LARGE-ACCEPTANCE LINAC FOR ACCELERATING LOW-ENERGY MUONS

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Abstract

We propose a high-gradient linear accelerator for accelerating low-energy muons and pions in a strong solenoidal magnetic field. The acceleration starts immediately after collection of pions from a target by solenoidal magnets and brings muons to a kinetic energy of about 200 MeV over a distance of the order of 10 m. At this energy, both an ionization cooling of the muon beam and its further acceleration in a superconducting linac become feasible. The project presents unique challenges – a very large energy spread in a highly divergent beam, as well as pion and muon decays – requiring large longitudinal and transverse acceptances. One potential solution incorporates a normal-conducting linac consisting of independently fed 0-mode RF cavities with wide apertures closed by thin metal windows or grids. The guiding magnetic field is provided by external superconducting solenoids. The cavity choice, overall linac design considerations, and simulation results of muon acceleration are presented. While the primary applications of such a linac are for homeland defense and industry, it can provide muon fluxes high enough to be of interest for physics experiments.

INTRODUCTION

Beams of accelerated muons are of great interest for fundamental research as well as for applications in homeland defense and in industry. When a proton beam hits a target, pions are produced, and after the short 26-ns life time they decay into muons. Most of the created muons have low energies and are spread in all directions from the target. The 2.2-μs life time of muons is long enough to accelerate them; accelerated muons live much longer due to relativistic effects. Muon accelerators are being studied for the Neutrino Factory and Muon Collider (NF/MC) [1] but their huge size and cost prohibit other applications. In the NF/MC projects only a small fraction of all produced muons, those with relatively high energies and traveling in the forward direction, is used. This is justified by the need to have very low emittances for MC but requires a high-power proton driver, which is a $1B-class machine, to provide a sufficient muon flux.

We suggest an alternative approach of collecting and accelerating the copious low-energy (tens of MeVs) muons that can lead to smaller and cheaper systems. In homeland defense, muon beams can enable unique element analysis of special nuclear materials (SNM) via muonic X-rays or detection of high-Z materials by muon radiography even under heavily-shielded conditions. For industrial applications, muon radiography of large-scale machinery using cosmic-ray muons is becoming popular, but a high-intensity pencil beam of accelerated muons would be a much more valuable tool for dynamic investigation of machinery. A compact and inexpensive muon accelerator is also desired for medical use. These applications have different beam requirements: for muon radiography, a mono-energetic μ$^+$ beam with minimal divergence is ideal, but μ$^-$ beams for SNM interrogation in cargo can benefit from a wide energy spread and large spot size. In all cases, however, the common task is to accelerate the low-energy muons to higher energies.

Therefore, there is a significant need to have a compact and efficient accelerator that can capture a large fraction of a divergent pion-muon beam from a production target and accelerate muons quickly. We propose a novel linear accelerator with large acceptance and high gradient that can provide an efficient capture and fast acceleration of low-energy muons.

LARGE-ACCEPTANCE LINAC DESIGN

Large transverse acceptances can be achieved with wide-aperture cavities. Keeping the "cloud" of pions and muons inside the aperture requires a strong continuous solenoidal magnetic field. The longitudinal acceptance can be increased by using high accelerating gradients. A potential solution that satisfies all these requirements is a normal-conducting (NC) linac with external solenoids.

Cavity Choice: π-mode versus 0-mode

NC linac structures with large beam apertures typically operate in the π-mode, with adjacent cells coupled via open apertures, mainly at beam velocities $\beta = v/c \approx 1$. Our linac should start at much lower β-values: around $\beta = 0.5$ for μ$^-$ produced by a proton beam (the peak of muon kinetic energy is ~16 MeV [2]), or even at $\beta = 0.25$ for μ$^+$ from a surface muon source (~4 MeV). Instead of π-mode, we suggest using the 0-mode – the TM$_{010}$ mode of a pill-box resonator – in a chain of independently-fed cavities with wide apertures electrically closed by thin metal windows or grids. The two modes – their electric field pattern and on-axis field profile along the cavity – are compared in Fig. 1 for 805-MHz cavities with the design value $\beta_g = 0.8$. In this example, the cavity length L_c = $\beta_g \lambda/2$ = 14.9 cm; the aperture radius is a = 6 cm, about 40% of the cavity inner radii $R \approx 15$ cm.
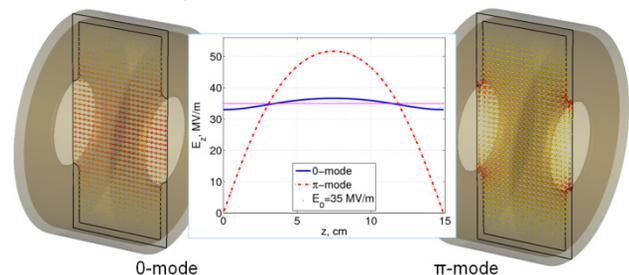

Figure 1: Two working modes for wide-aperture cavities.

One can see that the highest field (red) is near the axis in the 0-mode, while the maximum in the π-mode is at the septa, near the aperture edges. As the cavity lengths become shorter for smaller values of β, the π-mode cavity becomes more and more inefficient due to very large fields at the septa. This is illustrated in Fig. 2, where the maximal electric field and the cavity surface-loss power are plotted versus for 0- and π-modes in 805-MHz cavities with $a = 6$ cm at a fixed gradient of $E_0 = 35$ MV/m. E_{max} is normalized to the Kilpatrick field for 805 MHz, $E_K = 26.08$ MV/m. The maximum surface fields below $1.8E_K$ are usually considered safe with respect to RF breakdowns, but this limit can be reduced by a factor of 1.5-2 in solenoidal magnetic fields of a few T, e.g. [3].
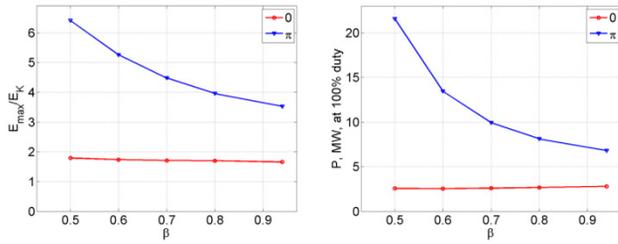

Figure 2: Cavity parameters for 0- and π-modes versus β.

The mode comparison becomes even more in favor of the 0-mode at larger values of a/R, i.e. wider apertures [4]. On the other hand, the transit-time factors are higher for the π-mode: 0.77 versus 0.65 for 0-mode for $a/R \approx 0.4$.

One should emphasize that a linac based on isolated cavities with apertures closed by thin metal windows can work efficiently only for muons, due to their high penetrating ability. Another feature related to the metal aperture windows is that a fraction of the power loss in the cavity is deposited on the windows, cf. Tab. 1, so their cooling must be addressed. The values in Tab. 1 are for the Cu cavities with $a = 6$ cm, the septum thickness 2 cm, at the fixed gradient of $E_0 = 35$ MV/m.

Table 1: Some 805-MHz 0-mode cavity parameters.

Parameter	$\beta_g = 0.5$	$\beta_g = 0.7$	$\beta_g = 0.94$
Length L, cm	9.31	11.17	17.50
Radius R, cm	14.86	14.67	14.55
$Z_{sh}T^2$, MΩ/m	18.4	25.6	32.3
Loss power P, MW*	2.56	2.60	2.80
Max P flux, W/cm^2*	1595	1409	1292
Aperture P_a, %/kW*	2.5 / 63	2.3 / 60	2.0 / 56

* = at 100% duty

Judging by the maximal values of the wall power-loss density in Tab. 1, these cavities can be operated at duty factors of a few percent. Still, the power deposited on the aperture windows will be in the kW range. For a given 0-mode RF cavity, $P_a \propto a^4$ when $a << R$, and the window cooling for large apertures can become an engineering challenge. One possible approach is an edge-cooled thin-wall window, with all cooling channels located in the septum. Another option is a double-wall window with supporting ribs between two thin metal sheets; its concept is shown in Fig. 3. The channels between the ribs serve for cooling, e.g. by a cold gas.
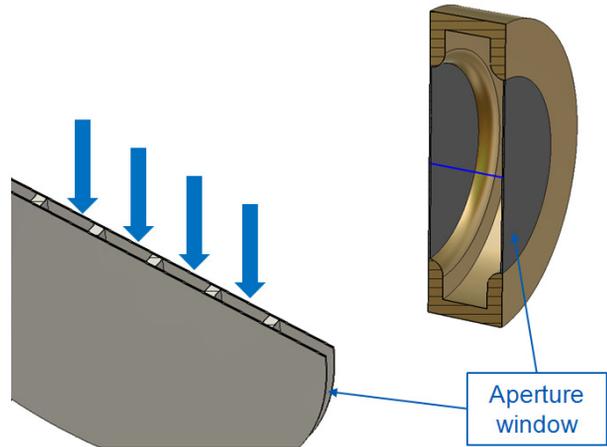

Figure 3: Concept of double-wall cooled aperture window with ribs (dark-grey) in an RF cavity (copper color).

The linac frequency choice is important. Obviously, lower frequencies lead to larger cavities. The aperture size can also be made larger, and the number of cavities is smaller. On the other hand, achieving higher gradients is easier at higher frequencies. Higher-frequency klystrons also provide higher peak power. The cavity comparison in [4] between 402.5, 805, and 1300 MHz indicates that $E_0 = 35$ MV/m is realistic in the latter case. There is some experimental evidence that in a pill-box cavity filled with high-pressure (HP, 15-30 atm) hydrogen gas the limiting value of the maximal electric surface field, even in high external magnetic fields, is restored to that without the external field [5] independent of frequency. A research program for HP cavities is being pursued in NF/MC R&D activities [5]. If this development succeeds, HP cavities would be uniquely suited for muon acceleration.

Linac Layout

One possible layout of a NC muon linac is illustrated in Fig. 4 where a linac segment consisting of adjacent RF cavities is shown. A close packing of the RF cavities maximizes the real-estate accelerating gradient.
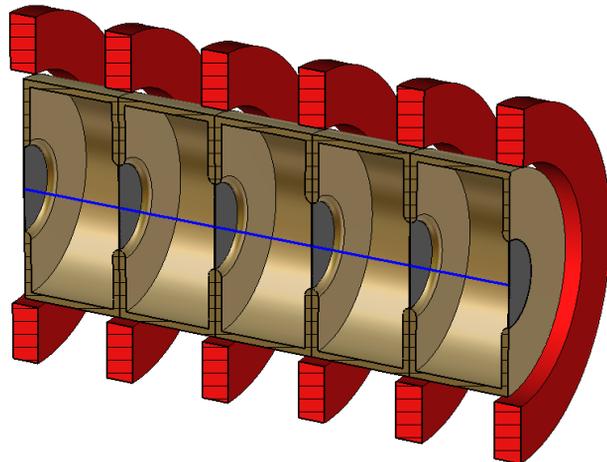

Figure 4: Muon-linac segment (cut view): five RF cavities with aperture windows surrounded by current coils (red).

We chose 805-MHz 0-mode RF cavities as a baseline for the μ^- linac starting at $\beta_g = 0.5$. To achieve the muon energy gain of 200 MeV in such a linac designed with continuously increasing cavity lengths ($\beta_g = 0.5$ to 0.94), gradient $E_0 = 35$ MV/m and synchronous phase $\varphi = -30°$ in all cavities, the required number of cavities is 76 [4]. The final energy of the synchronous particle is 216 MeV; the total linac length is 10.19 m. Having a phase ramp (synchronous phase adjusted along the linac) is better for beam dynamics: starting with a larger phase, $\varphi = -60°$, increases the phase acceptance and provides beam bunching; gradually reducing it along the linac to $\varphi = -20°$ restores the acceleration. Such a ramp leads to a higher muon flux from the linac as confirmed by simulations [2, 6]. It is customary in linacs to employ only a few types of cavities instead of making them all different: e.g. use a few $\beta_g = 0.5$ cavities, then switch to $\beta_g = 0.6$, and so on. The resulting muon linac then consists of a smaller total number of RF cavities, $N_{cav} = 67$ (for $E_0 = 35$ MV/m at $\varphi = -30°$). The final energy is 217 MeV, and the total linac length is 10.00 m. The T-factors, as well as synchronous and design β-values for this linac are shown in Fig. 5. The number of cavities of each type is 4, 6, 10, 22, and 25, for $\beta_g = 0.5, 0.6, 0.7, 0.8$, and 0.94, respectively.
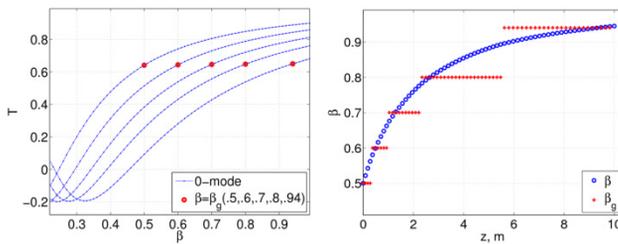

Figure 5: T-factors versus β and β versus z in the linac.

RF Considerations

The 0-mode RF cavities in the linac form a chain of independent (uncoupled) cavities so that the RF power should be fed into each of them separately: each cavity has an independent RF input. This provides flexibility in operating the linac (it can accommodate any phase ramp) but complicates the overall design since the RF feeds must fit between the solenoid coils. To arrange the proper accelerating phases (~180°-degree phase shift per cavity) in a 0-mode chain, the structure is fed inter-digitally from two RF inputs shifted by 180°, creating an accelerating field pattern in the linac similar to that in the π-mode. It is possible to reduce the number of RF feeds by a factor of two by employing pairs of coupled 0-mode cavities, with one RF input per pair. The two cavities should be coupled magnetically by slots in the common septum, while the apertures remain closed by windows. The anti-symmetric mode of the two-cell system will be the working mode.

An estimate of the required total peak RF power for the above muon linac with 67 cavities of 5 types is 180 MW. Adding usual 15% for a realistic surface conductivity and RF losses in waveguides (~5%) increase that by 20%. The power estimate for a similar linac at 402.5 MHz with the

same gradient is about 35% higher, and that at 1.3 GHz is 30% lower [4]. The minimal RF pulse length is defined by the cavity filling time of ~30 μs at 805 MHz. It may be advantageous to use klystrons with pulses of a few 100 μs that provide higher peak power. Nevertheless, finding ways to reduce the required peak RF power is important.

Beam Dynamics Simulations

The muon flux produced by the linac is estimated by simulations with a specialized Monte-Carlo tracking code [2, 6]. The code tracks particles in combined RF and magnetic fields taking into account pion and muon decays and particle interactions with window material. The 805-MHz linac described above with the magnetic field $B = 5$ T accelerates to 200 MeV about 10% of the muons at its entrance. Assuming a 50-μA 800-MeV proton beam on a 30-cm carbon target, the linac can deliver $3 \cdot 10^9$ μ^-/s at 200 MeV. Simulations show the muon-flux reduction by a factor of about 2 when either E_0 is reduced to 25 MV/m or B to 3 T. The reduction can be mitigated to some extent by optimizing the linac design for particular E_0 and B [6].

SUMMARY

We propose an approach for collecting and accelerating the low-energy muons produced in pion decays when a proton beam hits a target. This method is complementary to the NF/MC projects and can lead to smaller and cheaper systems for various applications. Properties of 0-mode RF cavities and considerations for designing a high-gradient large-acceptance muon linac are presented. Accelerating a divergent beam of pions and muons with a very large energy spread requires large longitudinal and transverse acceptances. Our baseline design is a normal-conducting (NC) linac consisting of independently fed 0-mode RF cavities with wide apertures closed by thin metal windows. The guiding static axial magnetic field is provided by external super-conducting (SC) solenoids and penetrates into the cavities through their NC metal walls.

Accelerating low-energy muons presents unique challenges but the proposed approach – large-acceptance NC linac with external solenoidal field – looks feasible. The main engineering challenge is to combine the RF system, cooling, and external SC solenoids.

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