Document Type	Project Report
Document Number	ESS-0150754
Date	Oct 06, 2017
Revision	1 (1)
State	Preliminary
Confidentiality Level	Internal
Page	1 (15)

Project CDR for the ESS Tuning Beam Dump Imaging System

Radiation Dose Estimates Document

	Name	Role/Title
Owner	M G Ibison	Researcher, University of Liverpool
Reviewer	E Adli C Thomas	In-kind manager, University of Oslo Responsible person, ESS Imaging Systems

TABLE OF CONTENT **PAGE**

1. SCOPE

This document describes the development of Monte-Carlo radiation transport models of the ESS Tuning Dump beam line and tunnel, and the results of the simulations carried out to obtain estimates of radiation dose in the vicinity of the Tuning Dump Imaging System, during both beam on dump operation and beam-off maintenance procedures.

It also covers the process of refinement of the design with the aim of dose minimisation, especially to the imaging cameras which are the most radiosensitive elements of the system.

2. CONTRIBUTORS

M G Ibison

C Thomas

T Grandsaert

E Adli

M Eshraqi

3. ISSUING ORGANISATION

University of Oslo (in association with the University of Liverpool)

4. INTRODUCTION

The Tuning Dump Imaging System will be located inside the beam line tunnel. Here it will be subject to significant ionising radiation exposure, which will affect both its operational performance and its useable lifetime. To assess the absorbed radiation dose, detailed simulations have been carried out based on the predicted beam parameters.

As the imaging equipment will require routine maintenance at intervals, including installation of replacements, residual dose-rates affecting human access to the tunnel during shutdowns, in areas adjacent to the imaging vessel, were also assessed.

The Monte-Carlo particle transport code FLUKA [1] was selected as the most appropriate software for the radiation simulations. It has tools for modelling complex geometries and for visualising the system within an integrated interactive environment (FLAIR), which is also used to control all parameter input and runtime execution. FLUKA provides output in terms of absorbed energy to the regions of interest, which is readily converted into radiation dose units. In addition, FLUKA is maintained and supported by CERN, and access is available to expert advice when required.

5. CONTEXT (ASSUMPTIONS)

It has been assumed that all critical parameters are known with sufficient precision, and that there will be no significant unforeseen modifications to the Dump beam line or to the projected operating conditions. Specific parameters include:-

5.1. Geometry

(a) Beam Line Dimensions

The nominal diameter of the final dump beam-pipe section is 250mm. During this work a change request was raised to modify this section 500mm. Objections to this very significant change were raised and it is assumed in this document that it will not be accepted.

(b) Materials

Typical compositions have been assumed for construction materials such as concrete and stainless steel, where exact data is not available.

(c) Other structures

Although all significant bodies in the vicinity of the dump, its beam-line and the tunnel housing it are modelled, there are structures not included which could affect results either negatively as shielding, or positively as extra scattering or beam-activated sources.

Gamma blocker

This is an insertable shielding block at the beam-line terminus, intended to reduce radiation in the tunnel from dump decay emissions.

Dump-Line Exit Window (Option)

Installation of a window terminating the dump-line vacuum beam-pipe before the gamma blocker has been suggested for consideration by ESS. This would contribute some further proton scattering to the radiation levels around the imaging system.

5.2. Beam Parameters

Values for beam conditions in the dump line have in general been taken from [3], with later revisions by ESS These include:

Parameter	Value	Notes
Maximum Beam Power	12.5 kW	Slow Tuning Beam (1 Hz)
Peak Average Current	6.3 μA	
Beam Energy (maximum)	2.0 GeV	Lower energy also used
Study Time (beam available to Dump)	500 h	
Fraction of Study Time (beam on Dump)	0.5	

5.3. Camera Radiosensitivity

Various sources have been referenced for data on the dose-rates and/or particle fluences above which observable effects may be expected in image quality. Studies have been made both of dose [6] and of neutron or proton fluence [7] in relation to these effects, which may include either or both of the following:

- permanent damage to sensor pixels
- 'upsets' to the camera electronics, recoverable after a reset
- permanent damage resulting in no image from camera, not recoverable

Based on these sources, an arbitrary target dose of ***< 20 Grays/year*** has been set for selection of the imaging camera locations, with any associated shielding.

6. DETAILS OF THE FLUKA MODEL

6.1. Geometry of the Tuning Dump Beam-Line

The Dump line is a continuation of the main LINAC tunnel, from the point of deflection of the beam from the horizontal into the inclined 'dog-leg' section, and thence towards the Target. The upstream boundary of the model is taken as the exit of the first dipole bending magnet and incorporates all of the subsequent vacuum pipes and vessels, and all of the enclosing shielding walls and floor, up to and including the dump itself and its own massive shield wall and its surrounding block. There is no ceiling as such, because immediately above the dump line is the upward-sloping section of the line continuing to the target, which has its own tunnel roof.

Where is has been necessary to make estimates because dimensions, materials or suppliers are not yet specified in detail, reasonable assumptions have been made, e.g. typical values of vacuum pipe wall thickness or camera dimensions, taken from manufacturers' data sheets.

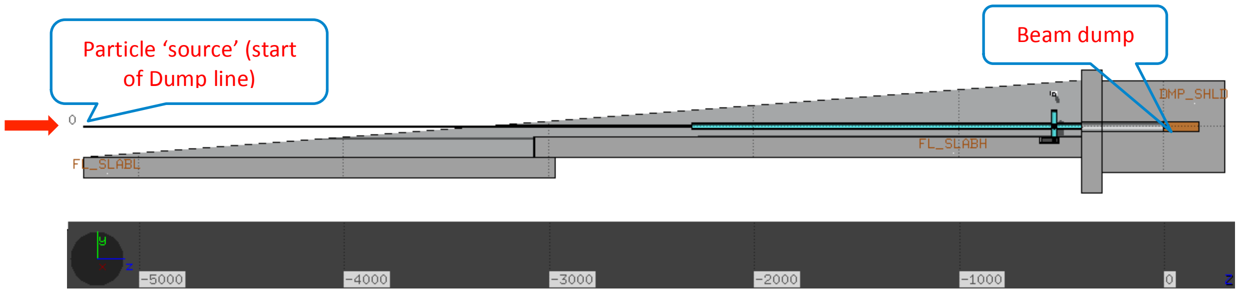
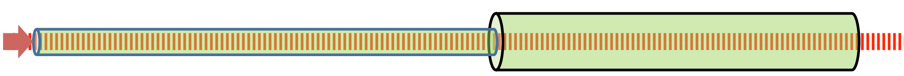


Figure 1 ESS Tuning Dump Line (FLUKA Model - elevation): beam enters from left. Dimensions are in cm.

6.2. Tuning Dump Beam Parameters

Under normal conditions, protons from the LINAC will only be admitted to the Dump line during tuning procedures. During tuning, beam properties will inevitably be different from their nominal beam-on-target values. No attempt has been made to model the profile of the beam-on-dump in detail; instead, a notional uniform circle with no divergence has



been assumed, having a fixed energy and zero energy spread. A beam radius of 4.5 cm has been chosen to fit the initial 10 cm diameter beam-pipe comfortably, ensuring that there are no losses in the dump-line; the first interaction of any particle is with the imaging screen.

Number of Particles

This is in one sense arbitrary for FLUKA Monte-Carlo simulations, in the sense that results are always normalised to a single input particle (neglecting collective effects which could introduce particle density dependence), e.g. ‘Dose/particle’. However, the statistical precision of the result *does* depend on this number, especially in problems such as this where only a very small fraction of source particles actually contribute to the result. In practice, runs of at least 200,000 particles have been found necessary.

In general, results quoted were based on at least 5 simulation ‘cycles’, which are independent repeated runs with exactly the same problem specification, differing only in the initial random ‘seed’ for Monte-Carlo particle generation. Besides improving confidence in the outcome, this enables the standard deviation in the result to be estimated. Where an occasional result of zero is returned for the estimator, as is always statistically possible, no reliance can be placed on any derived parameter, and an increase in the number of source particles is indicated to improve statistics.

Proton Energy

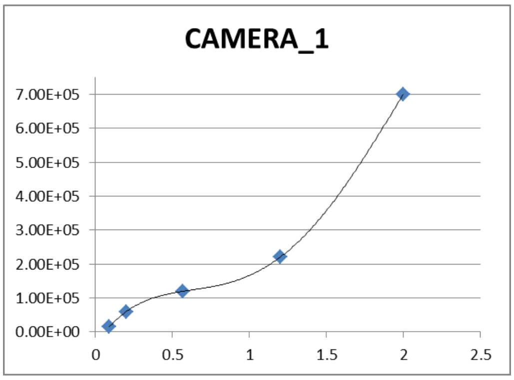


Figure 2 Dose (Arbitrary Units) vs. Energy of Protons (GeV)

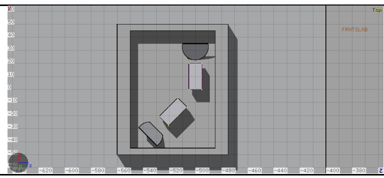
Initial energy will be variable during initial LINAC tuning, up to the maximum of 2.0 GeV, although certain special values have been identified as relevant. These are

90 MeV; 200 MeV; 570 MeV

Additionally, an arbitrary energy of 1.2 GeV was included, purely to give a better indication of the trend of dose with energy (see Figure 2). As it can be assumed that doses will increase with proton energy, in general the case of E_p = *2.0 GeV* has been used; this will lead to an overestimate of the total dose.

6.3. Camera Location

As the dose to the imaging cameras is to be minimised, subject to optical path constraints, a number of candidate locations have been investigated sequentially.

Ref	Location	Illustration
1	Shielded Bunker on Tunnel Floor	

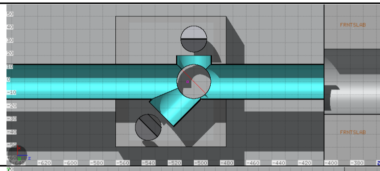
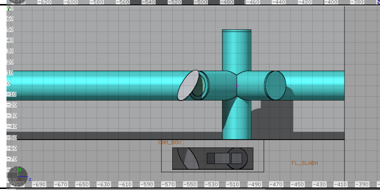
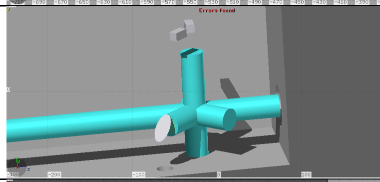
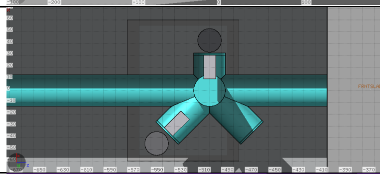
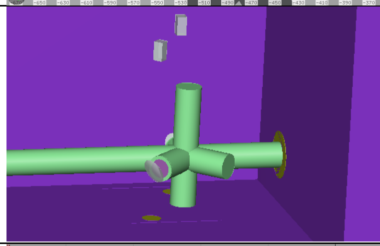
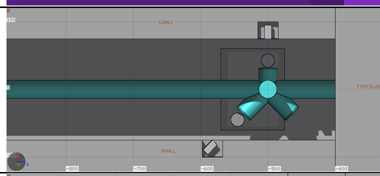
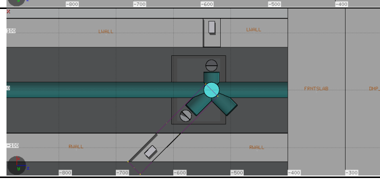
Ref	Location	Illustration
2	Shielded Bunker, thicker cover plate	
3	Shielded Trench excavated in Floor Slab	
4	High-Level, otherwise layout as for Bunker case	
5	High-Level, further displaced from beam axis	
6	High-Level, down-looking onto 1st mirrors	
7	High-Level, horizontal in wall 'niches'	
8	High-Level, set well back into walls	

Table 1 Possible camera locations investigated

For the 'bunker' cases (1 to 3), the viewing path is through open apertures in the shielding lid; for the 'high-level' cases (4 to 6), no additional shielding is included.

7. RESULTS OF FLUKA RUNS

7.1. FLUKA Modelling Process

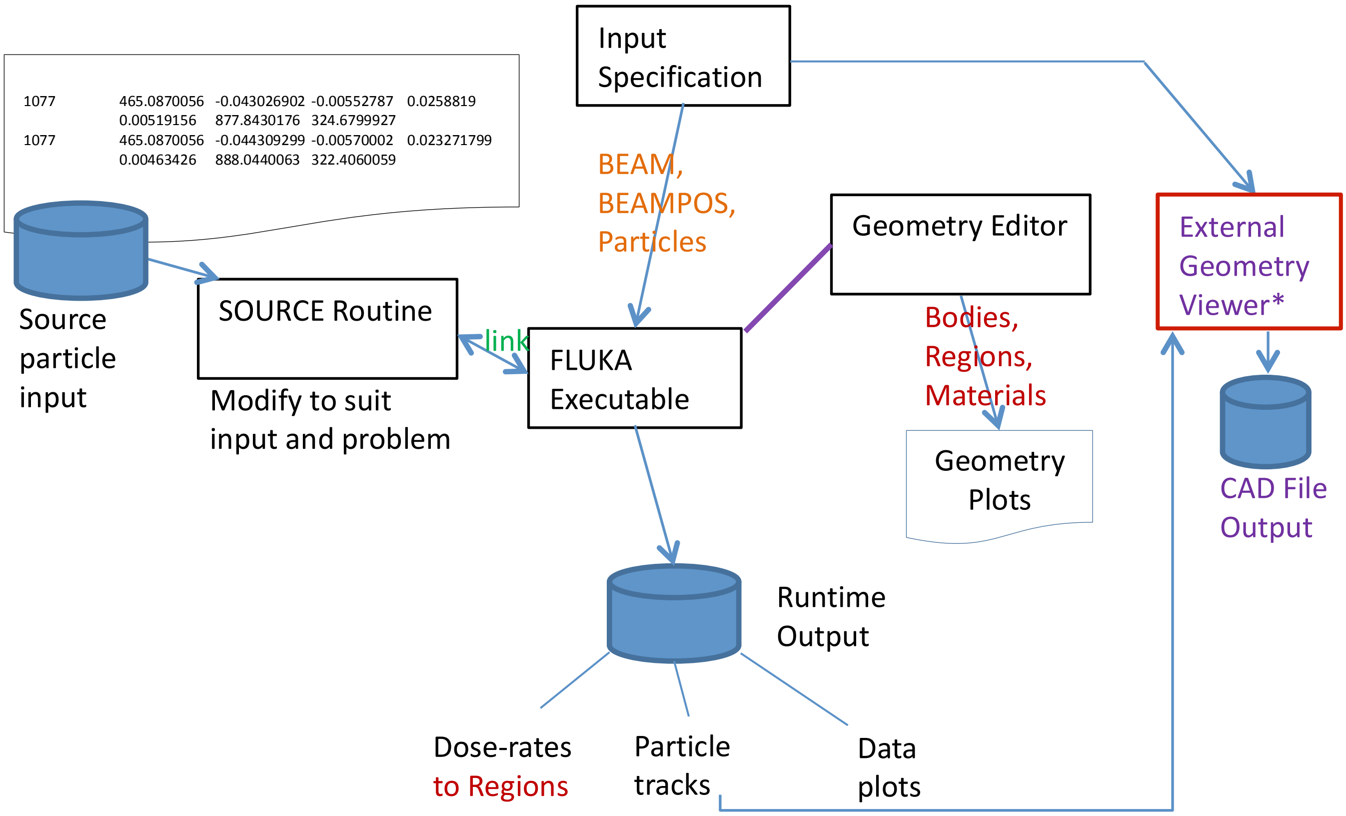


Figure 3 FLUKA Modelling process and Data flows

FLUKA models may be constructed and run, and output analysed, within the integrated environment, FLAIR. This considerably eases the problem of file-handling and simplifies error-checking during geometry editing and at run-time. The external viewer program SimpleGeo* has proved useful for preparing detailed 3-D geometry images and for the plotting of particle tracks, based on FLUKA data files.

7.2. Camera Doses – with Beam On

7.2.1. Dose from Lost Particles

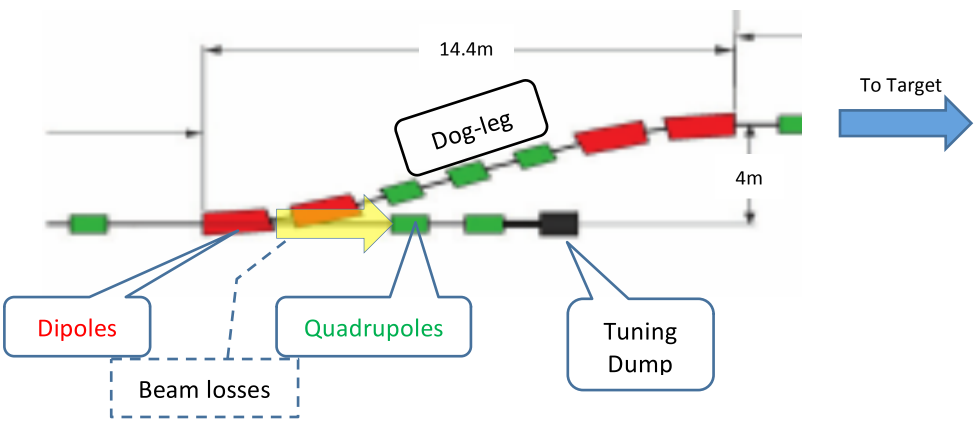


Figure 4 Schematic of Dump in relation to Target Line, showing beam loss (not to scale)

FLUKA Processing

In this mode of operation, the beam is directed onto the target by the dipole magnets in the first bend of the 'dog-leg' shown in Figure 4. Some of the particles lost from the beam in this region will enter the dump tunnel and contribute to the total dose received by the cameras. To model these losses, advantage was taken of earlier modelling work [5] to provide input data files which contained full parameter sets (position, direction vectors and energy) for each particle. It was necessary to build and link a customised code module SOURCE to read the pre-processed particle data into FLUKA, as indicated in Figure 3.

Results

To obtain the integrated Dose over the period (i.e. 1 year), it is necessary to estimate the incoming particle rate, calculated from the Average Beam Current (full power beam on target), the operating hours per year, and a value assumed for the fractional loss rate at the dipole. At 2.52 mA and 5 MW and operating for 5300 hours per year, with a loss fraction of 0.002% (advised by Y Levinsen & M Eshraqi):

$$
\begin{aligned}
&Proton\ Losses\ to\ Dump\ Tunnel\ per\ year \\
&\qquad = (5300 \times 3600) \times (2.52 \times 10^{-3}) \times (0.002 \times 0.01)\ /\ e \\
&\qquad = \ 6.00E18\ protons
\end{aligned}
$$

Based on this value,

Camera Dose from Particle Losses (upper limit) = 7.2 Gy per year

This result indicates that dose-rates from beam-on-target losses are less than 10% of those from the direct beam-on-dump radiation, and as this is well below the uncertainty level for these simulations, the beam-loss dose has been ignored in further assessments.

7.2.2. Dose from Beam on Dump

During tuning studies 'on dump', the beam is not deflected to target but enters the dump beam-line, passing through the imaging vessel and stopping in the dump itself. Radiation dose arises from particles back-scattered out through the dump entrance, both primary protons and secondaries, including penetrating neutrons and gamma-rays. Scattering also occurs in the scintillation screen as the protons pass through it, contributing to the dose to its surroundings.

A series of FLUKA models has been developed to investigate dose to the cameras, progressively refining the locations of the pairs of cameras as listed in 6.3, to optimise the appropriate parameter. The guiding principle has been to move to locations further from the main scatter zone, while maintaining accessibility and avoiding the addition of further shielding, with its attendant space and support constraints.

The raw FLUKA output tables give ENERGY in units of *GeV per particle per cm*^{3}, deposited in each 'region' of the geometry. Using appropriate multipliers, the Absorbed Dose per particle (in *Grays*) was derived and hence the Dose per Year specifically for the 'camera' regions, as listed in Table 2, using the predicted Tuning Dump Utilization and Average Beam Current [3]. Beam energy was taken to be 2.0 GeV in all cases.

Level	*Window Viewing System (Left side)*	*Screen Viewing System (Right side)*
Low	CAMERA 1	CAMERA 2
High	CAMERA 3	CAMERA 4

Note: 'Left' & 'Right' are relative to the beam direction.

Table 2 Camera Doses (per year) for different configurations. Cameras '1' and '2' refer to original (low level) locations, to be compared with Cameras '3' and '4' referring to the high-level locations. Errors where quoted are at the ±1σ level.

Configuration (see para 6.3)	*Dose (Grays yr^{-1})*				*Notes*
	Camera 1	*Camera 2*	Camera 3	Camera 4	
1	1490	460	--	--	Shielded bunker
2	740	940	--	--	Thicker lid
3	350	74	--	--	Below floor level
4	326	276	100*	39.3*	'High-Level' camera locations added*
5	254	137	118	54.5	Away from axis
6	200 ± 120	59 ± 30	30 ± 20	5 ± 3	Down-looking
7	370 ± 160	210 ± 130	45 ± 20	15 ± 9	In tunnel walls *Screen inserted*
	22 ± 11	*18 ± 7*	*5 ± 6*	*3 ± 5*	*Screen out of beam*
8	400 ± 130	270 ± 130	15 ± 25	12 ± 7	In deep wall niches

7.2.3. Particle Scattering from the Screen

The effect of screen insertion into the proton beam has been studied in FLUKA, and is shown qualitatively in the particle tracking plots in Figure 5; corresponding doses are listed in Table 3, which relates to Configuration 7 in Table 2. All analysis of camera doses is on the basis that the screen will be in use whenever there is beam to the dump, which is a conservative assumption.

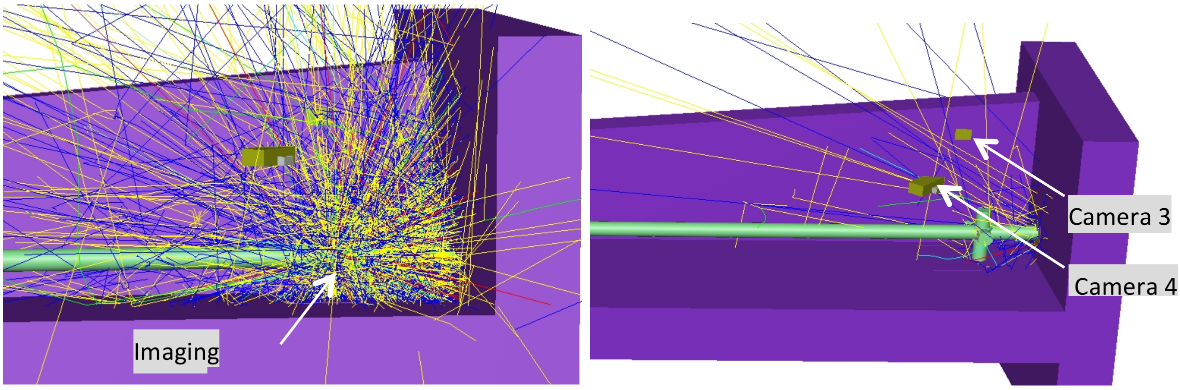


Figure 5 Particle tracking in FLUKA, showing effect of screen on scattering. (LEFT) Screen inserted into beam. (RIGHT) Screen removed from beam. Key: — protons; — neutrons; — photons

Location	Screen inserted Dose (Gy/yr) $\pm 1\sigma$	Screen removed Dose (Gy/yr) $\pm 1\sigma$
CAMERA 1	370 ± 160	22 ± 11
CAMERA 2	210 ± 130	18 ± 7
CAMERA 3	45 ± 20	5 ± 6
CAMERA 4	15 ± 9	3 ± 5

Table 3 Radiation doses at camera locations, with and without the screen deployed

7.3. Decay Dose-Rates

Using data from ESS predictions **Error! Reference source not found.**, the irradiation history of the dump during the normal operational cycle of beam-on-dump studies was modelled. Residual dose-rates due to activation by beam particles were calculated at significant locations, after selected cooling times, not only with FLUKA but also, for confirmation, by analytical formulae.

7.3.1. FLUKA Results

FLUKA provides built-in features for assessing radioactive decay after activation by particles, requiring only additional parameters for irradiation intervals and subsequent decay times. Dose-rate distribution in the vicinity of the imaging vessel was plotted in the vertical plane, at selected times post-irradiation. Results are quoted in mSv (equivalent dose) as this is the relevant quantity for human exposure.

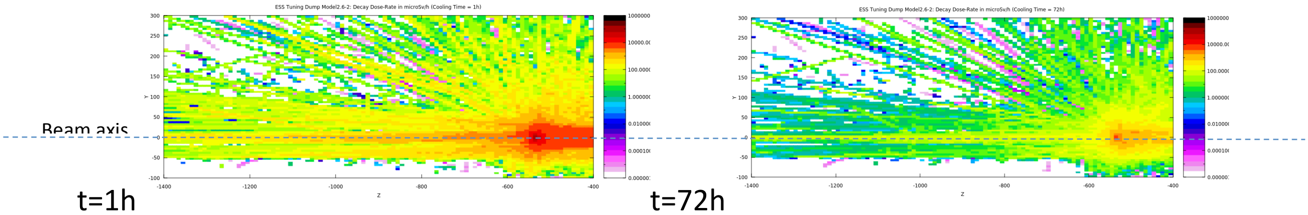


Figure 6 Decay dose-rate (Y-Z plots). Beam enters from left, dump and shield are to right of plot area.

Position	*Cooling Time (hours)*	*Dose-Rate (mSv/hr)*
On beam axis, downstream of screen	1	10-100
On beam axis	72	1-10

7.3.2. Analytical Calculation of Activation & Decay

In a high-energy proton fluence, the build-up of the radioactive products of nuclear reactions in the dump may be predicted from the Bateman equations. Then, allowing for decay after some cooling time, the residual activity can be assessed for its contribution to the gamma-ray dose at an external point, correcting also for geometry factors. Inevitably, simplifications are necessary to make the problem manageable, e.g. activated bodies such as the imaging screen are ignored, and the dump is treated as a simple Cu cylinder.

Proton Energy (GeV)	*Cooling Time (hours)*	*Position*	*Dose-Rate (mSv/hr)*
2	0	Screen	52.5
2	1	Screen	51.3

7.3.3. Comparison of Results from Alternative Methods

Within the limits of uncertainty in the estimates, the two independent methods give remarkably consistent results, even though the activated screen, showing as a prominent 'hot-spot' in the FLUKA plot, is ignored in the analysis. This helps to support the validity of the FLUKA dose data.

7.4. Dose and Heat Load on Screens

The imaging screens are subject to heating from the energy absorbed from the beam. The FLUKA results for Absorbed Dose have been used to calculate the temperature rise from beam heating which could be expected in the exposed area of a screen, due to a single proton pulse.

As a first approximation, Energy Deposition in the layers of the screen has been used as the parameter to estimate the instantaneous temperature rise from a single Full Pulse, assuming no heat loss mechanisms. Two cases are considered in Table 4: a 'standard' 4.5cm radius beam and a 'small' 1cm beam. The deposited energy is the same for both, but with the small beam, the temperature rise becomes much more significant because of the reduction in heated volume.

Screen Layer	Material	Density	Layer Thickness	Energy Deposited	Temp Rise (°C)	Temp Rise (°C)
			(cm)	(J)	R_{Beam} = 4.5cm	R_{Beam} = 1.0cm
Mirror	Al	2.699	0.002	2.5	5.9	118.6
Substrate	Si	2.329	0.04	44.6	7.8	158.5
Backing	Al	2.699	0.02	24.8	5.8	117.6
Coating	Al_2O_3	3.98	0.003	5.4	7.0	141.6

Table 4 Screen heating (instantaneous) by Full Pulse

A full thermal analysis has not been undertaken and therefore no account is made of heat transfer away from the irradiated region to its surroundings. The result is an indication only of the potential peak transient temperature, for a given beam-size.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1. Camera Location

The camera location has been chosen to minimise the total radiation dose to the cameras, so that off-the-shelf digital cameras can be used. The location corresponds to Configuration 8 in Table 2.

At the selected location, the assessed dose to the cameras is estimated to be acceptable for a useful operating lifetime of 1 year, although some image quality deterioration can be expected to be noticeable. In addition, the frequency of single event upsets requiring a camera reboot will depend on the camera type and should be investigated further. Charged particle fluxes at camera locations are sufficiently small that activation will have no impact on camera handling and maintenance.

8.2. Imaging System Maintenance

Personnel access under controlled conditions is predicted to be possible after a cooling period of at least 72 hours from beam shutdown. Dose-rates from some activated components, notably the imaging screens, will however require the use of remote handling facilities.

9. GLOSSARY

Term	Definition
Gray	Unit of Absorbed Dose, equal to 1 Joule/kg

Term	Definition
Gray	Unit of Absorbed Dose, equal to 1 Joule/kg
Sievert	Unit of Equivalent Dose, accounting for biological effects
SEU	Single Event Upset, disruption to electronics due to energetic particles

10.REFERENCES

[1] 'Target Proton Beam Imaging Systems PDR: Dump optical system preliminary design', ESS Document ESS-0066915
[2] 'System Design Document', ESS Document ESS-0150756
[3] 'Tuning Dump Utilization (draft)' (Tom Shea, Jan 10, 2014)
[4] 'Updated Report on Operations', ESS Document *ESS-0011768* (J Haines, Apr 27, 2016)
[5] 'BEAM DYNAMICS CHALLENGES IN THE ESS LINAC' in Proceedings of HB2016, Malmö, Sweden (Yngve Levinsen, M. Eshraqi et al., ESS, Lund, Sweden)
[6] 'RADIATION TESTS ON SOLID STATE CAMERAS FOR INSTRUMENTATION' in Proceedings of DIPAC 2005, Lyon, France (S. Hutchins, M. Facchini et al., CERN)
[7] 'PXI Performance [of digital cameras in the AWAKE Radiation Environment]', unpublished, Sept 2017 (S. Danzeca, S. Burger et al., CERN)

DOCUMENT REVISION HISTORY

Revision	Reason for and description of change	Author	Date
1	First issue	M G Ibison	<<YYYY-MM-DD>>