LCLS-II Technical Note

LCLS2 undulator beam dump vacuum chamber protection from beam mis-steering

LCLS-II-TN-19-05

4/8/19

(Updated on 6/26/20)

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SLAC

Abstract:

In this note we discuss tracking results related to mis-steered beam at the undulator dump area. Based on these results, we propose to insert a thin mask in the beamline just upstream of the dump. It would serve to prevent the possibility of mis-steered high power beam from the sc-linac hitting the dump vacuum chamber without first generating radiation that can be easily detected and used to trip off the beam before any damage occurs. The mask could consist of a modified Conflat flange gasket. The beam would pass through it and generate enough radiation to be easily detected using a PBLM (Santana-Leitner 2019).

1 Introduction

In an LCLS-II Memorandum (Welch 2018), possible damage of the dump vacuum chamber by a mis-steered high-power electron beam from the sc-linac has been discussed. This vacuum chamber is an aluminum tube that is welded to the dump and extends through the dump shielding. Damage to the vacuum chamber would necessitate replacing the dump. The MPS and BCS systems are already designed to protect this vacuum chamber from beam strikes by methods including BPM response, feedback system, beam loss monitors, etc., as discussed in the Memo. After discussion in several meetings, it was suggested that adding a thin mask and a radiation detector to each of the undulator beamlines could provide additional protection for the dump vacuum chambers. A special thin mask is not necessary for the BSY dump, since a bellows flange with a diameter of 3.402 inches right before the BSY dump already serves this purpose (Welch 2018). In this note, we focus on the undulator electron beam dump.

2 Undulator dump particle tracking simulations

LCLS2 has two undulator beamlines that provide FEL beams for users: one for hard x-rays and one for soft x-rays. In the dump area the design of the two beamlines is very similar, and we pick the hard x-ray undulator dump as an example for this study.

We start with an arbitrary (unlimited size and divergence) transverse phase space distribution before the XTCAV structure. The XTCAV structure, which exists in the hard x-ray line, is about 2-m long and has a 10-mm inside diameter. It provides effective collimation of the electron beam and defines the maximum initial transverse phase space distribution incident to the dump beamline. In the soft line, there will be a similar XTCAV structure. With a well-defined transverse phase space distribution at the exit of the XTCAV, we track the beam to the beam dump, including the varying apertures of the vacuum chamber, BPMs, and any other smaller structures such as the protection collimator PCPM1L. Note the BPMQD and BPMDD have a rectangular aperture (1.604 in x 3.75 in) and they are rotated by 90 degree, with BPMQD having a smaller aperture in x while the BPMDD having a smaller aperture in y. Figure 1, adapted from (Welch 2018), shows the beamline chamber near the dump including magnets and BPMs. The inside diameter of the dump vacuum chamber is 95.25 mm. The dashed lines show the beam stay clear (BSC) requirement, and the three red lines are examples of the possible traced rays. Ray-1 shows the possibility of hitting the dump vacuum chamber but is only possible in the horizontal plane. Ray-2 and Ray-3 are possible extreme rays that only can happen in the vertical plane (Ray-3 is from a much stronger BPMDQD quad setting). Note this figure does not include the small vertical aperture from BPMDD, which would block Ray-3. So adding a thin mask is mainly to block the horizontal Ray-1.

We consider two possible locations for adding a mask, labeled "a" or "b" in Figure 1. In the Elegant tracking, the mask is treated as an opaque collimator (1mm thickness) and we optimize the aperture size of the mask to make sure that no simulated particle will hit on the wall of the dump vacuum chamber (the light blue part before the dump core in Figure 1). Without considering any alignment errors, the required thin mask aperture radius size is not larger than 32 mm at location "**a**", or 37 mm at location "**b**". This insures that any track that would have hit the vacuum chamber would have hit something upstream first. We summarize the parameters in Table 1 and discuss the details in the following.

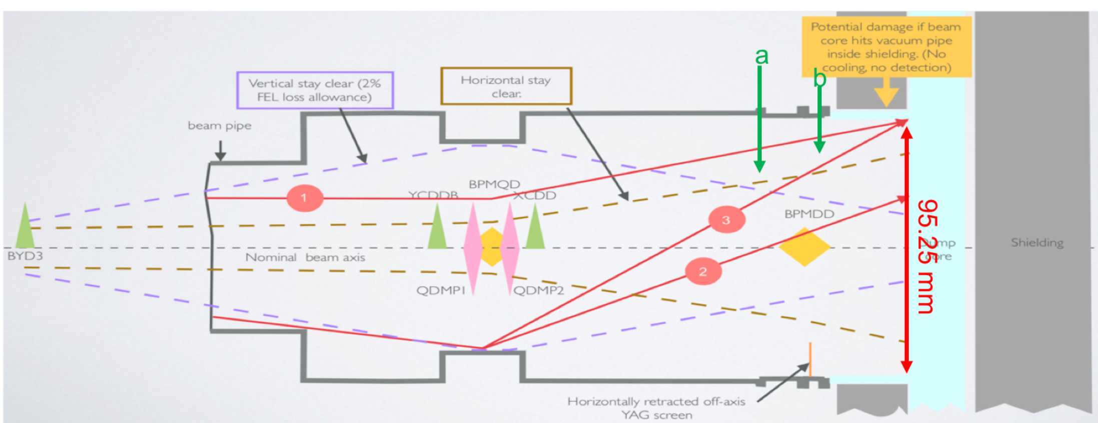

Figure 1: Elevation view of mis-steering rays near Undulator Dump. The vertical scale is 100 times larger than the horizontal scale [1]. The "a" and "b" are two potential positions to add a mask.

Table 1: Thin mask and BSC parameters for the two locations.

Location	Z location relative to BPMDD	BSC, (mm) [X_half, Y_half]	Required circular mask aperture radius (mm)
a	1.35 m upstream of BPMDD	[24.0 21.7]	32
b*	0.37 m downstream of BPMDD	[27.7 17.7]	37

*: **b** location is at the deferred RFBDD location in MAD deck.

It is easy to understand that for a location closer to the dump, less collimation (larger aperture) is required to intercept the mis-steered beam. At either location **a** or **b**, the mask aperture size is larger than the BSC requirement (see Table 1). This is good for operation and also gives some alignment tolerance for the thin mask and the dump. Location **b** has a bigger tolerance: 37 – 27.7 = 9.3 mm. So we recommend to add the thin mask at the location "**b**", and in the following we only show the simulation results for the case with the thin mask at location "**b**".

In Figure 2 we show a few simulated beam transverse distributions to illustrate the function of the thin mask at the "**b**" location. The electron beam energy is 4 GeV. A worst case scenario was assumed by combining the following errors and settings together: -3% dump bending magnets BYD strength, -1 mrad kick from horizontal correctors XCD3 and XCDD, +1 mrad kick from vertical correctors YCD3 and YCDD, and 20% increases of quadrupoles QDMP1 and QDMP2 strength. We can see the XTCAV structure defines a round beam with 10 mm diameter, and BPMQD helps filter out particles having large horizontal offset. The proposed thin mask further truncates particles in the horizontal dimension. After several iterations varying the mask inside diameter, we found that when the mask inside diameter is not bigger than 74 mm, there will be no particle loss on dump vacuum chamber (the last two pictures show the beam at the beginning and the end of the aluminum chamber that we are trying to protect).

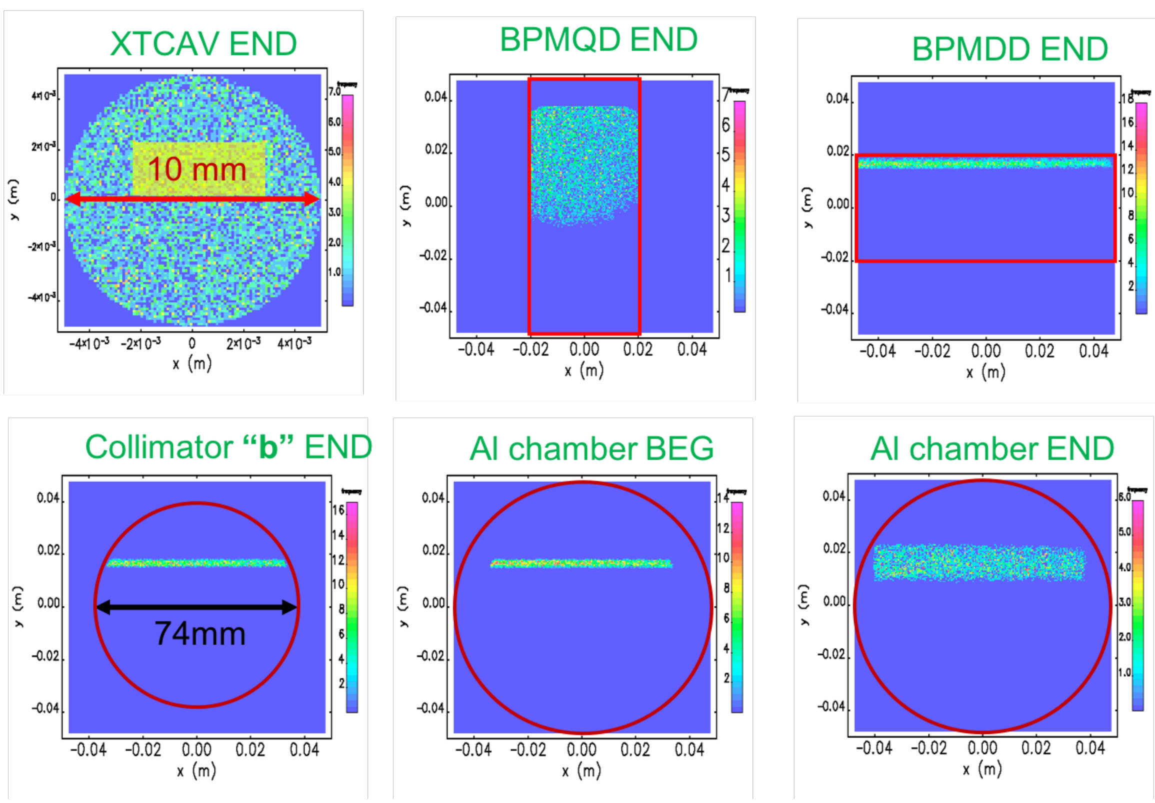

Figure 2: Tracking examples of the beam transverse distribution along the beamline before the undulator dump. The rectangular or circular red shape represents the mask inner diameter at that location. This setup uses a circular mask (radius 37 mm) at the proposed location **"b".**

3 Summary

We discussed adding a thin mask near the dump to protect the final vacuum chamber from mis-steered beam. At either of the two proposed locations, it could work and the required aperture size is larger than the beam stay-clear requirement, as shown in Table 1. Comparing to the BSC requirement, at the location "**b**" it has larger contingency so the location "**b**" should be the first choice. Considering the alignment tolerance, the actual thin mask aperture size should be smaller than that listed in the Table 1. For example, if the relative alignment error between the thin mask and the dump core is 3 mm, then the required thin mask aperture radius at location "**b**" would be 34 mm.

In these tracking studies, we assumed the BYD bending magnets to be set to the beam energy within ±3%, and the quadrupoles QDMP1/QDMP2 to be set at +20% higher than the nominal strength. Note reducing the quadrupole strength of QDMP1/QDMP2 comparing to the nominal value will weaken the kick on the beam and will not cause additional beam loss on that chamber. The maximum corrector kick is limited by the power supplies to about 1 mrad with 4 GeV beam, as we used in the studies. With all these assumptions, we concluded the required aperture size of the thin mask at location "**a**" or "**b**", and the location "**b**" is the preferable choice. Note the energy error mainly affects the vertical missteering, and the mask here is to block horizontal missteered particles. But this is a 2-D problem, for particles with both horizontal and vertical missteering, we further verified that as long as the QDMP maximum strength is limited to 121% comparing to BYD setting, there will be no particle loss at the last section chamber, regardless of energy or BYD error. If the beam energy is lowered to 2 GeV, at location "**b**", the mask inner diameter needs to be 1 mm smaller in order to provide the same protection for the final vacuum chamber. The Z location of the proposed mask is not sensitive, tolerance can be at the 5 cm level.

Also note that although we used the XTCAV structure to define a phase space distribution in our tracking, we verified that even without the XTCAV structure, the conclusions are still valid. Starting from an unlimited phase space distribution after the XTCAV, the large divergence particles will be truncated by the small aperture devices downstream (mostly by PCPM1L here, 1.125-inch diameter). Finally, the upstream undulator chamber also limits the transverse phase space, so an unlimited phase space before XTCAV is really a conservative assumption.

4 Works Cited

Santana-Leitner, M. 2019. "Burn-through & detection studies for LCLS-II dump-line." *Talk given at the Monthly LCLS-II Radiation Protection Meeting* . February 20.

Welch, J. 2018. "Beam mis-steering, detection, and response at the LCLS-II beam dumps." *LCLS-II Memorandum.* November 1.

5 Appendix -1: verify the solution with reversing the polarities of QUE quads (Updated on 3/6/2020)

To achieve the best resolution of the XTCAV measurement, undulator dump area will adopt matching solutions according to beam energy and undulator gap, which are optimized by Y. Nosochkov. The QDMP1 and QDMP2 (also the QDMP1B/2B in the soft x-ray line) are all kept at the same K values in the solutions, which will allow the interlock of the quads to the BYD dipoles. On the other hand, both solutions in the hard and soft line would prefer a reverse of the polarities of the QUE1/2 (and QUE1B/2B in the soft line) comparing to the original MAD deck. The QUE1/2 quads are located upstream of the BYD bending magnets, one before the XTCAV and one after the XTCAV. One question coming up is that if the polarity reverses of QUE1/2 (and QUE1B/2B) would affect our conclusion.

In the standard setup for these simulations, we started with an unlimited phase space distribution before XTCAV, and used XTCAV as a long aperture to collimate the beam before tracking further downstream. As we discussed in the last paragraph of Section 3, even we don't use the XTCAV aperture, the conclusion is still valid. In this case, switching the polarities of quads before BYD should make no changes of the requirement for the mask aperture size. To confirm this, we did further tracking with changing the polarity and strength of QUE2, and verified our conclusions. We still start with an unlimited phase space before the XTCAV. Since the QUE1 is upstream of the XTCAV, we do not need to consider it.

We first show the X and Y half aperture of the beam pipe in this area in Figure 3 (this is an extension of the apertures as shown in Figure 1). The QUE2 is right after the XTCAV. During the tracking, we changed the QUE2 strength by a factor 4, and/or reversed polarity as well. Those changes mainly make small differences on the particle loss at BYD chamber and PCPM1L collimator, but no particle loss has been observed at the last 2-m long aluminum chamber in any case. We adopted the mask radius size of 37 mm at the "b" location as in Table-1 in our simulations.

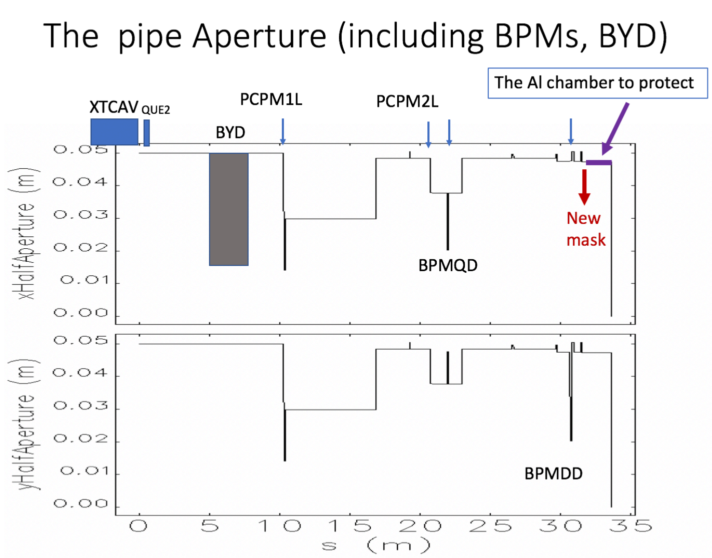

Figure 3: The beam pipe half aperture in the dump area (HXR line).

In the following Figure 4, we show the simulated beam images after the mask, before and after the aluminum chamber, based on the same worst combined configuration as discussed in Section 2: -3% dump bending magnets BYD strength, -1 mrad kick from horizontal correctors XCD3 and XCDD, +1 mrad kick vertical correctors YCD3 and YCDD, and 20% increases of quadrupoles QDMP1 and QDMP2 strength. The QUE2 strength was increased by a factor 4 with polarity reversed. We see with this worst scenario, the chosen mask aperture (37 mm radius) does the perfect collimation, which helps avoid particle loss on the aluminum vacuum pipe right before the dump face.

We conclude that, as expected, the solution of the added mask aperture (37 mm radius) at location "b" is still valid with reversing of the QUE1/2 (or QUE1B/2B) polarity.

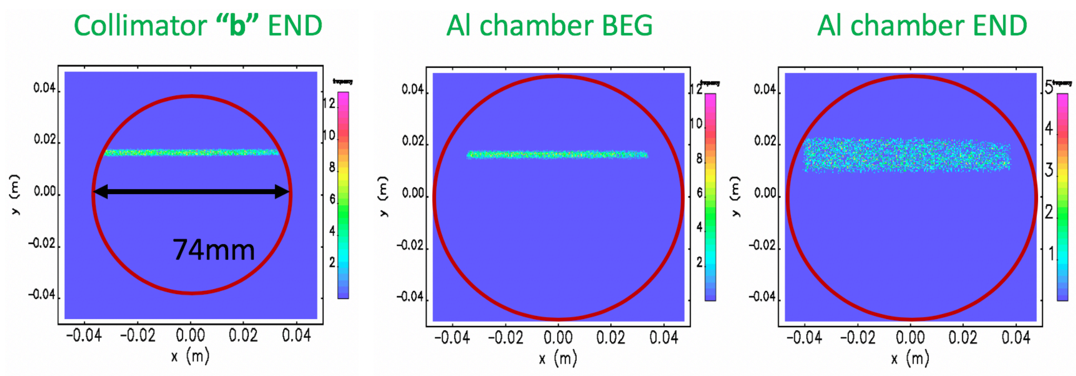

Figure 4: Tracking results after the mask collimator, before and after the ~2-m long aluminum chamber. The red circular represents the pipe size. In this extreme case with QUE2 polarity switched, there is no particle loss on this Al chamber.

6 Appendix -2: verify the required QDMP maximum limit vs energy error (Updated on 6/26/2020)

In this technote LCLS-II-19-05, there were studies about the required new mask aperture size that helps block any particle before hitting on the last section of the vacuum chamber. The proposed mask aperture radius is 37 mm (before considering alignment error). The result of mask aperture size was obtained based on the worst-case scenario of missteered beam. We have correctors (two in X and two in Y), QDMP1 and QDMP2 quads, and also the BYD bending magnets which could cause missteering in that area. In the technote, to make the conclusion of the required aperture size, we tested with setting the BYD bending magnets to be within ±3% comparing to design (reference) energy, and the quadrupoles QDMP1/QDMP2 within +20% higher than the nominal strength. Since the plan is to interlock the QDMP to the BYD, the numbers listed here are worth to further clarify.

One thing to point out first is that the BYD bends the beam vertically, and the last BPM (BPMDD, upstream the new mask) has smaller vertical aperture which already blocks any vertically missteered particle. The purpose of this new mask is mainly to block missteered particles in the horizontal dimension. But this is a 2-D problem, for particles having both horizontal and vertical offset, we need to understand better the required mask aperture size versus the BYD or energy error. For example, the solution works with a larger energy or BYD error?

Either we call it an incoming beam energy error or BYD bending magnet field error, it has a same effect of missteering the beam on the bending plane. In simulations, we can set the system with a design energy (or called reference energy), and vary the BYD magnet strength comparing to the nominal setting based on the design energy; Or we can set the BYD magnet on a reference design energy, but vary the incoming beam energy. We used these two ways to verify our conclusion in the technote.

(1) With incoming beam energy on design, vary the BYD errors and QDMP upper limit with the mask aperture size radius set at 37 mm.

In this case, the incoming beam energy is the same as the design (the reference), and the "nominal" setting for BYD and QDMP strengths are all referred to the design energy. This is the case such that the beam energy is calibrated at 4 GeV, but we can still tweak the magnets which would cause missteering and mismatching comparing to the design. For the test, the horizontal correctors XCD3 and XCDD are set at maximum +1 mrad, vertical correctors YCD3 and YCDD are also set at maximum +1 mrad, and the QDMP1/2 are set 30% more than the "nominal" referring to the design energy. Then we vary the BYD errors to check the possible particle loss on the last section of the vacuum chamber. Note here we used 30% increase of the QDMP in order to make some particle loss to find the worst case of particle loss vs BYD error. Later we will discuss that with reducing the upper limit of QDMP to some level, there will be no particle loss anymore.

Table-2: Particle loss vs. BYD errors (incoming beam is on design energy).

BYD error	QDMP error	Initial particles	Final particles on dump face	Particle loss at the last section chamber
0	+30%	100467	7748	1
1%	+30%	100467	8000	4
2%	+30%	100467	8203	4
3%	+30%	100467	8259	**9**
4%	+30%	100467	7698	3
5%	+30%	100467	6808	0

We can see that with BYD set 3% higher than design, we get the most particles loss on that last section chamber upstream the dump. Note in this worst scenario setup with positive BYD error, the nearby vertical corrector kicks oppositely comparting to BYD induced missteering .We confirmed that other combinations, for example, with BYD error -3%, we need to change YCD3 to be -1mrad to make the particle loss as much as possible at the last chamber section. The configuration in Table-2 with 3% BYD error makes the worst particle loss at the last section chamber.

After finding that the 3% error of BYD is the worst-case scenario, we then lower the QDMP upper limit to find the threshold that won't cause any particle loss on the last chamber. It turns out that as long as the QDMP strength is not larger than 24% comparing to nominal setting, there will be no particle loss problem for this case of 3% BYD error. Here both BYD and QDMP nominal are defined as reference to the design energy. If we use BYD as a reference, the QDMP upper limit should be set not higher than 21% comparing to BYD setting according to this worst case.

With all the BYD errors listed in Table-2, we checked the requirement for the QDMP upper limit which would not cause any particle loss with the mask aperture radius 37 mm. We plotted the result in Figure 5. The vertical QDMP error reference is the BYD setting. We see that an BYD error 3% gives the tightest QDMP maximum limit, requiring QDMP maximum strength no more than 21% than BYD setting. Setting an upper limit of 21% increase of QDMP strength would work well regardless of BYD error.

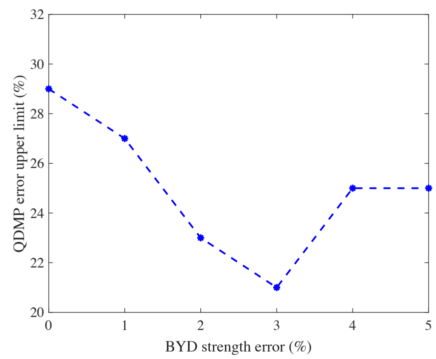

Figure 5: the required QDMP error upper limit vs BYD strength error that no particle would loss on the final vacuum chamber. The mask aperture radius is 37 mm. The QDMP strength is comparing to the BYD setting.

(2) With BYD setting on design, check the incoming beam energy error vs QDMP requirement.

We can check in a different way to verify the conclusion. We set the BYD at nominal on design energy. The horizontal correctors XCD3 and XCDD at set at maximum +1 mrad, vertical correctors YCD3 and YCDD are also set at maximum +1 mrad, and the QDMP1/2 are set 30% more than the design (with reference to the design energy). Now we vary the incoming beam energy with an error (comparing to the design energy) and look for any particle loss on the last section vacuum chamber. This is the case that we set all the magnets correctly according to design, but the incoming beam energy is uncertain with errors.

Table-3: Particle loss vs energy error. (BYD setting at nominal on design energy without errors)

Energy error	QDMP error	Initial particles	Final particles on dump face	Particle loss at the last section chamber
0	+30%	100467	7748	1
-1%	+30%	100467	7939	3

-2%	+30%	100467	8072	3
-3%	+30%	100467	8020	**20**
-4%	+30%	100467	7327	6
-5%	+30%	100467	6288	5
-6%	+30%	100467	5253	4
-7%	+30%	100467	3841	0

We see from Table-3, at an energy error -3%, we have the worst case of particle loss in the last chamber. Other combinations (positive energy errors, etc.) confirmed that -3% is the worst case. Now we lower the QDMP upper limit to find the threshold that no particle loss would happen for this worst case. It turned out that when the QDMP is set to not higher than 21% comparing to nominal, there will be no particle loss at the last chamber anymore. Since the BYD is set on nominal without errors, if we use BYD strength as a reference for QDMP, the upper limit for QDMP is still 21% increase comparing to BYD. We verified that with setting this 121% upper limit of QDMP, no particle loss at the last chamber could happen regardless of the incoming beam energy error. Figure 6 shows the required QDMP upper limit versus the beam energy error that makes no particle loss at the final chamber.

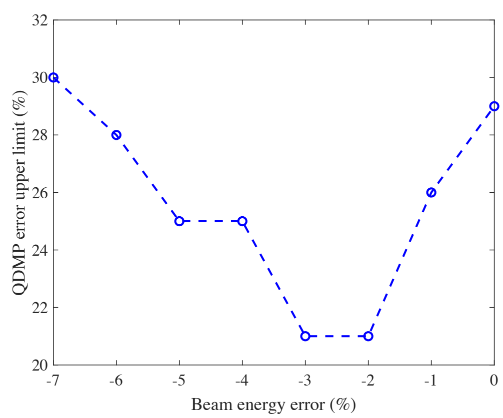

Figure 6: the required QDMP error upper limit vs beam energy error that no particle would loss on the final vacuum chamber. The mask aperture radius is 37 mm. The QDMP strength is comparing to the BYD setting.

Summary of Appendix-2:

We confirmed the worst-case scenario for particle loss at the last section chamber is at an energy error of 3%, verified through either changing the incoming beam energy or changing the BYD strength error. Larger energy error would cause stronger missteering in vertical plane, but does not make more chance for particle loss in the last chamber. As long as we set the QDMP strength upper limit at 121% comparing to the BYD setting, there will be no particle loss at the last section chamber, regardless of the incoming beam energy error.

Update history:

4/8/2019: first version.

3/6/2020: added Section 5 (Appendix-1) to discuss the effect of polarity reverse on the QUE quads.

6/3/2020:

Clarified that the QDMP limit requirement is only on the upper side, +20%. When reducing the QDMP strength comparing to the nominal value, it is safe and will NOT cause additional particle loss on that vacuum chamber upstream the dump.

Stated clearly the location "**b**" is the preferable choice.

In the Abstract and Introduction, added "from sc-linac" before the high power beam.

6/26/2020:

Added Section 6 (Appedix-2) to discuss the required QDMP maximum strength vs energy error. Concluded that with QDMP error upper limit 21%, there will be no particle loss on the last section chamber, regardless the energy error.