

A novel scheme of negative muon beam production

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Negative muon

- **Negative muons are produced in the decay of negative pions.**

- Mass : $105.7\text{MeV} \sim 200 \times$ electron mass

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

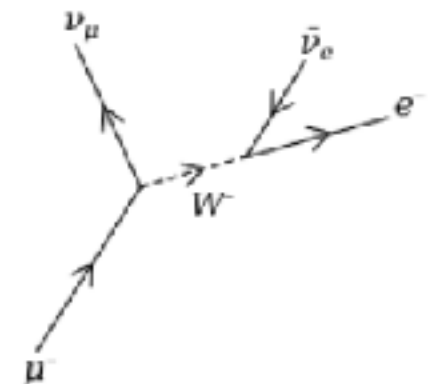
- Lifetime : $2.2\mu\text{sec}$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

- **Muonic atom**

- Muon X-ray : cf. 1.7 keV for μH^0 atom

- Captured by nucleus ($Z > 20$) : β decay, $Z \rightarrow Z-1$: nuclear transformation



- **Application**

- Muon Catalyzed Fusion

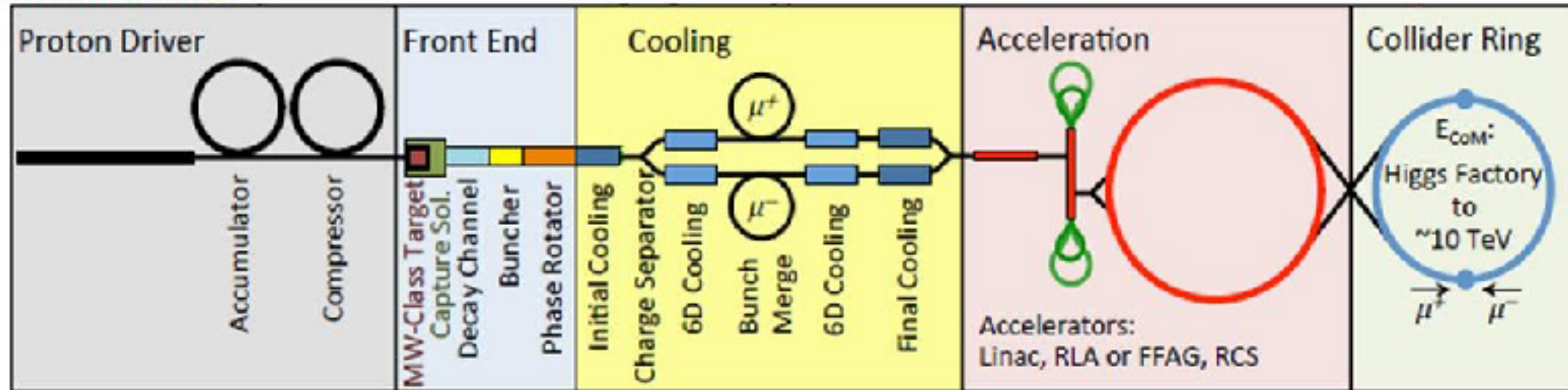
- μDT molecule formation : inter-distance of D and T nuclei $< 1/200$ small

- Muon Collider

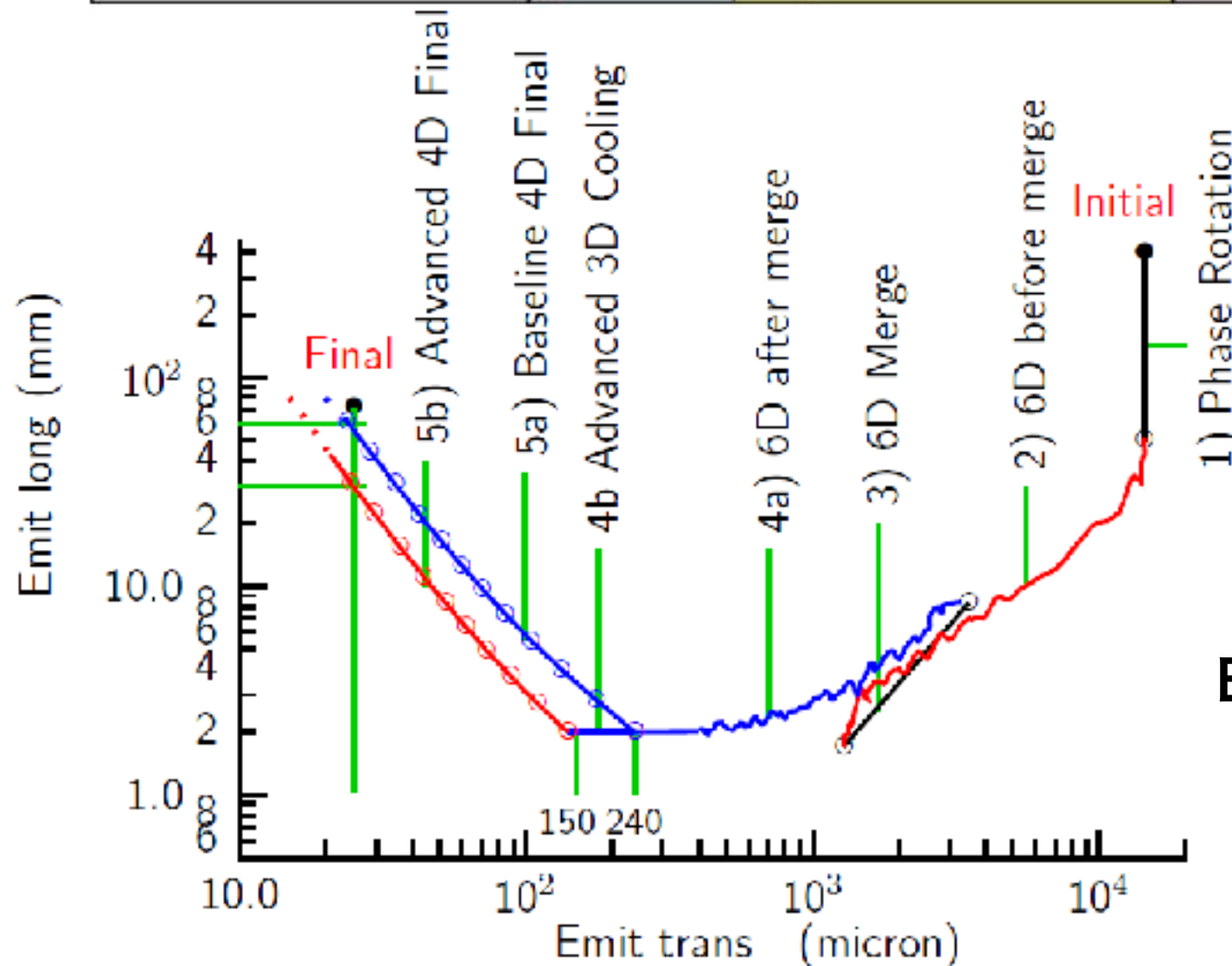
- Lepton collider : $\mu^+\mu^-$ $\sqrt{s} \sim 5-10\text{TeV}$

Muon Collider

Muon Collider



MAP scenario



Emittance reduction protocol by Ionization Cooling

Muon beam generation

-low emittance and continuous beam-

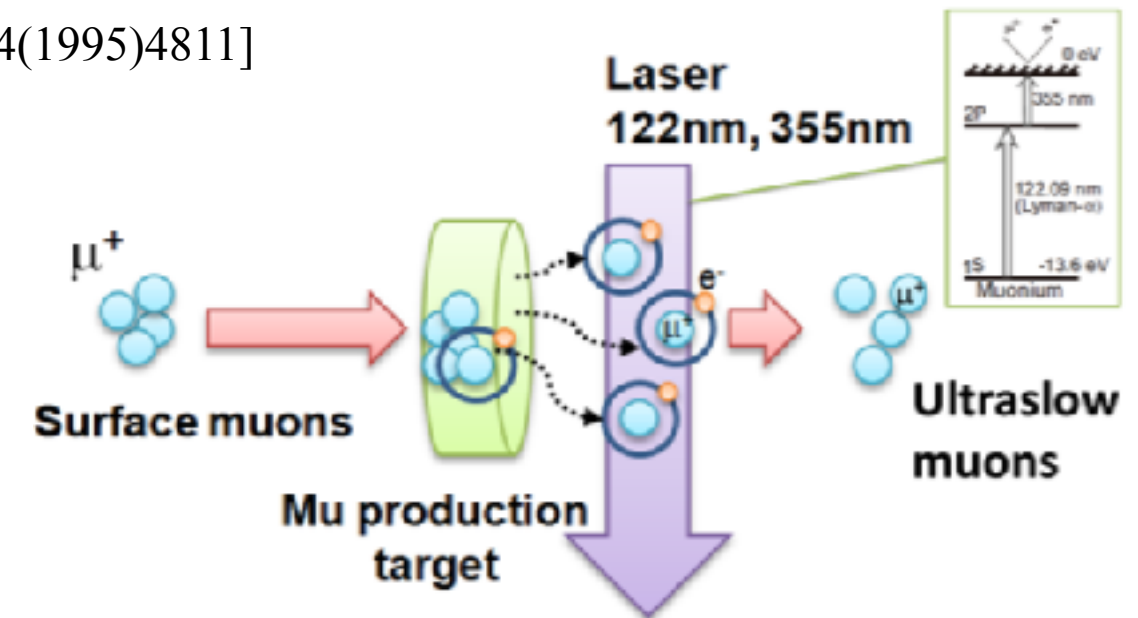
- **Positive muon: Two schemes(under development)**

- (1) Ionization of Muonium (Mu) : KEK-JPARC[PRL.,74(1995)4811]

- Laser ionization of Mu($1s \rightarrow 2p \rightarrow \text{free}$)

- (2) Frictional cooling : PSI[PRL., 125,164802(2020)]

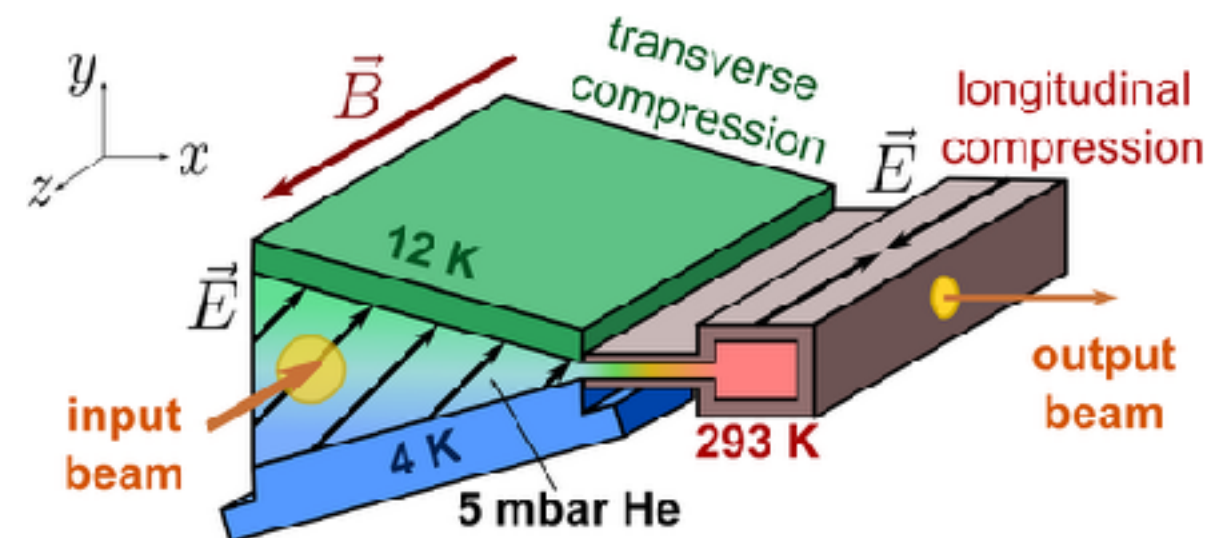
- Cooled by LT-helium & wall,
 - $\epsilon > 0.2 \text{ MeV}/c$ avoiding Mu formation



- **Negative muon: No practical scheme**

- Frictional cooling cannot be used because,

- Muonic atoms (MuX) form easily.
 - Hard to detach (strip) μ^- from MuX ,
 - BE is $(m_\mu/m_e)^2 \sim 40,000$ times large.



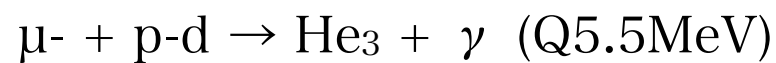
- **New scheme: low emittance μ^- beam with accelerated μHe^+ ions from MuCF**

Muon Catalyzed Fusion

- MuCF reaction

- First observation in LH2 Bubble chamber.

L.W. Alvarez, 1956.



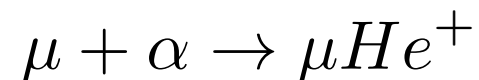
- Energy output

- d-t fusion : $n(14.1\text{MeV})$, $\alpha(3.5\text{MeV})$
- μDT molecule formation : $>1000\text{-}2000\text{cycles}/\mu\text{-life}$

Energy gain ideally $\rightarrow 20\text{-}30\text{GeV}/\mu^-$ but reality $2\text{-}3\text{GeV}$,

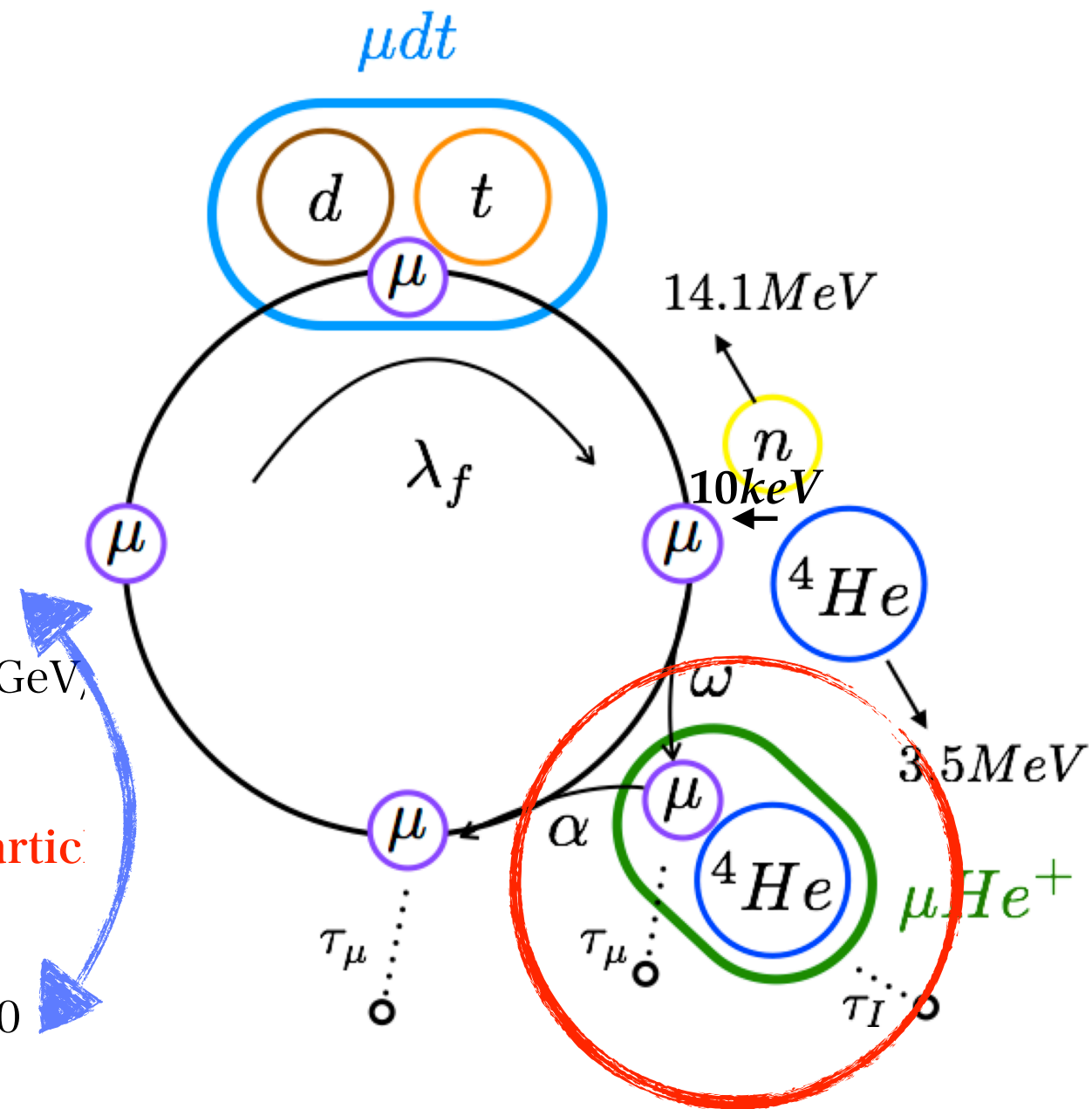
Muon production energy $\sim 5\text{GeV}/\mu$

- Restriction of energy gain \rightarrow **Muon trapping by α particle**



- Chain reaction stops. $\rightarrow 100\text{-}200\text{cycles}/\mu\text{-life} : \sim 1/10$
- Energy gain : $20\text{-}30\text{GeV}/\mu \rightarrow 2\text{-}3\text{GeV}/\mu$
- MuCF break-even ~ 2.5 times less.

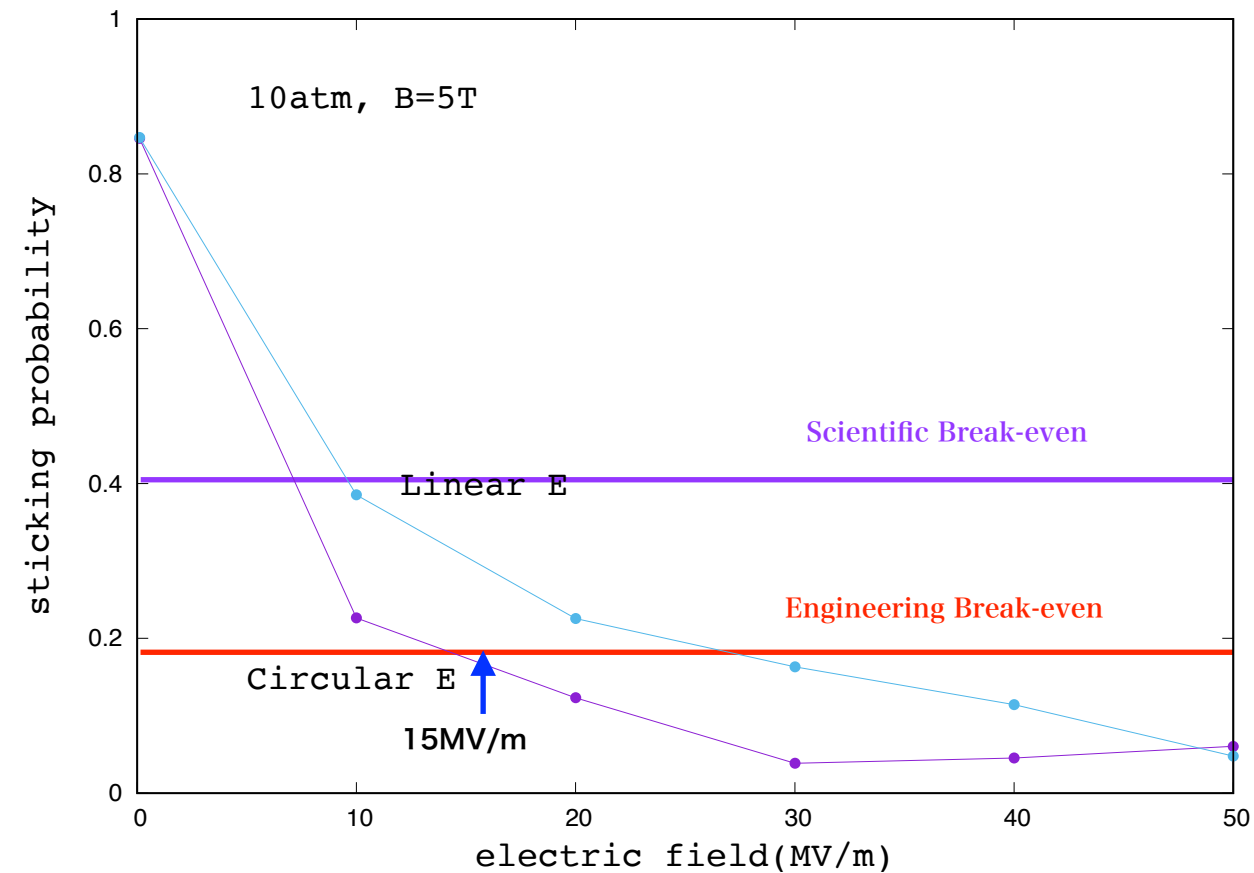
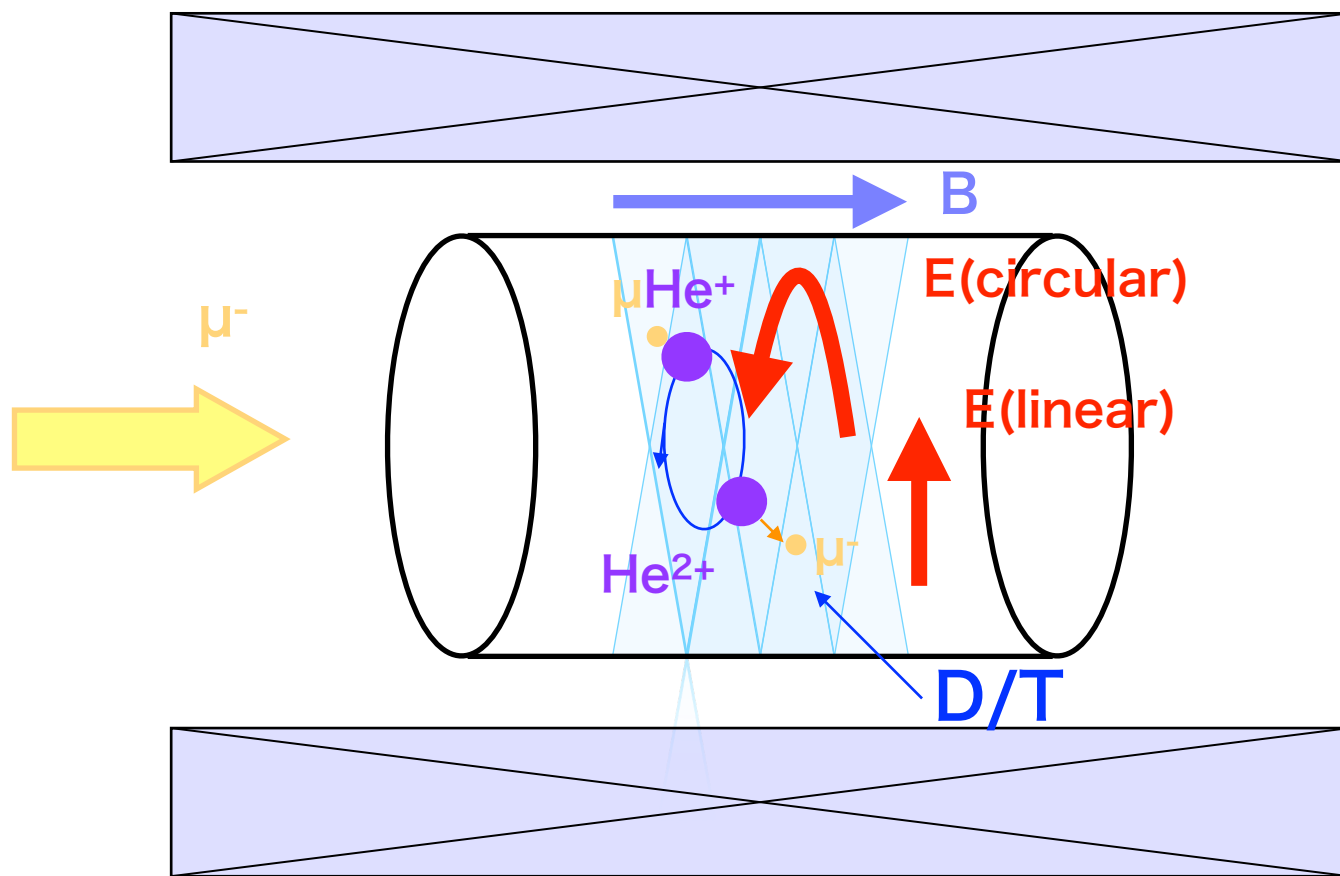
- To overcome restrictions : Y.Mori: <https://doi.org/10.1093/ptep/ptab111>



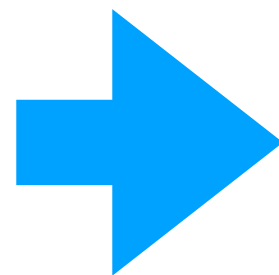
$$\frac{N_f^\infty}{N_\mu^0} = \left[\frac{1}{\lambda_f \tau_\mu} + W_0 \right]^{-1} \sim 100.$$

Cyclotron Resonance Acceleration of μHe^+ -simulation-

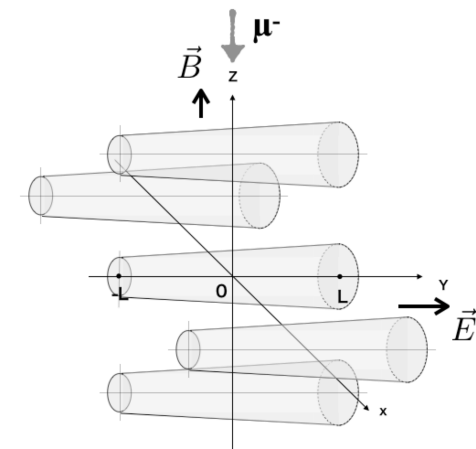
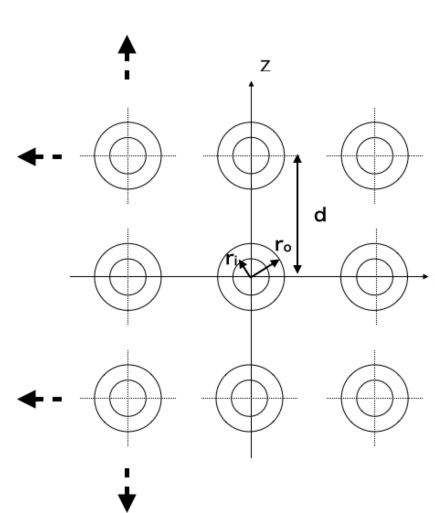
μHe^+ trajectory



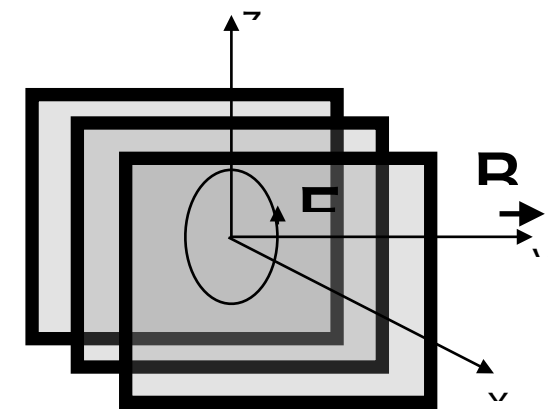
Cyclotron resonance acceleration of μHe^+ ions with RF field using localized DT target



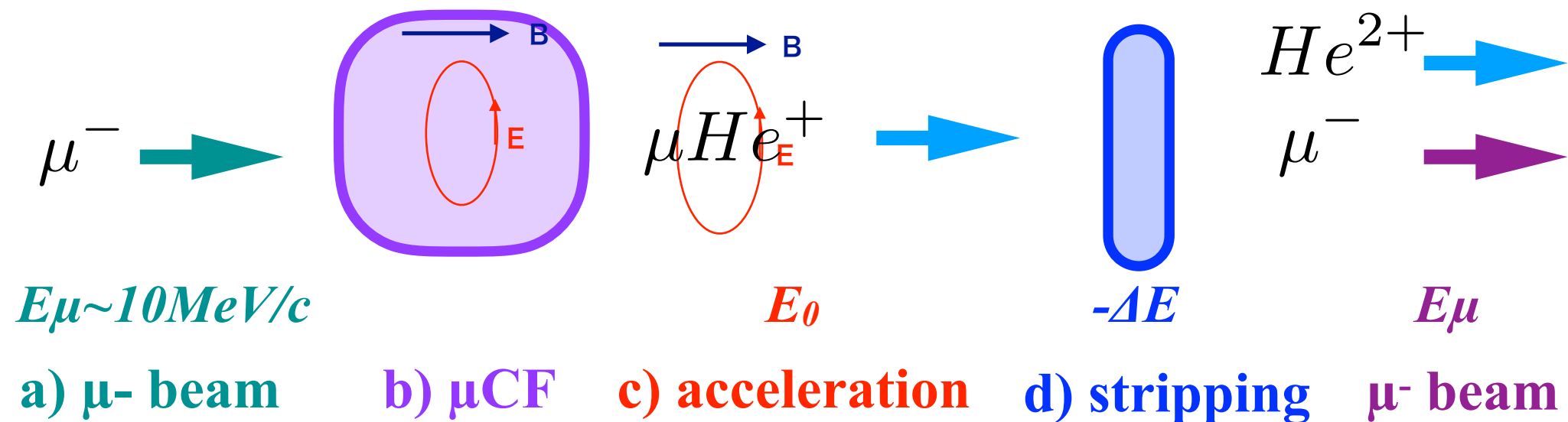
Localized DT target
(conical jets or liquid plates)



p Φ ~2-5atm
(Φ :occupation factor)



Generation of negative muon beam with accelerated μHe^+ ions



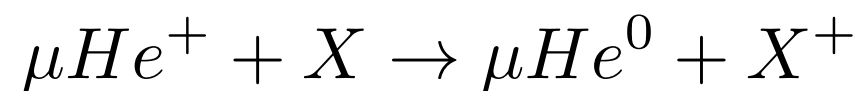
Scheme

- Negative muons produced by hadron accelerator
- Generation of μHe^+ ions with MuCF
- Acceleration of μHe^+ ions
- Stripping and formation of μ^- beam

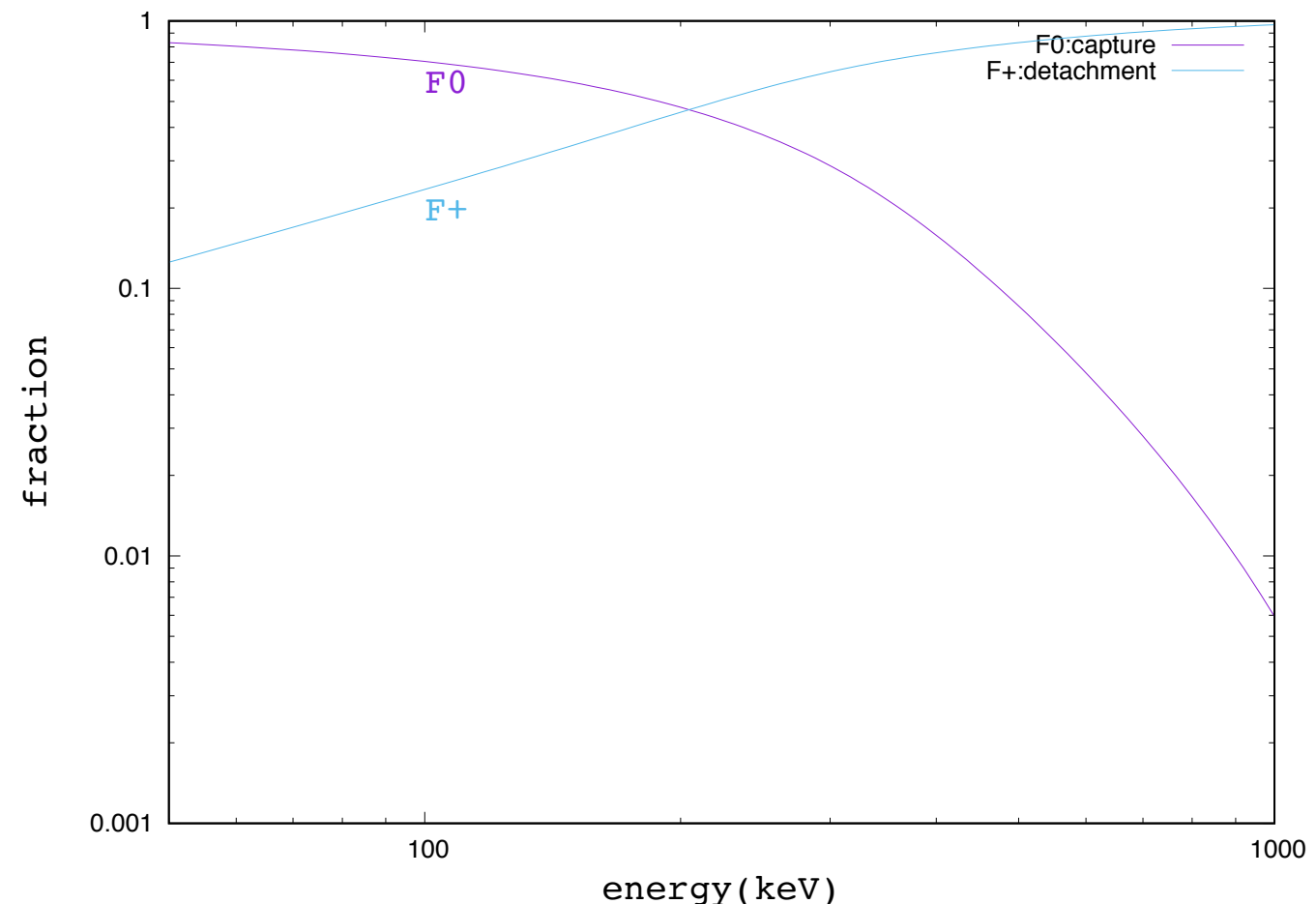
Difficulties

(1) Neutralization of μHe^+ ion by electron capture

- If μHe^+ ion energy is $< 1\text{MeV}$, μHe^+ ion captures an electron and neutralized.

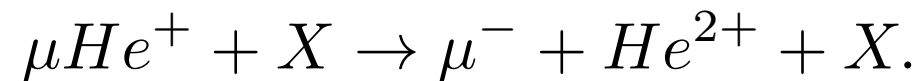


- The acceleration of μHe^+ ions become difficult.
- **In the MuCF reaction, fortunately, the initial energy of μHe^+ ion is 3.5MeV , which can escape neutralization.**
- **But, while passing through the medium, it is slowing down and captures an electron.**
- **Energy recovery and acceleration of μHe^+ ions are required to avoid neutralization.**



Equilibrium fraction of μHe^+ ions and μHe atoms as a function of μHe ion/atom energy

(2) Energy loss of μ^- through stripping



- $\Delta E(\mu\text{He}^+) = \Delta E(\mu)$ because $v_\mu = v_{\mu\text{He}}$. $\rightarrow E_\mu$ after stripping must be larger than ΔE .
- Stripping probability of μHe^+ ion into μ^- & He^{2+} can be evaluated by,

$$\alpha = \exp \left[- \int_{E_0}^{E_f} \frac{\sigma(E)n}{S(E)} dE \right]$$

- Thus, when $\alpha = 1/e$, the energy loss, $\Delta E = E_0 - E_f$, becomes,

$$\Delta E \simeq \frac{-S(E_0)}{\sigma(E_0)n}$$

- The energy of negative muon, E_μ , must be larger than ΔE because its energy loss at the stripping target also equals ΔE . Therefore, E_0 should be,

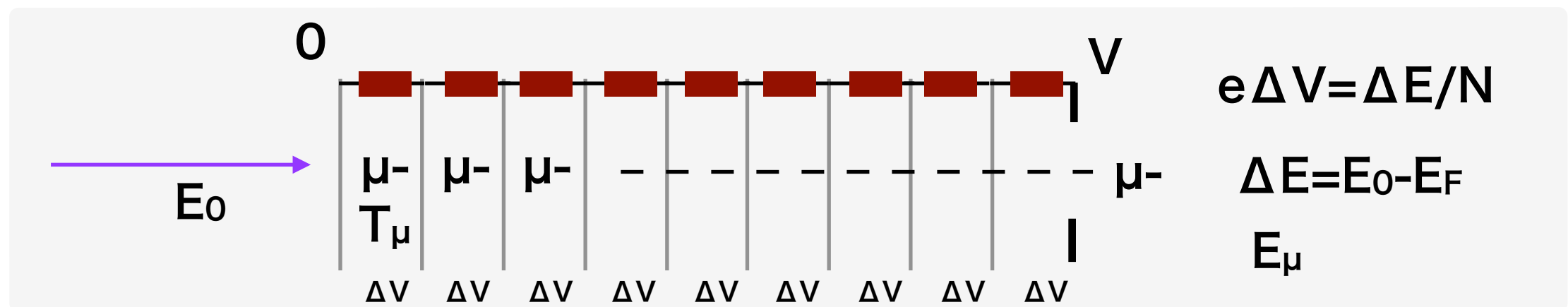
$$E_0 > \left[\frac{-S(E_0)}{\sigma(E_0)n} \right] \times \left(\frac{m_\mu}{m_{\mu\text{He}}} + 1 \right)$$

- cf. Stripping foil \rightarrow Be: thickness $50\mu\text{m}$

$\Delta E \simeq 2\text{MeV}$. Thus, $E_0 > 82\text{MeV}$. \leftarrow This is too high!

- E_0 can be low, if $S(E_0)$ decreases “effectively”. \rightarrow **Energy Recovery by re-acceleration**

Energy recovery of μ^- for relaxing the acceleration μHe^+ ions



- In order to lower the energy of μHe^+ ions, the stopping power $S(E)$ of negative muons at the stripping foil must be effectively decreased.
- For that purpose, the energy recovery of negative muon is useful.
- If $S(E)$ of the negative muon can be made virtually zero in the stripping process, E_0 can be greatly.
- This is also the “**Ionization Cooling**” of negative muons.

Ionization cooling of negative muon beam during stripping

- The energy recovery of negative muon beam through stripping is actually ionization cooling itself.
- Change in emittance evaluated by the rate equations ;
 - Energy of muon : $E_\mu = 0.5 \text{ MeV}$ ($E_0 = 20 \text{ MeV}$ for μHe^+)
 - Stripping foil : Beryllium(Be) , $t = 4.8 \mu\text{m} \times 20(N)$

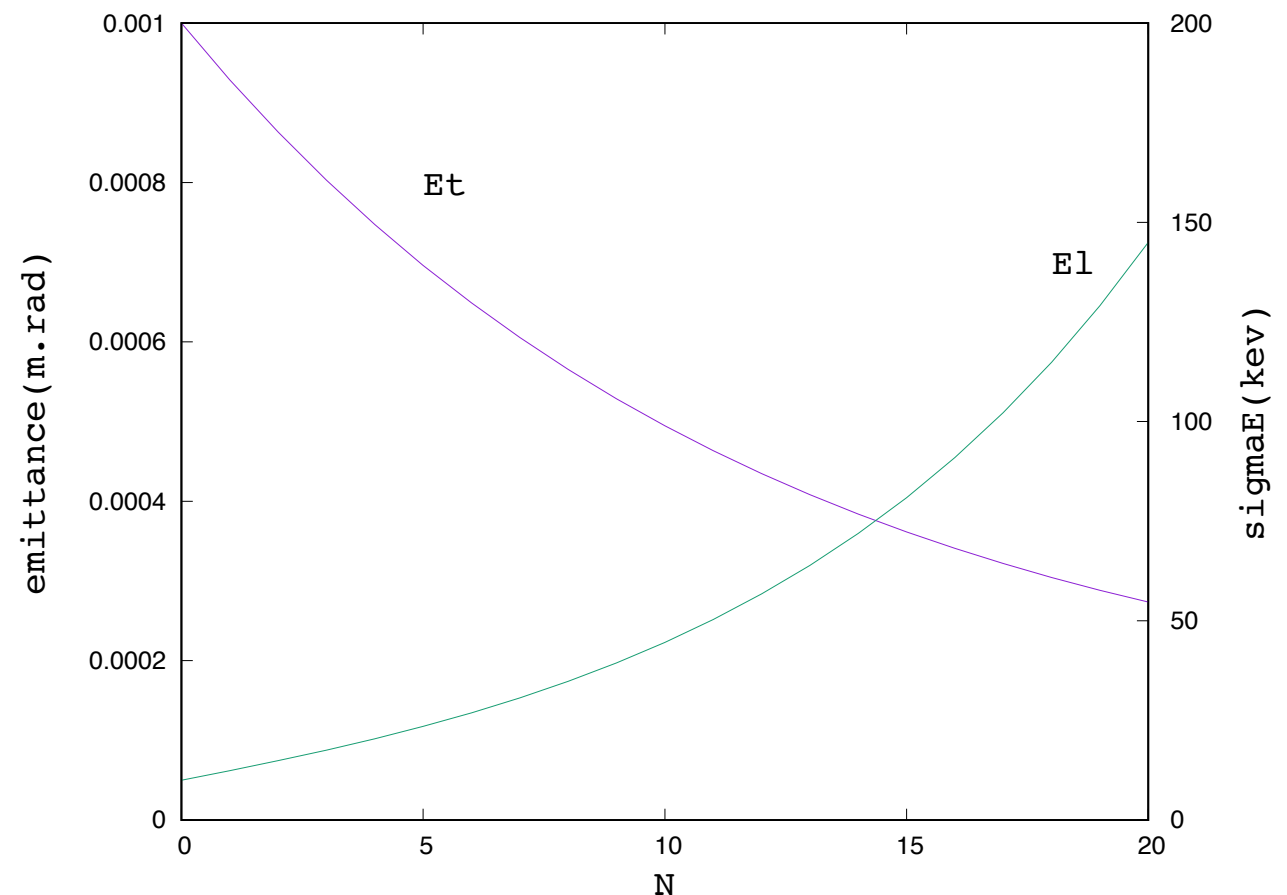
• Results

transverse emittance

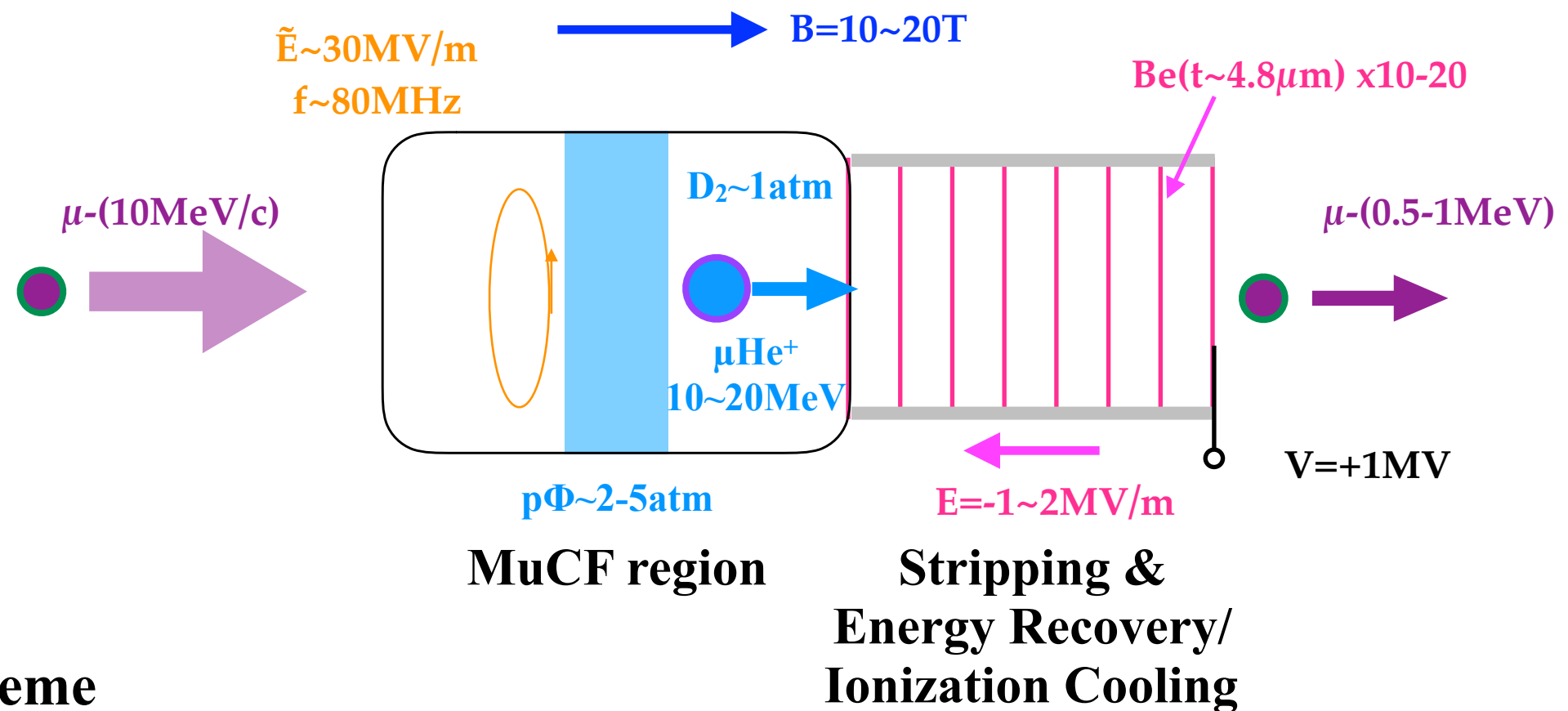
$$\varepsilon_t = 0.2 \pi \text{ mm}$$

energy spread

$$\sigma_E = 150 \text{ keV}$$



Characteristics of the negative muon beam created using MuCF reaction:simulation

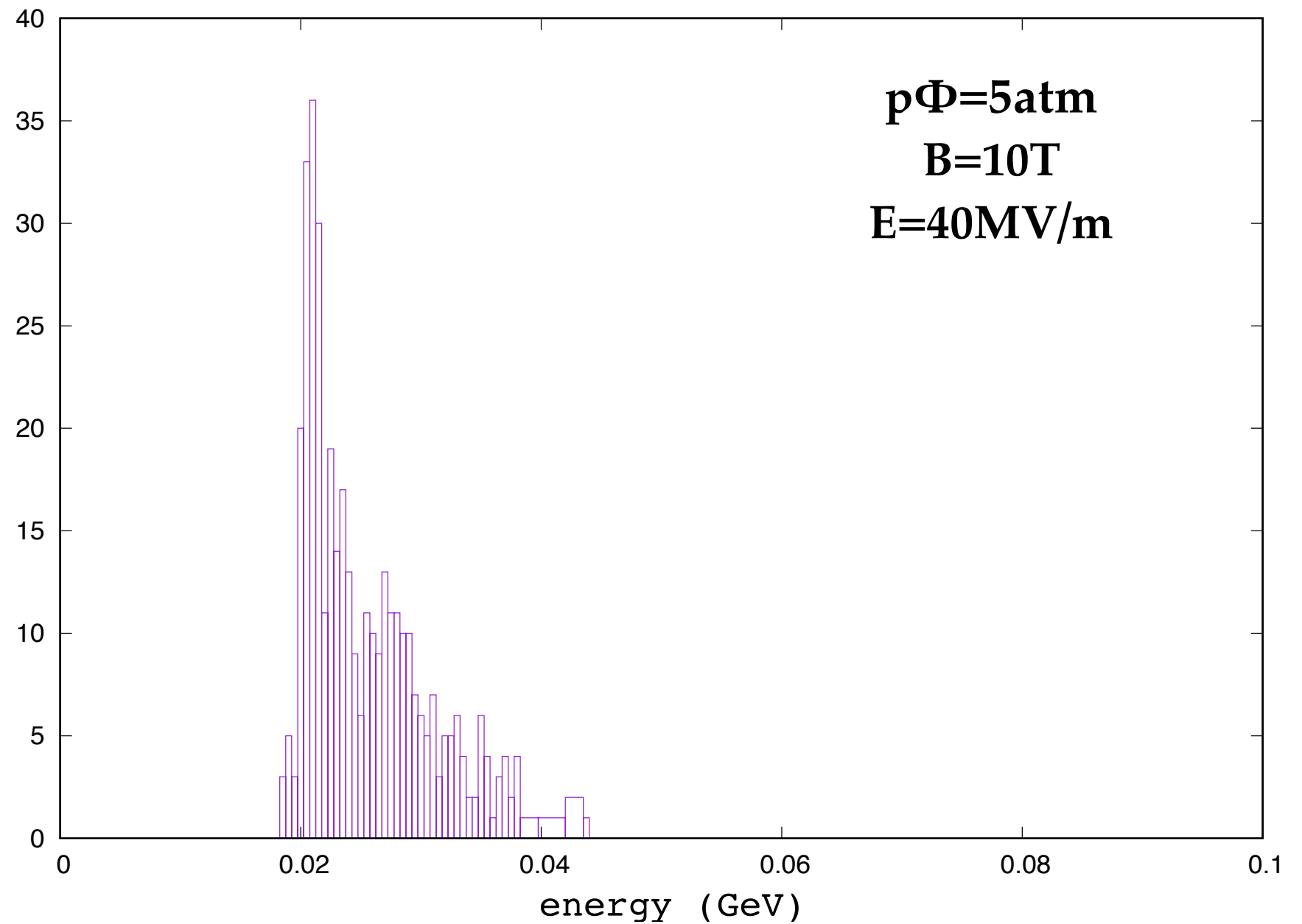


- **Scheme**

- MuCF region
 - Extract μHe^+ ions and acceleration.
 - $E(\mu\text{He}^+) : 10 \sim 20 \text{ MeV}$
- Stripping and Energy recovery/ionization cooling for negative muons
 - Thin foil (Be) or Gas(Ar)
 - Energy recovering $\sim 1.5 \sim 2 \text{ MeV}$

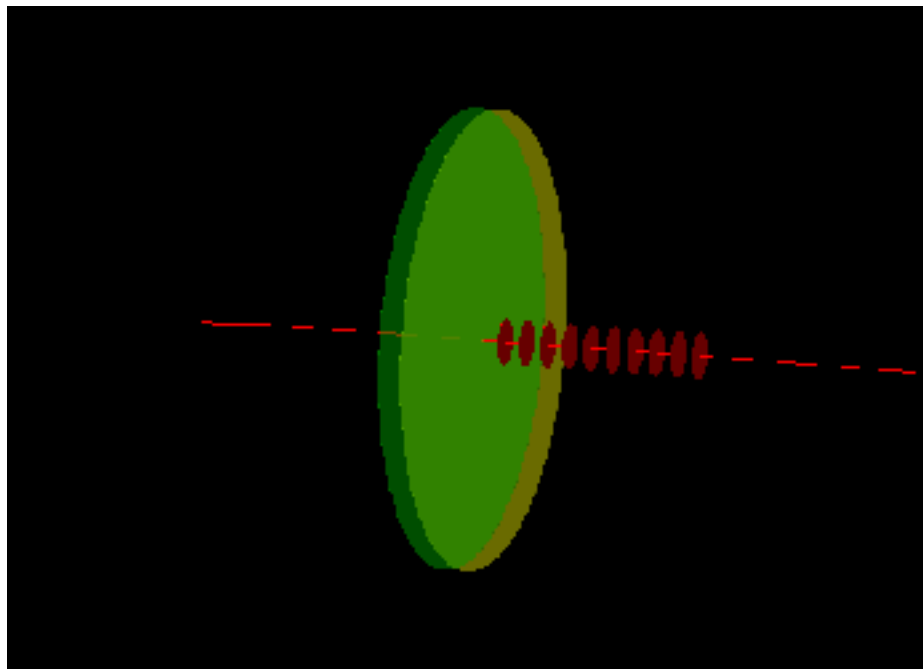
Simulations: Acceleration of μHe^+ ion

**Yield $\approx 20\%$ of
the incident negative
muons**



Simulations:G4BL

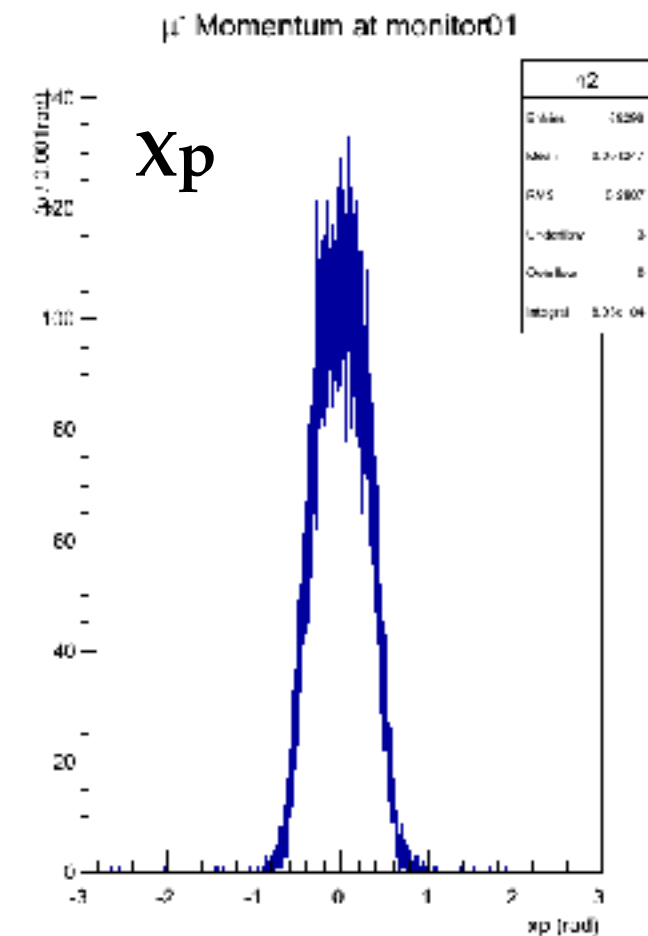
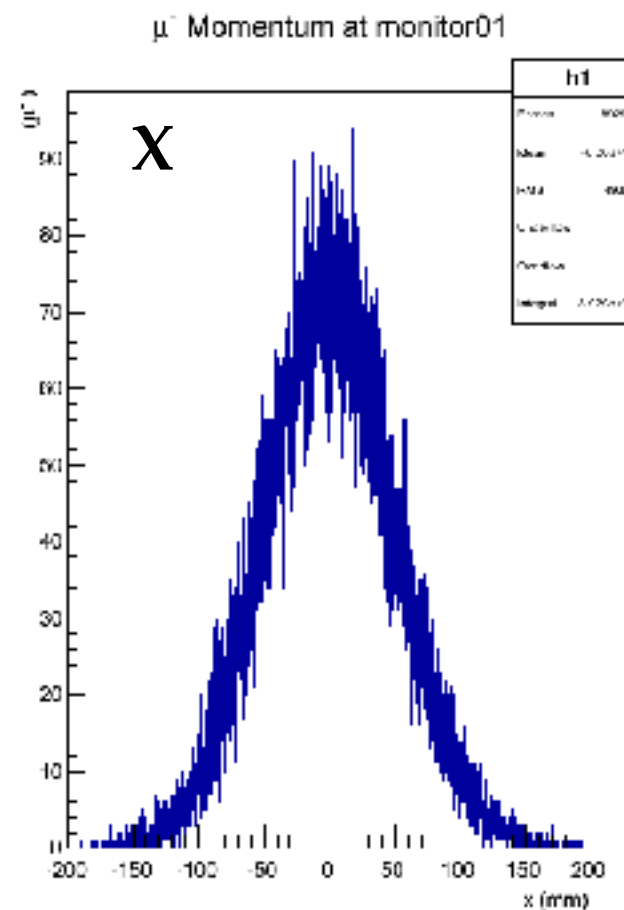
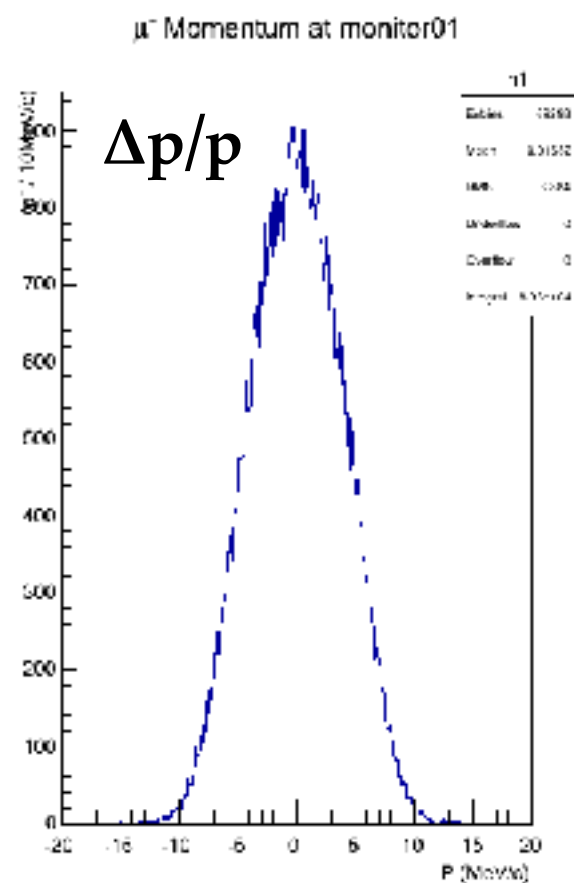
μ^- : $E_{\mu} = 0.5 \text{ MeV}$, $t = 0.0048 \text{ mm} \times 10 \text{ stages}$, $E = 2 \text{ MV/m}$



Emittance

$$\epsilon_T^N = 1.5\pi [\text{mm}]$$

$$\epsilon_L^N = 2.2\pi [\text{mm}]$$



Summary

- **Generation of low emittance negative muon beams with μHe^+ ions from MuCF**
 - Generation and acceleration of μHe^+ ions
 - Cyclotron resonance acceleration ($B=10\sim 20\text{T}$, $E_{rf}=10\sim 20\text{MV/m}$)
 - μHe^+ : $E\sim 10\text{-}20\text{MeV}$
 - Stripping and energy recovery of μ^- from μHe^+ ion
 - Stripping foil(Be) or gas target(Ar) $\Delta E \sim 2\text{MeV}$
 - Energy recovering : $E\sim 2\text{MeV/m}$
 - Ionization cooling
- **Emittance**
 - $\varepsilon_L=2.2[\pi\text{mm}]$, $\varepsilon_T=1.5[\pi\text{mm}]$
 - Comparable or even smaller than those in MAP strategy after ionization cooling.
- **The technical challenges**
 - Localized DT (liquid or gas) target in MuCF region
 - Acceleration of μHe^+ ions up to 20MeV or more.
 - Rotating (circularly polarized) RF field : $E\sim 15\text{ MV/m}$, $f\sim 76\text{MHz}$.