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A NOVEL RF POWER SOURCE FOR THE ESS-BILBAO ION SOURCE

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Abstract

This paper presents the improvements in the ESS Bilbao Proton Ion Source by replacing the amplified radio frequency (RF) pulse of a Klystron-based amplification system using a Solid-State Power Amplifier (SSPA). This new amplification system is based on a 1 kW SSPA (2.7 GHz), a Compact-RIO (cRIO) device, a voltage-controlled RF attenuator and auxiliary electronics. The Experimental Physics and Industrial Control System (EPICS) serves as distributed control system (DCS) for controlling and monitoring the data required to achieve a 1.5 ms flat and stable pulse at repetition rate of 10 Hz. The following lines describe the structural and control system changes done in the ion source due to the addition of the SSPA-based amplification system, along with the results of the proton beam extraction tests that demonstrate how this system can serve as a viable substitute for the Klystron-based amplification system.

INTRODUCTION

ESS Bilbao proton source was built as the first step towards an accelerator system able to generate proton beams up to ~32 MeV [1]. In order to handle not only the protons for which it was designed, but also to be adjustable and deal with a variety of positive ions [2], it was designed and built as an Electron Cyclotron Resonance (ECR) ion source, more precisely Microwave Discharge Ion Source (MDIS). Far from the typical design employed in these kind of ion sources that normally use a magnetron as a Radio Frequency (RF) source, ESS Bilbao proton source works with a klystron to feed the plasma chamber with an amplified RF signal. This was done as the K3564 klystron amplifier from CPI, provides a better performance in terms of stability than the magnetron and it is better suited to work in CW (Continuous Wave) and pulsed modes, up to 2 kW. Even if this solution is more expensive than working with the magnetron, the ESS Bilbao proton source klystron has proven to be able to operate properly in the lasts years in a variety of experiments, e.g. [3, 4]. The successive step is to upgrade the ion source amplification system and this was done by building an in-house developed Solid-State Power Amplifier (SSPA) based amplification system. Solid-State technology-based power sources have come into accelerator facilities due to their reliability and lower power supply voltage requirement in comparison with vacuum tubes and there are plenty of research centers using or developing this technology in a variety of accelerator sections [5–9] and even some of them have been designed to work in ion sources [10–12]. This paper describes the ESS Bilbao in-house-developed SSPA-based amplification unit and its effectiveness in the ESS Bilbao ion source in comparison with results obtained by the klystron amplifier employed in this facility during many years.

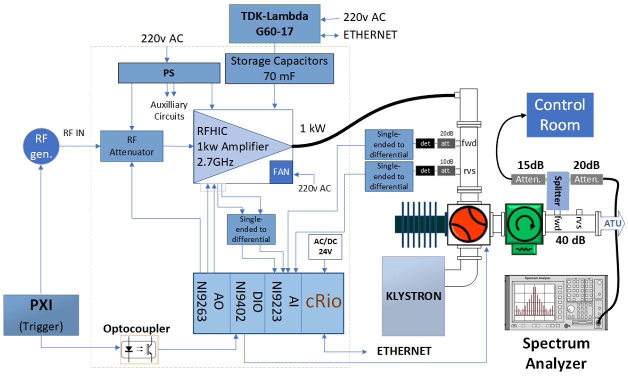

Figure 1: Injector SSPA-based amplification system scheme.

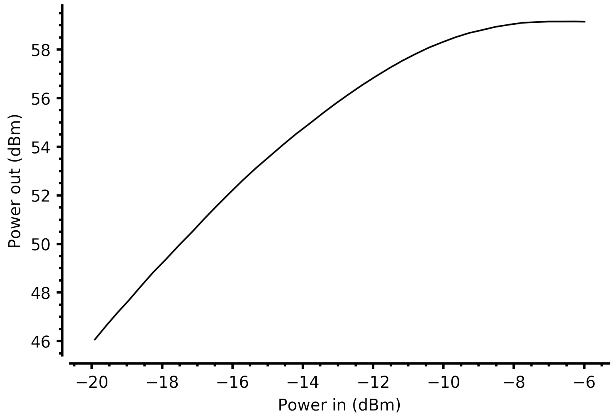

Figure 2: 1 kW SSPA amplifier Pin-Pout measurement (dBm).

HARDWARE SYSTEM

ESS Bilbao in-house developed SSPA-based RF power unit is mainly composed of a commercial Solid-state Power Amplifier [13], a voltage-controlled RF attenuator, a Compact RIO device and auxiliary electronics, shown in Fig. 1

SPA It is an on-shelf amplifier designed to work with pulsed RF signal at 2.7 GHz with 10 percent duty cycle. Based on GaN HEMT Technology provides up to 1 kW output peak power and 68 dB power gain as shown in Fig. 2.

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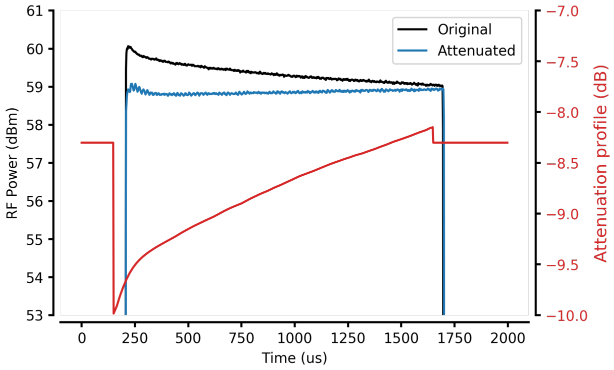

Figure 3: pycalc record process resulting pulse effect example.

Voltage-controlled RF attenuator ZX73-2500+ coaxial voltage-variable attenuator is placed at the SSPA input. It adjusts the RF power level at the input of the SSPA to control the RF pulse shape and amplitude. It can work with DC/constant attenuation control voltage or, alternatively, with an arbitrary control waveform to shape the RF signal envelope.

Compact RIO device cRIO-9075 works mainly as digitizer for the power measurement signals coming from SSPA input/output power detectors. DIO 9402 module acquires the TTL signal to trigger the system digitization process and synchronizes the device execution with the ion source control system. AI 9223 module holds a sample limited acquisition up to a 500 kHz sampling rate and AO 9263 generates either constant or variable attenuation pulse to control the RF pulse attenuation. The pulse generation module is limited to generate a 100 sample output array up to a 100 kHz sample rate.

Power Supply cRIO and SSPA need a DC supply voltage of 24 V and 50 V respectively. The cRIO is then fed with an AC/DC converter that generates a 24 V output DC voltage while the SSPA is supplied using a TDK-Lambda G60-17 remotely controlled from the ion source control room.

Auxiliary electronics As the RF power source unit was thought to be modular and to be installed as auxiliary amplification system for the ion source, additional electronics had to be included in the final design in order to protect the system from grounding issues as well as to provide power supply to the RF attenuator, the single-ended to differential circuits, buffers and optocouplers.

Injector RF Source Layout

In ESS Bilbao ion source, klystron and SSPA are connected with plasma chamber by a wave guide switch (shown in Fig. 1), so it can select which RF power amplifier one wants to use.

CONTROL SYSTEM

The SSPA amplification unit control system is based on Experimental Physics and Industrial Control System (EPICS) while the digitization is programmed using LabVIEW. This section describes the data acquisition layer as well as the RF pulse envelope shaping strategy.

LabVIEW

Data acquisition and the attenuation pulse generation are the main functions of the LabVIEW software in this system. Data acquisition was configured in the FPGA layer using the user-controlled I/O sampling technique described by NI [14] in order to reduce the sampling period down to 2 µs. Attenuation pulse generation works in two different cases, being continuous pulse attenuation and shaped pulse attenuation. Continuous pulse attenuation operation mode generates a maintained voltage signal through the 9263 AO module output channel. Shaped pulse attenuation waits for a trigger to output a 100 sample array, after a user-defined delay, that modifies the analog output voltage value over the attenuation pulse width also defined by the user. cRIO micro-controller layer works as middle-ware for the data communication between EPICS and LabVIEW FPGA. All the logic behind the proper array values for the pulse shape control are configured in EPICS as well as the RF pulse envelope shaping technique.

EPICS

ESS Bilbao proton source control system has been based in EPICS to build a DCS since its beginning [15]. Lately using NI devices mainly as digitizers, EPICS holds most of the data conditioning routines. In order to configure the desired RF pulse envelope shape at the output of the SSPA, the PyDev [16] module was installed in the proton source EPICS DCS to be able to run python code as part of the EPICS process variables (PVs) execution. This helped to handle array building routines easily using pycalc record [17], that builds the desired pulse shape array in python and divides it by the real RF power pulse array, both in W, resulting in a non-dimensional array of the same size as the divided arrays. Then the array size is reduced down to 100 samples so the LabVIEW FPGA can handle it and the resulting array multiplies the current attenuation value to generate a modified attenuation pulse synchronized by the proton source control system trigger.

An example of the pycalc record resulting pulse can be seen in Fig. 3 where the secondary Y-axis reflects the attenuation pulse value. This one was configured using a rectangular pulse as the desired pulse shape and it was generated with 150 µs delay and 1.5 ms pulse width.

Apart from the mentioned routines, Modbus relative communication channels were also added to the proton source control system to manage the RF switch shown in Fig. 1. This RF switch is wired to the PLC network that controls the alarm and interlock system, described in [2].

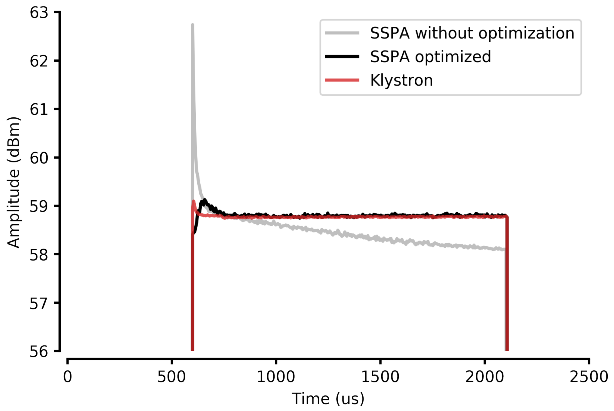

Figure 4: SSPA system optimized and without optimization RF pulses compared with the klystron RF pulse.

TESTS AND RESULTS

In this section, the results obtained in beam extraction and RF pulse shaping with the SSPA amplification unit are described and compared with the ones obtained with the klystron.

SSPA System Pulse Flatness Compared to the Klystron RF Pulse

In order to check that the SSPA amplification unit flattened pulse is similar to the klystron system RF pulse, both signals are compared in the same operating conditions, i.e. 750 W output power, 10 Hz repetition rate and 1.5 ms pulse width. The measurement is taken from a directional coupler placed right after the RF switch shown in Fig 1 using a spectrum analyzer and acquiring the signal by means of EPICS.

Figure 4 shows how the pulse flattening technique optimizes the SSPA system RF pulse and sets its shape close to the klystron system RF pulse, compensating the pulse droop and reducing the SSPA RF pulse overshoot caused by the capacitors bank employed in the SSPA system design [18].

Shaped RF Pulse Beam Extraction

The following step was to investigate the function of solid-state power amplifier on high voltage regime when the source generates proton beams. As shown in Fig 5, the SSPA amplification unit RF pulse is optimized and stable proton current has been measured. The operation conditions are 45 kV extraction voltage, 800 W output power, 10 Hz repetition rate, and 1.5 ms pulse width and the current shape is the same as that produced by the klystron.

Finally, apart from the pulse flattening technique, more shapes were added to the python program executed in EPICS. In Fig. 5 the SSPA unit RF pulses and the resulting beam current pulses final shape can be seen after setting a ramp up and Gaussian curves as the desired pulse array. Beam currents were measured using a current transformer located in the first vacuum vessel right behind the extraction system.

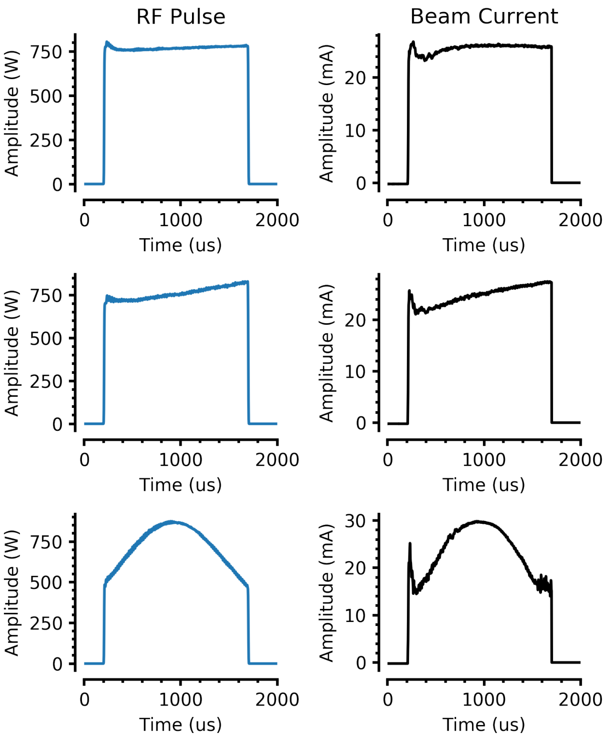

Figure 5: SSPA system RF pulses with different shaping techniques (left side) and the resulting beam current pulses for each shaping technique (right side).

As can be seen, RF pulse shaping has a direct effect in the extracted beam pulse shape.

DISCUSSION AND CONCLUSION

As it is shown in the test results, the SSPA amplification system is capable of imitating the RF pulse conditions and desired beam current according to ESS Bilbao proton source operating conditions. Moreover, the reliability added to the pulse control thanks to the flatness control routine gives the proton source an additional degree of freedom not achievable by the other RF sources.

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