APERTURE WINDOWS IN HIGH-GRADIENT CAVITIES FOR ACCELERATING LOW-ENERGY MUONS

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Abstract

A high-gradient linear accelerator for accelerating low-energy muons and pions in a strong solenoidal magnetic field has been proposed for homeland defense and industrial applications [1]. The acceleration starts immediately after collection of pions from a target in a solenoidal magnetic field and brings muons to a kinetic energy of about 200 MeV over a distance of the order of 10 m. At this energy, both ionization cooling of the muon beam and its further acceleration become feasible. A normal-conducting linac with external-solenoid focusing can provide the required large beam acceptances. The linac consists of independently fed zero-mode (TM_{010}) RF cavities with wide beam apertures closed by thin conducting windows. The high gradients lead to significant heat deposition on the aperture windows. Here we explore options for the edge-cooled thin windows in the zero-mode cavities. Electromagnetic and thermal-stress computations are complemented by thermal-test experiments to select the best solution for the aperture windows.

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) [2] 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 by itself, to provide a sufficient muon flux.

We consider 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. In industry, muon radiography of large-scale machinery using cosmic-ray muons is becoming popular, but a high-intensity directed beam of accelerated muons would be a much more valuable tool for dynamic investigation of machinery. A compact inexpensive muon accelerator is also desired for medical and research applications. 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 utilize 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 distribution from a production target and accelerate muons promptly. We proposed [1] a novel linear accelerator with large acceptance and high gradient that can provide efficient capture and fast acceleration of low-energy muons. Such a normal-conducting (NC) linac consists of independently fed zero-mode (TM_{010}) RF cavities with wide apertures closed by thin metal windows. A guiding axial magnetic field is provided by external super-conducting (SC) solenoids and penetrates into the cavities through their NC metal walls.

ZERO-MODE CAVITIES

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 broad peak of muon kinetic energies is 15-20 MeV [3]), or even at $\beta = 0.25$ for μ^+ from a surface muon source (~4 MeV). We suggested [1] using the 0-mode – the TM_{010} mode of a pill-box resonator – in independently-fed cavities with wide apertures electrically closed by thin metal windows. 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 $\beta_g = 0.8$. Here 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 radius $R \approx 15$ cm.

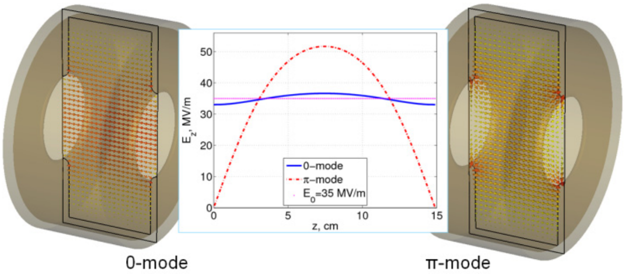

Figure 1: Two working modes in wide-aperture cavities.

As the cavity lengths become shorter for smaller values of β, the π-mode cavities become more and more inefficient due to very high fields at the septa [1, 4]. 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 $a/R \approx 0.4$.

A short 0-mode 805-MHz cavity (L_c = 10 cm) is shown in Fig. 2, as well as the contours of electric (center) and magnetic field (right). The aperture radius is a = 6 cm, the cavity inner radius R = 14.78 cm, the septum thickness 2 cm, and the aperture window thickness 0.5 mm. Table 1 presents EM parameters of the cavity calculated for ideal Cu walls at the gradient E_0 = 35 MV/m.

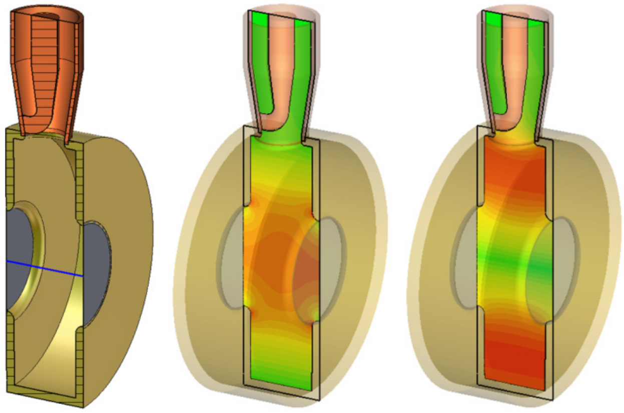

Figure 2: 0-mode cavity (β_g = 0.537) cut along the beam axis (blue), with aperture windows (grey) and RF coupler.

Table 1: EM parameters of the 0-mode cavity in Fig. 2.

Parameter (* = at 100% duty)	β_g = 0.537
Quality factor Q	22300
Transit-time factor T	0.642
Shunt impedance $Z_{sh}T^2$, MΩ/m	19.9
Max electric field E_{max}, MV/m	46.1 (1.77E_K)
Surface loss power P, MW*	2.53
Max power flux, W/cm^2* (coupler*)	1553 (6319)
Aperture power P_a, % of P / kW*	2.43 / 62

A linac based on isolated cavities with apertures closed by metal windows can work efficiently only for muons, due to their high penetrating ability. Unlike the NF/MC approach (where the forward-produced pions and muons already have significant energies, 100-300 MeV, near the minimal ionization loss ‹-dE/dx›), for low-energy muons the ionization losses are higher, so that the windows should be rather thin to gain any acceleration. One can estimate that the window thickness should be less 0.5 mm at E_0 = 35 MV/m if it is made of copper. On the other hand, some fraction of the RF power in the cavity is deposited on the aperture windows, see Tab. 1, so their cooling must be addressed. From the maximal values of the wall power-loss density in Tab. 1, the cavity 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, the window power $P_a \propto a^4$ when $a << R$, and the window cooling for large apertures becomes an engineering challenge. One option could be a double-wall window with thin supporting ribs between two thin metal sheets [1]. The channels between the ribs serve for cooling, e.g. by a cold gas. Here we explore another approach: an edge-cooled thin-wall window with cooling channels located in the septum.

Edge-Cooled Thin Aperture Windows

Initially we chose a very thin (0.125 mm) Cu window that was pre-bent (dished) to accommodate thermal expansion. Thermal analysis [5] indicated that such a window of 12-cm diameter would experience an axial displacement of a few mm, which leads to an unacceptable frequency shift of the cavity. Next we looked at corrugated windows, Fig. 3 (a, b). Their thermal displacements were smaller but still would cause noticeable frequency shifts. We found that flat metal windows with narrow radial cuts that do not interrupt surface currents, e.g. Fig. 3 (c), satisfy thermal and electrical requirements. However, mechanically they are not rigid enough, and would be prone to vibrations unless enforced by metal fins.

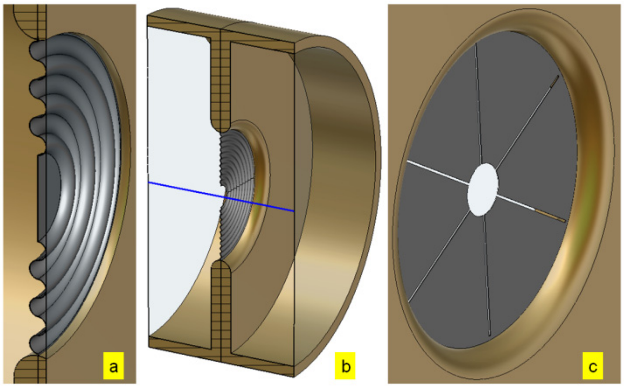

Figure 3: Aperture windows options: corrugated (a, b) and flat radially sliced (c).

Finally, we considered a thin (0.5 mm) flat carbon window made of graphite coated on both sides with two very thin copper layers (5 μm ≈ 2 skin depths) to carry surface currents. Due to the lower density, such a window can be ~4 times thicker than the copper one. Using a lower-Z material also reduces the nuclear scattering. Our expectation that good thermal properties of graphite and its low expansion coefficient reduce the stresses in this window was confirmed by the thermal-stress analysis [5]. The window was fabricated from Graphtek GM-10 [6] graphite and Cu electroplated, see in Fig. 4.

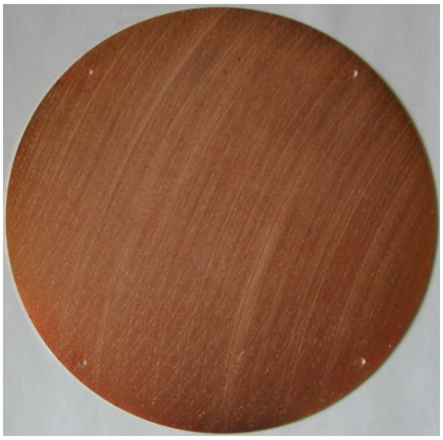

Figure 4: Copper-coated graphite aperture window.

The thermal-stress analysis [5] indicated that when the window edge was kept at 20°C, the maximal temperature in the window center was ≈50°C with the thermal load from Tab. 1 for the 2.5% duty operation. When the edge position is fixed, this leads to < 2 μm axial displacement that is negligible.

Thermal Performance Tests

To confirm the evaluated thermal performance of the windows, an experimental installation with heaters was implemented. The heaters do not produce the same radial power distribution on the window as the RF fields in the cavity: $\sim[J_1(2.405r/R)]^2$, with very small power deposited near the center. However, their nearly homogeneous heating should produce even stronger stress.

The windows were tested in vacuum to suppress convection. The window was clamped and bolted along its outer boundary between two halves of the septum plate, Fig. 5; the interfaces were coated by silver paste. The septum assembly was attached to the heater holding structure with two ceramic standoffs. Both septum plate and the aluminum heat sink plate, to which the heater and septum were mounted, were water-cooled.

The heat flux area was similar in size to the window. The electrical heater (Glowpanel, 1kW) was encapsulated within a ceramic structure with the only opening directed to the window. To maximize energy transmitted from the heater, both window faces were painted black with colloidal graphite. The window temperature was measured with the infrared camera (FSI FLIR) through the sapphire vacuum window.

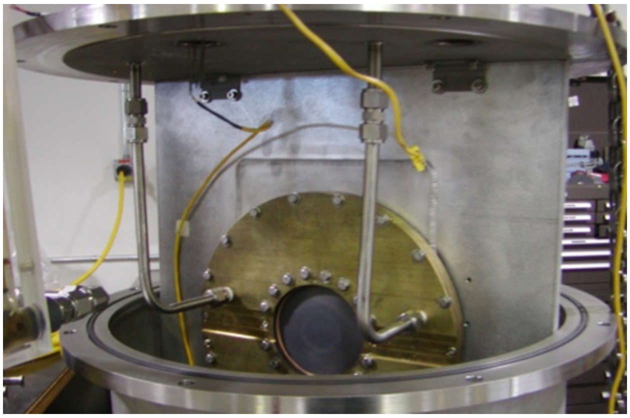

Figure 5: Experimental arrangement for window thermal tests: the window-septum assembly is shown before being inserted in the vacuum tank.

To compare the calculations to the experiment, calorimetric measurements were performed. The water flow rate and in / out temperature were measured. The temperature along the window was measured by the camera mounted on the precision table. The measurement results for the three different copper-coated carbon windows were in agreement with the thermal-analysis results. The measured temperature was within 10% of that calculated by the SolidWorks FE code [7] for the same power density distribution. All windows were inspected after heating cycles; no permanent deformation, delamination nor other damage was observed.

CONCLUSIONS

Performed thermal analysis and tests confirm that the copper-coated graphite windows satisfy the aperture-window thermal and mechanical requirements in the zero-mode cavities for accelerating low-energy muons. One of the important requirements for low-energy muons, which is different from those for the ionization cooling channel in NF/MC, is to keep the window thickness minimal. The thin copper-coated carbon windows perform well due the excellent thermal and mechanical properties of graphite. Our future plans include testing their RF performance in RF cavities.

There are other interesting options for the aperture windows in normal-conducting zero-mode cavities. In particular, high-pressure cavities filled with a low-Z gas that are studied for the NF/MC, could benefit from a gridded window that allows the gas flow to both cool the cavities and remove ions produced by passing beam bunches. One the other hand, the grid wires enhance the maximal electric field on the grid window compared to the flat one. Cooling flat windows by the gas flowing through high-pressure cavities was also considered [8]. Another approach for vacuum cavities is to use a low-Z metal, e.g. beryllium, in flat thin windows. This option is especially attractive if the cavities are operated at liquid-nitrogen (LN) temperatures, due to good electrical and thermal properties of Be in that temperature range. However, such a window should be LN cooled to take full advantage of these properties.

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REFERENCES

[1] S.S. Kurennoy, A.J. Jason, H. Miyadera, “Large-Acceptance Linac for Accelerating Low-Energy Muons.” IPAC10, Kyoto, Japan, p. 3518 (2010).
[2] J.S. Berg et al, Phys. Rev. ST-AB, 9, 011001 (2006).
[3] H. Miyadera, A. Jason, S. Kurennoy, “Simulations of a large acceptance linac for muons,” PAC09, Vancouver, BC, p. 3555 (2009), www.JACoW.org.
[4] S. Kurennoy, Tech notes AOT-ABS 09-004, -008 (TN), 2009; LA-UR-10-00246, Los Alamos, 2010.
[5] W. Tuzel, Tech notes ISR-6, 10/10/2010 and 03/08/2011, Los Alamos.
[6] Graphtek LLC, www.graphtekllc.com
[7] SolidWorks, Dassault Systèmes SolidWorks Corp., www.solidworks.com
[8] M. Alsharo’a et al, “Thin RF Windows for High-Pressure Gas-Filled Cavities,” PAC05, Knoxville, TN, p. 3224 (2005), www.JACoW.org.