OPERATION OF THE SOLEIL RF SYSTEM

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Abstract

The 352 MHz RF accelerating systems for the SOLEIL Booster (BO) and Storage Ring (SR) are in operation since mid 2006. In the BO, a 5-cell copper cavity of the CERN-LEP type is powered with a 35 kW solid state amplifier. In the SR, the required RF accelerating voltage (up to 4.4 MV) and power (560 kW at full beam current of 500 mA) will be provided by two cryomodules, each containing a pair of superconducting cavities, specifically designed for SOLEIL. The first cryomodule is operational, while the second one, which is being constructed by ACCEL (Germany), will be implemented in May 2008. Both cryomodules are cooled down to 4.2 K with liquid helium from a single 350 W liquefier and each cavity is powered by a 180 kW solid state amplifier. Using a single cryomodule and two amplifiers, the first objective of storing 300 mA stable beam was successfully achieved in 2006. The RF system commissioning and operation results are reported.

BOOSTER RF SYSTEM

In the SOLEIL BO, a single 5-cell copper cavity (figure 1a) of the LEP type (352 MHz) provides the required RF voltage, which is ramped from 100 kV up to 900 kV at the injection rate of 3 Hz. The total needed power, up to 25 kW (20 kW dissipation into the cavity walls and 5 kW into the beam), is supplied by a solid state amplifier, capable of delivering up to 35 kW CW.

The solid state amplifier (figure 1b) consists in a combination of 147 elementary modules of 330 W, with VDMOS transistor (D1029UK from Semelab), integrated circulator and individual power supply. The description of the amplifier and its first test results are detailed in [1,2], the associated LLRF and control systems in [3].

The complete BO RF plant was installed on site in spring 2005 and commissioned in July 2005. Up to now, it has run for about 6300 hours without any problem (no dead time due to the RF). In particular the amplifier, which is the most innovative part of the system, has proved to be quite reliable as well as very easy and flexible in operation. Only three module failures have occurred, due to bad soldering, which did not affect at all the operating conditions and could be quickly repaired during a scheduled machine shutdown.

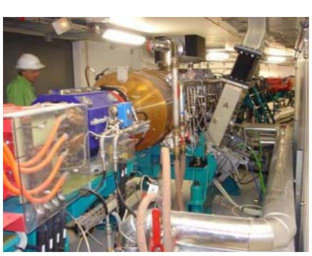

Figure 1a: Booster cavity

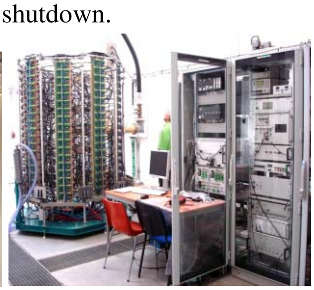

Figure 1b : RF room

STORAGE RING RF SYSTEM

In the SR, a RF voltage of 4.4 MV and a power of 560 kW are required for the nominal energy of 2.75 GeV with full beam current of 500 mA and all the insertion devices. It will be achieved using two cryomodules (CM), each containing a pair of single-cell superconducting cavities, especially designed for SOLEIL with strong HOM damping, located on the cavity connecting tube. Both CM are supplied with liquid Helium (LHe) from a single liquefier and each cavity is powered with a 180 kW solid state amplifier. The description of all the equipments (fig. 2 - 4) and their first test results are detailed in references [1,2,3,4].

During summer 2006, one half of the SR RF system (CM1, 2 amplifiers, the associated cryogenic plant, control and LLRF systems) was commissioned, as scheduled for the first year of SOLEIL operation with I_{beam} < 300 mA and a reduced number of insertion devices. The goal of storing up to 300 mA of stable beam, using a single CM, was quickly achieved [6]. At first, without RF feedback, the cavity was slightly detuned in order to cope with the Robinson instability, at the expense of some extra power : at 300 mA, 145 kW incident power, of which 10 kW reflected (1 kW from mismatch + 9 kW from detuning) with 1 MV on each cavity.

Figure 2 : Amplifiers 1 and 2 in the SR RF room

Figure 3 : CM1 in the SR

Figure 4 : The cryogenic area in the technical gallery

Fig. 5 shows the effect of detuning on the Robinson stability (ψ is the tuning angle which is automatically set by the tuning loop at any current level) : when fully compensating for the reactive beam loading, the beam was lost at a current threshold ~ 230 mA (upper graph); by introducing a tuning angle offset of 4° we could insure the stability up to 300 mA (lower graph), at the expense of 9 kW extra reflected power, as mentioned before.

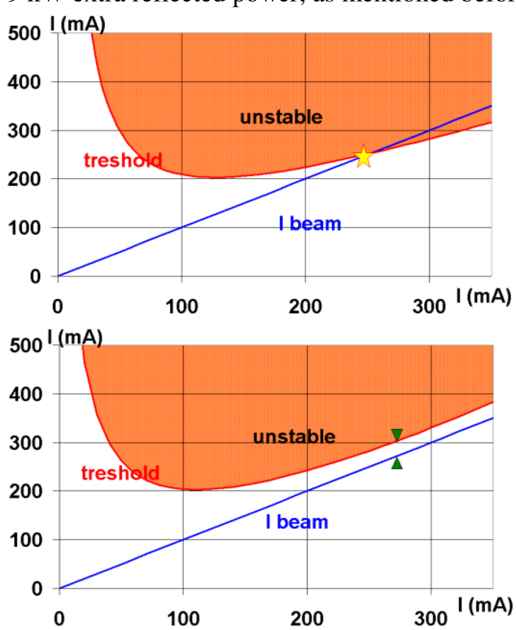

Figure 5 : Effect of detuning on Robinson stability for a cavity voltage of 1 MV

Operating at a larger voltage could also improve the stability but at the expense of an increased reflected power from mismatch. Later on, we have commissioned the RF feedback, which enabled to store up to 300 mA stable beam without any tuning offset, hence saving 9 kW of reflected power.

All results presented up to this point were obtained with the tuning loop continually active, compensating partially (without RF feed-back) or fully (with RF feed-back) for the reactive beam loading. The blue plot of figure 6 shows the required RF power versus beam current for the latter case with a cavity voltage of 1 MV : 28 kW, fully reflected (from mismatch) at 0-current, up to 135 kW at 300 mA (matched and tuned). Under these conditions, frequency changes of ~ 4 kHz, corresponding to about 10 000 motor steps, are required at each injection.

Considering the difficulties encountered on the Super-3HC cavities at ELETTRA with a similar tuning system, which happened to get stuck after roughly fifty millions of motor steps [7], it was proposed to operate at constant tuning during the injection, in order to use the tuners more sparingly [8].

Injection at constant tuning

The graph of figure 6 shows that injecting at constant tuning requires a ramping of the voltage; otherwise this would result in too large amount of reflected power at low beam current (red/black plots). Ramping the cavity voltage from 650 kV at 0-current, up to 1.4 MV at 300 mA, with a fixed tuning angle of 60°, allows to maintain the reflected power below 50 kW and the maximum required power at 145 kW (green plot). In return, at voltage as low as 1.3 MV (650 kV / cavity), the energy and phase acceptance are significantly reduced [8]. However, the experience has demonstrated that it is acceptable as the injection efficiency is nearly unaffected, even without any adjustment of the injection phase (from BO to SR) with the voltage.

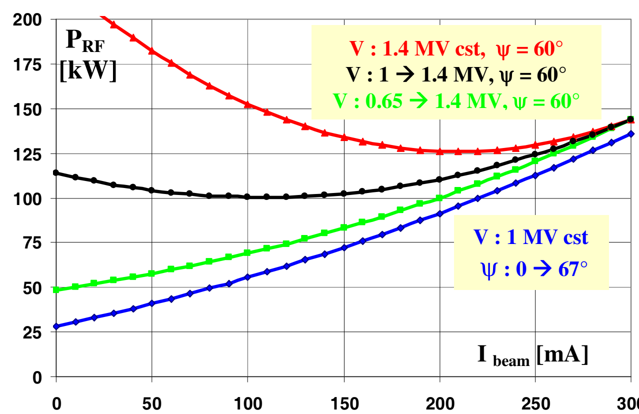

Figure 6 : Required cavity RF power vs I_{beam} for variable (blue) and constant (red, black, green) tuning cases.

Figure 7 shows that, at constant tuning, the shape of the Robinson stability limit (in red) is completely different than with variable tuning (lower graph of figure 5) : it has become quasi linear with the current and the stability margin remains quite comfortable up to 300 mA, even without RF feedback.

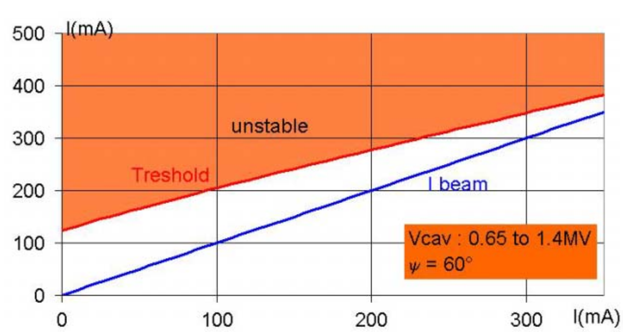

Figure 7 : Robinson stability for constant tuning case

The injection at constant tuning and ramped voltage is now routinely used in operation. A software application, programmed in the PLC dedicated to the RF control, set the cavity voltage and phase as a function of the stored beam current.

First RF operational experience

Cryogenic plant [4]

At the beginning of the commissioning, difficulties were encountered with the cryogenic system, in particular with pressure instabilities inside the cavity He tank, due to thermal oscillations. This was solved after bringing in slight modifications on the cryogenic valve box. The system has then become very reliable and the pressure variations could be kept below ± 2 mbar, namely ± 0.1° in phase. A few shutdowns, triggered by utility losses (water or electrical), have demonstrated the ability of the system to recover within a short time.

Cryomodules [1,5]

The conditioning of the cavities and their power couplers with beam went quite smoothly. A few coupler vacuum trips occurred at first when reaching power larger than 150 kW per cavity. Some further conditioning likely is required for operating at such power level. However, with proper settings, the power does not exceed 145 kW per cavity at 300 mA with a single CM, which is more demanding than reaching 500 mA with 2 CM.

Another successful result is that, there was no evidence of cavity HOM excitation, up to 300 mA. The power dissipation in the HOM loads always remained negligible and the residual beam phase oscillations below 0.1° rms.

As already reported, we took care of using the cavity tuners more sparingly. Moreover, we have recently implemented a rev counter aimed at detecting early possible missing motor steps which are signs heralding a sticking.

The second cryomodule is being fabricated by ACCEL GmbH. The two cavities were successfully tested at CERN in vertical cryostat (figure 8). The implementation of the complete CM2 in the SR is scheduled in May 2008.

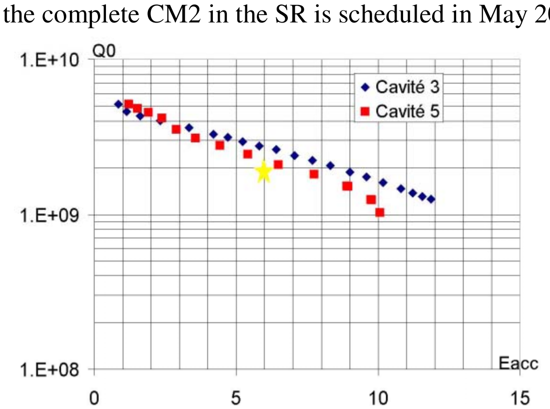

Figure 8 : Q0 vs. Eacc [MV/m] for the 2 first cavities

Amplifiers [2]

The two 180 kW solid state amplifiers for CM1 have demonstrated their good reliability and flexibility in operation. Up to date, they are not yet liable for any loss of beam time. The 1450 amplifier modules were supplied by BBEF - Beijing, integrating LR301 transistors from Polyfet. Although it was not perturbing for the operation, 24 transistor failures occurred after 4835 running hours, at a failure rate which is decreasing with time. The statistics is not yet sufficient to find out what comes from the infant mortality and what is the actual MTBF; longer running periods are required for that. The 100 available spare modules will enable to make a turn over : 50 usable in house while 50 are under repair.

Investigations of other suitable transistors are going on: samples of the BLF369, newly developed by Philips, are being tested and the first results are quite promising; that could be an interesting alternative.

Concerning the amplifiers 3 and 4 for the CM2, 6 of the 8 required 45 kW towers are already completed.

LLRF and controls [3]

With the fully analogue LLRF, presently in use, we can achieve a cavity voltage stability of ± 0.5 % in amplitude and 0.15° in phase without RF feedback and ± 0.1% and 0.05° with the RF feedback, respectively.

A fast digital FPGA based I/Q feedback, is currently under development; the first prototype is completed and should be tested in the real environment in forthcoming runs dedicated to machine development.

CONCLUSION

Up to date, the BO and one half of SR RF plants have been commissioned and the first operational experience is fully satisfactory. After 6300 running hours in the BO (4835 in the SR), they proved to be very reliable and flexible in operation.

Special emphasis is put on the success of the solid state amplifiers, which were the most challenging part of the system; they are not yet liable for any loss of beam time. Several laboratories have expressed their intention of adopting the solid state technology “à la SOLEIL”. Collaboration agreements for the transfer of technology are under elaboration.

The second half of the SR RF system, which is under fabrication, will be implemented in May 2008 for reaching the nominal performance (4.4 MV and 500 mA).

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