A COMPACT MUON ACCELERATOR FOR TOMOGRAPHY AND ACTIVE INTERROGATION*

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Abstract

Muons have been demonstrated to be great probes for imaging large and dense objects due to their excellent penetrating ability. At present there are no muon accelerators. Development of a compact system that can produce an intense beam of accelerated muons would provide unique imaging options for stockpile stewardship while delivering minimal radiation dose, as well as various homeland-security and industrial applications. Our novel compact accelerator approach allows a single linac to be used to first accelerate an electron beam to 800 MeV to generate muons by interacting with a production target in a high-field solenoid magnet and then to collect and accelerate these low-energy muons to 1 GeV to be used for imaging or active interrogation. The key enabling technology is a high-gradient accelerator with large energy and angular acceptances. Our proposed solution for efficient acceleration of low-energy muons is a 0-mode linac coupled with conventional electron RF accelerating structures to provide a compact system that could deliver a controllable high-flux beam of muons with well-defined energy to allow precise radiographic inspections of complicated objects. The details of the conceptual design will be discussed.

INTRODUCTION

Muons are elementary particles that make great probes for imaging large dense objects due to their excellent penetrating ability. While electrons are easily stopped in dense matter, muons have much higher penetrating ability due to their larger mass. As leptons, they do not experience strong interactions that are typical for protons or neutrons. This makes muons unique probes for large and dense objects. Muon radiography using cosmic muons has been demonstrated [1], but is limited by the relatively low rate and the large energy range of muons produced in cosmic ray showers. Availability of intense beams of mono-energetic muons would enable radiography for large-scale imaging, stockpile stewardship or industry applications, and valuable new tools for improved materials diagnostics (e.g., advanced muon spin relaxation / resonance / rotation). Applied to Homeland Security, beams of negative muons can provide unique elemental analysis of materials via muonic X-rays even under heavily-shielded conditions [2, 3].

The problem is how to make and accelerate enough muons. Muons are unstable particles, with a mean lifetime of 2.2 μs at rest. Nevertheless, this is long enough to accelerate them, increasing their lifetime in the lab frame due to relativistic effects. Muons are the most numerous energetic charged particles at sea level. Produced mainly by proton collisions in the upper atmosphere, muons arrive at sea level at an average flux of about $1/\mathrm{cm}^2$/minute, comprising roughly half of the total natural radiation background. The atmospheric muon flux depends on the muon incidence angle φ from the vertical direction ($\varphi = 0$) as $\sim\cos^2\varphi$ and also on incident muon energy. In the 1-GeV energy range, it decreases by 5 orders of magnitude between the vertical and horizontal directions [4]. In the lab, muons are produced by decays of pions, which are created when a high-energy particle beam hits a target. Most of the created muons have low energies (< 50 MeV) and are spread in all directions. Conventional muon experiments utilize such target-produced muons. Usually only a tiny fraction of all produced muons, those with highest energies and traveling in the forward direction, are captured and used; the resulting muon flux is therefore very low.

An accelerator-based system producing a higher muon flux, at least of order 10^3/s, with energies ~1 GeV or above in a well-directed beam would provide a game-changing advancement for several applications including muon tomography. A moderate-resolution reactor image (±10 cm) achieved by a month-long exposure to cosmic muons would be obtained within minutes. Much higher muon fluxes, up to 10^9/s, are required for active stand-off interrogation to identify nuclear materials in large targets such as a container ship [2, 3].

PRELIMINARY STUDIES

From 2009-2011, the Defense Threat Reduction Agency (DTRA) supported studies at Los Alamos to develop an active stand-off muon interrogation system for identifying special nuclear materials in cargo. Our concept was based on collecting and accelerating low-energy pions and muons to achieve the required very-high muon flux [5]. The key enabling element is a high-gradient muon accelerator with large energy and angular acceptances based on a 0-mode linac operating in a 5-T solenoidal magnetic field to keep particles with large transverse momenta within the linac aperture. The 0-mode linac accelerates low-energy

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muons to ~200 MeV, where they are almost ultra-relativistic; their further acceleration can then be accomplished by more conventional means. Special wide-aperture RF cavities that constitute the 0-mode muon linac were designed and optimized [6, 7]. A large 90-cm-bore, 5-T superconducting solenoid for the pion production target was also designed and built. A prototype 805-MHz cavity was developed by Los Alamos and built by Muons, Inc. [8]. It was tested at FNAL, demonstrating a world-record accelerating gradient of 25 MV/m in a 3-T magnetic field [9]. This 0-mode-type cavity was designed to operate either in vacuum or filled with high-pressure gas. Figure 1 shows a segment of the 805-MHz, 0-mode muon linac and cavity details.

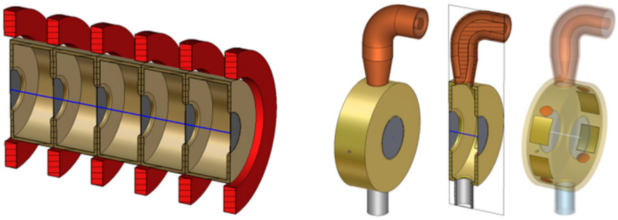

Figure 1: Left: segment of 805-MHz, 0-mode muon linac (5 RF cavities, copper color) for $\beta = 0.8$ with thin aperture windows of radius 6 cm (dark grey); outer current coils (red); RF couplers not shown. Right: 0-mode $\beta = 0.537$ RF cavity details [7].

SYSTEM FOR TOMOGRAPHY

We propose an accelerator-based system for tomography that provides a controllable high-flux muon beam. Our approach is to collect and accelerate the copious low-energy muons. The enabling element is a high-gradient accelerator with large energy and angular acceptances, taking advantage of our previous studies for DTRA.

In our concept, a large number of low-energy pions are produced at the target with an almost isotropic spatial distribution. They decay promptly (mean lifetime 26 ns) into low-energy (tens of MeV) muons. Collecting and accelerating such a muon "cloud" is the main point of our approach. This is especially attractive when compactness and cost are important. Because the number of low-energy muons produced is relatively large, a moderate proton or even electron accelerator can be used as a driver. A possible compact accelerator system for muon tomography is shown in Fig. 2. It consists of a simple production target and collection-transfer system of solenoids that brings muons to an initial large-acceptance, high-gradient, 0-mode radio-frequency (RF) linear accelerator that bunches muons and accelerates them to about 200 MeV. After that the main muon RF linac further accelerates the muons to their final energy, chosen to be 1 GeV in this example.

At 200 MeV, muons are nearly relativistic ($\beta = v/c = 0.94$), so the main linac can be built using conventional accelerator technology for electron linacs, with RF cavities designed for ultra-relativistic ($\beta = 1$) beams. This feature allows us to use the same linac first as an electron driver to accelerate an initial electron beam from an injector to 800 MeV. The accelerated electron beam is then transferred to the target for pion production (see Fig. 2). After muon capture and initial acceleration to 200 MeV, the main linac then accelerates the muon beam to 1 GeV. This leads to an overall compact muon linac design. Assuming an accelerating gradient of E_0 = 20 MV/m for the main linac results in a 40-m main linac length. If standard superconducting sections such as developed for the electron International Linear Collider (ILC) (frequency 1.3 GHz, $\beta = 1$, $E_0 = 31.5$ MV/m) are used, the main linac length will be reduced to approximately 25 m.

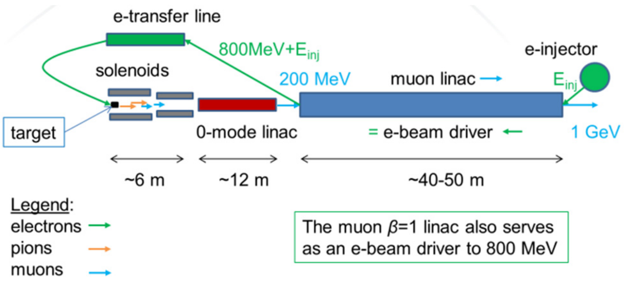

Figure 2: Concept of an accelerator-based system for muon tomography.

The RF cavities in the 0-mode linac (see Fig. 1) are electrically closed, e.g. by thin metal windows or grids [7]. This reduces the maximal surface electric field by a factor of up to 15 compared to the standard π-mode operation. Using the 0-mode allows achieving very high gradients while mitigating cavity RF breakdowns. Though such structures are not used in modern accelerators due to beam loss on the aperture windows, they will work well for accelerating muons, which easily penetrate thin low-Z windows.

For active interrogation, the design parameters of the 0-mode linac are quite challenging: an accelerating gradient of 35 MV/m in large-aperture cavities with surrounding solenoidal field of 5 Tesla were required to deliver a very high muon flux of 10^9/s. For muon tomography, many of these parameters can be relaxed (lower gradient, focusing field, and aperture size) or changed (e.g., higher RF frequency will reduce the transverse cavity size). Calculations of the muon capture and acceleration for interrogation with tracking codes showed that using the 805-MHz cavity parameters above resulted in about 7% of all produced muons being accelerated to 200 MeV [10]. Even an order of magnitude reduction of this output will still produce more than enough flux for muon tomography using the 0-mode linac.

The ionization energy loss in matter has a broad minimum for muon energies between 0.1 and 10 GeV, $|dE/dx|$ = 1.1-2 MeV·cm^2/g [11]. Therefore, 1-GeV muons can penetrate more than a meter of steel or about 3 m of concrete, which is sufficient for tomography of a nuclear reactor but not of a damaged reactor building. In the latter case, higher muon energies are required, e.g., 5 GeV. This can be achieved with a longer main linac in the scheme of Fig. 2, but a more compact solution is a racetrack scheme with two muon linacs connected by transfer arcs as shown in Fig. 3. Such a system can even be made portable if mounted on a barge. This scheme is similar to that used on a larger scale in the CEBAF facility at JLab to accelerate electrons to 12 GeV, although for muons there will be higher losses because of a narrow energy acceptance range of the arc magnetic bends.

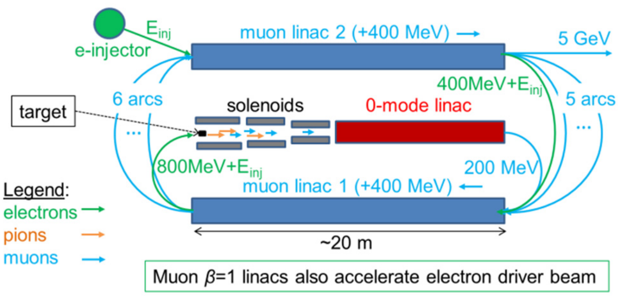

Figure 3: Higher energy accelerator system for muon tomography of large objects based on recirculating muon linacs.

For simple estimates of the expected muon flux at 1 GeV, we start from the flux of 10^9/s shown in simulations for muon interrogation. Replacing 800-MeV protons by electrons reduces the muon output by a factor of 100. Effects of simplifications in the 0-mode linac (smaller apertures, reduced solenoidal field) are more difficult to evaluate (eventually to be done by simulations), but let us assume an additional large reduction of another factor of 100. Even in this pessimistic case we still have a resulting muon flux of 10^5/s at 1 GeV (the losses in the main linac of Fig. 2 will be small). For higher muon energies in the scheme of Fig. 3, we assume that at least 10% of muons will be transferred via the arcs, with the largest losses in the first arc. Most likely this fraction can be increased by magnet optimization, but even without this effort we expect about 10^4 muons per second at 5 GeV. This is an order of magnitude higher than an estimated flux of 10^3/s required for providing high-resolution tomography of the Fukushima reactor buildings within minutes [12].

TECHNICAL CHALLENGES

The major technical challenges are related to the 0-mode linac and the main muon/electron linac. The 0-mode linac is a completely new accelerator technology. Since rather challenging linac performance parameters are needed for active interrogation as shown by our previous studies, additional work should first focus on meeting the comparatively relaxed requirements for radiography. Additional simulations are required to further the conceptual design. A demonstration of the first working 0-mode cavity including RF testing at LANSCE using existing 805-MHz klystrons and RF infrastructure and demonstrating sufficient muon production and capture to meet muon flux requirements for radiography could be planned. Design and optimization of the pion/muon production source includes selection of the material choice for the electron-beam target; possible candidates are carbon and tungsten. It should also include optimizing the target geometry, the capture solenoid, and transfer-channel solenoids. The best available tools for this study are Geant4 and G4beamline. The 0-mode linac parameters (RF frequency, gradient, aperture size, external solenoidal field, etc.) would be optimized using the CST Studio Suite. The goal would be to achieve the required muon flux from the 0-mode linac for radiography without the use of external solenoidal beam focusing.

For the main linac, accelerating both muons and electrons in one structure may be challenging; it has never been done before. Beam dynamics simulations using CST, LANL accelerator codes, and G4beamline could be used to further study the feasibility of this concept, including evaluation of the final muon flux. An alternative solution would use a separate linac for each beam. However, most likely a significant part of the linac could be used for accelerating both electrons and higher-energy muons, e.g., from 400 MeV ($\beta = 0.98$) either by extending the 0-mode linac or by using a separate section of the conventional RF linac for 200-MeV muons. Finally, it is unclear whether muons can be accelerated in superconducting structures at all: their decays may trigger RF breakdowns. Details of this option should also be studied in the future.

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