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How Many IVUs Can We Install without Sacrificing 16-mA Operation?

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Introduction

In this note, we examine the following hypothetical scenario: replacing existing 8-mm gap chambers with an in-vacuum undulator (IVU) one by one until we hit the boundary condition of 16-mA single-bunch operation. This is a continuation of a previous technical note [1] on the topic of IVUs.

Impedance Budget

Let's define the vertical impedance of an 8-mm gap chamber due to geometric variation as one unit of impedance with the symbol zu. Since the resistive wall impedance of an 8-mm gap chamber is 0.3 zu [2], the total impedance of an 8-mm gap chamber is 1.3 zu. The geometric impedance of a 5-mm gap chamber is 3.09 zu, which we obtained using the known scaling in Eq. (1) derived in [1]. Including 1.23 zu (0.3 zu of 8-mm gap scaled by $1/g^3$) for resistive wall, the total impedance of a 5-mm gap chamber will then be 4.32 zu. Thus, the nominal configuration of 1×29, which consists of one 5-mm and 29 8-mm gap chambers, will have a total ID chamber impedance of 42.02 zu. This is the reference impedance that will be used as a normalization factor for different configurations.

$$K_y(g) \propto \frac{1}{g^\alpha} \begin{cases} \alpha = 2.3, & \text{if IVU,} \\ \alpha = 2.4, & \text{if APS.} \end{cases} \tag{1}$$

We estimated the impedance of an in-vacuum undulator in units of zu in the appendix, and show some of the results in Table 1. The detailed computations reveal that the IVU gap producing the same impedance as a 5-mm or 8-mm out-vacuum chamber (OVU) will be 5.354 mm or 8.754 mm, respectively.

Table 1: Impedance of an In-Vacuum Undulator

Gap (mm)	8	7	6	5
Z_y (zu)	1.400	1.869	2.561	3.743

Now we estimate the impedance of N IVUs replacing N 8-mm gap chambers. The total impedance can be obtained by Eq. (2) The result is shown in Fig. 1, where we see that the total impedance is always greater than the present APS impedance budget.

$$Z(N, gap)=1\times 4.32 + (29-N)\times 1.3 + N\times Z(IVU,gap) \quad (2)$$

The corresponding single-bunch current operating limit is shown in Fig. 2. We used the polynomial fit in the appendix relating the current and impedance,

$$I = \frac{16.0}{23.3}\left(584.217 - 1388.3x + 1261.23x^2 - 511.822x^3 + 77.97x^4\right), \quad (3)$$

where x is the ratio of the impedance to the present impedance. The value in the parentheses without the 16.0/23.3 factor is the maximum current we predict to store in the ring. However, for reliable operations, we inject into a bunch with somewhat less charge than this limit. Our past experience shows that a factor of 16.0/23.3 is a reasonable choice for operational single-bunch current.

We note that the single-bunch current operating limit as we replace OVUs with IVUs is always less than 16 mA, because the total impedance is greater than the present APS_1x29 configuration. This will be true unless we use IVUs with gaps greater than 8.754 mm.

Alternatively, the geometric impedance of the OVU tapers can be optimized by using a nonlinear taper instead of the present linear taper [3]. This will create overhead in the achievable single-bunch current that will allow installing IVUs. Since the analytic form of the optimized profile is not practical for fabrication, we assumed a realistic piecewise linear transition. Then, the impedance formula Eq. (2) should be replaced by Eq. (4) below.

$$Z(N, gap)=1\times(3.09\times 0.627 +1.23) + (29-N)\times(1.0\times 0.81+0.3) + N\times Z(IVU,gap). \quad (4)$$

Note that Z(IVU,gap) is for optimized tapers in both equations 2 and 4. Then, the resultant total impedance and the corresponding current in the ring are shown in Fig. 3 and Fig. 4, respectively.

Conclusion

We evaluated the impedance of IVU for various gaps. The result showed that the present 8-mm gap chamber can be replaced by the 8.754-mm IVU while maintaining the same 16-mA operational current.

The estimates in this note make certain simplifying assumptions bearing on the effectiveness of nonlinear tapers. Subsequent evaluation of the effect of such tapers for APS parameters has cast considerable doubt on their usefulness [4]. This results from the fact that APS has a fairly short electron bunch compared to the vacuum chamber dimensions. Investigation of other methods to decrease the impedance is on-going.

References

[1] Y. Chae, private communication, 2009.

[2] Y. Chae, Y. Wang, A. Xiao, "Single-Bunch Instability Estimates for the 1-nm APS Storage Ring Upgrade with a Smaller Vacuum Chamber," Proc. of PAC2007, Albuquerque, NM, June 25-29, 2007,p. 4330 (2007); http://www.JACoW.org.
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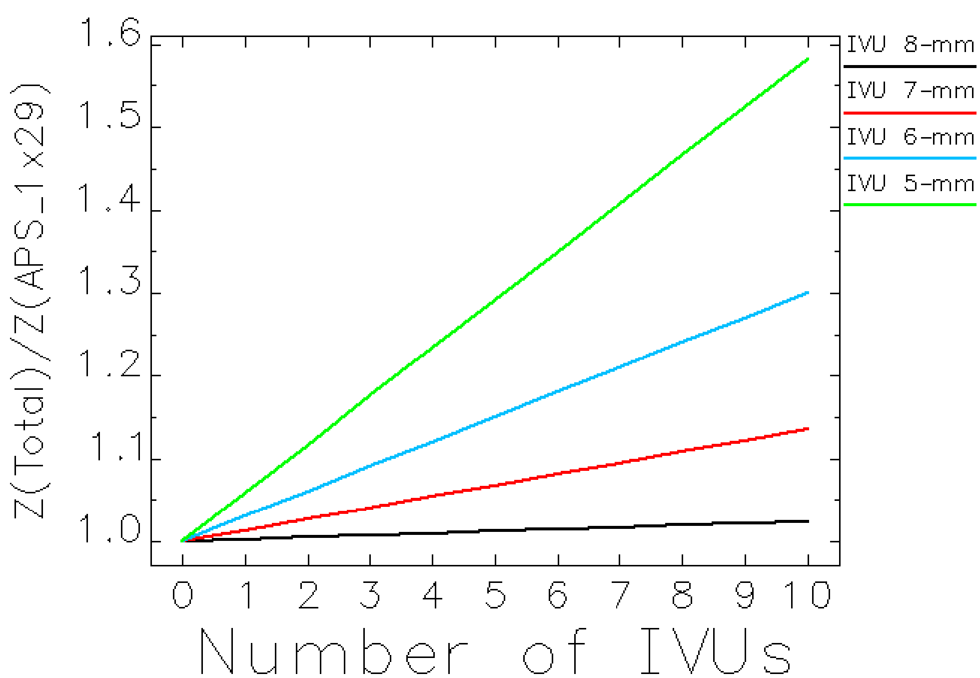

Figure 1: The total impedance of the APS ring if we replace 8-mm gap OVU with IVU. Then there will be one 5-mm OVU, (29-N) 8-mm OVU, and N IVU, where N is the number of IVUs.

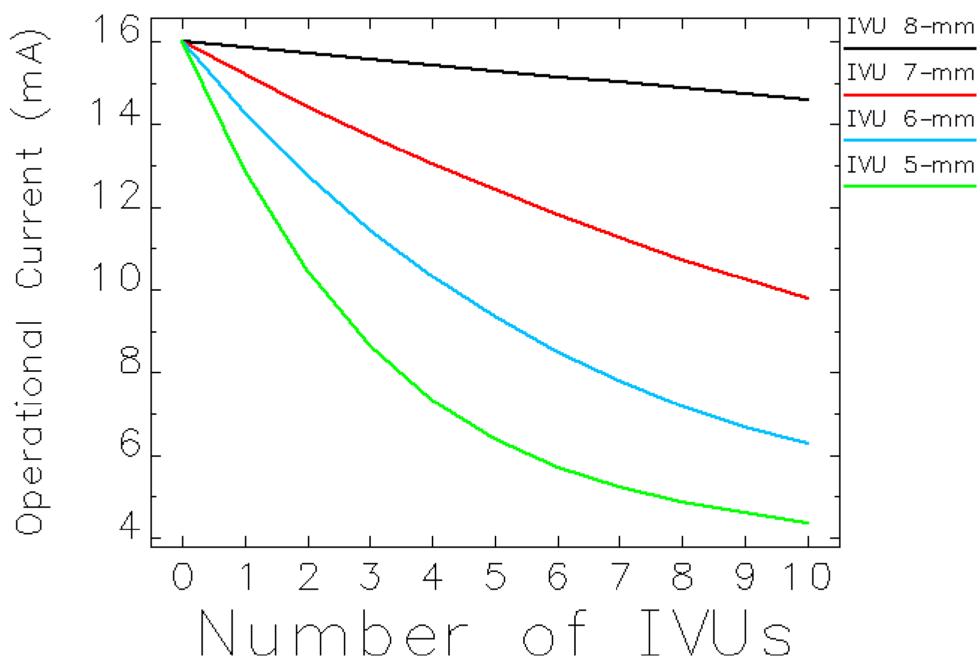

Figure 2: The single-bunch current in the ring with N IVU installed. This is the operational current; if we could tolerate the poor injection efficiency and shorter lifetime, then the limiting current could be greater than this value.

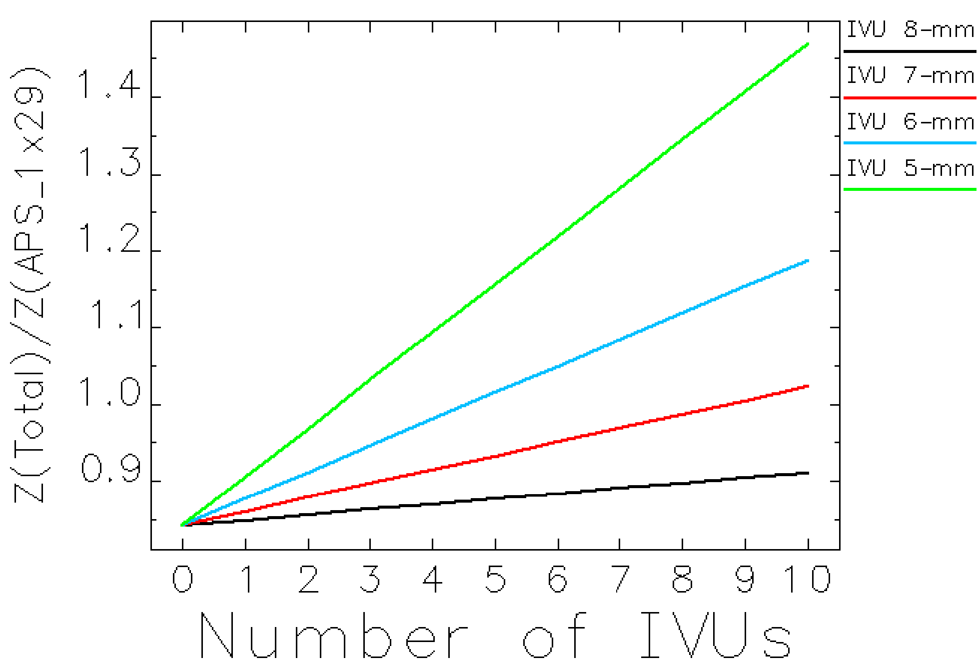

Figure 3: The impedance computed as in Figure 1, but with optimized tapers for OVUs.

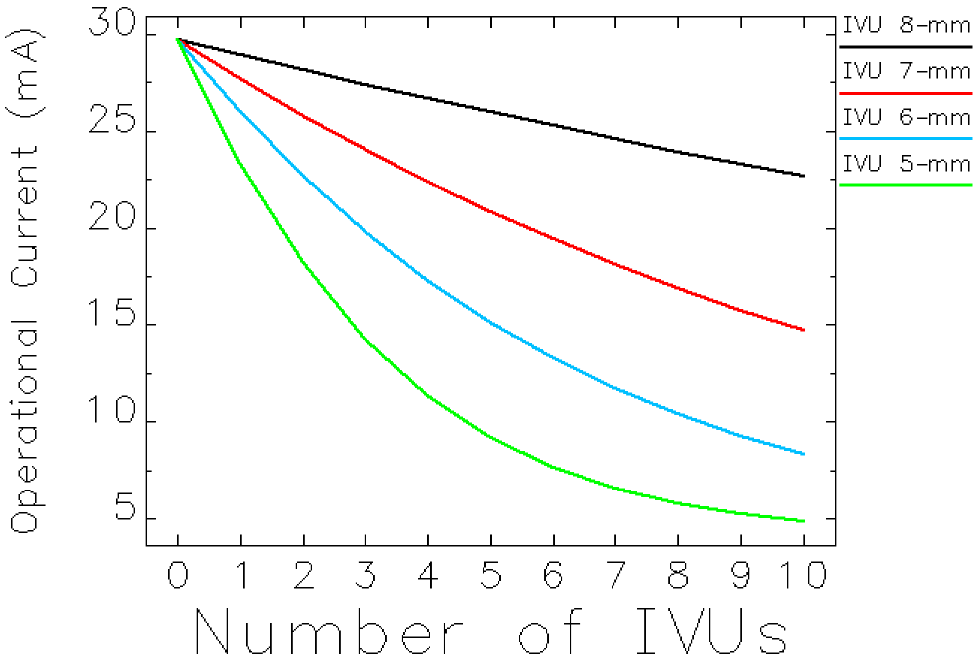

Figure 4: The operational current computed as in Figure 2 with optimized tapers for OVUs.

Appendix

Here we first explain how to get Table 1. We used these facts:

1. A factor 1.36 was derived in [1] when the convergent APS chamber is replaced by a flat chamber with constant width. This gives the increase in geometric impedance for an IVU compared to an OVU with the same inner gap.
2. Using a nonlinear taper will reduce the impedance compared to the linear taper as shown in [3]. The reduction factor obtained from the analytic formula should be increased by a factor 1.333 as determined by GdfidL simulation. The results reported in [3] were for confocal ellipses similar to the present APS undulator chambers.
3. The resistive wall impedance of 8-mm gap chamber is equivalent to the 30% of present geometric impedance, as shown in [2]. The wake potentials of 5-mm gap chamber broken down by geometric and resistive component are shown in Fig. A-1 as a reference.

Now we can evaluate the impedance for an 8-mm in-vacuum undulator,

- start from 8-mm out-vacuum, linear taper, geometric ➔ 1.0 zu
- factor 1.36 due to uniform width ➔ 1.36 zu
- factor 0.81 due to nonlinear taper ➔ 1.10 zu
- add 0.3 zu due to resistive wall ➔ 1.40 zu.

For a 7-mm in-vacuum undulator,

- start from 8-mm in-vacuum, linear taper, geometric ➔ 1.36 zu
- factor 1.36 due to scale 1/g^2.3 ➔ 1.85 zu
- factor 0.768 due to nonlinear taper ➔ 1.421 zu
- add 0.3*(8/7)^3=0.448 due to resistive wall ➔ 1.869 zu.

For a 6-mm in-vacuum undulator,

- start from 8-mm in-vacuum, linear taper, geometric ➔ 1.36 zu
- factor 1.938 due to scale 1/g^2.3 ➔ 2.636 zu
- factor 0.702 due to nonlinear taper ➔ 1.85 zu
- add 0.3*(8/6)^3=0.711 zu due to resistive wall ➔ 2.561 zu.

For a 5-mm in-vacuum undulator,

- start from 8-mm in-vacuum, linear taper, geometric ➔ 1.36 zu
- factor 2.948 due to scale 1/g^2.3 ➔ 4.009 zu
- factor 0.627 due to nonlinear taper ➔ 2.514 zu
- add 0.3*(8/5)^3=1.229 zu due to resistive wall ➔ 3.743 zu.

The above results are in Table 1, and we used the script to generate the IVU impedance as a function of IVU gap, whose result is shown in Fig. A-2. The impedances of 5-mm and 8-mm OVUs are drawn for comparison, from which we found that the equivalent IVU gap were 5.354 mm and 8.754 mm, respectively.

Now we need to explain how to get Eq. (3). We used the APS_1x29 configuration as the reference impedance. We then found the maximum single-bunch current as function of impedance, as shown in Fig. A-3. This is the new result, because we used the new impedance from Impedance Database II [6,7]. This one is very similar to the previous result obtained using the working impedance model [2,5,6]. We note that, with the present APS_1x29, the single-bunch current limit is predicted as 21 mA, which is very close to the measurement (the ring has been operating at 16 mA during user run for reliability reasons). The polynomial fit resulted in Eq. (A-1).

$$I = \left(584.217 - 1388.3x + 1261.23x^2 - 511.822x^3 + 77.97x^4\right). \tag{A-1}$$

At x=1 the fit predicts 23.3 mA instead of 21 mA. So, when we estimated the operational current shown in Fig. 2 and Fig. 4, we multiplied the above by 16.0/23.3, that is Eq. (3).

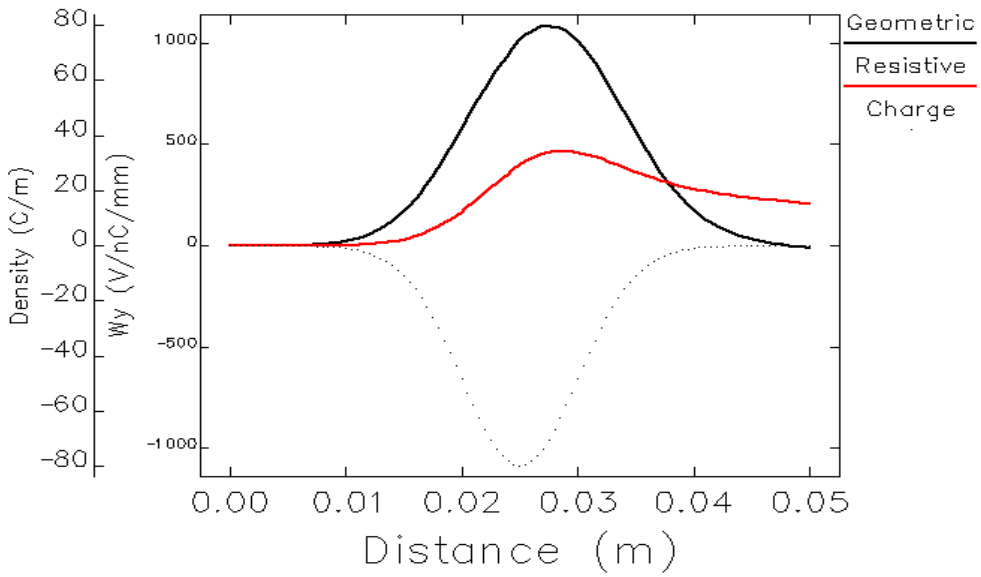

Figure A-1: The wake potential induced by a 5-mm undulator gap chamber. Geometric wake was computed by GdfidL, and resistive wake was computed by using analytic formula.

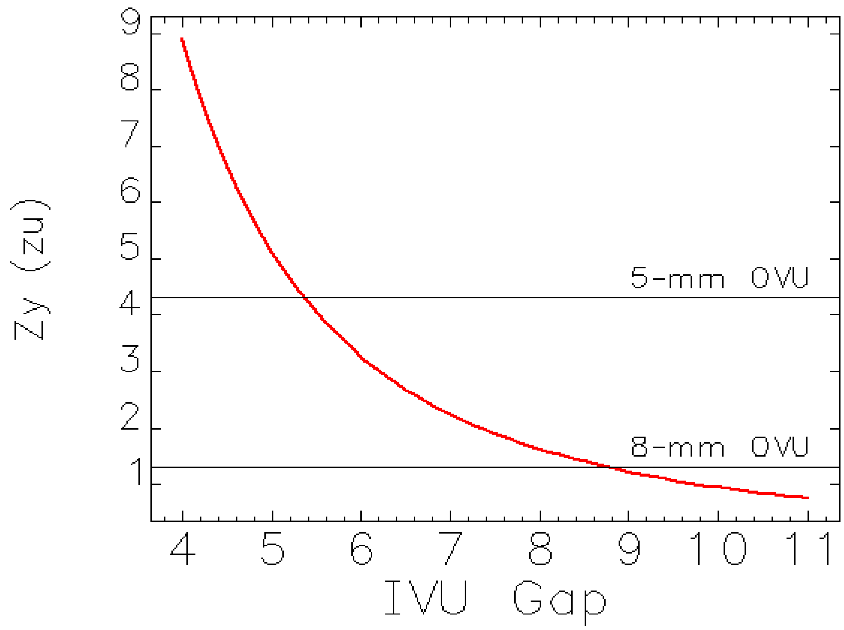

Figure A-2: The vertical impedance of IVU as a function of gap.

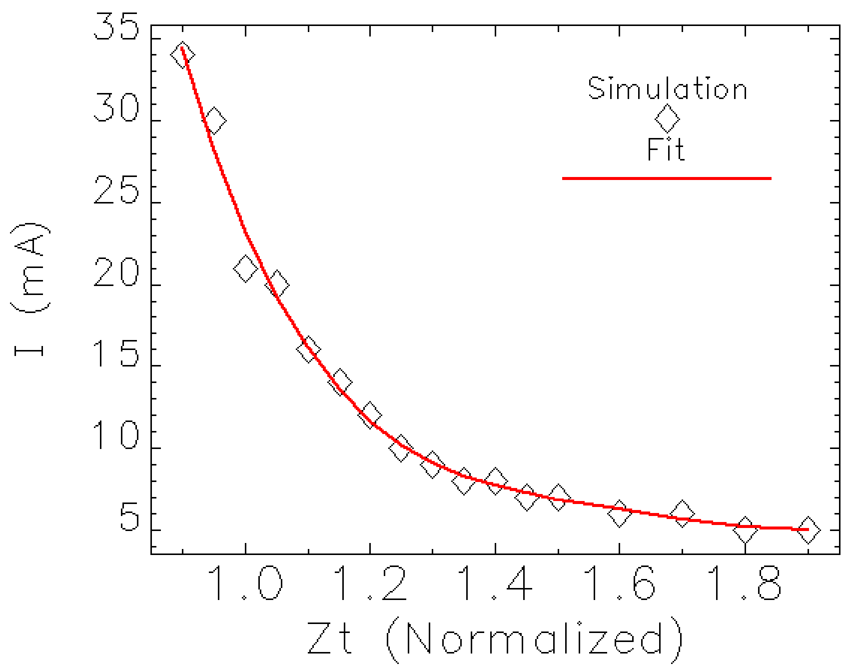

Figure A-3: The single-bunch current limit as function of ring impedance. The reference impedance was from the configuration APS_1x29. The similar result in refs. [2,5,6] was based on the working impedance model; however, this result is new and is based on the new impedance in refs. [6,7]. Note that the simulation predicts 21 mA of single-bunch current limit correctly, even if the ring is operated at 16 mA for reliability reasons.