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Stripping Foils at the RHIC Injectors: A History

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Abstract

Stripping foils are used throughout Collider-Accelerator Department to strip ions of unwanted electrons. This is done in stages throughout the complex to optimize the transmission of particles. For polarized protons, they are injected into the AGS Booster as H-, and then stripped to H+. For ions from the tandem source, there are two stripping foils: one at the center and the other at the end of the tandem. The tandem foils will not be covered in this document. For ions out of the EBIS source, there is no use of stripping foils upstream of injection into the Booster. All ions that are not fully stripped in Booster are stripped further in the Booster to AGS (BTA) transfer line stripping foil assembly. Finally, any ions that are not fully stripped in the AGS are either stripped in the AGS to RHIC transfer line stripping foil, or as they are being dumped in the AGS by the plunging stripping foil (PSF) dependant on the particles intensity and charge. The BTA foil is the workhorse of the complex, having to provide the desired charge state of ions as light as O, and as heavy as Uranium. Optimizing the stripping efficiency to the desired charge state, while minimizing the energy lost and emittance growth from transiting the foil, requires careful consideration of the foil materials and thicknesses. This paper serves an overview of stripping foils at C-AD, with a review of foils from the construction of the AGS Booster to now.

Contents

Chapter 1

Introduction

The stripping foils at the Collider-Accelerator Department (C-AD) complex are shown in Fig. 1.1, labelled as S* for:

1. Tandem terminal foil
2. Tandem object foil
3. Booster Injection Foil
4. BTA foil
5. ATR foil

Prior to the installation of the AGS Booster, the heaviest ion in the AGS was ^{28}Si. Due to the Booster's superior vacuum the stripping and capture probabilities was greatly reduced, ions as heavy as Uranium have been successfully accelerated in the AGS[1, 2]. Precisely controlling the charge state through the complex, allows for optimal operation of each accelerator.

The BTA stripping foil is the most interesting and difficult foil at our complex. Making the foil too thin, less electrons are stripped from the ions which leads to higher potential losses from vacuum. Making the foil too thick and there are effects such as: increased energy spread, and increased emittance. The thickness of the foil should be uniform while also being considerate of heating from the transiting particles. These stripping foils have to provide optimal stripping for a wide range of ions. The goal for heavy ions is to have a helium-like (2 electron) state in the AGS. For light ions the goal is to have them fully stripped. Some of the lighter ions are injected into the Booster full stripped, such as helions from EBIS.

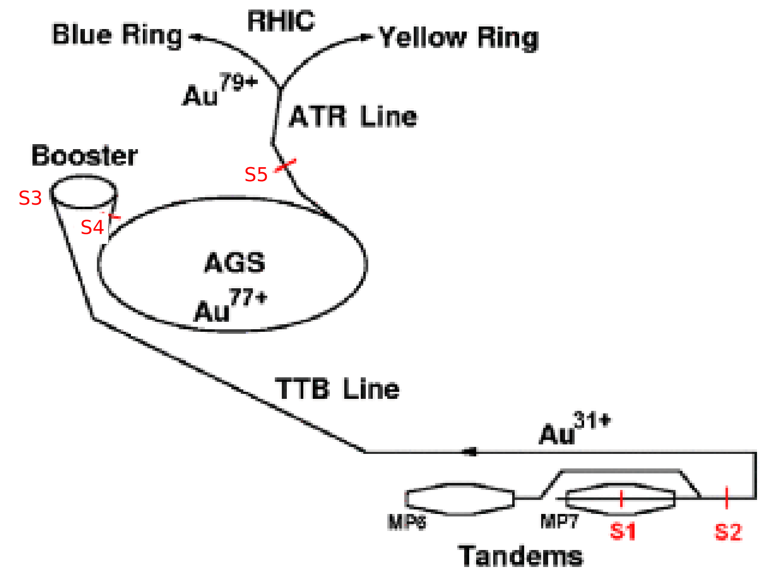

Figure 1.1: Overview of the C-AD injector complex with stripping foil locations, labelled as S1 to S5 in red.

The energy loss of intermediate energy particles transiting a solid is described with the Bethe-Bloch formula[3]:

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \tag{1.1}$$

with K=0.307075 MeV mol^{-1}, z is the particle charge, Z and A are the atomic numbers and relative mass, m_e is the mass, β is the relativistic velocity, γ is the Lorentz factor, and W_{max} is the maximum energy transfer from a single collision. This formula is valid in the region of $0.1 \leq \beta\gamma \leq 1000$. Emphasis should be placed on the energy loss being proportional to the square of the particle's charge. The energy is lost to the solid, which is why high charge ions, such as Au, can be destructive to the foils and other materials [4].

This energy loss can cause a mismatch of revolution frequency from one accelerator to the other [5].There is a spread in energy that comes about from the transiting particles interacting with the electrons and nuclei of the stripping foil, known as energy straggling. A non uniform foil thickness will also cause some particles to have more or less energy loss, as they transit various thicknesses of foil, resulting in an increase of momentum spread.

Meyerhoff and Anholt studies are the basis for the GLOBAL program [6, 7]. These researchers found an analytic solution for stripping of many electron ions on low Z ions. The ionization probability per electron in a shell after traversing a target of thickness T follows:

$$\sigma_i = \frac{1}{T} \ln \left[\left(1 + \frac{M - m}{m + 1 + g} \right) \frac{Y_m}{Y_{m+1}} \right] \tag{1.2}$$

where M is the initial number of electrons, m is the emerging number of electrons, g is a correction to account for stripping from inner shells, and Y_m, Y_{m+1} is the charge charge fraction in a shell based of target thickness, following

$$Y_m = \left[\frac{(M + g)!}{[(m + g)!(M - m)!]} \right] \tau^{m+g} (1 - \tau)^{M-m} \tag{1.3}$$

with $\tau = \exp(-\sigma_j T)$ and σ_j is the average one-electron ionization cross section.

Chapter 2

Stripping Foils at C-AD

2.1 Booster Injection Foil

H^- is injected into the Booster from the LINAC with the stripping foil assembly located after the C5 dipole. The foil assembly contains 6 slots, with one blank and 5 foils, as seen in Fig. 2.1 and described in Tab. 2.1 [8]. All these foils are made of carbon. These foils need to strip two electrons in order to produce protons and be correctly matched with the Booster. This is referred to as strip injection and uses a local orbit bump at the stripping foil which collapses in amplitude as the pulse of protons enter and circulate in the Booster [9, 10]. A pulse from LINAC is approximately 300 μs long. With $f_{rev,200MeV}$=842 kHz at injection, protons will pass through the foil hundreds of times before the bump amplitude is reduced to zero. Each pass causes energy loss and some diffraction which leads to emittance growth. The "stamp" and "strip" foils are designs to optimize the number of passes that the protons will transit the foil [8, 11].

Table 2.1: The carbon foil positions and thicknesses from [8].

Holder no.	Thickness	Design
1	-	empty
2	100 μg/cm^2	strip
3	75 μg/cm^2	full
4	200 μg/cm^2	full
5	135 μg/cm^2	full
6	100 μg/cm^2	strip

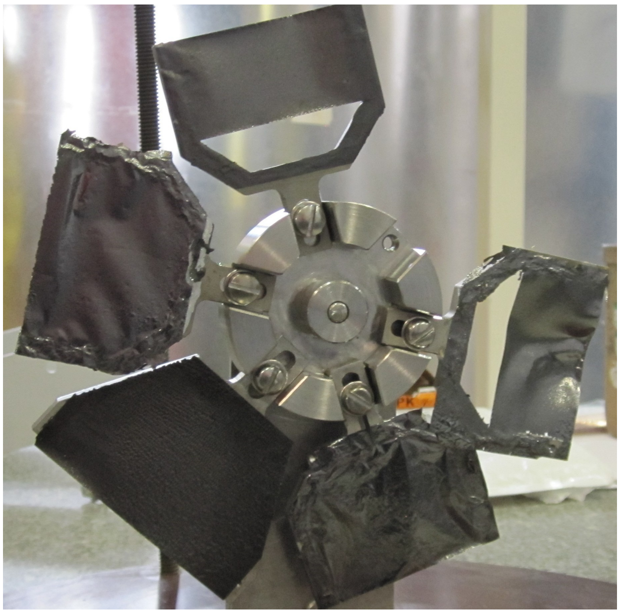

Figure 2.1: Image of the injection foil assembly with five foils installed updated 2017 [8].

2.2 The BTA Foils

The BTA foil assembly is located between BTA Q3 and Q4. The assembly contains 8 slots: one blank slot and 7 foils, as seen in Fig. 2.2. Due to the variation in particle types, energies and charge states, different foils are used to optimize the stripping efficiencies.

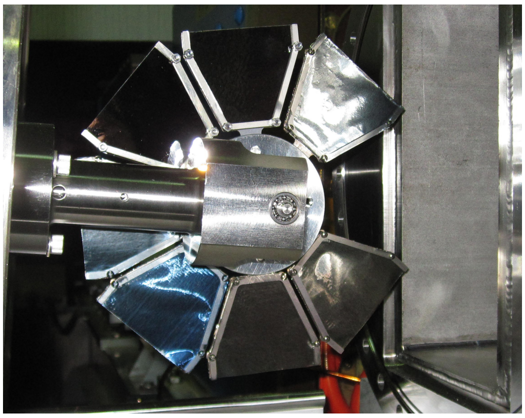

Figure 2.2: The BTA foil assembly with 7 foils installed.

The BTA foil studies began with T. Roser shortly after the completion of the AGS Booster [12]. The first study published is summarized in Tab. 2.2, which has measured stripping efficiencies for the 7 different foils being studied. The theoretical stripping efficiencies were calculated and added for the purpose of this document (organized in each column as: Theory, Measurement).

Table 2.2: From [12], Stripping efficiencies at different energies, organized in each column as: theory, measurement

		Beam Energy (MeV)				
Material	Thickness	65.01	74.86	84.71	104.41	124.11
Co	16 mg/cm^2	19.2%, 6.2%	30.6%, 7.5%	40.6%, 24.8%	55.4%, 53.0%	60.9%, 54.3%
Al	70 mg/cm^2	35.5%, 6.1%	53.0%, 11.6%	63.4%, 45.1%	67.8%, 54.0%	62.3%, 30.7%
Al	34 mg/cm^2	47.9%, 11.4%	60.3%, 25.6%	66.9%, 49.1%	67.4%, 57.2%	61.2%, 46.3%
Al	14 mg/cm^2	53.7%, 6.9%	63.3%, 25.8%	67.9%, 52.1%	71.8%, 65.3%	72.0%, 64.0%
C	56 mg/cm^2	71.2%, 24.9%	74.8%, 59.8%	75.6%, 64.7%	72.0%, 67.5%	67.9%, 65.1%
C	27 mg/cm^2	74.1%, 38.9%	76.2%, 59.4%	76.9%, 63.5%	75.9%, 61.9%	74.2%, 50.9%
C	18 mg/cm^2	70.8%, 36.3%	72.1%, 48.0%	71.3%, 45.3%	67.8%, 53.1%	62.9%, 36.1%

Energy loss from particles transiting the stripping foils has also been studied extensively [5], and was part of the main drive for developing the dual material foils [13]. Data from these documents have been compiled in Tab. 2.3 where theoretical stripping efficiencies (Eff. T %) have been added when not available.

Key documentation in this section (summarized in Tab. 2.2 and Tab. 2.3):

1. T. Roser. "Charge Exchange Studies with Gold Ions at the Brookhaven Booster and AGS" 1993.
2. L. Ahrens. "Calculation of the Mean Energy Loss in the BTA Stripping Foils and Comparison with Measurement" 2002.
3. C. Gardner. "Change and documentation of the BTA stripping foils 2020" 2021.
4. P. Thieberger. "Improved gold ion stripping at 0.1 and 10 GeV/nucleon for the Relativistic Heavy Ion Collider" 2008.
5. G. Marr. "Analysis from Beam Studies with BTA Stripping Foils" 2003.

Table 2.3: Summary of stripping foils used at C-AD, with what beams they were used with, what the theoretical (T) and measured (M) stripping efficiencies are, and where their documentation was found.

Material	Thickness (mg/cm^2)	Eff. (T, %)	Eff. (M, %)	Beam used (MeV/u)	Notes	Doc.
C	13.9	52.4(Au77+), 99.5(Fe26+), 99.9(Si11+)	46%(Au77+)	Au 100, Fe 100?, Si 100?		2, 4
C	18.5	69.8(Au77+)	-			2
C	23.1	75.3(Au77+)	64%(Au77+)	Au 100		2, 4
C	24.2	76.3(Au77+)	-	Au 100		5
C	24.6	75.8(Au77+)	65%(Au77+)	Au 100		4
C	32.4	75.3(Au77+)	-			2
C	46.2	73.2(Au77+), 99.6(Fe26+), 99.9(Si11+)	-	Fe 100?, Si 100?		2
Cu	22.8	50.7(Au77+)	-			2
Cu and C	22.8 and 13.9	76.2(Au77+)	-			2
Ni and Al	4.38 and 9.0	61.9(U90+)	37.0% (U90+)	U 107	C coated	3
Ni and Al	4.38 and 6.4	-	-	Au 100 ; Cu 100	C coated	3
Ni and Al	6.83 and 13.2	70.1 (U90+)	-	U 120	C coated	3
C and Al	9.24 and 6.4	9.5%(Au77+)	-	Au 100		~4
Al and C	6.4 and 9.24	74.2%(Au77+)	65%(Au77+)	Au 100		4
Al and C	6.45 and 8.39	91.2%(96Zr40)	87%(96Zr40)	Au 100 ; Zr 113		3
Al and C	6.32 and 8.50	73%(96Ru44)	63%(96Ru44)	Au 100 ; Ru 65 , Al 100	C coated	3
Al and C	6.26 and 7.93	-	-	Au 100		3
Al and C	6.26 and 8.11	-	-	Au 100		3
Al and C	6.26 and 8.78	-	-	Au 100		3
Al	4.56	36.6% (Au76+)	-	O 116		3
Al	10.7	70.7% (Au77+)	56%(Au77+)	Au 100		4
Al	12.7	71.6% (Au77+)	56%(Au77+)	Au 100		4
Mica	25.8	-	43%(Au77+)	Au 100		5
Ti	29.9	57.2%(Au77+)	25%(Au77+)	Au 100		5
Silica	22.5	-	53%(Au77+)	Au 100		5
Silica	27.7	-	-	Au 100		5
Be	23.2	50%(Au77+)	-	Au 100		5
Be	28.3	63%(Au77+)	-	Au 100		5

2.2.1 Dual Material Foils

To calculate the charge distribution from a multi-material foil, the following algorithm with GLOBAL should be used (see A.1)[14]:

- calculate distribution of charge states for first foil.
- calculate distribution of charge states for second foil for each of the charge states following the first foil.

From [13], "When mounting this assembly in stripper housing, it is important that the beam enters through the aluminum side and exits from the carbon side otherwise the results would be disappointing." This is observed in Fig. 2.3 where a comparison is shown between an Al-C and the same foil reversed (C then Al). Having the incorrect order for the Al-C sandwich pro-

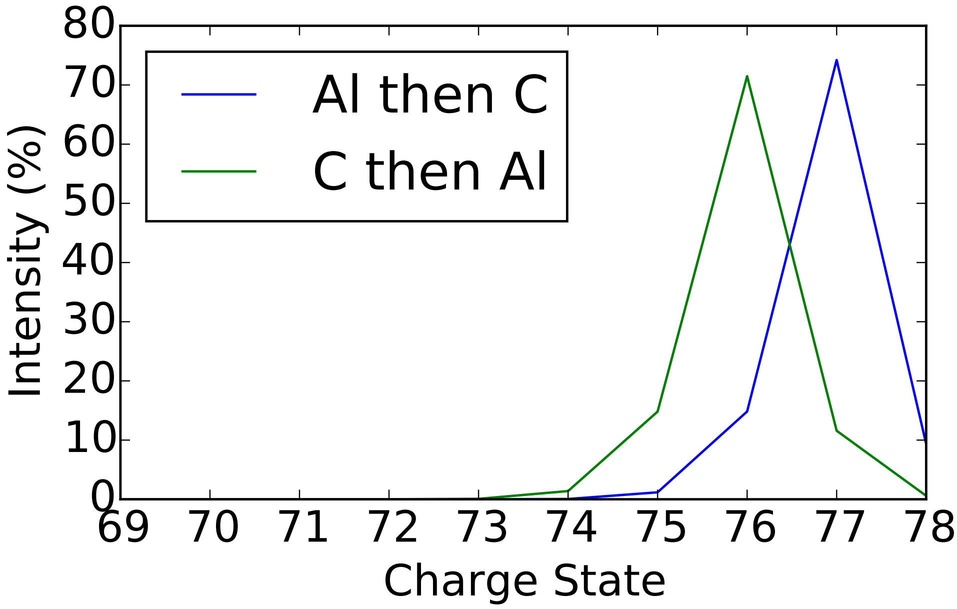

Figure 2.3: Image comparing the charge state distribution for an Al-C foil sandwich with a C-Al foil sandwich.

vides the incorrect charge-state and would truly give disappointing results.

From [13], it seems a parabola was fit between the peaks of Al and C foils to empirically determine the stripping efficiency of the sandwich foils, or a different foil thickness than quoted in paper was used (see right plot in

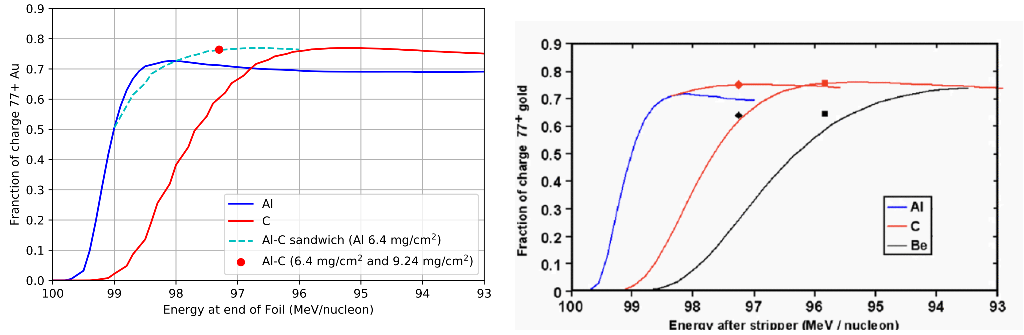

Figure 2.4: Comparison of 2022 dual foil calculation (left) compared to [13] calculation (right).

Fig. 2.4). The energy after transiting the Al foil of 6.4 mg/cm^2 is approximately 98.9 MeV, not 98.5 MeV.

The algorithm for calculating the stripping efficiency of the dual material for various thicknesses, is similar to the above, and follows:

1. Calculate the energy loss and charge distribution following the first foil
2. Loop over the Q state incident on the second foils (using GLOBAL) for various thicknesses.
3. Bin the resulting distributions by charge state to get the distribution at each thickness.

2.2.2 Comparison with Historical Data

As seen in Fig. 2.5, updated calculations using GLOBAL (dotted red line) are overlaid with data from [13]. This is done to ensure that historical results have been recovered through use of the GLOBAL program (as data in [13] was unable to be found). As noted previously, there is a difference between the predicted and the measured charge state distributions. The justification for this discrepancy is possible recapture or additional stripping of electrons as they interact with the material.As seen in Fig. 2.5, the state of Au^{77+} is less prevalent than expectations and Au^{76+} is more abundant. Uranium is slightly different where U91+ is more prevalent than U90+, in comparison with expectations.

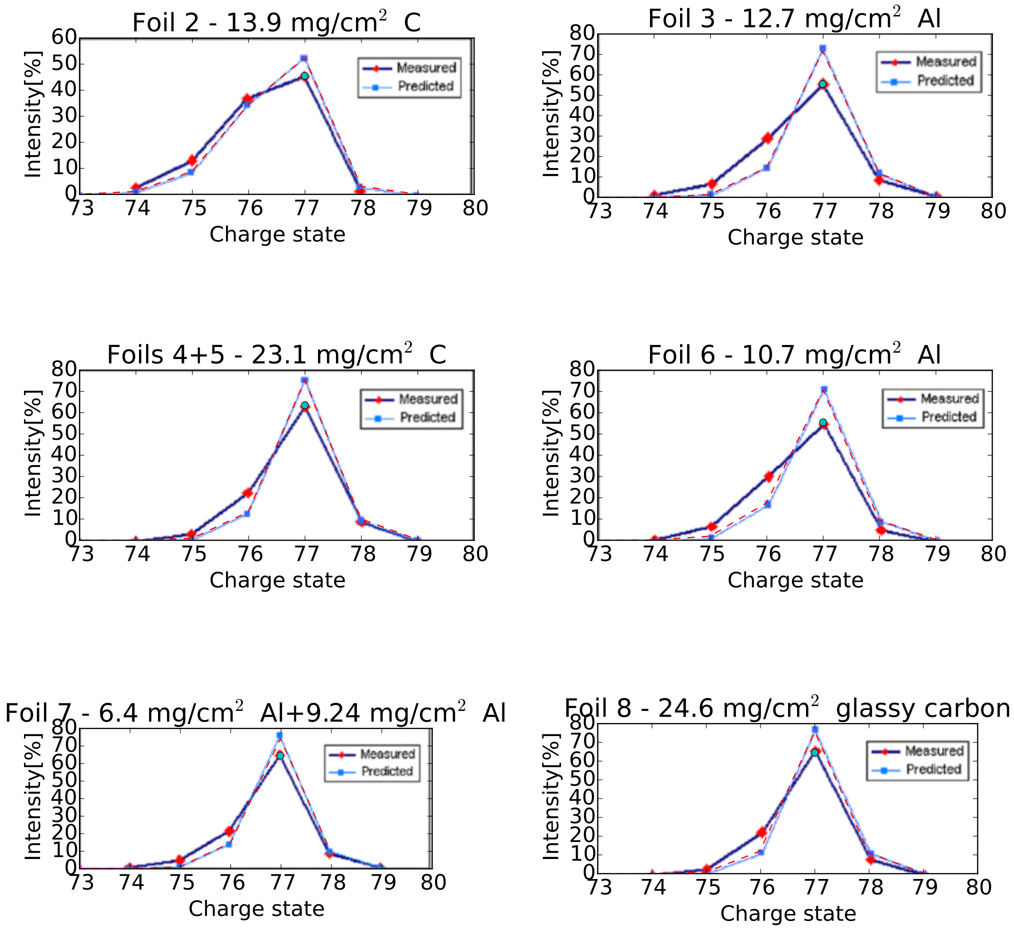

Figure 2.5: Measured and predicted 100 MeV/nucleon gold charge-state distributions from [13], with predicted calculations from this paper as overlaid dashed lines.

2.3 The ATR Foil

The ATR stripping foil assembly contains a single foil to fully strip non fully-stripped ions before injection into RHIC. Prior to 2007, the foil was Al_2O_3 (522 mg/cm^2) which generated 0.3% energy loss and 4% beam loss with Au beams. In 2007, the foil was changed to a 0.001" thick tungsten foil is used (48.9 mg/cm^2) with an estimated 0.1% in beam loss, and 0.02% energy loss [13].

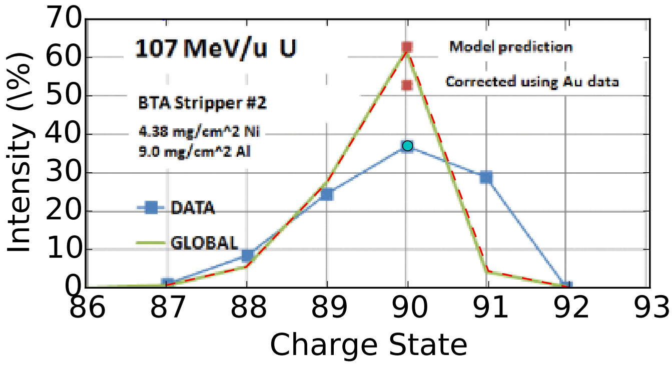

Figure 2.6: Measured and predicted 107 MeV/nucleon uranium charge-state distributions from [13], with predicted calculations from this paper as overlaid dashed lines.

2.4 The AGS Plunging Stripping Foil

Beams that are not extracted out of the AGS must be dumped. The PSF is a 0.001" (48.9 mg/cm^2)tungsten foil used to fully strip the circulating Au beam at the end of the cycle for more efficient deposition of particles on the beam dump[4]. This showed damage from the Run21 run conditions, and had to be replaced mid-run. This foil is a 0.001" (48.9 mg/cm^2) thick tungsten foil.

Chapter 3

Foil Failures

3.1 Overview of Foil Failures

Failed foils from Run20 are documented in [15] and observed in Fig. 3.1.

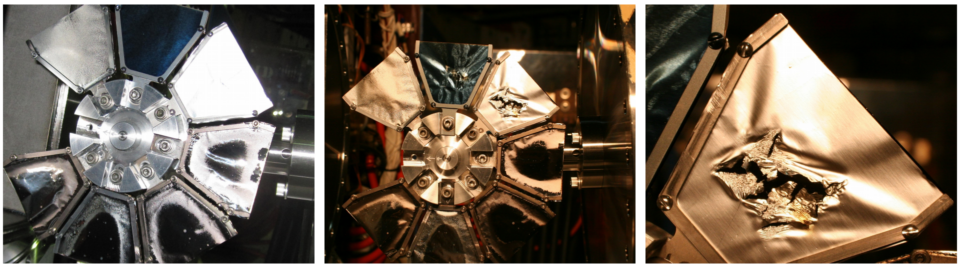

Figure 3.1: The BTA foils as installed in 2010 (left), from inspection and replacement during Run20 (middle), and a zoom in on the failed foil in slot 5 (right) as discussed in [15].

Following derivation in [16]: For a supercycle of length L (L=5.6 s), n (n=8) booster transfers every t (0.267 s) leads to a short period of rapid heating followed by a long cooling period. The instantaneous increase in temperature from N (20×10^9/n) particles transiting the foil is

$$\Delta T = -\frac{N}{cA}\frac{dE}{dx} \tag{3.1}$$

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 (Al) and 2 (C) in contact with vacuum chamber of temperature T_w follows

$$\frac{dT_1}{dt} = C_1 T_W^4 - C_1(2T_1^4 - T_2^4) \tag{3.2}$$

and

$$\frac{dT_2}{dt} = C_2 T_W^4 - C_2(2T_2^4 - T_1^4) \tag{3.3}$$

with $C_1 = 0.5880 \times 10^{-10}$, $C_2 = 6.6727 \times 10^{-10} s^{-1} K^{-3}$ (Al and C). These calculations are observed in Fig. 3.2. Details on heating of the AGS PSF,

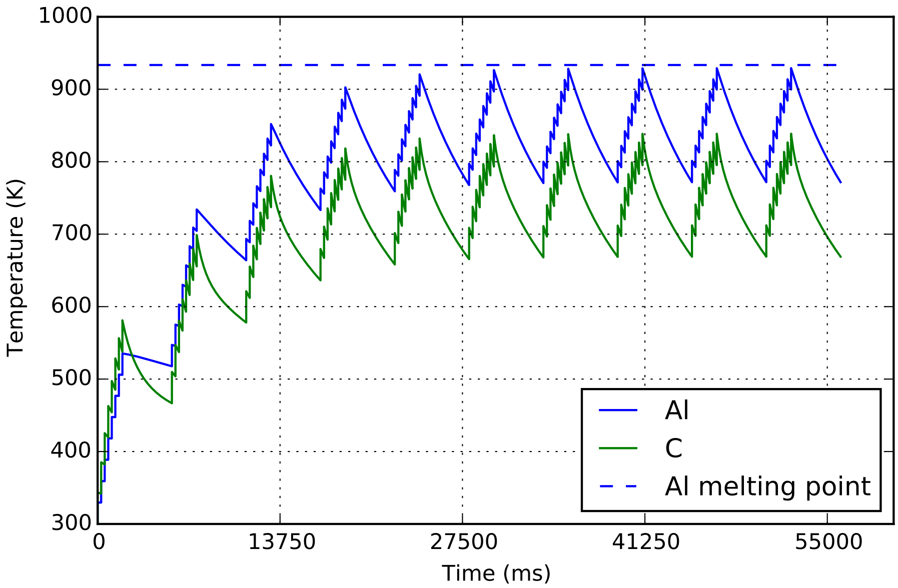

Figure 3.2: Heating of Al and C from incident Au beams from Tandem in run 2021.

U-line foil, and the AGS dump are also found in [16].

Deformation of the Al with the Al+C sandwich was noted in [13] and observed in Fig. 3.1. Run 2007 used Tandem beam with four Booster cycles at 3.3×10^9 Au ions per cycle. The Booster cycle length was 200 ms and the supercycle length was 4 s. Simulated temperature of Al would have reached a maximum of 892 K as seen in Fig. 3.1, close to the melting point of Al.

Figure 3.3: Deformation of the Al-C foil as documented in [13].

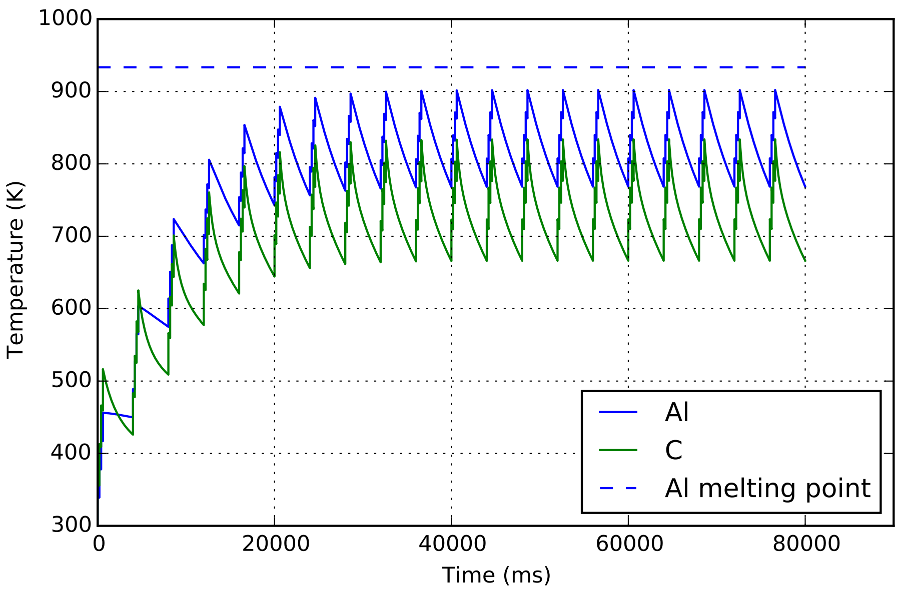

Figure 3.4: Heating of Al and C from incident Au beams from Tandem in run 2007.

3.2 Run 23 with Au from upgraded EBIS

Standard Au operation with EBIS uses a 6→3→1 merge (six bunches merged into one in AGS) with 12 transfers from Booster into AGS, and two extractions from AGS to RHIC. To reach 3.2×10^9 ions/bunch at RHIC injection requires 3.56 ions/bunch at AGS extraction (assuming 90% transfer efficiency). Note that 7.12×10^9 ions is near the limit of 8×10^9 ions in AGS. Assuming 50% efficiency from Booster to AGS, 14.24×10^9 total ions will be transferred from Booster to AGS per supercycle over 12 transfers. The maximum temperature of Al foil is T=807 K with a 6.6 s supercycle and 200 ms Booster cycle as seen in Fig. 3.2. This would increase to $T_{Al,max}$ =836 K with a total intensity of 16×10^9 ions and the Al will reach its melting point with 21×10^9 ions transferred per supercycle.

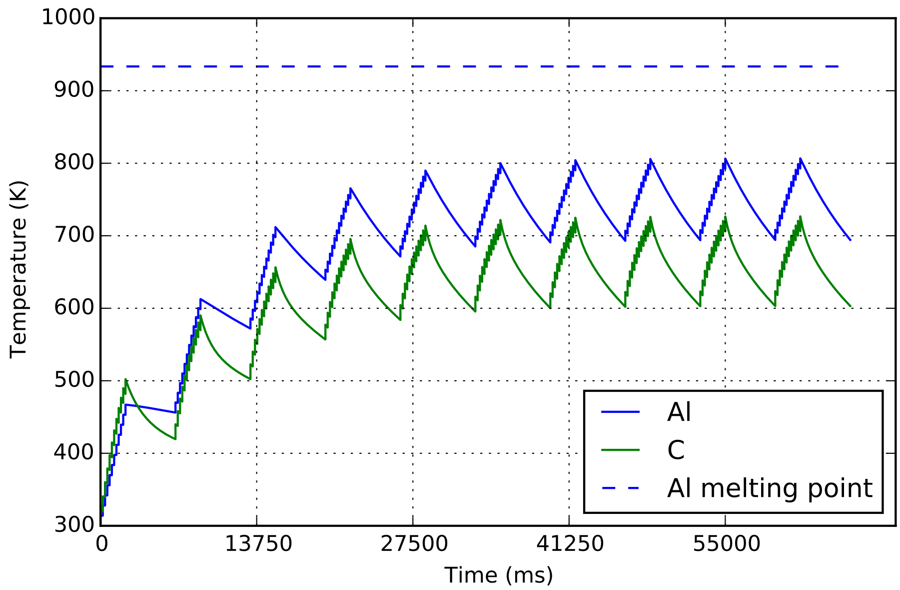

Figure 3.5: Foil heating from expected parameters from the Extended EBIS source.

3.2.1 Run 23 with Au from Tandem

From Sec. 3.1 and [13, 17, 18], caution should be used when tandem is used as a source to avoid damage to stripping foils, whereas Sec. 3.2 established significantly less heating when EBIS is the ion source. For the injector setup, there will be 4 to 8 transfers through BTA. The supercycle can be as low as 5.4s and the Booster cycle is 267 ms long. However, due to BMMPS issues, the supercycle (SC) length was constrained to a minimum of 6 s. The parameters given in [17] where degraded foil performance was observed corresponds to a temperature of 863 K. Tab. 3.1 describes the intensity limits for given supercycle lengths and number of tandem pulses to be under 863 K.

Table 3.1: Tandem beam summary of intensities to be under 863 K.

Tandem Pulses	Intensity ($\times 10^9$)	SC length
8	15.4	5.4 s
8	16.4	6 s
6	14.7	5.4 s
6	15.7	6 s
4	14.2	5.4 s
4	15.2	6 s

Due to the potential for tandem intensity to spike (coming back after a foil change for example), it was decided to go with the minimum intensity on the table (14×10^9). This was increased to 16×10^9 to better support the RHIC physics program.

3.3 A BTA foil for light ions

STAR has requested C, Al, and Fe beams for fixed target studies. Al in Run15 used 6.32 and 8.50 mg/cm^2 Al+C foil (removed) but is similar to the existing Al+C foils presently installed (6.26 Al and 7.93 C, and the 8.11 Al and 8.78 C, in mg/cm^2). Fe and Si beam used a 13.9 mg/cm^2 C foil for AGS slow extraction (and 46.2 mg/cm^2 C foil prior to 1997). The 4.56 mg/cm^2 Al foil (heavy duty Reynolds wrap) is presently installed in the foil wheel. This foil was used previously for O in run 21. This foil should provide near 100% stripping efficiency for C and Al, and 98.3% for Fe.

Chapter 4

Summary

Stripping foils at C-AD are essential for the efficient operation of each accelerator. A history and overview of foils at C-AD was given and discussed. Theoretical stripping efficiencies were calculated and provided when not available. The algorithm for calculating stripping efficiencies was given. As has been previously reported, heating of the foils is a concern and can lead to damage. Parameters for several setups to mitigate damage to the foils was given. To help prevent a loss of information, all relevant documents have been compiled in Sec. 5 and possible information gaps were determined and discussed.

4.1 Acknowledgements

As this paper is a summary of other documents, with added calculations and analysis, I would like to thank Kip Gardner, Thomas Roser, Peter Thieberger, and Keith Zeno who have made significant contributions to these studies.

Chapter 5

Documentation

The Basics

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Appendix A

Appendix

A.1 Applications

GLOBAL

- Used to calculate energy loss and charge state distributions for targets of specific elements+thickness.
- Has some loop capabilities for select manipulations.

SRIM/TRIM

- Can perform various calculations for particles in matter.
- Primary use is to calculate angular scattering and energy losses.

LISE++

- Complicated but does allow for many material foils.
- Can calculate energy straggling from foils.
- Also has ability to add in magnetic elements and many other features.

A.1.1 GLOBAL usage

The GLOBAL program is shown below in Fig. A.1. The different panes allow control of various aspects of the calculations.

Figure A.1: The global program.

Projectile Pane

- With the selection of the element, the atomic number (Z) and weight (A) will be updated automatically.
- Z-Q is the number of electrons with a maximum supported electron count of 28. For ions exceeding 28 electrons, the cross section for stripping of the additional electrons is very large and provide an insignificant contribution to the final charge state (assuming the desire is to have fully or near fully stripped ions).
- Initial energy is the energy of the projectile, typically ∼100 MeV for most species in the BTA transfer line.

Target Pane

- Describes the element of the foil, which will similarly have its weights and atomic number updates with a change of element.
- Foil thickness in mg/cm^2.

Loop Pane This pane has various parameters one can loop over for different types of calculations. The ability to loop is key for performing the scans as in Fig. 2.4

Output Window Important notes on the output are: Q(X) where X=Z-Q is the electron count, not the charge, so Q(0) is the relative abundance of fully stripped Au (Q=79+) given the input parameters. Similarly, Q(2) would be helium-like ion abundance.

If a loop routine is used, the table will continue to populate with the updated parameters.

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