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EUROPEAN FEL Design Study

Deliverable N°:	D5.13
Deliverable Title:	Analog RF control of ELBE modules
Subtask :	RF Control of CW Cavities
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1. Introduction

The operation of the major components used for controlling the phase and field level of the ELBE RF cavities is described. The ELBE RF system is designed as an analog and direct converting (without IF) system, each cavity is controlled by it´s own loop. The architecture of the system is the same for each of the 4 superconducting cavities and the 2 normal conducting bunchers /1/.

The paper considers suggestions outlined in the EUROFEL-Report-2005-DS5-010, /2/.
As far as recovery issues are concerned (ERL), not all measurements of relevant RF parameters made at ELBE can be transferred completely to an ERL design. One reason is the fixed tip length of the RF coupler at ELBE, designed for operation at full beam power (8.5 MeV, 1 mA, CW). This limit is set by the maximum available klystron power of 8.5 kW (at 1dB signal compression). Thus the operating bandwidth of the ELBE RF cavities is set to 114 Hz, corresponding to a loaded quality factor of 1.2 10^7. A waveguide 3 – stub tuner is used to compensate mechanical tolerances of the antenna tip length. This tuner allows a variation of the bandwidth manually. Operation at bandwidths below 50 Hz causes instabilities.

2. The ELBE RF-System

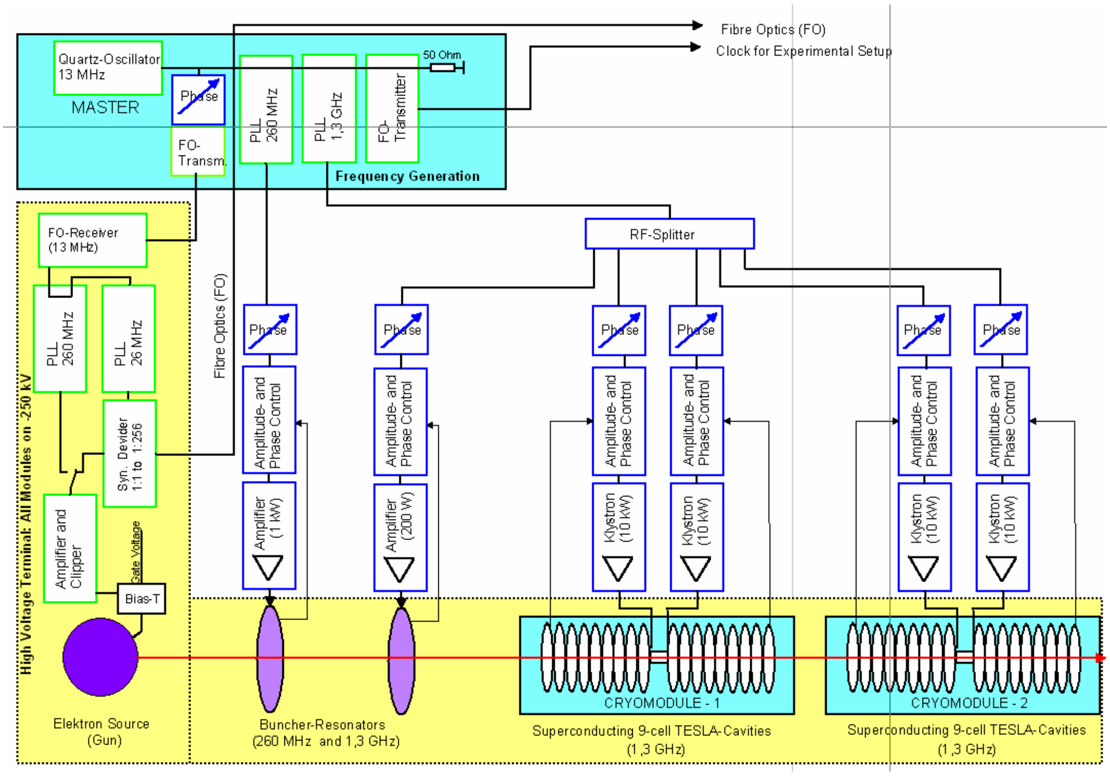

Figure 1: Block Diagram of the ELBE RF-System /3/.

Figure 1 is the layout of the system for 4 superconducting cavities (frequency 1.3 GHz) and 2 (normal conducting) bunchers (260 MHz and 1.3 GHz).The RF phase against the beam phase can be adjusted by remote controlled phase shifters (trombone-type with dc servo motors). Fibre links are used to control the electronics on the -250 kV platform. The RF system is controlled by a 13 MHz MASTER oscillator. Much care was taken to provide “very clean” oscillator signals because the phase noise affects the energy spread of the accelerated electron beam directly.

The 13 MHz master oscillator is housed in a temperature controlled, double shielded quartz oven. The long time stability is better than 1 10^8 per year. The 13 MHz clock signal is distributed via buffers to synchronize the 260 MHz and 1.3 GHz PLL´s . Fibre links with temperature stabilized light transmitters and receivers are used to distribute the clock signal within the labs and to the -250 kV terminal of the electron gun.

The excellent phase noise performance of the 1.3 GHz PLL, shown in figure 4, was obtained by implementing an stabilized “high - Q” quartz oscillator (144 MHz) into the PLL design and by a carefully optimized loop filter. Side band phase noise in terms of jitter (rms) is: 100 fs for the 13 MHz MASTER within 10 Hz to 10 kHz from carrier and 170 fs for the 1.3 GHz PLL within 10Hz to 10 kHz from carrier/5/.

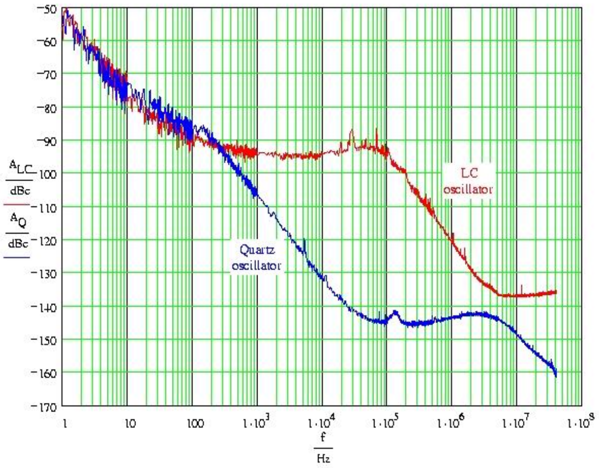

Figure 2: Phase noise characteristics of the 1.3 GHz PLL /5/.

3. The Low Level RF Controller

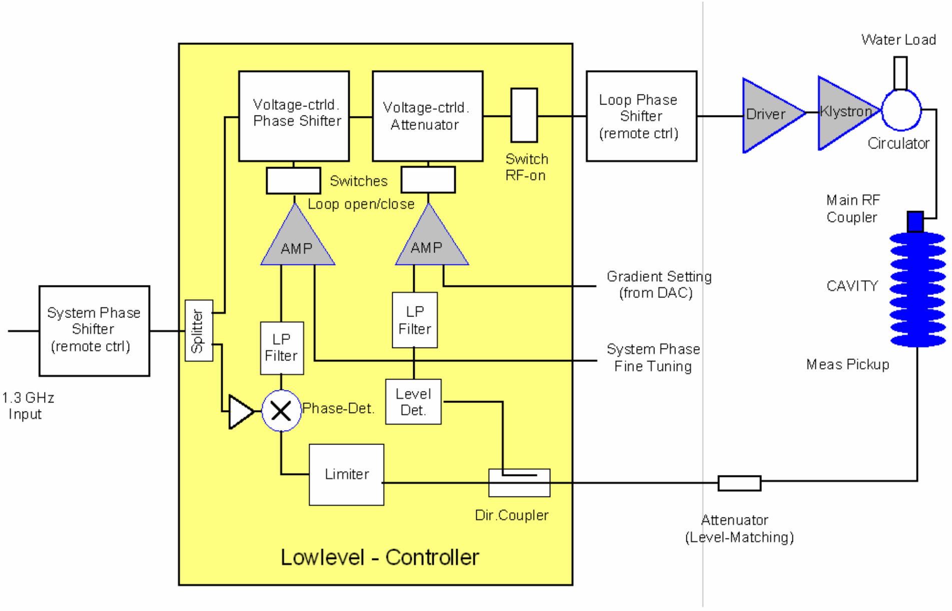

Figure 3: Block diagram of the Low Level RF Controller

In the block diagram, the 1.3 GHz input signal is fed via the system phase shifter (trombone-type with dc-servo motors) to the controller. This remote controlled system phase shifter is used to vary the RF phase against the beam phase. The signal is than split into two paths. The “lower path” drives a high level mixer (+17dBm) of the phase detector, the “upper path” is connected to the voltage controlled phase shifter (phase controller: setting range 60 deg) and the amplitude modulator (voltage controlled modulator). Passing the RF switch (RF on/off) and the loop phase shifter (loop stability) the signal is amplified to +4 …12 dBm and feeds the klystron driver. The input level requirement of the klystron rack is 0 dBm for 10 kW (+70 dBm) RF output.
The feedback line from the fundamental pickup of the cavity to the controller is aged coax cable (Andrews FSJ4-50B) to perform phase stability. The controller has two individual loops to control phase and amplitude. Attenuators in front of the controller are used to match the input level, depending on the cable length. A directional coupler is used to derive the pickup signal to the amplitude- and the phase detector. The phase dependency of the limiter in front of the phase detector is 4 deg within the dynamic range of the pickup signal (-2dBm to +16 dBm). All signals (settings, readings, switches) are controlled by a SPC (SIMATIC). The outputs of both detectors (amplitude and phase) are monitored.

4. Performance of the Low Level RF System

To keep the energy spread of the accelerated electron beam below 10^{-3}, the stability of the field amplitude has to be better than 0,5 % and a RF phase stability 0.3 deg rms /4/. The measured energy spread at ELBE is in the same order, exactly between 20 and 100 keV, depending on the setting of the machine. The measured stability of the field amplitude at ELBE is typically $2\ 10^{-4}$ rms /8/. The RF phase stability of the closed loop is 0.02 deg rms /8/. A proper adjustment of the gain of the control loops is needed as well as the minimization of all disturbances. For the loop amplifiers very fast low noise OPA’s are used to get a gain bandwidth product of about 800 MHz. The RF bandwidth of the controller is between 5 and 10 MHz, the loop gain is adjustable between 10 and 100. The overall 3 dB bandwidth of the RF system (without cavity) is limited by the klystrons (typically 4 MHz) and the circulators (typically 1.5 MHz).

Disturbances affecting the stability of the control

Lorentz Force Detuning

State of the art RF systems for pulsed operated LINACS use active cavity tuners to compensate for lorentz force detuning (and microphonics) to reduce the installed RF power. For CW machines like ELBE this is not a “must” because lorentz force detuning is only an issue during ramping up the gradient.
The cavity tuners are manually controlled to save lifetime of the tuner gears.

Pulsed RF operation at ELBE is planned in the near future. First experiments with pulsed RF have been done successfully to increase the field gradient within the limits of the helium consumption /7/.

Microphonics

Microphonics is an important issue also at CW LINACs. Figure 4 displays a typical FFT spectrum observed on the phase detector output of Cavity 1 (closed loop).

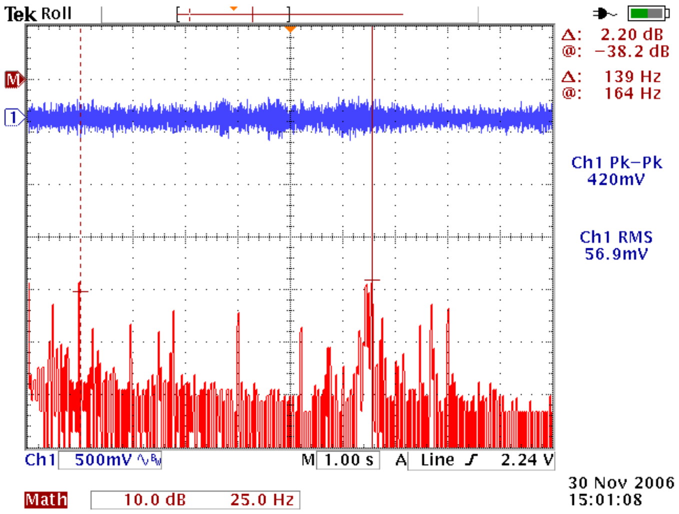

Figure 4: FFT Plot of Microphonics of Cavity C1 (example) /6/.

In the blue curve (phase detector output) the peak to peak value of 420 mV_{pp} is equal to a frequency deviation of 8 Hz, whereas 57mV rms is equal to 1.2 Hz rms respectively /6/. In the FFT-spectrum (red curve) the peaks represent sources contributing to microphonics. Some of them could be identified yet, e.g. the 48 Hz peak is allocated to a membrane pump. Systematic investigations on microphonics at ELBE are under way and will be presented in a further report.

Dynamic response of the Low Level RF Controller

The dynamic response of the phase controller is presented in figure 5. The upper trace represents the macropulse. The macropulse is gated with 100µs square wave pulses (middle curve) to test the response of the controller. The output signal of the phase detector (lower curve) is the response on the gated macropulse.

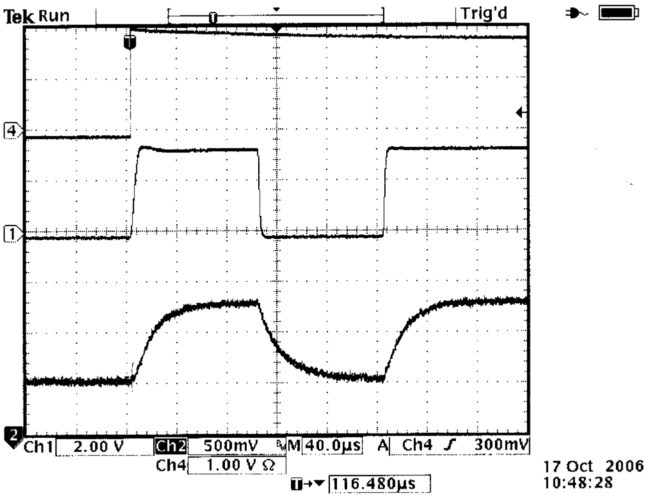

Figure 5: The dynamic response of the phase controller is 40 µs (lower curve)

Stability of the Helium pressure

The most sensitive source affecting RF stability is the He-pressure. At ELBE a lot of experimental work had been investigated to fix the best working point for the machine. Assuming no helium pressure fluctuations the measured phase stability of the phase controller is 0.02 deg rms. The working pressure of the He-plant at ELBE for best long time stability is 31 mbar. The pressure stability is +/- 0.05 mbar /8/. A deviation of 0.1mbar shifts the frequency of the accelerating Pi-mode about 40 Hz. This is within the cavity bandwidth of 114 Hz.

5. Performance of the RF-System (summary) /8/

Cavities:	**Nominal**	**Actual**
Frequency	1.3 GHz	1.3 GHz +/- 5 Hz
Bandwidth (3dB)	100 Hz	114 Hz
Phase noise related microphonics	1.5 … 3.5 deg rms (DESY)	2…6 deg peak-peak
RF System		
Frequency stability	$< 1\ 10^{-8}$	$< 1\ 10^{-}9$
Aging in 10 years		$< 3\ 10^{-7}$
Phase noise	< 0.1 deg rms	< 0.05 deg rms)*
Cavities and RF System		
Phase noise	< 0.1 deg rms	< 0.05 deg rms)*

Measurements at a gradient of 10 MV/m without beam

Phase stability	rms /< 1 sec	0.02 deg
	per day	< 1 deg
Amplitude stability (correlated and uncorrelated)	rms / < 1 sec	$2\ 10^{-4}$
	per day	$2\ 10^{-4}$
LHe pressure stability		+/- 0.05 mbar

6. References:

[1] A. Büchner, F. Gabriel, E. Grosse, P. Michel, W. Seidel, J. Voigtländer, "The ELBE-Project at Dresden-Rossendorf" EPAC'2000, Vienna, June 2000.

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[6] A.Buechner and F.Gabriel, private information, 2006.

[7] G.Staats, „Parameter Measurements with existing ELBE Moduls“, Deliverable 5.9, these EUROFEL proceedings , Dresden-Rossendorf, 2006.

[8] F.Gabriel, Documentation of the LLRF-Controller, internal paper,