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: $105.659 \text{ MeV} (206.768 \text{ m}_e c^2)$
  - Spin: $\frac{1}{2}$
  - Geomagnetic factor (g/2): $1.000165$
  - Decay(free) lifetime: $2.197 \mu\text{sec}: \mu^+ + \bar{\nu}_\mu + \nu_e$

- **Elementary particle physics**
  - $\mu_\gamma/\mu_e$ 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)

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ISSUES OF NUCLEAR ENERGY SYSTEM

Muon may provide the solutions.

- Controllability of energy generation
  - Fission    Criticality control, Radiation heating
  - Fusion    Plasma confinement and heating
- Radiation
  - Nuclear reactor wastes : long-lived species (LLFP, MA)
  - μCF (muon-catalyzed fusion)
  - MNT (muon nuclear transmutation): Nagamine & Mori
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)

Radioactive wastes from nuclear power plant

- Ordinary storage on the ground
- ADS/FR transmutation
- Deep underground storage

Long-lived species

Reuse
NUCLEAR TRANSMUTATION WITH NEGATIVE MUON

1st: Formation of muonic atom

\( \mu^- + {}^{99}\text{Tc} \rightarrow {}^{99}\mu\text{Tc} \)

Muonic_atom radius:

\[ R/a_\mu > 1 \quad \Rightarrow \text{Transmutation} \]

Nuclear radius:

\[ R/a_\mu \]

\[ = 1.20 \times 10^{-17} \text{ m} \]

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 \( 1s_\text{p} \) state, the probability of finding a muon within the nucleus is close to 50% (Devons and Duerdoth 1969).
$^{99}\text{Tc} (2.12 \times 10^5 \text{y}, 6.14\%)$

$^{129}\text{I} (1.72 \times 10^7 \text{y}, 0.84\%)$
Production of nuclear wastes from Uranium fuel (3% enriched U; 1 ton)

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

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

$$I_{\mu^-} > 1 \times 10^{16} \left[ \mu^- / \text{sec} \right]$$
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**: $\pi^-$ production reaction

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

- **2nd step**: Decay from $\pi^-$

  \[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \]
REQUESTED MUON PROPERTIES
FOR NUCLEAR POWER SYSTEM

- **Charge state**  → **Negative**: $\mu^-$ (decayed from $\pi^-$)

  - **Projectile particle**
    - Proton: $\pi^-/\pi^+ \sim 0.2$ ($E_p < 1$ GeV), $\sim 0.7$ ($E_p > 5$ GeV)
    - Deuteron: $\pi^-/\pi^+ \sim 1$ ($E_d > 0.5$ GeV/u)

- **Low energy**  →  $< 300$ MeV/c

  - Low magnetic rigidity  $B\rho < 1$ Tm
    - → Capture B field =2 T, $\rho=0.5$ m
  - Hard to degrade high energy muon: cf. Range ($1$ GeV/c) $> 3$ m (graphite)
High energy proton  \( E > 3 \) GeV
- Range(EM stopping power) \( \gg \) Target thickness(<nucl. int. leng.) \( \sigma(\pi-N) \gg \sigma(p\pi-) \)

Small Low energy \( \pi-(\mu-) \) fraction
\( \sim 0.02 \frac{\pi-}{p}(t=100 \text{ mm}) \)

Small Acceptance of capture magnet
- Acceptance: \( \sim 0.4 \text{ Sr} \) (SuperOmega:J-PARC)

Total Efficiency
- \( 0.004 \left( \frac{\pi^-}{300\text{MeV/c}} \right) \times 3.2 \times 10^{-2} \) (Acc.Mag.)
- \( \sim 1.3 \times 10^{-10} \) (\( \pi-/p \)); cf. J-PARC: \( \sim 2.6 \times 10^{11} \frac{\pi^-}{\text{sec}} \) @maximum: reality \( 10^8 \frac{\mu^-}{\text{sec}} \)
ISSUES FOR HIGH INTENSITY LOW ENERGY NEGATIVE MUONS

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

- **Problems**
  - Small production cross section
    - $\pi^- (<400 \text{ MeV/c})/p \sim 0.0028$ for $t=2.5$ g/cm\(^2\)

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

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**EFFECTIVE LONG TARGET RE-ACCELERATION**

- **Difficulties**
  - How capture $\pi/\mu$?
  - Long system $> 100$ m (unit~1 m); cost?
**Linear → Circular**

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

**Re-acceleration**

- $\Delta E$

**ENERGY RECOVER RING + INTERNAL TARGET - ERIT -**

IDEA & Proposal:

Emittance growth: Beam hits target many times. Beam survival?

- Transverse $\rightarrow$ Scatterings (Rutherford, elastic ...)
- Longitudinal $\rightarrow$ Straggling: energy spread

$\Rightarrow$ Need beam cooling $\rightarrow$ “Ionisation Cooling”

IDEA & Proposal:
IONISATION COOLING

Cold electrons (ionisation) Energy loss in 3-D

Beam Material

Large emittance

Small emittance

Acceleration (energy recovery purely for longitudinal direction)
The rate equations of beam emittance:

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

**Vertical**
\[
\frac{d\varepsilon_y}{ds} = -\frac{1}{\beta^2 E} \frac{dE}{ds} \varepsilon_y + \frac{\beta_y E_s^2}{2\beta^2 m_p c^2 L_R E} \varepsilon_y
\]

**Longitudinal**
\[
\frac{d\langle\sigma_E^2\rangle}{ds} = -2 \left. \left( \frac{\partial (dE/\partial E)}{\partial E} \right) \right|_0 \frac{dE}{ds} \frac{1}{p c\beta} \frac{D\rho'}{\rho_0} \langle\sigma_E^2\rangle + \frac{d\langle\Delta E_{\text{rms}}^2\rangle}{ds}
\]

Light element is preferred!

Large \( L_R \cdot dE/ds \rightarrow \) Good trans. cooling
EMITTANCE GROWTH

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

Summary
$\varepsilon_{T\text{rms}} \sim 450 \text{ mm.mrad}$
$\Delta p/p_{\text{rms}} \sim 5.7\%$
(after 200 turns)
DEMANDS FOR RING SPECIFICATION IN ERIT

- **Small beta function at target**
  - Strong focusing: weak focusing (Cyclotron) → not adequate

- **Large acceptance**
  - Transverse $A_{(rms)} > 500 \, \pi \text{mm.mrad}$
  - Momentum $\Delta p/p > 20\% \leftarrow \text{“Zero Chromaticity”}$

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-fuction (Kyushu Univ.)
PROOF OF PRINCIPLE

Experimental study of ERIT (2008)


- Neutron source
- Proton 11 MeV, 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

Injector: H- Linac, 11 MeV

ERIT: FFAG(FDF) ring

\[ Y \sim 5 \times 10^{12} \text{n/sec} \]
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

![Graph showing emittance growth with theory and experiment data with cooling and no cooling]
ERIT RING FOR MUON

**Specification (case #1: hadron beam)**

- Transverse acceptance: \( A > 2500 \text{ mm.mrad} \times 5 \varepsilon_{\text{rms}} \)
- Longitudinal acceptance: \( \Delta p/p > 20\% \times 3 \text{ rms} \)
- Particle: deuteron (proton: more turns)
- Magnetic rigidity: 2.18 Tm (B~1.5 T, \( \rho \sim 1.5 \text{ m} \))
- Target: 0.5-1 cm thick graphite
- Re-acceleration: 4-8 MeV/turn
- \( \beta \) (m) at target position: 0.5 m
SCHEMATIC LAYOUT OF MU_ERIT

- D-(H-) beam 500MeV/u
- Target
- Neutron dump
- Proton dump
- RF cavity (>2MV)
- B~2.5T(p)/5T(d)
Expected negative muon numbers

Assumption

- Specifications of Mu_ERIT are fully satisfied.
  - \( n \sim 150 \text{ turns} \) (limited by break-up for deuteron(<200t), more turns for proton)
  - Muon capture efficiency (cf. MUSIC) \( >0.8 \)
  - Beam current \( I_d \) \( >5-10 \text{mA} \)

\[ Y_\mu = 0.2(\pi-/\mu-/d) \cdot 0.8 \cdot I_d/e \sim 1.0 \times 10^{16}(\mu-/\text{sec}) \]
NEW SCHEME
VERTICAL FFAG FOR MU_ERIT

- Ordinary ERIT ← Full energy injection
  - Why not acceleration simultaneously?

- Issues for simultaneous acceleration
  - Keeping "Zero Chromaticity"
  - Constant RF frequency → semi_isochronous

- Serpentine(Bucket) Acceleration
  - Orbit path length → not change so much for $\beta > 0.5$
  - $\pi/\mu$ captured in the vertical $B$ field
  - $\rightarrow$ Vertical FFAG(v_FFAG)

- Beam moves vertically as the energy increases. Constant path length.

Vrf=9.3MV, f=18MHz

500MeV

200MeV

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**VERTICAL FFAG**

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

**G8. FFAG Electron Cyclotron.** Toshiro 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).
BETATRON MOTION AROUND CIRCULAR ORBIT

Eqs. of motion

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

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

Linearization

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

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

normal

skew
MAGNETIC FIELD FOR ZERO CHROMATICITY

(1) Ring

a) Normal: H-FFAG

\[ \frac{R}{\rho} = \text{const.} \quad \text{and} \quad \frac{R}{B_y} \left( \frac{\partial B_y}{\partial x} \right) = k \rightarrow B_y = B_y^0 \left( \frac{R}{R_0} \right)^k \]

b) Skew: V-FFAG

\[ R, \rho = \text{const.} \quad \text{and} \quad \frac{\rho}{B_y} \left( \frac{\partial B_y}{\partial y} \right) = n \rightarrow B_y = B_y^0 \exp \left( \frac{n}{\rho} \frac{y}{y} \right) \]

(2) Straight line

a) Normal: H-FFAG

\[ \rho = \text{const.} \quad \text{and} \quad \frac{\rho}{B_y} \left( \frac{\partial B_y}{\partial x} \right) = n \rightarrow B_y = B_y^0 \exp \left( \frac{n}{\rho} \frac{x}{x} \right) \]

b) Skew: V-FFAG

\[ \rho = \text{const.} \quad \text{and} \quad \frac{\rho}{B_y} \left( \frac{\partial B_y}{\partial y} \right) = n \rightarrow B_y = B_y^0 \exp \left( \frac{n}{\rho} \frac{y}{y} \right) \]
Re-acceleration

Target

Deuteron beam

B \sim \exp(m/\rho^*y)

B > 1T

target
D-(H-) beam

Carbon target

1 cm

RF cavity V~9.3MV

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<tr>
<td>edge angle (ent-ext)</td>
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x10
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 $\pi^-/\mu^-$. 
  - $\pi^-/\mu^-$ are captured and transported by strong magnetic field of Mu_FFAG.
  - $\mu^-$ yield $\sim 1 \times 10^{16} \mu^-$/sec (d)
  - $E_d=600\text{MeV/u}, I_d=1\text{mA}, t=1\text{cm(graphite)}, n=150\text{turns}, A>0.8$)
- 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-$\pi$ mode)
  - Target cooling, Radiation shielding, etc.
THANK YOU FOR YOUR ATTENTION!