ESS COLD LINAC BLM LOCATIONS DETERMINATION

M. Jarosz, A. Jansson, J.C. Kazantzidis, T. Shea, L.Tchelidze, European Spallation Source ESS, Lund, Sweden

Abstract

The linear accelerator of ESS will produce a 5 MW proton beam. Beam of this power must be strictly monitored by a specialized Beam Loss Monitoring (BLM) System to detect any abnormal losses and to ensure that operational losses do not lead to excessive activation. A long series of beam loss simulations was performed using MARS Monte Carlo code system in order to optimize the number and setting mounting locations of the detectors for best coverage, distinguishability and sensitivity. Simulations anticipated multiple possible beam loss scenarios resulting in different loss patterns. The results of energy deposition in air in the linac tunnel in multiple locations were analysed in several different ways. Incorporated methods varied from simple brute force approach to more sophisticated singular value decomposition based algorithms, all resulting in detector layout proposals. Locations selected for BLMs were evaluated for all methods.

INTRODUCTION

The linear accelerator of ESS will produce a 5 MW proton beam. Beam of this power must be strictly monitored by a specialized Beam Loss Monitoring (BLM) System to detect any abnormal losses and to ensure that operational losses do not exceed a limit of 1W/m [1]. CERN-type ionization chamber was chosen as the primary detector for the system [2]. The arrangements of the detectors along the whole machine still need to be fixed. This paper discusses the determination of the locations only in the cold linac.

SIMULATIONS

Different beam loss simulations were performed for four energies from ESS cold linac range, ranging from 220-2000MeV. For all of these energies 10 different possible locations along a pair cryomodule-quadrupole doublet were chosen (Fig. 1). At these locations three points on the beam pipe were treated as possible loss points. Losses were then simulated in MARS Monte Carlo code system [3] for 3 different angles relative to beam pipe wall: 1 mrad, 3 mrad and 1°.

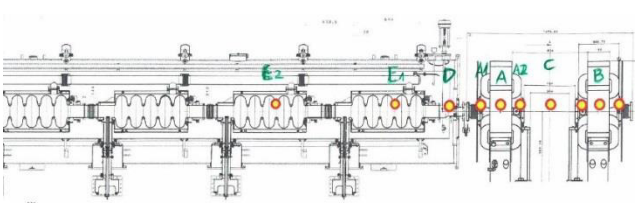

Figure 1: Loss point locations.

At the moment, the power deposited in air around a loss is used as primary indicator for suitable BLM locations as it is proportional to the BLM signal within certain limits. It can be therefore used as a good approximation for ionisation chamber response. For more accurate results, fluxes of various particles will be scored and converted into charge generated by the ionization chamber using the STRAM [4] tool described further in this paper.

MATRIX DESCRIPTION OF THE OPTIMIZATION PROBLEM

BLM's must be placed around the cryomodule-quad assemblies in the way that maximizes or at least optimizes three figures of merit: coverage, sensitivity and distinguishability of various losses. Evaluation in terms of distinguishability determines the number of beam loss scenarios possible to differentiate from each other judging by detector readings. Full coverage means reducing the number of cases which leave no traces in any of the detectors to zero and also equalising the sensitivity of the system to all loss points as much as possible. Maximizing sensitivity allows the detection of the smallest possible loss above noise level. Finally increasing resilience means minimising the loss of coverage due to failure of one or more detectors. This paper mostly focuses on maximization of coverage and distinguishability.

Let matrix M contain data on detector readings in all feasible locations. To make the situation realistic, one must select the number of monitors from the full list having in mind the optimization of coverage, sensitivity and distinguishability of losses. The problem could be described as:

$$d = M * l \tag{1}$$

where d is the vector (of length N_i – number of possible detectors) of detected losses in all possible detectors locations and l is the vector (of length N_j – number of simulated loss points) of losses at considered loss points. The set of loss point cases must be complete in order for the method to work. Excluding relevant loss points will lead to a bias in the result of monitor location selection. M therefore consists of N_j columns (different loss scenarios simulated) and N_i rows (different feasible detectors). At start the problem of finding l knowing d presented in eq. 1 is overdetermined with having more detectors then loss points, thus N_j is much smaller than N_i. By selecting a few monitor locations to place real detectors (reducing N_i to $n_i < N_j$) we introduce the underdetermination of the equation.

Decomposition of the matrix M produces the vector of its singular values. By checking its length one can judge what is the maximum number of loss scenarios that could be distinguished at all, using all feasible detectors. Using more detectors than this number doesn't increase the

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distinguishability further, but can be used for redundancy. Then one must work on the subsets of the M matrix ($M_{ni\ x\ Nj}$) determined by detectors settled in n_i chosen locations. Selection of submatrix rows could be done by excluding ones being under the certain threshold. Other possibility is hand-picking a number of reasonable detectors and proceeding with them.

Assuming that we will judge the occurrence of the loss by the weighted sum of selected detectors readings (S), we can write:

$$S = \sum_{i=1}^{n_i} c_i d_i = \sum_{i=1}^{n_i} c_i (\mathrm{M}_{n_i \times N_j} \mathrm{1})_i \qquad (2)$$

in other notation:

$$\begin{pmatrix} c_1 & \cdots & c_{n_i} \end{pmatrix} \begin{pmatrix} d_1 \\ \cdots \\ d_{n_i} \end{pmatrix} = \begin{pmatrix} c_1 & \cdots & c_{n_i} \end{pmatrix} \mathrm{M}_{n_i \times N_j} \begin{pmatrix} 1_1 \\ \cdots \\ 1_{N_j} \end{pmatrix} \qquad (3)$$

where c is the vector of detector weights. As what is scored in the end are actual detector readings $d_{1:ni}$, in order to make their weighted sum proportional to the sum of the losses in all loss points, $cM_{ni\ x\ Nj}$ should be proportional to the full vector of ones. This would ensure that the sum is independent of the loss location. The problem is overdetermined, so the best result that can be obtained is to have $cM_{ni\ x\ Nj}$ as close to (1…1) as possible – in other words one can only reduce the angle between them. The minimal angle α possible to obtain using $M_{ni\ x\ Nj}$ should be used as primary quantifier as it can be also expressed as the dependence of variation of the weighted sum on the loss location – the solution of the overdetermined problem in the least square sense, providing best possible coverage.

Other Quantifiers

Another important quantifier is κ, the condition number of matrix $M_{ni\ x\ Nj}$. κ is defined as a ratio between highest and lowest singular value of $M_{ni\ x\ Nj}$. Having κ close to the smallest possible value, being 1, means that all cases/detectors are equally important, as the rows and columns of $M_{ni\ x\ Nj}$ are orthogonal, and ensures that all losses are equally distinguishable. The number of the singular values of $M_{ni\ x\ Nj}$ cannot be bigger than the number of submatrix rows, implying a reduction in longitudinal resolution for the system.

This approach may by definition impact the redundancy of the system as with the loss of one detector the system loses its unique sensitivity pattern.

LOCATION SELECTION CRITERIA

α κ Optimization Algorithm

The results of simulations, being maps of power deposition in air, are converted from MARS output and further processed by custom MATLAB script.

Firstly, the requested number of detectors is selected. Then the script loads the simulation results for selected loss cases and scans all feasible detector locations. As the simulation output voxels are smaller than the physical sizes of detectors for flexibility reasons, average power densities in their locations are calculated for each loss case separately and then saved as column vectors. All these are then merged into big M matrix with its columns corresponding to the loss scenarios and with rows to separate detectors. Next steps are:

1. Generate unique combinations of all of the M rows, creating its subsets $M_{ni\ x\ Nj}$.
2. For each of these subsets, solve eq. 3 in the least squares sense. Save N_x smallest angle (α) cases that ensure good coverage.
3. Calculate κ for the N_x subsets.
4. From the group of N_x best cases in terms of α pick one with the minimal κ. Save the weights for this set.

The set chosen in step 4 is treated as the set representing the optimal beam loss monitor locations, as small α ensures coverage and small κ distinguishability.

It is possible to disable the κ criterium of the algorithm leaving only the coverage optimization. It is also possible to select whether or not the optimization allows negative signal weights. While these may be a possible outcome of the algorithm, achieving uniformity of sensitivity by subtracting BLM signals would lead to an unwanted failure scenario with BLMs fighting each other rather than helping to detect a beam loss.

These two last features were introduced to allow comparison with other algorithms lacking any constrains on them.

Other Location Selection Criteria

Another method of selection of the detector locations is simple brute force method. This algorithm calculates the absolute differences in signal between all pairs of losses in all detectors and normalizes them to the signal level. Technically this method is similar to the previous one run for pairs of only two detectors. The detectors are then sorted in descending order by the number of loss pairs they can differentiate the most. This approach should only ensure the optimization of the distinguishability of the losses and not the coverage.

The third selection method was utilized for the preliminary design of ESS tunnel layout [1]. The initial selection of BLM locations was based on MARS simulations, where a point beam losses were considered in the centre of adjacent quadrupole magnets. Locations with largest expected signals were chosen, thus the only criterium was the maximization of the signal.

RESULTS

Results for three approaches to BLM location selection were compared for the case of four detectors at 500 MeV. In Fig. 2 one can observe the locations determined by: a.) α optimization algorithm, b.) initial signal maximization, c.) brute force method, d.) angle optimization algorithm with only positive c allowed and e.) full α+κ optimization algorithm. Detectors are coloured yellow while cryomodules, quadrupoles and beampipe are green.

Setup d.) was obtained using angle optimization algorithm constrained by the requirement for all c weights being positive, what should ensure failure safe work. Analysis of case b.) showed negative weights for the angle minimizing case, thus it should be compared in the first place with a.), where those were also allowed. Most important quantifiers of detector layouts are as follows:

Table 1: Quantifiers of Different Detector Layouts

Layout	α [°]	κ	std
a	30.54	16.6	0.452
b	33.1	422.1	0.465
c	39.39	7.95	0.499
d	34.85	154	0.477
e	35.83	12.0	0.483

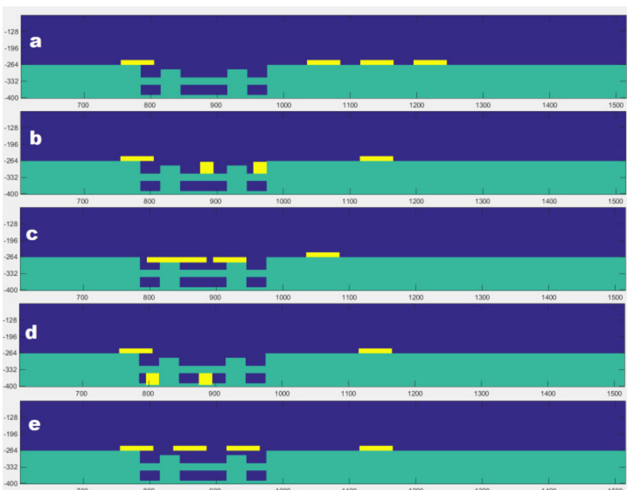

Figure 2: Layouts of detectors.

The last column of Table 1 contains the normalized standard deviation (std) over the loss points considered. One can observe that minimum of α and κ optimised separately do not coincide. The best results in terms of coverage uniformity to loss location are a.) and b.), but they cannot be used due to negative weights; moreover their κ's are high which reduces their differentiation ability. Brute force approach c.) minimized κ but might be insensitive to some losses while d.) presents the opposite properties. Case e.) utilizing the full algorithm described in this paper seems to balance between coverage and distinguishability.

It must be noted, that by judging by the α values it is not possible to find a linear combination of detectors that is independent on loss location and one can only minimize its influence.

FURTHER WORK

All simulations will be redone as new detailed models of the ESS quadrupoles and other beam line components became available. This change of geometry may induce a change in the particle shower patterns, thus change in the optimal locations for the detectors. For these new simulations a scoring of particle fluxes will be introduced. The results will be converted by STRAM directly into detector charge. Optimization algorithm will be improved with the redundancy component and automatic selection of α and κ trade-off.

STRAM [4]

As it was mentioned before, so far the power deposited in air in designed detector locations was used as the input of the algorithms. This value is close to proportional to the actual readouts of the detectors filled with nitrogen, but ultimately it will be changed to the real charge generated by the ionization chamber. MARS simulations will produce the energy distributions of fluxes of various particles: protons, neutrons, photons, electrons. In order to obtain charge from the flux, a specialized program STRAM will be used. This tool in general folds flux maps with response functions of material, in this case determining the produced charge. The response functions of the CERN type ionization chambers depending on particle type and energy are well known [5]. The results of STRAM output will be treated as the input for the location determination algorithms.

CONCLUSION

Locations for beam loss monitors in the ESS cold linac were obtained using three approaches, with one of them being the ακ optimization algorithm described in this paper. Using it, as it was showed in Table 1, seems to generate detector locations that ensure best possible ratio between the coverage and distinguishability parameters. Further improvements on the algorithm are planned to increase its efficiency.

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