SIMULATIONS AND RF MEASUREMENTS OF THE FUNDAMENTAL AND HIGHER ORDER MODES OF THE THOMX 500 MHz CAVITY*

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Abstract

The RF system of the ThomX storage ring consists in a 500 MHz single cell copper cavity of the ELETTRA type, powered with a 50 kW CW solid state amplifier, and the associated Low Level RF feedback and control loops. The low operating energy of 50–70 MeV makes the impedances of the cavity higher order modes (HOMs) particularly critical for the beam stability. Their parasitic effects on the beam can be cured by HOM frequency shifting techniques, based on a fine temperature tuning and a dedicated plunger. A typical cavity temperature stability of ± 0.05°C within a range from 35 up to 80 °C can be achieved by a precise control of its water cooling temperature. On the other hand, the tuning of the cavity fundamental mode is achieved by changing its axial length by means of a mechanical tuner. In order to insure a fine control of the HOM frequencies, a good knowledge of their characteristics is mandatory. The main parameters of the fundamental and of the HOMs up to 4 GHz have been calculated using the HFSS and CST MWS codes. Preliminary measurements results have been obtained and show a good agreement with the simulations.

INTRODUCTION

ThomX is a Compton source project in the range of the hard X rays (45/90 keV). The machine is composed of a 50-70 MeV injector Linac and a storage ring where an electron bunch collides with a laser pulse accumulated in a Fabry-Perot resonator. The final goal is to provide an X-rays average flux of $10^{11}/10^{13}$ ph/s. The ThomX project [1] was recently funded and a demonstrator will be built on the Orsay University campus.

The proposed RF system for the ThomX storage ring is described in [2]. It consists in a 500 MHz single cell cavity of the ELETTRA type [3], powered with a 50 kW CW solid state amplifier, and the associated Low Level RF feedback and control loops [4].

When a bunch traverses a high Q resonator like a RF cavity, it excites its higher order modes (HOMs). The induced long term electromagnetic wakefields act back on the bunch over many revolutions and therefore can cause beam instabilities resulting in degradation of the beam quality or even beam losses.

In a low energy ring like ThomX, the natural damping time is so weak (~ 1 s) that a stationary stable condition can never be reached during the beam storage time, which is as short as 20 ms. On the other hand, it is sufficient to maintain the instability growth time larger than the beam storage time in order to keep at tolerable level the effect on the beam. That requires very strong attenuation of the cavity HOM impedances, typically by a few 10^3.

There are essentially two methods of coping with such HOM impedances, either a strong de-Qing of the HOM resonances [5, 6] or a tuning of their frequencies away from the beam spectral lines to prevent resonant excitations. With the former it is difficult to reach attenuation factors larger than a few 10^2 over a wide frequency range. The latter, which consists in controlling the HOM frequencies, is better suited to a small circumference machine like ThomX, where the beam spectral lines spacing (18MHz) is very large as compared to the HOM bandwidth. As far as the HOM density is not too high and that they can be tuned far enough from the beam spectral lines ($\delta f >> f_{HOM} / Q_o$), it should be possible to reduce their effective impedances ("seen" by the beam) down to tolerable levels : $R_{eff} \approx R_s/(2Q_o.\delta f / f_{HOM})^2 << R_s$.

That led us to choose the ELETTRA type cavity which allows applying this technique in combining three tuning means. The HOM frequencies are precisely controlled by proper setting of the cavity water cooling temperature within 60 ± 25 °C with a stability of ± 0.05 °C, while the fundamental frequency is recovered by means of a mechanical tuning which changes the length of the cavity. Besides, a movable plunger provides another degree of freedom for tuning the HOM.

In order to insure a fine control of the HOM frequencies, a good knowledge of their characteristics is mandatory. The main parameters of the fundamental and the HOMs have therefore been calculated using the Eigenmode solver of the 3D Electromagnetic HFSS [7] and CST MWS [8] codes and compared the results with the measured values on the cavity.

STORAGE RING RF SYSTEM

The selection of 500 MHz as RF frequency leads to a quite good compromise in terms of cavity fundamental and HOM impedances, space requirements as well as the availability of RF power sources and other components.

500 MHz RF Cavity

One 500 MHz single cell cavity of the ELETTRA type, powered with a 50 kW CW solid state amplifier (SSA), will provide the required RF voltage of 500 kV. It is made out of OFHC copper and equipped with 8 equatorial

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outlet ports: 3 large ones for the input power coupler, the pumping system, the plunger tuner and 5 smaller ones for vacuum and RF monitoring. It is water cooled by means of copper pipes brazed on its external wall surface. Its temperature can be set within 60 ± 25 °C with a stability of ± 0.05 °C by re-circulating the cooling water through an appropriate heat exchanger (cooling rack). The cavity cutoff tube (Ø 100 mm) will be connected to the standard elliptical vacuum chamber (a=40mm, b=28mm) by means of two tapers, made of 316 L stainless steel and bellows. The cavity assembly is shown in Figure 1.

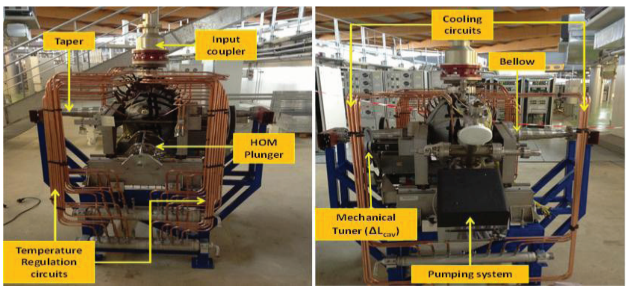

Figure 1: ThomX cavity assembly (front and back views).

500 MHz CW Solid State Amplifier (SSA)

Recently SYNCHROTRON SOLEIL has worked out modules, which can deliver up to 650 W at 500 MHz with a gain of 16.5 dB and an efficiency of 64 % [9]. About a hundred of such modules will be combined for achieving the required 50 kW power. A 10 kW prototype unit (16 modules) was successfully tested and validated by mid of 2012 at SOLEIL and the complete 50 kW CW SSA will be tested on a dummy load, by the end of 2013.

Low Level RF and Feedback Systems

The task of a Low Level RF (LLRF) system is to control the amplitude and phase of the cavity accelerating voltage and its resonance frequency. Three LLRF prototypes, including a fast longitudinal feedback (LFB) are being developed in parallel. The first version consists in separate analog control loops for frequency, amplitude and phase; the second version is based on analog IQ modulation/demodulation technique and the third one on digital FPGA processing. The cavity voltage shall be controlled with typical stability of ± 0.2 % and ± 0.2° by means of the conventional phase and amplitude loops (either analog or digital) of few kHz bandwidths. In addition the LFB, namely a fast phase feedback, combined with a high gain RF feedback acting directly on the accelerating cavity [4], will provide the longitudinal damping of a few 10 µs, which is required to preserve the beam quality during its storage time of 20 ms. This LFB shall cope with the beam oscillations, caused by injection transients as well as by the longitudinal HOM excitations, in addition to the frequency tuning technique. Besides, a transverse feedback (TFB), based on FPGA processing, similar to that used in SOLEIL [10], and acting on a dedicated stripline kicker shall cope with the transverse modes of both planes, horizontal (H) and vertical (V).

SIMULATIONS AND MEASUREMENTS

The characteristic parameters of a cavity mode are its resonant frequency, its unloaded quality factor Q_0, its R/Q (shape factor) and its shunt impedance, $R_s = (R/Q).Q_0$. They have been computed with the HFSS and CST MWS codes using Eigenmode solver with cylindrical symmetry for the longitudinal and transverse modes of the cavity, including its 30 cm long 316 L stainless steel tapers.

On the other hand, the frequency and the loaded quality factor, Q_L of the modes have been measured on the cavity at ambient temperature and under vacuum using a vector network analyzer (VNA) in transmission mode. The unloaded quality factor Q_0 values are deduced by taking into account the coupling coefficients of the input power coupler and monitoring pick-up.

Fundamental Mode Parameters

A comparison between the computed and measured parameters of the accelerating mode, that is the TM_{010} fundamental mode of the cavity, is shown in Table 1. The shunt impedance is defined as $R_s = V_{acc}^2 / 2P_d$, where V_{acc} is the accelerating voltage (transit time factor included) and P_d is the cavity wall dissipation.

Table 1: Fundamental Cavity Mode L0 (TM_{010})

	Computed values		Measured values
	CST	HFSS	
Freq. (MHz)	499.9	499.89	500
Q_L	---	---	15512
Q_0	44876	44426	41308
R_s (MΩ)	3.56	3.51	---
R/Q (Ω)	79.3	79	---
Loss factor(V/nC)	124.5	124	---

HOM Parameters

Simulations and measurements have been performed also for the HOMs of the cavity, terminated with its two tapers. The results are listed, in Table 2 and 3 for the monopole and dipole modes, which are trapped into the cavity, namely with a resonance that is lower than its tube (Ø 100 mm) cut-off frequencies, 2.3 GHz for monopole and 1.83 GHz for dipole modes. The two polarizations, H and V, of the dipole modes, are not distinguished here.

The goal of keeping the instability growth times larger than 20 ms requires HOM impedances lower than 0.5 GHz.kΩ for the monopole modes and 5 kΩ.m^{-1} for the dipole modes. One therefore can deduce from the below results that these HOM, which are trapped into the cavity, have to be attenuated by factors up to a few 10^3.

Table 2: Longitudinal (monopole) Modes

Mode	HFSS computed values				Measured values		
	Freq. (MHz)	Q_0	R_s (kΩ)	R/Q (Ω)	Freq. (MHz)	Q_L	Q_0
L1	948.65	45658	1340	29.3	950.6	32700	41954
L2	1064	60609	37.5	0.6	1055.8	5460	47011
L3	1422	53267	249	4.67	1419.5	13900	30648
L4	1517.2	62722	320	5	1514.4	27500	44385
L5	1618	72579	662	8.8	1602	16930	36805
L6	1880.7	53604	22.5	0.41	1877.6	36500	49494
L7	1951	77784	119	1.53	1949.8	8180	61776
L8	2098	55807	0.1	0.0018	2072.7	53000	57664
L9	2128	77985	583	7.4	2123.8	16600	39840

Table 3: Transverse (dipole) Modes

Mode	CST computed values				Measured values		
	Freq. (MHz)	Q_0	R_s (MΩ/m)	R/Q (Ω/m)	Freq. (MHz)	Q_L	Q_0
D1	744.2	47966	3.6	76	742.4	44300	47046
D2	749.4	50421	13	258	745.5	7640	42631
D3	1114	40971	12.8	314	1115	17880	52316
D4	1224	95336	0.23	2.5	1213.4	57000	58220
D5	1250	39726	4.5	114	1239.7	35400	37240
D6	1311	62710	0.2	3.1	1303	49900	52595
D7	1561	29480	0.03	1	1556	18200	26172
D8	1643	40494	3.2	79	1646	30900	33372
D9	1717	75798	1.3	17.5	1711.4	26500	27825
D10	1723	44231	2.3	50.5	1718.3	58500	58815
D11	1779	46762	1.6	33	1770.3	39200	45315
D12	1811	38748	1.24	32	1820	31900	37515

Preliminary simulations show that it is possible to achieve this goal by applying the HOM tuning technique (temperature + plunger) as described before [2].

Figure 2 shows the impedances of the HOMs which are trapped in the cavity and the ones which propagate into the tapers, with frequencies up to 4 GHz, the cutoff frequency of the standard ring vacuum chamber. Although the "propagating modes" are much less critical than the "trapped modes", their impedances are still above the specified thresholds.

As it will be hard to cope with all these modes only by applying the tuning technique, one relies on the LFB and TFB in order to bring additional damping.

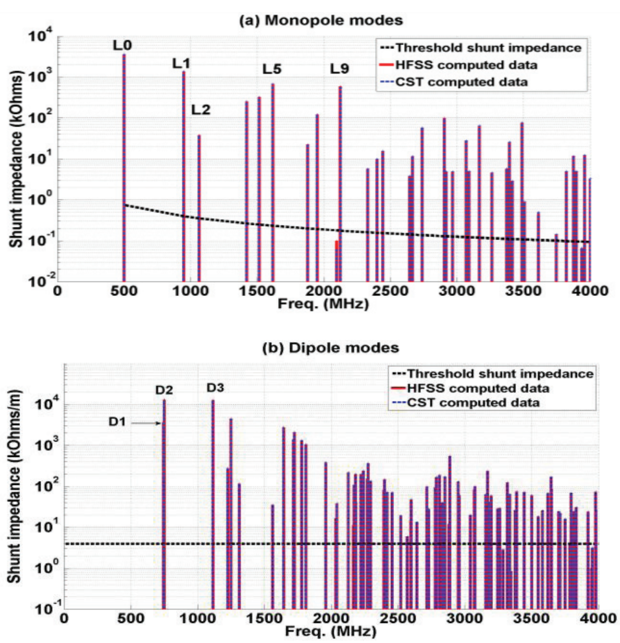

Figure 2: Shunt impedance spectrum for (a) monopole and (b) dipole modes.

Adjustable HOM Frequency Shifter (HOMFS)

The HOMFS is a plunger moving into one of the three equatorial ports, as shown in Figure 1, for shifting the resonant frequencies of harmful HOMs if a stable condition cannot be achieved only by temperature tuning.

Figure 3 shows the HOMFS effects on the trapped monopole and dipole modes for its full displacement range of 35 mm. The fundamental as well as the HOM frequencies vary linearly with the plunger position. Except for a few modes which are less sensitive, frequency shifts of 1 MHz or more are achieved.

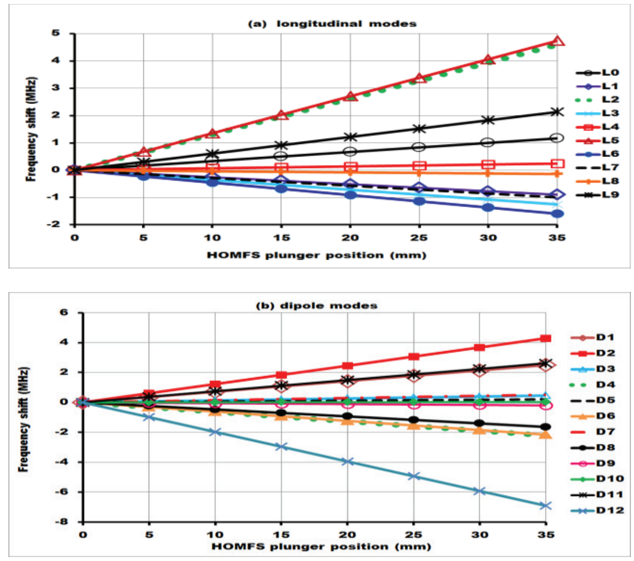

Figure 3: Frequency shift vs. HOMFS position (a) for monopole and (b) for dipole modes.

CONCLUSIONS

Electromagnetic parameter calculations using CST and HFSS codes as well as measurements have been performed on the ThomX cavity. The results show that a strong attenuation of the cavity HOM impedances is required in order to preserve the beam quality in the storage ring. It will be achieved by a proper control of the HOM frequencies in combining three tuning means and by the use of feedbacks for providing additional damping. During the next months, the characterization of the cavity HOM shall be completed.

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