A new scheme of negative muon beam generation with MuCF

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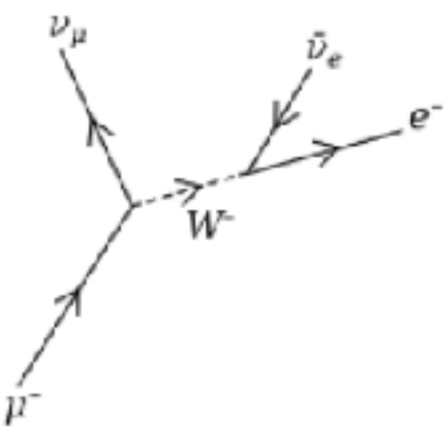
Negative muon

- **Negative muons are produced in the decay of negative pions.**
  - Mass : 105.7MeV ~ 200 × electron mass
  - Lifetime : 2.2μsec

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

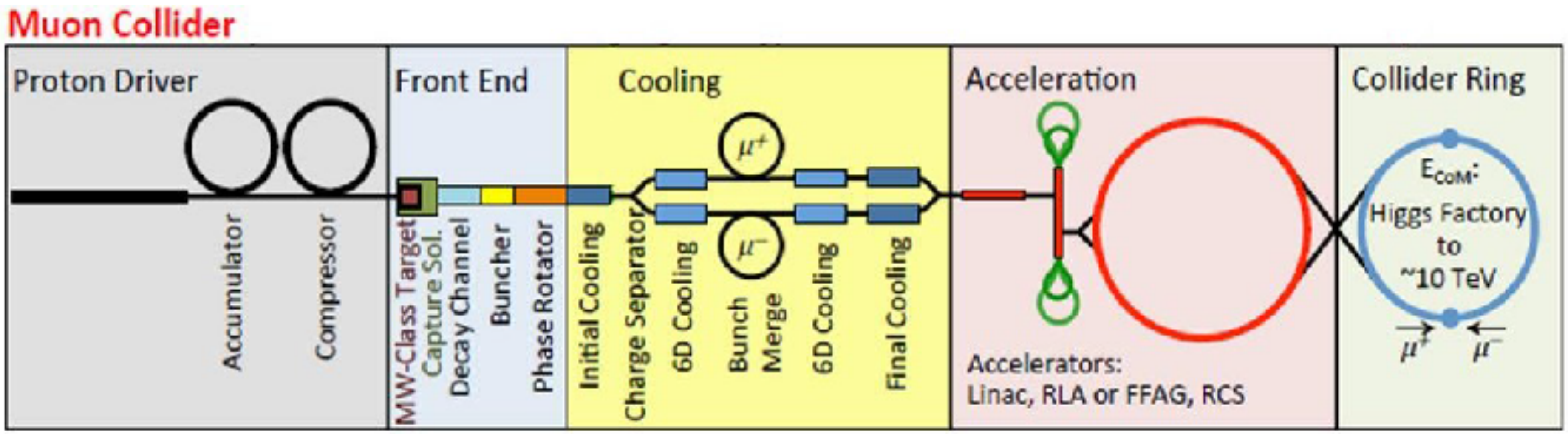
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

- **Muonic atom**
  - Muon X-ray : cf. 1.7 keV for μH^0 atom
  - Captured by nucleus (Z>20) : β decay, Z → Z-1 :nuclear transformation

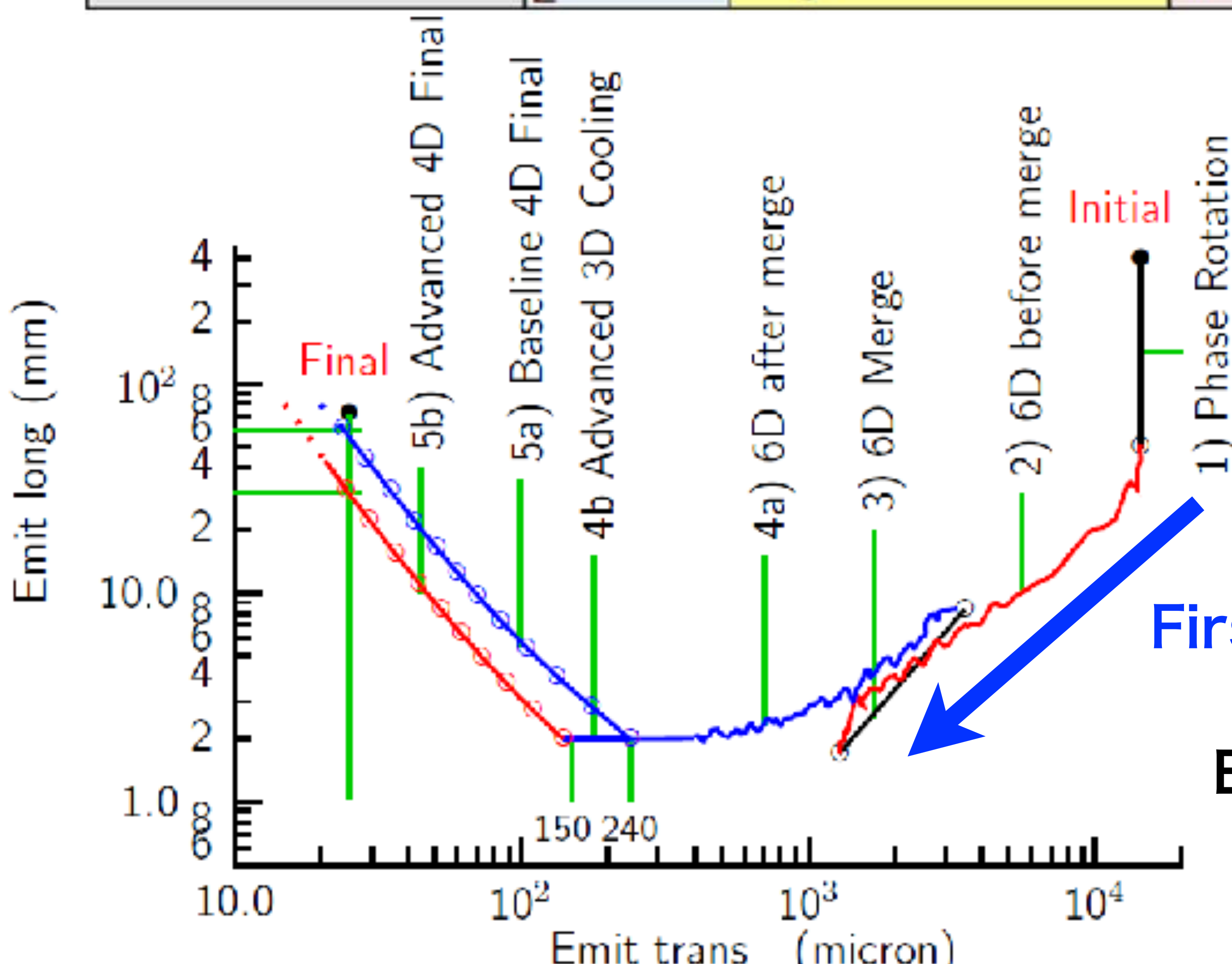


- **Application**
  - Muon Catalyzed Fusion
    - μDT molecule formation :inter-distance of D and T nuclei < 1/200 small → The chain reaction continues during the muon lifetime.
  - Muon Collider
    - Lepton collider : μ+μ-   √s ~ 5-10TeV

Muon collider



MAP scenario



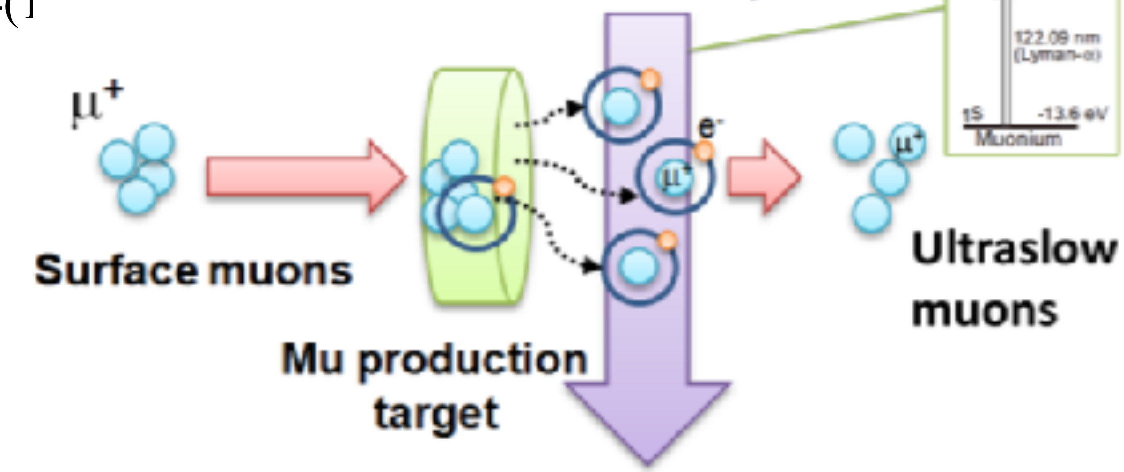
First stage cooling

Emittance reduction protocol
by Ionization Cooling

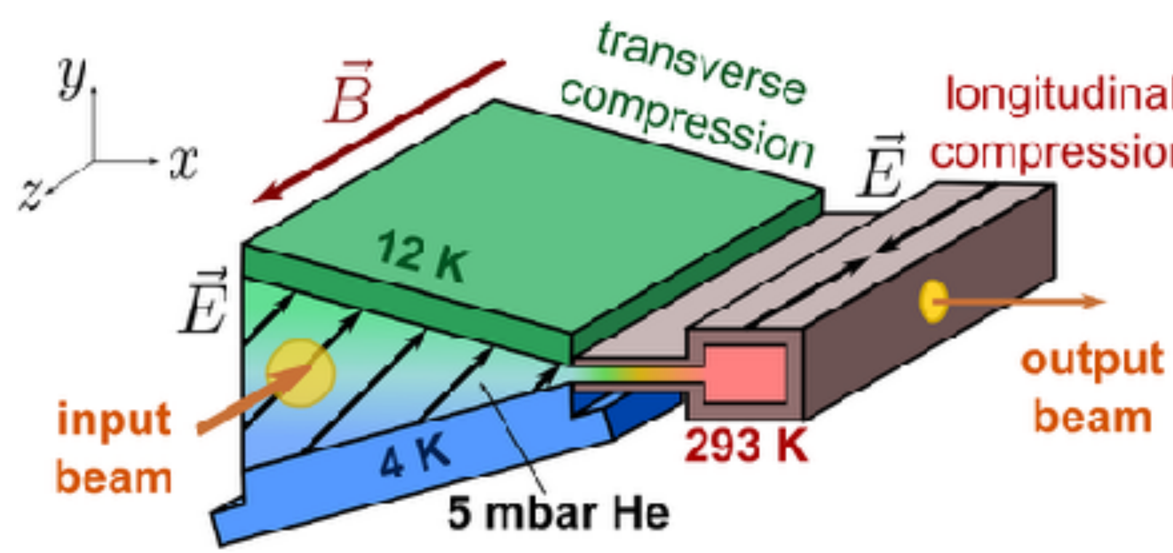
Muon beam generation -low emittance and continuous beam-

- **Positive muon: Two schemes(under developn**
  - (1) Ionization of Muonium (Mu) : KEK-JPARC[PRL.,74(1
    - Laser ionization of Mu(1s→2p→free)
  - (2) Frictional cooling : PSI[PRL., 125,164802(2020)]
    - Cooled by LT-helium & wall,
    - ε>0.2MeV/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 μX,
      - BE is (mμ/me)^2~40,000 times large.

(1)Ionization



(2)Friction



- **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. Alvaretz, 1956.

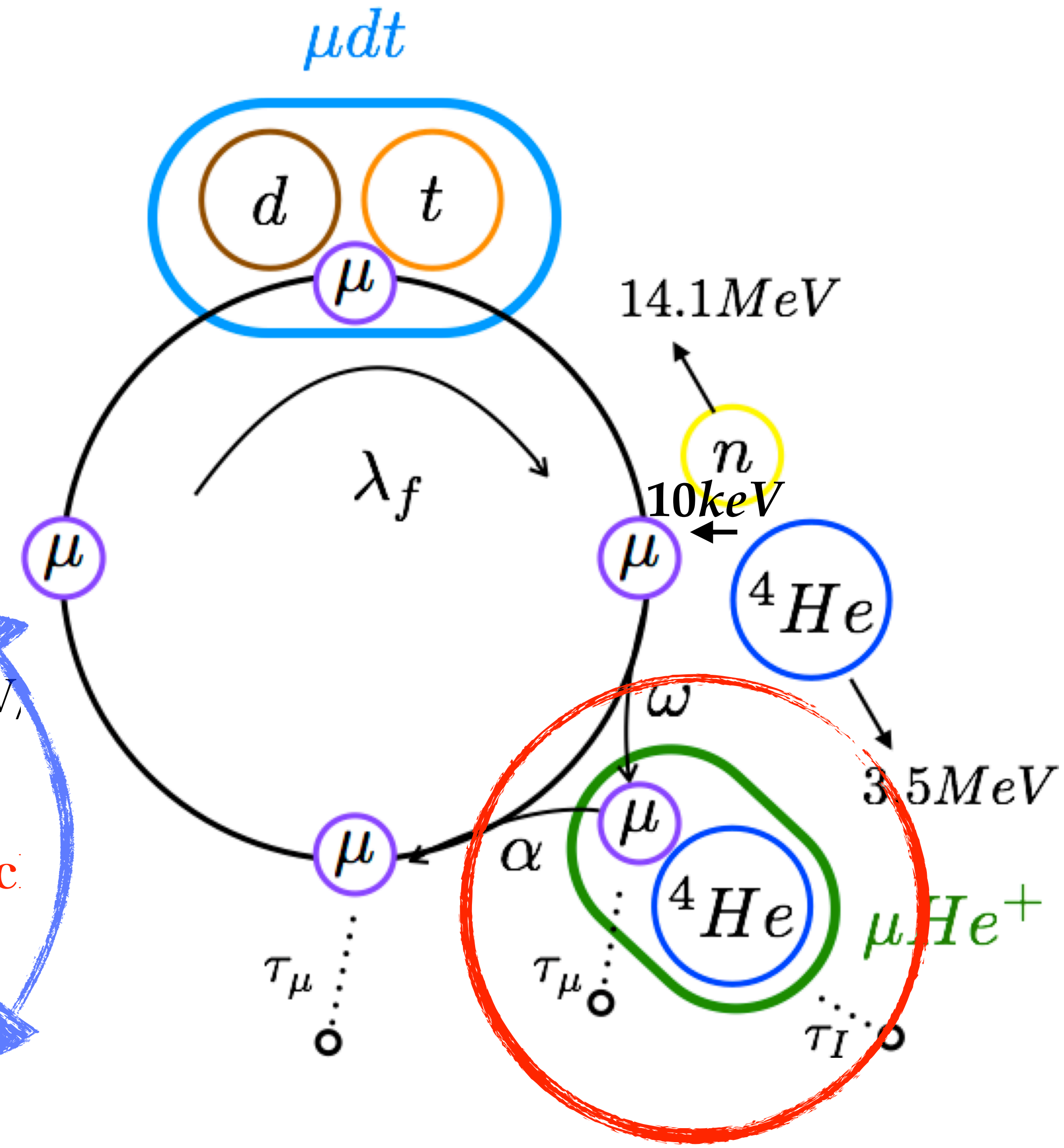
    μ- + p-d → He_3 + γ (Q5.5MeV)
- **Energy output**
  - d-t fusion : n(14.1MeV) , α (3.5MeV)
  - μDT molecule formation :>1000-2000cycles/μ-life

    Energy gain ideally → 20-30GeV/μ- but reality 2-3GeV/

    Muon production energy ~5GeV/μ
- **Restriction of energy gain→Muon trapping by α partic**

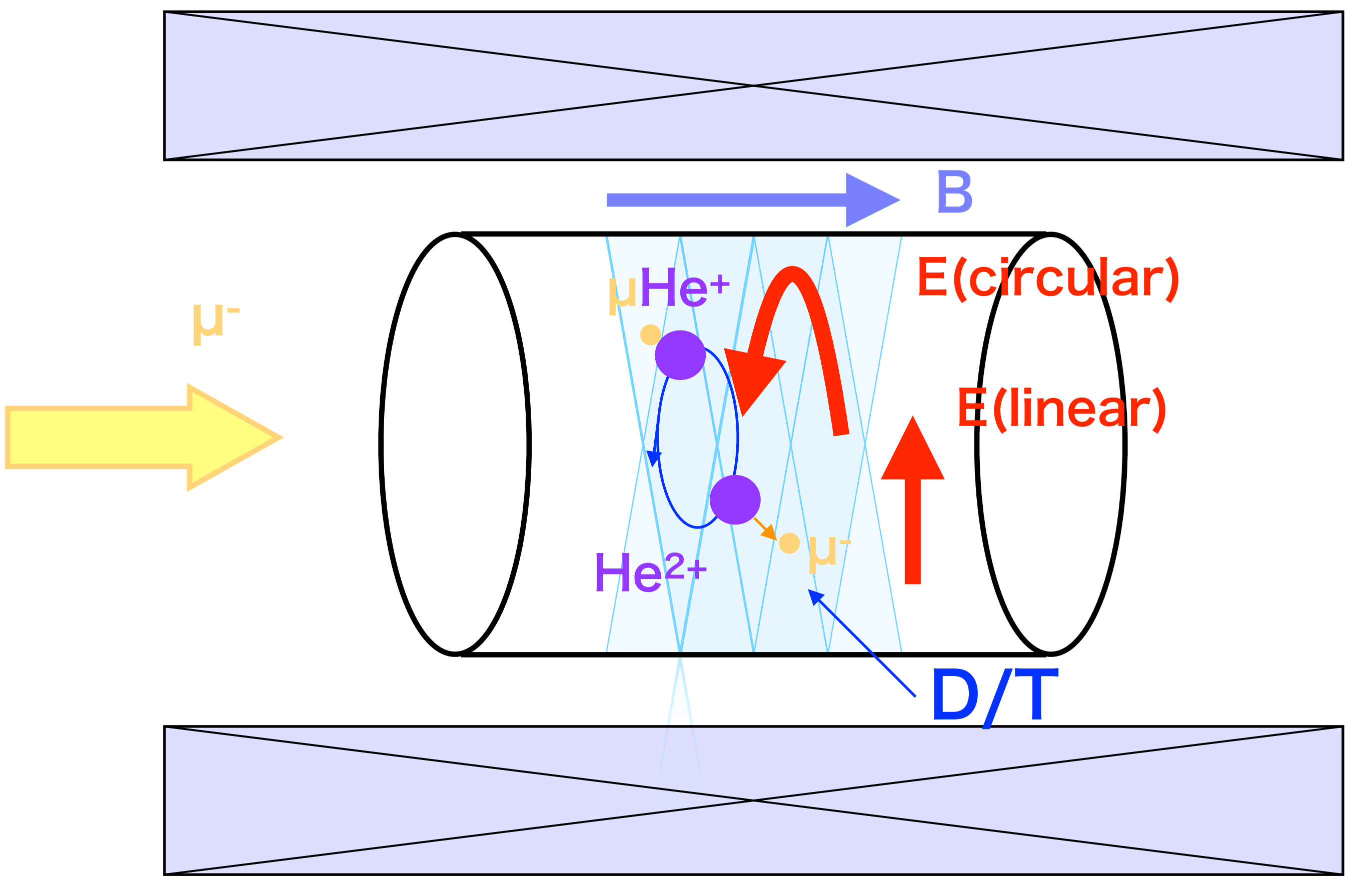
  $$\mu + \alpha \rightarrow \mu He^{+}$$

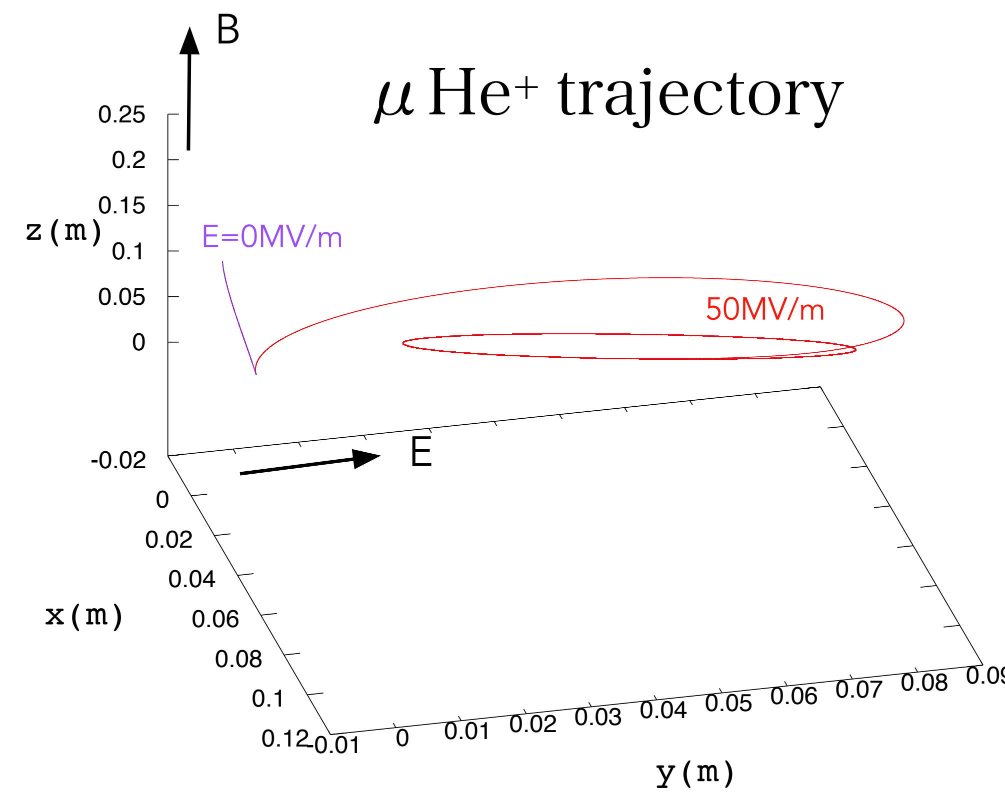
  - Chain reaction stops.→100-200cycles/μ-life : ~1/10
  - Energy gain : 20-30GeV/μ → 2-3GeV/μ
  - MuCF break-even ~ 2.5 times less.
- To overcome restrictions : Y.Mori: https://doi.org/10.1093/ptep/ptab111

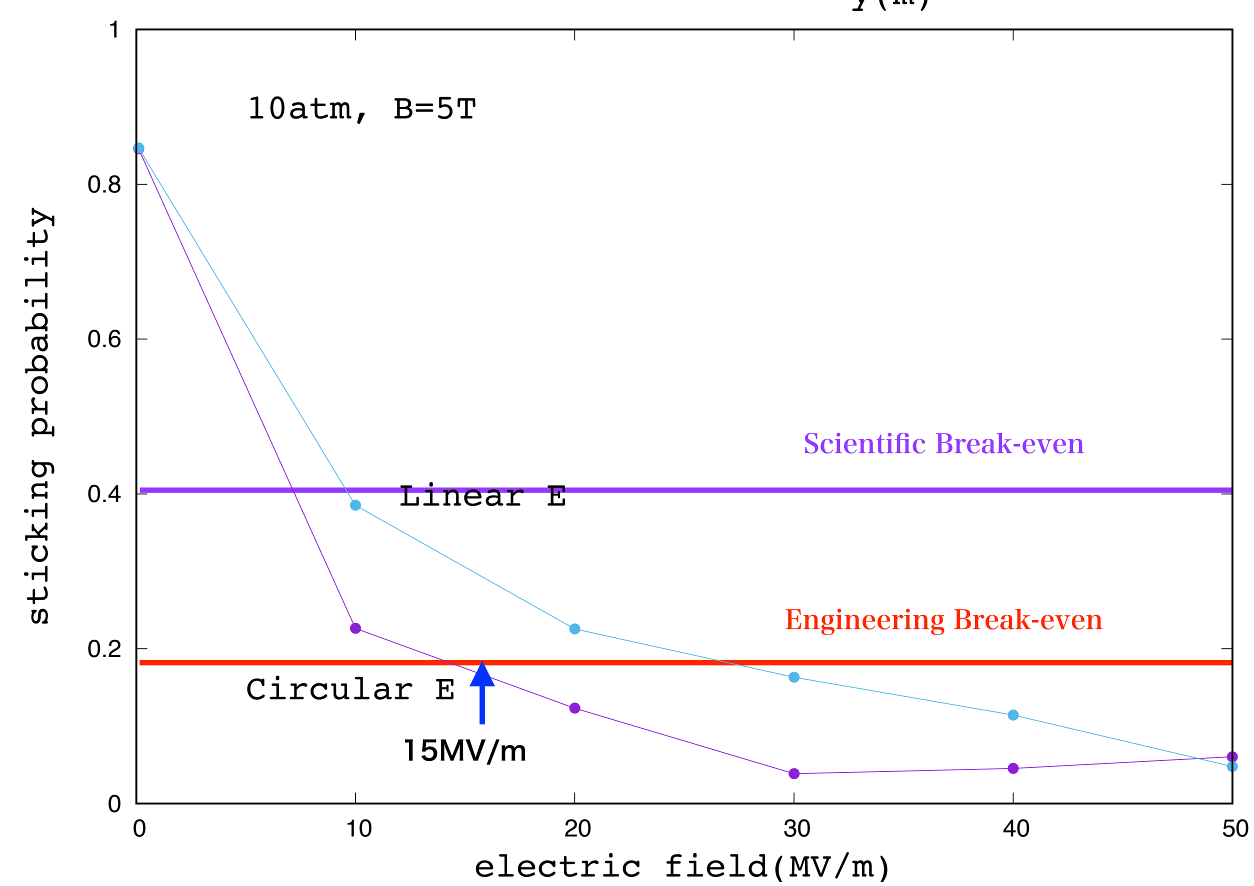


$$\frac{N_f^{\infty}}{N_{\mu}^{0}} = \left[\frac{1}{\lambda_f \tau_{\mu}} + W_0\right]^{-1} \sim 100$$

Cyclotron resonance acceleration of μHe+ ion

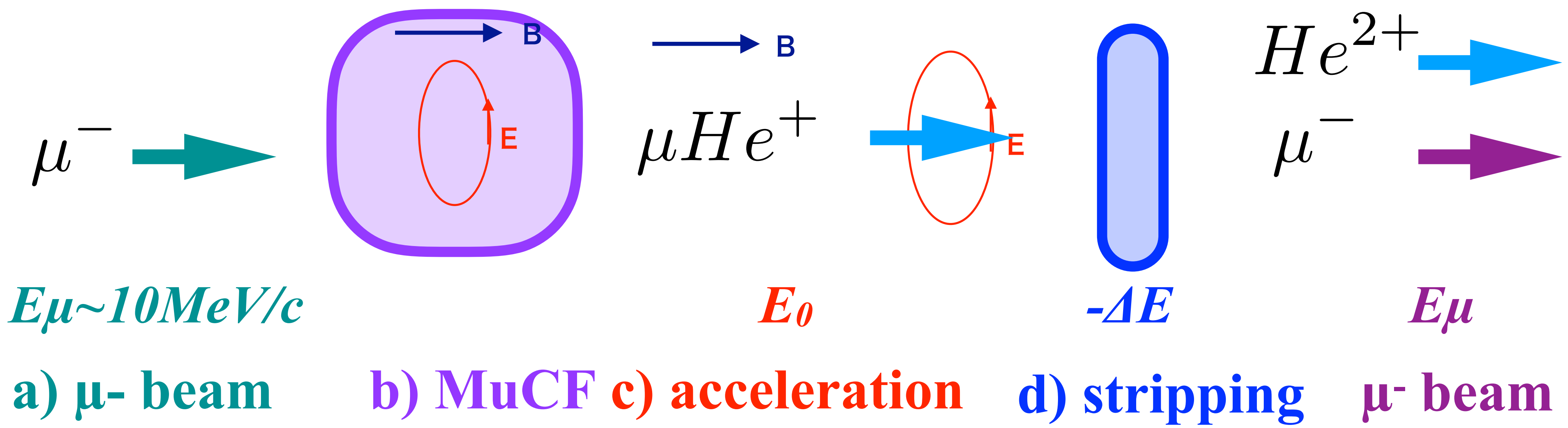






Cyclotron resonance acceleration of μHe^{+} ions with RF field using localized DT target

Generation of negative muon beam with accelerated μHe+ ions



Scheme

a)Negative muons produced by hadron accelerator

b)Generation of μHe^{+} ions with MuCF

c)Acceleration of μHe^{+} ions

d)Stripping and formation of μ^{-} beam

Difficulties

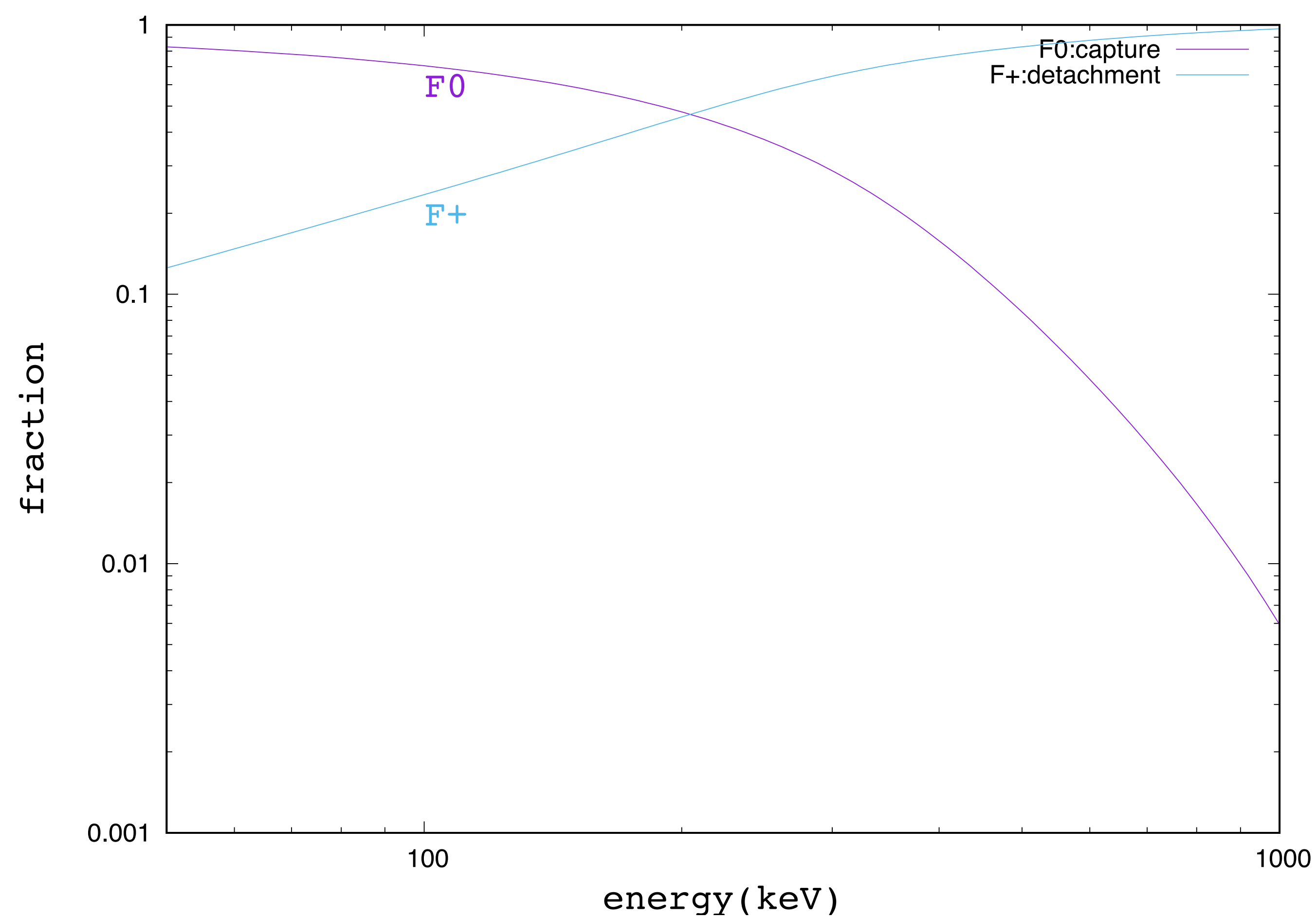
(1)Neutralization of μHe+ ion by electron capture

- If μHe^+ ion energy is < 1MeV, μHe^+ ion captures an electron and neutralized.

$$\mu He^+ + X \rightarrow \mu He^0 + X^+$$

- 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

$$\mu He^{+} + X \rightarrow \mu^{-} + He^{2+} + X.$$

- $\Delta E(\mu He^{+})=\Delta E(\mu)$ because $v_{\mu}=v_{\mu He}$. $\rightarrow$ $E\mu$ 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, $E\mu$, must be larger than ΔE because its energy loss at the stripping target also equals ΔE. Therefore, E_0 should be,

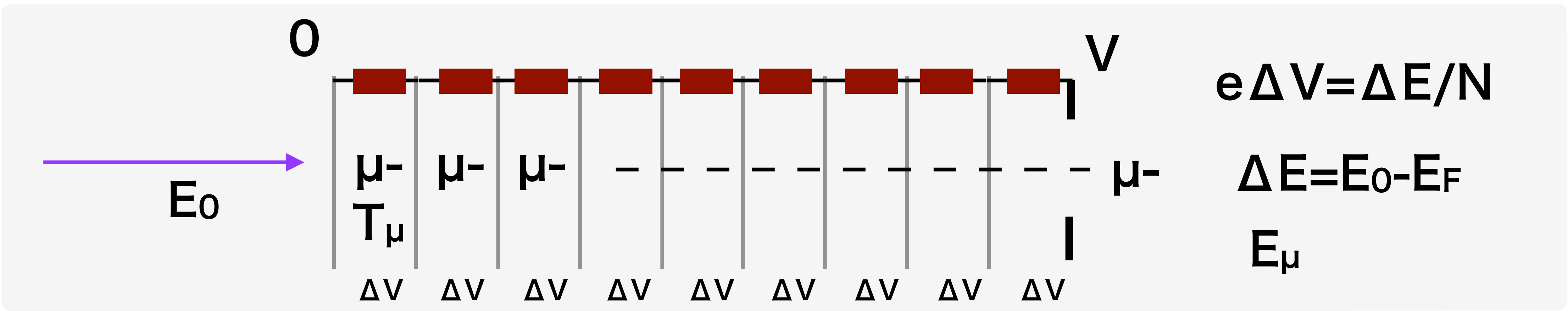
$$E_0 > \left[\frac{-S(E_0)}{\sigma(E_0)n}\right] \times \left(\frac{m_{\mu}}{m_{\mu He}} + 1\right)$$

- cf. Sripping foil → Be:thickness 50μm

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

- **E_0 can be low, if $S(E_0)$ decreases "effectively".→ 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 is virtually zero in the stripping process, E_0 could be large.**
- **This is also the "Ionization Cooling" of negative muons.**

Ionization cooling of negative muon beam

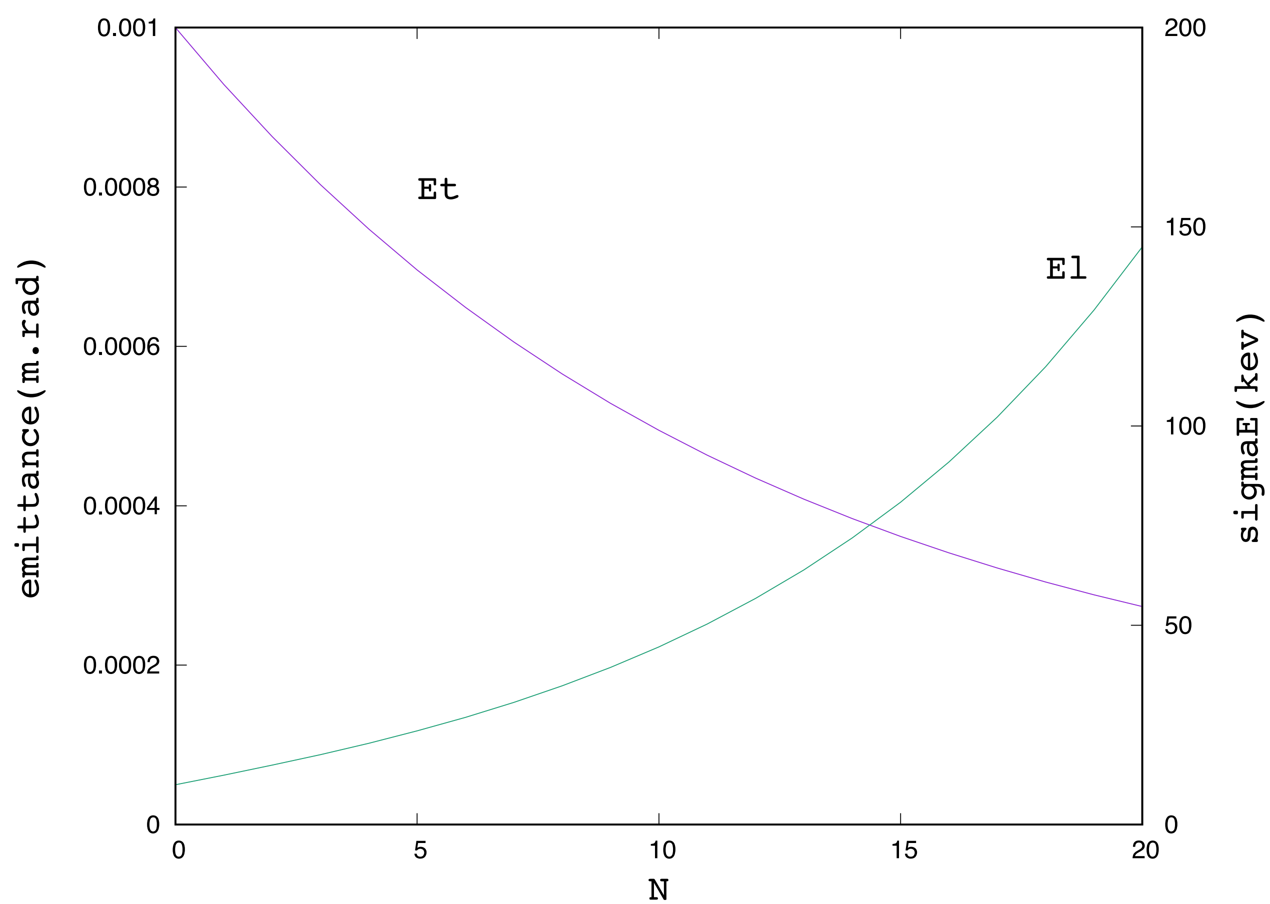
- **Th energy recovery of negative muon beam through stripping is actually ionization cooling itself.**
- **Change in emittance evaluated by the rate equations ;**
  - Energy of muon : $E\mu$=0.5MeV (E_0=20MeV for μHe^+)
  - Stripping foil : Beryllium(Be) , t=4.8μm × 20(N)
- **Results**

transverse emittance

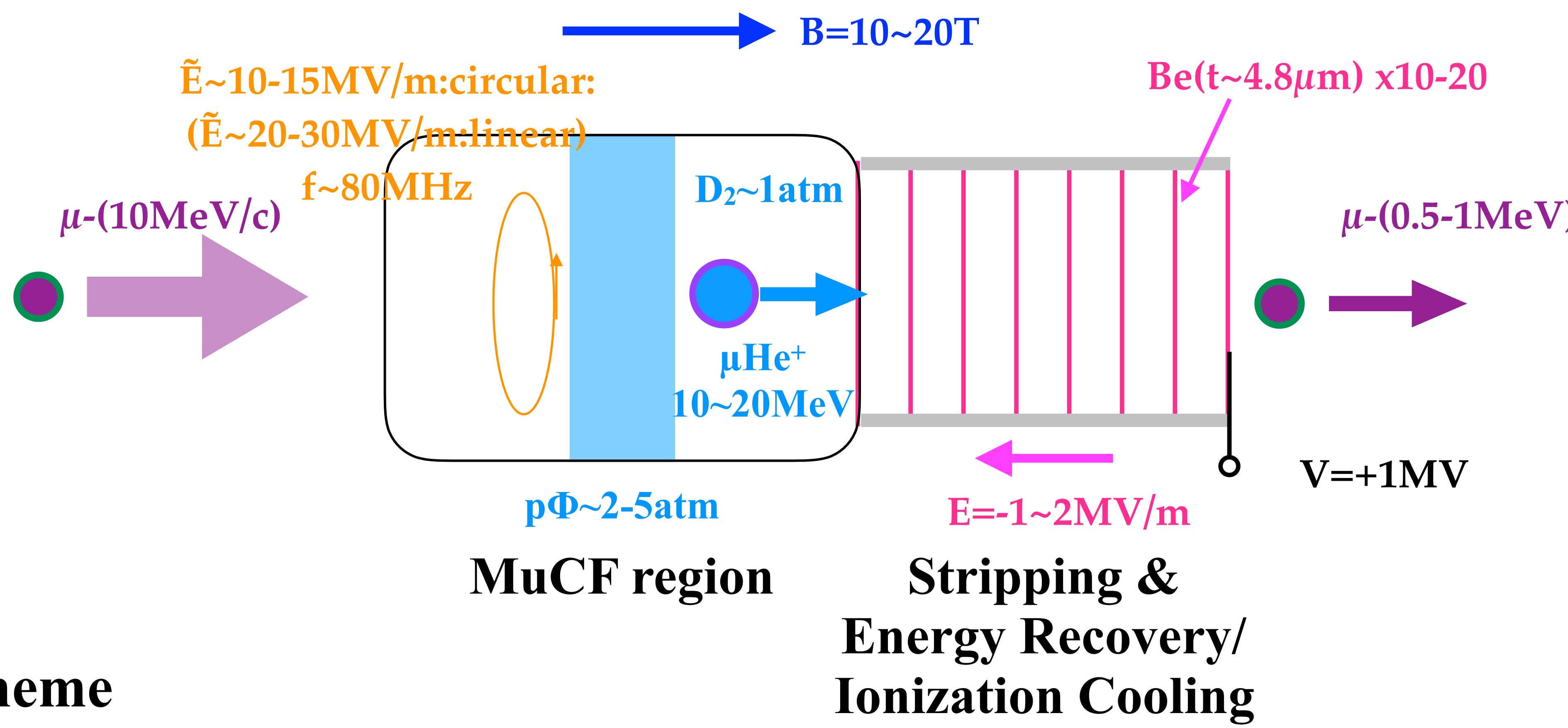
ε t=0.2mm

energy spread

σ l=150keV



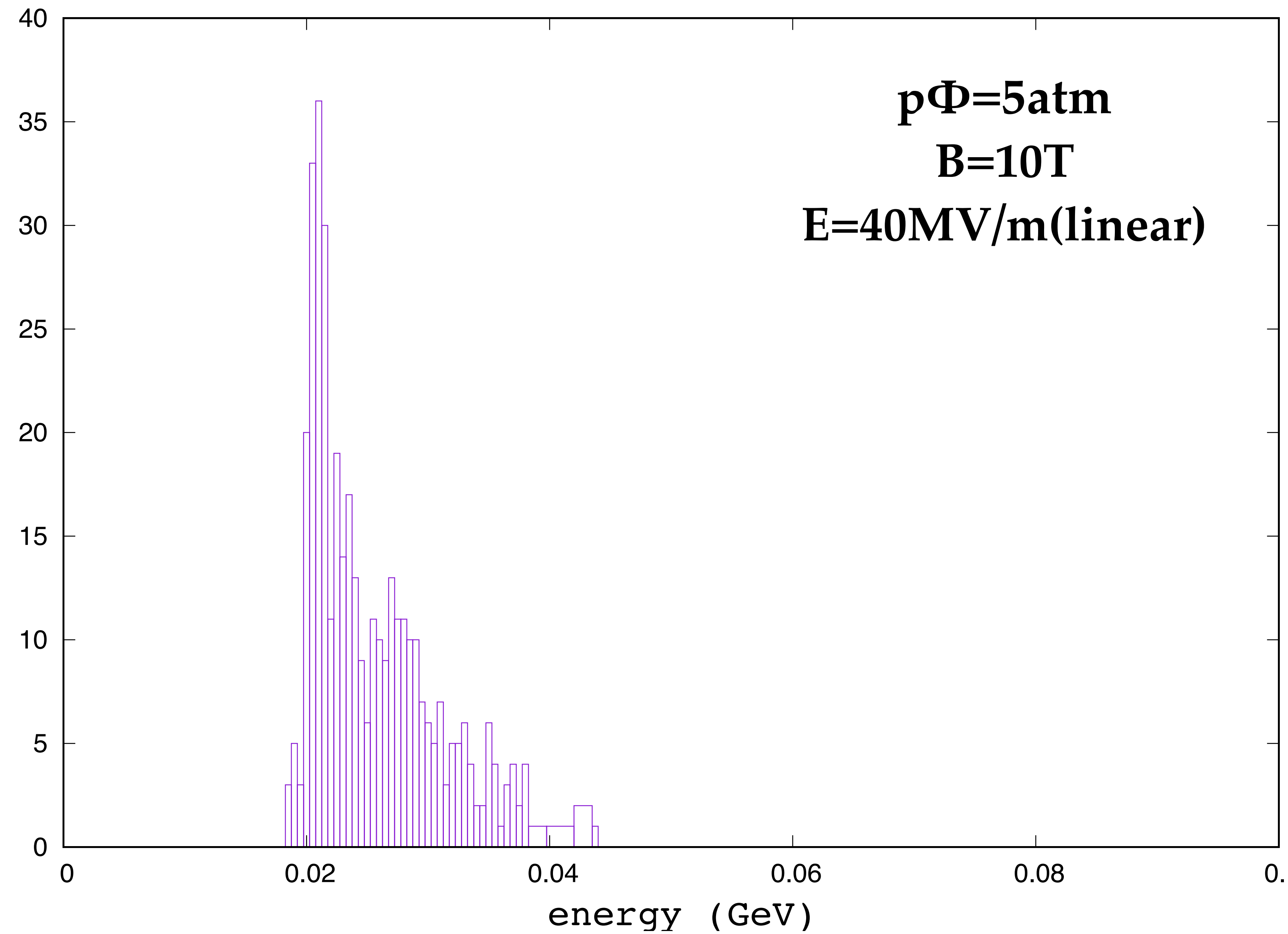
Characteristics of the negative muon beam created using MuCF reaction:simulation



- **Scheme**
  - MuCF region
    - Extract μHe+ ions and acceleration.
      - E(μHe+) : 10-20MeV
  - Stripping and Energy recovery/ionization cooling for negative muons
    - Thin foil (Be) or Gas(Ar)
    - Energy recovering ~1.5-2MeV

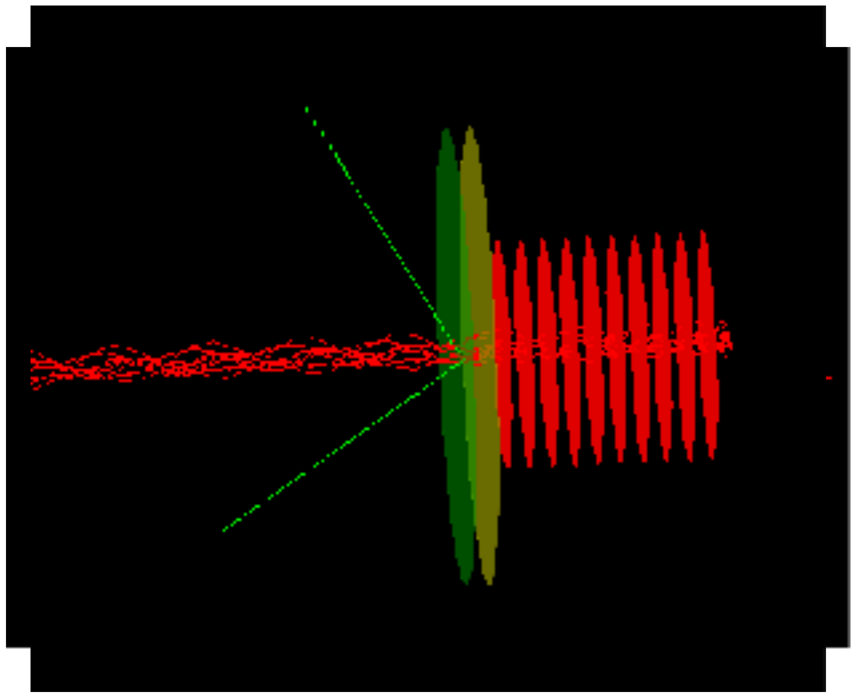
Simulations: Acceleration of μHe⁺ ion

Yield ≈ 20% of the incident negative muons



Simulations:G4BL

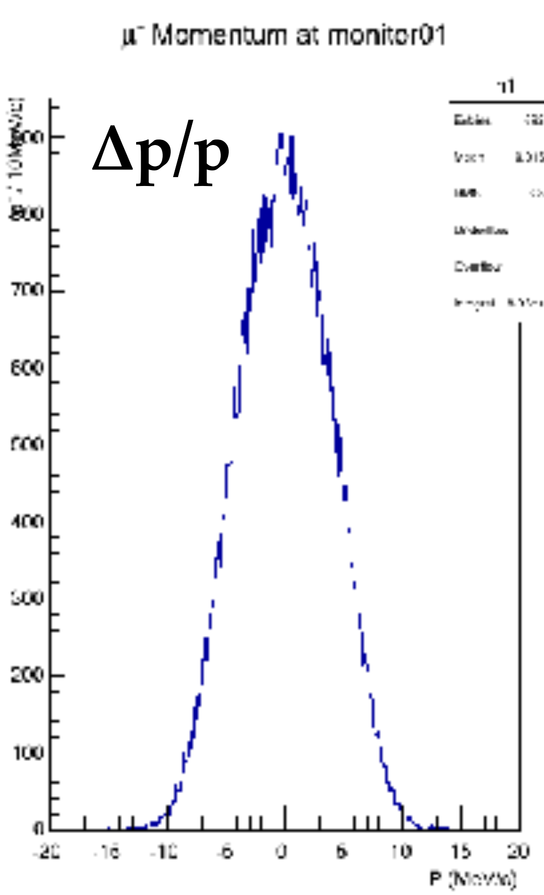
μ^-:Eμ=0.5MeV, t=0.0048mm×10stages, E=2MV/m

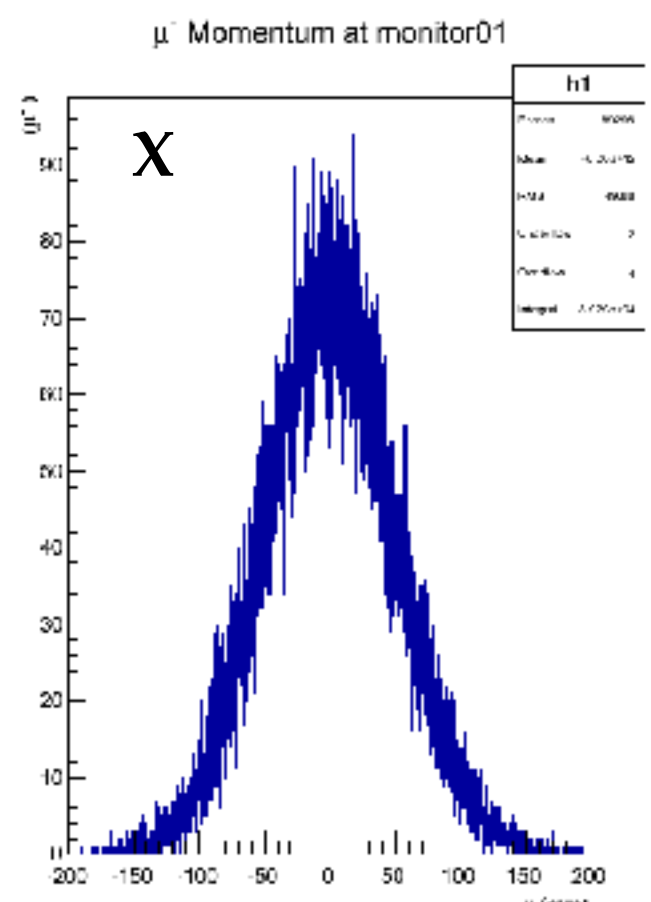


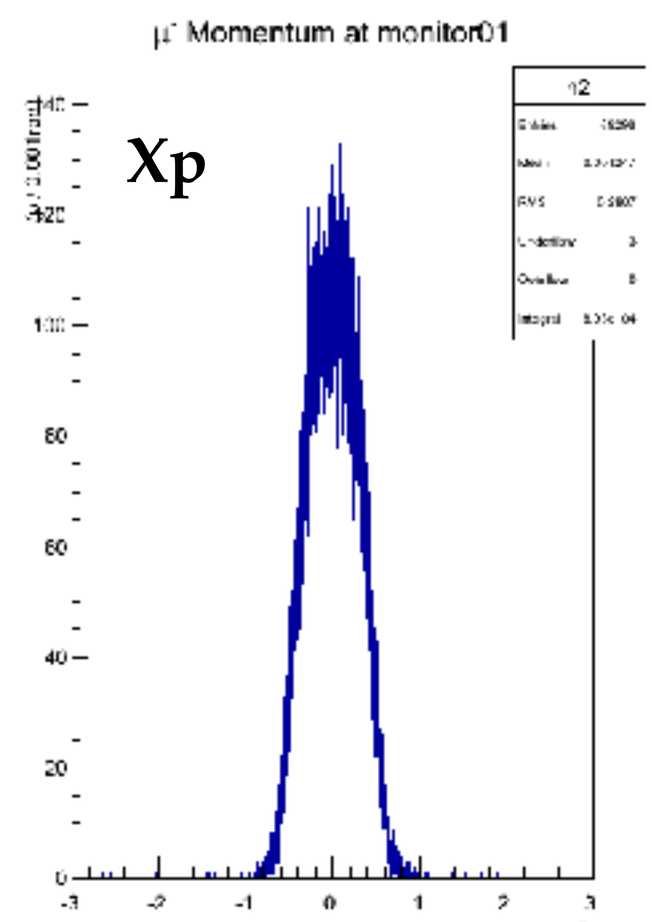
Emittance

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

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







Summary

- **Generation of low emittance negative muon beams with μHe^+ ions from MuCF**
  - Generation and acceleration of μHe^+ ions
    - Cyclotron resonance acceleration (B=10~20T, Erf=10~20MV/m)
    - μHe^+ : E~10-20MeV
  - Stripping and energy recovery of μ^- from μHe^+ ion
    - E_μ ~0.5-1MeV
    - Stripping foil(Be) or gas target(Ar)
    - Energy recovering : E~2MeV/m
    - Ionization cooling
- **Emittance**
  - ε_L=2.2[π mm], ε_T=1.5[π 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~ 15-20 MV/m, f~76MHz.