THE PS 10 MHz HIGH LEVEL RF SYSTEM UPGRADE

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Abstract

In view of the upgrade of the injectors for the High Luminosity LHC, significantly higher bunch intensity is required for LHC-type beams. In this context an upgrade of the main accelerating RF system of the Proton Synchrotron (PS) is necessary, aiming at reducing the cavity impedance which is the source of longitudinal coupled-bunch oscillations. These instabilities pose as a major limitation for the increase of the beam intensity as planned after LS2. The 10 MHz RF system consists in 11 ferrite loaded cavities, driven by tube-based power amplifiers for reasons of radiation hardness. The cavity-amplifier system is equipped with a wide-band feedback that reduces the beam induced voltage. A further reduction of the beam loading is foreseen by upgrading the feedback system, which can be reasonably achieved by increasing the loop gain of the existing amplification chain. This paper describes the progress of the design of the upgraded feedback system and shows the results of the tests on the new amplifier prototype, installed in the PS during the 2015-16 technical stop. It also reports the first results of its performance with beam, observed in the beginning of the 2016 run.

PS 10 MHz RF SYSTEM

The PS 10 MHz cavities are the main accelerating RF system of the PS. Besides performing beam acceleration they are also needed for RF manipulations, such as splitting and rotation, at various RF harmonics.

A cavity consists of two ferrite loaded $\lambda/4$ lines, with capacitive gaps at their input ends. They cover the frequency range of 2.8 MHz-10 MHz by means of a bias field which partially saturate the ferrite. An RF amplifier, based on electron tube technology for reasons of radiation hardness, feeds the two cavity gaps in parallel and provides the necessary voltage to accelerate the beam. Up to 10 kV_p per gap can be achieved.

The bare cavity resistance is quite high (about 22 kΩ at 3 MHz), mainly due to the ferrite losses, and it is in parallel to the anode resistance of the power amplifier (6 kΩ). The high-intensity proton beam passing through the gaps induces a strong voltage proportional to the cavity impedance, which causes a distortion of the RF voltage both in amplitude and in phase and acts back on the beam itself, leading to a significant modification in the dynamics of particles motion.

Beam Loading and Feedback Compensation

In order to keep the induced voltage under control the cavities are equipped with a direct wide-band feedback system [1]. A part of the cavity gap voltage is fed back into the power amplifier in antiphase.

The effect induced by the beam passing through a cavity gap is defined as beam loading. A bunched beam can be considered as a current source I_b with a frequency spectrum that depends on the bunch length, on the number of bunches and on the revolution frequency. Its components at harmonics of the revolution frequency are responsible for transient voltage induced in the gaps. When a bunch of current I_b travel across the gap, a beam voltage $V_b = -Z \cdot I_b$, proportional to the cavity impedance, is induced in the cavity.

In the following the equivalent system in Fig.1, where the cavity is modeled with an $R-L-C$ circuit, is considered.

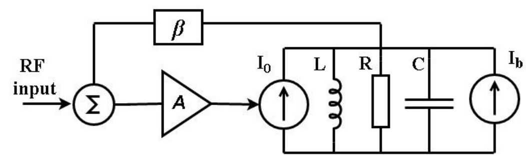

Figure 1: RF feedback schematic.

A is the forward voltage gain of the amplification chain and β the feedback attenuation. An ideal feedback reduces the gap voltage, and thus the impedance, by a factor proportional to the loop gain $G_L = A \cdot \beta$:

$$Z = \frac{Z_{cav}}{1 + G_L} \quad (1)$$

The Amplification Chain

The amplifier chain of the 10 MHz system (Fig. 2) is made of three main stages: pre-driver, driver and final stage. Four electron tubes are used: three YL1056 tetrodes for the first two stages (one for the pre-driver, two in parallel for the driver stage) and one RS1084CJ in the final stage.

The driver is loaded by a grid resonator that can be tuned continuously over the 2.8 MHz to 10 MHz frequency range, tracking the resonant frequency of the cavity. It also serves as impedance 1:4 transformer and provides a 180° phase shift for a local feedback. The pre-driver, being a wide-band amplifier stage, introduces a large phase shift between 3 and 10 MHz. In order to improve the phase stability of the system, a portion of the driver output voltage is re-injected back and added to the RF driving signal. Moreover, part of the anode signal is re-injected via a disc capacitor into the summing point, providing the cavity impedance reduction.

AMPLIFIER UPGRADE

To satisfy the requests of higher beam intensities, in the frame of the High-Luminosity LHC (HL-LHC) and LHC

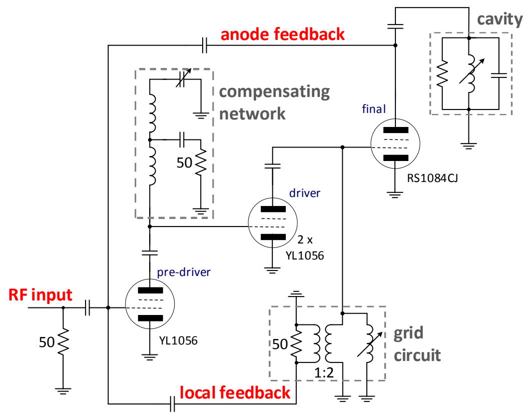

Figure 2: Simplified model of the 10 MHz RF system.

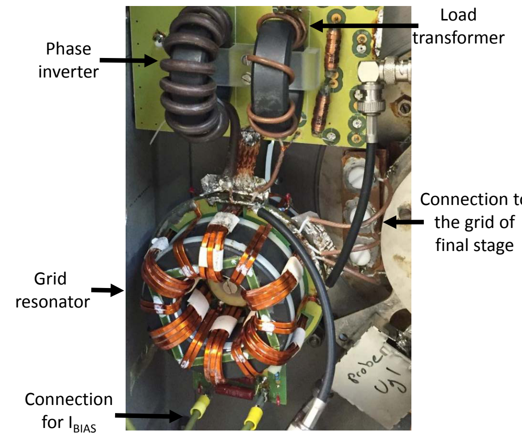

Figure 3: Prototype of the new resonator, transformer and inverter mounted in the amplifier.

Injectors Upgrade (LIU) projects, a reduction of the source of beam instabilities is necessary.

In order to lower the impedance of the cavity seen by the beam further, the wide-band feedback system of the PS 10 MHz cavities has been improved. The solution consists of increasing the loop gain of the present configuration, still providing a stable operation without a complete re-design of the system.

The factors that limit the increase of the loop gain are: the maximum power of the amplifier driving the system (150 W), the maximum voltage allowed on the pre-driver grid and the large phase shift introduced by the first stage at 10 MHz. Presently the 11 cavities in the PS ring are characterized by an impedance reduction factor ≤20, which is about the maximum that can be obtained with this configuration.

An important requirement of a well-performing feedback system is that the group delay must be reduced as much as possible, since a large phase shift (mainly caused by the system connections and electronics) in the feedback chain may drive the feedback amplifier into instability. The wide operating frequency range and the time delays and phase shifts produced by the cables, filters and amplifiers make the gain margins very small.

The aim of this upgrade therefore consists of improving the margins of the system, to allow an additional increase of the loop gain.

Grid Circuit Upgrade

Measurements show that the major contribution to the phase shift over the operational band is the first stage of amplification and the grid resonator. The latter, moreover, is quite lossy at 10 MHz, causing a relevant reduction of the forward gain.

The old grid circuit has been replaced by three independent devices [2], one for each function, shown in Fig. 3. The new 50 to 200 Ω load transformer is made of a coaxial cable wound on a ferrite core. The transformation ratio is reached with lower losses at 10 MHz.

The new variable inductance of the resonator uses 2 ferrite toroids with 6 sections of RF winding, forming two figure-of-8 turns around two rings. Between the RF sections there are 6 DC biasing sections of figure-of-0 wire turns. The figure-of-8 windings cancels the total RF voltage induced in the DC biasing path. This new resonator is characterized by less stray capacitance and leakage inductance, if compared to the previous device. As a consequence unwanted resonances are removed together with their contribution to the total phase shift, as shown in Fig. 4. Moreover the reduction of the stray capacitance also reduces the necessary tuning current. Another cable wound on a ferrite ring is used as inverter for the local feedback.

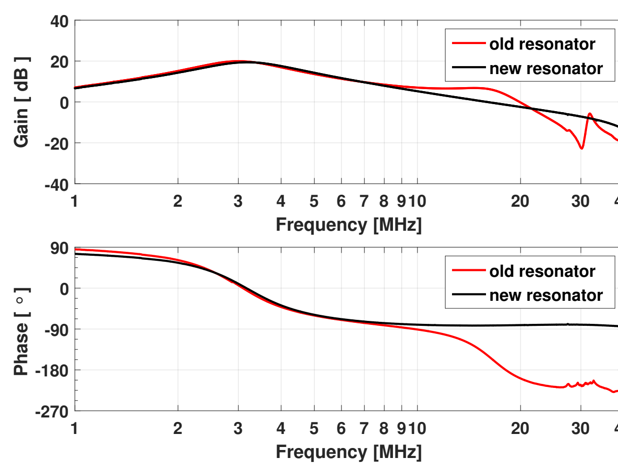

Figure 4: Comparison between the transfer function gain and phase of the new resonator and of the old one at 3 MHz.

In addition, the internal connections between the stages, which add a significant phase shift, were improved.

Change of Tubes Working Point

In order to get higher loop gain the working point of the tubes has been modified. This change improves the tubes trans-conductance and thus the amplifiers gain. The DC anode current of the YL1056 tubes has been increased, close to the maximum rating, while the anode voltage has been reduced to keep the total dissipation constant. In the final stage, the anode current was doubled, keeping the same

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anode voltage; as a consequence the realization and the installation of a new water cooling system became necessary to compensate the increased dissipation of the tube anode. About 2 dB of gain increase was obtained for each stage, resulting in 6 dB more overall gain.

The main advantage of the forward gain increase was the possibility to increase the bandwidth and lowering the phase shift of the first stage. This upgrade is described into details in the following.

A New Compensating Network

The phase shift of the pre-driver stage between 3 and 10 MHz (~30°) is one of the main limitations of the stability of the amplifier FB loop. In order to reduce this phase shift, the amplifier is equipped with a compensating network (see Fig. 2). The anode load of the pre-driver consists of the input capacity of the driver tubes in parallel with the pre-driver anode capacitance and the compensating network [3]. The latter reduces the pre-driver phase shift between 9 MHz and 11 MHz by a few degrees.

This compensating network was modified and optimized to reduce the phase shift as much as possible, with a consequent gain loss of about 3 dB. The shift between 3 and 10 MHz has been reduced from 30° of the old configuration to ~5° (Fig. 5).

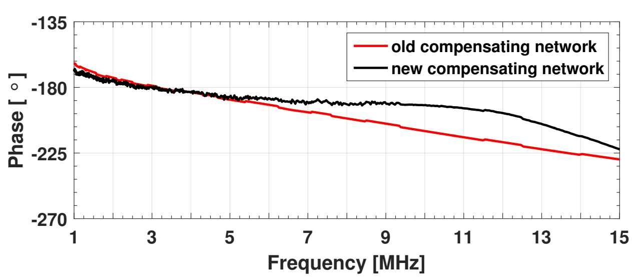

Figure 5: Phase shift of the pre-driver loaded with the old (red) and the new (black) compensating network.

Further Modifications

Additional improvements were implemented in the amplification chain. The 150 W Herfurth amplifier, which provides the RF input to the feedback amplifier, has been replaced by a new driver developed in house and able to deliver up to 400 W with a drastically reduced harmonic content. A new FPGA based circuit, which controls the bias of the new grid variable inductance, directly converts the cavity RF drive frequency, into the bias current needed to tune the resonator.

RESULTS

An upgraded amplifier, in which the modification described above have been implemented, is characterized by a loop gain of about 25 dB at 3 MHz and 30 dB at 10 MHz (Fig. 6). As a consequence, a reduction of the cavity impedance by a factor two, compared to the impedance of cavities operated with the standard amplifier, is expected. The new amplifier has been installed in the PS ring during the

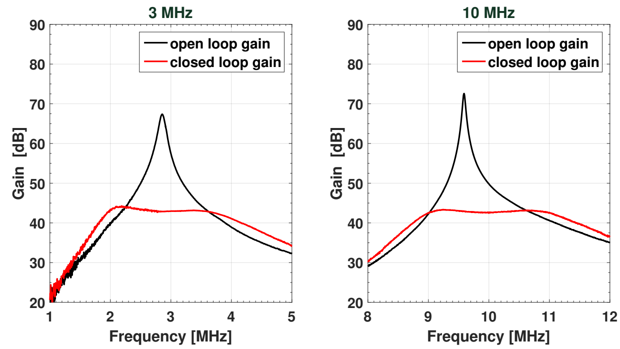

Figure 6: Loop gain of the new amplifier prototype measured at 3 and 10 MHz.

winter shutdown for measurements with beam. A dedicated measurement campaign, focused on the characterization of the beam-cavity interaction [4], led to an evaluation of the cavity impedance from beam induced voltage. These measurements confirm the expected reduction of the impedance, which is maintained across the full operating range of the cavity. Fig. 7 shows the measurement results of the real part of the the impedance of the PS cavity in straight section 11, at three cavity harmonics (*h*=8, 16, 21), when operated with a standard amplifier (blue traces) and the upgraded one (red traces). It is worth mentioning that the observed reduction

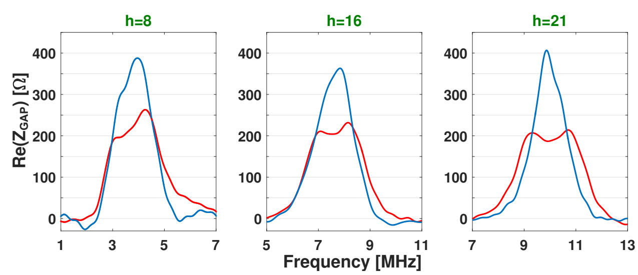

Figure 7: Real part of the gap impedance of PS cavity in straight section 11 operated with a standard (blue) and the upgraded amplifier (red).

at *h*=21 is crucial for the stability of the LHC type beams accelerated in the PS at that harmonic.

CONCLUSION

An upgraded prototype of the amplifier for the 10 MHz cavities has been built and tested. The new cavity-amplifier system features a significant reduction of the impedance, which is crucial for allowing higher beam intensities expected for LHC type beams in the framework of the injectors chain upgrade. An optimization of the system is ongoing to further improve its performance. Moreover, additional measurements will be carried out to fully validate the upgraded amplifier characteristics, in the perspective of replacing all the PS 10 MHz amplifiers. Finally, as suggested in [2], the possibility to implement a higher gain solid state amplifier stage in the amplification chain will be investigated.

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REFERENCES

[1] R. Garoby, J. Jamsek, P. Konrad, G. Lobeau and G. Nassibian, "RF system for high beam intensity acceleration in the CERN PS", Particle Accelerator Conference, 1989. Accelerator Science and Technology, Proceedings of the 1989 IEEE, Chicago, IL, 1989, pp. 135-137 vol.1.

[2] A. Labanc, "Reduction of the group delay of a wideband cavity power amplifier to permit the reduction of the cavity equivalent impedance by increased feedback", Diploma Thesis, CERN, Geneva 2000/2001.

[3] D. Grier, "The PS 10 MHz Cavity and Power Amplifier", PS/RF Note 2002-073, CERN, Geneva, Switzerland, 2002.

[4] G. Favia, H. Damerau, M. Migliorati, M. Morvillo, C. Rossi "Study of the beam-cavity interaction in the PS 10 MHz RF system", paper MOPOR012 this conference.

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