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CHARACTERIZATION OF HIGHER-ORDER-MODES (HOM) IN THOMX STORAGE RING RF 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 50-100 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 adjustable plunger. A cavity temperature stability of ± 0.1 °C within a range from 30 up to 70 °C is 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 2.2 GHz versus temperature have been measured at low power using a vector network analyzer (VNA).

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-ray average flux of 10^{12} – 10^{13} ph/s. The emitted flux will be characterized and used for experiments by a dedicated X-ray line [1]. Different users are partners in the ThomX project [2], especially in the area of medical science [3] and cultural heritage [4]. Their main goal is the transfer of experimental techniques currently developed on large synchrotron rings to more compact and flexible machines. ThomX is a demonstrator built on the Paris-Saclay university campus. The THOMX LINAC is presently under commissioning (Phase 1: 100 pC, 50 MeV at 10 Hz).

The RF system for the ThomX storage ring is described in [5]. It consists in a 500 MHz single cell cavity of the ELETTRA type, powered with a 50 kW CW solid state power amplifier (SSPA), and the associated Low-Level RF feedback and longitudinal and transverse feedbacks.

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 [6, 7] or a tuning of their frequencies away from the beam spectral lines to prevent resonant excitations [8]. 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 i.e. revolution frequency f_{rev} =16.67 MHz is very large as compared to the HOMs bandwidth.

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 a range from 30 up to 70 °C with a stability of ± 0.1 °C, while the fundamental frequency is recovered by means of a mechanical tuner which changes the cavity length. Besides, a movable plunger (HOMFS) provides another degree of freedom for tuning the HOM frequencies.

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 2.2 GHz versus temperature have been measured at low power using a vector network analyzer (VNA).

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

RF CAVITY

One 500 MHz single cell cavity of the ELETTRA type, powered with a 50 kW CW SSPA, will provide the required RF voltage of 500 kV. It is made out of OFHC copper and equipped with 8 equatorial connecting ports: 3 large ones for the input power coupler, the pumping system, the plunger tuner and 5 smaller ones for vacuum and RF monitoring and temperature monitoring sensors. It is water cooled by means of copper pipes, brazed on its external wall surface. Its temperature can be set within a range from 30 up to 70 °C with a stability of ± 0.1 °C by re-circulating the cooling water through an appropriate heat exchanger (cooling rack), The cavity cut-off tube (Ø 100 mm) will be connected to the octagonal shaped vacuum chamber by means of two 30 cm long tapers, made of 316 L stainless steel and bellows. The cavity assembly is shown in Fig. 1.

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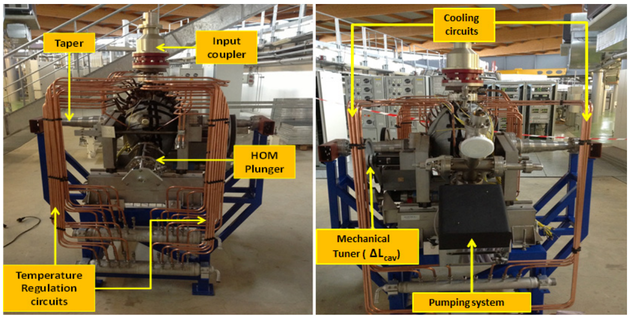

Figure 1: ThomX cavity assembly.

The frequency of the fundamental cavity mode is kept tuned to 500.023 MHz by means of the tuning cage that stretches or compresses the axial length of the cavity. The limit of the continuous frequency is given by the elastic limit of the copper in the neck region of the cavity. This limit corresponds to a maximum frequency change of ± 150 kHz. The main parameters of ThomX RF cavity are shown in Table 1.

Table 1: Fundamental Mode Parameters

Parameter	Value
Resonant Frequency	500.023 MHz
Unloaded Quality Factor	41308
Effective shunt impedance	3.56
Coupling factor	1.52
Max. Accelerating Voltage	600 kV
Power loss @ 600 kV	52.3 kW

HIGHER ORDER MODE TUNING

In the storage ring (SR), the interaction of the beam with a cavity HOM impedance can lead to Coupled Bunch Instabilities (CBI). The CBI growth rate, G_m depends on the frequency detuning between the HOM resonance and the coupled bunch mode frequencies:

$$G_m = \frac{k}{1+\left[2Q_m\frac{f_m-f_p}{f_m}\right]^2} \quad (1)$$

Where Q_m and f_m are respectively the HOM quality factor and HOM frequency; f_p $(p = 1, 2, \dots \infty)$ are the coupled bunch mode frequencies:

$$f_p = p.f_{rev} \pm \begin{cases} f_s & longitudinal\ case \\ f_{\beta_{H/V}} & transverse\ case \end{cases} \quad (2)$$

Where f_s, $f_{\beta\ H/V}$ and f_{rev} are respectively the synchrotron, betatron and revolution frequencies.

$$k = \begin{cases} \alpha.I_b.f_m.R_{sm}/(2.Q_s.(E/e))\ long.case \\ \beta_{H/V}.I_b.f_{rev}.R_{sm}/(2.(E/e))\ \ tran.case \end{cases} \quad (3)$$

Where α is the momentum compaction, Ib the stored beam current, R_{sm} the HOM shunt impedance, Q_s the synchrotron tune, (E/e) the energy of the electron beam and $\beta_{H/V}$ the betatron function, Horizontal/vertical, at the cavity location. The stability is ensured if the CBI growth rate is lower than the natural radiation damping rate.

The main parameters of the ThomX are shown in Table 2 which were considered in the calculation of the CBI growth rate.

Table 2: Nominal ThomX Parameters

Parameter	Value
Nominal energy, E/e	50 MeV
Maximum beam current, I_b	16.67 mA
Revolution frequency, f_{rev}	16.67 MHz
RF frequency, f_{RF}	500.023 MHz
Harmonic number, h	30
Circumference, C	18 m
Momentum compaction: α	0.0143
β_H, β_V @ cavity location	3.46 m, 2.66 m
Synchrotron frequency, f_s	337 kHz
Betatron frequency, $f_{\beta H}$ / $f_{\beta V}$	2.83/10.67 MHz

Following the technique developed at ELETTRA [8], the HOM tuning is controlled via the cavity temperature which can be set between 30°C and 70°C with accuracy better than ± 0.1 °C. For any change of temperature, the tuning loop keeps constant the fundamental frequency by mechanical deformation of the cavity. Adjustable HOM plunger (HOMFS) provides an additional degree of freedom for the optimization procedure.

The knowledge of the numerical and measured parameters of the most effective HOM is therefore mandatory to foresee any interaction with the electron beam. The cavity characterization is done with an input coupler (IPC) and all the RF picks up and choosing for each mode the ports that better suit the HOM frequency excitation. The cavity is tested at low power using a VNA after its final installation on the ThomX site to characterize all the HOM resonances up to 2.2 GHz (Fig. 2) in order to check and identify the monopole and dipole modes that could have the strongest impact on the beam stability.

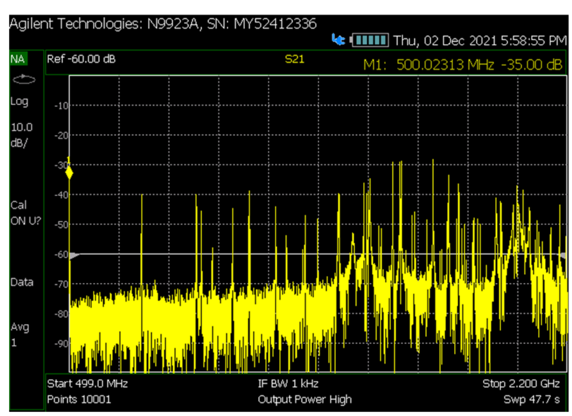

Figure 2: Frequency spectrum of all modes trapped into the cavity up to 2.2 GHz.

The results are listed, as an example at temperature 35°C, in Table 3 for the longitudinal and Table 4 transverse (dipole) modes, which are trapped into the cavity, namely with a resonance that is lower than 2.2 GHz. Overlapping between beam harmonics and harmful HOMs like L1, L3

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and T3 in the ThomX cavity can be avoided by choosing an appropriate cavity temperature and HOMFS position.

Table 3: Longitudinal Cavity Parasitic Modes

Mode	f_m(MHz)@35°C	Q_m	R_{sm} (kΩ)
L1	950.4	38412	1084.1
L2	1056.55	43532	24.12
L3	1417.06	33300	155.5
L4	1514.52	27750	138.5
L5	1603.65	21400	184.8
L6	1892.17	31500	12.7
L7	1956.22	51550	78.79
L8	2094.72	22650	2.3
L9	2102.97	27400	199.8

Due to the asymmetries in the cavity geometry, each dipole mode generates two polarizations, Horizontal (H) and vertical (V), resonating at slightly different frequencies. Only one polarization could be measured for mode T4.

Table 4: Transverse Cavity Parasitic Modes

Mode	f_m(MHz)@35°C	Q_m	R_{sm} (MΩ/m)
T1H	742.36	45840	3.58
T1V	742.51	44393	3.58
T2H	745.40	44272	11
T2V	746.33	43127	11
T3H	1114.48	48712	16.4
T3V	1115.13	37198	16.4
T4	1204.42	31983	0.14
T5H	1239.74	31974	4.25
T5V	1241.21	36665	4.25

From the measured HOM frequencies we could then compute the CBI growth rates and produce temperature maps as shown in Fig. 3 and Fig. 4. Experimental results show a large stable temperature window (50 – 60 °C) that can be used in operation with a beam to avoid any excitation of a longitudinal and transverse HOM.

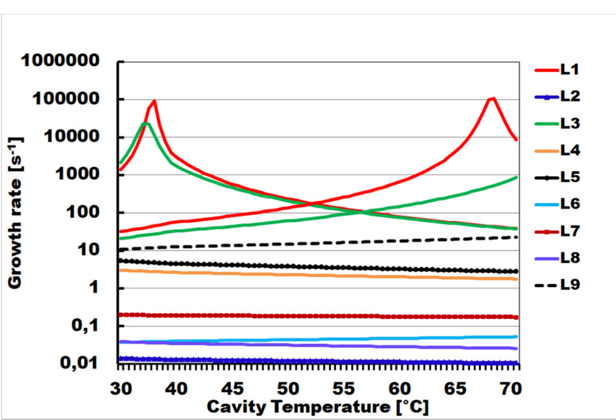

Figure 3: CBI Growth rate (G_m) of the longitudinal modes as a function of the cavity temperature.

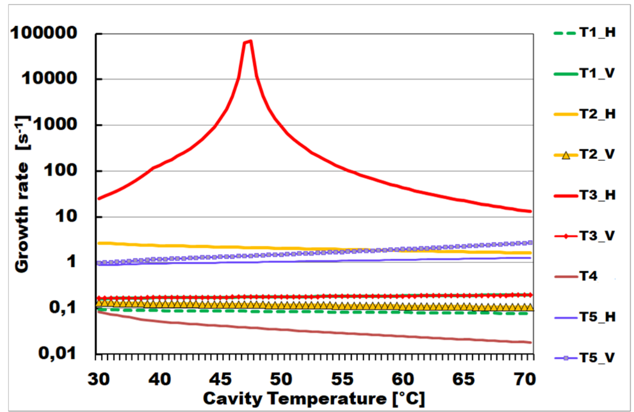

Figure 4: CBI Growth rate (G_m) of the dipole modes as a function of the cavity temperature.

In addition to the tuning technique, transverse and longitudinal feedbacks is implemented to bring additional damping.

CONCLUSION

ThomX cavity is fully equipped, intensively tested, checked and installed in the ThomX storage ring (SR) to be ready for RF conditioning and beam operation. Few days after the bake out the 10^{-10} mbar ultimate vacuum pressure range has been successfully reached. The commissioning of the ThomX SR "phase 2" will start after obtaining the authorization from the French Nuclear Safety Authority (ASN).

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