STATUS OF THE EUROPEAN HOM DAMPED NORMAL CONDUCTING CAVITY*

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Abstract

Cavities with Damped Higher Order Modes (HOMs) are an essential ingredient for state of the art storage ring based high brilliance synchrotron radiation (SR) sources to avoid degradation of the beam quality due to coupled bunch instabilities. Starting with a review of the concepts of existing HOM damped cavities the status of a normal conducting 500 MHz cavity is presented which has been developed for high brilliance SR sources within the frame of an EC funded collaboration. The results of numerical simulations and low power impedance measurements are reported together with conceptional improvements, expected performance, and first operational achievements in the Metrology Light Source in Berlin.

INTRODUCTION

The development of HOM damped cavities has been driven essentially by the requirements of high luminosity meson factories [1]. Only recently efforts have started to optimize such cavities also for the specific needs of SR sources. High brilliance photon beams are generated in 3rd generation SR sources by implementing many undulators in low emittance lattices leading to rings with a large number of cells and many magnets per cell which makes high brilliance rather expensive. To avoid brilliance reduction by coupled bunch oscillations (CBO) driven by cavity HOMs it is wise to adopt adequate counter-measures. With the use of HOM damped cavities it is possible to avoid (or at least minimize) the degrading effects of CBOs. Figure 1 shows a simulation of the bril liance degradation for the U49 undulator beam in BESSY II assuming a HOM induced increase in effective emittance and energy spread by a factor of 2 and 5 respectively. The reduction in brilliance is particularly strong for higher undulator harmonics which are increasingly used in modern SR facilities.

HOM DAMPED CAVITY CONCEPTS

The beam current thresholds for the excitation of coupled bunch instabilities are inversely proportional to the total HOM impedance $Z_{tot} = N_c\ (R/Q_0)_{HOM}\ Q_{ext}$. Thus we have to minimise the number of cavities (assumed to be identical), the R/Q_0 and the external Q of the HOMs. RF cavities have higher order modes up to very high frequencies. Above the cut- off frequency of the vacuum chamber (typically in the range of 3 GHz for SR sources) the HOMs are not trapped any more. They propagate down the vacuum chamber and are damped by the resistance of the chamber material. HOM damping is thus relevant in the frequency range from the first HOM above the fundamental mode to the vacuum chamber cut-off.

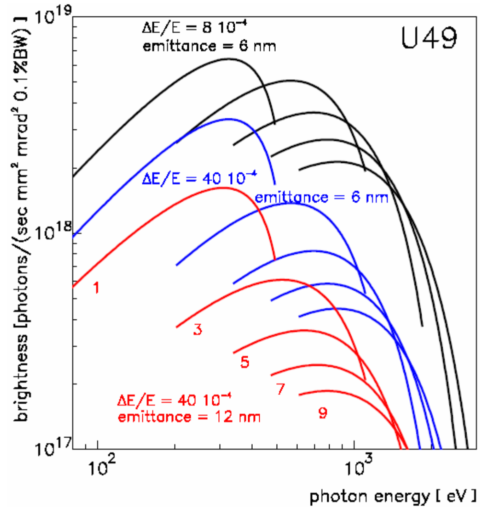

Figure 1: Spectral brilliance of the U49 undulator in BESSY II up to the 9th harmonic for different beam parameters (black: nominal parameters).

HOM energy can be coupled out of the cavity either by waveguide couplers or by the beam tubes (see Fig.2) making use of the high pass filter characteristic of waveguides. In both cases the cut-off frequency of the waveguide/beam tube must obey the condition $f_{rf} < f_{cutoff} < f_{HOM}$. Also a compromise must be found for the length of the waveguide/beam tube to allow the fundamental mode evanescent field to decay sufficiently before reaching the absorber. A minimum of three waveguides is necessary to couple to the different polarisations of dipole modes.

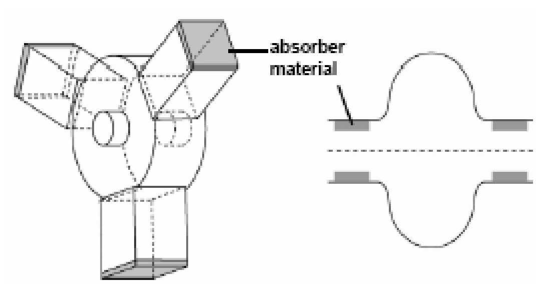

Figure 2: Concepts for HOM damped cavities.

NORMAL CONDUCTING CAVITIES

For the PEP II B factory a normal conducting HOM damped cavity has been designed. It has a spherical shape with nose cones optimized for a high impedance of the accelerating mode. Three rectangular waveguides are strategically placed on the cavity body to maximize

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coupling to the worst HOMs. Under typical operation conditions 103 kW are dissipated in the walls generating 850 kV of rf voltage. This gives a peak thermal surface power density of about 80 W/cm^2. The thermal layout is based on a power level of 150 kW leading to a complex hydraulical and mechanical design. The HOM loads are designed for a maximum power of 10 kW each using in vacuum AlN-40%SiC ceramics as absorber material. RF-power is fed into the cavity through a circular alumina vacuum window designed for 500 kW input power. Beam based measurements of the HOM damping characteristics are in agreement with numerical simulations of the HOM impedances as well as with bench measurements [2]. This cavity is also used for the SPEAR III SR facility.

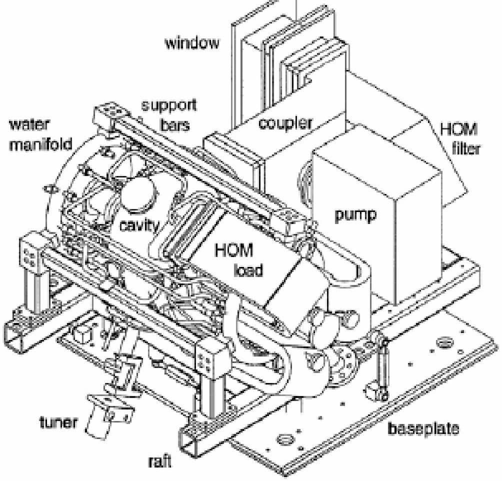

Figure 3: PEP II Cavity assembly.

For the ASP facility in Australia an attempt has been made to reduce the length of the KEK-PF cavity by increasing the beam pipe cut-off to f_{co}(TM01)=1.84 GHz [4]. With the help of 3 coaxial damping antenna the long. impedance below the beam pipe cut-off could be reduced below the critical impedance of the ASP ring.

At BINP/Novosibirsk HOM damped cavities have been developed for the VEPP2000 collider [5] and for the DUKE-FEL ring [6]. The 178 MHz DUKE cavity (Fig. 5) is made of copper clad stainless steel and HOMs are damped by a long cylindrical load connected to the cavity through a circular beam pipe of 700 mm diameter. The load consists of rf absorbing SiC cups which are bolted to the cooled copper wall.

For the KEK photon factory a 500 MHz cavity is in use where HOMs are damped via large diameter beam tubes and ring shaped SiC absorbers as shown in Fig. 4 [3]. To avoid coupling of the fundamental mode field with the absorber the total cavity length became rather large (1.4 m). Above the beam tube cut-off (f_{co}(TM01)=1.64 GHz) the long. impedance can be reduced to a level below 1 kΩ (see Fig. 4).

In Table 1 the essential performance parameters of most existing HOM damped storage ring cavities are summarised. For comparison also the superconducting SOLEIL cavity and the CESR-B cavity are included, the latter being used in several SR facilities.

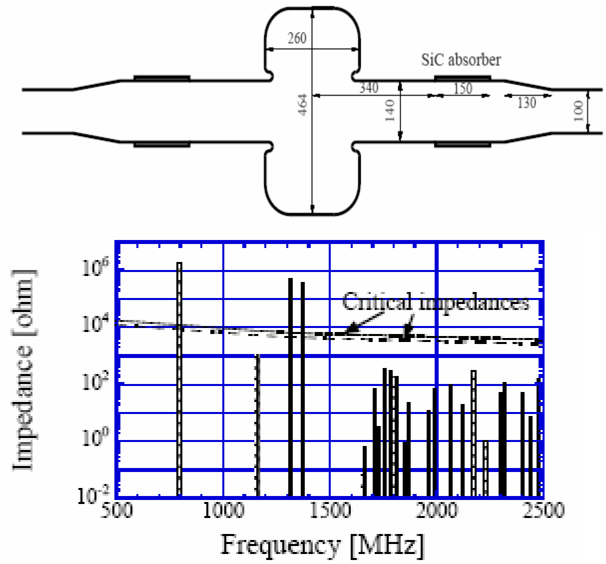

Figure 4: Top: KEK-PF cavity concept. Bottom: Longitudinal HOM impedances.

Below cut-off, however, the impedance of a few modes is still about 2 orders of magnitude above the critical impedance.

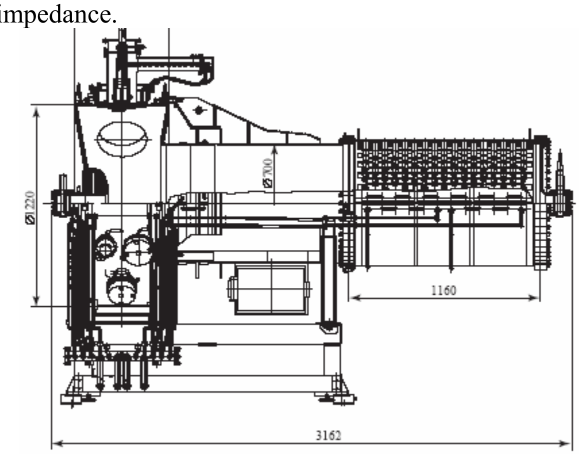

Figure 5: Cavity from BINP for the DUKE-FEL ring.

THE EC CAVITY PROJECT

In 3rd generation SR sources the straight sections are primarily foreseen for undulators, thus the length of the rf cavities should be small. As can be seen in Table 1 most of the existing cavities are longer than 1 meter, in part still with relatively large HOM impedances, and therefore not perfectly suited for SR sources. To provide an optimised cavity for the upgrade of existing medium and low energy 3rd generation SR sources a 500 MHz HOM damped cavity has been developed within the frame of an EC funded collaboration project by BESSY/ Germany, Daresbury Lab/England, DELTA/Germany, and Tsing Hua University/Taiwan starting in 2000.

The cavity has nose cones to improve the fundamental mode impedance and three circular damping waveguides equally spaced in azimuth by 120° (see Fig. 6). Circular waveguides offer considerable engineering advantages compared to rectangular waveguides as the joining of a

Table1: Performance parameters of HOM damped cavities ($R_s = V_{cy}^2/2P_{cy}$, L insertion length, R|| maximum longitudinal impedance, R⊥ maximum transverse impedance)

NC Cavities	f_0 MHz	V_{cy} kV	R_s MΩ	Q_0	P_{cy} kW	L m	f_{HOM} || MHz	R|| kΩ	f_{HOM} ⊥ MHz	R⊥ kΩ/m
PEP II [2]	476.	850.	3.8	32400	103.	~1.5	1295.	1.83	1420.[	144.
DAPHNE [7]	368.2	250.	2.	33000	16.	1.9	863.	259.	-	-
ARES [8]	509.	500.	1.75	118000	72.	~1.1	696.	1.35	989.	10.
VEPP2000	172.1	120.	0.23	8200	29.	0.95	246.0	0.4		<10.
DUKE-2 [6]	178.5	730	3.46	39000	77	3.16	-	-	-	-
KEK-PF [3]	500.	785	3.45	39500	90.	1.4	791.	1000.	792.	5100.
ASP/Toshiba	500.	750	3.8	40400	-	1.0	790.	25.	803.	8500.
BESSY	500.	780.	3.1	26700	100.	0.5	670.	1.6	1072.	54.
SC Cavities		V_{cy} MV	R_s/Q Ω							
CESR	500.	2.5	44.5	-	-	2.9	2253.	0.18	715.	32.
SOLEIL	352.	2.5	45.	-	-	3.65	699.	2.1	504.	49.

circular tube to a rotationally symmetrical cavity body is simpler. To reduce the waveguide diameter (f-cutoff = 615 MHz) two ridges are introduced. In the initial design the waveguides were tapered to provide a circular wave-guide to coaxial transition [9]. HOM energy is removed from the cavity via a broadband coaxial rf vacuum window and absorbed in a matched external load. This design avoids ferrites in vacuum and permits to sample the HOM power. The cavity was designed for a thermal power of 100 kW. The rf window is of DORIS type comparable with the PETRA window, which has been tested up to 250 kW.

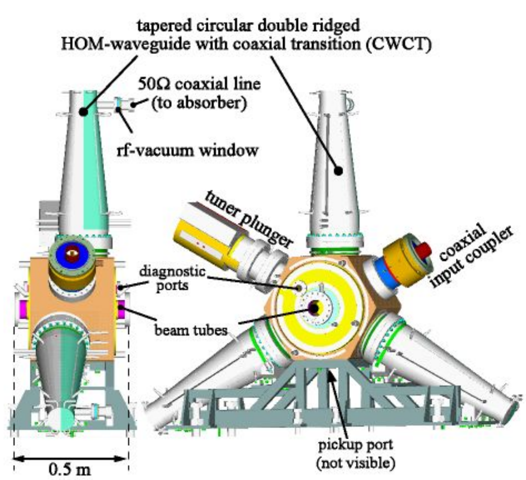

Figure 6: The 500 MHz HOM damped cavity.

A numerical method [2] has been used to evaluate the cavity impedance spectrum by the Fourier transform of the wake-field computed with the 3D time domain solver of the MAFIA code. The cavity geometry has been optimized for minimum HOM impedances by iteration of all relevant parameters.

LOW POWER MEASUREMENTS

The cavity impedances are plotted in Fig. 7, showing that for tapered waveguides the max. HOM impedances are in the range of 5 kΩ and 220 kΩ/m for the longitudinal and transverse case respectively in reasonable agreement with bead pull measurements [10]. Figure 7 also shows the calculated impedances for homogenous waveguides with constant cross-section which are significantly reduced down to the level of 2 kΩ and 60 kΩ/m respectively, assuming perfectly matched loads at the end of the waveguides. Simulations have shown that this reduction can be attributed to a stronger coupling of

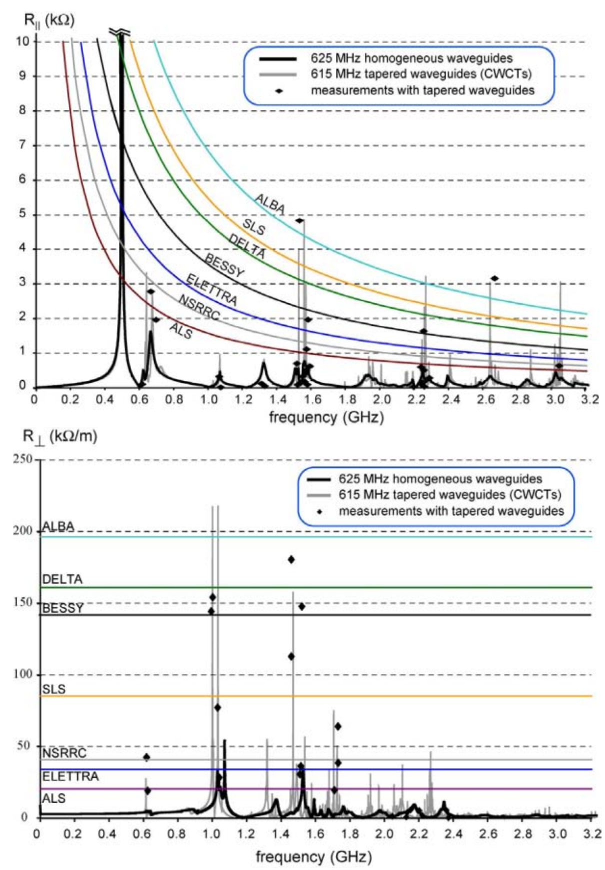

Figure7: Longitudinal (top) and transverse (bottom) impedance spectra and critical impedances for several rings.

the homogenous waveguides to the cavity HOMs as compared to the tapered ones. For comparison the critical impedances for the excitation of CBOs are also shown for several rings for their nominal operation parameters. It can be seen that with homogenous waveguides all considered machines can be operated without being affected by longitudinal multi-bunch oscillations and only a few rings may still be subject to transverse multi-bunch instabilities under these assumptions.

The prototype cavity has been installed in the DELTA ring at Dortmund University. Beam tests have demonstrated that no coupled bunch oscillations were exited by the residual HOM impedance [11].

To take advantage from the reduced HOM impedance achievable with homogenous waveguides, a damping waveguide with a cut-off at 625 MHz has been developed which terminates in a wedge shaped ferrite load (see Fig. 8). The load is designed for less than 20% reflection and a power level of 2.5 kW per waveguide. Details of the layout, the bonding technology of the ferrite on copper and a power test to check the quality of the bond are given in [12].

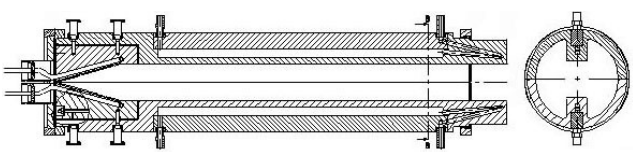

Figure 8: Homogenous ridged waveguide with 2 ferrite absorber elements on the left.

A cavity with ferrite loaded homogenous waveguides has been built and bead-pull measurements were performed to verify the HOM impedance characteristic. As a result (see Fig. 10) a transverse impedance limit < 60 kΩ/m could be confirmed as expected. The longitudinal impedance could be reduced generally below 2 kΩ except for the TM011 mode (680 MHz) where an unexpected high value of 10.8 kΩ has been measured. Simulations with MWS and GdfidL failed to predict this high value [13,14]. Therefore the cut-off frequency for the CELLS cavity was changed to 615 MHz in an attempt to reduce the TM011 impedance. Measurements at CELLS, however, have shown that this has no significant influence on the TM011 impedance [14].

These measurements also indicated that the TM011 impedance is related with the 1mm gap between the waveguide ridges and the cavity port inner wall as shown in Fig. 10 (although with tapered waveguides and a similar gap an impedance of only 3 kΩ has been measured in the same frequency range). Closing the gap provisionally with rf springs reduced the TM011 impedance to 5 kΩ [14]. This gap was not included in the MAFIA model because of mesh size and cpu time limitations. An attempt to get quantitative insight based on frequency domain calculations with the Micro-Wave Studio code was not successful due to mesh size limitations. Thus the TM011 impedance is not fully understood yet.

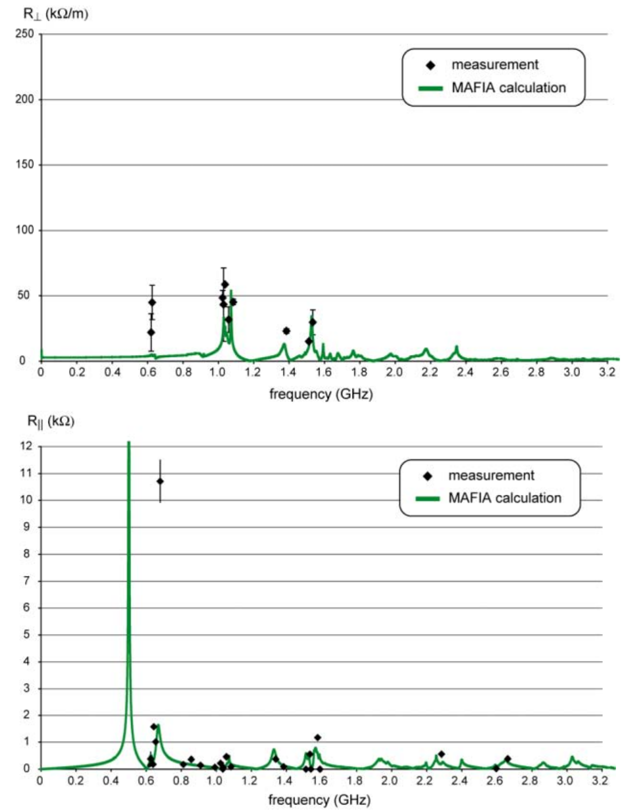

Figure 9: Longitudinal (top) and transverse (bottom) impedance measured with homogenous waveguides.

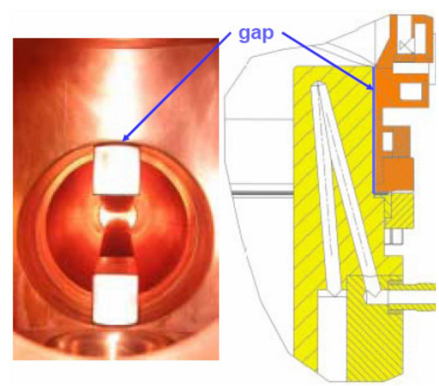

Figure 10: Gap between waveguide ridge and cavity port.

HIGH POWER COMMISIONING

After the installation in the Metrology Light Source in Berlin [16], the cavity was baked at 130°C for one week and then rf conditioned up to 40 kW cw within 4 days. No serious multipacting levels have been observed. Since 2008 this ring is in user operation with accumulated currents up to 200 mA and 140 mA accelerated to 600 MeV. Preliminary studies indicate that there are no HOM driven longitudinal and transverse multi-bunch oscillations.

When operating the cavity at 45 kW a vacuum leak occurred at the CF200 cavity flange connection for the waveguides. As shown in Fig. 11 the flange is heated locally in the region of the gaps with a measured temperature difference around the flange azimuth of 28°C (at 40 kW) leading to a differential deformation of 0.03 mm causing the gasket to leak.

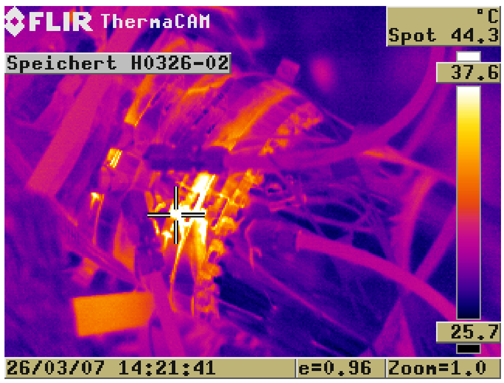

Figure 11: IR picture of the CF200 cavity/waveguide flange.

The reason of the problem is again the gap depicted in Fig.10. Calculations with the Microwave Studio code made at CELLS have shown that the magnetic rf field of the fundamental mode is enhanced in the gap region. Detailed heat transfer simulations indicate that with a small modification of the inner side of the cavity flange (replacing stainless steel by copper) the heat transfer can be improved sufficiently to allow operation up to at least 80 kW [15]. This modification has been adopted for the CELLS series cavities. Table 2 summarises the cavity fundamental mode performance parameters.

Table 2: Fundamental Mode Performance Parameters

Shunt impedance	3.4 MΩ
Quality factor	29600
Coupling (adjustable)	0.1 -8
Cavity power / rf-voltage	
reached	40 kW / 520 kV
expected with modifications	80 kW / 735 kV
expected without gaps	100 kW / 825 kV

It seems that both performance limitations of the cavity, TM011 impedance and fundamental mode power, are related with the gap shown in Fig. 10. This gap simplified the engineering design of the cavity (in particular the cooling design of the waveguide ridges near the cavity body) and thus minimised fabrication cost. Figure 12 shows an outline design to avoid the gap by machining the ridge inside the cavity port as part of the cavity body. Such a design provides the option to avoid the present limitations. A study is under way to evaluate the technical pro's and con's of such a design together with cost implications.

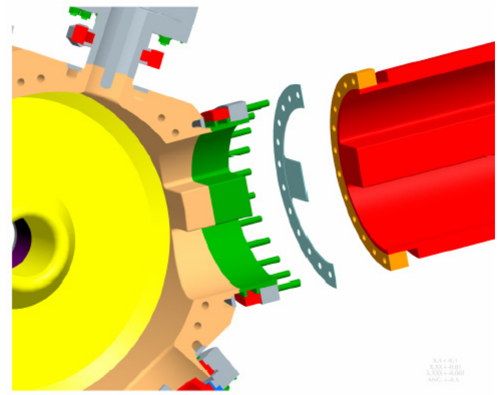

Figure 12: Conceptual mechanical design of a cavity without gaps between the ridges and the cavity.

CONCLUSIONS

A 500 MHz HOM damped cavity has been designed for the specific needs of SR sources with the potential to allow operation of many facilities below threshold for HOM driven multibunch instabilities. Work is going on to understand and reduce the TM011 impedance. Heat transfer simulations indicate that with the present cavity design a thermal power level of 80 kW can be reached after minor modifications in the cooling channel layout. This will be tested soon with the CELLS cavities. An engineering study is under way at BESSY to evaluate the pro's and con's of a design without gap between the ridges and the cavity. At ESRF work is under way to adopt this cavity concept to 352 MHz [17].

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