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High-Precision High-Voltage Detuning System for HIAF-SRing Electron Target

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Date: 2023-06-01T00:00:00+00:00

Abstract

Developing a detuning system for precisely controlling electron energy represents a significant challenge for electron targets in ion storage rings. To address this, the present work develops a high-precision, high-voltage detuning system for the HIAF-SRing electron target, enabling precise electron-ion relative energy modulation in experiments. The system comprises an auxiliary power supply and a high-voltage detuning power supply. The auxiliary power supply stage utilizes an LCC resonant converter operating in soft-switching mode and an LC filter to generate a sinusoidal waveform that powers the high-voltage detuning supply. The detuning power supply consists of a high-voltage pulse amplifier (HVPA) and a high-voltage DC (HVDC) module connected in series. This paper describes the design and development of the detuning system and presents a detailed experimental setup; test results confirm that the system meets the technical requirements for dielectronic recombination (DR) experiments. Finally, the Fe15+ DR spectrum was measured using the detuning method, with experimental data demonstrating excellent experimental resolution, thereby validating the reliability and feasibility of the approach.

Full Text

Preamble

High-Precision High-Voltage Detuning System for HIAF-SRing Electron Target

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Abstract— The development of a detuning system for the precision control of electron energy represents a major challenge when electron targets are employed in ion-storage rings. To address this, a high-precision, high-voltage detuning system was developed for the electron target of the High-Intensity Heavy-Ion Accelerator Facility—Spectrometer Ring (HIAF-SRing) to produce accurate electron-ion relative energies during experiments. The system comprises auxiliary and high-voltage detuning power supplies. The front stage of the auxiliary power supply employs an LCC resonant converter operating in soft-switching mode, followed by an LC filter to produce sinusoidal waveform output. The detuning power supply consists of a high-voltage pulse amplifier (HVPA) connected in series with a high-voltage DC (HVDC) module. This paper describes the design and development of the detuning system in detail and presents the test bench configuration. Test results demonstrated that the detuning system meets the technical specifications required for dielectronic recombination (DR) experiments. Finally, a Fe^{15+} DR spectrum was measured using the detuning system. The experimental data exhibited good resolution and verified the reliability and feasibility of the design.

Index Terms— Detuning system, Storage ring, Dielectronic Recombination

I. INTRODUCTION

More than 95% of visible matter in the universe exists in the plasma state, and controllable nuclear fusion—a clean energy source for humanity's future—also occurs in plasma environments. Consequently, understanding plasma properties and behavior is critical. Dielectronic recombination (DR) is one of the most fundamental electron-ion recombination mechanisms in various plasmas, significantly affecting ionization balance and level populations. The recombination rate coefficients obtained from DR experiments can be used to evaluate plasma environmental parameters (e.g., temperature and density) and serve as benchmark data for testing theoretical methods and codes [1, 2]. Additionally, DR plays an important role in fundamental research, having been employed to study Quantum Electrodynamics (QED) effects in few-electron ions [3, 4], isotope shifts [5], hyperfine quenching [6], and hyperfine splitting [7].

In recent decades, numerous DR experiments with Highly Charged Ions (HCIs) have been conducted at various storage rings, including the Test Storage Ring (TSR) at the Max Planck Institute for Nuclear Physics (MPIK) in Heidelberg [8], the Experimental Storage Ring (ESR) at GSI in Darmstadt [9], and CRYRING at the Manne Siegbahn Laboratory (MSL) in Stockholm [10]. CRYRING has recently been relocated to GSI, where CRYRING@ESR now serves as a high-resolution DR experimental spectrometer. Currently, DR experiments in storage rings utilize the electron beam from the electron cooler as the target. This method requires periodic detuning of the electron beam energy to obtain the desired relative energy between electron and ion beams in the center-of-mass (cm) frame. During detuning intervals, the electron energy must return to the cooling point to maintain the quality of the stored ion beams. However, this approach suffers from a low duty cycle—approximately 1/10 for the detuning process in measurement cycles—which significantly reduces experimental efficiency and limits its applicability to low-energy DR measurements.

A new project, the High-Intensity Heavy-Ion Accelerator Facility (HIAF), is currently under construction in China. The HIAF program aims to expand nuclear physics and related cutting-edge research into new areas and comprises five components: a superconducting electron-cyclotron-resonance ion source (SECR), superconducting ion linac accelerator (iLinac), booster ring (BRing), high-energy fragment separator (HFRS), and spectrometer ring (SRing) [11]. The SRing at HIAF provides an experimental platform for atomic and nuclear physics [12, 13]. Equipped with both an electron cooler and an independent electron target, SRing enables precision DR spectroscopy for highly charged ions across a broad energy range. The electron target operates at arbitrary energy levels while the ion beam is continuously cooled by the electron cooler, thereby significantly improving experimental measurement efficiency. Simultaneously, by adjusting the working point high voltage of the electron target, a substantially broader scan range of electron energy becomes available, enabling precise DR spectroscopy measurements in higher energy regimes.

The schematics of the HIAF-SRing construction and the DR experimental working method are shown in Fig. 1 [Figure 1: see original paper]. The electron cooling region and target are located in the long and short straight sections of SRing, respectively. The operation of the electron target in DR experiments proceeds as follows: Initially, the working energy of the electron target is set to coincide with the electron cooling point energy. Energy scans are performed to measure the DR process at low collision-energy levels. The working energy is then changed stepwise to measure the DR process at high CM collision energy levels. Furthermore, deceleration of highly charged ions is possible in SRing, which benefits DR measurements across a large CM collision energy range.

The key technology required for an electron target is the development of a fast electron energy detuning system to produce accurate electron-ion relative energies in experiments. To verify the DR experimental scheme for SRing, a high-precision, high-voltage detuning system was designed and developed for the SRing electron target. This system can output adjustable millisecond pulses that float on a high DC voltage, as shown in Fig. 2 [Figure 2: see original paper]. A bias voltage of up to -10 kV is provided by a high-voltage DC (HVDC) module to set the working energies shown in Fig. 1. A high-voltage pulse amplifier (HVPA) connected in series with the HVDC module provides precise detuning voltage. The maximum detuning voltage is 1 kV with a minimum voltage step of 1 V. The detuning voltage ripple must be less than 100 ppm to obtain accurate electron-ion relative energy. Rise/fall times must be less than 500 s for a 1 kV detuning voltage to avoid altering ion energy due to cooling drag force. Pulse width ranges from 5–20 ms, depending on the recombination rate. A demonstration experiment was conducted with this detuning system in the Cooling Storage Ring (CSR), a heavy-ion accelerator at the Institute of Modern Physics. This study describes the development, characteristics, and performance of the high-precision high-voltage detuning system. Good experimental test results were obtained, substantiating the accuracy of the proposed detuning system technology and providing a reliable technical solution for the HIAF electron target detuning system.

II. STRUCTURE AND CONNECTION OF DETUNING SYSTEM

The electron gun of the target (ET gun) was connected to the detuning system, which represents a significant capacitive load. The ET gun consists of a cathode, grid, anode, and filament, as shown in Fig. 3 [Figure 3: see original paper]. Electrodes extract electrons from the thermionic cathode, with the cathode directly connected to the detuning system output. The other electrodes connect to three individual DC power supplies that float on the detuning system. The main parameters of all power supplies used for the Fe^{15+} demonstration experiment are listed in TABLE I.

TABLE I: Main Parameters of all the Power Supplies for the Electron Gun and Collector

Electrode	Voltage Range	Fe^{15+} Experiment
Cathode	(0—10 kVDC) + (0–$±$1 kVAC)	-2368.5 VDC ± 360 VAC
Anode	0–3 kV	1.5 kV
Filament	-3.5 kV–3.5 kV	120 V
Collector	0–20 V	1.5 kV

III. HIGH-PRECISION HIGH-VOLTAGE DETUNING SYSTEM

The use of a low-frequency isolation power supply produces low-frequency conduction and radiation interference that is difficult to eradicate or shield. This significantly affects the control setting, which must reach reference voltage on a microvolt scale, while the overall detuning system must limit ripple voltage to below 100 ppm. Switching noise can be minimized by employing soft-switching state in discontinuous conduction mode (DCM), whereas high-frequency sinusoidal waveforms enable low-harmonic power transmission. Therefore, the main auxiliary power supply incorporates a front-stage LCC resonant converter operating in soft-switching state and a post-stage LC filter to provide high-frequency sinusoidal power transmission. This structure not only provides low-switching-noise, low-harmonic, high-frequency isolation voltage for all ET-gun power supplies but also presents effective resistance during rapid system energization (equivalent open circuit) and when the electron beam trajectory deviates (equivalent short circuit).

Including the HVPA and HVDC modules in the detuning system is key to producing the detuning waveform. The detuning power supply adopts a series structure of HVPA and HVDC modules. The unique properties of the HVPA enable it to drive the four-quadrant voltage and current required by the capacitive load of the ET gun, while the mature HVDC module ensures constant DC high-voltage output for electron cooling.

An overview of the high-precision high-voltage detuning system is presented in Fig. 4 [Figure 4: see original paper]. This section introduces the detailed design process for the main auxiliary power supply and high-voltage detuning power supply.

A. Main Auxiliary Power Supply

Zero-current soft-switching states of insulated gate bipolar transistors (IGBTs) can be achieved when the LCC converter operates in DCM, effectively reducing interference noise caused by hard-switching processes. The switching frequency of IGBTs must be less than 2 times the resonant frequency [14]. The LCC resonant square-wave voltage output uses an LC filter to form a double-resonant frequency point on the logarithmic frequency curve. By designing appropriate resonance and filter parameters and a voltage clamping capacitor determined by detuning load characteristics, the main auxiliary power supply can output a constant-amplitude, high-frequency sinusoidal waveform. The structures of the front-stage resonance converter and post-stage filter are shown in Fig. 4.

A transfer function was established for the front-stage LCC resonance converter and post-stage filter. The double-resonance frequency point can be obtained by setting the imaginary part of the transfer function to zero. Based on the structure shown in Fig. 4, the imaginary part transfer function is given by equation (1), where parameters a, c, and e are described in the appendix.

The filter resonant frequency f_1 and DCM resonant frequency f_2 can be obtained by solving equation (1), with approximate solutions given by equations (2) and (3).

Simplifying the post-stage filter and load of the main auxiliary power supply facilitates analysis of the complex structure. The post-stage filter and load are equivalent to impedance Z d, and the load current is treated as constant during the switching period [15, 16]. Under steady-state conditions, a closed-form solution can be derived from state equations by analyzing the resonance converter and filter structure using the state-space method [16]. The converter operates in state 1 when the parallel resonant capacitor voltage Vc_3 and supply voltage V b have the same polarity; otherwise, it operates in state 2. The angle of state 1 is set as ${}_1$, and the angle of state 2 as ${}_2$. When the next switch triggers, state 1 ends and output capacitor voltage Vc_3 changes polarity, transitioning to state 2. Consequently, the end of one state marks the beginning of another, with continuous state switching causing polarity changes in capacitor voltage Vc_3. The two different state relationships between Vc_3 and V b in DCM are shown in Fig. 5 [Figure 5: see original paper].

Based on this analysis, the parallel resonant capacitor voltage is zero during state polarity switching, expressed by equations (4), (5), and (6). The state equation can solve for the $_2$ value of state 2 in the Vc_3 polarity switching process, as shown in equations (7) and (8), where t_1 and t_2 are the durations of states 1 and 2, respectively, and A and B are coefficient matrices of the resonance converter and filter structure [14]. Matrix A describes the internal behavior, while matrix B represents the relationship between external conditions and the resonance converter/filter structure.

Combining equations (7) and (8) yields equation (9). Under steady-state conditions, equation (10) expresses the relationship, and substituting i_0, Vc_{10}, and Vc_{30} from equations (9) and (10) into equation (6) yields equation (11). Formulas for calculating ϕ_1, ϕ_2, and ϕ_3 are shown in the appendix.

The switch turn-off time range and the time for LCC resonant current passing 0 V must be further calculated using $_2$. Using these formulas, an LCC high-frequency series-parallel resonant sinusoidal power supply with a switching frequency of 22 kHz was designed. Design parameters are summarized in TABLE II. Fig. 6 [Figure 6: see original paper] presents logarithmic frequency curves of the double-resonant frequency point for different equivalent system loads, revealing that the voltage decay factor of the third harmonic or any higher-order harmonic remains unchanged during different load variations, maintaining sinusoidal output within a certain load range.

TABLE II: Design Parameters and Specifications of the LCC Resonant Sinusoidal Power Supply

Parameters	Value
Input DC bus voltage	250 V
Equivalent detuning PS load, R	100–1000 Ω
Turn-off time	$\pi/6$
Harmonic proportion	$< 15\%$
Filter resonance frequency, f_1	22 kHz
DCM resonance frequency, f_2	55.8 kHz
Series resonant inductance, L_1	350 H
Parallel resonant inductance, L_3	1.35 mH
Series resonant capacitor, C_1	30 nF
Parallel resonant capacitor, C_3	150 nF
Filter inductor, L_2	100 nF
Filter capacitor, C_2	200 nF
Clamping capacitor, C_4	20 nF

B. High-Voltage Detuning Power Supply

The high-voltage detuning power supply consists of an HVPA connected in series with an HVDC module using a special control method. The overall structure and feedback control methods are illustrated in Fig. 7 [Figure 7: see original paper]. An external extended high-precision 24-bit DAC controlled by a Zynq FPGA (Field Programmable Gate Array) provides reference voltage (V + V) to comparator A_1 shown in Fig. 7. This reference voltage is compared with overall feedback voltage measured by a high-precision high-voltage divider, enabling PI feedback control of the entire detuning power supply through loop control. The HVDC module control setting (V) is achieved using separate photoelectric conversion control. This control method's advantage is that the ET-gun load voltage can be quickly and dynamically compensated by the HVPA's four-quadrant output, allowing load voltage to accurately return to the HVDC module's initial high-voltage DC value after each detuning pulse despite parasitic parameters and capacitive load characteristics.

The series structure causes the HVDC module's output pulse current to match the HVPA's during detuning. Therefore, a parallel pulse capacitor between the HVDC module output terminal and HVPA output terminal serves as a current bypass. This structure effectively protects the HVDC module and filters its output voltage to reduce overall detuning power supply ripple.

The HVPA uses multiple MOSFETs (Metal Oxide Semiconductor Field Effect Transistors) and Darlington transistors in series to achieve positive and negative symmetrical cascade structures [17]. Multiple MOSFETs improve overall withstanding voltage, requiring strict high-voltage equalization protection circuits for each device. The symmetrical cascade's special structural design can rapidly drive the ET gun's capacitive load to the falling edge at positive pulse termination or the rising edge at negative pulse termination. In static states, the symmetrical cascade performs high-voltage equalization, while in dynamic states it must function as an AC circuit for high-voltage linear output. Therefore, each MOSFET requires sufficient driving voltage and correct operating state establishment to ensure symmetrical cascade stability in both static and dynamic operations. With equivalent load capacitance and ET structure capacitance of 5 nF, the instantaneous driving current for 1 kV high-voltage output may reach 10 mA, necessitating reasonable CH and CL front-stage energy storage capacitor design for the front-stage $±$2 kV high-voltage power supply at symmetrical cascade ends.

A linear optocoupler isolates high-voltage potential between weak current control voltage and Darlington transistor base electrode, enabling linear transmission of weak current control signals while safely driving the base electrode in the linear amplification range. A current-series negative feedback circuit between error output and optocoupler input increases optocoupler input impedance and stabilizes drive current. A voltage-parallel negative feedback circuit between optocoupler output and Darlington transistor base electrode performs I-V conversion on the drive signal output by the linear optocoupler while further regulating output current in the cascade amplifying loop, eventually stabilizing ET-gun load detuning voltage. The double-inner-loop feedback design process based on Fig. 7 is as follows.

In the current-series negative-feedback circuit, the mutual inductance gain of the peripheral circuit composed of operational amplifier A_3 is set as Agsf, input voltage as Vs, operational amplifier in-phase input voltage as Vi, closed-loop gain as Agf, operational amplifier open-loop gain as nearly infinite, closed-loop input resistance as Rif, optocoupler drive current as io_1, and feedback coefficient as Fr. Deep negative feedback conditions are given by equations (12) and (13).

In the voltage-parallel negative feedback circuit, the closed-loop mutual resistance gain of operational amplifiers A_4 and A_5 is set as Arf, optocoupler output to operational amplifier current as id, feedback current as if, feedback impedance as Zf, and feedback coefficient as Fg. Deep negative feedback conditions are expressed by equation (14). To improve HVPA relative stability, deep feedback should achieve the state where $|1 + AF|$ 1 [18]. Thus, Darlington transistors with large beta values were selected to improve open-loop gain.

Based on this analysis, the slew rate of HVPA output voltage in the fixed capacitive ET-gun load primarily depends on Fr, Fg, and Kp = Rp/Ri, while rapid stability mainly depends on C_2 in Fg and Ki = 1/(RiCi) in feedback control. Assuming optocoupler output resistance is RD and feedback resistance R_1 is generally less than RD, the zero frequency of the voltage-parallel negative feedback circuit is always lower than the pole frequency. Optimal pole frequency setting based on system stability is achieved when relative frequency lies on the open-loop gain curve. The pole frequency $f = 1/(2\pi R_1 C_2)$ indicates that high-frequency asymptotic noise gain is determined solely by C_2 value. The system's open-loop gain can be simplified as shown in equation (15), with C_2 value obtained by solving equation (16), where Cpd is linear optocoupler output inherent capacitance, Cid is op-amp differential capacitance, Cicm is op-amp common-mode capacitance, and GBW is operational amplifier A_4's gain bandwidth product.

To further analyze how various parameters of the HVPA and HVDC series structure influence the detuning waveform, this study established an overall transfer function model of an equivalent detuning power supply with nonzero initial conditions. This was achieved by simplifying MOSFETs, Darlington transistors, and external driving excitation sources as described in equation (17), where β is the Darlington transistor amplification factor and λ is the ratio of gate current to drain current in the symmetrical cascade MOSFET. Formulas for calculating A_1, A_2, B_1, B_2, C_1, C_2, D_1, D_2, E_1, and E_2 are shown in the appendix.

The main factors determining the detuning power supply's ability to achieve pulses within 500 s rise/fall time are ET-gun load capacity and the Kp, Fg, Fr parameters from the deep negative feedback analysis above. HVPA output ripple peak-to-peak voltage is primarily related to steady-state performance of design parameters. Therefore, detuning power supply parameters were optimized and simulated under ideal conditions using the transfer function in equation (17), providing strong rationale for the prototype design in Section IV.

Specifications and prototype parameters of the detuning power supply are listed in TABLE III. Fig. 8a [Figure 8: see original paper] presents simulation results of optimized overshoot and oscillation in the detuning power supply output waveform by adjusting Kp, Fg, and Fr parameters. Since Fg and Fr can be easily determined by designing required circuit component parameters, these were first fixed while optimizing waveform by changing Kp. If adjusting Kp achieves expected rise time but flat-top oscillations cannot be eliminated by tuning Ki, further fine-tuning of Fg and Fr combined with Kp optimization is necessary. The optimized rise time is controlled within 500 s, with overshoot and rising-edge oscillation well-improved. The Bode diagram in Fig. 8b shows the optimized detuning power supply passband reaching 10 kHz, satisfying DR detuning waveform response-time requirements.

TABLE III: Summary of Specifications and Design Parameters of the Detuning Power Supply Prototype

Parameters	Value
Maximum detuning pulse voltage	$\$\pm1000V\vert\vert MaximumElectroncoolingDCvoltage\vert -$ $10kV\vert\vert Detuningpulsefrequency\vert 2.5Hz\vert\vert Maximumdetunin$ $500\mu s\vert\vert DetuningVppripple(HVDC+$ $HVPA)\vert <$ $100ppm\vert\vert Minimumdetuningvoltagestep\vert >$ $10mV\vert\vert Maximumdetuningcurrent\vert 40mA\vert\vert Voltageparallel$
Voltage parallel negative feedback, C_2	20 pF
Current series negative feedback, R_{14}	430 Ω
Darlington transistor input resistor, R_3	100 Ω
Darlington transistor clamp resistor, R_4	1000 Ω
Darlington transistor FB resistor, R_2	10 kΩ
Darlington transistor emitter resistor, R_5	150 Ω
Pulse current bypass capacitor, CB	20 nF
Energy storage capacitor, CL and CH	200 nF
Equivalent Load, Cg	5 nF
High voltage divider resistor, RH	300 MΩ
High voltage sensing resistor, RL	30 kΩ

IV. EXPERIMENTAL RESULTS

A prototype detuning system was developed using design parameters verified by the simulation described in Section III. The main auxiliary power supply can produce soft-switching zero-current sinusoidal waveform outputs at 22 kHz with less than 15% harmonic components. Fig. 9 [Figure 9: see original paper] presents the measured sinusoidal voltage waveform from the LCC series-parallel resonant converter output and converter current in soft-switching state. The yellow C1 and orange C3 lines represent IGBT gate drive signals, the green C2 line shows resonant current achieving soft-switching zero-current operation during IGBT gate-drive signal dead time, and the blue C4 line represents the high-frequency resonant sine waveform with harmonic proportion below 15%.

The DR waveform high-precision setting and detuning power supply timing were managed by the developed controller. Maximum output voltage testing with a 5 nF load was conducted using a 1:10,000 high-precision high-voltage divider. DC ripple, pulse top ripple, and pulse rise/fall edge times satisfied all design requirements. The detuning power supply and complete DR sweeping period test results are shown in Fig. 10 [Figure 10: see original paper]. The oscilloscope displays DR sweep voltage of $0 -$ \$$\pm 1000Vwitha-10kVoffset.Thedesignedhigh-voltagedividerprovidestwo-wayvoltageoutput:oneforcomparatorA_\{1\}$\$ input shown in Fig. 7 and the other for voltage monitoring.

The \$±\$1 kV pulse voltage test result floating above -10 kV DC voltage is shown in Fig. 11 [Figure 11: see original paper]. Both pulse rise and fall times are less than 500 s. Front-stage energy storage capacitors (200 nF) assist in reducing front-stage \$±\$2 kV high-voltage power supply output instantaneous current despite operating at maximum detuning voltage with equivalent ET-gun load (5 nF). The 1 kV pulse rise time is 180.3 s and fall time is 323.7 s, meeting design requirements. The rise/fall time difference arises from different Fg parameters between positive and negative symmetrical cascades, preventing simultaneous turn-on during power-on. The simulated detuning pulse rise time in Fig. 8a is 230 s; the measured pulse in Fig. 11 shows faster rise time because using identical simulation parameters for positive and negative symmetrical cascades causes simultaneous turn-on issues, requiring positive pulse parameter adjustment. Additionally, detuning pulse rise time is affected by multiple MOS drives, with active components like multiple MOSs idealized in simulation.

As shown in Fig. 12a [Figure 12: see original paper], HVDC output ripple at 1000 V exceeds 100 ppm. However, within the normal DR experimental range, HVDC output ripples above 2000 V can be limited to the 100 ppm range. HVDC cannot meet specifications at low voltages due to background noise. Fig. 12b and Fig. 12c demonstrate ripple waveform and ripple FFT at maximum output, respectively. Main ripple harmonic components are 22 kHz and high-order harmonics because the system's floating series structure disturbs power-supply ripple through the isolated power supply. Greater isolated power supply output power produces stronger interference. An effective solution involves maintaining high-frequency sources distant from experimental equipment, employing appropriate electromagnetic shielding, and suppressing related common-mode interference.

To evaluate the developed fast electron-energy detuning system performance, the prototype was installed on a CSRm electron cooler [20] and tested with an online DR experiment using Li-like Fe^{15+} ions. In the experiment, Li-like Fe^{15+} ions were produced from an ECR ion source, accelerated to 4.35 MeV/u beam energy by a sector-focused cyclotron, and injected into the cooler storage ring CSRm [21]. Electron cooling HV was set at -2368.5 V with 46 mA electron current, achieving velocity matching between electron and ion beams (identical mean longitudinal velocity with zero relative energy). All electron gun power supply main parameters are listed in TABLE I.

After several seconds of electron cooling, the injected ion beam momentum spread (Δp/p) was reduced to approximately 10^{-4}. In DR measurement, electron energy was scanned from 0 to $±$360 V throughout the measurement cycle. For each detuning voltage point, electron energy was detuned for 20 ms and set to the cooling point (-2368.5 V) for 180 ms to maintain good ion beam quality. Relative energy between electron and ion beams in the cm frame was calculated using equation (18), where m and m are electron and ion rest masses, c is light speed, γ and γ are Lorentz factors, and v and v are beam velocities. The angle between beams was assumed zero. Space-charge effects were carefully considered, with drag-force effects found negligible.

For electron-ion recombination experiments at heavy ion storage rings, the recombination rate coefficient α can be deduced from recombination counting rate R at relative energy E using equation (19) [22], where N is the number of stored ions, n is electron beam density, L is effective interaction section length, and C is storage ring circumference.

Based on equations (18) and (19), measured electron-ion recombination spectra are shown in Fig. 13 [Figure 13: see original paper]. Spectra measured under positive and negative detuning voltages are represented by solid red and blue curves, respectively, covering 0–15 eV electron-ion collision energy and encompassing DR resonances from 3s$→$3p and 3d core excitations. The strong peak at 0 eV clearly indicates radiative recombination (RR) process contribution. Resonant positions in Fig. 13a and corresponding detuning voltages are shown in the lower panel. Measured DR spectra were compared in detail with TSR experimental results [23]; resonant parameters showed good agreement. Power supply ripple affected electron beam longitudinal temperature, with temperature changes reflected in DR resonance peak broadening. By fitting longitudinal temperature to DR resonance peak broadening between 1.0 eV and 2.5 eV in Fig. 13b and using constant parameter (C=2) in equation (23) [24-26], power supply ripple was determined to be approximately 116 ppm. The difference between theoretical calculation and power supply test results arises because theoretical longitudinal temperature is affected by many factors including space charge effect, longitudinal-longitudinal relaxation, and cathode temperature. Although calculated results do not perfectly match measured results, DR resonance peak broadening is highly compatible with ripple measurements.

V. CONCLUSION

This study presents analysis and design of the main auxiliary power supply featuring an LCC series-parallel resonant converter in the front stage and LC filter structure in the post-stage, which provides low-harmonic, low-switching-noise power transmission and protects the system under extreme conditions. Based on DR experimental waveform requirements and ET-gun load characteristics, a high-voltage detuning power supply with HVPA and HVDC modules in series was designed. Implementation and practical considerations of the overall detuning power supply structure were described. The proposed method achieves large instantaneous HVPA output current and solves simultaneous conduction issues in HVPA positive and negative symmetric cascades.

The designed auxiliary power supply provided high-frequency isolated power transmission for the detuning power supply. Using the special detuning power supply, 0 – $±1kVdetuningpulsesfloatingon0– − 10kVDCwereachievedonanequivalentET−gunload(5nF).Pulseripplewaslessthan100ppm,andrise/falledges experimental ion DR parameters, 0 – $±$360 V pulses floating above -2368.5 V DC system output were used for DR testing. Experimental resonant parameters were consistent with TSR DR test results, verifying that the detuning system achieved proposed technical indicators.

These results demonstrate the reliability and feasibility of the newly designed electron energy detuning system, providing early technical reserve and paving the way for future construction of the SRing electron target detuning system. Additionally, the designed detuning power supply offers an applicable technical solution for driving capacitive loads such as electron guns to achieve fast rise/fall edges and low top-ripple linear high-voltage pulses.

VI. APPENDIX

The components a, c, and e used in the imaginary transfer function calculation described in equation (1) were obtained using the following formulas:

The components ϕ_1, ϕ_2, and ϕ_3 used in formula (11) can be obtained by:

The components A_1, A_2, B_1, B_2, C_1, C_2, D_1, D_2, E_1, and E_2 in the transfer function of the equivalent detuning power supply described in equation (17) are obtained by:

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