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OPTIMIZATION AND UPGRADE OF SLOW EXTRACTION CONTROL SYSTEM FOR HIRFL CSR MAIN RING*

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Abstract

The heavy ion beam from Heavy Ion Research Facility in Lanzhou (HIRFL) CSR Main Ring (CSRm) is slowly extracted by using a third-order resonance driven by sextupole magnets and delivered to various experimental facilities. The slow extraction is driven by the transverse radio frequency knockout (RF-KO) exciter. Many physics and radiation medicine experiments require high-quality spill-structure. In other words, the extracted spill should have flat structure and low ripple noise [1]. Therefore, a novel RF-KO exciter and spill feedback control system has been implemented and tested in CSRm.

INTRODUCTION

The HIRFL accelerator complex is illustrated in Fig. 1. The particles accelerated by CSRm are slowly extracted to external experimental terminals, or extracted in fast extraction mode to CSR Experiment Ring (CSRe). In slow extraction mode, many physical, material, biological, and medical experiments require high-quality spill that has flat structure and low ripple noise. For CSRm, the resonant slow extraction is driven by RF-KO exciter. In the new spill control system of CSRm, the host machines are employed to calculate amplitude modulation curve and spill duty factor, publish the control variables, and manage the various parameters that are often stored in the database. In addition, two FPGA boards are dedicated to control RF power amplifier and a pair of fast quadrupole (FQ) magnets.

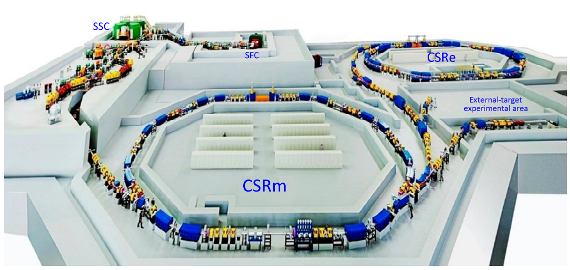

Figure 1: HIRFL accelerator complex.

SPILL CONTROL

In the HIRFL, the particles are extracted slowly out of the CSRm by using RF-KO exciter. The two FQ magnets are additionally used to achieve better spill quality. As shown in Fig. 2, the typical shapes of spill are achieved by RF-KO extraction without feedback unit at CSRm after upgrading. Fig. 3 shows the block diagram of the new spill control system. In the RF-KO method, the beam is partially moved into resonance by transverse excitation. The suitable parameters of the RF-KO exciter dose improve efficiency and spill quality reasonably. In the feedback unit, the spill signal is used to calculate the exciting signal for FQ magnets which is used to suppress the spill ripple noise and make rectangular-shaped spill structure.

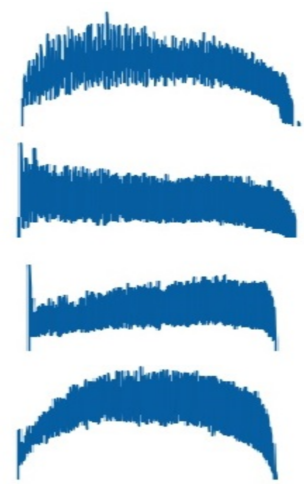

Figure 2: Typical spill shapes archived by RF-KO extraction without feedback control at CSRm. Here: Carbon beam, energy E = 190, 260, 330, and 400 MeV/u.

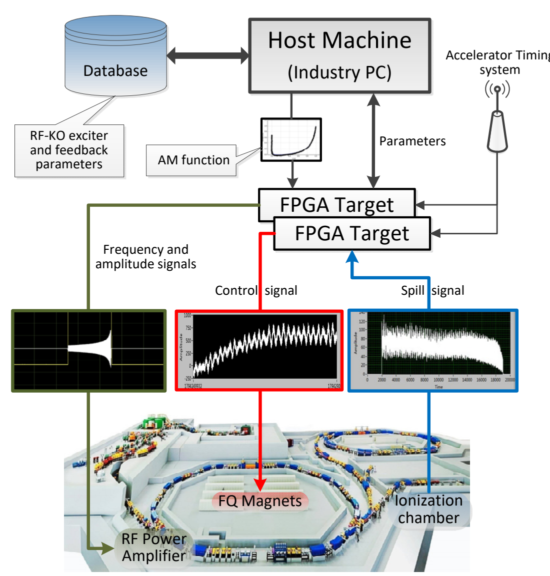

Figure 3: Block diagram of the spill control system.

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RF-KO Exciter Unit

Figure 4 shows the block diagram of RF-KO exciter unit. The host machine (Industrial PC) is used to manage parameters and database access, calculate amplitude modulation (AM) function, and publish the control variables to the network-based accelerator control system. The FPGA target is dedicated to control the amplitude and frequency of the output voltage for RF power amplifier, generate the white noise, and parse the event sequence number. The database stores the all relevant parameters of the RF-KO exciter.

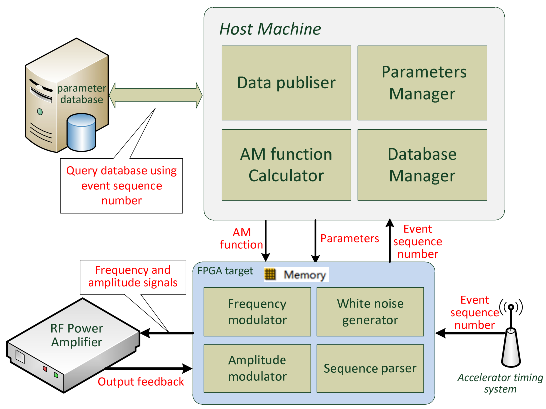

Figure 4: Block diagram of the RF-KO exciter unit.

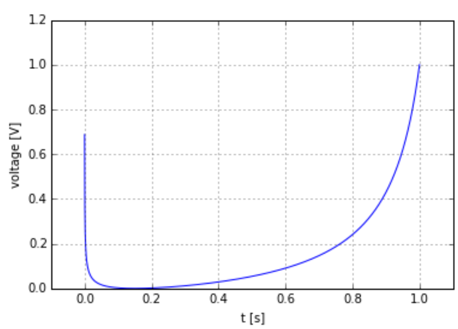

Figure 5: The best AM function curve for RF-KO exciter.

Indeed, to improve the slow extraction efficiency and beam time structure, frequency modulation (FM) based on white noise and amplitude modulation based on the best AM function curve, as shown in the Fig.5, had been introduced into RF-KO exciter control unit in the course of designing. The flow of updating the AM function curve is as follows:

1. The experimental terminal control system sends a beam request to the accelerator control system.
2. The accelerator control system notifies the timing system to generate the corresponding event sequence number.
3. The sequence parser in the FPGA target delivers the event sequence number to the host machine.
4. The host machine queries the database using the event sequence number.
5. The host machine updates the current parameters for RF-KO exciter depending on the query result.
6. The host machine calculates the AM function curve using the latest updated parameters.
7. The host machine updates the FPGA memory area, which is used for storing the current AM function curve.

Feedback Unit

Figure 6 shows the block diagram of feedback unit. It consists of the host machine to manage parameters and database access, to calculate the spill duty factor, and to publish the control variables that can be accessed by the other network devices, the FPGA target to handle the spill signals and to calculate the exciting current pattern for FQ magnets by using a digital PID controller, and the database for storing feedback parameters proportional gain (Kc), integral time (Ti, min), derivative time (Td, min), and PID loop rate.

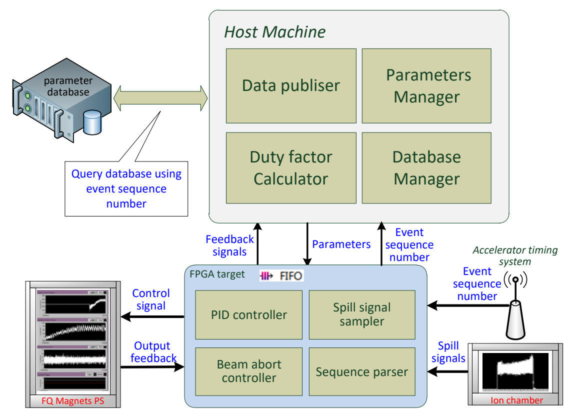

Figure 6: Block diagram of the feedback unit.

And besides, a couple of FQ magnets were symmetrically installed in CSRm, however, they make only a small contribution to the change of the lattice. Though, the excitation of the FQ magnets will change the horizontal and vertical tune values simultaneously, the effects of the vertical tune value change is often negligible[2, 3]. The beam intensity is monitored by ionization chamber in external-target experimental terminals, and a Q/f convector, which generate TTL pulse signal, is used for connecting the FPGA target and the ionization chamber.

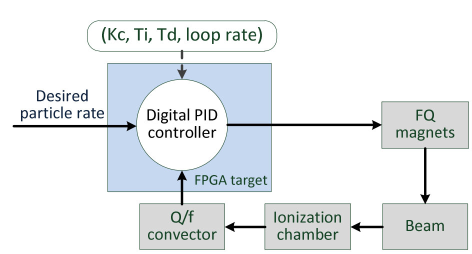

Figure 7: The spill feedback processing.

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To achieve the best beam time structure, the suitable RF-KO exciter and feedback parameters vary with beam parameter, e.g. ion species, energy and intensity. Once a beam switch is identified by the sequence parser, the host machine will immediately query the database with the specified event sequence number, which is generated by the accelerator timing system to uniquely identify the beam, and update the current parameters based on the query results.

EXPERIMENTAL RESULTS

The effectiveness of RF-KO exciter and feedback units had been verified by beam commissioning in HIRFL CSRm. We evaluate the beam time structure by spill duty factor.

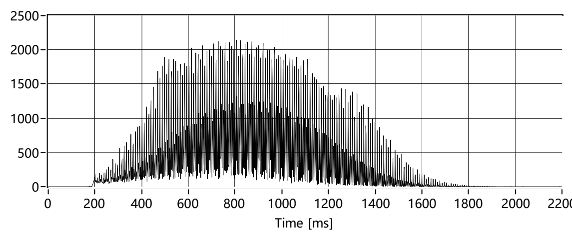

Figure 8: Beam structure before upgrading. Here: Carbon beam, energy E = 190 MeV/u.

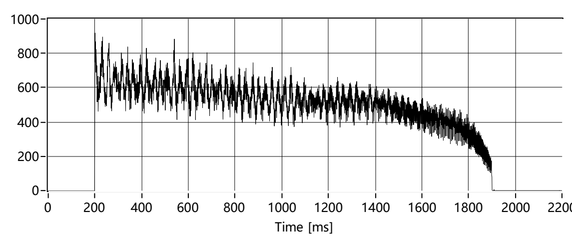

Figure 9: Beam structure without FQ feedback after upgrading. Here: Carbon beam, energy E = 190 MeV/u.

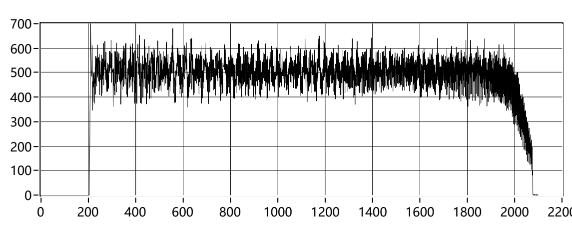

Figure 10: Beam structure with FQ feedback after upgrading. Here: Carbon beam, energy E = 190 MeV/u.

$$\text{Duty Factor} = \frac{\left[\int_0^T I(t)dt\right]^2}{\int_0^T dt \cdot \int_0^T I^2(t)dt} \qquad (1)$$

The formula (1) [4] is used to calculate the beam structure duty factor. A higher value of spill duty factor indicates that the beam time structure is closer to the flat structure. Fig. 8 shows the time structure of slow beam-extraction before upgrading. The spill duty factor is just 35.98%, so the flatness of beam structure needs to be further optimized by improving excitation and feedback methods. Fig. 9 shows the time structure of slow beam-extraction without feedback unit after upgrading. The spill duty factor is improved to 89.19%, but particles are not evenly distributed in phase space, thus it is very hard to achieve a smooth and flat spill by the RF-KO exciter unit alone [5]. Fig. 10 shows the time structure of slow-extraction with feedback unit after upgrading. The spill duty factor is further improved to 92.13%, and spill quality is much better.

CONCLUSION

We have finished the design and development of the new RF-KO exciter and spill feedback control system, which consist of host machine, database, and FPGA board, and carried out beam test in HIRFL CSRm. The effectiveness of our new design is verified by experimental results. The RF-KO exciter and feedback units do effectively improve the beam characteristics. The spill duty factor is improved from 35.98% to 92.13%. We expect the further improvement in beam time structure by optimizing the parameters of the RF-KO exciter and feedback units.

The old control devices will be soon replaced by new solution via FPGA-PC-Databse. This makes the slow extraction system more effective.

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