INTENSE (MONO-CHROMATIC) NEGATIVE MUON SOURCE

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- **Principle of ERIT (Emittance Recovery Internal Target) for muon production**
- **Experimental study : Proof of Principle**
- **Mu_ERIT with FFAG (Fixed-Field Alternating Gradient)**
- **New scheme**
- **Conclusion**

MUON

- **Muon (μ+/μ-) : elementary particle (lepton)**
  - Mass 105.659 MeV (206.768 $m_e c^2$)
  - Spin 1/2
  - Geomagnetic factor (g/2) 1.000165
  - Decay(free) lifetime 2.197 μsec: $e^+ + \bar{\nu}_\mu + \nu_e$
- **Elementary particle physics**
  - μ_γ/μ_e conversion findings: Good signal for new physics beyond SM model→Super symmetry/Super string etc.
  - Neutrino source : ν-mass oscillation (lepton flavour mixing), CP-violation in lepton sector
  - Ultra-high energy beyond LHC:muon collider
- **Solid-state physics**
  - μ-spin rotation/diffusion, μSR :
- **Non-destructive analysis**
  - Archeology, Osteoporosis, Eruption prediction, Medical Diagnostics
- **Nuclear energy system with μ^- ← New topics**
  - **Muon nuclear transmutation (μNT)**

ISSUES OF NUCLEAR ENERGY SYSTEM

Muon may provide the solutions.

- **Controllability of energy generation**
  - Fission   Criticality control, Radiation heating
  - Fusion   Plasma confinement and heating

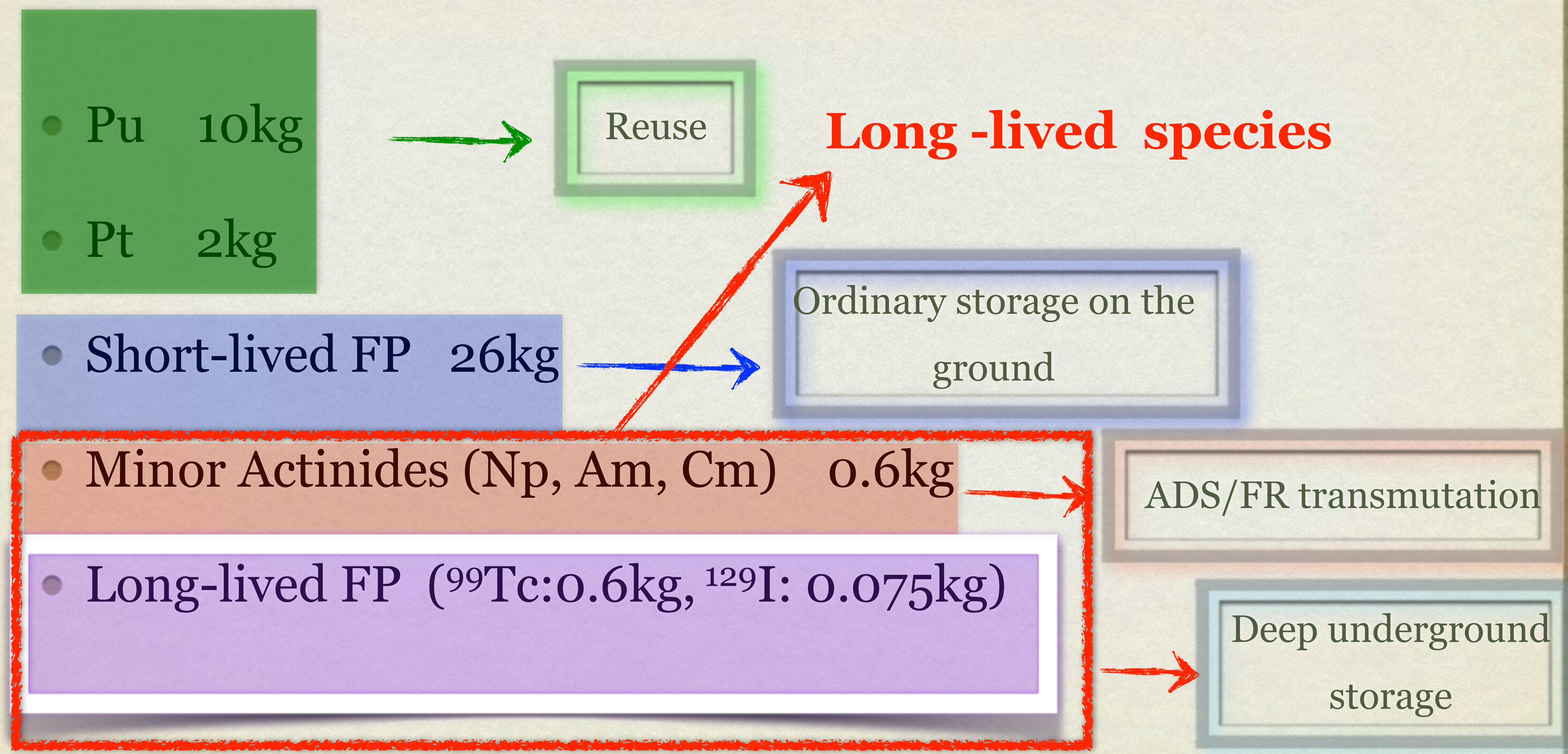
μCF (muon-catalyzed fusion)

- **Radiation**
  - Nuclear reactor wastes   : long-lived species (LLFP,MA)

MNT (muon nuclear transmutation): Nagamine & Mori

RADIOACTIVE WASTES FROM NUCLEAR POWER PLANT

Production of nuclear wastes from Uranium fuel (3% enriched U; 1ton)



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NUCLEAR TRANSMUTATION WITH NEGATIVE MUON

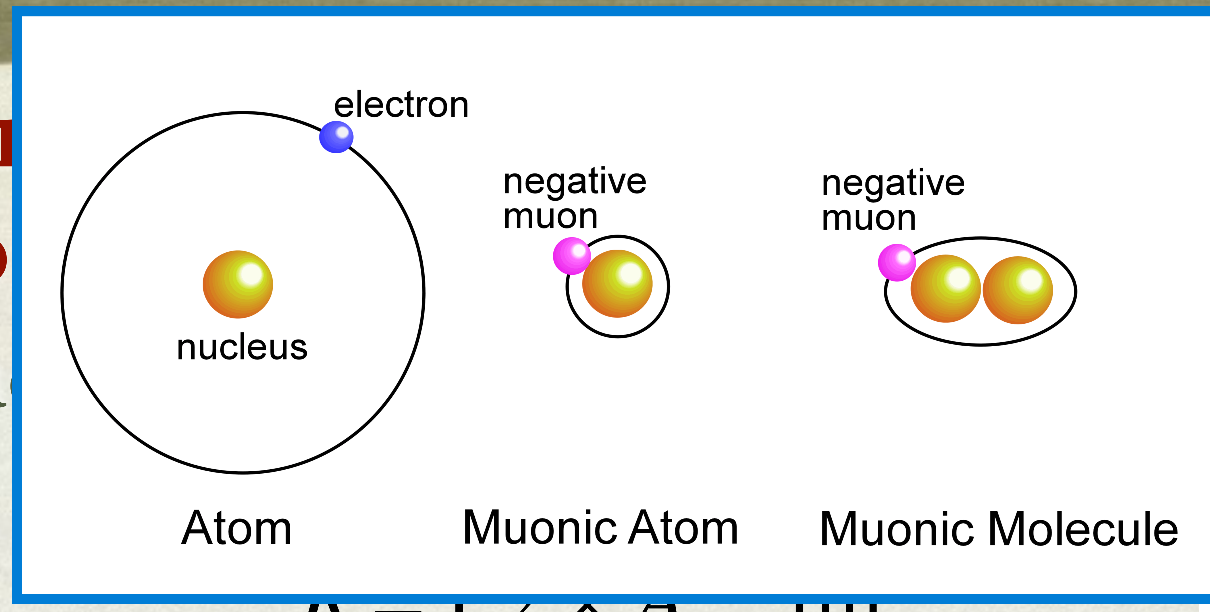
- **1st:Formatio**
transmutatio

Muonic_atom ra

Nuclear radius:

$R/a_\mu > 1 \quad \Rightarrow$ **Tr**

$\mu^- + {}^{99}$Tc(LLFP:2.1



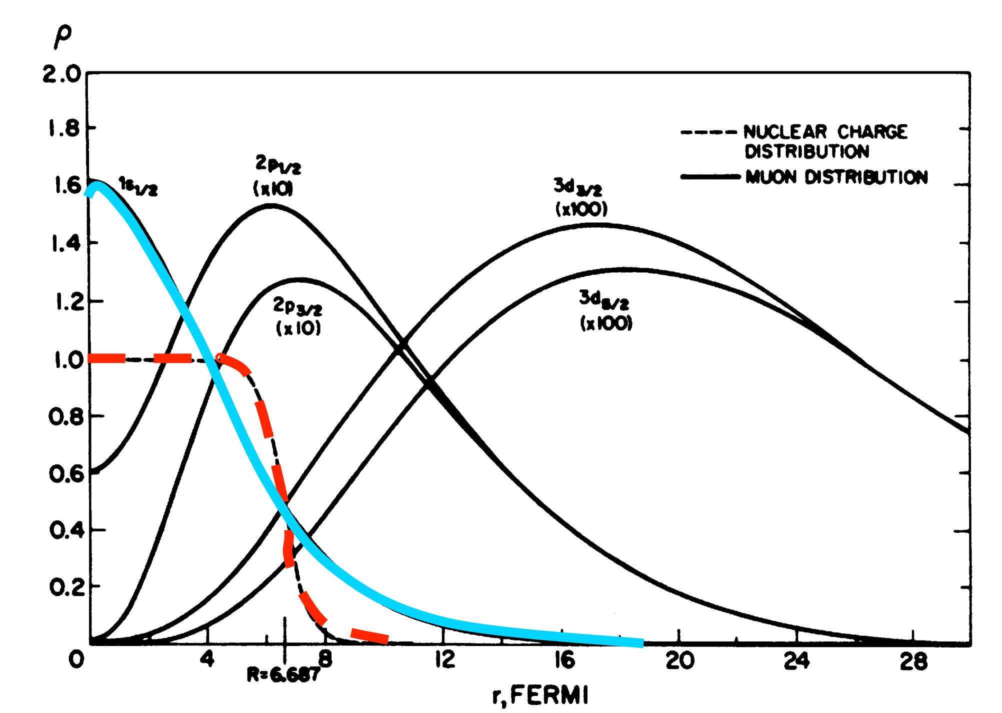
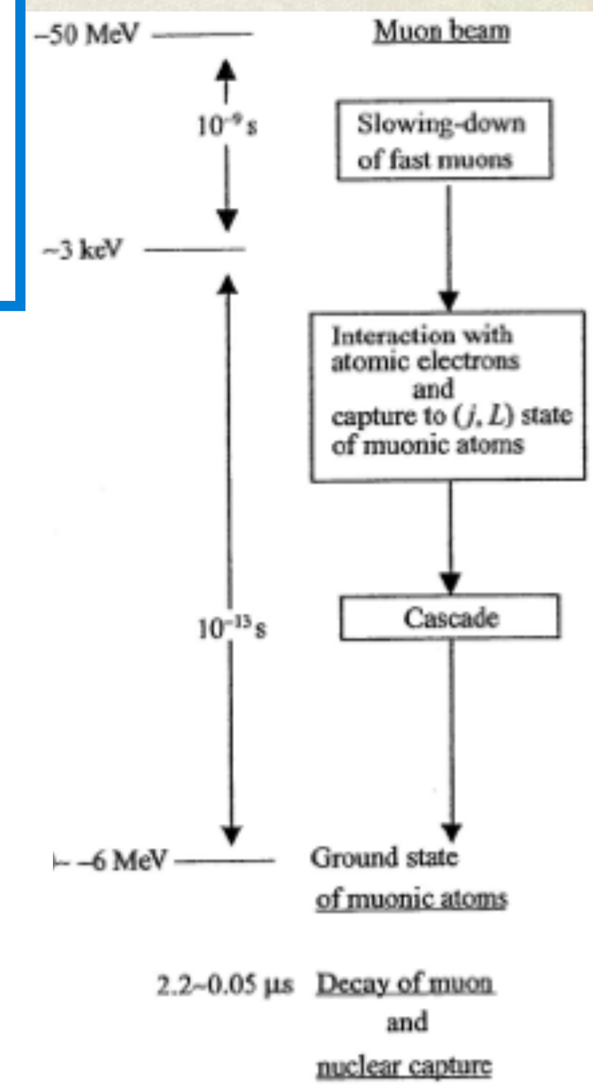
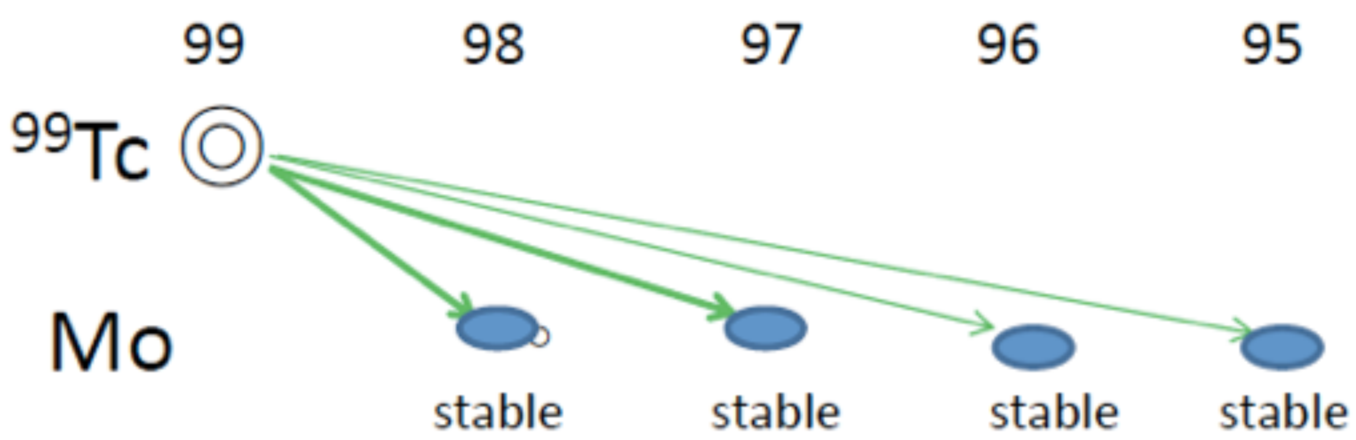


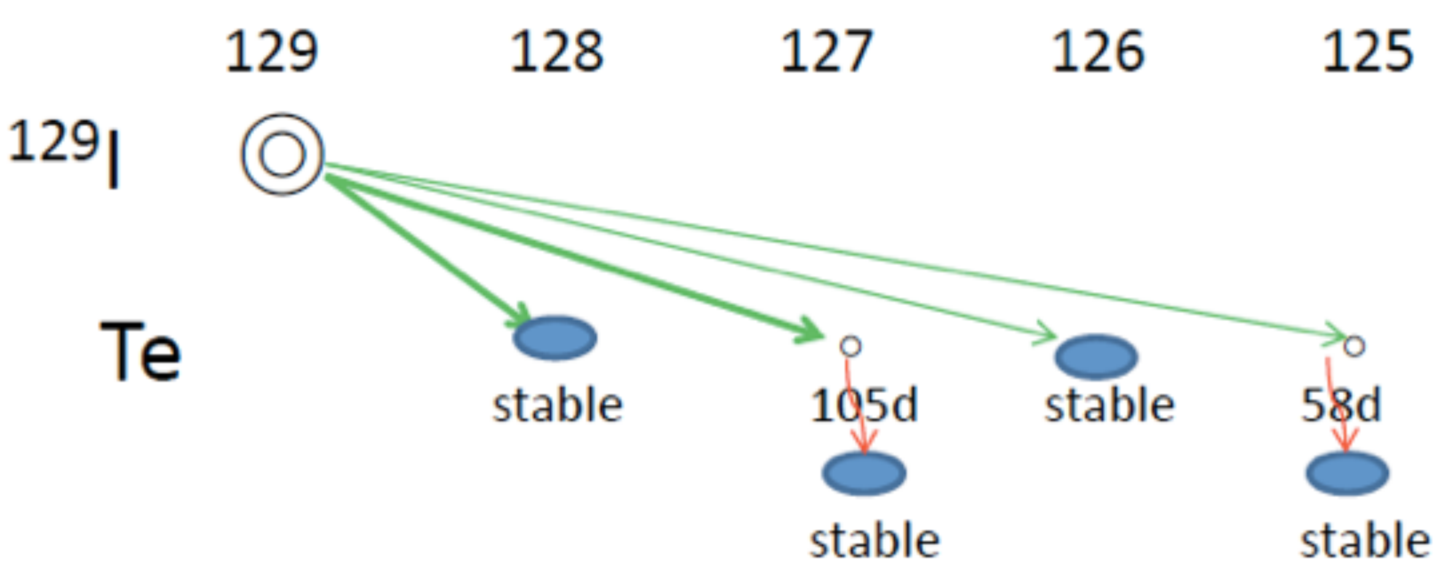
Fig. 15.8 The probability densities of finding a muon in the state indicated, at a distance *r* from the nuclear centre (full lines), are compared with the nuclear charge distribution in the case of lead. In the $S_{1/2}$ state, the probability of finding a muon within the nucleus is close to 50% (Devons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



^{99}Tc(2.12x10^5y, 6.14%)



^{129}I (1.72x10^7 y, 0.84%)



RADIOACTIVE WASTES FROM NUCLEAR POWER PLANT

Production of nuclear wastes from Uranium fuel (3% enriched U; 1ton)

- Long-lived FP (^{99}Tc:0.6kg, ^{129}I: 0.075kg)

↓

If Muon_NT can treat LL-FP(&someMA) with >a few mol/10y, a deep geological storage(GS) may not be necessary.

$$I_{\mu^-} > 1\times10^{16}\left[\mu^- / \mathrm{sec}\right]$$

FEATURES OF MUON_NT

- **High efficiency and high selectivity :**
  - Efficiency of NT:> 95% for heavy elements (Z> 30)
  - Selectivity for heavy element (Z-scaling) in compound materials.
- **Low radio-activity**
  - One negative muon creates almost one (Z-1)element, no others. (cf. Neutron induced nuclear transmutation).
- **Localised radiation shielding : mostly pion/muon production target area.**

NEGATIVE_MUON PRODUCTION

- **1st step : π⁻ production reaction**

$$p(d)\left[E > 250\,MeV/u\right] + X(n) \rightarrow \pi^{-} + p + X^{*}(n-1)$$

- **2nd step: Decay from π⁻**

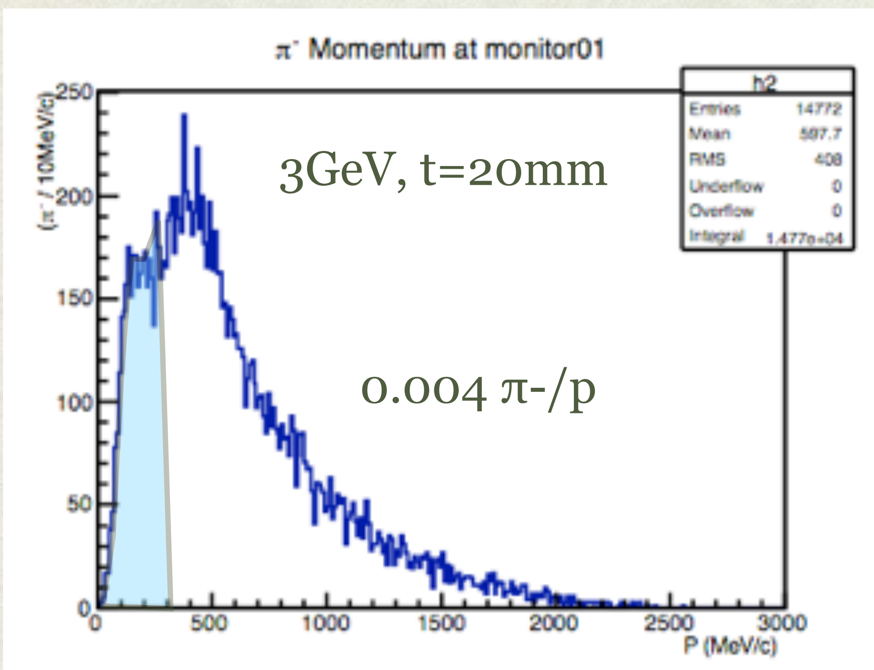
$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu}$$

REQUESTED MUON PROPERTIES FOR NUCLEAR POWER SYSTEM

- **Charge state →Negative: μ^- (decayed from π^-)**
  - Projectile particle
    - Proton: π^-/π^+~0.2 (E_p < 1 GeV), ~0.7 (E_p > 5 GeV)
    - Deuteron: π^-/π^+~1 (E_d > 0.5 GeV/u)
- **Low energy → < 300 MeV/c**
  - Low magnetic rigidity Bρ< 1 Tm
    - → Capture B field =2 T, ρ=0.5 m
  - Hard to degrade high energy muon:cf. Range (1 GeV/c) > 3 m (graphite)

CONVENTIONAL SCHEME FOR PRODUCING LOW-ENERGY NEGATIVE MUONS

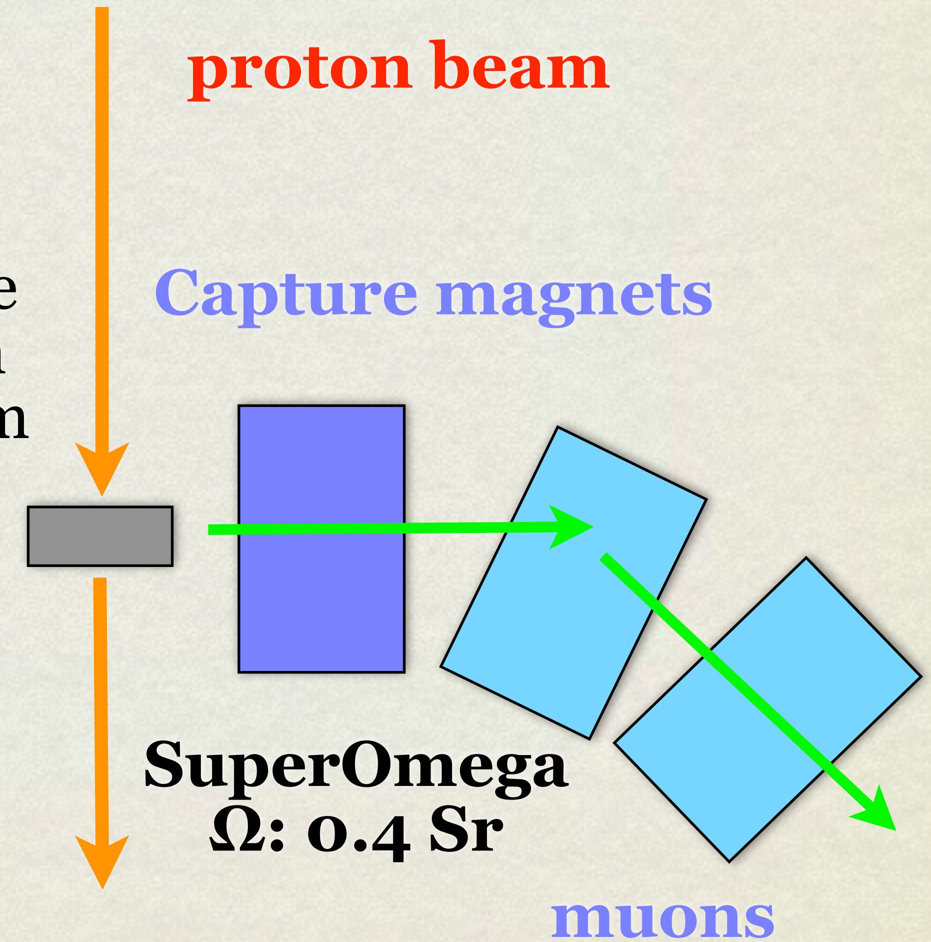
- **High energy proton E> 3 GeV**
  - Range(EM stopping power) >> Target thickness(<nucl. int. leng.) σ(π-N)>> σ(pπ-)
- **Small Low energy π-(μ-) fraction ~0.02 π-/p(t=100 mm)**



- **Small Acceptance of capture magnet**
  - Acceptance: ~0.4 Sr (SuperOmega:J-PARC)
- **Total Efficiency**
  - 0.004 (≲300MeV/c) x 3.2×10^{-2} (Acc.Mag.) ~1.3×10^{-4} (π /p); cf. **J-PARC: ~2.6×10^{11} π-/sec @maximum: reality 10^{8} μ-/sec**

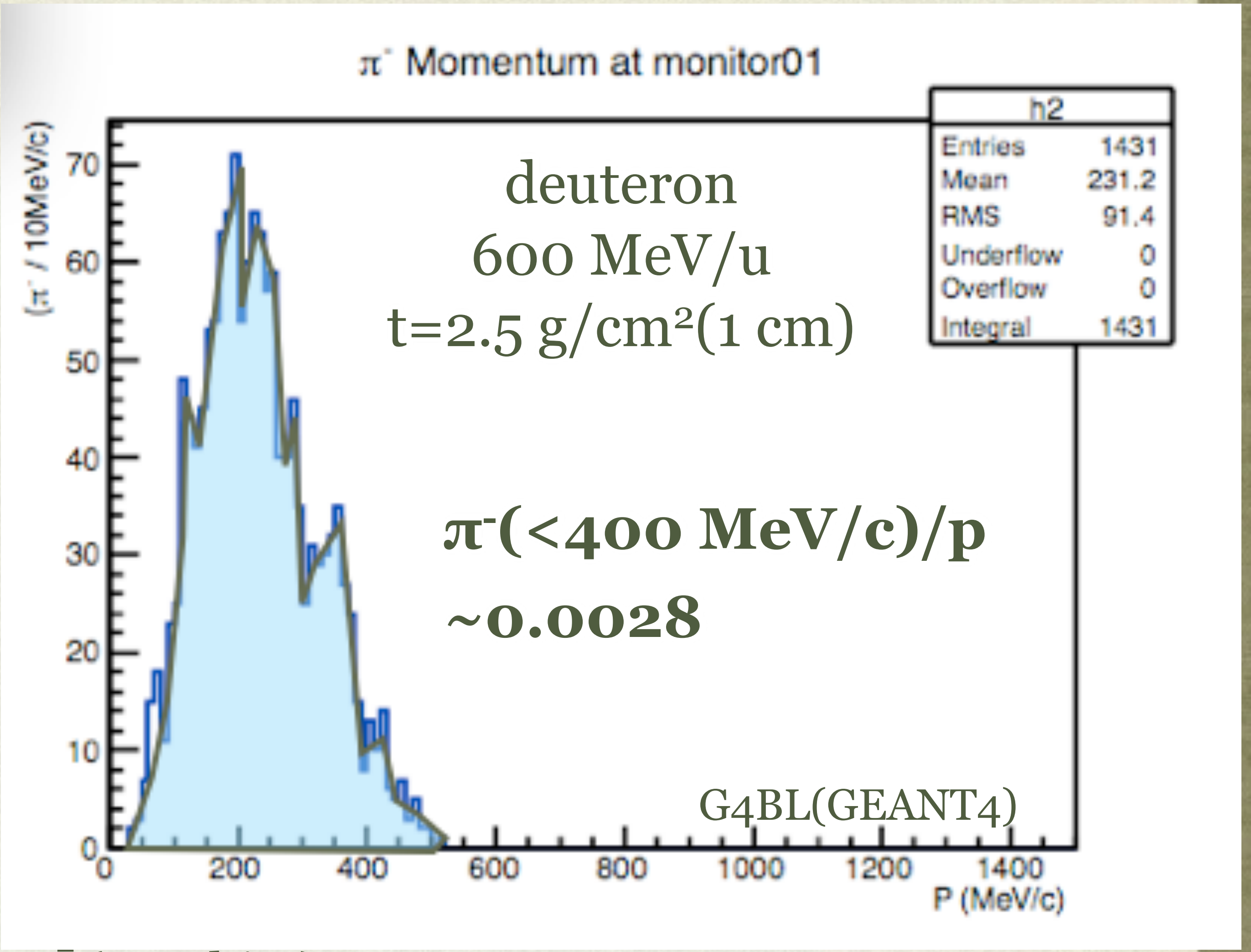
J-PARC MUSE proton beam
3 GeV
~1000 kW

Target
graphite
t20 mm
Φ70 mm



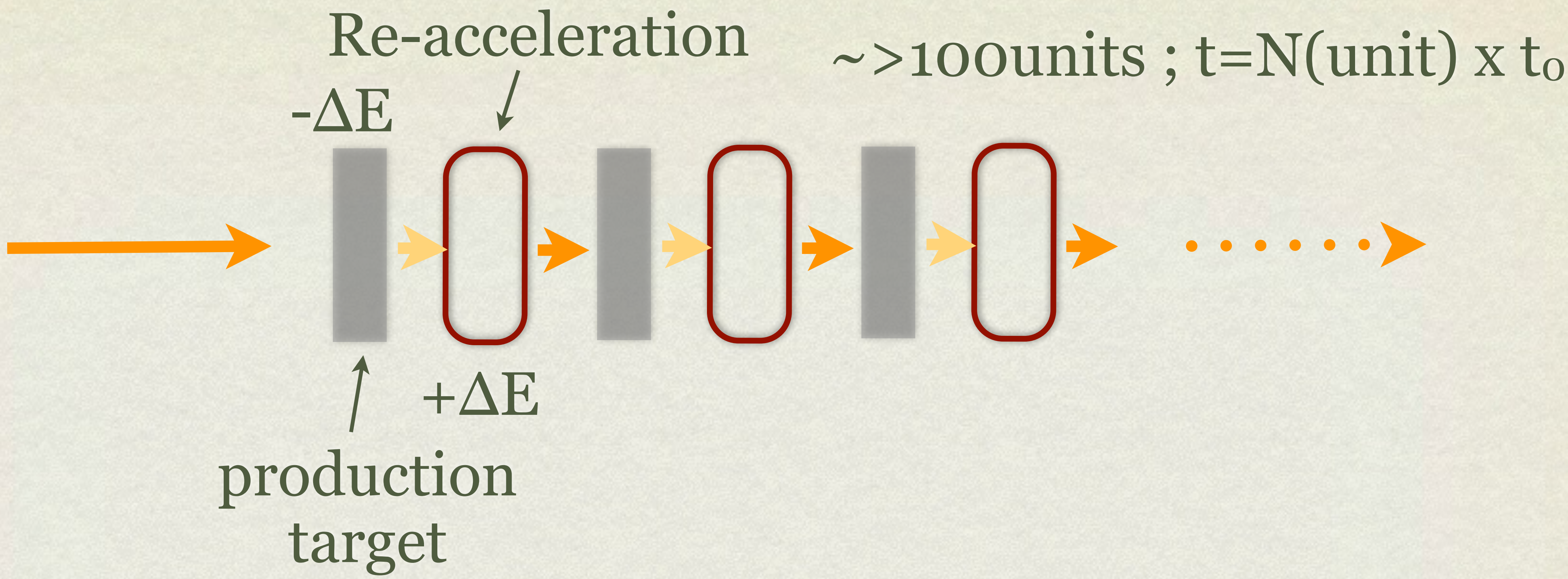
ISSUES FOR HIGH INTENSITY LOW ENERGY NEGATIVE MUONS

- **Improve the production efficiency**
  - **$p_{\pi-}$ <400 MeV/c**
    - Low energy projectile
      - Ep <~0.5-1 GeV/u
    - Thin target (<< Range: dE/dx & σ(π-,N))
      - t~ <2 g/cm^2 (graphite)
  - **Efficient collection of π-/μ-**
    - Target is placed in B field(solenoid).



- **Problems**
  - **Small production cross section**
    - π^-(<400 MeV/c)/p ~0.0028 for t=2.5 g/cm^2 (graphite)
      - **Need an effective longer (>100 times) target. For t_{eff} > 100 cm(250 g/cm²) → π^-/p > ~0.2.**

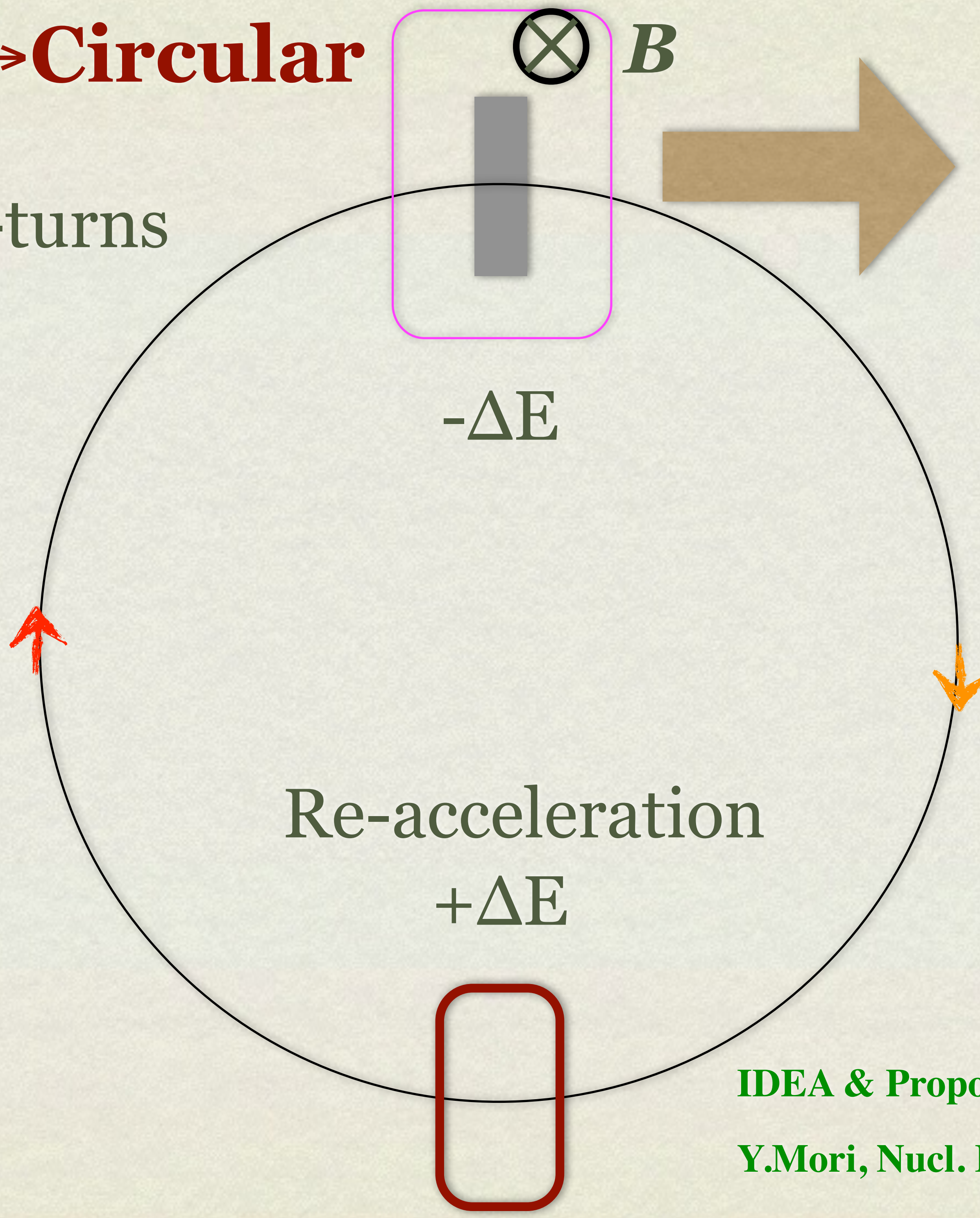
EFFECTIVE LONG TARGET RE-ACCELERATION

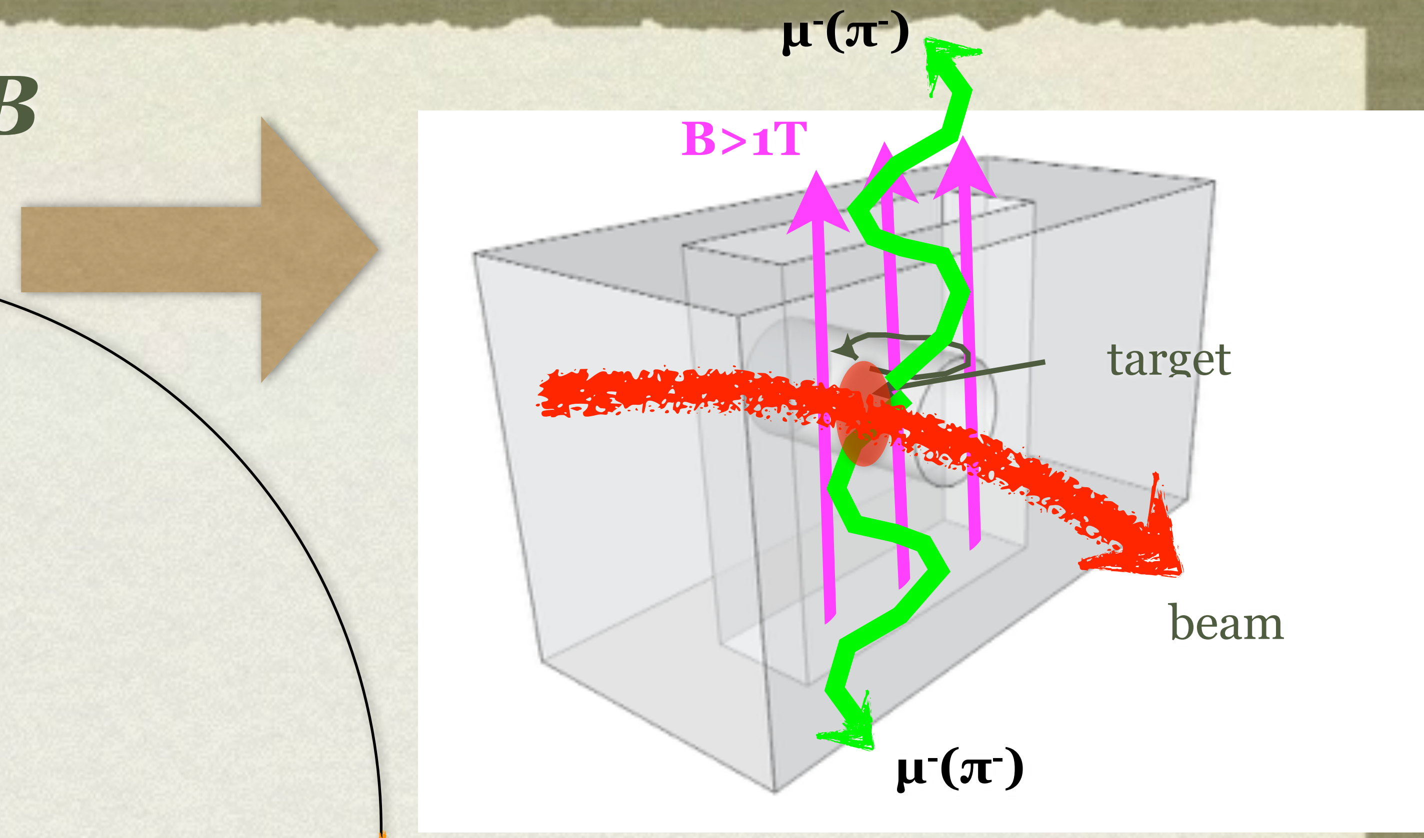


- **Difficulties**
  - How capture π/μ?
  - Long system > 100 m (unit~1 m); cost ?

ENERGY RECOVER RING + INTERNAL TARGET -ERIT-

- **Linear→Circular**
- t=n x t_0;n-turns





IDEA & Proposal:

Y.Mori, Nucl. Instr. Meth., PRS, A563(2006) 591-595.

ISSUES IN ERIT

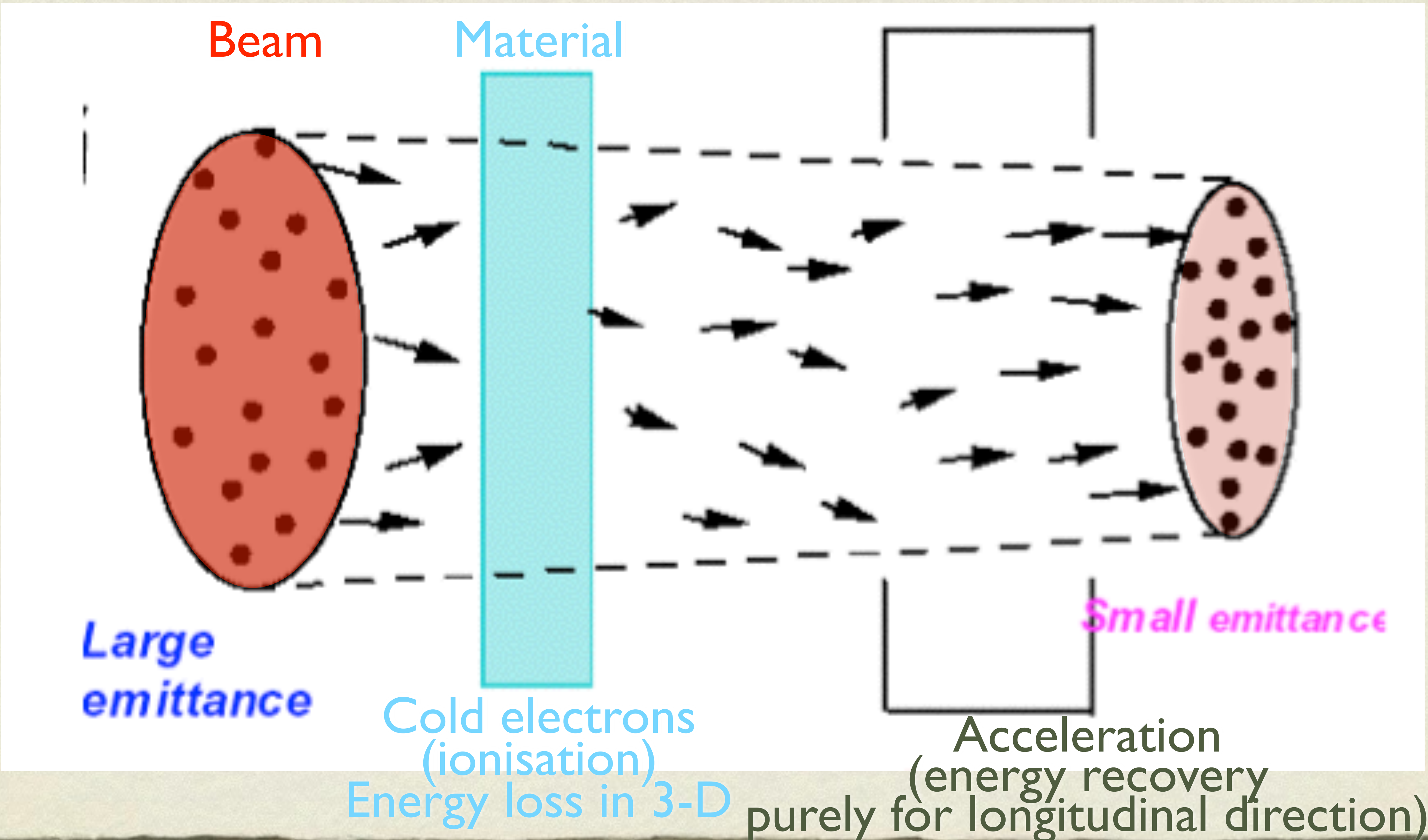
- **Emittance growth : Beam hits target many times. Beam survival?**
  - Transverse → Scatterings(Rutherford, elastic ...)
  - Longitudinal → Straggling:energy spread

➡**Need beam cooling → "Ionisation Cooling"**

IDEA & Proposal:

Y.Mori, Nucl. Instr. Meth., PRS, A563(2006) 591-595.

IONISATION COOLING



IONISATION COOLING

- **Theory**

cooling

heating

The rate equations of beam emittance:

Horizontal

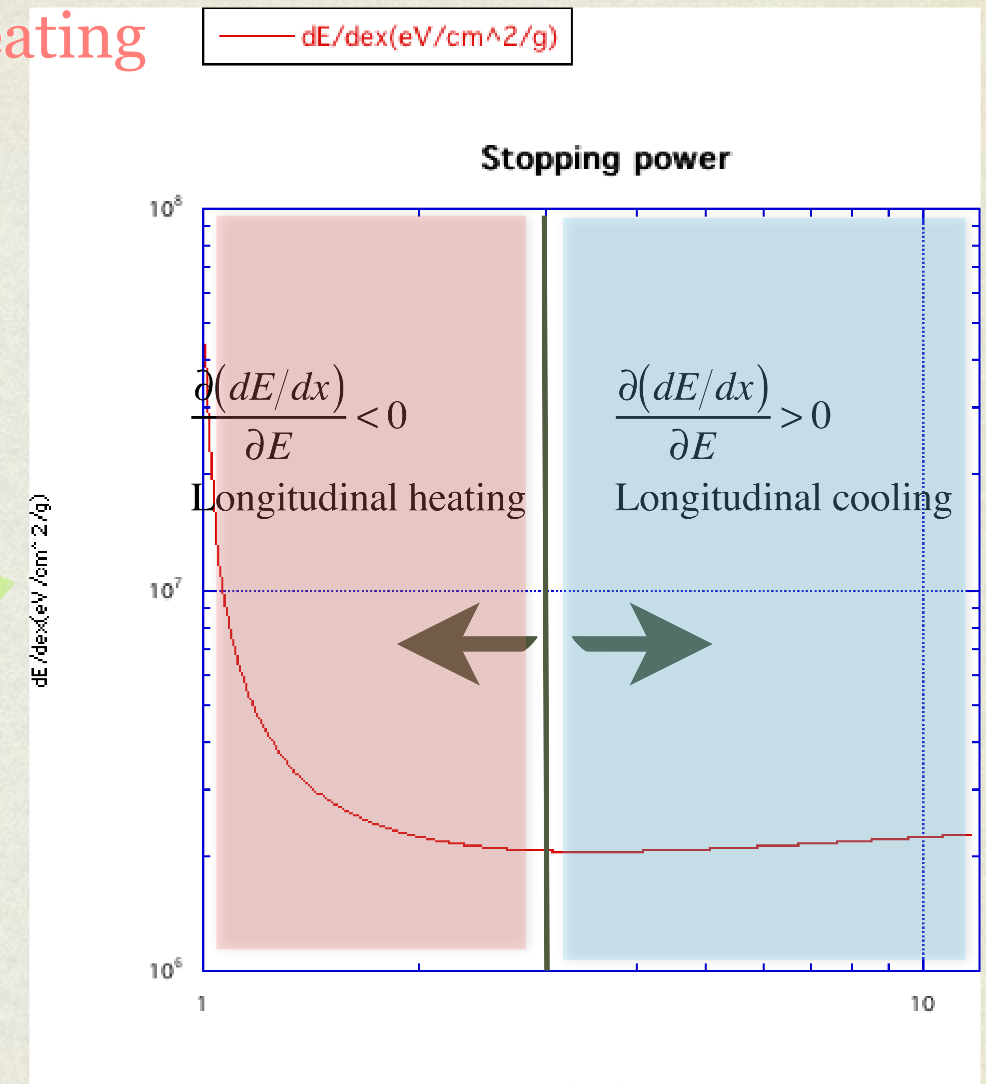
$$\frac{d\varepsilon_x}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\left(1-\frac{D\rho'}{\rho_0}\right)\varepsilon_x + \frac{\beta_x E_s^{\,2}}{2\beta^3 m_p c^2 L_R E}$$

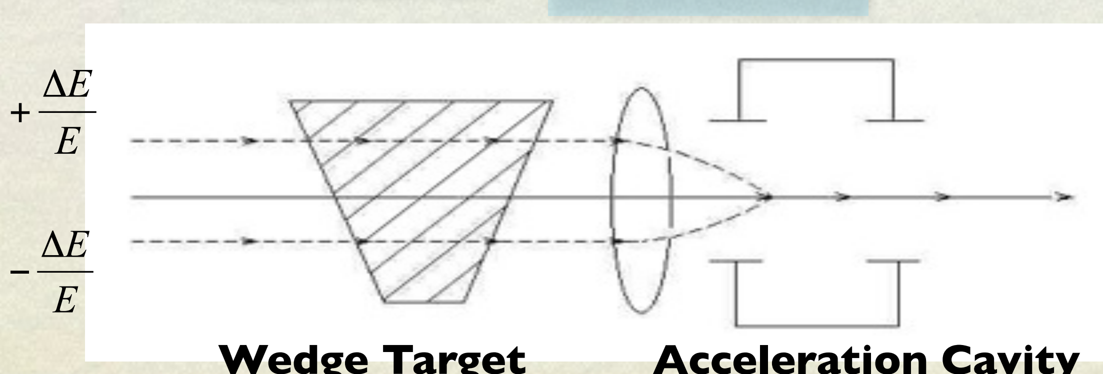
Vertical

$$\frac{d\varepsilon_y}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_y + \frac{\beta_y E_s^{\,2}}{2\beta^3 m_p c^2 L_R E}$$

Longitudinal

$$\frac{d\langle\sigma_E^{\,2}\rangle}{ds} = -2\left(\left.\frac{\partial(dE/ds)}{\partial E}\right|_0 + \frac{dE}{ds}\frac{1}{pc\beta}D\frac{\rho'}{\rho_0}\right)\langle\sigma_E^{\,2}\rangle + \frac{d\langle\Delta E^2{}_{rms}\rangle}{ds}$$





Large $L_R \bullet dE/ds \rightarrow$ Good trans. cooling

Light element is preferred!

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EMITTANCE GROWTH

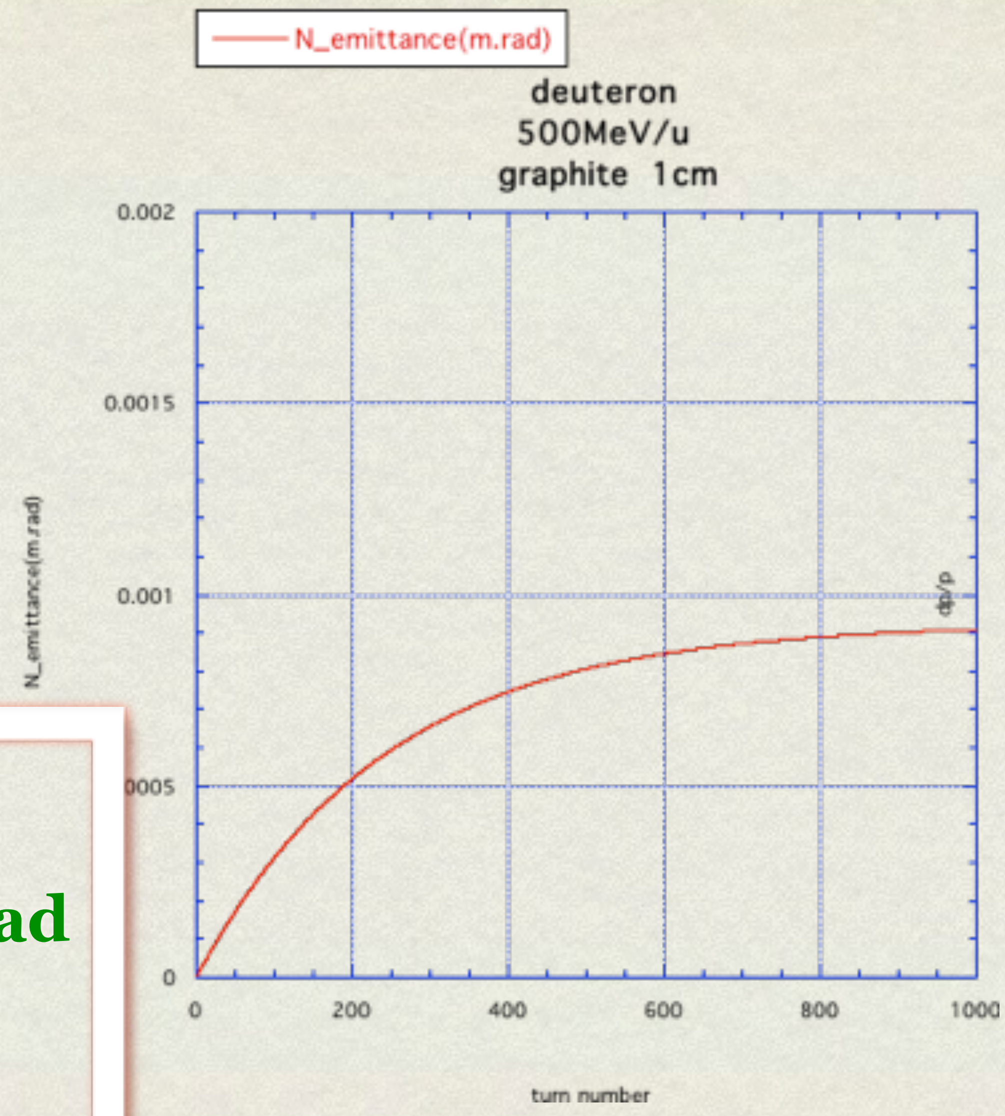
- **Mu_ERIT(case 1)**
  - Projectile : deuteron
  - Energy : 500MeV/u
  - Wedge : None
  - β(m) at target : 0.5m

Summary

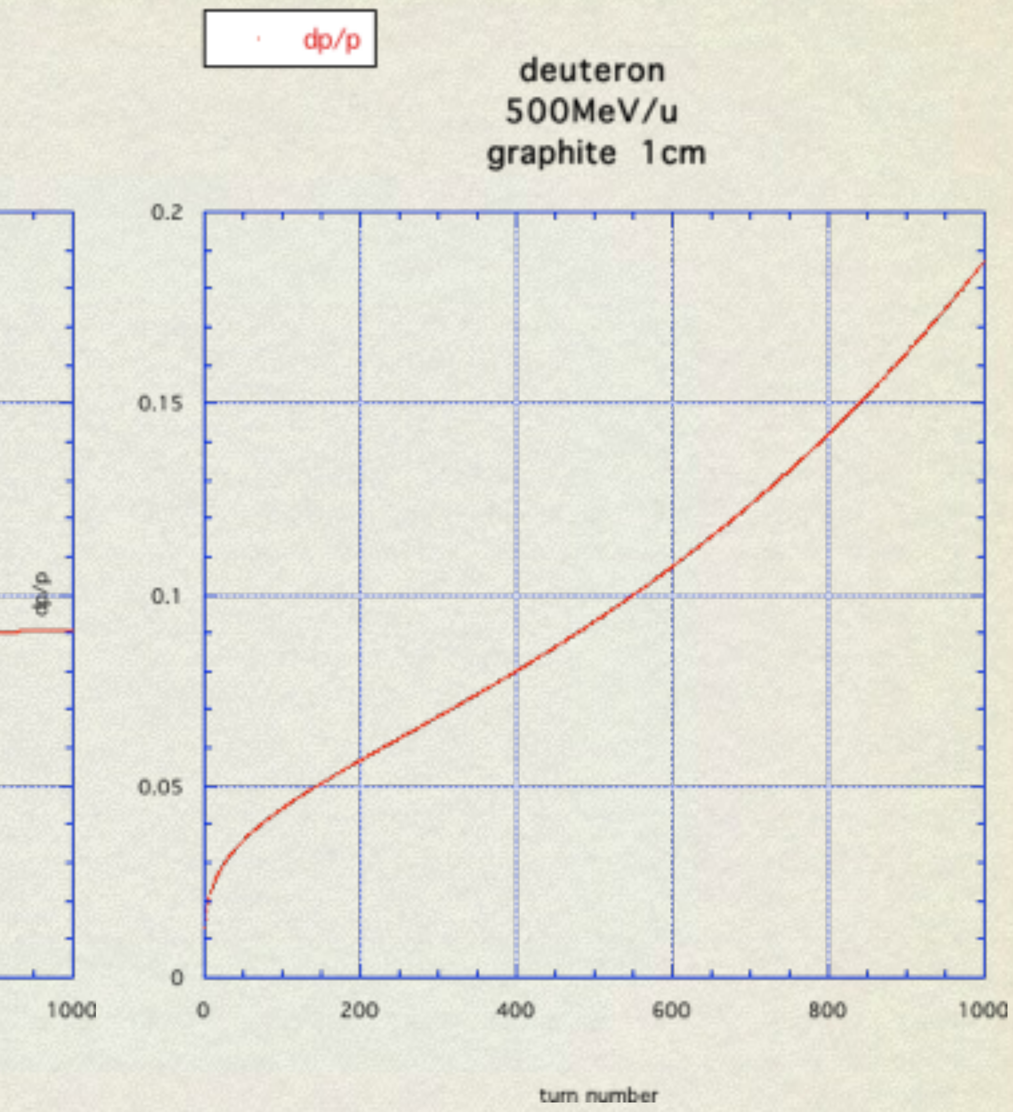
ε^{T}_{rms} ~ 450 mm.mrad

$\Delta p/p_{rms}$ ~ 5.7%

(after 200 turns)



Transverse



Longitudinal

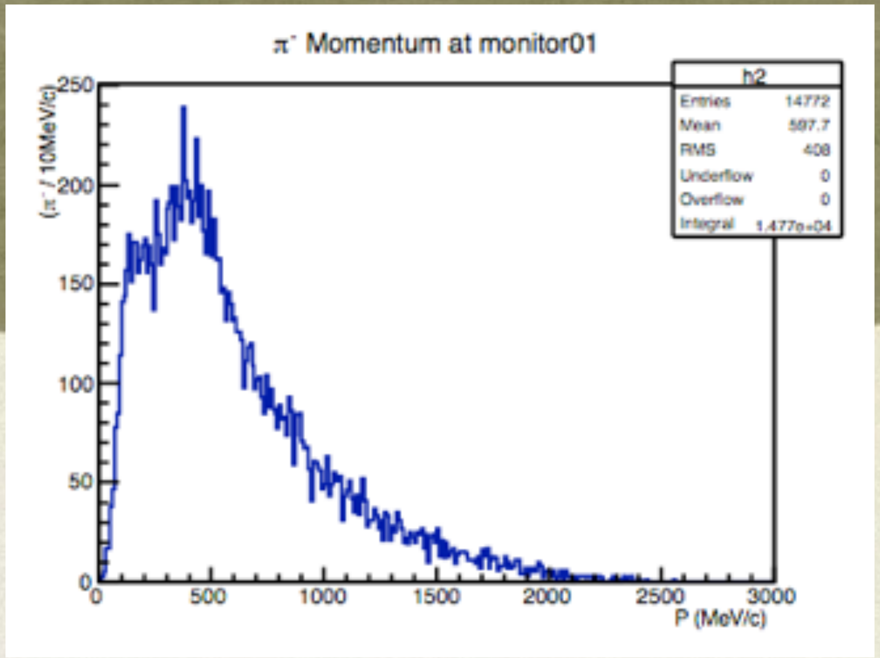
DEMANDS FOR RING SPECIFICATION IN ERIT

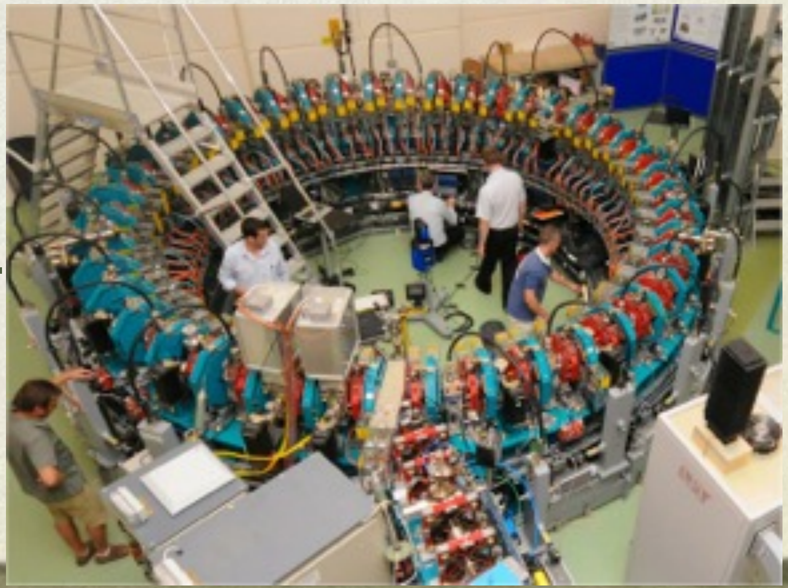
- **Small beta function at target**
  - Strong focusing: weak focusing (Cyclotron)→ not adequate
- **Large acceptance**
  - Transverse A (rms) > 500 πmm.mrad
  - Momentum Δp/p > 20% ← "Zero Chromaticity"

All satisfied only by
"FFAG(Fixed-Field Alternating Gradient)" .

FFAG

- **Invention 1950s**
  - T. Ohkawa (Japan)
  - Some developments (electron models)
- **Rebirth 2000s**
  - First proton FFAG (KEK,Japan)
- **Operation**
  - ADS study (Kyoto Univ.), EMMA(UK), Multi-Univ.)





PROOF OF PRINCIPLE

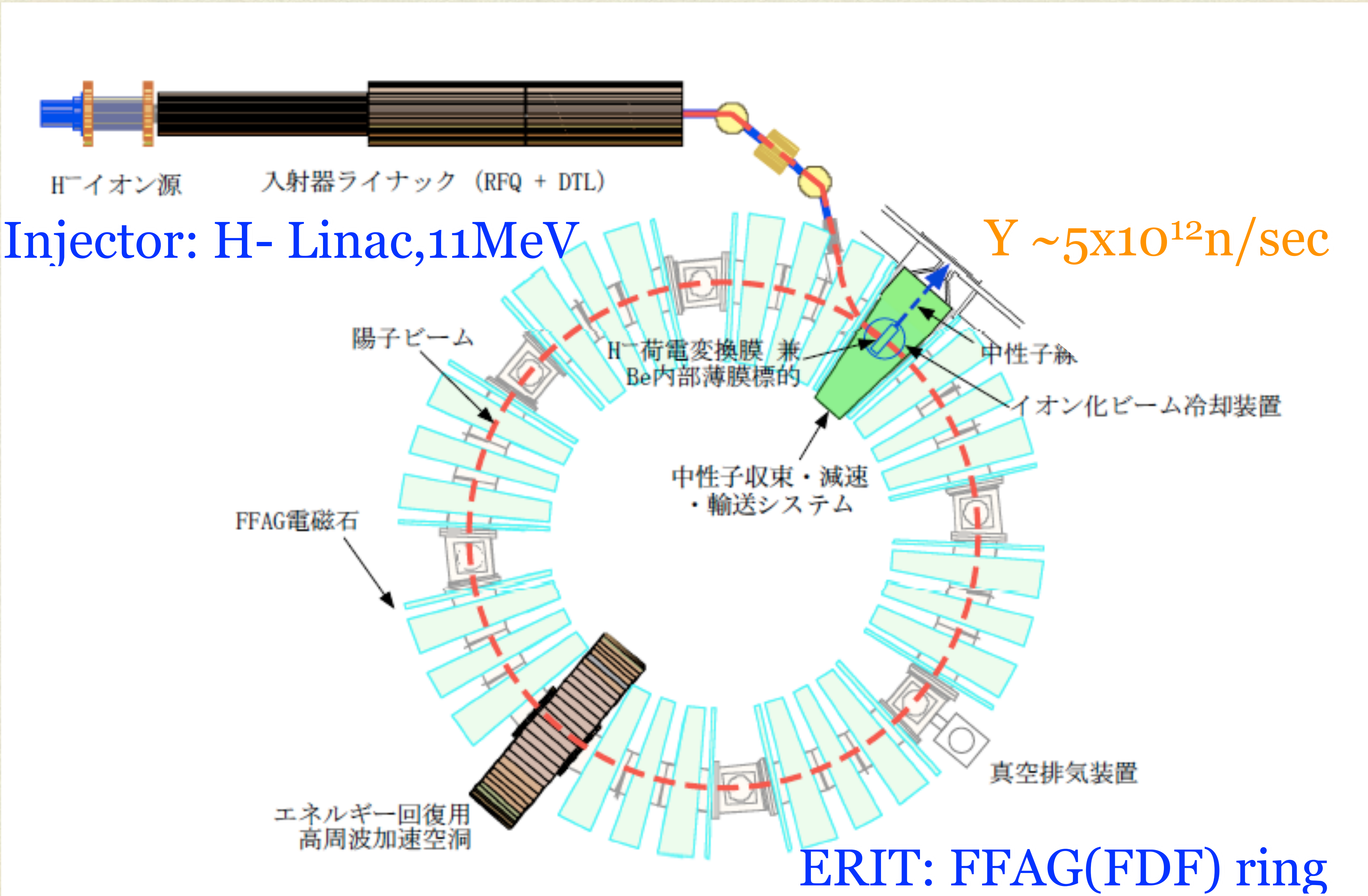
- **Experimental study of ERIT (2008)**

1)Y.Mori, et al.:Proc. of Particle Accelerator Conference(PAC09),Vancouver, 2009,pp.3145

2)K. Okabe,et al.:IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, Vol. 20, No. 3, (June 2010) pp. 740-743.

  - Neutron source
  - Proton 11MeV, 0.1 mA
  - Ring radius 2.35 m
  - Target Be (5 μm)
  - Yield ~5x10^{12} n/sec

TOP VIEW OF FFAG_ERIT RING FOR NEUTRON SOURCE



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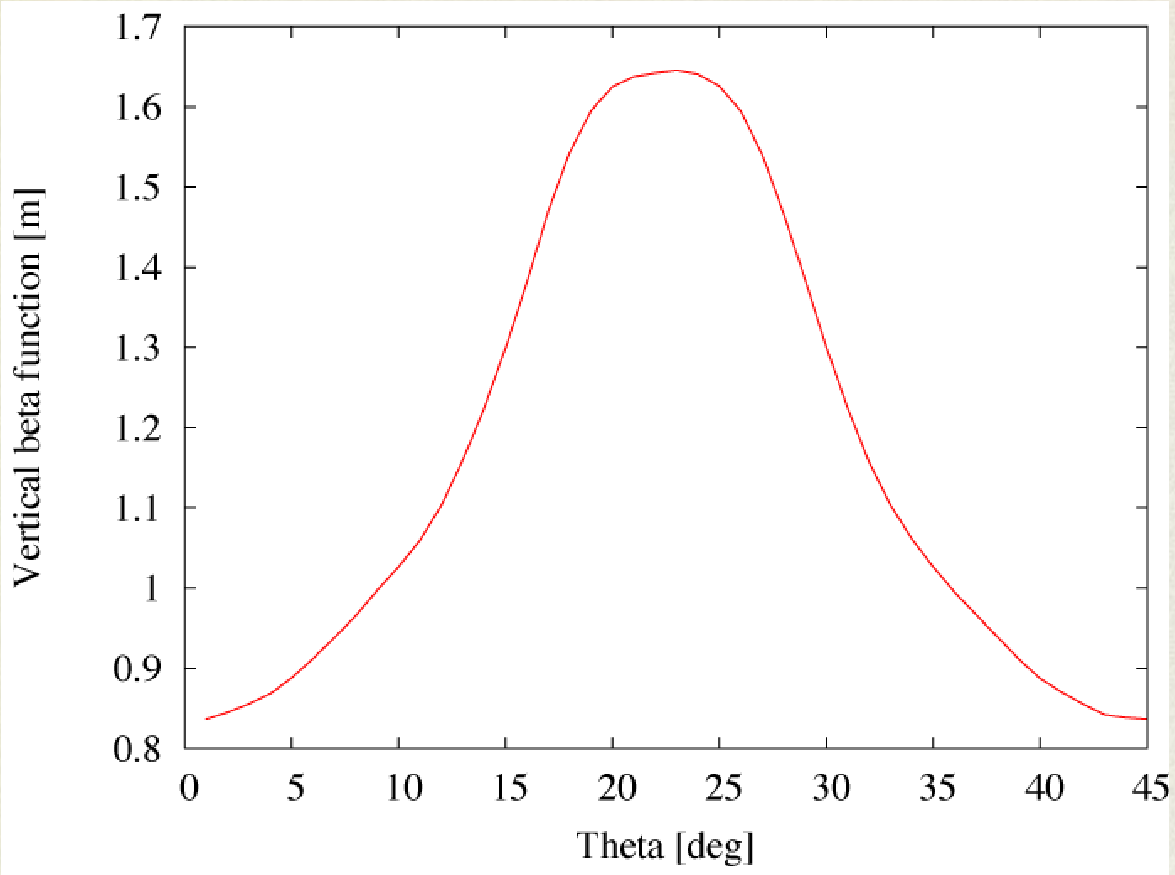
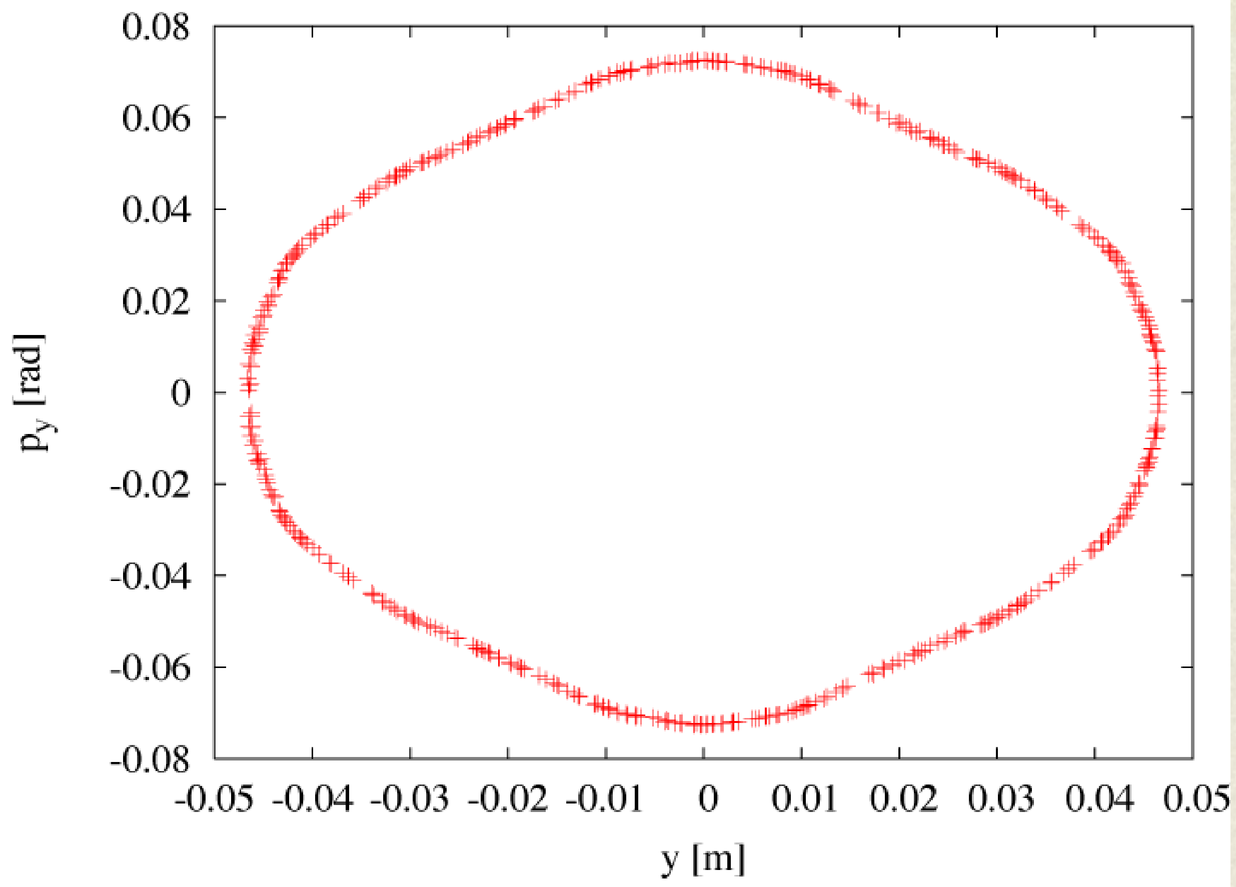
BETA FUNCTION(VERTICAL) & ACCEPTANCE

Beam tracking results with B field map (TOSCA_OPERA)





Vertical beta function@target ~ 0.83 [m]

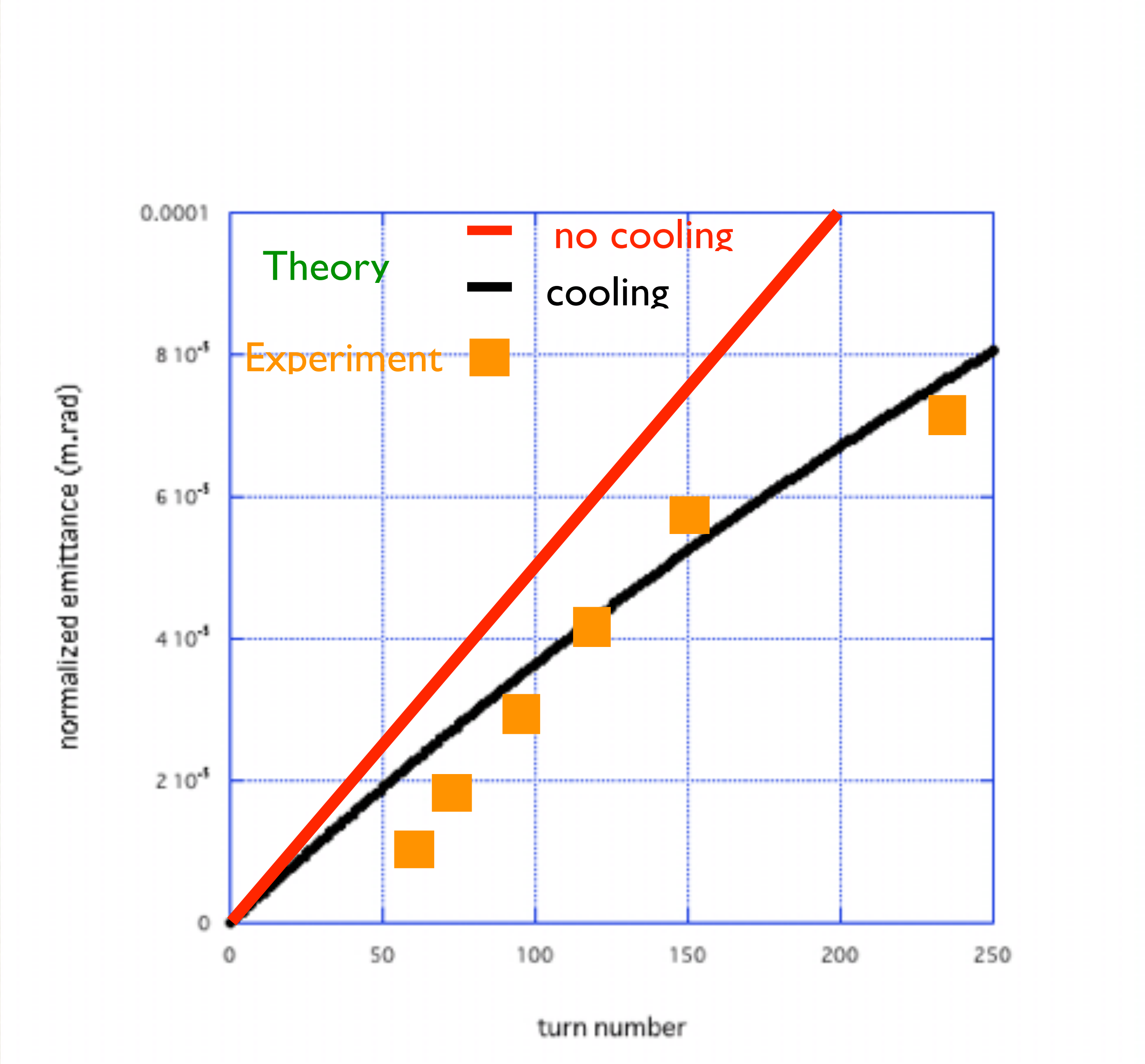
Vertical acceptance ~ 3000π [mm-mrad]

(Horizontal acceptance > 7000π [mm-mrad])

Longitudinal(momentum) acceptance ~ Δp/p >20%

EMITTANCE GROWTH

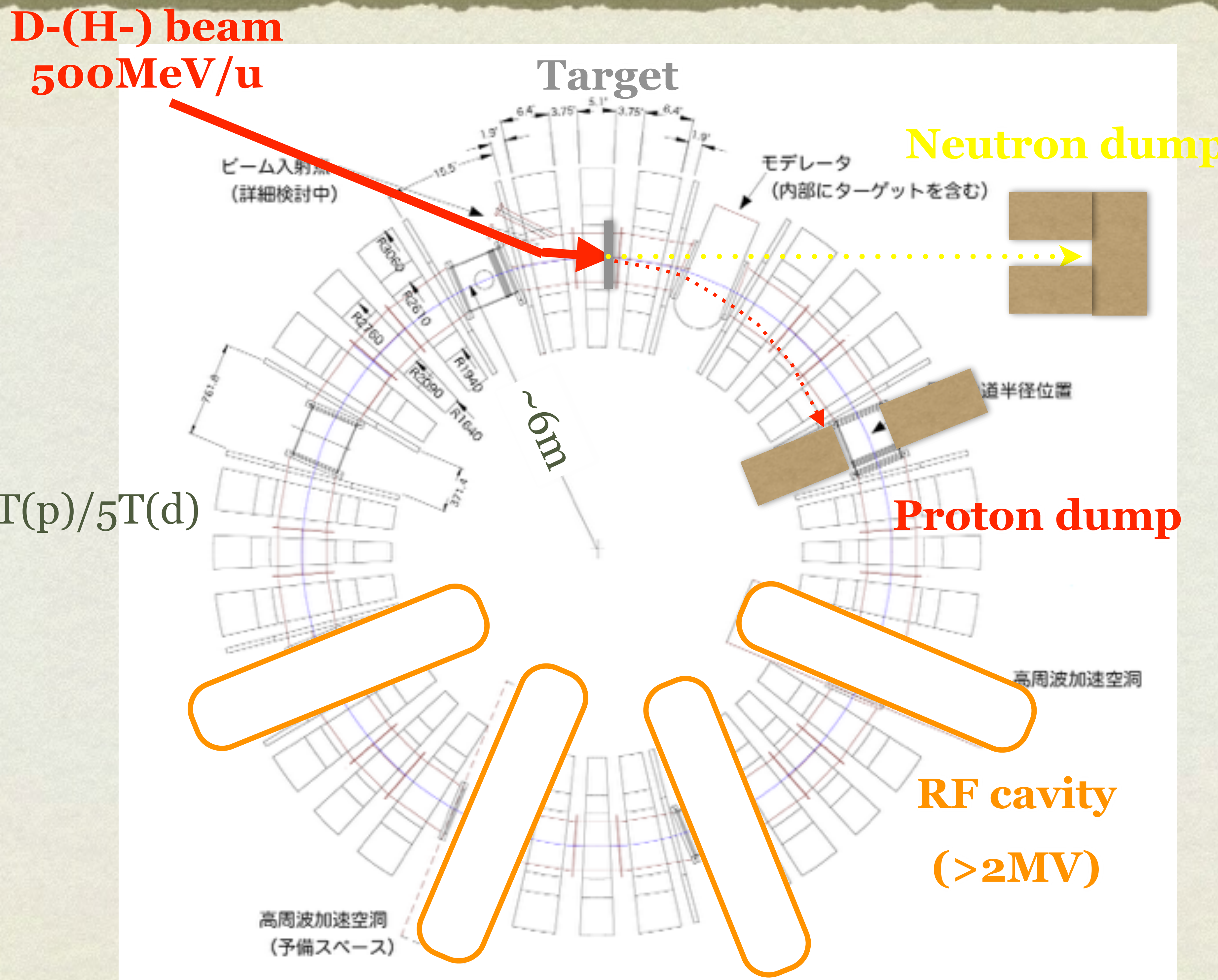
- **Measurement of emittance growth at FFAG_ERIT ring**
  - Beam scraper method
  - Beta function:calculated value



ERIT RING FOR MUON

- **Specification(case#1:hadron beam)**
  - Transverse acceptance A > 2500 mm.mrad (x 5 ε_{rms})
  - Longitudinal acceptance $\Delta p/p > 20\%$ (x 3 rms)
  - Particle deuteron (proton:more turns)
  - Magnetic rigidity 2.18 Tm (B~1.5 T, ρ~1.5 m)
  - Target 0.5-1 cm thick graphite
  - Re-acceleration 4-8 MeV/turn
  - β (m) at target position 0.5 m

SCHEMATIC LAYOUT OF MU_ERIT



B~2.5T(p)/5T(d)

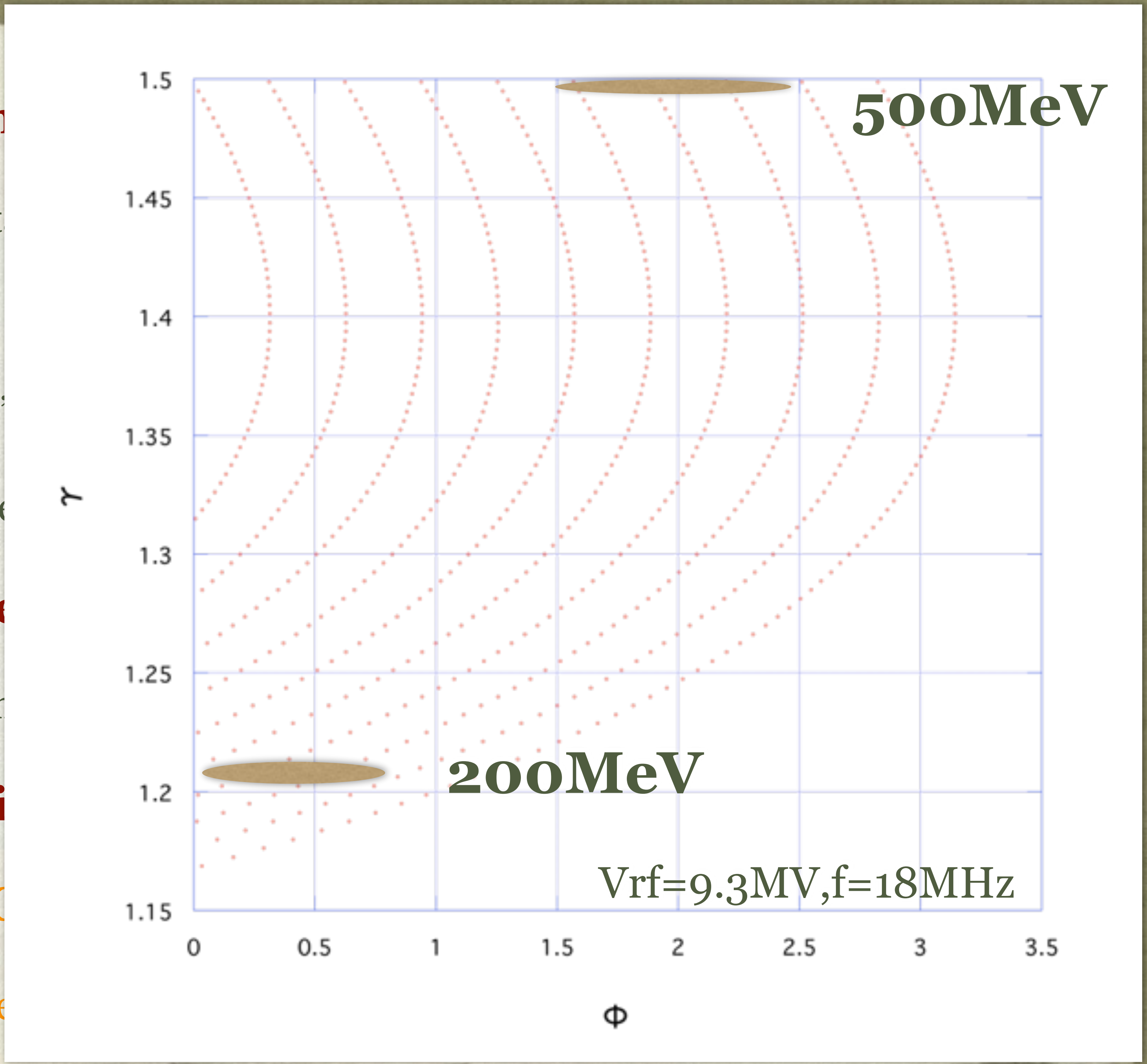
MUON

- **Expected negative muon numbers**
  - Assumption
    - Specifications of Mu_ERIT are fully satisfied.
      - **n ~ 150 turns** (limited by break-up for deuteron(<200t), more turns for proton)
    - Muon capture efficiency (cf. MUSIC) >**0.8**
    - Beam current I_d >**5-10mA**

$Y\mu = 0.2(\pi\text{-}/\mu\text{-}/d) \cdot 0.8 \cdot I_d/e \sim 1.0\text{x}10^{16}(\mu\text{-}/sec)$

NEW SCHEME
VERTICAL FFAG FOR MU_ERIT

- **Ordinary ERIT ← Full en**
  - Why not acceleration simult
- **Issues for simultaneous**
  - Keeping "Zero Chromaticity
  - Constant RF frequency → se
- **Serpentine(Bucket) Acce**
  - Orbit path length →not chan
- **π/μ captured in the verti**
- **→Vertical FFAG(v_FFAG**
  - Beam moves vertically as the



VERTICAL FFAG

- **Invention → T. Ohkawa (1953) again!**

G8. FFAG Electron Cyclotron.* TIHIRO OHKAWA, *University of Illinois*† (introduced by D. W. Kerst).—New types of FFAG[1] accelerators having the same orbit length for all momenta are proposed. In these types electrons, injected with an energy of a few Mev, are accelerated by a fixed frequency electric field until the radiation loss becomes serious, probably at a few Bev. The necessary cavity voltage is, for example, 200 Kev with 3 Mev injection energy. Two types of guiding fields, similar to Mark I (alternate field type) and Mark V (spirally ridged type) are used. In both, the magnetic field increases exponentially in the vertical direction so that as the particle energy increases, its orbit rises vertically. The field also depends on the radius and the azimuthal angle in such a way that the focusing properties are very similar, respectively, to Mark I and to Mark V. Other types of FFAG having the orbit surface not on a median plane are also proposed.

* Reported by the present author at the meeting of the Physical Society of Japan in June, 1955.
† On leave from the University of Tokyo.
[1] Reported by the present author at the meeting of the Physical Society of Japan in October, 1953; K. R. Symon Phys. Rev. 98, 1152(A) (1955).

Bull. APS 30,20(1955)

Phys. Rev., 100(1955)1247

BETATRON MOTION AROUND CIRCULAR ORBIT

Eqs. of motion

$$\frac{d^2x}{d\theta^2}+\left[\frac{e}{p}B_y(\rho+x)-1\right](\rho+x)=0,$$

$$\frac{d^2y}{d\theta^2}-\left[\frac{e}{p}B_x(\rho+x)^2\right]=0.$$

Linearization

$$\frac{d^2x}{d\theta^2}+x+\frac{\rho}{B_0}\left[\left(\frac{\partial B_y}{\partial x}\right)x+\left(\frac{\partial B_y}{\partial y}\right)y\right]=0,$$

$$\frac{d^2y}{d\theta^2}-\frac{\rho}{B_0}\left[\left(\frac{\partial B_x}{\partial x}\right)x+\left(\frac{\partial B_x}{\partial y}\right)y\right]=0.$$

normal (pink underline): $\frac{\partial B_y}{\partial x}$, $\frac{\partial B_x}{\partial y}$

skew (blue underline): $\frac{\partial B_y}{\partial y}$, $\frac{\partial B_x}{\partial x}$

MAGNETIC FIELD FOR ZERO CHROMATICITY

(1) Ring

a)Normal:H-FFAG $\frac{R}{\rho} = const.$ & $\frac{R}{B_y}\left(\frac{\partial B_y}{\partial x}\right) = k \longrightarrow B_y = B_y^0\left(\frac{R}{R_0}\right)^k$

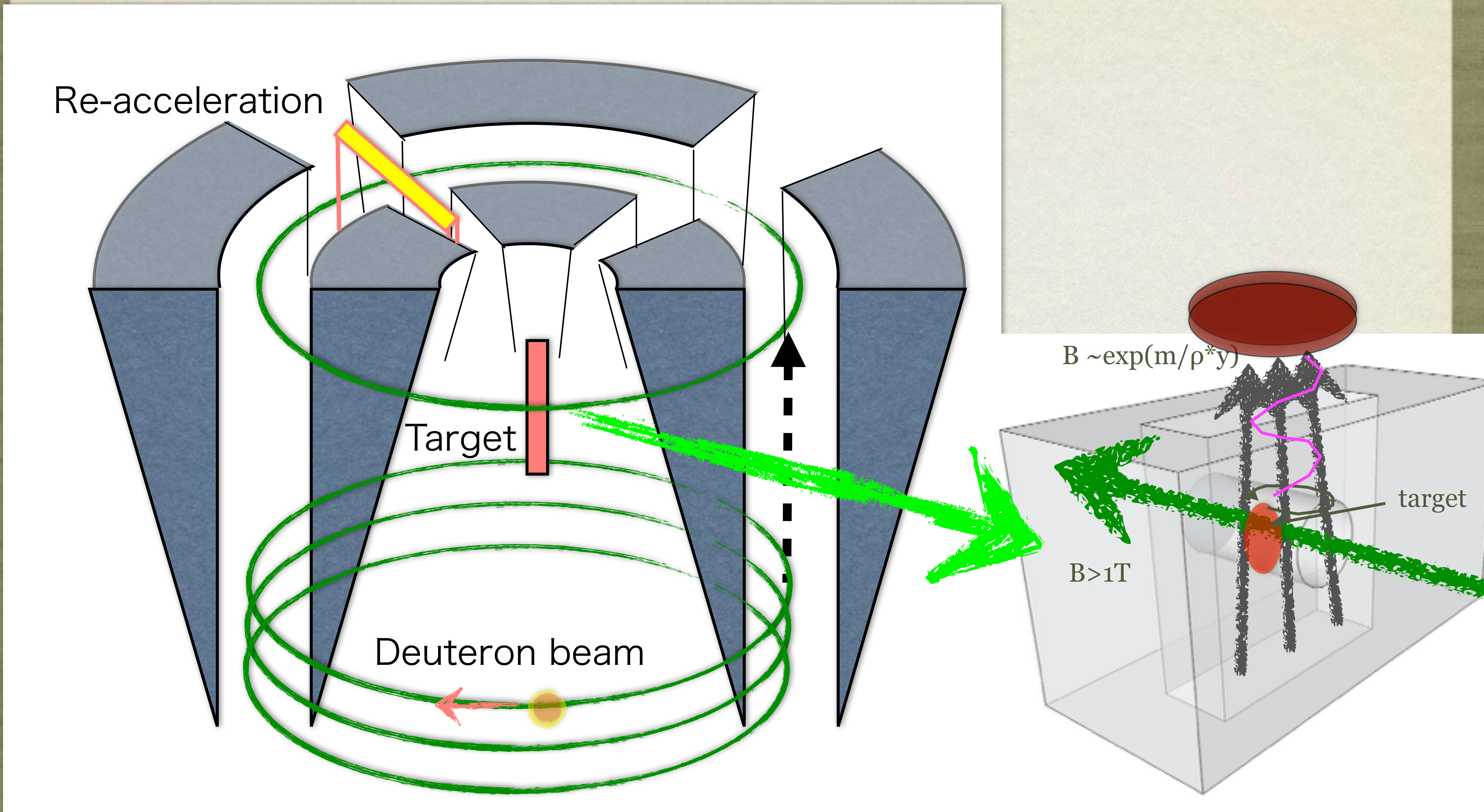
b)Skew:V-FFAG $R, \rho = const.$ & $\frac{\rho}{B_y}\left(\frac{\partial B_y}{\partial y}\right) = n \longrightarrow B_y = B_y^0 \exp\left(\frac{n}{\rho} y\right)$

(2) Straight line

a)Normal:H-FFAG $\rho = const.$ & $\frac{\rho}{B_y}\left(\frac{\partial B_y}{\partial x}\right) = n \longrightarrow B_y = B_y^0 \exp\left(\frac{n}{\rho} x\right)$

b)Skew:V-FFAG $\rho = const.$ & $\frac{\rho}{B_y}\left(\frac{\partial B_y}{\partial y}\right) = n \longrightarrow B_y = B_y^0 \exp\left(\frac{n}{\rho} y\right)$

MU_ERIT WITH V_FFAG



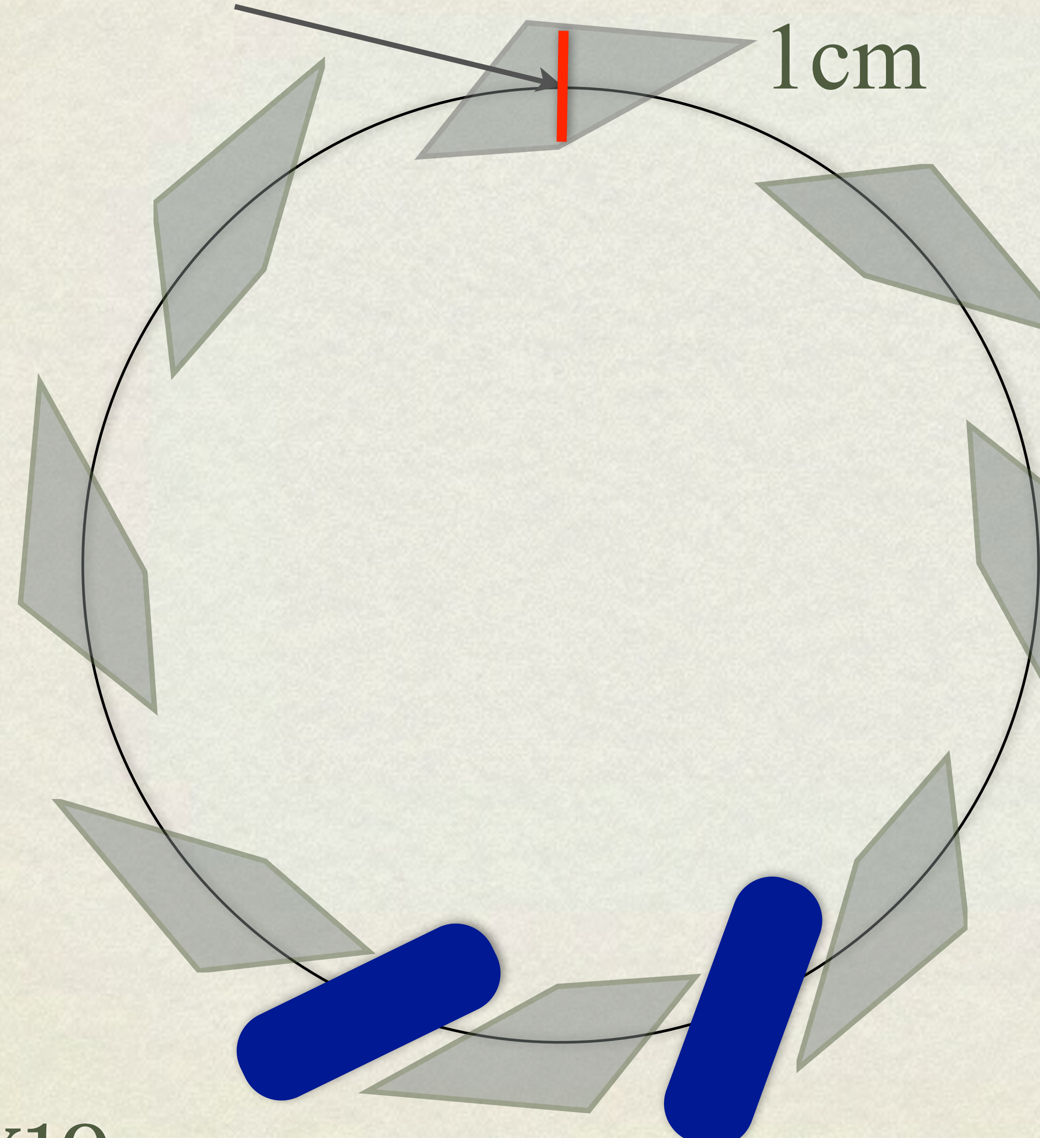
MU_ERIT(SPIRAL) WITH V_FFAG

type	vertical FFAG
energy	500[MeV/u]
numbers of cells	8
packing factor	0.5
m	0.5 [m-1]
radius	2(4) [m]
magnetic field	3.3[T]
edge angle (ent-ext)	50-50 [degree]

Carbon target

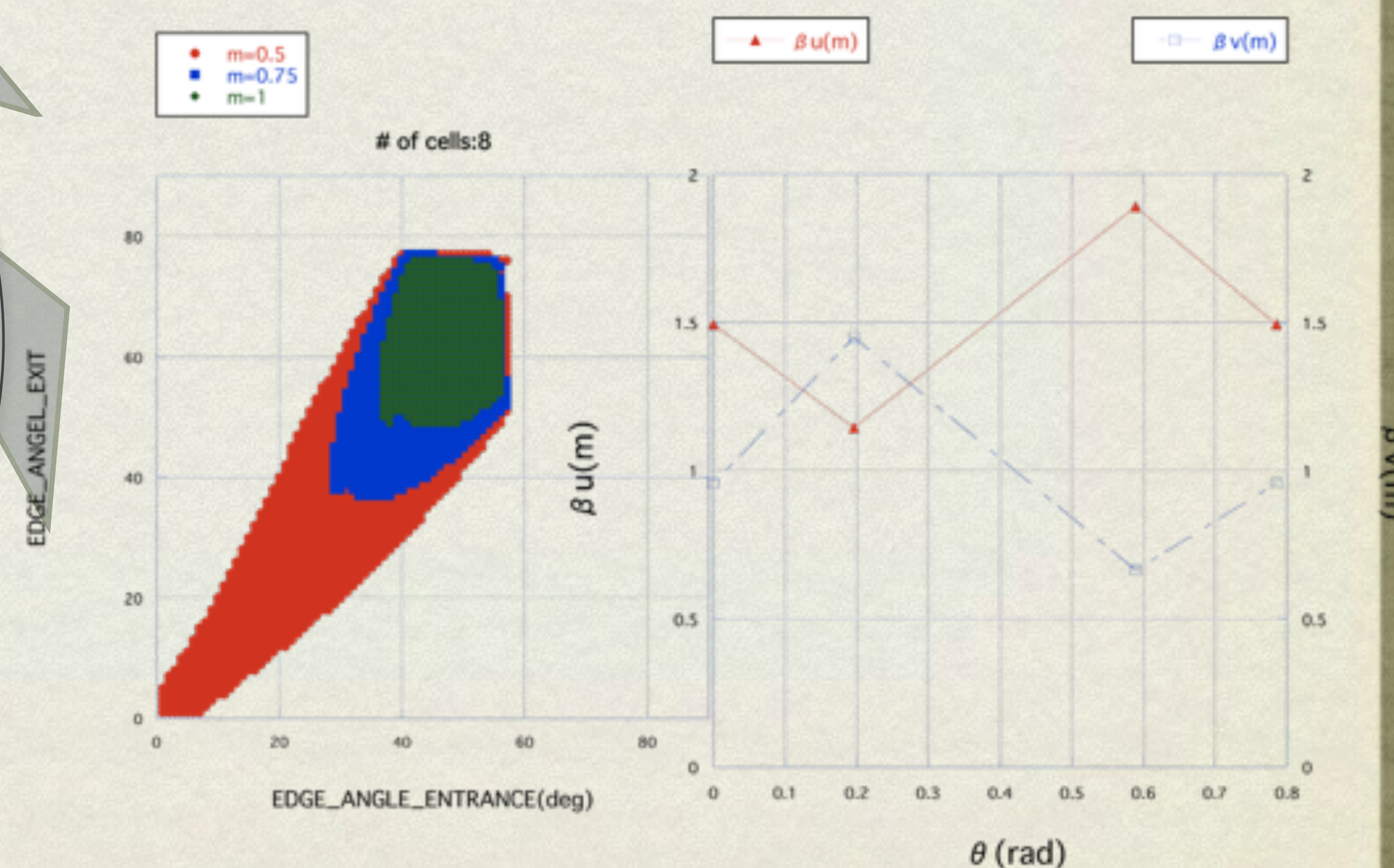
D-(H-) beam

1cm



x10

RF cavity V~9.3MV



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SUMMARY

- **Intense low energy muon source with ERIT on deuteron(proton)&electron Mu_FFAG is proposed.**
  - Very long production target can be effectively realised with p(d) ERIT scheme, which is good for production of slow π^-/μ^-.
  - π^-/μ^- are captured and transported by strong magnetic field of Mu_FFAG.
  - μ^- yield ~ 1×10^{16} μ-/sec (d)
    - Ed=600MeV/u, Id=1mA, t=1cm(graphite),n=150turns,A>0.8)
- **Compact and high efficiency muon source: Mu_ERIT with V_FFAG**
  - Acceleration : CW beam
  - Compact (C~ 15m(p), 30m(d): B>3T)
- **Technical issues;**
  - SC Magnet
  - SC RF cavity(TE-π mode)
  - Target cooling, Radiation shielding, etc.

THANK YOU FOR YOUR ATTENTION!