Intense Muon Source with MERIT_FFAG

Yoshiharu Mori
Kyoto University, RRI

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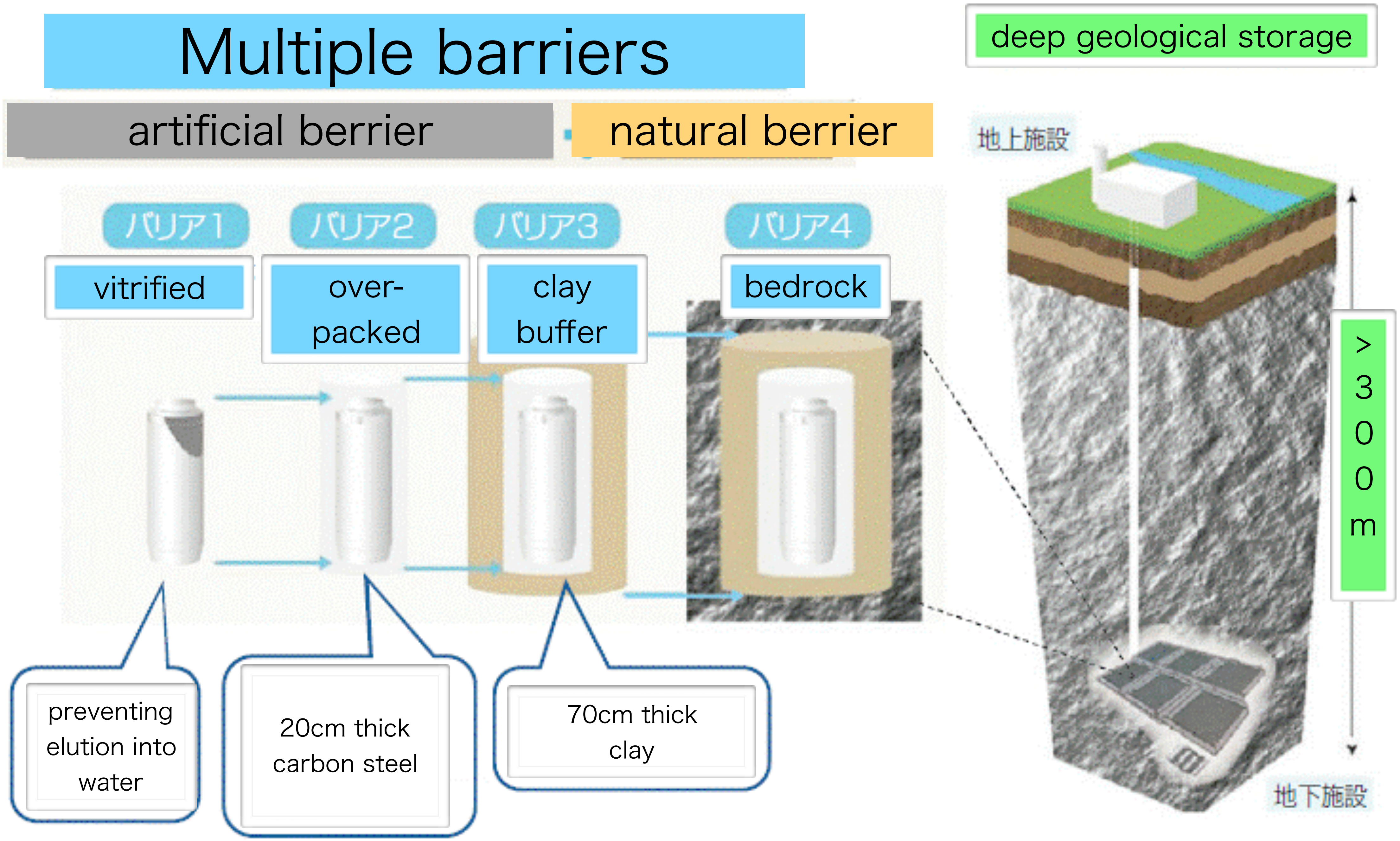
Problems in nuclear energy production

- **Treatment of radio-activities produced by nuclear reactor.**
  - Radio-active fission products
  - Plutonium
  - Minor actinide(MA;Am, etc.)
- **Deep underground storage: Long-lived species(τ >1,000y) → "Negative legacy"**
  - Long-lived fission products(Tc^{99}, I^{127}, Pd^{107},etc.)
  - Minor actinides(MA)

Underground nuclear waste disposal :outline



(C) Agency for Natural Resources and Energy

Nuclear wastes

- **Nuclear wastes from 1ton 3% enriched 1ton Uranium fuel (Wiikipedia)**
  - Pu 10kg
  - Pt 2kg
  - Short-lived FP (τ<100y):Sr90,Cs137,etc. 26kg

no practical way

  - Long-lived FP (τ>1000y):Tc99,Pd107,etc. 1.2kg
  - Minor Actinides : Np, Am, etc. 0.6kg

ADS, FBR(fission)

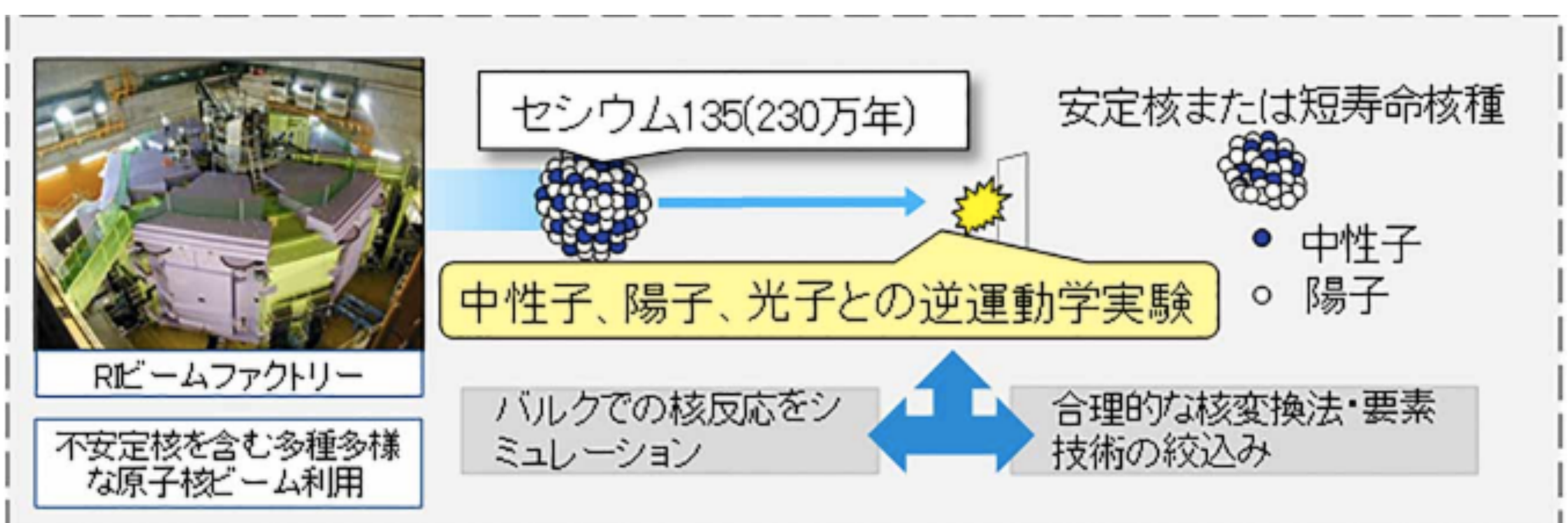
Deactivation and re-use of LLFPs(^{93}Zr, ^{79}Se, ^{107}Pd, ^{135}Cs)by nuclear transmutation with accelerator

ImPACT project

-Impulsing Paradigm Change through Disruptive Technologies Program of Council for

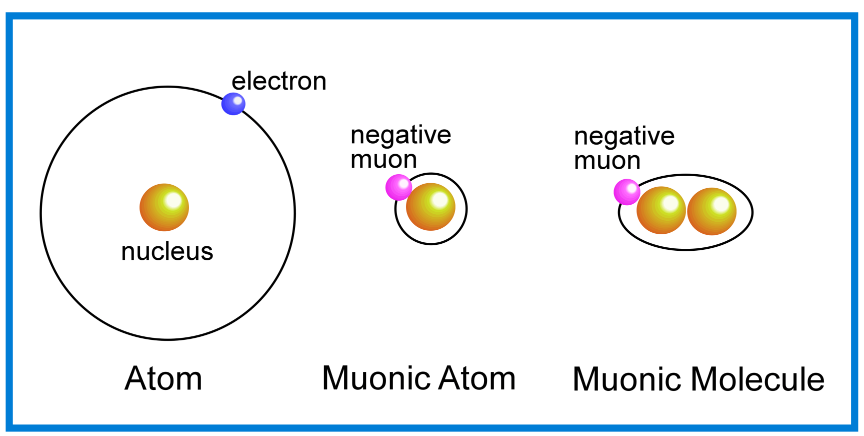
Nuclear transmutation by neutron, muon, etc.

- **Neutron: (n,γ)@RIKEN RIBF, Osaka, Kyusyu, JAEA etc.**
  - Precise cross section measurement
  - Inverse reaction : n+ ^{135}Cs→ ^{136}Cs+γ
    - HI(U) →fragmentation → ^{135}Cs + n(target like D_2,Li)
- **Muon: (μ-,p)n: @RIKEN, RCNP, JPARC,Kyoto U.**
  - Muon transmutation exp.**@RIKEN, RCNP, JPARC**
  - Muon source @**Kyoto, JPARC**



nuclear transmutation with negative muon

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



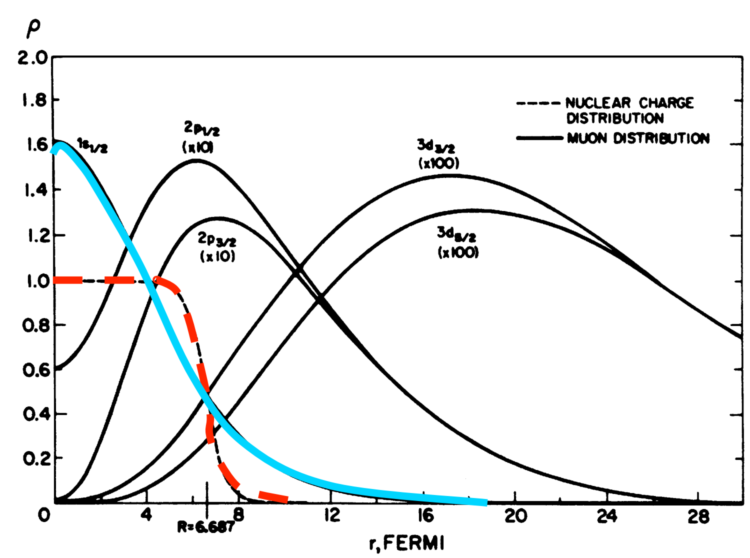
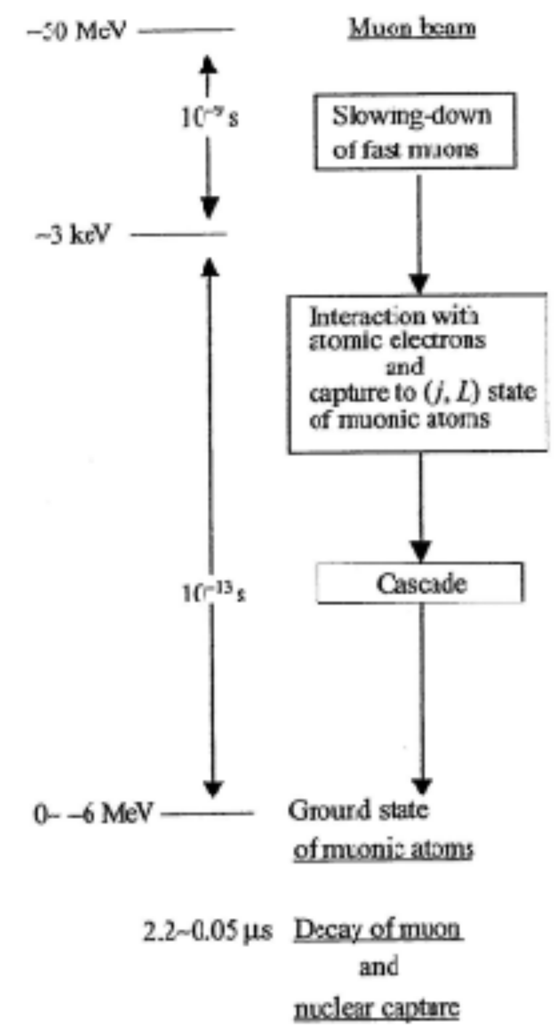
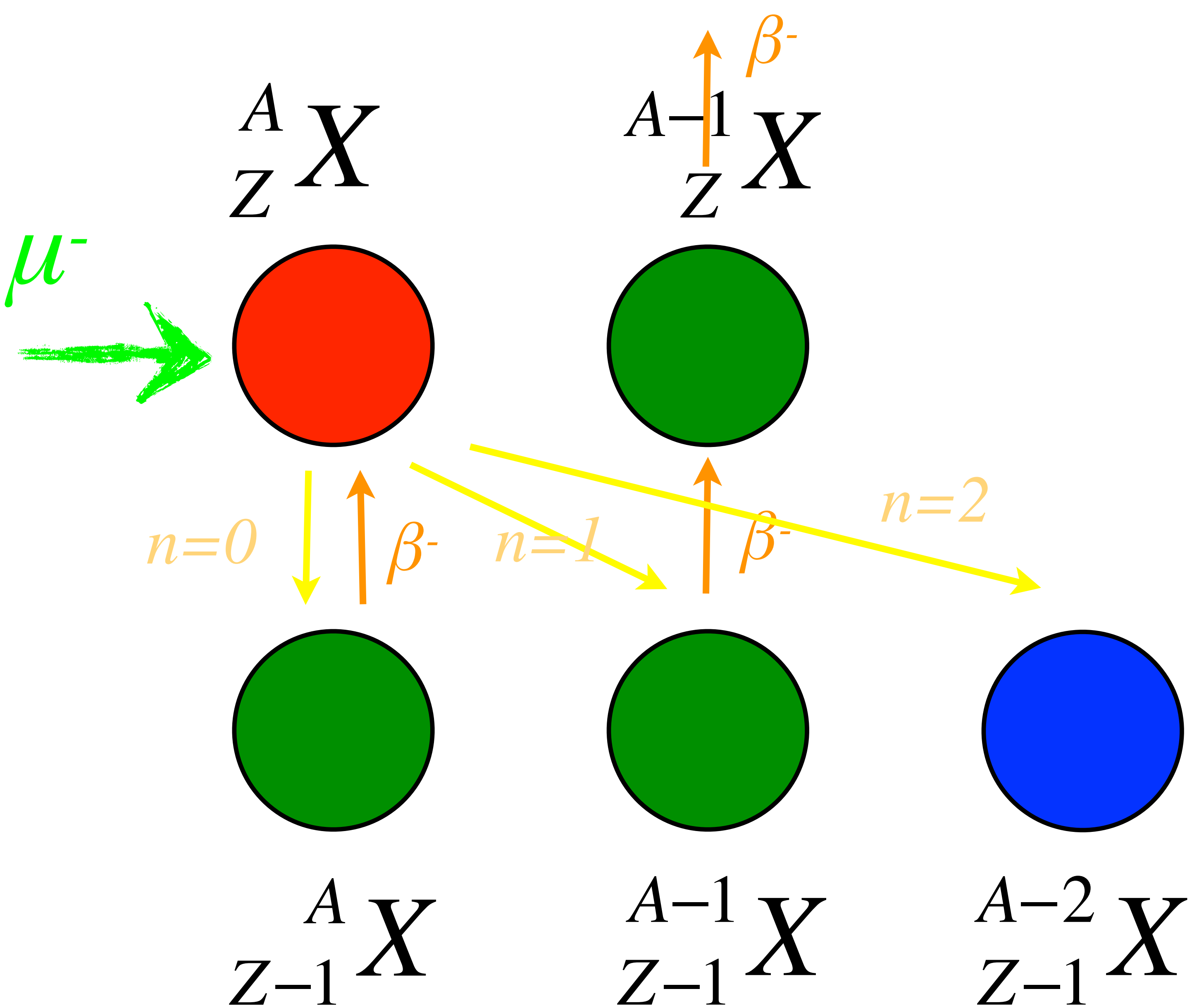


Fig. 15.8 The probability densities of finding a muon in the state indicated, at a distance r from the nuclear centre (full lines), are compared with the nuclear charge distribution in the case of lead. In the $S_{1/2}$ state, the probability of finding a muon within the nucleus is close to 50% (Devons and Duerdoth 1969).



Formation of non-radioactive (stable) nuclei



- **Muon pumping**
  - Neutron emission → Leading to form stabl nuclei.

$$\begin{aligned}\mu^- + {}^{99}\mathrm{Tc(LLFP{:}}2.15\times10^5 y) &\rightarrow {}^{99}\mathrm{Mo(stable)} + \nu_\mu \\ &\rightarrow {}^{98}\mathrm{Mo(stable)} + n + \nu_\mu \\ &\rightarrow {}^{97}\mathrm{Mo(stable)} + 2n + \nu_\mu \\ &\rightarrow {}^{96}\mathrm{Mo(stable)} + 3n + \nu_\mu\end{aligned}$$

Muon

- **Transmutation rate :estimated with rate equations**

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

$$i = 0, N$$

- **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* :β
  - *Emitted neutron numbers (f) are constant for parent isotopes.*

Example

- **Cs:cesium**
  - ^{137}Cs
    - Typical short-lived FP (half-life: 30.07y)
    - Strong γ emitter
      - Most problematic → high water solubility

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

  - ^{135}Cs
    - Long-lived FP (half-life: $2.3\mathrm{x}10^6$y)

$_{55}Cs + \mu^- \rightarrow {}_{54}Xe$

A(Cs)	137	136	135	134	133	132	131	130	129	128
NA(Pd)	0.4243	0	0.1287	0.0089	0.4382	0	0	0	0	0
DR(1/y)	0.0332	27.74	4.4E-07	0.484	0	56.33	37.67	17994	273.2	2.06E+05
A(Xe)	137	136	135	134	133	132	131	130	129	128
DR(1/y)	1.38E+05	0	958.4	0	69.62	0	0	0	0	0

Emitted neutron numbers	0	1	2	3	4	5
Yield	0.04	0.72	0.06	0.12	0.06	0

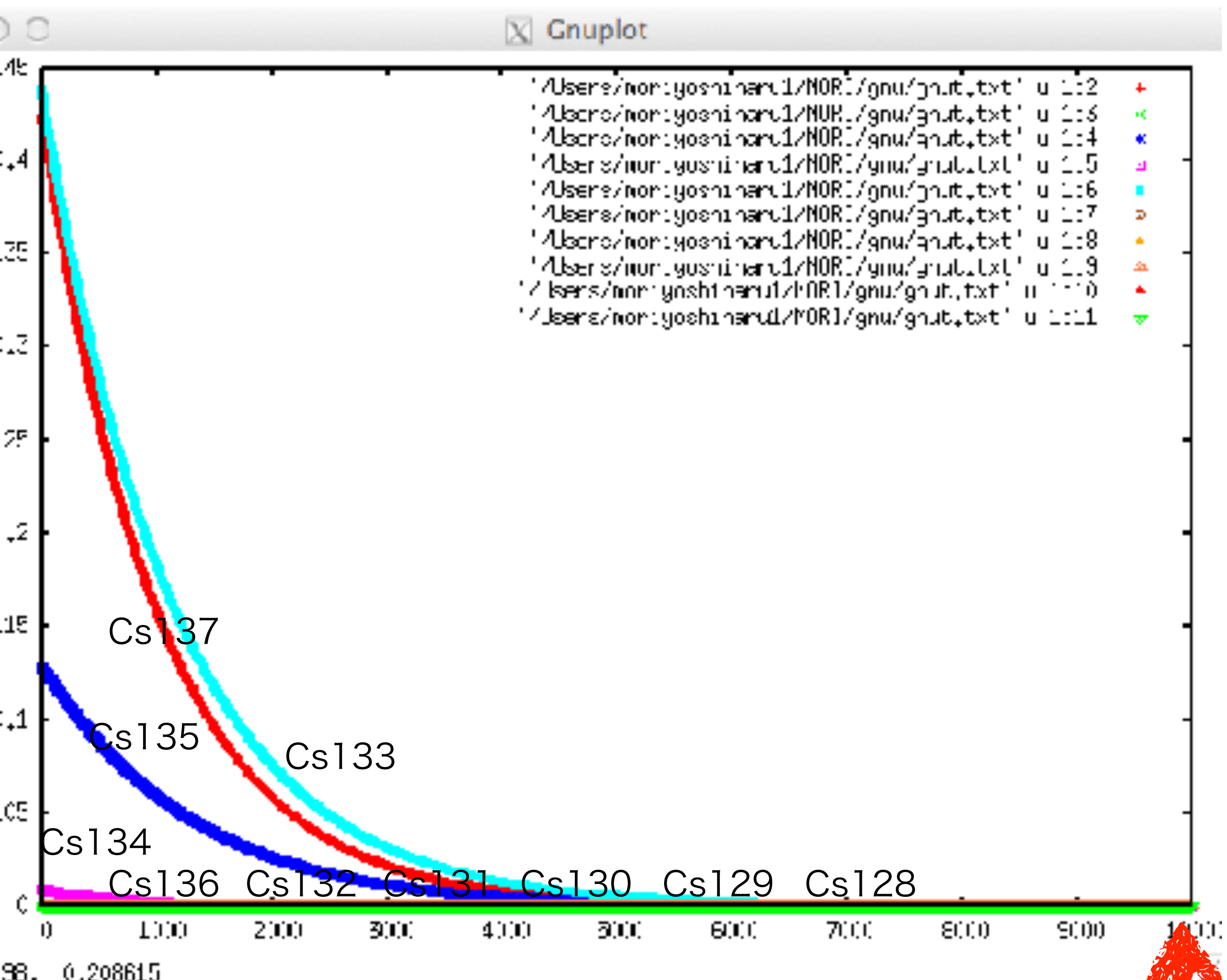
Preconditions

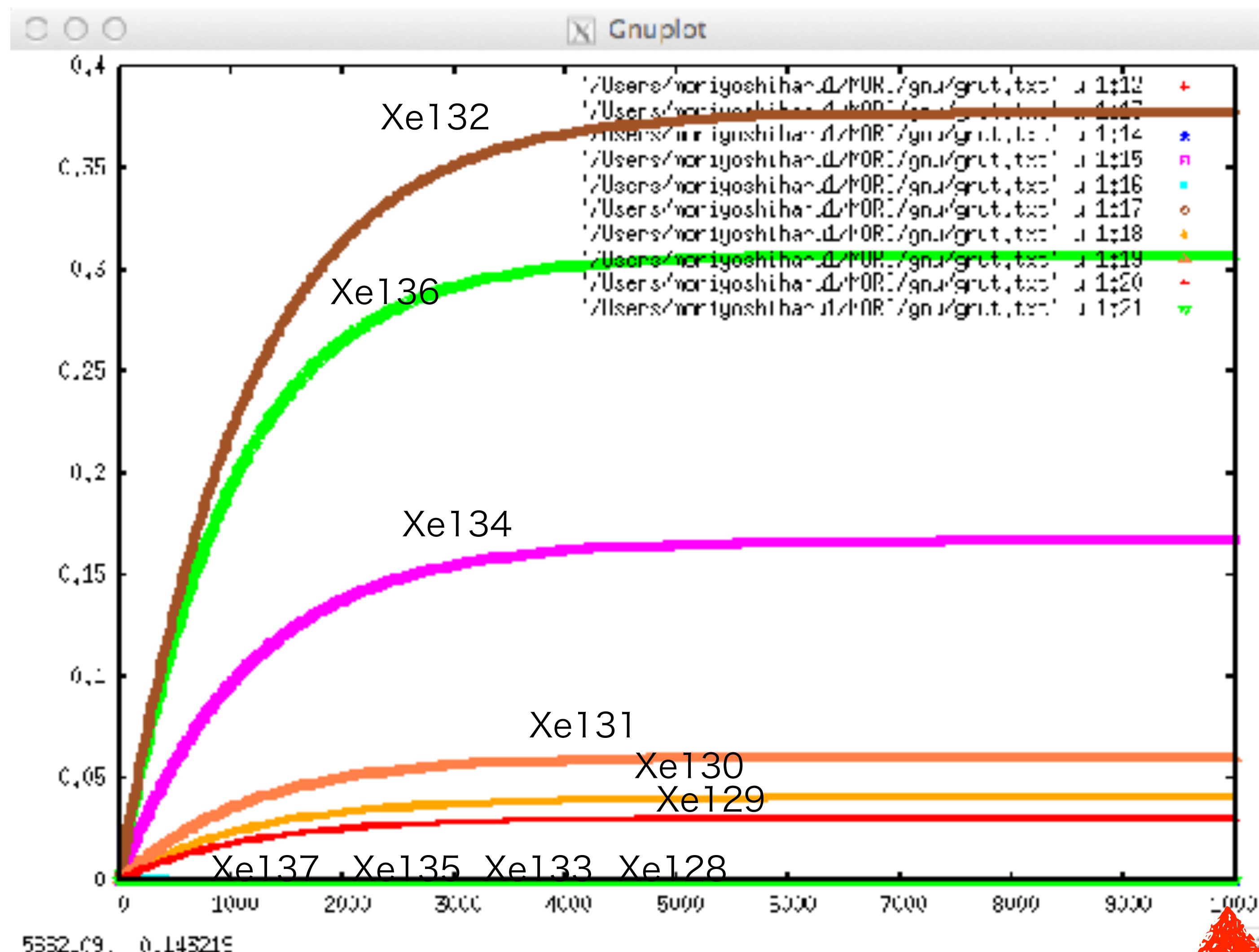
- Negative muon flux Q~$2x10^{16}$μ/sec (1mol/year eq.)
- 100% negative muon capture by nucleus is realized.
- Cesium amount : 1 mol → including all cesium isotopes. cf. ~mol Cs produced by 1ton 3%-enriched U nuclear fuel burn out.

Cs-Xe

μ-irradiation:Cs-137, 136, 135, 134, 133, 132, 131, 130, 129, 128

Daughter:Xe-137, 136, 135, 134, 133, 132, 131, 130, 129, 128





10years

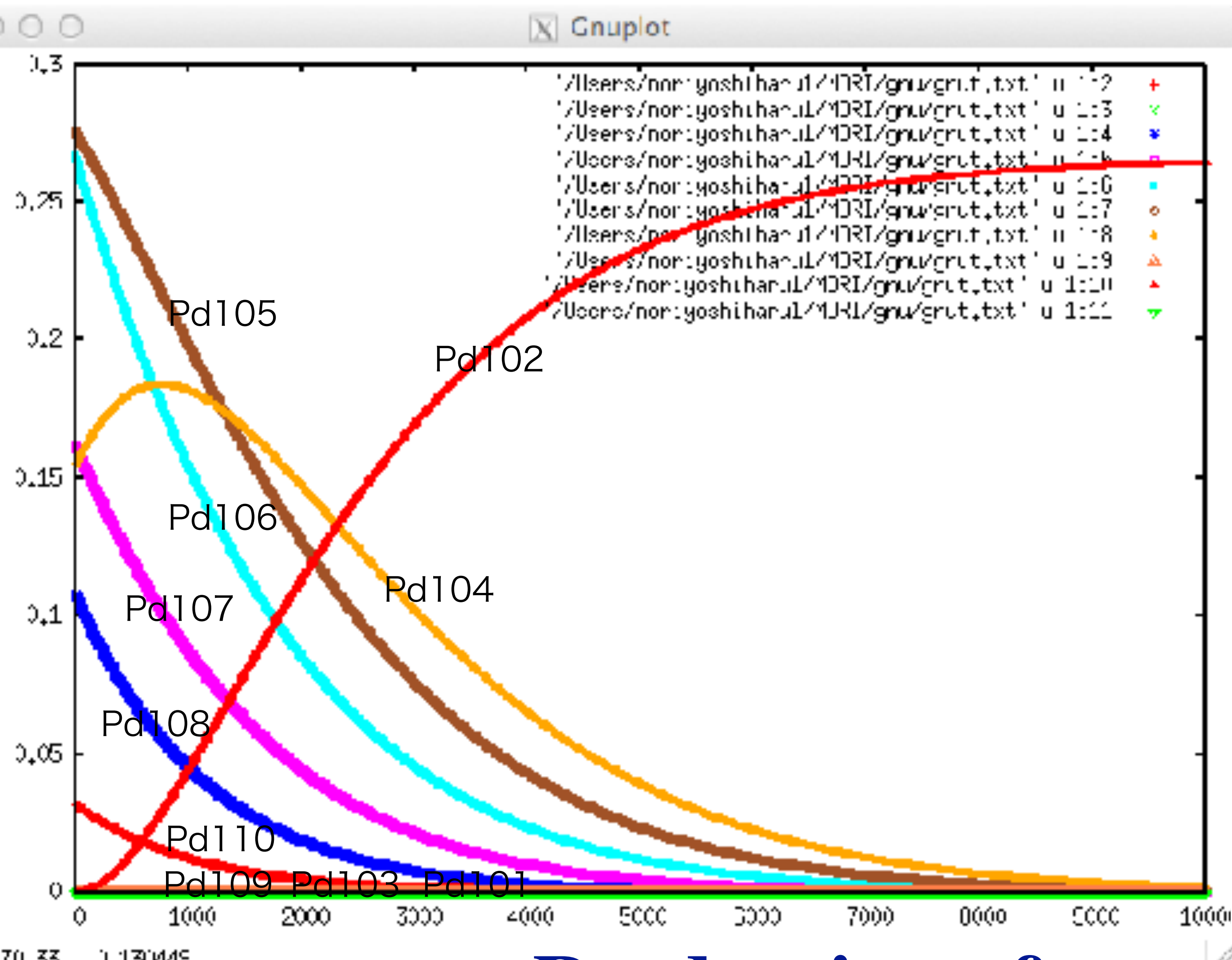
10years

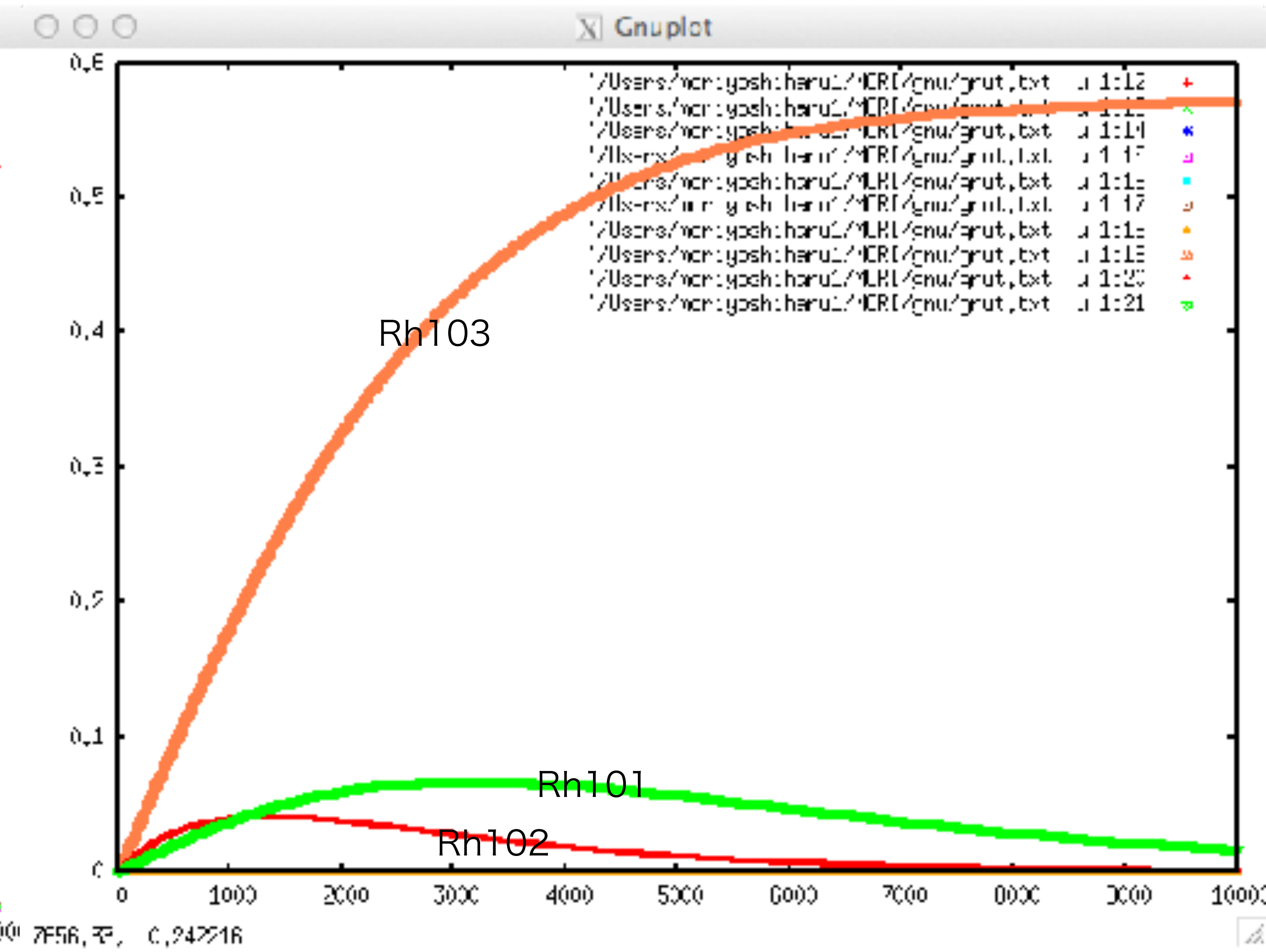
Half of Cesium(^{137}Cs,^{135}Cs) are transmuted to stable Xe isotopes within a year.

Pd-Rh

μ-irradiation:Pd-110,109,108,107,106, 105, 104, 103, 102, 101

Daughter:Rh-110,109,108,107,106, 105, 104, 103, 102, 101





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 <a year by negative muons with 2×10^{16} μ^-/s irradiation.
    - cf. All LLFPs from 1GWe nuclear reactor(30years operation)

      → **de-activated in 100years with 1×10^{18} μ^-/s**
    - cf. All MAs from 1GWe nuclear reactor(30years operation)

      → **de-activated in 25years with 1×10^{17} μ^-/s**
  - When lightest stable parent isotope mass < lightest daughter isotope→Both parent and daughter stable isotopes are left. (cf. Pd)
  - When lightest stable parent isotope mass > lightest daughter isotope→ 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

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

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 > $1\text{x}10^{16}\mu^-$/s
  - Muon (energy) cost < 5-10GeV/μ^-

    $$\varepsilon < \frac{\Gamma}{\rho} \simeq 5-10GeV. \quad (\Gamma \sim 200\mathrm{MeV/fission}, \rho \sim \mathrm{RI\text{-}mol\%})$$

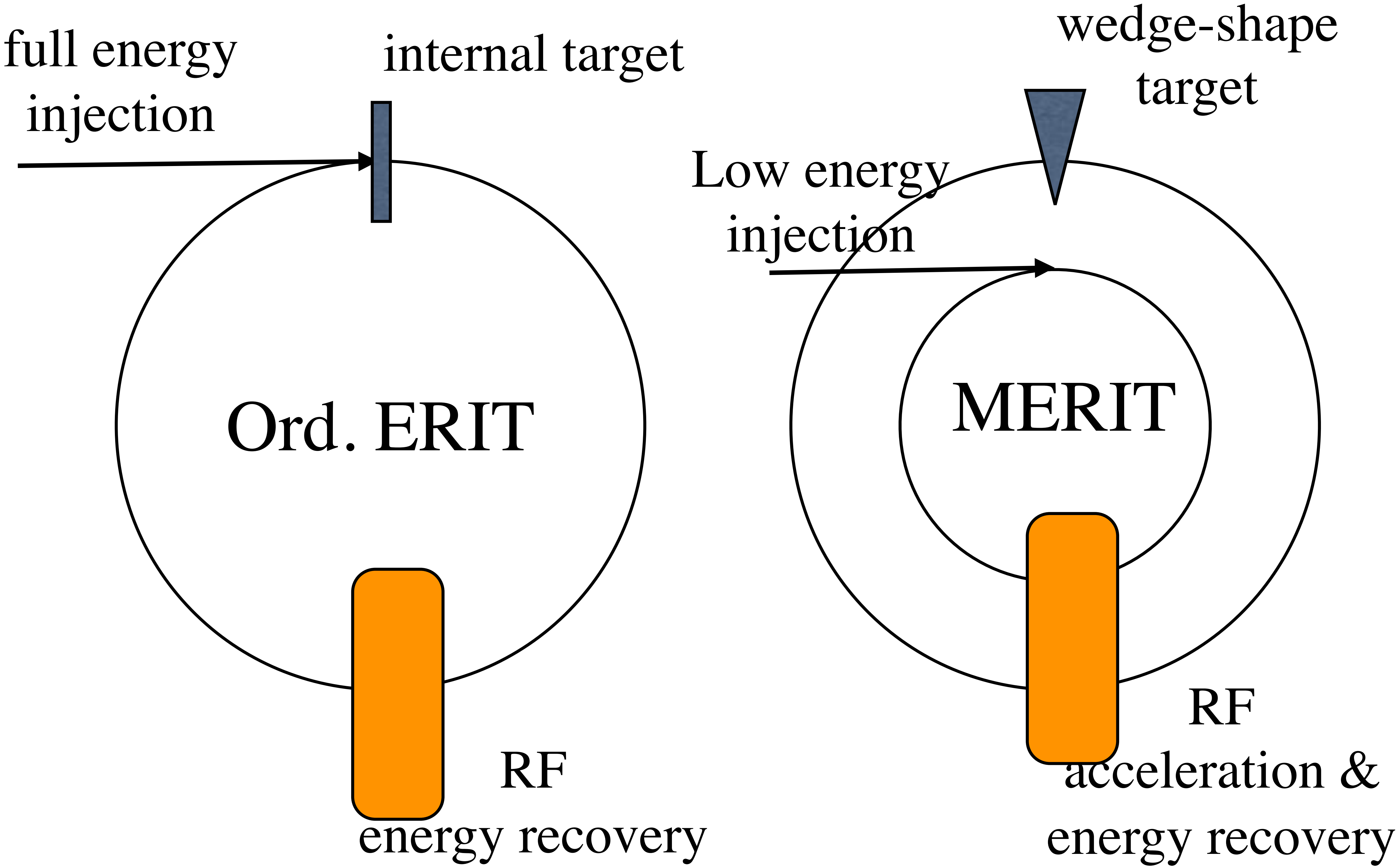
Ordinary scheme for μ^- production -Limitations-

- **Hadron interaction: p+A**
  - E_p~0.6GeV(th. energy ~0.3GeV) π prodction cross section $\sigma \approx 1\times 10^{-25}\,cm^2$
  - Target length : L(C) >> 2m for π^-/p~1
  - Limitations
    - Stopping power:dE/dx~20MeV/cm @Ep=0.4GeV → L_{target} <20cm :1/10
    - Extinction : π^- + A (3:3resonance)→ $\pi 0$ →2γ :1/10
  - Efficiency π^-/p~1/100
- **Photoproduction: γ+A** π prodction cross section $\sigma \approx 2\times 10^{-27}\,cm^2$
  - E_γ~300MeV(th. energy ~150MeV)
  - Target length : L(W) >> 100m for π/p~1
  - Limitations
    - L_R ~3.5mm → L_{target} <3.5mm
  - Efficiency π^-/p <1/10000
- **Fixed target → Muon energy cost >> 10GeV/μ- for both :Too high for**

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 μ(π) production**
  - Energy recovery : not only for EM but hadronic (nuclear) interaction → Acceleration + Storage
    - Threshold energy(p+p(n)) : ~230MeV for one π production.

Ord. ERIT vs. New ERIT for muon production (MERIT)



MERIT

- **Requirement**
  - Fixed(constant) magnetic field
  - Wide apertures:transverse & longitudinal
    - Zero-chromaticity
    - Strong(AG) focusing
  - **Scaling FFAG**
  - Fixed(constant) RF frequency
    - On-γ_t acceleration : β<1 for proton

Muon energy cost with MERIT(1)

- **Energy required for π production in ERIT**

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

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

E_μ : Muon cost

NA : Avogadro number

ρ : Density of target material

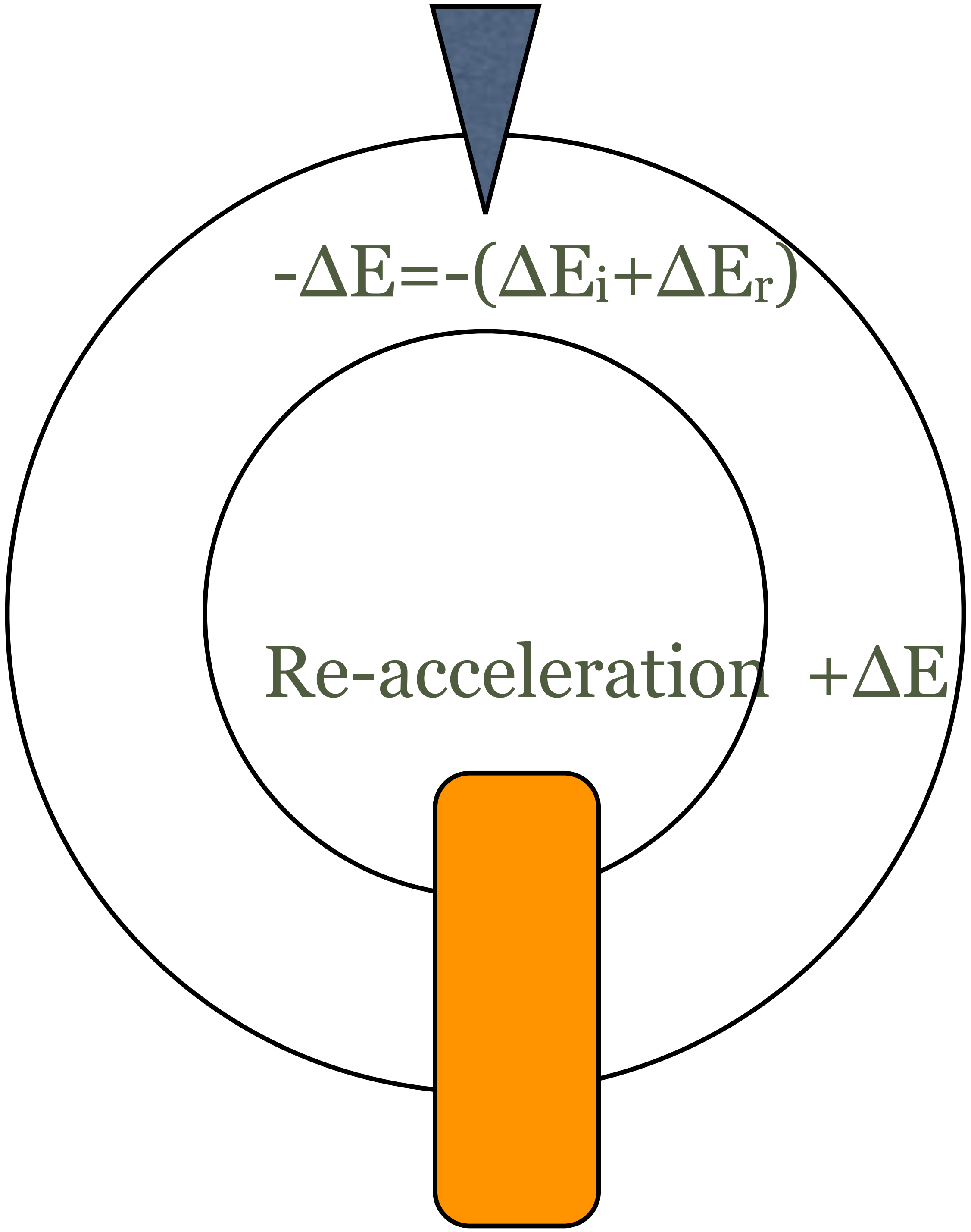
$\sigma(E)$: Density of target material

$\Delta\Omega$: Acceptance for secondary particles

β_i, β_r : Proportions of ionization and energy recovery-loss, respectively

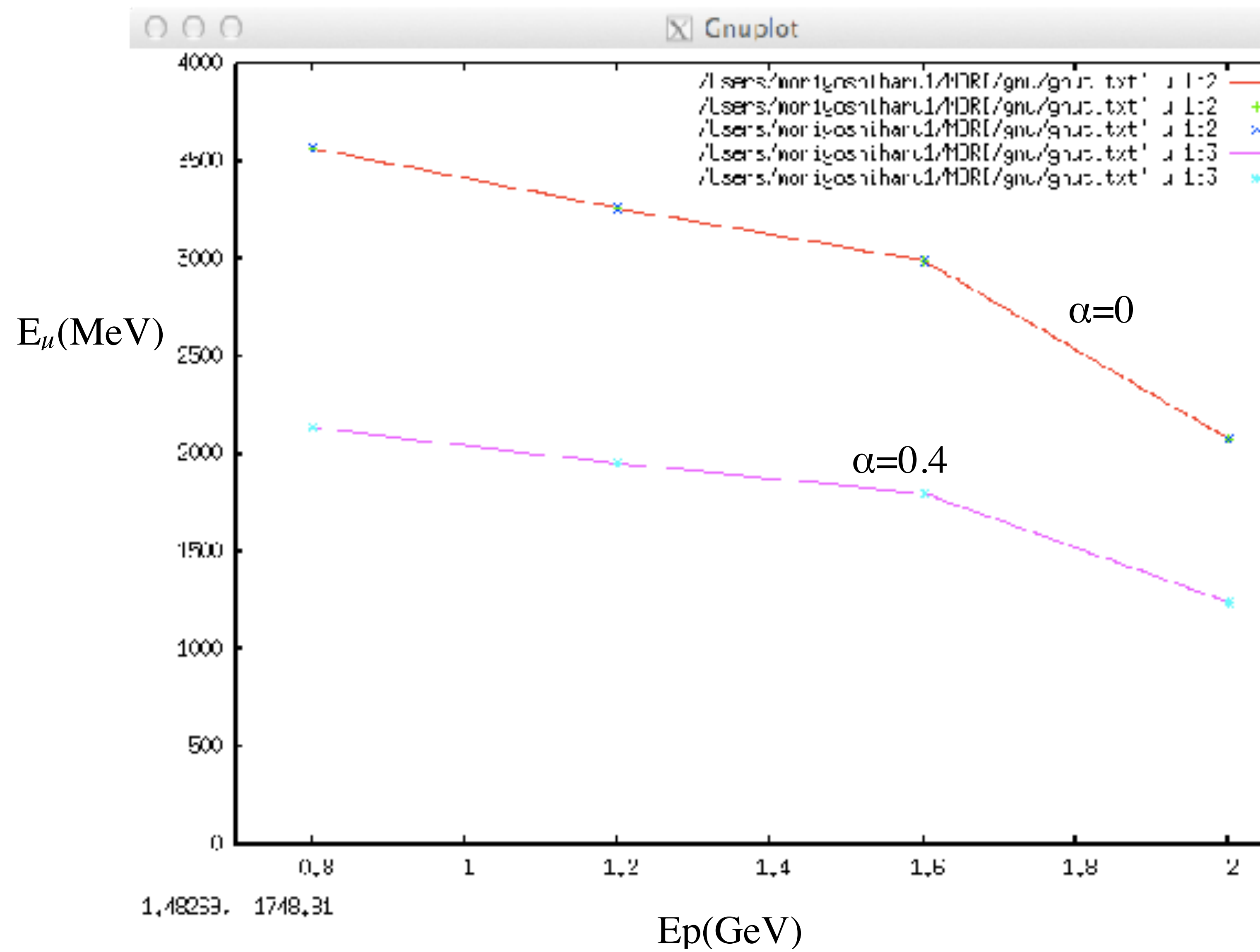
$\tilde{E}_r$: Energy loss including recovery

α : Conversion from thermal energy to electric power



Muon energy cost

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



(Summary)

Eμ<3.5GeV(α=0%)

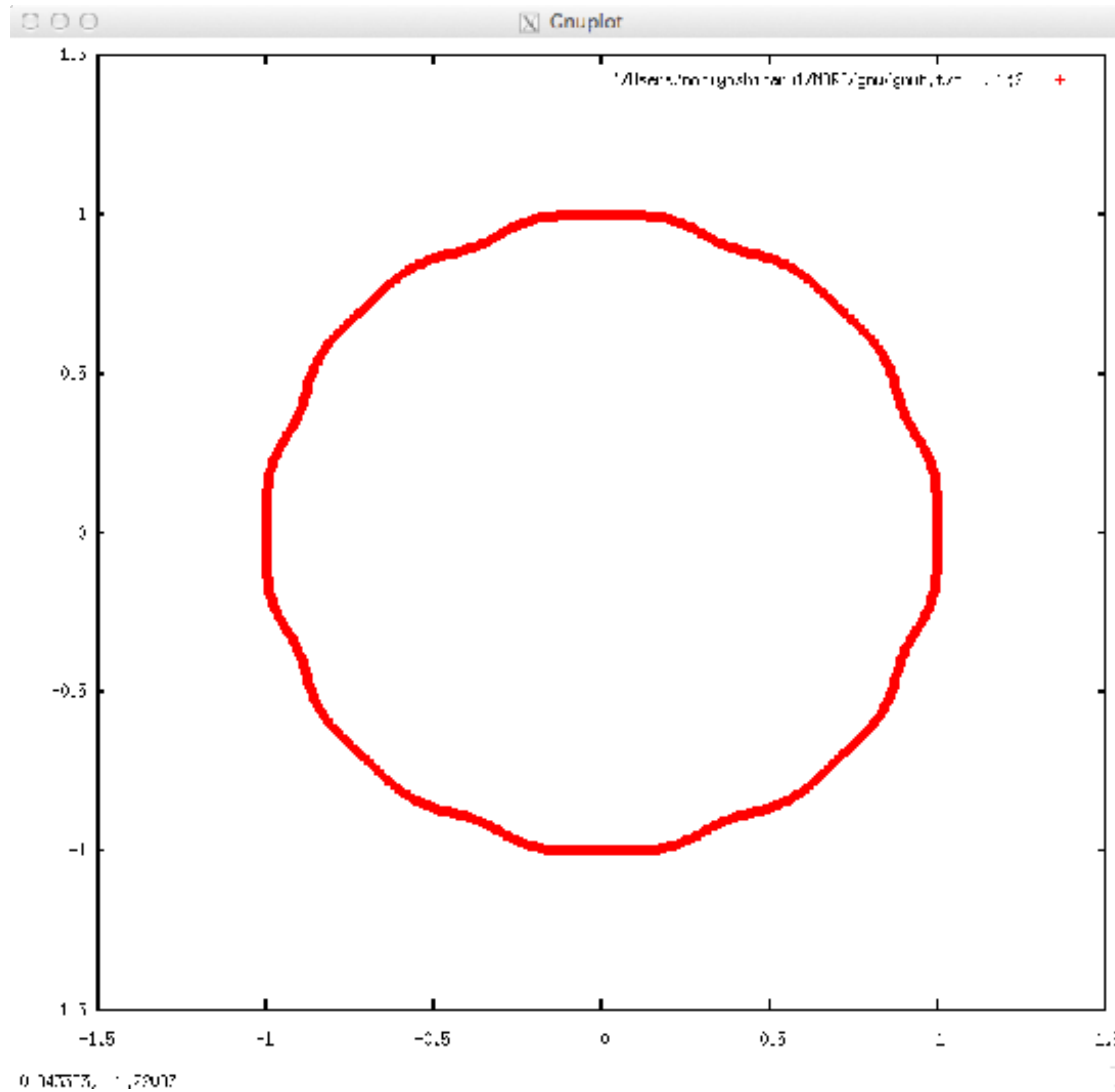
Eμ<2.1GeV(α=40%)

@Ep=0.8-2GeV

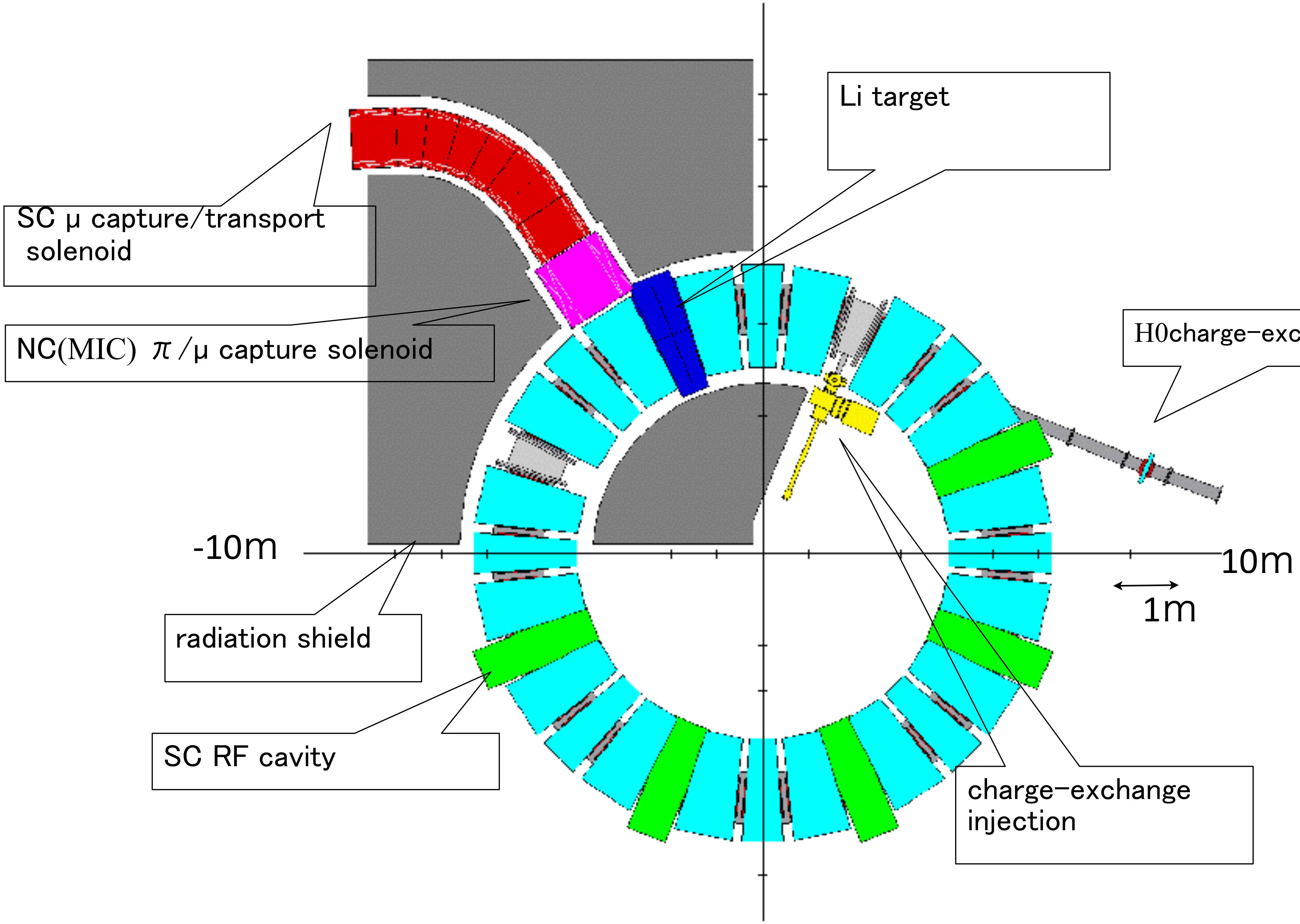
MERIT can satisfy the criteria!

MERIT with proton -basic optics-

Ring configuration	H_FFAG
Energy range	500MeV-800MeV
Magnetic rigidity	3.633 -4.877Tm
Lattice	FDF
Average radius	5.044-5.5m
Magnetic field(F)	1.96-2.41T
Magnetic field(D)	1.71-2.11T
Number of cell	8
Packing factor	0.7
Magnet opening angles	
Focusing	0.2032
Defocusing	0.1432
gap	0.01732
Geometrical field index	2.4
F/D ratio	1.1
k	2.4
Qh	0.2188
Qv	0.1797
ρf	2.0233m(2.411T)
ρd	2.3157m(2.106T)

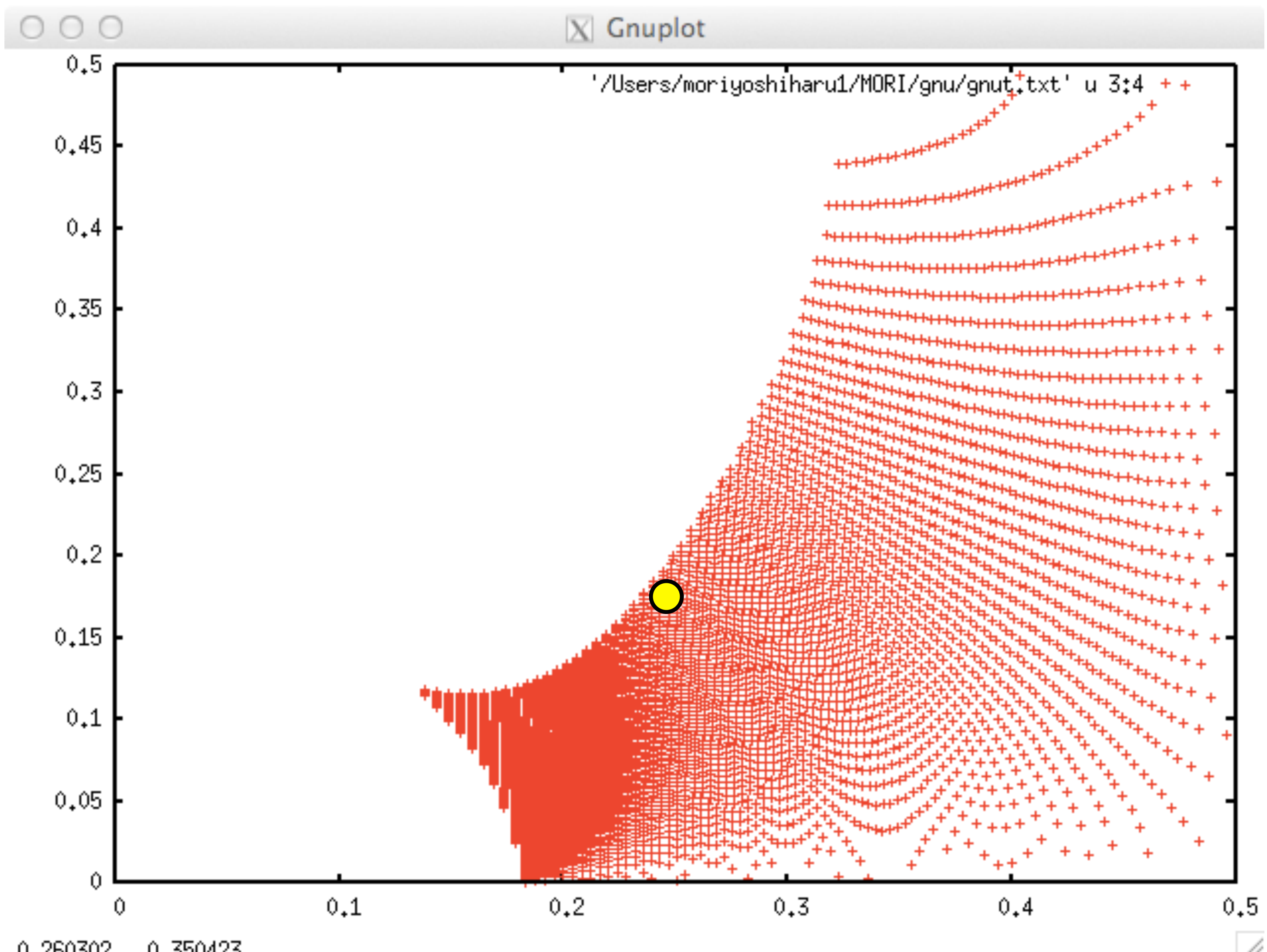


Schematic layout



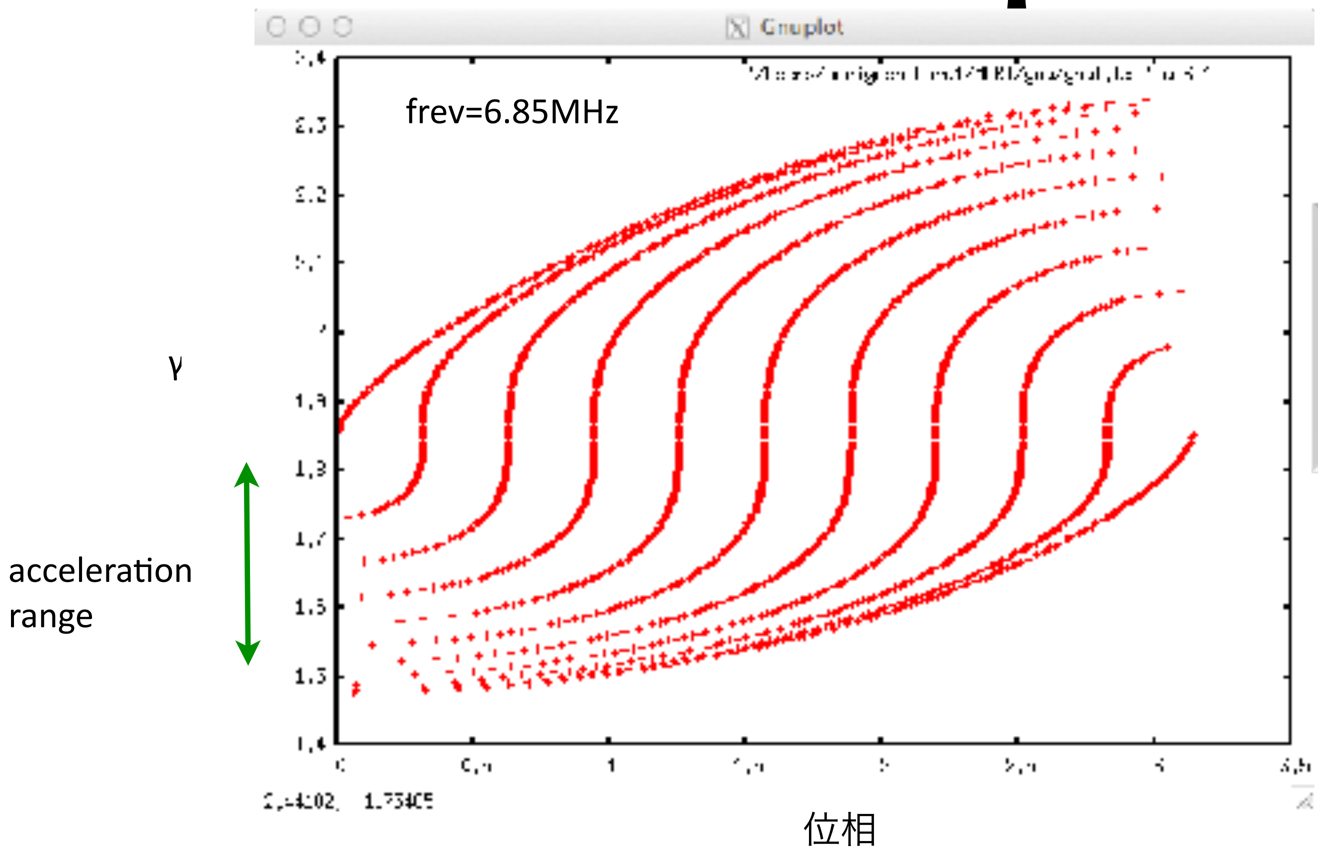
Stability diagram Qh-Qv

Qv



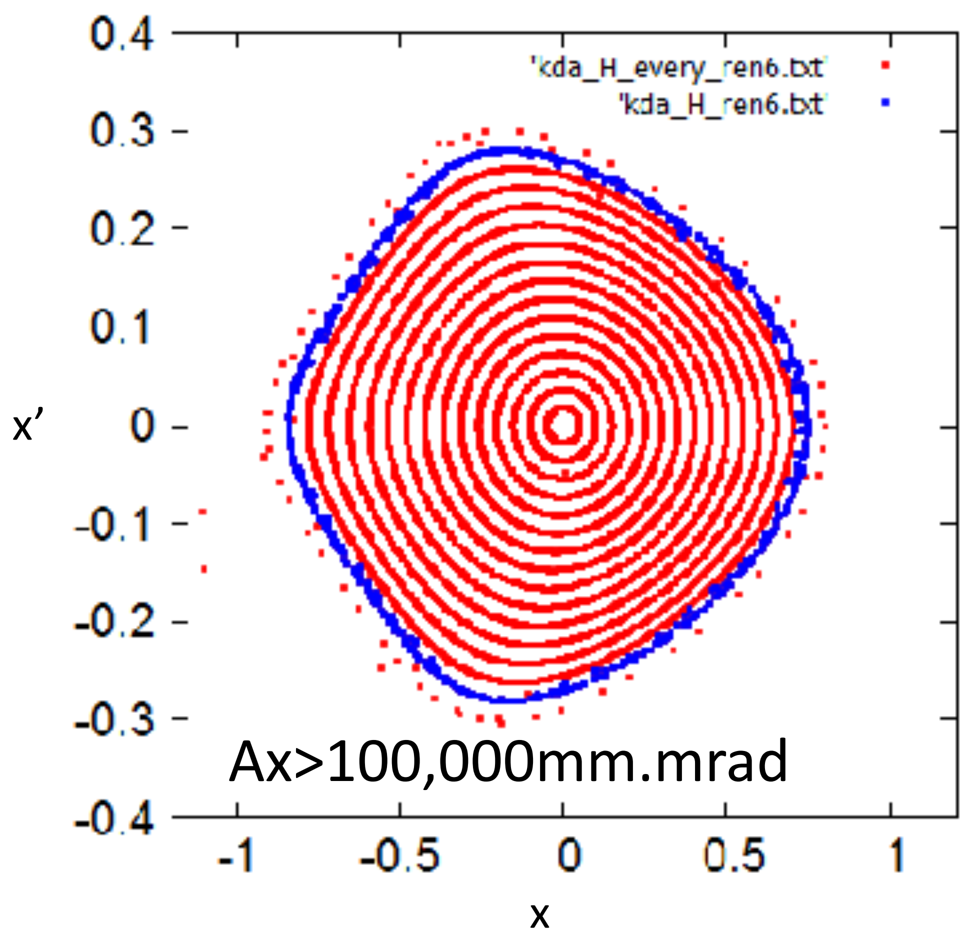
Qh

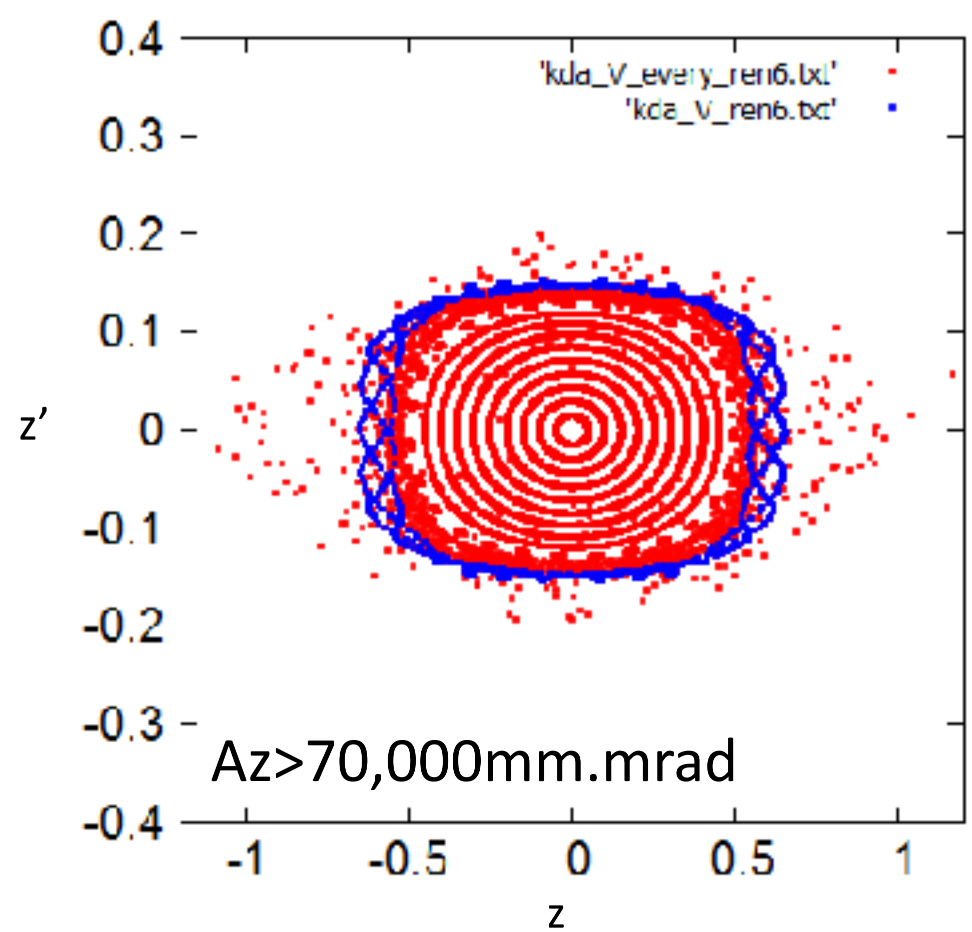
Acceptance



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

transverse acceptance





Simulation

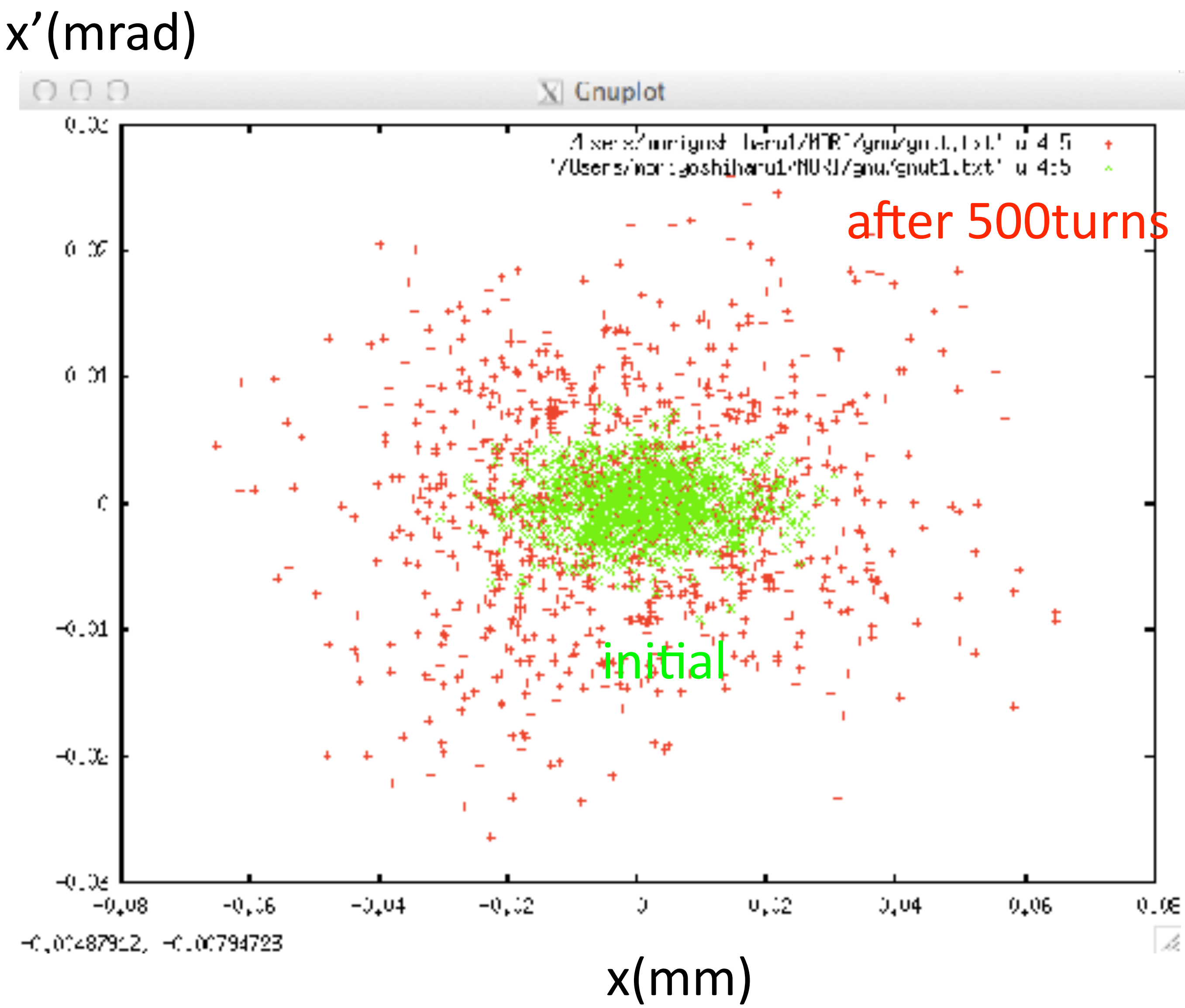
6D phase space:full tracking

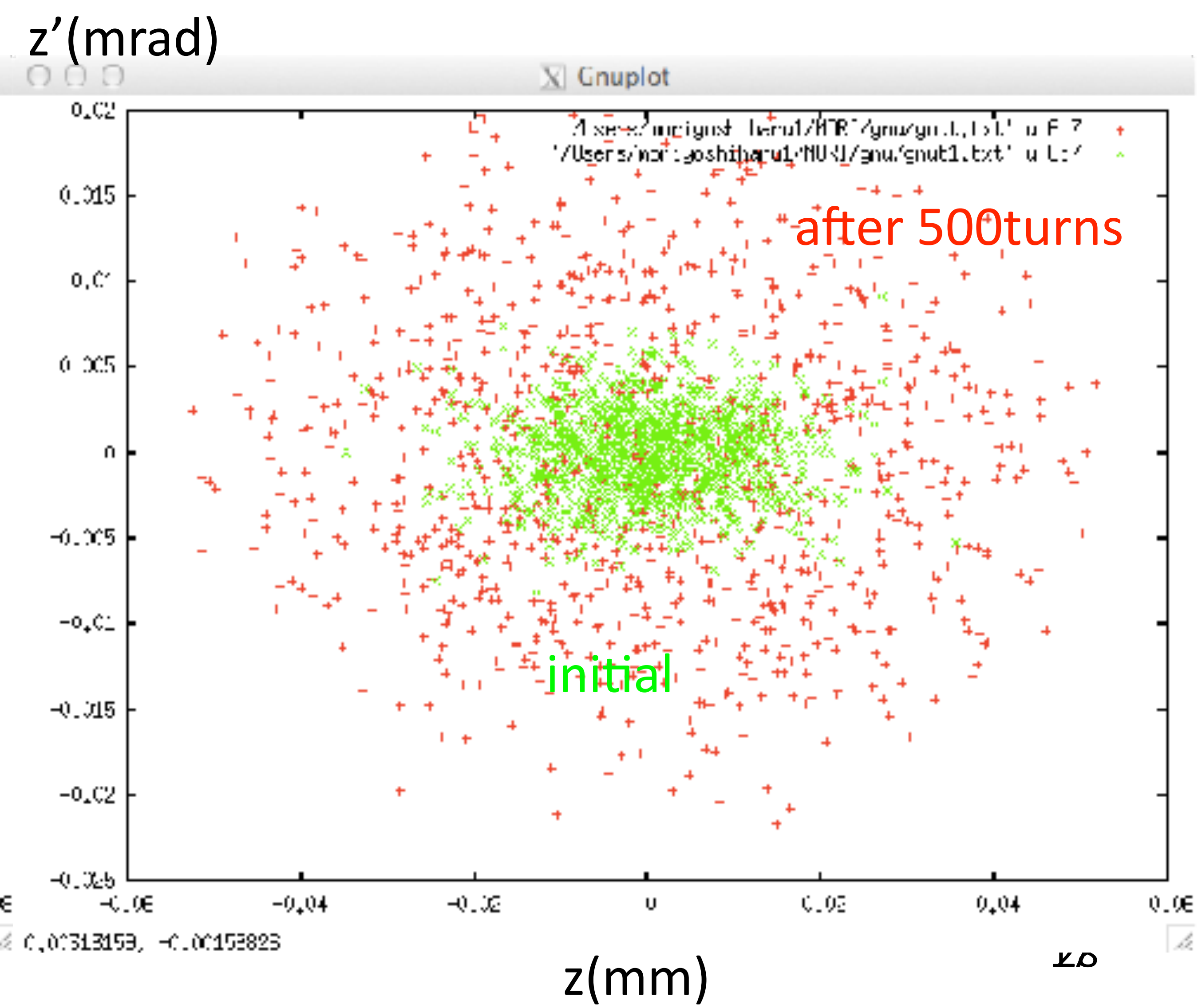
Transeverse

Beam emittance after 500turns :

hor.~2,100mm.mrad, vert.~1,200mm.mrad

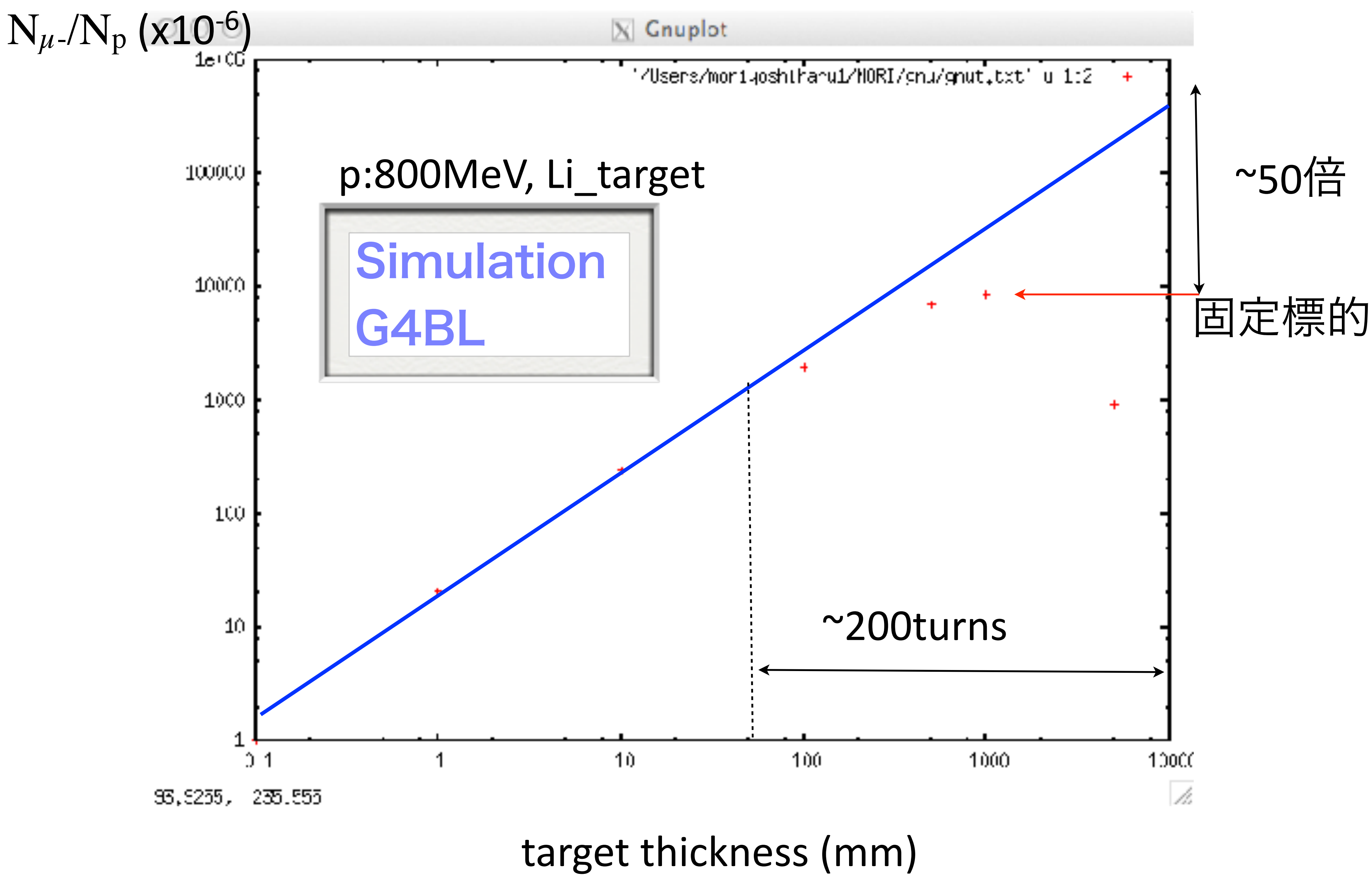
< acceptance (hor. :30,000mm.mrad,vert.:20,000mm.mrad)





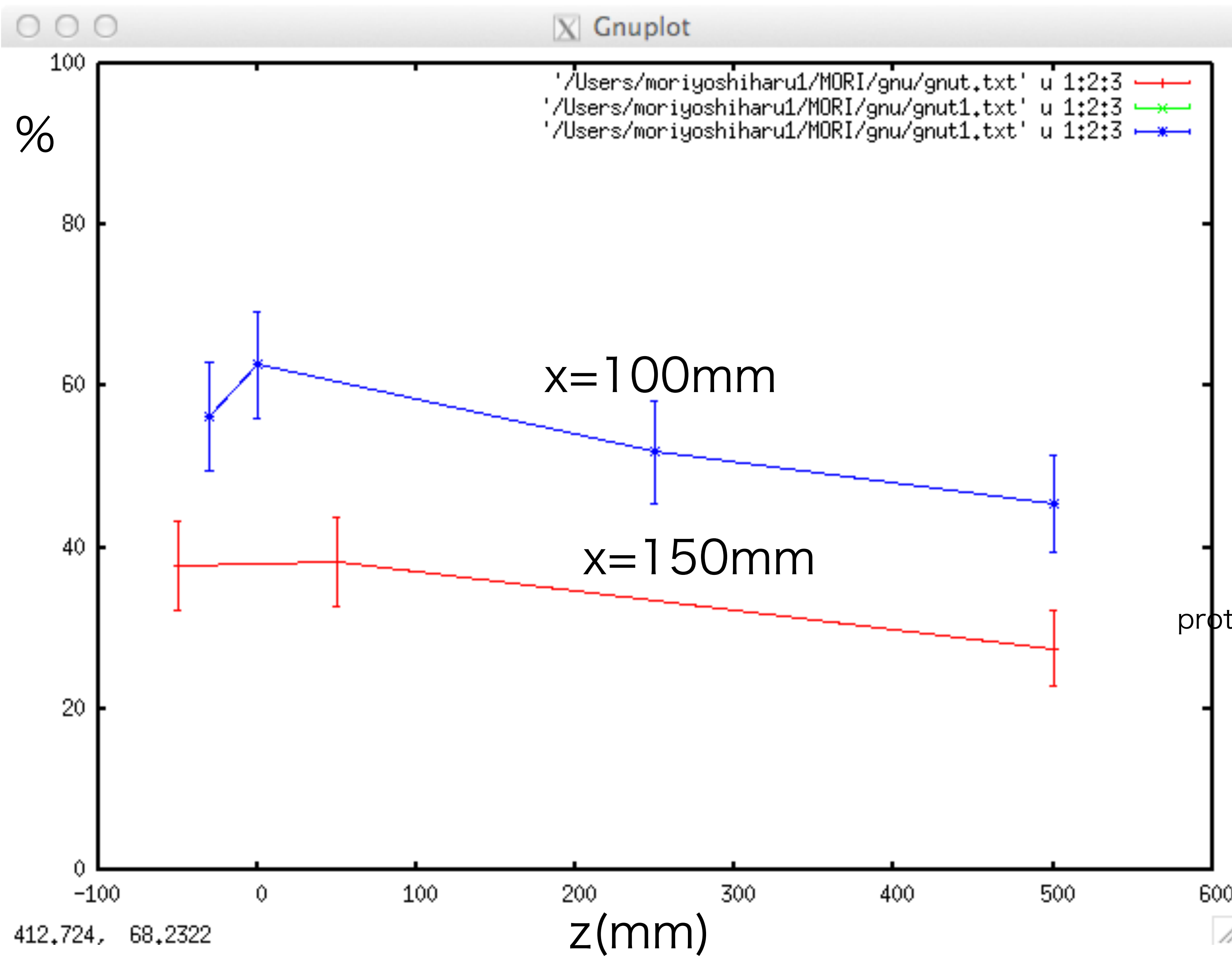
Number of turns in MERIT

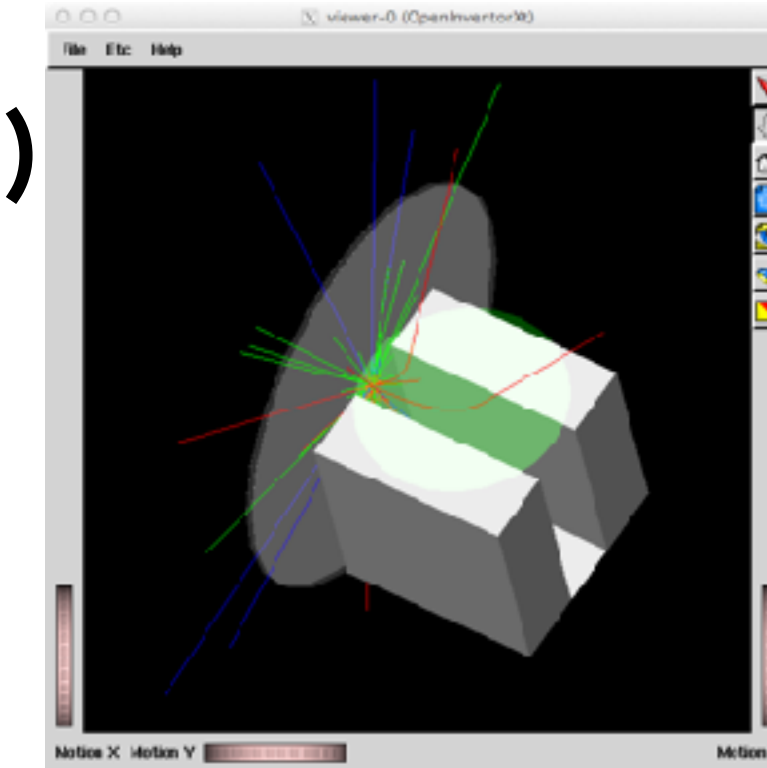
- **More than 200 turns → $N_{\mu-}/N_p$~0.25**
  - ~50 times better than fixed target

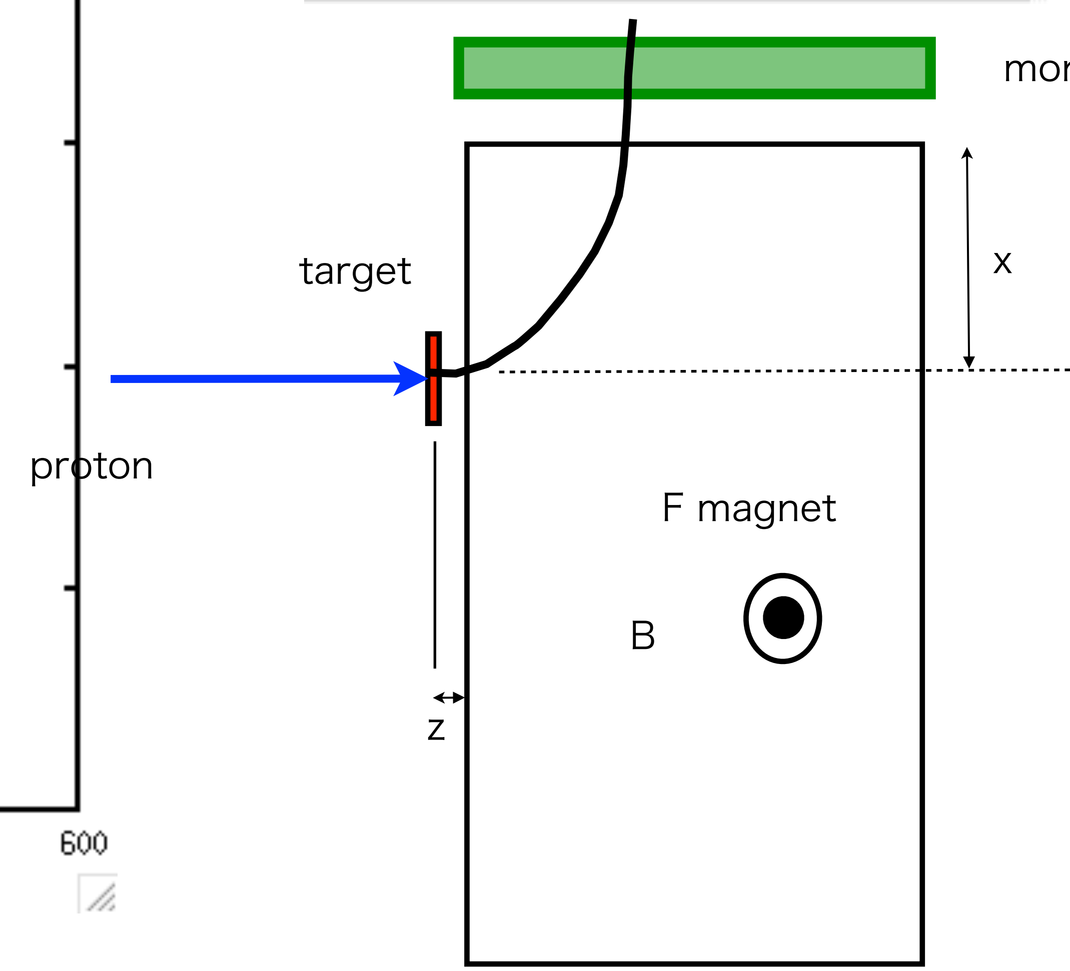


$\pi^-(\mu^-)$ capture

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







Summary(2)

- **Characteristics and Performance of MERIT (Multiplex ERIT)**
  - Proton accelerator and storage ring
    - Fixed magnetic field : Scaling FFAG(FDF)
    - Fixed RF frequency : On_γt acceleration
    - Wedge target (Li)
  - Muon cost : <~3.5GeV/μ-
  - Muon yield : 1×10^{16} μ-/s with I_p~2.5mA
- **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) < Nuclear interaction length
    - –Beam energy is lost before nuclear interaction.
    - –Nuclear interaction length for π production（NΔ) ~1m π 生成
      - **R [range:$\int$(dx/dE)dE]**
      - **L [nuclear interaction length:1/($\sigma N_a \rho$/A)]**
      - 例：Ep=500MeV, Be(p,π)reaction R~50cm, L~1m
  - Energy threshold (A(p,π):Ep~250MeV: proton)← R<L
  - Destruction (π- + A →X)
  - Thin target is needed. →

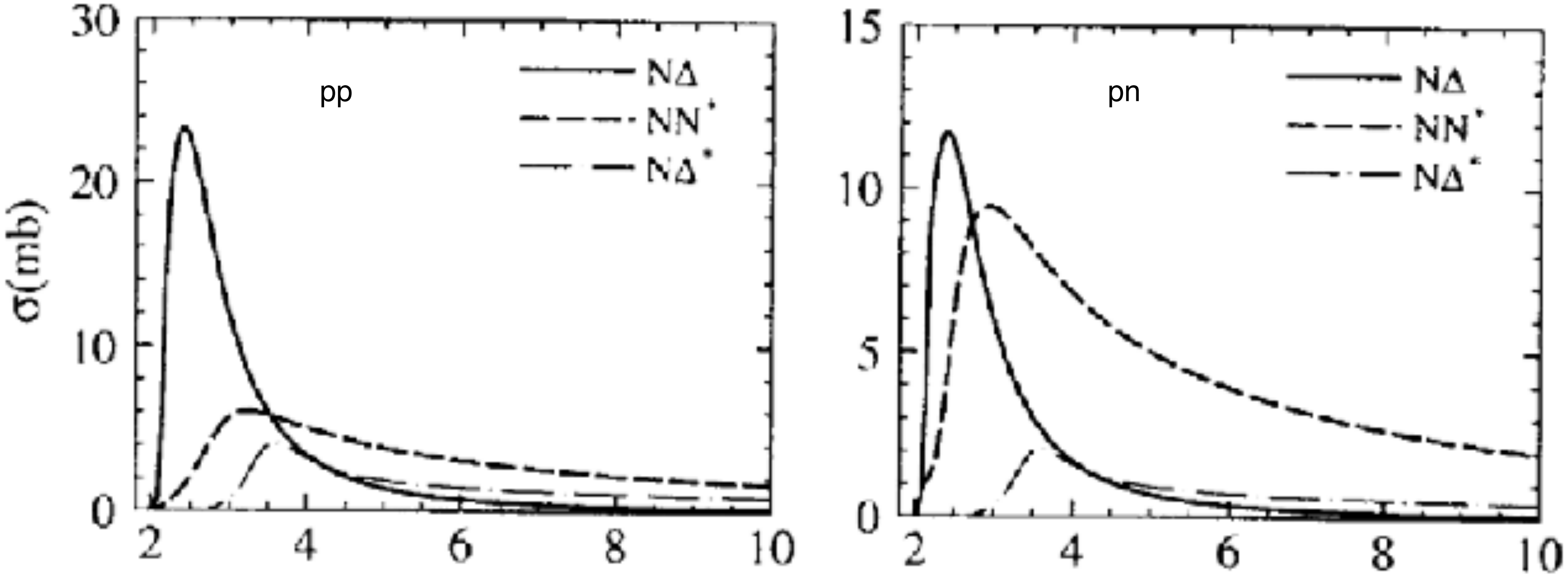
Energy recovery :E_{sp} ~ 300MeV(p-beam:Ep=800MeV, Li target)

Deuteron MERIT_FFAG

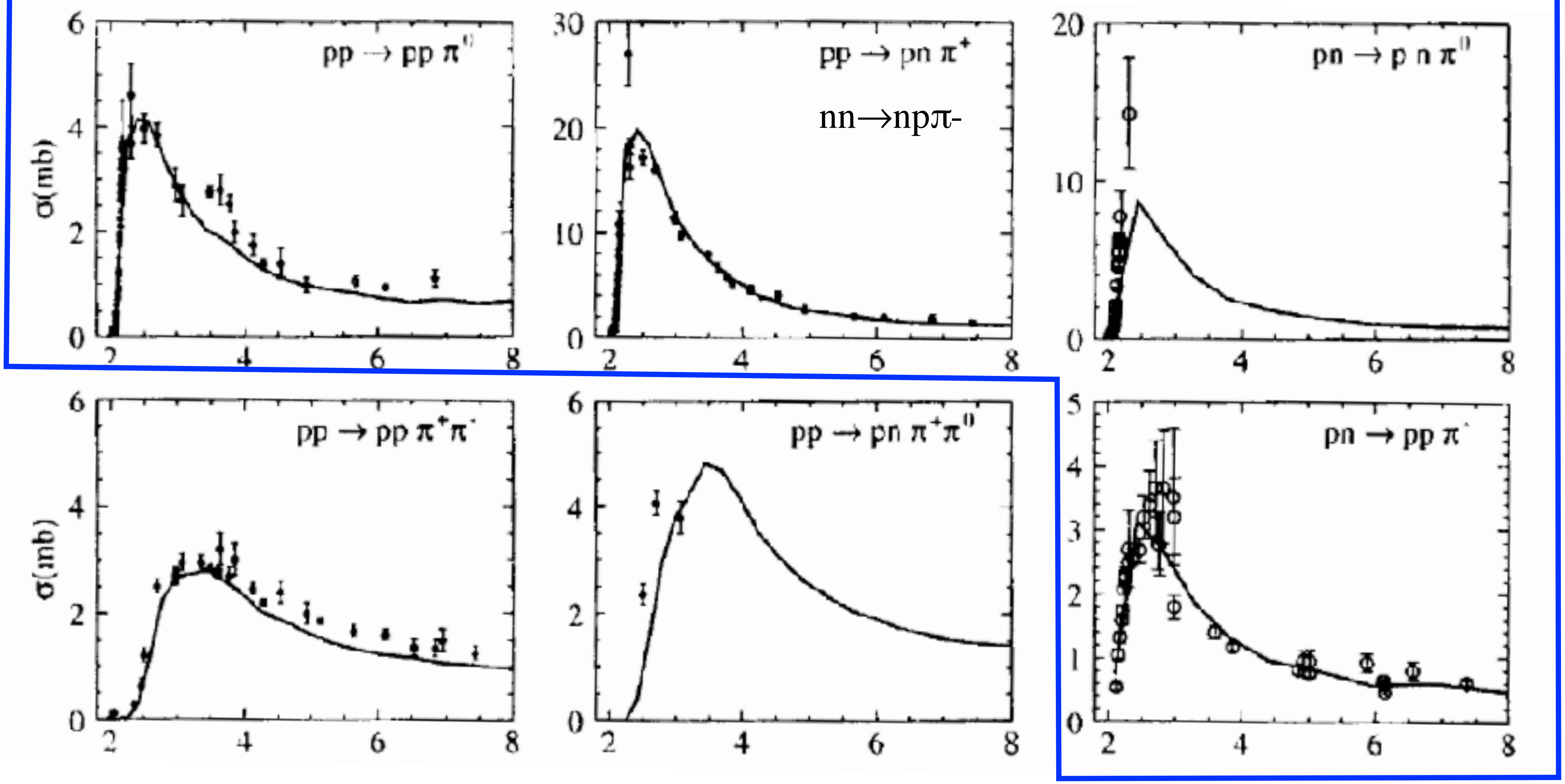
"Intense Muon Source with Energy Recovery Internal Target (ERIT) Ring Using Deuterium Gas Target"
Y.Mori, F.Okita,Y.Ishi,Y.Yonemura,H.Arima:Memoirs of the F.E.Kysyu University, vol.177, No.2,2017 (accepted)

- 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 π-(μ-) production.
    - Is that so？
- **Deuteron induced π- production cross section :σ(d,π-) > 6.6 x σ(p,π-).**

ref. JAERI-Tech-99-065, 仁井田他



NΔ



π- production with deuteron beam -Energy efficiency-

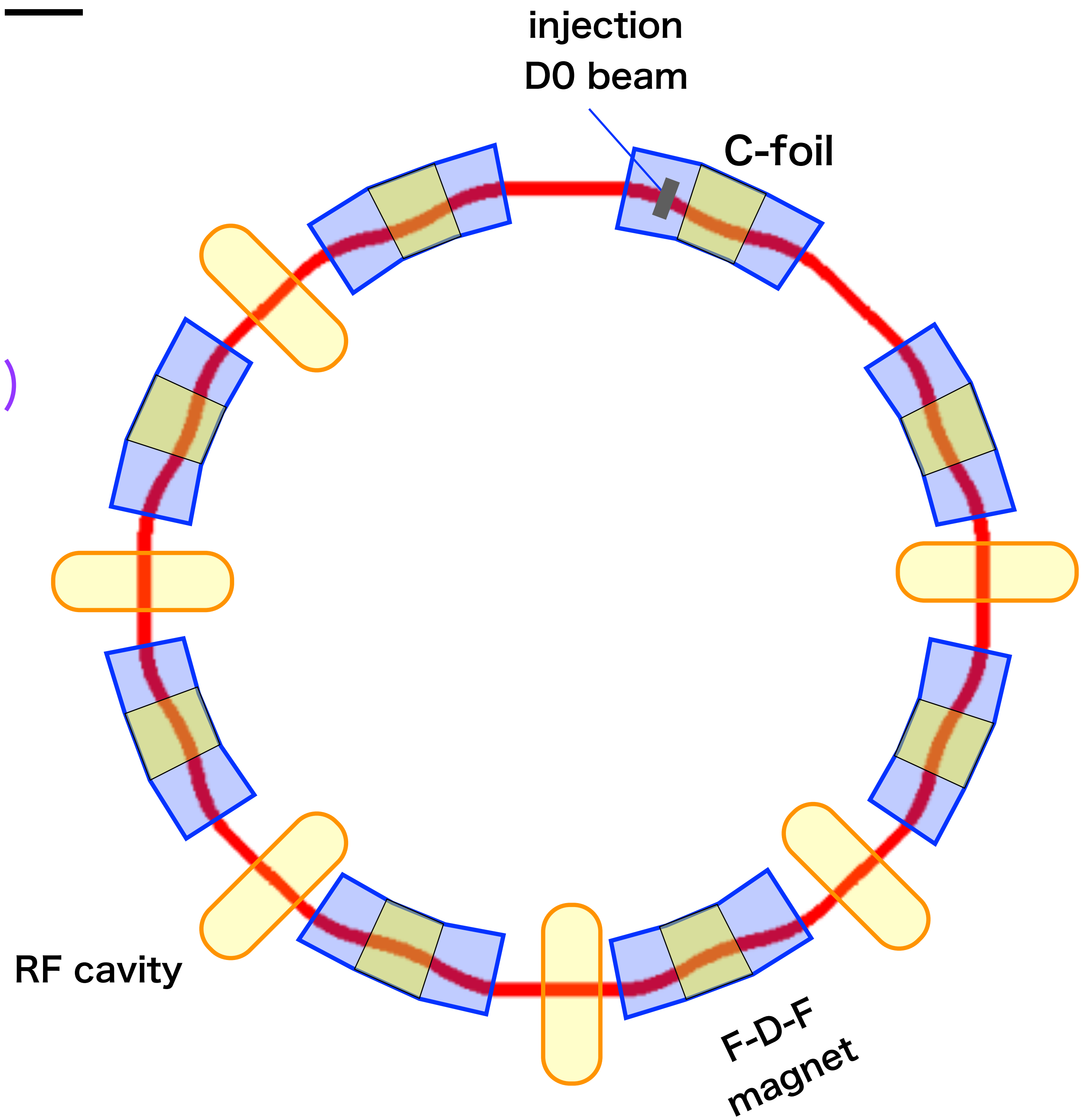
- π production :NΔ（σ_{pp}/σ_{pn} =2) resonance
  - pp/nn(I=1)→π(+,0,-), pn(I=0)→π(0,-)
- π productio with deuteron (pn)（target：light nuclei)
- $\sigma_{\pi+}:\sigma_{\pi 0}:\sigma_{\pi-}$ ~1:1:1
  - cf. proton $\sigma_{\pi+}:\sigma_{\pi 0}:\sigma_{\pi-}$ ~6:3:1
- Thus, $\sigma_{\pi-}(d)/\sigma_{\pi-}(p)$=(2x1/3)/(1/10)~6.6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

Deuteron beak-up

- break-up reaction : d+X → p+n+X
    - $\sigma_{bu} / \sigma_{\pi}$ ~ 2-3(Geant4)
- Energy efficiency of π- production: η (energy required for one π-production)
    - **η(d)/η(p)=[$\sigma_{\pi\text{-}}$(d)$_{/}$$\sigma_{\pi\text{-}}$(p)]/[$\sigma_{bu}$ / σ_{π}]x1/2 = 1.1-1.5 : η(d)≈η(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) ~MeV
        - →Energy can be recovered thermally. (Not by ERIT)

Deuteron MERIT_FFAG

- **Characteristic of d-MERIT_FFAG**
  - Gas target : deuterium gas (1atm)
  - Projectile : deuteron
  - Beam energy : 600MeV/u
  - Deuteron Intensity : 7.9×10^{11} particles/ring



Muon yield with d_MERIT_FFAG

- **π^- Yield** $$Y = L\sigma_{\pi}.$$
- **σ^- : π^- production cross section**
- **Luminosity** $$L = N_d v_d n_T.$$
  - N_d: number of deuteron/ring 7.9x10^{11} d/ring
  - v_d: deuteron velocity 600MeV/u
  - n_T: target particle density 1atm

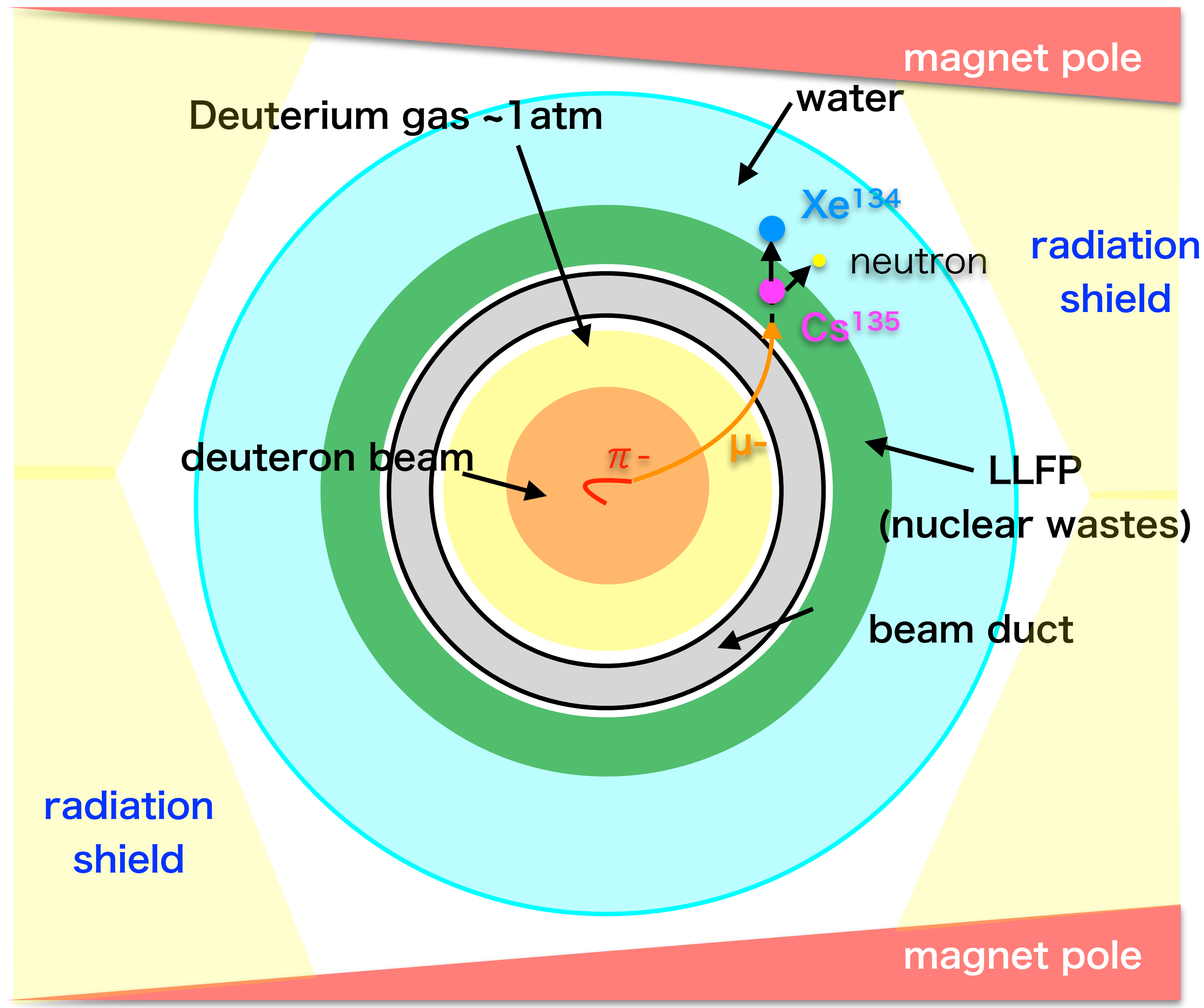
$$L = 5\times10^{41} cm^{-2}\cdot s^{-1} \rightarrow Y = 1\times10^{16} \mu^- / s$$

d_MERIT_FFAG ring parameter

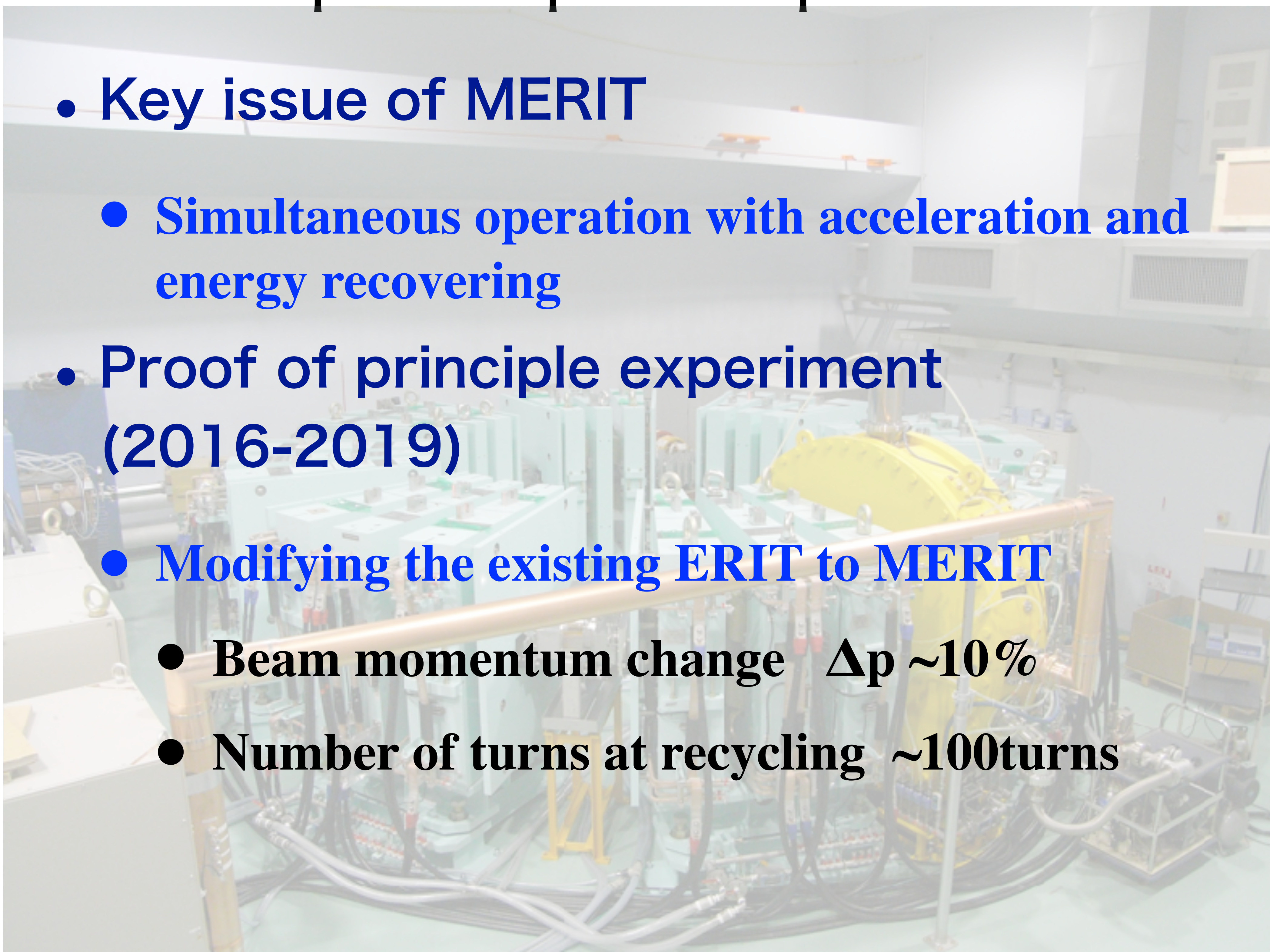
Energy	1200MeV(600MeV/u)
Magnetic rigidity	8.126Tm
Lattice	FDF
Average radius	5.5m
Magnetic field(F)	4.016T
Magnetic field(D)	3.509T
Number of cell	8
Packing factor	0.7
Opening angle	
Focusing magnet	0.2032rad
Defocusing magnet	0.1432rad
Gap	0.01732rad
Geometrical field index	2.4
F/D ratio	1.1
Betatron tune(H): Q_H	0.2188/cell
Betatron tune(V) : Q_V	0.1797/cell
Curvature(F): ρ_f	2.023m
Curvature(D): ρ_d	2.316m

Muon nuclear transmutation scheme with d_MERIT_FFAG ring

- LLFP(nuclear wastes) surrounds the beam duct.
- Beam duct is filled by ~1atm 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 ~100turns

Summary

- Muon nuclear transmutation looks useful for treatment of long-lived radio-activities.
    - cf. 1GWe nuclear reactor(30years operation)

      → **de-activated in 100years with 1x10^{18} μ^{-}/s**

      → **de-activated in 25years with 1x10^{17} μ^{-}/s**
- MERIT could satisfy the requirements for negative muon source.
- Proof-of-principle project of MERIT has started.
- Deuteron MERIT_FFAG is also interesting.