Intense Muon Source
with MERIT_FFAG

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*This work was funded by ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).
Problems in nuclear energy production

- Treatment of radio-activities produced by nuclear reactor.
  - Radio-active fission products
  - Plutonium
  - Minor actinide (MA; Am, etc.)

- Deep underground storage: Long-lived species ($\tau > 1,000$y) $\rightarrow$ “Negative legacy”
  - Long-lived fission products (Tc$^{99}$, I$^{127}$, Pd$^{107}$, etc.)
  - Minor actinides (MA)
Underground nuclear waste disposal: outline

**Multiple barriers**

- **artificial barrier**
  - vitrified
  - over-packed

- **natural barrier**
  - clay buffer
  - bedrock

- preventing elution into water
- 20cm thick carbon steel
- 70cm thick clay

**deep geological storage**

(C) Agency for Natural Resources and Energy
Nuclear wastes

- Nuclear wastes from 1 ton 3% enriched 1 ton Uranium fuel (Wikipedia)

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu</td>
<td>10 kg</td>
</tr>
<tr>
<td>Pt</td>
<td>2 kg</td>
</tr>
<tr>
<td>Short-lived FP ($\tau &lt; 100$y): Sr90, Cs137, etc.</td>
<td>26 kg</td>
</tr>
<tr>
<td>Long-lived FP ($\tau &gt; 1000$y): Tc99, Pd107, etc.</td>
<td>1.2 kg</td>
</tr>
<tr>
<td>Minor Actinides: Np, Am, etc.</td>
<td>0.6 kg</td>
</tr>
</tbody>
</table>
Deactivation and re-use of LLFPs (Zr, Se, Pd, Cs) by nuclear transmutation with accelerator

**ImPACT project**

-Impulsing Paradigm Change through Disruptive Technologies Program of Council for
Nuclear transmutation by neutron, muon, etc.

- Neutron: \((n, \gamma)\) @RIKEN RIBF, Osaka, Kyusyu, JAEA etc.
  - Precise cross section measurement
  - Inverse reaction: \(n + ^{135} \text{Cs} \rightarrow ^{136} \text{Cs} + \gamma\)
  - HI(U) \(\rightarrow\) fragmentation \(\rightarrow\) \(^{135}\text{Cs} + n\) (target like D\(_2\), Li)

- Muon: \((\mu^-, p)n\) @RIKEN, RCNP, JPARC, Kyoto U.
  - Muon transmutation exp. @RIKEN, RCNP, JPARC
  - Muon source @Kyoto, JPARC
nuclear transmutation

with negative muon

- 1st: Formation $\mu_{\text{atom}} \rightarrow 2$nd: Nuclear transmutation
  - $\mu$-atom radius: $a_\mu = \left(\frac{1}{207}\right) \times Z^{-1} \times 10^4$ fm.
  - Nuclear radius: $R = 1.2 \times A^{1/3}$ fm.
- Transmutation probability $\rightarrow$ 95% for $Z>30$ nuclei
  - $R < a_\mu$ for $Z>30$ nuclei

Fig. 15.8 The probability densities of finding a muon in the state indicated, as a distance $r$ from the nuclear center (full lines), are compared with the nuclear charge distribution in the case of lead. In the $S_{10}$ state, the probability of finding a muon within the nucleus is close to 50% (Devons and Duerloo 1969).
Formation of non-radioactive (stable) nuclei

- Muon pumping

\[ \mu^- + {}^{99}\text{Tc}(\text{LLFP}:2.15 \times 10^5 \text{y}) \rightarrow {}^{99}\text{Mo}(\text{stable}) + \nu_{\mu} \]
\[ \rightarrow {}^{98}\text{Mo}(\text{stable}) + n + \nu_{\mu} \]
\[ \rightarrow {}^{97}\text{Mo}(\text{stable}) + 2n + \nu_{\mu} \]
\[ \rightarrow {}^{96}\text{Mo}(\text{stable}) + 3n + \nu_{\mu} \]
Muon

- Transmutation rate: estimated with rate equations

\[
\frac{d}{dt} \begin{bmatrix}
\frac{A-i}{Z} X \\
\frac{A-i}{Z-1} X
\end{bmatrix} = \begin{bmatrix}
-Q - \beta_{Z}^{A-i} & \beta_{Z-1}^{A-i} \\
-f_i^n Q & -\beta_{Z-1}^{A-i}
\end{bmatrix} \begin{bmatrix}
\frac{A-i}{Z} X \\
\frac{A-i}{Z-1} X
\end{bmatrix}
\]

\[i = 0, N\]

- Model hypothesis

  - Parent and daughter isotopes are concerned and other elements are removed from the system: Chemical separation, etc.
  
  - 100% negative muon capture by nucleus is realized.
  
  - Negative muon flux : \(Q\)
  
  - Beta decay rate : \(\beta\)
  
  - Emitted neutron numbers (f) are constant for parent isotopes.
Example

- Cs: cesium
  - $^{137}\text{Cs}$
    - Typical short-lived FP (half-life: 30.07y)
    - Strong $\gamma$ emitter
      - Most problematic $\rightarrow$ high water solubility

\[ ^{137}_{55}\text{Cs} \xrightarrow{\beta^- \text{ 512.0 keV \ 30.07 \ ans}} ^{137m}_{56}\text{Ba} \xrightarrow{\gamma \text{ 661.7 keV \ 2.552 \ min}} ^{137}_{56}\text{Ba} \]

- $^{135}\text{Cs}$
  - Long-lived FP (half-life: $2.3 \times 10^6$ y)
\[ ^{55}\text{Cs} + \mu^- \rightarrow ^{54}\text{Xe} \]

<table>
<thead>
<tr>
<th>A(Cs)</th>
<th>137</th>
<th>136</th>
<th>135</th>
<th>134</th>
<th>133</th>
<th>132</th>
<th>131</th>
<th>130</th>
<th>129</th>
<th>128</th>
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<tbody>
<tr>
<td>NA(Pd)</td>
<td>0.4243</td>
<td>0</td>
<td>0.1287</td>
<td>0.0089</td>
<td>0.4382</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>DR(1/y)</td>
<td>0.0332</td>
<td>27.74</td>
<td>4.4E-07</td>
<td>0.484</td>
<td>0</td>
<td>56.33</td>
<td>37.67</td>
<td>17994</td>
<td>273.2</td>
<td>2.06E+05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A(Xe)</th>
<th>137</th>
<th>136</th>
<th>135</th>
<th>134</th>
<th>133</th>
<th>132</th>
<th>131</th>
<th>130</th>
<th>129</th>
<th>128</th>
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<tbody>
<tr>
<td>DR(1/y)</td>
<td>1.38E+05</td>
<td>0</td>
<td>958.4</td>
<td>0</td>
<td>69.62</td>
<td>0</td>
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<table>
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<tr>
<th>Emitted neutron numbers</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tr>
<td>Yield</td>
<td>0.04</td>
<td>0.72</td>
<td>0.06</td>
<td>0.12</td>
<td>0.06</td>
<td>0</td>
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</tbody>
</table>
Preconditions

- Negative muon flux $Q \approx 2 \times 10^{16} \mu / \text{sec}$
  (1 mol/year eq.)

- 100% negative muon capture by nucleus is realized.

- Cesium amount: 1 mol $\rightarrow$ including all cesium isotopes.
  cf. $\sim$mol Cs produced by 1 ton 3%-enriched U nuclear fuel burn out.
Half of Cesium($^{137}\text{Cs},^{135}\text{Cs}$) are transmuted to stable Xe isotopes within a year.
Pd-Rh


Production of resources with muon nuclear transmutation from LLFP

cf. Pd, Rh, Xe etc.
Summary(1)

- Muon nuclear transmutation has the potential to reduce or extinct radioactive wastes greatly.
  
  - 1 mol radio-active isotopes, whatever their lifetimes are short (<100y) or long (>1,000y), are completely transmuted to stable isotopes within <1 year by negative muons with \(2 \times 10^{-\mu} \text{s}^{-1}\) irradiation.
    
    - cf. All LLFPs from 1GWe nuclear reactor (30 years operation)
      
      \[\rightarrow \text{de-activated in 100 years with } 1 \times 10^{18} \mu/s\]
    
    - cf. All MAs from 1GWe nuclear reactor (30 years operation)
      
      \[\rightarrow \text{de-activated in 25 years with } 1 \times 10^{17} \mu/s\]
  
- When lightest stable parent isotope mass < lightest daughter isotope \(\rightarrow\) Both parent and daughter stable isotopes are left. (cf. Pd)

- When lightest stable parent isotope mass > lightest daughter isotope \(\rightarrow\) Only daughter stable isotopes are left. (cf. Cs)

- Muon nuclear transmutation allows to re-produce valuable resources (Pd, Xe, etc.) from radioactive wastes.
Intense negative muon source

$I > \sim 10^{16} \mu /\text{sec}$

**MERIT**: Multiplex Energy Recovery
Internal Target
Muon source
for nuclear transmutation

- Issues
  - Low energy (<~300MeV/c) negative muon (μ⁻) production ⇐ Efficient muon capture.
    hadron: \( p + n \rightarrow p + p + \pi^−, \pi^- \Rightarrow \mu^- + \bar{\nu}_\mu \)
    photon: \( \gamma + n \rightarrow p + \pi^−, \pi^- \Rightarrow \mu^- + \bar{\nu}_\mu \)
  - Intensity > \(1 \times 10^{16}\)μ⁻/s
  - Muon (energy) cost < 5-10GeV/μ⁻
    \( \varepsilon < \frac{\Gamma}{\rho} \approx 5 - 10 GeV. \quad (\Gamma \sim 200 MeV/fission, \rho \sim RI-mol\%)\)
Ordinary scheme for $\mu^-$ production
-Limitations-

- **Hadron interaction: p+A**
  - $E_p \sim 0.6\text{GeV (th. energy)} \sim 0.3\text{GeV}$
  - $\pi$ production cross section $\sigma \approx 1 \times 10^{-25} \text{cm}^2$
  - Target length: $L(C) \gg 2\text{m}$ for $\pi /p-1$
  - Limitations
    - Stopping power: $dE/dx \sim 20\text{MeV/cm} @ E_p = 0.4\text{GeV} \rightarrow L_{\text{target}} < 20\text{cm} : 1/10$
    - Extinction: $\pi + A (3:3\text{resonance}) \rightarrow \pi 0 \rightarrow 2\gamma : 1/10$
  - Efficiency $\pi /p \approx 1/100$

- **Photoproduction: $\gamma + A**
  - $E_\gamma \sim 300\text{MeV (th. energy)} \sim 150\text{MeV}$
  - $\pi$ production cross section $\sigma \approx 2 \times 10^{-27} \text{cm}^2$
  - Target length: $L(W) \gg 100\text{m}$ for $\pi /p-1$
  - Limitations
    - $L_R \sim 3.5\text{mm} \rightarrow L_{\text{target}} < 3.5\text{mm}$
    - Efficiency $\pi /p < 1/10000$

- **Fixed target** → Muon energy cost $>> 10\text{GeV}/\mu$ - for both: Too high for
  • Applications
  • Technical limitations
ERIT for muon production
-MERIT-

- **ERIT:** Energy Recovery Internal Target
  - Storage ring + Internal target + Energy recovery per turn
  - Ordinary ERIT: Particle energy lost by Coulomb(EM) interaction
    - Rutherford scattering, ionization

- **MERIT for $\mu(\pi)$ production**
  - Energy recovery: not only for EM but hadronic (nuclear) interaction $\rightarrow$ Acceleration + Storage
    - Threshold energy($p+p(n)$): $\sim$230MeV for one $\pi$ production.
Ord. ERIT vs. New ERIT for muon production (MERIT)

Ord. ERIT
- Full energy injection
- Internal target
- RF energy recovery

MERIT
- Low energy injection
- Wedge-shape target
- RF acceleration & energy recovery
MERIT

- Requirement
  - Fixed(constant) magnetic field
  - Wide apertures: transverse & longitudinal
    - Zero-chromaticity
    - Strong(AG) focusing
- Scaling FFAG
  - Fixed(constant) RF frequency
    - On-$\gamma_t$ acceleration: $\beta < 1$ for proton
Muon energy cost with MERIT(1)

- Energy required for \( \pi \) production in ERIT

\[
E_\mu = \frac{A}{N_A \rho} \int_{\Delta \Omega} d\sigma(E_b) \frac{d\omega}{d\omega} \left( \frac{dE}{dx} \right)_{\text{eff}} \cdot (1 - \alpha)
\]

\[
\left( \frac{dE}{dx} \right)_{\text{eff}} = \beta_i \left( \frac{dE}{dx} \right)_i + \beta_r \left( \frac{d\tilde{E}_r}{dx} \right)_r
\]

\( E_\mu \): Muon cost

\( N_A \): Avogadro number

\( \rho \): Density of target material

\( \sigma(E) \): Density of target material

\( \Delta \Omega \): Acceptance for secondary particles

\( \beta_i, \beta_r \): Proportions of ionization and energy recovery-loss, respectively

\( \tilde{E}_r \): Energy loss including recovery

\( \alpha \): Conversion from thermal energy to electric power

\(-\Delta E = -(\Delta E_i + \Delta E_r)\)

Re-acceleration + \(\Delta E\)
Muon energy cost

- energy cost for $\mu$- production in MERIT
  - Geant4 simulation($\sigma, E_i, E_r$)
  - $\Delta \Omega$: described later

(Summary)
$E_\mu < 3.5\text{GeV}(\alpha=0\%)$
$E_\mu < 2.1\text{GeV}(\alpha=40\%)$
@$E_p = 0.8-2\text{GeV}$

MERIT can satisfy the criteria!
### MERIT with proton -basic optics-

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring configuration</td>
<td>H_FFAG</td>
</tr>
<tr>
<td>Energy range</td>
<td>500MeV-800MeV</td>
</tr>
<tr>
<td>Magnetic rigidity</td>
<td>3.633 -4.877Tm</td>
</tr>
<tr>
<td>Lattice</td>
<td>FDF</td>
</tr>
<tr>
<td>Average radius</td>
<td>5.044-5.5m</td>
</tr>
<tr>
<td>Magnetic field(F)</td>
<td>1.96-2.41T</td>
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<tr>
<td>Magnetic field(D)</td>
<td>1.71-2.11T</td>
</tr>
<tr>
<td>Number of cell</td>
<td>8</td>
</tr>
<tr>
<td>Packing factor</td>
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</tr>
<tr>
<td>Magnet opening angles</td>
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<td>Focusing</td>
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<tr>
<td>Defocusing</td>
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<tr>
<td>gap</td>
<td>0.01732</td>
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<tr>
<td>Geometrical field index</td>
<td>2.4</td>
</tr>
<tr>
<td>F/D ratio</td>
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<tr>
<td>k</td>
<td>2.4</td>
</tr>
<tr>
<td>Qh</td>
<td>0.2188</td>
</tr>
<tr>
<td>Qv</td>
<td>0.1797</td>
</tr>
<tr>
<td>( \rho f )</td>
<td>2.0233m(2.411T)</td>
</tr>
<tr>
<td>( \rho d )</td>
<td>2.3157m(2.106T)</td>
</tr>
</tbody>
</table>
Stability diagram $Q_h$-$Q_v$
Acceptance

frev=6.85MHz

longitudinal: acceleration
E=800MeV, k=2.433, γs=1.853, V=0.01

transverse acceptance

Ax>100,000mm.mrad

Az>70,000mm.mrad
Simulation

6D phase space: full tracking

Transverse

Beam emittance after 500 turns:
- hor. \( \sim 2,100 \text{mm.mrad} \), vert. \( \sim 1,200 \text{mm.mrad} \)

< acceptance (hor. : \( 30,000 \text{mm.mrad} \), vert. : \( 20,000 \text{mm.mrad} \))

\[ x'(\text{mrad}) \]

\[ z'(\text{mrad}) \]
Number of turns in MERIT

- More than 200 turns $\rightarrow N_{\mu-}/N_p \approx 0.25$

$\sim 50$ times better than fixed target
$\pi^-(\mu^-)$ capture

- **F_magnet** (B=2.5T: Bend outside) Solenoid

![Graph showing percentage vs. z(mm) for x=100mm and x=150mm](image)

- Target
- Proton
- F magnet

412.724, 68.2322
Summary (2)

- Characteristics and Performance of MERIT (Multiplex ERIT)
  - Proton accelerator and storage ring
    - Fixed magnetic field: Scaling FFAG(FDF)
    - Fixed RF frequency: On $\gamma$ t acceleration
    - Wedge target (Li)
  - Muon cost: $\leq 3.5\text{GeV}/\mu$-
  - Muon yield: $1 \times 10^{16} \mu-/s$ with $I_p \sim 2.5\text{mA}$

- Beam injection, target, radiation shield → Okabe-san’s
Deuteron
MERIT_FFAG
Energy efficiency of MERIT_FFAG

- Validity of ERIT scheme compared with a solid fixed target
  - Range \((dE/dx) < \text{Nuclear interaction length}\)
    - Beam energy is lost before nuclear interaction.
    - Nuclear interaction length for \(\pi\) production (NΔ) \(\sim 1\,\text{m}\)
      - \(R [\text{range:} \int (dx/dE)dE]\)
      - \(L [\text{nuclear interaction length:} 1/((\sigma\,N_a\,\rho/A)]\)
    - Example: \(E_p=500\,\text{MeV},\, \text{Be(}p,\pi\text{)reaction}\, R\sim 50\,\text{cm},\, L\sim 1\,\text{m}\)
      - Energy threshold \((A(p,\pi): E_p\sim 250\,\text{MeV: proton}) \leftrightarrow R<L\)
      - Destruction \((\pi^- + A \rightarrow X)\)
      - Thin target is needed.

Energy recovery: \(E_{sp} \sim 300\,\text{MeV}(p\text{-beam}: E_p=800\,\text{MeV}, \, \text{Li target})\)
So far, we believe proton is better than deuteron.

Because →

- Deuteron breaks up easily to proton and neutron.
  - Difficult to recover the beam energy.
  - →Poor energy efficiency for \( \pi^-(\mu^-) \) production.

Is that so?

- Deuteron induced \( \pi^- \) production cross section: \( \sigma (d, \pi^-) > 6.6 \times \sigma (p, \pi^-) \).
ref. JAERI-Tech-99-065, 仁井田他
π - production with deuteron beam
-Energy efficiency-

- π production :NΔ (σ_{pp}/σ_{pn} =2) resonance
  - pp/nn(l=1)→π (+,0,-), pn(l=0)→π (0,-)
- π productio with deuteron (pn) (target : light nuclei)
  - σ_{π+}:σ_{π0}:σ_{π-} ~1:1:1
  - cf. proton  σ_{π+}:σ_{π0}:σ_{π-} ~6:3:1
- Thus, σ_{π-}(d)/σ_{π-}(p)=(2x1/3)/(1/10)~6.6
  - (ref. JAERI-Tech-99-065, Niita et al.)
Deuteron break-up

- break-up reaction: \( d + X \rightarrow p + n + X \)
  - \( \sigma_{bu} / \sigma_{\pi} \sim 2-3 \) (Geant4)
- Energy efficiency of \( \pi^- \) production: \( \eta \) (energy required for one \( \pi^- \) production)
  - \( \eta (d)/\eta (p) = [\sigma_{\pi^-}(d)/\sigma_{\pi^-}(p)]/[\sigma_{bu} / \sigma_{\pi}]x1/2 = 1.1-1.5 : \eta (d)\approx \eta (p) \)
- Moreover,
  - Total kinetic energy (Ep+En) after break-up reaction is almost same as that of incident deuteron.
    - Small binding energy (d=p+n) \sim MeV
    - \( \rightarrow \) Energy can be recovered thermally. (Not by ERIT)
Deuteron

MERIT_FFAG

- Characteristic of d-MERIT_FFAG
  - Gas target: deuterium gas (1 atm)
  - Projectile: deuteron
  - Beam energy: 600MeV/u
  - Deuteron Intensity: $7.9 \times 10^{11}$ particles/ring
Muon yield with d_MERIT_FFAG

- $\pi^-$ Yield
  \[ Y = L\sigma_\pi. \]
- $\sigma^-$: $\pi^-$ production cross section
- Luminosity
  \[ L = N_d\nu_d n_T. \]
  - $N_d$: number of deuteron/ring 7.9x10^{11} d/ring
  - $\nu_d$: deuteron velocity 600MeV/u
  - $n_T$: target particle density 1 atm
  \[ L = 5 \times 10^{41} \text{ cm}^{-2} \cdot \text{s}^{-1} \rightarrow Y = 1 \times 10^{16} \mu^- / \text{s} \]
# d_MERIT_FFAG ring parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td><strong>Energy</strong></td>
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<td>Magnetic rigidity</td>
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<td>FDF</td>
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<td>Magnetic field (F)</td>
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<td>Magnetic field (D)</td>
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<td>F/D ratio</td>
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<td>Betatron tune (H) : Q_H</td>
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<td>Betatron tune (V) : Q_V</td>
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<tr>
<td>Curvature (F) : ( \rho_f )</td>
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<tr>
<td>Curvature (D) : ( \rho_d )</td>
<td>2.316m</td>
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</table>
Muon nuclear transmutation scheme with d_MERIT_FFAG ring

- LLFP (nuclear wastes) surrounds the beam duct.
- Beam duct is filled by ~1 atm deuterium gas.
- Negative muons are slowed down by deuterium gas and beam duct, then captured by LLFP nuclei.
MERIT
-proof of principle experiment-

- Key issue of MERIT
  - Simultaneous operation with acceleration and energy recovering
  - Proof of principle experiment (2016-2019)
    - Modifying the existing ERIT to MERIT
      - Beam momentum change $\Delta p \sim 10\%$
      - Number of turns at recycling $\sim 100$turns
Summary

- Muon nuclear transmutation looks useful for treatment of long-lived radio-activities.
  - cf. 1GWe nuclear reactor (30 years operation)
    - de-activated in 100 years with $1 \times 10^{18} \mu /s$
    - de-activated in 25 years with $1 \times 10^{17} \mu /s$
- MERIT could satisfy the requirements for negative muon source.
- Proof-of-principle project of MERIT has started.
- Deuteron MERIT_FFAG is also interesting.