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LINAC LLRF Technical Specifications

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Riassunto / Abstract

Technical specifications for CNAO LINAC Low Level Radio Frequency (LLRF) control migration to a new digital LLRF control system.

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	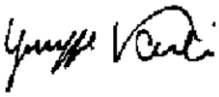		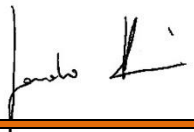

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SUMMARY

1 CONTEXT AND INTRODUCTION

The CNAO (National Center for Oncological Hadrontherapy, www.fondazionecnao.it), based in Pavia, is an innovative and technologically advanced structure, established by the Ministry of Health with the aim of treating patients suffering from solid radioresistant tumors through the use of protons and carbon ions, particles called hadrons (hence “hadrontherapy”). For this reason, a "synchrotron" was created at CNAO to accelerate both particles. The generated beams are used for both therapeutic and clinical and physical research purposes.

CNAO is the Lombard research organization leader of the INSPIRIT project, conducted in partnership with INFN and the PMI Hifuture, (PROJECT ID 1161908 CUP E18I19000180007) funded by the Lombardy Region under the POR FESR 2014-2020 Call Hub Research and Innovation. The project has among its objectives the realization of an innovative source capable of producing new ionic species that will be accelerated by the synchrotron and directed to the experimental room to be made available for research and industrial activities. The project includes a series of machine upgrades necessary for the operation of the new source, including the supply in question, consisting of a new digital LLRF (Low Level Radio Frequency)

Below is the description of the components of the particle accelerator present at the CNAO of Pavia.

LINAC

The Linac (LINear ACcelerator) has the function of accelerating particles coming from a source, towards the synchrotron, at an energy of 7 MeV / u.

It is made up of three elements:

- RFQ;
- IH;
- DEBuncher.

Each element consists of:

- An LLRF;
- A single-stage or multi-stage RF amplifier unit;
- An accelerating cavity;
- A cavity tuning system called "Resonance Frequency controller (RES_Contr)"

The three systems differ in maximum output power:

- RFQ = 200KW;
- IH = 1400KW;
- DEbuncher = 4 KW.

The LINAC is a synchronous system as it has a single RF reference source.
The cavities are located in the synchrotron room. The RF signal is instead generated and amplified at a distance of 40 m and transmitted on a waveguide to the cavity. Three probes take the RF signal from the cavity: one of them is used for monitoring, while the other two are used by the LLRF. Of the two probes used by the LLRF, one (called *amp-tank-probe*) is sampled to measure the amplitude of the signal in the cavity, while the other one (called *phase-tank-probe*) is sampled to measure its phase.

Each cavity is tuned through a mechanical element called "plunger".
The "Plunger" is managed by the module called "resonance Frequency controller" with the following functions:

- To measure forward and reflected power and to calculate the VSWR (Voltage Standing Wave Ratio) from them;
- To minimize VSWR by moving the plunger in and out of the cavity.

Figure 1 presents above described system.

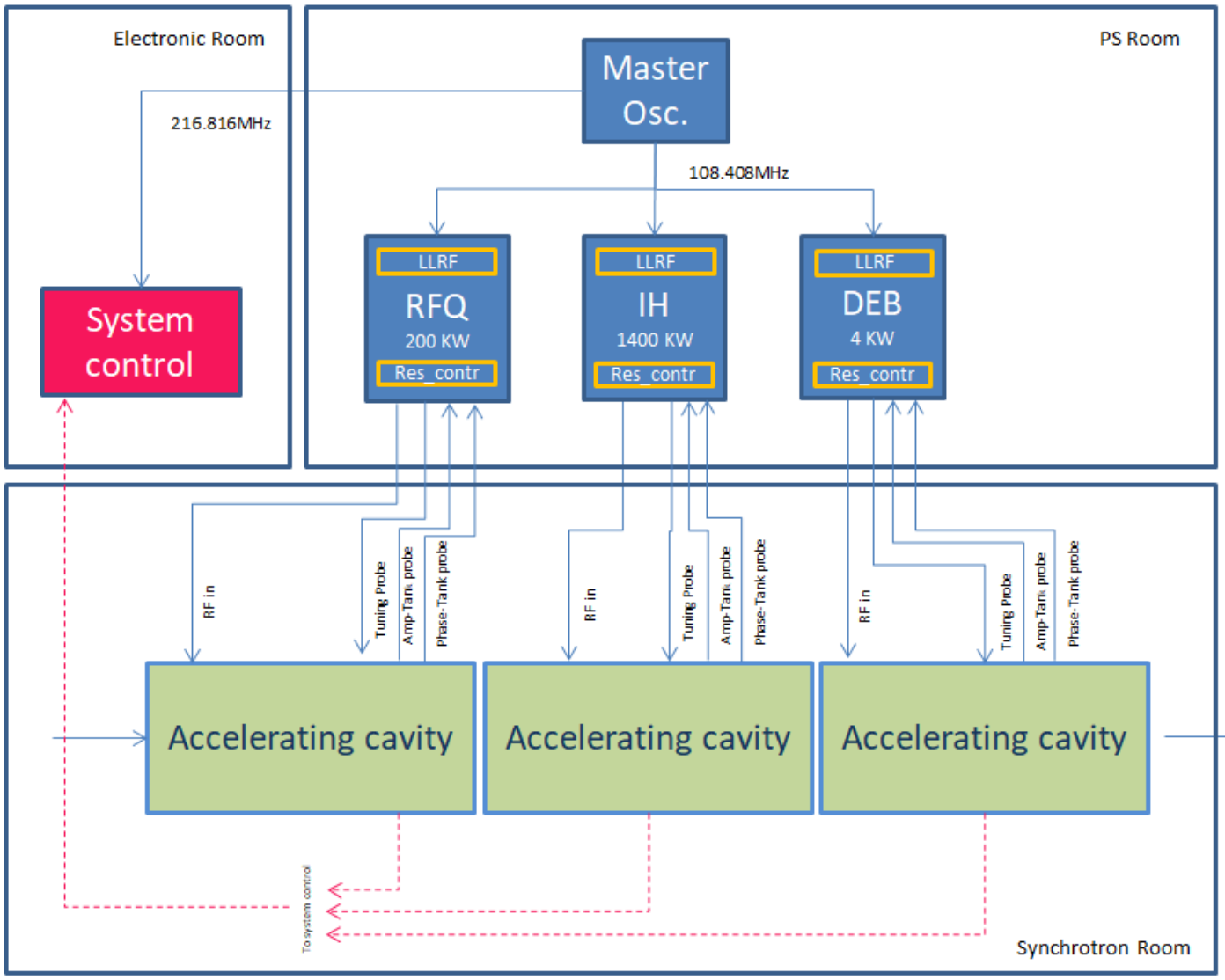

Figure 1 - LINAC system overview.

The probes used by the resonance frequency controller are installed just downstream each amplifier and provide measurements of forward (FWD) and reversed (REV) power; fwd and rev powers are measured by the LLRF system, too.

Figure 2 shows system layout for the IH, from LLRF board to the IH cavity.

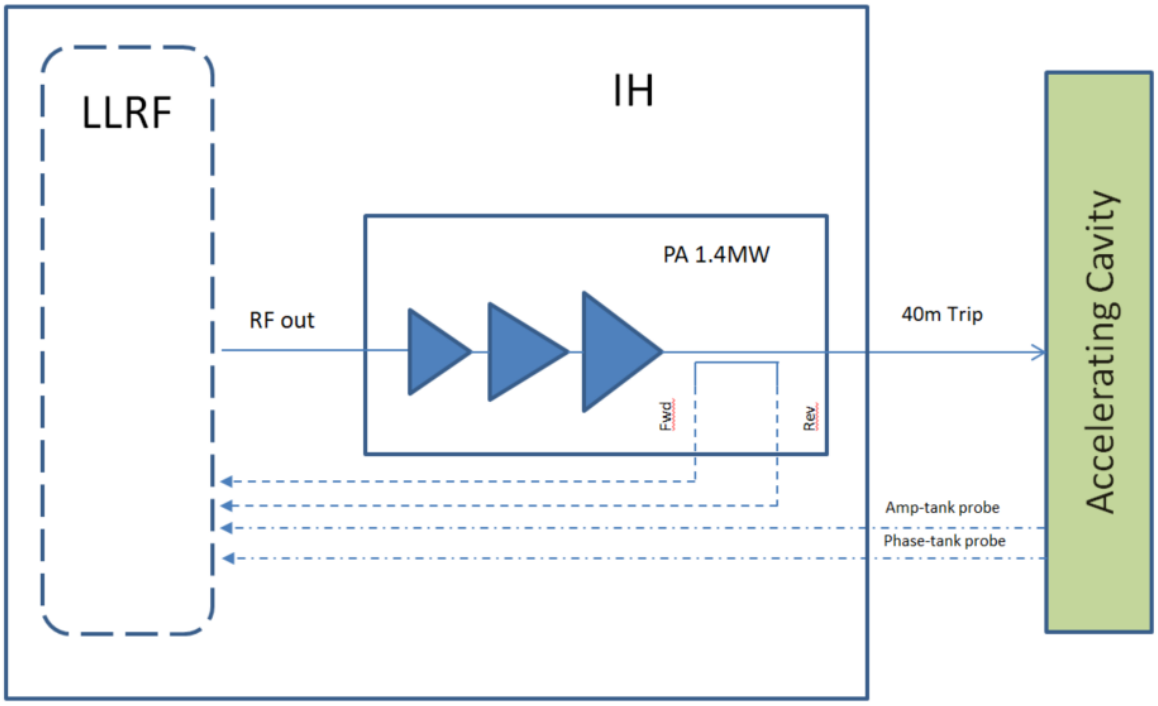

Figure 2 – Details of the IH system: LLRF, amplifier and cavity. Tuning probe is not sketched since it is not connected to the LLRF board.

LINAC working frequency is 216.816 MHz; the RF signal is a continuous (CW) not-modulated sinusoid. On the other hand, LINAC itself works in pulsed mode: it supplies power for 500µs only, every 100ms.
The RF pulse is generated at the occurrence of either, the *stability pulse* trigger or the *beam pulse* trigger. They are two physical triggers, with different purposes, and the RF pulse they trigger is different in amplitude and phase, as consequence. The *stability pulse* trigger aims to maintain the cavity at constant temperature, while the *beam pulse* trigger makes the LINAC ready for beam injection. When the *beam pulse* trigger occurs, a 100µs-long beam pulse is injected into the LINAC cavity, time-centred with respect to the 500µs-long RF pulse.

LLRF system always receives a trigger every 100ms; a priori, it is not known if it is going to receive the *stability pulse* trigger or the *beam pulse* trigger. Tipically, the *beam pulse* trigger either occurs every 1-to-15 seconds, or it is absent for long periods (minutes or hours).

At now, LINAC LLRF system is made up of fully analogic boards.

2 OBJECT OF THE SUPPLY

The object of this contract is the supply of n. 6 digital electronic LLRF boards which, with an appropriate firmware configuration, are able to implement the RF signal control for IH, RFQ and DEBuncher on the FPGA.

The implementation must comply with the technical specifications and functions described in this document.

We require the creation and supply of the following objects:

- 6 identical LLRFs configured in software and firmware as described in the following paragraphs;
- User Manual;

- Service manual;
- Test results;
- Certification of conformity according to European directives of the board (EN61010-1, EN61326-1, IEC 60601-1-2, ISO9001);
- Software and firmware sources and binaries and any tools (e.g. software and cables) needed to download them on the cards;
- Guarantee of being able to supply identical or fully compatible cards within 10 years following installation.

The supply shall also include the delivery, installation and testing of all LLRFs as well as the specific assistance described in paragraph 4 of this document and the minimum guarantee of 12 months.

3 NEW DIGITAL LLRF FUNCTIONALITIES

The new digital LLRF shall warrantee the following functionalities:

- It shall be able to generate the RF input signal for a power amplifier, with either open or closed loop, with amplitude and phase control.
- It shall operate with local and remote control.
- It shall allow external RF synchronization (reference clock input 216.816 MHz).
- It shall allow RF signal acquisitions.
- The new system shall work with the CNAO controller, in the CNAO Control System framework.
- It shall foresee communications on the proper functioning of the board (temperature, power supplies, other).
- It shall receive digital input and generate digital signals.

3.1 NEW DIGITAL LLRF SPECIFICATIONS

3.1.1 RF System

- Operating frequency generated: 216.816 MHz (ref. Input).
- Generated signal: pulsed and not-modulated.
- RF I / O port impedance: 50 Ω single ended.
- Spectral purity: harmonics and spurious <-50 dBc.
- Frequency stability in 24h <1 ppm.
- Maximum output power = 10dBm.
- Control dynamics: 30 dB.
- Powers: see table in paragraph 3.8
- Phase loop precision: 0.1Deg.
- Signal amplitude precision: see in paragraph 3.8
- Pulse duration: 50-500 µs @ step 1 µs.
- Pulse rate: 1-10 Hz @ step 1 Hz.
- Pulse rise time: 0-99% 1-40 µs.
- Pulse fall time: 99-0% 1-40 µs.
- Pulse delay: 0-100 ms, step 1µs.
- Input RF sampling point: Forward.
- Input RF sampling point: Reflected.
- Input RF sampling point: Amp tank probe.
- Input RF sampling point: Phase tank probe.

3.1.2 Digital I/O

- Master Pulse: Digital Output (single ended 15V 1 MΩ enable control grid).
- Sample Pulse: Digital Output (single ended 15V 1 MΩ enable measurement PLC).
- W0 Pulse: Digital Output (single ended 5V TTL 1 MΩ Enable plunger measurement).
- PSS-out: DC-voltage on a LEMO-TWIN connector; value defined by the supplier.
- PSS-in (personal protection): Digital Input.
  PSS-out signal is read and sent to relays inside the amplifier module. In case the PSS-in signal is absent, RF signal shall be interrupted immediately (within 1ms). PSS-out shall be read-out on LEMO-TWIN connector.
- Beam Pulse trigger: digital input, 5V TTL on 50 Ω.
- Stability Pulse trigger: digital input, 5V TTL on 50 Ω.
- Tank-in-resonance: digital input from plunger board; it reports the cavity resonance status. The signal is 24V on 33kΩ (): signal is high when cavity is resonant; signal is low when cavity is not resonant and thus the LLRF shall limit the output power. The limit depends on the amplifier:
  - IH: 100 kW;
  - RFQ: 10 kW;
  - DEB: 0.100kW.

  When the signal switches from low to high, the LLRF shall output the regular power within 8 sec, with a slow automatic increasing up to the programmed set-point.
- RF interlock: digital input from VG board, TTL 15V (on 1 MΩ). If this signal is high, RF signal shall be disabled within 1μs. ()
- RF IL: input from ME cards: TTL 15V (1 Mega Ω) .When the signal is high RF must be disabled within 1µs.
- RF ON from PLC: input 24 V on 1 Mega Ω: if it is low RF must be disabled

- RF-pulse: digital output, 15 V on 1 MΩ. This signal shall be always on; it shall be set low only a programmed delay after the trigger. It corresponds to RF signal generation. (

Figure 3 shows the time-diagram of most of the I/O digital signal.

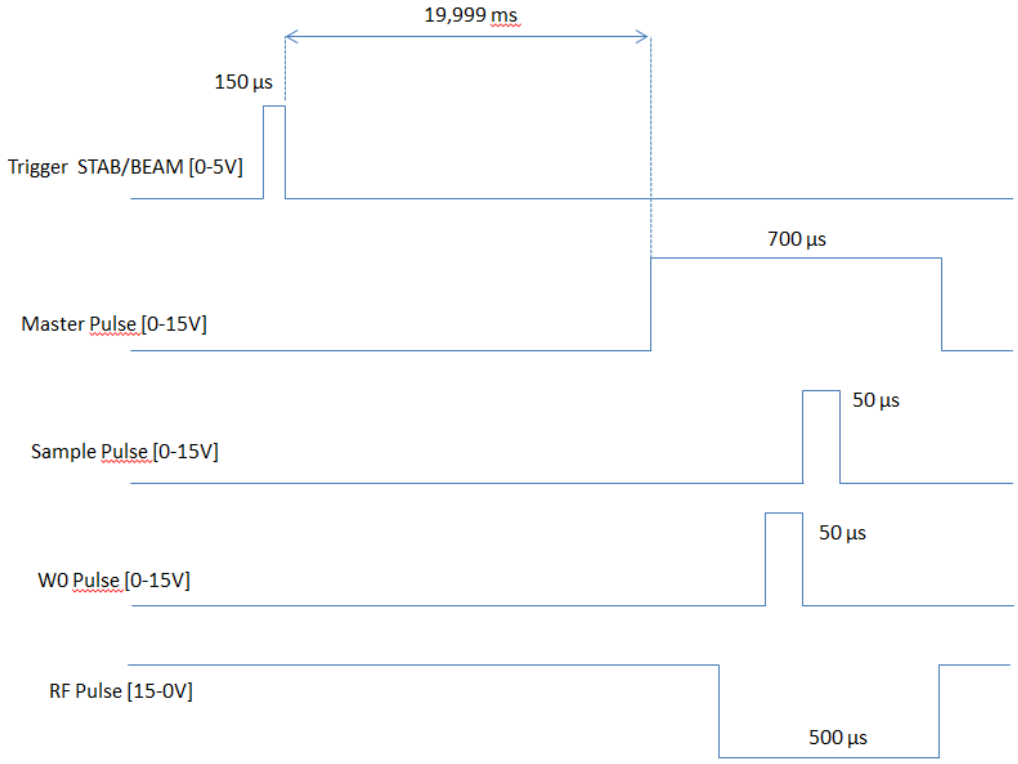

Figure 3 - Time-diagram of some of the described I/O digital signals.

3.2 ADDITIONAL FEATURES

- It shall be foreseen a local interface and a procedure that allows a partial exclusion of the remote interface. The supplier and the CNAO shall agree on the mode to achieve it.

3.3 MAIN POWER SUPPLY

- AC line single phase 230VAC

3.4 MECHANICAL SPECIFICATIONS

- Rack 19” enclosure (3U max) with depth not larger than 35cm.
- Boards shall be removable from the rack without crate dismantling.
- Signal connections shall be on the front and not on the back.
- It shall be possible to replace boards easily, without the use of proprietary tools.
- All boards shall be removable from outside the crate.

3.5 ENVIROMENT SPECIFICATIONS

- Working Temperature: +15 ÷ +35°C.
- Max Humidity 80 %, non-condensing.

3.6 PRODUCT QUALITY SPECIFICATIONS

- MTBF(mean time between failures) > 100000 hours.

3.7 SOFTWARE SPECIFICATIONS

- The firmware shall be saved on the LLRF digital board on non-volatile memory, in such a way the firmware can be uploaded on the FPGA as soon as the board is powered-on.
- LLRF shall generate the RF-signal in both the modes: open and closed loop. Closed loop shall be based on *Amp-Tank-Probe*. signal.
- It shall be foreseen a Ethernet TCP-IP comunication between the inner controller of the LLRF board (server) and an external controller (client) developed by CNAO.
- CNAO controller shall comunicate to LLRF inner controller for the following operations:
    - To send configuration parameters for RF signal and digital signals (*Send_Par*).
    - To ask LLRF status (*Request_Status*).
    - To require measurements on the RF-pulse generated by the stability pulse (*Acq-Stab*).
    - To require measurements on the RF-pulse generated by the beam pulse (*Acq-Beam*).

3.7.1 Send_Par

- Configuration parameters are shared in 3 groups: RF-par-gen, RF-par-beam and RF-par-stab. Each group of parameters can be sent independently from the others. The LLRF shall warrantee to make the new parameters effective within 100ms from the reception. Latest received parameters shall be stored in a non-volatile memory inner the LLRF board and be available to the board in case it is restarted.
- LLRF board shall answer CNAO controller at parameters reception sending back the entire message.
- RF-par-gen are general parameters:
    - Parameters to generate the RF-pulse:
        - *RF-Delay*: Delay to wait before starting the RF-pulse, after beam pulse and stability pulse triggers.
        - *RF-Rise-time*: RF-pulse rise-time.
        - *RF-Fall-time*: RF-pulse fall-time.
        - *RF-Duration*: RF-pulse duration.
        - *Pmax-Out*: maximum amplifier output power (kW). This value shall be used to convert the RF-pulse required power into binary.
        - *Pmax-LLRF:* maximum output power (dBm). This value shall be observed by the LLRF in order not to damage the amplifier.
        - *ParaLoop:* the LLRF boards for RFQ, IH and Debuncher shall be identical, but loop parameters are different, since amplifiers are different. Loop parameters (integral and proportional parameters) shall be communicated, consequently. Integral and proportional parameters shall be fined by the supplier. Calibration curve of the present LLRF is known; a new calibration curve shall be found out using the new LLRF board in open-loop mode and reading the actual power from amplifier PLC.
        - *ParaPLLRF:* they are 7 parameters needed to reconstruct the 6-degrees polynomial, fitting kW-power vs dBm-power curve. This relationship is needed to work in open-loop mode and to have the initial condition in closed-loop mode. Calibration curve of the present LLRF is known; a new calibration curve it shall be found out using the new LLRF board in open-loop mode and reading the actual power from amplifier PLC. CNAO and the supplier shall agree on the type of variables to exchange.

- *ParaPTank:* they are 7 parameters needed to reconstruct the 6-degrees polynomial, fitting amp-tank-probe kW-power vs amp-tank-probe dBm-power curve. This relationship is needed to work in closed-loop mode. CNAO and the supplier shall agree on the type of variables to exchange.

- Parameters to generate digital signals:
  - *Master-Pulse-Delay*: delay to wait before starting the Master-Pulse generation, after the trigger.
  - *Master-Pulse-Duration*: Master-Pulse duration.
  - *Sample-Pulse-Delay*: delay to wait before starting the Sample-Pulse generation, after the trigger.
  - *Sample-Pulse-Duration*: Sample Pulse duration.
  - *W0-Pulse-Delay*: delay to wait before starting the W0-Pulse generation, after the trigger.
  - *W0-Pulse-Duration*: W0-Pulse duration.

  Parameters precision shall be agreed between CNAO and the supplier.

- RF-par-Beam are phase (Beam-Phase) and amplitude (Beam-Amp) of the RF-signal generated after the beam pulse trigger.
- RF-Par-Stab are phase (Stab-Phase) and amplitude (Stab-Amp) of the RF-signal generated after the stability pulse trigger.
- Amp-parameters give amplifier output power (kW). Amp parameters full scale depends on the amplifier and they are normalized to Pmax-Out parameter of the RF-Para-gen subset.
- Phase-parameters are given in degrees.

3.7.2 Request_status

- CNAO controller asks LLRF status at a variable frequency, not larger than 1Hz. LLRF shall answer within 100ms with either an "OK" message or an alarm message. Board alarm codes shall be defined and provided by the supplier.

3.7.3 Acq-Stab

- CNAO controller asks RF-pulse actual parameters at a variable frequency, not larger than 1Hz. LLRF shall answer with a 6-entries array providing measured value of: amp-tank-probe RF-signal amplitude, RF-signal amplitude on LLRF output, FWD power amplitude, REV power amplitude, amp-tank-probe phase, the phase calculated by the amp-Tank-Probe.
  These 6 parameters shall be measured on the first RF-pulse triggered by the stability-pulse after the request, with sampling rate larger than 1MHz. The delay between stability-pulse and RF-pulse shall be taken into account for the measurement.

3.7.4 Acq-Beam

- This request is equivalent to Acq-Stab request, but it concerns the RF-pulse pulse triggered by the first beam-pulse after the request (instead of the first stability-pulse).

3.8 AMPLIFIER POWER TABLES (IH/DEB/RFQ)

Table 1, Table 2 and Table 3 collect power parameters for RFQ, IH and DEB amplifiers, respectively. They are:

- Pout(kW): amplifier output power in kW;
- Pout (dBm): amplifier output power in dBm;
- Pin(dBm): amplifier input power (namely, LLRF output power);

- FWD (dBm): forward power;
- Ref (dBm): reflected power. It depends on the VSWR value and thus only a max-min range is given. Namely:
  - RFQ reflected power: (+3.9; -7.6) dBm;
  - IH reflected power: (+13.3; +11.7) dBm;
  - DEB reflected power: (+1.5; -1.9) dBm.

Table 1 – RFQ parameters.

RFQ					
Pout (KW)	Pout(dbm)	Pin (dBm)	FWD (dbm)	Tank (dbm)	Power precision
0.1	50	-19,9	2,9	-2,45	
10	70	-7,89	17,7	11,38	1%
20	73,01	-5,65	22,3	17,8	1%
50	76,98	-3,1	26,5	20,09	1%
100	80	-1,1	29,1	22,47	1%
150	81,76	0,5	30,6	24,04	0,30%
170	82,3	1,5	31,27	24,75	0,3%
190	82,78	2,3	31,6	25,1	0,30%
200	83,01	2,8	32,01	25,4	0,30%
220	83,42	4,9	32,6	25,82	0,30%

Table 2 – IH parameters.

IH					
Pout (KW)	Pout(dbm)	Pin (dBm)	FWD (dbm)	Tank (dbm)	Power precision
1	60	-9,85	-3,9	-14,5	
50	76,98	-3	16,65	9,1	1%
100	80	-1,5	19,35	12	1%
150	81,76	-0,6	21,2	13,8	1%
300	84,77	1,1	24,12	17,14	1%
400	86,02	1,8	25,5	18,42	1%
600	87,78	2,8	27,5	20,15	1%
800	89,03	3,95	28,35	21,2	0,30%
900	89,54	4,5	28,82	21,65	0,30%
1000	90	4,9	29,3	22,05	0,30%
1100	90,41	5,23	29,7	22,35	0,30%

Table 3 – DEB parameters.

DEB					
Pout (KW)	Pout(dbm)	Pin dBm	FWD (dbm)	Tank (dbm)	Power precision
0,1	50	-7,85	20,32	19,08	1%
0,7	58,45	-4,95	23,85	22,3	1%
1	60	-4	23,53	23,23	0,50%
1,5	61,76	-2,5	25,8	24,51	0,50%
2	63,01	-1,9	26,5	25,18	0,50%
3	64,77	0,5	27,85	26,61	0,50%

4	66,02	3,5	29,21	27,65	0,50%

3.9 TRANSMISSION LINES GROUP DELAYS: MEASUREMENTS

Measurements of the transfer functions (amplitude and phase) of the entire system (from LLRF output to amp-tank-probe signal) are reported below for RFQ, IH e DEB.

The measurements show propagation delays between the 3 systems due to different geographic layouts. For each (RFQ, IH and DEB) system, the global delay is calculated, due to the amplifier circuit and the transmission lines. These values are mandatory to determine parameters and performances of the LLRF feedback.
Global delay results of 547ns for the RFQ, 611ns for the IH and 471ns for the DEB.

3.9.1 RFQ Transfer Function

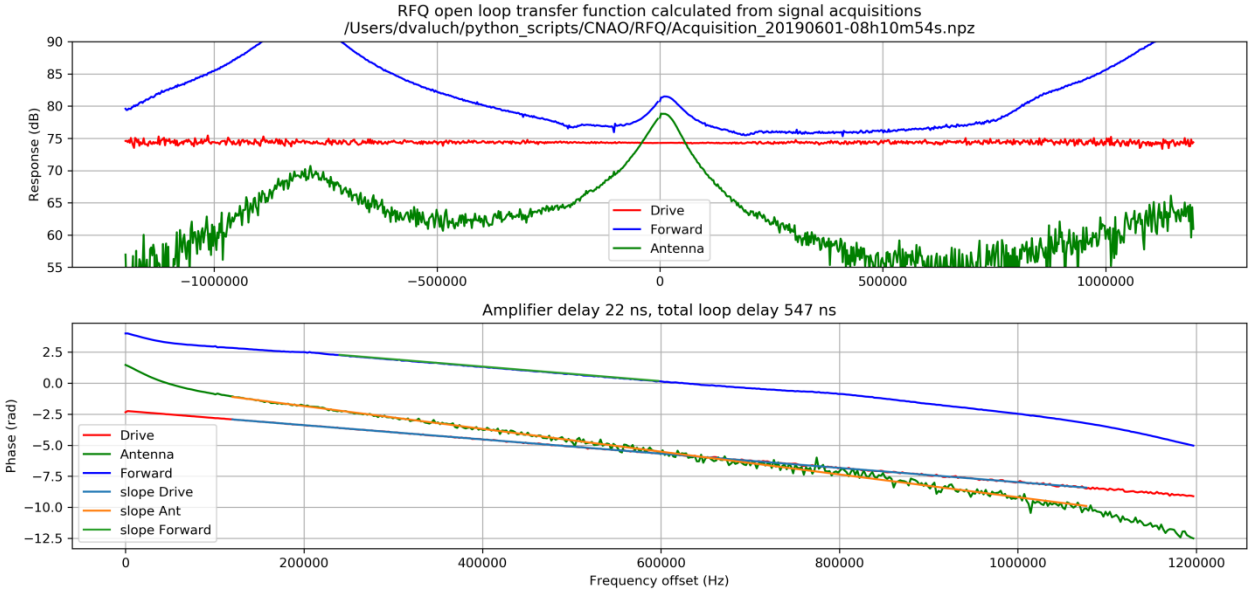

Figure 4– RFQ transfer Function

3.9.2 IH Transfer Function

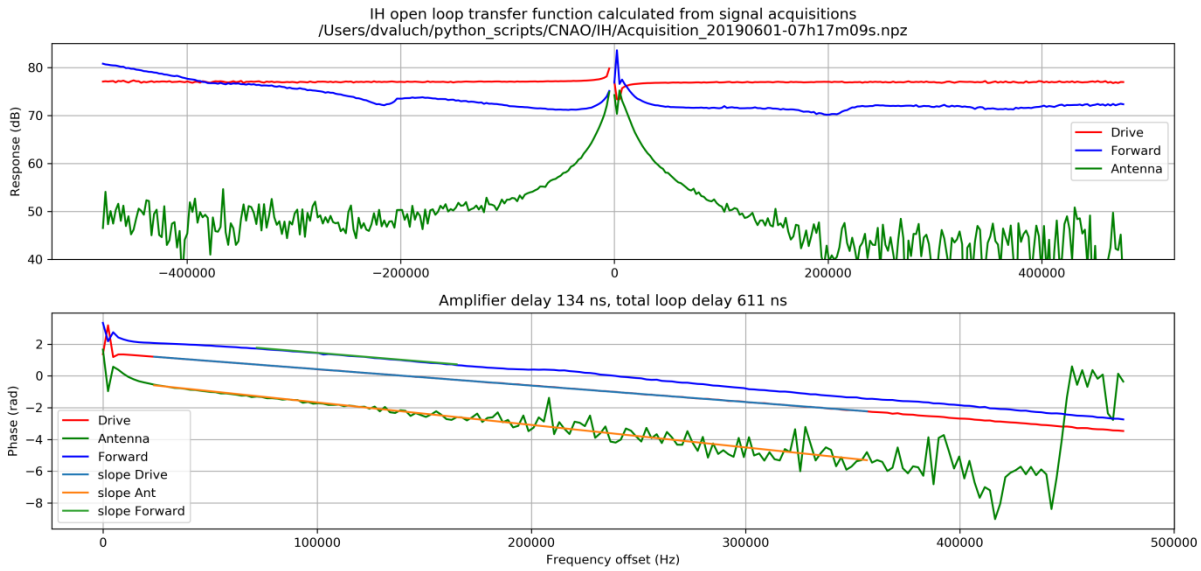

Figure 5 – IH Transfer Function

3.9.3 DEB Transfer Function

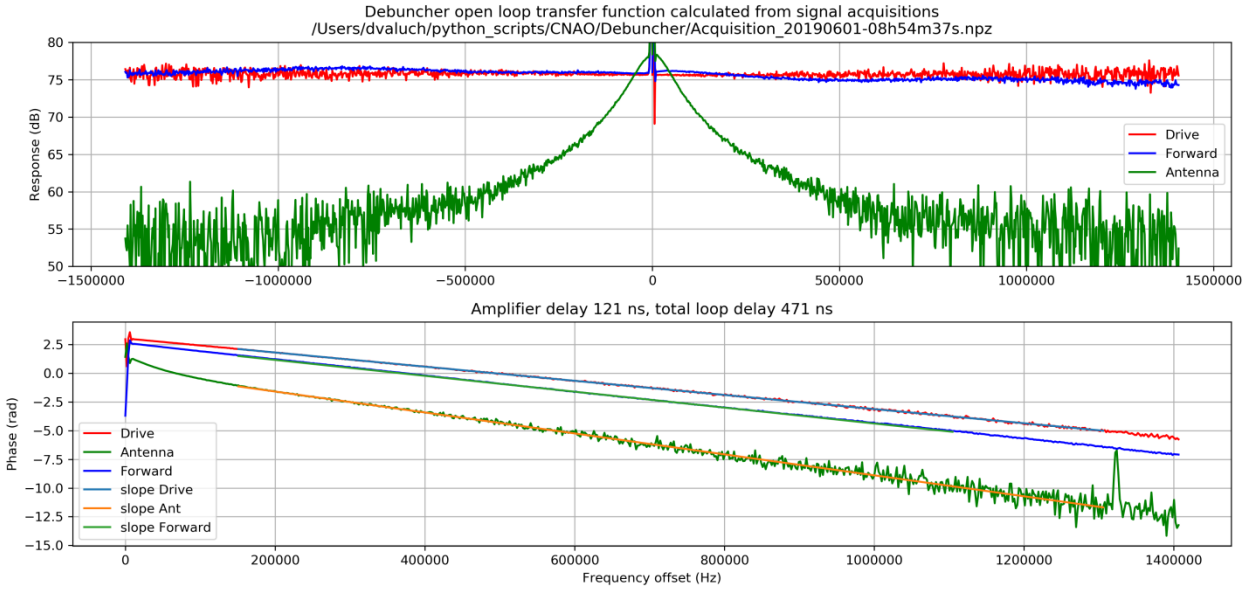

Figure 6 – DEB Transfer Function

4 ASSISTANCE AND WARRANTY

After the approval of the design documents (ref. chapter 5 – "Timeplan and Deliveries") in the period from T1 to boards acceptance tests, the CNAO Foundation will proceed with the implementation of the control interface.
During this period, the winning company shall provide, at no additional cost to the CNAO Foundation:

- telephone and / or remote assistance support available every working day of the contractual period, excluding Saturdays, Sundays and holidays, from 8:00 to 17:00 and shall guarantee an answer within 48 hours of the telephone request and / or remote assistance and / or email;
- on-site assistance both for testing activities and for setting up and acceptance tests, as indicated in chapter 5 – "Timeplan and Deliveries").

The minimum guarantee of n. 12 months from the acceptance date with positive acceptance test of the supply. The economic operators participating in the tender procedure relating to the contract in question will be able to offer an extension of the guarantee beyond the aforementioned term, which will be evaluated by the Contracting Authority as indicated in **point 6.1 of the Tender Rules**.

In any case, the guarantee shall cover, without further costs for the CNAO Foundation, any type of non-conformity related to characteristics and functionalities of the supplied products in relation to this Technical Specification, the design documents drawn up by the manufacturer and accepted by CNAO and the manuals provided by the contractor.
During the warranty period, the contractor undertakes to carry out, at no additional cost to the CNAO Foundation, any activity and supply that may be necessary to restore the correct working of the supplied equipment.

Telephone and / or remote assistance support is also required, every working day of the contractual period, excluding Saturdays, Sundays and holidays, from 8:00 to 17:00 and shall guarantee a response within 48 hours of the telephone request and / or remote assistance and / or email.
On-site assistance for any problems that may arise related to the normal operation of the card.

Malfunctioning and / or faulty components shall be repaired and / or replaced ensuring the restoration of the correct functioning of the equipment within 15 days from the request of intervention by the CNAO Foundation. The methods of repair and replacement will be chosen by the contractor.
The above requirements are intended as mandatory minimum requirements that shall be given in the warranty.

The contractor shall ensure the use of adequately trained and qualified technical personnel equipped with the tools and knowledge necessary for the proper execution of all the activities covered by this contract.

5 TIME PLAN AND DELIVERY

From the effective start date of the contract (time T), the time schedule foresees the following milestones:

- T+1 month:

  Within 1 month from the effective start date of the contract, the supplier shall submit to CNAO the design documents, drawn up on the basis of what is indicated in this Technical Specification. These documents shall be discussed in any case, agreed with the CNAO technicians and formally approved by the Contracting Authority before the supplier can start production of the supply.

- T > T+1 month

  Technical assistance, telephone support and / or remote assistance shall be available every working day of the contract period, excluding Saturdays, Sundays and holidays, from 8:00 to 17:00 and shall guarantee the response within 48 hours of the telephone and / or remote assistance request and / or email.

- T+ 8 months:

  The contractor shall provide a board for carrying out some tests within 8 months of the tender start date. The CNAO Foundation technicians will verify amplitude and phase loops.

  As proposed in Figure 7, a delay line equal to the real one is prepared and the correspondence between LLRF output and amp-tank-probe value is reproduced by mean of an attenuator.

  While the testing board receives the trigger (equivalent to the Stability Pulse) through an external tool (provided by CNAO), RF performances and the correspondence of the digital signals produced by LLRF are measured.

  During the tests at CNAO, digital signals generated by LLRF are verified and local and remote control of the board is checked.

  The contractor shall provide in-situ assistance during these tests.

  The test system will be free-running left for 1 month, as stability test.

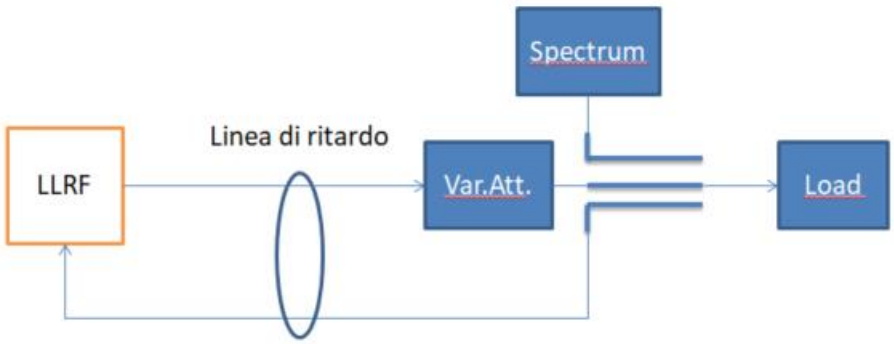

Figure 7

- T+12 months:

  The remaining part of the supply shall be delivered within the 12th month from the effective start date of the contract, with Free Destination procedure at the CNAO Foundation located in Strada Campeggi 53 in Pavia (Italy). Delivery acceptance does not constitute confirmation of supply conformity to what is indicated in this Technical Specification and in the design documents prepared by the supplier and formally approved by the CNAO. Supply conformity will be verified at the acceptance tests.

  Upon completion of the supply, work sessions at CNAO will be scheduled with contractor direct attendance to carry out the installation, the commissioning and the acceptance tests of the 3 amplifiers. Tests duration shall not overcome 16 hours per amplifier. Tests will be scheduled on weekends.

6 CHANGES FROM SPECIFICATIONS

Any variation to what is described in this technical document shall be submitted, discussed and formally approved by CNAO, without involving changes to the price offered.