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Fermilab Engineering Specification
A target omitting the beryllium cover
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1. Introduction

Currently we are planning to start assembling of a spare target for the g-2 target station. Unfortunately, the part needed for the first step of the assembling process, Beryllium cover, is not on hand. In actuality, we have a few graphite covers which were mis-labeled as beryllium.

The beryllium manufacturer Materion has provided a quotation which shows an extended price of $47,952 for Qty. 2 of beryllium covers, plus a $3,060 service charge, with a 20 weeks delivery time [1]. In Sep. 2009, the cost was $26,530 for the same Qty. 2 of beryllium covers [2].

Due to this unexpected cost and the long lead time, a study was performed to evaluate the possibility of omitting the beryllium cover. Other options are listed at the end of this report.

2. Target design

The target assembly is made of an Inconel cylinder, with cooper balls in the cored target center providing airflow passages to cool the target, shown in Fig.1. An outer beryllium cover is shrink-fit to the Inconel cylinder. The air excluded from this shrink-fit interface prevents the Inconel material from oxidation. Historically, during Pbar operations, the oxidized materials were known to be sputtered onto the nearby lens. For this reason, a target design with a beryllium cover was introduced in the target production since 2008.

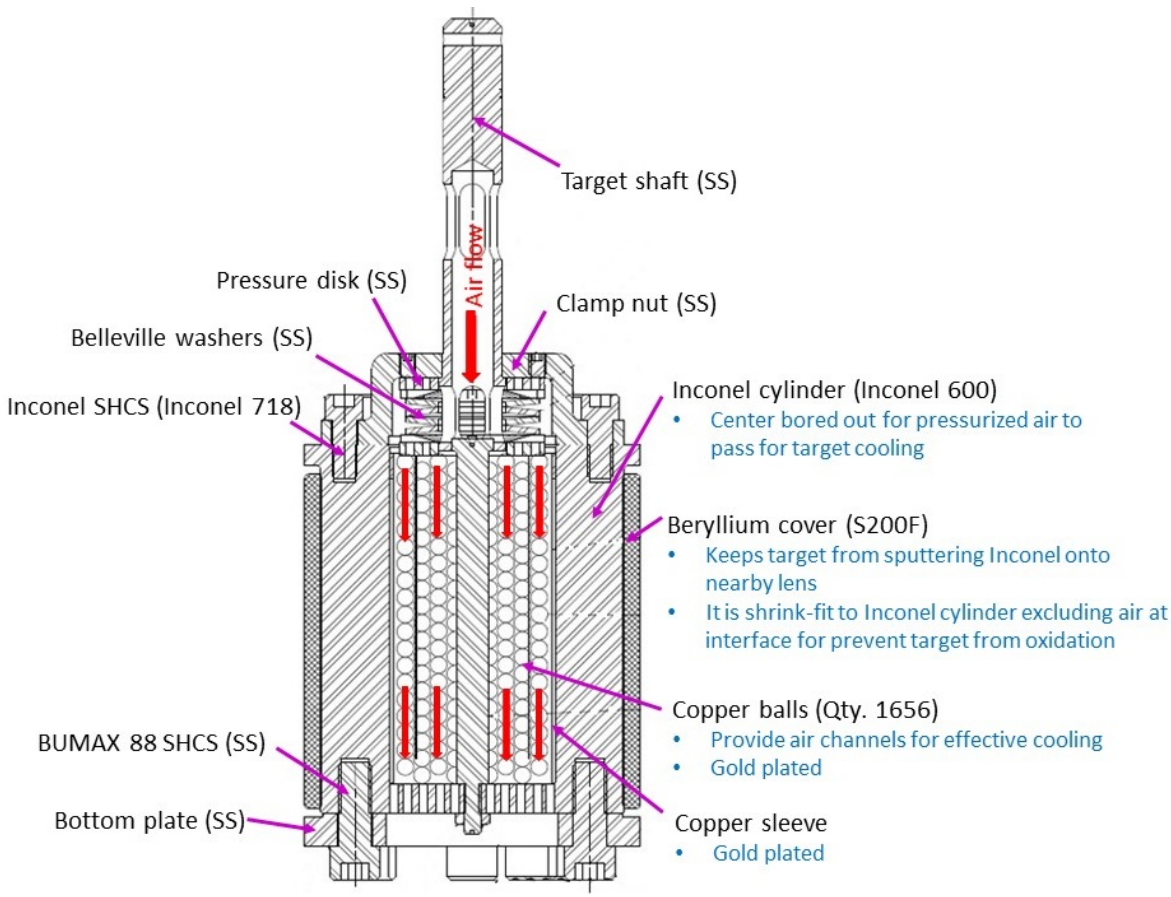


Figure 1: Target design Mark-Vb (MC-413931) [3]

3. Beam power on target for g-2 operations vs. Pbar operations

For Muon g-2 experiment, batches of 8 GeV protons strike the Inconel target with 16 number of pulses every 1.33 seconds, with an intensity of 10^{12} protons per pulse [4]. The target is rotated one turn per 45 second and is moved vertically by 1 mm after each 2 x 10^{16} protons to spread the depletion and damage uniformly around its body. The combination of proton beam intensity and small beam size induces a localized region of intense energy deposition in the target. However, due to pulsed beam operation mode and target motion, the overall beam power deposited in the target is relatively small.

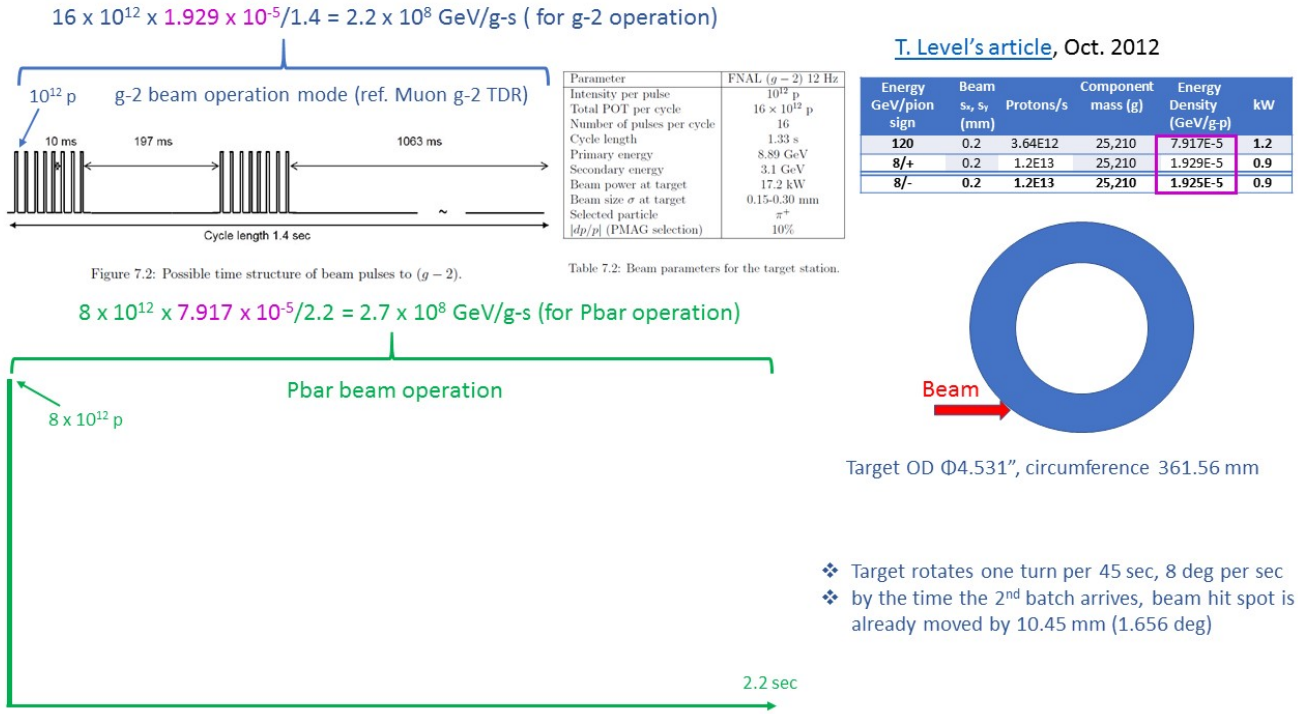
Compared to the Pbar operations, the incident beam power on target for muon g-2 experiments is reduced to 15 kW from 60 kW, shown in Table 1.

Table 1: Comparison of beam power on target

	g-2	Pbar
Beam parameters	8 GeV, 1E12ppp, 12 Hz [5]	120 GeV, 7E12ppp, 2.2 sec cycle time [5]
Beam power on target	15.36 kW [5] 15 kW [6]	61.09 kW [5] 70 kW [6]
Beam size	0.15 – 0.30 mm [4]	0.15 mm
Energy density on target*	1.93E-5 GeV/g-p	7.92E-5 GeV/g-p

*from MARS simulations [6]

Compared to the Pbar operation mode, the beam power on g-2 target is more spread over time and over the target body, shown in Fig. 2.



Parameter	FNAL $(g-2)$ 12 Hz
Intensity per pulse	10^{12} p
Total POT per cycle	16×10^{12} p
Number of pulses per cycle	16
Cycle length	1.33 s
Primary energy	8.89 GeV
Secondary energy	3.1 GeV
Beam power at target	17.2 kW
Beam size σ at target	0.15-0.30 mm
Selected particle	π^+
$\lvert dp/p \rvert$ (PMAG selection)	10%

Energy GeV/pion sign	Beam s_x, s_y (mm)	Protons/s	Component mass (g)	Energy Density (GeV/g-p)	kW
120	0.2	3.64E12	25,210	7.917E-5	1.2
8/+	0.2	1.2E13	25,210	1.929E-5	0.9
8/-	0.2	1.2E13	25,210	1.925E-5	0.9

Figure 2: Comparison of beam power on target

The target currently in operation for the Muon g-2 experiment is Target #18, which was installed on May 12, 2011[7]. Prior to the Tevatron shutdown on Oct. 1, 2011, 3.074 x 10^{19} protons were integrated. Since target station re-startup for g-2 experiment in May 2017, the target beryllium cover has been in an excellent condition, providing an evidence that the impact of beam power on target for g-2 operation is relatively tolerable.

4. History of collide program Run II target performances and failures

Historically during Pbar collider operation, the peak energy deposition on target went up dramatically due to the increase in beam intensity and the reduction in beam size. The maximum integrated protons by a target before the failure occurred is shown in Fig. 3 [8]. The target failures are usually associated with the following reasons [9]:

1. The rapid heating and expansion of the target material causes shock waves to develop that can cause mechanical damage to the target;
2. A molten channel can form in the target that reduces antiproton yield due to reduced density.

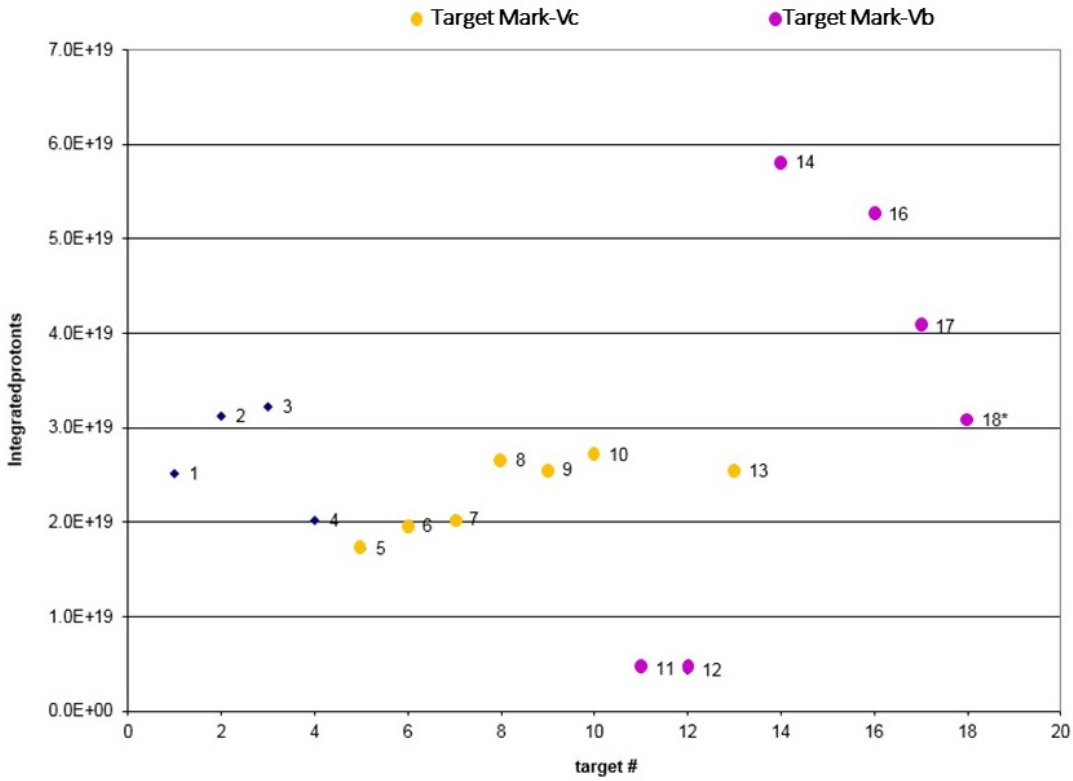


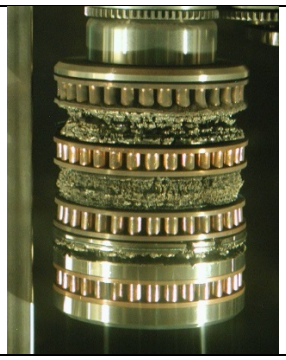
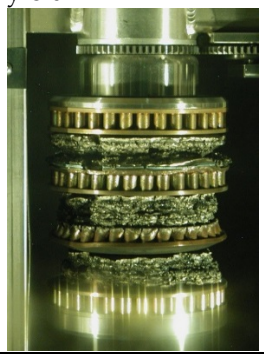
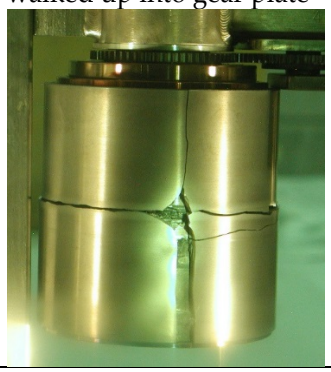
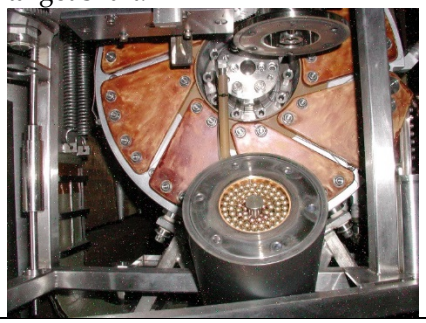
Figure 3: History of Run II target integrated protons received by each target

In 2008, the target design incorporated with a beryllium cover, Target Mark-Vb, started to be used. Since then, the target service time became longer, however most of the target failures were due to the damage of the beryllium cover. The detailed Run II target history of performances and failures [8][10][11] are listed in Table 2.

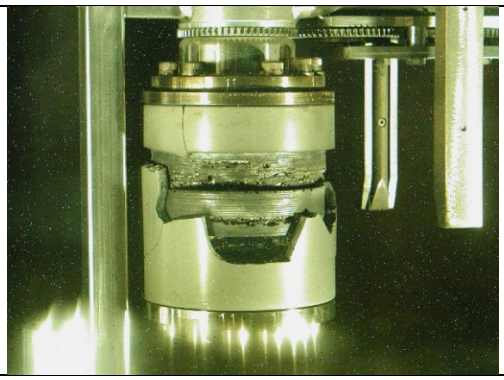
Table 2: Run II target history (Target #1-4 are older designs, and are skipped in this list)

Target #	Integrated protons (x 10^{19})	Type	Failure
5	1.7	Mark-Vc	Target rotation stopped, a sheared pin on gearmotor coupler.

6	2.0	Mark-Vc	Accumulated damage results in a significant loss of yield
7	2.0	Mark-Vc	Accumulated damade results in a significant loss of yield
8	2.65	Mark-Vc	Although the bottom disk was unused, it was removed from service during the summer shutdown.
9	2.55	Mark-Vc	Accumulated damade results in a significant loss of yield

			
10	2.71	Mark-Vc	Accumulated damade results in a significant loss of yield 
11	0.445	Mark-Vb	Balls fell out. rotation stopped, cover cracked and walked up into gear plate 
12	0.435	Mark-Vb	Top plate bolt broke, target cylinder fell off from the target shaft. 
13	2.54	Mark-Vc	Accumulated damade results in a significant loss of yield

14	5.81 Flat yield throughout service period.	Mark-Vb	Had an approx. 1/8′ gap between clamp nut and target cylinder. This led to decreased air pressure. Be Cover had a vertical crack. Fracturing of SS SHCS heads.
16	5.26 Was the second best target so far; it took about 90% of the total protons that Target 14 had, but with a significantly reduced spot size over its entire service life.	Mark-Vb	Be cover broke – pieces missing.
17	4.07	Mark-Vb	Be cover broke - pieces missing. The Be cover expanded to fill the 1/8″ top/bottom clearance gaps. Top bolt #11 missing

			
18	3.07	Mark-Vb	In operation, and in a good condition.

5. Inconel 600's resistance to oxidation at high temperature

Inconel (nickel-chromium-iron) alloy 600 has excellent mechanical properties of high strength and good workability for applications which require resistance to corrosion and heat. The high chromium content provides resistance to oxidizing conditions at high temperatures, making it widely been used in the furnace and nuclear reactions. The alloy's resistance to oxidation is shown in Fig. 4. The weight-loss determinations used to obtain the curves in the figure indicate the ability of a material to retain a protective oxide coating under conditions of cyclic exposure to the temperature. It shows that Inconel 600 has a good resistance to oxidation below the temperature of 980 °C.

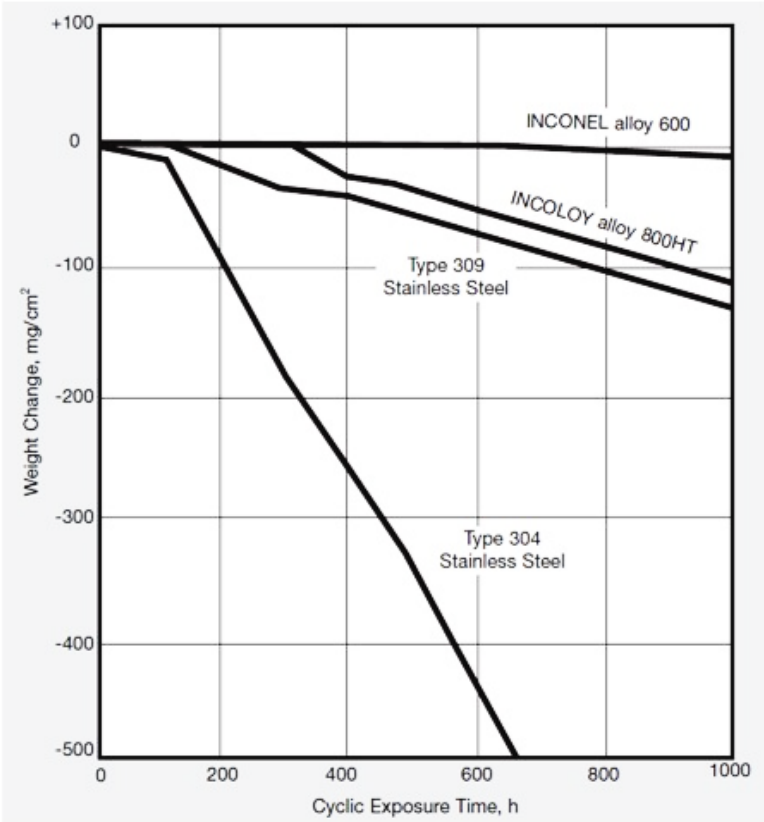


Figure 4: Results of cyclic oxidation tests at 1800°F (980°C). Cycles were 15 minutes of heating and 5 minutes of cooling in air [12]

With a 75% temperature reduction of the target for g-2 operation, we could assume the target temperature is well below the Inconel oxidation threshold.

6. Other options

Based on the above studies, it is recommended that we dispense the beryllium cover so we could start assembling the spare target #19 without significant delays. Currently we have all other parts machined and quality inspected. Other options are listed in Table 3.

Table 3: Other options [13]

Option	Description	Comments
1	Purchase 2 Be covers	• Downside is cost and delivery • Might have 1 unit on the shelf indefinitely • Be cover worked well during Pbar operation
2	Order only 1 Be cover	• Still 20+ weeks delivery • Could order now, $24k more than the previous $13k but overall $11k extra is not excessive considering other options • Will need to qualify this: To reduce risk of ordering 1 cover will need close attention to shrink tolerances and ideally more engineering involvement and oversight on the shrink fit

		• Maybe make more robust tooling for shrink fit to mitigate risk • -Be cover worked well during Pbar operation
3	Investigate Graphite Cover	• Did not work in the past during Pbar operation • Would require significant analysis to ensure proper mounting conditions • Likely would have to redesign for no shrink fit but close slip-fit (perhaps 0.001” or 0.002” clearance fit • Analysis stretches an already overbooked TSD engineering core • - Will perhaps only build 1 spare, so any cost savings in material will be offset by engineering effort (no economies of scale realization)
4	Do Nothing	• Maybe use graphite sheet between lens and target
5	Wait for More Secure Funding	

Regarding the option #3, it has turned out that the graphite cover [14] was designed and used on the V-Cylinder type target assembly, and its inner diameter is 0.167” bigger than the Inconel cylinder outer diameter. Parts need to be modified to fit on Target #19.

References

[1] Materion quotation 20243239, Nov. 19, 2018
[2] Fermilab purchase order PO588575, Sep. 25, 2009
[3] Target Mark-Vc Drawing Set MC-413931, Feb. 13, 2006
[4] Muon g-2 Technical Design Report, March 1, 2017 (Fermilab-FN-0992-E, Original June 15, 2015)
[5] Jim Morgan and Kris Anderson, Private communications, Apr. 05, 2018
[6] T. Leveling, An Estimation of Antiproton Source Target Station Performance for Muon g-2, Oct. 26, 2012
[7] T. Leveling, Antiproton Source Target Station, Oct. 3, 2011
[8] T. Leveling, Target Intensity Data History, May 12, 2011
[9] Jim Morgan, Pbar Production Target Performance in Run II, April 28, 2003
[10] T. Leveling, Target History, May 12, 2011
[11] T. Leveling, Antiproton Source Target Station Elog
[12] Inconel 600 material properties, www.specialmetals.com
[13] Kris Anderson, Private communications, Nov. 21, 2018
[14] Target graphite cover, MB-413509, Sep. 09, 2004