LA-UR-17-20025

Approved for public release; distribution is unlimited.

Title: Report on study of accelerating structures for muons in the velocity range of $\beta=v/c=0.08-0.3$ for J-PARC (g-2)/EDM experiment

Author(s): Kurennoy, Sergey S.

Intended for: External distribution

Issued: 2017-01-04

Disclaimer:

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Technical Note

Accelerator Operation and Technology

AOT-AE Group:

Accelerators & Electrodynamics

To/MS: Distribution

From/MS: Sergey Kurennoy, AOT-AE / H817

Phone/Fax: 505-665-1459 / 505-665-2904

E-mail: kurennoy@lanl.gov

Symbol: AOT-AE: 16-010 (TN)

Date: September 7, 2016

SUBJECT: Report on study of accelerating structures for muons in the velocity range of $\beta=v/c=0.08-0.3$ for J-PARC (g-2)/EDM experiment.

During my visit to J-PARC Aug. 20 – Sep. 3 2016, a few possible structures at 324 MHz for accelerating muon in the velocity range of $\beta=0.08-0.3$, after the RFQ but before the disk-and-washer structure, were considered and compared using CST 3D electromagnetic calculations and particle modeling. This short report summarizes our results.

Distribution:

AOT-AE			(e-mail copy)
R.W. Garnett	AOT-DO	MS H817	(e-mail copy)
Y.K. Batygin	AOT-OPS	MS H817	(e-mail copy)

1. Introduction.

For the planned experiment E34 at J-PARC to measure with high precision (g-2)/EDM for muons, a cold muon beam has to be accelerated to 212 MeV [1]. The baseline design anticipates an interdigital H-mode structure with alternative-phase focusing (IH-APF) at 324 MHz [2] that follows an RFQ and should accelerate muons from 0.34 MeV ($\beta = 0.08$) to about 4-5 MeV ($\beta = 0.26-0.3$) to bring them to the disk-and-washer (DAW) structure. Using CST [3] 3D EM analysis and particle modeling, we consider this structure and a few possible alternatives for accelerating muons in the velocity range of $\beta=0.08-0.3$, to compare them and chose the best option.

One should take into account some particular features of the cold muon beam after the RFQ and corresponding requirements: (i) very low current ($<1 \mu\text{A}$); (ii) relatively high RF frequency, (iii) high accelerating gradient is required to minimize muon decay losses, (iv) required high beam quality, hence, one should minimize beam emittance growth, and (v) practical considerations of structure efficiency and reasonable fabrication cost.

2. Muon accelerating structures at intermediate velocities.

There are three classes of structures potentially suited for the beam velocity range $\beta = 0.08-0.3$: drift-tube linac (DTL) operating in TM_{010} mode, interdigital H-mode structure (IH-DTL or IH for short) operating in $\text{TE}_{11(0)}$ mode, and cross-bar H-mode structure (CH-DTL or CH) operating in $\text{TE}_{21(0)}$ mode. One should note that typically the range of best efficiency for IH is somewhat lower, $\beta = 0.01-0.1$, see e.g. [4] and references therein.

2.1. DTL

The DTL can be easily designed using standard LANL accelerator codes [5] SUPERFISH and PARMILA. We considered two versions: a 7-cell DTL with the design average cell field $E_0 = 4.5$ MV/m that brings muons to 4.2 MeV, see in Fig. 1; and a longer, 9-cell DTL with $E_0 = 4$ MV/m that accelerates muons to 5.1 MeV.

Fig. 1: 7-cell DTL structure: CST model (left); the number of macro-particles vs time in CST Particle Studio run (right).

The CST 3D models of DTL tanks were constructed, the modes are calculated with MicroWave Studio, and beam dynamics simulations performed with Particle Studio. The initial transversely matched muon

beam distributions were provided by M. Otani, with normalized transverse rms emittances $\varepsilon_x = 0.297 \pi \mu\text{m}$ and $\varepsilon_y = 0.167 \pi \mu\text{m}$.

Some results are summarized in Table 1. The power loss values assume ideal copper surface; for realistic surfaces, they should be increased by 15%. The Kilpatrick field at 324 MHz is $E_K = 17.84$ MV/m. One can see that the maximal electric fields are rather low for both DTL versions, so the gradient E_0 can still be safely increased. The emittance increase is moderate and can be further reduced with better matching.

Table 1. DTL cavity dimensions and EM parameters.

Parameter	7 cells	9 cells
Cavity length L , cm	112.6	156.0
Cavity inner radius R , cm	26.5	26.5
Aperture radius a , cm	1	1
Outer drift-tube radius, cm	5	5
Quality factor Q	44769	46577
Average cell accelerating gradient E_0 , MV/m	4.5	4
Effective shunt impedance $Z_{sh}T^2$, $\text{M}\Omega/\text{m}$	39.2	40.7
Total averaged wall power dissipation P , kW, 100% duty	392	414
Maximal peak electric field E_{max} , MV/m	29.2 (1.64 E_K)	26.4 (1.48 E_K)
Maximal peak surface magnetic field H_{max} , kA/m	32.5	30.7
Maximal surface power density dP/dS , W/cm^2 , 100% duty	196	175
Muon energy gain, MeV, for synch phase -30° (Part. Stud.)	3.88	4.80
Output norm horizontal rms emittance ε_x , $\pi \mu\text{m}$ (Part. St.)	0.317	0.350
Output norm vertical rms emittance ε_y , $\pi \mu\text{m}$ (Part. Stud.)	0.188	0.171

The strengths of focusing quadrupoles are relatively low, $G' = 25\text{-}35$ T/m, which gives a choice of using either PMQs or regular EM quadrupoles. The last option provides more flexibility for tuning focusing. In any case, the number of required quadrupole magnets is low: only 8 quads for the 7-cell DTL, and 10 quads for the 9-cell one.

One can see in Fig. 1 (right) that the accelerated muon bunch at the structure exit is compressed longitudinally compared to the input bunch: the second step of the curve (down) is shorter than the first one (up). The total time for the beam to traverse the structure is about 21.5 ns.

2.2. IH

The IH-APF [2] is the current baseline option. We performed an MWS EM analysis of the IH-APF CST model provided by M. Otani, and the results are mainly in agreement with those reported in [2]. Still there are some reasons for concern. First, the transverse (vertical) electric field component on the axis is rather large in the last few gaps, see in Fig. 2. This is a known effect in IH structures, but here it becomes especially noticeable due to wide gaps for APF, as was already noticed in [2], and may cause beam quality degradation.

Fig. 2: The magnitude of the unscaled electric field (longitudinal E_z - red, vertical E_y – green) of the operating mode on the IH-APF tank beam axis.

The second observation is that the maximal electric field is somewhat higher than in [2], about $2.5E_K$, see in Fig. 3. For the skinny drift-tubes (DTs) that make IH-APF efficient, there is no easy way to reduce the maximal surface electric field $E_{\max}$ by reducing edge curvature, like in DTLs. Still $E_{\max}$ reduction may become possible if the rather large beam apertures in DTs are reduced while keeping the outer DT radii fixed. The resulting DTs will become thicker and additional edge rounding will be possible.

Fig. 3: The magnitude of the unscaled surface electric field of the operating mode on the drift tubes and stems near the exit of the IH-APF tank.

Finally, the power dissipation is likely higher than 250 kW reported in [2]; we estimate it now at about 400 kW for ideal copper surface. The cause of uncertainty here and above is the scaling factor s for the MWS-normalized RF fields; it was estimated to be between 1.33 and 1.5. The best obtained Particle Studio results so far were with $s = 1.5$, but we didn't have time to run many combinations.

We also considered a draft version of the IH structure with PMQ focusing [4] for this application but the preliminary results are not encouraging. The thicker DTs are required in IH-PMQ to place permanent-magnet quadrupoles inside them, and at such a high RF frequency the structure becomes not very efficient. Still for completeness we list some results in Table 2. The maximal electric field for IH-PMQ is very high; though it can probably be reduced by optimization, bringing it into the safe range, below $2E_K$, seems unlikely.

Table 2. IH cavity dimensions and EM parameters.

Parameter	IH-APF	IH-PMQ (draft)
Cavity length L , cm	134.0	148.65
Cavity inner radius R , cm	<12.9 (cone)	9.4
Aperture radii, cm	1.11-1.29	0.6
Outer drift-tube radius, cm	1.71-1.98	1.5
Quality factor Q	10168	8518
Average cell accelerating gradient E_0 , MV/m	>3.5	3
Effective shunt impedance $Z_{sh}T^2$, M Ω /m	92 [2]	46.5
Total averaged wall power dissipation P , kW, 100% duty	~400	265
Maximal peak electric field E_{max} , MV/m	~45 ($2.5E_K$)	84 ($4.7E_K$)
Maximal peak surface magnetic field H_{max} , kA/m	~80	63
Maximal surface power density dP/dS , W/cm ² , 100% duty	~1190	737
Muon energy gain, MeV, for synch phase -45° (Part. Stud.)	4.04	~3.7
Output norm horizontal rms emittance ε_x , $\pi \mu\text{m}$ (Part. St.)	0.333	-
Output norm vertical rms emittance ε_y , $\pi \mu\text{m}$ (Part. Stud.)	0.197	-

2.3. CH

We suggested that some problems of the IH-APF design can be addressed if the IH cavity is transformed into CH, so the resulting structure will be a CH-APF. To our knowledge, nobody considered such structures before. However, it looks like a natural choice that definitely eliminates the transverse electric field on the axis, and at high frequencies can be more efficient than IH-APF. M. Otani very quickly transformed his IH-APF CST model into CH-APF, tuned the field profile by adjusting the outer DT radii, see in Fig. 4. Our preliminary EM results look rather promising; the transverse on-axis electric field is eliminated and the maximal electric field is reduced.

Fig. 4: CH-APF CST model (left); the magnitude of the on-axis electric field (right).

Some results are summarized in Table 3. The estimates for maximal surface electric field and power dissipation are obtained assuming the scaling factor $s = 1.5$. This still has to be checked in Particle Studio simulations.

Table 3. CH cavity dimensions and EM parameters.

Parameter	CH-PMQ	CH-APF (draft)
Cavity length L , cm	148.45	144.18
Cavity inner radius R , cm	15.03	17.4
Aperture radius a , cm	0.75 (DT1-11) / 1	1
Outer drift-tube radius, cm	2	1.6-2.5
Quality factor Q	11536	14360
Average cell accelerating gradient E_0 , MV/m	3	-
Effective shunt impedance $Z_{sh}T^2$, M Ω /m	36.8	-
Total averaged wall power dissipation P , kW, 100% duty	325	~320
Maximal peak electric field E_{max} , MV/m	33.9 (1.9 E_K)	~36 (~2 E_K)
Maximal peak surface magnetic field H_{max} , kA/m	52.9	-
Maximal surface power density dP/dS , W/cm ² , 100% duty	518	-
Muon energy gain, MeV, for synch phase -30° (Part. Stud.)	~3.65	~4
Output norm horizontal rms emittance ε_x , π μ m (Part. St.)	-	-
Output norm vertical rms emittance ε_y , π μ m (Part. Stud.)	-	-

3. Summary.

We explored three types of structures for muon acceleration in the beam velocity range $\beta = 0.08$ -0.3. Somewhat surprisingly, the venerable DTL looks like the best option based on its low maximal field, reasonable efficiency, and simplicity. It also provides the largest flexibility of the beam focusing options. The accelerating gradient for the DTL is the highest of the considered designs and can be farther increased if needed.

The IH-APF structure, the baseline choice, is very attractive due its efficiency and potentially lower fabrication cost. However, detailed EM analysis indicated some reasons for concern, mainly related to the high maximal electric fields, as discussed in Sec. 2.2. We suggested to change the cavity design to CH type, which leads to a novel type of structure, CH-APF. Dr. M. Otani produced the CST model of CH-APF, and preliminary results of its EM analysis are encouraging. Unfortunately, the fabrication of CH-APF structure is likely more complicated than for IH-APF.

4. References.

1. Y. Kondo et al., “Muon linac for g-2/EDM experiment at J-PARC,” Talk at Muon Acceleration Mini-workshop, J-PARC, Tokai, 2016/08/30.
2. M. Otani et al., PRAB **19**, 040101 (2016).
3. CST Studio Suite, CST, www.cst.com
4. S. Kurennoy et al., PRSTAB **15**, 090101 (2012).
5. Los Alamos Accelerator Code Group, laacg.lanl.gov