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A NEW EPICS BASED FREQUENCY SYNTHESIZER AND POWER CONTROL SYSTEM FOR THE H$^-$ RF ION SOURCE AT ISIS

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Abstract

A Low-Level RF and Power Control system based on EPICS has been developed for the new H$^-$ RF Ion Source on the Pre-Injector Test Stand at ISIS Spallation Neutron and Muon source, UKRI-STFC Rutherford Appleton Laboratory. The Ion Source LLRF system provides a 2 MHz signal to a Solid-State 100 kW RF Amplifier that drives the Ion Source Plasma, the changing Plasma load requires fast Frequency agility and closed loop Power Control. This paper will detail the design and performance of the LLRF system.

MEBT UPGRADE

An upgrade is being made to H- pre-injector at the ISIS spallation neutron and muon source to include a new RF-Driven inductively coupled plasma (ICP) H$^-$ ion source operating in frequency range of 2 - 3 MHz followed by a new medium energy beam transport (MEBT) consisting of a 202.5 MHz, 665 keV radio frequency quadrupole (RFQ). The new and upgraded MEBT is intended to improve the beam transport and matching into the first accelerating tank of the ISIS 70 MeV drift-tube linear accelerator (DTL) which injects beam into the ISIS synchrotron, the improved beam transport allows for the use of the new more reliable RF-Driven ion source. The design of pre-injector upgrade project has been previously described [1].

Current Progress

In order to test the viability of the ion source and MEBT a pre-injector test stand (PITS) is currently in the final stages of being commissioned. The commissioning has proceeded in steps from the first RF plasma being ignited through to a process of optimising the various parameters (Gas flow, RF Power, Filter field etc) of the ion source in order to maximise H$^-$ beam output. During these early stages of development the ancillary equipment for operating the ion source has been in a temporary developmental stage and undergone numerous modifications and improvements, some having been previously been detailed [2], with the PITS now moving to a phase of long-term operation and soak testing it has been necessary to focus on improving reliability, remote control and automated data collection.

RF-DRIVEN H$^-$ ION SOURCE

The ion source technology currently in development is a non-caesiated RF volume-type H$^-$ ion source with an external antenna driving an ICP at 2 - 3 MHz and 50 - 70 kW RF power, an Aluminium Nitride plasma chamber and a small 2.45 GHz electron cyclotron resonance (ECR) ion source as an aid to plasma ignition as shown in Fig. 1. The design of the ion source has been optimised to minimise surfaces exposed to attack by plasma with the promise of providing considerably longer life-times than the current Penning-type ion source, a design goal of at least 6 months continuous operation has initially been considered.

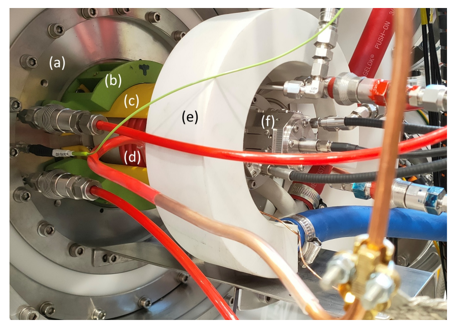

Figure 1: Main components of the RF ion source include the mounting flange (a), filter magnets (b), main housing (c), RF antenna coil (d), cooling jacket (e), and ECR ignition gun (f).

After the initial plasma commissioning with extraction voltage applied the ion source gave a beam current of around 15 mA, this was however before any attempt was made to optimise any of the key ion source parameters.

Improvements to RF Systems

During the initial commissioning of the RF systems a significant problem with RF leakage was discovered, RF power leaking from the RF systems into nearby electrical distribution wiring was found to be causing interference issues with the ion source diagnostic and control equipment. In order to mitigate this changes were made to the layout of RF systems, the most significant of these was to more substantially isolate the RF power amplifier, RF coaxial line and RF matching network from other electrical systems through the use of a low-pass filter network and the remaking of all control and timing connections through optical-fibre.

A further change was made to the location of the 100 kW RF amplifier, the amplifier was initially situated near to the ion source control and diagnostics equipment, however after re-routing the RF coaxial connection from the amplifier to the matching box the amplifier was possible to re-locate it away from the sensitive equipment and form an "Island" with a dedicated RF ground connection run through an RF choke to provide a high impedance for RF current.

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Table 1: RF Amplifier Specifications.

Parameter	Specification
Peak RF Output	100 kW
Bandwidth	2.2 MHz
Max Pulse Width	1 ms
Repitition Rate	50 Hz
Output Impedance	50 Ohm

RF AMPLIFIER CONTROL

RF power to ignite and sustain the ion source plasma is generated by a solid-state 100 kW peak RF amplifier manufactured by R and K Co Ltd shown in Fig. 2, the amplifier specifications are shown in Table 1. RF power from the amplifier is transmitted to the ion source antenna coil through a broad-band RF transformer with high-voltage DC isolation, this necessary to isolate the RF amplifier at ground potential from the ion source ”Platform” which is brought up to -35 kV to extract beam. The high-voltage side of the transformer connects directly to a capacitive impedance matching circuit that matches the low plasma impedance to that of the amplifier. For remote operation, the amplifier has an external control and interlock interface and requires a timing pulse to enable amplification and the 0 - 10 mW RF low-level RF signal to be amplified.

Figure 2: RF Amplifier.

Due to the measures taken to mitigate the RF interference issues, the amplifier control and LLRF needed to be an isolated and self-contained system connected directly to the amplifier. The existing controls infrastructure was unable to accommodate the requirement to be on an isolated ”Island”, the solution was found with the Experimental Physics and Industrial Control System (EPICS) [3].

EPICS is an open-source collection of tools and applications for implementing distributed control systems for particle accelerators and other large scale science and industrial facilities, with ISIS currently undergoing a migration to EPICS, The RF ion source and PITS project offered a unique opportunity to trial the use of EPICS to implement the RF amplifier control and LLRF system using a commercially available System on Chip (SoC) called the ”Red Pitaya STEMlab” [4] card shown in Fig. 3.

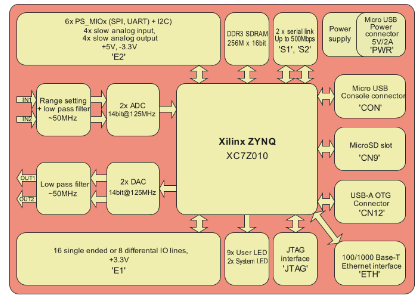

Figure 3: Red Pitaya Architecture.

CONTROL HARDWARE

The Red Pitaya STEMlab board is an adaptable and powerful single-board computer, requiring only a 5 V power supply and an Ethernet connection, however due to it being fundamentally a low-voltage logic device, without modification it is not directly compatible with the standard industrial control interfaces found within particle accelerator facilities which are 24 V relay contacts.

Figure 4: Interface PCB.

In order make use of the Red Pitaya in this application, a custom printed circuit board (PCB) shown in Fig. 4 was designed and manufactured to create a galvanically isolated interface from the amplifier control connection at 24 V levels to the Red Pitaya SoC at 3.3 V levels. The PCB provided not only the isolation interface but a dedicated power supply

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to provide power to the Red Pitaya. Running on the SoC is an EPICS Input-Output Controller (IOC), the IOC provides a database structure to interface between the low-level hardware of the Red Pitaya EPICS control system and allows the system operator to interact with individual pins or RF inputs and outputs of SoC through a control screen a remote computer system. The ISIS facility has decided to use Control System Studio (Phoebus) for its EPICS control screens

FUTURE DEVELOPMENTS

There has been a limited amount of time test the system due to other work packages taking precedence which has precluded running of the ion source. However some initial results have been obtained before the shutdown, the results have been quite satisfactory, with these positive results a plan has been made to extend the functionality of the current prototype to include closed-loop RF power control and fast frequency switching. The most important of these is the fast frequency switching, due to the fluctuating plasma loading on the RF system during ignition it is desirable to have the ability to ignite the plasma at a frequency below the nominal operating frequency, the exact difference needs to be determined experimentally but would usually be on the order of 50 kHz. The frequency change must happen on the time scale of 50 - 100 µs within the pulse, in order to achieve a response of this speed a dedicated external RF switch [5], shown in Fig. 5, triggered from the timing system must be used. As the Red Pitaya SoC has two RF output channels capable of generating arbitrary waveforms of differing frequency and amplitude simultaneously, the phase of both channels is locked to a master oscillator.

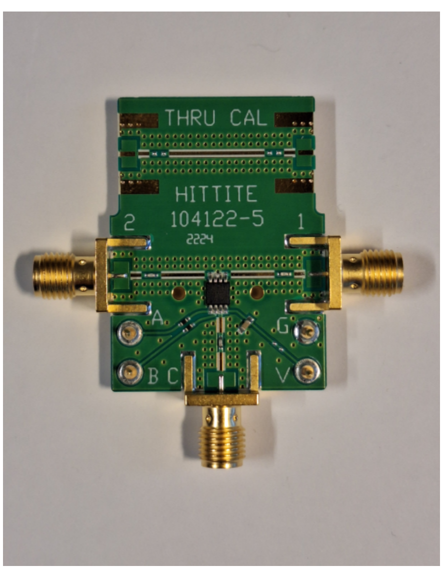

Figure 5: Fast RF Switch.

To obtain a fast frequency hop during the plasma ignition, one channel is set to the low frequency and the other channel is set to the high frequency with fast RF switch selecting between the two when triggered. Automatic closed-loop control of RF level (ALC) is a standard feature in many RF signal generators and would be a very useful addition this system, again due to changing plasma loading which can cause the RF power output from the amplifier to vary under changing gas flow rates and temperatures. The development of an ALC feedback loop requires further work to integrate into the system the measurement of forward and reflected RF power from the directional coupler at the amplifier RF output and the measurement of RF voltage and current directly at the ion source antenna. It is this measurement that presents the most challenge both due to high RF voltage present within the RF matching circuit and antenna itself along with -35 kV high-voltage DC bias applied to ion source to extract and accelerate the beam.

CONCLUSION

With the completion work the electrical systems and interlocks the PITS project is now entering its main operation and soak testing phase which requires that the ion source RF amplifier system be operated in more reliable and automated way. The Red Pitaya has proven to be a viable method of connecting the ancillary equipment of the ion source into the EPICS control system and the ease of development provided by the Red Pitaya and the open-source EPICS software packages has allowed fast pace of prototyping.

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[3] EPICS website, https://epics-controls.org

[4] Red Pitaya STEMlab, https://www.redpitaya.com

[5] HMC574 Analog Switch,https://www.analog.com