# STATUS OF RF DEFLECTING CAVITY DESIGN FOR THE GENERATION OF SHORT X-RAY PULSES IN THE ADVANCED PHOTON SOURCE STORAGE RING*

G. Waldschmidt†, M. Borland, Y.C. Chae, K. Harkay, D. Horan, A. Nassiri
ANL, Argonne, IL 60439, U.S.A.

*Abstract*

The Advanced Photon Source (APS) at Argonne National Laboratory is exploring the possibility of using radio frequency deflection to generate x-ray radiation pulses on the order of 1 pico-second (Delta t – 70%) or less [1]. This scheme is based on a proposal by A. Zholents et al. [2] that relies on manipulating the transverse momentum of the electrons in a bunch by using an rf deflecting cavity to induce a longitudinally dependent vertical deflection of the beam. The beam will then travel through a number of undulators before arriving at a second set of deflecting cavities where the deflection is reversed such that the remainder of the storage ring is largely unperturbed [3]. Considerable effort has been expended on the design of a superconducting rf deflecting cavity operating in the S-band at 2.8 GHz to address fundamental design issues including cavity geometry, deflecting voltage, rf power coupling, tuning, and damping of higher-order and lower-order modes. In this paper we present simulation results and analysis of an optimized superconducting rf deflecting cavity design for the APS storage ring.

## INTRODUCTION

There is growing interest within the user community of conventional third-generation light sources to provide x-ray radiation pulses two orders of magnitude shorter than the 100-ps pulses routinely generated. A. Zholents et al. proposed a scheme requiring a set of deflecting cavities to create a temporal correlation within an electron bunch by delivering a longitudinally dependent vertical kick to the beam, thus exciting longitudinally correlated vertical motion of the electrons. The center of the bunch would be timed such that it crosses the center of the cavity at an rf null and experiences no net deflection. The head and tail of the bunch, on the other hand, would be chirped in opposite directions. This makes it possible to spatially separate the radiation coming from different longitudinal parts of the beam. An optical slit can be used to slice out a portion of the radiation pulse, or an asymmetrically cut crystal can be used to compress the radiation in time. After the chirped bunch passes through a number of undulators, another set of deflecting cavities is used to deflect the beam to its nominal orbit.

* Work supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.
† waldschm@aps.anl.gov

## CAVITY DESIGN

In order to achieve 1-ps pulse widths without adversely affecting the beam lifetime, a 6-MV deflecting voltage at 2.8 GHz was chosen [4]. Due to the large deflecting voltage and resultant power loss, superconducting cavities operating at $2^{o}$ K were necessary for CW operation. Multi-cell cavity options were initially considered to improve the fill-factor since only three meters is available for insertion of the cavities at the APS. However, three-, four-, and six-cell cavity geometries were eventually disregarded since heavy damping of parasitic modes was required. Further consideration of the deflecting cavity showed that damping may be more difficult since the operating mode of the cavity was not the lowest-order $TM_{010}$ mode. As a result, the lower-order-fundamental mode (LOM) needed to be externally extracted in a nonstandard manner from the superconducting cavity.

### *KEK Deflecting Cavity*

Due to the complexity of damping the parasitic modes, a single-cell cavity arrangement was designed. KEK-B and Cornell have pioneered the effort in deflecting cavity design [5] in order to improve luminosity in the KEK-B collider. KEK has performed extensive analysis and prototype testing over the last decade for a 500-MHz cavity. As a result, their design was originally adopted and scaled to 2.8 GHz for analysis for use at the APS.

KEK built a "squashed-cell" cavity shape with a transverse aspect ratio of approximately 1.8 in order to create a large separation of the degenerate $TM_{110}$ dipole modes. They used a novel coaxial beampipe transmission line in order to couple out the LOM and HOMs as TEM and higher-order coaxial modes and terminate them to a load located in the beampipe. Since the damper load was necessarily located more than two meters from the cavity, the total length of the cavity and damper assembly was too long given the space limitations at the APS. As a result, a more compact design was proposed (see Fig. 1). The LOM/HOM power is extracted from the coaxial beampipe damper with four, radially directed coaxial transmission lines and a notch rejection filter of the deflecting mode. The damping of the LOM was very effective with a loaded Q of about $10^3$, which was well below the stability threshold. However, difficulties in aligning, manufacturing, and cooling the coaxial beampipe damper at 2.8 GHz prevented any further consideration of this design.

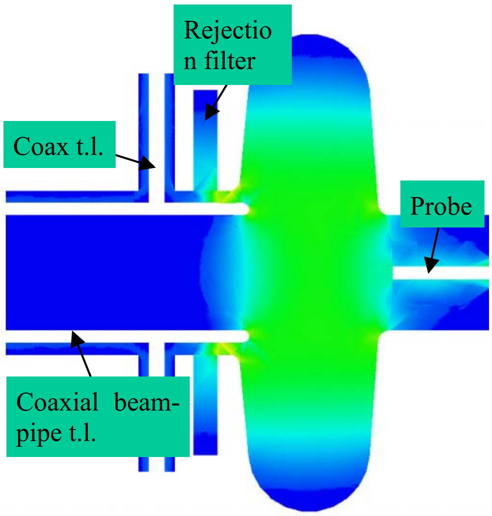



Figure 1: Magnitude of electric field of the TM010 mode in a KEK-type deflecting cavity with coaxial beam pipe transmission line and rejection filter.

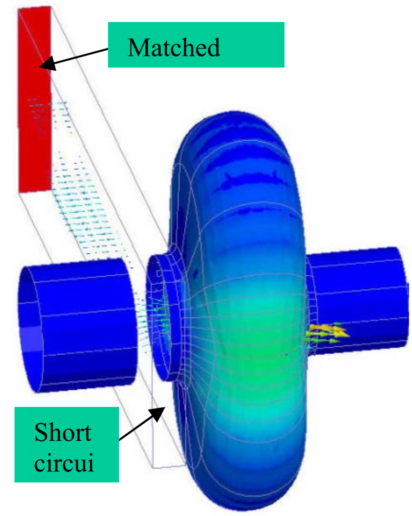



Figure 2: Power density and vector electric field plot of the TM010 mode in the cavity and in the waveguide damper. The red color represents maximum power loss, while blue is little or no loss.

### *LOM Waveguide Damper*

An alternate damper design uses a waveguide to couple to the monopole modes in the cavity and to naturally reject the deflecting mode [6] (see Fig. 2). The monopole modes, including the LOM, couple as the lowest-order $TE_{10}$ waveguide mode while the deflecting dipole mode couples as a $TE_{20}$ mode and is below cutoff, so it is rejected to a value dependent upon the waveguide length. On the other hand, the dipole mode in the "degenerate"-mode orientation also couples as the lowest-order waveguide mode and is strongly damped. The waveguide damper's performance was found to be similar to the coaxial beampipe damper. However, its ease of construction and elimination of an explicit rejection filter substantially simplifies its implementation.

Since the waveguide damper also strongly damps the degenerate dipole mode, the severely elongated shape of the cavity was reconsidered for a symmetric cavity. Several disadvantages of the asymmetric squashed-cell cavity shape were noted such as the necessity of rib supports determined after a structural analysis by KEK thus limiting tuning options, and possible difficulty in fabrication and maintaining surface quality for the atypical cavity shape. However, it was determined that the structural supports would not jeopardize mechanical tuning capabilities, and the cavity construction was not deemed to be substantially more difficult to fabricate [7]. On the other hand, the symmetric cavity shape had a lower frequency LOM that reduced the effectiveness of the natural rejection of the deflecting mode by the waveguide damper. More importantly, the symmetric cavity had distinctly higher peak surface magnetic fields, requiring additional cavities to prevent field quenching (see Table 1). As a result, a deflecting, squashed-cell cavity with waveguide damper was adopted at the APS. However, in order to reduce the peak surface magnetic fields, a minimum of ten single-cell cavities will be required.

Table 1: Symmetric and Squashed Cavity Parameters without LOM Damper

| | Symmetric | Squashed |
|---|---|---|
| Frequency | 2.815 GHz | 2.815 GHz |
| No. Cavities | 10 | 10 |
| Beam radius | 2.4/1.9 cm | 2.4/1.9 cm |
| $R_T$ / Q | 47.2 Ω/m | 46.8 Ω/m |
| Deflecting Voltage | 6 MV | 6 MV |
| Deflecting Gradient | 11.3 MV/m | 11.3 MV/m |
| $E_{sp}$ | 44.6 MV/m | 41.5 MV/m |
| $B_{sp}$ | 146 mT | 111 mT |
| $E_{sp}$ / Vkick | 74.3 MV/m/MV | 69.2 MV/m/MV |
| RF loss at 2K | 7.6 W × 10 | 7.7 W × 10 |

## BEAM STABILITY

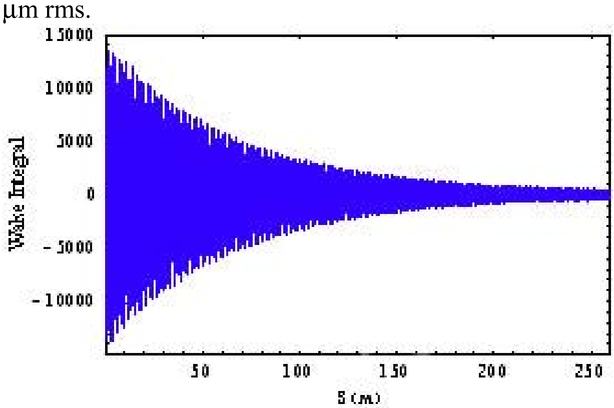
The stability criterion for the APS storage ring was derived from [8], where the growth rate for the longitudinal instability is defined as

$$\tau_g^{-1} < \frac{\alpha I_{tot}}{2(E/e)v_s}(R_s \times f_p)\ ,$$

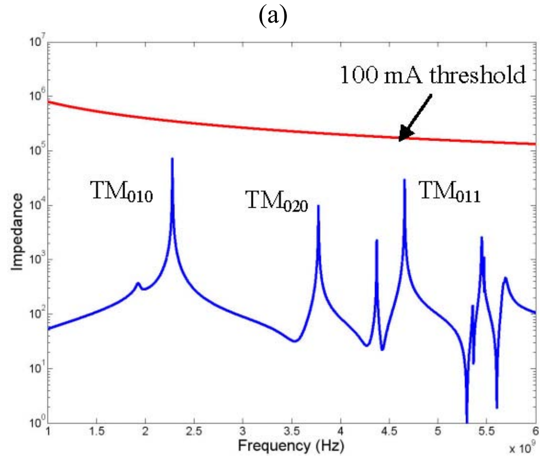
where α is the momentum compaction factor, E is the electron energy, $v_s$ is the tune, and $R_s$ is the typical circuit definition for shunt impedance. With 100-mA beam current and 7-GeV energy, a conservative requirement for longitudinal stability for the APS is $R_s \times f_p < 0.8$ MΩ-GHz. Figure 3(a) shows the long-range longitudinal wake integral calculated by Mafia [9] for a single-cell cavity with waveguide damper. Since the fundamental $TM_{010}$ mode, as well as the other monopole modes are heavily damped, the wake integral decays relatively quickly. Fig.

3(b) shows the results of calculating the impedance and comparing with the stability threshold for the APS storage ring.

Another consideration is the compensation of beam loading for orbit offset errors at the cavities; this dominates the rf power requirements. A 20-kW amplifier allows an offset of up to 0.6 mm at 100 mA, which is conservative compared to normal APS orbit stability of 2 μm rms.




(a)




(b)

Figure 3: (a) Longitudinal wake integral and (b) longitudinal impedance of a single-cell cavity with a thin waveguide damper.

## *Beam Quality*

After the deflecting cavity has returned the beam to its nominal orbit, the beam quality must not be perceptibly degraded. This creates strict requirements for the phase and amplitude control of the rf system, namely, < 0.04 deg. phase difference and < 0.25% voltage difference [3]. These extremely tight specifications will have an impact on the cavity design: stiffness and microphonics, cavity tuning schemes, etc. Also, unwanted transverse forces orthogonal to the engineered deflecting force must be controlled. The effective peak unwanted transverse voltage experienced by the bunch was 4 kV due to the effect of the cavity irises alone. The waveguide power coupler, as shown in Fig. 4, produced an additional 2.4-kV kick, as compared with 11 kV due to a single coaxial coupler. The inclusion of the single-ended waveguide damper as previously described produced an additional 2.2-kV kick, which was reduced to 0.3 kV with a two-sided symmetrically loaded damper at the expense of an additional load and penetration into the cryostat for each single-cell cavity.

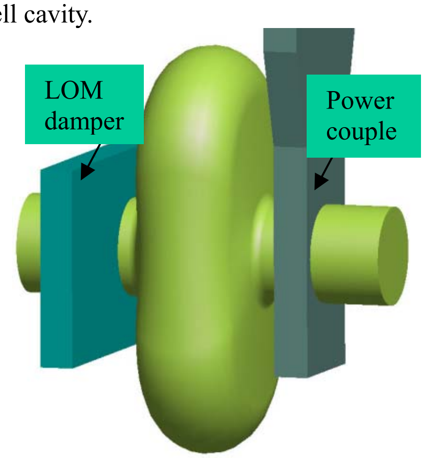



Figure 4: Unit cell of cavity, LOM waveguide damper and input power coupler assembly.

## SUMMARY

Deflecting cavity designs at 2.8 GHz were investigated for implementation at the APS for the purpose of creating 1-ps x-ray pulses based on a proposal by A. Zholents. Methods for LOM and HOM damping were investigated, as well as a comparison of performance parameters for a symmetric and asymmetric cavity shape. Using Mafia simulation results, the damping method was shown to be very effective at reducing the longitudinal impedance of the parasitic modes.

## ACKNOWLEDGEMENTS

The authors would like to thank R. Rimmer from JLAB for many useful discussions and insights regarding rf cavity design and wakefield calculations, and D. Li from LBNL and L. Bellantoni from Fermilab for many useful insights regarding deflecting cavity design issues.

## REFERENCES

[1] K. Harkay et al., Proc. of 2005 PAC, Knoxville, TN, 2005, p. 668, www.jacow.org.
[2] A. Zholents et al., Nucl. Instrum. Methods, A425, 385 (1999).
[3] M. Borland and V. Sajaev, Proc. of 2005 PAC, Knoxville, TN, 2005, p. 3886, www.jacow.org.
[4] M. Borland, Phys. Rev. ST Accel. Beams 8, 074001 (2005).
[5] K. Hosoyama et.al, Proc. of 1998 APAC, Tsukuba, p. 828, www.jacow.org.
[6] Private communication with D. Li.
[7] Private communication with K. Shepard.
[8] A. Mosnier, Proc. of 1999 PAC, New York, 1999 p. 628, www.jacow.org.
[9] Mafia, CST, www.cst.de.