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# ADVANCEMENTS IN MAGNET POWER SUPPLY SYSTEMS AT KARA: ENHANCING STABILITY, EFFICIENCY, AND OPERATIONAL CAPABILITIES

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*Abstract*

The Karlsruhe Research Accelerator (KARA) has undergone a significant modernization of its power supply infrastructure, including dipole, quadrupole and sextupole magnet systems. These updates, completed by replacing the storage ring quadrupole power supplies in summer 2024, introduce improved stability, reduced energy consumption, and advanced control capabilities. The new controls and control system integration enable new operational modes, including energy ramp-down to refill the storage ring or reduce radiation by dumping the beam at lower energy. This allows consecutive beam optics and collective effects testing at high beam currents without creating too high radiation losses. The upgrades to the quadrupole power supplies further support these advancements by improving compatibility with modern control systems, ensuring reliable and efficient operation, and enabling more flexible operation modes.

This paper summarizes over a year of operational experience, comparing the new systems with the old ones. It highlights key improvements in control interface capabilities, reliability, and overall performance, demonstrating the benefits these upgrades bring to KARA.

## INTRODUCTION

KArlsruhe Research Accelerator (KARA) provides a 2.5-GeV storage ring and light source for experiments with electron beams and intense electromagnetic synchrotron radiation. These capabilities enable deep insights into matter, biological structures, and advanced materials [1]. The power supplies for the storage ring dipole and sextupole magnets, as well as the booster dipole and quadrupole magnets, were replaced earlier [2]. These upgrades improved efficiency, stability, and control system integration. The next step in the modernization process was to replace the storage ring quadrupole magnet power supplies. There are 40 quadrupole magnets in the storage ring, each connected to one of five power supplies. Each family of eight magnets is connected in series to a single power supply. Initially, the feasibility of individual powering for these magnets was explored, as it could provide more flexibility in beam tuning. However, due to the necessity of keeping the storage ring available for user operations, this option was considered impractical. Implementing individual magnet power supplies would require significant investment in infrastructure, followed by extensive commissioning and tuning. As a result, the decision was made to continue with the existing family powering scheme, balancing modernization efforts with operational demands.

In this paper, we will briefly describe the process of replacing the quadrupole magnets power supplies, which was similar to the procedure for the sextupole magnets power supplies. We will then discuss the improvements in stability and efficiency brought by the new power supplies.

Additionally, we will highlight the new operational capabilities made possible by this upgrade. This includes exploring the feasibility of down-ramping and recycling the beam, its impact on radiation and safety, and how improved quadrupole stability affects low-alpha operation conditions [3]. These upgrades represent an important step in improving KARA's performance and flexibility (see Fig. 1).

Figure 1: Comparison of old (left) and new (right) quadrupole power supplies. The new units are more compact, modern, and equipped with advanced control systems.

## ENHANCING STABILITY AND EFFICIENCY

For the quadrupole power supplies, the decision was made to use commercially available units that allow multiple devices to be easily connected in parallel. This setup enables higher power ratings by configuring a master unit with multiple slave units. The selected commercial model, NGPS 150A 70V, from CaenELS [4] was configured as follows:

- Q1, Q2, Q4, Q5: Three power supplies in parallel.
- Q3: Two power supplies in parallel.

The parallel connection is established directly at the output terminals, with the units communicating through a high-speed SFP interface on the front panel. This configuration

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allows the bundled power supplies to function as a single logical unit, controlled via a unified communication interface. A major advantage of the new system is its improved energy efficiency. A comparison between old and new power supplies is shown below (Table 1):

Table 1: Efficiency Comparison of Old and New Power Supplies

| Power Supply | Old Eff. (%) | New Eff. (%) |
|---|---|---|
| Q1 | 86 | 92.3 |
| Q2 | 86 | 92.4 |
| Q3 | 86 | 93.9 |
| Q4 | 85 | 92.3 |
| Q5 | 85 | 92.0 |

This efficiency improvement results in a total power consumption reduction of 6.54 kW, contributing to lower operational costs and supporting more sustainable accelerator operation.

In addition to improved efficiency, the new power supplies show significantly better current stability and current ripple performance. For all five quadrupole families, the current stability was measured to be less than 10 ppm at full scale, which meets the requirements for stable beam optics and supports sensitive operational modes such as low-alpha. The output current ripple is measured using the CT-BOX [5] and processed with a Python script, which calculates the RMS noise and ripple within a bandwidth range of 0.01 Hz to 1 kHz.(see Figs. 2 and 3).

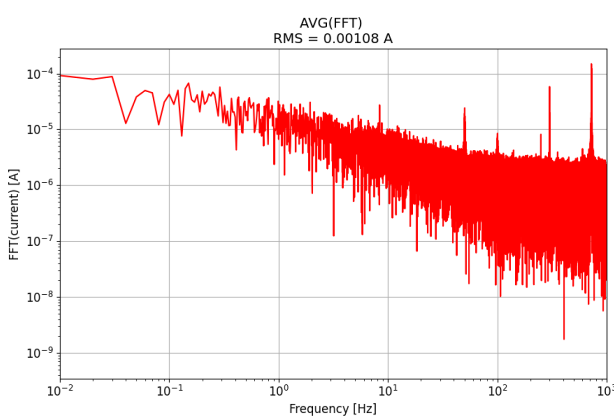


Figure 2: Q3 Output current ripple at 288 A is 1.08 mA.

# OPERATIONAL CAPABILITIES

## *Ramping Down and Beam Recycling*

At KARA, the electron beam is initially injected into the storage ring at an energy level of 500 MeV from the booster synchrotron. Once injected, the beam undergoes a ramp-up process, gradually increasing to its final operating energy of 2.5 GeV. During normal user operation, the beam remains stored for approximately 23 hours.

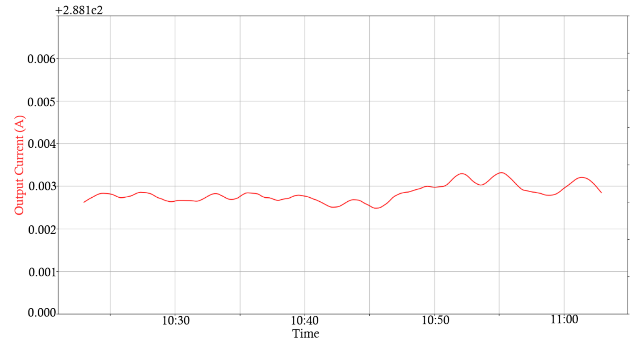


Figure 3: Q3 30-min output current stability test at 288 A The peak-to-peak variation is less than 1.0 mA.

Previously, due to a combination of limitations in the old power supplies and their integration with the control system, ramping the beam energy down was not possible. As a result, the beam had to be dumped each morning before starting a new injection cycle. With the upgraded power supplies and improved control system integration, a ramp-down procedure was tested and a dedicated ramp-down table was developed to ensure beam stability during this process and prevent beam loss.

The ramp-down table is carefully developed by gradually decreasing the beam energy while simultaneously adjusting the Betatron X and Y tunes. Initial tests confirmed that ramping the beam down to 500 MeV was achievable without excessive beam loss.

Further experiments were conducted to investigate the feasibility of beam recycling. In these tests, the beam was successfully ramped down to 500 MeV, topped up with a fresh injection, and then ramped back up to 2.5 GeV (see Fig. 4).

The following observations were recorded during this sequence of test cycles:

- **First Cycle (10:25–10:40):** The beam was ramped down and back up without significant losses, indicating a stable ramping process.
- **Second Cycle (10:40–11:20):** The beam was re-injected at 500 MeV, reaching a current of over 70 mA. A similar ramping sequence was executed. While minor losses were observed during the ramp-up, the beam current was largely preserved. This cycle demonstrated that beam recycling is feasible.
- **Third Cycle (11:25–12:10):** After another reinjection at 500 MeV, the beam current exceeded 90 mA. The ramp-up was performed with minimal losses. However, a significant drop in beam current was observed during the ramp-down ( 95 mA → 20 mA), This suggests that the observed losses were more likely due to magnet hysteresis effects at higher beam currents rather than any instability of the new power supplies.
- **Fourth Cycle (12:10–12:50):** Some adjustments were made to the tuning parameters, and the ramping se-

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quence was repeated. Beam losses occurred during both ramp-down and ramp-up phases, indicating that further optimization of the ramping table is still required.

These results demonstrate that the new power supplies enable controlled energy ramping and open the possibility for beam recycling. However, beam stability during ramping remains sensitive to initial beam current and hysteresis behavior in the magnets, showing that the ramping process still needs improvement to compensate magnet hysteresis effects at low energy.

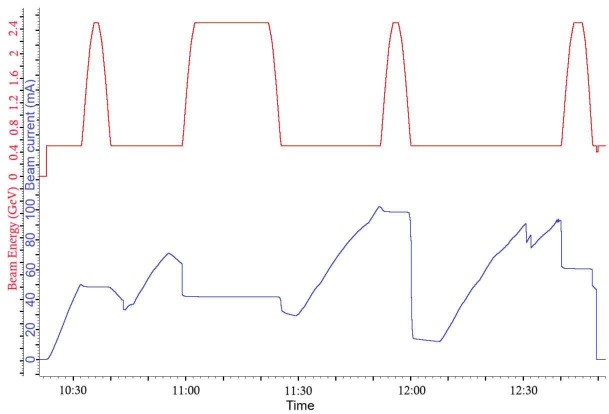


Figure 4: Energy ramp-up and ramp-down cycles .

Successfully implementing beam ramp-down at KARA will have multiple benefits. The first is in radiation safety, as dumping the beam at a lower energy significantly reduces radiation exposure, particularly gamma and neutron radiation. Furthermore, when beam recycling proves to be successful, radiation levels could be even further minimized.

Another advantage of this capability is the potential for a faster morning injection cycle. When the beam is recycled, only a top-up injection would be required instead of a complete re-injection, reducing injection time and increasing the user time.

## *Low alpha and Stability*

Low-alpha operation in a synchrotron reduces the momentum compaction factor ($\alpha_c$) to shorten electron bunches, enabling the production of high-intensity coherent synchrotron radiation in the THz range for advanced experiments or ultra-short synchrotron radiation pulses in the X-ray range.

**Challenges with Stability in Low alpha Mode:** The momentum compaction factor ($\alpha_c$) determines how the electron beam's path length changes with energy. If $\alpha_c$ reaches zero, it leads to beam loss, making stability a critical concern. At the KARA storage ring, The quadrupole magnets Q3 are located in dispersive sections, and $\alpha_c$ can mainly be controlled by adjusting the Q3 current. One of the main difficulties is the fluctuation of quadrupole power supplies, which directly impacts beam stability. Since low-alpha operation requires a precise and small $\alpha_c$ even minor current deviations in Q3 can disrupt beam conditions. To maintain $\alpha_c = 10^{-5}$, the quadrupole Q3 current must remain within $\pm 50ppm$. Note, that this is the absolute deviation, not RMS. This requirement underscores the necessity for highly stable power supplies that can deliver precise current control without excessive fluctuations.

**Improvement with New Power Supplies:** The previous quadrupole power supplies lacked the necessary stability to maintain these conditions reliably. Their fluctuations contributed to variations in $\alpha_c$, limiting the ability to sustain low-alpha operation. The new power supplies with enhanced current stability and precision significantly reduced deviations in quadrupole currents. A plot of Q3 current deviation versus the momentum compaction factor $\alpha_c$ (see Fig. 5) shows that as Q3 current fluctuations decrease, it becomes possible to achieve lower alpha values without increasing the risk of a beam loss.

By stabilizing low-alpha operation, these upgrades open new possibilities for research, particularly for short-bunch generation experiments.

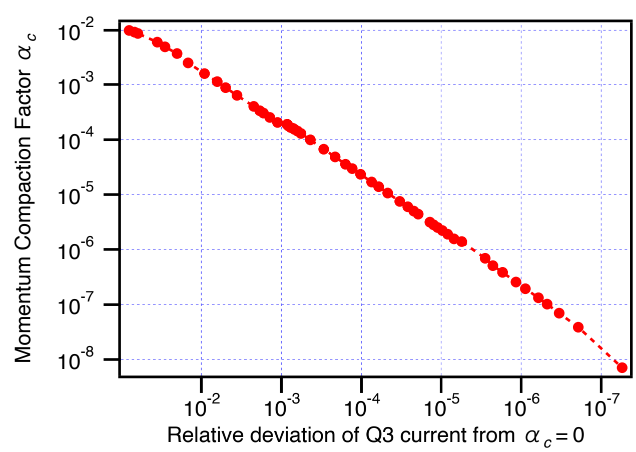


Figure 5: Based on OPA simulations: Maximum allowable deviation of Q3 current to maintain an average momentum compaction factor $\alpha_c$ without beam loss.

# CONCLUSION

The modernization of KARA's quadrupole power supplies, following earlier upgrades to the dipole and sextupole magnets, has resulted in significant improvements in beam stability, energy efficiency, and operational flexibility. The successful implementation of beam ramp-down and recycling enhances both radiation safety and machine availability. Additionally, the improved current stability of the new quadrupole power supplies enables more reliable low-alpha operation, supporting advanced research in beam dynamics and short-bunch experiments.

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