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Improvements to Stripping Foils in BTA

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Abstract

To achieve the desired charge state in the Alternating Gradient Synchrotron (AGS), there is a stripping foil in the Booster to AGS (BtA) transfer line. For light ions, such as p, d, and h, they are already fully stripped in the Booster, or ions such as O have few electrons to be stripped off, and a thin foil of aluminum is used. For medium weight ions, such as Zr and Ru, they use what foils are available which have been optimized for heavy and light ions at 100 MeV/u. This worked well in the Zr case which achieved a measured stripping efficiency of 87%, contrary to the Ru case which achieved a measured stripping efficiency of 63%. For the EIC early science, Ag is currently intended to be the first ion. Using our existing foils, this would, at best, yield a helium-like charge state with a theoretical stripping efficiency of 50%. To improve on this, two foils of Ti or Nb have been selected to provide optimal stripping efficiency of Ag, and other energetic medium ions, which can reach 90% efficiency to fully strip the Ag ions. For heavy ions, the Al+C or Al+Ni stripping foils (sandwich foils) are used to produce helium-like charge states. For high intensity operation of Au, the Al foil nears its melting point and, in some cases, has been severely damaged. To maximize foil lifetime, there is a maximum intensity per unit time in BTA dependent on the Booster and AGS timing configurations. To mitigate the risk of melting the Al, replacement foils that use Ti, Nb, or anodized Al have been evaluated for their improved thermal qualities. At the selected thicknesses, each foil has equivalent charge distributions before entering the C foil, and should provide the same stripping efficiency through the entire sandwich.

Introduction

The Relativistic Heavy Ion Collider (RHIC) has run a range of ions which include: p, d, He, O, Cu, Zr, Ru, Au, U. The lightest ions, such as p, d, and h, are already fully stripped in the Booster and do not need the BTA stripping foil. For O and other light to medium ions, a 4.56 mg/cm^2 Al foil was used. In RHIC run 18, ^{96}Zr and ^{96}Ru were both used and are the medium weight ions, along with Cu, that the BTA foils have been used for. In BTA, Zr had a transfer energy of 113 MeV/u and was incident on a 6.45 mg/cm^2 Al and 8.39 mg/cm^2 C sandwich foil, which had a theoretical stripping efficiency of 91.2% and a measured efficiency of 87%. This left little room for improvement. In BTA, Ru had a transfer energy of 65 MeV/u on a 6.32 mg/cm^2 Al and 8.5 mg/cm^2 C sandwich foil, which had a theoretical stripping efficiency of 63.9% and a measured efficiency of 62.3% [1]. Stripping efficiency calculations use the Global program [2].

The stripping efficiency of Ru could be improved upon with the first being an increase to the Booster charge to provide a more favorable energy for stripping. The higher charge-state would be a trade-off with the optimal efficiency obtained at the source to maximize the intensity. It is likely that an increase in energy at the expense of increased charge would not translate to higher intensity. If the BTA extraction energy was increased, this would allow for higher energy extraction with the same charge state. A lower Z material, such as a pure C foil with a thickness of 20 mg/cm^2 C foil would result in a 64.3% stripping efficiency and a ΔE =-3.3 MeV/u, a -5% change. Increasing the energy to 100 MeV/u, the stripping efficiency is raised to 70.3% with ΔE =-2.4 MeV/u, a -2.4% change. The Al+C foil at 100 MeV/u would result in a stripping efficiency of 73.9%. A comparison for Ru at 100 MeV/u and 65 MeV/u is shown in Fig. 1.

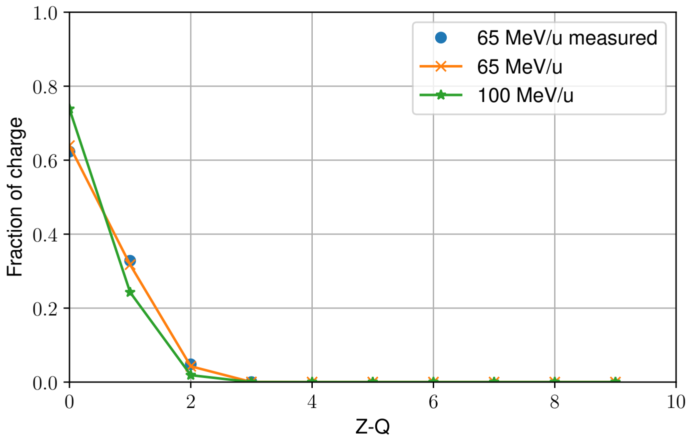

Figure 1: Comparison of stripping foil efficiencies for the Al+C foil used in Run18 for Ru at 65 MeV/u and 100 MeV/u.

For heavy ions, the sandwich foils are exclusively used. For Au, the measured stripping efficiency for a Al+C foil with weights of 6.4 mg/cm^2 and 9.25 mg/cm^2 is 65% and a theoretical efficiency of 74.2%. The drawback of these foils is when operating at maximum intensity drives the Al to its melting point, severely reducing foil lifetime. To maximize foil lifetime, limitations are put on the total intensity transferred per unit time through BTA.

Foil heating limiting intensity

The foil heating follows the method established in [3]. The instantaneous increase in temperature from n particles transiting the foil is

$$\Delta T = -\frac{n}{cA}\frac{dE}{dx} \tag{1}$$

with c being the heat capacity of the foil material, A (A=0.5 cm^2) is the area area of the interaction, and dE/dx is the rate of energy loss to the foil. The rate of change in temperature for foil 1 and 2, currently Al and C, in contact with vacuum chamber of temperature T_w follows

$$\frac{dT_1}{dt} = C_1 T_W^4 - C_1(2T_1^4 - T_2^4) \tag{2}$$

and

$$\frac{dT_2}{dt} = C_2 T_W^4 - C_2(2T_2^4 - T_1^4). \tag{3}$$

Here,

$$C = \frac{\epsilon\sigma}{c\rho d} \tag{4}$$

with ϵ being the emissivity, c the specific heat capacity, ρ the target density of thickness d, and σ being the Stefan-Boltzmann Constant, which for Al and C, $C_{\mathrm{Al}} = C_1 = 0.5880 \times 10^{-10}$, $C_C = C_2 = 6.6727 \times 10^{-10} s^{-1} K^{-3}$.

For stripping of Au, the Al foil can reach its melting point as documented in [3–6]. To prevent melting of the Al foil, a margin on our operating current has been implemented to maximize the lifetime of the foils. The intensity of beam transferred each booster cycle with a total intensity transferred per supercycle of N_b, the booster cycle length ($t_{Booster}$) , the total number of transfers through BTA per supercycle ($N_{Booster}$), and the time of each SC (SC Length) will all affect the temperature of the foil. Relevant physical properties to determine the temperature are the specific heat capacity, emissivity, the dE/dx from the ion which is lost to the material, density and surface thickness. Typical timing for beam from Tandem is shown in Tab. 1.

Table 1: Parameters for different operating scenarios with beam from Tandem and the associated T_{max}.

SC Length	$t_{Booster}$	$N_{Booster}$	N_b	T_{max}
6.0 s	267 ms	8	16.0×10^9	856 K
6.0 s	267 ms	8	16.4×10^9	863 K
5.4 s	267 ms	8	16.0×10^9	873 K
5.4 s	267 ms	8	15.4×10^9	863 K
4.8 s	267 ms	8	16.0×10^9	892 K
4.8 s	267 ms	8	14.3×10^9	863 K
4.8 s	267 ms	8	12.0×10^9	820 K
4.8 s	267 ms	8	9.0×10^9	754 K

For the standard EBIS Au operation with 12 transfers, a 6.0 s SC length, a 200 ms SC length, and operating at Tandem intensities with 16.0×10^9 total ions transferred per supercycle (nominal EBIS intensity was 12.5-14$\times10^9$ ions transferred per supercycle), the foil reaches a temperature of $T_{max} = 866\ K$. This is below the Tandem operating with a SC length 5.4 s and 8 transfers. Equivalent heating from EBIS at elevated intensity would be achieved with a SC length of 5.2 s. The 12:6:2 merge would be supported with a SC length as low as 5.4 s [7].

Medium Ion Stripping

EIC commissioning currently calls for Ru, Cu, Nb, or Ag with the current emphasis on Ag. In BTA, 107Ag+29 will have a transfer energy of 239.4 MeV/u at $B\rho = 8.73$ Tm. Our standard Al+C sandwich would have a theoretical stripping of 55% to produce helium-like Ag, as shown in Fig. 2. Performance is similar to the thickness of heavy duty reynolds wrap with a thickness of 4.56 mg/cm^2. Energy after transiting both foils 239.4→238.4 MeV/u. Historical data shows that the measured stripping efficiency is up to 10% lower than the theoretical value [6]. Having a foil with an optimized thickness to fully-strip the Ag will allow for maximizing the efficiency.

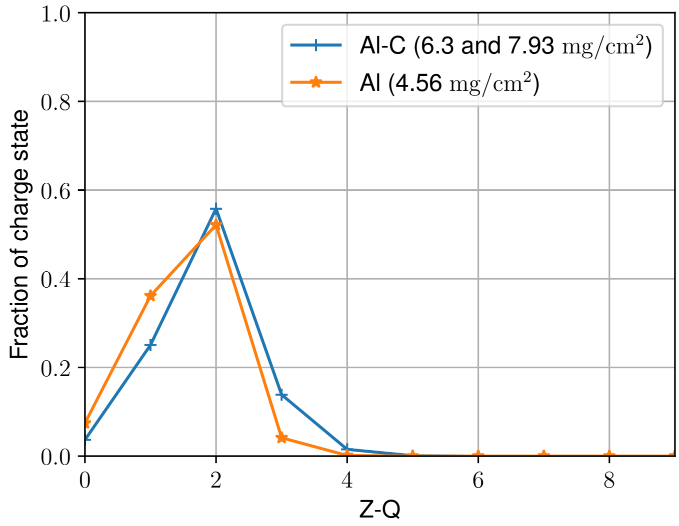

Figure 2: Stripping efficiencies of 239.4 MeV/u Ag on Al+C foil and pure Al foil.

Titanium or Niobium as a stripping foil

Investigating a single material foil for Ag with a medium Z, Nb and Ti are considered as candidates. Ti and Nb have a density of $\rho = 4.51$ g/cm^3 and $\rho = 8.57$ g/cm^3 respectively. With Ag at 239.4 MeV/u and using a single foil of Ti with a thickness of 0.0035 cm would have a theoretical stripping efficiency of 90.5% and a ΔE =-0.9 MeV. Alternatively, using single foil of Nb with a thickness of 0.00125 cm yields a surface thickness of 10.7125 mg/cm^2, a theoretical stripping efficiency of 88.44% for Z-Q=0. If the Nb foil has a thickness of 0.002 cm yields a surface thickness of 17.14 mg/cm^2 and has a theoretical stripping efficiency of 90.31% for Z-Q=0 and a ΔE =-0.9 MeV. To reach this stripping efficiency with a lower Z material, such as C, the thickness would need to be at minimum 60 mg/cm^2 with a stripping efficiency of 90.6% and a ΔE =-4.4 MeV. This comparison is shown in Fig. 3.

Improvements to Heavy Ion stripping

Heavy ion stripping use the existing sandwich foils, Al+C for Au, and Ni+Al for U. The Al foil nears its melting point with a Booster cycle of 267 ms, a SC length of 5.4 s, 8 booster cycles/SC, and a transfer intensity of 16×10^9 ions/SC. Fig. 4 shows temperatures of Al+C foils, the melting point of Al and the margin to prevent foil degradation. Relevant thermal properties for material candidates are given in Tab. 2.

If the thickness of the Al replacement material is selected so the same distribution of charge states after the foil is achieved, the distribution after the second foil will also be the same. The charge distribution following the first and second foil are shown in Fig. 4.

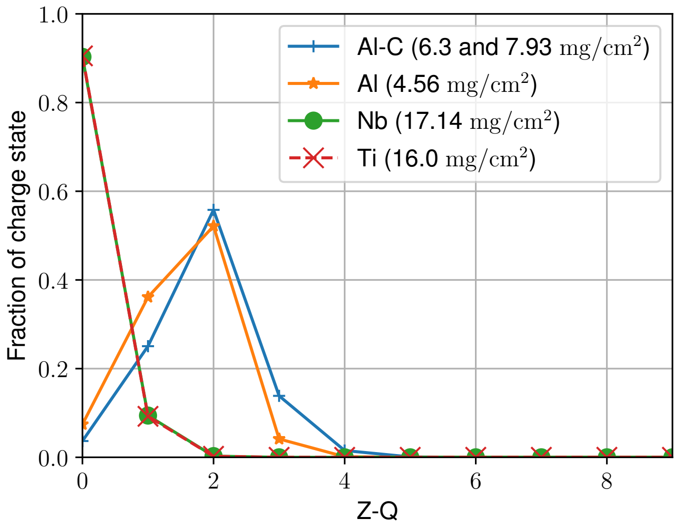

Figure 3: Stripping efficiencies of 239.4 MeV/u Ag on Al+C foil, pure Al, Nb, and Ti foils.

Table 2: Table of relevant thermal properties for different materials.

	dE/dx	density	emissivity	heat capacity	melting point
	GeV cm^2/g	g/cm^3		J/(gK)	K
Al	-33.137	2.7	0.06 (@773 K)	0.897	933
Al (anodized)	-33.137	2.7	0.77 (@300 K)	0.897	933
Ti	-29.612	4.51	0.19 (@300 K)	0.52	1941
Nb	-25.815	8.57	0.19 (@1500 K)	0.32	2750

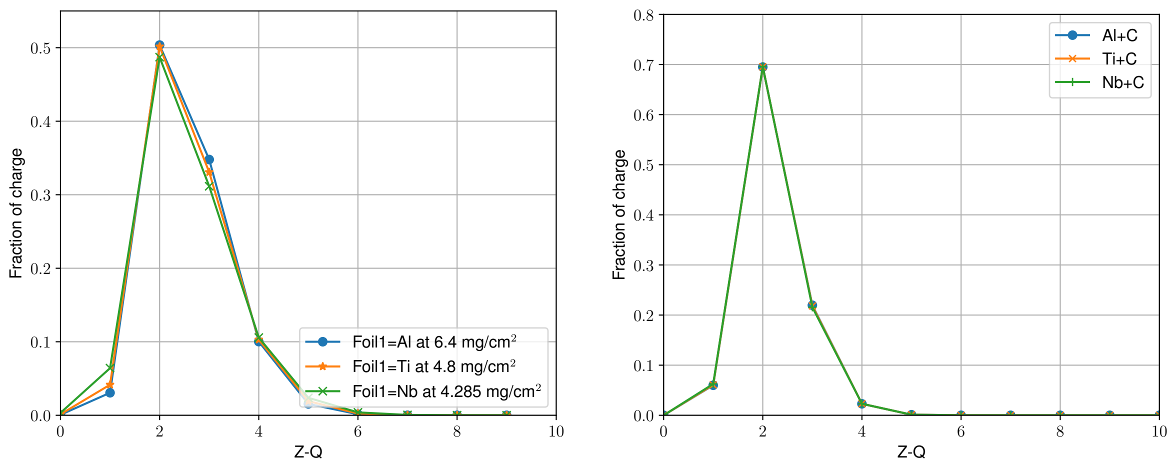

Figure 4: Stripping efficiency of Au at 100 MeV/u on foils of Al, Nb, and Ti (left) and after transiting the entire sandwich (right).

Replacement of Al with Anodized Al

The oxide layer formed on anodized Al, greatly improves the emissivity, as seen in Tab. 2 [8]. The higher emissivity from the oxide layer greatly improves the emissivity of the material. Coated foils, such as the C-coated Al have been used perviously with mixed results [9]. It is not known how this oxide layer would tolerate beam. Anodizing Al could be a cost-effective option for improving foil lifetime. A comparison of the foil temperature in the Al+C sandwich and the anodized Al+C sandwich is shown in Fig. 5.

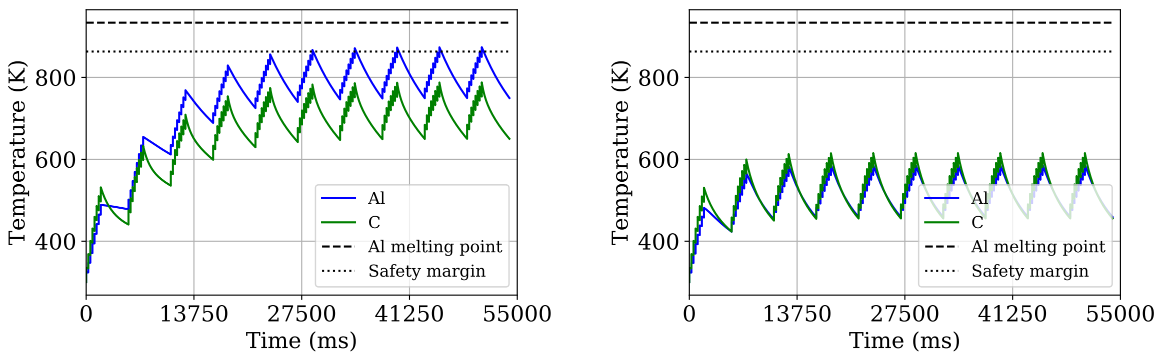

Figure 5: The heating of the Al and C foil layers with pure Al (left) and anodized Al (right), with $16{\times}10^9$ transfer intensity, 5.4 s SC length, 8 booster cycles with a time of 267 ms.

Replacement of Al with Ti

Titanium provides improved thermal properties relative to Al with ρ = 4.51 g/cm^3, a specific heat capacity of 0.52 J/(gK), an emissivity of 0.19 at 300 K, and a melting point of 1941 K. A Ti foil with a thickness of 4.8 mg/cm^2 would provide the same charge distribution as the 6.4 mg/cm^2 Al foil. A comparison of the foil temperature in the Al+C sandwich and the Ti+C sandwich is shown in Fig. 6.

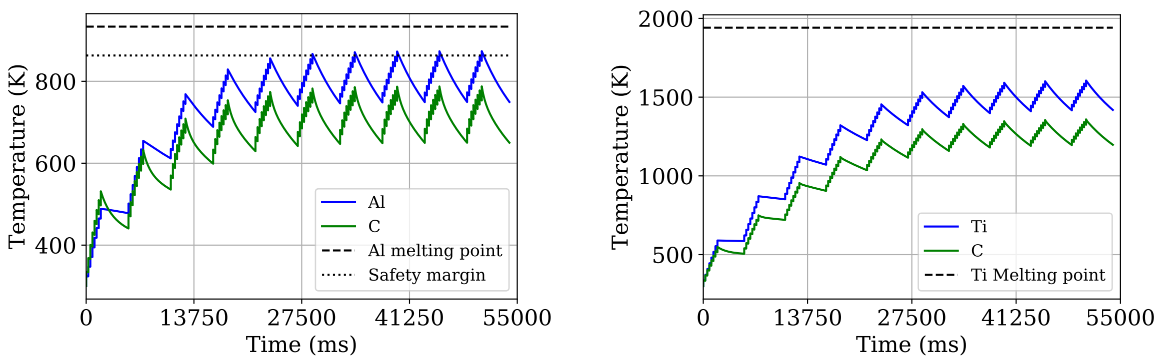

Figure 6: Comparison of using Al (left) and Ti (right) as the first foil. Note the change in scale.

Replacement of Al with Nb

Niobium is more dense than Ti, with ρ = 8.57 g/cm^3, a similar emissivity, and a further improvement on the melting point of $T_{melting}$=2750 K. A foil of Nb would be 67% of the Al thickness to achieve the same stripping profile. The Nb reaches a much higher temperature at the area considered, as seen in Fig. 7. However, the maximum temperature reached, T_{max}=1702 K, still provides a margin of 1000 K on the melting point. Increasing the intensity per SC to 20×10^9 where a foil's usefulness was found to be seconds to minutes. Here the maximum temperature reached by Al is 935 K, where as the maximum temperature reached by Nb is higher, T_{max}=1854 K, but with a margin of 900 K on the melting point.

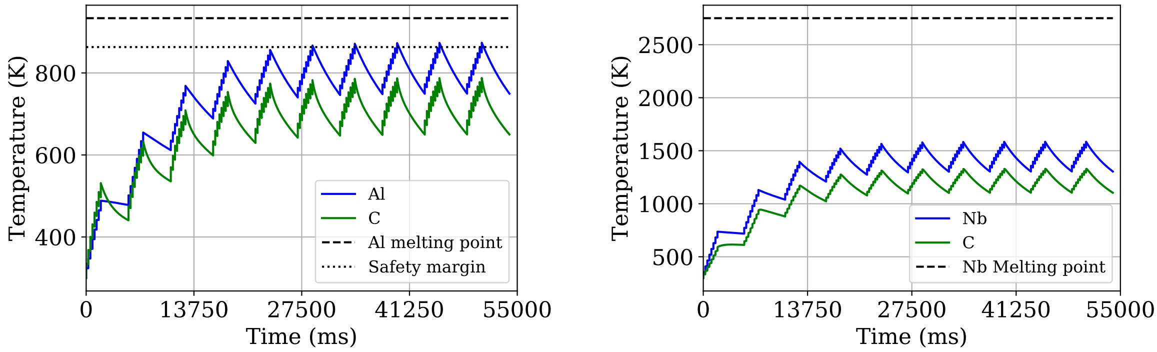

Figure 7: Comparison of using Al (left) and Nb (right) as the first foil. Note the change in scale.

Summary

For the single foil stripping of Ag at 235 MeV/u, the Ti foil would be ideal, providing optimal stripping with minimal energy loss. This Ti foil would need a thickness of at least d=0.0035 cm. For the sandwich foils, anodized aluminum, titanium, and niobium are assessed as replacements for Al. The anodized Al would provide the best thermal properties but it is unknown how the oxide layer would hold up under bombardment from heavy ions. Titanium provides an improvement on foil temperature but would have a smaller margin than Niobium. Niobium would provide the largest margin for heating with an insignificant difference in the final charge state. These calculations are summarized in Tab. 3. The Ti foil would need a thickness of d=0.001 cm and the Nb foil would need a thickness of d=0.0005 cm.

Table 3: Summary of foil temperatures for different materials at an intensity of 16×10^9 and 20×10^9.

Material	SC length	$t_{Booster}$	$N_{Booster}$	N_b	T_{max}	T_{melt}
Aluminum	5.4	267 ms	8	16×10^9	873 K	933 K
Aluminum	5.4	267 ms	8	20×10^9	935 K	933 K
Ano. Aluminum	5.4	267 ms	8	16×10^9	585 K	933 K
Ano. Aluminum	5.4	267 ms	8	20×10^9	628 K	933 K
Titanium	5.4	267 ms	8	16×10^9	1605 K	1941 K
Titanium	5.4	267 ms	8	20×10^9	1718 K	1941 K
Niobium	5.4	267 ms	8	16×10^9	1584 K	2750 K
Niobium	5.4	267 ms	8	20×10^9	1702 K	2750 K

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