Doc Number: Beams-doc-3980
Version: 2.0
Category: Note

Analysis Procedures for Al Activation Studies

Bruce C. Brown
Accelerator Division, Main Injector Department
Fermi National Accelerator Laboratory *
P.O. Box 500
Batavia, Illinois 60510

9 April 2012

Contents

Abstract

Using a HPGe detector at the Fermilab Radiation Analysis Facility, we measure the 1274 keV γ ray from activation of ^{22}Na induced in Al tags in order to provide a measure of the hadron flux in the collimation region of the Main Injector. Using a constant to relate flux to absorbed dose rate, the absorbed dose is measured. Procedures, data and some results will be documented.

---

*Operated by Fermi Research Alliance under contract with the U. S. Department of Energy

1 Introduction

The activation of ^{22}Na in an ^{27}Al target by a flux of secondary hadrons is represented adequately by a constant cross section of 10.1 millibarns per nucleus above a threshold of 30 MeV. For most applications, the half life is sufficiently long (2.60 years) that a measurement of the induced activation can be converted to a fluence estimate (integrated hadron flux). We will document that procedure along with a more accurate measure of the fluence which uses the history of the activation flux.

As a part of the Main Injector Collimation effort, a set of 15 locations in the MI300 collimator region were selected for using aluminum tags to document the fluence of hadrons created by the collimation of beam loss. A set of 4 tags was placed at each location prior to the commissioning of the collimators and a tag from each location was removed at intervals of one year, two years and three years. The hadron fluence at shielded locations beside the secondary collimators, on the aisle side of the steel and concrete masks (STCM) and on the aisle side of the steel and marble masks (STMM) will be compared with predictions of MARS[1][2] to help assure compliance with environmental limits on radiation. Tags at the upstream or downstream end of main quadrupoles allow the same comparisons but also provide a direct estimate of radiation damage (absorbed dose) and a more refined dose estimate when compared using the MARS results. Tags were secured with 'duct' tape but on the side of the STCM devices the tape failed so the location of the tags during activation was less well determined and didn't match fully the location simulated in MARS.

2 Formulas

2.1 Activity and Activation

For a sample with N_I atoms of isotope I which has a half life of $t_{1/2}$ (or mean lifetime of τ), the number of atoms changes by decay in accordance with

$$\mathcal{N}(t) = N_I e^{-\frac{t}{\tau}} = N_I 2^{-\frac{t}{t_{1/2}}} \tag{1}$$

The number of decays, S, also known as the activity of the sample, is thereby

$$S(t) = -\frac{d\mathcal{N}}{dt} = \frac{N_I}{\tau} e^{-\frac{t}{\tau}} \tag{2}$$

So the initial activity is

$$S = \frac{N_I}{\tau} = \frac{N_I \ln 2}{t_{1/2}} \tag{3}$$

This is the activity in becquerel (Bq). To get the activity in Curies, one divides by 3.7×10^{10}. For the activity in pico Curies (pCi) one divides by 3.7×10^{-2}.

To obtain the specific activity, S_A, one expresses the number of atoms in moles (m) or grams (M). For a material with atomic mass A, the number of moles is $m = \frac{M}{A}$.

$$S_A(Bq/mole) = \frac{S}{m} = \frac{N_A \ln 2}{t_{1/2}} \tag{4}$$

$$S_A(Bq/gm) = \frac{S}{M} = \frac{N_A \ln 2}{A t_{1/2}} \tag{5}$$

$$S_A(pCi/gm) = \frac{S}{3.7 \times 10^{-2} M} = \frac{N_A \ln 2}{3.7 \times 10^{-2} A t_{1/2}} \tag{6}$$

where N_A is the Avogadro Constant.

2.2 Cross Sections and Fluence

In a beam of particles, nuclear interactions produce new isotopes. The number of new nuclei is proportional to the fluence, Φ, measured in particles per unit area (particles-cm^{-2}); the rate of production is proportional to the flux, $\frac{d\Phi}{dt}$ (particles-cm^{-2}sec^{-1}). In a material with n_T target atoms per unit volume, an interaction with cross section σ will produce n_I atoms per unit volume of isotope I

$$n_I = \Phi n_T \sigma. \tag{7}$$

The activity, S_A (Bq per cm^3), produced by n_I atoms per cm^3

$$S_A = \frac{n_I \ln 2}{t_{1/2}} = \frac{\Phi n_T \sigma \ln 2}{t_{1/2}} \tag{8}$$

We will want the specific activity per gram of target material, $S_A = S/\rho_T$ (Bq per gram).

$$S_A(Bq/gm) = \frac{n_I \ln 2}{\rho_T t_{1/2}} = \frac{\Phi n_T \sigma \ln 2}{\rho_T t_{1/2}} \tag{9}$$

Substituting for n_T with $\rho_T N_A / A_T$ we have

$$S_A(Bq/gm) = \frac{\Phi N_A \sigma \ln 2}{A_T t_{1/2}} \tag{10}$$

$$S_A(pCi/gm) = \frac{\Phi N_A \sigma \ln 2}{A_T t_{1/2} 3.7 \times 10^{-2}} \tag{11}$$

We calculate the fluence from the Specific Activity as

$$\Phi = \frac{S_A A_T t_{1/2} 3.7 \times 10^{-2}}{N_A \sigma \ln 2} \tag{12}$$

2.3 Activation of ^{27}Al

The reaction $^{27}\mathrm{Al} \rightarrow {}^{22}\mathrm{Na}$ has a total cross section, $\sigma = 10.1 \times 10^{-27}$ cm^2 per atom with a threshold at about 30 MeV (see Fig. IV.28 on Barbier[3], Page 194). Taking $N_A = 6.022 \times 10^{23}$, $A_T = 26.98$, $t_{1/2} = 2.6027$ years or 82.135×10^6 seconds we find

$$\Phi(hadrons/cm^2) = 1.9448 \times 10^{10} S_A(pCi/gm) \tag{13}$$

2.3.1 Particle Flux with Decay Correction from Exposure History

For a hadron flux produced by 8 GeV proton beam losses, we assume that the spatial distribution of shower particles remains relatively fixed with time variations being due to beam quality (halo) and/or program requirement changes[4]. This implies that the fluence of hadrons, Φ, at a sampling point near a secondary collimator, for example, will be proportional to the signal integral on a nearby loss monitor, L.

$$\Phi = \varepsilon L \tag{14}$$

When we relate activity of ^{22}Na to the fluence we will correct for decays. For Main Injector operation, loss monitor sums, L_i, are recorded for each acceleration cycle. As developed in [4], tools are available for adding these to provided loss history in either 10 minute or 1 week intervals. Weekly sums are sufficient for correcting for ^{22}Na decay (2.6027 year half life).

$$LI_j = \sum_{t=t_j}^{t_j+T_s} LI(t) \tag{15}$$

To account for decays, we will weight these to provide an exponentially weighted sum but express the life time using the half life

$$LW(I,T_M) = \sum_j LI_j \frac{\ln 2}{t_{1/2}} 2^{-(T_M-T_j)/t_{1/2}} \tag{16}$$

where T_M is the radiation measurement time, T_j is the quanta time and $t_{1/2}$ is the half life for isotope I. With times in seconds, LW is in units of Rads/sec. We will also want the sum loss without half life weighting

$$L(I,T_M) = \sum_j LI_j \frac{\ln 2}{t_{1/2}} \tag{17}$$

One can alternatively express these sums in Rads rather than in Rads/sec by $LWu(I,T_M)$ and $Lu(I,T_M)$ where

$$LWu(I,T_M) = \sum_j LI_j 2^{-(T_M-T_j)/t_{1/2}} \tag{18}$$

and

$$Lu(I,T_M) = \sum_j LI_j \tag{19}$$

We can provide the fluence (corrected for decays) by correcting the uncorrected fluence in Eq. 13 using

$$\Phi = \Phi_{total} = \Phi_{uncorr} \frac{L(I,T_M)}{LW(I,T_M)} = \frac{Lu(I,T_M)}{LWu(I,T_M)} \tag{20}$$

where Φ_{uncorr} (or Φ_{meas}) is calculated using Eq.13 from the measured activity.

It will be useful to have the ratio of activation divided by fluence. The fluence or activity (corrected for decays) by

$$\frac{\Phi_{total}}{\Phi_{weighted}} = \frac{S_A}{S_{A(meas)}} = \frac{L(I,T_M)}{LW(I,T_M)} \tag{21}$$

where $\Phi_{weighted} = \Phi_{uncorr}$ is corrected for the isotope decay to get Φ_{total}, the fluence integrated over the observation time.

$$\frac{\Phi_{weighted}}{LW(I,T_M)} = \frac{\Phi_{total}}{L(I,T_M)} \tag{22}$$

$$\frac{S_A}{\Phi_{total}} = \frac{S_{A(meas)}}{\Phi_{uncorr}} \tag{23}$$

$$\frac{S_A}{L(I,T_M)} = \frac{S_{A(meas)}}{LW(I,T_M)} \tag{24}$$

and/or

$$\frac{S_A}{Lu(I,T_M)} = \frac{S_{A(meas)}}{LWu(I,T_M)} \tag{25}$$

2.3.2 Particle Fluence for Uniform Irradiation

To compare with some typical formulas for activation analysis, we will consider the case where the fluence is delivered in a flux which is uniform in time. For $d\Phi/dt$ a constant for irradiation time from 0 to t_i (from Barbier[3], p 15). This will produce n_I nuclei of isotope I per unit volume

$$n_I(t) = n_T\sigma\frac{d\Phi}{dt}\int_0^{t_i} e^{-(t_i-\tau)/\tau_I}d\tau \tag{26}$$

$$n_I(t) = n_T\sigma\frac{d\Phi}{dt}\tau_I(1-e^{-t_i/\tau_I}) \tag{27}$$

After a cooling time, t_c, the number of atoms will have decayed to

$$n_I(t_c) = n_T\sigma\frac{d\Phi}{dt}\tau_I(1-e^{-t_i/\tau_I})e^{-t_c/\tau_I} \tag{28}$$

So if $n_I(t_c)$ atoms per cm^3 of isotope, I, remain after a uniform irradiation for t_i and cool down t_c, we will have activity of $S_A(Bq/gm) = n_I/(\tau_I\rho_T)$. Again we can substitute for n_T

$$S_A(t_c)(Bq/gm) = \frac{N_A}{A_T}\sigma\frac{d\Phi}{dt}(1-e^{-t_i/\tau_I})e^{-t_c/\tau_I} \tag{29}$$

alternatively, using $M/A_T = N_T/N_A$ we have

$$S_A(t_c)(Bq/gm) = \frac{N_T}{M}\sigma\frac{d\Phi}{dt}(1-e^{-t_i/\tau_I})e^{-t_c/\tau_I} \tag{30}$$

Now, using pCi rather than Bq, we calculate the flux

$$\frac{d\Phi}{dt} = \frac{M\,3.7\times10^{-2}}{N_T\sigma}\frac{e^{t_c/\tau_I}}{(1-e^{-t_i/\tau_I})}S_A(t_c)(pCi/gm) = \frac{A_T\,3.7\times10^{-2}}{N_A\sigma}\frac{e^{t_c/\tau_I}}{(1-e^{-t_i/\tau_I})}S_A(t_c)(pCi/gm) \tag{31}$$

We convert this corrected flux to a fluence by multiplying by the irradiation time, t_i.

$$\Phi(hadrons/cm^2) = \frac{d\Phi}{dt}t_i = \frac{A_T\,t_i\,3.7\times10^{-2}}{N_A\sigma}\frac{e^{t_c/\tau_I}}{(1-e^{-t_i/\tau_I})}S_A(t_c)(pCi/gm) \tag{32}$$

For the uniform exposure assumption we find

$$\Phi(hadrons/cm^2) = \Phi_{total} = \Phi_{uncorr}\frac{t_i\ln2}{t_{1/2}}\frac{e^{t_c/\tau_I}}{(1-e^{-t_i/\tau_I})} \tag{33}$$

2.3.3 Check Uniform Irradiation Against Irradiation History

For long half life isotopes, the correction for irradiation exposure in the Main Injector is relatively easy since the flux relation between BLM locations and residual radiation locations has remained sufficiently constant at most locations. For ^{22}Na with its 2.6027 year half life, corrections using weekly exposure sums are adequate. To obtain fluence corrected for decays at the locations used for Al Tags, we identify a nearby loss monitor and use Eq 20 for correction. In Table 1 we show the correction for uniform exposure assumption along with the exposure-weighted results for our six BLM's. Al Tags were installed on 10/12/2007.

Table 1: Comparison of Fluence Exposure Corrections

BLM	End Irradiation	Unweighted Dose (Rads)	Weighted Dose (Rads)	Weighted Irradiation Correction	Uniform Irradiation Correction
LI230	10/08/2008	939837.4272	857958.3111	1.095	1.138
	08/26/2009	2804366.275	2334284.604	1.201	1.270
	08/12/2010	3282460.675	2229548.281	1.472	1.424
LI301	10/08/2008	258874.9632	236336.3585	1.095	1.138
	08/26/2009	523647.936	420592.0558	1.245	1.270
	08/12/2010	1339301.174	1056773.802	1.267	1.424
LI302	10/08/2008	718681.4208	655374.0178	1.097	1.138
	08/26/2009	1419595.632	1139964.994	1.245	1.270
	08/12/2010	3369995.798	2652941.871	1.270	1.424
LI303	10/08/2008	1266726.384	1158874.657	1.093	1.138
	08/26/2009	2381237.309	1892791.13	1.258	1.270
	08/12/2010	4540779.734	3380354.205	1.343	1.424
LI307	10/08/2008	363648.096	341515.3697	1.065	1.138
	08/26/2009	1061289.734	878593.2369	1.208	1.270
	08/12/2010	1761611.846	1290676.984	1.365	1.424
LI309	10/08/2008	521118.0576	484220.0908	1.076	1.138
	08/26/2009	1278976.608	1040719.564	1.229	1.270
	08/12/2010	2124588.01	1540207.644	1.379	1.424

Note that we seek the fluence produced by a proton loss. To get the Activation/BLM with correction one increases the Activation by the correction or decreases the unweighted BLM reading. The uniform irradiation correction is typically a few percent larger than the weighted correction. This is because the collimation system commissioning during this period saw increased losses later in the exposure. The exception is for LI230 for the longer period since the tuning eventually improved the loss at the primary collimator.

A step in understanding the precision of the activation analysis can be obtained by comparing the activation (pCi/gm) with the BLM loss (Rads) with decay correction for two successive measurements. Table 2 shows the ratio S_A/L and S_A/LW for collimator, quadrupole and some of the mask locations. Unfortunately the installation of samples secured to the side of the concrete mask material by duct tape failed during the first or second year, yielding no data for comparison at those locations. The addition of masks between C307 and C308 may have modified the flux at the C308 tag location so we do not include that location in this comparison. For the (appropriately) corrected data, the average ratio for 2009/2008 is 1.022 with a Standard Deviation of 0.099. Unsurprisingly,

Table 2: Comparison of One Year and Two Year Activation per Loss are shown in Columns 3 and 4 where Lu is total recorded loss and LWu is loss weighted for ^{22}Na decay. Comparisons including the 2010 tag analysis are shown in Columns 5 and 6, expressed as averages and standard deviations.

Tag Location	BLM	S_A/Lu	S_A/LWu	3 Yr Average	3 Yr StDev/$< M >$
		2009/2008	2009/2008	S_A/LW	
C301	LI302	0.955	1.085	0.000423	0.239
C303	LI303	0.945	1.087	0.000770	0.163
C307	LI307	1.031	1.170	0.001167	0.152
STMM301	LI302	0.853	0.969	0.009192	0.193
STMM303	LI303	0.734	0.845	0.005600	0.117
STMM308	LI309	0.864	0.987	0.006968	0.167
Q301DS	LI301	0.834	0.948	0.014152	0.047
Q303DS	LI303	0.888	1.021	0.001838	0.122
Q307DS	LI307	0.981	1.113	0.001912	0.136
Q230DS	LI230	1.009	1.107	0.003552	0.199
Q302US	LI302	0.803	0.912	0.013054	0.129
Average Ratio		0.900	1.022		
StDev Ratio		0.093	0.099	Average StDev	0.151

the uncorrected ratio is only 0.900 corresponding to the difference in cooling factors. We consider the tags measured in 2010 by taking the mean and standard deviation of S_A/LW for sets of three tags at one location. Table 2 shows these values in its last two columns. The agreement is not as good with the average StDev = 0.151.

2.4 Estimate of Energy Deposition

In the Main Injector tunnel, the most common concern about radiation damage is degradation of the epoxy insulated magnet coils. Various components of the hadronic shower due to interaction of 8 GeV protons contribute to radiation damage, an estimate of the total energy deposit is a useful guide. We will estimate this from an estimate of the ionization energy deposited in a volume. Some of the Al tags were placed for the purpose of evaluating the absorbed dose at coils. The fluence estimate provided by Al activation measurements counts the hadrons above a threshold of about 30 MeV. Although neutrons dominate this spectrum, the shower process develops an equilibrium distribution among charged and neutral components (as well as between hadronic and electromagnetic components) such that energy deposition estimates can simply relate the ionization loss to the typical minimum ionization energy loss for a hadronic charged particle of 2 MeV/gm-cm^{-2}. For an absorbed dose, d, we use the following:

$$d = C\sum_j \int_0^\infty dE\Phi_j(E)\frac{dE}{dx}(E,j) \tag{34}$$

where where $\frac{dE}{dx}$ is in MeV-cm^2/gm-cm, Φ_j is the flux of particles of type j in particles/cm^2 and C a constant discussed below. The approximation we will use is

$$d \sim C\Phi_j < \frac{dE}{dx} > \tag{35}$$

where we get d in Rad or Gray (Gy) using $C = 1.602\text{E-}8$ Rad-gm/Mev or $C = 1.6\text{E-}10$ Gy-gm/Mev and we take $< \frac{dE}{dx} >= 2$ MeV/gm-cm^2. Using Eq. 13, we find

$$d(Rad) \sim 1.602 \times 10^{-8} Rad - gm/Mev \times < \frac{dE}{dx} > \times 1.9448 \times 10^{10} S_A(pCi/gm) = 623 S_A(pCi/gm) \tag{36}$$

This is only a crude estimate. The MARS simulation will more carefully relate the Al tag activation to the absorbed dose.

3 Calibrations of BLM to Lost Protons

Using the Al Tags activation to determine the fluence gives a ratio of fluence at the tags to BLM signal at a nearby loss monitor. Calibration of the BLM to the lost beam can be done based on either sums from weekly or longer times or on measurements on one or a few pulses of ordinary operation. See below for calibration using aperture scans. For this note we will calibrate to the distribution of uncaptured beam loss on one pulse. Using the uncaptured beam loss and the signals of all the BLM's in the collimation region as recorded by Application Program I129, we get a crude loss measurement. Almost all loss is from 8 GeV beam either before acceleration begins or at uncaptured beam time. We assume that the loss distribution and thereby the BLM calibration will be similar for injection loss and uncaptured beam loss. Comparisons with other loss determinations will be done later. MARS results for the fluence can be compared with these measurements based on the proton loss in each secondary collimator.

Using a single pulse of $23 Cycle Beam (PBar plus NuMI beam), a measurement of the collimator loss was used for a crude calibration of the beam loss monitor response. The uncaptured beam loss from a pulse in which 34.83E12 protons was injected was 1.12E12 (3.2%). This was allocated to the 4 secondary collimators in accordance with the sum of BLM signal in the two adjacent loss monitors (LI301 + LI302 for C301); (LI303 + LI304 for C303); (LI307 + LI308 for C307); (LI309 for C308). These loss monitors accounted for 78% of the total loss. The other 22% of the loss includes BLM signal from protons which interacted in the secondary collimators but had leakage particle which escaped to nearby regions. It is then assumed that either of the pair of loss monitors can be used to determine the protons lost on that collimator. Applying this to LI308 would be OK for a fixed geometry but masks were added twice since the initial collimator installation so we will avoid further use of LI308 for this study. Data was recorded in file pfl-11June13-143510-amc01.csv and analyzed in same file name with extension .xlxs. Table 3 shows the calibration values used.

3.1 Calibration Using Aperture Scan

An alternative method to calibrate the Beam Loss Monitors to the local beam loss is to move the beam with a 3-bump until the local loss monitor shows a sufficient signal and note the change in transmission which resulted. Performing such a calibrated loss measurement at many or all of the loss monitors would be helpful in further understanding of the BLM's, the apertures and the loss around the ring. For this study, we have crude calibrations using the method above. For the loss monitor at the primary collimator, the loss due to striking the primary collimator is mostly distributed to the various secondary collimators. Using the I79 MI Aperture Scan console application program, the beam was moved radially outward with the I:H230:3 bump while a fast time plot recorded I:BEAM, I:BMLOST, I:HP230, and I:LI230. With an injection bump of +30 mm, about

Table 3: Calibration of BLM readings

BLM	Rads/E12Protons
LI230(Aperture Scan)	0.34
LI301	0.11465
LI302	0.33161
LI303	0.36167
LI304	0.08459
LI307	0.24201
LI308(skip)	0.20425
LI309	0.44626

10% of the beam was lost ($29 cycle at 8E12). The result is a signal for radial outward loss of 0.34 Rad/1E12 protons lost.

Table 4: Results for Activation Analysis for Al Tags installed 10/12/07
* indicates tag not found at installation position.

Location	Tag ID	Date Removed	Activ pCi/gm	BLM	UnWt BLM Rads	fluence hadrons/cm^2	Lost Protons	Fluence per Proton Lost
C301	6510	10/08/08	230	LI302	7.187E+05	4.90523E+12	2.167E+18	2.263E-06
	6198	08/26/09	434		1.420E+06	1.05111E+13	4.281E+18	2.455E-06
	6187	08/12/10	1430		3.370E+06	3.53282E+13	1.016E+19	3.476E-06
C303	6368	10/08/08	777	LI303	1.267E+06	1.65178E+13	3.502E+18	4.716E-06
	6503	08/26/09	1380		2.381E+06	3.37647E+13	6.584E+18	5.128E-06
	6548	08/12/10	3080		4.541E+06	8.04643E+13	1.369E+19	5.876E-06
C307	6325	10/08/08	339	LI307	3.636E+05	7.02029E+12	1.503E+18	4.672E-06
	6168	08/26/09	1020		1.061E+06	2.39624E+13	4.385E+18	5.464E-06
	6559	08/12/10	1740		1.762E+06	4.61877E+13	5.312E+18	8.695E-06
C308	6318	10/08/08	1690	LI309	5.211E+05	3.53724E+13	1.168E+18	3.029E-05
	6833	08/26/09	5210		1.279E+06	1.24523E+14	2.866E+18	4.345E-05
	6534	08/12/10	6020		2.125E+06	1.61501E+14	6.407E+18	2.521E-05
STCM301	6820*	10/08/08	2310	LI302	7.187E+05	4.92656E+13	2.167E+18	2.273E-05
	6834*	08/26/09	14300		1.420E+06	3.46333E+14	4.281E+18	8.090E-05
	6507*	08/12/10	28800		3.370E+06	7.11506E+14	1.016E+19	7.001E-05
STCM303	6842	10/08/08	7430	LI303	1.267E+06	1.5795E+14	3.502E+18	4.510E-05
	6167*	08/26/09	6660		2.381E+06	1.62952E+14	6.584E+18	2.475E-05
	6811*	08/12/10	26600		4.541E+06	6.94919E+14	1.369E+19	5.075E-05
STCM308	6828*	10/08/08	1210	LI309	5.211E+05	2.53258E+13	1.168E+18	2.169E-05
	6822*	08/26/09	10300		1.279E+06	2.46179E+14	2.866E+18	8.590E-05
	6319*	08/12/10	25800		2.125E+06	6.92149E+14	6.407E+18	1.080E-04
STMM301	6841	10/08/08	5440	LI302	7.187E+05	1.16019E+14	2.167E+18	5.353E-05
	6821*	08/26/09	9170		1.420E+06	2.22089E+14	4.281E+18	5.188E-05
	6110*	08/12/10	29800		3.370E+06	7.36211E+14	1.016E+19	7.244E-05
STMM303	6502	10/08/08	6690	LI303	1.267E+06	1.42219E+14	3.502E+18	4.061E-05
	6538	08/26/09	9230		2.381E+06	2.25832E+14	6.584E+18	3.430E-05
	6659	08/12/10	20800		4.541E+06	5.43395E+14	1.369E+19	3.968E-05
STMM308	6169	10/08/08	3070	LI309	5.211E+05	6.42563E+13	1.168E+18	5.503E-05
	6335	08/26/09	6510		1.279E+06	1.55594E+14	2.866E+18	5.429E-05
	6523	08/12/10	12800		2.125E+06	3.43392E+14	6.407E+18	5.360E-05
Q301DS	6195	10/08/08	3510	LI301	2.589E+05	7.4774E+13	2.258E+18	3.312E-05
	6605	08/26/09	5920		5.236E+05	1.43346E+14	4.567E+18	3.139E-05
	6200	08/12/10	14300		1.339E+06	3.52465E+14	4.039E+18	8.727E-05
Q303DS	6831	10/08/08	1960	LI303	1.267E+06	4.16665E+13	3.502E+18	1.190E-05
	6330	08/26/09	3270		2.381E+06	8.00077E+13	6.584E+18	1.215E-05
	6511	08/12/10	7090		4.541E+06	1.85225E+14	1.369E+19	1.353E-05
Q307DS	6516	10/08/08	573	LI307	3.636E+05	1.18662E+13	1.503E+18	7.897E-06
	6515	08/26/09	1640		1.061E+06	3.85278E+13	4.385E+18	8.786E-06
	6344	08/12/10	2830		1.762E+06	7.51213E+13	5.312E+18	1.414E-05
Q230DS	6327	10/08/08	2570	LI230	9.398E+05	5.47525E+13	2.764E+18	1.981E-05
	6513	08/26/09	7740		2.804E+06	1.80845E+14	8.248E+18	2.193E-05
	6521	08/12/10	9690		3.282E+06	2.77454E+14	9.898E+18	2.803E-05
Q302US	6275	10/08/2008	8320	LI302	7.187E+05	1.77441E+14	2.167E+18	8.187E-05
	6504	08/26/2009	13200		1.420E+06	3.19692E+14	4.281E+18	7.468E-05
	6508	08/12/2010	39500		3.370E+06	9.7585E+14	1.016E+19	9.603E-05

Table 5: Further Results for Activation Analysis for Al Tags installed 10/12/07
* indicates tag not found at installation position.

Location	Tag ID	Activity pCi/gm	BLM ID	Wt BLM(LWu) Rads	S_A/LWu pCi/gm/Rad	AbsDose Rads	AD/BLM Rads/Rad	AbsDose/p_{lost} Rads/proton
C301	6510	230	LI302	655374.0178	3.509E-04	1.433E+05	0.219	6.613E-14
	6198	434		1139964.994	3.807E-04	2.704E+05	0.237	6.317E-14
	6187	1430		2652941.871	5.390E-04	8.911E+05	0.336	8.768E-14
C303	6368	777	LI303	1158874.657	6.705E-04	4.842E+05	0.418	1.382E-13
	6503	1380		1892791.13	7.291E-04	8.599E+05	0.454	1.306E-13
	6548	3080		3380354.205	9.111E-04	1.919E+06	0.568	1.402E-13
C307	6325	339	LI307	341515.3697	9.926E-04	2.112E+05	0.619	1.406E-13
	6168	1020		878593.2369	1.161E-03	6.356E+05	0.723	1.449E-13
	6559	1740		1290676.984	1.348E-03	1.084E+06	0.840	2.041E-13
C308	6318	1690	LI309	484220.0908	3.490E-03	1.053E+06	2.175	9.018E-13
	6833	5210		1040719.564	5.006E-03	3.246E+06	3.119	1.133E-12
	6534	6020		1540207.644	3.909E-03	3.751E+06	2.436	5.855E-13
STCM301	6820*	2310	LI302	655374.0178	3.525E-03	1.439E+06	2.196	6.642E-13
	6834*	14300		1139964.994	1.254E-02	8.911E+06	7.817	2.082E-12
	6507*	28800		2652941.871	1.086E-02	1.795E+07	6.765	1.766E-12
STCM303	6842	7430	LI303	1158874.657	6.411E-03	4.630E+06	3.995	1.322E-12
	6167*	6660		1892791.13	3.519E-03	4.150E+06	2.193	6.303E-13
	6811*	26600		3380354.205	7.869E-03	1.658E+07	4.903	1.210E-12
STCM308	6828*	1210	LI309	484220.0908	2.499E-03	7.540E+05	1.557	6.457E-13
	6822*	10300		1040719.564	9.897E-03	6.418E+06	6.167	2.239E-12
	6319*	25800		1540207.644	1.675E-02	1.608E+07	10.438	2.509E-12
STMM301	6841	5440	LI302	655374.0178	8.301E-03	3.390E+06	5.172	1.564E-12
	6821*	9170		1139964.994	8.044E-03	5.714E+06	5.013	1.335E-12
	6110*	29800		2652941.871	1.123E-02	1.857E+07	6.999	1.827E-12
STMM303	6502	6690	LI303	1158874.657	5.773E-03	4.169E+06	3.597	1.190E-12
	6538	9230		1892791.13	4.876E-03	5.751E+06	3.039	8.736E-13
	6659	20800		3380354.205	6.153E-03	1.296E+07	3.834	9.465E-13
STMM308	6169	3070	LI309	484220.0908	6.340E-03	1.913E+06	3.951	1.638E-12
	6335	6510		1040719.564	6.255E-03	4.057E+06	3.898	1.415E-12
	6523	12800		1540207.644	8.311E-03	7.976E+06	5.179	1.245E-12
Q301DS	6195	3510	LI301	236336.3585	1.485E-02	2.187E+06	9.255	9.687E-13
	6605	5920		420592.0558	1.408E-02	3.689E+06	8.771	8.077E-13
	6200	14300		1056773.802	1.353E-02	8.911E+06	8.432	2.206E-12
Q303DS	6831	1960	LI303	1158874.657	1.691E-03	1.221E+06	1.054	3.487E-13
	6330	3270		1892791.13	1.728E-03	2.038E+06	1.077	3.095E-13
	6511	7090		3380354.205	2.097E-03	4.418E+06	1.307	3.226E-13
Q307DS	6516	573	LI307	341515.3697	1.678E-03	3.571E+05	1.045	2.376E-13
	6515	1640		878593.2369	1.867E-03	1.022E+06	1.163	2.330E-13
	6344	2830		1290676.984	2.193E-03	1.763E+06	1.366	3.320E-13
Q230DS	6327	2570	LI230	857958.3111	2.995E-03	1.601E+06	1.867	5.793E-13
	6513	7740		2334284.604	3.316E-03	4.823E+06	2.066	5.847E-13
	6521	9690		2229548.281	4.346E-03	6.038E+06	2.708	6.100E-13
Q302US	6275	8320	LI302	655374.0178	1.270E-02	5.184E+06	7.911	2.392E-12
	6504	13200		1139964.994	1.158E-02	8.225E+06	7.215	1.921E-12
	6508	39500		2652941.871	1.489E-02	2.461E+07	9.278	2.422E-12

4 Results

In order to provide flexibility in employing this data, we will supply raw data with only fundamental corrections and various ratios using the BLM's and calibrations of protons lost in terms of the BLM's which are not yet determined with good accuracy. We will expect to compare with MARS calculations in terms of ratios to both the BLM's and to protons lost.

The RAF Reports which provide the measured activities and their error (corrected to the sampling time when the samples were delivered to RAF) are provided as separate files in this Beams Document Database document. The uncertainty on the activity measurement is about 15% plus a small contribution for counting error. The data and analysis of these aluminum tags activations are carried out with a spreadsheet, AlActData.xls which is another file incorporated in the Beams Document Database with the document. An analysis which provides flux and fluence estimates by RAF are included as a worksheet. BLM data is incorporated in the spreadsheet and the ^{22}Na decay correction is calculated there. The main body of analysis is carried out in worksheet ColAlTags.

The raw activation and BLM data are recorded here and used in the analysis. The decay correction for cooling time has been applied at RAF. We correct for decay during irradiation using the weekly BLM summed data.

Using BLM calibration values above for RADS per protons lost , we now provide the Fluence at the Al Tag locations normalized to the lost protons inferred from nearby loss monitors. Table 4 shows the data from this activation study. We include the tag and BLM locations, activation, BLM sum, fluence, lost protons and fluence per lost proton. Note that the fluence is calculated after correcting the activation for decay during irradiation.

Additional results including the activity (again), absorbed dose and ratios: Activity/BLM, Absorbed dose /BLM and Absorbed Dose/Protons lost are provided in Table 5. For these ratios, we used the measured activity and LW, the loss monitor sum weighted for decay. We note that the calibration of the BLM in Rads is accepted from the BLM system based on a calibration of the ionization monitor from two decades ago whereas we use a fluence to dose constant for calibration of the Al Tag results. We find that tags shielded by the C301, C303 and C307 collimators see less dose than the BLM's which are placed on the wall of the MI tunnel. We presume that the tag at C308 was exposed to losses not fully absorbed in C307 since it was not protected by masks (STCM nor STMM) during the time of this sampling. Similarly the tags on the masks and the quadrupoles see more absorbed dose than the BLM but all these results fall in the range of 0.2 to 10. If better calibrations of the BLM's in terms of lost protons are obtained, new calibrations should be applied to this data.

With these measurements, we are able to address one of the concerns about the collimation

Table 6: 5 Year Absorbed Dose at Some Collimator Region Quadrupoles based on Using Fluence to Dose Constant. BLM losses summed from Oct 2006 through Oct 2011.

Location	BLM	<Abs Dose>/BLM Rads/Rad	5 Yr BLM Rads	5 Yr AbsDose Rads
Q301DS	LI301	8.82	2.361E+06	2.082E+07
Q303DS	LI303	1.15	6.959E+06	7.973E+06
Q307DS	LI307	1.19	2.288E+06	2.726E+06
Q230DS	LI230	2.21	3.614E+06	8.000E+06
Q302US	LI302	8.13	6.303E+06	5.127E+07

installation. Radiation damage to accelerator components in the collimation region has the extra penalty, beyond the usual issue of spares and downtime due to the higher radiation levels in this region. Radiation damage due to interactions in the primary collimator create dose at the downstream end of Q230. Shine downstream of C301 produces loss on the upstream end of Q302. Backscatter from C301, C303, and C307 produces radiation at the downstream end of Q301, Q303, and Q307 respectively. Polyethylene blocks were installed on the upstream end of the collimators to mitigate some of this problem but we installed Al tags to measure activation which we relate to the absorbed dose. While the uncertainties in the fluence to dose calculation are substantial, our knowledge of the radiation hardness of the epoxy used in the insulation of the magnet coils is also uncertain. In TM-2391, a damage concern at 4 MGy (400 MRad) absorbed dose is quoted based on information from the Proton Driver design study. In the Main Injector Design Handbook (Chapter 3.1 p. 25), studies were reported which assure resistance to 100 MRad and limited measurements to 1 GRad showed retention of good physical properties. In Table 6 we use the average of our measurements of absorbed dose normalized to the BLM reading and the full 5 years of loss data at these locations since the current BLM electronics provided recorded data. The collimation system has been in use for about 3.5 years of this interval. We find that Q301DS has an absorbed dose of 20 MRad, Q302US has 50 MRad and others have less absorbed does. We should still be several years from problems with radiation damage to coils.

5 Conclusions

The activation of aluminum tags by production of ^{22}Na provides a measure of the hadronic flux at fifteen locations in the Main Injector Collimation region. A high purity germanium spectrometer is used to measure the activation. Using detailed loss history in nearby beam loss monitors (BLM's), we have corrected for decay during the irradiation period. Samples removed after irradiation for 1 year, 2 years and 3 years show activation proportional to the loss at the nearby loss monitor with uncertainties of 15%. We convert the activation to a fluence of hadrons using the known spallation cross section on Al of 10.1 microbarns. Using a crudely determined BLM sensitivity to proton losses, we provide the results as a ratio to the BLM reading or to the lost protons. These results are suitable for comparison with simulations of the collimator system using the MARS code. Additional activation studies on Al, Cu and steel at collimator C307 which were carried out in 2011 are reported in Beams-doc-4046[5].

6 Acknowledgments

This note is intended only to document this effort. The contributions from Vernon Cupps, Gary Lauten and others are the basis for this report.

7 Appendix A - List of Symbols

A Atomic Mass Number or Atomic Weight

N_A Avogadro Constant (Avogadro's number), $6.02214179(30) \times 10^{23}$ mol-1 (gram).

S_A Specific activity (in Bq) – number of decays per second per amount of substance

Φ fluence in particles per unit area (particles-cm^{-2})

$\frac{d\Phi}{dt}$ flux in particles per unit area per second (particles-cm^{-2}-s^{-1})

References

[1] Nikolai V. Mokhov. The MARS code system user's guide version 13(95). FN 628, Fermilab, April 1995.

[2] N. V. Mokhov and S. I. Striganov. MARS15 overview. *AIP Conf. Proc.*, 896:50–60, 2007. Also available as FERMILAB-CONF-07-008-AD.

[3] Marcel Barbier. *Induced Radioactivity*. North-Holland Publishing Company, Amsterdam, London, 1969.

[4] Bruce C. Brown and Guan Hong Wu. Measuring Correlations Between Beam Loss and Residual Radiation in the Fermilab Main Injector. In Jan Chrin, editor, *Proceedings of the 46th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB2010)*, Morschach, Switzerland, 2010. Also available as FERMILAB-CONF-10-368-AD.

[5] Bruce C. Brown. Activation of Steel and Copper Samples in the Main Injector Collimator Region. Beams-doc 4046, Fermilab, January 2012.