Mu Target Design Study for g-2 Experiment at J-PARC

J-PARC Summer Student Project Report

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Abstract

The g-2 experiment at Japan Proton Accelerator Complex (J-PARC) aims to study the anomalous magnetic moment of the muon at an unprecedented precision. The experiment utilized a low emittance muon beam which helps measure the anomalous magnetic moment of muon ('g-2') at a higher precision than previous experiment. One of the key part in the experiment is the production of muonium (Mu), followed by ionization process to produce low emittance muon. In this work, several Mu target designs were studied. The results of current design were reproduced and simulation's validation was checked. Based on these steps, Several new target design geometries were tested with some preliminary results, hopefully to enhance the Mu yield efficiency.

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1 Introduction

Ultra slow muon production is a crucial step to the high precision measurement for g-2/EDM experiment at J-PARC. The thermalization process is the key to cool down the muon beam and obtain the required low-emittance muon beam for further acceleration[1]. It includes muonium production, the thermal emission into a vacuum and the ionization process with the laser.

Silica aerogel was been tested for the low-emittance muon production for the first time at TRIUMF experiment (referred to as S1249) [1, 2]. Currently, with laser-ablated aerogel, Mu emission efficiency at g-2/EDM experiment is about 0.38% [3], which is enough to achieve the required phase 1 goals (0.46 ppm sensitivity). However, higher Mu yield to reach the final goal 0.1 ppm is needed. Thus some possible new Mu target geometry design might be helpful.

Table 14.1: *Efficiency and beam intensity*

Quantity	Reference	Efficiency	Cumulative	Intensity (Hz)
Muon intensity at production target	[2]			1.99E+09
H-line transmission	[2]	1.62E-01	1.62E-01	3.22E+08
Mu emission	[3]	3.82E-03	6.17E-04	1.23E+06
Laser ionization	[4]	7.30E-01	4.50E-04	8.97E+05
Metal mesh	[5]	7.76E-01	3.49E-04	6.96E+05
Init.Acc.trans.+decay	[5]	7.18E-01	2.51E-04	5.00E+05
RFQ transmission	[6]	9.45E-01	2.37E-04	4.72E+05

Figure 1: the Mu emission efficiency from TDR, defined as the number of Mu yield in the laser region at laser time out of the total surface muon in the beam

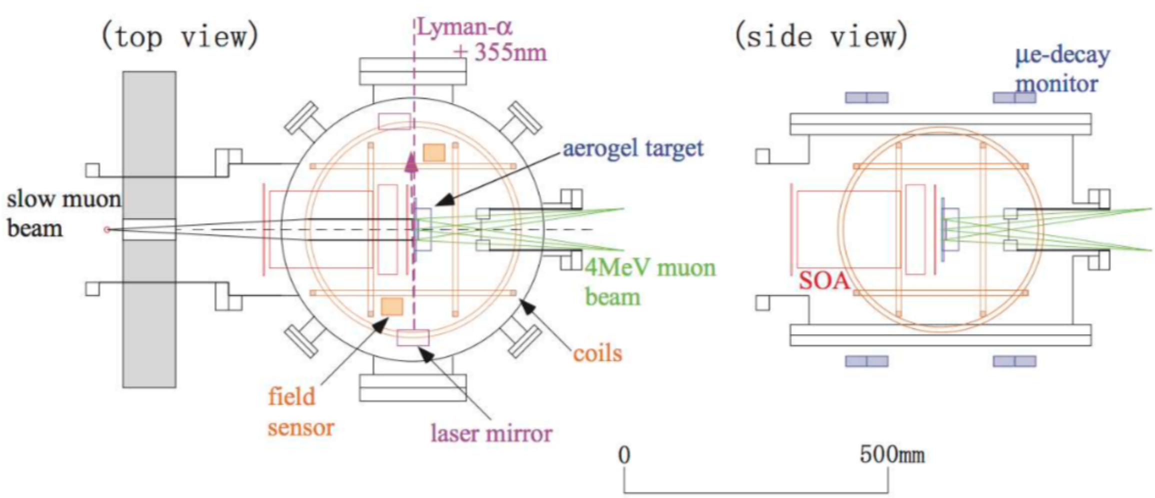

Figure 2: Current Mu target geometry design, from TDR

Detailed description on silica aerogel and the target design configuration can be found at TDR chapter 5.

2 Simulation Methodology

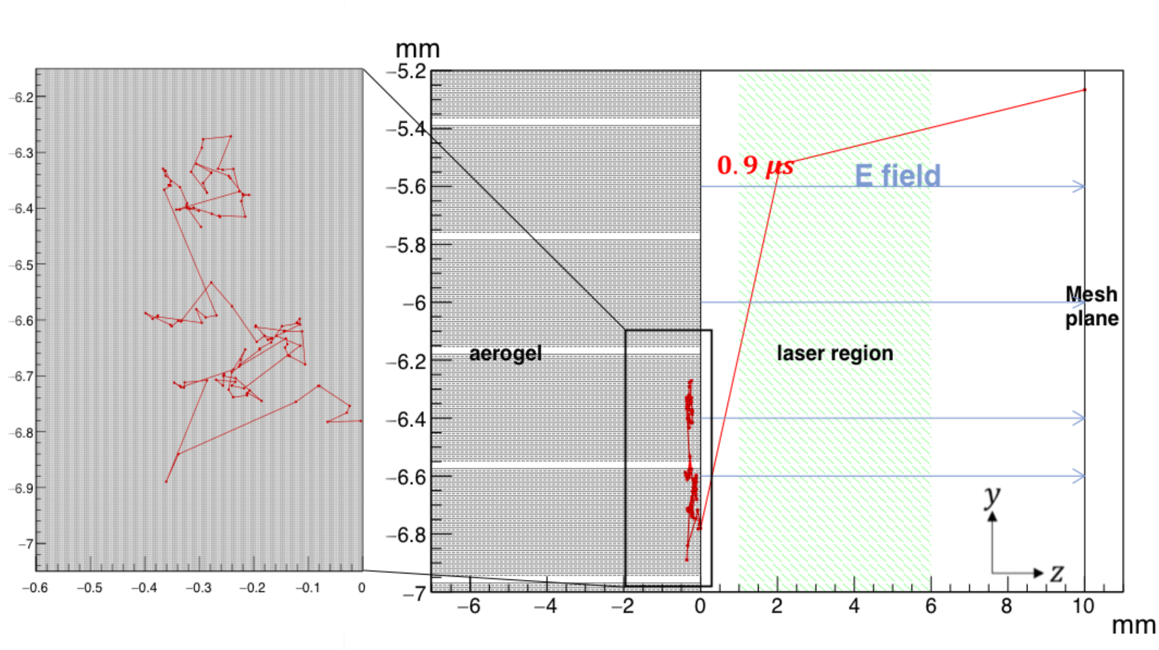

Figure 3: Part of the current Mu target geometry design

Here we briefly summarize the main idea of previous simulation [4]. 7.12 thickness aerogel with optimized 475 μm degrader were used as the surface muon target. The Geant-4 beamline simulation of H-line was used for optimizing the number of surface muons in the region of $|x, y| < 20mm$. 3.23×10^6 surface muons was used as input to the ultra-slow muon simulation. The energy degradation and stopping of the muons in the target were calculated by a separate G4 simulation [3].

Then, laser region was set from 1 mm to 6 mm away from the target in z direction, as shown in Fig. 3. Thus laser exposure area is 5 mm in the z direction, and area of 200 mm^2 in x-y plane. After most of the Mu emitted out into the laser region, laser was shoot for 1 nano-sec at 0.9 micro-sec after the second muon pulse (1.2 micro-sec from the first muon pulse). If using the collinear laser region, we might be able to free the X direction limit to expand more in the laser region.

Mu in the laser region would next be ionized and extracted by electric field to the mesh plane waiting for the further acceleration by SOA, RFQ, etc.

In our simulation program, we basically followed the main steps of previous simulation, which can be divided into three main steps: the beam structure, the diffusion model of stopping muon and the extraction simulation. The space and time distribution from G4 H-line would be useful.

From these distributions we were able to conduct toy Monte-Carlo simulation and G4 simulation was needed no more.

We start at the surface muon beam, which would be gaussian distribution in x and y plane according to TDR [3]. Part of the surface muon would be stopped inside the aerogel. Given the 475 μm aerogel, we have almost the uniformed surface muon distribution inside the aerogel along the z direction. Only about half (52%) of those stopping muons would be able to form muonium (Mu). In our simulation, however, we safely assume 100% Mu formation. This factor can be scaled later.

After the Mu formation, they would be scattering inside the aerogel, which could be described by the diffusion model.

2.1 Diffusion model

From the muon stopping position, muonium diffusion is switched on. The diffusion parameter was used as obtained from the analysis of TRIUMF S1249 experiment. The following simulation was set up according to the reports and slides by Prof. Glen Marshall at the collaboration meeting [4].

Once the Mu formed, diffusion model started to simulate the random walk. Velocity was generated randomly based on the Maxwell distribution with thermal energy

$$< v >= \sqrt{\frac{8kT}{\pi m_\mu}} \tag{1}$$

with a particular temperature from the result of S1249.

Each step of the random walk would follow the diffusion equation in 3D:

$$\lambda =< r^2 = x^2 + y^2 + z^2 >= 6Dt \tag{2}$$

and exponential distribution of displacement:

$$P(r) = \frac{1}{l_{mlf}} e^{-\frac{r}{l_{mlf}}} \tag{3}$$

where the D is the diffusion coefficient. t is the time interval and l_{mfp} means the mean free path between two scattering. Each step in the random walk has different step length L from exponential of mean free path.

From above equation, we obtain on average:

$$D = \frac{\pi l_{mfp} < v >}{12} \tag{4}$$

The diffusion parameter D and optimized temperature T were obtained from the analysis of TRIUMF S1249 experiment. The best fitted value for D = 870 cm2s-1 and T = 322 K. They are the only two parameters we need as input to decide the whole model.

It is worth noting that the D we used here was the fitting result from the laser ablated aerogel, which implies the assumption that the flat target with D = 870 cm2s-1 is equivalent to ablated target. It is a very important idea and we will carefully check its validation in the following section.

2.2 Ionization and extraction

If the muon is emitted in vacuum as a result of diffusion before it decayed, its velocity in vacuum remained the same as at the surface of target. Then the laser irradiation area and timing was chosen so as to maximize the number of ionized muons, obtained as the number of muoniums in the laser region with time went. Here we use the 0.9 micro-sec shooting time from TDR.

After the laser shooting in the laser area, ultra-low emittance muon would be extracted by uniformed E field powered by two meshes. one of the meshes was set up at the surface of the target and the other at the entrance of the SOA electrode. This initial acceleration gives muon velocity traveling to the SOA for further acceleration.

Parameters are listed in the Table 1. They are basically the same as described in the Prof. Marshall's slides and from TDR.

Table 1: Simulation parameters

Pulses	Two square pulses, FWHM: 100 ns, interval: 600ns
Pulses-x	Gauss(0, 31.96 mm)
Pulses-y	Gauss(0, 14.36 mm)
Aerogel Size	103 mm * 130 mm * 7.12 mm
Maxwell velocity T	322K
Diffusion coefficient	870 cm^2/s
Laser region	1 mm $<$ z $<$ 6 mm, $|Y|<$20 mm
Laser time	0.9μs
Voltage between meshes	100 V from 0 mm to 10 mm

3 Validation on current target design

Validation of the simulation code will be divided into three parts: the reproduction of TRIUMF S1249 results, the Mu yield for H-line G4 beam input and the results on my own MC samples.

3.1 TRIUMF results reproduced

First step was trying to reproduce the results in the TRIUMF experiment S1249, in which the laser ablated aerogel was tested for the Mu production for the first time. In order to measure the muon decay events outside the aerogel, the vacuum region 10 mm - 40 mm away from the surface of aerogel was set up in the z direction, which was different from laser region 1 mm - 6 mm at J-PARC experiment, as shown in the Fig. 4[3]. Because the muon decay events are proportional to the total muon events in the particular volume, we can estimate the yield number by summing up the decay events in the vacuum.

The results are on the Fig. 5, from which my results are consistent with the results on the published paper [2] in the four vacuum regions both in shapes and in Mu yield numbers: the Mu yield numbers were calculated to be about 30 per stopping muon, which is the same as the number in the TDR.

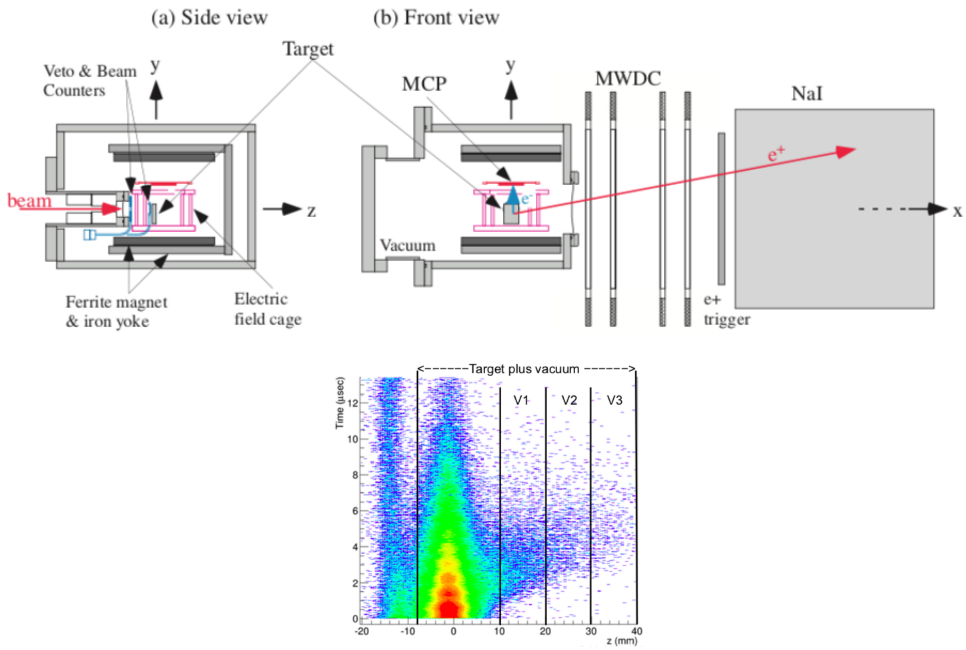

Figure 4: TRIUMF experiment set up and vacuum region

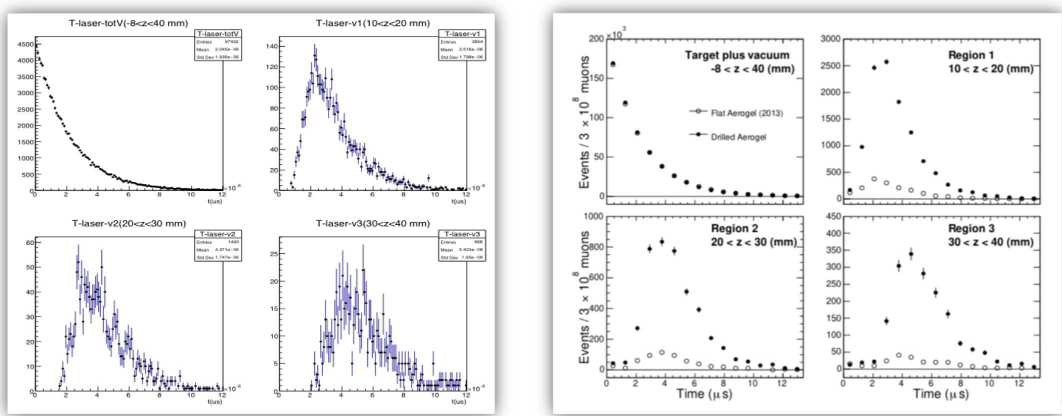

Figure 5: Comparison of our simulation with TRIUMF results in four vacuum regions. Both the shape and the numbers are quite consistent.

3.2 H-line Geant-4 input

The second step of validation includes the Geant-4 based input of surface muon samples in the H-line Beam. This was also the input that resulted the Mu yield efficiency in the TDR. The beam structure distributions (x, y distribution and time structure) are in the Fig. 6.

The stopping locations of the individual muons were then used as initialization locations in the diffusion simulation. Following the same procedure, we obtain the Mu yield results. Fig. 6 shows the number of muonium atoms in a laser irradiation region between 1mm and 6mm from the aerogel surface and within $\pm 20mm$ of both x and y axis, as a function of time from the average of the two accelerator beam pulses. The graph corresponds to the total number of 3.23^6 surface muons in the beam and 100% of Mu formation.

From the plot, the maximum rate exceeds 1.2^4 at the laser time $0.9\mu s$ after the mean time of the two muon beams. and the scaled number was calculated to be 0.18% with the x-limited condition and 0.36% (0.38% in the TDR) with x-free condition respectively. They were also consistent with Prof. Marshall's results and TDR's.

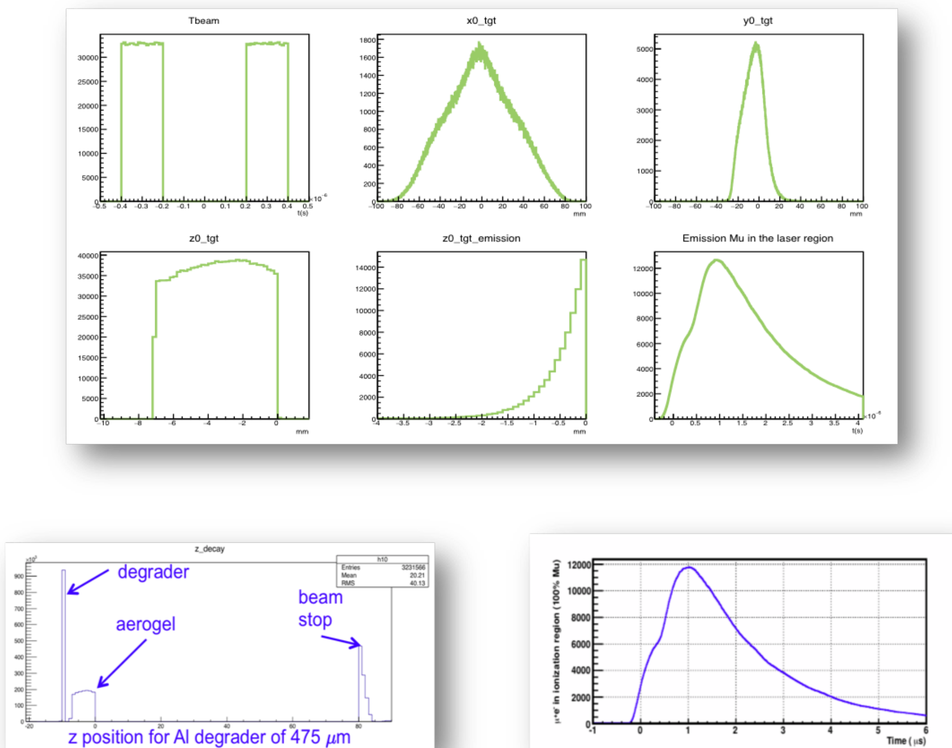

Figure 6: H-line Geant-4 input result. above are the distributions of beam time, beam structure in x, y, z direction and the Mu yield with time. Below are TDR result of stopping muon distribution and Mu yield with time. The Mu yield results are consistent.

3.3 Our own MC samples

Last part of validation was to use our own MC samples, of which the only difference from the H-line G4 samples in the previous subsection was the beam structure. According to TDR, the beam structure should be gaussian distribution in the x (sigma = 31.96 mm) and y (sigma = 14.36 mm) directions respectively in J-PARC condition.

Some of the distributions for each steps are on the Fig. 7. We also checked the distributions of Mu events at the surface of aerogel, at the laser region, at the mesh plane respectively. For the numbers at the laser region, Mu yield calculated to be 0.35%, still close to the 0.38% in the TDR.

More study was done after yield numbers: after laser region, those events were inputed into the initial and SOA acceleration with the help of Otani-san, who got the G4 package for acceleration. Fig. 7 shows the emittance results and energy and time spread results compared with TDR after initial SOA acceleration (the entrance of RFQ). The normalized RMS emittance in the x and y-directions are 0.42 (0.37 in TDR) and 0.13 (0.11 in TDR) π mm mrad, respectively. Deviation of RMS emittance may be due to beam halo components.

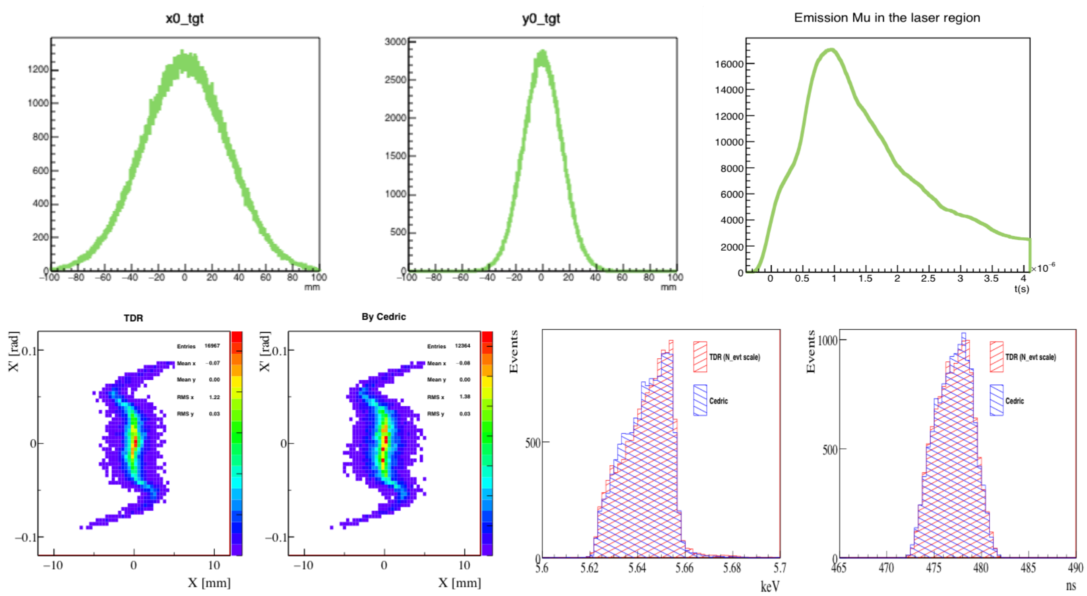

Figure 7: Results of our own samples. Above are the distribution of beam in x, t direction, which are gaussian distribution. Below are emittance results and energy and time spread.

4 Preliminary result on New designs

After the validation, the simulation program was used for some new geometry designs.

4.1 New design No.1: A multi-piece design

New design No.1 scheme is shown in the Fig. 8. In this new design, beam muons hit the target along the y axis. Aerogel slot was divided into several thiner pieces. Each piece for now is 2 mm thickness for better Mu emission. Laser regions were sandwiched between aerogel so that collinear laser shots along the x direction, which is perpendicular to the plane. The meshes then were set up on the two sides of the aerogel providing the E field along the z axis. The ionized muon then could be extracted to the mesh plane. For simplicity, we only have 3 pieces drawn here in the Fig. 8.

Comparing to the current design, we doubled the emission surface for each laser region. Also the number of laser regions increased. Considering 6 or 7 piece of aerogel with 2 mm thickness, we may stop over 80% of surface muon and create 4 or 5 laser regions along the y axis with the total length of about 50 mm.

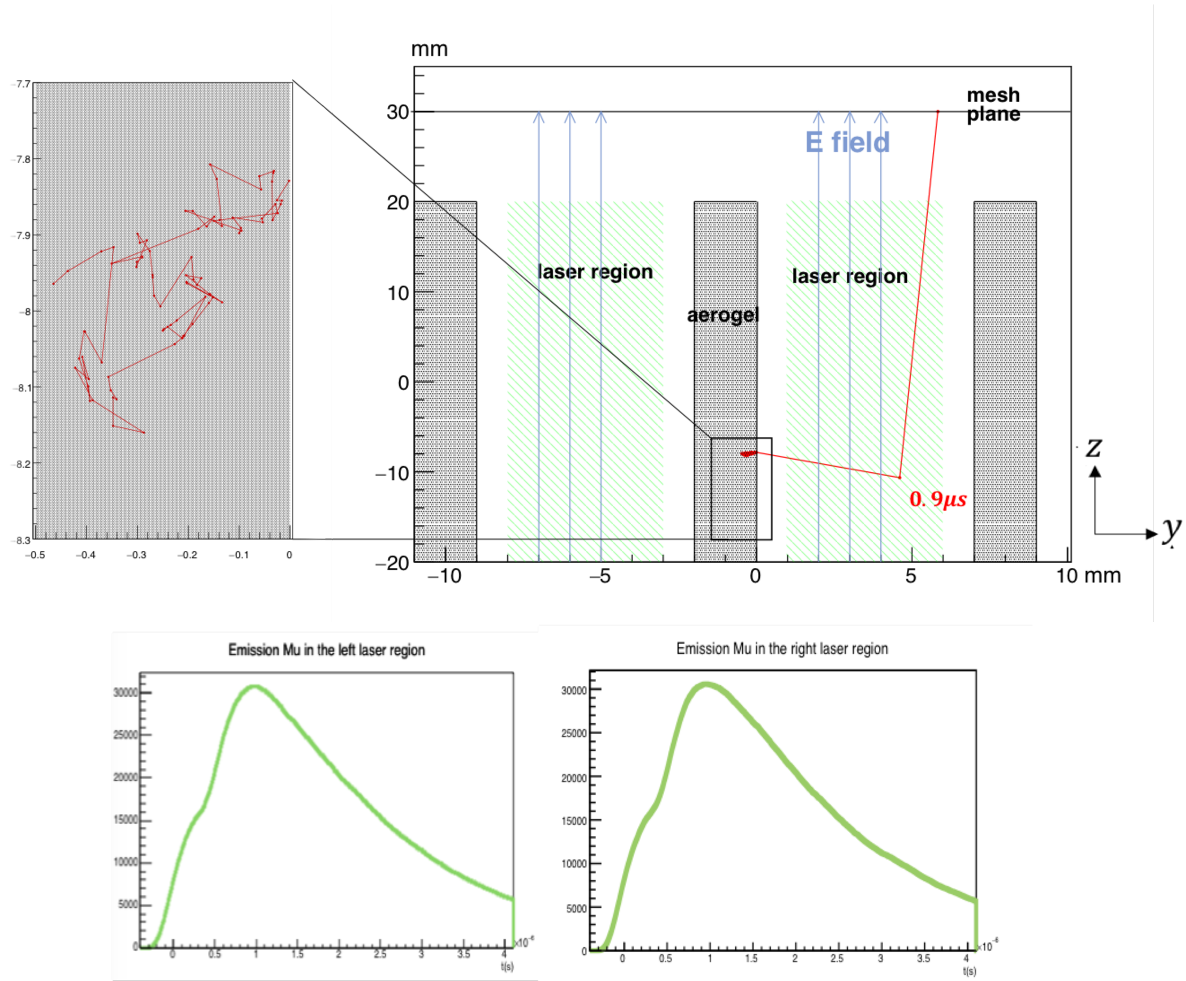

Figure 8: New Mu target geometry design No.1 and corresponding Mu yield in two laser regions

Under this new design, the yield number with time were plotted in the Fig. 8. They were the number from only two laser regions. The scaled number indicated about 4 times larger of yield number than current design.

4.2 New design No.2: A more conservative test

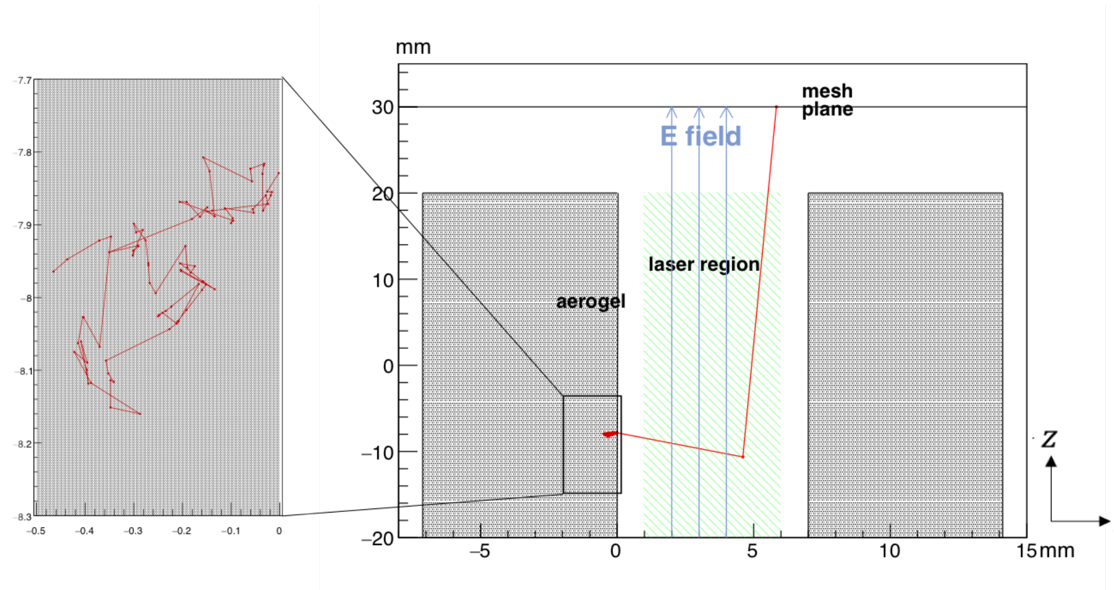

Figure 9: New Mu target geometry design No.2.

Considering the potential challenge on the fabrication of thin aerogel, we also tried another design with currently used 7.12 mm aerogel. the laser region was sandwiched between two aerogel slots. The laser and the E field were the same as the new design No.1.

Now only one laser region left and we could reasonably expect the yield number to be almost doubled as the current one.

Also in the Fig. 10, we can see the initial z position inside the aerogel of yield muon, in which we may conclude that the effective emission depth is about 2 mm and the thicker aerogel like 7 mm might not help a lot.

After the yield number in the laser region, events were accelerated by initial E field to the mesh plane. Fig.10 shows the distribution of X, X'(vx/vz), Y, Y' and energy and time spread. Also using the acceleration package by Otani-san, we obtained the distribution at the entrance of RFQ. The new design significantly changed the emittance shape and also enlarge the time and energy spread. The x emittance is 0.95 (Geo 0) and 0.95 (Geo 1) π mm mrad and the y emittance is 0.06 (Geo 0) and 0.08 (Geo 1)π mm mrad. We suspect the current focusing structure in the SOA might not match the new design emittance well. And also the initial acceleration configuration such as the voltage would change the energy and time spread. Discussions later on these issues in needed to carefully check the feasibility.

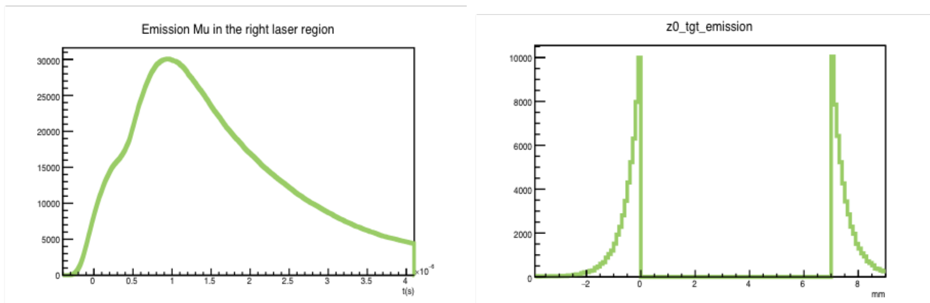

Figure 10: The corresponding Mu yield (the number is not scaled), and also the the emission muon with the depth of aerogel.

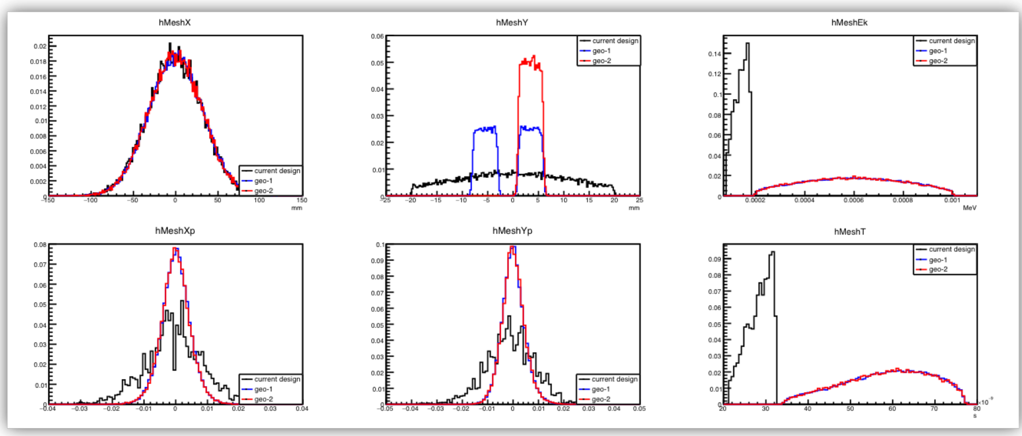

Figure 11: Distributions at Mesh plane, for x, x', y, y' and the energy and time spread. The change of set up and initial acceleration significantly enlarge the time and energy spread compared to the current design.

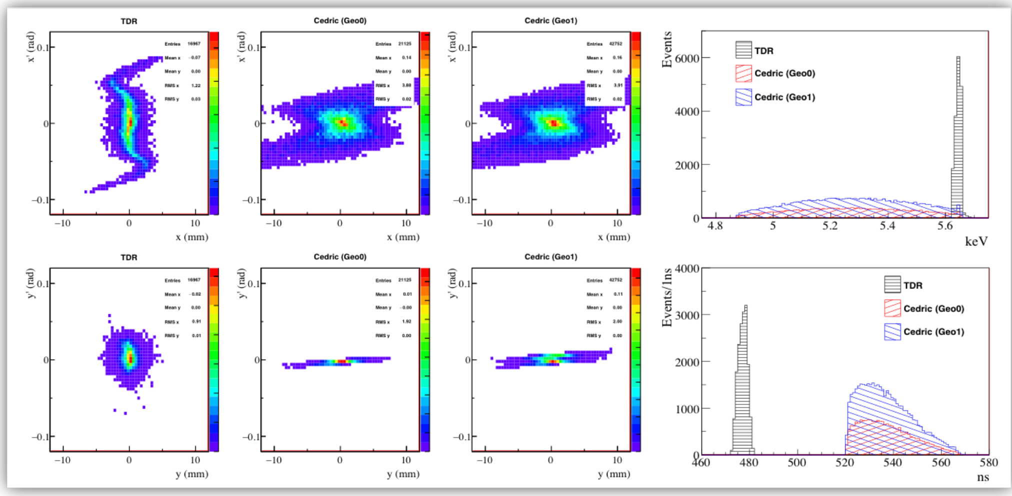

Figure 12: Distributions at the entrance of RFQ after SOA. The emittance increase and the energy and time spread also enlarged.

4.3 New design No.3

Also, we considered another the new design which set the aerogel in a tilt angle along z axis so that the laser region was put aside, as shown in the Fig. 13. However preliminary study shows the very low Mu yield compared even to the current design. So this study was very quickly abandoned.

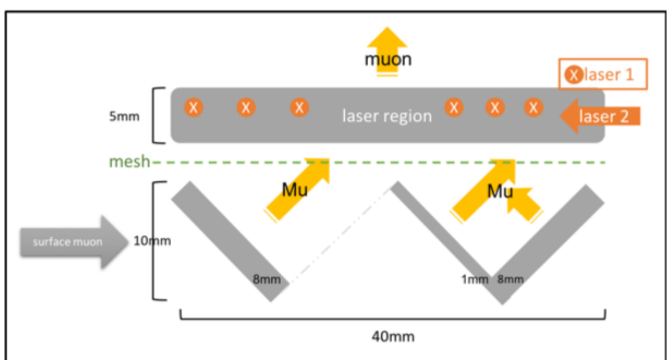

Figure 13: New design No.3, abandoned.

5 Summary and discussion

Table 2 summarized the results for different geometry designs (They are all under free x condition). Number flows were scaled for directly comparison. For the numbers at the entrance of the RFQ, the yield number for new geometry design 1 would be about 3.5 times lager than the current design. Given the entire 6 or 7 pieces, this factor would be 9. Thus this new geometry would bring about an order of increment in the number.

Table 2: Simulation parameters

Number flow	TDR	Simulation on current design	NewGeo-1	NewGeo-2	NewGeo-3	Remarks
Number of muon stopped in aerogel	1.31E6	1.31E6	1.1E6	2.62E6	1.1E6	surface muon from G4: 3.23e6
Number of Mu in the laser region	24000	22239	79906	39233	2190	-
Number of Mu at the Mesh plane	-	21923	77716	38298	-	-
Number of Mu at the Entrance of RFQ	16967	16197	56005	27674	-	-

The result above is only preliminary. Optimization can be the next step, including the thickness of aerogel, the width of the laser region, the voltage between the meshes, etc.

In summary, using toy MC simulation program we have successfully reproduced the current Mu target design results. And the same program was applied into several new geometry designs. Some preliminary results showed the significant increment of Mu yield number by almost an order, hopefully to match our Phase 2 goals. Other effects brought by new design such as time and energy spread need further discussion.

Acknowledgement

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Also my thanks are given to students in the office, Sirui, Ushizawa-san, Nishimura-san, Yasuda-san, Summer students Jaewhan and Sasha etc. Discussion in the office were always inspiring.

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