Design of a higher harmonic RF system for the Advanced Light Source ⋆

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Abstract

We report on the design and fabrication of a third harmonic radiofrequency (RF) system for the Advanced Light Source (ALS) to be used for lengthening the bunch and increasing the Touschek–dominated beam lifetime. We plan to install five single–cell 1.5 GHz copper RF cavities in one–half of an ALS straight section with a predicted increase in the lifetime by a factor of 3. Each RF cell is designed to sustain a maximum voltage of 125 kV with a power dissipation of 5 kW. We present measurements made on an aluminum cavity model characterizing the RF properties of cavity such as the cavity R/Q and higher order modes (HOMs). In particular, resonances in the cavity tuners were studied in order to avoid heating of the tuner bellows. Initial measurements of the copper cavities indicate a Q value of 21000, resulting in a shunt impedance is 1.69 $M\Omega$ per cell.

Keywords: Storage rings; Radiofrequency cavities; Touschek lifetime; Coupled bunch instabilities;

1 Introduction

In low to medium energy storage ring light sources, the beam lifetime is usually dominated by large–angle intrabeam (Touschek) scattering in which elastic collisions of electrons within the bunch have a finite probability of transferring

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enough longitudinal momentum to each electron such that they no longer are within the momentum acceptance of the storage ring and are lost. This process is particularly important for storage rings such as the Advanced Light Source (ALS) because of the high density of electrons resulting from the small transverse beam size. One method for increasing the lifetime from Touschek effect without compromising the transverse beam brightness or increasing the beam energy spread is to reduce the peak longitudinal charge density of an electron bunch by stretching the bunch using a secondary RF system.

Consider the voltage seen by the bunch generated by the main RF system as shown in Fig. 1. Near the bunch center, the restoring force of the RF voltage is approximately linear. Given a gaussian energy spread, the resulting longitudinal distribution is also gaussian. If another voltage is added to the main RF voltage with an amplitude and phase such that the slope at the bunch center is zero, the energy distribution is unaffected but the bunch lengthens and the peak charge density decreases and the lifetime improves. To achieve cancellation on every RF cycle for every bunch, the frequency of the secondary voltage must be a higher harmonic of the main RF voltage. For a harmonic n, the harmonic voltage required to cancel the slope of the main voltage is approximately V_{rf}/n.

A higher harmonic cavity has several other benefits to machine operation. When the phase of the harmonic voltage is adjusted such that the bunch lengthens, there is an increase in the spread of synchrotron frequencies within the bunch. This spread can help in damping coherent instabilities such as the longitudinal coupled bunch instabilities through an effect known as Landau damping. For this reason, harmonic cavities are sometimes called "Landau" cavities. Harmonic cavities have been used in a number of storage rings, either for lifetime improvement, curing beam instabilities, or both[1–5].

The primary aim of the harmonic system at the ALS is to increase the Touschek-dominated lifetime, currently at a value of several hours, depending on the beam energy and emittance coupling, by a factor of three. A secondary benefit would be additional control of longitudinal coupled bunch instabilites, which are currently damped by a feedback system. Furthermore, lengthening of the bunch will reduce higher order mode heating of all vacuum chamber components, improving stability in general. A more detailed discussion of the beam dynamics with the harmonic system is given in ref.[6].

This paper presents the design of the harmonic RF system for the Advanced Light Source (ALS), an electron storage ring optimized for high brightness synchrotron radiation. Additional details on the design can be found elsewhere[7–9]. Several general ALS parameters are listed in Table 1. The ALS is operated at 1.9 GeV about 2/3 of the time and the rest at 1.5 GeV. A discussion of the requirements of a harmonic RF system is given in Section II. The RF and mechanical design of the ALS harmonic cavities is given in Section III. Measurements characterizing an aluminum model of the RF structure as well as initial measurements of the copper cavities are discussed in Section IV. Conclusions are given in Section V.

2 Harmonic cavity requirements

The total voltage seen by the beam is given by

$$V(z) = V_{rf}\left[\sin\left(\frac{\omega_{rf}}{c}z+\phi_s\right)+k\sin(n(\frac{\omega_{rf}}{c}z+\phi_h))\right] \tag{1}$$

where the longitudinal coordinate z is taken from the position of the synchronous particle. V_{rf} is the main RF voltage, n is the harmonic relative to the RF frequency, and k is the fraction of the harmonic to main RF voltage. To maximize the lengthening from a harmonic voltage without generating multiple stable points in the RF bucket, the phase and amplitude of the harmonic voltage are adjusted to zero both the first and second derivatives of the total voltage[2,10]. This yields the condition on the harmonic voltage

$$k = \sqrt{\frac{1}{n^2} - \frac{(U_0/V_{rf})^2}{n^2 - 1}} \tag{2}$$

and

$$\sin n\phi_h = \frac{-U_0/V_{rf}}{n^2-1} \tag{3}$$

The synchronous phase angle, ϕ_s, is given by

$$\sin\phi_s = \frac{n^2}{n^2 - 1}\frac{U_0}{V_{rf}}. \tag{4}$$

The calculated bunch distributions for the main RF voltage and with the harmonic voltage adjusted according to Eqs. 2 and 3 are shown in Fig. 2. Note that these conditions do not necessarily optimize the Touschek lifetime. If the harmonic voltage shown in Fig. 1 were phased such that the slopes of the main and harmonic voltages added rather than cancelled, the bunch would be shortened. This mode of operation may be of interest to some users where lifetime is a secondary concern.

The choice of harmonic number is made primarily from space considerations. At the ALS, our main constraints are that the system occupy as little space as possible and the minimum aperture be no less than 40 mm to maintain the beam stay clear. For the main RF frequency for the ALS of 500 MHz, it is impractical to choose a harmonic greater than 4 due to the relative size of the cavity to beam pipe. The second harmonic gives a greater lengthening due to a longer flat region. However, the total voltage required is only half the main voltage, and the cavities are only half the size of the main RF cells. For these reasons we settled on the third harmonic at 1.5 GHz. Both Max–II[4] and the Synchrotron Radiation Research Center[5] have installed third harmonic systems at that frequency.

The principle of passive operation of the cavities is as follows. Consider the interaction of the 1.5 GHz component of the beam current with the cavity impedance as shown in Fig. 3. The horizontal scale is shown as a frequency difference from $3\times f_{rf}$ (1.5 GHz). If the cavity is tuned to give the correct phase as shown in the figure, either the beam current or the cavity shunt impedance must be adjusted to the give the optimum voltage. For a fixed cavity Q, it is clear that the optimum conditions can be met at only a single beam current when the cavity is excited in passive mode. The shunt impedance required to reach the bunch flattening condition at a given beam current is given by

$$\begin{aligned} R_{s,opt} &= \frac{kV_{rf}}{2I_{DC}}\left(\cos^4\psi_h + \sin^2\psi_h\cos^2\psi_h\right)^{-1/2} \\ &\approx \frac{V_{rf}\tan\psi_h}{2I_{DC}n} \end{aligned} \tag{5}$$

where

$$\psi_h = \frac{\pi}{2} + n\phi_h \tag{6}$$

is the tuning angle of the harmonic cavity, given by

$$\tan\psi_h = 2Q\frac{\omega_{rh} - n\omega_{rf}}{\omega_{rh}} \tag{7}$$

where ω_{rh} is the harmonic cavity resonant frequency. For bunch lengthening, the harmonic cavity is always operated at positive tuning angle and the main RF is at negative tuning angle to compensate for reactive beam loading. This is discussed in more detail in ref. [6].

We have designed our harmonic RF system to achieve the stretching condition described above at the maximum current of 400 mA for the range of operating conditions listed in Table 2.

3 Cavity design

Our harmonic cavity design was constrained by several requirements. The total impedance of the cavities must be sufficient to reach the optimum stretching condition as discussed above. The cavity must be compatible with active operation, requiring at least one azimuthal port. The cavity higher order modes (HOMs) must be sufficiently damped or tuneable such that the existing multi-bunch feedback systems can control the resulting instabilities. Finally, the cavity design must be simple enough to allow rapid fabrication but sophisticated enough to allow for high power operation. This section describes the RF and mechanical design of the cavity as well as the fabrication process.

A cross-sectional view of the cavity is shown in Fig. 4. The cavity shape is based on a conventional re-entrant profile but because of the high frequency and the large beam stay clear required, the beam-pipe diameter is a significant fraction of the cavity diameter, leading to some loss in shunt impedance. The use of nose cones and careful optimization of the cavity shape to maximize the shunt impedance result in a useful improvement over pill-box or bell-shaped designs with the same bore. This also minimizes the number of cavities required and the power dissipated per cavity. The parameters of the cavity are listed in Table 3. The center of the cavity body is made to be a section of a sphere, as illustrated in Fig. 5, rather than the more common toroid, which greatly simplifies the machining of the port penetrations, which can be lathe turned rather than milled [7].

The nosecone radius is chosen to keep the electric field enhancement to a reasonable level of 5.3 times the effective accelerating field and the peak field of 8.3 MV/m is well below the Kilpatric level of 34 MV/m at 1.5 GHz. The wall power density is within reasonable limits for 5 kW total dissipation (125 kV). There is about a factor of two increase in the power density where the wall current is concentrated around the port openings.

The design of the harmonic cavities employs many technologies developed for the 476 MHz PEP-II RF cavities[11], allowing rapid development of a robust design using tried and tested construction methods. The new spherical geometry allows the use of simple round ports and many common parts. This and other simplifications allowed the elimination of many parts and manufacturing steps to minimize the overall cost and fabrication time. There are six openings on the cavity: two beam ports in the end caps and four ports in the spherical body section (two tuner ports, pick-up port and a coupling port). All of these except the coupling port are the same diameter. The coupling port is slightly larger but the manufacturing processes are similar. All of the ports and their interfaces with the body are simple figures of revolution and can be turned in a lathe. The inside and outside contours of the cavity can also be turned, with internal access through one of the end openings. The cooling passages were N.C. milled, like the PEP-II cavities, but with much simpler programming. The cavity body was made from OFE high conductivity copper except for the plating over the water passages which uses the so-called “brightened” copper, which has additives to improve the plating process, see Fig. 4.

The center section of the body including the four round ports on the equator has been machined from a solid billet of copper. This eliminates a number of joints and machining operations compared to an assembly fabricated from separate parts. The end caps have been machined from plate stock and are identical parts through most of the fabrication processes. Approximately 2 mm of stock were left on all interior surfaces for the finish operations. The water passages are milled on the outside of all three parts. One end cap is then joined by e-beam welding to the body, which also has some excess material. After the weld the inner contour of the cavity is turned through the remaining opening to a finish of 0.6 μ Ra or better. The other end cap is then put in place, the frequency is measured, and a final tuning cut can be made on the nose if necessary. Once the frequency is correct the second end cap is e-beam welded in place. Any frequency change from the final weld can be taken out by the tuner.

The beam-port extensions are e-beam welded to the end caps and the body is leak-checked. The body assembly is then sealed for the plating process. Plating wax is cast into the cooling channels and the surface is made conducting with silver powder and activated. A thick jacket of plated copper is grown over all of the channels in one operation. By using a brightened copper plating it is possible to eliminate the intermediate turning stage necessary for the pure copper jacket used on the PEP-II cavities. The separate brazed water channel covers used on the port assemblies of the PEP-II cavities can also be eliminated, reducing the number of parts and processes. Once plating is completed the wax is melted and flushed out of the channels. The e-beam joints are treated the same as the water channels. The passages are hydrostatically tested to 150 psi (1 MPa). The flanges are then attached by e-beam welding. These are standard stainless steel circular knife-edge flanges with copper inserts. The final process is to clean the inside of the cavity using a mild chromic acid bright dip. This removes any residue from the e-beam welding that may have condensed on the inside surface and improves the surface finish to 0.4 μ Ra or better. The cavity is then blanked off, leak-checked and backfilled with dry nitrogen at atmospheric pressure for shipping.

We are including two simple piston type tuners for tuning the fundamental mode (bottom port) and HOMs (side port). Both are adjusted using a commercial stepper-motor driven actuator. The fundamental tuner will be controlled by a feedback loop which will be used to maintain a constant voltage in each cell as the beam current decays. The tuner plug dimensions are chosen so that the fundamental mode can be tuned from $\pm 1.5\times$rotation frequency around 1.5 GHz, corresponding to ~ 4.5 MHz range. The smallest tuner step size gives a tuning sensitivity of less than 2 kHz which we estimate will allow us to come to within 1% of the optimum lifetime. The piston is water cooled along the length of the tuner. Furthermore, the dimensions of the tuner/bellows structure have been carefully chosen to avoid harmful resonances that may cause heating of the bellows. In this way, we can avoid the mechanical complication of sliding contacts in the tuner. This is discussed further in the next section.

The cavity will be initially operated in passive mode without an RF window, with the top flange flange blanked off. Future options include attaching an input waveguide with an adjustable matching stub and external load which will allow adjustment of the cavity Q, allowing the ideal cavity amplitude and phase to be maintained for a wide range of beam currents. The window and coupler have been designed to be compatible with an active (powered) system if such an upgrade is desirable in the future. Because of the large beam-pipe diameter there are relatively few HOMs trapped in the cavity below cut-off. The trapped modes are listed in Table 4 and are discussed in more detail in the next section.

The harmonic cavities will be installed in part of one of the straight sections of the ALS, close to the existing RF system, occupying about half of the straight section. This will simplify cabling, interlocks, water and controls which may be shared between the two systems. The harmonic cavities are pre-assembled and aligned on a support raft along with tuners, couplers, pumps, masks etc., and have been baked out before installation. This should allow the assembly to be installed during a short shutdown, and to be commissioned expeditiously.

4 Cavity measurements

During early stages of the cavity fabrication, we constructed an aluminum model of the cavity which was primarily used to test the machining process. We have used this model to characterize the several aspects of the cavity performace such as the frequency and R/Q of the fundamental mode and HOMs, as well as their frequency shift with tuner position. Because we wished to avoid the mechanical complication of sliding RF contacts (i.e. spring fingers) in the tuner, we also used the model to study and identify resonances in the tuner/bellows assembly. A MAFIA computer model of the cavity and tuner was useful to help identify HOMs and tuner resonances. All of the results described below were checked with the model. We also report initial measurements of the copper cavities received following fabrication.

4.1 Cavity resonances

The cavity and tuner was designed such that the cavity was tuned to 1.499 GHz ($3\times f_{rf}$) with the tuner flush with the inner surface of the cavity. Our first measurements verified that the model frequency fell within a few MHz of the nominal frequency with a Q of 11000. All of the cavity monopole and dipole modes up to cutoff are listed in Table 4. Both the measured and MAFIA resonant frequency and Q are given. We expect the Q in the copper structures to be about a factor of two larger than in the model. The MAFIA mode designation is also listed in the last column.

The measured dependence of the fundamental frequency with tuner position is between 320 and 400 kHz/mm in the range from flush position to 6 mm into the cavity, in good agreement with MAFIA calculations. The expected tuning range over a fill is about a millimeter. We also measured the R/Q of several of the stronger cavity monopole modes using a dielectric bead technique, described in ref. [12]. An example of a measurement of the fundamental and the first monopole HOM is shown in Fig. 6a and is in good agreement with the MAFIA calculation.

Several of the cavity HOMs are capable of exciting both transverse and longitudinal coupled bunch instabilities, particularly the monopole mode at 2.3 GHz and the dipole modes at 1.95 and 2.33 GHz. Our strategy for maintaining beam stability is to use the combination of the existing longitudinal and transverse multibunch feedback systems, and appropriate tuning of the HOM frequencies using the two tuners. Thus we have carefully identified and characterized the HOM frequencies and tuner dependencies using rotateable probes in combination with MAFIA field maps. Given the measured Q values and nominal damping time of the feedback system of less than half a millisecond, we believe this will not require additional damping of the HOMs.

Initial measurements of the copper cavities were made prior to their installation. We verified the fundamental frequency and adjusted the coupling of the signal probe. Measurements of the Q give and average value of 21000 for the five cavities. Unfortunately, time did not permit a detailed measurement of the HOM Qs. This will be done following completion of the spare sixth cell.

4.2 Tuner resonances

Past experience with piston-type tuners has shown that many designs suffer from coupling of cavity field into the bellows at certain tuner positions, resulting in either heating, sparking, multipacting, and general damage to the tuner/bellows assembly. For this reason, most designs include sliding RF contacts near the tuner tip to short any resonances in the structure. However, these designs have their own difficulties. In our effort to avoid this, we have experimentally and numerically studied the modes in the coaxial resonator formed by the tuner/bellows and adjusted the length of the tuner such that none of the resonances coincides with either a cavity resonance or a multiple of the 500 MHz component of the beam current over the normal operating range of the tuner. As there is no straightforward method for determining a threshold below which any power coupled to the bellows is of concern, we decided to try to avoid any interaction between those resonances and the beam as much as possible. With this, we hope to passively avoid bellows heating.

A mechanical drawing of the tuner/bellows assembly is shown in the top of Fig. 7. To search for tuner resonances, we inserted two small RF probes at the base of a spare tuner actuator and measured the transmission between the two probes and also between one of these and another in the cavity beam pipe. The modes were identified using a crude MAFIA model of the bellows. The tuner resonances that could be measured and identified are shown in bottom of Fig. 7. The MAFIA calculations showed that the frequency of resonances with field concentration in the volume near the bellows convolutions were dependent on the length of the bellows. We used this to adjust the total length of the bellows by adding a spacer as indicated in Fig. 7 such as to avoid dangerous resonances. The design still accommodates the addition of RF sliding contacts if needed.

5 Conclusions

We expect about a factor of 3 increase in the Touschek lifetime at the maximum current in multibunch mode from the use of a third harmonic RF system in the ALS. We plan to install five 1.5 GHz copper single-cell cavities to be operated in passive mode with the option to upgrade to active mode. The cavities have been designed and constructed and are currently awaiting an accelerator shutdown for installation. Our measurements of an aluminum model have confirmed the cavity design and have characterized the fundamental and HOM structure. Considerable effort has been made to avoid resonances in the tuner structure in order to avoid the mechanical complication of RF sliding contacts. Initial measurements of the copper cavities indicate Q values of 21000, yielding a shunt impedance of 1.7 $M\Omega$ per cell. Cavity commissioning is expected to begin in mid-June 1999.

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Table 1
Nominal ALS parameters.

Parameter	Description	
E	Beam energy	1.5–1.9 GeV
C	Circumference	196.8 m
f_{rf}	RF frequency	499.654 MHz
h	Harmonic number	328
α	momentum compaction	1.6e-3

Table 2
Effects of optimized harmonic voltage.

Parameter	Description		
E	Beam energy [GeV]	1.5	1.9
σ_ϵ	RMS $\delta E/E$	6.5e-4	8.1e-4
U_0	radiation loss/turn[keV]	130	350
V_{RF}	main RF voltage[MV]	1.1	1.1
Q_s	Synchrotron tune	0.0078	0.0068
σ_ℓ	RMS bunch length[mm]	4.2	6.0
V_{harm}	harm. RF voltage[MV]	0.36	0.35
$\sigma_{\ell h}$	RMS bunch length w/HHC [mm]	15.6	19.3
	optimum lifetime increase	3.5	2.9
$R_{s,min}$	min. optimum R_s at 0.4 A [MΩ]	9.86	3.56

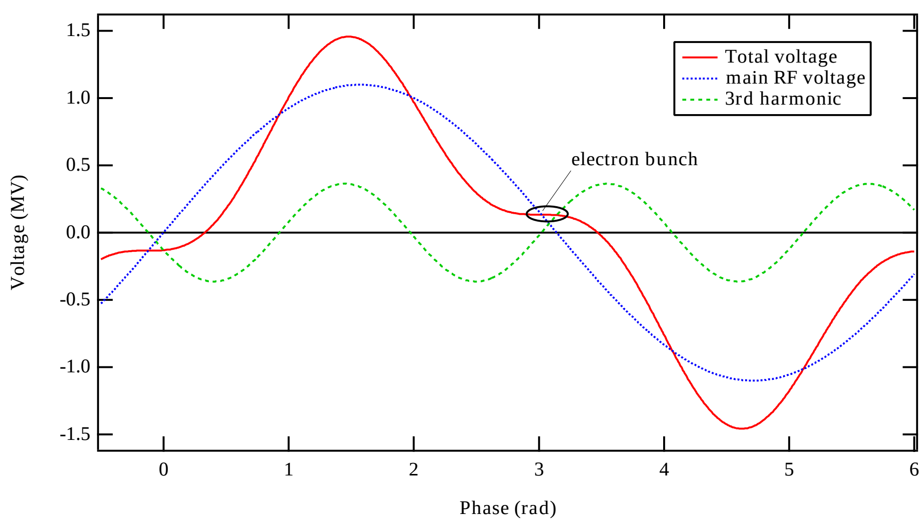

Fig. 1. RF voltage seen by the bunch for main RF and higher harmonic cavity.

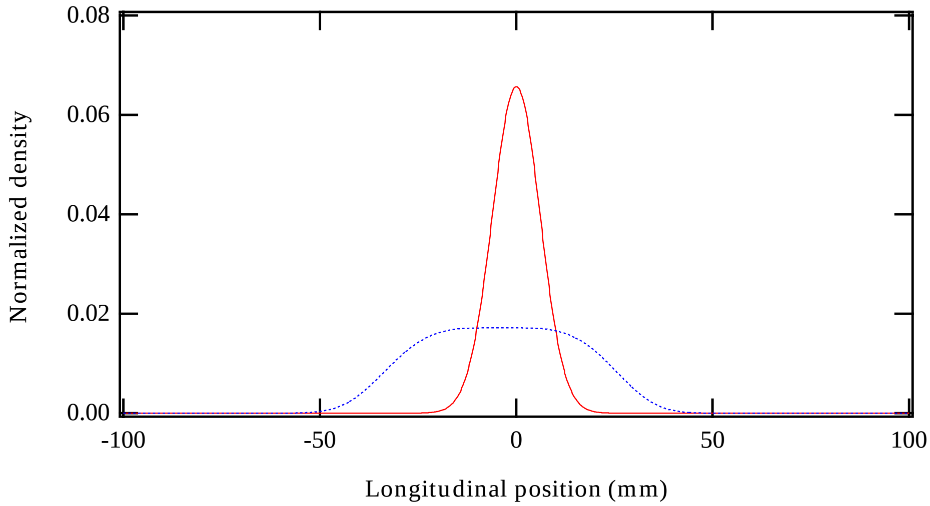

Fig. 2. Longitudinal distribution with and without optimized harmonic voltage.

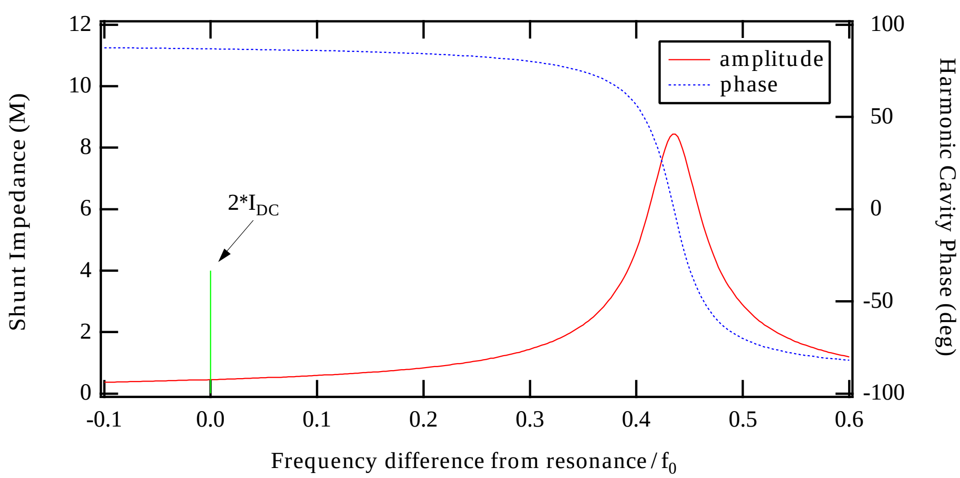

Fig. 3. Tuning of passive harmonic cavity for bunch lengthening.

Table 3
ALS harmonic cavity parameters. Both the theoretical and measured values are given. Shunt impedance is defined by $P = V^2/2R_s$.

Frequency	1.499 GHz
maximum voltage/cell	125 kV
bore diameter	5 cm
R/Q	80.4
calc. Q	27677
calc. R_s	2.23 MΩ
meas Q	21000
meas R_s	1.69 MΩ
number of cells	5
power per cell	4.6 kW

Table 4
Monopole and dipole modes in the aluminum cavity model. The TM_{01} cutoff is 4.59 GHz and the TE_{11} is 3.514 GHz.

Mode	F_{meas} (GHz)	F_{calc} (GHz)	Q_{meas}	Q_{calc}	$R/Q_{calc}(\Omega)$	$R_s(M\Omega)$
monopole modes						
0-E-1	1.4964	1.4912	11900	27336	80.6	0.959
0-M-1	2.319	2.295	3100	23517	36.8	0.114
0-E-2	3.156	3.135	4000	24704	1.01	0.004
dipole modes						$R_s(M\Omega/m)$
1-M-1v	1.94	1.948	6000	11681	37.3	8.813
1-M-1h	1.915	1.915	5200	26471	1.4	0.290
1-E-1v	2.27	2.272	3500	26714	0.37	0.044
1-E-1h	2.336	2.334	6000	18492	10.3	2.021
1-M-2v	2.915	2.918	1000	22258	13	0.341
1-M-2h	2.926	2.921	5400	24441	0.24	0.034
1-E-2v	3.249	3.274	2000	34852	0.24	0.011
1-E-2h	3.244	3.27	2700	43784	0.015	0.001

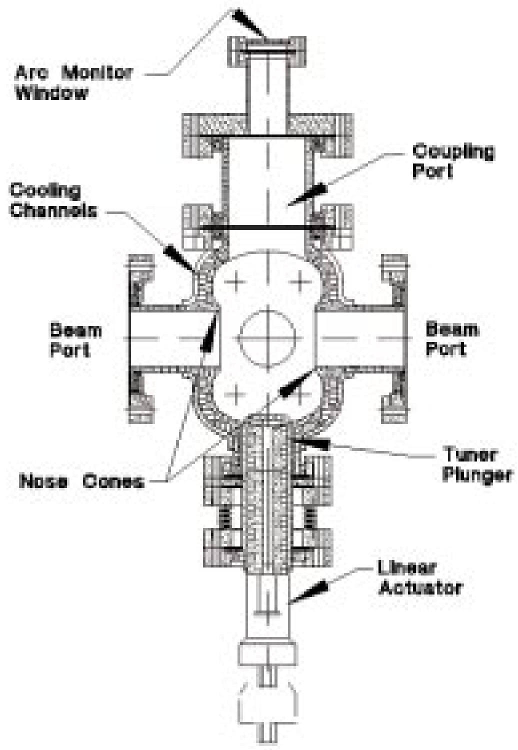

Fig. 4. Cross section of the 1.5 GHz harmonic cavity.

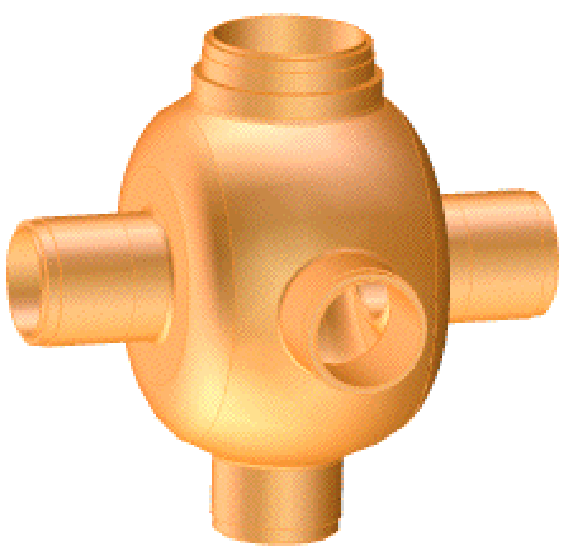

Fig. 5. Three dimensional model of the harmonic cavity.

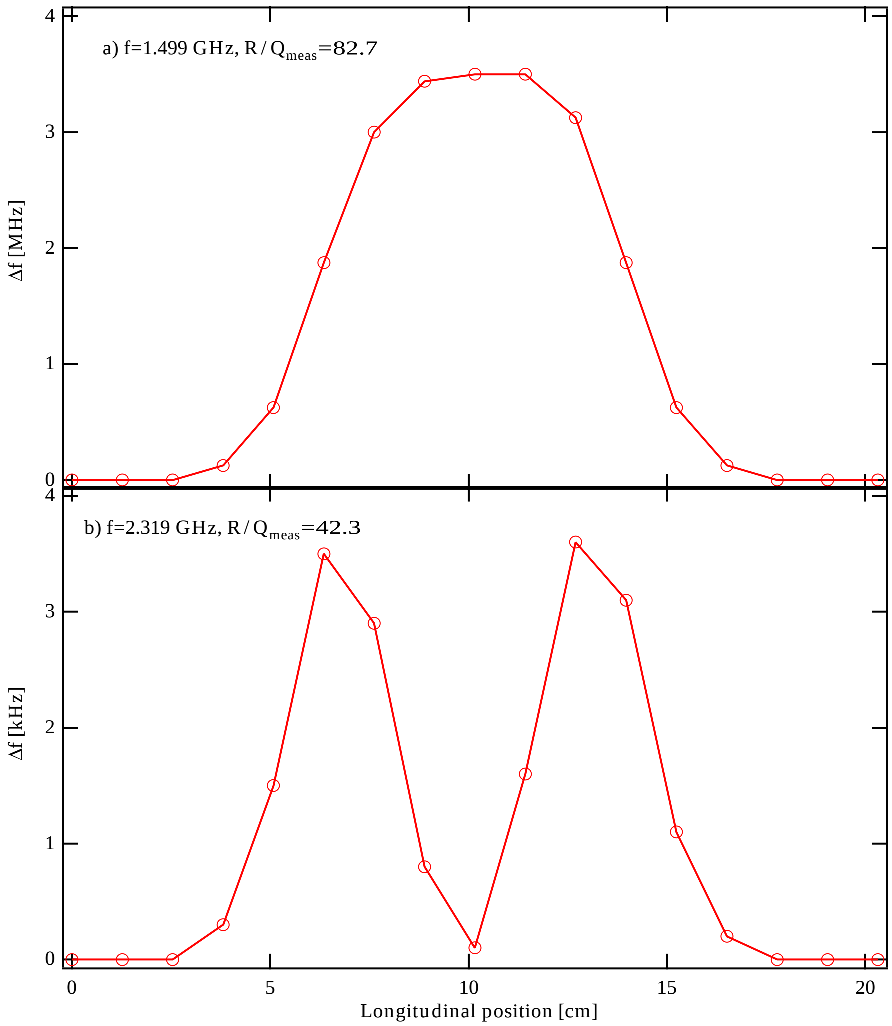

Fig. 6. Bead pull measurements of a) the fundamental mode and b) first monopole HOM.

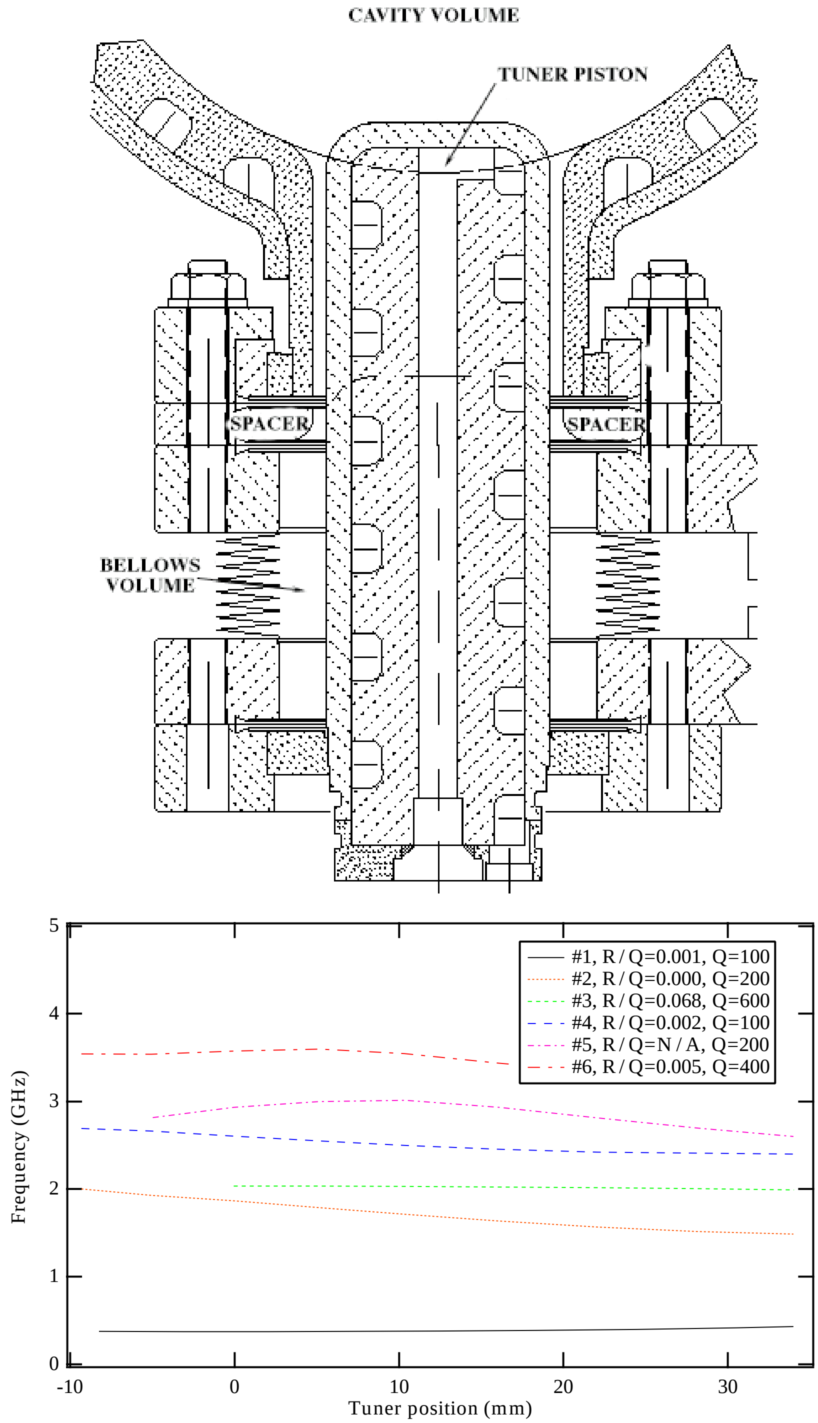

Fig. 7. Top) Mechanical drawing of the tuner bellows assembly. Bottom) Frequency dependence of the tuner resonances with tuner position with an 8.6 mm spacer added to the bellows assembly.