DESIGN AND CONSTRUCTION OF A HIGH-GRADIENT S-BAND RF LABORATORY AT IFIC-VALENCIA

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Abstract

The IFIC High-Gradient (HG) Radio Frequency (RF) laboratory is designed to host a high-power infrastructure for testing HG S-band normal-conducting RF accelerating structures and has been under construction since 2016. The main objective of the facility is to develop HG S-band accelerating structures and to contribute to the study of HG phenomena. A particular focus is RF structures for medical hadron therapy applications. The design of the laboratory has been made through collaboration between the IFIC and the CLIC RF group at CERN. The layout is inspired by the scheme of the Xbox-3 test facility [1, 2] at CERN, and it has been adapted to S-band frequency. In this paper we describe the design and construction status of such a facility.

INTRODUCTION

Significant progress has been made over the past decade by studies of normal-conducting linear colliders to raise the achievable accelerating gradient from the range of 20-30 MV/m up to 100-120 MV/m. The gain has come through a greatly increased understanding of the high-power RF phenomena, the development of quantitative HG-RF design methods, refinements in cavity fabrication techniques and through the development of high peak RF power sources.

Today we can identify a number of applications which could potentially exploit the advance in HG normal conducting-linac technology as: medical linacs, FELs and Compton-scattering gamma ray sources. The process of transferring the technology to these fields has already begun and some projects are making parameter studies of facilities based on HG technology.

Linacs, as opposed to rings, are of particular interest for medical applications because they can provide a high degree of flexibility for treatment. For example, proton and carbon ion linacs running at 100-400 Hz have the capability of varying the beam energy (and intensity) in the 2.5-10 ms separating two consecutive pulses. This allows the ‘multi paint’ of the tumour target while using a 3D feedback system to deliver the dose to a moving organ by applying the spot scanning technique.

The linacs need to provide the energy in the range 70-230 MeV for protons and 100-400 MeV/nucleon for carbon ions. In order to best integrate them in a treatment facility building and minimize costs, the length of linac should be as short as possible.

The design and fabrication of a high-gradient prototype for medical proton linacs has been performed by the Knowledge and Transfer (KT) group at CERN, under the project 'High-gradient accelerating structures for proton therapy linacs' [3]. Tests of one of the KT structures should be performed at IFIC HG-RF laboratory.

THE S-BAND TEST FACILITY

A new HG-RF lab is being constructed under a FEDER-funded collaboration agreement between the University of Valencia and the Spanish General Administration (MINECO) for the building integration and the equipment of scientific instrumentation.

The design has been made in cooperation with the IFIC's Group of Accelerator Physics and the CLIC RF group at CERN under KE contract [4]. The layout is based on the scheme of the Xbox-3 test facility, which is currently under commissioning at CERN [1, 5-6], and it has been adapted to a frequency of 2.9985 GHz. The system will be prepared for the conditioning and test of two S-band TW structures.

High Power RF and Waveguide Network

A scheme of the high-power components of the test facility is shown in Fig. 1, and the 3D integration of the network at the HG-RF lab building can be seen in Fig. 2. The system makes use of two S-band (2.9985 GHz) klystrons, powered by two solid-state modulators of up to 150 kV.

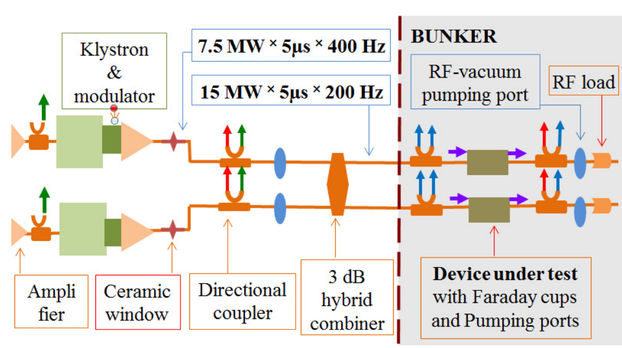

Figure 1: Layout of the high-power subsystem of the IFIC HG RF laboratory.

In a first step, the klystrons RF inputs are driven from a preamplifier stage consisting on a 400 W solid state amplifier with a gain of ~56 dB (model AM10-3S-55-55R from Microwave Amplifiers). The input for these amplifiers is a 5 μs length pulsed RF signal of 2.9985 GHz coming from the LLRF system.

The two klystrons are capable of providing a maximum RF peak power of 7.5 MW with a pulse length up to 5 μs

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and a repetition rate up to 400 Hz. The tubes are a VKS8262G1 model built by CPI [7]. The output power of both klystrons is combined in a 3 dB hybrid, where depending on the relative phase between the two RF waves, the total achievable power at one of the two lines at a time can reach up to 15 MW, at the cost of reducing the pulse repetition rate by a half, ie. 200 Hz. The RF power of each line is sent through WR-284 waveguides to the structures under test, installed inside the bunker, which will be equipped with the experimental setup required for BD studies.

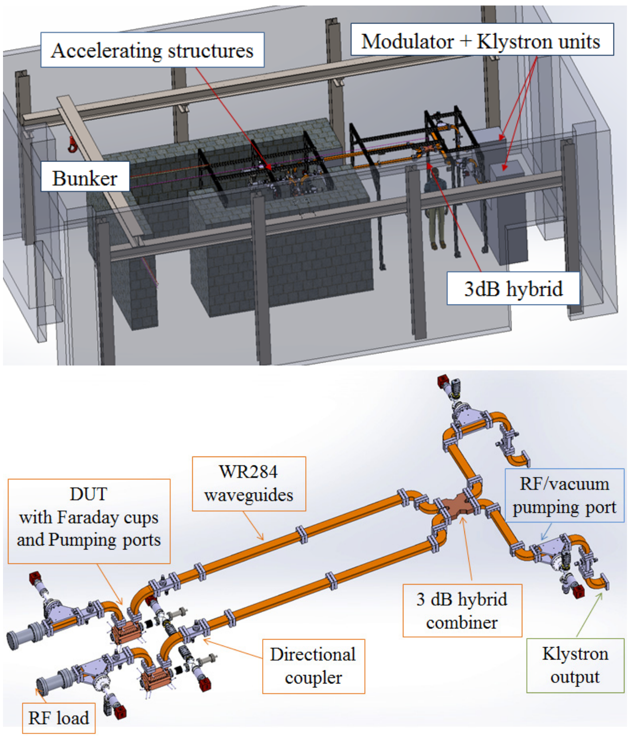

Figure 2: 3D design of the high-power network of the IFIC HG RF laboratory. Top picture: integration in the laboratory enclosure of the building. Bottom picture: detail of the assembly of the high-power and vacuum components from the klystron output.

The klystrons are powered with solid-state modulators made by JEMA [8] with the specs as shown below (see Fig. 3).

Peak RF power: 7.5 MW
Pulsed voltage: 150 kV
Pulsed current: 105 A
Pulse length: 5 µs
Rep. rate: 400 Hz
Voltage flatness: ≤ ± 0.25%
Stability, pulse to pulse: ≤ 0.1%
Risetime: ≤ 2µs
Falltime: ≤ 2µs

Figure 3: Picture of the JEMA modular and klystron assembly along with the maximum specified parameters.

The RF power amplitude of each klystron can be controlled pulse to pulse, which offers the required flexibility to test different prototype designs or structures that present different conditioning states. The optimization of the repetition rate and peak power implies important reductions of the time required to condition and test a structure.

Thus the combination of the two klystrons with a 3 dB hybrid provides a cost-effective design of the test facility for the optimization of both peak power and repetition rate. Another advantage of this scheme is the possibility of testing two different prototypes simultaneously.

LLRF and Diagnostic Setup

The facility will be controlled by a National Instruments [9] PXI real-time system in charge of the low-level RF generation (LLRG), the acquisition of signals for diagnostics, the signal processing and the trigger control and interlock of the hardware.

Two PXI RF generators provide the amplitude and phase modulated RF pulse which drives the preamplifiers, which in turn drive the klystrons. The forward and reflected RF signals into the waveguide system and structure under test are diagnosed thanks to the use of directional couplers, as shown in Fig. 2. A downmixing system moves the RF signals down to 62.5 MHz and the 250 MSPS ADCs and FPGA modules in the PXI system allow for a real-time IQ demodulation and the data processing needed for BD detection. Some signals are also used to perform a reliable closed loop control of the input power of the structure and phase of the signals.

The reflected power from the structure towards the klystron, caused by the BDs, requires a robust interlock system in order to avoid damage to the structure. Excessive high reflection over many pulses could also result in damage to the waveguide components and the klystron's output window. The interlock system consisting of RF logarithmic detectors has to be able provide reliability and redundancy. Finally, the signals of the faraday cups placed in the upstream and downstream directions along the structure's beam axis to measure dark currents are also digitized.

A system with some similar essential elements is being tested at CERN since second half of 2016.

Cooling

In order to cool down the modulators and klystrons the HG-RF laboratory is equipped with a cooling system able to provide 162 KW of cooling power and fed with ultra-pure water. A demineralizer plant installed together with the cooling system provides this water with a conductivity of 0.1 µS/cm.

The cooling system consists of two water circuits and a heat exchanger between both circuits. The primary circuit includes the cooling machine and uses normal water from the network, whereas the secondary circuit includes the modulators and klystrons and runs demineralized water. The system parameters such as pressures, temperatures and flowrate are controlled by the computer.

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Vacuum

The waveguide networks as well as the cavities under test are running in ultra-high vacuum (UHV, ~10^{-8} mbar). To achieve and monitor this vacuum level the RF laboratory is equipped with UHV system. For the primary pumping, a turbo group with 67 l/s N_2 pumping speed is used. To keep the UHV level three Nextorr pumps (ion pump + NEG cartridge) [10] per waveguide line are used, with a pumping speed of 100 l/s for H_2 each.

According with the Molflow [11] simulations the expected vacuum level is ~ $5x10^{-8}$ mbar. Single line of vacuum simulation is shown in Fig. 4.

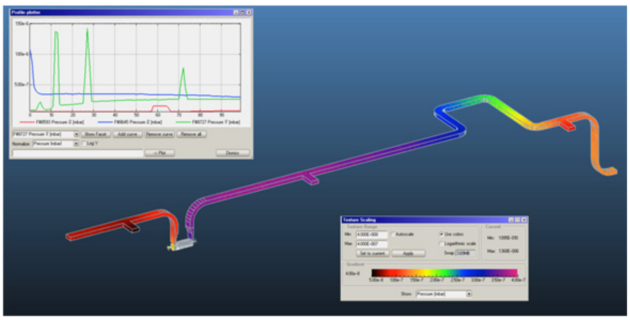

Figure 4: Single line Molflow vacuum simulation plot.

DATA ACQUISITION AND ANALYSIS DEVELOPMENTS

The HG RF-lab has similar configuration to the Xbox-3 test facility at CERN. The diagnostic and control system are designed to be flexible to allow any possible changes that might be required during the testing of the structure. Directional couplers, placed in the input and output of the structure, are used to measure the incident, reflected and transmitted RF signals. Threshold detection on the reflected signal from the structure and the dark current signals, measured from the upstream and downstream Faraday cups, are used to establish if a BD has occurred. In addition, the ion gauge readouts monitor the pressure level in the vicinity of the structure. A schematic layout of diagnostics systems of Xbox-3 [5] is shown in Fig. 5.

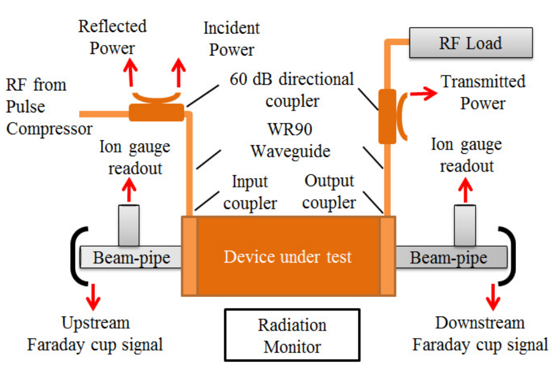

Figure 5: Schematic layout of the device under test and the various diagnostic systems. The red arrows show the signals that are sent to the NI PXI crate for acquisition and analysis.

The control and acquisition systems used for the operation of the high power test are managed by a NI PXI crate that allows stable, fast and real-time programming. The software for the high power operation is based on NI's LabVIEW Real-Time OS. Acquisition and interlock cards use also FPGA interface for added reliability and speed.

The conditioning process will follow that of the X-boxes [6] using the same computer controlled algorithm described in [12]. During this procedure, the input power in the structure is raised in a controlled manner, while maintaining a constant breakdown rate of about 3x10-5 BDs per pulse. A small initial pulse width is used until the power is increased to the target value. The pulse length is then increased to the desired value in small steps. Each step is followed by a progressive power ramp.

The data collected by the acquisition system is analysed offline to locate where inside the structure the breakdown occurred. Similar data analysis methods to those used for the X-boxes are planned after the necessary modification to the HG-RF lab at IFIC.

At the moment, two methods are known to determine the BD location using the RF signals [13]: the *edge* and the *correlation* methods. They are based on the time difference between the transmitted and reflected signals and the incident and reflected signals respectively. In addition, the phase measurement of the signals can be combined with the aforementioned methods to increase their sensitivity. Finally a third method of localizing the breakdown exists by measuring the time difference between the dark current bursts caused by a breakdown and the falling edge of the transmitted signal.

The instrumentation for breakdown detection will be used to develop the best techniques to localize vacuum arcs inside the structure. This analysis is essential for the evaluation of the performance of the HG structure, since it is required that breakdowns are distributed uniformly along all the cells [14].

CONCLUSION

HG-RF technology offers the possibility of constructing very compact linear accelerators for different applications. However, the performance of HG linacs is limited by the occurrences of BD. The IFIC HG-RF test facility at IFIC will support the development of a wide experimental programme of testing HG accelerating structures and breakdown phenomenology studies for S-band HG linacs.

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