# SUPERCONDUCTING RF DEFLECTING CAVITY DESIGN AND PROTOTYPE FOR SHORT X-RAY PULSE GENERATION

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## *Abstract*

Deflecting RF cavities are proposed to be used in generating short x-ray pulses (on $\sim$ 1-picosecond order) at the Advanced Photon Source (APS) at Argonne National Laboratory (ANL) [1] using a novel scheme by Zholents [2]. To meet the required deflecting voltage, impedance budget from higher order, lower order and the same order modes (HOM, LOM and SOM) of the APS storage ring, extensive deflecting cavity design studies have been conducted with numerical simulations and cavity prototypes. In this paper, we report recent progress on a single cell S-band (2.8-GHz) superconducting deflecting cavity design with waveguide damping. A copper and a niobium prototype cavity were fabricated and tested, respectively to benchmark the cavity and damping designs. A new damping scheme has been proposed which provides stronger damping to both HOM and LOM by directly coupling to a damping waveguide on the cavity equator.

## INTRODUCTION

Deflecting RF cavities have been proposed for the generation of short x-ray pulses in light sources. Normal conducting (NC) and superconducting (SC) cavity designs have been evaluated at the APS of ANL and the Advanced Light Source in Lawrence Berkeley National Laboratory (LBNL). Studies at the APS indicated that as high as 4-MV deflecting voltage is required in a continuous wave (CW) superconducting RF structure at 2815-MHz, the eighth harmonic of the storage ring RF frequency [3].

Unlike an accelerating RF cavity, a deflecting RF cavity operates at a dipole mode. Therefore, the impedance from both the HOMs and LOMs in a deflecting cavity must be damped to a level that no beam instability could be introduced. The most recent and successful application of the deflecting cavity is at KEK-B collider in Japan where a pair of single cell 500-MHz SC crab cavities were installed and commissioned at the Lower Energy and High Energy Rings (LER and HER), respectively for luminosity upgrade [4]. Damping of LOMs in a deflecting cavity is difficult in general. The KEK-B crab cavity design uses a squashed cavity geometry to separate the degenerate dipole modes, and a coaxial insertion through beampipe to effectively damp the LOMs. Research groups at Tsinghua University and LBNL have been collaborating and focusing on studying and developing waveguide damping on cylindrical symmetric single and multi-cell deflecting cavities for the ALS [5].

A new collaboration was formed between ANL, J-Lab, LBNL and Tsinghua University to develop SC deflecting RF cavities for the APS. Extensive numerical studies have been conducted, a new optimized squashed geometry deflecting cavity with waveguide damping has been designed. A copper and a Nb cavity were fabricated and tested at J-Lab. The measurement results in comparison with simulations are presented below. Taking advantage of the operating dipole mode where maximum peak magnetic field is usually at open beam iris, a new damping scheme is proposed by opening a coupling slot at the cavity equator. Preliminary numerical studies indicate that very strong damping can be achieved without significant increase of peak magnetic field.

Simulation tools and techniques for the deflecting cavity design have been developed during this collaboration that can easily be applied to multi-cell cavity studies for other light sources and colliders such as the Large Hadron Collider (LHC) and the International Linear Collider (ILC).

## THE SQUASHED CAVITY

Similar to the KEK-B squashed crab cavity design, both cylindrical symmetric and squashed cavity geometries have been analyzed. A parameterized 3-dimensional numerical model was built for the study[1]. Table 1 summarizes the study results where the squashed cavity has an optimized squash aspect ratio of 1.76, the cavity height versus cavity width. The cavity has the lowest peak magnetic field for a given deflecting voltage, namely minimum $B_{\max}/V_{\mathrm{def}}$(mT/MV) at this aspect ratio. Surface peak magnetic field is an important parameter in SC RF cavity design, but it is difficult to accurately determine its value by numerical simulations due to approximation to cavity surface and limited meshes. Simulation results using CST MWS show a ±3% of fluctuation of $B_{\max}/V_{\mathrm{def}}$(mT/MV)

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[1] The definition we used for $(R/Q)^*_\perp = V^2_{\mathrm{def}}/\omega U$, where $V_{\mathrm{def}} = |\int_0^L E_z(r = r_0)e^{-jkz}\mathrm{d}z|/(kr_0)$ is the deflecting voltage, $U$ is the stored energy in the cavity.

Table 1: Comparison study of the cylindrical symmetric cavity versus the squashed cavity (aspect ratio = 1.76)

| Mode | Parameters | Unit | Symm. | Sqsh. |
|---|---|---|---|---|
| TM$_{110}$, $y$ | $f$ | MHz | 2801.5 | 2800 |
| (Working) | $(R/Q)^*_\perp$ | Ω | 43.1 | 37.8 |
| | $Ep/V$ | 1/m | 65 | 69 |
| | $Bp/V$ | mT/MV | 194 | 160 |
| TM$_{010}$ | $f$ | MHz | 2018.8 | 2375 |
| ( LOM ) | $(R/Q)$ | Ω | 103.8 | 76.7 |
| TM$_{110}$, $x$ | $f$ | MHz | 2801.5 | 3667.0 |
| | $(R/Q)^*_\perp$ | Ω | 43.1 | 12.0 |

from coarse to fine meshes up to 100 lines per wavelength. This is adequate for the design study.

Two prototype cavities (Nb and copper) have been fabricated based on the optimized geometry from numerical design studies. The Nb cavity was constructed for vertical tests, while the copper cavity was used for both bench measurements and damping studies, photos of the cavities are shown in Figure 1. The copper half-cells can be assembled as dumbbell for 1-cell and multi-cell cavity configurations. In the vertical test conducted at J-Lab, the single-cell Nb cavity reached to maximum surface magnetic filed of $\sim$100-mT and $Q_0$ of $10^9$ at 2°K. The test was limited by the unstable RF system caused by a large Lorentz Detuning Force ($\sim -0.6\,\mathrm{Hz/mT^2}$).

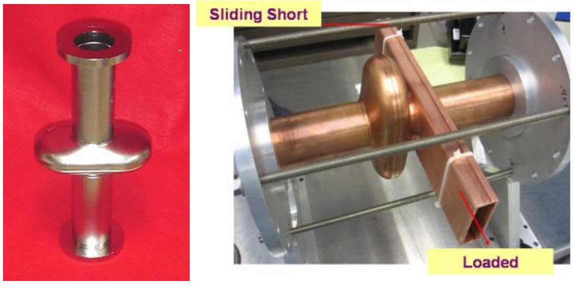

Figure 1: Niobium prototype (LEFT) and copper model with LOM damping waveguide (RIGHT)

## LOM DAMPING WAVEGUIDE

Since the operating mode is not the fundamental mode for a deflecting RF cavity, the TM$_{010}$-like accelerating mode must be damped. Its frequency is typically below the pipe cut-off. Therefore, a modest coupling could be achieved by placing a waveguide near the end of the cavity on beam pipe. Moreover, the waveguide also couples to the other polarization (TM$_{110}$-like mode) and other HOMs.

Extensive studies of waveguide damping of multi-cell cylindrical symmetric deflecting cavities had been previously conducted for the ALS of LBNL [5]. The same concept has been applied for the squashed cavity. Significant efforts have been spent on bench-marking simulation techniques and codes. CST MAFIA, Microwave Studio (MWS), HFSS and GdFidl have been carefully investigated and cross-checked in both the frequency and the time domain [6]. Good agreements were achieved. The CST MWS is chosen as the main tool for the design studies. As a variation from previous waveguide damping, where a waveguide is terminated with matched broadband load (absorbers) on both ends, we terminate one end of the waveguide with a variable short and the other one with a matched load. Therefore two coupled LOM exist: one is in the cavity and the other one is in waveguide. Coupling strength between the two modes depends on the position of the variable short; resembles closely to a classical two-coupled-harmonic-oscillator system. Frequency domain simulations confirmed the existence of the two modes at frequency of $\sim 2.4$-GHz. There must be an optimum short position that gives the strongest coupling to the mode in the cavity when damping through the waveguide. Figure 2 shows the simulation results: mode frequencies and $Q$s by varying the short position in the waveguide. Maximum damping, lowest external $Q \approx 200$ is reached when the cavity and waveguide resonant frequency are equal at the stub length (or short position) of $\sim$105-mm.

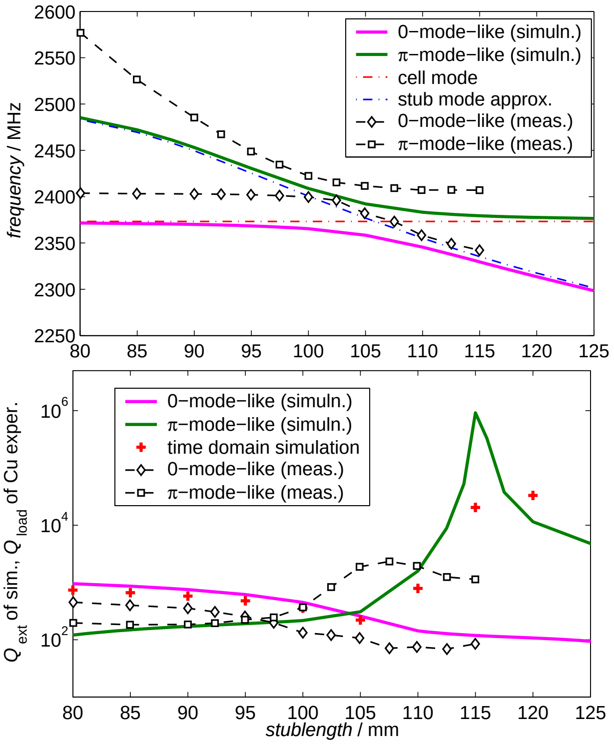

Figure 2: Simulated mode frequencies and $Q_{\mathrm{ext}}$s of the LOM with different stub lengthes using CST MWS in comparison with the bench measurements.

Damping becomes weaker if the short position moves away from the optimum position, and eventually reaches a minimum damping (peak of external $Q$). It corresponds to a short position where the electric field is zero (or node) on the axis of the beam pipe. The simulated external $Q$s from time domain are also shown in Figure 2. As the two mode frequencies are so close and coupled together, it is difficult to resolve them by FFT; the computed $Q_{\mathrm{ext}}$ is dominated by the mode with higher $Q$.

The waveguide damping scheme has been studied experimentally using the copper prototype cavity built at J-Lab, as shown in Figure 1, where a copper waveguide with a sliding short was fabricated. The LOMs are excited either by a probe or coupling loop in the beam pipe. As shown in Figure 2, the measurement results exhibit the same features with the numerical simulations. The conclusions of the numerical study were confirmed except for a ∼60-MHz frequency discrepancy (or offset) between the simulations and measurements. Further measurements and simulations are being conducted to study where the discrepancy comes from.

## OPEN CELL DAMPING

Taking advantage of the field distribution of the operating dipole mode, where the peak magnetic fields are typically in iris region, an open coupling slot at the cavity equator was proposed which would couple the LOMs and HOMs directly to a waveguide attached to the cavity [7], as shown in Figure 3.

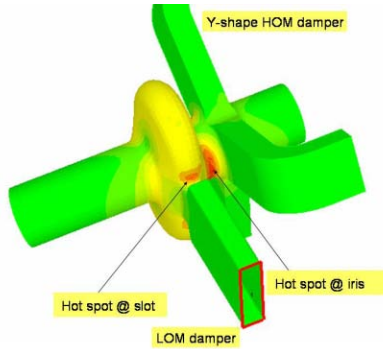

Figure 3: Surface magnetic field distribution of a deflecting cavity with the open cell damping scheme simulated using CST MWS.

The simulation results show that it provide much stronger damping. However, there is a local magnetic field enhancement due to the presence of the coupling slot, and the enhancement depends strongly on the slot dimensions, as indicated in Figure 4. Nevertheless, the field enhancement, namely peak surface magnetic field at the coupling slot, can be controlled to be below or comparable to the maximum magnetic field near beam iris. This is achieved by optimizing the slot dimensions while still providing stronger damping due to the enhanced damping properties of the open cell scheme.

Preliminary simulation results, as shown in Figure 4, are very promising, where the damping increases ∼ exponentially with the increase of the coupling slot length and the peak magnetic field increases ∼ linearly in mean time. The enhanced damping capability of the open cell scheme is clearly evident from Figure 4. For a 55-mm slot length, $B_{\max}/V_{\rm def} \approx 220 \pm 10\,$mT/MV, which is slightly below the peak magnetic field on the iris. For this slot dimension, $Q_{\rm ext} \approx 20$, which is one order of magnitude lower than what had been achieved using waveguide damping on the beam pipe.

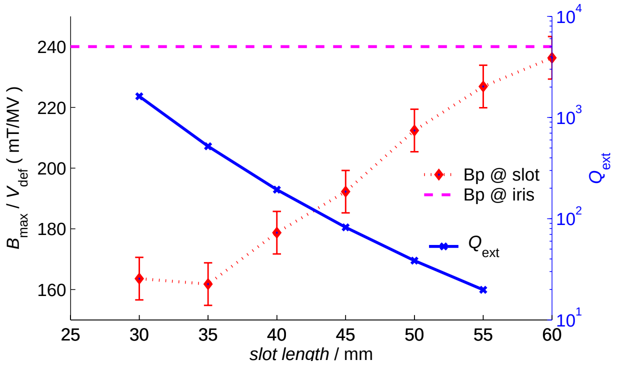

Figure 4: Peak magnetic field and $Q_{\rm ext}$ are simulated as a function of the coupling slot length for a given width.

## SUMMARY

A squashed single-cell SC deflecting cavity design, with waveguide damping at beam pipe, was evaluated with detailed simulations and bench measurements. Damping of the LOM to $Q_{\rm ext} \approx 200$ has been achieved.

A new, alternate damping scheme was proposed which provided stronger damping by having a direct coupling from cavity to a waveguide. Preliminary studies show that as low as $Q_{\rm ext} \approx 20$ can be achieved. A more compact and multi-cell cavity design will be further studied using this scheme.

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