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UPGRADE OF ELSA'S BOOSTER SYNCHROTRON RF WITH A SOLID STATE POWER AMPLIFIER

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Abstract

The 1.6 GeV booster synchrotron of the ELSA facility at the University of Bonn uses a DESY-type RF resonator which has been driven by a conventional klystron amplifier since its early days in 1967. The setup was modified to serve the ELSA stretcher ring as booster synchrotron in 1987, but the RF infrastructure was barely altered. As repairs of the reliable, but antiquated RF source became foreseeingly impossible due to the lack of spare part availability, the replacement of the klystron amplifier chain in favour of a state-of-the-art solid state amplifier was carried out. We describe the replacement and the operation experience with the new RF power amplifier.

INTRODUCTION

From 1967 to 1987 today's *booster* synchrotron of the ELSA facility was operated as 2.5 GeV machine serving nuclear physics experiments [1]. The RF system consisted of two 500 MHz DESY-type resonators powered by a single 40 kW CW klystron of type *F 2008* or *KAP 1216A*[1]. The RF was guided through $3\frac{1}{8}$" and *43-98* rigid coaxial lines towards both operating resonators through a "T-junction" splitter, before which the line impedance was pre-matched from 50 Ω to 25 Ω. In front of the cavity in each branch the RF was coupled via a *door-knob coupler* into a *WR*1800 waveguide, in which a 11 dB water-cooled ferrite isolator with insertion loss < 0.4 dB protected the source from reflections, e.g. when the beam loading changed with beam current or impedance mismatching occurred from cavity detuning.

Serving as 1.2 GeV injector for the ELSA storage ring [2], the synchrotron has been operated with a single cavity, fed through the original klystron and power transmission setup with decommissioned "T-junction". The original analogue low-level RF (LLRF) system remained operational, but the RF magnitude feed-forward generator was upgraded from analogue circuitry to a microcontroller-based version in 2011 [3]. A replacement of the klystron amplifier was recently carried out and first beam was accelerated using the new solid-state power amplifier in February 2022.

BOOSTER OPERATION SCHEME

The synchrotron is a strong focusing combined-function machine operating at a 50 Hz cycle. The magnetic guiding field is produced by a power supply combining AC and DC currents at a ratio of $I_{AC}/I_{DC} = 1.0689$. To increase the dynamic aperture at injection, the RF power is switched on with delay, allowing the orbit to drift away from the injection septum with increasing bending field. At the zero-crossing and at the peak field two trigger signals $t(B = 0)$ and $t(B_{max})$ are generated. The derivative of the magnetic field $\dot{B}$ is measured through a pick-up coil.

The required acceleration voltage U_{acc} corresponds to the increasing guiding field ($\propto \dot{B}$), the losses due to the emission of synchrotron radiation ($\propto B^4$) and beam loading:

$$U_{acc} = c_0 + c_{\dot{B}}\dot{B} + c_{B^4}B^4 + U_{bl}\,, \tag{1}$$

where c_0, $c_{\dot{B}}$ and c_{B^4} are machine-specific coefficients and U_{bl} is the induced beam load voltage. The operation scheme is visualized in Fig. 1 for different selectable extraction energies.

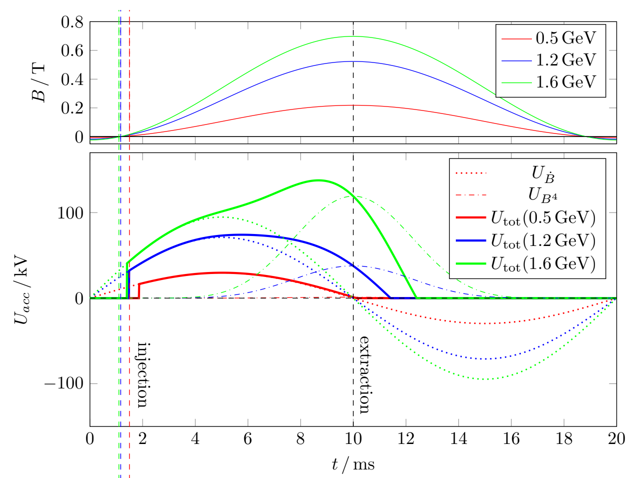

Figure 1: Magnetic guiding field (top) and corresponding feed-forward signal for the RF amplitude (bottom) for different extraction energies and negligible beam loading. The RF power remains switched off at injection and after extraction.

To accelerate I_{beam} = 15 mA to 1.2 GeV at an overvoltage factor of $q = U_{cav}/U_{acc} = 1.4$, amplifier RF power

$$P_{amp} = \frac{U_{cav}^2}{2R_s} + U_{acc} \cdot I_{beam} + P_{loss} \tag{2}$$

of ∼ 1.7 kW peak is required for ideal booster operation. Therein, the cavity's shunt impedance is R_S =9 MΩ and we assume an ideal coupling coefficient of $\kappa \sim 1$, resulting in a loaded shunt impedance of $R_{SL} \approx R_S/2$. The power loss due to the 15 m long transmission line (including the ferrite isolator) is P_{loss} < 0.5 dB. For low current applications (e.g. serving the detector test community), nano-ampere beam currents are injected into the storage ring, which is achieved

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by intentionally reducing the booster RF power to favour the loss of electrons at the injector.

RF AMPLIFIER UPGRADE

Despite of reliable and robust RF operation over multiple decades, the consequence of potential failure of antiquated components with limited or no spare part availability and the corresponding risk of significant machine downtime (compare e.g. with [4]) has lead to the decision to replace the klystron amplifier system. As solid state power amplifiers are well established and generally have reduced footprints and power consumption, at ELSA this omits the necessity to operate an outdated 10 kV dry-type transformer, which is currently located within the booster ring.

Solid State Power Amplifier

A commercially available 10 kW solid state power amplifier[2] (SSPA) was purchased, installed and connected to the existing *43-98* coaxial line close to the center of the booster synchrotron, where convenient adaption was possible (see Fig. 2). The key performance parameters of the amplifier

Figure 2: Image of the solid state RF amplifier with connected coaxial line in front of the former klystron rack gallery.

are listed in Table 1. The device is of modular design and consists of two interchangeable transistor racks with 8 power transistors mounted on each. The SSPA was fully compatible with the existing low-level RF system, merely the input power level had to be limited to the maximum allowed power level of −5.4 dBm. The RF rise time of 50 ns is about two orders of magnitude faster than the cavity rise time of $\tau \approx 12\ \mu$s.

Device Control

The SSPA operates an internal safety PLC which monitors the states of various subcomponents as well as internal and external interlocks. For example, RF amplification is

Table 1: Performance Parameters, Manufacturer Test Report

Performance parameter	value
max. output power	10 965 W
max. power gain	76.4 dB
# of transistors	16 (~ 625 W / unit)
Wall plug efficiency	ϵ = 49.8 % @ 10 kW 20 % @ 2 kW
max. input power	−5.4 dBm
RF rise time and fall time	τ_{rise} = 50 ns, τ_{fall} = 17 ns

prohibited if the cavity condition is in an unready state due to insufficient water flow, body temperature or vacuum pressure. A TCP/IP interface allows communication via MODBUS protocol and updates the accelerator control system with multiple status values and internal measurements, such as input, forward and reflected RF powers or the individual transistor currents. This allows for online monitoring and early identification of ageing and deviating components. For example, Fig. 3 shows the monitored transistor currents and their power-normalized standard deviations for multiple accelerator runs at differently set output powers.

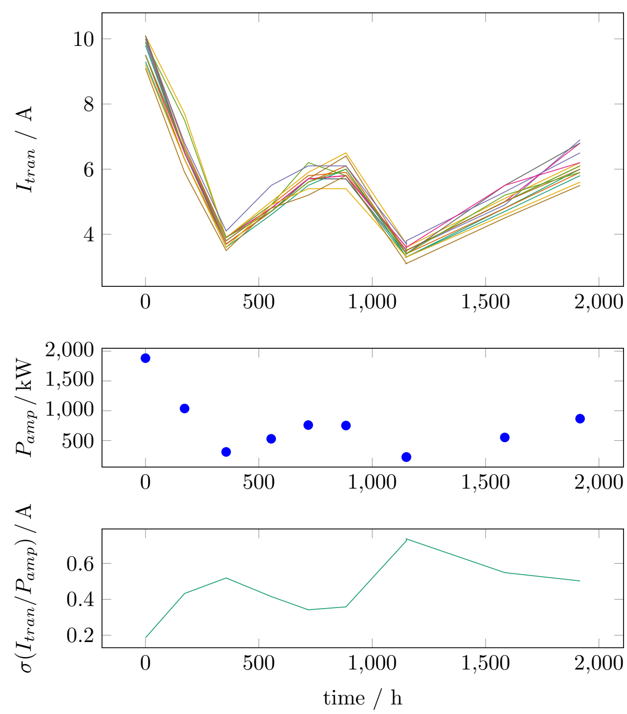

Figure 3: Currents from the 16 power transistors (top), the corresponding forward power (center) and the standard deviation for the different power-normalized transistor currents (bottom) for different booster runs since February 2022.

SYSTEM PERFORMANCE

The SSPA input power level (compare with Fig. 1) is modulated by an LLRF feed-forward signal. The RF control assembly, including the SSPA, is illustrated in Fig. 4. The

[2] Manufactured by SigmaPhi (JEMA), France

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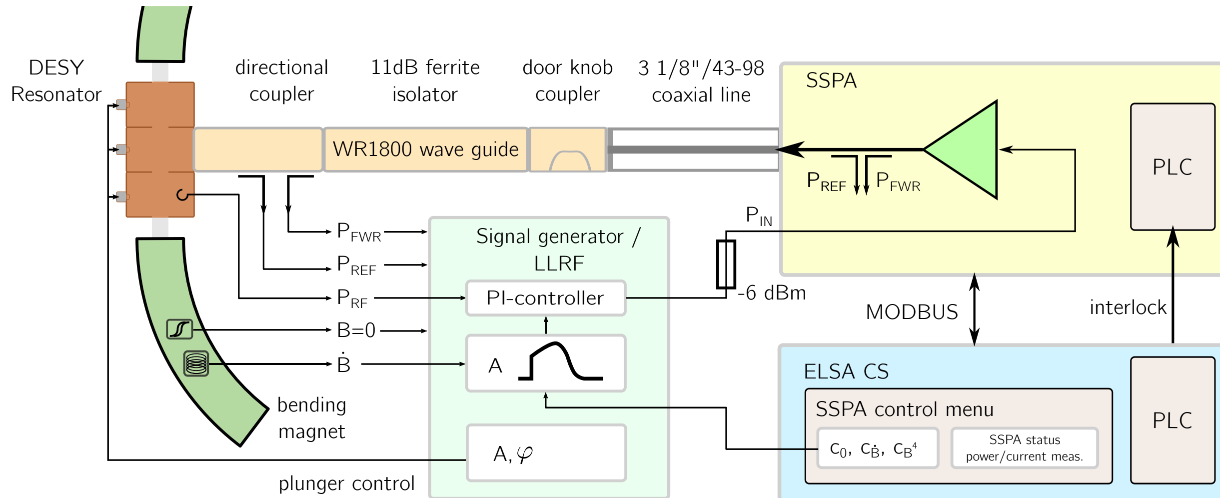

Figure 4: Assembly of the SSPA and LLRF system of ELSA's booster synchrotron. A feed forward power level signal is computed and amplified while a PI-controller compensates the voltage drop due to beam loading. In addition, plungers dynamically optimize the resonance condition. SSPA conditions and power measurements are communicated to the accelerator control system through a MODBUS TCP/IP interface.

signal amplitude is generated by a variable attenuator, whose input voltage function is computed by a microcontroller. It utilizes the before-mentioned signals to determine the starting-point and B-field dependence of the RF amplitude (see Eq. (1)). The coefficients $c_{\dot{B}}$ and c_{B^4} are set numerically with an 8-bit scaler. In addition, the resonator is dynamically tuned through plungers, whose positions are controlled and adjusted to optimize the resonance conditions based on the measured forward and reflection signal from a directional coupler in front of the resonator coupling slit. To achieve Robinson damping, the plunger control loop includes slight capacitive detuning of $\Delta\omega \approx 1.4\,\text{kHz}$.

The dynamic magnitude adjustment and phase correction influences the quality of the internally measured forward and reflected power levels of the SSPA, whose data communication rate is in the order of Hz. For initial operation, the RF feed-forward amplitude was therefore set to a square function. In this mode, the voltage standing wave ratio

$$VSWR = \frac{\sqrt{P_{\text{fwd}}} + \sqrt{P_{\text{ref}}}}{\sqrt{P_{\text{fwd}}} - \sqrt{P_{\text{ref}}}}$$

was determined, resulting in a VSWR up to 1.4 at the amplifier and up to ~ 3.5 between resonator and circulator. As beam is successfully transferred to the storage ring, this mode has been established for standard operation, despite of the consequent dynamical change of the synchrotron frequency during the acceleration process

$$\omega_s \propto \sqrt{U_{\text{cav}} \cos \varphi_s} \neq \text{const.}\,.$$

Subsequent dynamical particle behaviour is sufficiently damped after injection into the storage ring and no beam loss nor beam quality reduction occurs when the amplifier is operated as low as $\sim$1 kW, accelerating 10 mA of beam current to 1.2 GeV.

CONCLUSION

The SSPA has been successfully installed and used routinely as power amplifier for the booster RF cavity since February 2022 for several machine runs. A stabilization of the synchrotron frequency through an optimized feed-forward signal is yet to be implemented for future applications where more stable longitudinal beam dynamics are required.

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REFERENCES

[1] K. H. Althoff *et al.*, "The 2.5 GeV Electron Synchrotron of the University of Bonn", *Nucl. Instrum. Methods*, vol. 61, 1968. doi:10.1016/0029-554X(68)90443-6

[2] W. Hillert *et al.*, "Beam and spin dynamics in the fast ramping storage ring ELSA", *EPJ Web of Conferences*, vol. 134, pp. 05002, 2017. doi:10.1051/epjconf/201713405002

[3] J. P. Thiry, "Mikrocontrollerbasierte Regelung der Hochfrequenzamplitude des ELSA Booster-Synchrotrons", diploma thesis, University of Bonn, 2011.

[4] D. Proft, K. Desch, D. Elsner, and M. T. Switka, "Upgrade of the 25 MW RF Station for the Linear Accelerator LINAC2 at ELSA", presented at IPAC'22, Bangkok, Thailand, Jun. 2022, paper TUPOST002, this conference.