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Technical Specification

for

36 MHz and 108 MHz Solid State RF Amplifier Systems

Abstract

This technical specification concerns the supply of
36 MHz and 108 MHz pulsed solid-state RF amplifiers
for accelerating structures in the range of 40 kW to 2.4 MW.

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LINAC RF Systems
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Glossary

Acronym	Definition
CDD	Conceptual Design Document
CDR	Conceptual Design Review
DTL	Drift Tube Linac
EMC	Electro Magnetic Compatibility
ER	EinzelResonator (Single Gap Resonator)
ESR	ExperimentierSpeicherRing (Experimental Storage Ring)
FAIR	Facility for Antiproton and Ion Research
FAT	Factory Acceptance Test
FDD	Final Design Document
FDR	Final Design Review
GSI	GSI Helmholtzzentrum für Schwerionenforschung GmbH
GUI	Graphical User Interface
HMI	Human Machine Interface
HLI	HochLadungsInjektor (High Charge Injector)
HSI	HochStromInjektor (High Current Injector)
IEC	International Electrotechnical Commission
IH	Interdigital-H-Mode Structure
ISO	International Standards Organization
LLRF	Low Level Radio Frequency
MCCB	Molded Case Circuit Breaker
PLC	Programmable Logic Controller
PS	Post Stripper
RCBO	Residual Current Circuit Breaker with Overcurrent Protection
RFQ	Radio Frequency Quadrupole
SAT	Site Acceptance Test
SIS	Schwer-Ionen-Synchrotron (Heavy Ion Synchrotron)
TK	Transfer-Kanal (Transfer Channel)
TÜV	Technischer Überwachungsverein
TVS	TürVerriegelungsSystem (Door Interlock System)
UNILAC	UNIversal Linear ACcelerator
UVR	Under-Voltage Release

Term	Definition
Solid State Power Amplifier (SSPA)	The Solid State Power Amplifier denotes an entire amplifier unit. It comprises all power supply units, RF amplifier modules, RF components, safety circuits, monitoring circuits, measurement devices, voltage distribution, control, cooling, wiring, interfaces, mechanical infrastructure etc.
HSI-300	The HSI-300 denotes a 36 MHz SSPA with a nominal output power of 300 kW.
HSI-2400	The HSI-2400 denotes a 36 MHz SSPA with a nominal output power of 2.4 MW.
PS-40	The PS-40 denotes a 108 MHz SSPA with a nominal output power of 40 kW.
PS-80	The PS-80 denotes a 108 MHz SSPA with a nominal output power of 80 kW.
PS-300	The PS-300 denotes a 108 MHz SSPA with a nominal output power of 300 kW.
PS-1800	The PS-1800 denotes a 108 MHz SSPA with a nominal output power of 1.8 MW.
RF Power Supply Unit (RFPSU)	The RF Power Supply Units are swappable modules that deliver the required voltage and current for the appropriate RF Power Modules.
RF Power Module (RFPM)	The RF Power Modules are swappable units that contain the RF Power transistors, circulators (if applicable) and first-stage combiners. Following stages combine the power of each module to the desired output of the amplifier.
RF Pallet (RFP)	The RF Power Modules consist of a certain amount of RF Pallets, custom designed RF-PCB-boards with mounted RF-transistors.

1. Introduction

1.1. GSI and FAIR

The GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany, operates a unique ion accelerator complex, currently centred around the UNILAC (Universal Linear Accelerator), the SIS18 synchrotron or ring accelerator, and the ESR storage ring. Serving an international research community, GSI enables ground-breaking experiments in nuclear physics, materials science, and biophysics. Currently, GSI is transitioning to become the primary injector for the future FAIR (Facility for Antiproton and Ion Research), significantly increasing the requirements for beam intensity and system reliability. Figure 1 summarises the existing GSI facility (blue) and the upcoming FAIR facility (red). The existing UNILAC, approximately 120 meters long, accelerates particles as high as twenty percent of the speed of light. The following SIS18 synchrotron, which has a circumference of 216 meters, accelerates all kind of particles to ninety percent of the speed of light. This is the precondition to inject particle beams into the upcoming FAIR facility, where particles will be accelerated in a superconducting ring accelerator (SIS100) with a circumference of 1,100 meters to almost the speed of light with outstanding intensity and quality. This will allow researchers to solve secrets regarding the structure of matter and the evolution of our universe.

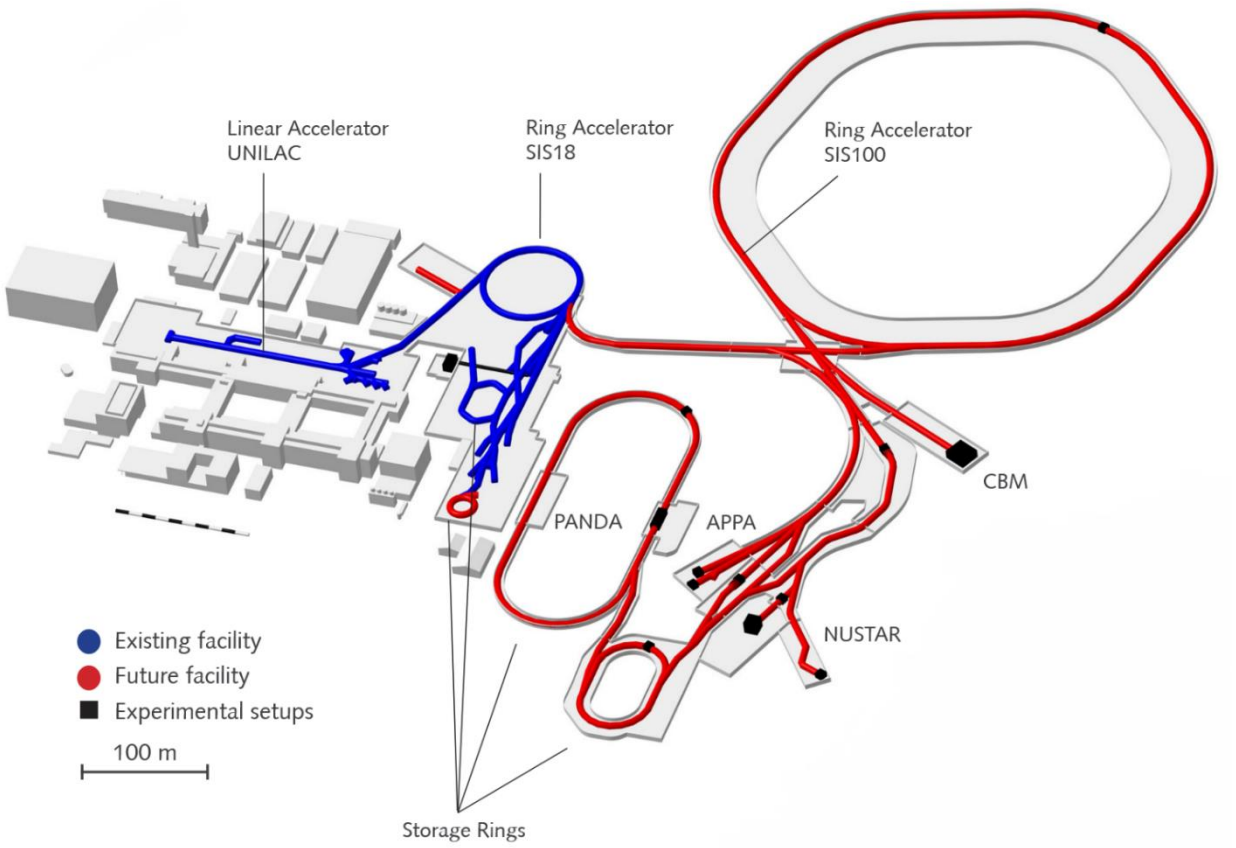


Figure 1: GSI and FAIR Accelerator Facility

1.2. UNILAC

The UNILAC (UNiversal Linear ACcelerator) at GSI is an RF LINAC, which is capable of accelerating a large variety of ions ranging from hydrogen to uranium up to 11.4 MeV/u. It comprises two injectors, the High Current Injector (Hochstrominjektor, HSI) as well as the High Charge State Injector (HochLadungsInjektor, HLI) plus a Post Stripper (PS) section in addition. Figure 2 illustrates the UNILAC basic setup including the specific cavities, bunchers and single gap resonators.

The HSI operates at a frequency of 36.136 MHz and consists of a Radio Frequency Quadrupole (RFQ) cavity, a short 11 cell RFQ called Superlens (SuperLinse, SL) and two interdigital H-type (IH) cavities. The RFQ and IH structures require a maximum RF power of 2.4 MW for each cavity.

The HLI, located north of the UNILAC, operates at a frequency of 108.408 MHz and is implemented by an RFQ, an IH cavity and two small buncher cavities. The RFQ and IH cavities require a RF power of maximum 150 kW and the HLI is rather developed for longer beam pulse length compared to the HSI.

The HSI as well as the HLI inject ion beams in the Post Stripper section of the UNILAC. The Post Stripper includes several Alvarez cavities (A1 – A4), buncher cavities (BB3 – BB4) and single gap resonators (EinzelResonator, ER1, ER10). All Post Stripper cavities except BB3 run at a frequency of 108.408 MHz. BB3 uses the HSI frequency of 36.136 MHz. The RF power requirements of the Post Stripper cavities range from 40 kW until 1.8 MW and are depicted in Figure 2. Finally, there are additional buncher cavities (BB11, BB12) in the transfer line (TransferKanal, TK), which optimizes the beam parameters for the SIS18 injection.

It has to be mentioned that the quality factors of the different cavities in the HSI, HLI and Post Stripper section differ from 5000 to about 100000 and the RF coupling is realised inductively via coupling loop.

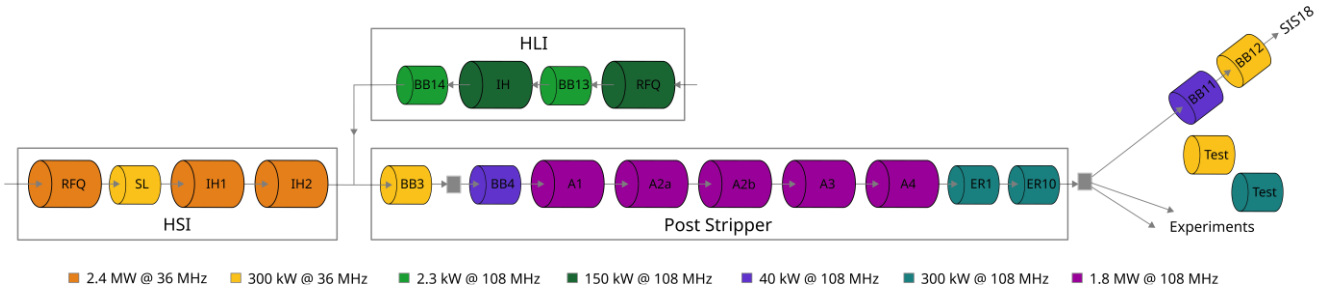


Figure 2: UNILAC Setup at GSI

The RF systems for each cavity of the previously introduced UNILAC, except HLI, are located at the RF gallery in an adjacent building of the UNILAC tunnel. A floor plan of the existing RF gallery is shown in Figure 3. It has a length of about 110 meters and includes the required infrastructure for the RF systems requested in this tender. Due to installation optimization purposes of the RF coax lines the RF gallery is divided into an HSI and PS section, regarding the cavity allocation in the UNILAC tunnel. These sections are also depicted in Figure 3. Dimensions concerning firewalls are provisional and subject to change.

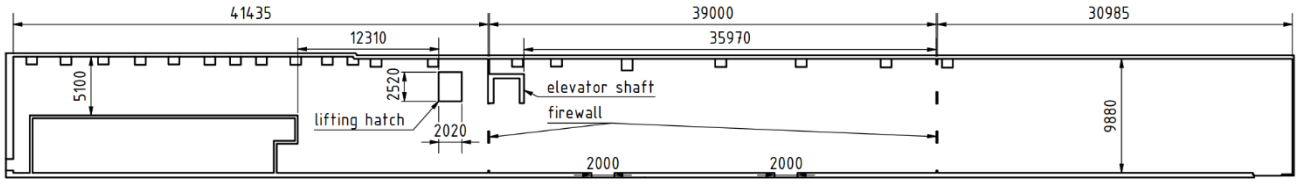


Figure 3: RF Gallery Floor Plan

The new Alvarez 2.0 Drift Tube Linac (DTL) will replace the more than 50-year-old UNILAC Post Stripper accelerating structures and will serve as an injector chain for FAIR. The 108.4 MHz Alvarez 2.0 DTL consists of five Alvarez cavities and several bunchers and single gap resonators. The future UNILAC operation with heavy ions will focus on producing short beam pulses with output energies up to 11.4 MeV/u. The proposed single gap resonators will facilitate an energy variation and adaption for the operators and users of the GSI/FAIR facility.

2. Scope

2.1. General Description

This tender concerns the design, manufacturing, testing at the contractor's premises, delivery to GSI and commissioning at GSI SSPAs, which shall be designed according to this extended specification with a nominal output power ranging from 40 kW to 2.4 MW at the operating frequencies of 36.136 MHz (HSI) and 108.408 MHz (Post Stripper) as shown in Table 1. The amplifier systems shall be able to produce RF pulses with a length up to 2 ms and a repetition rate up to 10 Hz. The average duty cycle is 2 %. The SSPA comprises all components and modules required to amplify RF signals, including power supplies, RF amplifier devices and circuits, interlock circuits, monitoring circuits, cabling, interfaces, and mechanical infrastructure. Modularity and system interoperability is a key feature and of utmost importance, see section 3.2.

Table 1: Overview SSPAs

Quantity	Frequency	Nominal power	Nomenclature
4	36 MHz	300 kW	HSI-300
3	36 MHz	2,400 kW	HSI-2400
2	108 MHz	40 kW	PS-40
1 (optional)	108 MHz	80 kW	PS-80
2	108 MHz	300 kW	PS-300
5	108 MHz	1,800 kW	PS-1800

2.2. Content of the Supply

GSI intends to place a contract for the supply of SSPAs including a test stand, optional spare parts and an optional PS-80. The contractor shall provide the supply as defined in this technical specification, including its annexes.

1. Development and production of SSPAs (see section 2.1, chapter 3 and chapter 4)
2. Factory Acceptance Test (FAT) at the contractor's location (see section 7.1)
3. Delivery of the amplifier systems to GSI, installation and commissioning at GSI (see section 7.3)
4. Delivery of optional spare parts (see section 3.10) and optional PS-80 if assigned
5. Site Acceptance Test (SAT) at GSI (see section 7.3)
6. Complete technical documentation (see chapter 5)
7. Delivery of the test stand (see section 3.9)

All non-standard tools and devices required for routine work (e.g. for exchange of RFPMs or RF combiners) as well as for maintenance and repairs at GSI must be included in the scope of delivery.

2.3. Required Technical Bidding Documents

In addition to the bidding documents required in the commercial tender documents, the offer shall contain the following technical documents:

- System design overview,
- Preliminary bill of materials (BOM),
- Draft drawings of the amplifier system showing:
    - RF circuits, including the preliminary transistor RF pallet and the printed RF combiners,
    - wiring diagrams and
    - mechanical drawing of the amplifier system.

- Technical reports of the coaxial combiners including a breakdown strength analysis of the electrical fields (RF field simulation results and detailed calculations respectively),
- The design and the specification of the circulator technology shall be submitted. If the circulator is an in-house product, RF and magnetic field simulations are required to assess the performance of the circulator. If the circulator belongs to the purchased parts, a technical report that shows the circulator performance under the required RF parameters is mandatory.
- GSI provides a mandatory spare part list which shall be included in the offer as an option. Additionally, the bidder shall submit an optional list with recommended spare parts including prices, quantities and delivery times. Furthermore, a detailed description of the spare part management and support management in case of a malfunction of a SSPA at GSI shall be submitted and will be assessed.
- The contractor shall include one additional PS-80 as an option in the offer. The PS-80 shall be based on the PS-40 and PS-300 design, respectively.

Additional technical documents that verify the technical maturity and technological readiness of the provided SSPA will be positively assessed.

3. Technical Specification

3.1. Description

For future UNILAC operation state-of-the-art solid state power amplifiers featuring low maintenance are required to assure a continuous and reliable operation over the next decades. It has also to be assured that all implemented electrical circuits and devices as well as all mechanical parts of the SSPA system are repairable or replaceable for at least the next 25 years. Therefore, a modular design and a maintenance concept that guaranties low operational costs as well as reduced staff requirements will be favourably assessed. The usage of the latest LDMOS transistor type with RF power higher than 3 kW is preferred, e.g. Ampleon ART4K0FX.

A key feature of the required amplifier is its ability to resist fully reflected power at any phase and at any time. Due to load variations, reflections will regularly occur at rising and falling RF pulse edges as well as during the RF pulse based on other mismatch effects like sparking in the cavity or beam load. It is mandatory to present a suitable proven concept for amplifier protection against fully reflected RF power at the output. That includes for example the implementation of circulators in the respective RF paths or over-dimensioning of RFPMs. A design with circulators is preferred for 36 MHz SSPAs and mandatory for 108 MHz SSPAs. The final offer shall contain a detailed description of the amplifier protection concept, including test measurements obtained by previous amplifiers built for similar projects or by an equivalent demonstrator.

The future UNILAC operation does not only require pulse to pulse variation of ion species and ion charge states, additionally there will also be a significant beam load which requires a very high dynamic power range over a short time from the SSPA system. A separate and independent low-level RF (LLRF) system controls the variable RF pulse power by regulating the input power of the SSPA. The LLRF system also provides fast amplitude and phase modulation during each RF pulse triggered by beam loading compensation. This LLRF system is not covered by this call for tender and will be provided by GSI.

An essential feature of the required SSPA system is highest reliability and maintainability to minimize downtimes and to increase durability. This includes the availability of appropriate spare parts and of individual components or subsystems during the desired long lifetime of the amplifier. As depicted in Figure 4 the SSPA comprises all components and modules required to amplify RF signals to the requested output power level including power supplies, RF amplifier devices and circuits, interlock circuits, monitoring circuits, cabling, user interface, control units and mechanical infrastructure.

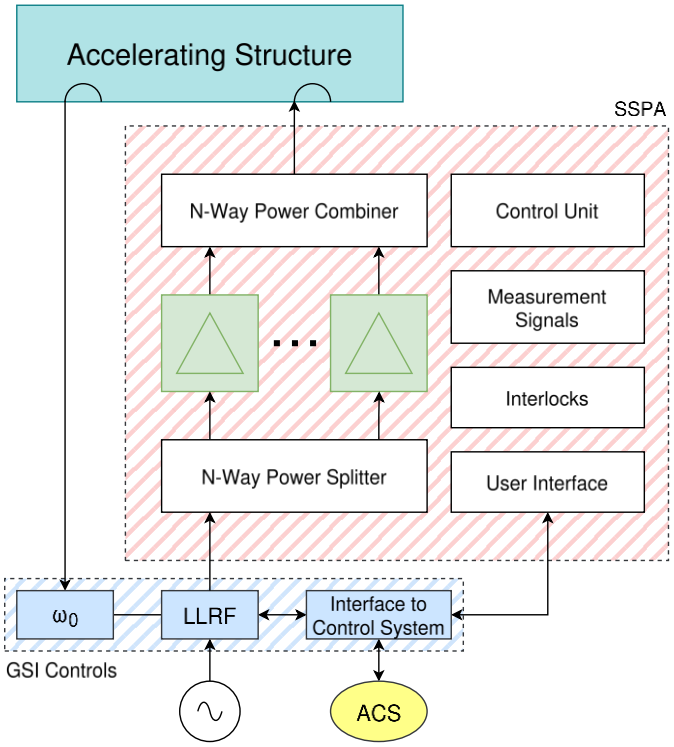


Figure 4: Basic Amplifier System Design for the UNILAC

3.2. Compatibility and Interoperatibility

3.2.1. Design Motivation

This tender aims at two aspects: the urgent re-establishment of scientific operation at the UNILAC for the FAIR project and to ensure a solid technological base for the next 30 years. This consequently results in the setting of a new, high standard of RF amplifiers as well as auxiliary systems at GSI. Therefore, all SSPAs shall be engineered as a unified product family which offers modularity and scalability for both the respective frequencies and across the entire the power range of 40 kW up to 2.4 MW. To reduce the need of special trained personnel it is crucial that the new SSPAs offer uniform usability and simplified maintainability. This results in a minimisation of operational risks and in case of malfunction in a rapid restoration of operational conditions. Unified components benefit the mean time to repair, enhance the availability of spare parts and reduce the risk of operation-threatening procurement lead times.

3.2.2. Mandatory Technical Measures

The following measures shall be implemented to guarantee system compatibility:

Modular Amplifier Blocks

The RF rack of the 300 kW SSPA shall serve as building block for the high-power SSPAs. A single RFPM design shall be used across the entire power range for the respective frequencies.

The PS-40 shall share the same rack setup as the PS-300. With this in mind a maximum power per RFPM of 40 kW seems reasonable.

Standardised Components

All frequency independent auxiliary hardware shall be strictly standardized and cross-compatible. This includes e.g., electrical installation, PLC, HMI, data acquisition, RFPSU, mechanical footprint, connectors.

Unified Software and HMI

All SSPAs shall utilise an identical PLC code base and HMI layout. Operating and diagnostic procedures shall be identical and interchangeable.

Standardized Interface

Identical communication protocols (e.g., Ethernet/IP, OPC UA) and a unified data structure for seamless integration into the GSI control system shall be implemented across all SSPAs.

3.3. Technical Maturity

Owing to the very short target delivery time the offer shall demonstrate a very high level of technological readiness of the proposed SSPA solution. The contractor shall provide verifiable evidence that the system can be delivered, commissioned and operated within the fixed project deadlines.

All components within the offer, especially key components like RF pallets, circulators and combiners shall be evaluated, simulated and in best case realised and tested before contract award. Special care shall be taken for bought-in components (e.g. second source, long term availability, substitutability of components according the required system granularity).

Any proposal shall include a comprehensive risk mitigation plan, detailing proof of concept, modular redundancy strategies and a proven track record in high-power RF applications to ensure long-term operational stability.

3.4. Technical Design

3.4.1. Radio Frequency Requirements

The following data shall be achieved:

Table 2: General RF Requirements

Parameter	Value
RF transistor nominal output power	≥ 3000 W
Gain linearity 15 % - 90 % of max. RF power 2 % - 15 % of max. RF power	 ≤ 1.5 dB ≤ 3 dB
Δ gain stability over cooling-water temperature at 100 % nominal power	≤ 3 % / °C
Max. intra pulse amplitude variation	≤ 0.5 dB
Max. harmonic level at resistive load at nominal power	≤ -24 dBc
Max. level of non-harmonic frequencies at resistive load at nominal power	≤ -60 dBc
Bandwidth @1 dB	≥ +/- 1.0 MHz
Power rise time	< 5 µs (10 % to 90 %) < 1 µs (50 % to 80 %)
Δ Phase over 0 % to 100 % nominal power @ 23 °C	≤ 40°
Δ phase stability over cooling-water temperature at 100 % nominal power	≤ 2° / °C
Duty factor	≤ 2 %
Pulse duration	≤ 2 ms
Average pulse repetition rate	≤ 10 pulses per second[1]
Minimum time between pulses	70 ms
Input impedance	50 Ω
Input VSWR	≤ 1.2
Input power at nominal power	≤ 7 dBm
Input power maximum	≤ 10 dBm
RF input connector	N-type, female
Output impedance	50 Ω
Amplifier load	Resonant loads with Q-factors (unloaded) in the range of 5000 and about 100000
Reflected power	100 % of max. level, any phase

[1] The repetition scheme can be asynchronous and the medium pulse repetition rate is from 0.1 Hz to 10 Hz, see section 3.4.2.

Table 3: Specific RF Requirements

Parameter	HSI-300	HSI-2400	PS-40	PS-300	PS-1800
Operating frequency	36.136 MHz	36.136 MHz	108.408 MHz	108.408 MHz	108.408 MHz
Nominal RF output pulse power, max. 1 dB compression	≥ 300 kW	≥ 2.4 MW	≥ 40 kW	≥ 300 kW	≥ 1.8 MW
Nominal RF output average power	6 kW	48 kW	0.8 kW	6 kW	36 kW
RF output connector	EIA 4 $^{1}/_{2}$"	EIA 9 $^{3}/_{16}$"	EIA 4 $^{1}/_{2}$"	EIA 4 $^{1}/_{2}$"	EIA 9 $^{3}/_{16}$"

3.4.2. Pulse and Repetition Scheme

The high-power amplifier systems at GSI work in a pulse mode operation illustrated in Figure 5.

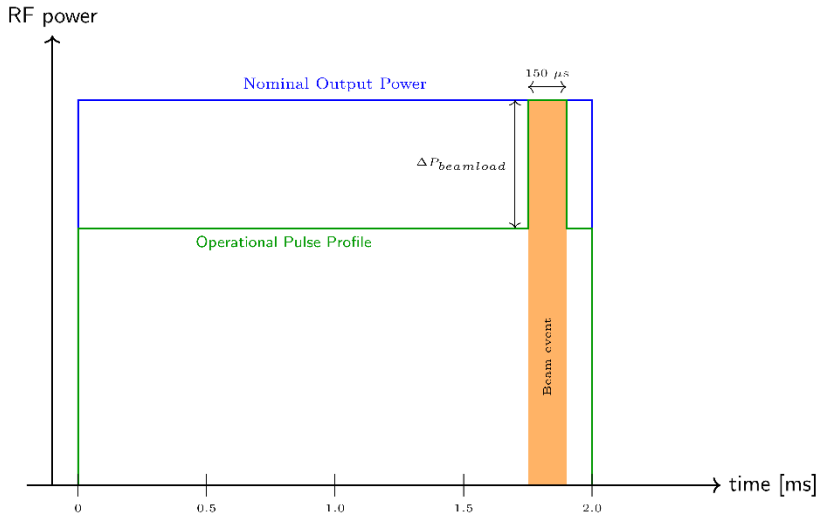


Figure 5: Example RF Pulse

The RF amplitude requirements can vary from time slot to time slot. The nominal RF output power shall be guaranteed at 10 Hz average repetition rate and 2 ms pulse duration. It shall be considered that the repetition scheme can be arbitrarily chosen by the accelerator operators and ranges from less than 0.1 Hz up to approximately 10 Hz. It shall also be considered that the ion beam within the RF active window depicted in Figure 5 requires a rapid power adaption. The length of a flat-top beam pulse can vary from 30 µs to 1 ms. The typical additional power for the ion beam depends on the ion charges and can be approximatelly 30 % of the operational RF power and shall be available almost instantaneously. All parameters of the specified SSPAs are summarized in Table 2 and Table 3.

3.4.3. Reflected Power

The SSPA shall be able to resist fully reflected power at any phase and at any time, an adjustment of the length of the transmission line is not an option. The use of circulators for transistor protection in the RF path is mandatory for PS-SSPAs at 108 MHz and preferred for HSI-SSPAs at 36 MHz.

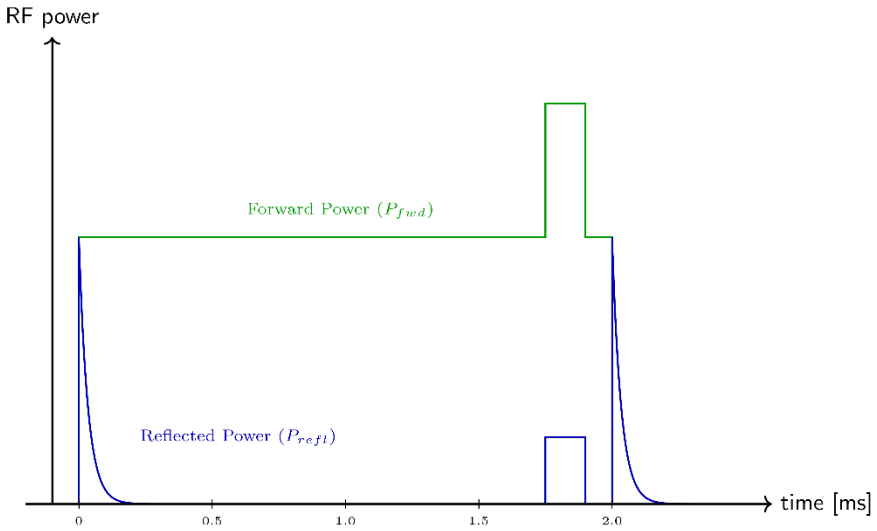


Figure 6: Reflected Power

The green line in Figure 6 depicts the forward power of the SSPA, the blue one shows the reverse power. At the beginning of the RF pulse most of the power is reflected by the non-steady state cavity. Due to mismatch during beam loading power reflection will occur and shall be tolerated for a certain amount. At the end of the RF pulse stored energy is transferred from the cavity to the SSPA.

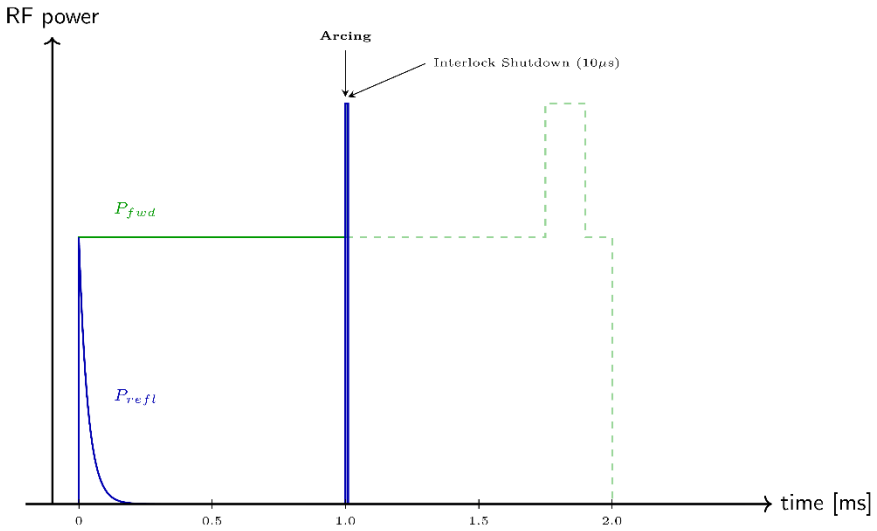


Figure 7: Arcing

In the event of arcing within the cavity (see Figure 7), a total reflection of the SSPA output power shall be anticipated at any time for the entire duration of the RF pulse. The SSPA shall withstand a fully reflected power of the nominal power at a pulse length of 2 ms and a repetition rate of 10 Hz indefinitely. Compliance with this criterion shall be verified during Factory Acceptance Testing (FAT) and Site Acceptance Testing (SAT).

Notwithstanding the amplifier's inherent ruggedness, a fast-shutdown feature with adjustable parameters for absolute reverse power and time delay shall be provided. The minimum achievable shutdown latency shall be ≤ 10 µs. This function is intended solely for the protection of the transmission line and shall be distinct from the SSPA's internal hardware protection (e.g., circulators). Following a shutdown event, the subsequent RF pulse shall be available at full specified performance without any restrictions.

3.4.4. Fast-Shutdown Interlocks

Analogous to the fast-shutdown feature for reverse power described in section 3.4.3 an additional set of in-pulse-interlocks for absolute forward power and analogue vacuum signals (0 V to 10 V) shall be implemented. Following a shutdown event, the subsequent RF pulse shall be available at full specified performance without any restrictions.

3.4.5. Power Requirements

Each SSPA including all necessary auxiliary power supplies and systems shall be supplied via exactly one 400 V three phase circuit. All subsequent 230 V/400 V circuits derived from it shall be rated for a prospective short-circuit current of 50 kA at the main input terminals

The first switching device connected to the input terminals shall be a main circuit breaker. All power and auxiliary circuits shall be branched off from subsequent, individually protected subcircuits. Only the device-off system acting on the main circuit breaker's under voltage relay may be supplied directly from the main input terminals. The circuit up to and including the main circuit breaker's input terminals shall be especially separated from other parts of the system and well protected against direct contact with active parts, because it may remain energized during maintenance work when the subsequent circuitry is de-energized by means of opening the main circuit breaker (MCCB + UVR, see Figure 8).

At the input and output terminals of the main circuit breaker additional means of phase voltage indication and verification of absence of voltage for the purpose of de-energizing the system shall be foreseen, e.g. 3-phase indicator lights.

The device-off buttons and through them the undervoltage relay of the main circuit breaker may be supplied from a safety low voltage power supply derived from the main input terminals.

For permanent monitoring capability an internal 230/400 V supply feeding the control unit shall be provided as depicted in Figure 8. This line shall be protected by a separate RCBO.

A minimum of one power outlet (CEE 7/3, 230 V, 10 A) to connect external measurement equipment shall be installed.

Figure 8 shows a block diagram of the proposed AC distribution. Regarding safety relay see section 3.4.8 and 3.5.6, respectively.

Insulating materials shall be halogen-free and self-extinguishing. In case of fire, they must not release toxic or corrosive substances. The following deviations are permitted pending compelling technical reasons: sheaths of RF coaxial cables may be made from polyvinyl chloride (PVC). RF dielectrics may be polyethylene (PE) or polytetrafluoroethylene (PTFE).

The contractor shall provide calculations for the maximum inrush current during power-up and recommendations for the upstream AC circuit protection.

For further requirements and general information see also "Technical Guideline – Electrical Design Rules and Regulations" and "Technical Guideline – Quality of switch cabinets and wiring" in section 6.1.

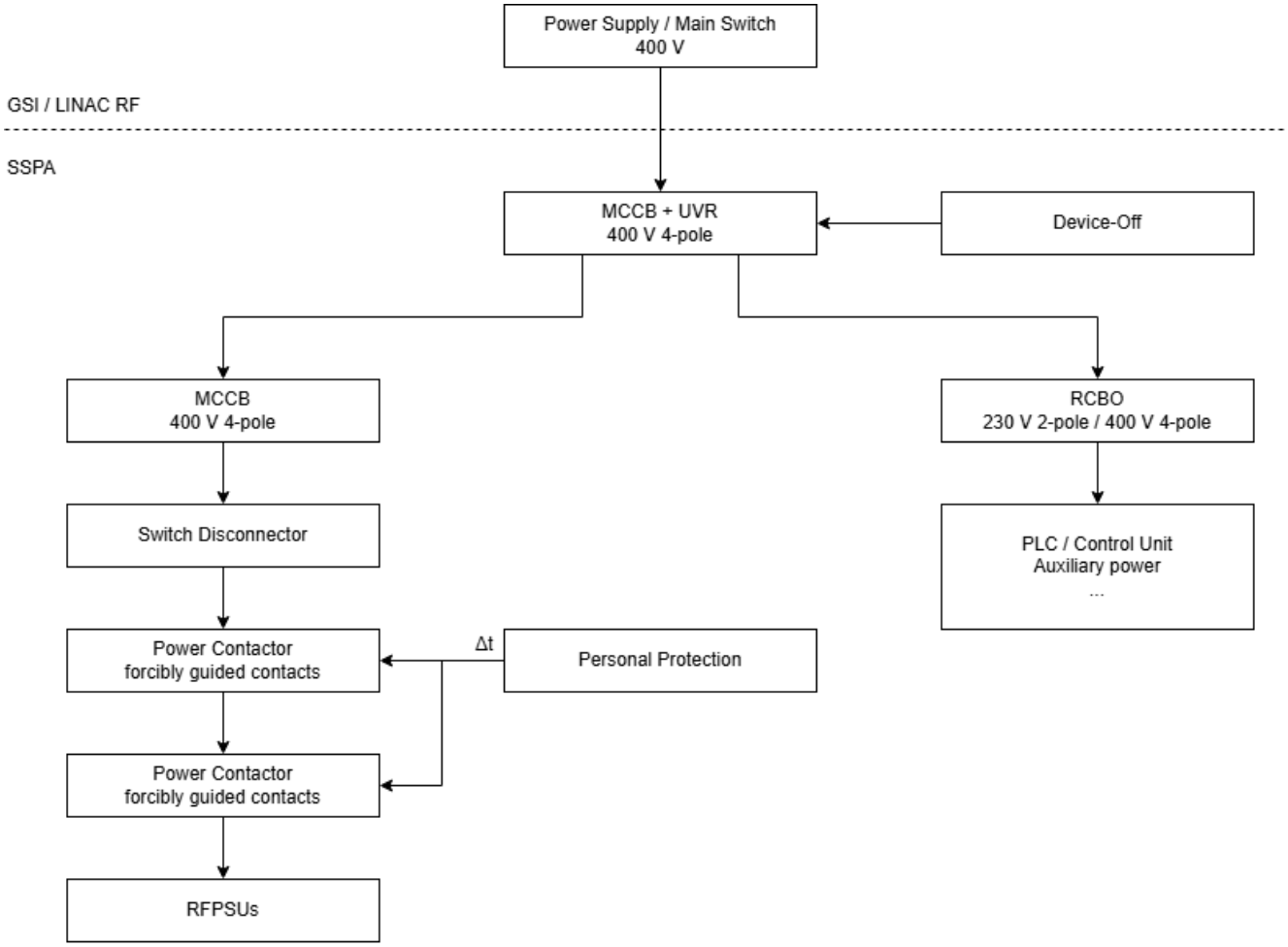


Figure 8: Proposed Block Diagram of the AC Distribution

3.4.6. Cooling Requirements

The water-cooling of the SSPA shall be directly connected to the water-cooling system provided by GSI. The implementation of any separate water-chiller system in the required amplifier system shall be strictly avoided.

Allowed materials for the cooling-water circuit are stainless steel, copper, and suitable plastic materials. The use of water-cooling is mandatory, forced-air cooling is not an option.

Air-cooling for low dissipation components is permitted below a total sum threshold regarding heat loss to ambient air, see Table 4.

The acoustic noise level will be measured under nominal operation conditions i.e. nominal power, 2 ms pulse length, 10 Hz repetition rate and 25 °C ambient air temperature.

Table 4: Cooling and Environmental Requirements

Parameter	Value
Cooling medium	Deionized water (down to 1 µS/cm)
Cooling-water temperature	23 °C +/- 3 °C
Cooling-water forward pressure	< 8 bar
Cooling-water return pressure	≈ 1.5 – 2.0 bar
Nominal flow rate cooling-water	1 m/s (copper), 2 m/s (stainless steel)
Ambient temperature	15 – 45 °C
Maximum heat loss to ambient air SSPA ≤ 300 kW	< 1 kW
Maximum heat loss to ambient air SSPA ≥ 1.8 MW	< 2 kW
Acoustic noise level @ 1 m and 25 °C	< 60 dB(A)
Acoustic noise level between racks rows and 25 °C	< 63 dB(A)

3.4.7. Operational Requirements

The planned annual operation of the SSPA is at least 300 days (24/7) for the next 25+ years. Maintenance is only possible during short breaks up to two times a year. Unscheduled downtime for repair shall be minimised by design.

To comply with these requirements redundancy is demanded (see section 3.8).

To optimise the stock of spare parts and maintenance usage of compatible components, e.g. power supplies, is preferred across all SSPAs.

3.4.8. Personal Safety Requirements

Personal safety comprises user safety as well as RF interlock.

The rack doors shall be monitored and locked for protection against electrical hazard. Personal safety shall be guaranteed at any time. In particular, the following safety features shall be implemented:

- Rack doors with live parts shall be locked as long as internal AC voltages are over 25 V, DC voltages are over 60 V or stored energy is over a threshold of 350 mJ.
- Door switches are required for safety and monitoring. An open rack door shall prevent the system to transit to a potentially dangerous state.
- Rack doors with no live parts shall be monitored, but not be part of the personal safety interlock. The state shall be displayed on the HMI.
- The use of a safety relay is mandatory. The performance level of the used safety devices shall be PLc or higher.
- All doors shall be outfitted with a lock and shall have identical profiles on all SSPAs. The preferred profile is double-bit (Doppelbart). Pin tumbler locks or similar are not permitted.

An additional personal safety requirement is the TVS personal safety interlock of the UNILAC which prohibits any RF power while access to the accelerator is granted.

- In this case, the generation of any RF power shall be made impossible. Therefore, at least one RF relay at the input of the SSPA shall be foreseen.
- Both RF signals and DC power supplies shall be shut down. The RF signal shall be shut down in a time span of $t_{off,rf}$ = 1 µs or less. Eventually the AC contactors shall open in a time $t_{off,ac}$ (Figure 8, Δt) which will be specified during the conceptual design phase.
- The shutdown shall be made in a controlled, load-less way for device protection. A staggered shutdown is permitted, as long the critical time requirements are met. Figure 9 illustrates an exemplary shut down sequence.
- The use of a safety relay is mandatory. The performance level of the used safety devices shall be PLd or higher.
- The safety state of the SSPA shall be provided to the external interlock system TVS.

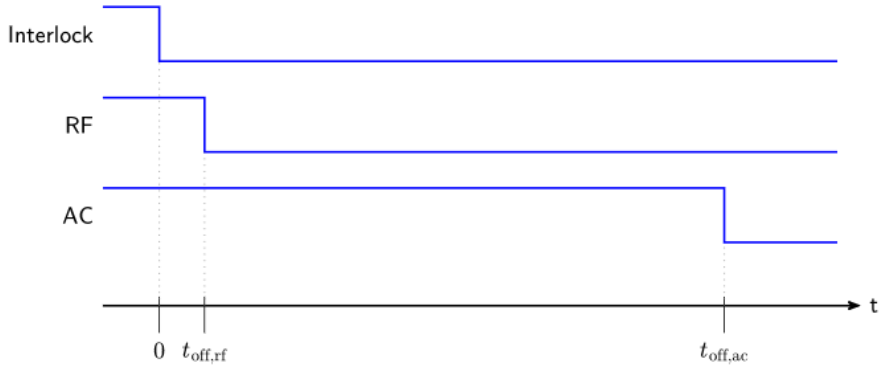


Figure 9: Example for a TVS RF Interlock

For further information see technical guideline “Electrical Design Rules and Regulations” (F-TG-ET-01e).

The SSPA shall be designed to be arc-fault-proof in accordance with IEC 61641 and shall meet the following requirements:

Table 5: Arc-fault-proof Parameters

Parameter	Value
Rated voltage	400 VAC
Rated frequency	50 Hz
Rated short-circuit withstand current ($I_{cw} = I_{p,arc}$)	50 kA (rms)
Arcing class	B (the arc fault shall be confined to a single rack)

3.4.9. Machine Safety

Two keyless black device-off buttons per rack row shall be installed at the SSPA front and back side, respectively. In case of a device off event, the 400 V mains supply shall be disconnected by opening the main circuit breaker. The SSPA system shall transition to a safe state. This includes the internal 230 V voltage supply of the control unit as well.

In case of permanent loss of one or multiple phase voltages or in case of transient voltage dips beyond its hold-up capabilities, the SSPA system shall transition to the same safe state.

The SSPA shall monitor all relevant signals concerning its safety. In the case of an error, it shall protect itself by taking appropriate measures e.g., turning off the RF or shutting down the amplifier. All critical errors shall be acknowledged by a reset before returning into operational state.

At least the following features are required:

- Water-cooling circuits shall be monitored. Parameters such as flow, pressure and temperature shall be considered. Additional active leakage detection is required. In case of leakage, they shall notify the control unit and open the main circuit breaker. The exact behaviour will be discussed during the design phase.
- The installation of fire detectors is mandatory. In case of fire, they shall notify the control unit and open the main circuit breaker. The exact behaviour will be discussed during the design phase.
- RF power i.e., forward as well as reflected power, shall be monitored on global and modular level. If thresholds are reached the SSPA shall react in such a way that no component gets damaged.

- Comprehensive monitoring of critical parameters such as voltages, currents and temperatures is mandatory at the modular level. This applies to the RF power supply units and RF power modules, extending down to the individual RF pallets, combiners, circulators and loads. Malfunctioning components shall be reliably identified by the control unit.

3.5. Signals and Interfaces

3.5.1. RF Measurement Signals and Connectors

To connect the LLRF to the SSPA a panel with the signals listed in Table 6 is required. The connectors shall be of N-type.

Table 6: LLRF RF Connection Points

Source	Type	Label	Quantity	Level
Input RF power	input	LLRF_RF_In	1	≤ 10 dBm
SSPA RF power fwd	output	LLRF_SSPA_fwd	1	≤ 20 dBm
SSPA RF power refl	output	LLRF_SSPA_refl	1	≤ 20 dBm

It is mandatory to monitor the RF power at different stages of the SSPA. The appropriate signals are summarized in Table 7. Therefore, another panel with N-type connectors is required.

Table 7: RF Measurement Output per SSPA

Source	Direction	Label	Quantity
Input RF power	forward	RF_In	1
SSPA RF power	forward	SSPA_fwd	2
SSPA RF power	reflected	SSPA_refl	2

HSI-2400 as well as PS-1800 require additionally the signals given in Table 8.

Table 8: RF Measurement Output per RF Rack

Source	Direction	Label	Quantity
Rack Input RF power	forward	Rack_n_In*	1
Rack Output RF power	forward	Rack_n_fwd*	1
Rack Output RF power	reflected	Rack_n_refl*	1

** n denotes the identifier of the RF Rack.*

To ensure an unaffected RF operation the amplifier shall be equipped with an independent 2-way directional coupler for those measurements. The required parameters of the couplers at the output of the SSPAs are given in Table 9.

Table 9: Parameters RF Directional Couplers

Parameter	Value
Coupling factor SSPA ≤ 300 kW	-50 dB
Coupling factor SSPA ≥ 1.8 MW	-60 dB
Accuracy	± 0,1 dB
Directivity	>30 dB
Impedance	50 Ω

3.5.2. Digital LLRF Interface

The digital communication between the LLRF and the SSPA shall run over Ethernet (1000BASE-T or 100BASE-T) via OPC-UA. An appropriate RJ45 connector shall be provided. A detailed list of signals and commands will be defined during the design phase.

3.5.3. LAN Interface

An additional LAN interface (isolated port) is required that provides all available status and measurement signals. Furthermore, the warning / error list of the amplifier system and each amplifier module shall be available via the LAN interface. A DHCP client shall be implemented to connect easily to the amplifier. The interface shall be platform independent, a browser-based solution for remote access is preferred. The additional provision of internal data of the SSPA via OPC-UA server will be positively assessed. A detailed concept will be discussed during the design phase.

3.5.4. Gating Signal

A gating signal is provided that represents the RF pulse cycle. For this reason, a BNC connector is required. A signal level of 0 V indicates RF operation and 5 V indicates that there is no RF operation. The RF operation starts with a delay with respect to the rising edge of the gating signal which shall be defined during the design phase. The major reason for the gating signal is to reduce energy consumption and control the operating point / biasing of the transistors. If the gating signal is constantly 0 VDC the amplifier system is still operational and the transistors are permantly biased.

3.5.5. Cavity Water and Vacuum Interlocks

A connector for the cavity water-cooling and vacuum interlock signal is required:

Table 10: Interlock Signals Connector Vacuum/Water

Signal name	Unit	Level at pin	Pin #	Signal direction	Comment
Vacuum interlock supply	V	24V	1	Amp out	Power supply for vacuum interlock
Water interlock supply	V	24V	2	Amp out	Power supply for water interlock
Vacuum interlock	V	alarm = open OK = closed	3	Amp in	Global safety interlock signal
Water interlock	V	alarm = open OK = closed	4	Amp in	Global safety interlock signal

3.5.6. TVS Personal Safety Interlock

To accommodate the site’s Personnel Safety System (PSS), the amplifier's safety interface shall be designed as a universal, fail-safe interface compliant with ISO 13849-1 (Min. PL d).

- Input (Command): The contractor shall provide a dual-channel, redundant input circuit. This interface shall be compatible with both potential-free safety contacts and electronic safety outputs. The system shall detect cross-circuits and external voltage injection as a fault state.
- Output (Feedback/Status): To enable external device monitoring, the amplifier shall provide a dual-channel, potential-free feedback signal (utilizing forced-guided relays or equivalent safety-rated electronics). This feedback shall directly represent the "safe state" (e.g., high voltage off and RF drive inhibited).

- Connector: The physical interface shall use a standardized, ruggedized industrial connector (e.g., M12 or Han-Series) with the pinout to be finalized during the design review phase.

Table 11: Safety Interlock Signals Connector PSS

Signal name	Level at pin	Pin #	Signal direction	Comment
PSS supply	24V	1	Amp out	
PSS interlock A		2	Amp in	Global safety interlock signal
PSS interlock B		3	Amp in	Global safety interlock signal
PSS interlock reference	0V / GND	4	Amp out	
PSS status reference A	Potential-free	5	Amp in	
PSS status A	Potential-free	6	Amp out	Safe state = closed operational = open
PSS status reference B	Potential-free	7	Amp in	
PSS status B	Potential-free	8	Amp out	Safe state = open operational = closed

3.6. Internal Controls and Graphical User Interface

For the implementation of control and state machine of the SSPA, GSI permits only the use of a Siemens S7-1500 series PLC. In addition, each SSPA shall provide an HMI / GUI for the user. It shall comprise at least the following features:

- Control buttons for the state machine,
- Visualisation of the state machine,
- Display of current errors,
- Display of current warnings,
- Archives for errors and warnings with sub-second precise timestamps,
- Each archive shall be capable of saving at least the last 1000 entries,
- Synchronisation over time server,
- Implementation of an OPC-UA server.

Furthermore, an expert user interface which enables the trained user to adjust settings like thresholds within reasonable limits is mandatory. With respect to sustainable operation notifications of upcoming maintenance are desirable for all critical components.

3.6.1. Control: Hand / Remote

A rotary switch is required which determines if the SSPA is controlled locally by the GUI or by remote control via commands from GSI’s side. It shall be located close to the HMI.

3.6.2. Reset

A reset button close to the HMI is mandatory. It shall work both in local mode and during remote control. An additional depiction of a received reset at the GUI is requested.

3.7. Mechanical Design

3.7.1. Rack Configuration

SSPA ≤ 300 kW

The HSI-300, PS-40 and PS-300 systems have to be arranged in two racks. The first comprises the control units, HMI, the AC feeding and, if necessary, low level RF components like RF driver or RF splitter. The second rack exclusively contains all RFPM and RF combiners as well as RFPSU.

SSPA 2.4 MW and 1.8 MW

The HSI-2400 and PS-1800 systems shall include a dedicated control/low level RF components rack and an AC feeding rack, respectively. For a two-row rack arrangement, a clear space of about 1800 mm shall be forseen. The exact value shall be defined during the conceptual design phase.

3.7.2. Maximum Dimensions

The maximum mechanical rack dimensions of the various SSPAs are given in Table 12. A single rack shall not exceed a width of 1000 mm. The final dimensions of the amplifier systems will be specified during the conceptual design phase and finalised in the CDD.

Table 12: Maximum Rack Dimensions

System	Maximum dimensions (W x H x D)
HSI-300	2000 mm x 2300 mm x 1400 mm
HSI-2400	4800 mm x 2300 mm x 4300 mm
PS-40	2000 mm x 2300 mm x 1400 mm
PS-300	2000 mm x 2300 mm x 1400 mm
PS-1800	3800 mm x 2300 mm x 4300 mm

The final mechanical design of the amplifier system shall be submitted in the FDD and will be approved by GSI in the CDR. Each cabinet shall be equipped with height-adjustable feet for levelling. The maximum height of the SSPA (PS-1800 and HSI-2400) including the RF combiner, directional coupler and rigid lines (90° elbow) to the cavity shall not exceed 3600 mm due to constructional limitations of the RF gallery. Additional space for a frame (TÜV-certified) supporting the higher weights of the final RF combiner, the cooling water supply, all power supply and signal cables as well as the rigid lines to the cavity and a reasonable safety margin will be discussed in the conceptual design phase.

3.7.3. Connector Arrangement

All global connectors for mains supply, cooling-water, RF input, RF output and signal ports as well as communication ports shall be arranged at the top of the amplifier system. The side rack walls shall remain clear for side-by-side installation. Installation on a raised floor is not an option.
Appropriate connectors will be specified during the conceptual design phase and finalised in the CDD.

3.7.4. Enclosure Rating

The enclosure rating shall be at least IP51.

3.7.5. Transportation

The racks of each SSPA shall be separable for transportation. Final assembly is done at the installation location. The separate SSPA racks shall be liftable by crane. Therefore, appropriate transport lugs are required. The size of the clear opening is 2020 mm x 2520 mm. Furthermore, a cargo lift is at disposal though its exact dimensions are undefined at this point due to pending restoration.

For further requirements and general information see also “Technical Guideline – Transport” in section 6.1.

3.8. Redundancy

The SSPA architecture shall be designed for high availability and fault tolerance. It is understood that the failure of a single RF component (e.g., transistor or circulator) may lead to disproportionate power losses due to resulting mismatches and dissipation within the combining structures. Consequently, the contractor is required to provide comprehensive simulations and a failure mode analysis for the entire RF chain.

The simulations shall demonstrate the impact on total output power, phase stability and the 1dB compression point for the following scenarios:

- Transistor failure: Failure of one individual RF transistor,
- Pallet failure: Failure of one individual RF pallet,
- Module failure: Complete loss of one RF Power Module,
- Rack failure (only valid for HSI-2400 and PS-1800): Complete loss of an entire RF rack,
- Passive component failure: Malfunction of circulators or isolation resistors within the combiner tree,
- Power supply failure: Loss of one or more DC power units.

Minimum demands concerning redundancy are given in Table 13.

Table 13: Redundancy Requirements

Device	Minimum redundancy
DC supply for control unit	100 %
DC supply for RF power modules	Minimum 20 %

3.9. Test Stand

A test stand for maintenance purposes as well as verification of repaired RFPMs is demanded and shall be delivered with the first RF system (PS-1800). Further testing equipment for components such as RF pallets, RFPSUs, control unit etc. is optional.

Details will be specified during the conceptual design phase and finalised in the FDR.

3.10. Spare Parts

Spare parts shall be offered as an option. A list of mandatory spare parts is given in Table 14. A set comprises the respective components of a single 300 kW SSPA. A list of additionaly recommended spare parts including prices and quantities as well as a list of essential special tools and equipment shall be submitted with the final design documents (FDD), see chapter 4. The assignment of these optional components and the requirements for the delivery (e.g. test reports) will be discussed in the design phase.

Table 14: Mandatory Spare Parts

Quantity	Quantity unit	Item description
3	Sets	RFPMs for HSI-300
3	Pcs	Final RF Combiner for HSI-300
1	Pc	Final RF Combiner for HSI-2400
5	Sets	RFPMs for PS-300
4	Pcs	Final RF Combiner for PS-300
1	Pc	Final RF Combiner for PS-1800
10	Pcs	RFPSU
100	Pcs	RF Power Transistors @ 36 MHz
100	Pcs	RF Power Transistors @ 108 MHz
1	Set	Circulators for HSI-300
1	Set	Circulators for PS-300
5	Sets	Combiners for RFPM @ 36 MHz
5	Sets	Combiners for RFPM @ 108 MHz
10	Sets	RF Power Resistors for circulators and/or RF combiners in RFPMs @ 36 MHz
10	Sets	RF Power Resistors for circulators and/or RF combiners in RFPMs @ 108 MHz
5	Pcs	Control Unit (configurable for HSI-300, HSI-2400, PS-40, PS-300, PS-1800 systems)

4. Project Organization and Production Release

This call for tender implies a multi-stage development process in close interaction with the LINAC RF department at GSI. The participants of this tender shall submit a conceptual design of the amplifier system, which convinces GSI.

After the application process, a kick-off meeting will take place with the contractor to discuss technical details and issues regarding project management. Following up the kick-off meeting, the contractor shall submit a conceptual design document (CDD) that summarizes the discussed issues and presents feasible solutions. This document shall pass the conceptual design review (CDR) by GSI. The final design document (FDD) will complete the planning phase. This document shall include:

- System design overview,
- BOM of the amplifier system,
- Design document of each module (RF modules and power supply modules),
- BOM of each module,
- Schematics, board layouts and assembly drawings of each PCB,
- Wiring diagrams,
- Mechanical drawings including a 3D model of the SSPA,
- Description of the HMI,
- Description of all interlocks,
- Technical report including simulation and measurements of the thermal modelling regarding the RF modules (especially transistor cooling),
- Manufacturing time, as progress diagram (time schedule) including the expected dates for FAT and delivery,
- A list of recommended spare parts including prices and quantities.

GSI will schedule a review period of up to 20 workdays to approve the FDD with its technical details and drawings. The review includes a quality assurance that verifies all submitted documents. As a result of the successful final design review (FDR) GSI will grant a production release and the contractor shall build the amplifier systems according to this specification and the FDD.

In the following development time, an effective collaboration between the contractor and GSI shall be ensured. This collaboration shall be enabled by monthly progress reports of the contractor to GSI. Upcoming technical and organizational issues of the amplifier system during this project phase shall be discussed and solved in strong cooperation. Furthermore, GSI shall release each developed unit of the SSPA based on the documentation provided by the contractor before the module production starts. These acceptance tests are a mandatory prerequisite for continuing the project.

Inspections by GSI staff members during manufacturing time shall be possible after announcement.

5. Documentation

The following documents shall be supplied at delivery (one set in paper form and digital version):

- User manual including detailed descriptions of all interfaces,
- General description, maintenance and calibration instructions,
- Overview drawing of the amplifier system,
- BOM of the amplifier system,
- Source code and associated source code files,
- Design document of each module (e.g., RFPM and RFPSU),
- BOM of each module,
- Complete circuit diagram of the amplifier system and each module,
- Wiring diagrams and terminal connection table of each module,
- Layouts of electric and electronic schemes including circuit board arrangements (production files),
- Description of analogue and digital circuits, as well as service and adjustment (calibration) instructions,
- Documentation of the test stand and testing procedures,
- Mechanical drawings (PDF, STEP and DWG files or similar CAD files),
- Test and acceptance certifications,
- CE-compatibility statement, declaration of incorporation (“Einbauerklärung”),
- List of recommended spare parts, including recommended quantities and costs,
- Risk assessment (“Gefährdungsbeurteilung”, etc.).

Schematics created by a CAD system, also text based on Microsoft Word©, shall be delivered on an adequate data medium. Documentation language is to be stipulated by order.

6. Standards and Technical Guidelines

6.1. GSI Documents

Table 15 shows the Technical Guidelines provided by GSI. Regulations and standards given in these guidelines are only binding if they are not in conflict with the definitions and requirements given in the detailed specification.

Table 15: Technical Guidelines

Technical guideline	File name
Electrical design rules and regulations	F-TG-ET-01e Electrical Design Rules and Regulations_v3
Quality of switch cabinets and wiring	C-TG-GAT-en-Quality-of-switch-cabinets-and-wiring-V002
Transport	F-TG-T-01e_Transport_V002

6.2. EMC Compatibility and Requirements

The compliance with the EMC standards shall be verified by an accredited EMC laboratory.
RF radiation shielding shall fulfil all related standards, in particular:

- EN IEC 61000-6-4:2020-09,
- EN IEC 55011:2026-05,
- EN IEC 61326-1:2022-11.

The required SSPA systems will be treated as a Class A, Group 1 equipment according to EN 55011. At the operating frequency of 36.136 MHz and 108.408 MHz the radiated emission limit is relaxed from 50 dB µV/m to 60 dB µV/m at 3 m measurement distance.

It is not mandatory to perform the surge test according IEC 61000-4-5 in an accredited EMC laboratory. Nevertheless, the contractor shall show that the required SSPA system has the ability to withstand the defined surge test parameters defined in IEC 61000-4-5.

Furthermore, the amplifier system shall fulfil the attached GSI/FAIR technical guideline “Electrical Design Rules and Regulations”.

6.3. Safety Requirements

The device shall match all CE requirements and a statement of CE-compatibility (declaration of incorporation). A risk assessment document shall be submitted at delivery.

6.4. Quality Management

Finally, the contractor shall be certified by an accredited certification body according to ISO 9001.

7. Delivery and Acceptance

7.1. Factory Acceptance Test (FAT)

Precondition for the FAT is an operation of the amplifier system at design parameters shown and documented in the stipulated monthly progress reports. Furthermore, all RF equipment used for the FAT shall be calibrated. The contractor shall set up the technical equipment to perform the factory acceptance tests at full peak and average power as required by this specification to a 50 Ω dummy load. GSI shall be informed at least 20 days before start of the FAT. GSI may also request test data in advance. A written test report containing all tests shall be provided by the contractor to GSI after the test. A 100-hour test at the maximum output level shall be demonstrated on a dummy load.

The contractor shall present a draft of an acceptance test template latest two weeks before acceptance test. GSI has to agree to this template before the FAT.

The FAT shall include at least following items:

- Verification of correct amplifier system start up and all defined interlock functions.
- Control panel check and verification of all control functions and status indications, respectively.
- RF measurements with a signal generator as source and a 50 Ω load at the amplifier output:
    - All specified parameters of Table 2 and Table 3 can be tested.
    - Demonstration of the maximum output power and check of the internal power measurements by the amplifier system. This test also includes the verification of the integrated monitoring.
    - Evaluation of the harmonic and non-harmonic distortions at maximum output power measured with an external coupler and spectral analyser.
    - Verification of the input/output characteristics especially according to the required linearity.
    - Test of external triggering with a pulsed signal generator (AM mode) and an independent TTL-trigger.
- System test with different and arbitrary RF pulses regarding pulse durations, repetition rates and RF pulse power will be defined at the FAT according to specified parameter range:
    - The specified rise time of RF output pulses,
    - The distortion/droop of the pulse shape during the RF pulse,
    - Test with adequate load and short at the output port of the amplifier system at any given phase (details to be discussed),
    - Test with different rising edges and times,
    - All tests can be executed with arbitrary RF phase and RF power level.

7.2. Delivery and Installation

After the FAT the SSPAs shall be demounted, delivered to GSI and installed at the final location by the contractor. GSI connects the interfaces of the SSPAs to GSI's side e.g., the AC input to the 400 V net, water supply and the RF output to a 50 Ω dummy load.

7.3. Site Acceptance Test (SAT)

The SAT includes commissioning and RF tests of the SSPAs at GSI. The date of the SAT has to be scheduled according to the operating conditions at GSI. All tests of the FAT can be requested by GSI. The SAT will be performed in two separate phases:

- Phase 1: Operation on 50 Ω dummy load,
- Phase 2: Operation on resonant load (accelerator cavity).

Both phases will take place at two separate appointments and include a 2-hour test at the maximum output level.