Compact Muon Source with Electron Accelerator
for a Mobile μSR Facility

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Abstract

In order to increase accessibility to the μSR spectroscopy for people in various fields of science and engineering, a conceptual design study was made to realize a compact and inexpensive muon source by using 300-MeV electron microtron and a large-acceptance muon-capture. Advanced radiography imaging with muon spin probes will become possible for bio-medical studies, inspection of re-enforced architectures, etc.

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1. Introduction; Need of a compact μSR facility

In order to enlarge the application fields of μSR spectroscopy, it is essential to increase the number of muon-producing accelerators beyond that of the existing major facilities. As a possible approach, a conceptual design study was made on compact (within a trailer size) and inexpensive (below 10 M$) muon source.

At the final goal of development, the compact muon source proposed here, will be used for the following purposes; 1) exploring magnetic order in new materials [1] at the sites of sample preparation, 2) monitoring spintronics materials by measuring conduction electron polarization at the device-producing factory [2], 3) measurement of magnetism in blood flow in the human brain, related to brain function at medical laboratories or hospitals [3], 4) probing the iron rods in re-enforced concrete used for large-scale architectures and industrial machinery [4] and 5) apart from the μSR spectroscopy, detection of hidden special nuclear materials in cargo container which has encouraged promotion of the present investigation [5]

2. Choice of electron accelerator

In general, there are practically the following two methods of pion/muon production by using accelerator beams. A) Hadron nuclear reaction by using proton or heavy ion accelerators; p(n) + A → π+ + B, where an energy above 280 MeV/nucleon is required for a stationary target. B) Photo-nuclear reaction by using an electron accelerator; e+ + A → e+ + B + γ, γ + A → D + π+. where an energy above 140 MeV is required. For the compact muon source, an electron accelerator is the only choice: 1) for ring accelerator such as cyclotron, synchrotron, FFAG (Fixed Field Alternating Gradient) machine or microtron, the proton machine, because of larger magnetic rigidity, needs a substantially larger radius; 2) for a linear accelerator, due to the complexity in
the non-relativistic region, it is difficult for the hadron machine to take a compact form; 3) because of lower threshold energy, the electron machine is preferable for the compactness.

Among the possible candidates of three types of electron accelerators, the following comparison has been made to select a microtron as the best compact muon source using the present accelerator technology. **Electron Linac**; Electrons are accelerated by a RF electric field along the linear accelerating tube. At high-energy physics laboratories, development of the high acceleration-gradient linear accelerator has recently made a remarkable progress such as 50 MeV/m. However, among the commercially available products for a 150-MeV machine, the realistic compactness is still well behind the circular machine. **Electron FFAG**; Recently, a rapid progress is taking place for the technical development of the FFAG accelerator, where electrons are accelerated along the circular orbit by a frequency-changing RF field. Some design work on the electron FFAG for a muon source was carried out. Although high duty factor as well as a possibly higher current is favourable for the possible muon source, there are the following difficulties; 1) the RF power supply for the compact electron FFAG is not matched to the frequency region of the powerful RF source material FINEMET, 2) because of a narrow turn separation and rapid circular frequency, a suitable magnetic kicker can not be prepared for the beam extraction and 3) at present, there is no commercially available electron FFAG. **Electron Microtron**; The electron is repeatedly accelerated by a 10-MeV-level linear accelerator in the re-circulated orbits, reaching beyond 100 MeV. Compact and table-top electron microtrons are now commercially available for use as injector to SOR (synchrotron orbital radiation) light sources. In principle, by increasing the electron energy beyond the pion-production threshold, one can use it as a compact muon source. The most serious problem is the limit of the current. It is not easy to realize the average current higher than 10 μA.

### 3. Realistic form of compact muon source from electron accelerator

Muons are usually produced by the decay of pions. There are three processes to produce muons/pions from the reactions of high energy electrons.

1. Photo-production $\sigma_{\text{ph}}(E_{\gamma})$ (real-photon process); bremsstrahlung real-photon production followed by the pion photo-production by the produced real photons, $e^- + Z_1 \rightarrow \gamma + Z_1, \gamma + Z_2 \rightarrow \pi^\pm + Z_3$.

2. Electro-production $\sigma_{\text{el}}(E_{\text{e}})$; pion production in the inelastic electron scattering by virtual photons, $e^- + Z_1 \rightarrow (e^-') + Z_1 + \pi^\pm + Z_2$.

In order to identify each of these two processes, the thickness dependence of the pion yields was proposed and measurement was done by using the activation method [6]. The experimental results of $\sigma_{\text{el}}(E_{\gamma})/\sigma_{\text{ph}}(E_{\gamma})$ are well below around 0.1.

3. Muons from muon pair creation $\sigma_{\text{pair}}(E_{\gamma})$

Muon can also be produced by the photon-pair-production process, which does not proceed through pion production and decay, $\gamma + Z \rightarrow \mu^-\mu^+$ anything

The quantitative estimation of this process following a review article by Y.S. Tsai [7] is in progress [8]. Some preliminary estimations suggest $\sigma_{\text{pair}}(E_{\gamma})/\sigma_{\text{ph}}(E_{\gamma})$ is around $10^{-3}$ to $10^{-4}$ for electron energies below 1 GeV.

Therefore, the major pion production in the electron-nucleus reaction takes place through the real photon process. As for the conceptual design, the following guiding principles should be considered:

(a) As for the cross section of the bremsstrahlung production at high electron energy ($\geq$50 MeV) and at high photon energy $k$, the value of $\langle k/Z^2 \rangle$ do/dk is almost constant up to the k of just below the electron energy [9], where the photon angular distribution is roughly confined to a cone with the size of 2x100 degree$\times$MeV for relativistic electrons on 0.1 radiation length W [9]; (b) As seen in Fig. 1, as an example for the case of carbon, the low-energy component of the photo-pion production stays constant, while at higher k of photon energy gives an increase of the constant tail towards higher energy pions [10]. The Z-dependence of photo-pion cross section for the different target has a $Z^{2/3}$ dependence, as demonstrated in the theoretical model based upon Delta doorway-state model [8].

In order to achieve the desired compactness, the lowest possible energy electron accelerator should be used. Let us try to use commercially available 300 MeV microtron, which is above the threshold energy and close to the energy frequently adopted for the table-top synchrotron light source. In such a situation, it is essential to collect produced muons as much as
possible. For this purpose, the large-acceptance axial-focusing magnetic field system (LA-Omega) like Dai-Omega of KEK [11] will be employed and the production target as well as the beam dump will be placed inside the magnetic coil of LA-Omega.

Depending upon placement of each of the two production targets, photon production and pion/muon production, there are the following two possible schemes: 1) a combined target, where the electron beam will be introduced into the production target and the optics of electron extraction and transport is required; 2) A separated target, where the two targets are placed in a separated position and the bremsstrahlung real photon is delivered from some distance. The advantage of the separated target can be summarized as follows: 1) the major radiation background from the primary electrons can be removed by sweeping the electron orbit so that the beam dump inside LA-Omega is only due to photons; 2) the handling of the production target of the photo-pion production becomes easier so that optimization of the target will be made easily.

In the separated target system, efficiency of the bremsstrahlung has to be considered. Following Fig. 25 of the reference [9], one can obtain a qualitative estimate of the efficiency for high-energy electrons.

4. Intensity estimation of electron muon source

The pion yield needed for muon-intensity estimation from the direct photo-pion process can be estimated by the following formula,

\[
Y(\pi) = I_\text{e} \int \int \frac{d\sigma_{\text{e}}(E, k, Z_1)\varepsilon(E, Z_1, t)(nt)}{dT \, d\Omega_x} (nt) \, dT \, d\Omega_x
\]

where \(Y(\pi)\), pion yield; \(I_\text{e}\), electron intensity; \(\sigma_{\text{e}}\), bremsstrahlung cross section; \(E, k\), electron energy; \(Z_1\), Z number of photon production target; \(\varepsilon(E, Z_1, t)\), photon production efficiency for \(E\) and \(Z_1\) target (t thick); \((nt)_\text{a}\), atomic-number thickness of photon-production target; \(\sigma_{\text{p}}\), photo-pion cross section; \(Z_2\), Z number of pion-production target; \(T_\pi\), pion energy; \(\theta_\pi\), pion emission angle; \((nt)_\text{t}\), atomic-number thickness of photon-production target.

In order to simplify the argument, based upon photo-pion data, following assumptions are adopted.

1. Concerning the region of pion photo-production conditions of \(T_\pi\) and \(\theta_\pi\) for our purpose, the \(\sigma_{\text{e}} dT \, d\Omega_x\) is constant against \(k\), as seen in \(^{12}\text{C}\) data [1] and Fig. 1.
2. Concerning the region of the photon production, the \(\sigma_{\text{e}}\) is approximately written as \(10(Z)^2/\text{k (mb)}\) [2].
3. The bremsstrahlung photon at 0 degree is delivered to the pion-production target without significant loss.

Then the formula is written as follows,

\[
Y(\pi) = I_\text{e} \times I_{\text{e}} \times I_{\text{p}}
= I_\text{e} \times \{10^{-26}(Z)^2\ln(E/m_e)(E, Z_1, t)(nt)\}
\times \{[d\sigma_{\text{e}}(k, Z_2, T_\pi, \theta_\pi)/dT \, d\Omega_x] (nt) \, dT \, d\Omega_x\}
\]

The estimation for the case of 300-MeV and 10-μA microtron with the use of 0.1 radiation length W for a 0-degree photon source and 1 cm carbon for 45-degree pion extraction for LA Omega is given as follows.

\[
I_\text{e} (0.63 \times 10^{14}/\text{s}, 10\mu\text{A}), (Z_2)^2 ((74)^2, W),
\varepsilon(E, Z_1, t) (0.1, 300\text{MeV electron and 0.35mm W} [9]),
[d\sigma_{\text{e}}/dT \, d\Omega_x] (0.4 \times 10^{-30} \text{ (cm)}^2/\text{MeV/Sr}),
(nt)_\text{a} (0.22 \times 10^{22} \text{ (cm)}^{-3}, 0.35\text{mm W}),
(nt)_\text{t} (1.0 \times 10^{23} \text{ (cm)}^{-3}, 10\text{mm C}),
dT \, d\Omega_x (10\text{MeV, LA Omega [13]}), d\Omega_x (1\text{Sr, LA Omega})
\]
\[ Y(\pi) = (0.63 \times 10^{14}) \times (0.92 \times 10^{-3}) \times (4 \times 10^{-7}) / s = 2.3 \times 10^5 / s \]

As a confirmation, similar estimations can be made for the case of pion production at Saclay, where 420-MeV, 600-\(\mu\)A electron beam is bombarded to 10-mm Cu to produce pions at 120-degree. There, in addition to the direct photo-pion process, the inelastic electro-pion process contributes. Therefore, estimation should be considered to check qualitative agreement. The estimated value of 5.4\(\times\)10\(^7\) /s is 30 times larger than the reported experimental value, 1.8\(\times\)10\(^6\) (3000x600) [12]. As a further confirmation, the MARS calculation was applied to the case of the Saclay machine, the result is 1.7\(\times\)10\(^7\) /s.

5. Conclusion and future extension

As shown above, a 300-MeV and 10-\(\mu\)A electron microtron (with a necessary utility of 0.2 MW and 300 l/min water) coupled with LA muon capture will produce 10 MeV pions with 2.0\(\times\)10\(^5\) /s intensity, corresponding to the surface \(\mu^+\) of 8\(\times\)10\(^3\) /s. Further advancement of the produced muon beam-quality will be realized by using the recently developed concept of the muon micro-beam [13]; because of the conservation law of phase-space volume, acceleration of the degraded muons will produce a beam with a sub-mm size, with an efficiency determined by the degrader. The proof of this concept has been obtained either in the simulation calculation [13] or in the DC acceleration of the ultra-slow muon [14]. Thus, by placing a wedge-absorber at the dispersive-focus point of the LA-Omega, 100-keV degraded muons are obtained with 0.5 % efficiency. They will be fully captured and accelerated by a RFQ-DTL linear accelerator to produce a 10 MeV muon micro-beam [13]. The obtained beam, as seen in Fig. 2, can be applied to the functional imaging of the human brain at the regular hospital. As shown in our recent experiments [3], the muon spin probe can detect time-dependent density profile of oxy- and deoxy-Hb independently at \(\geq 10\) cm depth and mm-size local area. Thus, new information of the brain function, which MRI is unable to detect, can be obtained.

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References