TESTING OF SUPER CONDUCTING LOW-BETA 704 MHZ CAVITIES AT 50 HZ PULSE REPETITION RATE IN VIEW OF SPL - FIRST RESULTS *

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Abstract

In the framework of the preparatory phase for the luminosity upgrade of the LHC (SLHC-PP) it is foreseen to characterize two superconducting RF cavities and demonstrate compliance of the required SPL field stability in amplitude and phase using a prototype LLRF system. We report on the preparation for testing of two super-conducting low-beta cavities at 50 Hz pulse repetition rate including the setting-up of the low level RF control system to evaluate the performance of the piezo-tuning system and cavity field stability in amplitude and phase. Results from tests with 50 Hz pulse repetition rate are presented. Simulations of the RF system will be used to predict the necessary specifications for power and bandwidth to control the cavity field and derive specifications for the RF system and its control. Exemplary results of the simulation are presented.

SPL RF SYSTEM

At CERN a design study is under way for the construction of a high power H- Linac (SPL) using super conducting cavities [1, 2]. The SPL should provide a beam power of 4 MW at a maximum energy of 5 GeV using 40 mA beam pulses from Linac 4, under construction at CERN [3], at a 50 Hz repetition rate. An upgrade to Linac 4 is necessary to achieve the pulse repetition rate and beam current required for the SPL.

LLRF SYSTEM SIMULATIONS

The control of the cavity field requires a sophisticated LLRF system similar to SNS [4]. For the development of the overall system and drafting of the specifications for the components of the power system it has been found necessary to resort to simulations. A simulation program has been developed in order to evaluate the operation of up to four cavities supplied by a single klystron. The aim of the modelling effort is to demonstrate under which conditions the field stability required for operation (+/- 0.5 degrees and +/- 0.5 %) during the beam pulse can be achieved. Lorentz Force detuning is taken into account by a simplified model using a first order response with one pole to include the response in terms of detuning due to the field rise.

The simulation model tracks the in-phase (I) and quadrature (Q) components of the cavity voltage, as well as klystron forward and reflected wave. A PID regulation loop is used in addition to a pre-programmed set-point which permits the feedback loop to be closed during the rise of the field in the cavity.

Table 1: Cavity and Operating Parameters for Feedback Simulation (high energy part of SPL)
($\beta = 1$ cavity case)

cavity	R/Q	525 Ω
max field	E_{acc}	25 MV/m
loaded Q	Q_L	1.31×10^6
Lorentz Force (static detuning)	K_L	- 1 Hz/(MV/m)^2
time constant detuning (Lorentz Force)	τ_L	10 ms
beam current	40	mA
flat top (RF pulse length)	1.2	ms
feedback delay	5	µs
proportional gain	50	
integral gain	0.01	

Table 1 shows the parameters used in the simulations to determine the necessary overhead in power required by the feedback in order to obtain the stability in field in absence of active Lorentz Force detuning compensation. These parameters correspond to the SPL high energy part [2] in which 5-cell cavities optimized for a β=1 are proposed. Options with 1, 2 and 4 cavities per klystron were investigated and are being considered.

Figure 1 shows some typical results for the case of one cavity fed by one klystron. The field stability can be achieved very well, despite the large delay in the loop, both in amplitude and phase, with the largest deviation being in phase at the start of the beam pulse. The large delay accounts for waveguide and cable delay which will dominate the overall delay in a layout where the klystrons feeding the cavities are installed on the surface and the accelerator is situated in an underground tunnel.

The beam is exactly injected when reaching the flat top field level. The feedback loop is closed during the cavity field rise. Closing the loop during the field rise creates a transient which turns out to dominate the excess power required on top of what is required for filling and later during the beam pulse for acceleration. This transient can be reduced by closing the feedback loop in a smooth way increasing the gain slowly.

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With the aid of the graphical user interfaces it is easy to evaluate different cases. The most likely scenario is in a staged approach to the SPL construction, feeding the higher energy part with one 1.5-1.6 MW klystron per group of two cavities at a beam current of 20 mA, and in an upgrade to 40 mA install additional klystrons arriving at a single power source per cavity. This configuration is also the choice for the low energy part where the field stability is more critical. For the dual cavity case the investigation was concentrated on the effects of varying parameters across cavities on the stabilisation effectiveness.

There is a partial compensation of the effect of beam loading and Lorentz Force detuning occurring. Excess power is limited to approximately 30 kW and only required at the start of the beam pulse and during loop transients at closing and opening the feedback loops. The model also permits simulations over several RF pulses at the required full rate of 50 Hz.

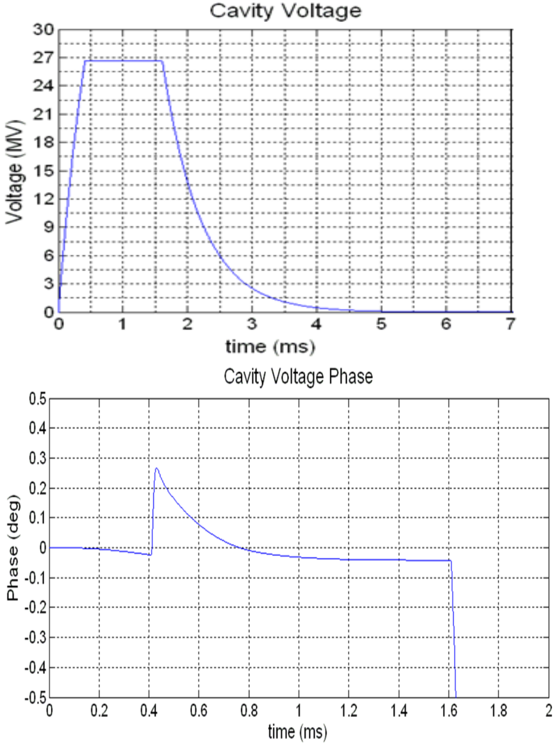

Figure 1: Cavity voltage in simulation, amplitude (top), phase (bottom)

TEST STAND FOR 50 HZ OPERATION AND CAVITIES

The test-stand available for 50 Hz pulsing at CEA Saclay [5] comprises a 1 MW 704 MHz klystron supplied by a modulator capable of the required pulse rate of 50 Hz. The cavity under test is housed in an experimental Cryostat "Cryholab" permitting operation with superfluid He at 2 K, the choice for the SPL design. An IOT amplifier is under commissioning which will permit measurements under static conditions in cw mode, essential for exact calibrations for future measurements. Power couplers with waveguide-to-coaxial transitions have been developed and conditioned up to 1 MW in pulsed operation and are available to feed the cavities [6].

Two superconducting cavities are being tested, developed by CEA Saclay [7] and INFN/LASA, Milano [8], respectively. The CEA Saclay cavity has been successfully tested at 50 Hz pulse repetition rate and preparations are under way for testing of the second cavity. This second cavity features a blade tuner mechanism. Both cavity tuner designs integrate a piezo tuning mechanism for dynamic control of the tune and Lorentz Force detuning compensation. Fig. 2 shows operation of cavity field and klystron power for the tests.

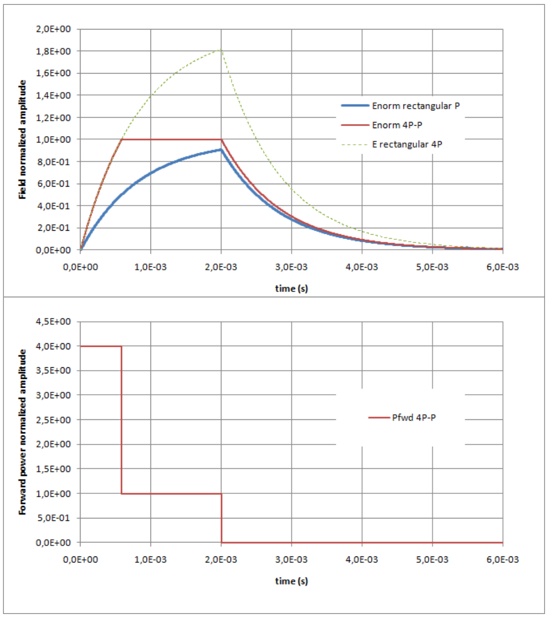

Figure 2: Pulse shape of cavity field and necessary klystron power pulse in tests without beam.

LLRF PROTOTYPE SYSTEM

Based on the LHC LLRF platform [9] key VME boards were modified to work at the SPL frequency of 704 MHz The tuner control board [10] comprises four channels for I,Q demodulation of RF signals and control of a tuner. Signal processing is shared between FPGA and a DSP opening the possibility to more complex control algorithms. Following the installation of this LLRF board at the test stand at CEA Saclay the system was used to acquire cavity field, forward and reflected wave between circulator and cavity as well as the klystron output waveform (between klystron and circulator).

The down conversion uses an LO generated by a PLL at 39/40 f_{RF} = 686.79 MHz resulting in an IF signal at f_{IF} = 17.61 MHz. I and Q IF signals are sampled at $f_S = 4*f_{IF}$ = 70.44 MHz using 14 bit ADCs. On Board memory permits the simultaneous recording of the signals of the four channels. At full sampling rate the memory depth of 128 k samples per channel permit the recording of a time period of 3.7 ms. Decimation is possible in powers of 2, increasing the recording length to 127 s, with lower sampling and frequency resolution (1 kS/s). The system has been used to obtain the results described in the following paragraph.

LORENTZ FORCE DETUNING MEASUREMENTS AND COMPENSATION

During a measurement campaign in 2009 the CEA Saclay cavity has been cooled down and tests performed at different pulse rates. Initial testing started in October 2009 at a pulse repetition rate of 5 Hz. A maximum field of just over more than 15 MV/m was reached in November 2009 using 147 kW forward power for cavity filling and 38 kW during the flat top. The full repetition rate of 50 Hz was first reached in January 2010 at a field level of 13.3 MV/m.

The prototype LLRF system has been used for evaluating the detuning during the RF pulse as well as to record cavity field in amplitude and phase. A separate amplitude loop was used to control the klystron drive signal in amplitude to match the required pulse shape depicted in Fig. 3. A feed-forward for the phase was added to compensate for the klystron output phase change as the power level is decreased at the start of the flat top.

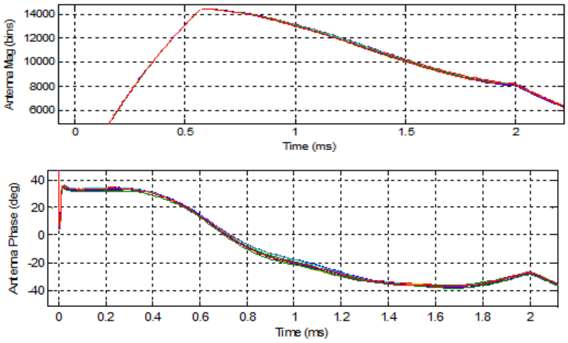

Figure 3: Cavity field stability in open loop without any stabilization, Lorence Force detuning visible

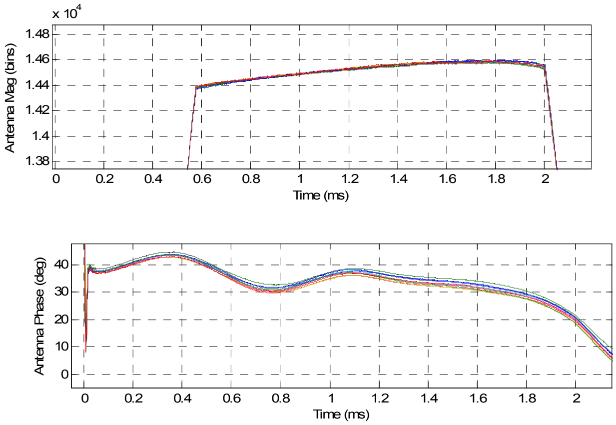

Figure 4: Cavity field stability in open loop using piezo for compensation

Feedback around the cavity was not yet employed, the aim being first to characterize the tuning mechanisms and the degree to which the piezos can be used to compensate for detuning. Fig. 4 shows the field decay in magnitude and phase. The field starts to drop as soon as the cavity tune is noticeably changed. Maintaining the flat top field by a feedback system would require excess power becoming prohibitive at high fields and large detuning. Using a manually optimized piezo pulse starting 940 µs before the RF pulse we could maintain the tune with remarkable precision: 1.4 % flatness in amplitude and +/- 8 degrees in phase were achieved. Application of the piezo pulse hence minimizes the additional power required in closed loop operation.

CONCLUSIONS

50 Hz operation of a low beta cavity has been demonstrated. The piezo tuner has been used to obtain a good flat top with the remaining stabilization easily obtained by standard feedback techniques with a minimum overhead in power. Results from the cavity tests are being fed back to simulations to check the overall performance. Future directions include extending the LLRF to include the full control of the piezo as well as feedback and feed forward on the cavity field.

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