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<b>University of Wisconsin-Synchrotron Radiation Center TECHNICAL NOTE</b>	<b><u>File No.</u> SRC-207</b>	<b><u>Page</u> 1 of 18</b>
<b><u>Subject:</u> Longitudinal broadband impedance of the Aladdin vacuum chamber and new dipole chamber design</b>	<b><u>Author(s):</u> R. A. Bosch and M. V. Fisher</b>	
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<p>An estimate of the longitudinal broadband impedance is obtained by summing estimated impedance contributions from the radiofrequency (RF) cavities, bellows, beam position monitors, Q electrode, vacuum chamber transitions, dipole chambers, pumping holes and slots, kickers, flanges, sector valves, resistive walls and space charge. The estimated total reduced impedance is <math> Z_n/n  = 11.5 \Omega</math>. The RF cavities are estimated to contribute <math>5.8 \Omega</math> to the reduced impedance <math> Z_n/n </math>, while the vacuum chamber is estimated to contribute <math>5.7 \Omega</math>. The vacuum chamber impedance of <math>5.7 \Omega</math> is expected to excite the microwave instability.</p> <p>If the dipole vacuum chambers are replaced by a design with an antechamber connected by a slot of height 24 mm, and the attached large formed bellows are effectively shielded (or shortened), the estimated ring impedance is decreased by <math>0.5 \Omega</math>. This impedance reduction may improve performance of the standard low-emittance lattice at high ring currents, where increased beam dimensions attributed to the microwave instability are observed.</p>		

## 1. Introduction

An estimate of Aladdin's longitudinal broadband impedance is obtained by summing the contribution of the RF cavities, vacuum chamber discontinuities (such as bellows, beam position monitors, Q electrode, vacuum chamber transitions, dipole chambers, pumping holes and slots, kickers, flanges and sector valves) and the ring's resistive wall and space charge impedance. The ring's broadband impedance is roughly expected to be a resonance with quality factor  $Q \approx 1$  whose resonant angular frequency is the vacuum chamber's cutoff frequency  $\omega_c$ , which is on the order of the speed of light  $c$  divided by the beam-pipe radius  $b$  [1]. For  $b = 36$  mm,  $\omega_c \approx 8 \times 10^9$  rad/s. We estimate below that the broadband impedance at angular frequencies  $\omega \ll \omega_c$  obeys  $|Zn/n| \equiv |Z(n\omega_0)/n| \approx 11.5 \Omega$ , where the RF cavity modes contribute  $5.8 \Omega$  while the vacuum chamber contributes  $5.7 \Omega$ . Here,  $\omega_0$  is the angular revolution frequency of the ring and  $|Zn/n|$  is called the reduced longitudinal broadband impedance.

A new dipole vacuum chamber design that incorporates an antechamber connected by a slot (whose height is 24 mm) is also considered. A slight impedance reduction of  $0.025 \Omega$  is expected if the existing dipole chambers are replaced by the new design. If the attached large formed bellows are shielded or shortened, the estimated decrease of the reduced impedance is  $0.5 \Omega$ . This impedance reduction may improve performance of the standard low-emittance lattice at ring currents exceeding 180 mA, where increased beam dimensions attributed to the microwave instability are observed.

## 2. Radiofrequency (RF) cavities

The contribution of an RF cavity's trapped longitudinal mode to the broadband impedance may be estimated by its "equivalent broadband impedance." When the angular frequency  $\omega$  is small compared to the resonant angular frequency  $\omega_j$  of the  $j$ -th mode, the mode's impedance is inductive, obeying [1]

$$Z(\omega) \approx -iR_j\omega / Q_j\omega_j, \quad (1)$$

where  $R_j$  is the resonant impedance and  $Q_j$  is the quality factor of the mode. The contribution of the  $j$ -th mode to the magnitude of the "reduced" broadband impedance is:

$$|Zn/n| \equiv |Z(n\omega_0)/n| = R_j\omega_0 / Q_j\omega_j, \quad (2)$$

where  $\omega_0 = 2.12 \times 10^7$  rad/s is the angular revolution frequency of the ring.

Equations (1) and (2) are valid for  $\omega \ll \omega_j$ . In contrast, the microwave instability driven by the broadband impedance typically has oscillation frequency greatly exceeding the resonant frequency of the cavities' fundamental modes and lower-frequency higher order modes (HOMs). Thus, the equivalent broadband impedance from the RF cavities' fundamental modes and lower-frequency HOMs may not contribute to excitation of the microwave instability.

For the fundamental RF cavity, the file in Appendix A was used as input to the URMEL code [2]. The input value of RKAPPA describes its aluminum composition. For each mode, the values of  $C$  and  $S$  are stated in the URMEL output file, so that the peak accelerating voltage including transit-time effects is  $V = (C^2 + S^2)^{1/2}$  [3]. Since URMEL also gives the power dissipation  $P$ , the resonant shunt impedance is  $R_j = V^2 / 2P$ , equaling one-half of the "LINAC" definition [3]. The resonant shunt impedance  $R_j$  equals the resistance in the RLC-circuit model of the impedance [3]. For the fundamental mode, eq. (2) gives  $|Zn/n| = 4.31 \Omega$ . Summing  $R_j\omega_0 / Q_j\omega_j$  for the 14 lowest-frequency HOMs gives  $|Zn/n| = 0.36 \Omega$ .

For the fourth harmonic cavity, the file in Appendix B was input to URMEL; the default value of RKAPPA describes its copper coating. For the fundamental mode,  $|Zn/n| = 1.01 \Omega$ . Summing  $R_j\omega_0 / Q_j\omega_j$  for the 14 lowest-frequency HOMs gives  $|Zn/n| = 0.10 \Omega$ .

Therefore, the total contribution of both RF cavities to the longitudinal broadband impedance  $|Z_n/n|$  is estimated to be  $5.78 \Omega$ . A summary of the modes computed by URMEL is in Table I.

### 3. Bellows

Reference [4] calculates the longitudinal impedance of a bellows in a beam pipe of radius  $b$ , where the pipe radius periodically increases to a value of  $b + \delta$  over an axial distance of length  $g$ . Here,  $\delta$  is called the corrugation depth while  $g$  is called the gap width. For low frequencies where the wavelength exceeds the corrugation period, the impedance is inductive, and the impedance per corrugation is

$$Z(\omega) = \frac{-i\omega g Z_0}{2\pi c} \ln(1 + \delta/b). \quad (3)$$

Here,  $Z_0 = 120\pi \Omega = 377 \Omega$  is the impedance of free space and  $c$  is the speed of light. The magnitude of the reduced impedance per corrugation obeys

$$|Z_n/n| = \frac{\omega_0 g Z_0}{2\pi c} \ln(1 + \delta/b). \quad (4)$$

A. Small formed SD bellows with 8 corrugations (located in SD- and near SF- sextupoles).

The ring contains 12 bellows of this type, with  $b = 1.4375'' = 36.5$  mm,  $g = 0.125'' = 3.175$  mm, and  $\delta = 0.3125'' = 7.9375$  mm. The reduced impedance per corrugation from eq. (4) is  $|Z_n/n| = 2.65$  m $\Omega$ . Multiplying by 12x8 gives the total impedance for this type of bellows:  $|Z_n/n| = 0.25 \Omega$ .

B. Small formed SD bellows with 6 corrugations (located in SD- and near SF- sextupoles).

The ring contains 12 bellows of this type, with  $b = 1.4375'' = 36.5$  mm,  $g = 0.125'' = 3.175$  mm, and  $\delta = 0.3125'' = 7.9375$  mm. The reduced impedance per corrugation from eq. (4) is  $|Z_n/n| = 2.65$  m $\Omega$ . Multiplying by 12x6 gives the total impedance for this type of bellows:  $|Z_n/n| = 0.19 \Omega$ .

C. Welded 12-corrugation bellows located by standard ID sections.

The ring contains 8 bellows of this type (including two similar bellows in LSS4), with  $b = 1.5'' = 38.1$  mm,  $g = 1/24'' \approx 1$  mm, and  $\delta = 0.5'' = 12.7$  mm. The impedance per corrugation from eq. (4) is  $|Z_n/n| = 1.22$  m $\Omega$ . Multiplying by 12x8 gives the total impedance for this type of bellows:  $|Z_n/n| = 0.12 \Omega$ .

D. Larger formed bellows located downstream of dipoles, with 22 corrugations.

The ring contains 12 bellows of this type, with  $b = 1.5625'' = 39.7$  mm,  $g = 0.108'' = 2.74$  mm, and  $\delta = 0.3125'' = 7.94$  mm. The impedance per corrugation from eq. (4) is  $|Z_n/n| = 2.12$  m $\Omega$ . Multiplying by 12x22 gives the total impedance for this type of bellows:  $|Z_n/n| = 0.56 \Omega$ .

The total contribution of bellows to the reduced longitudinal broadband impedance  $|Z_n/n|$  is estimated to be  $1.12 \Omega$ .

### 4. Stripline beam position monitors (BPMs)

For low frequencies where the wavelength exceeds the stripline length, the broadband longitudinal impedance of a stripline with characteristic impedance  $Z_s$  terminated at both ends by impedance  $Z_s$  is [5]

$$Z(\omega) = \frac{-i\omega l}{c} Z_s \left( \frac{\phi_0}{2\pi} \right)^2, \quad (5)$$

where  $l$  is the stripline length, and  $\phi_0$  is the angle subtended by the stripline with respect to the axis. The magnitude of the reduced impedance per stripline is

$$|Z_n/n| = \frac{\omega_0 l}{c} Z_s \left( \frac{\phi_0}{2\pi} \right)^2. \quad (6)$$

#### A. Standard 3-blade BPMs (2 striplines plus 1 clearing electrode)

The ring contains 40 BPMs of this type, where each stripline has  $l = 14\text{-}3/8'' = 0.365$  m,  $\phi_0 = 0.59$  radians, and  $Z_s = 50 \Omega$ . The reduced impedance per stripline from eq. (6) is  $|Z_n/n| = 11.4$  m $\Omega$ . Assuming effective termination, the clearing electrodes have  $l = 0.365$  m,  $\phi_0 = 0.73$  radians, and  $Z_s = 50 \Omega$ . The reduced impedance per clearing electrode from eq. (6) is  $|Z_n/n| = 17.4$  m $\Omega$ . For a BPM with clearing electrode, the reduced impedance is  $2 \times 11.4 + 17.4 = 40.2$  m $\Omega$ . Multiplying by 40 gives the total impedance for this type of BPM:  $|Z_n/n| = 1.61 \Omega$ .

#### B. Forty-five-degree 4-blade BPMs

The ring contains 6 BPMs of this type, with  $l = 15'' = 0.381$  m,  $\phi_0 = 0.59$  radians, and  $Z_s = 50 \Omega$ . The reduced impedance per stripline from eq. (6) is  $|Z_n/n| = 11.9$  m $\Omega$ . Multiplying by  $6 \times 4$  gives the total impedance for this type of BPM:  $|Z_n/n| = 0.29 \Omega$ .

#### C. LSS4 2-blade BPMs in the Q1s, Q2s and Q3s

The ring contains 6 BPMs of this type, with  $l = 14\text{-}3/8'' = 0.365$  m,  $\phi_0 = 0.73$  radians, and  $Z_s = 50 \Omega$ . The reduced impedance per stripline from eq. (6) is  $|Z_n/n| = 17.4$  m $\Omega$ . Multiplying by  $6 \times 2$  gives the total impedance for this type of BPM:  $|Z_n/n| = 0.21 \Omega$ .

#### D. Electrodes for tune excitation and pickup, and RF-phase feedback

The ring contains 6 striplines of this type, with  $l = 17.8'' = 0.452$  m,  $\phi_0 = 0.73$  radians, and  $Z_s = 50 \Omega$ . The reduced impedance per stripline from eq. (6) is  $|Z_n/n| = 21.6$  m $\Omega$ . Multiplying by 6 gives the total impedance for this type of BPM:  $|Z_n/n| = 0.13 \Omega$ .

The estimated contribution of all BPMs to the reduced broadband impedance  $|Z_n/n|$  is  $2.24 \Omega$ .

### 5. Q electrode

The Q electrode is a round pipe of length  $l = 4\text{-}1/2''$  and inner diameter  $2\text{-}3/8''$  terminated at the center by an impedance  $Z_s = 50 \Omega$ . We estimate its impedance as that of a stripline BPM that subtends  $\phi_0 = 2\pi$  radians, whose low-frequency impedance is given by eqs. (5) and (6), which also apply to center-terminated striplines [5]. This gives a reduced broadband impedance of  $|Z_n/n| = 0.40 \Omega$ .

### 6. Vacuum chamber transitions to insertion-device chambers

To estimate the impedance of tapered transitions between two different sizes of vacuum chamber, we use a formula that describes a tapered transition between round vacuum chambers with radii of  $a$  and  $b$ . For a shallow linear taper over a length  $l$ , the impedance for frequencies near cutoff is approximately [6]

$$Z(\omega) = \frac{-i\omega Z_0 (b-a)^2}{4\pi c l}, \quad (7)$$

so that

$$|Zn/n| = \frac{\omega_0 Z_0 (b-a)^2}{4\pi c l}. \quad (8)$$

We expect that the impedance from tapered transitions is dominated by the 8 tapered transitions associated with insertion devices. We let  $a = 9.5$  mm to represent the insertion-device vacuum chamber half-height (whose half-width is  $1.5'' = 38.1$  mm), while  $b = 35$  mm describes the round vacuum chamber upstream and downstream of the insertion devices. The transition taper is 1:10, so that its length is  $l = 255$  mm. Eq. (8) gives the reduced impedance per transition as  $|Zn/n| = 5.4$  m $\Omega$ . This value may be an overestimate since the chamber is tapered only in the vertical direction, while eq. (8) describes tapers in both the horizontal and vertical directions. Multiplying by 8 gives the total reduced impedance from insertion-device transitions:  $|Zn/n| = 0.043$   $\Omega$ .

## 7. Resistive wall impedance

In SI units, the longitudinal broadband impedance from a circular vacuum chamber of length  $L$ , radius  $b$ , and conductivity  $\sigma$  is [7]:

$$Z(\omega) = \frac{Z_0 L}{4\pi b} \left( \frac{2\varepsilon_0}{\sigma} \right)^{1/2} |\omega|^{1/2} [1 - i \operatorname{sgn}(\omega)]. \quad (9)$$

For a rectangular chamber with half-height  $b$  whose width exceeds its height, this formula gives a value of impedance that is accurate within 6% [8]. The reduced broadband impedance is

$$\frac{Z(n\omega_0)}{n} = \frac{Z_0 c}{2b} \left( \frac{2\varepsilon_0}{\sigma \omega_0} \right)^{1/2} |n|^{-1/2} [\operatorname{sgn}(n) - i], \quad (10)$$

with magnitude

$$|Zn/n| = \frac{Z_0 c}{b} \left( \frac{\varepsilon_0}{\sigma \omega_0} \right)^{1/2} |n|^{-1/2}. \quad (11)$$

Since the resistive wall impedance is proportional to the wall's length, the impedance of a vacuum chamber with several types of pipe equals the weighted average of the values computed for each type with eq. (11), weighted by the proportion of the ring circumference with each type.

The microwave instability is most easily excited at an angular frequency comparable to  $1/\sigma_t$ , where  $\sigma_t$  is the rms bunch length in seconds. An effective value of the resistive wall impedance is given by letting  $n = \omega/\omega_0 = 1/\omega_0 \sigma_t$ . Therefore, for consideration of the microwave instability

$$|Zn/n|_{\text{effective}} = \frac{Z_0 c}{b} \left( \frac{\varepsilon_0}{\sigma \omega_0} \right)^{1/2} \left( \frac{1}{\omega_0 \sigma_t} \right)^{-1/2} = \frac{Z_0 c}{b} \left( \frac{\varepsilon_0 \sigma_t}{\sigma} \right)^{1/2}, \quad (12)$$

where  $\sigma_t = 1$  ns with the harmonic bunchlengthening cavity.

Approximately 18% of the vacuum chamber consists of stainless steel undulator tanks with half-height of 9.5 mm. About 1% consists of titanium-coated ceramic kicker sections (with coating thickness exceeding the skin depth at microwave-instability frequencies) that we model as circular pipe of radius 36 mm. We model the remaining chamber as circular stainless steel pipe of radius 36 mm. A rectangular stainless steel chamber with half-height  $b = 9.5$  mm and conductivity of  $1.4 \times 10^6$   $\Omega^{-1}\text{-m}^{-1}$  has  $|Zn/n|_{\text{effective}} = 0.94$   $\Omega$ . A circular titanium chamber with  $b = 36$  mm and conductivity of  $2.4 \times 10^6$   $\Omega^{-1}\text{-m}^{-1}$  has  $|Zn/n|_{\text{effective}} = 0.19$   $\Omega$ . A circular stainless steel chamber with  $b = 36$  mm has  $|Zn/n|_{\text{effective}} = 0.25$   $\Omega$ . Thus, the estimated broadband effective impedance from the resistive walls is  $|Zn/n|_{\text{effective}} = (0.18)(0.94 \Omega) + (0.01)(0.19 \Omega) + (0.81)(0.25 \Omega) = 0.37 \Omega$ .

## 8. Existing dipole vacuum chambers

At the beginning and end of each of the 12 dipole chambers, the beam pipe undergoes a 1" linear transition between a round pipe with inner radius of 35 mm and a rectangular 3" x 1-7/8" pipe. The inner wall of the rectangular pipe contains 325 pumping slots with rounded ends, whose length  $l = 1/2$ " and height  $h = 1/8$ ". The outer wall of the rectangular pipe contains three extraction ports that are 1-7/8" wide and 7/8" high. The extraction ports are attached to the dipole chambers at an angle, so that the hole in the outer chamber wall has length  $\gg 1-7/8$ ".

### A. Linear transitions

The ring contains 24 of these 1" linear transitions between a round pipe with inner radius of 35 mm and a rectangular 3" x 1-7/8" dipole-chamber pipe, which we approximate as a round pipe of radius 1.25" = 31.75 mm. Eq. (8) gives the impedance per transition as 0.88 m $\Omega$ . Multiplying by 24 gives the total estimated impedance from these transitions:  $|Z_n/n| = 0.021 \Omega$ .

### B. Pumping slots

In a thin vacuum pipe of radius  $b$ , the low-frequency impedance of a small rectangular slot with rounded ends whose length exceeds its height is approximately [9]

$$Z(\omega) = \frac{-i\omega Z_0 h^3}{4\pi^2 c b^2} (0.1334 - 0.0500h/l), \quad (13)$$

where  $c$  is the speed of light and  $Z_0$  is the impedance of free space. Thus,

$$|Z_n/n| = \frac{\omega_0 Z_0 h^3}{4\pi^2 c b^2} (0.1334 - 0.0500h/l). \quad (14)$$

Letting  $b$  equal the chamber's half-width of 1-1/2" gives the estimated impedance per slot as  $|Z_n/n| = 1.8 \mu\Omega$ . Multiplying by 12x325 gives the estimated impedance from all pumping slots:  $|Z_n/n| = 7 \text{ m}\Omega$ .

### C. Extraction ports

In a thin vacuum pipe of radius  $b$ , the low-frequency impedance of a small rectangular slot with straight ends, whose length exceeds its height, is approximately [9]

$$Z(\omega) = \frac{-i\omega Z_0 h^3}{4\pi^2 c b^2} (0.1814 - 0.0344h/l), \quad (15)$$

where  $c$  is the speed of light and  $Z_0$  is the impedance of free space. Thus, for  $h \ll l$ ,

$$|Z_n/n| \approx \frac{\omega_0 Z_0 h^3}{4\pi^2 c b^2} (0.1814). \quad (16)$$

Using  $h = 7/8$ " and  $b = 1-1/2$ " in the above formula gives the impedance per extraction port:  $|Z_n/n| = 0.93 \text{ m}\Omega$ . Since the walls of the extraction ports extend outward much more than 7/8", they may behave as a hole in a thick-walled vacuum chamber, with impedance modified by approximately the factor 0.56 that applies for a circular hole [9], giving  $|Z_n/n| = 0.52 \text{ m}\Omega$ . Multiplying by 3x12 gives the total estimated impedance from extraction ports as 19 m $\Omega$ .

The total contribution of the existing dipole vacuum chambers to the longitudinal broadband impedance  $|Z_n/n|$  is estimated to be 0.047  $\Omega$ .

## 9. New dipole vacuum chamber design with antechamber.

A dipole vacuum chamber design is being considered in which the beam travels in a rectangular 3” x 1-7/8” pipe, where extraction ports are attached to an antechamber that is located radially outward of the beam pipe. By connecting the chamber and antechamber with a long slot whose height  $h$  is  $\leq$  one-half that of the beam pipe, and whose width  $w$  is  $\geq h$ , the beam is isolated from discontinuities in the antechamber [10].

In a rectangular beam pipe whose width  $a$  exceeds the height  $b$ , the beam-excited electromagnetic field is expected to be large for frequencies near the  $TE_{10}$  cutoff frequency of  $f_{c10} = c/2a$ , the  $TE_{01}$  cutoff frequency of  $f_{c01} = c/2b$ , and the  $TM_{11}$  cutoff frequency of  $f_{c11} = c(a^2 + b^2)^{1/2}/2ab$  [11]. The beam-excited field excites a mode in the long slot that propagates radially outward; i.e., a  $TM_{11}$  “slot-mode” whose cutoff frequency is  $f_{slot} \approx c/2h$ . At frequencies near  $f_{c10}$ , this slot-mode is evanescent with e-folding length  $(c/2\pi)(f_{slot}^2 - f_{c10}^2)^{-1/2}$ . At frequencies near  $f_{c01}$ , this slot-mode is evanescent with approximate e-folding length  $(c/2\pi)(f_{slot}^2 - f_{c01}^2)^{-1/2}$ , while at frequencies near  $f_{c11}$ , this slot-mode is evanescent with approximate e-folding length  $(c/2\pi)(f_{slot}^2 - f_{c11}^2)^{-1/2}$  [11]. For  $h < b/2$ , the e-folding length for frequencies near  $f_{c10}$ ,  $f_{c01}$  and  $f_{c11}$  approximately equals  $h/\pi$ . The interaction of the beam with a discontinuity in the antechamber requires a round trip through the slot with trip-length equaling  $2w$ , which is therefore attenuated at wavelengths near  $f_{c10}$ ,  $f_{c01}$  or  $f_{c11}$  by the factor  $e^{-2\pi w/h}$ . The calculated attenuation factor  $e^{-2\pi w/h}$  is in agreement with numerical computations for  $0 < w/h < 3$  [12]. For  $w \geq h$ , the attenuation factor  $e^{-2\pi w/h}$  is smaller than 0.002, resulting in extremely low impedance from discontinuities in the antechamber for frequencies at or below the beam-pipe cutoff frequency.

In a new-style dipole chamber serving the infrared beamline, consider a slot of 48-mm width connecting the antechamber. The slot forms a vertical aperture of height  $h$  at a distance  $R = 0.6$  m downstream of the edge radiation source, which is a short straight section of length  $L = 3$  m between dipole magnets with radius of curvature equaling 2.083 m. The half-aperture  $\theta_{ap\_1/2} = h/2R$  will cut off edge radiation at wavelengths  $\lambda$  exceeding [13]

$$\lambda_{max} = [RL/(R+L)]\theta_{ap\_1/2}^2. \quad (17)$$

To avoid impacting the infrared beamline,  $\lambda_{max}$  should comfortably exceed the  $\sim 100$ - $\mu\text{m}$  wavelength cutoff from the beamline’s entrance aperture [13]. To obtain  $\lambda_{max} > 100 \mu\text{m}$  requires that  $h > 17$  mm. For  $h = 24$  mm,  $\lambda_{max} = 200 \mu\text{m}$ , which should be acceptable. For  $h > 24$  mm, the slot height exceeds one-half that of the beam pipe, reducing the effectiveness of the slot in isolating the antechamber.

In a dipole chamber serving an insertion device beamline, radiation from the upstream end of the insertion device is produced  $\sim 8.5$  m upstream of the straight-section end. The radiation enters the beamline through an aperture of height 22 mm located 1.5 m downstream of the straight-section end. To avoid intercepting far-field radiation that passes through this aperture, the antechamber slot height  $h$  should be  $\geq 19$  mm.

Thus, a slot height of 24 mm appears to be a good choice for the dipole chambers. This slot height nearly equals the height of the existing extraction ports, so that the heating of the beam pipe and slot should not exceed that of the present dipole vacuum chambers.

For ease of construction, a rectangular antechamber slot may be used. For a small slot width (i.e., a slot in a thin wall), eq. (16) gives an estimated impedance per slot  $|Zn/n| = 1.2 \text{ m}\Omega$ . Multiplying by 0.56 gives a rough estimate of the impedance when the slot width exceeds the slot height (i.e., a slot in a thick wall):  $|Zn/n| = 0.66 \text{ m}\Omega$  per slot. A 26% impedance reduction is expected if the corners are rounded.

Since a slot with height equaling half that of the beam pipe may not be well described by eq. (16), we examined impedance computations for several antechamber-style vacuum chambers performed with the

3-dimensional MAFIA code [14]. The computed inductance per slot is  $2.4 \times 10^{-13}$  H for BEPCII [15],  $5.7 \times 10^{-13}$  H for PEP-II [16],  $2.75 \times 10^{-12}$  H for NLC [17], and  $3.6 \times 10^{-11}$  H for APS [18]. For APS, NLC, and possibly PEP-II, the computations are for a slot height of 10 mm. Equations (13)–(16) give impedance proportional to  $h^3$ , so multiplying the 10-mm computations by  $(24/10)^3$  gives inductance estimates for an antechamber slot of height 24 mm in the range of  $7.9 \times 10^{-12}$  to  $5.0 \times 10^{-10}$  H. Since  $|Z_n/n|$  equals  $\omega_0$  times the inductance, the above computations yield a range for the impedance of the Aladdin antechamber slot:  $0.17 \text{ m}\Omega \leq |Z_n/n| \leq 11 \text{ m}\Omega$ .

The calculated impedance per antechamber slot of  $|Z_n/n| \approx 0.66 \text{ m}\Omega$  is in this range, so that it appears to be a reasonable value. The antechamber slots in 12 dipole chambers will therefore contribute  $|Z_n/n| = 7.9 \text{ m}\Omega$ . This is 58% smaller than the estimated impedance from the existing extraction ports of  $19 \text{ m}\Omega$ .

The existing 1" linear taper between the rectangular dipole chamber and round vacuum chamber has a relatively large taper angle of  $\sim 30^\circ$  so that the total impedance from these tapers may exceed the value of  $|Z_n/n| = 0.021 \Omega$  given by eq. (8), which applies for "shallow" transitions. It may be prudent to use a 3" taper in the new dipole chambers, in which case the estimated impedance from all 24 tapers is  $|Z_n/n| = 0.007 \Omega$ .

The large formed bellows attached to the downstream end of the dipole vacuum chambers are estimated to contribute impedance of  $|Z_n/n| = 0.56 \Omega$ . A reduction in impedance may be realized if these bellows are effectively shielded (or shortened) while replacing the dipole vacuum chambers, so that their impedance is reduced by an order of magnitude to  $|Z_n/n| \approx 0.06 \Omega$ .

Suppose the existing dipole chambers are replaced with a design incorporating an antechamber attached by a slot with height of 24 mm, with 3" linear transitions between the rectangular dipole vacuum chamber and the round pipe upstream and downstream of the dipole. Suppose also that the large formed bellows are effectively shielded while the chambers are being replaced. Then, the estimated broadband impedance is reduced by  $0.011 \Omega$  from using antechambers rather than extraction ports,  $0.014 \Omega$  from using 3" transitions rather than 1" transitions, and  $0.5 \Omega$  from shielding the bellows. The total estimated impedance reduction is  $0.53 \Omega$ . This impedance reduction may improve performance of the low-emittance LF15 lattice at ring currents exceeding 180 mA, where increased beam dimensions attributed to the microwave instability are observed [19].

## 10. Pumping holes and slots in straight sections

### A. 2-7/8" ID pumping pipes attached to round vacuum pipe

Each quadrupole doublet has a 2-7/8" ID pumping pipe at a radius of 36 mm, with the exception of the doublets near the fundamental and harmonic RF cavities and the injection region. Each quadrupole triplet also contains a pumping pipe. Thus, there are 17 of these pumping pipes. Their impedance may be roughly estimated by the formula for a small circular hole of radius  $a$  in a thick-walled pipe of radius  $b$  that is obtained for  $a \ll b$  [9]:

$$Z(\omega) = \frac{-i(0.56)\omega Z_0 a^3}{6\pi^2 c b^2}, \quad (18)$$

so that

$$|Z_n/n| \approx \frac{(0.56)\omega_0 Z_0 a^3}{6\pi^2 c b^2}. \quad (19)$$

Letting  $a = b = 1-7/16'' = 36$  mm in eq. (19) gives an impedance per pumping pipe of  $|Z_{n/n}| = 9$  m $\Omega$ , so that the total impedance of 17 pumping pipes is  $|Z_{n/n}| = 0.15$   $\Omega$ . Since an unknown number of these pumping pipes are screened to reduce their impedance, 0.15  $\Omega$  may be an overestimate.

## B. Pumping slots and pipes in insertion-device tanks

The U1 undulator tank has pumping ports that are covered by metal plates with 90 slots with rounded corners. The slot length is  $l = 1/2''$ , height  $h = 1/8''$ , at a distance from the beam of  $b = 1-1/2''$ . These slots are identical to those in the existing dipole vacuum chambers, with impedance per slot given by eq. (14) as  $|Z_{n/n}| = 1.8$   $\mu\Omega$ . Multiplying by 90 gives the estimated impedance from all U1 pumping slots:  $|Z_{n/n}| = 0.16$  m $\Omega$ .

The U2 undulator tank has pumping ports that are covered by metal plates with 36 slots with rounded corners. The slot length is  $l = 1.275''$ , height  $h = 0.135''$ , at a distance from the beam of  $b = 1-1/2''$ . The impedance per slot given by eq. (14) is  $|Z_{n/n}| = 2.4$   $\mu\Omega$ . Multiplying by 36 gives the estimated impedance from all U2 pumping slots:  $|Z_{n/n}| = 0.086$  m $\Omega$ .

The U3 undulator tank is thought to have approximately the same geometry as that of U1, so the estimated impedance from its pumping slots is  $|Z_{n/n}| = 0.16$  m $\Omega$ .

The U4 undulator tank has two 2-7/8'' ID pumping pipes at a distance  $b = 1-1/2''$ . The estimated impedance from eq. (19) is  $|Z_{n/n}| = 8$  m $\Omega$  per pipe, for a total of  $|Z_{n/n}| = 16$  m $\Omega$ . In addition, there is a third pumping port covered by a thin plate with slots. There are 27 slots with rounded corners, with length  $l = 1/2''$ , height  $h = 1/8''$ , at a distance from the beam of  $b = 1-1/2''$ . The impedance per slot given by eq. (14) is  $|Z_{n/n}| = 1.8$   $\mu\Omega$ , so that 27 slots have  $|Z_{n/n}| = 49$   $\mu\Omega$ . There are also 6 slots with rounded corners, with length  $l = 1/4''$ , height  $h = 1/8''$ , at a distance from the beam of  $b = 1-1/2''$ . The impedance per slot given by eq. (14) is  $|Z_{n/n}| = 1.6$   $\mu\Omega$ , so these 6 slots have  $|Z_{n/n}| = 10$   $\mu\Omega$ . Summing the impedances of the pumping pipes and slots gives the estimated impedance from U4:  $|Z_{n/n}| = 16.1$  m $\Omega$ .

The total estimated impedance from pumping holes and slots in straight sections is therefore  $|Z_{n/n}| = 0.17$   $\Omega$ .

## 11. Injection region

In the region where electrons are injected into the storage ring, there is an enlarged beam pipe over a distance of 18'' that contains the septum magnet. Where this enlarged pipe joins the standard 2-7/8''-ID pipe, its ID is 4.62''. The change in pipe radii is not tapered.

Consider an ultrarelativistic electron that travels from  $z = -\infty$  in a beam pipe of radius  $b$ , whose radius suddenly decreases to  $a$ . For radii  $r$  with  $a < r < b$ , the Lorentz-transform of the electron's Coulomb field strikes the discontinuity. For sufficiently long wavelengths  $\lambda > 2\pi b/\gamma$  (i.e.,  $\omega < \gamma\omega_c$ ), where  $\gamma$  is the relativistic factor, the electric field striking the discontinuity at radius  $r$  is equivalent to a radiation field with  $E(\omega) = e/2\pi\epsilon_0 cr$ , where  $e$  is the electron charge [20]. The same magnitude of the electric field is produced on the discontinuity at a distance  $L$  downstream of a straight section entrance for  $\lambda > L/\gamma^2$  [20].

Therefore, a beam current  $I_0 \cos(\omega t)$  produces a field on the discontinuity of  $E_0 \cos(\omega t)$  with  $E_0 = I_0/2\pi\epsilon_0 cr$ . Effective reflection of the radiation is expected from the region where the incident field does not vary greatly over one wavelength, i.e. from the region where  $r > \lambda/2\pi$  [20]. The reflected power, called backward diffraction radiation, is approximately given by integrating the irradiance  $(c\epsilon_0/2)|E_0|^2$  over the region of efficient reflection:

$$Power \approx \frac{I_0^2}{4\pi\epsilon_0 c} \ln \left[ \frac{b}{\max(a, \lambda/2\pi)} \right]. \quad (20)$$

In eq. (20), the *Power* is taken to be zero when the RHS of eq. (20) is negative, i.e. for  $\omega < \omega_c = c/b$ . Since the power equals  $(I_0^2/2)\text{Re}(Z)$ , we have

$$\text{Re}(Z) \approx \frac{Z_0}{2\pi} \ln \left[ \frac{b}{\max(a, \lambda/2\pi)} \right] \quad (21)$$

for frequencies  $\omega_c < \omega < \gamma\omega_c$ . Provided that  $b/a$  is not too large, the above value of  $\text{Re}(Z)$  corresponds to a broadband impedance which obeys for  $\omega < \omega_c$

$$Z(\omega) \approx \frac{-i\omega}{\omega_c} \frac{Z_0}{2\pi} \ln \left( \frac{b}{a} \right) \quad (22)$$

so that the reduced broadband longitudinal impedance is

$$|Zn/n| \approx \frac{\omega_0}{\omega_c} \frac{Z_0}{2\pi} \ln \left( \frac{b}{a} \right). \quad (23)$$

Since an equivalent amount of forward diffraction radiation is emitted when the beam pipe radius increases from  $a$  to  $b$ , eq. (23) is also applicable when the vacuum pipe radius is suddenly increased. Therefore, for a pair of transitions, the real impedance is twice that given by eq. (21), in agreement with eq. (A6) of Ref. [21]. For a pair of transitions, the impedance is twice that given by eqs. (21)–(23), in approximate agreement with numerical computations shown in figs. (8) and (9) of Ref. [21].

To apply eq. (23) to the injection region, we have  $\ln(b/a) = \ln(4.62/2.875) = 0.47$ , giving  $|Zn/n| = 0.07 \Omega$  per transition, for a total of  $|Zn/n| = 0.14 \Omega$ .

Eq. (23) may also be applied to estimate the broadband impedance of a mirror with a hole that has been previously considered for extraction of edge radiation within a straight section [20]. For  $b = 35$  mm and  $a = 9.5$  mm,  $\ln(b/a) = 1.3$ , giving  $|Zn/n| = 0.2 \Omega$  per transition, for a total of  $|Zn/n| = 0.4 \Omega$ . For a mirror with a slot whose half-height is 9.5 mm, the extracted flux and power are 40% lower [22], so the total estimated impedance is also 40% lower:  $|Zn/n| = 0.24 \Omega$ .

## 12. Kickers

At the location of the two fast kicker magnets, the vacuum chamber is titanium-coated ceramic. The contribution of the resistive walls has been evaluated above. Additional impedance is expected from the 4 untapered transitions between round pipe with diameter of 36.6 mm and the kicker sections consisting of 3" x 2.5" rectangular pipe with rounded corners (radius = 0.5").

Consider the entrance of a kicker section whose dimensions are comparable to the radius of the round pipe. As discussed in the previous section, for angular frequency  $\omega$  in the range  $\omega_c < \omega < \gamma\omega_c$ , a beam current  $I_0 \cos(\omega t)$  produces a field of  $E_0 \cos(\omega t)$  with  $E_0 = I_0/2\pi\epsilon_0 cr$ , which is effectively reflected. Therefore, backward diffraction radiation produces a power of

$$\text{Power} \approx \frac{I_0^2}{8\pi^2 \epsilon_0 c} \int \frac{dA}{r^2}. \quad (24)$$

where the integral is over the region inside the round pipe that is outside of the kicker pipe. The real impedance from backwards diffraction radiation is

$$\text{Re}(Z) \approx \frac{Z_0}{4\pi^2} \int \frac{dA}{r^2} \quad (25)$$

for frequencies  $\omega_c < \omega < \gamma\omega_c$ . The above value of  $\text{Re}(Z)$  corresponds to a broadband impedance from backwards diffraction radiation which obeys for  $\omega < \omega_c$

$$Z(\omega) \approx \frac{-i\omega}{\omega_c} \frac{Z_0}{4\pi^2} \int \frac{dA}{r^2} \quad (26)$$

so that the reduced broadband longitudinal impedance from backwards diffraction radiation is

$$|Z_n/n| \approx \frac{\omega_0}{\omega_c} \frac{Z_0}{4\pi^2} \int \frac{dA}{r^2} . \quad (27)$$

Forward diffraction radiation also obeys eqs. (24)–(27), where the integral is over the region outside the round pipe that is inside the kicker pipe. The total broadband impedance from the transition is the sum of the impedances from backward and forward diffraction radiation.

For the kicker sections, the computed integral  $\int dA/r^2$  equals 0.1980 for backward diffraction radiation, giving reduced broadband impedance  $|Z_n/n| = 0.00502 \Omega$ . The integral  $\int dA/r^2$  equals 0.4646 for forward diffraction radiation, giving reduced broadband impedance  $|Z_n/n| = .01177 \Omega$ . The total impedance per transition is therefore  $|Z_n/n| = 0.01679 \Omega$ . Multiplying by four gives the total reduced broadband impedance from the kicker section geometry:  $|Z_n/n| = 0.0672 \Omega$ .

In addition, there is one shadow plate that protects a kicker section from synchrotron radiation. The plate occupies the region inside the round pipe where  $x > 1.065'' = 27.051 \text{ mm}$ . The backward diffraction radiation is described by eqs. (24)–(27), where the integral is over the shadow plate. The computed integral value is  $\int dA/r^2 = 0.30314$ , giving a reduced broadband impedance from backward diffraction radiation of  $|Z_n/n| = 0.0077 \Omega$ . An equal impedance arises from forward diffraction radiation, giving a total reduced broadband impedance of  $|Z_n/n| = 0.0154 \Omega$ .

Summing the impedance of the kicker section transitions and the shadow plate gives the geometric broadband impedance from the kicker section regions:  $|Z_n/n| = 0.0826 \Omega$ .

### 13. Flanges and transitions from 2-7/8" ID to 2-3/4" ID pipes

For a flange joining round vacuum pipes with 2-7/8" ID ( $b = 1.4375''$ ), the vacuum pipe radius increases to  $b + \delta_1$  over a distance  $g_1 = 0.012''$ , with  $\delta_1 = 0.2375''$ , where a knife-edge defines the radius. Then the vacuum pipe radius is  $b + \delta_2 = 1.5''$  over a distance  $g_2 = 0.08''$ , with  $\delta_2 = 0.0625''$ , where a copper gasket defines the radius. The vacuum pipe radius again increases to  $b + \delta_1$  over a distance  $g_1 = 0.012''$ , with  $\delta_1 = 0.2375''$ , where a knife-edge defines the radius.

We estimate the impedance using eq. (4), by summing the impedance of two convolutions of bellows with parameters  $g_1$  and  $\delta_1$  plus one convolution with parameters  $g_2$  and  $\delta_2$ , to obtain  $|Z_n/n| = 0.76 \text{ m}\Omega$  per flange. Multiplying by 112 flanges gives a total impedance of 85 mΩ for this type of flange.

For a flange joining round vacuum pipes with 2-3/4" ID, the parameters are  $b = 1.375''$ ,  $g_1 = 0.012''$ ,  $\delta_1 = 0.3''$ ,  $g_2 = 0.08''$ ,  $\delta_2 = 0.125''$ , yielding  $|Z_n/n| = 1.26 \text{ m}\Omega$  per flange. Multiplying by 12 flanges gives total impedance of 15 mΩ for this type of flange.

For a flange that joins a pipe with 2-7/8" ID to a pipe with 2-3/4" ID, we estimate the impedance as the sum of a flange's impedance plus that of an untapered transition in pipe radius. The flange's estimated impedance is  $|Z_n/n| = 0.76 \text{ m}\Omega$ , while the impedance of an untapered transition in pipe radius is given by eq. (23) as  $|Z_n/n| = 7.08 \text{ m}\Omega$ . Thus, the total estimated impedance is  $|Z_n/n| = 7.84 \text{ m}\Omega$  per flange. Multiplying by 43 flanges gives total impedance of 337 mΩ for this type of flange.

In addition, there are 13 untapered transitions between a pipe with 2-7/8" ID to a pipe with 2-3/4" ID that are adjacent to bellows (whose impedance has already been considered). The impedance of the transition is given by eq. (23) as  $|Z_n/n| = 7.08 \text{ m}\Omega$ . Multiplying by 13 gives  $|Z_n/n| = 92 \text{ m}\Omega$ .

The total estimated reduced longitudinal broadband impedance from flanges and transitions from 2-7/8" ID to 2-3/4" ID pipes is  $|Z_n/n| = 0.53 \Omega$ .

The planned upgrade of the vacuum chamber in long-straight-section 4 will modify the number of flanges joining round vacuum pipes with 2-7/8" ID from 112 to 106. The number of flanges that join a pipe with 2-7/8" ID to a pipe with 2-3/4" ID will be modified from 43 to 51. As a result, the estimated impedance from flanges and transitions from 2-7/8" ID to 2-3/4" ID pipes will be modified to  $|Z_n/n| = 0.59 \Omega$ .

#### 14. Sector valves

During ring operation, the ring's 11 sector valves are open, in which case the round vacuum pipe with radius  $b = 1.4375''$  is enlarged to a square pipe with  $4-1/8''$  side over an axial distance of  $g = 7/8''$ . To underestimate the impedance, we consider a single bellow corrugation where the corrugation is round with diameter equaling  $4-1/8''$ . From eq. (4), the underestimated reduced longitudinal broadband impedance of a sector valve is  $|Z_n/n| = 0.034 \Omega$ . To overestimate the impedance, we consider a single bellow corrugation where the corrugation is round with diameter equaling the diagonal of the square pipe:  $2^{1/2} \times 4-1/8''$ . From eq. (4), the overestimated reduced longitudinal broadband impedance of a sector valve is  $|Z_n/n| = 0.067 \Omega$ . Taking the average of the underestimate and overestimate gives a rough estimate of the impedance as  $0.0505$  ohms/valve.

Multiplying by 11 gives the total estimated impedance from sector valves:  $|Z_n/n| = 0.56 \Omega$ . This impedance may be greatly reduced by using sector valves whose open position is a round pipe of constant radius.

#### 15. Space charge

For an ultrarelativistic round beam of radius  $a$  in a round vacuum pipe of radius  $b$ , the reduced broadband impedance from space charge obeys [1]

$$|Z_n/n| = \frac{Z_0}{2\gamma^2} \left[ 1 + 2 \ln \left( \frac{b}{a} \right) \right], \quad (28)$$

where  $\gamma$  is the relativistic factor. Using  $\gamma = 1567$  to represent an 800-MeV beam and  $a = 100 \mu\text{m}$  to approximate the Aladdin beam size gives, for  $b = 35 \text{ mm}$ ,  $|Z_n/n| = 1 \text{ m}\Omega$ .

#### 16. Additional discrete elements

In addition to the impedance sources considered above, several other items are expected to contribute to the impedance. These include a few irregular bellows, a unique BPM in LSS4 whose removal is planned, two retractable scrapers, a DC current transformer and coherent synchrotron radiation. The neglected discrete elements are small in number, the DC current transformer was designed for negligible impedance, while the relatively long bunch length should minimize effects of coherent synchrotron radiation. Hopefully, the impedance sources that we evaluated constitute most of the ring's broadband impedance.

#### 17. Summary

The estimated sources of impedance are summarized in Table II. The major contributors to the estimated impedance are the RF cavities, BPMs, bellows, sector valves, flanges and the associated round-

pipe diameter transitions, and the Q electrode. The estimated reduced impedance from the RF cavities is  $|Z_n/n| = 5.8 \Omega$ , while the reduced impedance of the vacuum chamber is estimated to be  $5.7 \Omega$ . The total estimated reduced impedance is  $|Z_n/n| = 11.5 \Omega$ . This value is comparable to values of  $12 \Omega$  and  $13 \Omega$  obtained from measurements when the ring had a different fundamental RF cavity and no harmonic cavity [23], and a value of  $10 \Omega$  estimated from recent measurements of energy spread as a function of single-bunch current [24].

We considered replacement of each dipole vacuum chamber by a chamber connected to an antechamber by a slot. The performance of the infrared beamline and undulator beamlines should be maintained if the slot height is approximately 24 mm. To isolate the beam from the antechamber, the slot width should exceed its 24-mm height. In this case, the estimated impedance of the new chambers is slightly less than that of the existing chambers. The reduced ring impedance  $|Z_n/n|$  may be decreased by  $0.5 \Omega$  if the large formed bellows attached to the dipole vacuum chambers are shielded or shortened when new dipole vacuum chambers are installed. This impedance reduction may improve ring performance at high ring currents, where increased beam dimensions attributed to the microwave instability are observed.

The microwave instability is driven by the broadband impedance's value at frequencies exceeding the inverse bunch length. These frequencies exceed the resonant frequencies of the RF cavities' fundamental modes and many of the HOMs considered, so that the RF modes will primarily contribute capacitive impedance much smaller than their reduced broadband (inductive) impedance. Consequently, we expect that the microwave instability will be excited mainly by the broadband impedance from the vacuum chamber, without inclusion of the RF modes. Our estimate of this impedance is  $5.7 \Omega$ .

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**Table I. RF modes computed by URMEL**

Fundamental cavity: frequency $f$ [MHz]	$R$ [k $\Omega$ ]	$Q$	$\omega_0 R / (2\pi f Q)$ [ $\Omega$ ]
50.3219	905.3	14113	4.305
233.621	112.0	24389	0.0664
375.270	188.2	24418	0.0694
457.069	19.53	33766	0.00427
487.265	31.80	27802	0.00793
568.290	351.6	28975	0.0721
640.264	362.0	25529	0.0748
673.988	46.29	33807	0.00686
766.287	50.85	36555	0.00613
862.202	9.737	34697	0.00110
883.901	46.74	43134	0.00414
922.512	175.3	38809	0.0165
939.310	70.18	41082	0.00614
996.650	274.1	38025	0.0244
1048.78	5.588	35559	0.000506
Harmonic cavity: frequency $f$ [MHz]	$R$ [k $\Omega$ ]	$Q$	$\omega_0 R / (2\pi f Q)$ [ $\Omega$ ]
202.608	1365	22576	1.008
727.336	1.823	28059	0.0003019
798.648	247.9	33562	0.03124
1059.97	186.0	28240	0.02099
1421.19	385.3	39266	0.02333
1458.29	17.13	38851	0.001021
1578.45	165.1	38682	0.009135
1642.17	0.649	32680	0.00004088
1901.40	272.6	43008	0.01126
2110.58	19.85	37476	0.0008478
2201.94	1.157	52153	0.00003404
2239.05	39.68	52687	0.001136
2310.51	6.910	39348	0.000257
2427.08	85.77	50908	0.002345
2653.84	15.77	42537	0.0004720

**Table II. Estimated impedance of ring components**

<b>Ring element(s)</b>	<b><math> Z_n/n </math> [ohms]</b>
Fundamental RF cavity's fundamental mode	4.31
Harmonic RF cavity's fundamental mode	1.01
RF cavities' higher order modes (HOMs)	0.46
Bellows	1.12
BPMs	2.24
Q electrode	0.40
Transitions to insertion-device chambers	0.043
Resistive wall effective impedance	0.37
Existing dipole vacuum chambers	0.047
Pumping holes and slots in straight sections	0.17
Injection region	0.14
Kickers	0.083
Flanges and round pipe diameter transitions	0.53
Sector valves	0.56
Space charge	0.001
<b>Total:</b>	<b>11.5</b>
<b>Total without RF cavity modes:</b>	<b>5.7</b>

## Appendix A. URMEL input file for fundamental RF cavity

```
$FILE ITEST=0, LPLO=.T., LSAV=.F. $END
PROTOTYPE ACTUAL DIMENSIONS 3 IN GAP 27-NOV-1989
$BOUN IZL=1, IZR=1 $END
$MESH NPMAX=5000, NRMAX=301, NZMAX=301 $END
#CAVITYSHAPE
0.00
0.0 0.
.0365 0.
.0365 .075
.4412 .075
.4412 .7080
-1 -.16981 ! should be -.1698
.1016 .7080
.1016 .2020
.2349 .2020
-1 .02541 ! should be .0254
.2349 .1512
.0465 .1512
-1 .01001 ! should be .01
.0365 .1612
.0365 .9
0. .9
0. 0.
9999. 9999.
$MODE MROT=0, NMODE=15, PRLIM=1.0D-40, FLOW=0.0, FUP=1.0D+3,
NMAX=1000, NCLOSE=2, NCL=2, NNNORM=5, NRNDM=1, DVLIM=.03,
RKAPPA=2.63D+7, BETAZ=1., RWAKZ=0.,
PFRAC=.5 $END
$PLOT LHDCOP=.T. LCAVUS=.F. $END
$PRIN LPLE=.F. LPLH=.F. LDEL=.F. LDMAG=.F. LTRANS=.F.
MODPR=15 LPOWER=.F. LMATPR=.F. $END
```

## Appendix B. URMEL input file for fourth harmonic RF cavity.

```
$FILE ITEST=0, LPLO=.T., LSAV=.F. $END
HARMONIC CAVITY OF SRC-137 TECHNOTE
$BOUN IZL=1, IZR=1 $END
$MESH NPMAX=5000, NRMAX=301, NZMAX=301 $END
#CAVITYSHAPE
0.00
0.0 0.
.0365 0.
.0365 .0898
-1 .0102
.0467 .10
.3048 .10
.3048 .28034
-1 -.0254
.2794 .30574
.12446 .30574
-1 -.0254
.09906 .28034
.09906 .15334
-1 .01016
.0889 .14318
.04666 .14318
-1 .01016
.0365 .15334
.0365 .35
0. .35
0. 0.
9999. 9999.
$MODE MROT=0, NMODE=15, PRLIM=5.0D-40, FLOW=0.0, FUP=3.20D+3,
      NMAX=1000, NCLOSE=2, NCL=2, NNNORM=5, NRNDM=1, DVLIM=.03,
      BETAZ=1., RWAKZ=0.,
      PFRAC=.5 $END
$PLOT LHDCOP=.T. LCAVUS=.F. $END
$PRIN LPLE=.F. LPLH=.F. LDEL=.F. LDMAG=.F. LTRANS=.F.
      MODPR=15 LPOWER=.F. LMATPR=.F. $END
```