THE RF SYSTEM OF THE ELI-NP GAMMA BEAM SOURCE

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Abstract

ELI-NP is a linac based gamma-source under construction in Magurele (RO) by the European consortium EuroGammaS led by INFN. Photons with tunable energy (from 0.2 to 19.5 MeV) and with unprecedented intensity and brilliance will be produced by Compton back-scattering between a high quality electron beam (up to 740 MeV), and a 515 nm intense laser pulse. In order to increase the gamma photon flux, the accelerator will operate in multi-bunch at 100 Hz repetition rate, with 32 bunches separated by 16 ns. Three S-band (2856 MHz) RF power plants will feed two room temperature Travelling Wave (TW) structures, a 1.6 cell Standing Wave (SW) S-band gun (which has been manufactured by means of a new technique based on clamped gaskets without brazing) and two SW RF deflectors for longitudinal beam diagnostics. Ten C-band (5712 MHz) RF power plants will feed 12 TW high-order-modes (HOM) damped structures. In this paper, we review the whole ELI-NP RF architecture including the Low Level RF (LLRF) system.

INTRODUCTION

The Extreme Light Infrastructure (ELI) project will be the world's first international user facility for laser based applications. Unprecedented interdisciplinary research opportunities will be available to the international scientific user community for a wide spectrum of applications, such as nuclear physics, astrophysics, materials science and life sciences. Three sites with complementary scientific programs are being constructed in Romania, Czech Republic and Hungary respectively. In particular, an advanced source of gamma-ray photons will be built in Magurele (Bucharest) in the framework of the ELI Nuclear Physics (ELI-NP) project [1] by the EuroGammaS consortium led by INFN. The photons will be generated by Compton back-scattering in the collision between a high quality electron beam and a high power laser (200 mJ, 3.5 ps, 515 nm). The machine is expected to produce photons with tunable energy between 0.2 and 19.5 MeV with a narrow bandwidth (<0.5 %) and a high spectral density (0.8-4 $\times$ 10^4 ph/s eV) [2].

The accelerator layout is based on a C-band (5712 MHz) RF linac with a S-band photo-injector, similar to that of SPARC_LAB at LNF-INFN (Frascati, Italy) [3], able to deliver a high phase space density electron beam in the 300-740 MeV energy range. In order to fulfill the stringent requirements on photon fluxes, the machine is foreseen to work at 100 Hz repetition rate and in multi-bunch (32 electron bunches per RF pulse). The main parameters of the electron beam of the ELI-NP Gamma Beam System have been summarized in Table 1. In the next sections the whole RF architecture will be described, with a particular emphasis on the RF power generation and distribution and the LLRF system main features.

Table 1: ELI-NP Electron Beam Parameters

Parameter	Value
Electron beam energy	300 - 740 MeV
Energy spread	< 0.1 %
Normalized beam emittance	0.4 mm mrad
Number of bunches per RF pulse	32
Bunch charge	250 pC
Bunch length	< 300 µm
Bunch separation	16 ns
Repetition rate	100 Hz

RF POWER GENERATION AND DISTRIBUTION

Linac Overview

ELI-NP photo-injector comprises a 1.6 cell S-band RF-gun, which has been manufactured employing a new fabrication technique without copper brazing [4, 5], and 2 TW S-band constant gradient 3 m long accelerating structures. The S-band system is completed by two deflecting cavities for longitudinal beam diagnostics, that are supplied with a fraction of the RF power derived from the first klystron. The linac booster is composed of 12 TW C-band disk loaded accelerating structures. Each section is 1.8 m long, quasi-constant gradient with a $2\pi/3$ field phase advance per cell and will operate at an average accelerating gradient of 33 MV/m. In order to avoid beam break up instabilities, the structures have been designed with a waveguide HOM damping system, that employs four SiC RF absorbers for each cell [6–8].

RF Power Plant

In order minimize the energy spread along the bunch train due to beam loading effects, the RF pulses have to be properly shaped by the LLRF system. Therefore, the choice of RF pulse compression schemes, that in principle would allow to reduce the number of required klystrons, has not been pursued. Thus, each structure is individually fed by a dedicated power station (except for the last 4 TW sections that are powered by 2 klystrons), which also allows to have a higher operational flexibility. Moreover, in order to reduce bunch-by-bunch energy spread due to structure beam loading (BL),

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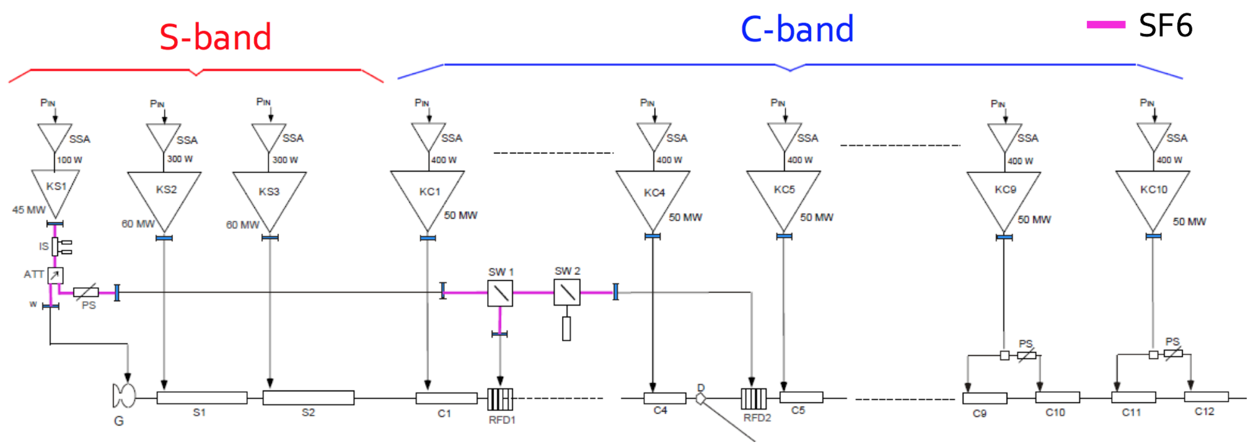

Figure 1: ELI-NP RF power generation and distribution system. 3 power units are used for the S-band injector, 10 units for the C-band booster. In magenta the two sections of sulfur-exafluoride (SF_6) components (isolator, attenuators, phase shifters and RF-switches) are highlighted.

a tailored pulse shaping compensation has to be provided by the LLRF system. A schematic sketch of ELI-NP RF power plant is shown in Fig. 1. Overall there are 13 power units, each consisting of a ScandiNova (SE) pulsed HV solid state modulator, a Toshiba (JP) klystron tube and a Microwave Amplifier (GB) 400 W solid state driver amplifier. A 45 MW unit feeds all the SW cavities: the RF-gun and two RF deflectors, while two 60 MW power units are needed for the two S-band TW structures of the photo-injector. The remaining 10 C-band power sources are 50 MW units. The modulators have been manufactured using solid-state technology that offers, with respect to the standard pulse forming network and tube switching devices, excellent performance in terms of repeatability and amplitude stability of the high voltage pulses, compactness, ease of maintenance and operational safety.

RF Distribution Network

The RF power is distributed to each accelerating structure by means of a network of copper rectangular waveguides. The S-band injector makes use of standard WR284 waveguides (inner dimensions of 72 mm × 34 mm), while the C-band booster adopts the WR187 (inner dimensions of 47 mm × 22 mm). The waveguides operate in ultra-vacuum, with a pressure lower than 10^{-7} mbar, to avoid internal arcs due to the high peak power conveyed to the accelerating structures. The resistive losses in copper at nominal operating frequencies for WR284 and WR187 are 0.02 dB/m and 0.035 dB/m respectively. The modulators position optimization is, therefore, of paramount importance to reduce as much as possible the RF power dissipated by the distribution system. For this reason, all the power units have been evenly distributed on the building roof above the accelerator bunker. A few segments of the RF-gun waveguide network must be pressurized to 2 atm with sulfur-exafluoride (SF_6) because some devices (e.g. the one employing ferrite materials or movable components such as isolators or RF switches), are not suitable to operate in ultra-high vacuum, due to their high out-gassing rate. To separate the linac vacuum (of the order of 10^{-9} mbar) from the waveguide one, RF ceramic windows have been inserted at each accelerating section input. Furthermore, where the SF_6 is used as insulating medium, a double window system is adopted to prevent beam pipe contamination in case a window should break. The vacuum of the waveguides is maintained at the optimal pressure by means of 70 ion-pumps distributed every 4-6 m along the network, which are connected to the waveguides with T pumping units.

LLRF SYSTEM AND BEAM LOADING COMPENSATION

The aim of any LLRF system is twofold: it generates the RF pulses used to drive the power units, and it acquires and monitors the RF signals picked-up along the accelerator (e.g. from the waveguide network, the accelerating sections or inside the RF cavities). Moreover, it must allow to generate suitable control signals, either manually or automatically (feedback loops), to set the required levels and phases of the RF fields in any RF device of the machine. The ELI-NP LLRF system, “Libera LLRF” manufactured by Instrumentation Technologies (SI), consists of 13 temperature stabilized digital boards (one for each power unit): 3 S-band and 10 C-band. This choice has been made in order to guarantee the maximum flexibility in terms of pulse shaping and machine operation stability. One of the main advantages of a digital LLRF system is, in fact, the possibility to perform a pulse-by-pulse feedback interactively choosing from control system the target signals for amplitude and phase loops. Moreover, the pulse shape can be arbitrarily chosen (e.g. for BL compensation, as it will be shown in the next paragraph) simply loading a spreadsheet to Libera FPGA. The request for thermal stabilization has been introduced to compensate the long-term effect of temperature drifts, that must not exceed 100 fs for normal operation: (24 ± 2) °C. Each board contains four main elements: (i) an analog front-end with 8 RF inputs per module (a board can host up to 4 modules), (ii) an analog back-end (with 1 RF output from vector modulator

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- I/Q), (iii) the main CPU (which hosts the sampling cards, the FPGA and the EPICS control system server), and (iv) the LO generator and timing unit (with 1 input for the RF reference, 1 input for the trigger of FPGA, DAC and ADC and the interlock I/O). The main parameters of Libera LLRF boards have been summarized in Table 2. Each board monitoring the TW structures will acquire 6 RF signals (solid state amplifier output, klystron output and section output forward and reflected power), with the exception of the last four sections that will be squeezed in two boards equipped with two sampling modules each, in order to manage 12 RF signals. All the signals from the SW cavities, instead, will be acquired by the first S-band board. In this case also three RF probes will be acquired to monitor the electric fields in the cavities, for a total of 13 RF signals.

Table 2: Libera LLRF Main Specifications

Parameter	Value
Resolution	Amplitude: 0.1 %
	Phase added jitter: <10 fs
Long term stability	100 fs at T = (24 ± 2) °C
Analog front-end	BW: 5 MHz
	Max RF level: 20 dBm
Analog back-end	BW: 16 MHz
	Max RF level: 13 dBm
LO gen. and timing	Min RF ref. level: 15 dBm
	Sampl. clock: 119 MHz, 16 bit
	IF: 44.625 MHz

C-band TW Structures BL Compensation

A first order study on the wakefields excited in the C-band TW structures by the 32 electron bunches has been performed, in order to compensate this effect exploiting LLRF pulse shaping capabilities. Assuming each bunch to be a point-like charge, the wake generated by a single bunch (per unit charge) is given by:

$$W(z) = \frac{1}{2}\omega_{RF}\frac{r}{Q} = \alpha v_g r \tag{1}$$

where ω_{RF} is the C-band angular frequency, r is the shunt impedance, Q the quality factor, α the field attenuation in the structure and v_g the group velocity. Every 16 ns a new bunch arrives and consequently a new wake is produced, travels and is attenuated along the structure. Since the section filling time is ≈ 314 ns, after the passage of 20 bunches the structure is "fully loaded". A snapshot of the wake as experienced by the 20th bunch and by the following ones while travelling along the structure is shown in Fig. 2. Then, the total wake potential is simply given by the sum of the 20 propagated single-bunch wakes times their charge. The actual accelerating field is the difference between the ideal electric field in the structure and the total wake contribution. Thus, in order to have a net average accelerating field of 33 MV/m (design value), the structure has to be pre-loaded with a tailored power pulse to compensate for the BL transient effects, as shown in Fig. 3. However, it has to be taken into account that the shape of the actual vector modulator pulse will be somewhat different from the one shown in Fig. 3, mostly due to the limited bandwidth of the backend (≈16 MHz). Furthermore, a significant contribution from the bandwidth of the klystron-modulator system, which is expected to be of the order of 10 MHz, has to be considered. As far as the BL compensation is concerned, an integrated test of Libera LLRF and a C-band power unit will be very useful to check and improve the BL compensation capabilities of ELI-NP RF system.

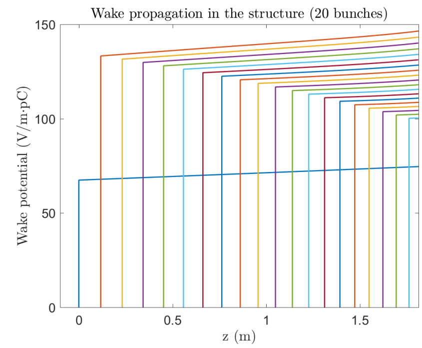

Figure 2: Snapshot of 20 wakes propagating within the TW C-band structure.

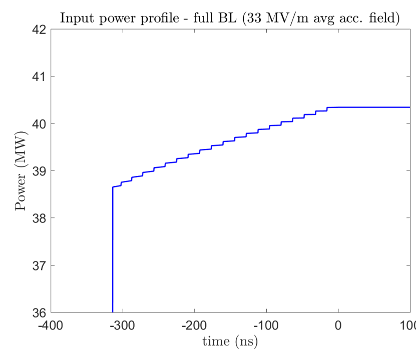

Figure 3: Input RF pulse for ideal beam loading compensation. The first bunch has to be injected at t=0.

CONCLUSION

The RF system of the ELI-NP research infrastructure has been presented. A detailed description of the 13 RF power plants, the distribution network and the Libera LLRF system has been given. Moreover, a first order study of the beam loading in the C-band sections has been performed. This effect has to be compensated with the LLRF pulse shaping, in order to limit the bunch energy variation along the train. A combined test of LLRF, modulator and klystron system is of paramount importance to estimate the bandwidth limitations on the proposed BL compensation method.

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