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CHARACTERIZATION OF AUTOMATIC FREQUENCY CONTROL SYSTEMS FOR S-BAND PROTON LINAC "TOP-IMPLART"

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Abstract

The TOP-IMPLART (Intensity Modulated Proton Linear Accelerator for RadioTherapy) proton linear accelerator is under development at ENEA-Frascati. It is composed by a 7 MeV, 425 MHz injector followed by a sequence of 2997.92 MHz accelerating modules. Four 10 MW klystrons will be used to power all high frequency structures up to a beam energy of 150 MeV. The first section, consisting of 4 SCDTL modules (7 to 35 MeV) is operational at low repetition rate (up to 50 Hz).

Whereas beam acceleration is effective even without closed loop control, to ensure high beam current stability the resonance frequency variation must be kept for each SDCTL module within few kHz. This is achieved implementing an automatic frequency control (AFC) loop that detects structure detuning caused by thermal drifts and produce an error signal fed to a tuning motor.

Different AFC systems have been tested on TOP-IMPLART linac including a prototype of a custom solution derived from a medical electron linac. This was originally designed for magnetron frequency tuning with much larger frequency span. Other AFC systems with different components have been evaluated in order to reach the high required resolution.

ACCELERATOR DESCRIPTION

The TOP-IMPLART project, funded by Regione Lazio, aims at the realization of a compact, high-frequency LINAC for proton therapy [1].

General Layout and Status of the Accelerator

Presently the first section up to 35 MeV, comprised of 4 SCDTL accelerating modules powered by a single 10 MW klystron, is under commissioning. Short and long term beam current stability, in particular, are under investigation in order to validate this accelerator scheme for the purposes of clinical treatment [2]. In this contribution we will focus on the application of an Automatic Frequency Control system on the SCDTL tanks to ensure the prescribed electric field stability.

Figure 1 outlines the SCDTL section layout together with the RF distribution system. The RF power is provided by a TH2157A klystron driven by a solid-state modulator K1 by SCANDINOVA . The RF power distribution system, based on a main power divider, two splitters and three phase shifters, partitions the input power setting the correct RF level and phase relations for the four SCDTL modules. Several -55/-60 dB calibrated directional couplers are placed in the RF line to retrieve information on the amplitude of the signals driving the structures. The main characteristics of the output beam are reported in Table 1.

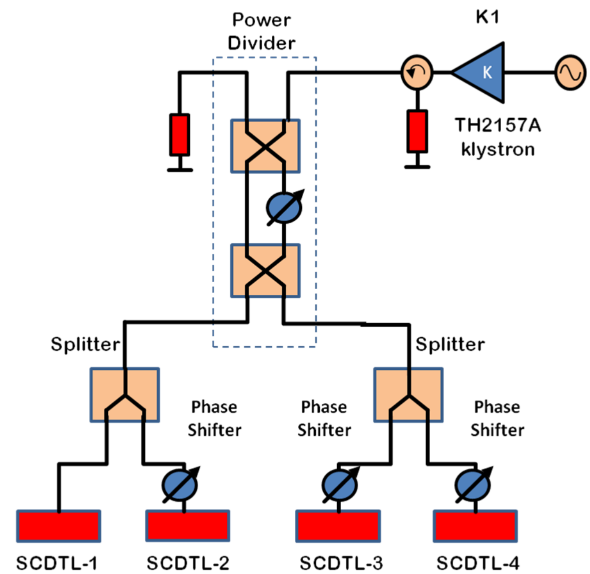

Figure 1: SCDTL section and RF distribution system layout of TOP-IMPLART accelerator.

Table 1: Extracted Beam Properties from 35 MeV Section

Parameter	Value	Unit
Energy	35	MeV
Current	1 - 40	µA
Pulse length	4	µs
Repetition frequency	20 - 50	Hz

STABILITY REQUIREMENTS

To guarantee the desired current stability the RF amplitude and phase stability requirements for the accelerating field of the SCDTL structures are ±0.5% and ±2 degrees, respectively. Since the RF frequency is set for all the cavities by the Klystron seed to 2997.92 MHz, these specifications allow each SCDTL module a maximum detuning of the order of ± 10 kHz, the specific tolerance depending on the Q_{Load} of each structure due to the relation between the field phase and detuning:

$$\phi = -atg(Q_{Load}\chi) \tag{1}$$

where $\chi = \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}$ is the detuning parameter and ω_0 the nominal frequency.

The main contributor to frequency detuning of the cavities is thermal expansion. In the S-band frequency range

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the resonant frequency shift per degree centigrade is 50 kHz. For this reason, while each module is independently thermo-regulated at a target temperature to reach the nominal resonant frequency, they are also equipped with a motor actuated tuner, i.e. a 4 mm diameter copper rod that can be inserted in the central tank of each module with a maximum excursion of 10 mm, varying the resonant frequency on a ≈ 70 kHz span allowing compensation of temperature fluctuations up to ≈ 1.5 °C of amplitude. Figure 2 shows the tuner calibration data for SCDTL-2. Data are obtained at low RF power with a network analyzer.

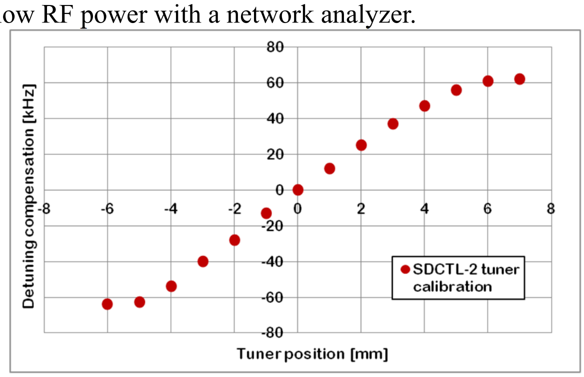

Figure 2: Calibration of SCDTL-2 tuner showing tuner position (in mm) vs detuning compensation (in kHz).

This device when coupled with a detuning measurement and feedback loop, constitutes the Automatic Frequency Control system which allows the compensation of thermal instabilities.

AFC PRINCIPLE

The Automatic Frequency Control system relies on the property of 90° hybrid to produce an output signal whose amplitude is dependent on the relative phase of the input signals, while the output phase is insensitive to the input phase difference (see Fig 3).

The output ports signals amplitude difference is proportional to the sinus of the input signal phase difference and the product of their amplitude.

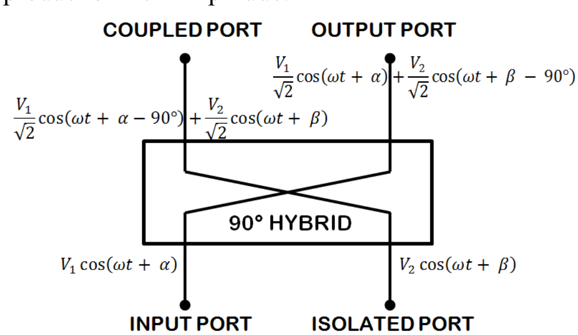

Figure 3: Input and output signals for a 90° hybrid

In typical AFC implementations the output port signals are converted into video signals by RF power detectors whose outputs are then processed by a comparator: if the power detectors response is linear the AFC signal can be written as:

$$AFC = K\, V_1 V_2 \sin(\alpha-\beta) \tag{2}$$

K is a parameter that takes into account signal attenuations, the power detectors response coefficient and amplification.

The input signals for the TOP-IMPLART AFC system are the Forward and Reflected power. The detuning-phase relation for reflected power is:

$$\phi_r = -atg\left(\frac{2\beta Q_0 \chi}{\beta^2-1-Q_0^2\chi^2}\right) \tag{3}$$

For TOP-IMPLART structures typical β and Q values, the reflected power phase error is approximately ten times the field one (Eq. 1) therefore allowing greater sensitivity to the detuning.

The signal amplitude for the reflected power is proportional to the S11 parameter, which, in steady state approximation, is:

$$S11 = \sqrt{\frac{(\beta-1)^2+(Q_0\chi)^2}{(\beta+1)^2+(Q_0\chi)^2}}$$

Assuming the Forward power is constant, Eq. (2) thus becomes:

$$AFC = K' \cdot S11 \cdot \sin\phi_r$$

AFC PROTOTYPE DESCRIPTION AND EXPERIMENTAL TESTS

Preliminary tests of an AFC system on one of the SCDTL modules have been performed using an AFC prototype (Fig. 4) manufactured by Sordina IORT Technology (SIT) [3], a firm producing electron linear accelerators for intraoperative radiotherapy. This prototype derives from the AFC system for magnetron frequency control of their linacs.

The RF input signals are acquired on the front of the crate (box 1 of Fig. 4) and processed by the 90° hybrid (box 2 of Fig. 4) and amplified (box 4 of Fig. 4). Amplified video signals for AFC, Reflected, Forward and Field Power are available on the rear of the crate (box 5 of Fig. 4). A tuneable phase shifter for AFC signal zeroing is highlighted in box 3 of Fig. 4.

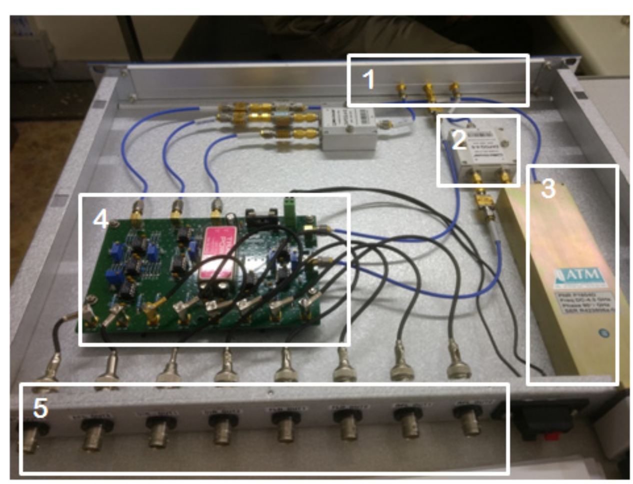

Figure 4: Picture of prototype AFC by SIT.

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AFC Prototype Test on SCDTL-3

Output charge beam measurements have shown that most of the variability in the output is produced by the second and third SCDTL modules where the maximum temporal long-term oscillation of electric field occur. For this reason we choose to test the only AFC system available at the time on SCDTL-3 module, where the effect is more pronounced. Table 2 summarizes SCDTL-3 parameters relevant to the AFC system. Note that the power level reported are those typical at the 90° hybrid ports.

Table 2: SCDTL-3 Parameters Relevant for AFC System

Parameter	Value	Unit
Q_0	9163	-
β	1.05	-
RFL power @ hybrid input	< 0.7	mW
FWD power @ hybrid input	≈ 300	mW

The AFC signal is an input for the tuner motor control: the tuner is moved at fixed speed and variable direction minimising the difference between the measured AFC value and a reference value corresponding to a minimum reflected power.

Figure 5 compares the AFC, reflected power and cavity field pick-up signals of SCDTL-3 acquired in two consecutives run of the accelerator (5k pulses at 20 Hz repetition frequency each) without and with the AFC loop. Data were acquired with the method described in [2]. All signals are the output of RF Schottky diodes detectors which yield a voltage linearly proportional to the input power (N.B. cavity field pick-up signal is therefore proportional to the square of the electric field).

Through analysis of the reflected power we obtain an estimate of the typical detuning of SCDTL-3 structure: ≈ ± 22 kHz, well within the tuner range of compensation.

The corresponding maximum phase error for the cavity field and for the reflected power (from Eq. (1) and Eq. (3)) are ≈ ± 4° and ≈ ± 75°, respectively.

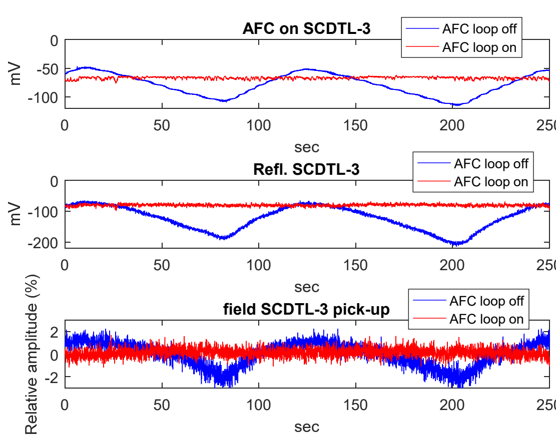

Figure 5: AFC, Reflected power and Cavity field signals comparison without and with AFC loop.

Without any frequency control the electric field amplitude oscillation, caused by the temperature cycle of the thermo-regulator, is a little over ± 1%. This effect is cancelled by the use of the AFC loop.

PRELIMINARY CHARACTERIZATION OF COTS AFC SYSTEM

A different AFC system manufactured by AFT microwave [4] was acquired in order to test it on our accelerator. With respect to the SIT prototype its main advantage would be its availability, being a COTS product, the drawback the need to provide an external differential amplifier (see Figure 6).

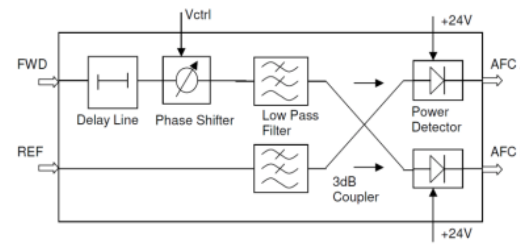

Figure 6: AFC circuit block diagram from AFT microwave datasheet [4].

Preliminary characterization of this system on RF bench and comparison to similar measurement on SIT prototype were carried out to assess the relative sensitivity of the two AFCs and dimension the amplifier for the AFT module.

While in the real application the input power of reflected and forward signals are very different (see Table 2) in these measurements we used for the two AFC systems a low power RF source as input for both forward and reflected signal: the signal is split by an additional 90° hybrid and the phase difference is introduced with a calibrated phase shifter. The input power was set to 13 mW: this power level is consistent in terms of average power (proportional to V_1V_2) with the experimental setting in the tests of the SIT system mounted on SCDTL-3 (see Table 2). The measured sensitivity in the bench tests was 5 mV/deg for SIT system and 0.9 mV/deg for AFT system (both read on the scope @ 1 MΩ). The much lower sensitivity of the AFT system depends on the fact that it is designed for much higher input power level with respect to SIT AFC prototype. Therefore in our configuration the use of the AFT system will require to reduce the attenuation level of the input power: we expect to use as optimal values 1.5 mW for RFL power and 2400 mW for FWD power, resulting in an average power of 60 mW. Assuming the system response is linear between this two power levels, we expect a response at 60 mW of the order of 4 mV/deg, not too different from SIT AFC prototype. For this reason we expect the same differential amplifier could be used for both AFC systems.

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