

# THE HIGH-LEVEL SOFTWARE OF THE BEAM POSITION LIMITS DETECTOR SYSTEM FOR THE ADVANCED PHOTON SOURCE UPGRADE STORAGE RING\*

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## Abstract

A new Machine Protection System (MPS) and Beam Position Limits Detector (BPLD) system have been developed for the APS Upgrade storage ring. The BPLD system is designed to provide synchrotron radiation protection using Libera BPM electronics as inputs: BPLD-ID for protecting insertion device front-ends and BPLD-BM for protecting the vacuum chamber of the accelerator arcs. This paper highlights the high-level software that will be used to run orbit bump-based validation procedures on the storage ring, verifying all the functionalities of the BPLD system. This high-level software was, in turn, tested and debugged by running the same orbit-bump-based procedures on the EPICS simulator of the ring running on a Linux cluster at APS, saving time that otherwise may be used during beam commissioning. In addition, the EPICS simulator tests led to further understanding of the constraints the ring sextupoles impose in limiting the amplitude and number of orbit bumps used in the validation procedures.

## INTRODUCTION

The Machine Protection System (MPS) and Beam Position Limits Detector (BPLD) system comprises the Main MPS (MMPS) and twenty distributed Local MPS/BPLD (LMPS) controllers installed at every odd sector around the storage ring. Each LMPS handles the inputs from two adjacent sectors, i.e., a "double" sector. Each double sector is equipped with seven Libera beam position monitor (BPM) electronics units [1], and each Libera unit processes four BPMs at a turn-by-turn (TbT) rate of 271 kHz. These Libera BPM data are transmitted to the LMPS through seven small form-factor pluggable fibers. Thus, 28 BPMs' TbT data are available directly to the LMPS to determine unsafe beam orbits.

The BPLD provides two types of protection systems: the BPLD-ID for protecting insertion device (ID) front ends and the BPLD-BM for protecting the vacuum chamber from the accelerator arcs.

The BPLD-ID is designed to protect the APS storage ring in the event of beam missteering at the IDs resulting in radiation hitting unwanted areas in the front end. BPLD-ID protection is enabled at the arming current threshold of say, 2 mA (user-configurable) and provides protection for an upstream sector insertion device ID(N-1) and a downstream

sector insertion device ID(N), where N is the odd sector number of the LMPS controller. The BPLD-ID protection system normally uses data on each side of the insertion device straight section and performs the calculations of the beam position/angle in the ID to be compared against a set of user-configurable limits. If the limit is exceeded, a beam trip request signal is generated and sent to the Main MPS. If the BPLD-ID is armed (ID gaps closed and above some current limit), the Main MPS processes the incoming trip request, provides a time stamp of the beam abort request, and then sends the appropriate signals for initiating the beam abort.

The BPLD-BM protection is designed to protect the accelerator components against damage from synchrotron radiation coming from the bending magnets (including stored beam strikes). Any BPM within a double sector can be selected for protection from the double sector arcs. A number  $M$  is given to the BPLD-BM controller, which will be used as a "voting" threshold for BPMs that are exceeding their position limits before a trip signal is forwarded to the Main MPS. For example, a value of  $M = 1$ , is a conservative setting (only one BPM needs to say that the conditions are unsafe), while a larger value for  $M$  may allow for the occasional false reading that would not be coincident on the same turn with other BPMs. The Main MPS processes the incoming trip requests by providing a time stamp of the beam abort request and then providing the appropriate signals for the beam abort.

## LINUX CLUSTER SIMULATOR

In the years leading up to the commissioning with beam, it was deemed important to be able to test all manner of operational and machine physics software while the old machine was still running. Plus we didn't have that much time allocated to debugging software during beam commissioning. An existing APS computational Linux cluster was utilized to run soft IOCs hosting thousands of EPICS process variables (PVs), many of which were placeholders for physical values that were externally generated by Linux processes that simulated beam physics. The initial goal was to ensure that newly written high-level software made the correct connections to the new PVs that will exist in the new storage ring. In addition, all tools available in EPICS can be used for checking the software we intend to run on the real storage ring. In particular the orbit could be simulated by a linear matrix continually being multiplied by a vector of dipole perturbers (the simplest and fastest mode). Alternatively, the orbit can be simulated by communicating the PVs' values to a tracking

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codes such as `elegant` using Linux pipes and constantly updating data files reflecting quadrupole and dipole changes. The latter tracking method, though slower, produced a realistic nonlinear orbit with some coupling effect (through the sextupoles) and tuning of the ring. This ring simulator was particularly suitable for creating the orbit bumps used in actual BPLD trip validations. In fact, we eventually realized by accident the need to run the full nonlinear simulations of the orbit calculation from `elegant`, as the nonlinearities limited the amplitude of orbit bumps and the number of simultaneous bumps, something that might have surprised us during beam commissioning. We were helped by the contemporaneous simulation of BPM offset measurements [2], which needed the same level of simulation.

In general, when an orbit bump is effectuated for a local BPLD validation, the orbit may change through a sextupole, which changes the tunes of the ring somewhat. A sufficient number of simultaneous bumps may push one of the tunes to a resonance, which may cause beam loss (and numerical problems for the simulator!). Thus the optics of the simulated ring was modified to increase the "distance" to the resonance. This optics modification will be carried forward for the actual ring as well, not necessarily for normal operations, but for the validation procedure.

## BPLD-ID VALIDATION SOFTWARE

The APS-U BPLD-ID high level validation software includes three parts:

**BPLD-ID BPM Configuration** In a double-sector controller, four BPMs are designated for determining the position/angle of the two IDs situated in the odd and even sectors. Typically, two "P0" BPMs at each end of an ID straight section are utilized. However, should a P0 BPM malfunction, a neighboring P1 BPM can serve the purpose. (The BPMs are labeled "0" to "6", starting from the straight section to the middle of the arc.) A high-level software tool has been developed to configure the BPM limits for operation based on delineated boundaries of the photon phase space.

**BPLD-ID Phase Space Display** The BPLD-ID boundary in phase space takes on a diamond shape plus angle constraints, making a hexagon in general. In Fig. 1, an illustration is provided with position constraints of  $\pm 1$  mm and angle constraints of  $\pm 0.25$  mrad in the horizontal (x) plane, depicted on the left side of the figure. On the right side of Fig. 1, the phase space boundary in the vertical (y) plane is depicted with position constraints of  $\pm 0.5$  mm and angle constraints of  $\pm 0.25$  mrad. Unlike the x-plane, the phase space shape in the y-plane forms just a diamond rather than a hexagon. This distinction arises because the position limit in the y-plane is half that of the x-plane. Electron beams traversing within the phase space boundary of the ID are deemed safe. Whenever the ID interlock boundary is breached upon closure of the ID gap, a rapid beam abort signal will be disseminated by the BPLD/MPS system. It

is noteworthy that the values of 1 mm and 0.25 mrad in the figure are provisional and subject to adjustment, if needed. A sophisticated software has been developed to exhibit the real-time phase space and boundaries of the APS-U BPLD-ID in both the x and y planes.

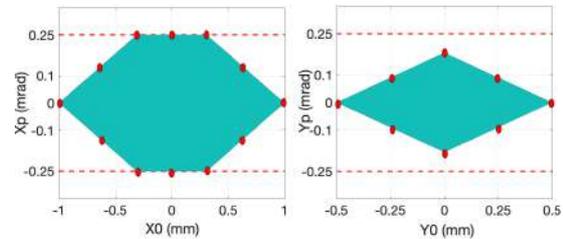


Figure 1: BPLD-ID boundaries using two P0 BPMs: (left) x plane, (right) y plane.

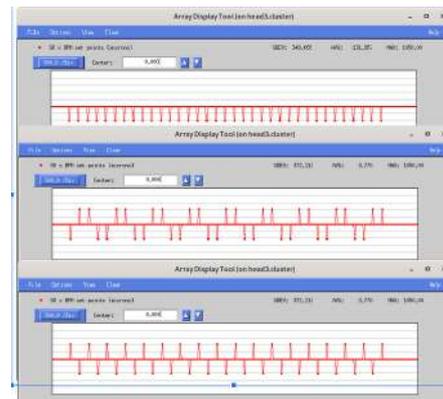


Figure 2: BPLD-ID orbit bump in the x plane.

**BPLD-ID Validation** To validate the BPLD-ID MPS system, a dedicated orbit correction configuration tailored for APS-U BPLD-ID validation has been developed and rigorously tested on the APS-U simulator [3]. This orbit correction runs to minimize or zero the error of the BPM readings relative to a set point reference, and runs continuously during the BPLD-ID validation process. To ensure comprehensive validation, all 12 red points delineated in Fig. 1 are utilized to calculate set points for the real BPMs situated upstream and downstream of the ID. In the case of two P0 BPMs, the relationship between the phase space contour point and the BPMs is defined by Eqs. (1) and (2), where  $L$  represents the distance between the two BPMs,  $x_s$  and  $x'_s$  denote the position and angle of the phase space, and  $x_1$  and  $x_2$  represent the position offsets of the upstream and downstream P0 BPMs. The computed offsets are then applied to the BPMs to generate orbit bumps, as depicted in Fig. 2. These orbit bumps intentionally violate the BPLD-ID interlock boundary and are subsequently detected by the BPLD-ID MPS system.

$$x_s = \frac{x_1 + x_2}{2} \quad (1)$$

$$x'_s = \frac{x_2 - x_1}{2L} \quad (2)$$

Three methods of applying orbit bumps in the nonlinear optics of the storage ring were tested on the simulator cluster, as illustrated in Fig. 2:

1. All IDs bumped in the same direction (top).
2. The bump direction alternating by double sector (each sector containing two IDs) (middle).
3. The bump direction alternating by ID (bottom).

The analysis revealed that method 2 had minimal induced tune changes from the sextupole magnets and maintained a stable orbit elsewhere, presumably because of the placement of sextupoles within each double sector. Consequently, method 2 was selected for BPLD-ID validation.

For each point on the boundaries, an orbit bump is generated, and a BPLD-ID validation is conducted by the MPS/BPLD system. Successful validation of the BPLD-ID system requires passing the validation for all 12 contour points. While all IDs can undergo validation simultaneously, each the orbit through each ID must traverse through the 12 contour points.

## BPLD-BM VALIDATION SOFTWARE

The APS-U BPLD-BM validation software includes two parts:

**BPLD-BM BPM Configuration** Besides the 4 BPMs for the BPLD-ID, the remaining 24 BPMs of the double sector can participate in the BPLD-BM. All 28 BPMs can be selected for maximum protection. Unlike the BPLD-ID, angle calculations are not involved in the BPLD-BM, only positions are limited at the BPMs. If any of the BPMs detect beam positions outside of the predetermined limits, a BPLD-BM interlock signal is generated. Initially the BPLD-BM will be set with a nominal arming current threshold of 25 mA and some predefined position limits [4]. Given the possibility of BPM malfunctioning, provisions are made to exclude malfunctioning BPMs from the BPLD-BM without affecting machine operations. The BPLD-BM BPM configuration software has been developed to facilitate the selection of suitable BPMs for the BPLD-BM and to configure the corresponding BPLD-BM limits.

**BPLD-BM Validation** Similar to the BPLD-ID, a specialized orbit correction configuration has been developed for the validation of the APS-U BPLD-BM, and it has undergone testing on the APS-U simulator [3]. To ensure comprehensive validation of all BPMs within each double sector, unique orbit bumps have been devised specifically for BPLD-BM validation. Unlike the BPLD-ID, where orbit bumps can be applied at all sectors simultaneously with a stable orbit, the BPLD-BM orbit bumps are limited to a

maximum of 4 double sectors simultaneously because of nonlinear optics presence of sextupole magnets in the arcs. Moreover, these 4 double sectors must be spread apart as much as possible, as seen in Fig. 3. Figure 3 depicts the orbit bump simultaneously occurring on 4 double sectors in both planes, revealing the orbit's movement through other sectors. The orbit bump should occur solely in one plane at a time. With the APS-U comprising 40 sectors or 20 double sectors, this necessitates 5 validations for each plane, resulting in a total of 10 validations.

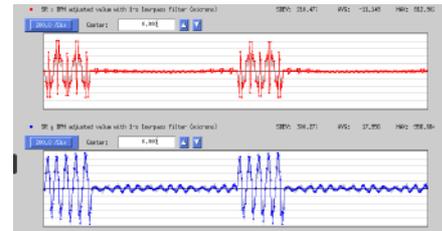


Figure 3: BPLD-BM orbit bump in the x (top) and y (bottom) planes.

## SUMMARY

High-level validation software for the BPLD-ID and BPLD-BM have been developed to validate the MPS system of the APS-U storage ring. The validation of MPS functionality was carried out using simulated beams on a cluster running EPICS on several nodes, mirroring the real validation procedure. Using a simulator for testing saved us time in code debugging and helped us understand the importance of nonlinear optics.

To ensure the significance of BPLD system testing, it is imperative to validate the system both with and without the presence of the beam. Validation without the beam has been conducted by adjusting the BPLD/MPS BPM offsets using the high-level validation software. Once the APS-U achieves a stable stored beam, the MPS system will undergo validation with real orbit bumps, facilitated by the high-level validation software.

## ACKNOWLEDGEMENTS

We extend our gratitude to the APS Controls group for their implementation of the simulator on a cluster. This tool has been instrumental in enabling us to test the orbit bump for BPLD validation in advance, ensuring readiness for the APS-U commissioning phase.

## REFERENCES

- [1] W. Cheng, internal document.
- [2] M. Borland, internal document.
- [3] N. Arnold *et al.*, internal document.
- [4] P. Kallakuri *et al.*, internal document.