

INTENSE(MONO-CHROMATIC) NEGATIVE MUON SOURCE

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CONTENTS

- **Introduction**
- **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**

- $\mu\text{-}\gamma/\mu\text{-}e$ conversion findings: Good signal for new physics beyond SM model→Super symmetry/Super string etc.
- Neutrino source : ν -mass oscillation (lepton flavor 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 Diagonastics

- **Nuclear energy system with μ^- ← New topics**

- **Muon nuclear transmutation (μNT)**

ISSUES OF NUCLEAR ENERGY SYSTEM

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 - Fission Criticality control, Radiation heating
 - Fusion Plasma confinement and heating

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Muon may provide the solutions.

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RADIOACTIVE WASTES FROM NUCLEAR POWER PLANT

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

- Pu 10kg

- Pt 2kg

- Short-lived FP 26kg

- Minor Actinides (Np, Am, Cm) 0.6kg

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

Long-lived species

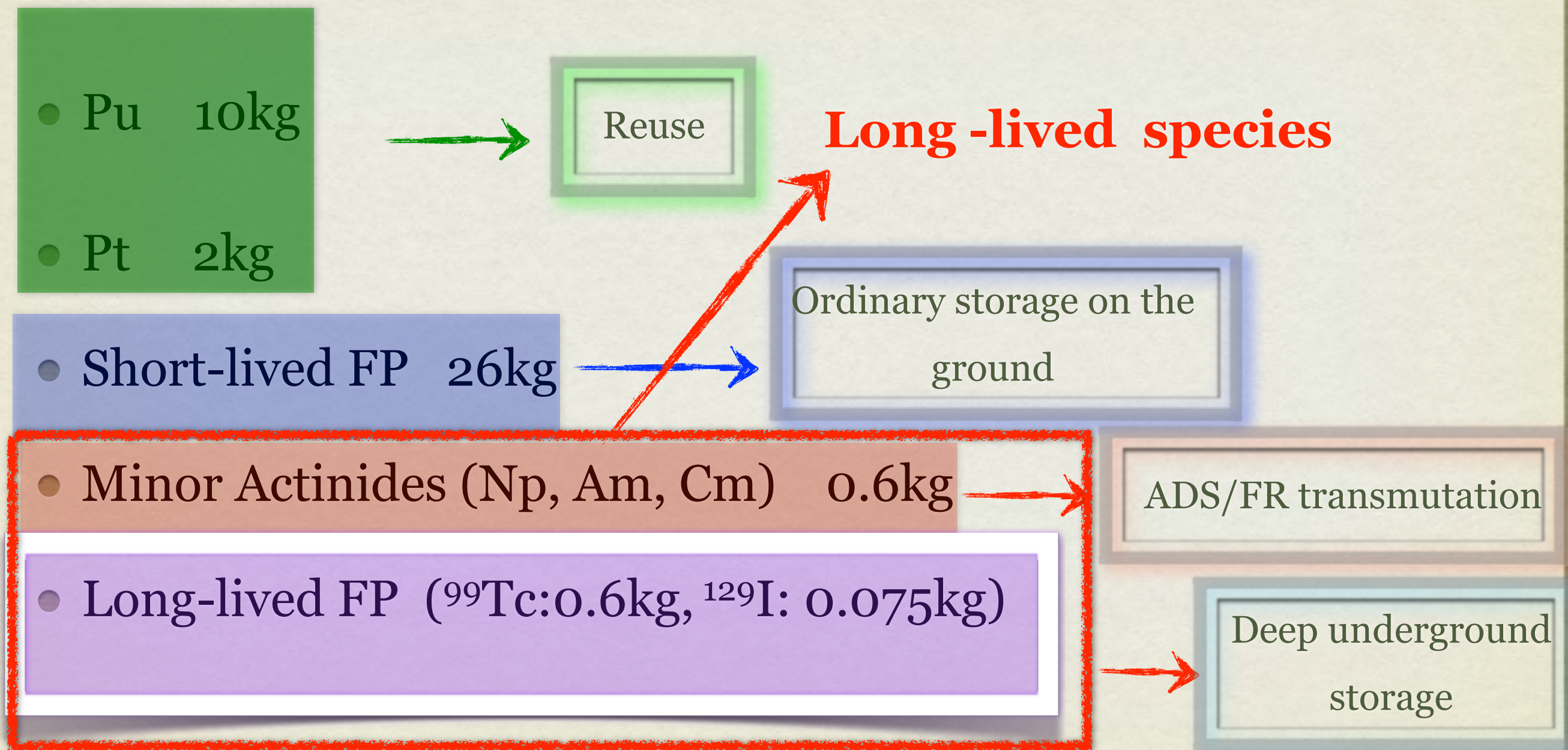
Ordinary storage on the ground

ADS/FR transmutation

Deep underground storage

RADIOACTIVE WASTES FROM NUCLEAR POWER PLANT

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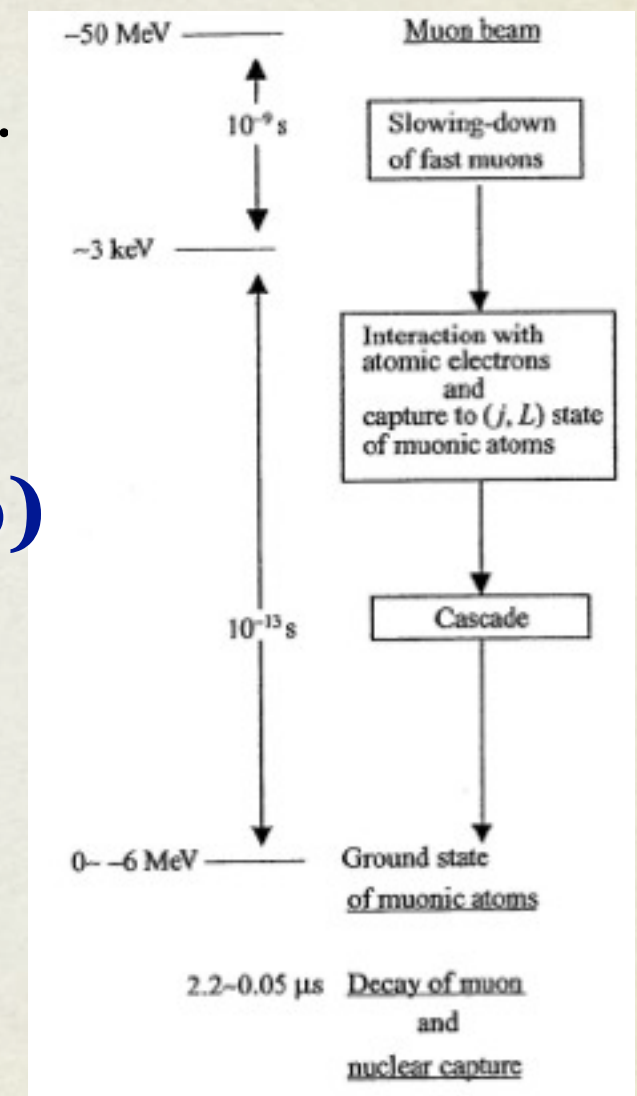
NUCLEAR TRANSMUTATION WITH NEGATIVE MUON

- **1st: Formation μ_{atom} → 2nd: Nuclear transmutation**

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

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

$R/a_{\mu} > 1 \Rightarrow$ **Transmutation (95% for $Z > 30$)**



NUCLEAR TRANSMUTATION WITH NEGATIVE MUON

- 1st: Formation of muonic atom

Muonic atom

Nuclear radius

$$R/a_\mu > 1$$

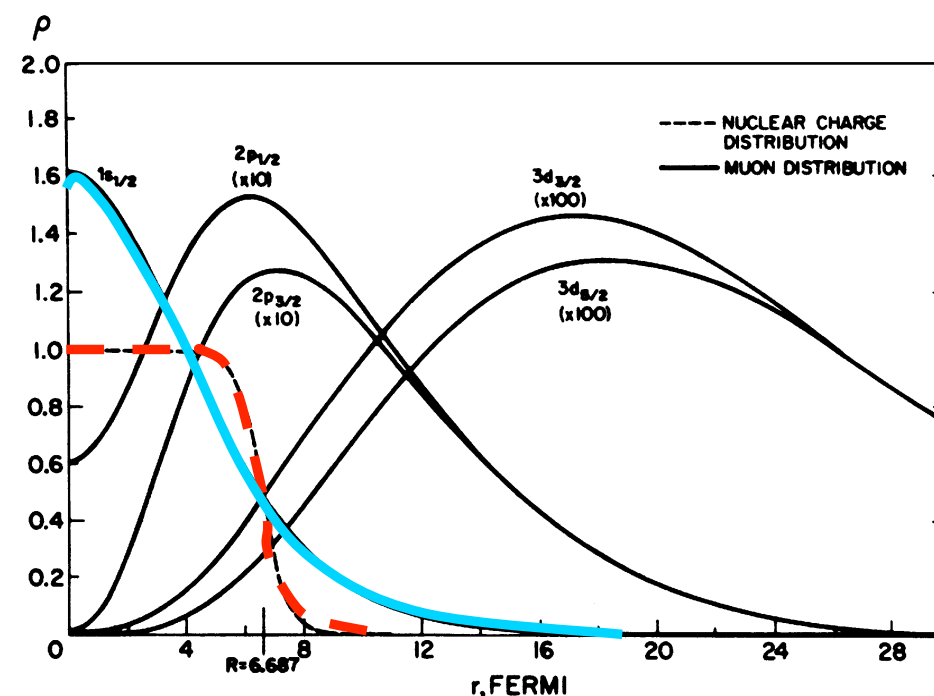
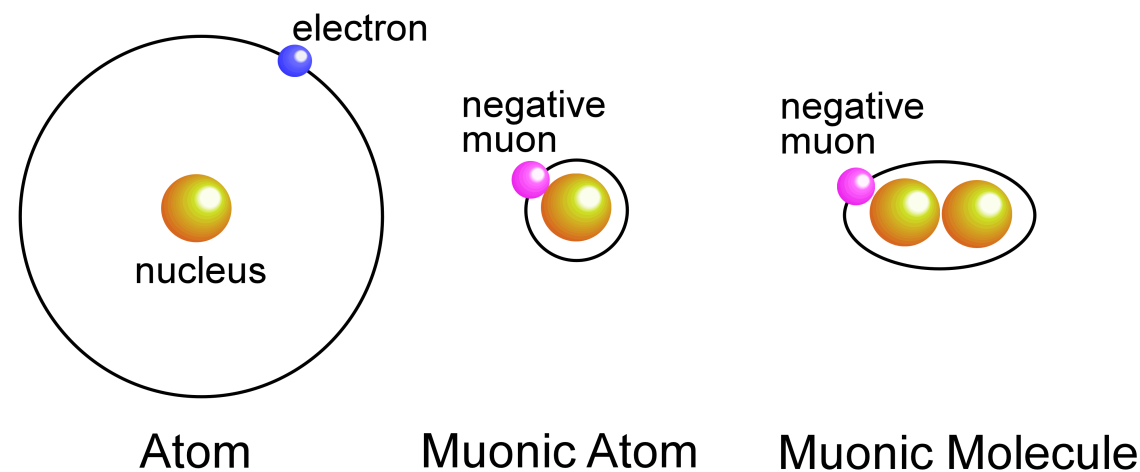
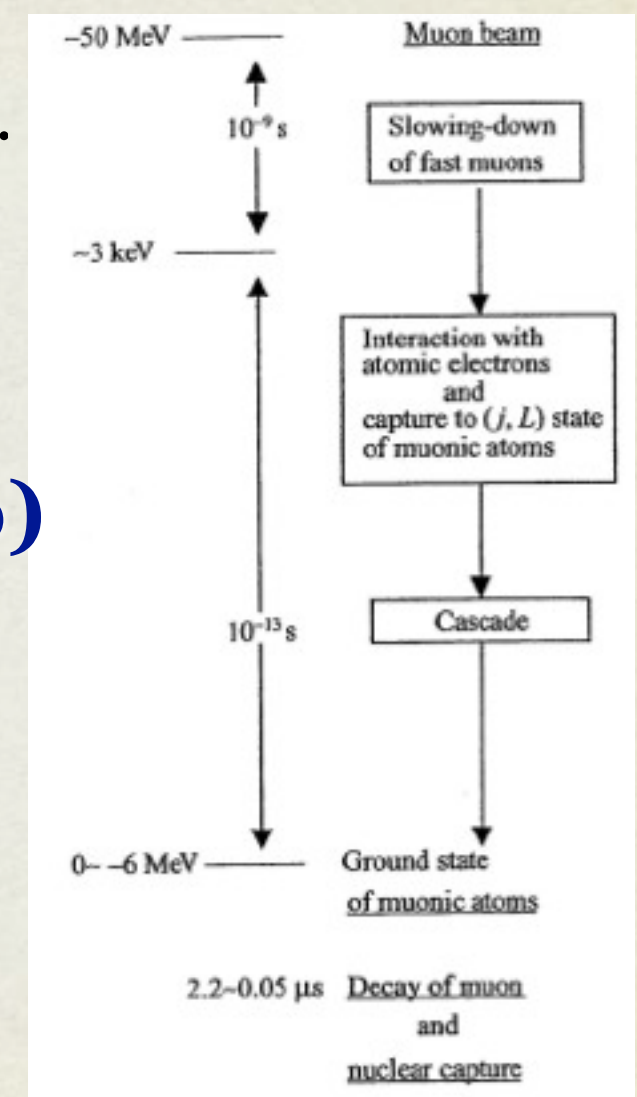


Fig. 15.8 The probability densities of finding a muon in the state indicated, at a distance r from the nuclear centre (full lines), are compared with the nuclear charge distribution in the case of lead. In the $S_{1/2}$ state, the probability of finding a muon within the nucleus is close to 50% (Devons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



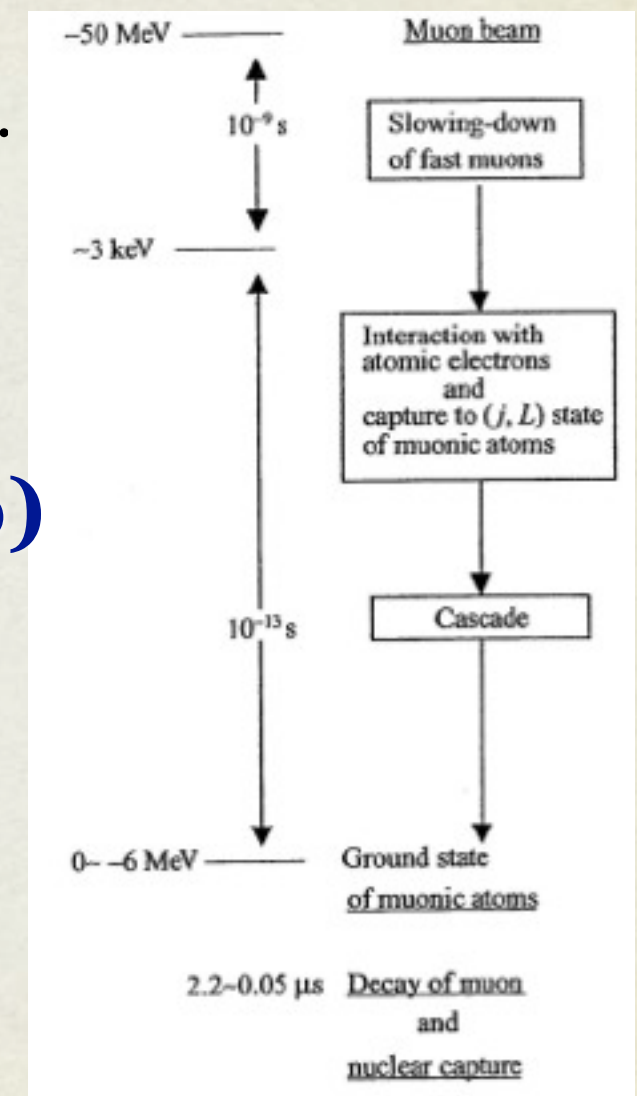
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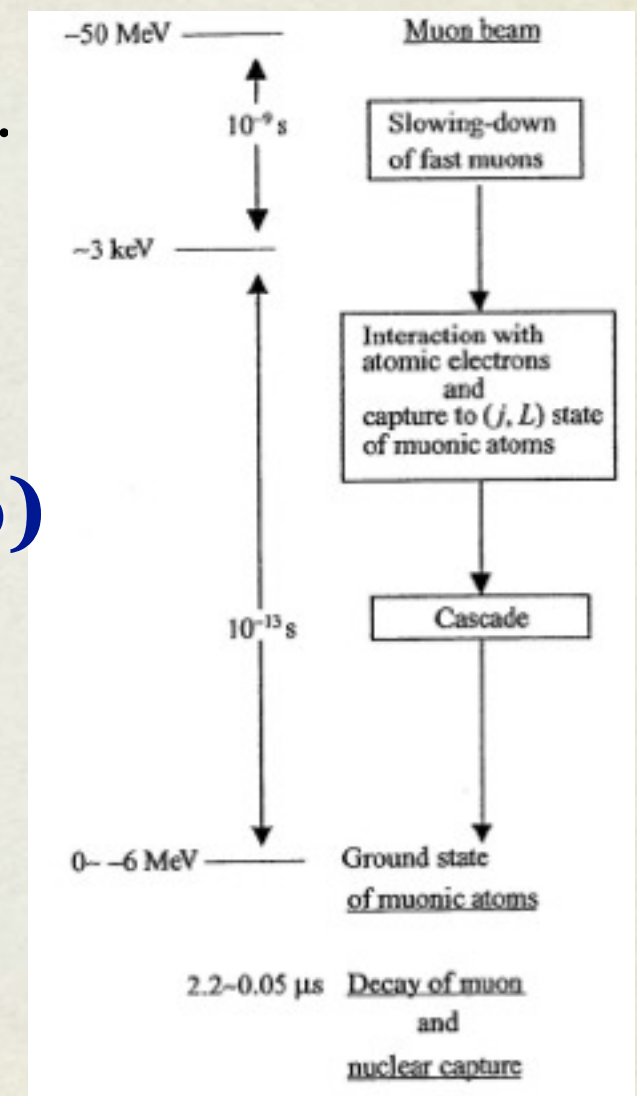
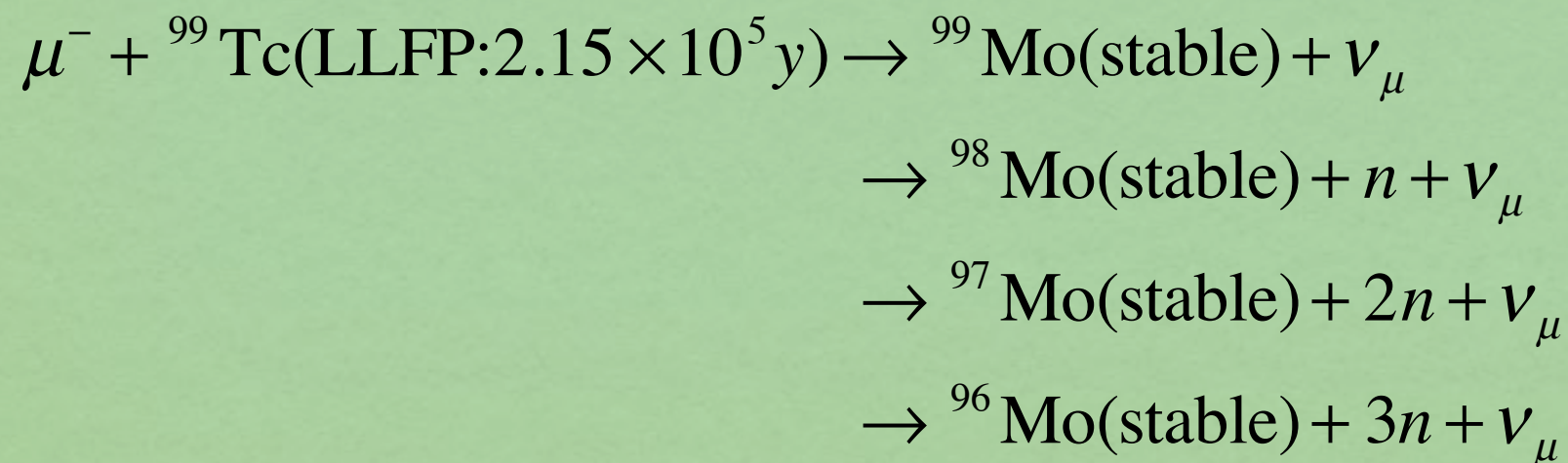
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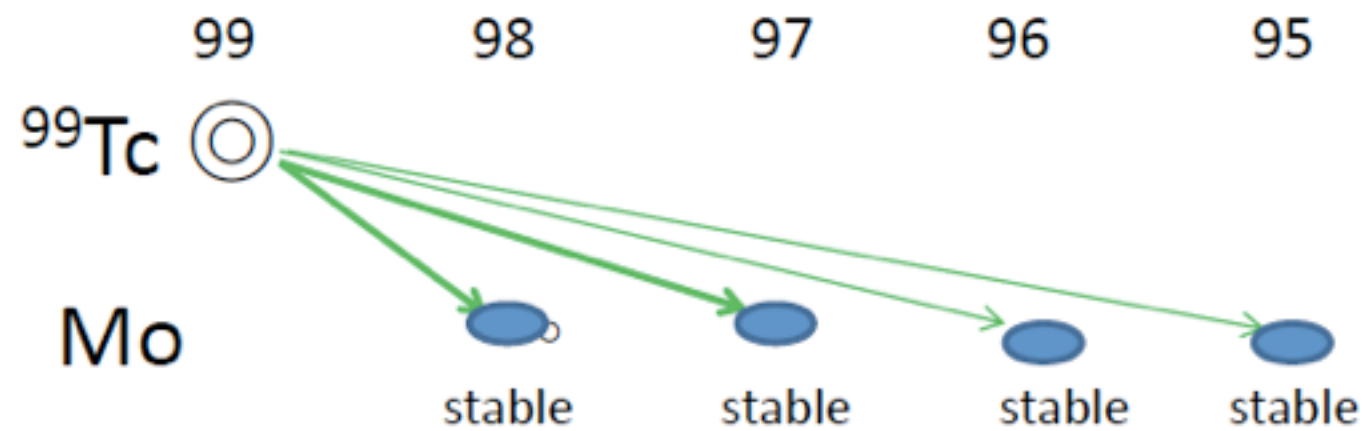
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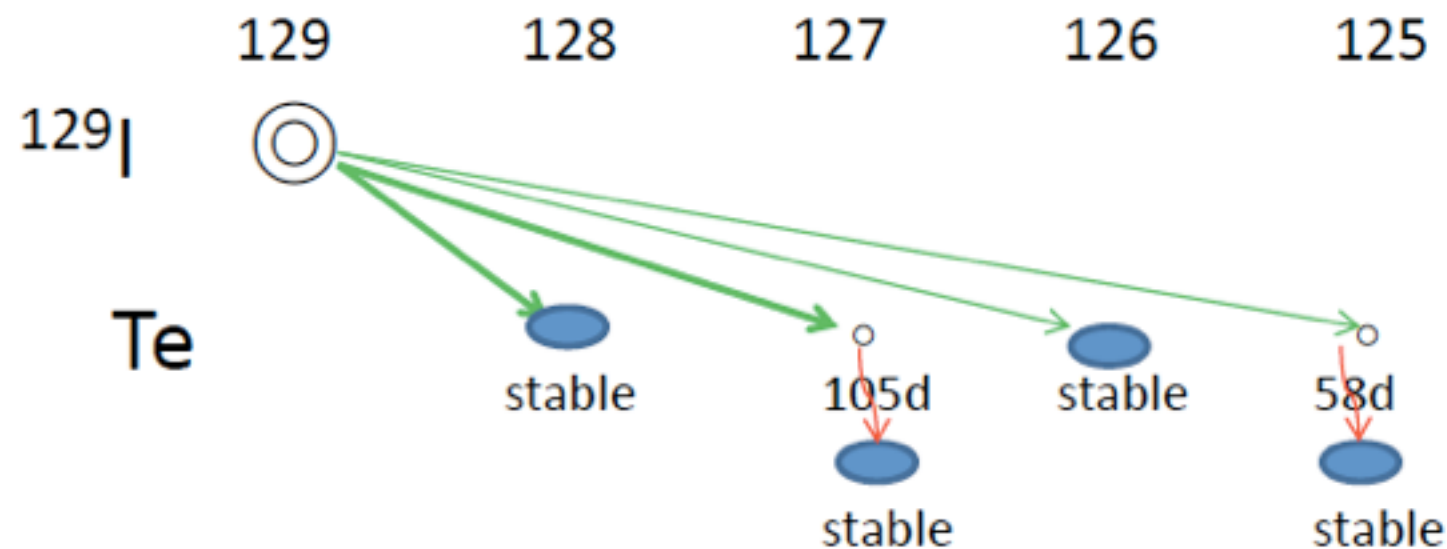
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^{99}Tc ($2.12 \times 10^5 \text{ y}$, 6.14%)



^{129}I ($1.72 \times 10^7 \text{ y}$, 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.

$$I_{\mu^-} > 1 \times 10^{16} [\mu^- / \text{sec}]$$

FEATURES OF MUON_NT

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- **Localized radiation shielding : mostly pion/muon production target area.**

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

REQUESTED MUON PROPERTIES FOR NUCLEAR POWER SYSTEM

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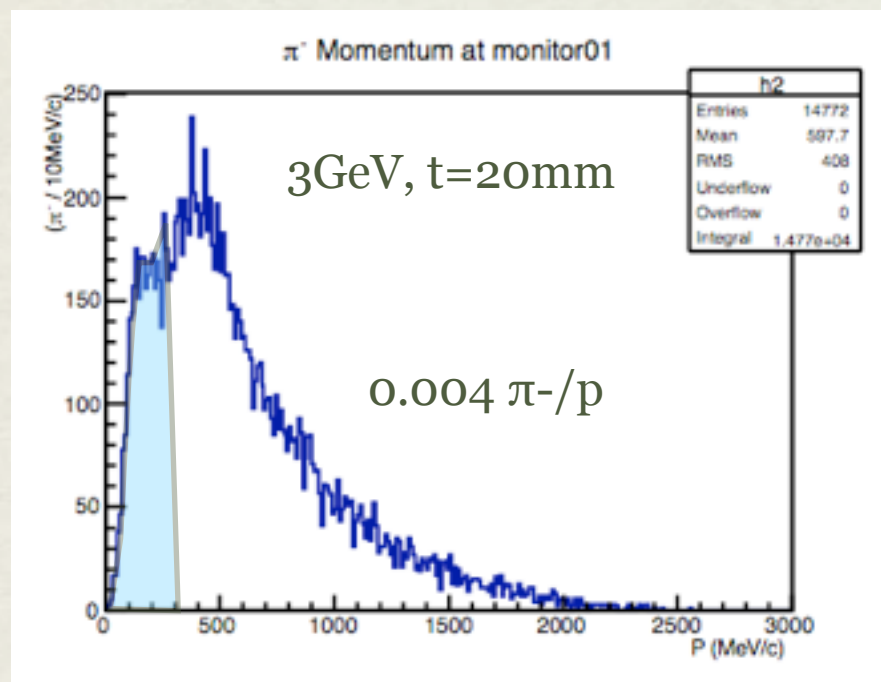
- **Charge state** → **Negative: μ^- (decayed from π^-)**
- Projectile particle
 - Proton: $\pi^- / \pi^+ \sim 0.2 (E_p < 1 \text{ GeV}), \sim 0.7 (E_p > 5 \text{ GeV})$
 - Deuteron: $\pi^- / \pi^+ \sim 1 (E_d > 0.5 \text{ GeV/u})$

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- **Low energy** → **$< 300 \text{ MeV/c}$**
- Low magnetic rigidity $B\rho < 1 \text{ Tm}$
 - → Capture B field = 2T, $\rho = 0.5 \text{ m}$
- Hard to degrade high energy muon: cf. Range(1 GeV/c) $> 3 \text{ m}$ (graphite)

CONVENTIONAL SCHEME FOR PRODUCING LOW-ENERGY NEGATIVE MUONS

- **High energy proton $E > 3\text{GeV}$**
 - Range(EM stopping power) $\gg$ Target thickness($<$ nucl. int. leng.) $\sigma(\pi^-N) \gg \sigma(p\pi^-)$
- **Small Low energy π^- -(μ^-) fraction $\sim 0.02 \pi^-/p(t=100\text{mm})$**



- **Small Acceptance of capture magnet**
 - Acceptance: $\sim 0.4\text{Sr}$ (SuperOmega:J-PARC)
- **Total Efficiency**
 - $0.004 (<300\text{MeV/c}) \times 3.2 \times 10^{-2}(\text{Acc.Mag.})$
 $\sim 1.3 \times 10^{-4}(\pi^-/p)$; cf. **J-PARC: $\sim 2.6 \times 10^{11} \pi^-/\text{sec}$**
@maximum: reality $10^8 \mu^-/\text{sec}$

J-PARC MUSE
proton beam
 3GeV
 $\sim 1000\text{kW}$

Target
 graphite
 t20mm
 $\Phi 70\text{mm}$

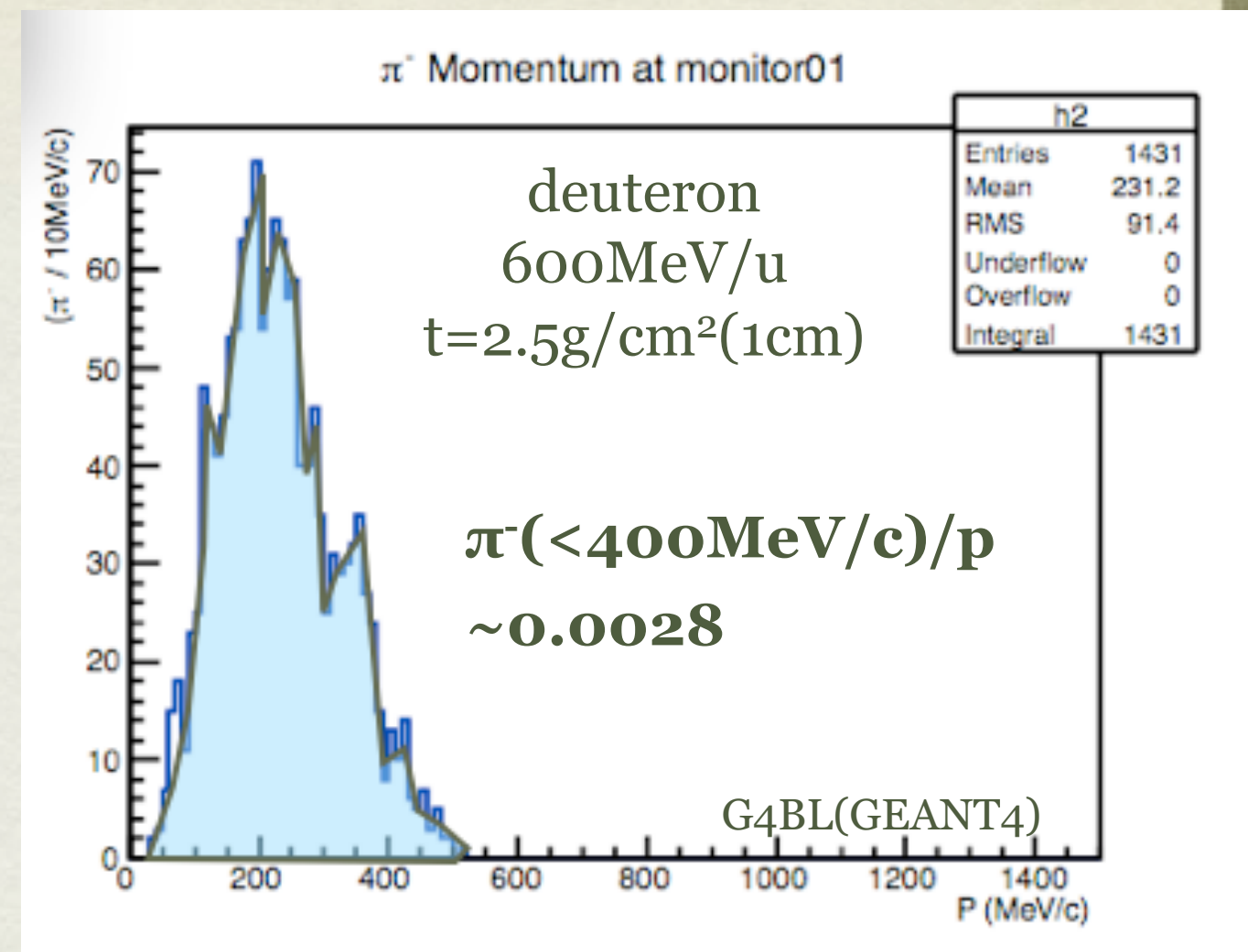
proton beam

Capture magnets

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 $\Omega: 0.4\text{Sr}$

muons

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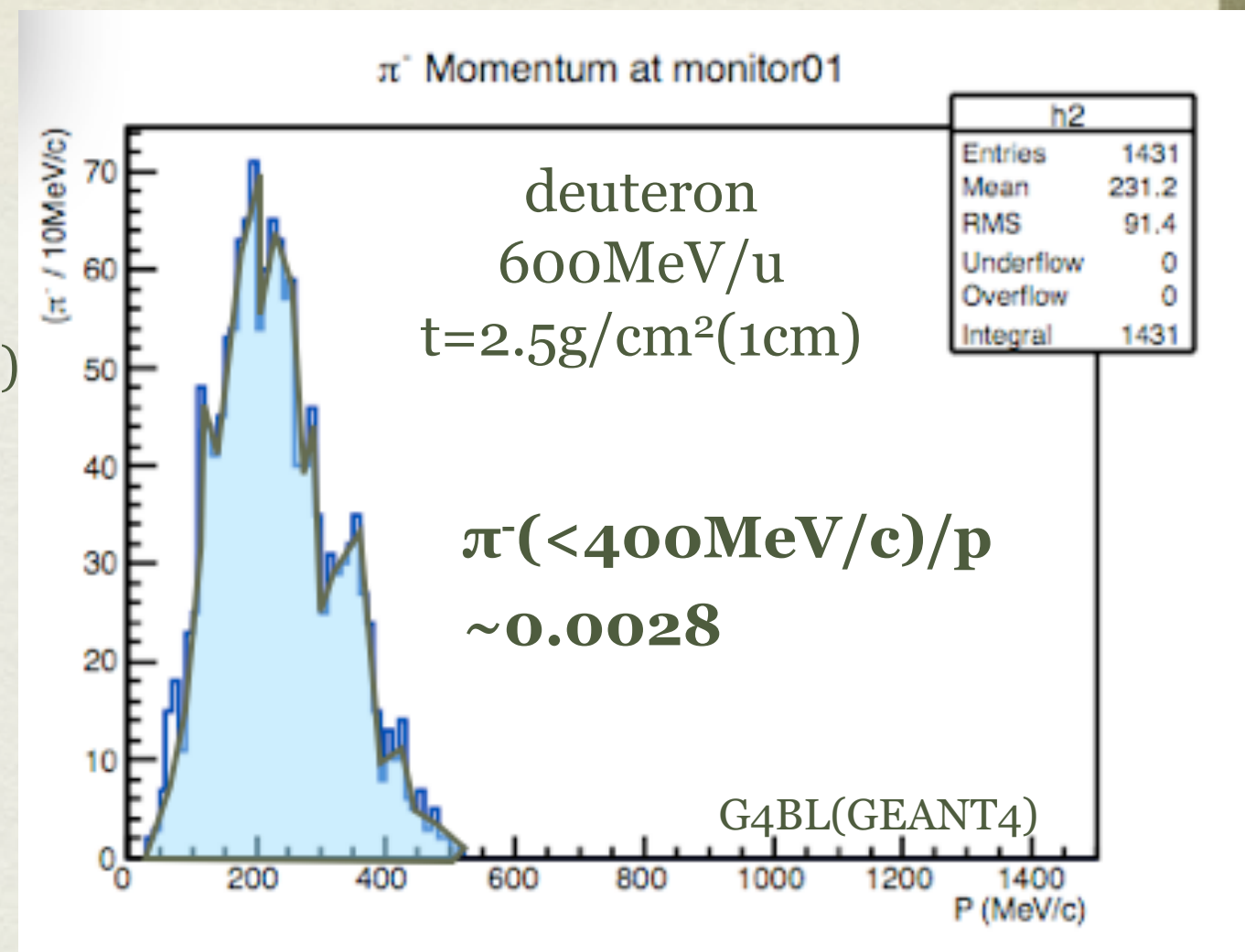
- **Improve the production efficiency**

- **$p_{\pi^-} < 400 \text{ MeV/c}$**

- Low energy projectile
 - $E_p < \sim 0.5\text{-}1 \text{ GeV/u}$
- Thin target ($\ll$ Range: dE/dx & $\sigma(\pi^-, N)$)
 - $t \sim < 2 \text{ g/cm}^2$ (graphite)

- **Efficient collection of π^-/μ^-**

- Target is placed in B field(solenoid).



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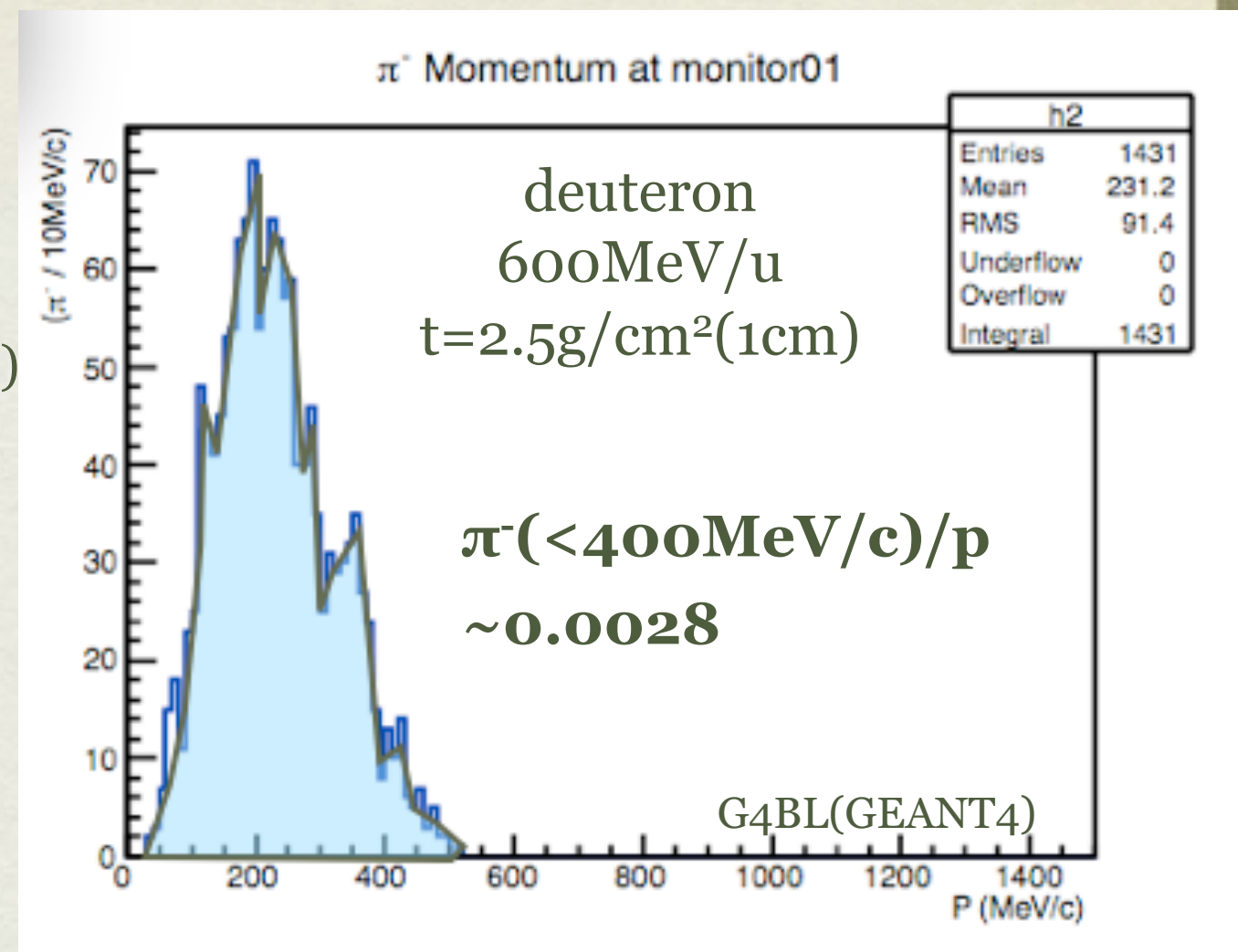
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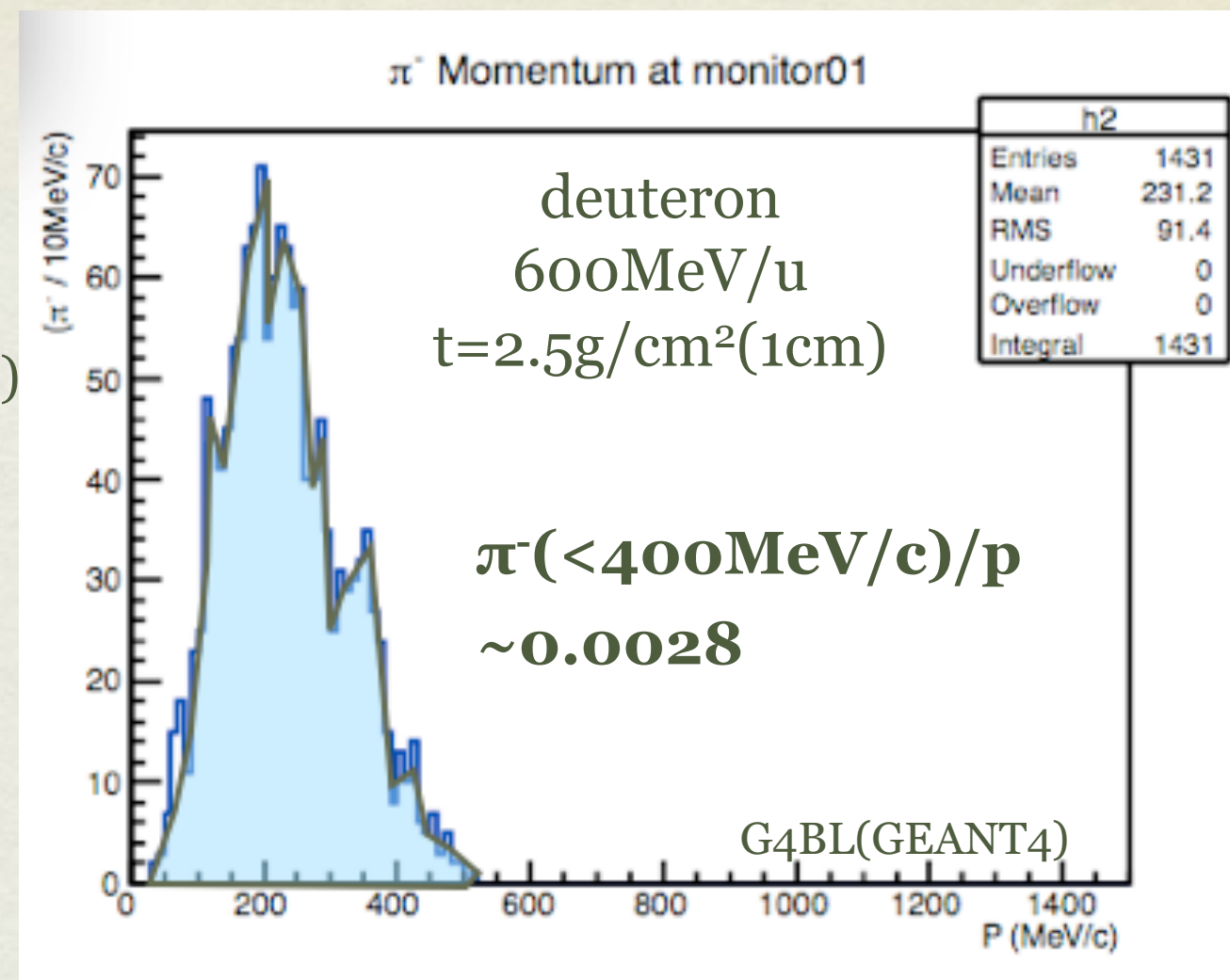
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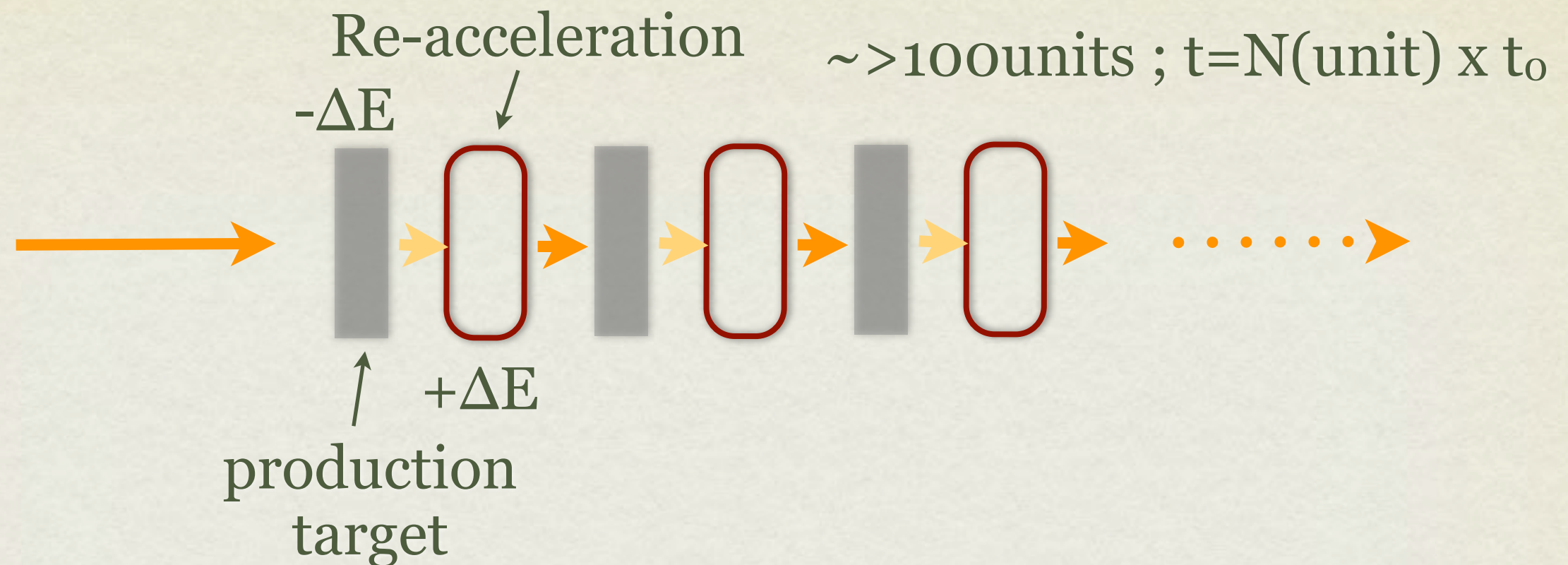
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- **Need an effective longer(> 100 times) target.**
For $t_{\text{eff}} > 100 \text{ cm} (250 \text{ g/cm}^2) \rightarrow \pi^-/p > \sim 0.2$.



EFFECTIVE LONG TARGET RE-ACCELERATION



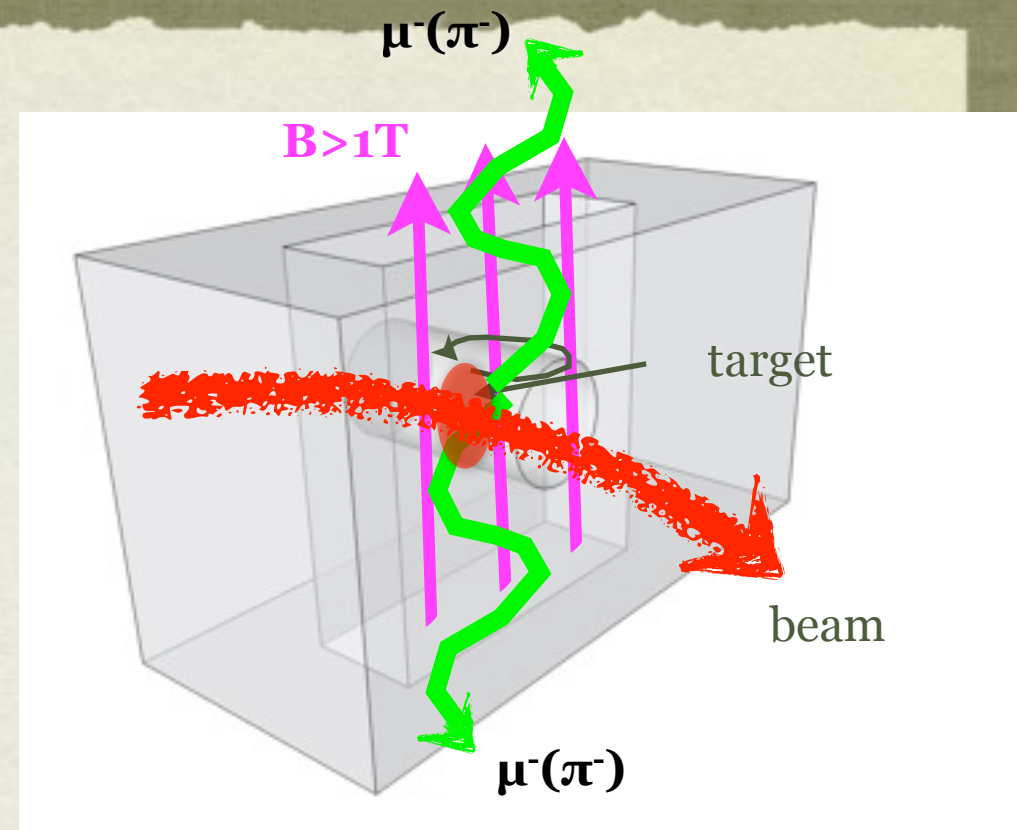
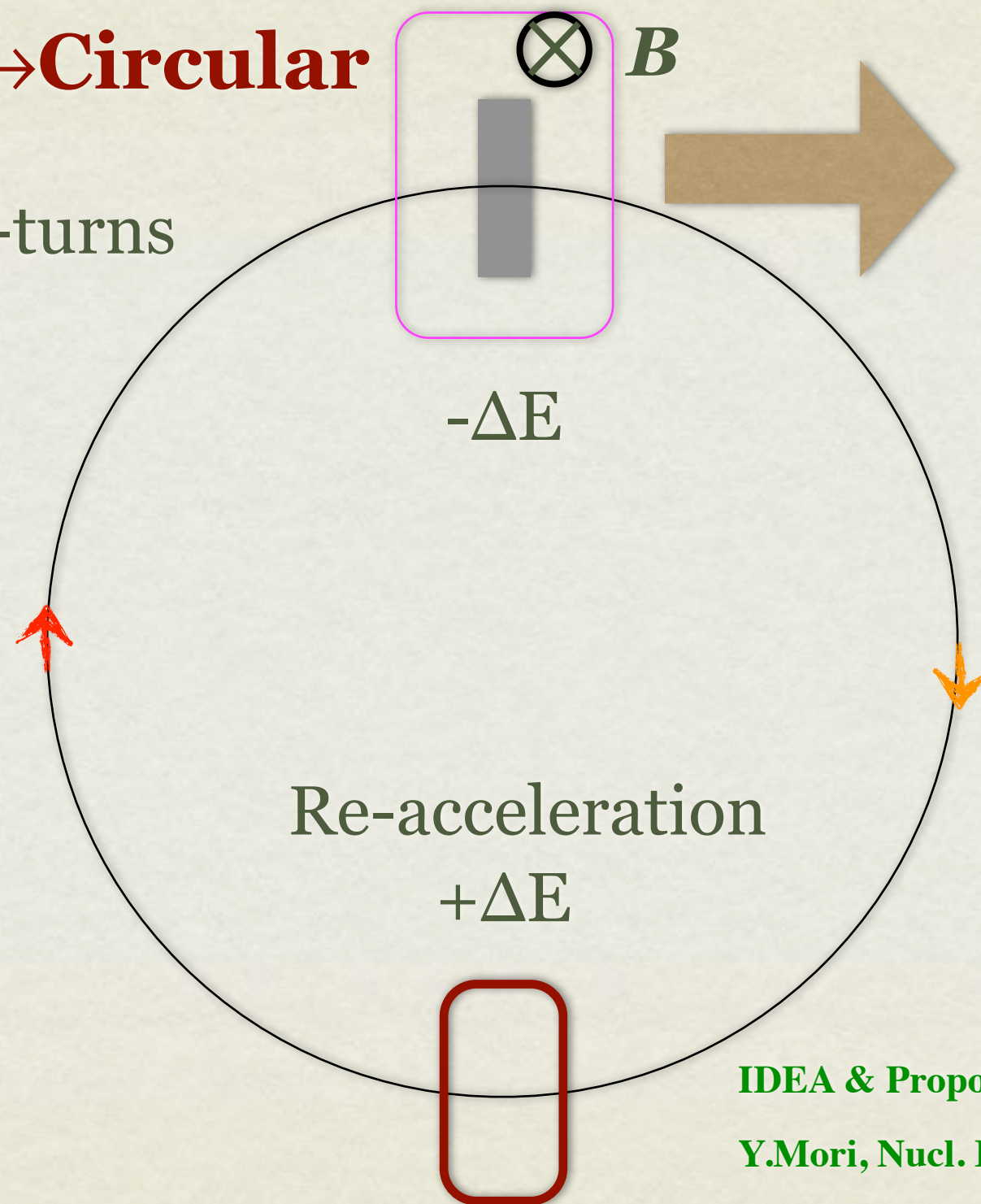
- **Difficuties**

- How capture π/μ ?
- Long system $> 100 \text{m} (\text{unit} \sim 1 \text{m})$; cost ?

ENERGY RECOVERY RING+INTERNAL TARGET -ERIT-

- **Linear→Circular**

- $t = n \times t_0$; n -turns



IDEA & Proposal:

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

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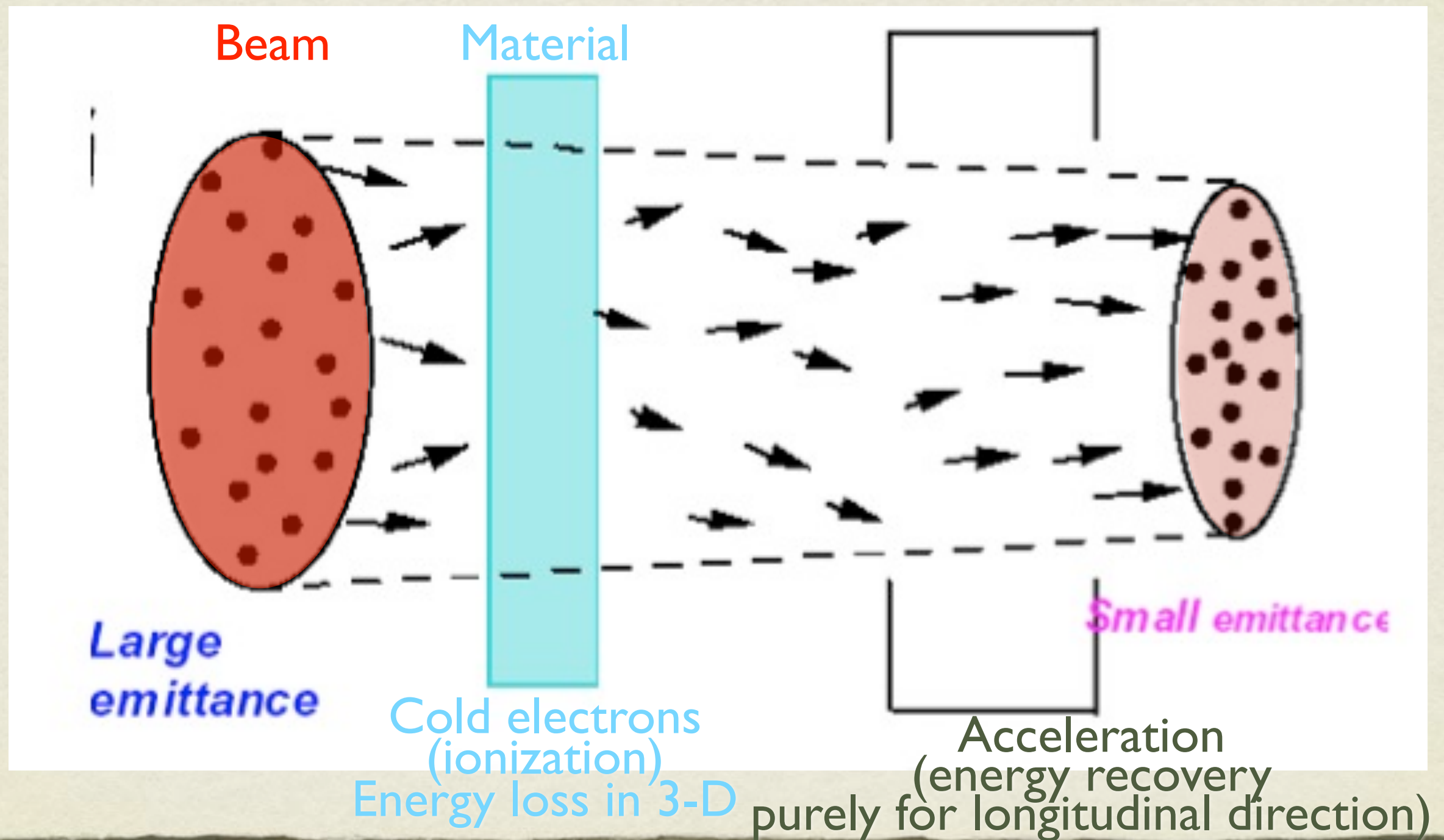
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IONIZATION COOLING



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● Theory

The rate equations of beam emittance:

Horizontal

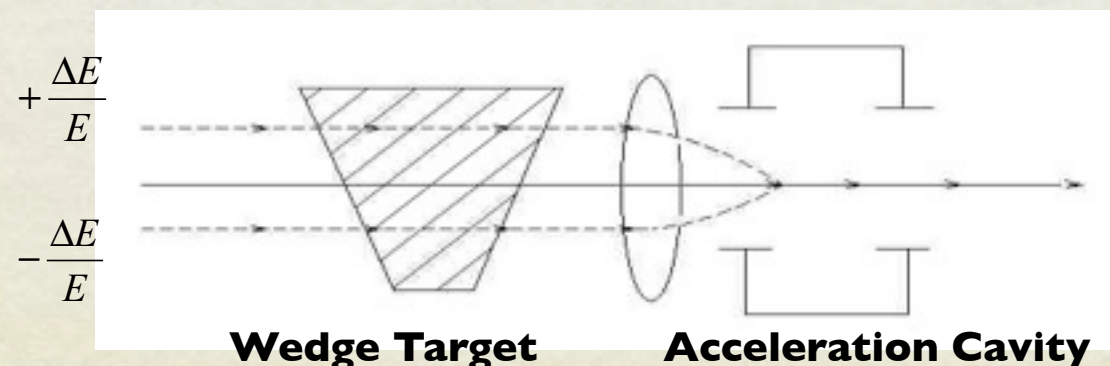
$$\frac{d\epsilon_x}{ds} = -\frac{1}{\beta^2 E} \frac{dE}{ds} \left(1 - \frac{D\rho'}{\rho_0}\right) \epsilon_x + \frac{\beta_x E_s^2}{2\beta^3 m_p c^2 L_R E}$$

Vertical

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

Longitudinal

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



IONIZATION COOLING

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cooling

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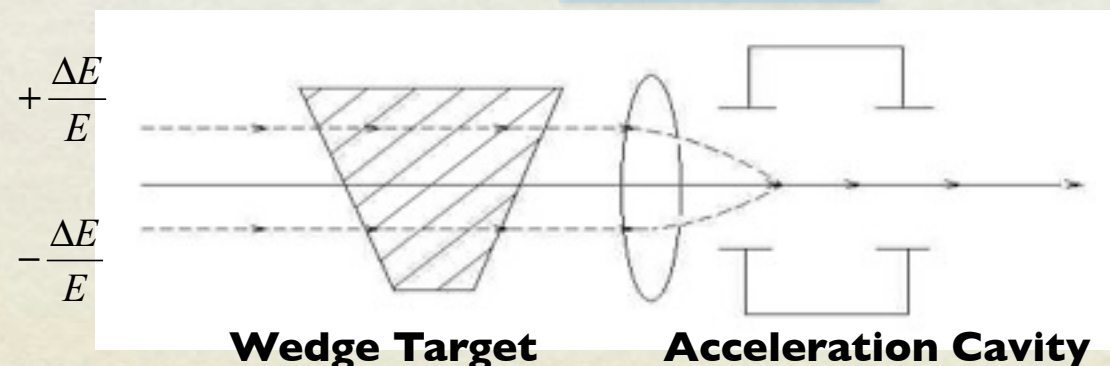
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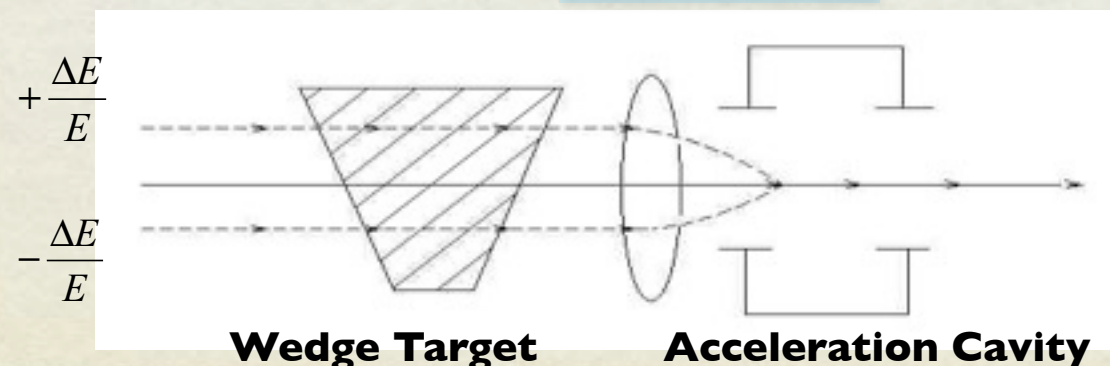
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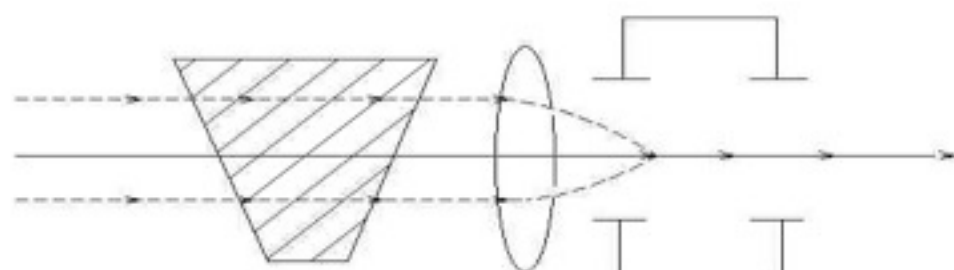
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$$+\frac{\Delta E}{E}$$

$$-\frac{\Delta E}{E}$$



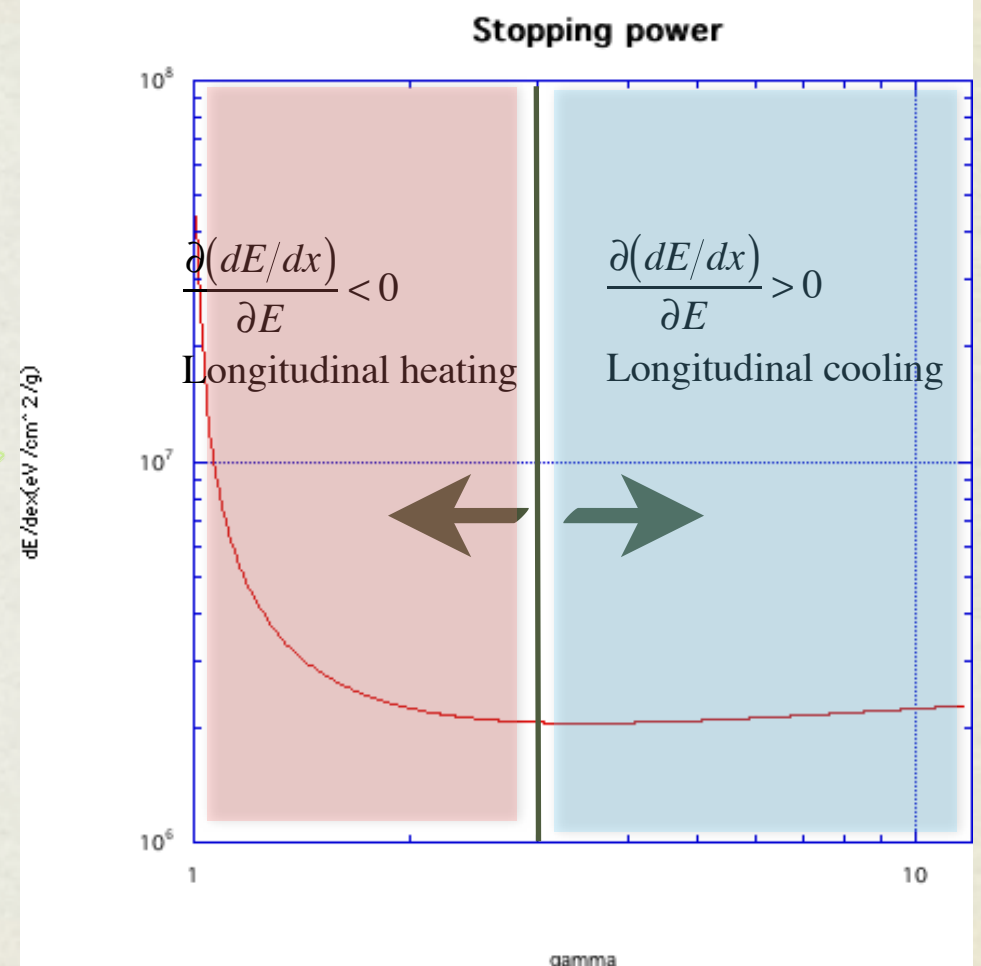
Wedge Target

Acceleration Cavity

cooling

heating

— $dE/dx(\text{eV/cm}^2/\text{g})$



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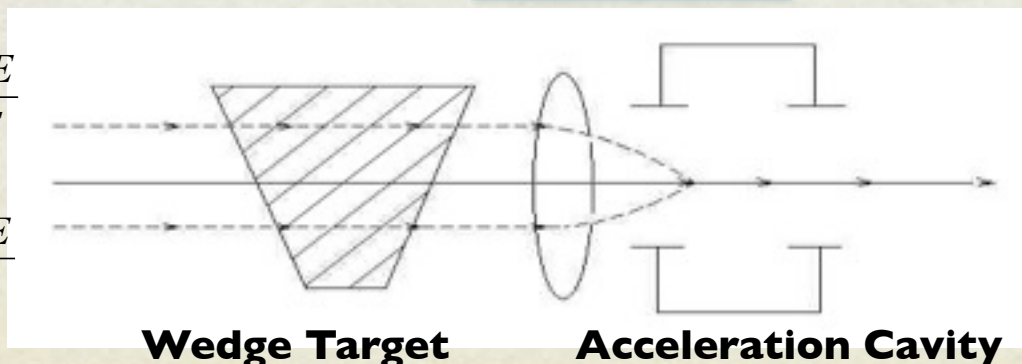
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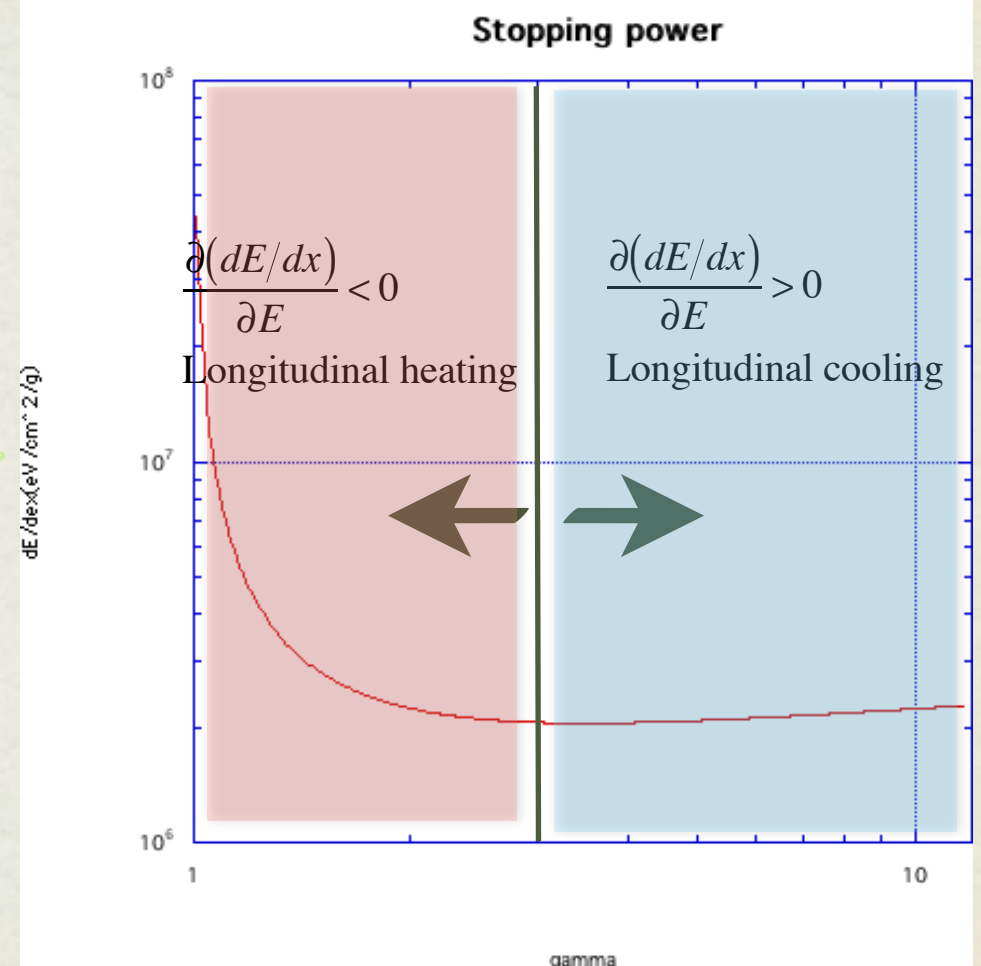
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cooling

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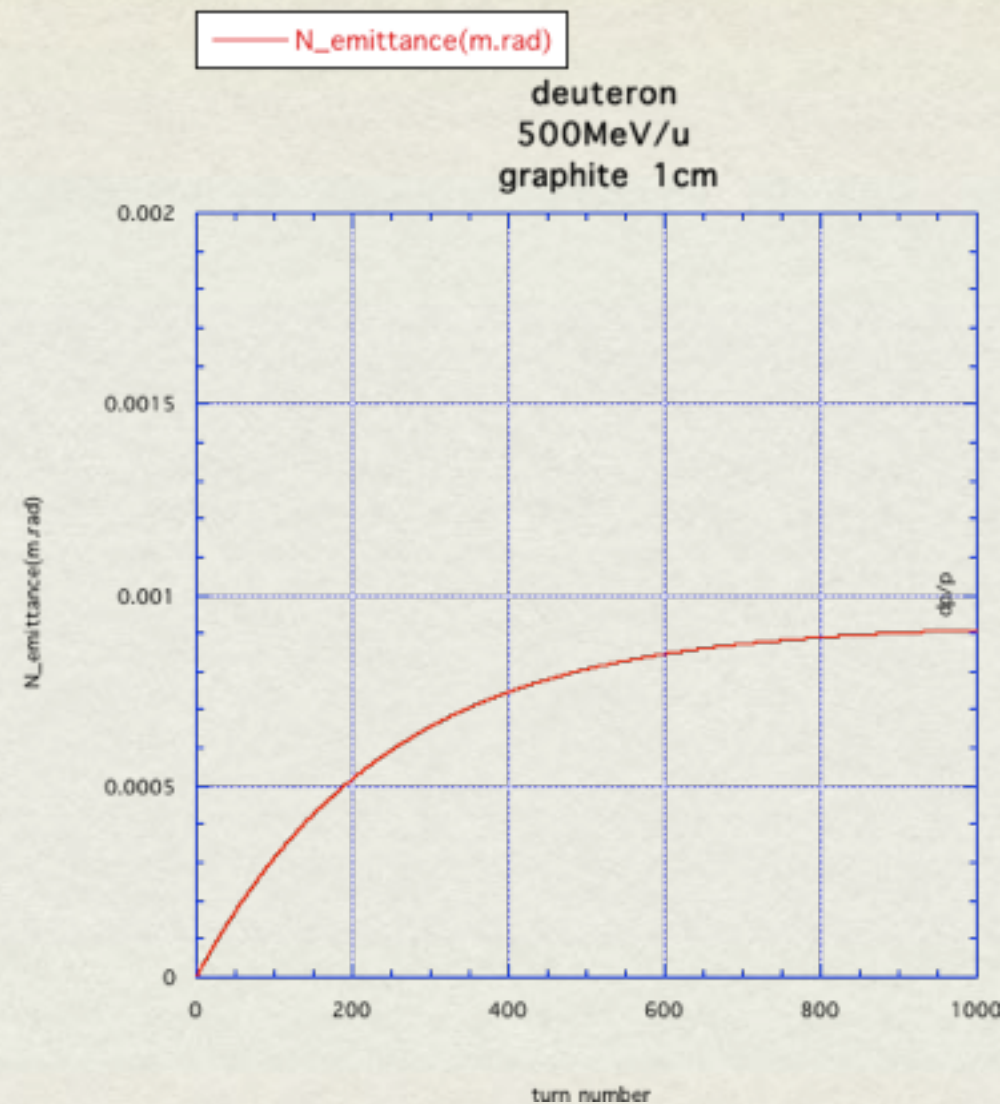
Large $L_R \cdot dE/ds \rightarrow$ Good trans. cooling

Light element is preferred!

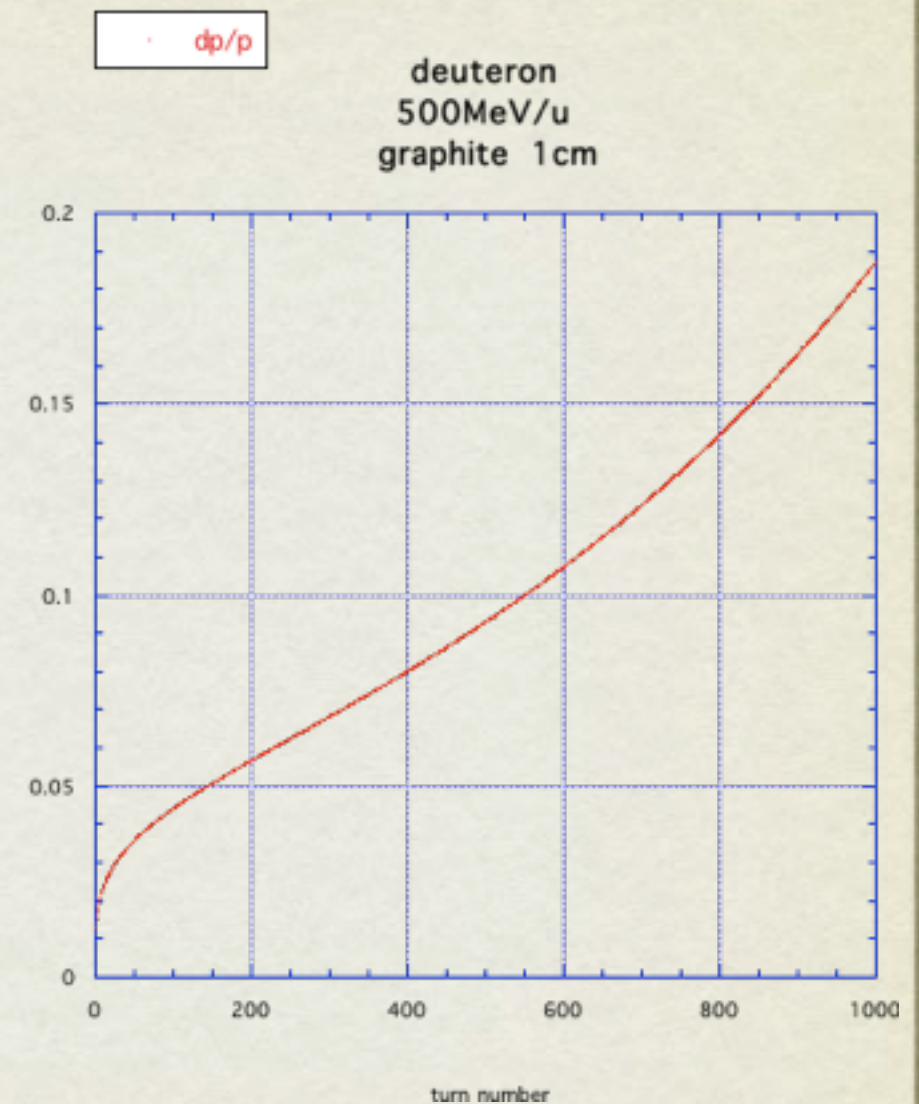
EMITTANCE GROWTH

- **Mu_ERIT(case 1)**

- Projectile : deuteron
- Energy : 500MeV/u
- Wedge : None
- $\beta(m)$ at target : 0.5m



Transverse



Longitudinal

EMITTANCE GROWTH

● Mu_ERIT(case 1)

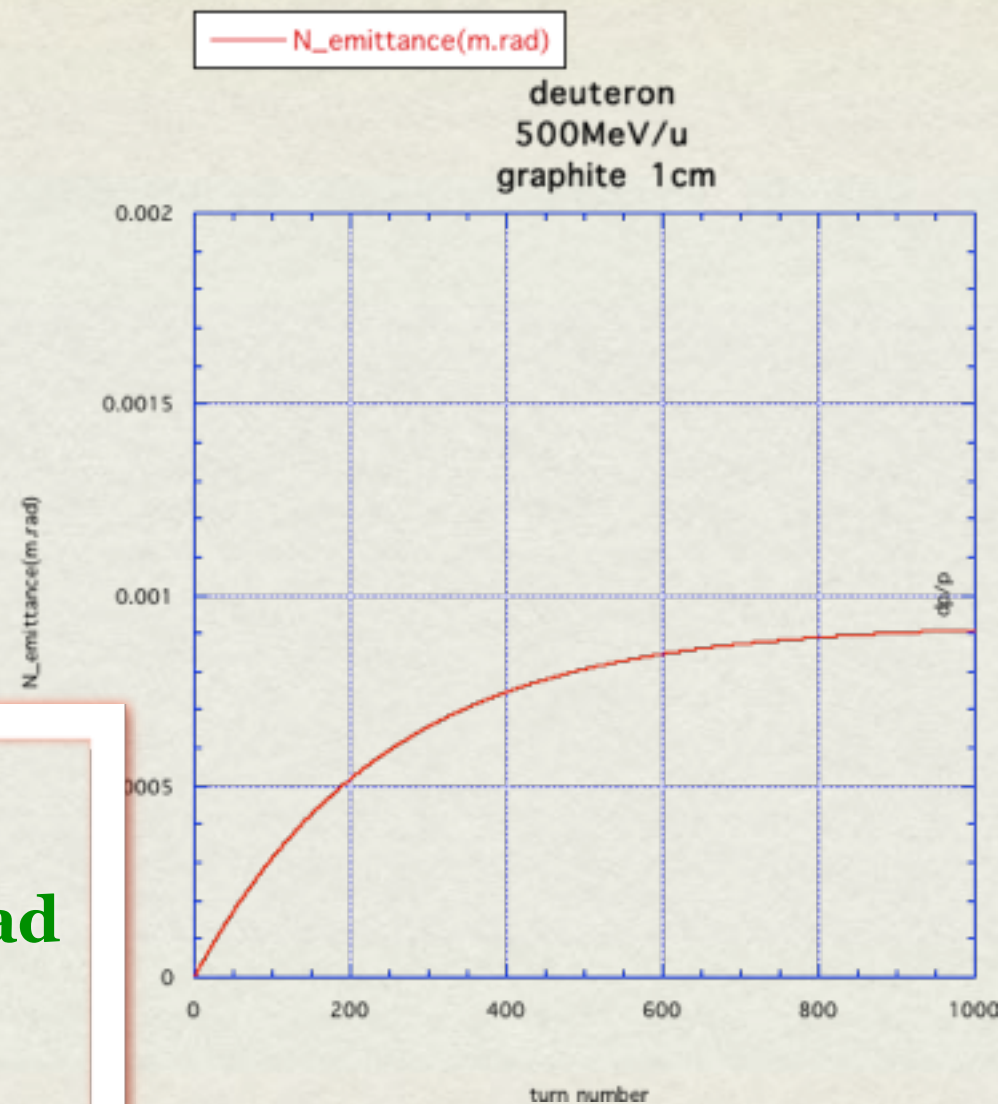
- Projectile : deuteron
- Energy : 500MeV/u
- Wedge : None
- $\beta(m)$ at target : 0.5m

Summary

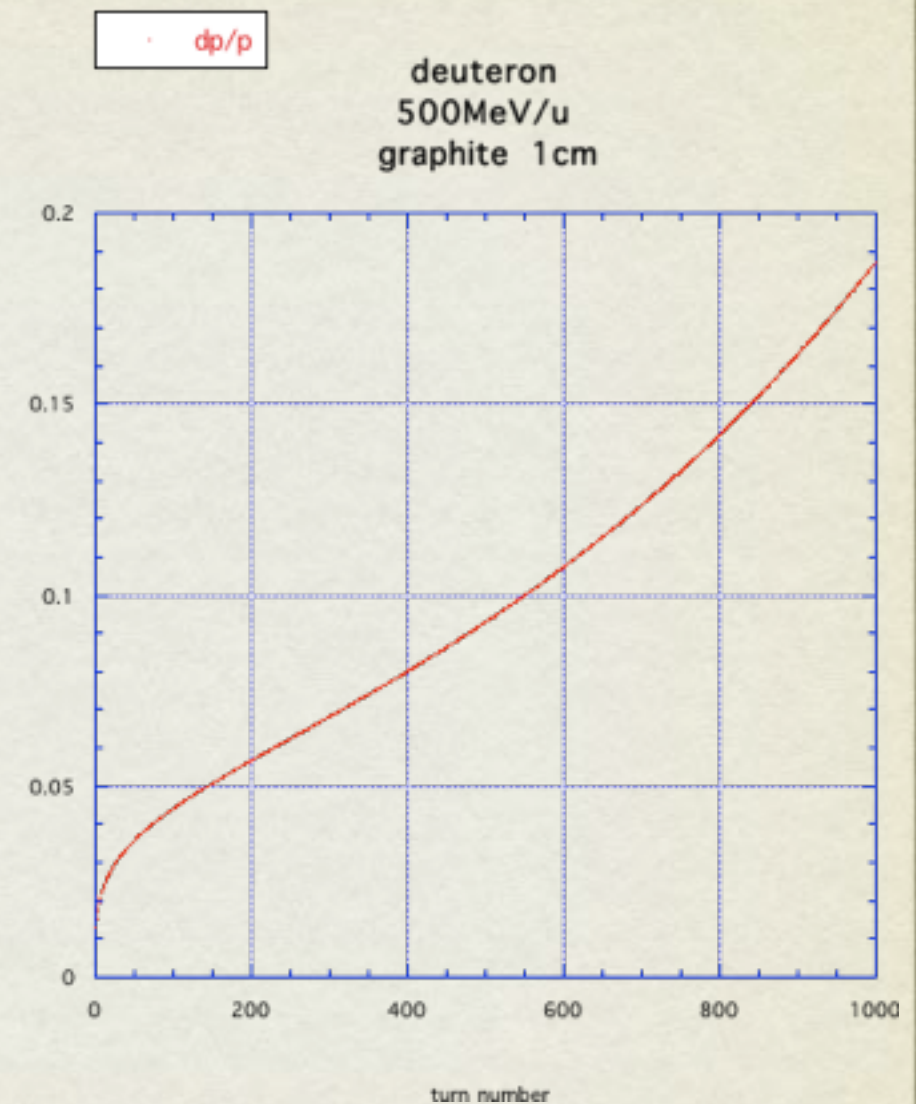
$$\epsilon_{rms}^T \sim 450 \text{mm.mrad}$$

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

(after 200 turns)



Transverse



Longitudinal

DEMANDS FOR RING SPECIFICATION IN ERIT

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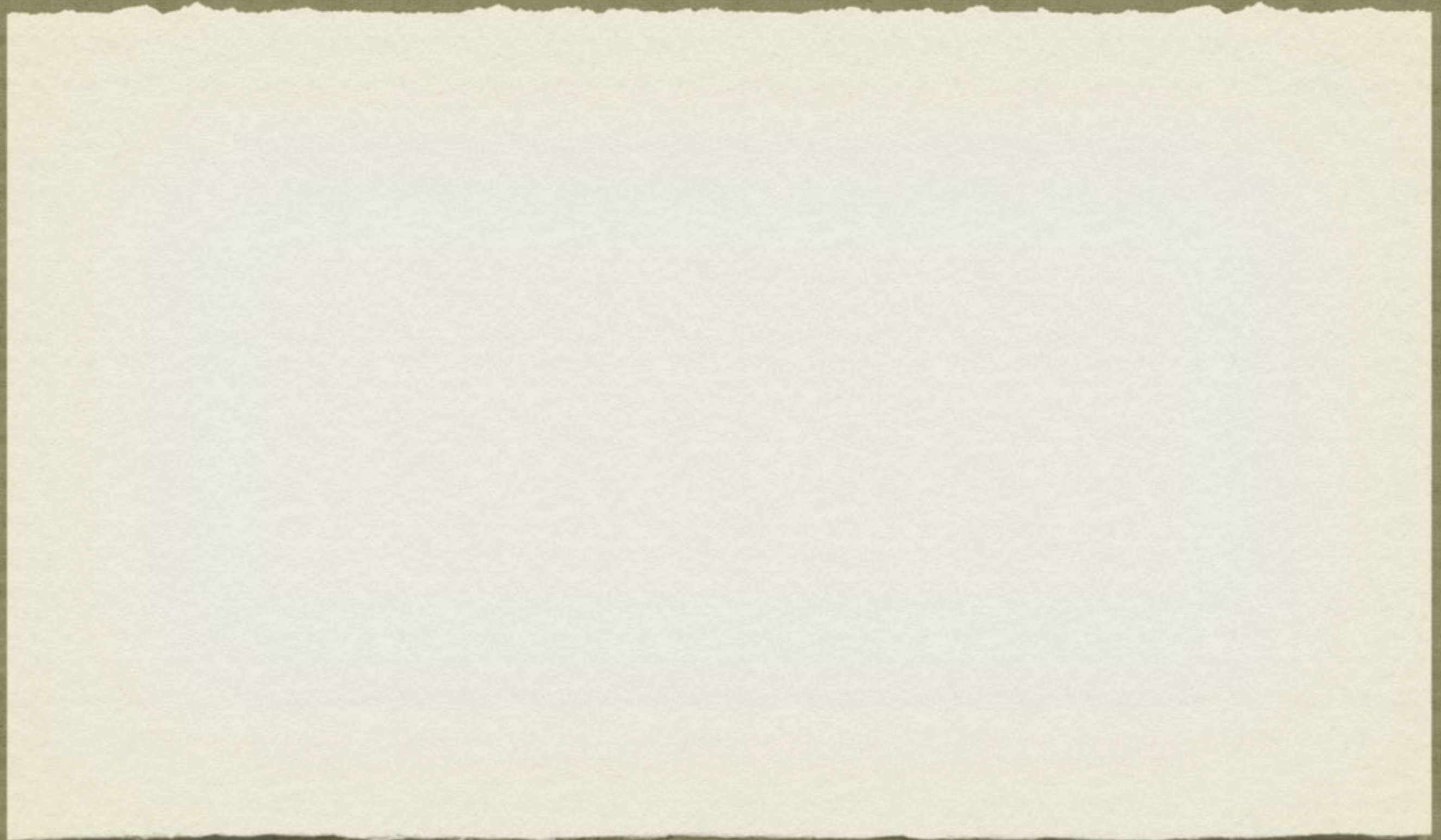
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 - Momentum $\Delta p/p > 20\%$ ← “Zero Chromaticity”

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

FFAG



FFAG

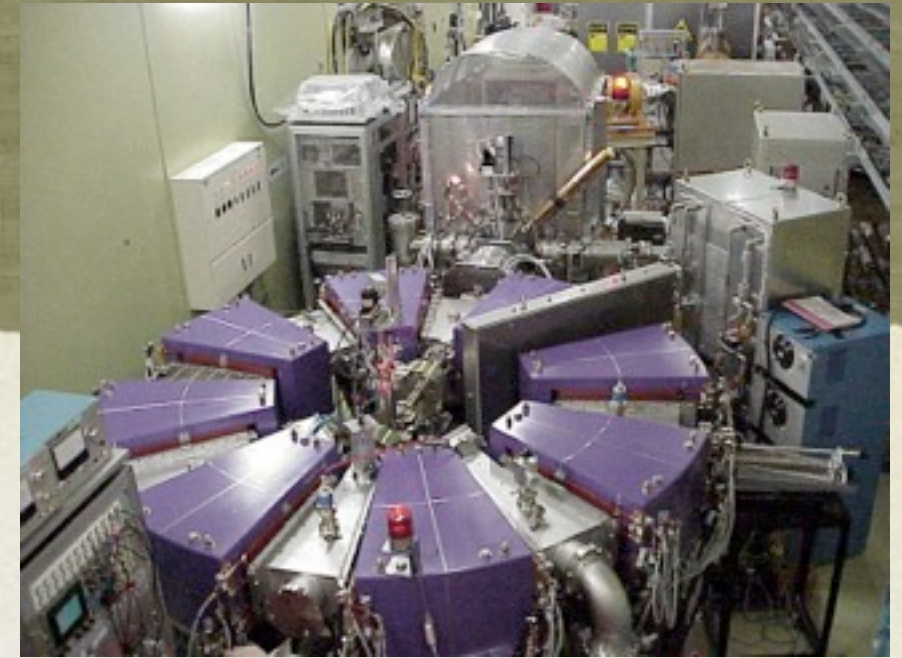
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 - First proton FFAG (KEK,Japan)

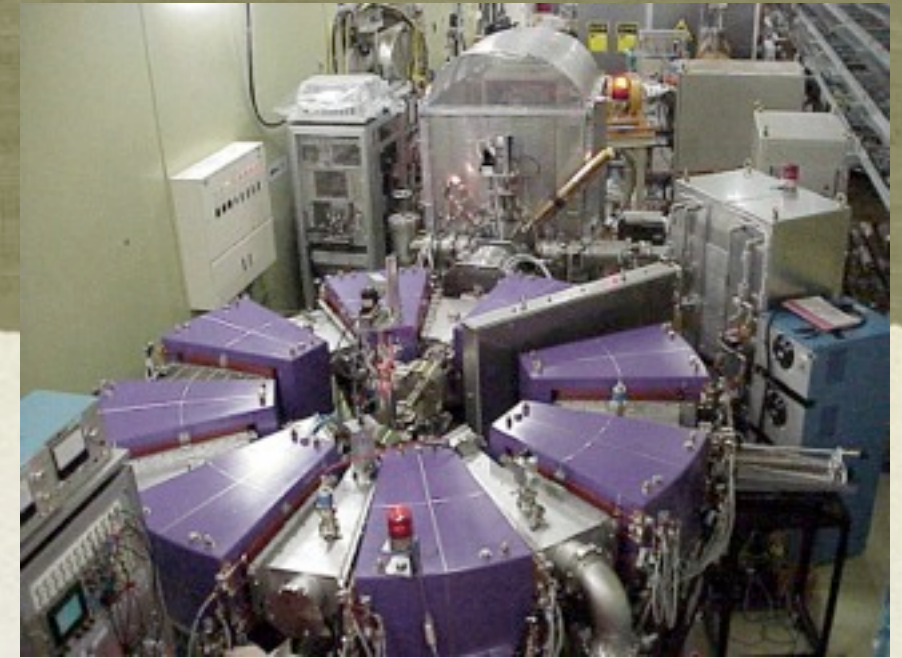
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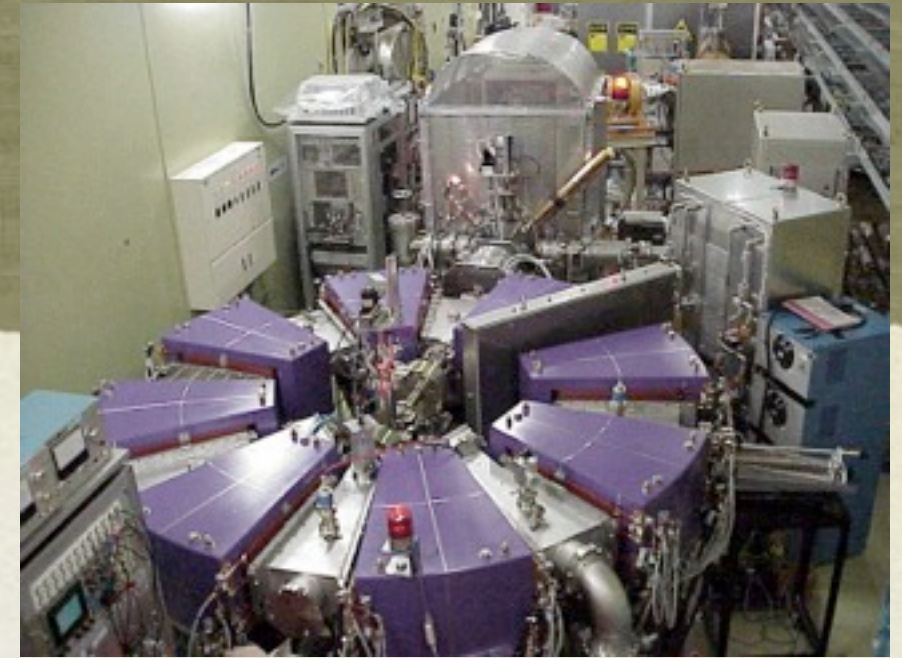
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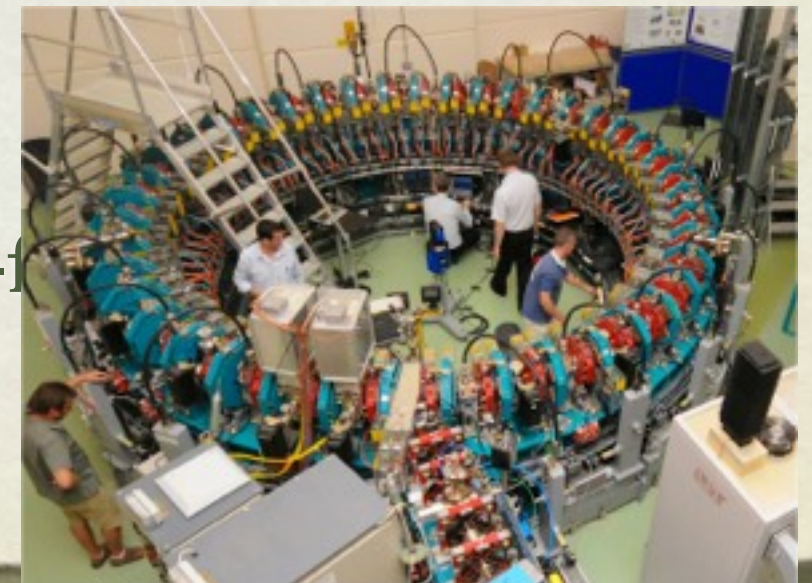
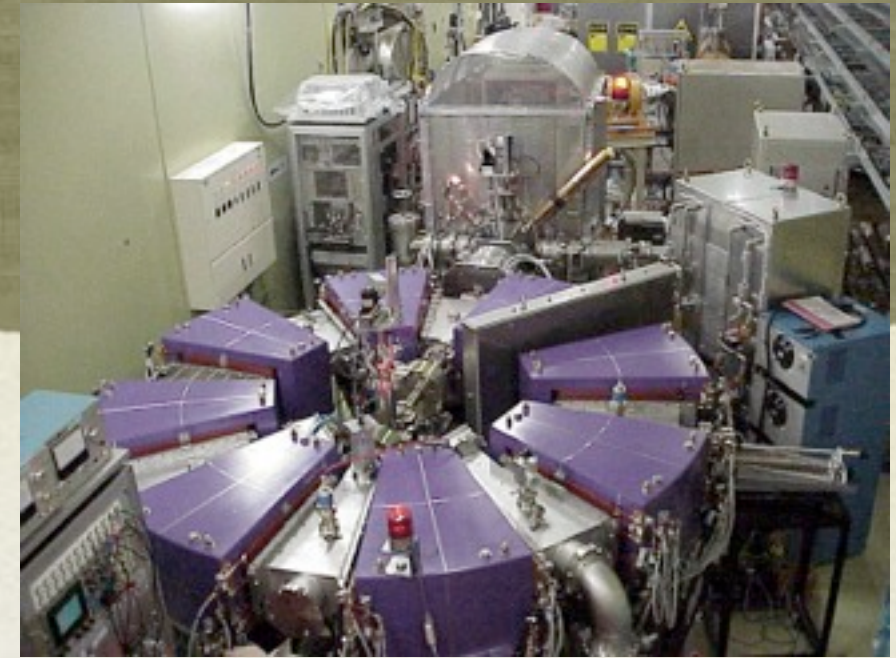
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PROOF OF PRINCIPLE

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

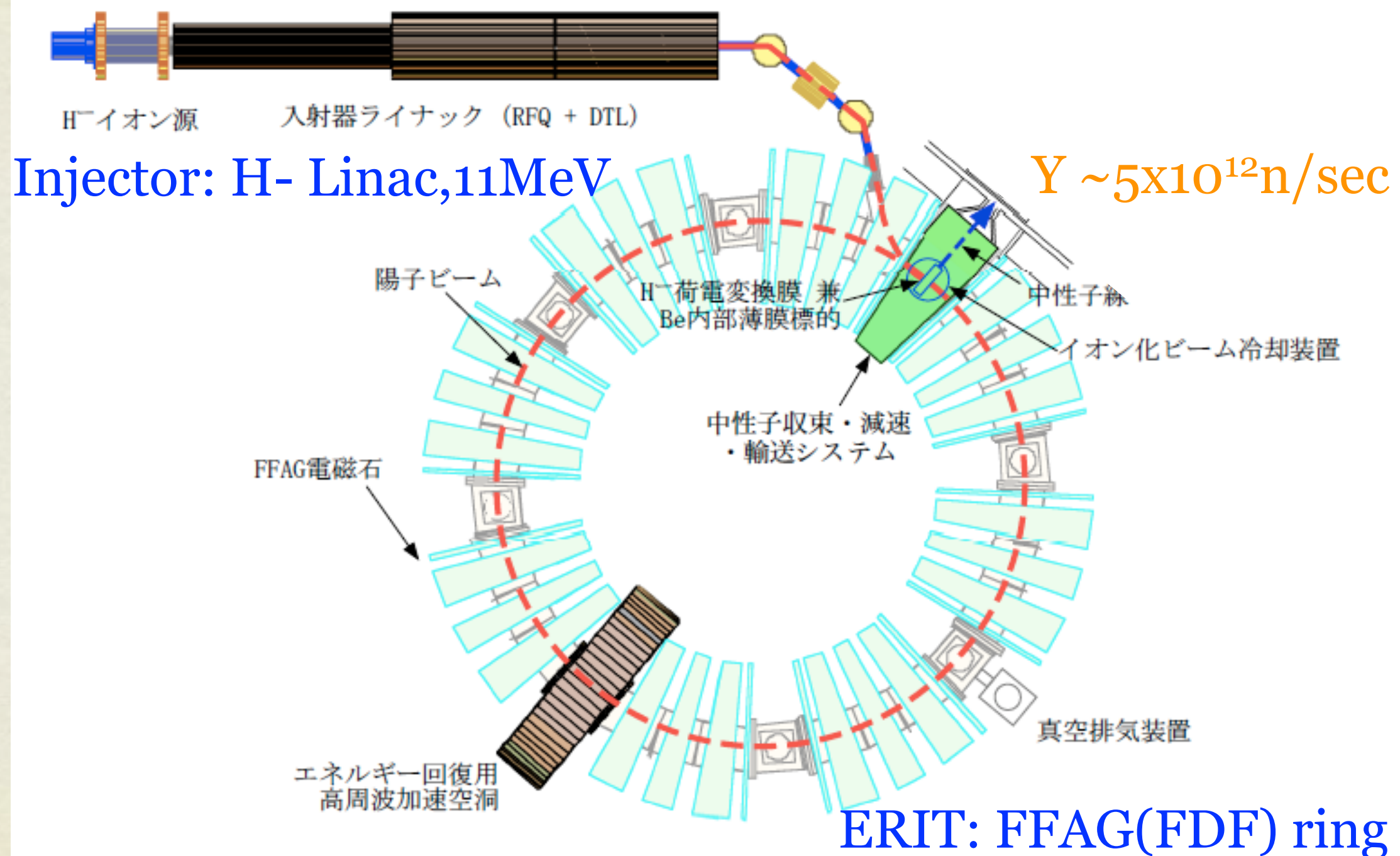
1) Y. Mori, et al.: Proc. of Particle Accelerator Conference (PAC09), Vancouver, 2009, pp. 3145

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

- Neutron source
- Proton 11 MeV, 0.1 mA
- Ring radius 2.35 m
- Target Be (5 μ m)
- Yield $\sim 5 \times 10^{12}$ n/sec

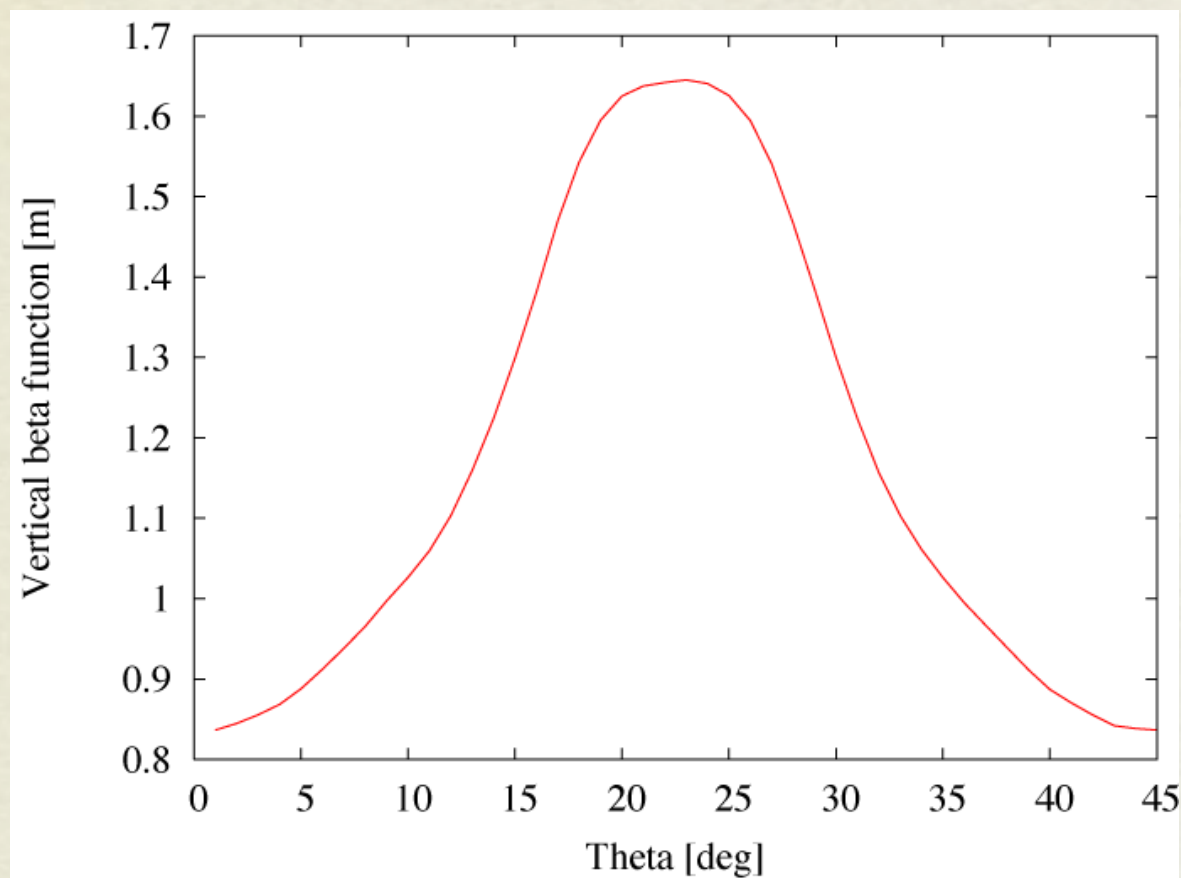


TOP VIEW OF FFAG_ERIT RING FOR NEUTRON SOURCE

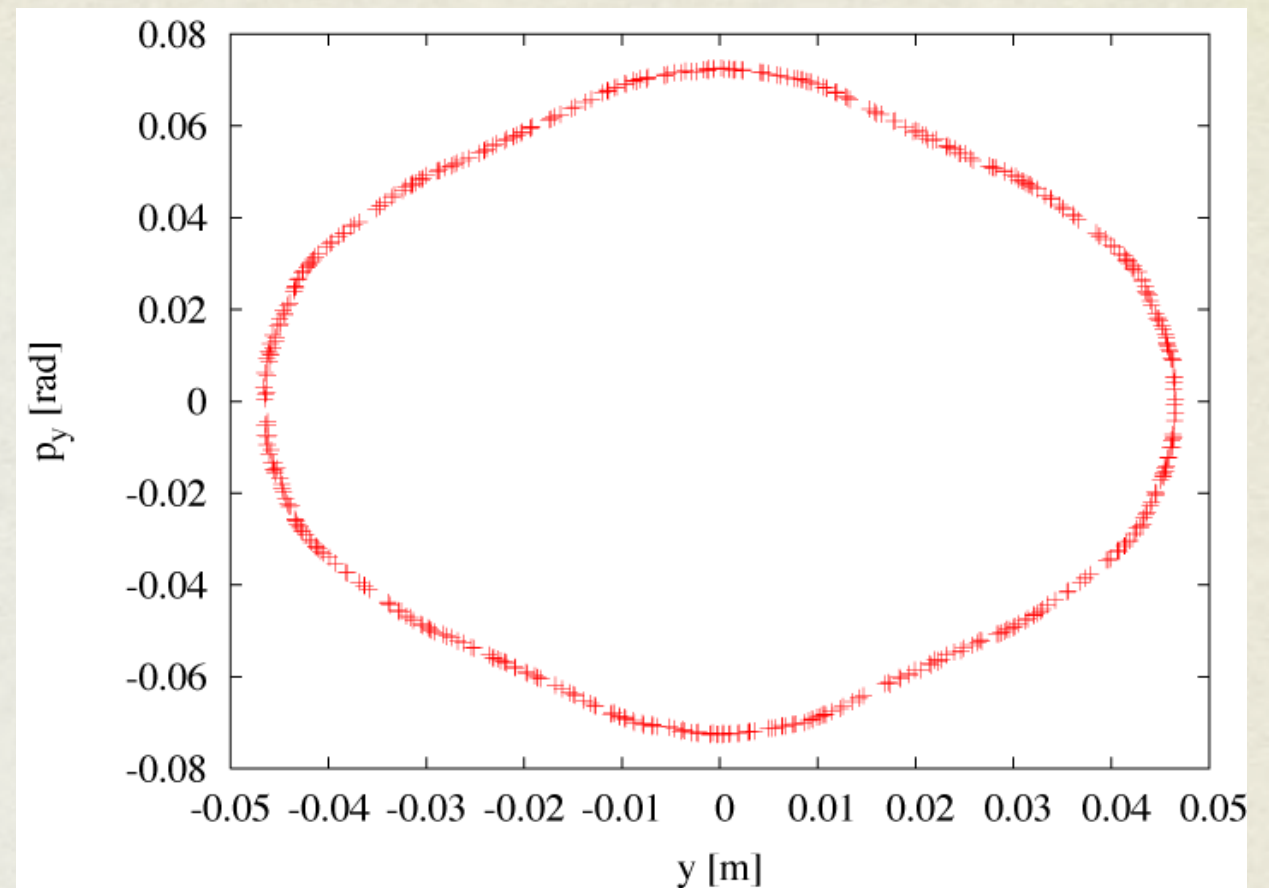


BETA FUNCTION(VERTICAL) & ACCEPTANCE

Beam tracking results with B field map (TOSCA_OPERA)



Vertical beta function@target ~ 0.83 [m]



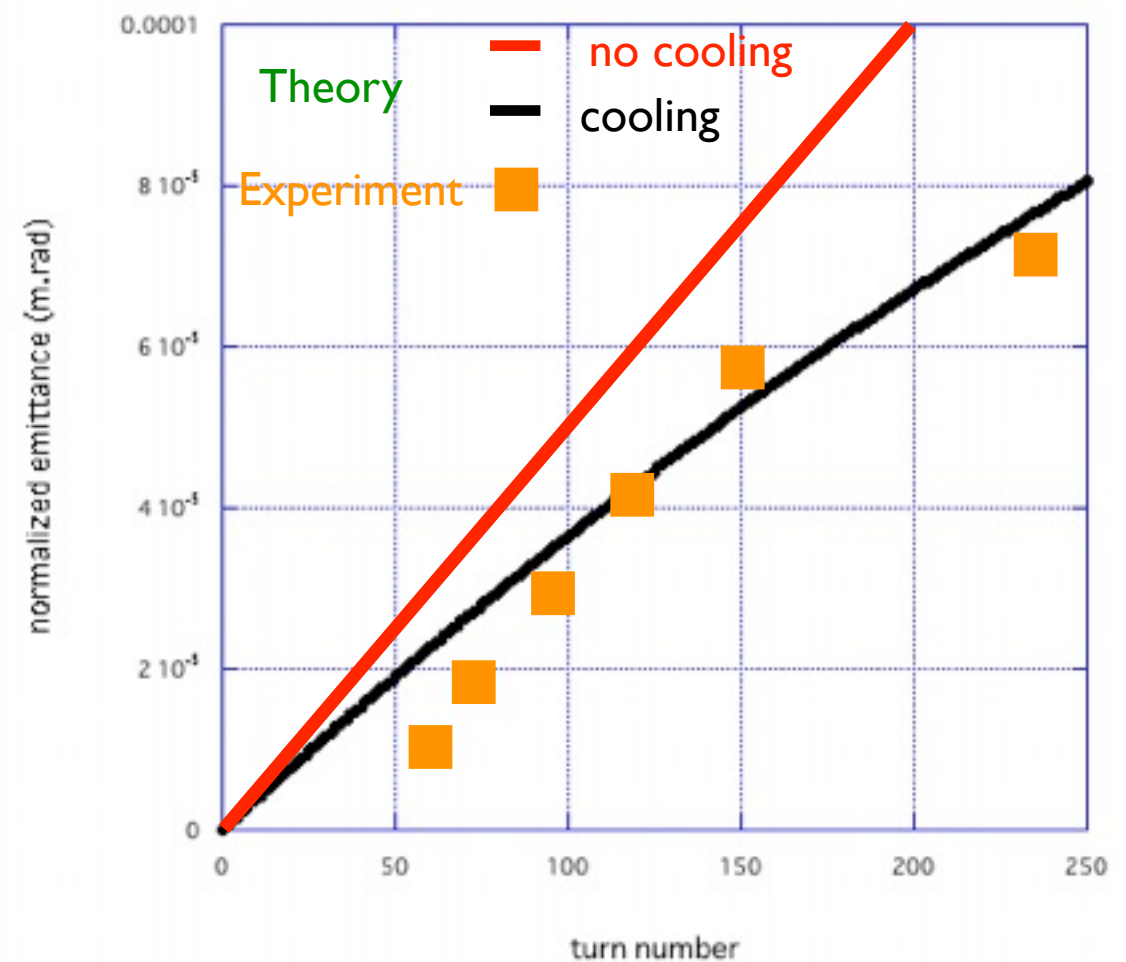
Vertical acceptance $\sim 3000\pi$ [mm-mrad]

(Horizontal acceptance $> 7000\pi$ [mm-mrad])

Longitudinal(momentum) acceptance $\sim \Delta p/p > 20\%$

EMITTANCE GROWTH

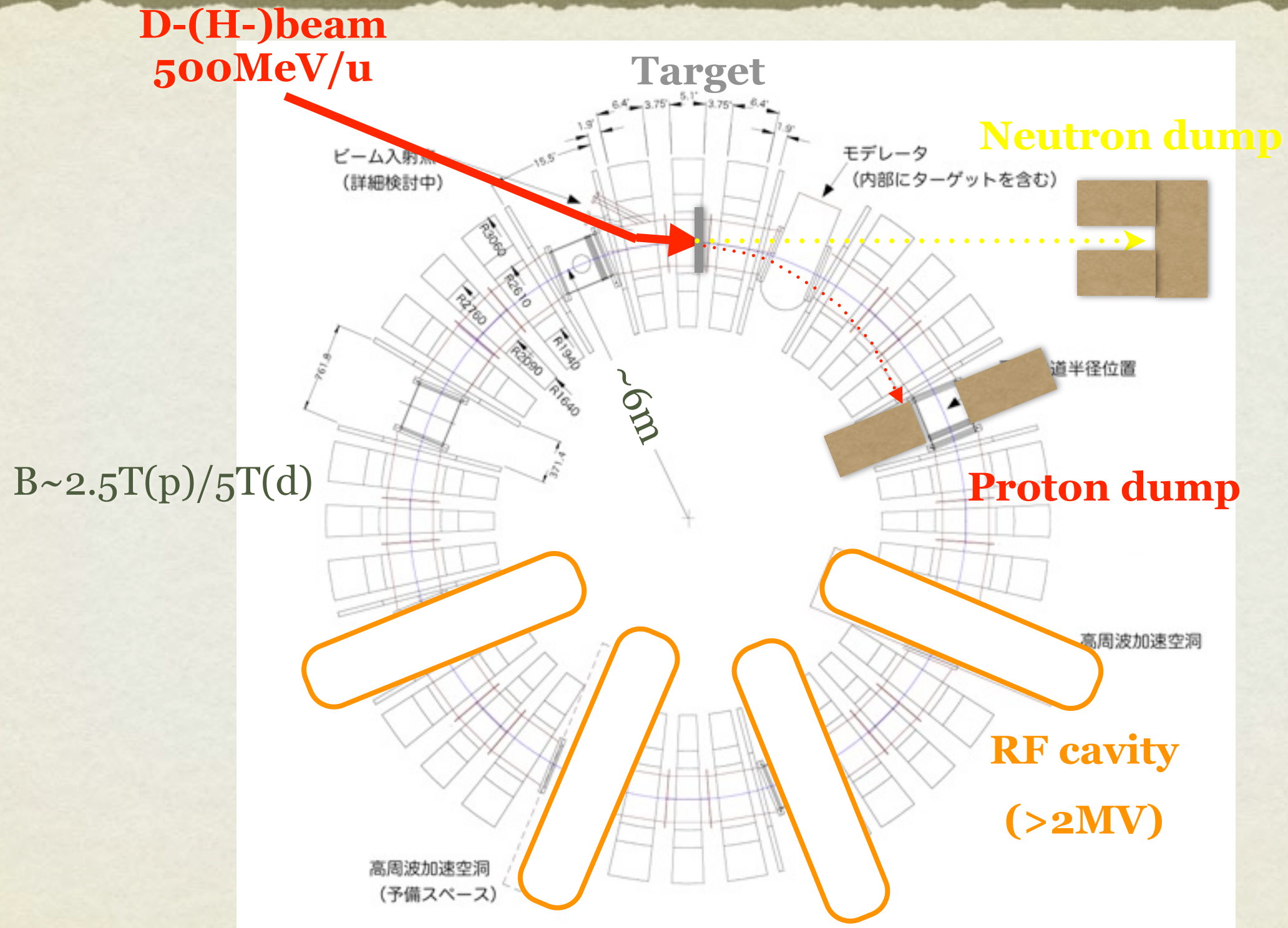
- **Measurement of emittance growth at FFAG_ERIT ring**
 - Beam scraper method
 - Beta function:calculated value



ERIT RING FOR MUON

- **Specification(case#1:hadron beam)**
 - Transverse acceptance $A > 2500\text{mm.mrad}(x5\varepsilon_{\text{rms}})$
 - Longitudinal acceptance $\Delta p/p > 20\%(x3\text{rms})$
 - Particle deuteron(proton:more turns)
 - Magnetic rigidity $2.18\text{Tm}(B\sim 1.5\text{T}, \rho\sim 1.5\text{m})$
 - Target $0.5\text{-}1\text{cm}$ thick graphite
 - Re-acceleration $4\text{-}8\text{MeV/turn}$
 - $\beta(\text{m})$ at target position 0.5m

SCHEMATIC LAYOUT OF MU_ERIT



MUON YIELD ESTIMATION

- **Expected negative muon numbers**
 - Assumption
 - Specifications of Mu_ERIT are fully satisfied.
 - **$n \sim 150$ 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**

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

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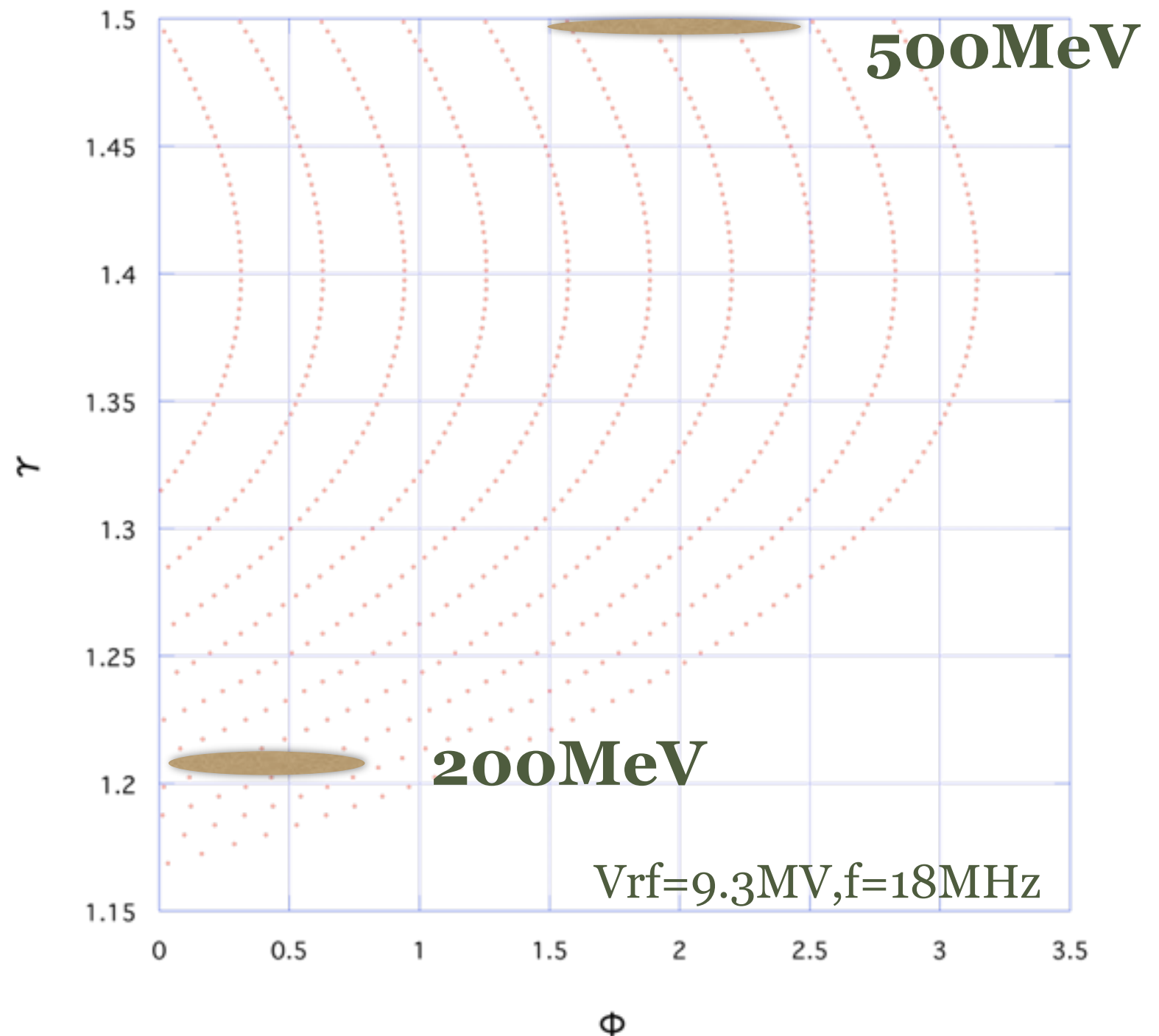
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- **→ Vertical FFAG(v_FFAG)**
 - Beam moves vertically as the energy increases. Constant path length.

VERTICAL FFAG

● Invention → T. Ohkawa (1953)again!

G8. FFAG Electron Cyclotron.* TIHIRO OHKAWA, *University of Illinois*† (introduced by D. W. Kerst).—New types of FFAG¹ 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

skew

MAGNETIC FIELD FOR ZERO CHROMATICITY

(1) Ring

a) Normal:H-FFAG

$$\frac{R}{\rho} = \text{const.} \quad \& \quad \frac{R}{B_y} \left(\frac{\partial B_y}{\partial x} \right) = k \longrightarrow B_y = B_y^0 \left(\frac{R}{R_0} \right)^k$$

b) Skew:V-FFAG

$$R, \rho = \text{const.} \quad \& \quad \frac{\rho}{B_y} \left(\frac{\partial B_y}{\partial y} \right) = n \longrightarrow B_y = B_y^0 \exp \left(\frac{n}{\rho} y \right)$$

(2) Straight line

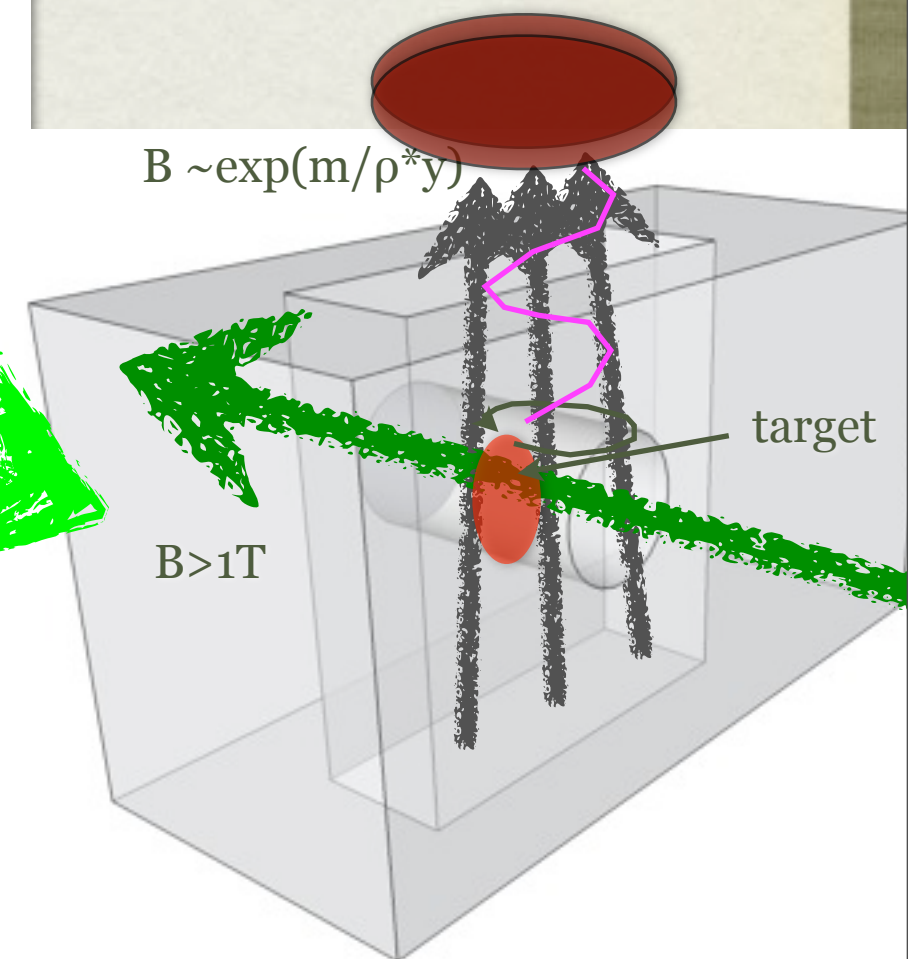
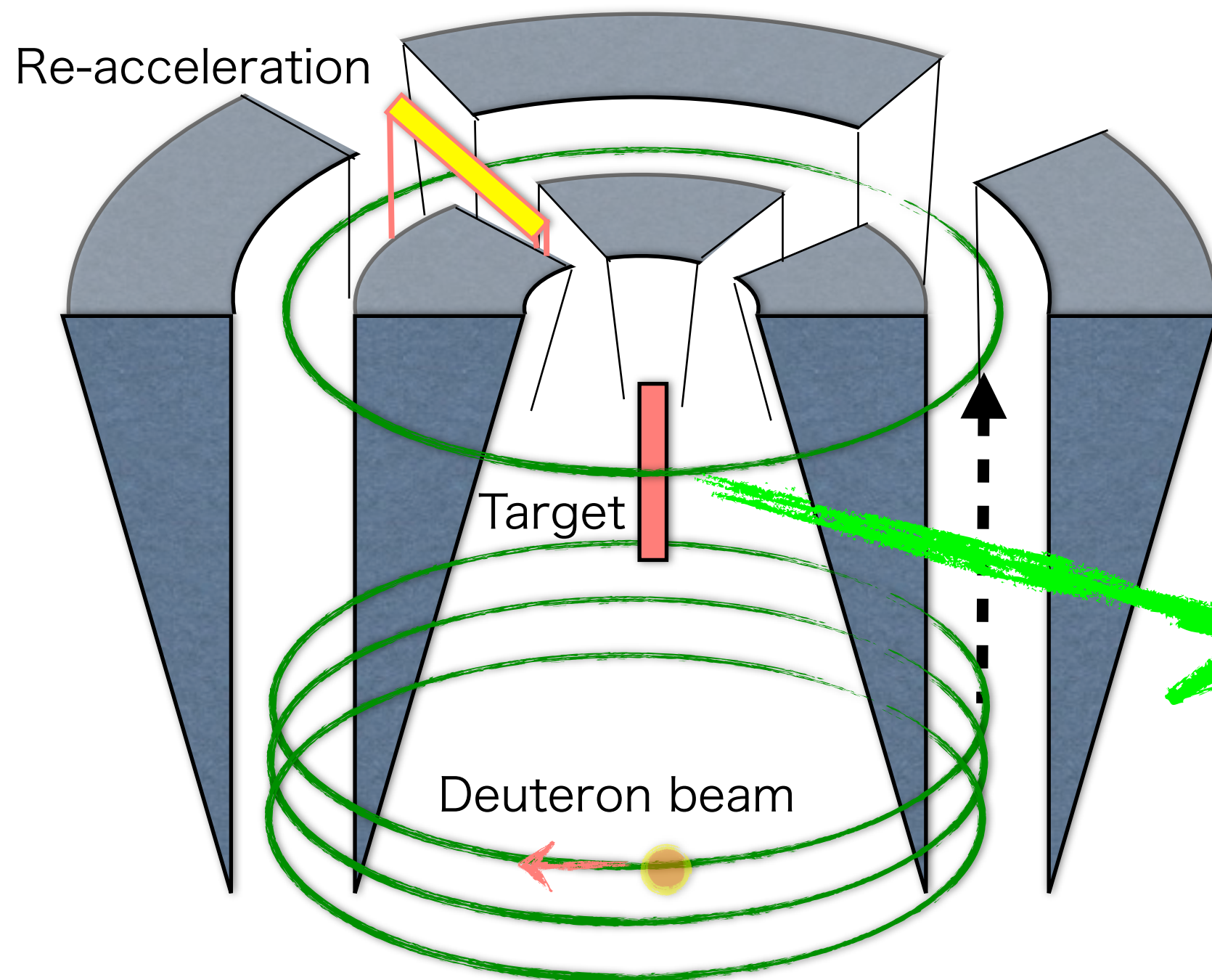
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MU_ERIT WITH V_FFAG



MU_ERIT(SPIRAL) WITH V_FFAG

D-(H-) beam

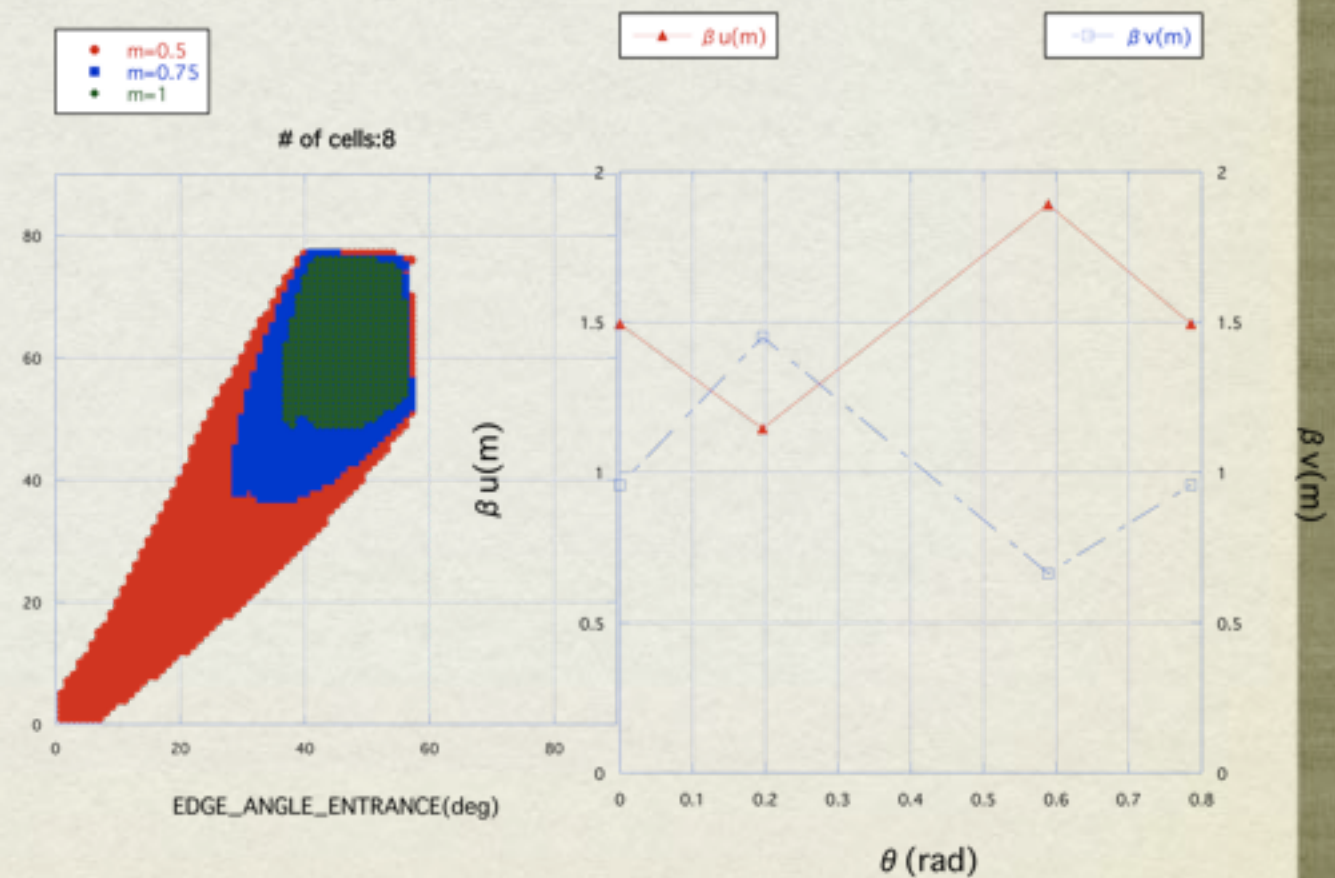
Carbon target

1cm

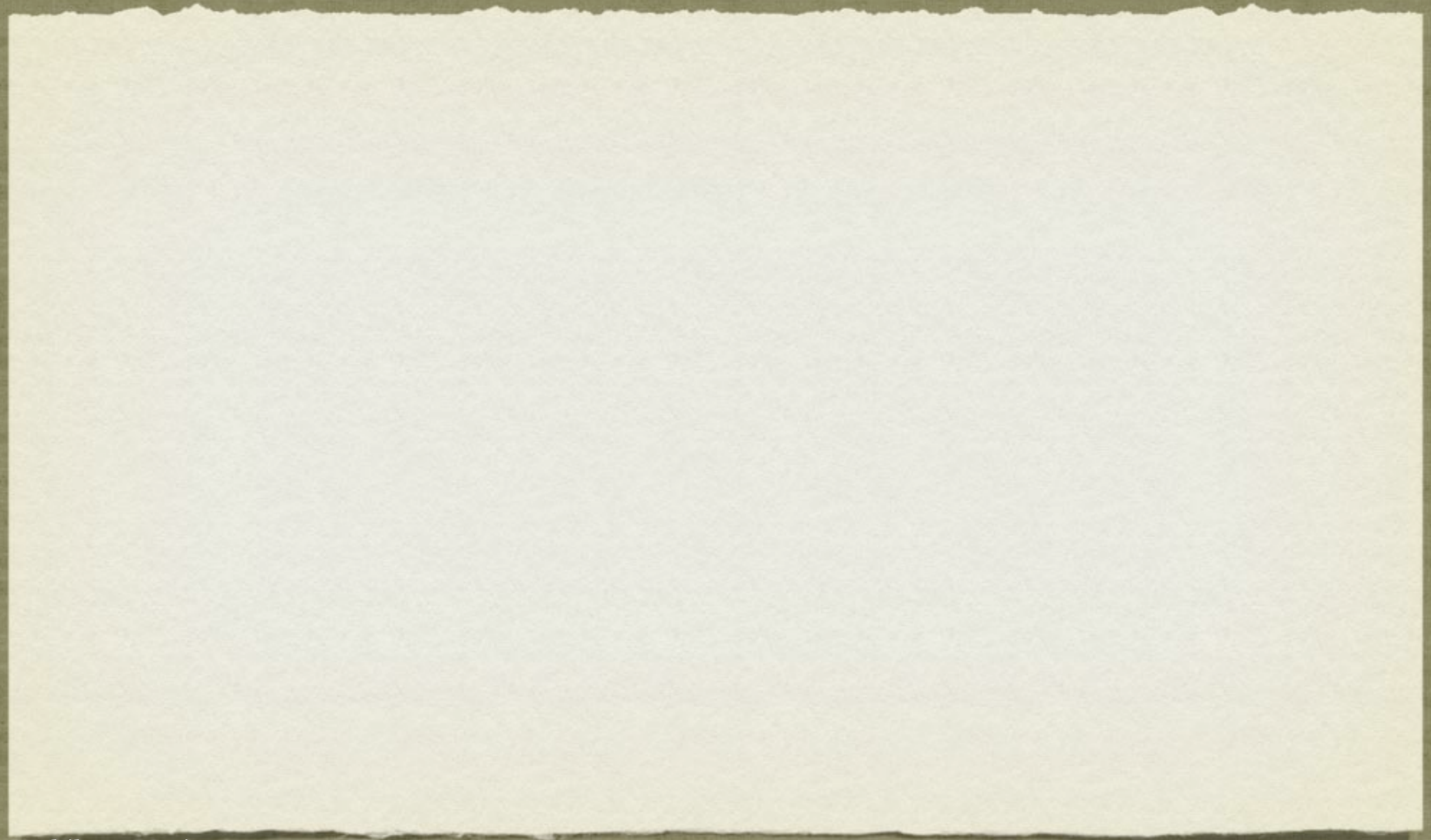
X10

RF cavity $V \sim 9.3\text{MV}$

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]



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- **Intense low energy muon source with ERIT on deuteron(proton)&electron Mu_FFAG is proposed.**
 - Very long production target can be effectively realized 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 $\sim 1 \times 10^{16} \mu^-/\text{sec (d)}$
 - $E_d=600\text{MeV/u}$, $I_d=1\text{mA}$, $t=1\text{cm}(\text{graphite})$, $n=150\text{turns}$, $A>0.8$)

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- **Technical issues;**
 - SC Magnet
 - SC RF cavity(TE- π mode)
 - Target cooling, Radiation shielding, etc.

THANK YOU FOR
YOUR ATTENTION!