BLM over-sensitivity checks via harp swipes
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Background

During the two months of physics running beginning June 8 CEBAF experienced an extraordinary number of Beam Loss Monitor (BLM) trips, up to 18/hour. These had a severe impact on Physics productivity. Since June 1 there have been 10,788 BLM trips recorded by the Downtime Manager, corresponding to 53.3 hours of lost beam time; physics time lost is larger. Extensive optics and steering checks determined that the trips were not due to poor beam transport. Among the elogs documenting this are https://logbooks.jlab.org/entry/4013985 https://logbooks.jlab.org/entry/4019395 https://logbooks.jlab.org/entry/4031765 and https://logbooks.jlab.org/entry/4032898 . 4019395 and 4031765 show distributions of the BLA loss signal centered close to zero. 4013985 is an old style aperture scan with the 30 Hz correctors. Since in 2018 CEBAF had been able to support 375 uA in the linacs at 1050 MeV/linac, changes in the linacs since then became the prime suspects: C75 modules 1 (1L05) and 2 (1L10) and the associated LLRF 3.0 software. This software is also installed in C100 zone 1L22 for test purposes. The BLMs react in 50-200 μs. CEBAF has no other beam diagnostics which react that quickly except the Beam Loss Accounting (BLA) system. Since neither the vacuum system nor radiation surveys show any evidence of sustained beam loss and the BLM trips are downstream of dispersive regions, it is hypothesized that the BLMs are reacting to beam halo being swept into beam pipe in dispersive regions due to RF transients of duration comparable to BLM comparator firing time. The BLA system, which will react if more than 2 μA CW is lost or an integrated loss of 15000 μA-μs occurs, does not trip.

It must be noted that BLM trips are much reduced as of this writing, to about 5/hour. ILM8E02 and ILMAD00 sensitivities were reduced at the first author's urging (ranting). Likely more important, many GSETs in 1L05, 1L10 and 1L22 were substantially reduced over time by operators citing "caused beam instability." 1L05 provides 60.7 MeV, 1L10 56.0 MeV and 1L22 77.6 MeV on 22 August, versus design intent of 75, 75 and 100 MeV.

Nonetheless, a global reduction in MPS (Machine Protection System) BLM gains should be considered. The system was conceived and specified before there was any beam in a CEBAF arc. The specification is in TN-94-024, 6 April 1994, C.K. Sinclair
https://jlabdoc.jlab.org/docushare/dsweb/Get/Document-31360/94-024.pdf
The physical motivation for the specification is "Time response requirement for the BLM/FSD system"
https://jlabdoc.jlab.org/docushare/dsweb/Get/Document-34139/92-046.pdf
The first circuit implementation is documented even earlier
https://jlabdoc.jlab.org/docushare/dsweb/Get/Document-34121/92-033.pdf
Beam loss monitor sensor calibration system also antedates the 1994 specification.
https://jlabdoc.jlab.org/docushare/dsweb/Get/Document-34304/93-060.pdf

The analysis done in 92-046 and 94-024 assumes normal impact of 200 μA on thin metal. In establishing BLM performance requirements in 94-024, several factors were built in to ensure that the BLMs would trip well before the melt-through threshold for this worst-case scenario was met: overestimating energy deposition in stainless steel and niobium, underestimating minimum melt-through time, and disregarding considerations like latent heat of fusion and changes in specific heat gave a conservative starting estimate, on top of which further safety margins were applied. From the summary paragraph of 94-024:

I [CKS] believe that the proper requirements for the BLM/FSD system are that (1) the BLMs produce a trip signal following a time integrated beam loss of 2500 μA-μs, and that (2) the FSD system shut off beam at the site of the localized beam loss no longer than 50 μs after receipt of a BLM trip signal.

If one assumes 25 nA halo on the C beam from Hall D measurements, 0.1 seconds of halo being swept into the wall in a dispersive region by an RF transient is required to trip the BLM if operating as specified. Even the old RFCM has an internal cycle rate no less than 200 Hz; LLRF 2.0 and 3.0 are orders of magnitude faster so transients of this long duration do not occur. Current noise in the 11 kHz range is sometimes seen in FFTs of the Beam Current Monitor signals, 0.1 ms versus 0.1 s. If there is 50 nA of halo and 50 μs response of the BLMs, they are responding to 2.5 μA-μs rather than the specified value, a factor of a thousand more sensitive than the spec. There is some multiplication in the shower from wherever the halo hits the wall to the BLM location; detailed simulation is required if one wishes to quantify it.

In the present CEBAF there is no possibility of full current hitting thin metal at normal incidence given the diagnostics developed since 1994, except for one case called out in 94-024: instantaneous failure of an RF separator causing beam to impact a septum magnet. Since cavity Q~10000, “instantaneous” is not an appropriate description on the time scale of the present CEBAF control system. There have been RF separator trips while beam was being delivered and these trips have not resulted in equipment damage.

The SEE BPM electronics did not exist when the analysis was done and the spec written; viewers with 1 cm holes were the sole mechanism used to steer multiple beams through the linacs. There did not exist the S00 (R10A) BPMs to locate the first three passes after the first BCOM in the spreaders and before the last BCOM in the recombiners. The BLA system was not trusted. The aperture check tool (30 Hz beam loss) did not exist. For that matter, the entire 30 Hz system and fast-optics data acquisition was the initiative of Valeri Lebedev and came well after the BLM system was defined. The dumplets, which allow arc-by-arc steering with tune beam, did not exist. Today, there are still regions containing up to six dipoles without BPMs due to lack of available space, but radiation surveys confirm that steering in these areas has been greatly improved since the advent of a method to set up the machine starting from design values specified in the elegant model and downloaded to the control system via eDT. Spreader/recombiner screens have been developed to aid manual steering where it is still required, further reducing error. We’ve come a long way.

Test

Test plans to check BLM sensitivity were run with tune beam using the West Arc and East Arc harps as internal targets. https://tasklists.jlab.org/bslist/tasks/107043 on 7/19 in the West Arc and https://tasklists.jlab.org/bslist/tasks/107118 on 7/28 in the East Arc. Tune beam consists of 250 μs macropulses at 60 Hz. There is a 4 μs macropulse which trails the longer one by 100 μs to allow for pass-by-pass steering in the linacs. Tune beam macropulses are within the response time of BLMs.

The results of the test were startling to those in the control room. The very first harp, 2S10, tripped the 1L02 BLM at the front of the North Linac ~1060' (350 m) away when swept through 10, 4 and 1 μA tune beams. The harps are strung with 20 μm tungsten wire so maximum occlusion of the beam was under 20% given measured sigmas. The radiation length of tungsten is 3.5 mm and the nuclear collision length 5.72 cm, so the fraction of beam scattered must have been much less than 20%. Detailed simulation is required to determine how much was scattered out of the core. It can be concluded that some of the scattered beam had its momentum reduced by less than 0.2%, as that is the energy acceptance of the first pass and loss was detected on the other side of the arc at 1L02. Third and fourth pass beam scattered by harps 6E01 and 8E01 wrapped all the way around to the other spreader, ~1990' (~600 m), through arc and linac, with 10, 4, and 1 μA tune beam. Energy acceptance of the higher arcs in sequence is smaller than that of arc 2. For five pass CEBAF, energy acceptance is about ±0.1%.

East Arc harp results were equally startling. Electrons scattered by the 1E01 harp tripped the 3S00 BLM 190' upstream (non-physical) or 4110' downstream – the scattered electrons made a full pass around the machine! 5E01 harp at 10 and 4 μA tripped the 7S01 BLM 160' upstream (non-physical) or 4140' downstream. The 9S00 BLM, about 10' upstream of 7S01, was also tripped by 5E01 scan at both currents. 7E01 harp tripped 8S01 BLM (1980') at both currents. 1 μA tune beam tests were not performed in the East Arc due to time constraints.

BLM_testplan_summary.ods gives complete results of the two tests. The elogs are referenced in the BSList tasks linked above. BLM_compendium.ods provides information about the BLMs and the devices they were meant to protect, compiled originally by Ops and updated with the authors' commentary.

Conclusion

The authors contend that the BLM system in its current implementation is not fit for purpose. There is at present no way to calibrate for its intended function. Given that harps occluding less than a fifth of 1 μA tune beam tripped some BLMs, a gain reduction of 200 V should be applied to all BLMs to approach the desired loss sensitivity of 2.5 μA. Since ILM8E02 is now at 500 V and still trips, 300 V is the suggested setting for all MPS BLMs. It would be preferable to make all the BLMs diagnostic and put them in the alarm handler, but this is perhaps politically unfeasible.

Appendix: selected SSG input to email discussions on this topic

Jerry Kowal responded 8/5 to Jay's email request to reduce the voltage on ILMAD00 as follows.

Jay,

Before I go to yes/no answers, here are couple of points:

I think we can assume right now that the BLM trips around the machine are due to RF instabilities.
Lots of tests and tweaking and tuning led to significant improvements but it's still not enough.
If machine could run cleanly there would very few BLM trips.
I don't think we fully understand what exactly happens when RF instability occurs.
What exactly happens with the beam?
How this instability propagates through machine?
How much radiation is created? What pattern?
Is such loss tolerable from the MPS point of view?
Could there be long term implications?
Are these beam instabilities acceptable to physics?
What we know for sure is that it is enough to trip BLMs as they are currently set (location, orientation, sensitivity, trip levels)

There is also a pressure to support physics program best we can in these circumstances, which might cloud our vision a little bit.

So in short this is less than ideal situation to make good decisions.
The best would be to first answer the above questions (and most likely even more) and then with consensus of involved parties decide about course of action.

Anyway, considering the low beam current as described in your email, I think, we can reduce the high voltage to a proposed 500keV for the ILMAD00.
This BLM is installed in the heavily shielded Tagger Dump, and monitors the beam line upstream of the Tagger Dump, up to the Beam Dump Wall.
Based on conversation with Keith Welch, I understand that beam loss in this area and at assumed current level should not pose any radiological personnel hazards. He's best to make comments about it himself.
Other than modification of the HV for ILMAD00, the MPS protection in the Tagger Vault will remain intact (Ion chambers etc.).

Jerry

Paul Metcalf also responded to the ILMAD00 request:

Jay,

By all means the voltage can be lowered if needed. Jerry can organizer that through software.

But a couple of corrections for the record. None of the BLM are at minimum threshold. The default value is set to around 60% of the maximum value.

Secondly, Jerry and I did not design this system or specify the locations of the BLM. We inherited it and maintain it. I understand we have requested a systematic review of the placement and orientation of BLM's several times but this has not yet occurred. Most recently I made this comment about a month ago and didn't receive a reply. The best people to undertake that work would be Ops/CASA who have far more experience with beam operation.

Paul