LOW LEVEL RADIO-FREQUENCY DEVELOPMENTS TOWARD A FAULT-TOLERANT LINAC SCHEME FOR AN ACCELERATOR DRIVEN SYSTEM

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Abstract

In view of the construction of the MYRRHA ADS demonstrator in Mol (Belgium), that requires a highly reliable MW-class proton driver, an analysis was carried out to evaluate the fault-tolerance capability of the superconducting linac in the particular case of a radiofrequency (RF) cavity failure. As a complement to past beam dynamics studies, extensive simulations on the RF behaviour of a 700 MHz superconducting cavity as well as its tuning and feedback loop systems have been performed in the case of fast fault-recovery procedures. A prototypical digital Low Level RF (LLRF) system suited to such scenarios is also proposed.

INTRODUCTION

To feed its sub-critical core with an external neutron flux source, the MYRRHA facility requires a 2.4 MW proton accelerator (600 MeV, 4 mA max) operating in CW mode, and producing a very limited number of unforeseen beam interruptions per year. This stringent reliability requirement is motivated by the fact that frequently-repeated beam interruptions can induce high thermal stresses and fatigue on the reactor structures, the target or the fuel elements, with possible significant damages especially on the fuel claddings. The present tentative limit for the number of allowable beam trips is therefore 10 transients longer than 3 seconds per 3-month operation cycle [1].

The conceptual design of the MYRRHA accelerator has been developed during the PDS-XADS and the EUROTRANS projects, following reliability-oriented design practices from the early design stage. It is a superconducting linac-based solution with in particular an excellent potential for reliability in the highly modular main linac, which is designed to be intrinsically "fault-tolerant". The linac is composed of an array of independently-powered spoke and elliptical cavities with high energy acceptance and moderate energy gain per cavity in order to increase as much as possible the tuning flexibility and provide sufficient margins (20 to 30%) for the implementation of the fault-tolerance capability. As a matter of fact, such a scheme should allow to pursue operation despite some major faults in basic RF components: in the case of a loss of any cavity or power loop unit, beam dynamics simulations show that it should be possible to fairly easily and quickly recover the nominal beam characteristics on target by increasing the accelerating fields and retuning the phases of the RF cavities directly neighboring the failed one [2]. This method is of course rather demanding in terms of linac length – about +20% – and installed RF power budget, but is on the other hand totally in-line with the ADS over-design criterion, and in any case seems to be required to try to reach the specified reliability level.

Transient beam dynamics have been performed to better analyze what happens to the beam during such retuning procedures, keeping in mind that they have to be performed in less than one (or a few) second. From this work [3], a reference "fast failure recovery scenario" has been defined, that consists in stopping the beam for 1 sec maximum while achieving the retuning using the following sequence: 1. the RF fault is detected (or anticipated) via suited dedicated diagnostics and interlocks, and a fast beam shut-down is triggered; 2. the new correcting field and phase set-points (previously stored in the low level RF boards' memory during the commissioning phase) are updated; 3. the failed cavity is quickly detuned (using piezoelectric actuators) to avoid the beam loading effect, and the associated failed RF loop is cut off; 4. once steady-state is reached, beam re-injection is triggered.

SIMULATIONS OF A FAST FAULT-RECOVERY PROCEDURE

To evaluate the technical feasibility of such retuning procedures and forecast the future reliability tests of the 704 MHz prototypical ADS cryomodule [4], we computed a model of the cavity with the main characteristics of its LLRF system in the MATLAB Simulink® environment. We established our calculation on a simple model (see Fig. 1) in the frequency domain to estimate the gain and the integration time of the correctors (PI), taking into account the operation in a digital system. A delay and a sampling time (Zero Order Hold function, ZOH) were introduced. The variations of the gain of the 80 kW RF amplifier (IOT) as function of the power delivered and its non linearity have also been taken into account. The cavity accelerating voltage is deduced by modelling the cavity as an RLC resonating circuit. Since the digital LLRF system is using I/Q signals, the differential equation of the cavity voltage is expand in the complex plane: real part (Vc_I) and imaginary part (Vc_Q). This differential equations system is then transformed to the Laplace domain to obtain the cavity transfer functions system [5]. The detuning induced by the Lorentz forces is modelled by a first order differential equation, by assuming that the mechanical modes of the cavity are not significantly excited by the RF power jumps [6]. In this equation the Lorentz coefficient (in Hz/(MV/m)) and the global mechanical constant τ_m of the cavity are taken into

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account. The microphonics perturbations are also implemented as well as the fast cold tuning system (FCTS) control loop. The FCTS model has been extrapolated from room temperature measurements of its transfer function; more details are given in [4].

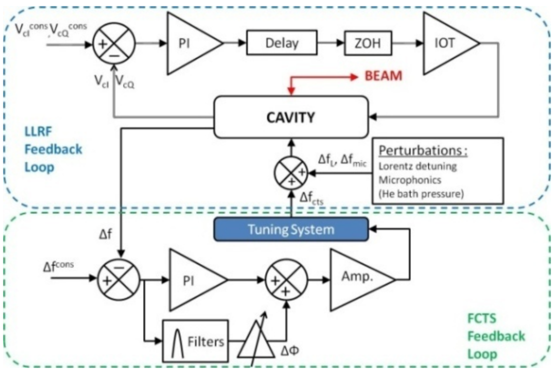

Figure 1: Bloc diagram describing all the modeled elements of the LLRF and tuning System feedback loops.

Results from these simulations study show that during a short beam interruption, it is very feasible to quickly detune a cavity, which of the power supply failed, while the neighbour cavity's set points are updated to compensate for this failure. The main simulation parameters are summarized in Table 1. Pessimistic assumptions were chosen: for example, the external coupling Q_L is twice as much bigger than the optimum one, and the sampling capacities of the digital system is underestimated by a factor of 4. The proportional and integral correctors of the I and Q RF feedback loops were tuned separately and the found optimum values are given in the Table 1. We finally assumed that two main microphonics perturbations were detuning the cavity by several dozen of Hertz. Their frequencies were chosen to be very close to the measured mechanical modes of the cavity [4]. A solution to compensate the microphonics effects would consist in providing a gain only at those perturbations frequencies, as shown in [7]. Therefore, some band-pass filters were added to the PI corrector of the FCTS feedback loop.

Table 1: Simulations Parameters

Parameter	Value	Parameter	Value
Frequency	704.4 MHz	Acc. Gap	0.5 m
(r/Q)	160 Ω	Beam current	4 mA
Coupling Q_L	$3.6.10^7$	Synch. Phase	-30°
Lorentz Coeff.	-5 Hz/(MV/m)	Loop Delay	3 µs
τ_m	1 ms	Sampling time	1 µs
Acc. Field	8.5 MV/m	Max. power	80 kW
Microphonics frequency	80 &120 Hz	Correction gain (I&Q)	110 & 130
Microphonics amplitude	25 Hz max.	Integration time (I&Q)	37.5 ms &16 ms

Figure 2 shows the simulation results in such a scenario. Initially, both adjacent cavities (the n^{th} and $n\text{-}1^{th}$) are in similar conditions. At time t = 0.1 s the beam is injected in the cavities, and a beam loading effect is observed but compensated to ensure a maximum field error not higher than 0.2%. At t = 0.3 s, the n^{th} cavity power supply fails. It is supposed to be detected in 150 µs, and the beam is switched-off. The retuning procedure is engaged 50 ms after the beam stop. To minimise the beam losses, the useless n^{th} cavity is detuned: quickly by 1 kHz with the FCTS, and more slowly, but with a bigger amplitude (20 kHz/s), thanks to the stepper motor. To compensate the faulty cavity, the $n\text{-}1^{th}$ resonator is retuned. Its accelerating field is here increased by 20% while its phase is changed by 20°, which induce a ~50 Hz retuning. By taking into account the capabilities of the digital I/Q feedback system, one can show that stable RF conditions can be achieved in ~50 ms. Finally, 150 ms in total after the incident, the beam can be switched-on again.

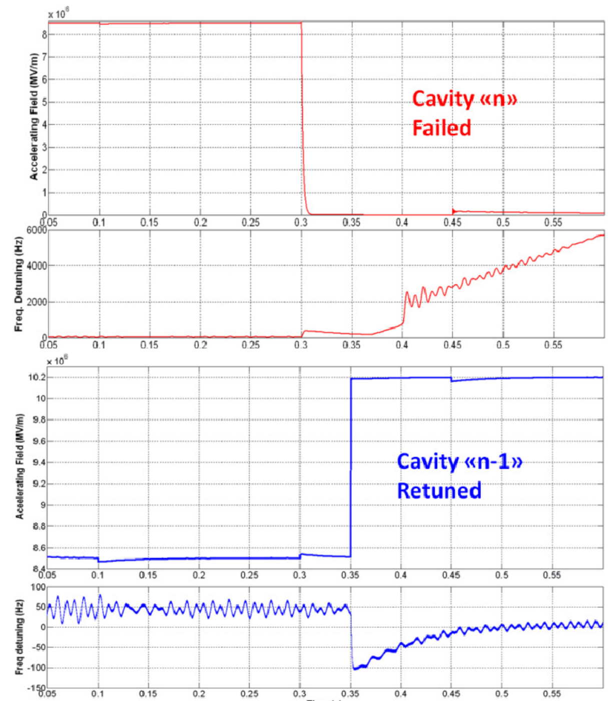

Figure 2: Simulation results for the update of two adjacent cavities during a "fast fault-recovery" scenario.

CONCEPTUAL DESIGN OF A SUITED LLRF SYSTEM

In this context, a conceptual design of a suitable Low Level RF (LLRF) system has been performed [8]. Apart from the requirements linked with fault-tolerance aspects, this LLRF has of course to ensure the stability of the amplitude and the phase of the accelerating cavities' voltage. Beam dynamics extensive simulations have been performed on the MYRRHA linac design with randomly distributed errors. They show that to ensure the < ±1 MeV specification on the energy jitter at the linac exit [1], stabilities better than ±0.5% and ±0.5° total are needed for the field amplitude and phase respectively.

A generic scheme of the Ads-type LLRF system is proposed on Fig. 3. The regulation loop principle is based on the processing of the transmitted RF signal coming directly from the RF cavity pick-up. This signal is first down-converted to an IF signal (here 10 MHz) and then sampled by an ADC with a defined sampling rate (e.g. 40 MHz) to be processed by the digital LLRF board. I/Q demodulation is then performed and the I/Q parameters, which describe the in-phase (I) and quadrature (Q) components of the cavity field vector, are filtered by a low pass filter to reduce high frequency noise, and then compared to the stored nominal set-points. The obtained differences are then corrected by a control algorithm for both I and Q components. Different feedback control algorithms can be implemented. The most usual one is the PID controller, but more sophisticated algorithms such as Kalman filter, Smith predictor or time-optimal controller could be used; feed-forward capability can also be implemented if needed. Finally, the I/Q calculated control signals are converted by 2 DACs and used to modulate, via a vector modulator, the input signal of the RF power source feeding the cavity.

The digital LLRF board itself is driven by a FPGA microchip, able to process the feedback control algorithms while minimizing the latency, which corresponds to a direct limitation of the maximum gain allowed by the stability of the system. Several ADCs and DACs are used to convert the received and produced signals, and a RAM memory is foreseen to store set-points or save operating parameters. A classical bus will ensure the link with the general control/command system, while an additional fast serial bus (e.g. Rocket IO) will be used to communicate with adjacent boards and ensure that adjacent cavities are quickly informed in the event of a failure.

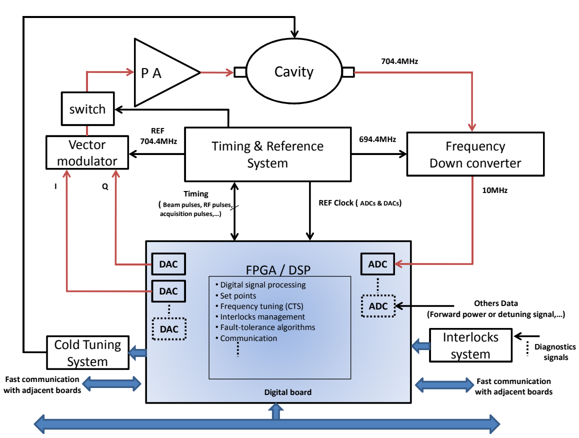

Figure 3: ADS-type LLRF system general scheme.

Two prototypes of such digital boards have been developed so far. These digital PID-based LLRF systems have been first tuned and tested successfully at room temperature with a copper model of a spoke cavity. It was then tested at 4K and 2K on a beta 0.15 spoke cavity equipped with its cold tuning system inside an horizontal cryomodule. Very good results have been obtained, especially on the new version of the digital board (V2), with an achieved regulation precision better than 0.15% and 0.1° rms in amplitude and phase respectively (Fig. 4). This LLRF digital system will be used with the 700 MHz superconducting cavity test bench [4], to pursue analysis on fast recovery procedures of the MYRRHA fault tolerant linac project.

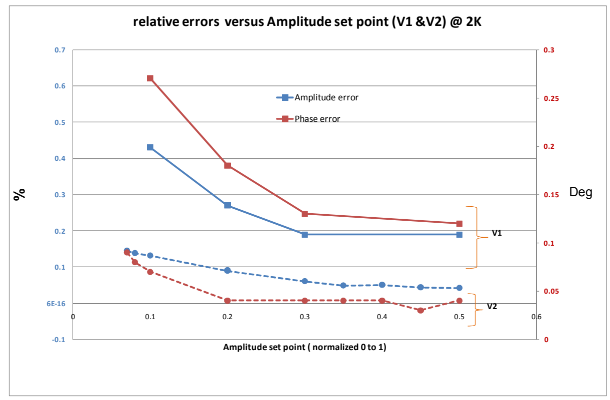

Figure 4: Measured performances on a Spoke cavity at 2K of the two prototype DLLRF systems (rms values).

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REFERENCES

[1] J-L. Biarrotte et al, “Accelerator reference design for the MYRRHA European ADS demonstrator”, these proceedings.

[2] J-L. Biarrotte et al., “Beam dynamics studies for the fault tolerance assessment of the PDS-XADS linac design”, Proc. HPPA 2004, Daejeon, Korea.

[3] J-L. Biarrotte, D. Uriot, “Dynamic compensation of an rf cavity failure in a superconducting linac”, Phys. Rev. ST – Accel. & Beams, Vol. 11, 072803 (2008).

[4] F. Bouly et al., “Developments, tests and reliability considerations of a 700MHz prototypical cryomodule for the MYRRHA ADS proton linear accelerator”, these proceedings.

[5] T. Schilcher, “Vector Sum Control of Pulsed power accelerating Field”, Phd Thesis, Universität Hamburg, Hamburg, 1998.

[6] A. Mosnier, “Control of SCRF cavities in High power proton Linac”, EPAC’08, Paris, June 2002.

[7] M. Luong et al, “Analysis of microphonics disturbances and simulation for feedback compensation”, EPAC’06, Edinburgh, June 2006.

[8] O. Piquet et al, “Task 1.3.4 final report”, EUROTRANS deliverable, D1.66, December 2008.