FFA'20, TRIUMF

Applications of ERIT_FFA

-Mitigation of long-lived nuclear wastes–

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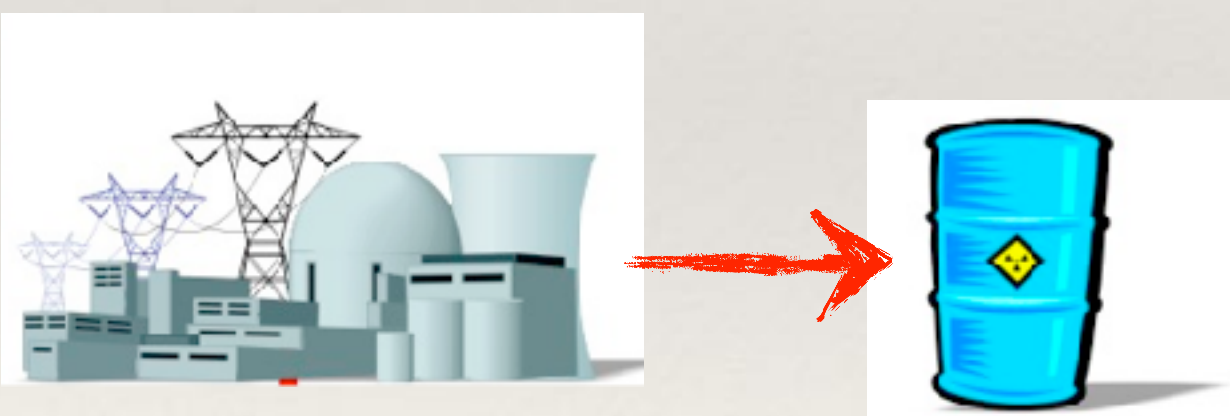
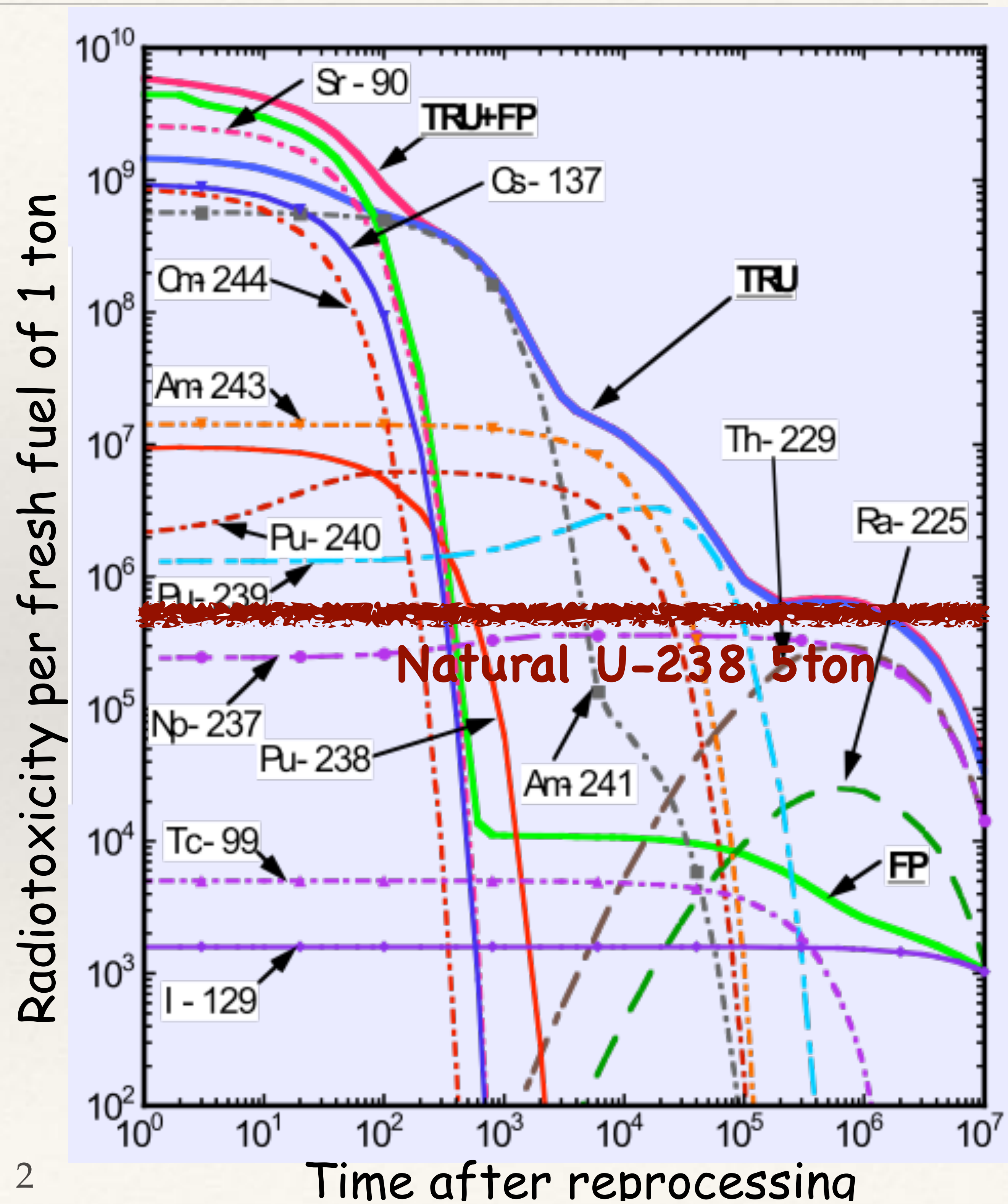
Radio toxicity from long-lived nuclear wastes

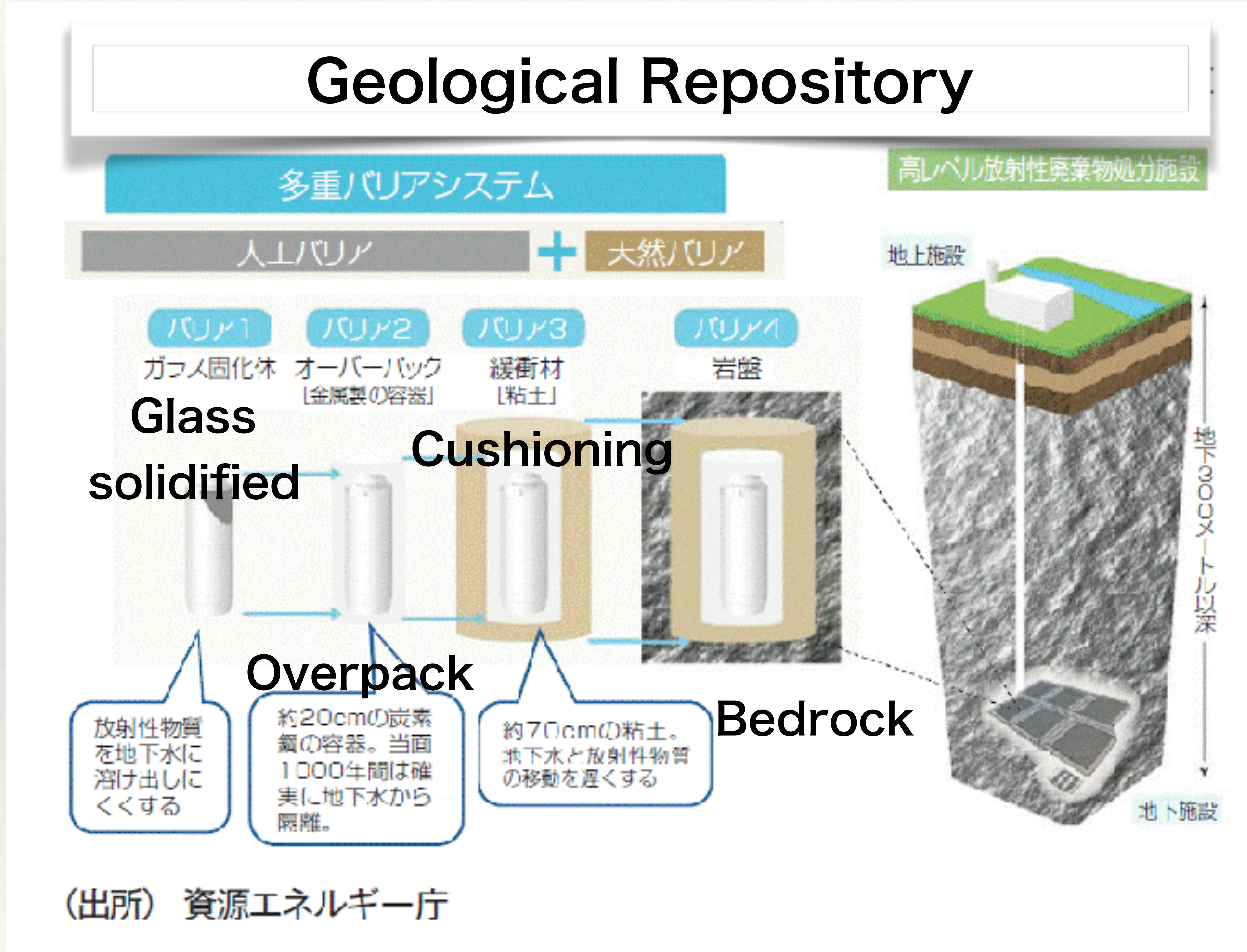
- 1GWh nuclear plant
  - Fresh fuel : U(3%-enriched) ~300ton





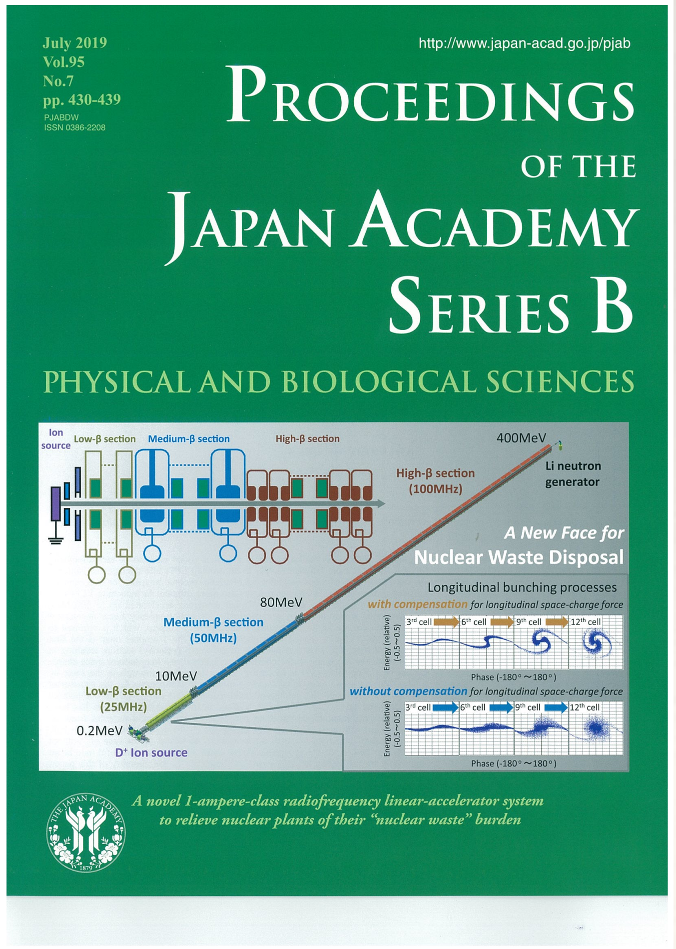
Geological repository

- Amount of long-lived nuclear wastes generated in one year of operation at 1-GWh nuclear plant
  - LLFPs(Long lived fission products):
    - Tc-99, I-129 , etc
  - 12kg/year
  - MA(minor actinides)
    - Np-237,Am-241
  - 6kg/year



NX:Nuclear Transmutation

- Neutron induced nuclear transmutation:NNX
  - Transform the radioactive nuclei(LLFP and MA) in stable or short lived nuclei.→ ADS can treat MA but not LLFP efficiently.
  - Require, however, a large neutron flux for LLFP and MA.
  - High power deuteron accelerator: **1A-200MeV/u(400MW)!**
    - cf. ‘Proposal of a 1-ampere-class deuteron single-cell linac for nuclear transmutation’, **Proc.Jpn.Acad.Ser.,B95(2019)430**.
  - **Muons Catalyzed Fusion(MuCF) mitigate the beam power → 1/5-1/10**
    - 14-MeV neutrons produced by **MuCF** chain reactions.
    - Transmute the long-lived FPs(fission product) and MAs(Minor Actinide) with <1/5 of the electric power generated by a nuclear plant.



MuCF:Muon Catalyzed Fusion

- MuCF process

  1.μ- absorption into D-T mixture

  2.μdt molecule formation

  - Formation rate ~ 0.5x10^9/s

    → ~1,000 μdt molecules per muon life (2.1μs).

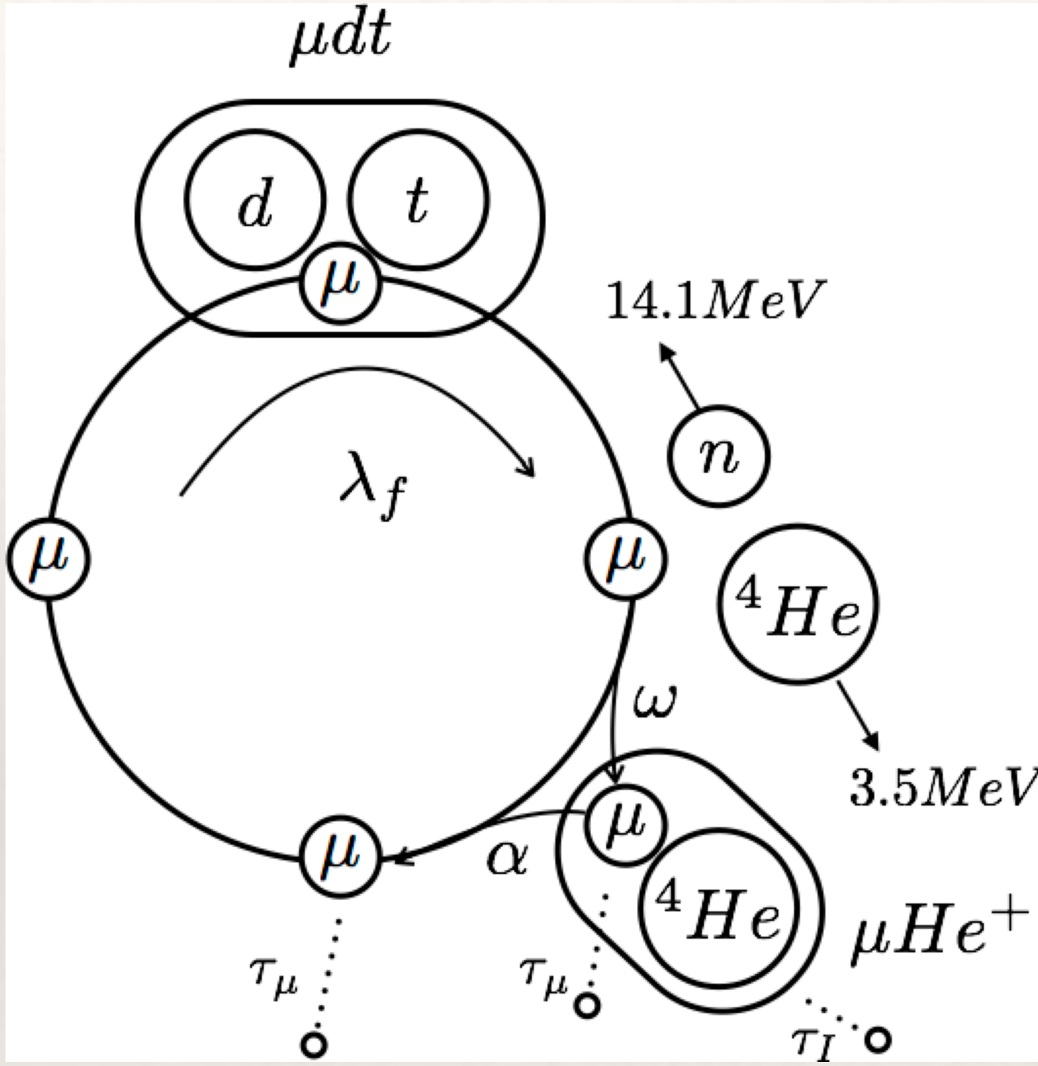
  - Fusion reaction

    - Distance of d-t:~1/200

$$\mu dt \rightarrow \alpha + n + \mu^- + Q(17.6MeV).$$

  3.Chain cycle

  - ω~0.6-0.7%→Nc ~100-150 fusion/μ



$$N_c = \left[\frac{1}{\lambda_f \tau_\mu} + \frac{\omega}{\lambda_f}\right]^{-1}$$

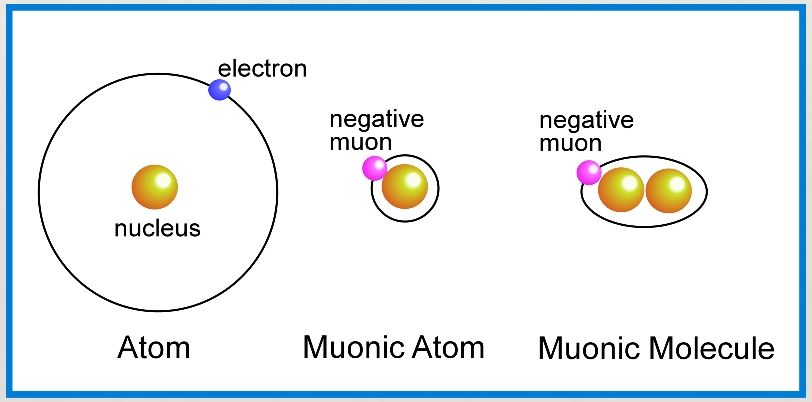
- **100-150 neutrons/single negative muon**

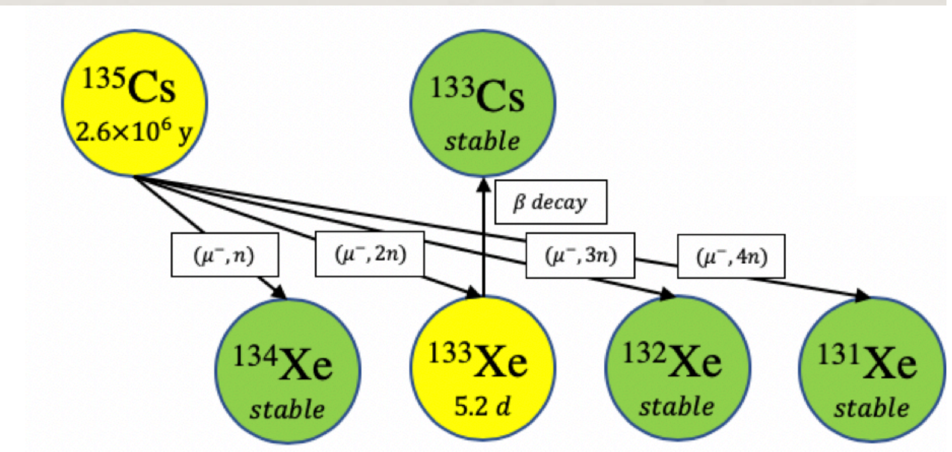
Muon Nuclear Transformation

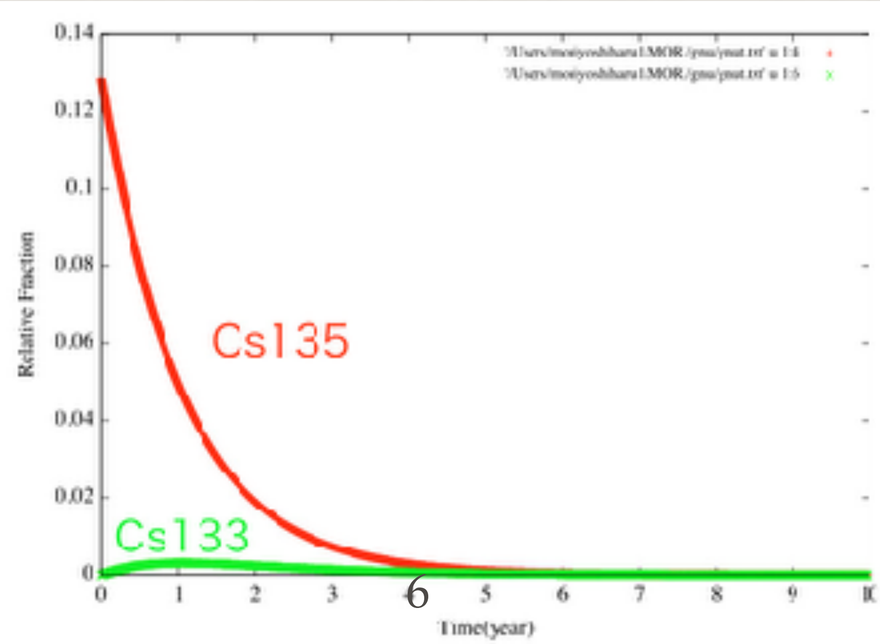
- Nuclear transformation in muonic atom
  - 1st:Formation μ_atom → 2nd:Nuclear transmutation
  - Transmutation probability →>95% for Z>30 nuclei.
- Radioactive nuclei such as Cs-135 which are inadequate for neutron.

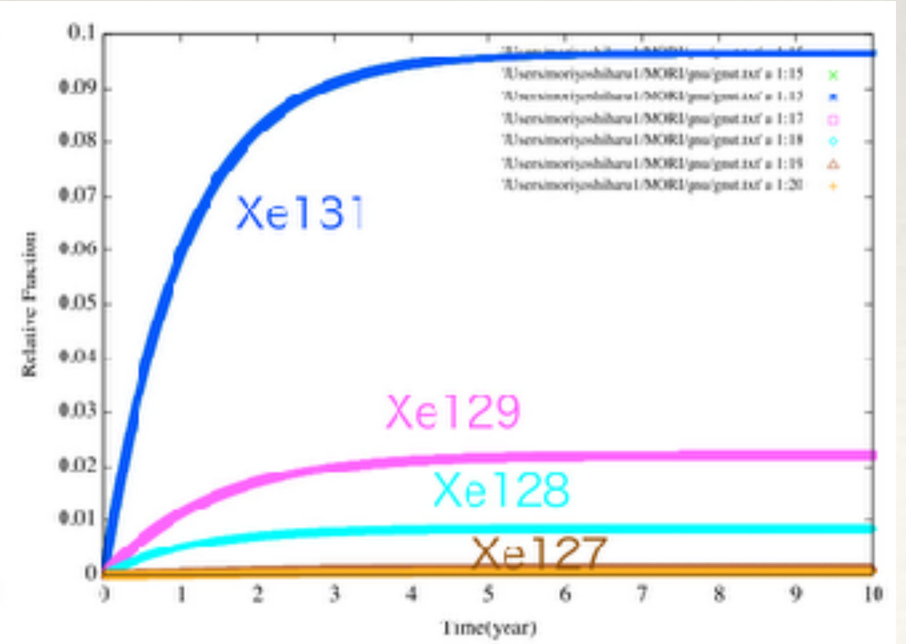
$$a_\mu = \left(\frac{1}{207}\right) \times Z^{-1} \times 10^4 \text{ fm.}$$

$$R = 1.2 \times A^{1/3} \text{ fm.}$$









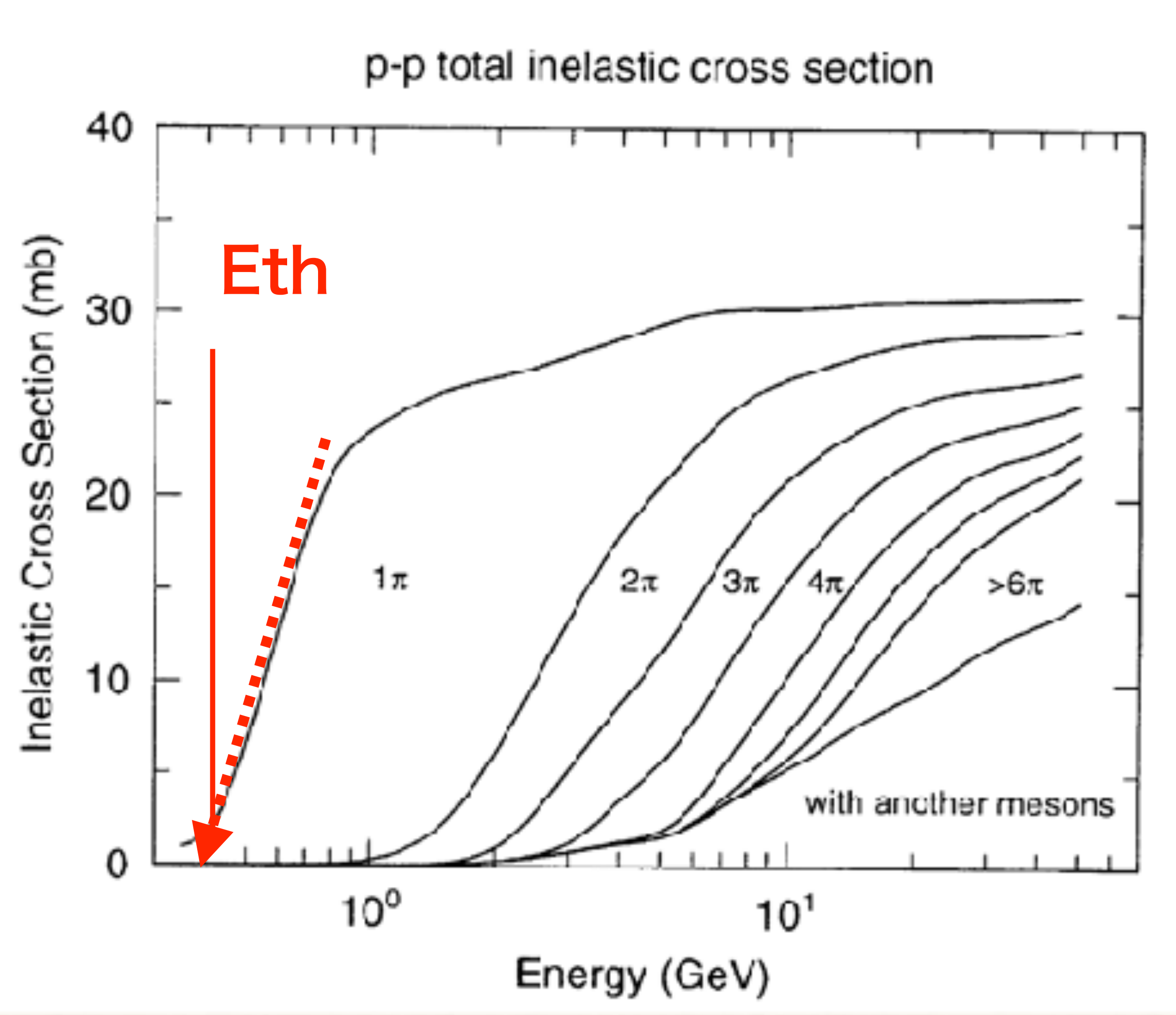
Negative Muon Production

- Pion production and decaying to μ-

$$d + A \to \pi^- + A^* ...,\Rightarrow \ \pi^- \to \mu^- + \bar{\nu}_\mu \quad : \tau_\pi \sim 30ns.$$

- Threshold energy **>250MeV/u**
- Cross section:very energy dependent

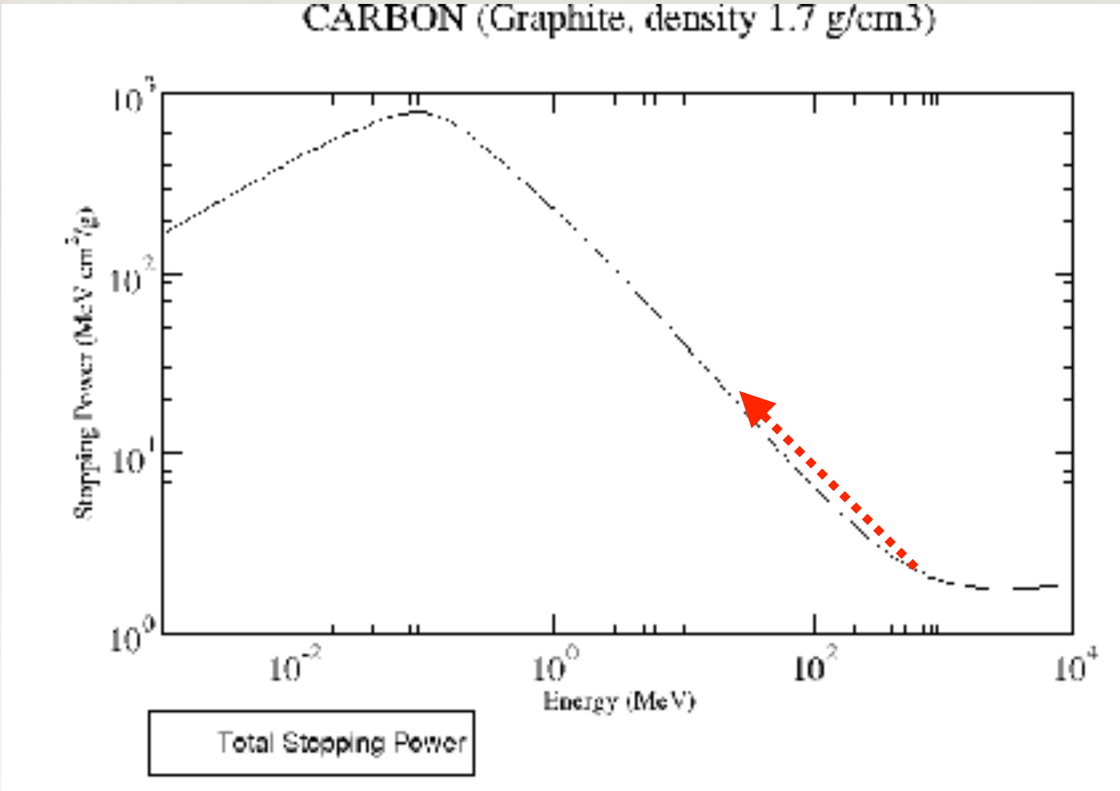
$$\sigma_{\pi^-} \approx 10\text{mb at } 400\text{MeV/u}.$$



Efficiency of Particle Production

- Difficulties for π- production
  - σ_π depends on the energy. → energy loss of the projectile particle by ionization of target
  - Absorption of π- in the target
- Efficiency of particle production

$$\eta \simeq 1\text{-}\exp\left[-\int_{E_f}^{E_i} \frac{\sigma(E)\,n}{S(E)}\,dE\right]$$



- cf, 500MeV/u, d-beam, Li target

$$\eta < 0.1 \Leftarrow \int_{E_f}^{E_i} \frac{\sigma(E)\,n}{S(E)}\,dE < 0.1$$

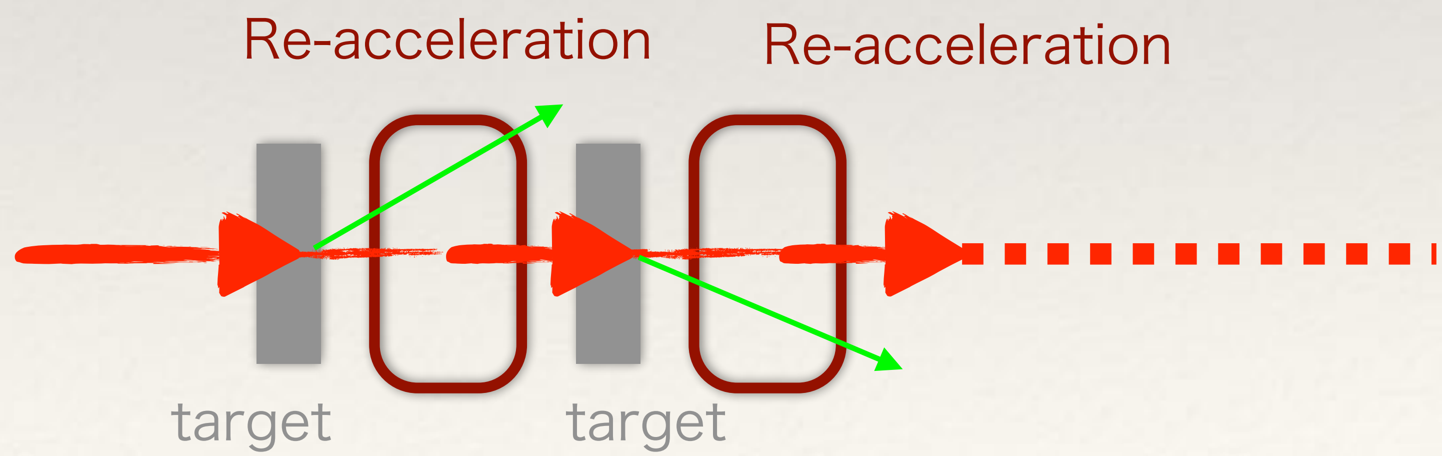
Energy Recovery Scheme

- Efficiency of particle production

$$\eta \simeq 1\text{-}\exp\left[-\int_{E_f}^{E_i} \frac{\sigma(E)n}{S(E)} dE\right], \quad S(E): \text{stopping power.}$$

- **If S(E) can be effectively zeroed, η becomes 1.**
- The energy loss at the target recovers by re-accelerating.

$$\eta \simeq 1 \Leftarrow S(E) \doteq 0$$



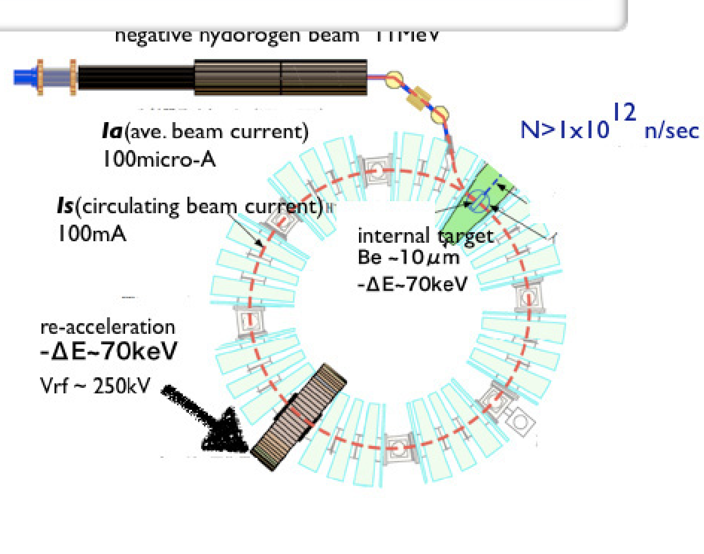
Energy Recovery Scheme

ERIT(Energy Recovery Internal Target) ring

- Principle of ERIT
  - Storage ring and thin target
  - Energy recovery by rf re-acceleration
  - Ionization cooling
- Requirements for ring performance
  - Large energy and transverse acceptances →**FFA**

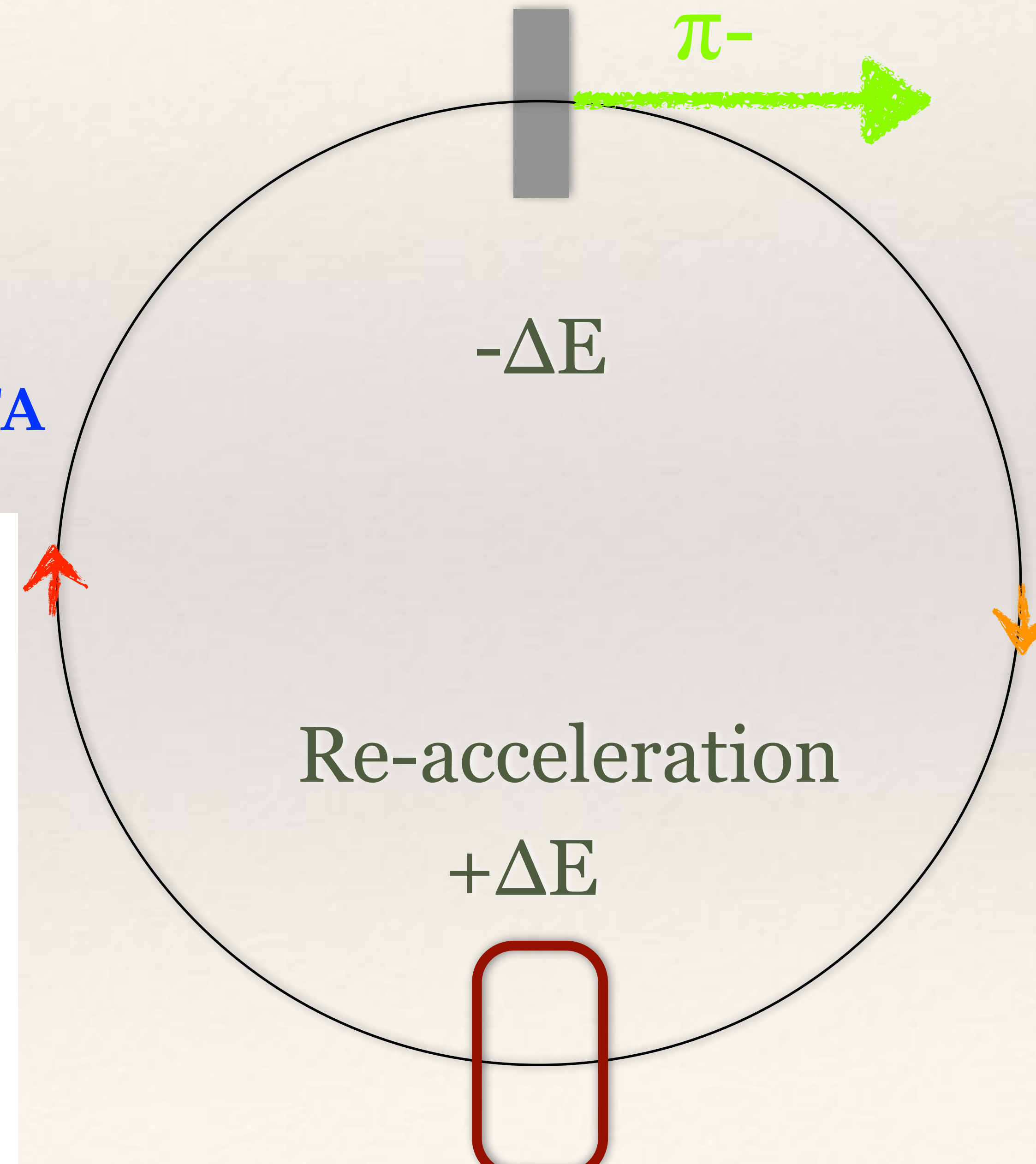
Demonstration: neutron source

(a)



(b)

Y. Mori, et al., Neutron source with emittance recovery internal target, in: Proc. Particle Accelerator Conference (PAC09), 2009, pp. 3145–3149.



Multiplex ERIT:MERIT

- MERIT : Hybrid ring for beam acceleration and circulation on target
  - Acceleration: fixed rf frequency
    - Serpentine path rf bucket

$$\alpha \sim \frac{1}{\gamma_s^{\,2}} = \frac{1}{k+1}$$

  - Circulation: wedged target

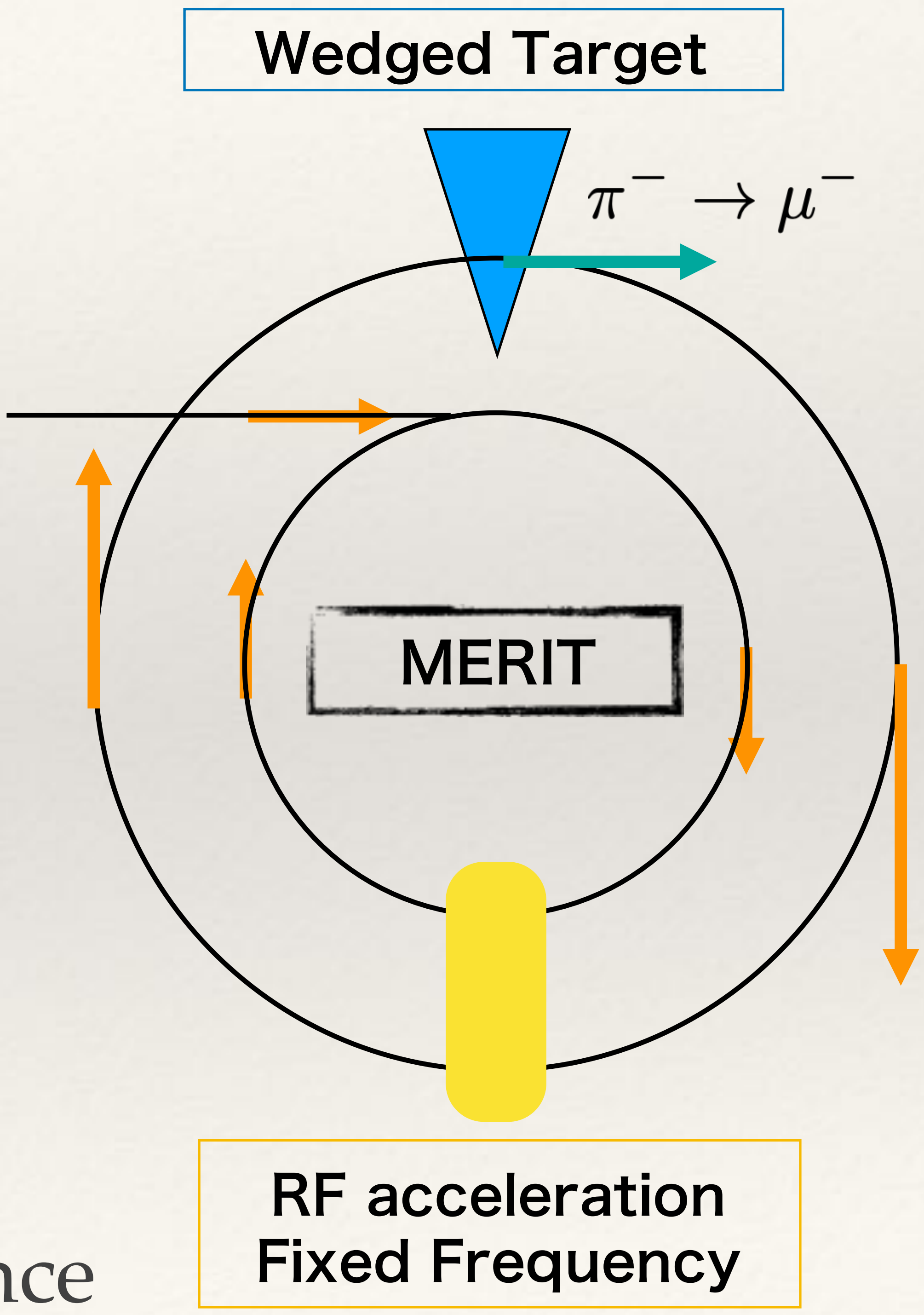
$$\frac{\Delta E}{l(E)} + S(E) \simeq 0.$$

ΔE:energy gain per turn

$S(E)$:stopping power

$l(E)$:target thickness

  - Ionization cooling: modest acceptance

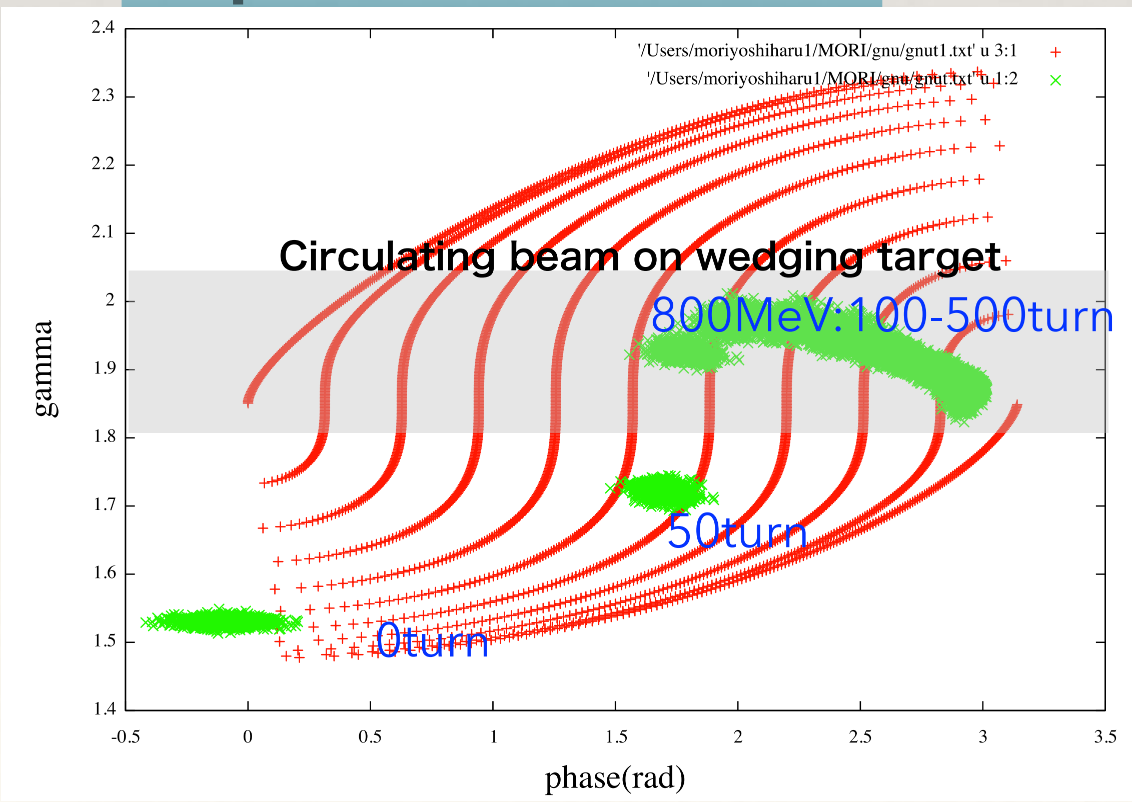


MERIT :π/μ production ring(1)

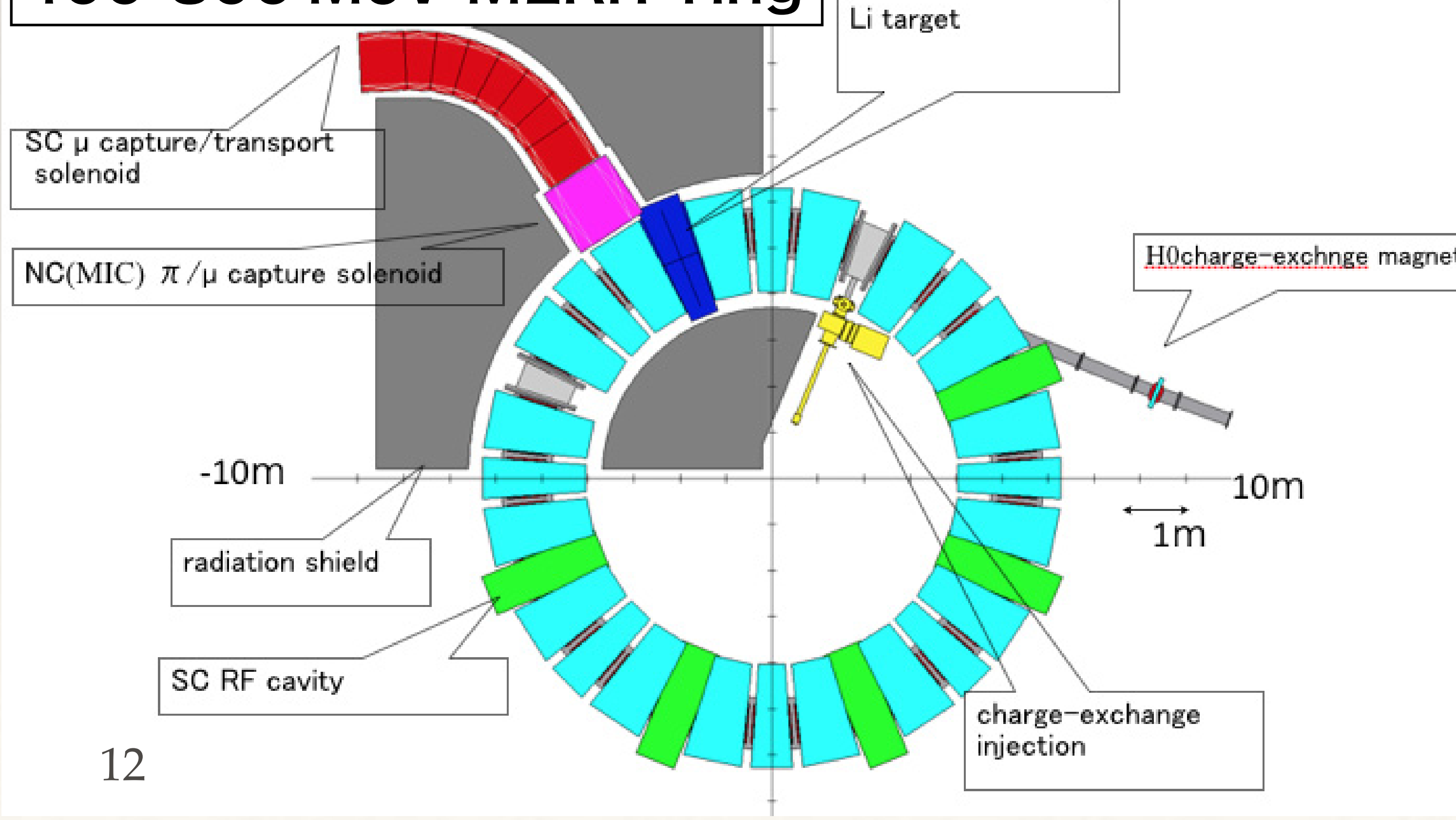
- Proton
  - Acceleration :500MeV - 800MeV
  - Circulation on target : 800MeV for π production

Ring configuration H-FFAG
Energy range(MeV) 500-800
Magnetic rigidity(T.m) 3.633 -4.877
Lattice FDF
Average radius(m) 5.044-5.5
Magnetic field(T):F 1.96-2.41
Magnetic field(T):D 1.71-2.11
Number of cell 8
Geometrical field index 2.43
Cell tune:H 0.212
Cell tune:V 0.180
Beta function(m) @SS:H 2.5
Beta function(m) @SS:V 2.8
Dispersion function(m) 1.5

Serpentine Acceleration

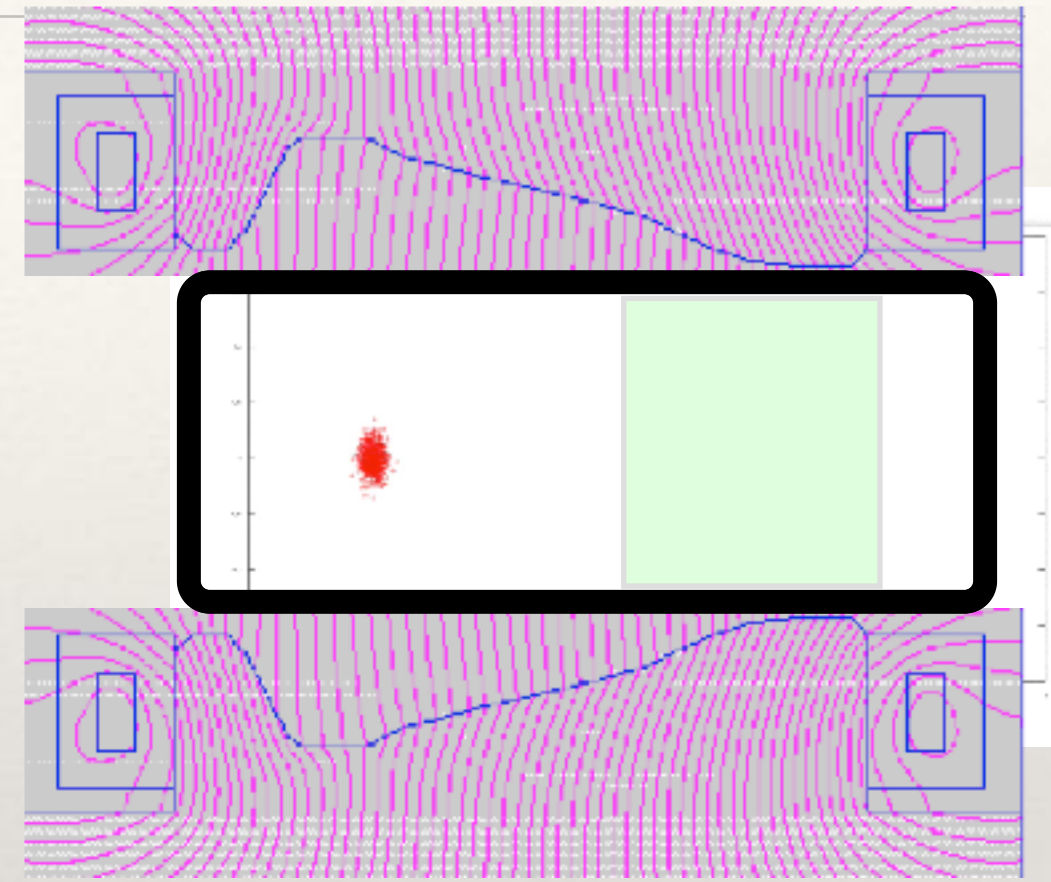


400-800 MeV MERIT ring

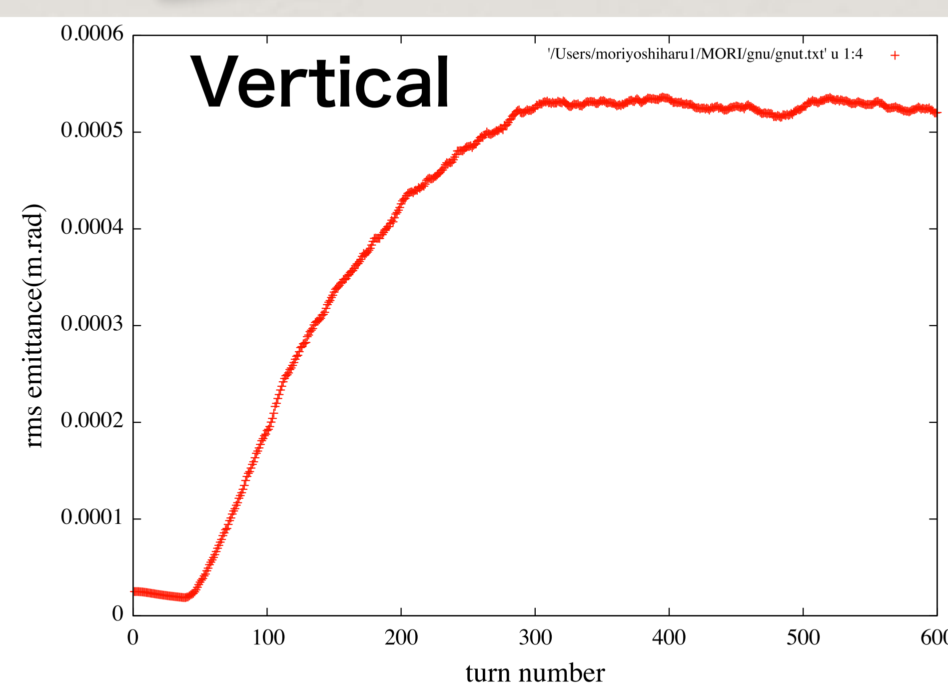


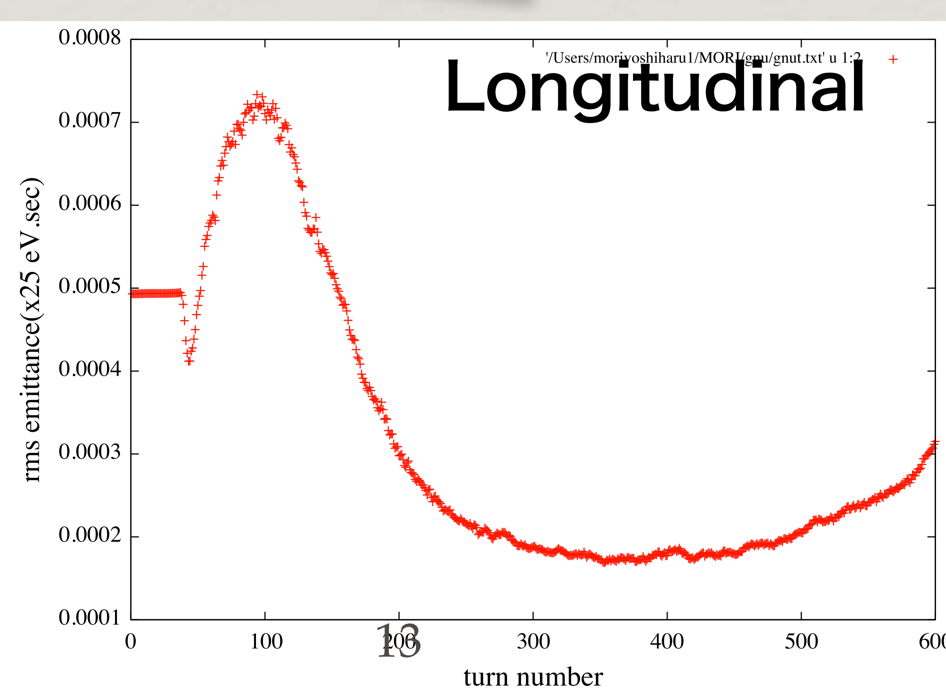
MERIT :π/μ production ring(2)

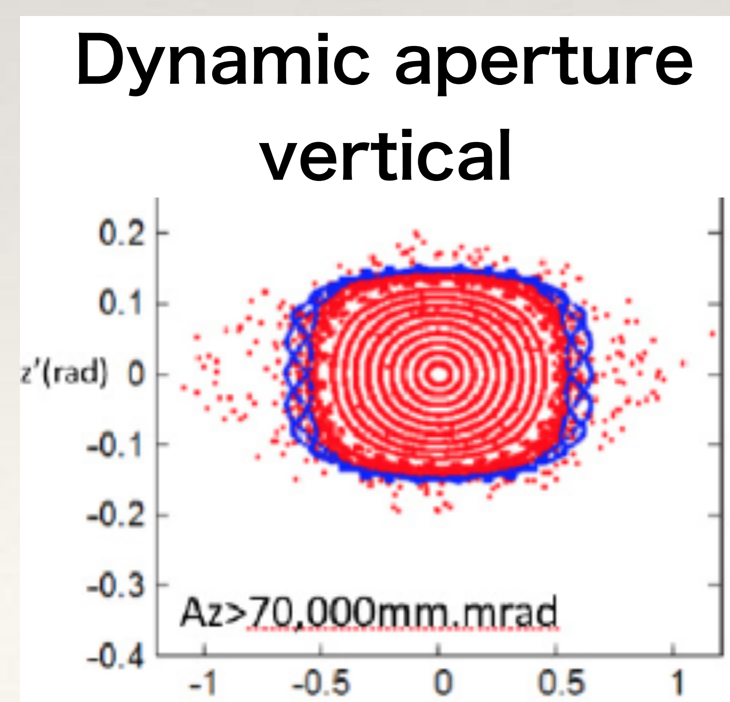
- Beam blow-up : ionization cooling
  - Suppressed for 3-D directions
    - horizontal: $6x10^{-4}$ m.rad.
    - vertical:$7x10^{-4}$ mrad.
    - Longitudinal:$3x10^{-3}$ eV.s



Well below dynamic apertures

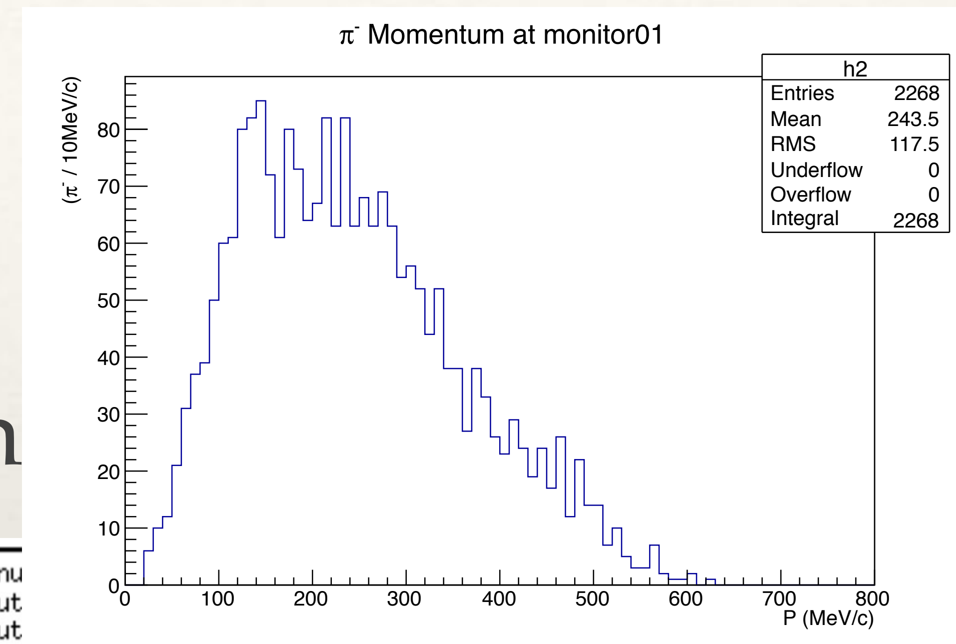


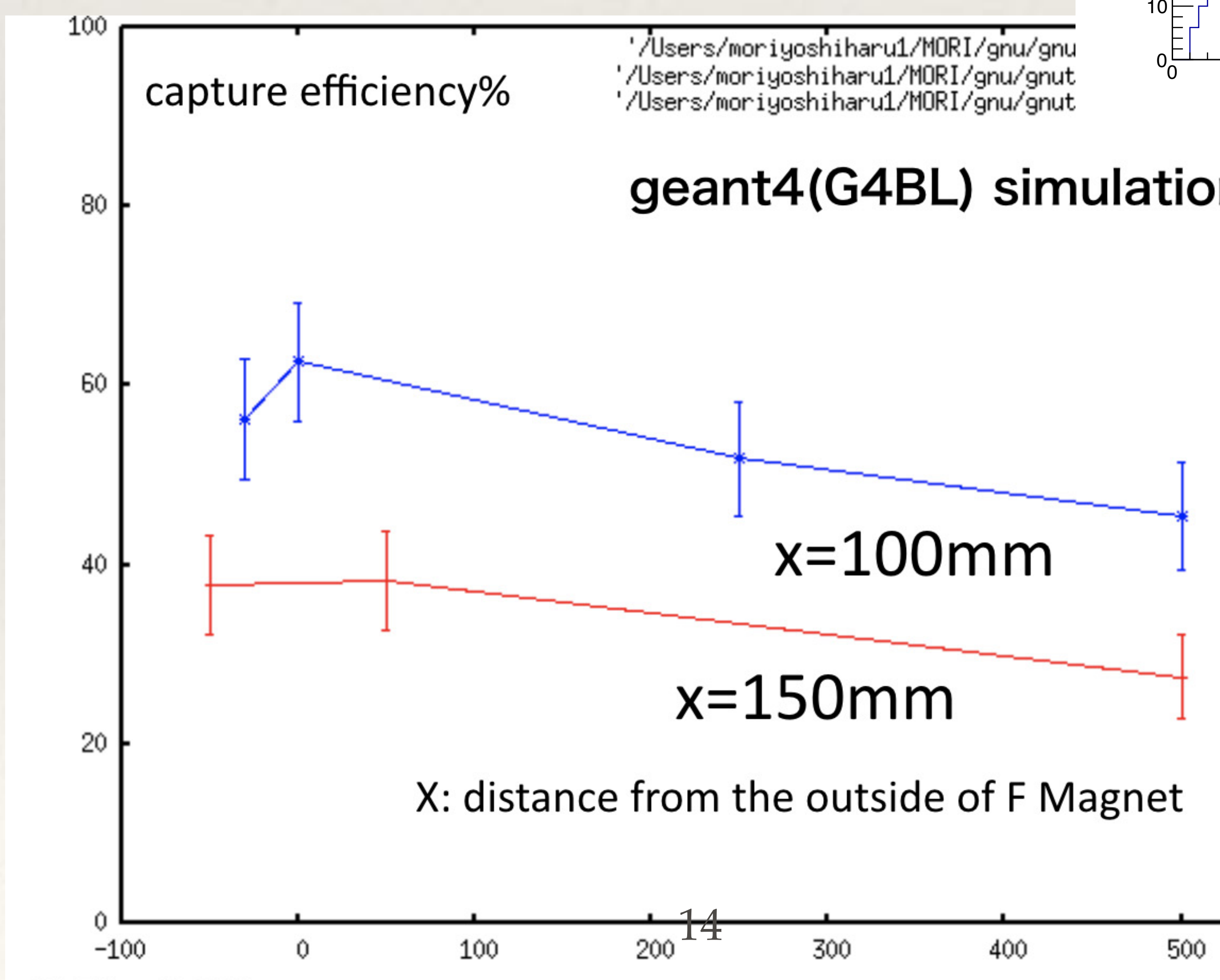


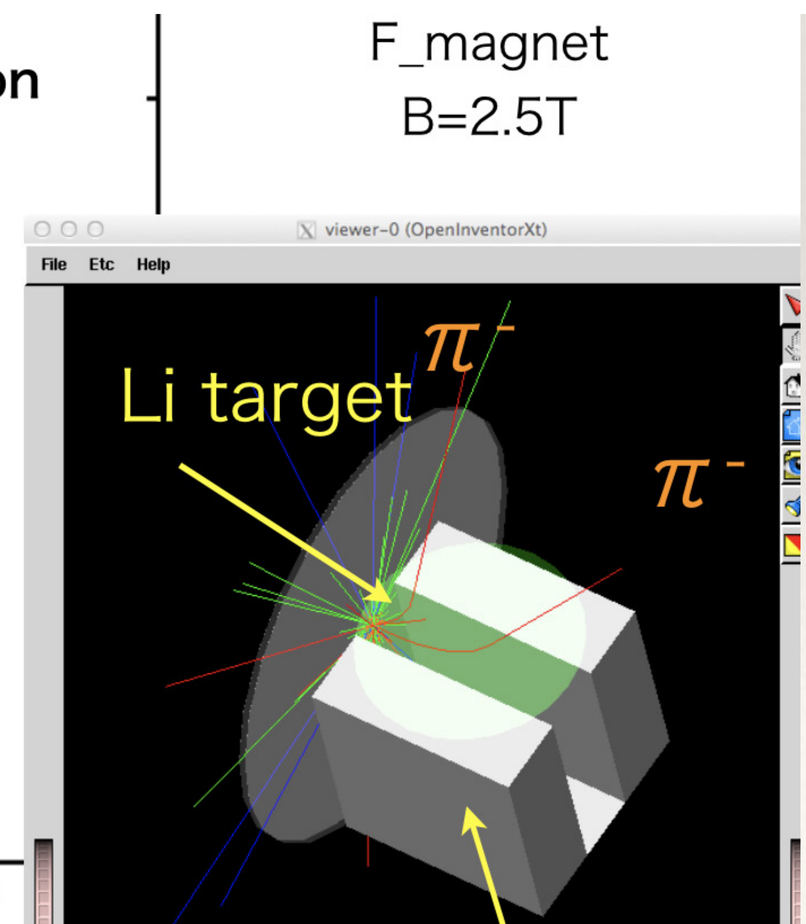


MERIT :π/μ production ring(3)

- Capture and transport (π/μ)
  - F-magnet and Solenoid (2T)
  - Efficiency ~ 50% : G4BL simulation







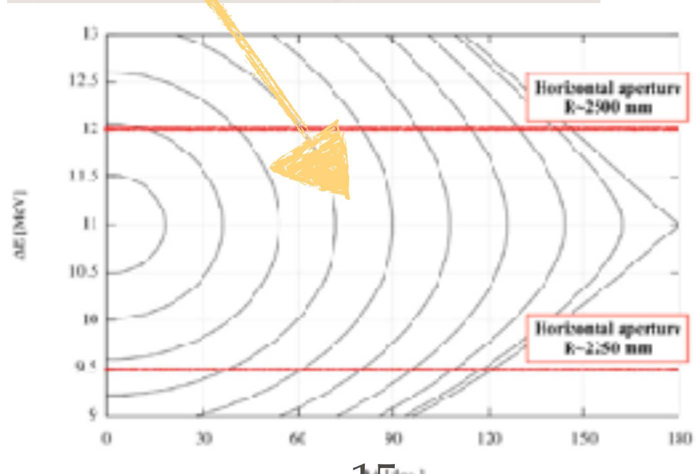
MERIT:Demonstration(1)

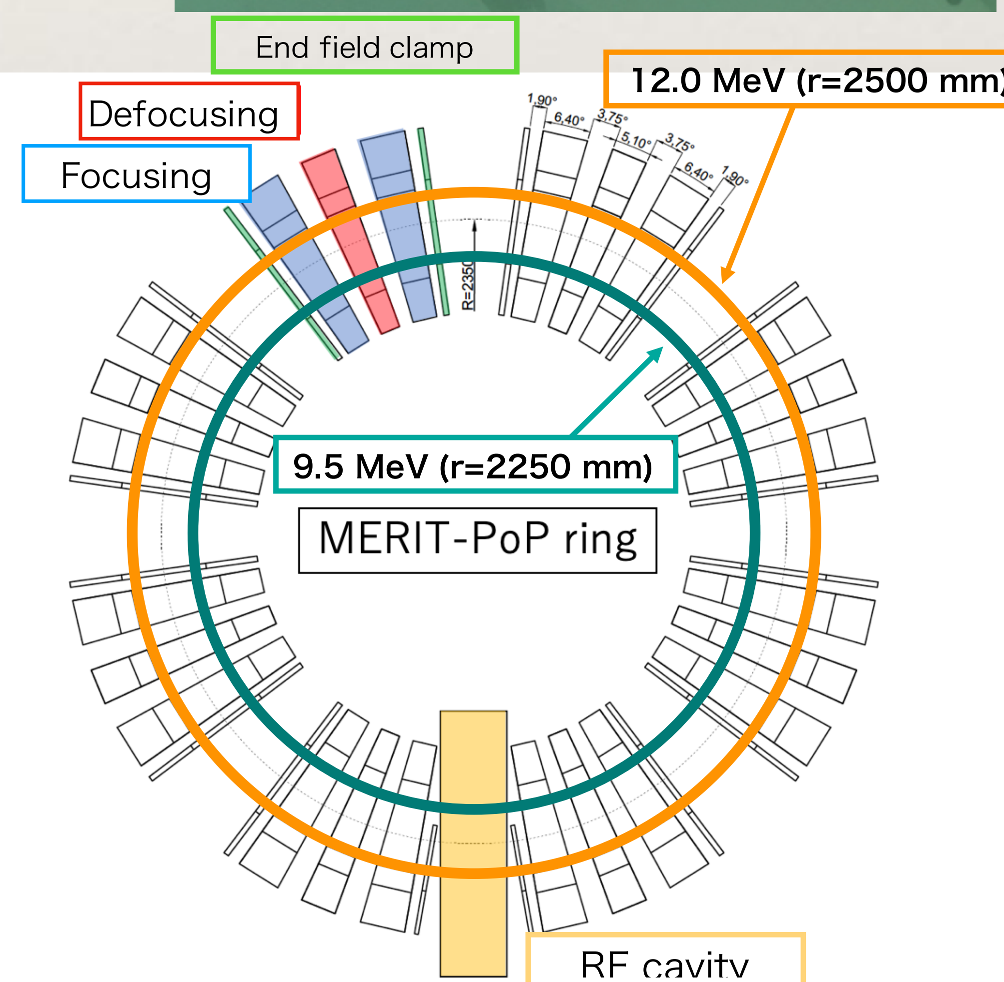
- Modify the ERIT 11MeV ring → **'MERIT-POP' ring** : Nucl. Instrum. Method, A953 (2019)
  - Acceleration
    - Serpentine path acceleration
    - k=2.5 →0.07 : **modifying the magnet** poles
      - 11MeV(fix) → **9.5 - 12MeV**
    - Close to integer resonance:

$$\eta = \frac{1}{k+1} - \frac{1}{\gamma^2} \approx -0.044$$

$$Q_H \sim \sqrt{k+1} = 1.03$$

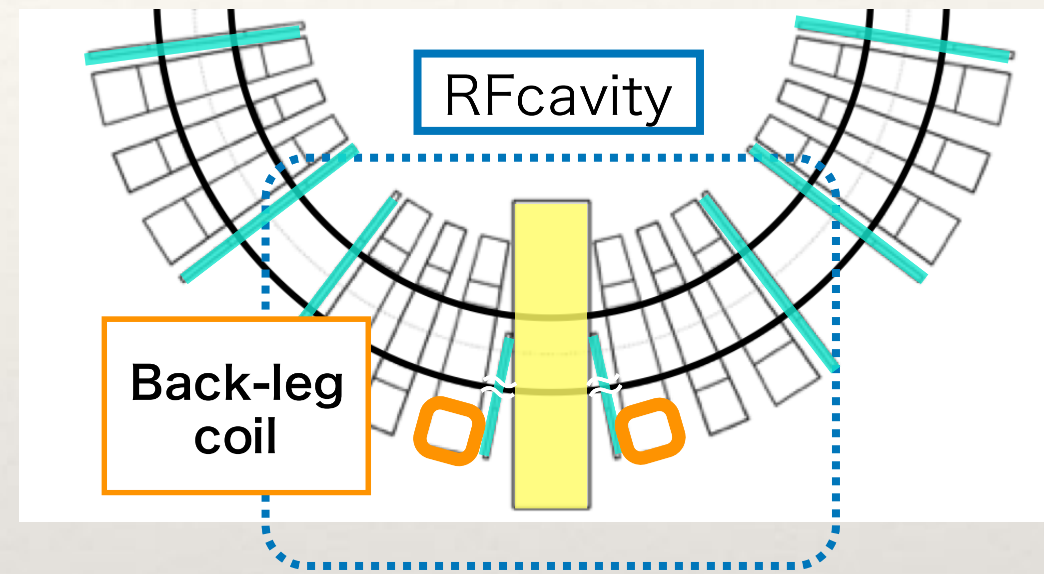
rameters of MERIT-PoP ring.	
article	Proton
umber of cells	8
attice	FDF-triplet
ield index k	0.07
nergy range [MeV]	9.5 – 12.0
rbit radius [mm]	2250 – 2500
lippage factor η	0.044
une H/V	1.03/1.25
arameters of F/D magnet	
agnetic field [T]	0.59/0.14 (at r 2350 [mm])
pening angle of magnet [deg.]	5.1/6.4
inimum half pole gap [mm]	84.0/85.2
arameters of RF cavity	
F voltage [kV]	75 – 225
armonic number	6
F Frequency [MHz]	18.12



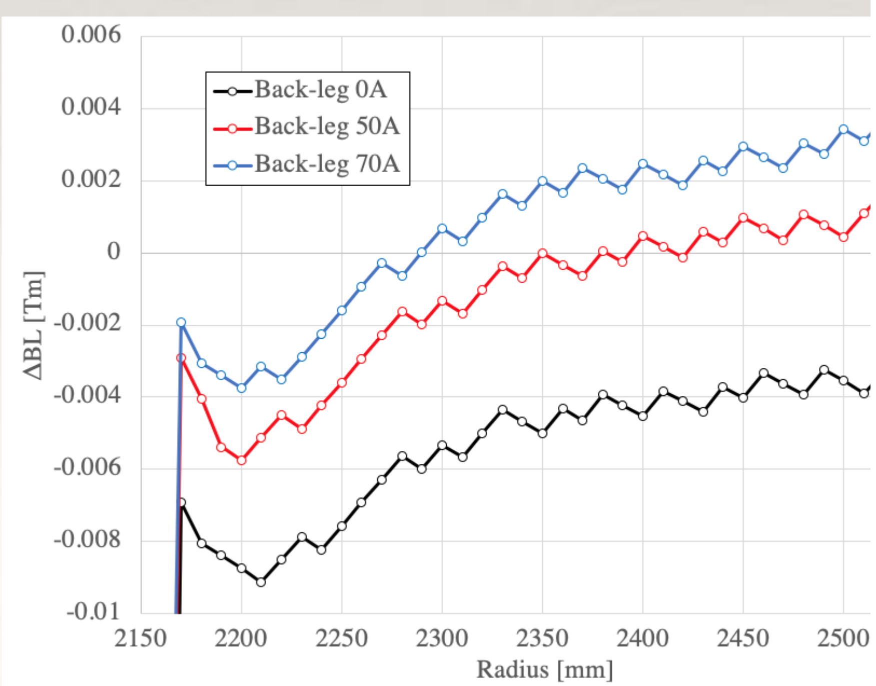


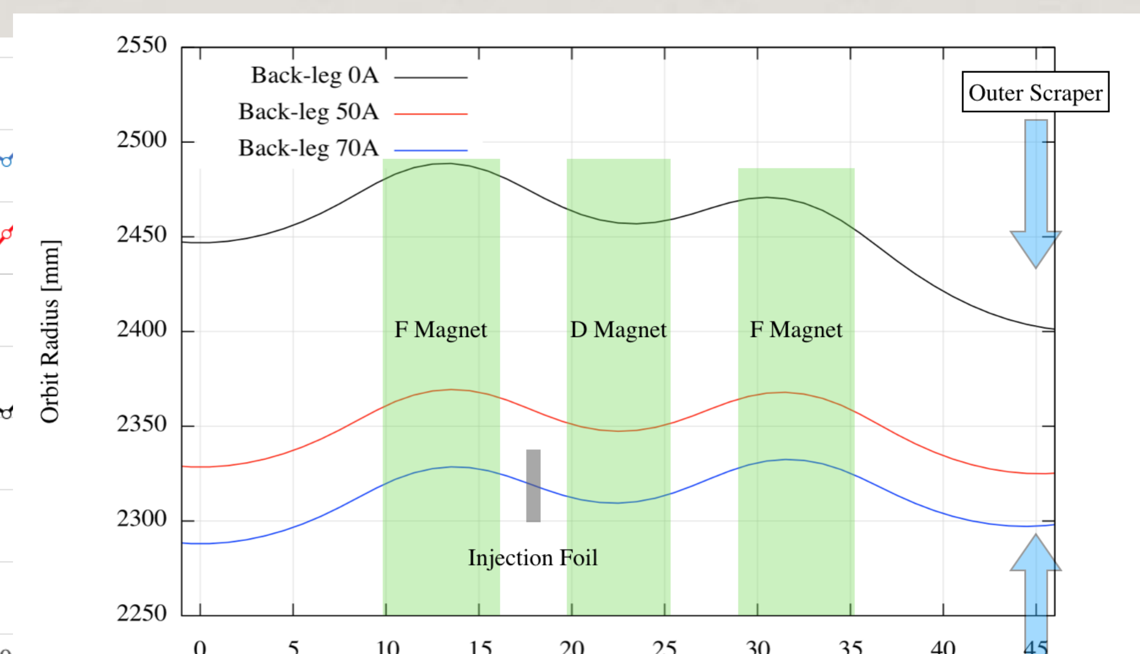
MERIT:Demonstration(2)

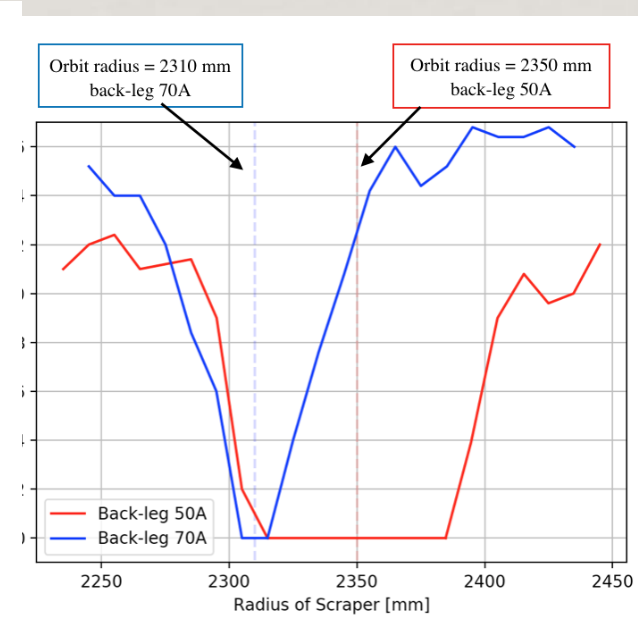
- Orbit correction
  - COD source : RF cavity (made of copper plating iron)
- COD correction and injection matching
  - A pair of back-leg coils wound around the magnet yokes



$$x(s) = \left[\frac{\sqrt{\beta(s)\beta(s_0)}}{2\sin(\pi\nu_H)} \frac{\delta(Bl)}{B\rho} \right] \cos(\pi\nu_H - |\psi(s) - \psi(s_0)|)$$

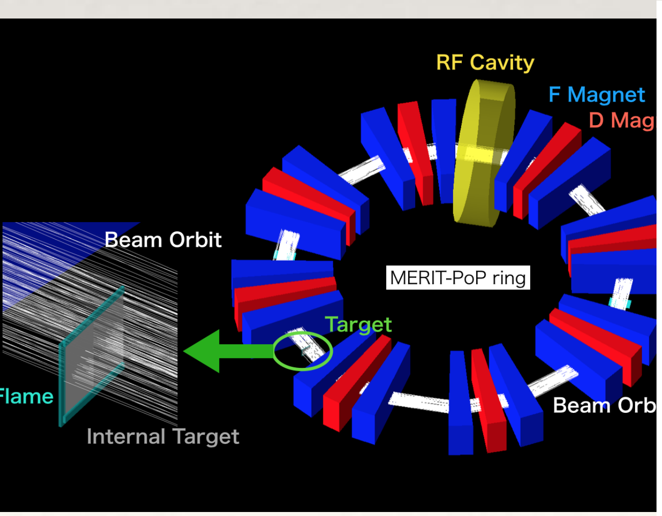


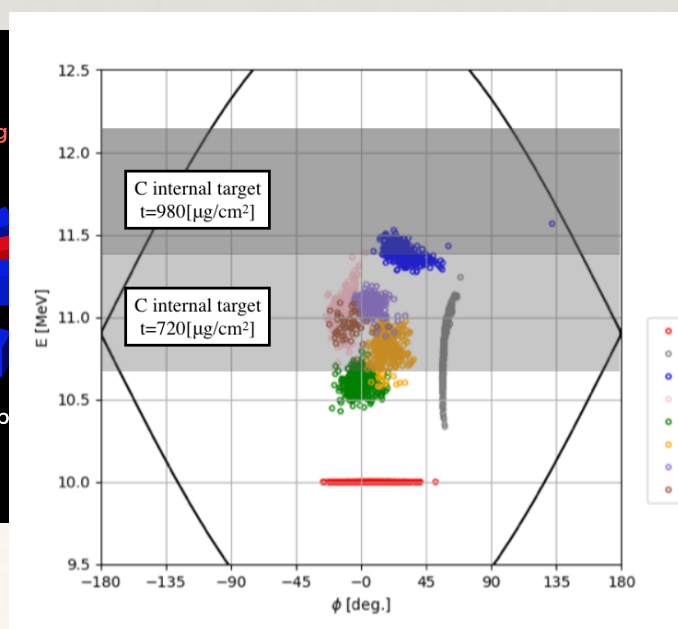


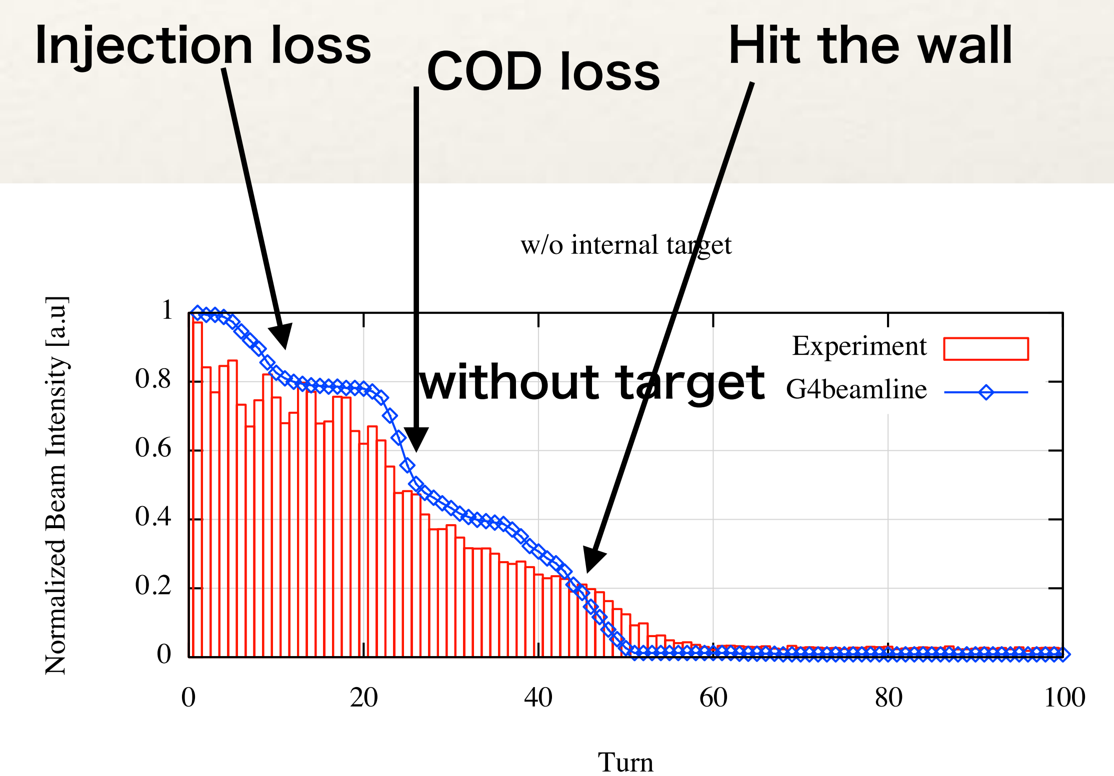


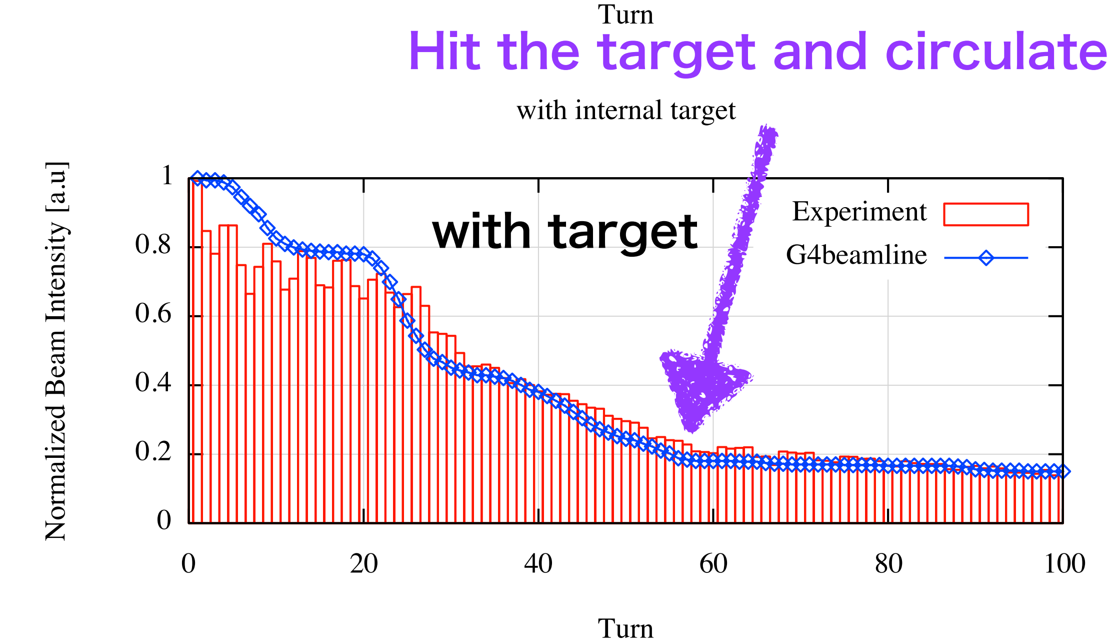
MERIT:Demonstration(3)

- Experiment
  - Wedge target: C, t=720-980[g/cm²]→ ΔE=27-37keV
- Particle tracking
  - G4beamline(G4BL) code
  - B-Field map 3D: OPERA3D/TOSCA
- **Experiments and simulations showed good agreement.**



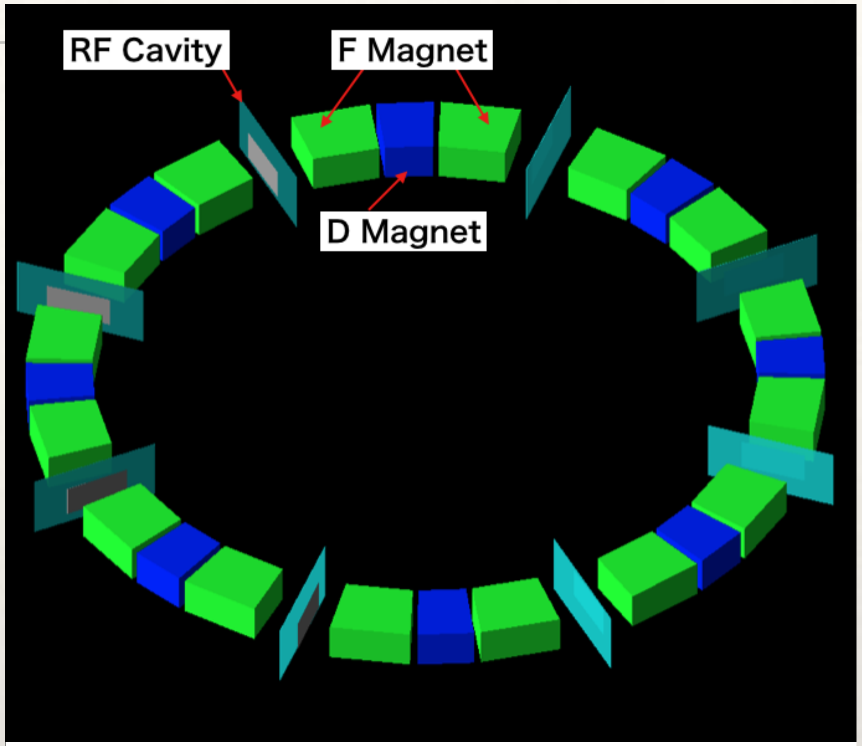


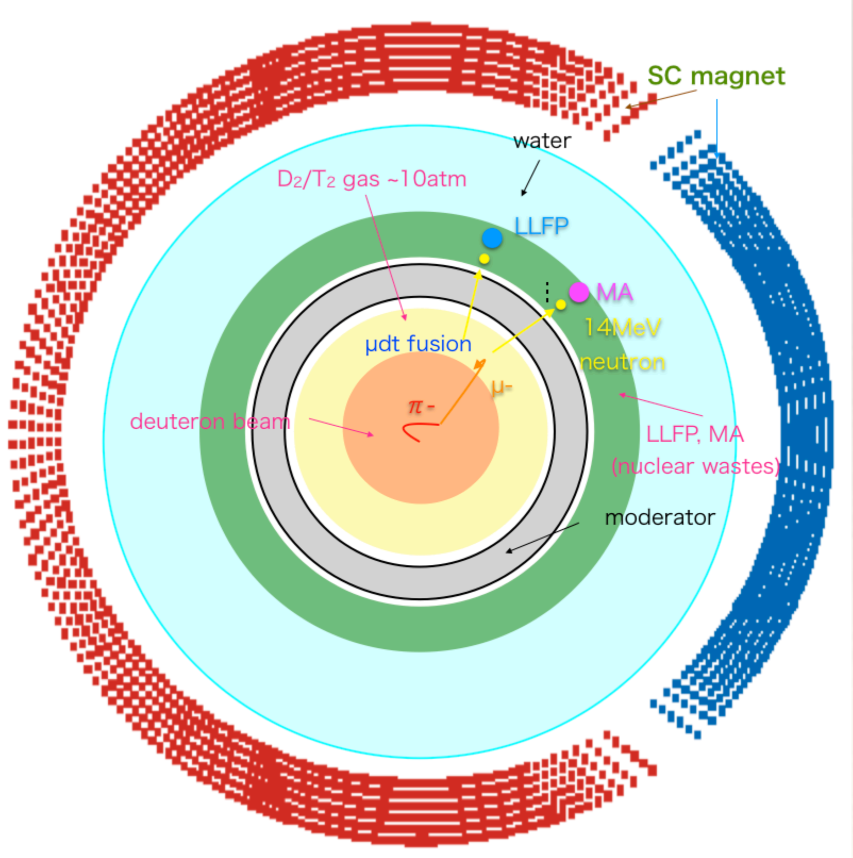




NX:Hybrid of MuCF and ERIT(1)

- Advances of ERIT for nuclear transmutation
  - Hybrid system of MuCF and ERIT
    - D/T gas target ~ 1-10atm
    - Neutron flux $\phi(n)$: 10^{19}n/s
      - Muon flux required:$\phi(\mu^{-})$= $7\text{x}10^{16}\mu$/s
      - d beam : 400MeV/u - 60mA(50MW:D^0 incident)
        - [Nucl. Instrum. Method, A982 (2019)]
  - Electric power required : <10% of 1GWe nuclear plant generating capacity
    - MuCF fusion output power (~20MW) assists.



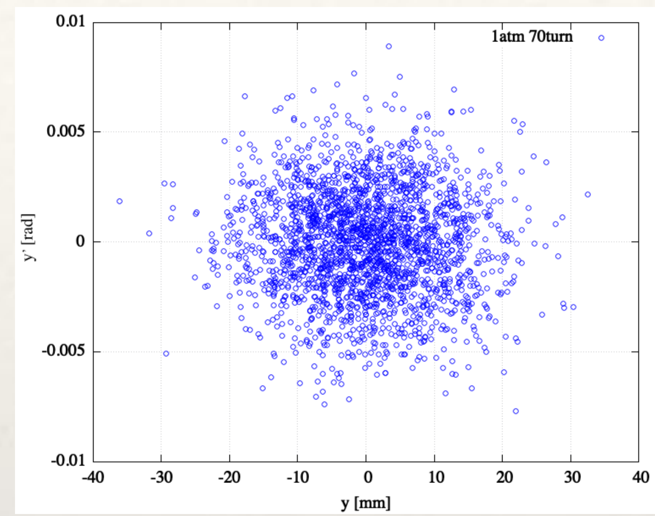


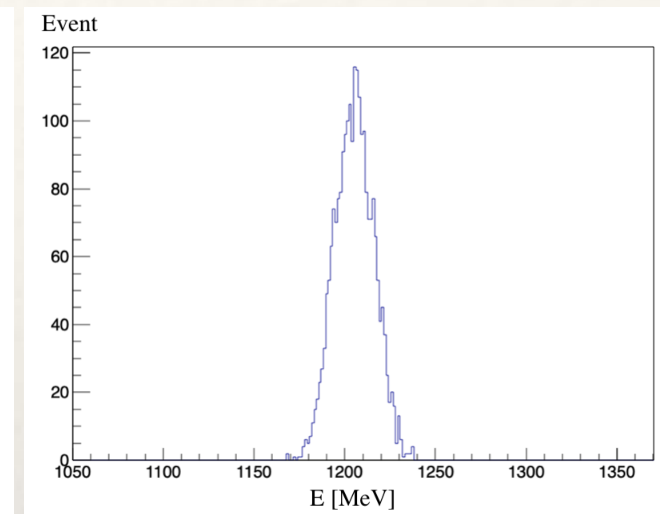
NX:Hybrid of MuCF and ERIT(2)

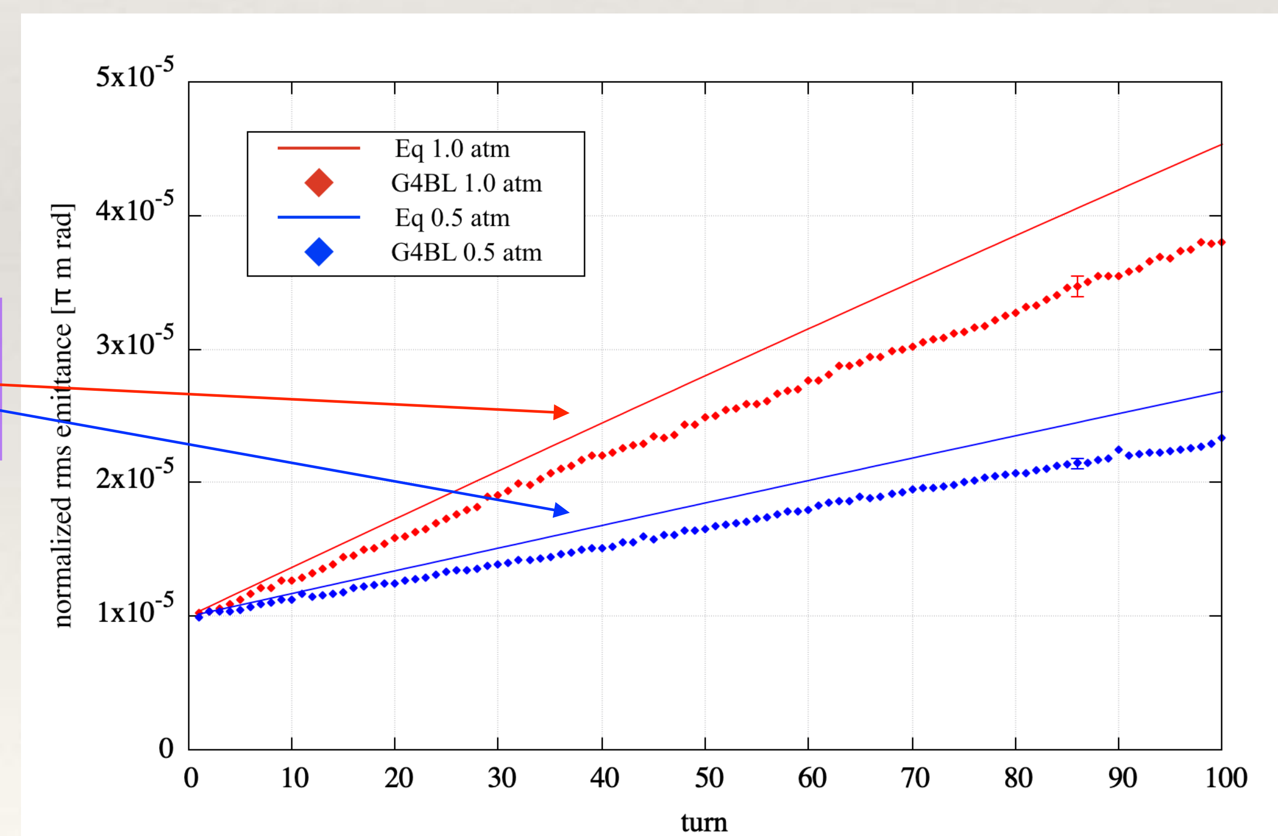
- Gas filling ERIT
  - D2 gas, 1atm
- Emittance growth
  - Longitudinal : ΔE/E ~2.5% (FWHM)
  - Transverse: 3×10^{-5}m.rad after 70 turns.

$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\epsilon_N + \frac{\beta\gamma\beta_T}{2}\frac{d<\theta^2_{rms}>}{ds}.$$

- Acceptance
  - Energy acceptance : >+-10%
  - Transverse: 4×10^{-3}m.rad







Summary

- Applications of Energy Recovery Internal Target(ERIT) with FFA accelerator
  - Mitigation of long-lived nuclear wastes with negative muons
    - Neutron source : Muon Catalyzed Fusion
    - Direct nuclear transmutation : Muonic atom
- MERIT :a new scheme that achieves acceleration and circulation.
  - Design of negative muon source with MERIT
  - Demonstration of MERIT principle
- Hybrid system for NX: MuCF and ERIT