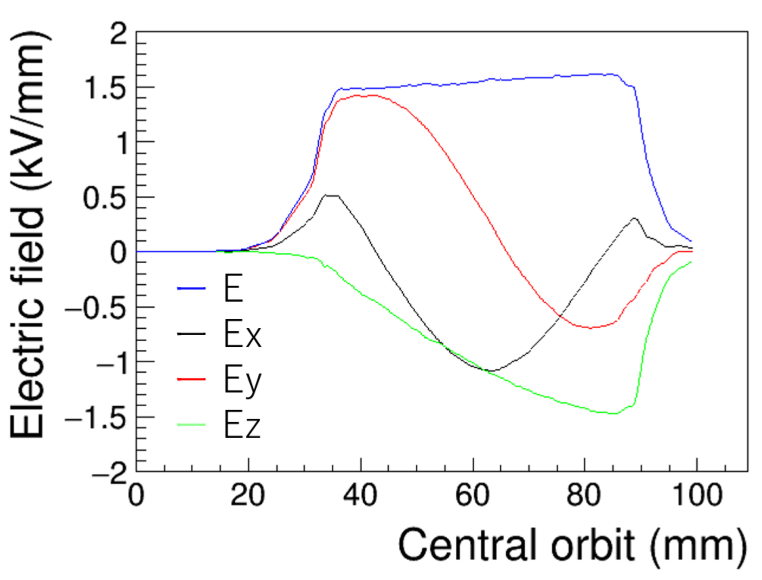


- f_0(3f) = 324 MHz
- Q_0(3f) = 5650



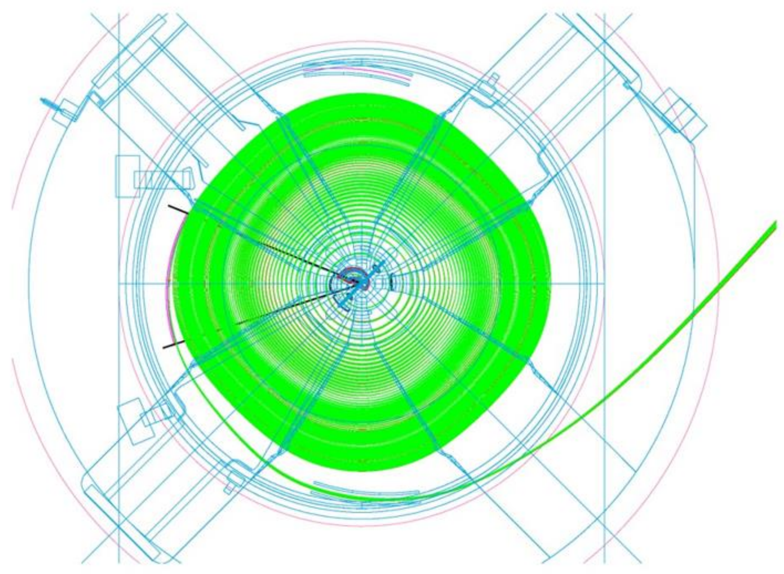
Spiral Inflector simulated using Opera-3D





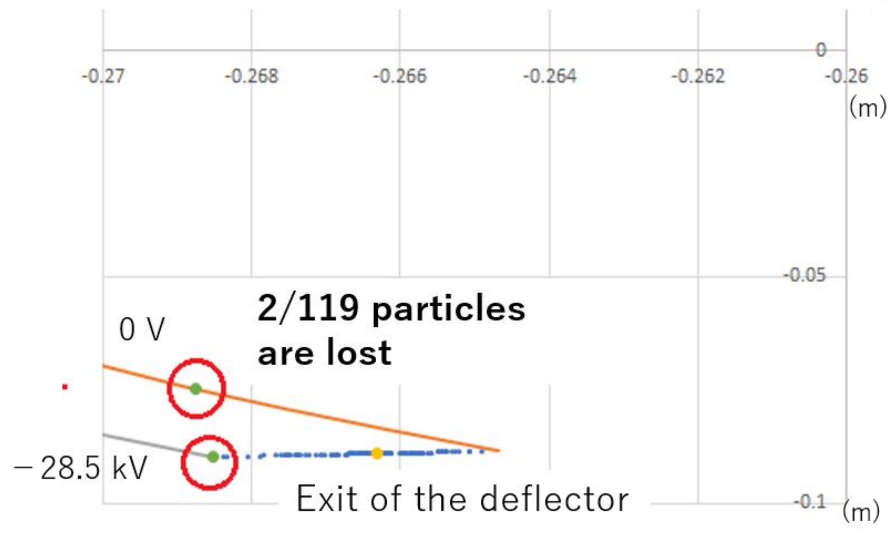
Orbit Calculation

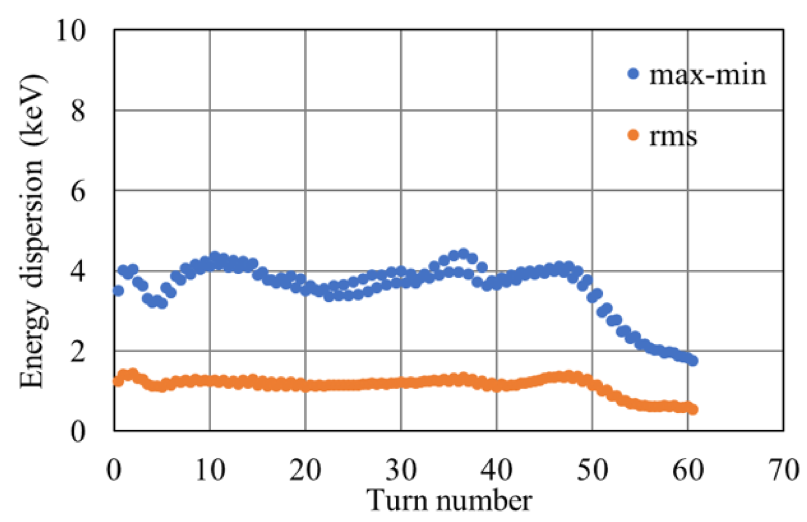
The 4th order Runge-Kutta method is used.



Current results

- 5 MeV by 59 turns (=1.1 μs < τ_{μ})
- ε_R and ε_z ~ 0.3π mm mrad
- Extraction loss is only 2% in the deflector
- ΔE/E < 2 × 10^{-4}





To reduce ΔE/E and ε furthermore, we are redesigning the central region of the cyclotron now.

Summary

- An AVF cyclotron with a flat-top RF system is under development to realize a muon microbeam for the transmission muon microscope project at the J-PARC muon facility (MUSE).
- The muon cyclotron is designed in detail using 3D EM simulations (OPERA, CST) and multiparticle orbit calculation.
- Energy spread less than 2 × 10^{-4} has been achieved already, but we are trying to reduce it down to O(10^{-5}) by optimizing the central region.