**KSTAR ECH high voltage power supplies**

**Revision history**

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**Table of contents**

[1. Introduction 4](#_Toc488860757)

[1.1. Objectives 4](#_Toc488860758)

[1.2. Scope and standard 5](#_Toc488860759)

[2. CPS 7](#_Toc488860760)

[2.1. Functionality 7](#_Toc488860761)

[2.1.1. Summary of Specification 7](#_Toc488860762)

[2.1.2. Soft starter 7](#_Toc488860763)

[2.1.3. Multi-secondary transformer 8](#_Toc488860764)

[2.1.4. Rectifier 8](#_Toc488860765)

[2.1.5. HVDC cable 9](#_Toc488860766)

[2.1.6. Termination box with crowbar circuit 9](#_Toc488860767)

[2.1.7. CPS controller 10](#_Toc488860768)

[2.1.8. Operation mode 11](#_Toc488860769)

[2.1.9. HV on/off control 11](#_Toc488860770)

[2.1.10. Communication parameters 12](#_Toc488860771)

[2.1.11. Interlocks 14](#_Toc488860772)

[2.2. Tests 14](#_Toc488860780)

[2.2.1. FAT 14](#_Toc488860781)

[2.2.2. SAT 15](#_Toc488860782)

[3. BPS 17](#_Toc488860783)

[3.1. Functionality 17](#_Toc488860784)

[3.1.1. Summary of Specification 17](#_Toc488860785)

[3.1.2. Body Power Supply system 17](#_Toc488860786)

[3.1.3. HVDC cable 17](#_Toc488860787)

[3.1.4. BPS controller 18](#_Toc488860788)

[3.1.5. Operation mode 19](#_Toc488860789)

[3.1.6. HV on/off control 19](#_Toc488860790)

[3.1.7. Communication parameters 19](#_Toc488860791)

[3.1.8. Interlocks 20](#_Toc488860792)

[3.2. Tests 20](#_Toc488860793)

[3.2.1. FAT 20](#_Toc488860794)

[3.2.2. SAT 21](#_Toc488860795)

[4. Installation 22](#_Toc488860796)

[4.1. Installation plan 22](#_Toc488860797)

[4.2. Controller cables and connections 23](#_Toc488860798)

[4.3. Cable tray and building penetration 23](#_Toc488860800)

[4.4. Current return and ground 23](#_Toc488860801)

[5. Instrumentation and operating interface 24](#_Toc488860802)

[5.1. General 24](#_Toc488860803)

[5.2. Local operating interface 24](#_Toc488860804)

[6. Quality management 25](#_Toc488860805)

[6.1. General requirements 25](#_Toc488860806)

[6.2. Quality assurance in design stage 25](#_Toc488860807)

[6.3. Quality assurance in procurement 25](#_Toc488860808)

[6.4. Quality assurance in production 26](#_Toc488860809)

[6.4.1. Preparation for production 26](#_Toc488860810)

[6.4.2. Execution of production 26](#_Toc488860811)

[6.5. Quality tests 27](#_Toc488860812)

[7. Design review 28](#_Toc488860813)

[8. Spare components 28](#_Toc488860814)

[9. Documentation 28](#_Toc488860815)

[10. Schedule 28](#_Toc488860816)

# Introduction

Based on the successful results of the electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD) in KSTAR tokamak at the National Fusion Research Institute (NFRI), NFRI will complete installing six sets of ECH system to deliver a total microwave power of 6 MW into the KSTAR plasma before the KSTAR plasma campaign in 2020.

Currently, one ECH set is under operation and another set is being manufactured. Therefore, four additional sets should be installed to meet the goal.

An ECH system consists of a 1) gyrotron, 2) high-voltage power supplies, and 3) auxiliaries that include an integrated control and microwave power transmission. Among these subsystems, the procurement of high-voltage power supplies, which mainly comprise a cathode power supply and body power supply, are expected to start midway through 2017. The first of the four sets is expected to be completed before the campaign in 2019, and the consecutive commissioning of the three sets before the campaign in 2020. The procurement of the gyrotron and auxiliaries will be proceeded separately.

As the subsystems are procured separately, the high-voltage power supplies should tolerate the range of load variations. The ranges of resistive and reactive load components shall be estimated from the characteristics of typical megawatt-scale high-power gyrotrons unless otherwise specified in this document.

In addition, the high-voltage power supply will be highly subjected to the integrated control system, as it will be remotely controlled in most cases. This requires the basic properties of the power supply system to be completely controlled by external means. One of the easiest solutions to this is to follow exactly the reference voltage within a specified bandwidth. An unacceptable reference shall be corrected internally without terminating the output. The power supply shall protect itself internally from any event that allows maximum usage of the output voltage, current, power, and transients within this specification. Another essential component is a transparent power supply control system. It shall expose every control parameter necessary for operation and maintenance to the operator unless it is harmful or dangerous to the power supply itself.

This technical specification document presents the minimum set of the technical parameters and minimal requirements, which shall be executed by the vendor in accordance with the contract, statement of work, this technical specification, and contractor’s proposal, in that order of precedence.

## Objectives

1. This document describes the technical specifications for the indoor **cathode power supply** (**CPS**) system and **body power supply (BPS)** system of a single high-power gyrotron for the KSTAR tokamak. The gyrotron is capable of continuously delivering 1 MW of RF power. The characteristics described in this document is the minimum performance requirement of the CPS and BPS
2. The CPS shall be a **pulse step modulator** (**PSM**) type. Four sets of the **CPS** will be purchased together and installed on the third floor of the PS-3 power supply building.
3. Four sets of the **BPS** will be purchased together and installed on the second deck of the heating device room.
4. The commissioning of the first set of the four power supply systems (CPS and BPS) for the gyrotron shall be completed before **early 2019**. The delivery of the remainder shall be mutually agreed upon during contraction.
5. The vendor who is willing to join the tender process of this procurement shall submit technical and financial proposals to fulfil this technical specification as a minimum requirement. The technical proposal shall include electrical/mechanical design, calculation, performance, and plans for delivery, installation, and test as a minimum. If the proposed equipment has been delivered before, detailed test results and operation history shall be included in the proposal.

## Scope and standard

1. The scope encompasses the **designing, fabrication, factory acceptance test (FAT), delivery, installation on site,** and **site acceptance test (SAT)** of the four power supply systems (CPS and BPS) in accordance with this specification, which includes designing, performing thermal and mechanical analyses, and performing harmonic and short-circuit current calculations to demonstrate compliance with the specifications, and providing the installation and maintenance manual and sufficient drawings for the system operation and maintenance.
2. The vendor shall be responsible for the delivery and installation of all equipments supplied by the vendor.
3. The vendor shall be responsible for the testing of all installed equipments and the performance of all equipments supplied by the vendor.
4. The following equipments for the CPS as a minimum requirement shall be supplied by the vendor.

* AC 22.9kV-3PH main power shall be provided by NFRI
* **Soft start circuit breaker** for AC 22.9 kV-3PH mains power with manual **ground switch**
* **Multi-secondary transformer**
* **Rectifier** including **PSM** modules, **output filter**, and **current measurement system**
* **Redundancy power modules comprising 5% of the total number of modules**
* **High-voltage direct-current (HVDC) coaxial cable**
* **Termination box** with independent **crowbar circuit** and **voltage measurement**
* **CPS controller, local control interface** and **control cable**
* **Monitoring system (See the** Table 1. Example of controller signals between CPS controller and EC-ICS**)**
* **Interlock system**

1. The following equipment for the BPS as a minimum shall be supplied by the vendor.

* **BPS power supply assembly**
* **HVDC coaxial cable between BPS and gyrotron**
* **BPS controller, local control interface** and **control cable**
* **Monitoring system (See the** Table 3**)**

1. Figure 1 shows an example circuit displaying the equipments for the CPS as a minimum.
2. Figure 2 shows an example circuit displaying the equipments for the BPS as a minimum.
3. The equipment furnished under this specification shall comply with IEC in preference and shall comply with all laws, regulations, and standards of good practice commonly accepted in the high-voltage power supply community.

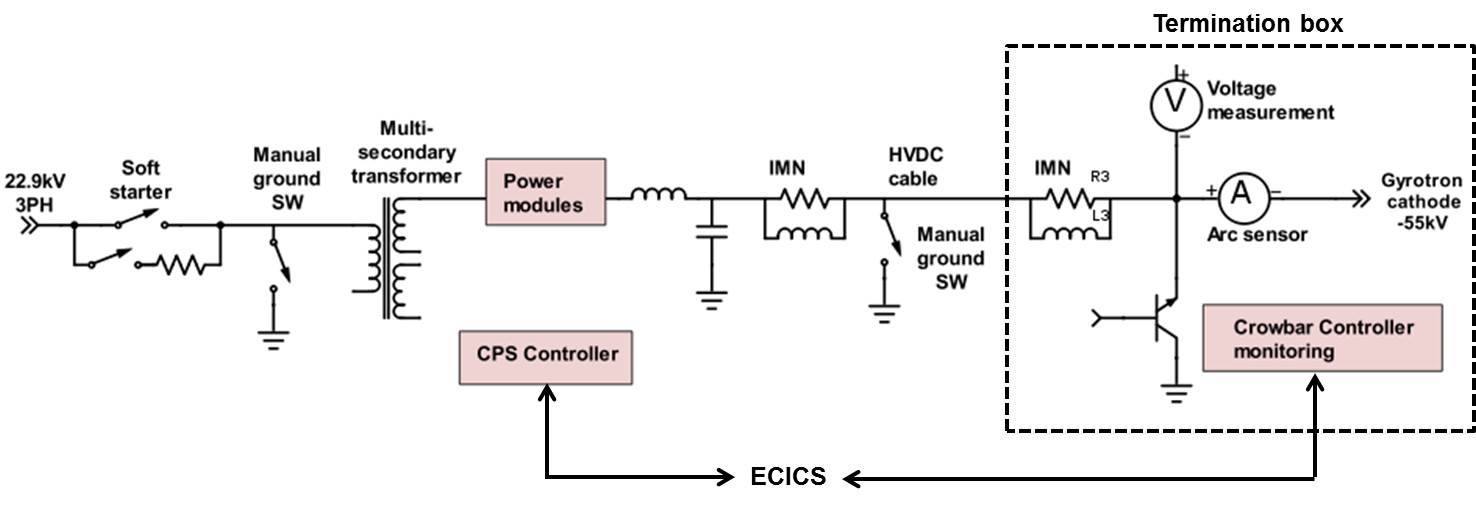


Figure 1. Schematics of cathode power supply

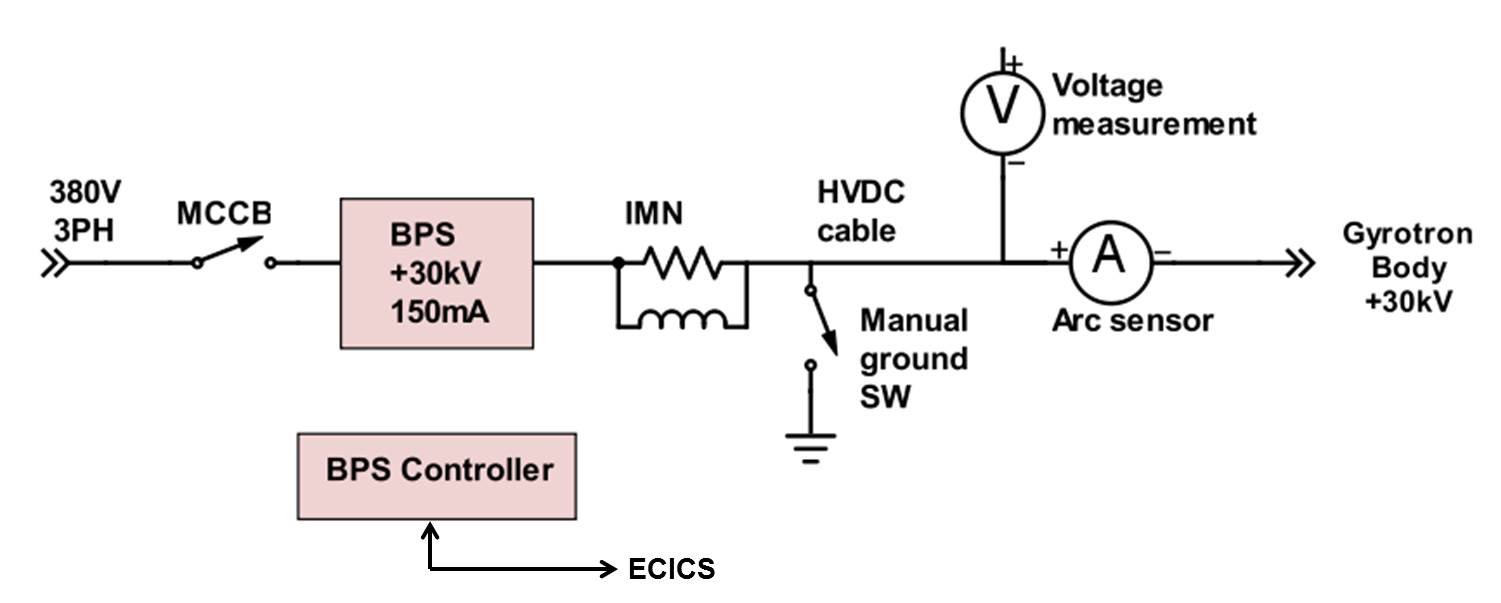


Figure 2. Schematics of body power supply

# CPS

## Functionality

### Summary of Specification

1. Line frequency 60 Hz ± 2%
2. Line voltage 22.9 kV ± 5%
3. Line phase Delta-3 phase
4. Nominal transformer power rating 3.5 MVA
5. Control power frequency 60 Hz ± 2%
6. Control power voltage 220 V ± 5%
7. DC output voltage at termination box 0 – negative 55 kV
8. DC output control step 0.1 kV
9. DC operating current range 0–55 A
10. DC maximum power output 3025 kW
11. Pulse length and duty cycle 300 s, repetition period: 1500 s
12. Maximum DC voltage ripple < ± 200 V
13. Modulation frequency range 0–5 kHz adjustable
14. Modulation depth 0–100% adjustable
15. On-line external voltage control True
16. Voltage rising/falling time (10–90%) < 35 µs
17. Overshoot < 1% of settled voltage
18. Voltage settling time\* < 50 µs
19. Output turn-off time < 10 µs
20. Output voltage stability < 1%
21. Short-circuit energy < 10 J
22. Overall efficiency > 95% except HVDC cable and termination box
23. Ambient temperature range Heating device room: 20–40 °C, PS-3: 10–40 °C

*\* The time required for the output voltage to reach and stay within ripple voltage range from the initiation of voltage rising command.*

### Soft starter

**The soft starter** shall be installed between the AC mains and **multi-secondary transformer** to reduce stress on the transformers at the both the input and output. It is also a circuit breaker.

1. The nominal power input is three-phase at 22.9 kV.
2. The soft starter can consist of **two sets of three pole vacuum circuit breakers** and **three high-power resistors**.
3. **The manual ground switch** shall be equipped at the input of the multi-secondary transformer to protect users from the malfunction of the soft starter in the case of service.
4. All functions of the soft starter can be **remotely controlled** and monitored except for the ground switch.
5. The status of the ground switch shall be remotely monitored.
6. The standard terminals of the AC 22.9 kV mains will be mutually agreed upon during the design stage.

### Multi-secondary transformer

1. The transformer shall be cooled by natural air convection.
2. The transformer shall be cast in a resin transformer without any liquids
3. The structure of the transformer shall be designed to be unaffected by dust accumulation.
4. The isolation voltage between ground and secondary winding shall be > 80 kVDC.
5. **Short-circuit detection and protection** shall be proposed by the vendor during the design stage.

### Rectifier

1. **The rectifier** consists of PSM power modules, an output filter, and output current measurement.
2. The number of power modules depends on the overall specification.
3. The number of **redundancy power modules** shall be > 5% of the total number of power modules.
4. The **fault of module** shall not affect the normal operation, unless the maximum output from the remaining modules is smaller than the requested output voltage.
5. The load shall be evenly distributed along all power modules including the redundant power modules.
6. Any malfunctioning power modules shall be easily identified through the controller.
7. **The output filter** shall regulate the ripples and waveforms in accordance with this specification.
8. **The output current measurement** shall provide real-time current signals to an external data acquisition (DAQ) system, which will be provided by NFRI. The output current measurement equipment can be instead placed in the **termination box**.

### HVDC cable

1. **The HVDC cable**, which shall be provided by the vendor, runs from the rectifier output filter installed on the third floor of the PS-3 power supply building to the gyrotron complex located on the second deck of the heating device room, as shown in Figure 3.
2. The installation of the **cable tray** will be provided by NFRI.
3. The termination of each end shall be in compliance with the relevant industrial standards. To determine the specification of the HVDC cable, modulation specification shall be considered during the design stage.

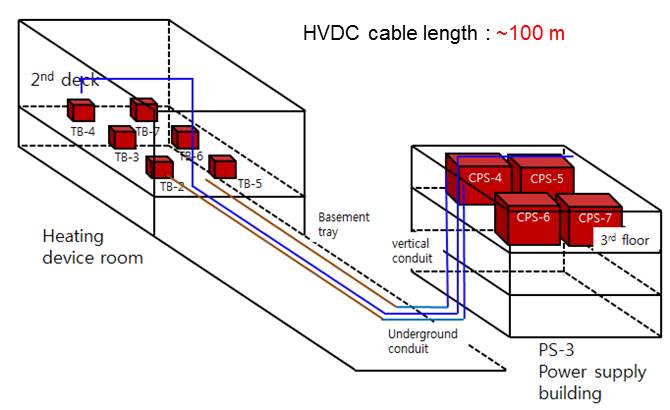


Figure 3. HVDC cable route

### Termination box with crowbar circuit

1. **The termination box** includes the **impedance matching network (IMN), voltage sensor, manual DC ground switch, and crowbar circuit** with an arc sensing current sensor, crowbar controller and semiconductor switch.
2. The **IMN** shall dissipate the stored energy in the HVDC cable in the case of HVDC turn-off due to an arc in the load or modulation.
3. The **IMN** shall passively regulate the voltage waveform in conjunction with the rectifier output filter.
4. **DC short-circuit energy** < 10 J shall be accomplished by the IMN, HVDC cable, rectifier output filter and rectifier
5. **The voltage sensor** provides real-time voltage signals to the DAQ system.
6. **The crowbar** circuit is a redundant circuit to protect the gyrotron in the case of IMN and/or PSM malfunction. A commercially available **semiconductor switch** shall be used as the crowbar switch.
7. The arc current sensor and **independent crowbar controller** shall detect the gyrotron cathode arc and ignite the crowbar switch to dump energy stored in the HVDC circuit.
8. After initiation, the crowbar controller and switch shall remain in a closed state and generate TTL digital output(DO) signals until they receive a reset command through the fiber optic digital input (DI) (momentary binary).
9. The DC connection between the termination box and gyrotron cathode will be a low inductance/capacitance bar. The DC output terminal of the termination box will be mutually agreed upon during the design stage.
10. The Crowbar shall be operated so that the energy transferred to the load or gyrotron in case of arc should be less than 10J when the PSM fails to turn-off.

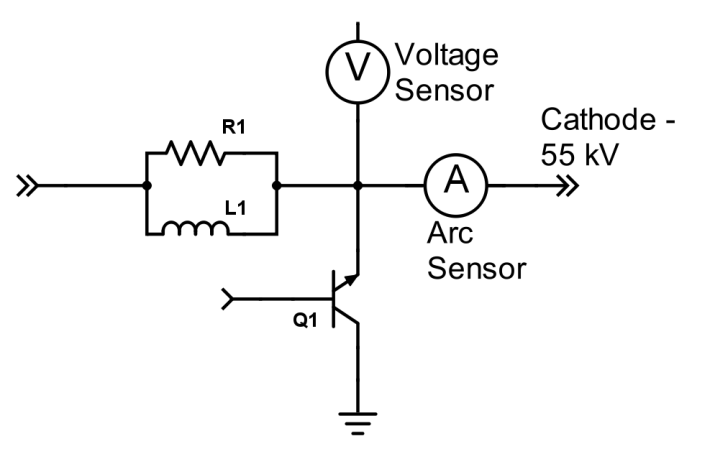


Figure 4. Example of termination box

### CPS controller

The CPS controller controls all system behaviour including the **on/off** of system, output voltage, and arc protection, receiving commands from the external controller, which will be provided by NFRI.

The CPS controller shall be as transparent as possible. Every control parameter necessary for operation and maintenance shall be transparent unless it is harmful or dangerous to the power supply itself.

1. The CPS controller communicates with the EC integrated control system (EC-ICS) which will be provided by NFRI.
2. The output voltage at the output terminal of the termination box shall be completely controlled by the EC-ICS using the reference voltage. An unacceptable reference voltage should be corrected internally without terminating the output.
3. The power supply shall protect itself internally from any event that allows maximum usage of the output voltage, current, power, and transients within this specification.
4. The communication protocols between the EC-ICS and power supply controller shall be:

* **EPICS CA** through **TCP/IP KSTAR machine network (> 1 Gbps)**
* Fiber optic **DIO –** internal latency < 1 µs
* Analog voltage reference **Vref** – internal bandwidth < 5 µs
* Analog voltage **Vout**, and **Iout** for voltage and current readings.

1. The analog signal such as **Vref**, **Vout**, and **Iout** will be connected to a 10G SDN (10 Gigabit Synchronized Data Network developed by ITER) by NFRI. The reference of all analog signals shall be the system ground.
2. The CPS controller shall protect the CPS system and gyrotron by immediately initiation of the HVDC turn-off within specified output turn-off time in any case, such as:

* Transformer short-circuit
* Over current > **Imax**=55 A or **Ioc**
* Over voltage > **Vmax**=55 kV or **Vov**
* Under voltage< **Vu**\***Vref** after **Tdelay**
* **Cathode arc**
* **Over temperature** at multi-secondary transformer, HVDC output filter, HVDC cable, IMN, crowbar > [**Tovt**]
* External **HVDC turn-off** command
* Any other event that requires HVDC turn-off to protect the equipment provided by the vendor, gyrotron, user, and related equipment.

1. Sufficient information showing the status of the CPS system, e.g. status of individual power modules, shall be transmitted through EPICS CA.
2. In the case of a cathode arc, the independent crowbar switch shall be fired at the same time as the high-voltage turn-off. The crowbar switch is a redundant component to protect the valuable gyrotron in the case of malfunction.
3. When HVDC turn-off is initiated for protection, the immediate transmission of the **fast-fault** notification through **DO** shall be followed within 5 µs. This signal will be mainly used to turn off the body power supply.
4. When **fast-fault** is activated, the **event list** and **first event** shall be recorded in **EPICS CA** for an operation reference.
5. When the high-voltage turn-off and/or crowbar are initiated, the system shall remain in a fault status. The status shall be recovered by the **reset** command.
6. All controls shall be performed in either **local mode** or **remote mode** with/without connection to the control network provided by NFRI.
7. All signals and control devices names shall be named according to the KSTAR naming convention. NFRI will provide the necessary assistance in order to enable the vendor to carry out this task during the design stage.

### Operation mode

1. The output control modes shall be divided into the **internal reference** mode and **external reference** mode.
2. In the **external reference** mode, the reference analog voltage will be supplied by NFRI.
3. In the **internal reference** mode case, the output voltage shall be set by the signal **Vrefint** from EPICS CA.

### HV on/off control

1. **The output enable** command will be supplied through optical fibers from the EC-ICS.
2. At any **operation mode**, the output shall be enabled by the logical high level of the **output enable** command. The logical low level of the **output enable** command shall disable the output.
3. **The output enable** command performs output synchronization with KSTAR.
4. Output **modulation** shall also be also performed through the **output enable** command.

### Communication parameters

1. Example operation commands, parameters, and values between the CPS controller provided by the vendor and external EC-ICS provided by NFRI are listed in Table 1.
2. Example operation commands, parameters, and values between the crowbar controller provided by the vendor and external EC-ICS provided by NFRI are listed in Table 2.

BM: Momentary binary

MB: Multi-bit

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Name** | **Dir.** | **Network** | **Description** | **Type** | **Default** |
| **On** | **In** | **EPICS** | **System stand-by** | **BM** | **Off** |
| **Off** | **In** | **EPICS** | **System off** | **BM** | **Off** |
| **Status** | **Out** | **EPICS** | **0:off, 1:stand-by** | **Binary** | **N/A** |
| **Watch dog** | **Out** | **EPICS** | **½ Hz** | **Binary** | **N/A** |
| **Remote** | **In** | **EPICS** | **0: local, 1: remote** | **Binary** | **0** |
| **Remote status** | **Out** | **EPICS** | **0: local, 1: remote** | **Binary** | **N/A** |
| **Ioc** | **In** | **EPICS** | **Over current** | **Float** | **55 A** |
| **Ioc\_r** | **Out** | **EPICS** | **Over current ret.** | **Float** | **N/A** |
| **Vov** | **In** | **EPICS** | **Over voltage** | **Float** | **55 kV** |
| **Vov\_r** | **Out** | **EPICS** | **Over voltage ret.** | **Float** | **N/A** |
| **Reference** | **In** | **EPICS** | **0: internal reference, 1: external reference** | **Binary** | **0** |
| **Reference status** | **Out** | **EPICS** | **0: internal reference, 1: external reference** | **Binary** | **N/A** |
| **Out enable** | **In** | **Fiber DI** | **Rising edge: output enable, Falling edge: output disable** | **Binary** | **Low** |
| **Vrefint** | **In** | **EPICS** | **Internal reference voltage** | **Float or array of float** | **0** |
| **Vrefint\_r** | **Out** | **EPICS** | **Internal reference voltage ret.** | **Float or array of float** | **0** |
| **Vref** | **in** | **Analog** | **Reference voltage** | **Bandwidth < 5 usec,**  **10 kV/V** | **0** |
| **Vout** | **Out** | **Analog** | **Output voltage** | **Bandwidth < 5 usec,**  **0.1 V/kV** | **N/A** |
| **Iout** | **Out** | **Analog** | **Output current** | **Bandwidth < 5 usec, 0.1V/A** | **N/A** |
| **Vu** | **in** | **EPICS** | **Under voltage ratio** | **Float** | **0.5** |
| **Vu\_r** | **Out** | **EPICS** | **Und. Volt. Ret.** | **Float** | **N/A** |
| **Tdelay** | **In** | **EPICS** | **Und. Volt. delay** | **Float** | **100 usec** |
| **Tdelay\_r** | **Out** | **EPICS** | **Und. Volt. delay Ret.** | **Float** | **N/A** |
| **[Tovt]** | **In** | **EPICS** | **Over temperature** | **Float** | **-** |
| **HVDC Turn off** | **In** | **Fiber DI** | **External fast HV turn off** | **BM** | **False** |
| **Fast fault** | **Out** | **Fiber DO** | **Fast fault** | **Binary** | **False** |
| **First event** | **Out** | **EPICS** | **First fault event** | **MB** | **0x0** |
| **Event list** | **Out** | **EPICS** | **Event List** | **MB** | **0x0** |
| **Reset** | **In** | **EPICS** | **Fault reset** | **BM** | **0** |

Table 1. Example of controller signals between CPS controller and EC-ICS

BM: Momentary binary

MB: Multi-bit

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Name** | **Dir.** | **Network** | **Description** | **Type** | **Default** |
| **Crowbar** | **Out** | **Fiber DO** | **0: Normal, 1: Crowbar ignited** | **Binary** | **0** |
| **Crowbar enable** | **In** | **Fiber DI** | **0: Enable, 1: disable** | **Binary** | **0** |
| **Crowbar status** | **Out** | **Fiber DO** | **0: Disabled, 1: enabled,** | **Binary** | **0** |
| **Crowbar reset** | **In** | **Fiber DI** | **Crowbar reset** | **BM** | **0** |

Table 2. Example of controller signals between crowbar controller and EC-ICS

### Interlocks

The interlocks protect user and equipment from hazardous high voltages in the case of equipment malfunction or human error.

1. **The ground switch** in between the **soft starter** and **multi-secondary transformer** and around the **output filter** shall be protected by a chained **interlock key**.
2. The first **interlock key** shall be at the **CPS controller**, the **second interlock key** shall be at **the soft-starter ground switch, and** the **third interlock key** shall be at the **output-filter ground switch.** All **keys** are interconnected to **interlock switches.**
3. **The discharge rods** shall be installed by the vendor at the area of the **output filter** and **termination box**. The **interlock switches** shall be activated when removing/mounting discharge rods from/at their resting position.
4. All interlock switches shall be electrically connected so as to protect users and/or equipment.

## Tests

1. The following **factory acceptance test (FAT)** and **site acceptance test (SAT)** shall be conducted on the system in accordance with this specification and accepted industrial standard.
2. The FAT shall be conducted at the vendor’s site before delivery, and the SAT shall be conducted at the installed site at NFRI after delivery. Both tests shall be conducted under vendor’s responsibility.
3. The tests shall be requested by the vendor in accordance with the delivery plan in contraction.
4. In the test condition, “Full load” implies a parallel connection of resistance, R = 55 kV/55 A, and capacitance, C = 1000 pF, at the HVDC output of the termination box.
5. For the open load test, voltage falling time will be evaluated separately from specified in 2.1.1 upon mutual agreement.

### FAT

1. During the FAT, all functionalities, all specification, including communication and interlock, etc., of the system shall be demonstrated in accordance with this specification and be applicable to be accepted industrial practice.
2. All required equipments for the transformer test shall be prepared by the vendor.

* Transformer turns ratio test : Voltage measurement for all secondary winging
* AC high potential test on the transformer primary
* DC high potential test on the secondary and rectifier system
* Temperature rising test

1. The detailed conditions for the performance test will be mutually agreed upon during the design stage.
2. Individual temperature test of PSM under full load condition.
3. **The HVDC cable** can be replaced with the relevant elements simulating the real length of the cable. The relevant elements shall be provided by the vendor.
4. The crowbar shall be disabled for the following tests.

* DC 300 s test with open load at selected voltages
* DC voltage response test with external voltage reference with open load, and with full load at selected voltages
* The pulse length of full load test shall be > 0.5 s
* DC modulation test with open load, and with full load at selected voltages
* DC wire-burning test with open load, and with full load at selected voltages

1. The crowbar test shall be conducted with following condition

* DC wire-burning test with full load at selected voltages

### SAT

1. During the SAT, all functionalities, including communication and interlock etc, of the system shall be demonstrated in accordance with this specification.
2. The preparation of the required equipment for the test will be mutually agreed upon before the SAT.
3. The detailed conditions for the performance test will be mutually agreed upon during the design stage.
4. The following tests shall be conducted with all installations **with no gyrotron**. The **crowbar shall be disabled** for this test. The following tests shall be **repeated three times** in succession without fault or abnormal operation.

* DC modulation test with open load at selected voltage
* DC 300 s test with open load at selected voltage
* DC voltage response test with external voltage reference
* DC wire-burning test with open load at selected voltages
* The above DC tests shall be repeated for a full load test with a pulse length of 0.5 s

1. The **crowbar test** shall be conducted with the following condition.

* DC wire-burning test with open load

1. The following tests shall be conducted with all **installations with a gyrotron**. If a test gyrotron is not available, the characteristics of the gyrotron cathode can be simulated by the relevant elements. The crowbar shall be enabled for these tests. The following tests shall be **repeated five times** in succession without fault or abnormal operation.

* DC modulation test at selected voltage
* DC 300 sec test at selected voltage
* DC voltage response test with external voltage reference

# BPS

## Functionality

### Summary of Specification

1. Line frequency 60 Hz ± 2%
2. Nominal output voltage 0 – positive 30 kV
3. Nominal output control step < 0.2 kV
4. Maximum output current 150 mA
5. Maximum voltage ripple ± 50 V
6. Output stability < 0.5%
7. Pulse length and duty cycle 300 s, repetition period: 1500 s
8. On-line external voltage control True
9. Maximum overshoot < 1% of settled output voltage
10. Voltage settling time\* < 70 µs
11. Modulation frequency range 0–5 kHz adjustable
12. Modulation depth 0–100% adjustable
13. Voltage rising/falling time < 50 µs (10–90%)
14. Input mains 380 V – 3-phase
15. Maximum volume 2.5 × 1.5 × 2.5 m3
16. Maximum weight < 1 ton/m2
17. Safety and interlock according to CPS
18. Control power shared input mains 380 V
19. Ambient temperature range 20–40 °C

*\* The time required for the output voltage to reach and stay within ripple voltage range from the initiation of voltage rising command.*

### Body Power Supply system

1. The BPS supplies the acceleration voltage at the body electrode in between the negatively biased cathode and grounded collector.
2. The load characteristic of the body electrode is mainly capacitive, roughly 500 – 1000 pF depending on the gyrotron model.
3. The **BPS** consists of a DC power supply, controllers, and associated auxiliaries.
4. All components of the BPS including the transformer and output passive components shall be enclosed in a single cabinet.

### HVDC cable

1. **The HVDC cable**, which shall be supplied by vendor, runs from the output terminal of the BPS installed on the second deck of heating device room, to the gyrotron complex located on the first deck of the heating device room.
2. The distance between the BPS output terminal and body electrode will be less than 10 m.

### BPS controller

The BPS controller controls all system behavior including the **on/off** system, output voltage, and arc protection, receiving commands from the external controller, which will be provided by NFRI.

The BPS controller shall be as transparent as possible. Every control parameter necessary for operation and maintenance shall be transparent unless it is harmful or dangerous to the power supply itself.

1. The BPS controller communicates with the EC-ICS, which will be provided by NFRI.
2. The output voltage at the output terminal of the BPS shall be completely controlled by the EC-ICS through the reference voltage. An unacceptable reference shall be corrected internally without terminating the output.
3. The power supply shall protect itself internally from any event that allows maximum usage of the output voltage, current, power, and transients within this specification.
4. The communication protocols between the EC-ICS and BPS controller shall be:

* **EPICS CA** through **TCP/IP KSTAR machine network (Gbps)**
* Fiber optic **DIO** –internal latency < 1 µs
* Analog voltage reference **Vref** – internal bandwidth < 5 µs
* Analog **Vout** and **Iout**

1. The analog signals such as **Vref**, **Vout**, and **Iout** will be connected to a 10G SDN (10 Gigabit Synchronized Data Network developed by ITER) by NFRI. The reference of all analog signals shall be the system ground.
2. The BPS controller shall protect the BPS system and gyrotron by immediate initiation of the HVDC turn-off within the specified output turn-off time in any case, such as:

* Over current > **Imax** = 150 mA or **Ioc**
* Over voltage > **Vmax** = 30 kV or **Vov**
* External **HVDC turn-off** command
* Any other event that requires HVDC turn-off to protect the equipment provided by the vendor, gyrotron, user, and related equipment.

1. Sufficient information showing the status of the BPS system shall be transmitted through the EPICS CA.
2. When HVDC turn-off is initiated for protection, the immediate transmission of the **fast-fault** notification through the **DO** shall be followed within 5 µs. This signal will mainly be used to turn off the cathode power supply.
3. When **fast-fault** is activated, the **event list** and **first event** shall be recorded in the **EPICS CA** for operation reference.
4. When high-voltage turn-off is initiated, the system shall remain in the fault status. The status shall be recovered by the **reset** command.
5. All controls shall be performed in either **local mode** or **remote mode** with/without connection to the control network provided by NFRI.
6. All signal and control device names shall be named according to the KSTAR naming convention. NFRI will provide the necessary assistance to enable the vendor to carry out this task during the design stage.

### Operation mode

1. The output control modes shall be divided into the **internal reference** mode and **external reference** mode.
2. In the **external reference** mode case, the reference analog voltage shall be supplied by NFRI.
3. In the **internal reference** mode case, the output voltage shall be set by the signal **Vrefint** from the EPICS CA.

### HV on/off control

1. **The output enable** command will be supplied through optical fibers from the EC-ICS.
2. At any **operation mode**, the output shall be enabled by the logical high level of the **output enable** command. The logical low level of the **output enable** command shall disable the output.
3. The **output enable** command performs output synchronization with KSTAR.
4. Output **modulation** shall also be performed through the **output enable** command.

### Communication parameters

Example operation commands, parameters, and values between the **BPS controller** provided by the vendor and external EC-ICS provided by NFRI are listed in Table 3.

BM: Momentary binary

MB: Multi-bit

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Name** | **Dir.** | **Network** | **Description** | **Type** | **Default** |
| **On** | **In** | **EPICS** | **System stand-by** | **BM** | **Off** |
| **Off** | **In** | **EPICS** | **System off** | **BM** | **Off** |
| **Status** | **Out** | **EPICS** | **0:off, 1:stand-by** | **Binary** | **N/A** |
| **Watch dog** | **Out** | **EPICS** | **½ Hz** | **Binary** | **N/A** |
| **Remote** | **In** | **EPICS** | **0: local, 1: remote** | **Binary** | **0** |
| **Remote status** | **Out** | **EPICS** | **0: local, 1: remote** | **Binary** | **N/A** |
| **Ioc** | **In** | **EPICS** | **Over current** | **Float** | **150 mA** |
| **Ioc\_r** | **Out** | **EPICS** | **Over current ret.** | **Float** | **N/A** |
| **Reference** | **In** | **EPICS** | **0: internal reference, 1: external reference** | **Binary** | **0** |
| **Reference status** | **Out** | **EPICS** | **0: internal reference, 1: external reference** | **Binary** | **N/A** |
| **Out enable** | **In** | **Fiber DI** | **Rising edge: output enable, Falling edge: output disable** | **Binary** | **Low** |
| **Vrefint** | **In** | **EPICS** | **Internal reference voltage** | **Float or array of float** | **0** |
| **Vrefint\_r** | **Out** | **EPICS** | **Internal reference voltage ret.** | **Float or array of float** | **0** |
| **Vref** | **in** | **Analog** | **Reference voltage** | **Bandwidth < 5 usec,**  **10 kV/V** | **0** |
| **Vout** | **Out** | **Analog** | **Output voltage** | **Bandwidth < 5 usec,**  **0.1 V/kV** | **N/A** |
| **Iout** | **Out** | **Analog** | **Output current** | **Bandwidth < 5 usec, 0.1V/A** | **N/A** |
| **[Tovt]** | **In** | **EPICS** | **Over temperature** | **Float** | **-** |
| **HVDC Turn off** | **In** | **Fiber DI** | **External fast HV turn off** | **BM** | **False** |
| **Fast fault** | **Out** | **Fiber DO** | **Fast fault** | **Binary** | **False** |
| **First event** | **Out** | **EPICS** | **First fault event** | **MB** | **0x0** |
| **Event list** | **Out** | **EPICS** | **Event List** | **MB** | **0x0** |
| **Reset** | **In** | **EPICS** | **Fault reset** | **BM** | **0** |

Table 3. Example of controller signals between BPS controller and EC-ICS

### Interlocks

The interlocks protect users and equipment from hazardous high voltages in the case of equipment malfunction or human error.

1. The **interlock key/safety key will be used for user and equipment protection.** All **keys** are interconnected to **interlock switches.**
2. All interlock switches are electrically connected to protect users and/or equipment.

## Tests

1. The following **FAT** and **SAT** shall be conducted on the system in accordance with this specification and applicable accepted industrial practices.
2. The FAT shall be conducted at the vendor’s site before delivery, and the SAT shall be conducted at the installed site at NFRI after delivery. Both tests shall be conducted under vendor’s responsibility.
3. The tests shall be requested by the vendor in accordance with the delivery plan in contraction.
4. In the test condition, “full load” implies a parallel connection of resistance, R = 30 kV/100 mA, and capacitance, C = 1000 pF.
5. For the open load test, voltage falling time will be evaluated separately from specified in 2.1.1 upon mutual agreement.

### FAT

1. During the FAT, all functionalities, including communication and interlock, etc., of the system shall be demonstrated in accordance with this specification.
2. The detailed conditions for the performance test will be mutually agreed upon during the design stage.
3. The **HVDC cable** can be replaced with the relevant elements simulating the real length of the cable. The relevant elements shall be provided by the vendor.
4. The following tests should be conducted:

* DC modulation test with open load, and with full load at selected voltages
* DC 300 s test with open load, and with full load at selected voltages
* DC voltage response test with external voltage reference with open load, and with full load at selected voltages

### SAT

1. During the SAT, all functionalities, including communication and interlock, etc., of the system shall be demonstrated in accordance with this specification.
2. The preparation of the required equipment for the test will be mutually agreed upon before the SAT.
3. The detailed conditions for the performance test will be mutually agreed upon during the design stage.
4. The following tests shall be conducted with all installations **with no gyrotron** and shall be **repeated three times** in succession without fault or abnormal operation.

* DC modulation test with open load at selected voltage
* DC 300 s test with open load at selected voltage
* DC voltage response test with external voltage reference
* The above DC tests shall be repeated for a full load.

1. The following tests shall be conducted with all **installations with a gyrotron and CPS.** If a test gyrotron is not available, the characteristics of the gyrotron cathode can be simulated by the relevant elements. The following tests should be **repeated five times** in succession without fault or abnormal operation.

* DC modulation test at selected voltage
* DC 300 s test at selected voltage
* DC voltage response test with external voltage reference

# Installation

## Installation plan

1. The vendor shall be responsible for the installation including the positioning, hardening, and connecting of all equipment provided by the vendor, including ground connection and cable trays needed for cables connecting equipment provided by the vendor.
2. The scope of installation includes, but not limited to, the positioning, hardening, and connecting , including ground connection. The ground terminals at the third floor of PS-3 building and second deck of heating device room will be provided by NFRI.
3. The exact position of all equipment will be mutually agreed upon during the design stage.

(Figure 3 and Figure 5 shows the conceptual schematics)

1. The soft starter, transformer, PSM module block, and output filer shall be installed on the third floor of the PS-3 power supply building, as shown in Figure 3.
2. An example of the installation position and cable routing is illustrated in Figure 5.
3. The termination box of the CPS and DC power supply for the BPS shall be installed on the second deck of the heating device room.
4. The HVDC cable and controller cable shall be installed in the designated cable tray between the output filter and termination box.
5. The EC-ICS, which will be provided by NFRI, will be positioned on the second deck of the heating device room.
6. A drawing of the PS-3 building is illustrated in Figure 6, Figure 7, Figure 8, and Figure 9.

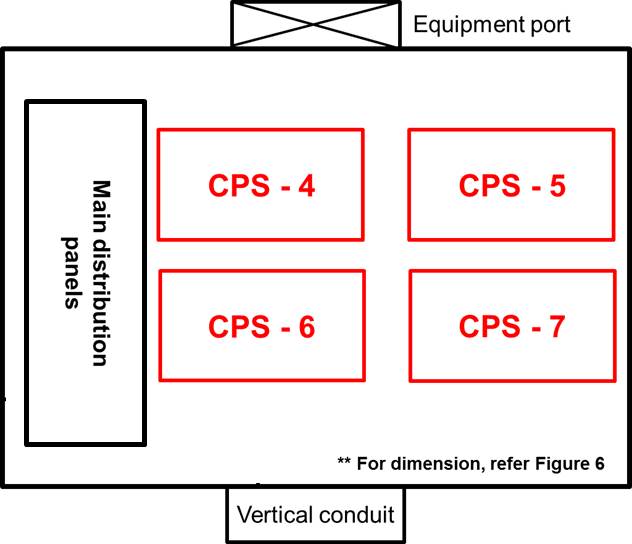


Figure 5. Tentative installation plan of power supply building (Conceptual schematic)

## Controller cables and connections

1. **The controller cables, including all connectors or terminals** connecting the equipment provided by the vendor, shall be prepared by the vendor.
2. **Mains 22.9 kV cables from soft starter and HVDC cables including connectors or terminals** shall be installed under the vendor’s responsibility.
3. **Mains 22.9 kV cables to soft starter** will be prepared by NFRI upon agreement of standard terminal type.
4. **The controller cable tray** will be prepared in parallel to the HVDC cable tray by NFRI.
5. **Ethernet switches** for the **KSTAR machine network** will be installed on the third floor of the **PS-3** power supply building and the second floor of heating device room by NFRI.
6. The types of connectors for the NFRI-supplied cables shall be agreed upon during the design stage

## Cable tray and building penetration

1. NFRI will provide four vertically stacked 200 × 600 mm2 cable trays for the cables running from the PS-3 building to the heating device room.
2. In the underground conduit shown in Figure 3, all cables will penetrate through four 200 mm bores.
3. Figure 10 shows the actual underground conduit.
4. The cables in the cable tray and bore shall be arranged to reduce noise and increase safety, following standard practice.

## Current return and ground

1. NFRI will provide the ground terminals at both the PS-3 building, GTB1, and second deck of the heating device room, GTB2.
2. All ground connections of the equipment provided by the vendor shall follow one point grounding policy, using GTB1 or GTB2.
3. The CPS and BPS current return ground will be connected from the gyrotron collector to the GTB2.
4. All instrument enclosures or cabinets shall be electrically isolated from the building except for the well-defined low-impedance ground cable.

# Instrumentation and operating interface

## General

1. All electrical equipment, materials, control and power cables, hardware controls, and drawings shall comply with the relevant standards, recommendations, and report, including the latest revisions. The cable insulation and the supports and guides of all cables shall be flame-retardant.
2. The vendor shall provide all instrumentation and control equipment necessary for automatic, unattended, and continuous operation over long periods and for remote control.
3. The control system shall store important waveforms (digital and analog) for a given time period at the time of request and/or a given event for later revision.
4. The vertical and horizontal resolutions of the stored waveform shall be sufficient to revise the transient performance of the power supply.

## Local operating interface

1. The CPS and BPS controllers shall have a local operating interface, having input and output devices.
2. The local operating interface shall provide complete controllability to control the output as the remote access listed in sections 2.1.7 and 3.1.4.
3. The important operating values, which are selected by the operator, shall be graphically displayed in real-time.
4. Internally stored waveforms shall be displayed and transferred to external memory for revision of the power supply performance.
5. The local operating interface shall also provide complete accessibility to the internal parameters, which are necessary for operation and maintenance. These include parameters that are necessary to be revised for the tuning of the power supply performance besides normal operation.
6. The local operation interface shall be remotely accessed through standard network methods such as “Remote Desktop,” “No Machine,” or “X service.” The details shall be agreed upon during the design stage

# Quality management

A high degree of quality consciousness is necessary for the manufacture of high voltage power supplies. Therefore, the contractor shall be required to use a suitable quality management system. The EN ISO 9001 standard shall be the basis for all quality assurance measures.

For execution of this contract, the contractor shall have a documented and supervised quality management system described in a quality management handbook. This contains the quality policy of the contractor, the definition of responsibilities, and the processes, procedures and means for quality assurance.

During the execution of the contract, the contractor shall pay special attention to the following points, which are to be implemented in his/her quality management plan:

## General requirements

1. Quality assurance shall be independent of any business interests of the contractor’s execution department. Organizationally, it shall be subordinated to the management department.
2. The quality management officer assigned by the managing direction, who shall be named in the quality management plan, shall possess all necessary competence. If required, he/she shall be authorized to interrupt the production process in order to initiate corrective measures and to supervise and evaluate the implementation and results of these measures.
3. The contractor agrees to system, process and product audits carried out by NFRI throughout the duration of the contract depending on the respective contractual content.
4. The suitability of production, test and assembly procedures for which there is no previous experience or established regulations shall be verified and documented by means of a qualification procedure in co-ordination with NFRI.

## Quality assurance in design stage

1. The plans shall describe the different design and engineering activities including the definition and regulation of organizational and technical interfaces between various groups that contribute to the design process.
2. All plans shall be shared with NFRI.
3. The plans shall be documented and submitted to NFRI.

## Quality assurance in procurement

The procurement documents for third-party parts and services shall include all required information, such as:

1. Product specification
2. Product requirements
3. Conditions of acceptance
4. Quality certificates and reports to be submitted
5. Descriptions of functions and operating manuals
6. Labelling

## Quality assurance in production

Production shall take place in compliance with the requirements of this technical specification. The contractor shall fulfill the following tasks and requirements during production.

The contractor shall:

1. Recognize critical production steps and supervise these with particular care
2. Take special measures, such as separate inspections in order to ensure compliance with the quality requirements
3. Prepare a test plan and a test sequence plan specifying the testing processes used and to what extent, in addition to when, how, where and by whom
4. Take suitable corrective measures in case of defects and faults and verify the suitability and effectiveness of such measures
5. Prevent recurrence of known faults

Quality assurance in production shall be managed separately from production preparation and production execution.

### Preparation for production

The production documents for the high voltage power supply shall include at least the following documents plus any other documents that may be needed for the production processes. These documents shall be submitted to NFRI no later than fifteen workdays before the production of the respective item starts.

1. Planning documents with schedules, including exact information on all work processes with a duration of more than one week, as well as the regulation of mutual influences resulting from dependencies for the work processes and the resulting chronological classification
2. Description of the necessary preliminary tests for the production
3. Detailed description of all production processes
4. Parts lists and drawings
5. Quality plans for production and inspection with processes and work instruction
6. Necessary forms (measuring reports, process reports etc.)

The contractor is responsible for the design, construction and manufacture of all equipment required for the following tasks.

1. Tests
2. Production
3. Inspections
4. Handling, storage, packing and transport

### Execution of production

Production shall be executed under conditions that are appropriate to the technical requirements of the respective production step. The necessary standards of cleanliness shall be maintained. All materials shall be clearly identified and stored so as to involve no danger of confusion. Special emphasis shall be placed on problems in production steps affecting quality. The obligations of the contractor concerning production include, but are not limited to, the following tasks.

1. Procurement of material and supplied parts
2. Production of components
3. Production of spare parts
4. Assembly
5. Execution of inspection and tests
6. Cleaning and packing

Intermediate inspections are required for critical production steps and shall be defined by the contractor in a schedule. Acknowledged inspection procedures shall be defined and followed for these inspections. These inspection procedures will be prepared by the contractor and approved by NFRI. NFRI will notify the contractor in due time whether NFRI personnel will be present at these events. As a general rule, the contractor and NFRI shall have fifteen workdays to solve any problems that arise during an inspection. Continuation of the work after the stopping point requires the written confirmation of NFRI.

## Quality tests

The obligations of the contractor concerning quality assurance for this contract include, but not limited to, the execution of all inspections and tests as described in chapter 2.2 and chapter 3.2 of this technical specification. If necessary, the contractor shall recommend and agree upon with NFRI’s own test procedures.

All tests shall be conducted according to detailed written test procedures, which shall be submitted to NFRI for approval at least four weeks before the first test.

The suitability of special test procedures shall be verified and documented on a qualification process base.

Forms are to be prepared for all tests, indicating the type and extent of the tests (the specified values to be tested, the test conditions and limiting values to be observed, test frequency, extent, type, procedure, tests means used, evaluation criteria). The test forms shall be submitted to NFRI at least fifteen workdays before the first test.

All required documents, such as pre-test documents, drawings, reports, specifications, test sequence plans, etc. shall be made available by the contractor for each test. The contractor is responsible for providing and supervising suitable test means and test equipment.

NFRI assumes that all test means used comply with the relevant standards, are in perfect condition and are calibrated.

NFRI shall be notified in writing at least fifteen workdays in advance of the first test and five workdays in advance of all other tests. NFRI shall notify the contractor in due time whether it will be present for a test.

The contractor shall submit a copy of the completed test form to NFRI no later than two weeks after completion of a test.

If the result of a test does not fulfill the requirements of the valid regulations and this technical specification, then the evident deviations shall be eliminated and the affected component shall be subject to a new test at the expense of the contractor.

# Design review

1. During design review (DR), the results of the thermal, mechanical, and electrical analyses shall be demonstrated in compliance with this specification.
2. The delivery plan and installation plan shall be fixed based on the construction plan of the relevant building and conduit provided by NFRI.
3. The vendor shall request the DR from NFRI with the relevant documents.
4. The results of the DR shall be documented by the vendor in the proper format.

# Spare components

The following parts shall be delivered in spare.

* Four modules for CPS
* One output voltage sensor for CPS
* One output voltage sensor for BPS
* Other parts that NFRI reasonably requires

# Documentation

1. The vendor shall submit the following documentation with each system in an electronic file format.

* Design and analysis report (DOC)
* All assembly and sub-assembly drawings and schematics (DWG and DSN)
* Complete parts list with manufacturer's name and model/part number (DOC or XLS)
* User manual of the third part components (DOC or PDF)
* Test procedure and test results (DOC)
* Installation and maintenance manual (DOC)
* Operation Manual (DOC)
* Complete list of remote signals (DOC or XLS)
* Vendor’s in-house technical specifications (DOC)
* Documents mentioned in chapter 6. Quality management

# Schedule

1. The DR shall be completed no later than six months after the contract is signed.
2. The scope and schedule of the witness points and holding points shall be mutually agreed upon during the design stage.
3. The timeline of the FAT and delivery will be mutually agreed upon during contracting.
4. The SAT of the first CPS and BPS systems shall be completed no later than 1st May 2019.



Figure 6. Third floor of power supply building PS-3. The equipment positioned inside the bounding wall is an example. The top of the figure is north and the right is east



Figure 7. Vertical section of PS-3 viewed from the south.



Figure 8.Vertical section of PS-3 viewed from the north.

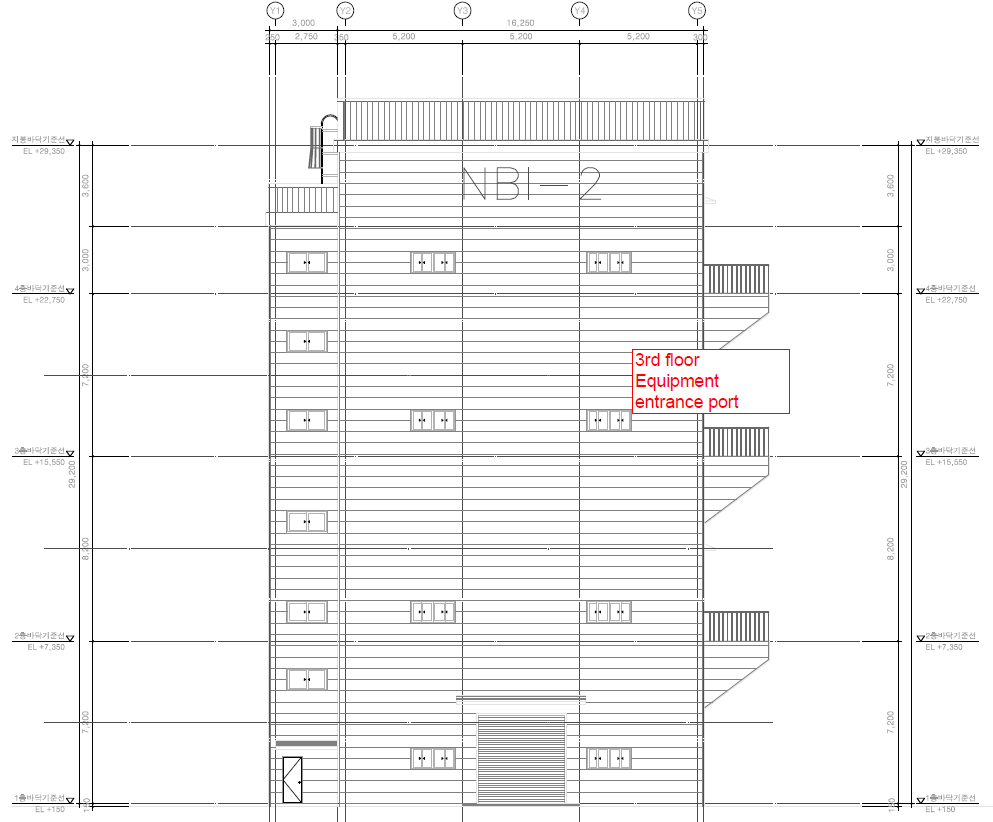


Figure 9. Vertical section of PS-3 viewed from the east.

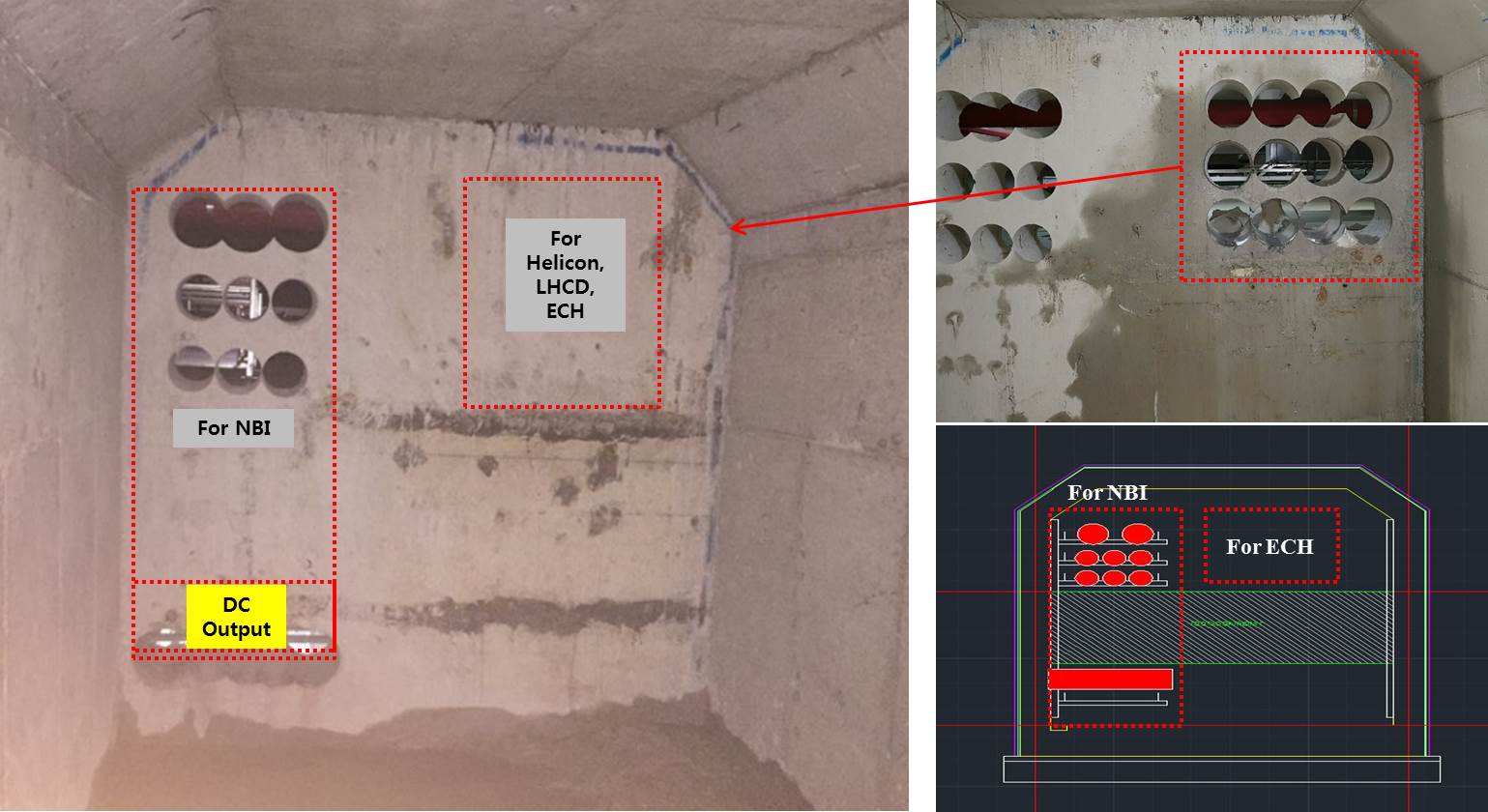


Figure 10. Underground conduit of heating device building