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DESIGN OF NEUTRAL BEAM INJECTION POWER  
SUPPLIES FOR ITER

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## Design of Neutral Beam Injection Power Supplies for ITER

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Design study on a power supply system for the ITER neutral beam injector(NBI) has been performed. Circuits of converter/inverter system and other components of the acceleration power supply whose capacity is 1 MV, 45 A have been designed in detail. Performance of the negative ion production power supplies such as an arc and an extraction power supplies was investigated using EMTDC code. It was confirmed that ripples of 0.34 %p-p for the extraction power supply and 1.7 %p-p for the arc power supply are small enough. It was also confirmed that an energy input to a negative ion generator from the arc power supply at an arcing can be suppressed smaller than 8 J. The extraction power supply was designed to suppress the energy input lower than 13 J at the breakdown in the extractor. These performances satisfy the required specification of the power supply system.

Keywords; ITER NBI, Power Supply, Circuit, Inverter, Converter, Negative Ion

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## ITER 用中性粒子入射装置電源の設計

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(2000年2月24日受理)

ITER 用中性粒子入射装置 (NBI) 電源の設計を行った。本設計では、負イオンビーム加速電源の制御部であるコンバータ／インバータシステムの回路設計の他、加速電源機器の設計検討を実施した。さらに、負イオン生成のためのアーク電源と負イオン引き出し電源の動作特性を回路解析コード EMTDC を用いて検討した。その結果、リップルは、アーク電源が 0.34 %p-p、引き出し電源 が 1.7 %p-p であり、ビームの安定生成に十分な性能であることを確認した。また、プラズマ源内でアーキングが発生した場合、アーク電源からの流入エネルギーは 8 J 以下に抑制できることを確認した。引き出し電極での放電破壊の際には、引き出し電源からの流入エネルギーは 13 J 以下に抑制できることを確認し、十分な保護が可能なことを確認にした。これら NBI 電源の設計の結果、NBI 電源に要求される性能を十分に満足できることを確認した。

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## 1. Introduction

A high power neutral beam injection system(NBI) is one of the effective heating and current drive machines in International Thermonuclear Experimental Reactor(ITER)[1][2]. Required neutral beam power from one module is 17 MW at a beam energy of 1MeV for a duration of >1000s. To produce such high power beams, it is essential to develop a power supply system for the negative ion beam source. In the preliminary design study, specifications of the power supply system and a dynamic performance of the acceleration power supply were designed[3]. As the second step of the design study, power supply circuits of the acceleration and negative ion production have been designed in detail. Performance of the negative ion production power supplies has been studied by circuit simulation.

In the present report, design studies on the acceleration power supply and the negative ion production power supplies are reported. A control system of the power supply, assembly and maintenance strategy are also described.

## 2. Acceleration power supply

The acceleration power supply has been designed to produce a DC ultra high voltage of 1 MV with the intermediate potentials of 200, 400, 600, and 800 kV for the ion source accelerator. The power supply consists of converters, inverters, transformers and rectifiers. An AC power is rectified by the converter to the low voltage DC power. The rectified DC power is supplied to the inverter system which generate a high frequency of 150 Hz AC power to the high voltage transformer and rectifier system. The inverter system controls the out put voltage and the switching of the ultra high voltage of 1 MV at low voltage side. The high voltage power supply has five sets of DC 200 kV power supplies which are connected in series at the out put. Fig.2.1 shows a schematic diagram of acceleration power supply. Detail design of main components in the acceleration power supply have been studied.

## 2.1 Converter/inverter system

### 2.1.1 Circuit of converter/inverter

A circuit diagram of a thyristor converter system is shown in Fig.2.1-1. This system rectifies and serve the DC power to the inverter system. Two sets of a 6 pulse thyristor converter are connected in parallel at the DC output through a DC reactor of 0.3 mH. An AC voltage of three phase 2720 V is supplied from a transformer to the converters. Configuration of the 6 pulse thyristor converter is illustrated in Fig. 2.1-2. Detailed connection of thyristor elements for one arm is shown in Fig. 2.1-3. Twelve elements of the thyristors (2 series x 3 parallel x 2 sets) are adopted for the arm.

A schematic diagram of a capacitor unit for the inverter is shown in Fig. 2.1-4. 324 pieces (12 series x 27 parallel) of capacitor elements are utilized in the filter. To detect breakdowns in the capacitor elements, a voltage imbalance sensor is installed in the circuit.

A circuit diagram of the inverter system with transformers and rectifiers is illustrated in Fig.2.1-5. Detailed connection of GTO elements in the single phase inverter is shown in Fig. 2.1-6. Three sets of the single phase inverter are utilized for one phase. 45 units of the single phase inverter are required for the five stage power supply.

### 2.1.2 Main component in the converter/inverter panels

Layout of the main components in the converter panel is shown in Fig.2.1-7. Thyristor system, DC reactors and pulse generators for the gate control units of the thyristors are mounted in the panel of 9 m x 3 m x 3 m.

Internal layout of the inverter panel is shown in Fig. 2.1-8. GTO valves, capacitors

and control system are installed in the panel whose dimensions are 2.3 m x 2.5 m x 3.5 m.

### **2.1.3 Dimensions of the converter/inverter panels**

Dimensions of the converter/inverter panels are shown in Fig. 2.1-9. In this figure, the inverter panels are arranged to three groups. Each group has five panels of the inverter. Space of 2 m between the rows of the panels is considered to be enough for maintenance. Detail layout of the panels are described in chapter 2.5.

## **2.2 Main transformer**

The DC high voltage of 1 MV is generated by the transformer and rectifier system. The main high voltage transformers of the acceleration power supply are designed based on the JT-60U N-NBI power supply. The specifications of the main transformer are shown in Table 2.2-1. Outline drawing of the main transformer is illustrated in Fig. 2.2-1. Configuration of the main transformer is shown in Fig.2.2-2. Insulation materials of the transformer are also indicated in the same figure.

**Table 2.2-1 Main high voltage transformer**

Rated Voltage	2286V/177kV
Rated Current	2158A/48.2A
Rated continuous power	14.8MVA
Connection	Open Delta /Star
Short circuit impedance	16%
Frequency	150Hz
One-turn Voltage	115V
Number of winding	20turn/887turn
Area of core section	0.17m <sup>2</sup>
Diameter of core	0.49m

Short circuit impedance of the main transformer is calculated as follows;  
 Symbols used in the calculation are shown below

$$X = 8\pi^2 \times f \times n^2 \times 10^{-7} \times \Delta \times R \times 0.96 (\Omega)$$

$$\%IX = \frac{I \times X}{E} \times 100 (\%)$$

$$\Delta = \frac{d_1 \times Lm_1}{3h} + d_2 \times \frac{Lm_2}{h} + \frac{d_3 \times Lm_3}{3h}$$

$$R = 1 - \frac{d_1 + d_2 + d_3}{\pi h}$$

$$Lm_1 = \pi \times (0.53 + 0.02) = 1.73$$

$$Lm_2 = \pi \times (0.57 + 0.215) = 2.47$$

$$Lm_3 = \pi \times (1.0 + 0.04) = 3.27$$

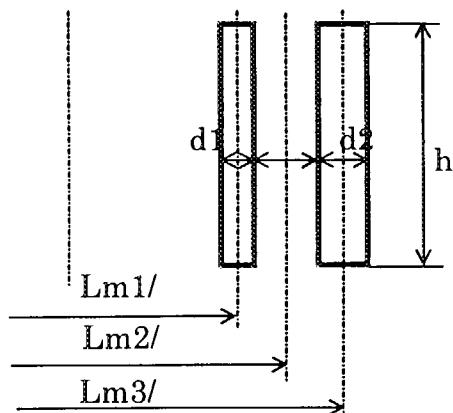
$$\Delta = \frac{0.02 \times 1.73}{3 \times 1.5} + 0.215 \times \frac{2.47}{1.5} + \frac{0.04 \times 3.27}{3 \times 1.5} = 0.391$$

$$R = 1 - \frac{0.02 + 0.215 + 0.04}{\pi \times 1.5} = 0.941$$

$$X = 8 \times \pi^2 \times 150 \times 887^2 \times 0.391 \times 0.941 \times 0.96 \times 10^{-7} = 329 (\Omega)$$

$$\%IX = \frac{\sqrt{3} \times 48.2 \times 329}{177 \times 10^3} \times 100 = 15 (\%)$$

where, symbols in the above equations are described in the following figure.



### 2.3 HV rectifier of the acceleration power supply

Specifications of the high voltage rectifier in the acceleration power supply are shown in Table 2.3-1. The rectifier is mounted on the HV transformer (see Fig. 2.2-1).

Table 2.3-1 Specifications of HV Rectifier

Rated Voltage	DC200kV X 5 Stage
Rated Current	59A
Connection	3 Phase Full Bridge
Frequency	150Hz
Cooling	Self Cooling
Power Dissipation	28kW X 6 Arm
Diode element	
Repetitive Peak Reverse Voltage	2500V
Average Forward Current	150A
Surge Forward Current	5000A
Maximum Operating Junction Temperature	125°C
Steady State Thermal Impedance	
Junction to Case	0.13°C/W
Case to Fin	0.10°C/W
Fin to Gas	1.5 °C/W

The number of diode element (N) required for the bridge is designed as follows;

$$N = \frac{177kV \times \sqrt{2} \times 2 \times 1.2}{2.5kV} = 240$$

where,

- 177kV : Secondary voltage of the HV main transformer
- 2 : Surge factor
- 1.2 : Voltage fluctuation factor

Temperature rise of the diode at steady state operation is estimated. The temperature of 95°C is lower than the allowable temperature of 125 °C.

$$T = 20W \times (0.13 + 0.10 + 1.5) + 60^\circ\text{C} = 95^\circ\text{C} < 125^\circ\text{C}$$

where,

- 20W : Power dissipation at 59A/3
- 60°C : Temperature of surrounding gas

Temperature rise of the diode by short circuit current is calculated. The short circuit current is estimated by following equation.

$$I = \frac{59\text{A}}{0.16} \times 1.95 = 719\text{A}$$

where,

- 1.95 : Impedance factor
- 0.16 : Impedance of the main transformer

The temperature is calculated as follows;

$$T = 2.5\text{V} \times 719\text{A} \times 0.014^\circ\text{C/W} + 95^\circ\text{C} = 120^\circ\text{C} < 125^\circ\text{C}$$

where,

- 2.5V : Forward voltage drop
- 0.014°C : Transient thermal impedance at 7ms
- 95°C : Steady state temperature

The obtained temperature of the diode of 120 °C is lower than the allowable temperature of 125 °C.

Total power loss in the diode bridge is estimated. Radiator is required to cool the gas surrounding the diode bridge.

$$P = 20\text{W} \times 240 \times 6 = 29\text{kW}$$

where,

240 : The number of diodes in one bridge  
6 : The number of bridge

Configuration of the rectifier tank is shown in Fig. 2.3-1. Diode bridges are shown in Fig. 2.3-2.

## 2.4 DC filter capacitors

Electrical specification of the DC filter have already been designed with consideration of the following condition in the design task N42TD02FJ.

Surge current at breakdown :  $\leq 3\text{kA}$   
Energy input to the accelerator :  $\leq 10\text{J}$   
Ripple :  $\leq 10\%\text{pp}$

Specification of the filter :  $C=0.098 \mu \text{F}$  ( $0.94 \mu \text{F} \times 5 \text{ stage}$ )  
 $R=340\Omega$  ( $68\Omega \times 5 \text{ stage}$ )

Mechanical structure of the DC filter is designed in this task. Two sets of  $0.98 \mu \text{F}$  capacitors are connected in parallel. Four sets of these paralleled capacitors are connected in series. Eight sets of the capacitors are utilized for each stage of the acceleration voltage. These capacitors are installed in the gas insulated tank for the high voltage insulation. Configuration of the capacitors are shown in Fig. 2.4-1.

## 2.5 Layout of the power supply yard

A schematic view of the layout in the power supply yard is illustrated in Fig.2.5-1. Switch gear system, transformer, converter, inverter, HV transformers and rectifiers, insulated transformers, voltage and current measurement system, filter capacitor(over voltage suppressor), surge suppression LRs and transmission lines are mounted in the NBI power supply yard. The space for three module system is  $50 \text{ m} \times 70\text{m}$ . Converter and inverter systems are mounted in the

buildings. Output cables from the inverter system are connected to the high voltage transformer. A DC high voltage with intermediate voltages are connected to the transmission line. All of the high voltage parts and conductors are enclosed by outer vessels which are grounded.

A layout of the converter and inverter panels in the building is shown in Fig. 2.5-2. The building of about 10 m (D) x 14 m (W) x 11 m(H) is required for each module.

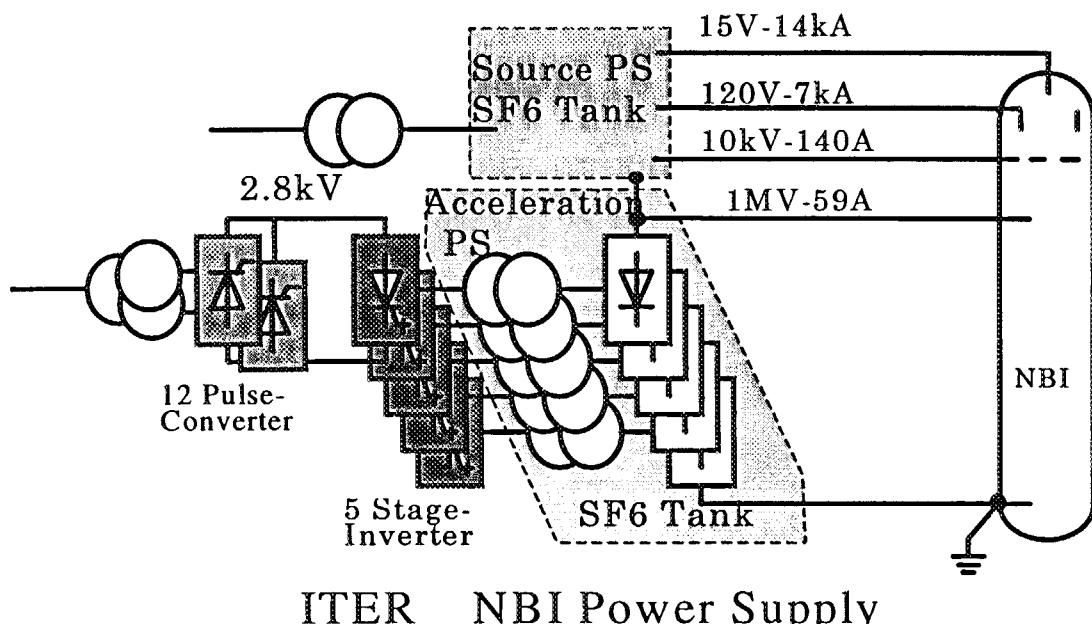
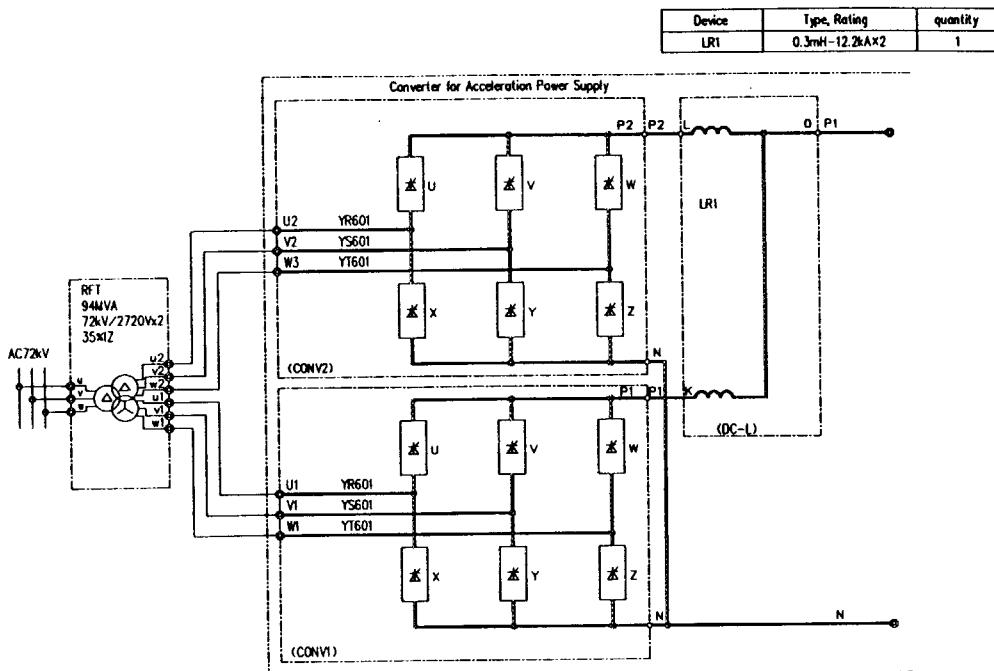


Fig.2.1 A schematic diagram of the NBI power supply.



12-Pulse Thyristor Converter

Fig. 2.1-1 Circuit diagram of 12-pulse thyristor converter.

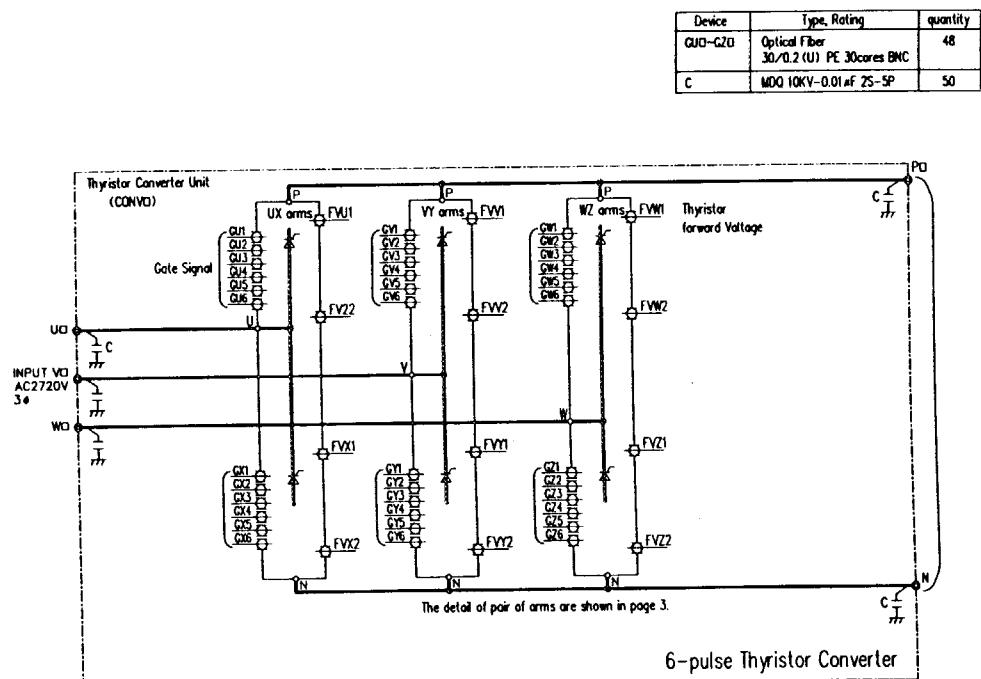


Fig. 2.1-2 Circuit diagram of 6-pulse thyristor converter.

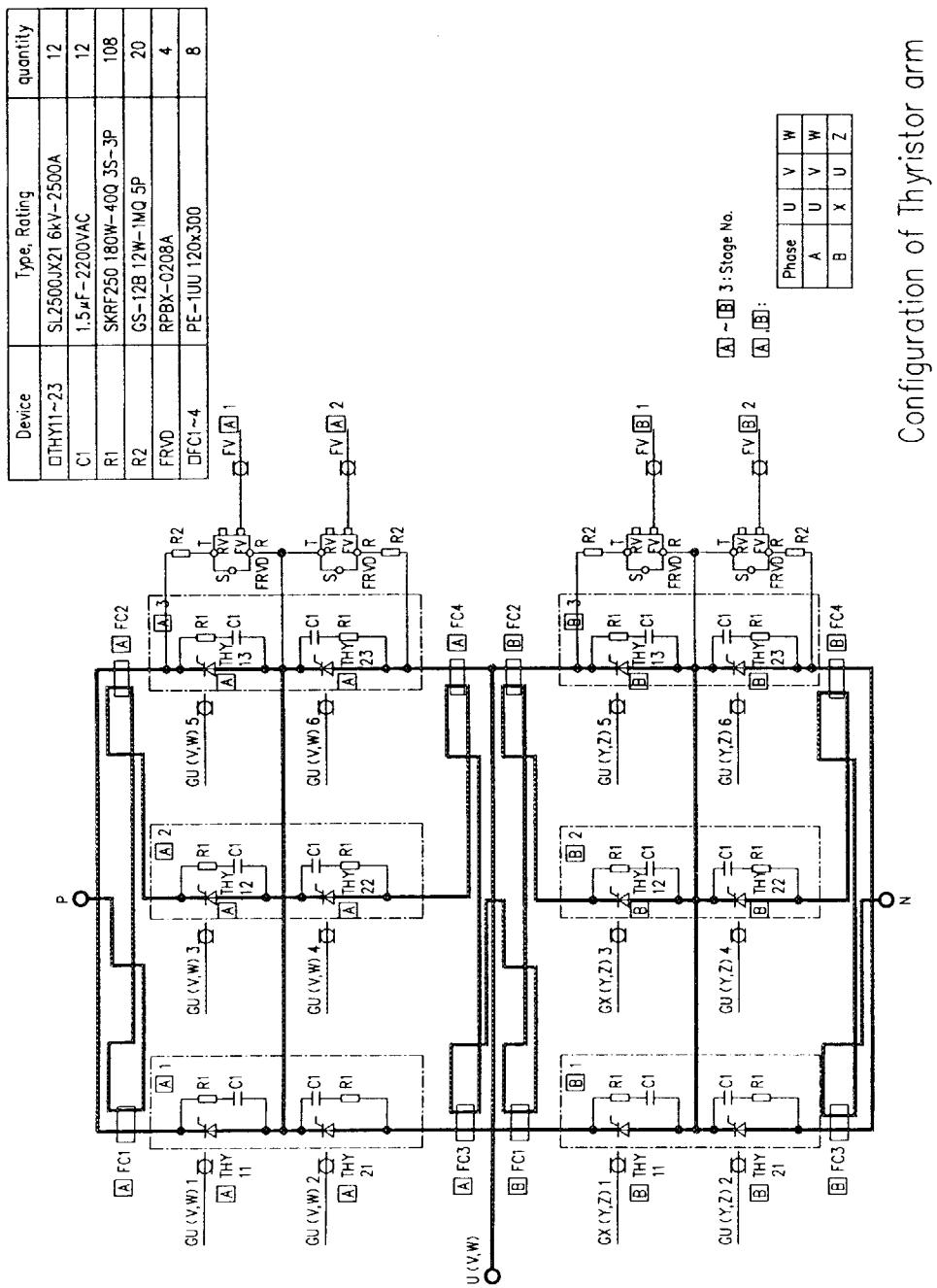


Fig. 2.1-3 Configuration of thyristor arm.

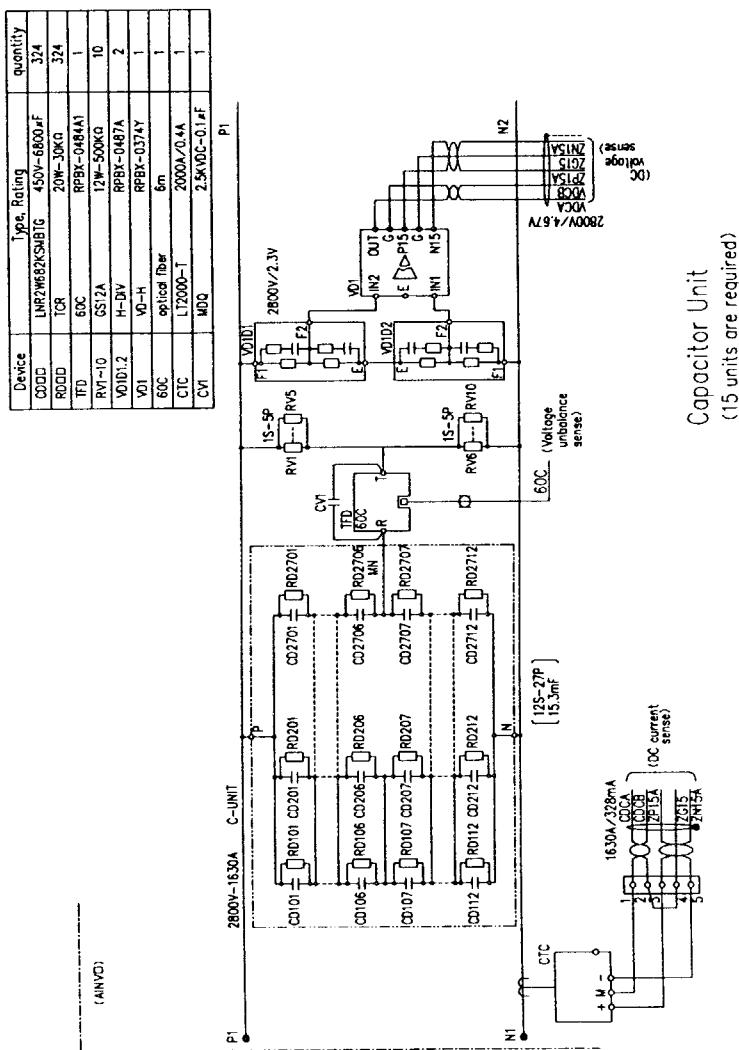


Fig. 2.1-4 Capacitor unit.

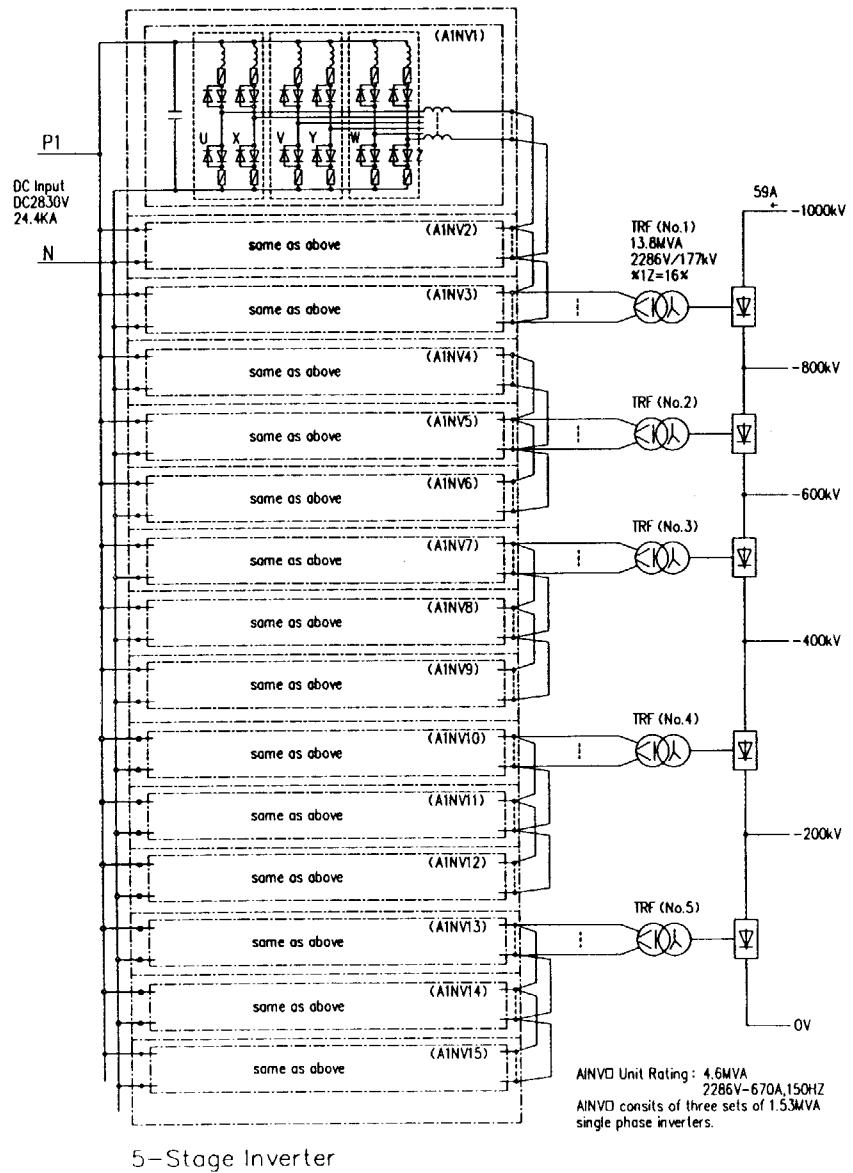


Fig. 2.1-5 Inverter, transformers and rectifiers for the acceleration p.s

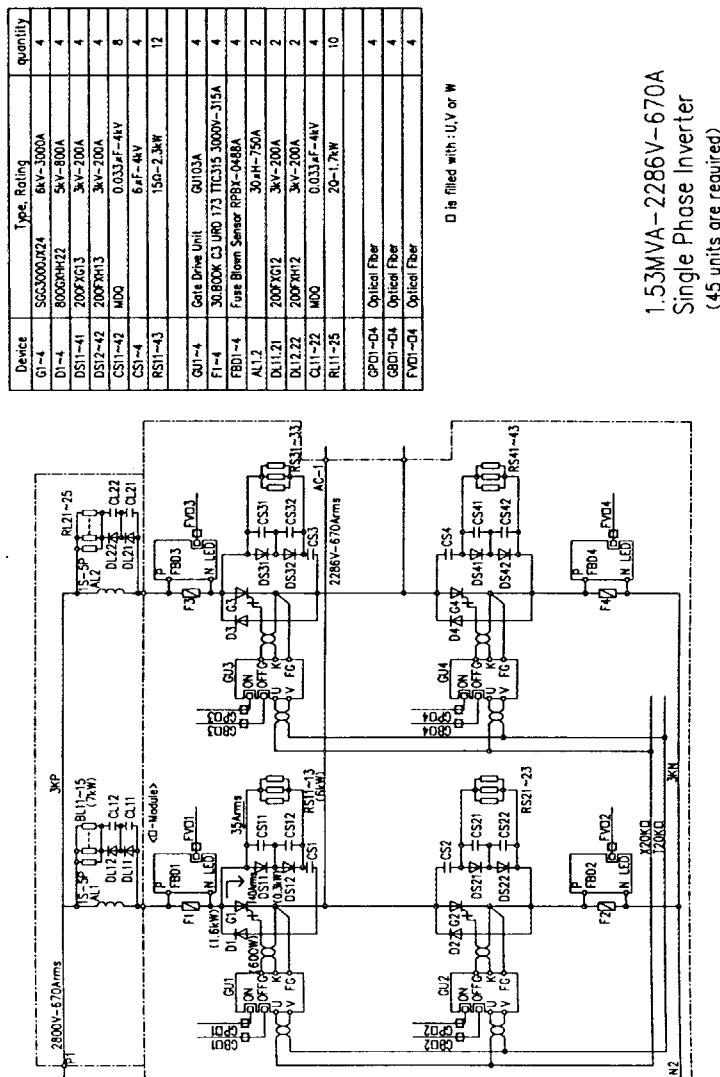


Fig. 2.1-6 Circuit diagram of single phase inverter.

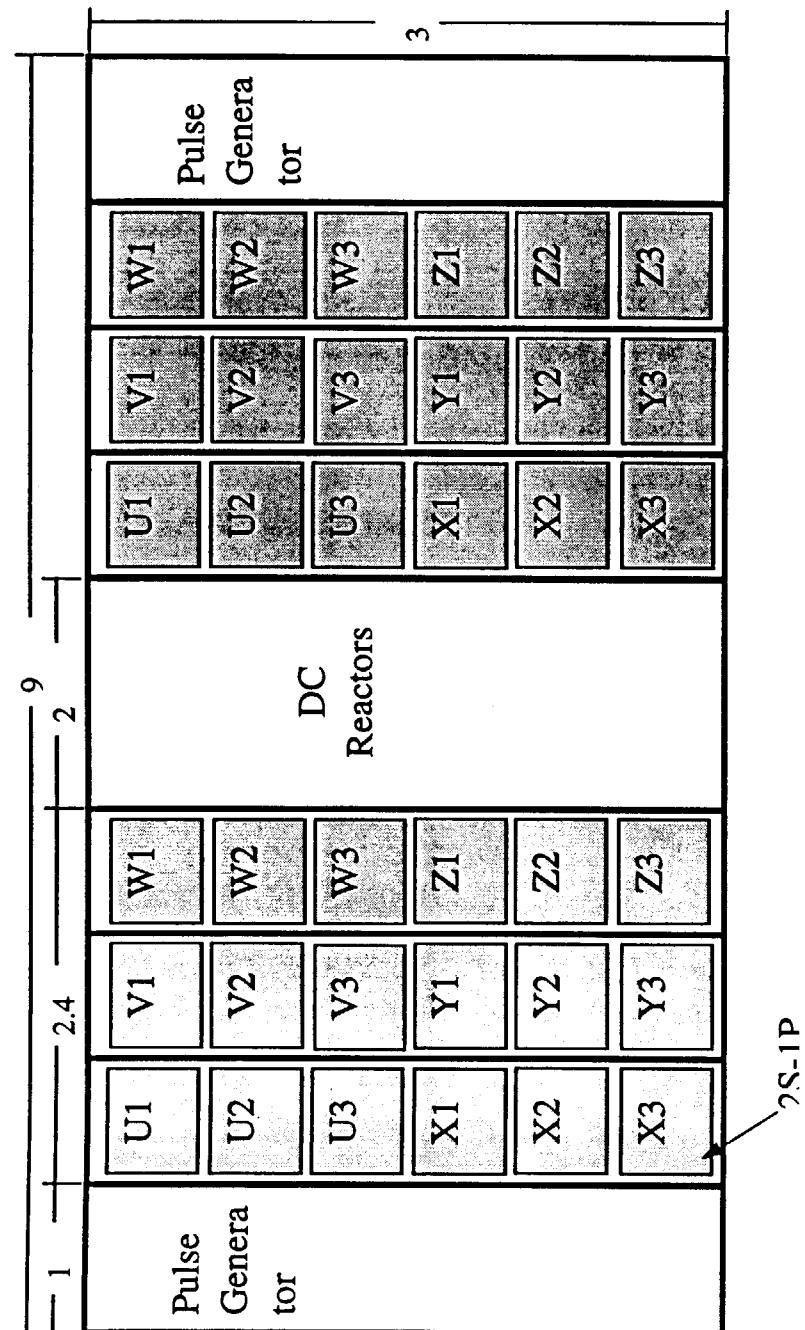


Fig. 2.1-7 Layout of converters in the panels (unit = m).

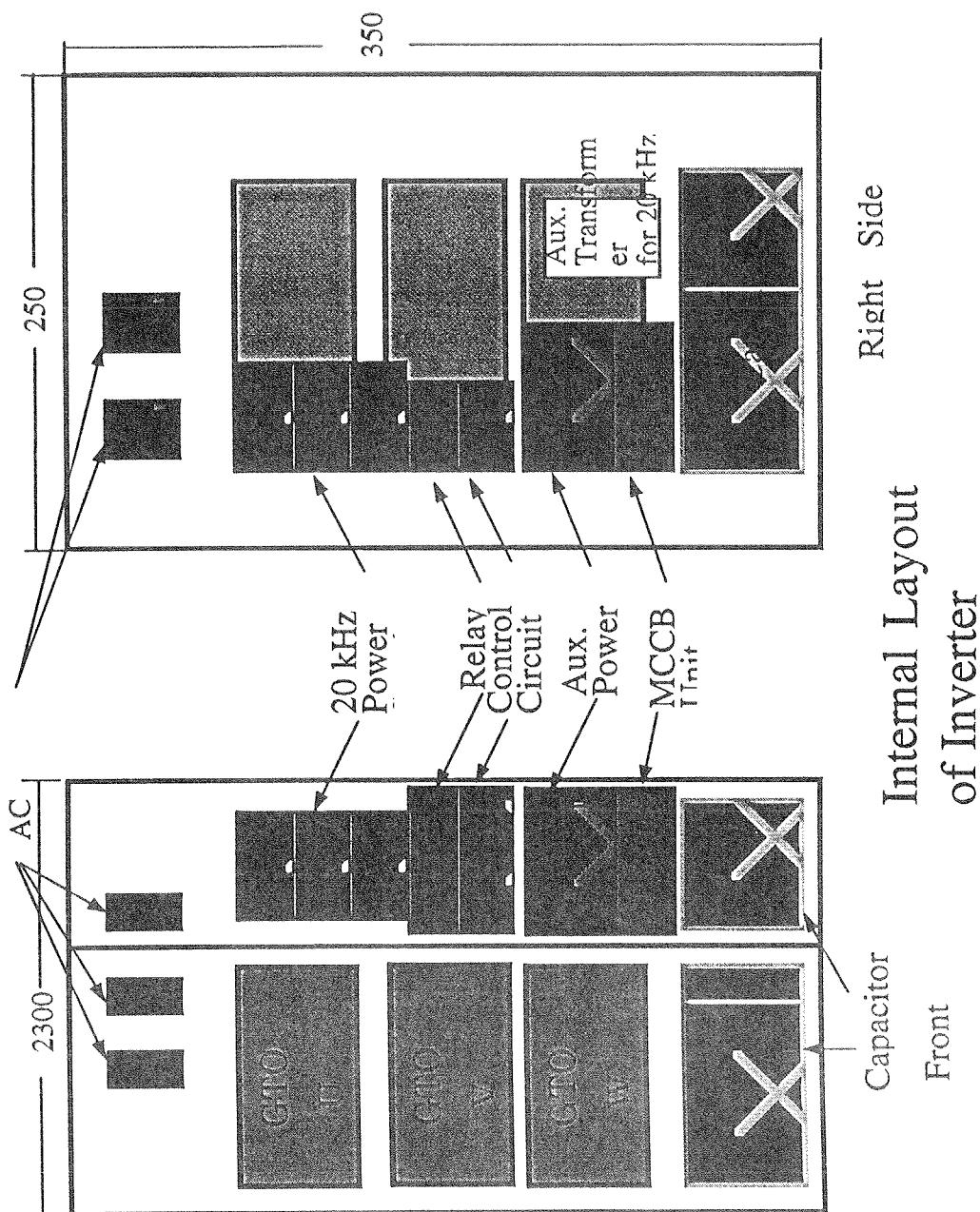


Fig. 2.1-8 Layout of the inverter parts in the inverter panel.

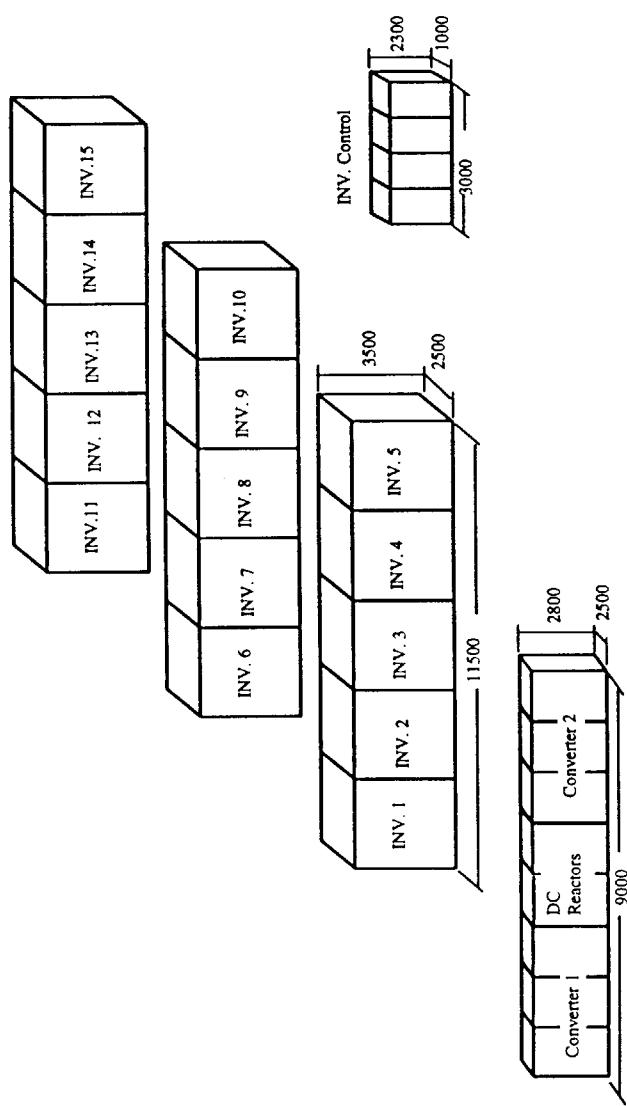


Fig. 2.1-9 Layout of the inverter panels and converter panels.

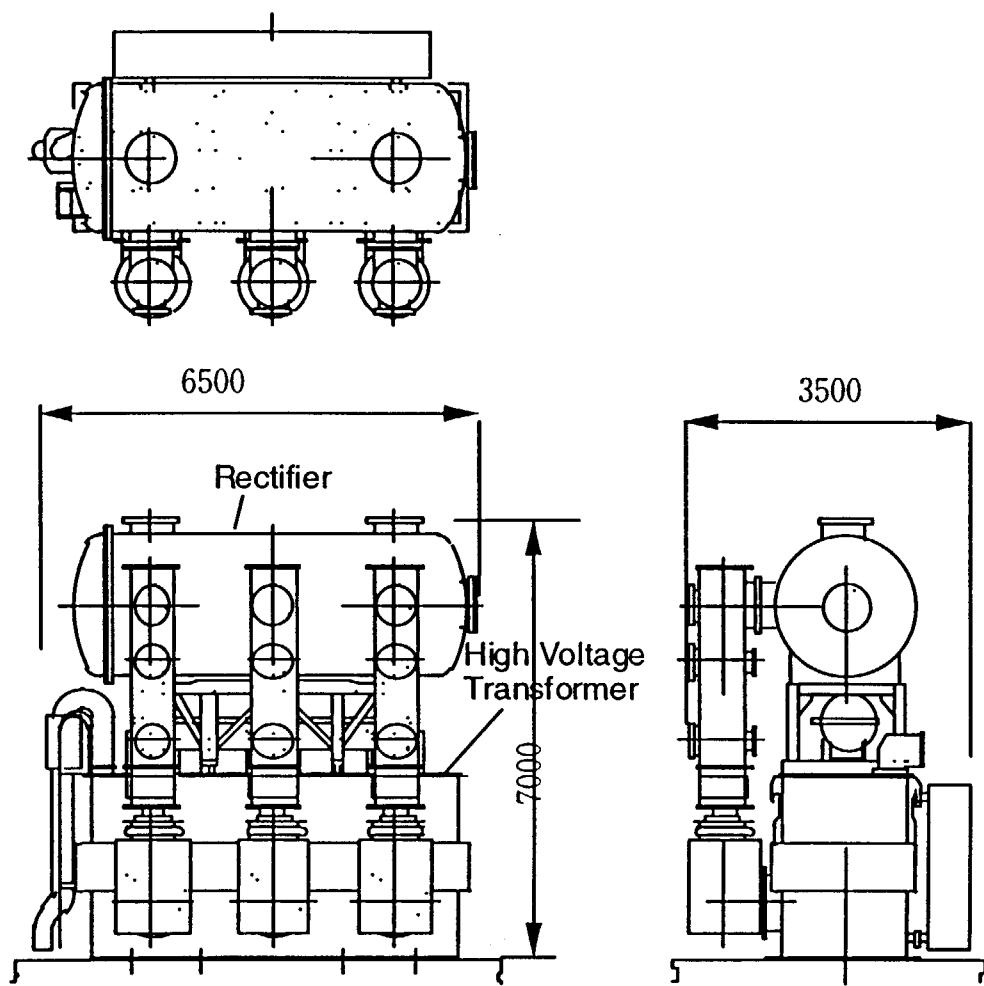
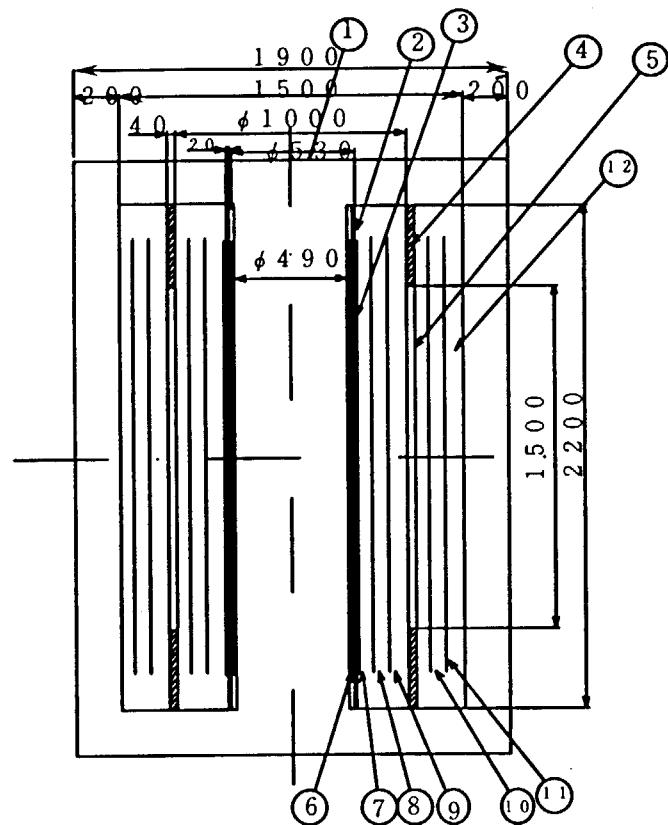


Fig. 2.2-1 Configuration of main transformer for the acceleration power supply.



No.	Parts	Material
1	Core	Silicon steel
2	Ring insulator	Press board
3	Primary coil	Copper, insulation paper
4	Ring insulator	Press board
5	Secondary coil	Copper, insulation paper
6	Cylindrical insulator	Press board
7	Cylindrical insulator	Press board
8	Cylindrical insulator	Press board
9	Cylindrical insulator	Press board
10	Cylindrical insulator	Press board
11	Cylindrical insulator	Press board
12	Oil	Transformer oil

Fig. 2.2-2 Configuration and materials of the transformer.

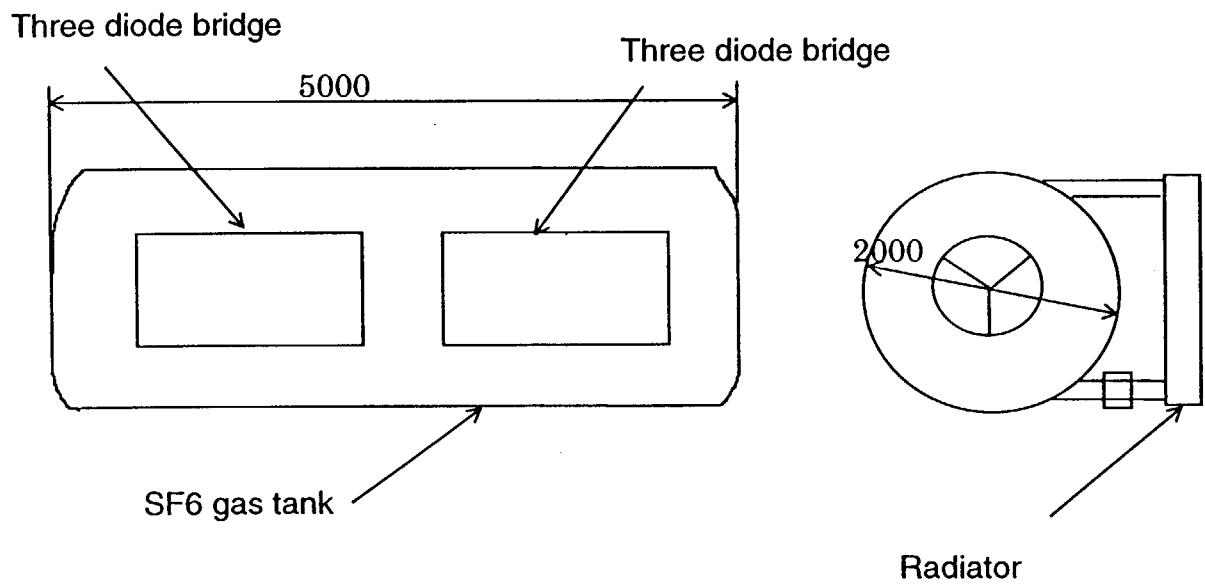


Fig2.3-1 Configuration of the rectifier tank.

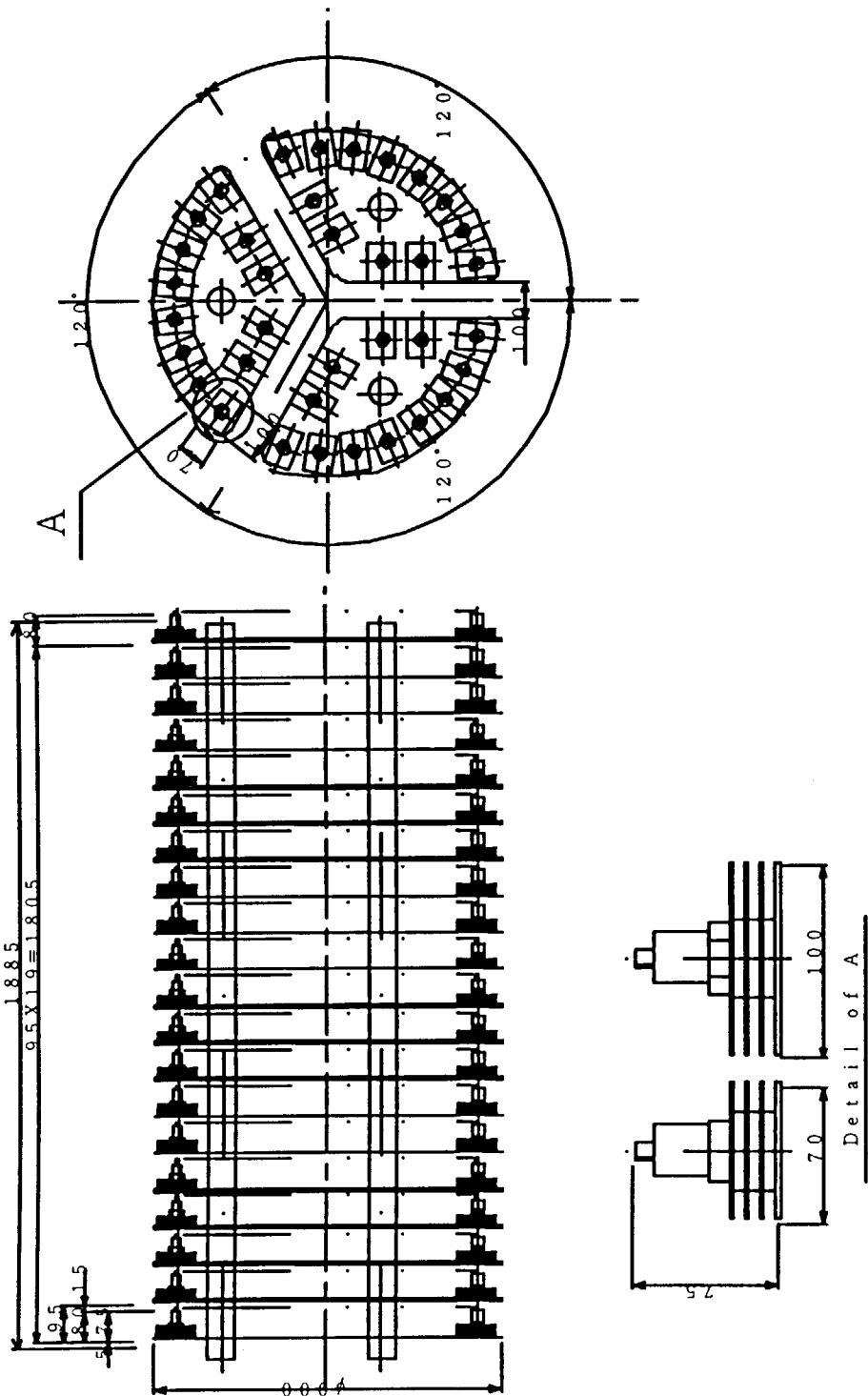


Fig. 2.3-2 Rectifiers for the acceleration power supply.

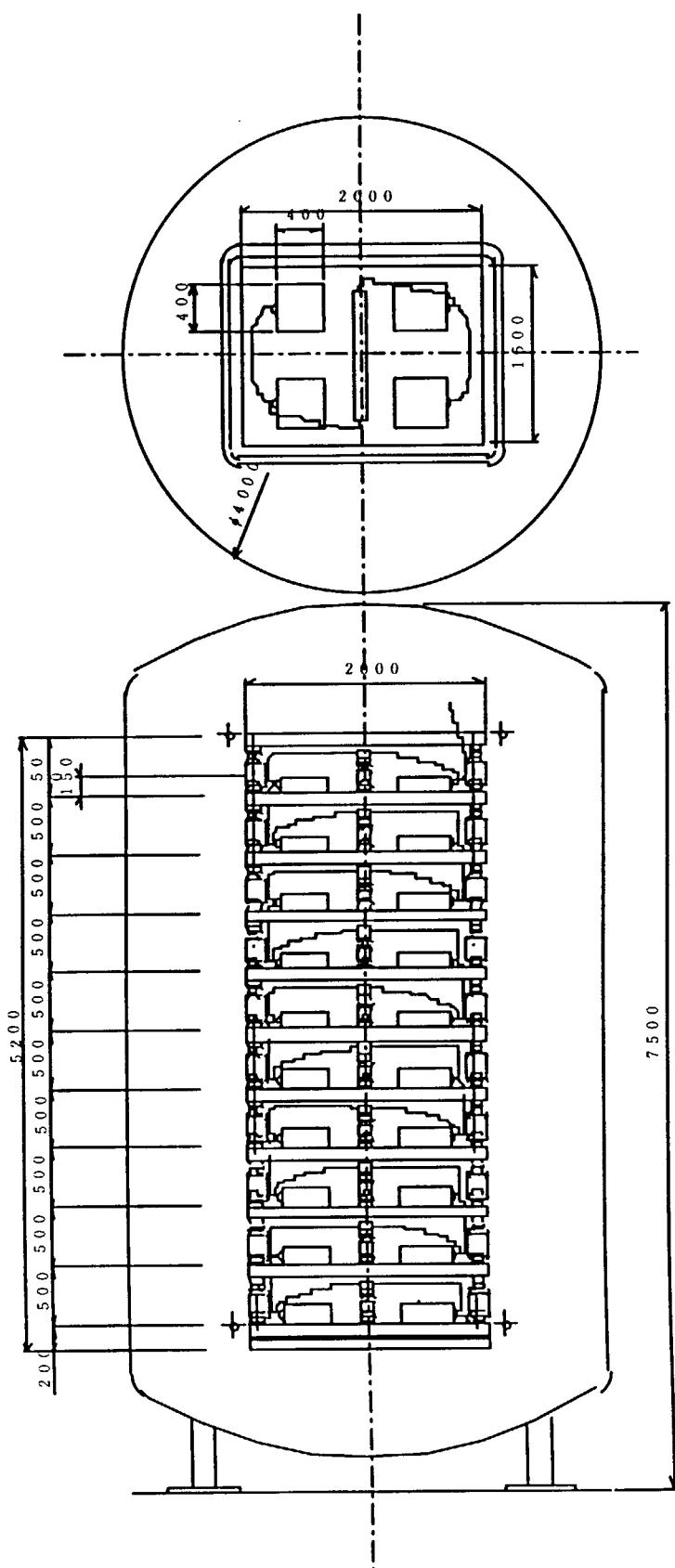


Fig. 2.4-1 Filter capacitor for DC high voltage.

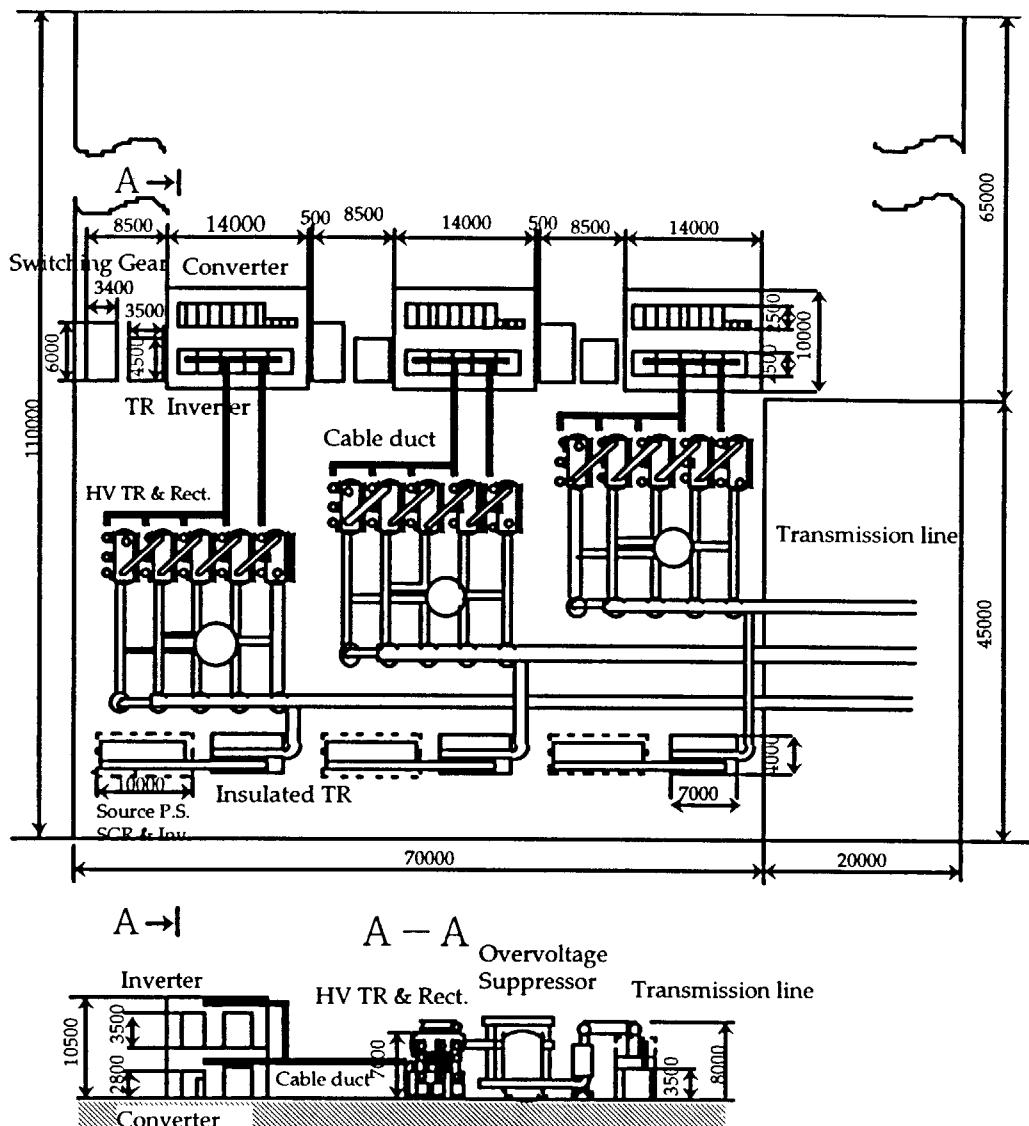


Fig. 2.5-1 Layout of the power supply system in the power supply yard.

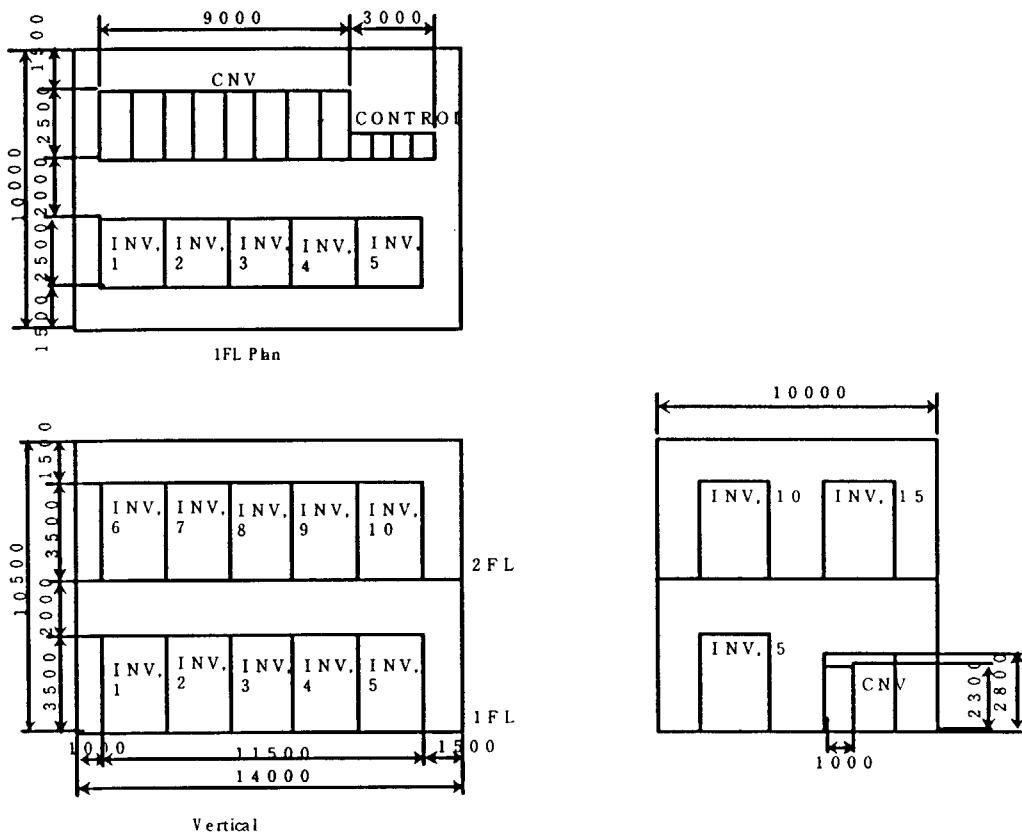


Fig. 2.5-2 Layout of the converter/inverter panels in the building.

### 3. Negative ion production power supplies

The negative ion production power supply system consists of a cathode power supply, an arc power supply, a bias power supply, a PG filter power supply, and an extraction power supply. These power supplies are electrically floated by the acceleration voltage of 1 MV to produce the negative ions on the 1 MV potential. The insulated transformer is utilized to supply the electric power to the source power supplies from the ground potential side. Detail design for the following components will be described in this chapter.

#### 3.1 Insulating transformer

Outline drawing of insulating transformers is shown in Fig.3.1-1. These transformers are installed in one big tank filled with insulation oil. Surge suppression reactor for each power supply winding is installed in the upper part of the tank. Output cables are connected to SF6 gas insulation duct through oil/gas bushing.

In this design study, laminated silicon steel plates are adopted for the transformer core. It is assumed that the frequency is 200Hz for this design. However, the core materials will be selected according to the frequency of the inverter system. Specifications of the insulating transformer are listed in Table 3.1-1.

**Table 3.1-1 Insulating transformer of negative ion production and extraction**

Term	Extraction	Arc	Filament	Bias	PG
Primary Voltage (V)	1000	1000	420	420	420
Secondary Voltage (V)	13000	1000	420	420	420
Primary Current (A)	1495	1030	412	69	165
Secondary Current (A)	115	1030	412	69	165
Capacity (kVA)	2600	1800	300	50	120
Frequency (Hz)	200	200	50	50	50
One turn Voltage (V)	102	85	21	10	13
Number of primary Winding	10	12	20	42	32
Number of secondary Winding	127	12	20	42	32
Area of core section (m <sup>2</sup> )	0.14	0.12	0.095	0.045	0.059
Diameter of core (m)	0.44	0.41	0.36	0.25	0.28
Height of coil (m)	1.2	1	0.8	0.6	0.7
Short circuit Impedance (%)	14.6	17.0	12.8	10.0	13.0

### 3.2 Arc and extraction power supplies.

Specifications of the source power supplies are listed in Table 3.2-1. Simulation studies using EMTDC code are concentrated on the arc power supply and the extraction power supplies. Because these power supplies require the functions of high speed control and input energy suppression to protect the ion source from the breakdowns at the extractor or arcing in the plasma generator.

Circuit diagrams of the filament, the arc, the bias, the PG filter and the extraction power supplies are shown in Fig. 3.2-1, 3.2-2, 3.2-3, 3.2-4 and 3.2-5, respectively.

The arc power supply and the extraction power supply requires high speed control to protect the ion source plasma generator and the extractor respectively. For the high speed control and to increase reliability of the power supplies, high frequency inverter systems are adopted to these power supplies. The inverter systems can control the output and switching at the grounded potential side as the same as the acceleration power supply.

An original 6 pulse converter is modified to a 12-pulse converter in order to reduce the ripple voltage of DC input voltage for the inverter. Further the DC voltage of

the converter is increased to 1000V from the original 400 V to allow the practical leakage inductance of inverter transformers. Then we selected the switching frequency of 1 kHz for the inverter.

At the original design, 12-pulse (two sets of three phase) inverter was designed. To reduce the ripple of the output with keeping the small DC filter capacitor, two sets of 12-pulse (three sets of single phase) inverters are introduced. By the EMTDC simulation, the following results shown in Table 3.2-1 are obtained. In this simulation, two feedback control systems for the converter and the inverter were utilized. Table 3.2-2 shows the simulation results for the extraction and the arc power supplies with the converter voltage feedback control and inverter voltage open loop control. Waveforms of the simulations are shown in Fig.3.2-6(1-3), 3.2-7(1-3), 3.2-8(1-3), 3.2-9(1-3). The number of the figure corresponds to the simulation is indicated in the above two tables.

Table 3.2-1 Results of the simulation. In case that converter voltage feedback control and inverter voltage feedback control are adopted.

	Extraction	Arc
Rating	DC 10kV 50 A	DC 120V 7kA
Ripple <sub>(p-p)</sub> :Spec.(%)	2	3
Ripple :Obtained (%)	1.15	1.67
Input Energy : Obtained (joules)*	13	7.6
Rise time Obtained	Less than 7ms	less than 7ms
Switching Frequency(Hz)	1k	1k
Result of waveforms	Fig.3.2-6(1,2,3)	Fig.3.2-7(1,2,3)

\*Note :The arcing voltage was assumed to be 10V for the plasma generator and to be 100 V for the extractor.

Table 3.2-2 Results of the simulation. In case that converter voltage feedback control with Inverter voltage open loop control are adopted.

	Extraction	Arc
Rating	DC 10kV 140A(50A)	DC 120V 7kA
Ripple <sub>(p-p)</sub> :Spec.(%)	2	3
Ripple :Obtained (%)	0.34	1.67
Input Energy : Obtained (joule)*	13	7.9
Rise time Obtained	Less than 4ms	Less than 4ms
Switching Frequency(Hz)	1k	1k
Result of waveforms	Fig.3.2-8(1,2,3)	Fig.3.2-9(1,2,3)

\*Note :The arcing voltage was assumed to be 10V for the plasma generator and to be 100 V for the extractor.

### 3.3 Layout in the HVD

A skeleton diagram of the source power supplies for negative ion production and extraction is shown in Fig. 3.3-1. A layout of the source power supplies in the HVD (High Voltage Deck) is shown in Fig 3.3-2. Dimension of the assembled power supplies is 3 m x 3 m x 5 m. Only transformers, rectifiers and filters for each power supply are mounted in the HVD. Protection resistors and filter reactors are cooled by water.

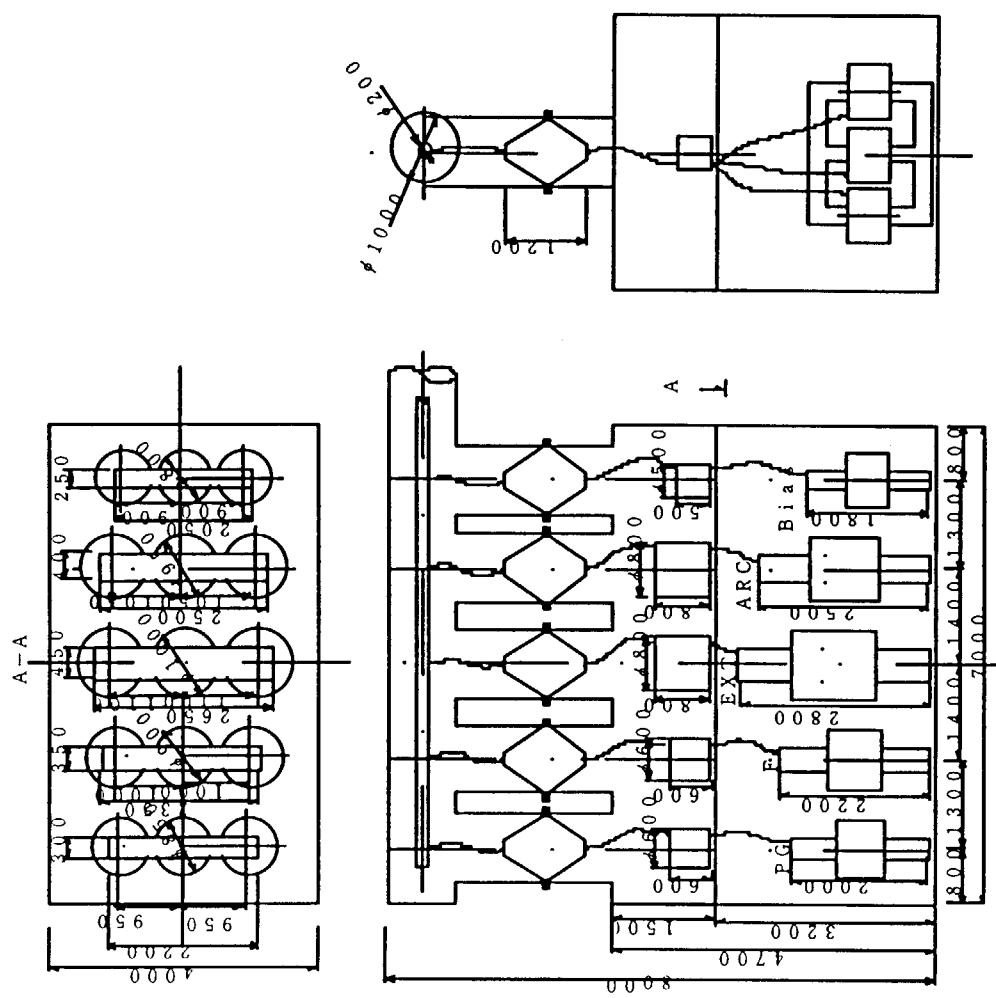


Fig. 3.1-1 Insulation transformer for the source power supplies.

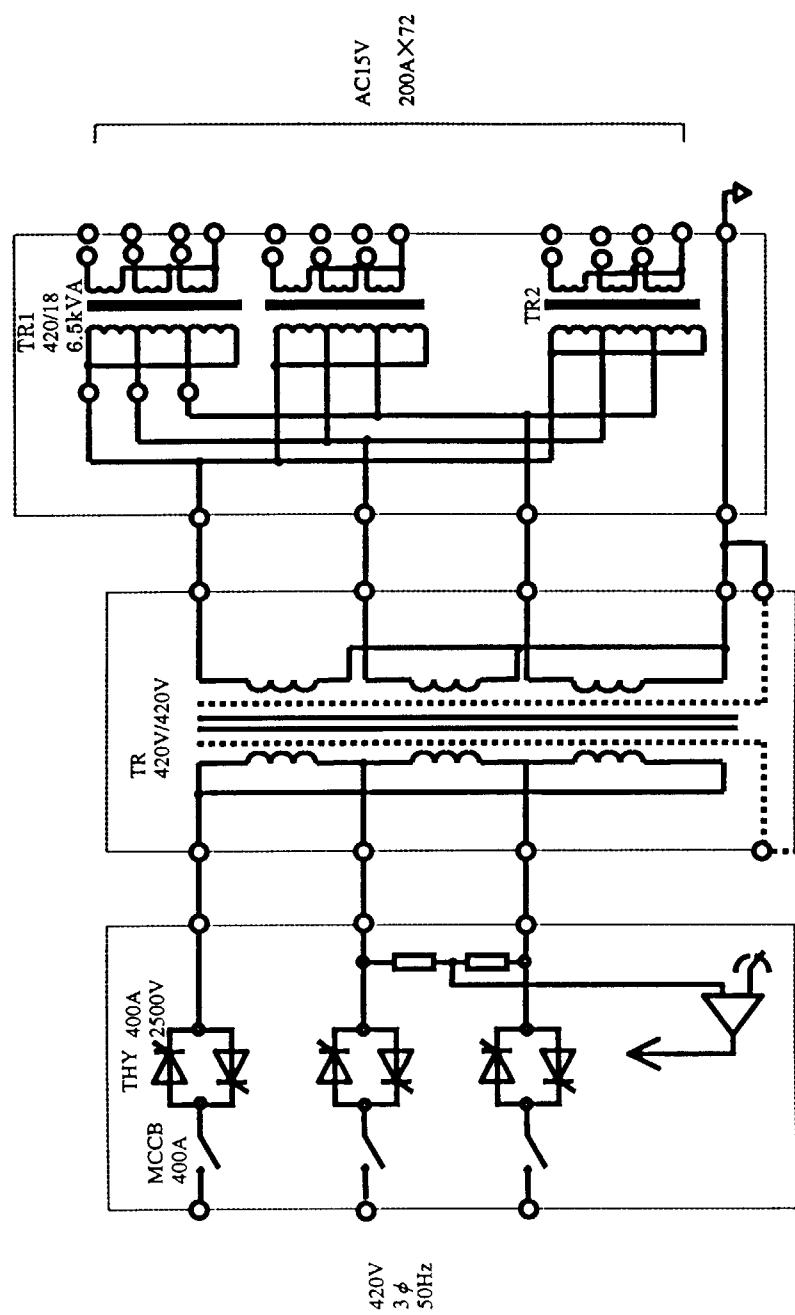


Fig.3.2.1 Circuit diagram of the filament power supply.

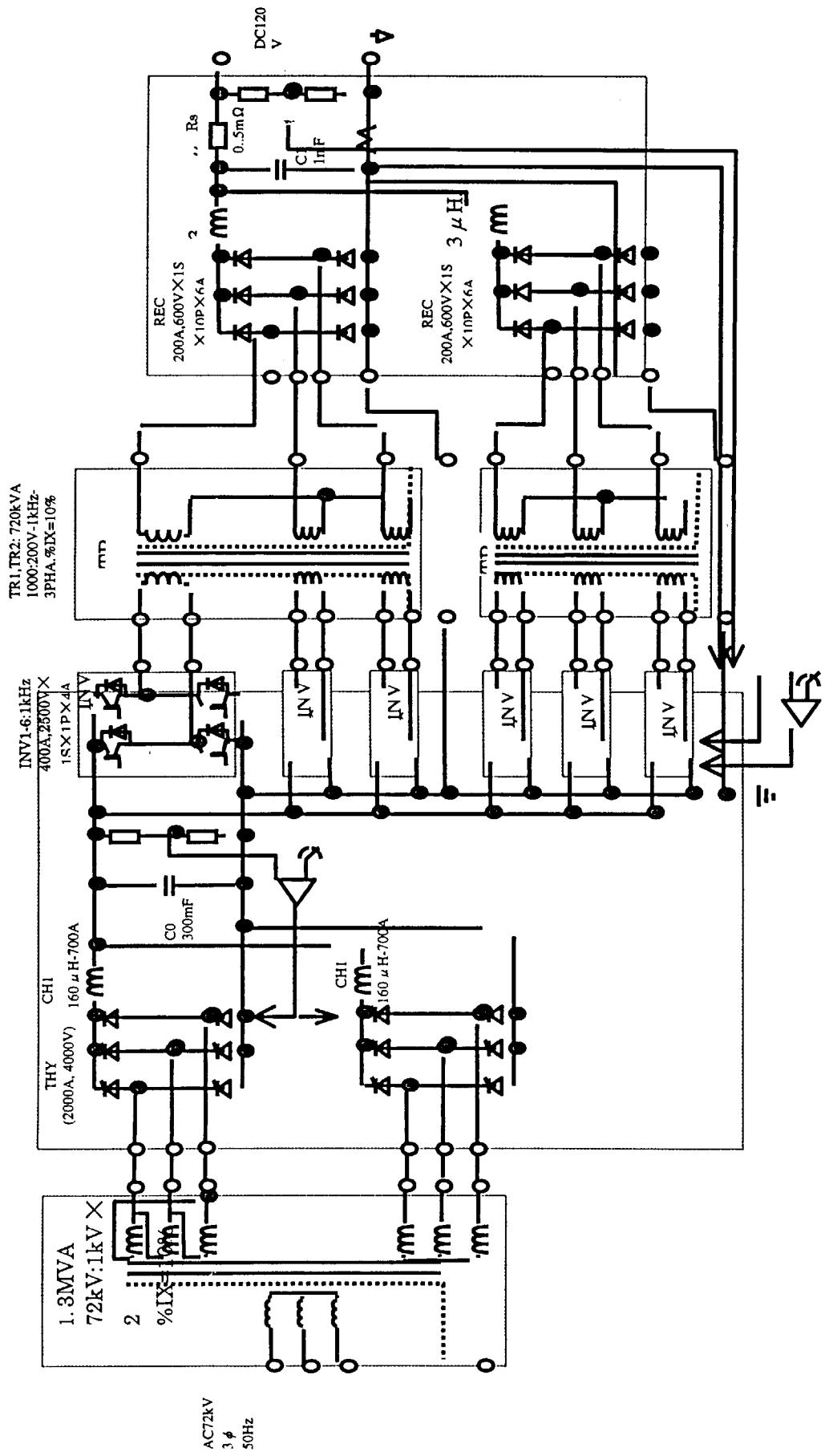


Fig. 3.2-2 circuit diagram of the arc power supply.

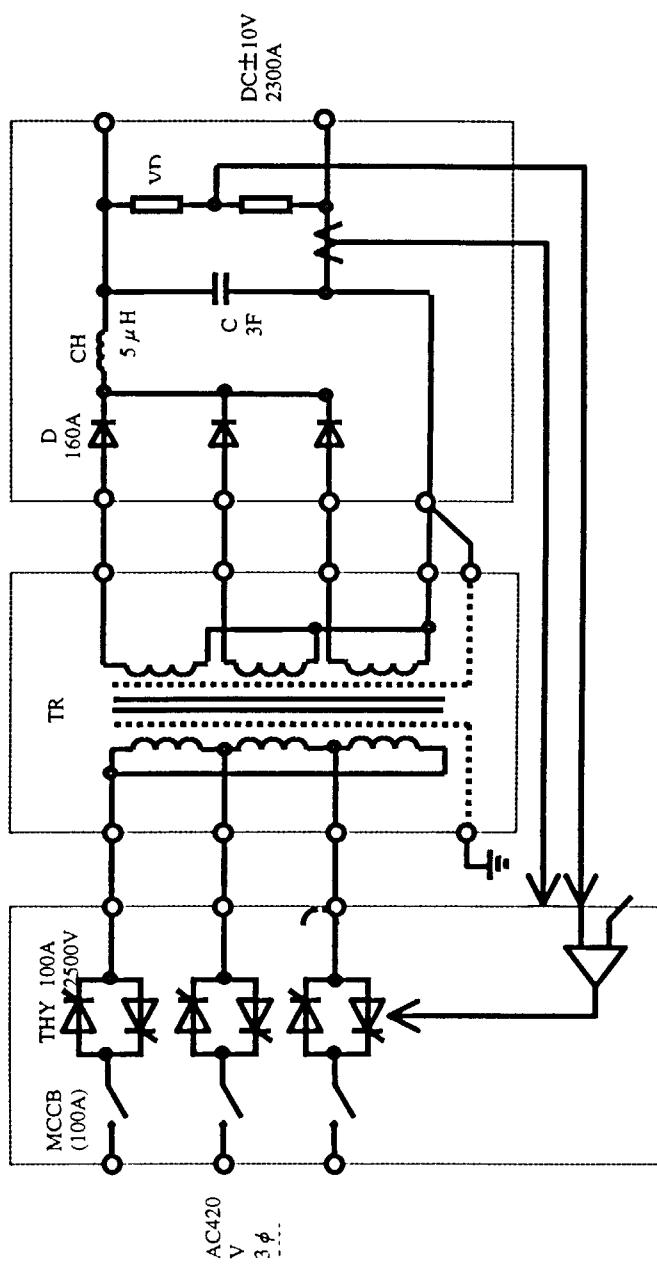


Fig. 3.2-3 Circuit diagram of the bias power supply.

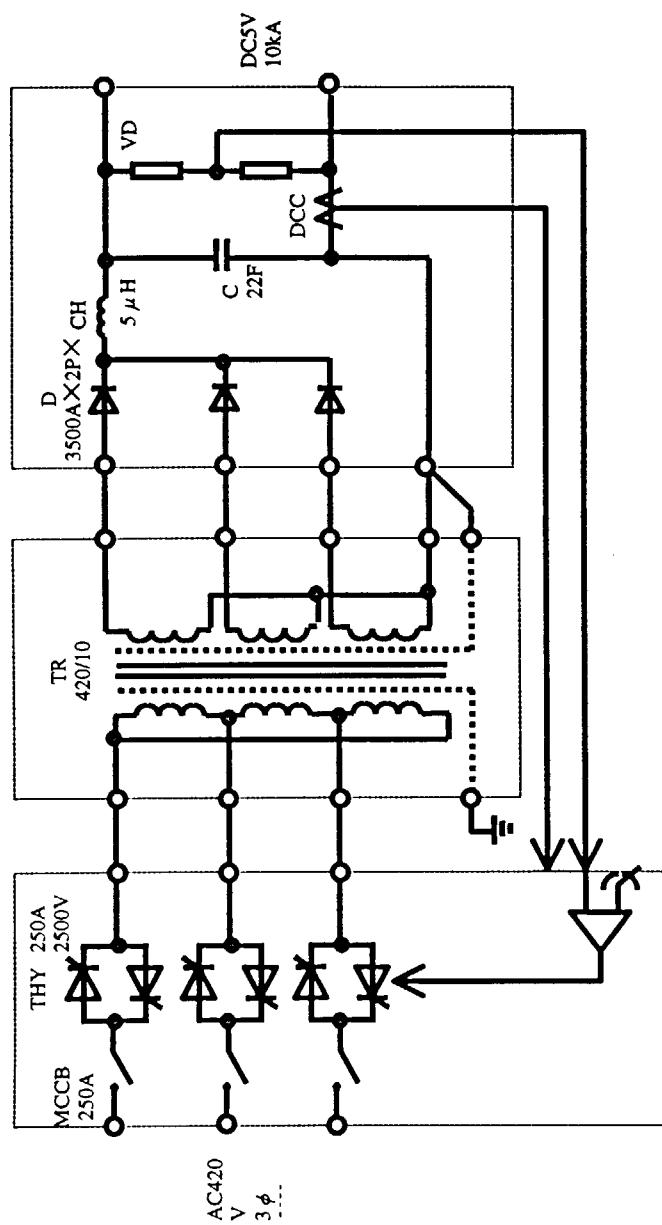


Fig. 3.2-4 Circuit diagram of the PG filter power supply.

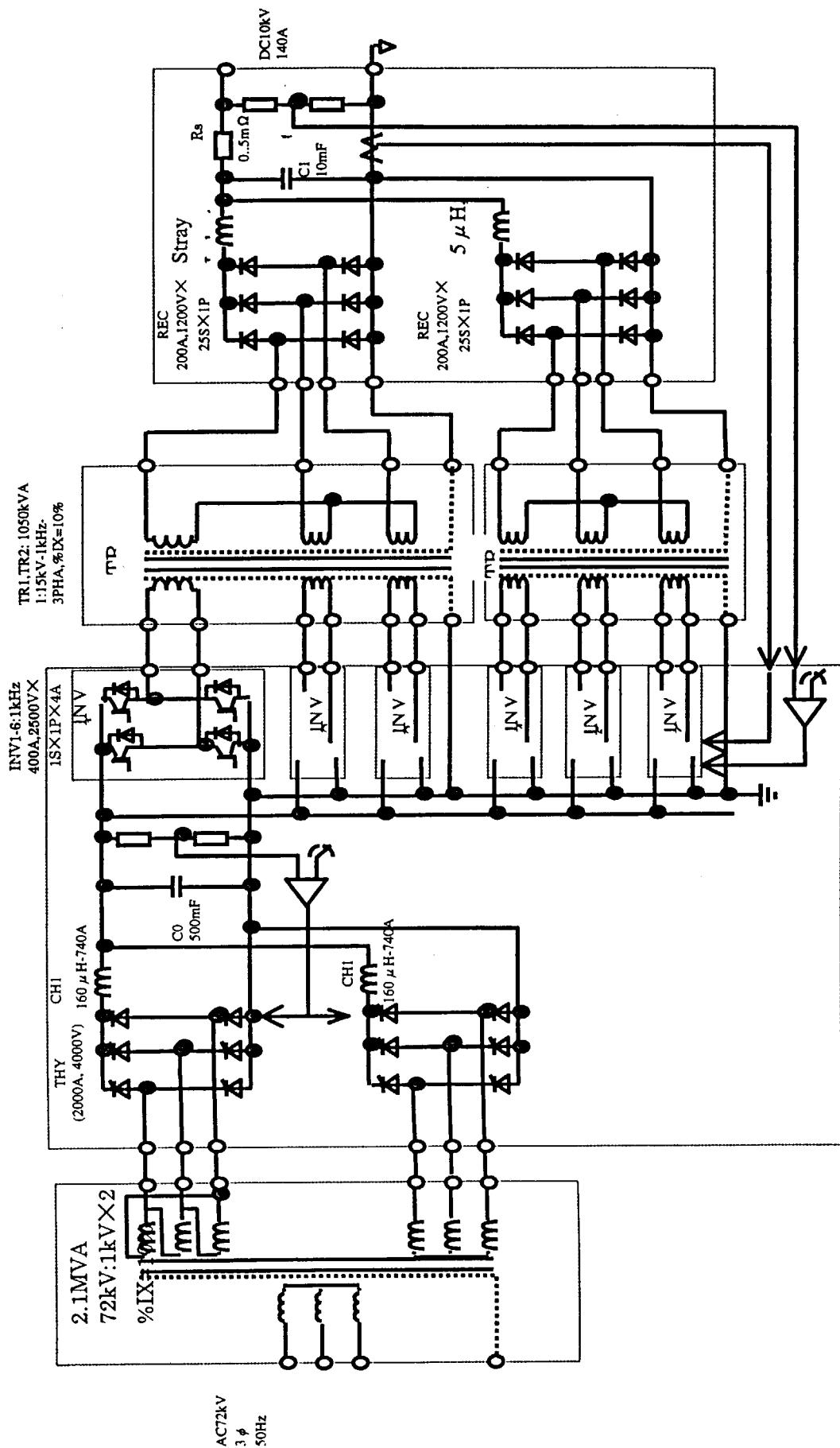


Fig. 3.2-5 Circuit diagram of the extraction power supply.

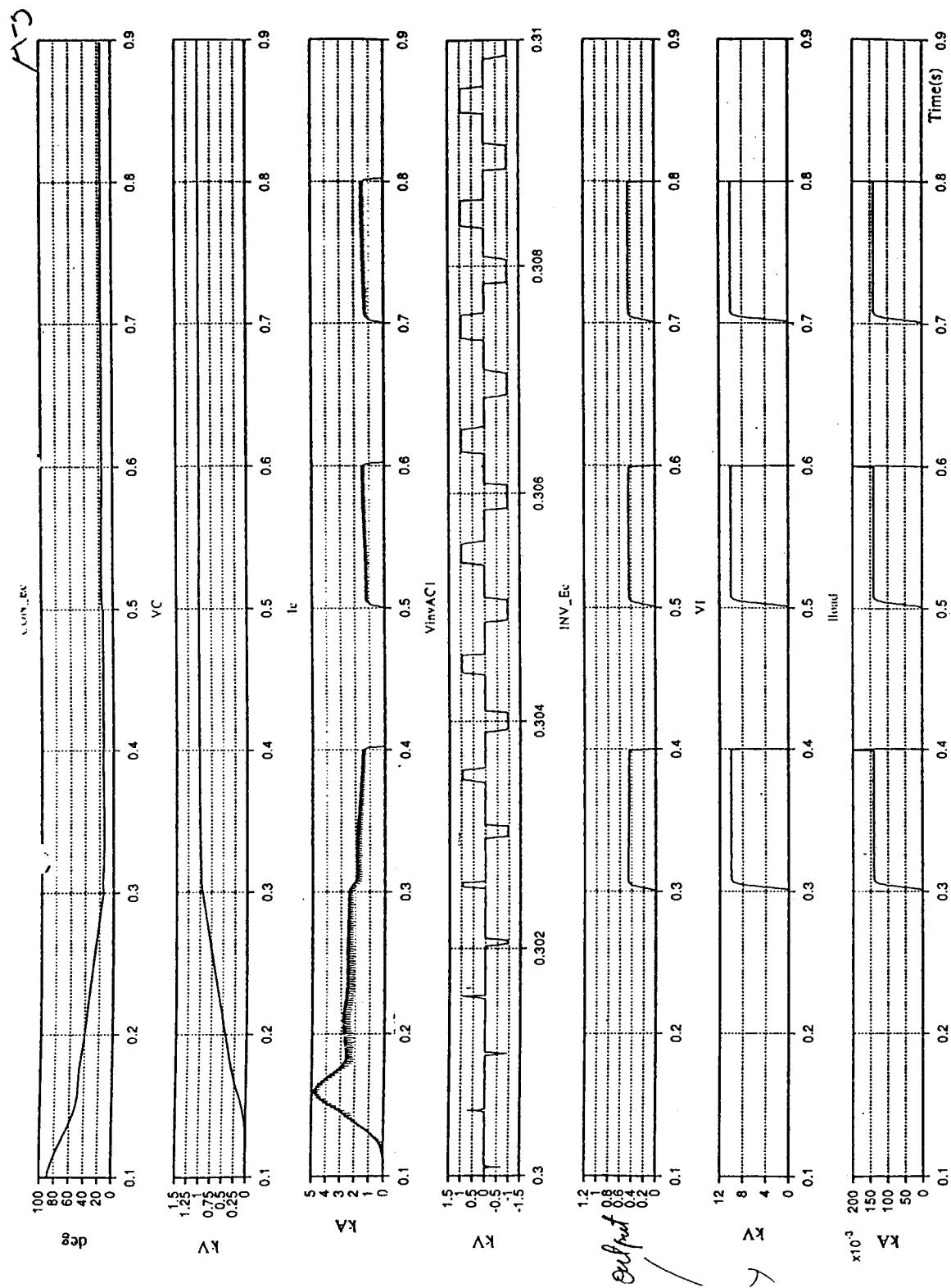


Fig. 3.2-6(1) Simulation result on the extraction power supply.

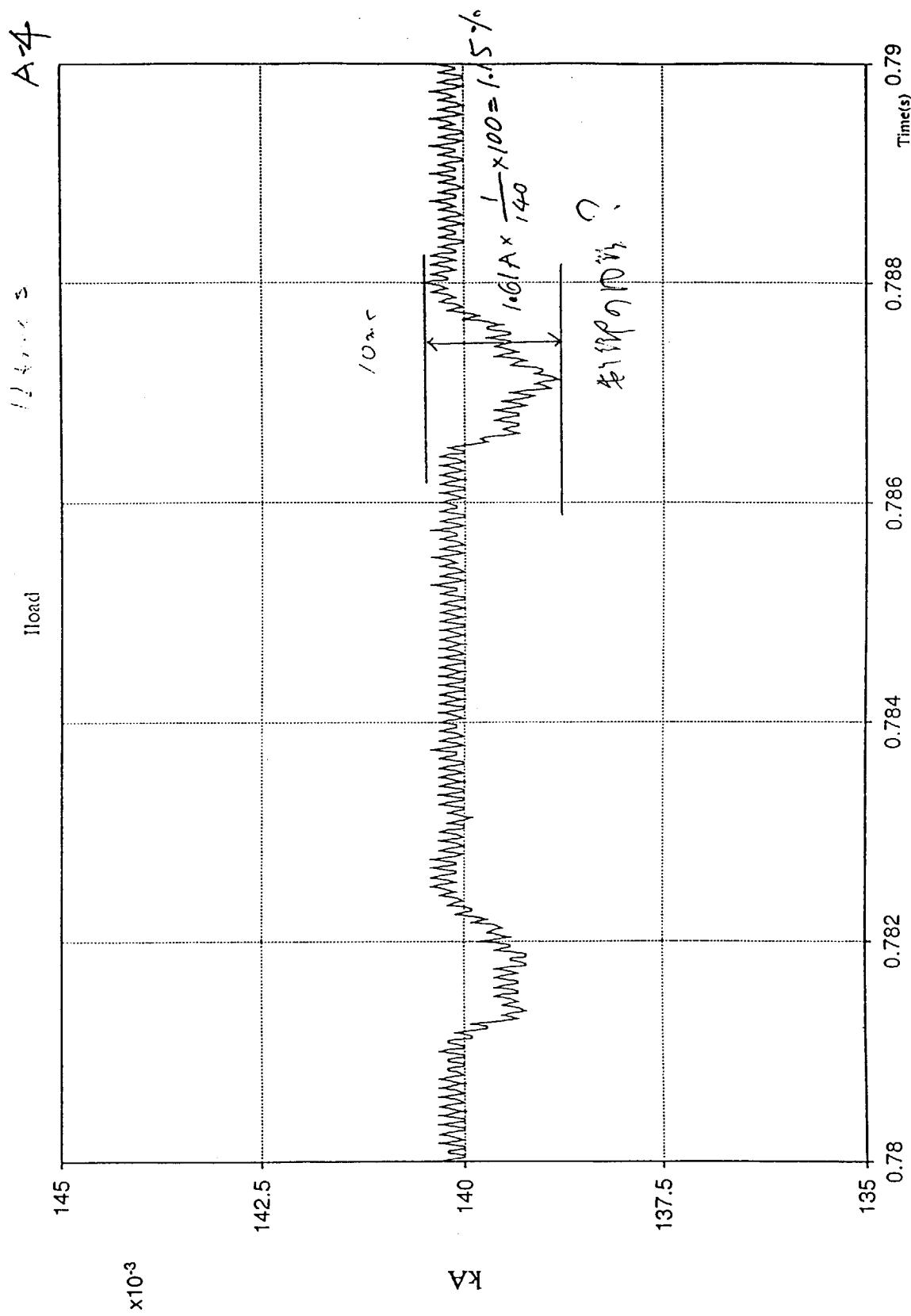
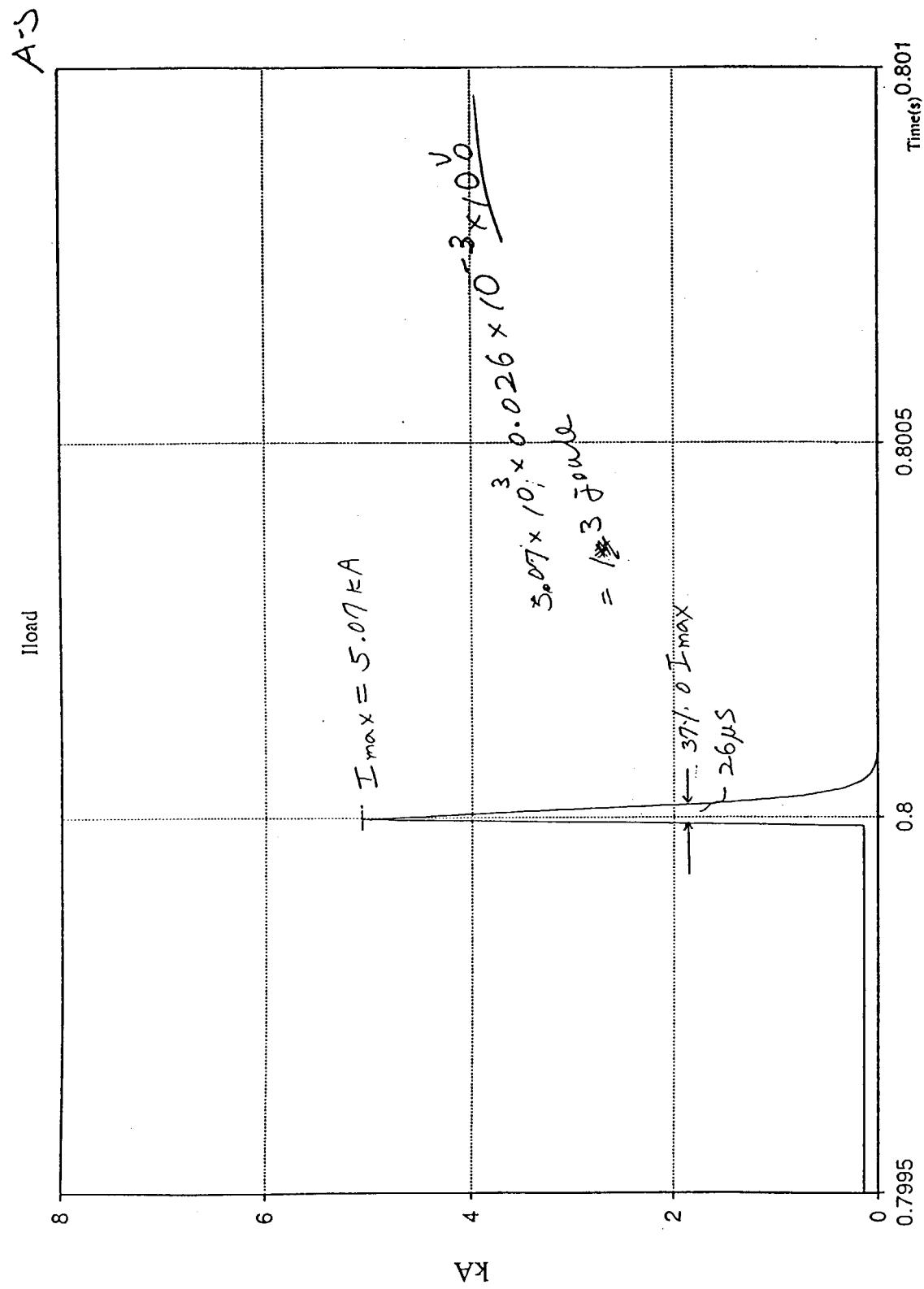


Fig. 3.2-6(2) Simulation result on the extraction power supply.



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Fig. 3.2-6(3) Simulation result on the extraction power supply.

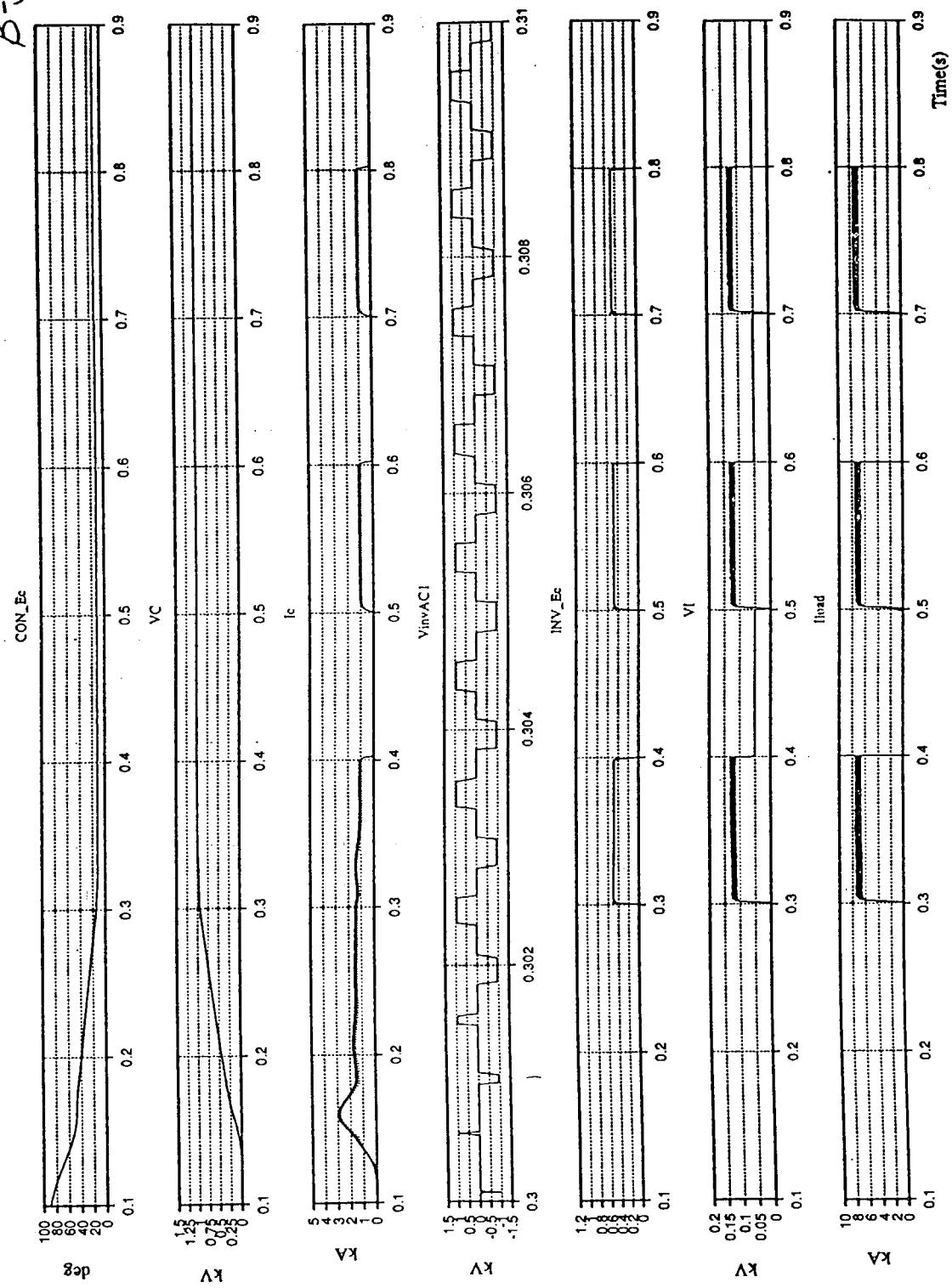
$\beta-3$ 

Fig. 3.2-7(1) Simulation result on the arc power supply.

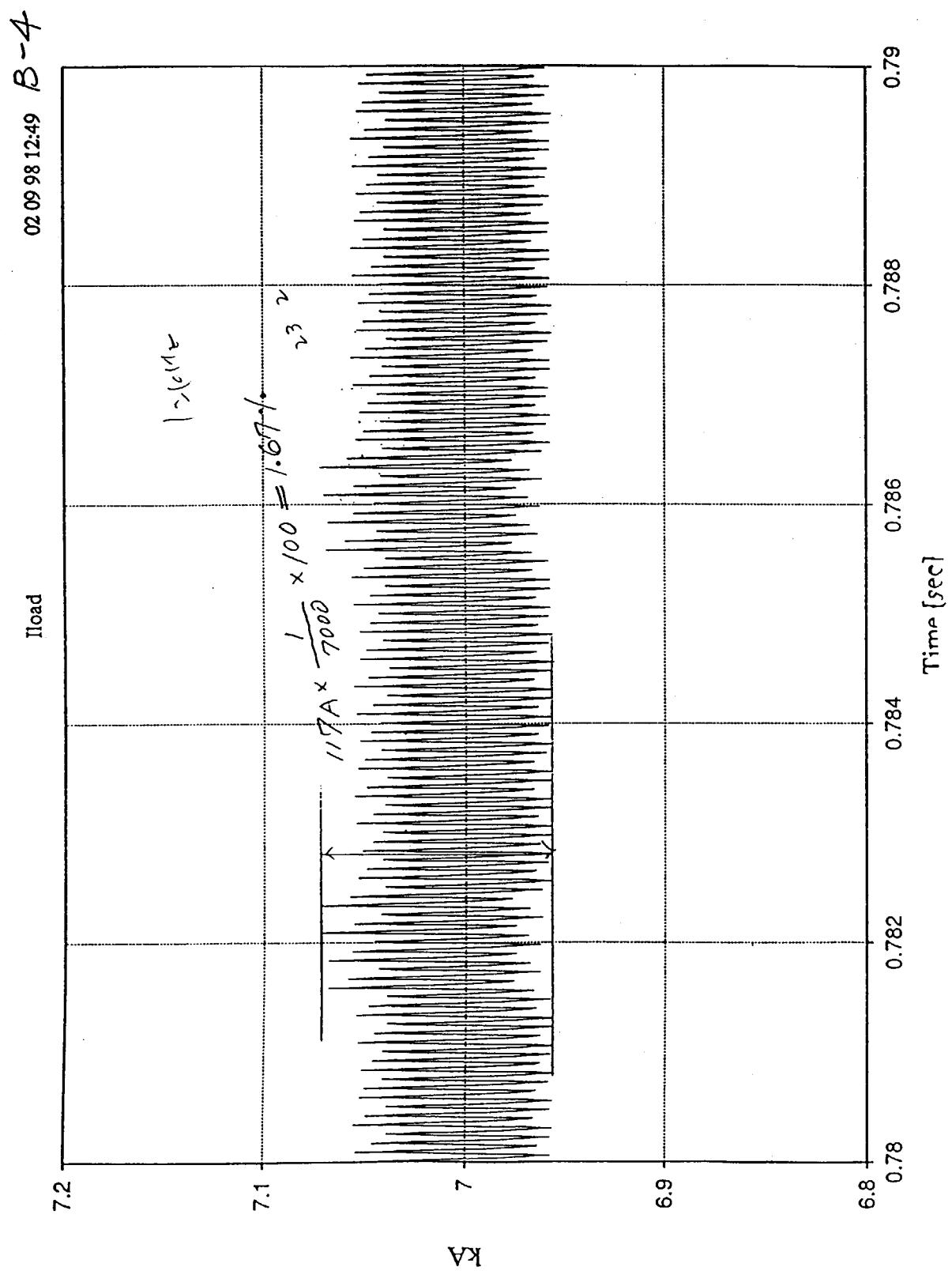


Fig. 3.2-7(2) Simulation result on the arc power supply

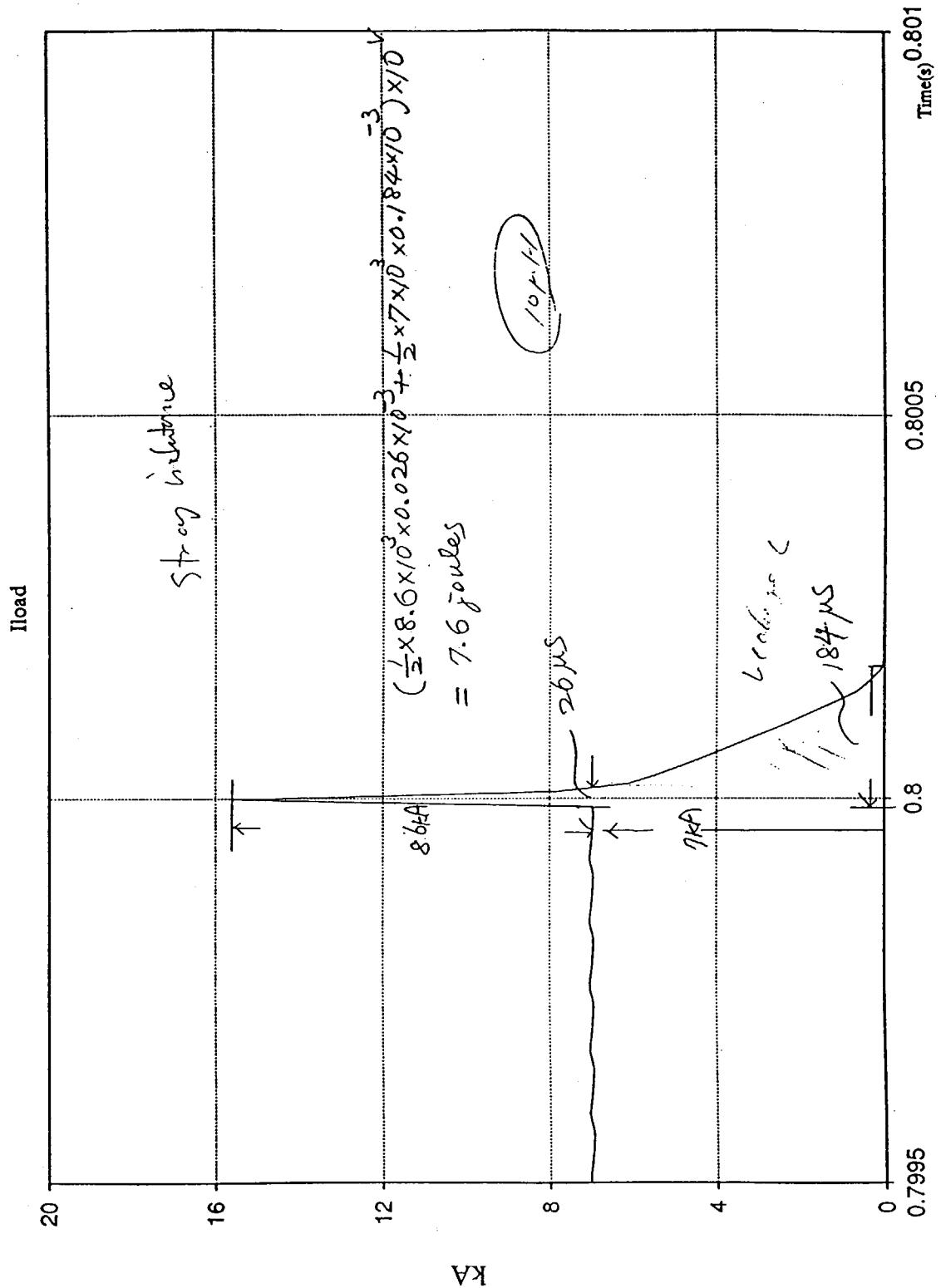


Fig. 3.2-7(3) Simulation result on the arc power supply

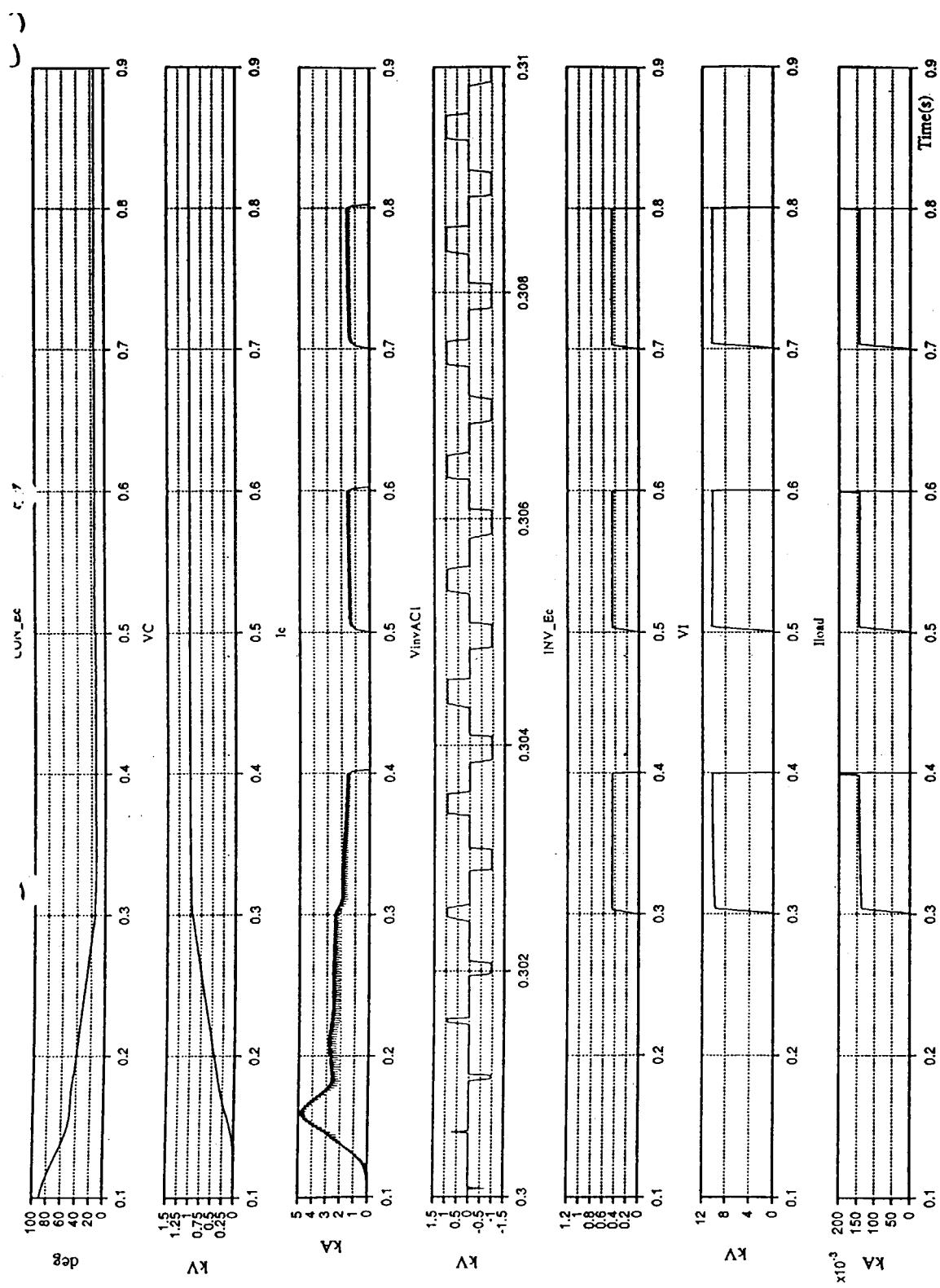


Fig. 3.2-8(1) Simulation result on the extraction power supply

C-4

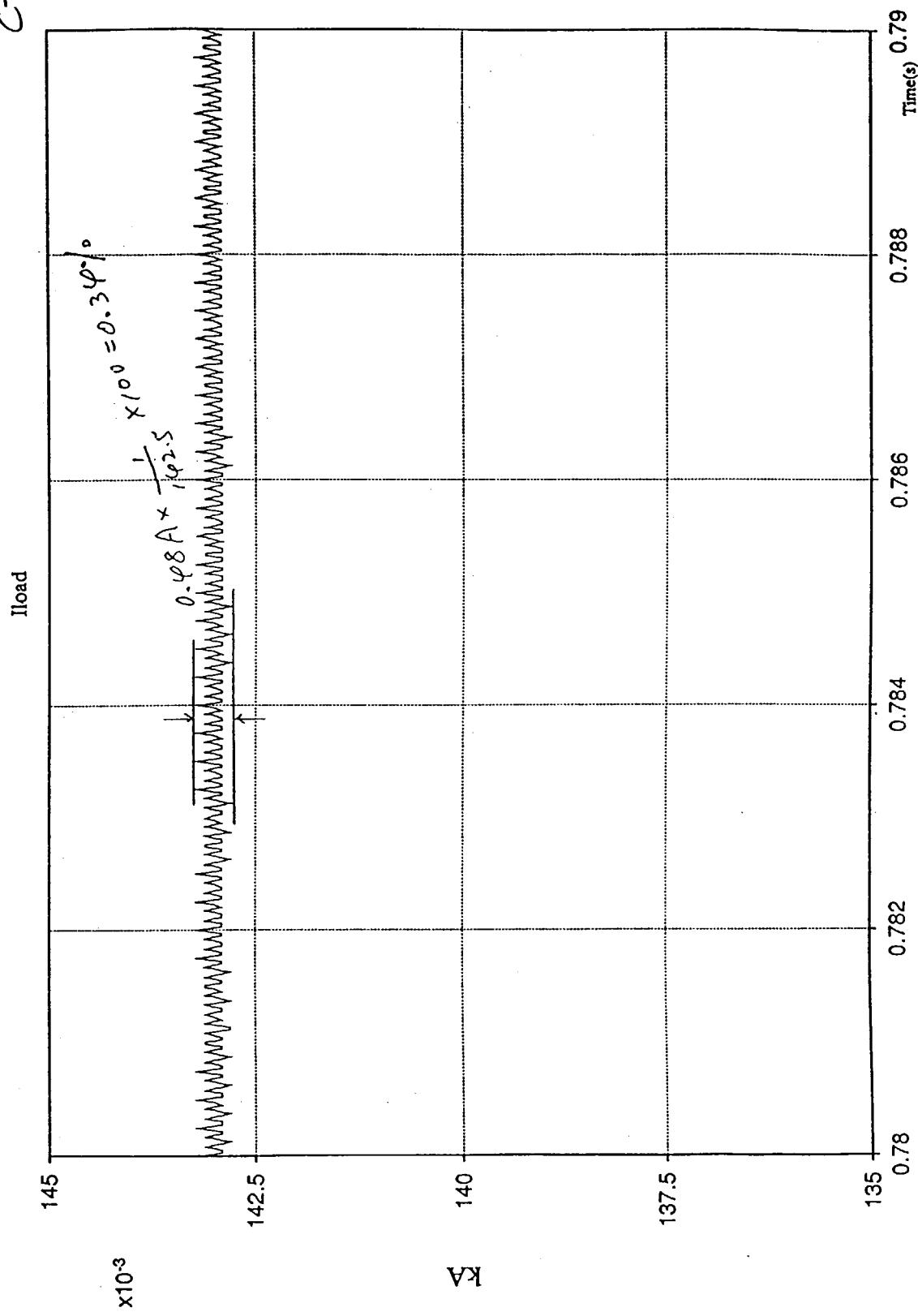


Fig. 3.2-8(2) Simulation result on the extraction power supply.

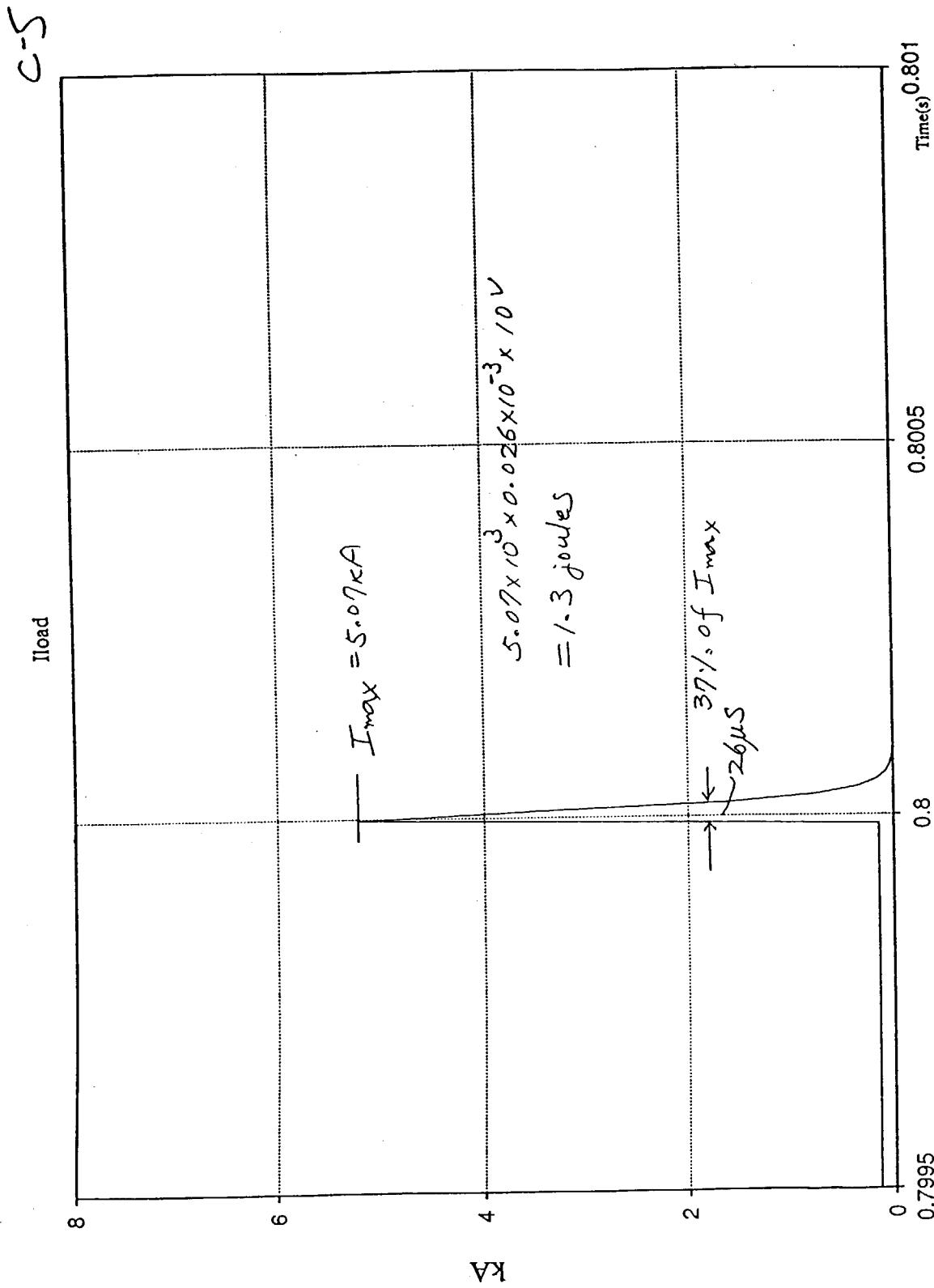


Fig. 3.2-8(3) Simulation result on the extraction power supply.

Ext Power Supply Rev. 03

D3

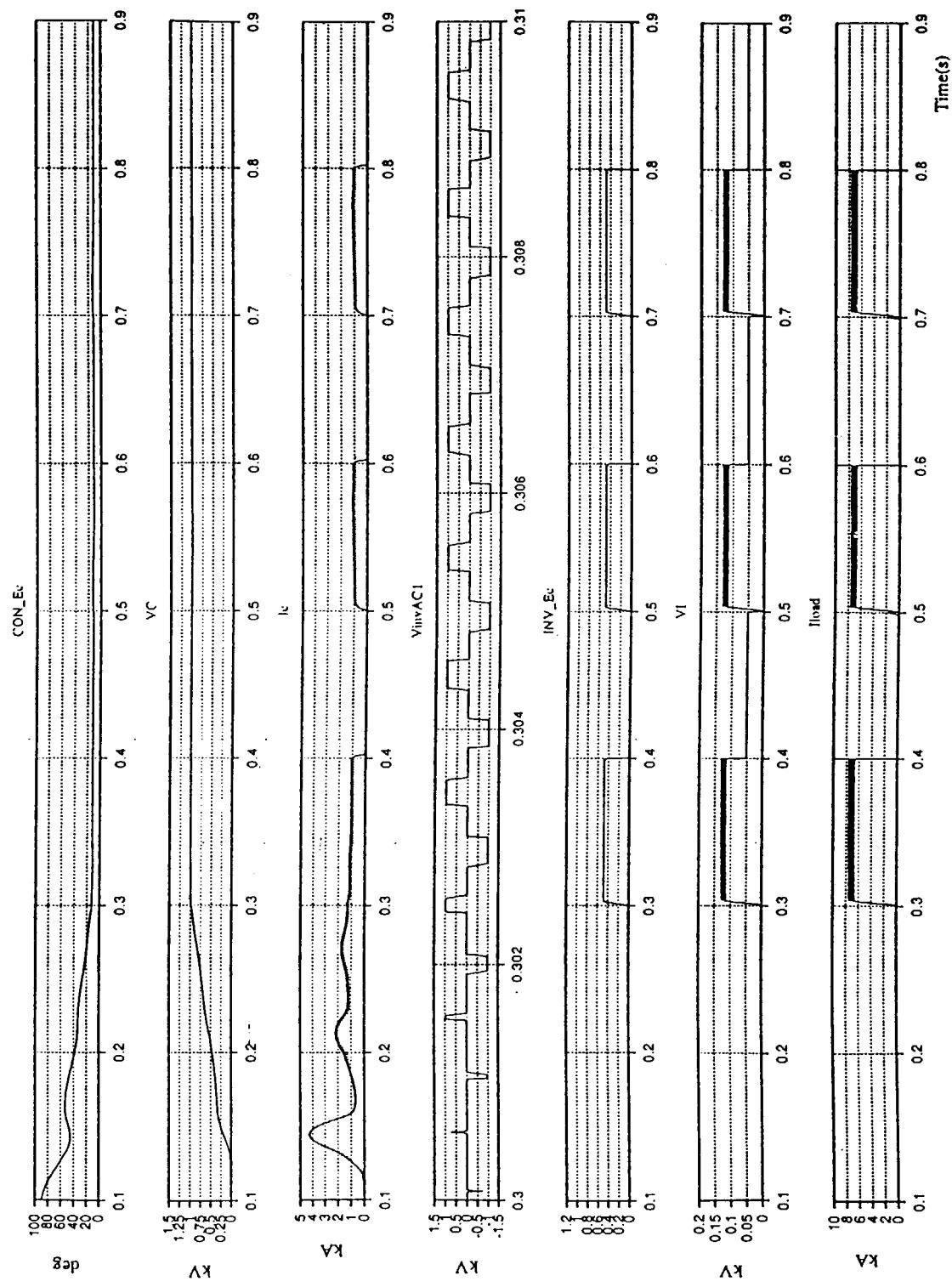


Fig. 3.2-9(1) Simulation result on the arc power supply.

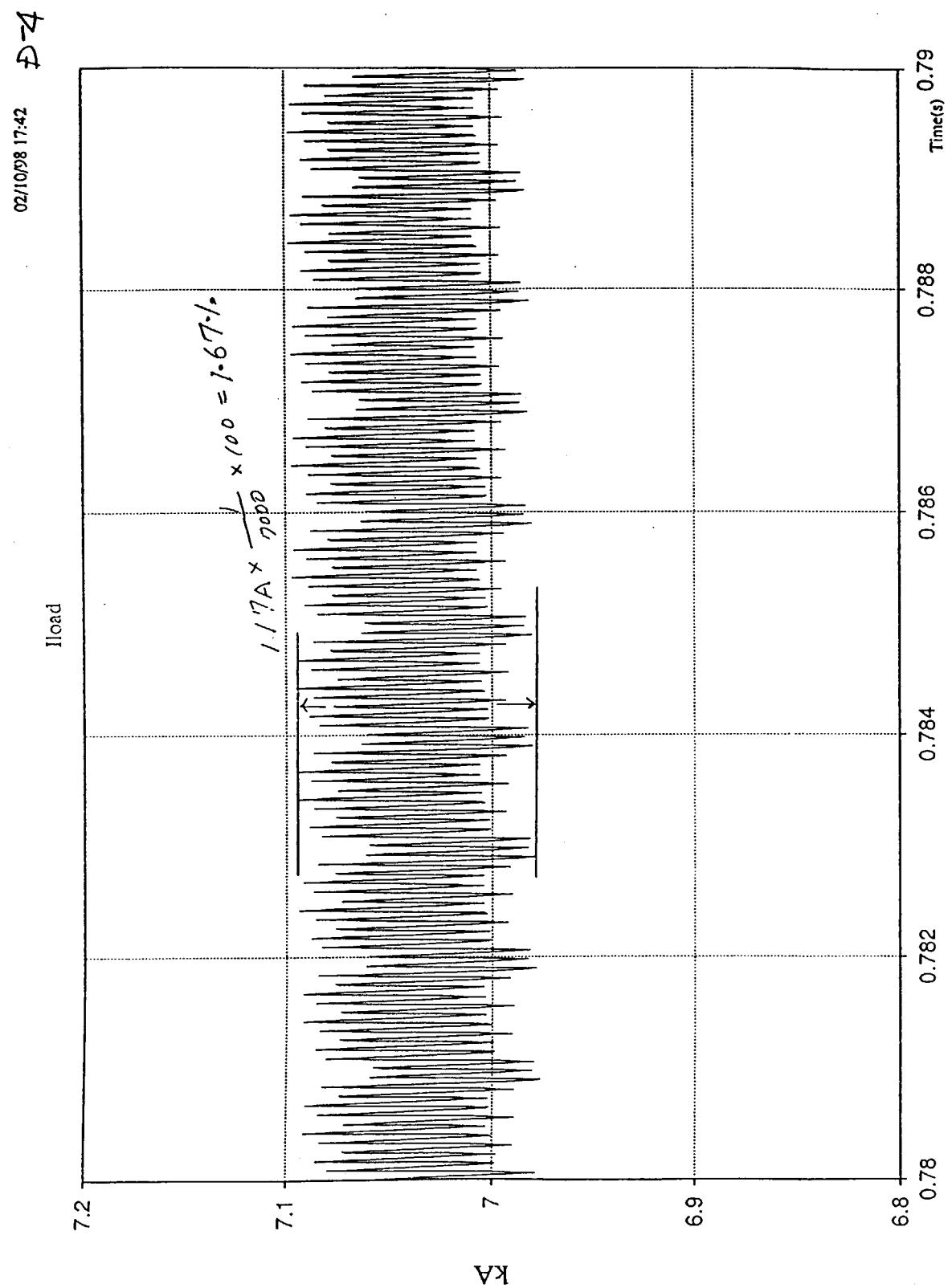
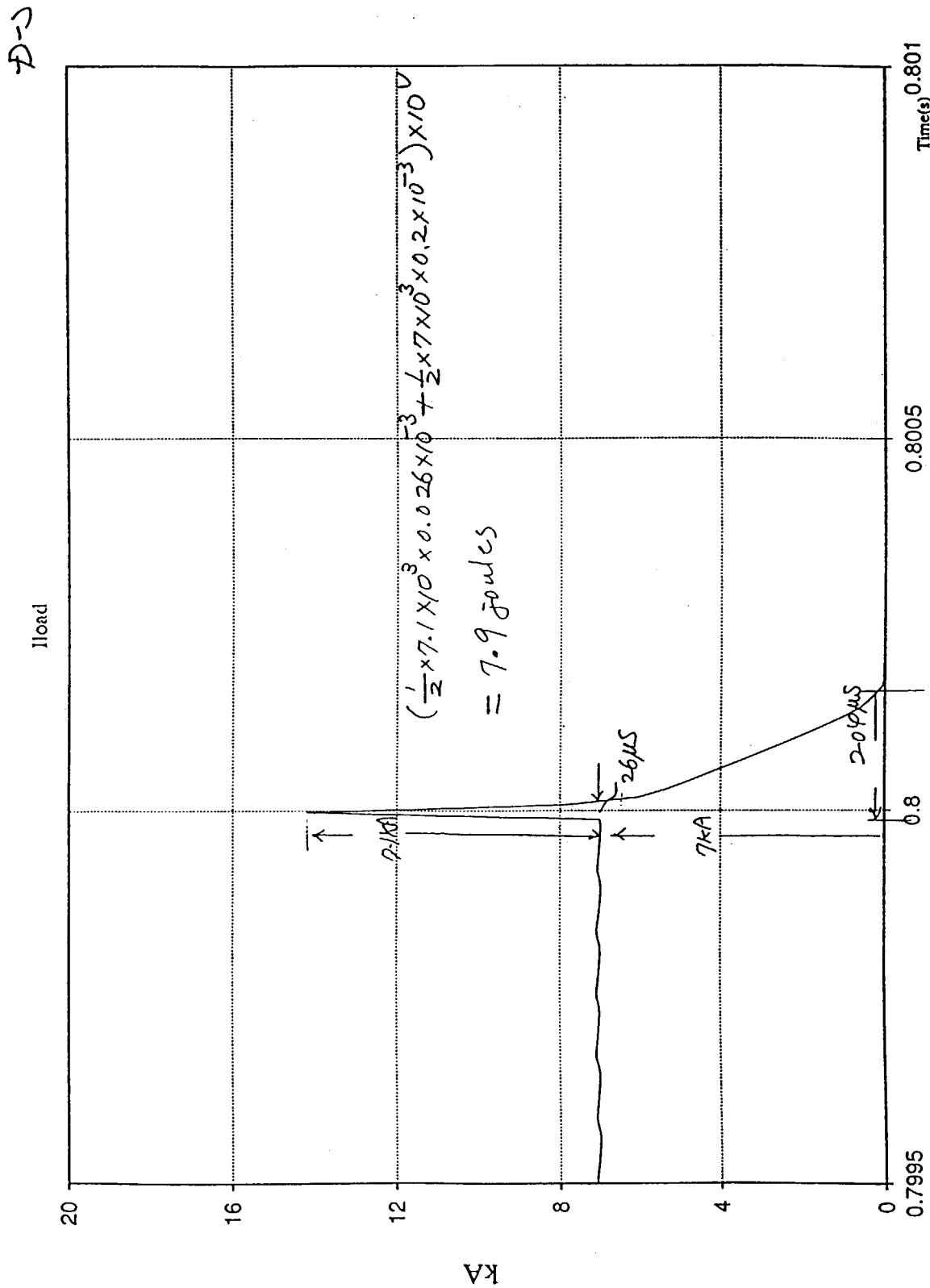


Fig. 3.2-9(2) Simulation result on the arc power supply.



Arc Power Supply Rev.3a

Fig. 3.2-9(3) Simulation result on the arc power supply.

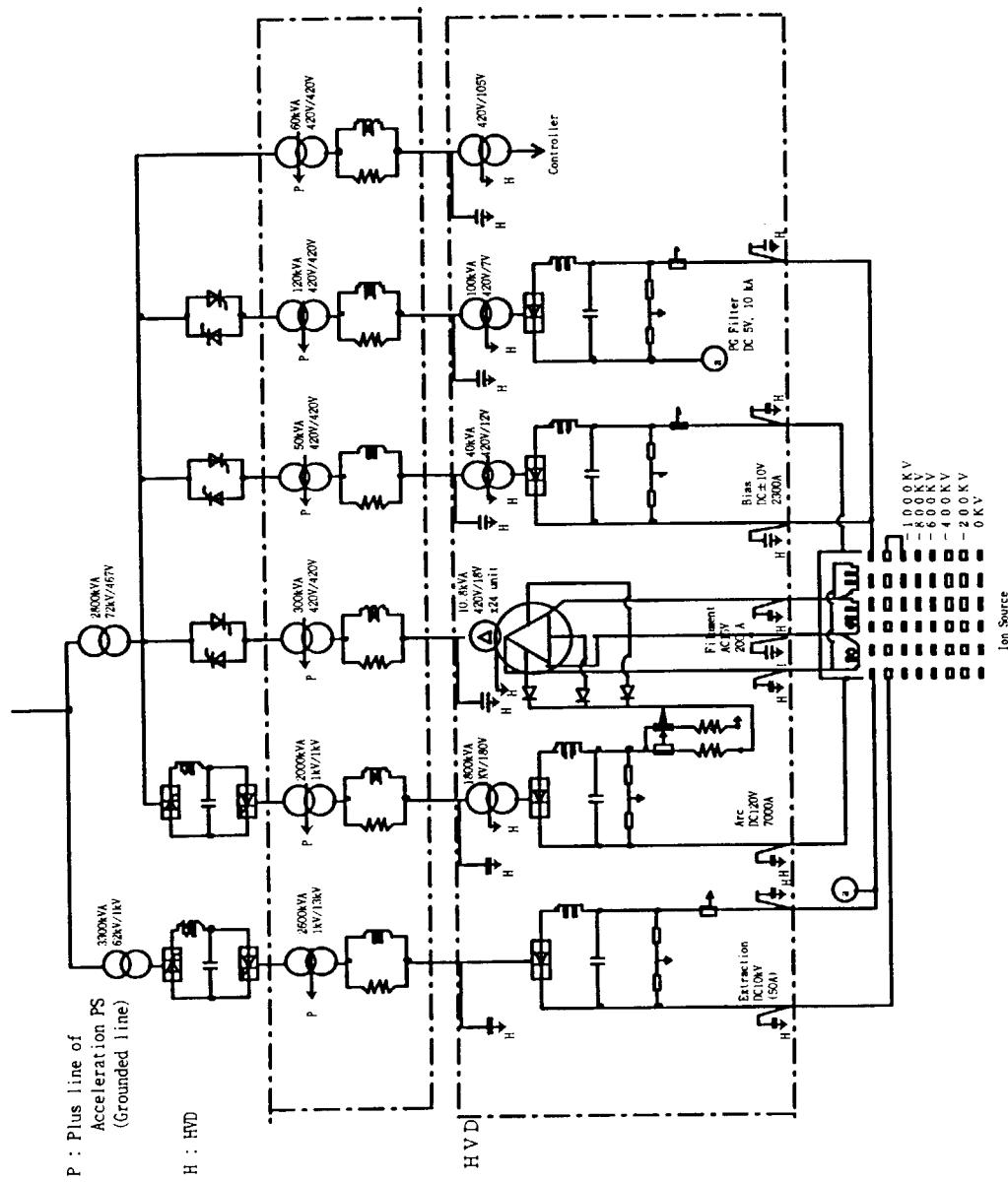


Fig. 3.3-1 Skeleton diagram of the source power supplies.

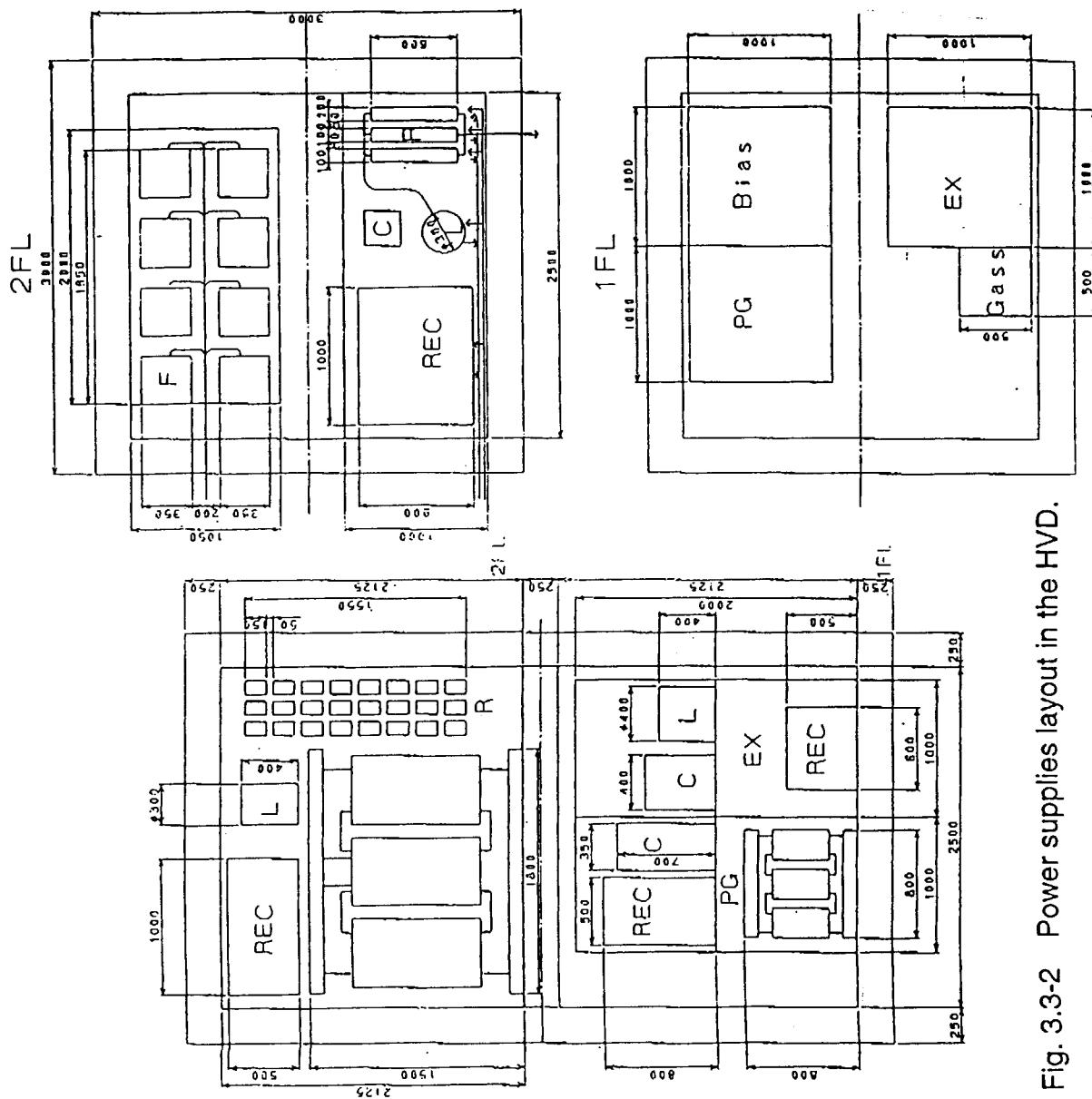


Fig. 3.3-2 Power supplies layout in the HVD.

#### 4. Transmission Line

The transmission line (Transmission line I) between HVD and insulated transformer in the power supply yard are designed. Cross sectional view of the transmission line is shown in Fig. 4.1. A 1 MV conductor has AC cables for the source power supplies on the HVD. Metal tubes are installed in the transmission line as the intermediate potential conductors. These conductors are supported and insulated with epoxy insulators.

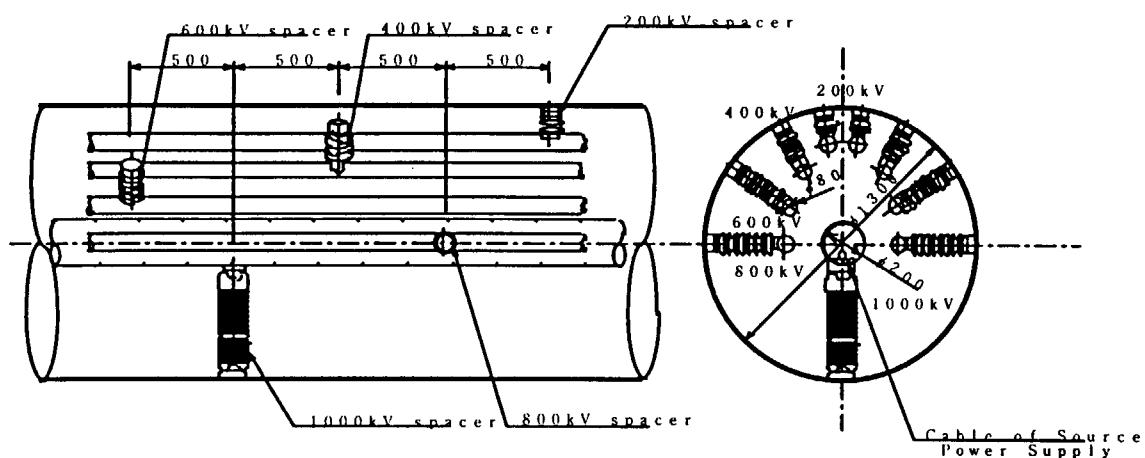


Fig.4.1 Transmission line I.

## 5. Ground level power supplies and auxiliary services

### 5.1 Ground level power supplies

The magnetic field reduction system for the beam line is designed in the NB design task of N53TD18FJ. Required capacities of the coils are presently 220 kAT for two coils and 510 kAT for one coil. Required power supplies for the magnetic coils are about 1000V, 1800 A and 1200 V, 1800 A, respectively. Table 5.1 shows the specifications of the power supplies for the magnetic reduction system.

Table 5.1 Specifications of the coil power supplies.

Magnetic coil	DC output	Transformer	Rectifier	Dimensions
220 kATx2	1000 V, 1800 A	3000 kVA	Thyristor	1mx1mx2m
510 kAT	1200 V, 1800 A	3600 kVA	Thyristor	1.2mx1.2mx2m

Power supplies for the beam steering system is also built at the ground potential. Low voltage DC power supplies correspond to the steering electrodes are utilized. All beamline power supplies are built at ground potential. Therefore, there is no special difficulty.

### 5.2 SF6 storage system

Transmission lines and HVD are insulated with pressurized SF6 gas. The storage system for SF6 gas is designed. A required volume of SF6 gas for the NB system is estimated as follows;

Transmission line I x 3 modules

$$(\pi/4) \times 1.3^2 \times 100 \text{ m} \times 4.5 \text{ bar} \times 3 = 1800 \text{ Nm}^3$$

Transmission line II x 3 modules

$$(\pi/4) \times 1.8^2 \times 10 \text{ m} \times 10 \text{ bar} \times 3 = 763 \text{ Nm}^3$$

here, the average pressure of 10 bar is assumed.

HVD for 3 modules

$$(\pi/4) \times 5^2 \times 7 \text{ m} \times 4.5 \text{ bar} \times 3 = 1855 \text{ Nm}^3$$

Total gas of 4418 Nm<sup>3</sup> is required for the three modules.

Dimension of the storage tank for one module is estimated from the SF6 volume. Stored pressure of the gas is assumed to be 10 bar. A volume of 1473 Nm<sup>3</sup> can be stored in the tank whose volume is 80 m<sup>3</sup> × 2 sets. The size of the tank is 3.5 m in diameter and 10 m in height.

At the maintenance for the HVD and transmission lines, SF6 gas is recovered to the storage tanks and the air is introduced. After the maintenance, the line is evacuated and SF6 gas is introduced up to the pressure.

## 6. Control system

A block diagram of the control system for the NB injection power supplies are shown in Fig. 6.1. The NB power supplies are controlled by a NB control system. A high speed interlock system is required to stop the beam injection to the tokamak for protection of first wall. The CODAC system gives the control signals to the NB control system for permission of the operation. Table 6.1 and Table 6.2 show the list of the control signals in the NB power supply system.

Operation mode of the NB system is investigated. Conditioning of the ion source accelerator will be performed at the conditioning mode. Beam injection into the tokamak is done at the injection mode. These operation modes are described in Fig. 6.2. Typical time sequences for each mode are illustrated in Fig. 6.3, 6.4, 6.5. and 6.6.

Table 6.1 Measurements and control signals in the power supply system.

		Measurement	Measurement	Control
Source PS				
	Filament	Voltage	Current	ON/OFF
	Arc	Voltage	Current	ON/OFF
	Bias	Voltage	Current	ON/OFF
	PG filter	Voltage	Current	ON/OFF
	Extraction	Voltage	Current	ON/OFF
	D2 Gas feeding	Pressure		ON/OFF
		Flow rate		Flow rate
	Cs oven	Temperature		Heater ON/OFF
				Valve ON/OFF
Acc. PS				
	Converter	Voltage	Current	ON/OFF
	Inverter	Voltage	Current	ON/OFF
	1MV	Voltage	Current	
	800 kV	Voltage	Current	
	600 kV	Voltage	Current	
	400 kV	Voltage	Current	
	200 kV	Voltage	Current	
	Ground Switch			CLOSE/OP EN
Beamline PS				
	Magnetic coil	Voltage	Current	ON/OFF
	Beam Steering	Voltage	Current	ON/OFF
	Beam Separator	Voltage	Current	ON/OFF
Ion Source				
	Pressure	Source Pressure		
	Temperature	Plasma Grid		
		Water IN/OUT		

Table 6.2 Control signals for safety operation.

	Position/Part	Action	Beam
Water Flow			
	PS. Beamline	All PS OFF	STOP
Pressure			
	Ion source	All PS OFF	STOP
	Neutralizer	Arc Ext Acc CUT OFF	STOP
	Tokamak	Arc Ext Acc CUT OFF	STOP
Temperature			
	Accelarator	Arc Ext Acc CUT OFF	STOP
	Neutralizer	Arc Ext Acc CUT OFF	STOP
	Ion Dump	Arc Ext Acc CUT OFF	STOP
	Calorimeter	Arc Ext Acc CUT OFF	STOP
	Port	Arc Ext Acc CUT OFF	STOP
	Opposite Wall	Arc Ext Acc CUT OFF	STOP
Magnetic field			
	Beamline	Arc Ext Acc CUT OFF	STOP

## Block Diagram of Control System

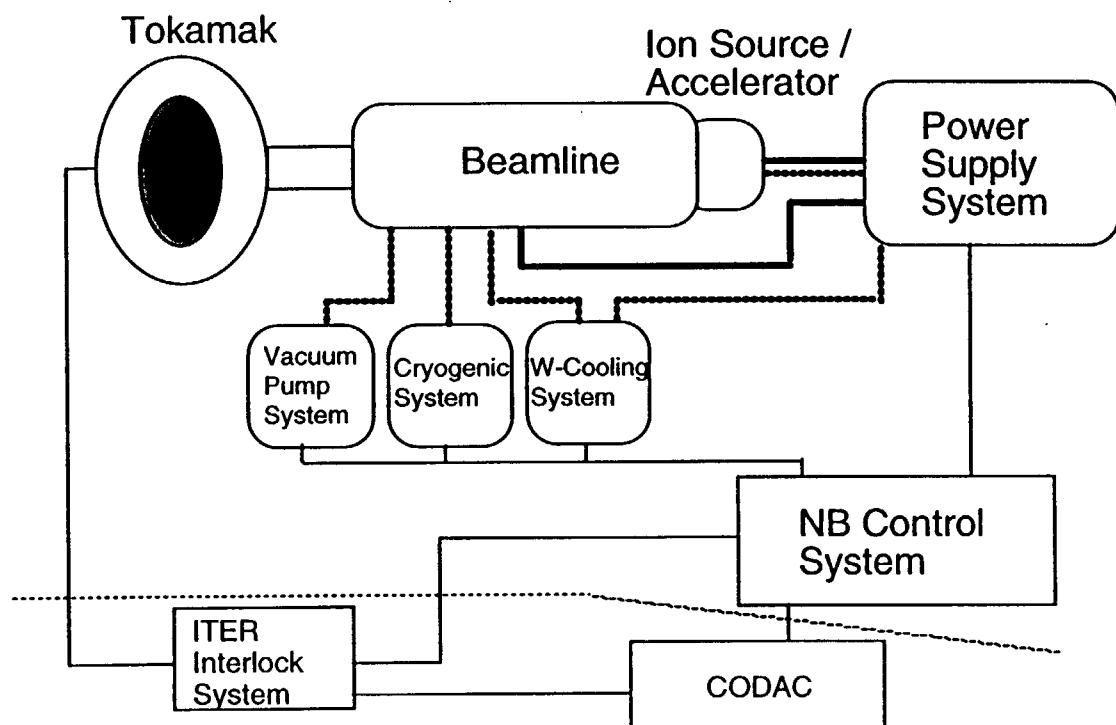


Fig. 6.1 Block diagram of the control system for the NB power supply.

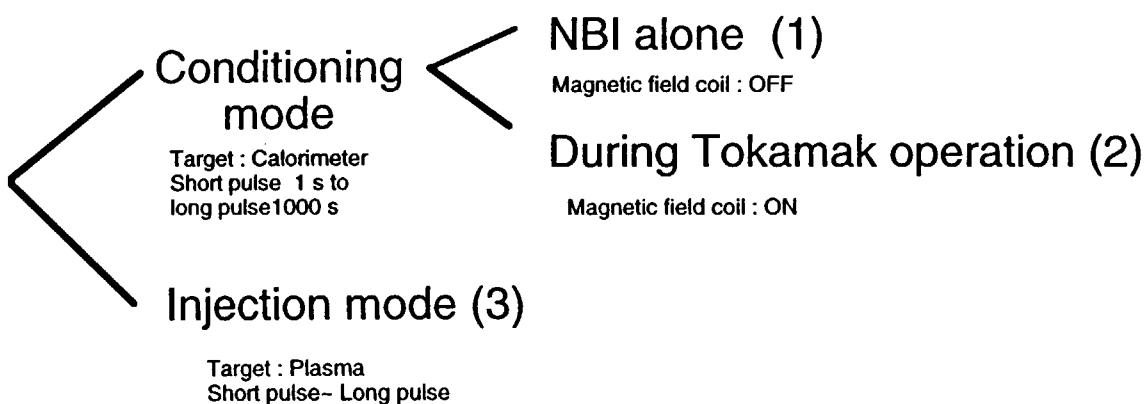


Fig. 6.2 Operation mode of the NB system.

## Time sequence of the ITER NBI Power Supply System Conditioning Mode (1), (2)

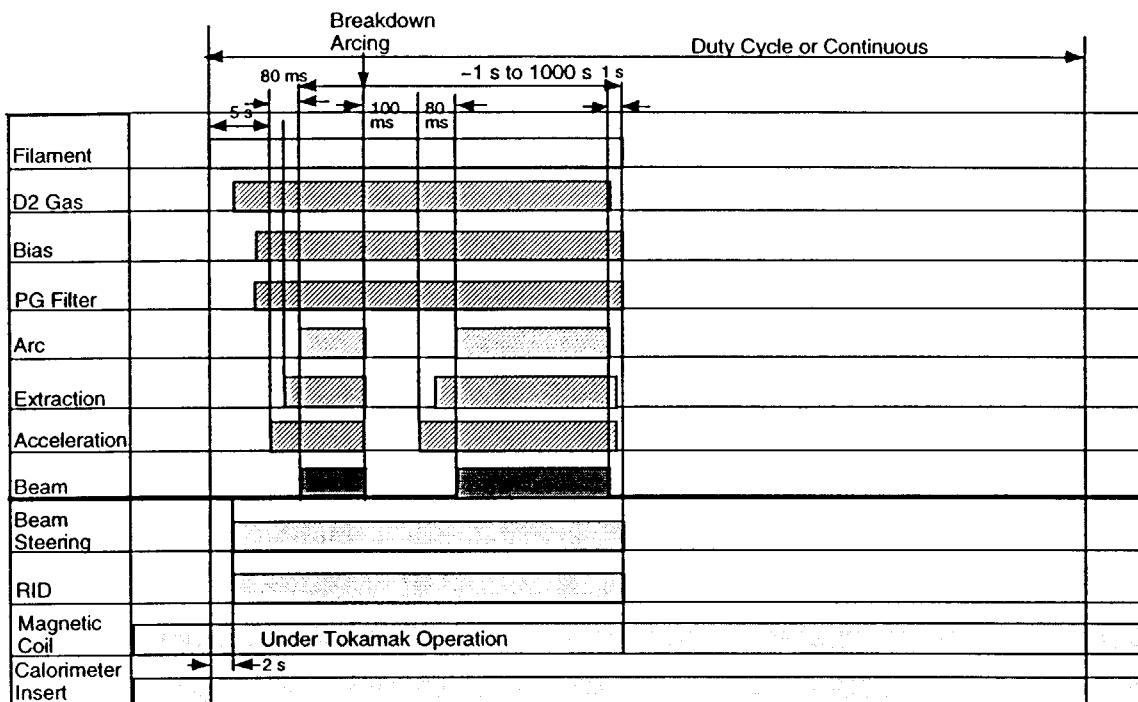


Fig. 6.3 Time sequence of conditioning mode.

## Time sequence of the ITER NBI Power Supply System Beam Injection Mode (3)

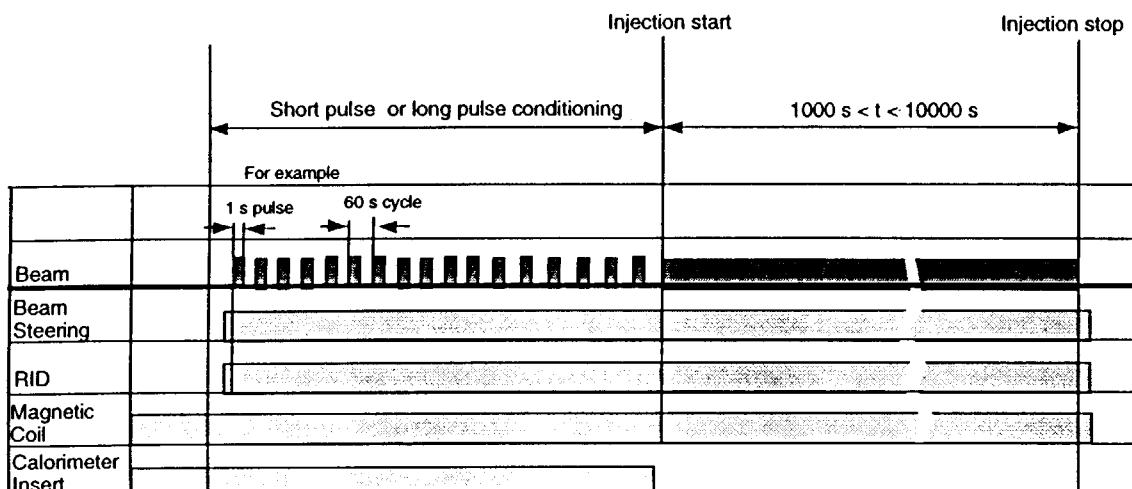


Fig. 6.4 Injection mode.

### Time sequence of the ITER NBI Power Supply System (3)-1

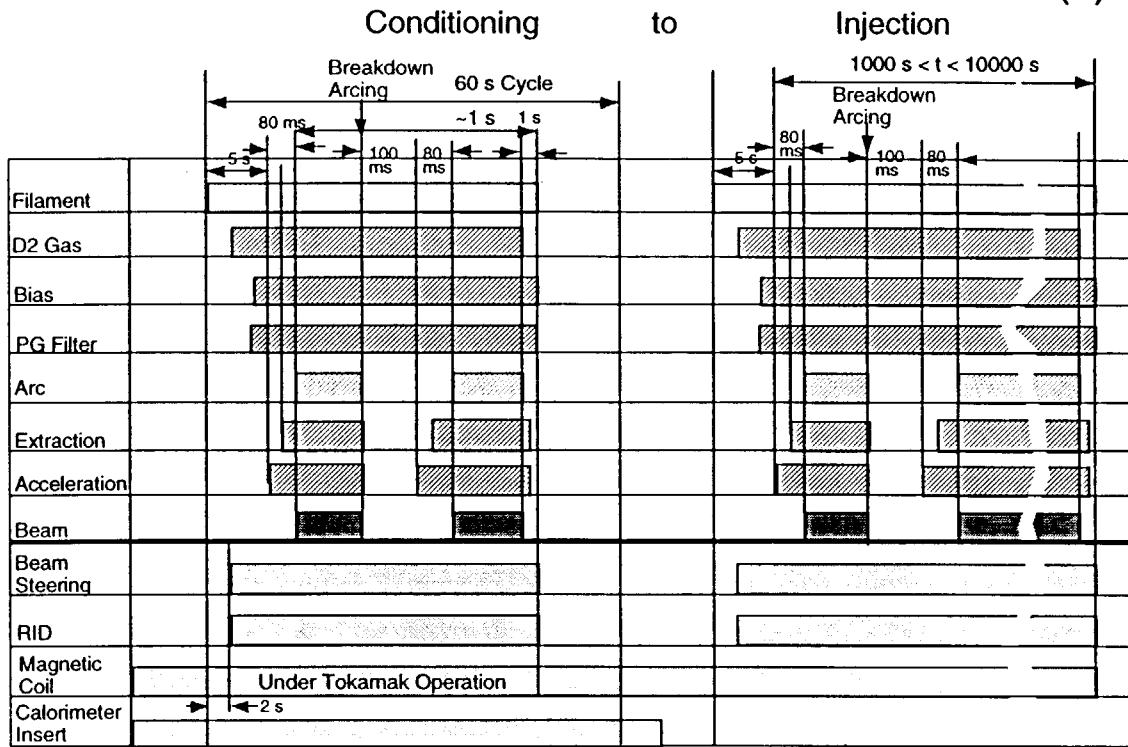


Fig. 6.5 Conditioning to injection.

### Time sequence of the ITER NBI Power Supply System (3)-2 In Case of Breakdown or Arcing during Injection

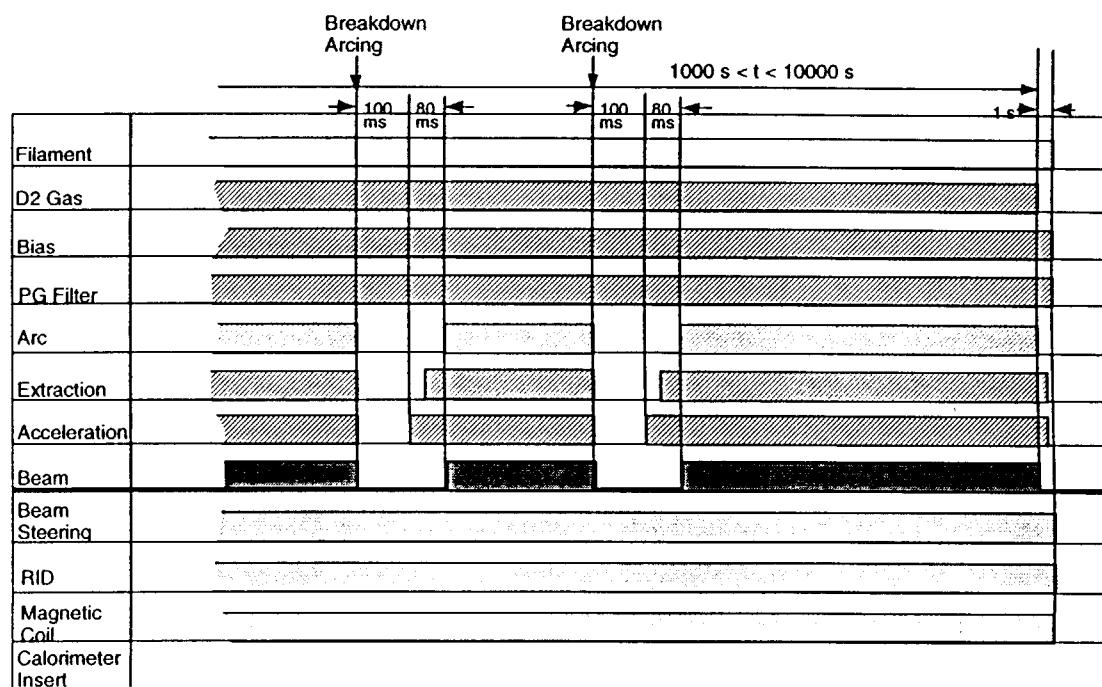


Fig. 6.6 Time sequence when breakdown or arcing occurs.

## **7. Assembly and maintenance strategy**

Assembly and maintenance procedures of HVD and the transmission line were designed, because these parts are considered to have much influence on other system.

### **7.1 HVD**

#### **7.1.1 Assembly procedure of HVD**

Assembly of HVD will be done according to the following process.

- 1) Carry a HVD tank to an assembly place
- 2) Install power supply devices in the HVD tank
- 3) Mount the HVD tank to the building
- 4) Connect the conductors, cables and water choke
- 5) Connect the transmission lines
- 6) Evacuate air and introduce the insulation gas

#### **7.1.2 Maintenance of HVD**

When some devices in HVD have trouble, repairing procedure will be done as follows.

- 1) Recover the insulation gas, introduce air and open manholes
- 2) Repair devices on HVD or takeout the devices and repair
- 3) Close the manholes
- 4) Evacuate air and introduce the insulation gas

### **7.2 Transmission line**

#### **7.2.1 Assembly procedure of transmission line**

Assembling of the transmission line will be done according to the following process.

- 1) Carry divided units and mount to the place

- 2) Connect the units and conductors
- 3) Wiring
- 4) Close the transmission line
- 5) Evacuate air and introduce the insulation gas

### **7.2.2 Maintenance of transmission line**

When some parts in the transmission line have trouble, repairing procedure will be done as follows.

- 1) Recover the insulation gas, introduce air and open manholes
- 2) Repair or change damaged parts
- 3) Close the manholes
- 4) Evacuate air and introduce the insulation gas

## **8. Reliability assessment of HVD and transmission lines**

Reliability of HVD and transmission lines was evaluated. A block diagram of reliability for the insulated transformers, the surge suppression LR, the transmission line I, the step-down transformer, the diode rectifiers, the measurement system and the transmission line II are connected in series. The block diagram is shown in Fig. 8.1-1.

A failure rate, repair time, repair rate and availability of each devices are shown in Table 8.1-1. The failure rate was estimated based on the existing DC transmission devices. A total availability of 0.845 was estimated. In this estimation, spare parts for the power supply system were not considered.

Table 8.1-1 Failure rate and availability.

No.	Equipment	Number	Failure rate $\lambda$ (1/year)	Time for repair (year)	Repair rate $\mu$ (/year)	Availability A
1	Insulated transformer	5	0.02	0.25	4	0.9756
2	Surge suppression LR	5	0.02	0.25	4	0.9756
3	Transmission line I	1	0.05	0.167	6	0.9917
4	Step-down transformer	5	0.02	0.167	6	0.9836
5	Diode rectifier	5	0.05	0.167	6	0.9599
6	Measurement equipment	5	0.05	0.167	6	0.9599
7	Transmission line II	1	0.05	0.25	4	0.9877
8	Total		0.9			0.8449

where;  $\lambda = \sum n_i \times \lambda_i$

$$A_i = \mu_i / (\lambda_i + \mu_i)$$

$$A = \prod A_i$$

$\lambda$  : Total failure rate

$\lambda_i$  : Failure rate

$n_i$  : Number of parts

$A_i$  : Availability

$\mu_i$  : Repair rate

A : Total availability

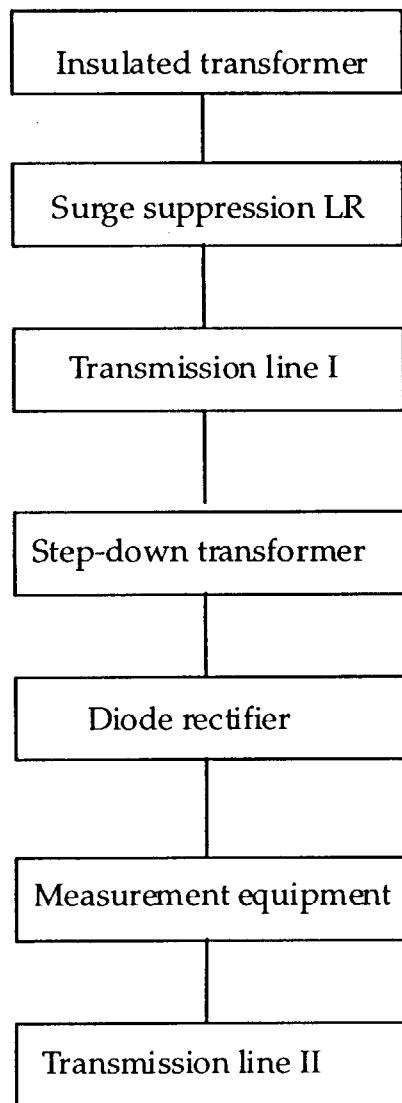


Fig. 8.1-1 Reliability block diagram of the NB power supply system.

## 9. Technical data table

Technical data for the main components of the NB power supply system are listed in the following tables.

**Table 9-1 Technical Data Table for the NBH PS AC/DC rectifier**

Data category	Parameter	Value
General	Applicable IEC standards	IEC 146
	Frequency of the AC input (Hz)	50
	Rectification type	12 pulse
Current	Rated continuous output current (kA)	13
Operation Under Short circuit	Designed to withstand short circuit operation	yes
	Peak current	29 kA
	Max. supplied I <sub>2</sub> t in case of: electronic protection:	180x10 <sup>5</sup> A <sup>2</sup> s
Voltage	Rated no-load output voltage (V)	3672
	Peak no-load output voltage (V)	3835
	On load voltage at full output current (V)	2830
Insulation Configuration	Rated insulation level to ground, according IEC 71 (kV)	3.6
	Component data: (Diode)	SL2500JX21
	type	150
	diameter (mm)	2500
	I <sub>av</sub> (A)	3926
	I <sub>rms</sub> (A)	6000
	V <sub>drm</sub> (V)	6000
	V <sub>rmm</sub> (V)	6000
	Number of devices in each arm: in parallel	3
Endurance	in series	2
	Design voltage safety factor	4.5
	Life time (years)	15
Cooling	Cooling system	Water cooled
	Max. power to be dissipated in the cooling water(kW)	200
	Max. power to be dissipated in the room air(kW)	10
	Demineral. water:	max. conductivity(uS/cm)
		45
		max. inlet temperature( °C)
		48
		max. outlet temperature(°C)
		0.01
		water flow (m <sup>3</sup> /s)
		0.49
		max. inlet pressure (MPa)
		-
		min. inlet pressure (MPa)
		0.31
		max. pressure drop (MPa)
	Max. operating time without forced cooling (air flow and/or	2

	<b>water flow) at rated operating current(sec)</b>	
AUXILIARIES	AC power (kVA) for firing, control and monitoring	10
	AC power (kVA) for forced cooling (if any)	20
Ambient Conditions	Location	Indoor
	Max. magnetic field	
	Max. magn. field derivative	
	Max. earthquake withstand acceleration	
	horizontal (g)	0.1
	vertical (g)	TBD
Sizes and weights	Dimension (mm):	
	length	9000
	width	2500
	height	3000
	Total weight (kg)	15000
	Weight of the heaviest piece in shipping configuration(kg)	100
	Weight of the heaviest piece to be handled during installation(kg)	100
	Sizes of the largest piece:	
	length (mm)	600
	width	800
	height	400

Table 9-2 Technical Data Table for the NBH PS DC/AC inverter

Data category	Parameter	Value
General	Applicable IEC standards	IEC 146
	Frequency of the AC output (Hz)	150
	Rectification type	PWM 6pulse x 5 bridges
Current	Rated continuous output current	2160
Operation Under Short circuit	Designed to withstand short circuit operation (A)	yes
	Peak current	3 kA
	Max. supplied I <sub>2t</sub> in case of Electronic protection: (MA <sup>2</sup> s)	2.6 (16 kA - 10 ms)
Voltage	Rated no-load output voltage (V)	2286
	Peak no-load output voltage (V)	2515
Insulation Configuration	On load voltage at full output current (V)	2286
	Rated insulation level to ground, according IEC 71 (kV)	3.6
	Component data: (GTO) type diameter I <sub>tav</sub> I <sub>rms</sub> (A) V <sub>dfrm</sub> (V) V <sub>rfrm</sub> (V) Number of devices in each arm: in parallel in series	SG3000JX24 108 mm - 1200 6000 16 1 1
Endurance	Design voltage safety factor	2.6
	Life time (years)	15
Cooling	Cooling system	Water cooled
	Max. power to be dissipated in the cooling water(kW)	900
	Max. power to be dissipated in the room air(kW)	40
	Demineral. water: max. conductivity(uS/cm) max. inlet temperature(°C) max. outlet temperature(°C) water flow (m <sup>3</sup> /s) max. inlet pressure (MPa) min. inlet pressure (MPa) max. pressure drop (MPa)	0.2 45 48 0.05 0.5 MPa - 0.31
	Max. operating time without forced cooling (air flow and/or water flow) at rated operating current(sec)	2
	AC power (kVA) for firing, control and monitoring	75
	AC power (kVA) for forced cooling (if any)	100
	Location	Indoor
Ambient Conditions	Max. magnetic field	
	Max. magn. field derivative	
	Max. earthquake withstand acceleration horizontal (g) vertical (g)	0.1 TBD
Sizes and weights	Dimension mm: length	6900
	width	2500

	height	3600
Total weight (kg)		24000
Weight of the heaviest piece in shipping configuration(kg)		100
Weight of the heaviest piece to be handled during installation(kg)		100
Sizes of the largest piece:	length (mm)	600
	width	800
	height	400

**Table 9-3 Technical Data Table for NBH PS HV Trancformer**

Data category	Parameter		
General	Applicable IEC standards		IEC76
	Operating frequency (Hz)		150
Power	Rated continuous power (MVA)		14.8
	Short circuit impedance between primary and secondary at rated continuous power (%)		16 %
Voltage	Rated voltages (kV)	primary	2.286
		secondary	177
Short circuit current	Connection group		Open delta-star
	Primary system highest voltage (kV)		DC-1000
	Tap changer (if any)	on load automatically operated number of taps max. range of voltage	
	Max. withstand short circuit current (A)	primary secondary	23,300 300
Losses	No load losses		0.4 %
	Total on load losses at rated continuous power		1 %
Insulation	Rated insulation level to ground, according IEC 71 (kV )	primary secondary	DC -1000 10
	Life time		20 Years
Endurance	Max. number of shorts at secondary side(times)		10 <sup>6</sup> (or 10 years)
	Cooling system		Self cooled
AUXILIARIES	Max. power to be dissipated in the room air(kW)		150
	AC power (kVA) for control and monitoring		0
Ambient Conditions	AC power (kVA) for forced cooling (if any)		(Self cooling) 0
	Location		Out door
Sizes and weights	Max. magnetic field		
	Max. magnetic field derivative		
	Max. earthquake withstand acceleration		
	horizontal (g)		0.1
	vertical (g)		TBD
	Dimension mm:	length	6500
		width	3500
		height	4500
	Total weight (kg)		55000
	"Dry weight" (kg)		30,000
Weights	Weight of liquids (oil) (kg)		25,000
	Weight of the heaviest piece in shipping configuration(kg)		30,000
	Weight of the heaviest piece to be handled during installation(kg)		30,000
	Sizes of the largest piece:	length(mm)	5,500
		width	3,500
		height	3,000

**Table 9-4 Technical Data Table for the HV rectifiers**

Data category	Parameter	Value
General	Applicable IEC standards	IEC 146
	Frequency of the AC input (Hz)	150
	Rectification type	Diode 6 pulse
Current	Rated continuous output current (A)	59
	Designed to withstand short circuit operation	yes
	Peak current (kA)	2
Operation Under Short circuit	Max. supplied I <sub>2t</sub> in case of: electronic protection:	
	Rated no-load output voltage(kV)	230
	Peak no-load output voltage(kW)	230
Insulation	On load voltage at full output current (kV)	200
	Rated insulation level to ground, according IEC 71	Not applicable 1 MV DC
Configuration	Component data: (Diode)	70 HA160
	type	14.6
	diameter (mm)	70
	I <sub>tav</sub> (A)	150
	I <sub>rms</sub> (A)	-
	V <sub>drrm</sub>	1600
	Number of devices in each arm: in parallel	1 P
	in series	328 S
Endurance Cooling	Design voltage safety factor	2.5
	Life time (years)	20
	Cooling system	Self cooled
	Max. power to be dissipated in the room air(kW)	30
AUXILIARIES	AC power (kVA) for control and monitoring	0
	AC power (kVA) for forced cooling (if any)	(Self cooling) 0
Ambient Conditions	Location	Out door
	Max. magnetic field	
	Max. magn. field derivative	
Sizes and weights	Max. earthquake withstand acceleration	
	horizontal (g)	0.1
	vertical (g)	TBD
	Dimension mm:	
	length	5500
	width	3500
	height	2500
	Total weight (kg)	10000
	Weight of the heaviest piece in shipping configuration(kg)	8,000
	Weight of the heaviest piece to be handled during installation(kg)	8,000
	Sizes of the largest piece:	
	length (mm)	5,500
	width	2,500
	height	2,500

## 10. Cost and procurement schedule

The cost estimate was revised based on the latest design developed by JCT and JA HT. Total of three power supply systems for 1 MV, 50 MW DC neutral beam injection is estimated. Companies' cost estimates on some major components are taken into consideration together with our experience on the construction of 500 keV NBI system and 1 MeV Test Facility. Factory management cost (10 % of the factory prime cost), and general management cost (10% of the total cost, including profit) are assumed. Installation cost is assumed to be 10 % of the components to be installed. Major R&D is assumed to be completed before start of construction.

The cost estimation in detail is shown in Table 10.1. The total cost of the power supply system for the 1 MeV, 50 MW NBI is estimated to be 18.086 Billion Yen.

In the procurement schedule, there is no special matter that extend the procurement period estimated in the design task N42TD02FJ. It is foreseen that it takes full three years to complete one system.

**Table 10.1 JA Cost Estimate for ITER-NBI Power Supply System**

WBS	Component Name	Sub-Component Name	Basic Specifications	Manpower			Total cost of subcomponent MYen	Total cost of component MYen	Percentage Cost %	Total cost MYen
				Material cost MYen	Man-hours	Cost per unit MYen				
4.2.C	<b>Neutral Beam Power Supply</b>	1 MeV 45 A DC × 3								100.0
1	<b>Manufacturing Design</b>			20	17500	350	370	1	370	2.0
	Manufacturing									
	Project Engineering									
	Quality Assurance									
	Quality Control									
2	<b>Fabrication, Purchasing &amp; Factory Testing</b>									
	Source Power Supplies		DC120V 7000A Cutoff<0.1ms 3% p-P Water 100 l/m	50	10	60	60	3	180	
	Arc P/S		AC15V 8300A Phase 1/m	12	4	16	16	3	48	
	Filament P/S		DC+/-10V 2300A3%P-P Water12 l/m	12	3	15	15	3	45	
	Bias P/S		DC5V 10kA 3%P-P Water 60	20	8	28	28	3	84	
	PG Filter P/S		DC10kV 50A Cutoff<0.1ms 2%P-P Extraction P/S	20	8	26	26	3	78	
			P Water 120 l/m	60	15	75	75	3	225	
	Transformer I		3.6MV A 3000x1500x2200h 15t	25	7	32	32	3	96	
	Transformer II		3.4MV A 3000x1500x2200h 15t	25	7	32	32	3	96	
	Switch gears		VCB × 2 2500x1500x2200h 3t	18	8	26	26	3	84	
	High Voltage Deck									705
	Deck & insulators		5000x3000x3000h	30	30	60	60	3	180	
	Water choke		2400 l/min Ion Vessel	20	25	45	45	3	135	
	Vessel		5000OD × 7500 3.5bar SF6	30	100	130	130	3	390	
	Source P/S Insulated Transformer		8MVA 8000x3500x5000 50t Outdoor Oil immersed self cooled Oil 20m3	100	40	140	140	3	420	2.3
	Acceleration P/S		1MW, 50MW, 5-stages							5655
			50Hz 8000x4000x5000 80t 2sets							31.3
	Step down transformer		Outdoor Oil immersed air cooled 37MW 2830V/13kA DC	50	30	80	80	3	240	
	Converter		9000x2500x3000 15t 2sets	120	70	190	190	3	570	

**Table 10.1 IA Cost Estimate for ITER-NBI Power Supply System**

**Continued**

	Inverter	14.8MVA 2286V 2160A 3Phase- 150Hz DC 6900x2500x3600 24t 5sets Water 2400 l/m	500	320	820	3	2460	
		14.8MVA 2286V 177kV 3Phase 150Hz 16%IZ CW						
		11.8MW 200kV 59A CW 4800x500x5000 55t 5sets						
	Insulated Trans./Rect.	Outdoor Oil immersed self cooled	400	230	630	3	1890	
	Auxiliary Components	SF6 3.5bar	20	15	35	3	105	
		C-R Filter 0.49 $\mu$ F 68Ω 5stages						
		Surge Suppressor (ZNR)	15	5	20	3	60	
		V-limit 240kV 5stages						
		200kV 100MQ 5stages	20	15	35	3	105	
		200kV 1A 200kOhm 5stages						
		200kV 1A 200kOhm 5stages	10	5	15	3	45	
		4000OD x 5000lh	55	5	60	3	180	
	SF6 Transmission						2280	12.6
	I/S - HVD	1700mm diam x 25m 3.5bar ~ 20bar						
		Isolation Bushing 1700diam. x						
		200mm, Epoxy, 2pcs	40	80	120	3	360	
		Outer Cylindrical Vessel 1700ID x 5000L SUS304	50	80	130	3	390	
		Inner shell and cables	8	12	20	3	60	
	HVD - P/S	1700mm diam x 120m 3.5bar						
		Isolation Bushing 1700diam. x						
		200mm, Epoxy, 2pcs	40	80	120	3	360	
		Outer Cylindrical Vessel 1700ID x 120mL SS400	150	150	300	3	900	
		Inner shell, cables, and stud	40	30	70	3	210	
	Surge Suppression System	<10], <3kA					651	3.6
		AC Reactor 0.5mH x 1set	10	6	16	3	48	
		DC Reactor 0.5mH x 6sets	60	36	96	3	288	
		Surge Blocker 1VS	50	20	70	3	210	
		Resistors for the Intermediate Grids	100W x 4	20	15	35	3	105

**Table 10.1 IA Cost Estimate for ITER-NBI Power Supply System****Continued**

Auxiliary Systems	D2 Gas Supply System	I/S Ceramic Tube	6	4	10	3	30	860	4.8
	Neutralizer		3	2	5	3	15		
Insulation Gas Handling System			100	30	130	1	130		
Reservoir Tank	3000OD x 10000h x 2		100	20	120	1	120		
Insulation Gas	SP6 1000m3 x 4.5atm	45	0	45	1	45			
Power Supply Cooling System	Inv./Conv., Compensator 2500 l/min x 3	100	150	250	1	250			
Ion Source Cooling System	Ion source, Source P/S 2700 l/min x 3	110	160	270	1	270			
Auxiliary Power Supplies							255	1.4	
Canceled Coil Power Supply	300kAT 1.5kA x 1.5kV	30	15	45	3	135			
Beam Steering Power Supply	20kV 2A 25Output with Variable Resistors	16	4	20	3	60			
Ion Dump Power	10kV 10A	16	4	20	3	60			
Power Distribution System	Switchgear	30	25	55	3	165	765	4.2	
	Power Fluctuation Compensator	100	100	200	3	600			
Control System	Local control system	70	35	105	3	315	315	1.7	
Factory Management Cost	Workstation & Software --> See Central control system 5.3.F.01						13128	1313	7.3
3 Transportation	Depending on the site						100	0.6	
4 Installation	10% of the components installed incl. cabling & piping						12758	1276	7.1

**Table 10.1 IA Cost Estimate for ITER-NBI Power Supply System**

**Continued**

<b>5</b>	<b>Site Commissioning</b>	<b>2% of the factory prime cost</b>																	
	Off Load Test																		
	On Load Test																		
	Dummy Load			50	50														
<b>6</b>	<b>Documentation and Quality Assurance</b>	<b>1% of the factory prime cost</b>																	
<b>7</b>	<b>Spares</b>	<b>1% of the factory prime cost</b>																	
		Minimum initial spares only																	
<b>8</b>	<b>All other cost</b>															<b>0</b>	<b>0.0</b>		
<b>9</b>	<b>General Management Price including Profit</b>	<b>10% of the total cost</b>													<b>16442</b>	<b>1644</b>	<b>9.1</b>		

## 11. Summary

Design of the power supply system for the neutral beam injector has been performed under the ITER EDA. Main results obtained in the design study are summarized as follows;

1. Detail circuits of converter/inverter system for the acceleration power supply were designed.
2. Layout of the converter/inverter system was designed.
3. High voltage main transformers for the acceleration power supply were designed.
4. High voltage rectifier and filter system were designed.
5. An insulating transformer for the negative ion production power supply was designed.
6. Characteristics of the arc and extraction power supplies were investigated using EMTDC code. Ripple specifications and energy input to the ion source were confirmed to be allowable values.
7. Transmission line I which connects the power supply yard and HVD was designed.
8. Ground level power supplies and SF6 gas storage system were designed.
9. Control system of the NB system and operation modes were investigated.
10. Reliability of HVD and transmission lines of the NB power supply system was estimated without spare parts.

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# 国際単位系(SI)と換算表

表1 SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表3 固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s <sup>-1</sup>
力	ニュートン	N	m·kg/s <sup>2</sup>
圧力、応力	パスカル	Pa	N/m <sup>2</sup>
エネルギー、仕事、熱量	ジュール	J	N·m
工率、放射束	ワット	W	J/s
電気量、電荷	クーロン	C	A·s
電位、電圧、起電力	ボルト	V	W/A
静電容量	ファラード	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m <sup>2</sup>
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	°C	
光束度	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m <sup>2</sup>
放射能	ベクレル	Bq	s <sup>-1</sup>
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表2 SIと併用される単位

名 称	記 号
分、時、日	min, h, d
度、分、秒	°, ', "
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV = 1.60218 × 10<sup>-19</sup> J

1 u = 1.66054 × 10<sup>-27</sup> kg

表5 SI接頭語

倍数	接頭語	記号
10 <sup>18</sup>	エクサ	E
10 <sup>15</sup>	ペタ	P
10 <sup>12</sup>	テラ	T
10 <sup>9</sup>	ギガ	G
10 <sup>6</sup>	メガ	M
10 <sup>3</sup>	キロ	k
10 <sup>2</sup>	ヘクト	h
10 <sup>1</sup>	デカ	da
10 <sup>-1</sup>	デシ	d
10 <sup>-2</sup>	センチ	c
10 <sup>-3</sup>	ミリ	m
10 <sup>-6</sup>	マイクロ	μ
10 <sup>-9</sup>	ナノ	n
10 <sup>-12</sup>	ピコ	p
10 <sup>-15</sup>	フェムト	f
10 <sup>-18</sup>	アト	a

表4 SIと共に暫定的に維持される単位

名 称	記 号
オングストローム	Å
バーン	b
バル	bar
ガル	Gal
キュリ	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å = 0.1 nm = 10<sup>-10</sup> m

1 b = 100 fm<sup>2</sup> = 10<sup>-28</sup> m<sup>2</sup>

1 bar = 0.1 MPa = 10<sup>5</sup> Pa

1 Gal = 1 cm/s<sup>2</sup> = 10<sup>-2</sup> m/s<sup>2</sup>

1 Ci = 3.7 × 10<sup>10</sup> Bq

1 R = 2.58 × 10<sup>-4</sup> C/kg

1 rad = 1 cGy = 10<sup>-2</sup> Gy

1 rem = 1 cSv = 10<sup>-2</sup> Sv

(注)

1. 表1～5は「国際単位系」第5版、国際度量衡局1985年刊行による。ただし、1 eVおよび1 uの値はCODATAの1986年推奨値によった。

2. 表4には海里、ノット、アール、ヘクタールも含まれているが日常の単位なのでここでは省略した。

3. barは、JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。

4. EC閣僚理事会指令ではbar、barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

## 換 算 表

力	N(=10 <sup>5</sup> dyn)	kgf	lbf
1	0.101972	0.224809	
9.80665	1	2.20462	
4.44822	0.453592	1	

粘度 1 Pa·s(N·s/m<sup>2</sup>) = 10 P(ポアズ)(g/(cm·s))

動粘度 1 m<sup>2</sup>/s = 10<sup>4</sup> St(ストークス)(cm<sup>2</sup>/s)

圧力	MPa(=10 bar)	kgf/cm <sup>2</sup>	atm	mmHg(Torr)	lbf/in <sup>2</sup> (psi)
力	1	10.1972	9.86923	7.50062 × 10 <sup>3</sup>	145.038
0.0980665	0.0980665	1	0.967841	735.559	14.2233
0.101325	0.101325	1.03323	1	760	14.6959
1.33322 × 10 <sup>-4</sup>	1.33322 × 10 <sup>-4</sup>	1.35951 × 10 <sup>-3</sup>	1.31579 × 10 <sup>-3</sup>	1	1.93368 × 10 <sup>-2</sup>
6.89476 × 10 <sup>-3</sup>	6.89476 × 10 <sup>-3</sup>	7.03070 × 10 <sup>-2</sup>	6.80460 × 10 <sup>-2</sup>	51.7149	1

エネルギー・仕事・熱量	J(=10 <sup>7</sup> erg)	kgf·m	kW·h	cal(計量法)	Btu	ft · lbf	eV	1 cal = 4.18605 J(計量法)	
								= 4.184 J(熱化学)	
1	0.101972	2.77778 × 10 <sup>-7</sup>	0.238889	9.47813 × 10 <sup>-4</sup>	0.737562	6.24150 × 10 <sup>18</sup>			
9.80665	1	2.72407 × 10 <sup>-6</sup>	2.34270	9.29487 × 10 <sup>-3</sup>	7.23301	6.12082 × 10 <sup>19</sup>			
3.6 × 10 <sup>6</sup>	3.67098 × 10 <sup>5</sup>	1	8.59999 × 10 <sup>5</sup>	3412.13	2.65522 × 10 <sup>6</sup>	2.24694 × 10 <sup>25</sup>			
4.18605	0.426858	1.16279 × 10 <sup>-6</sup>	1	3.96759 × 10 <sup>-3</sup>	3.08747	2.61272 × 10 <sup>19</sup>	仕事率 1 PS(仏馬力)		
1055.06	107.586	2.93072 × 10 <sup>-4</sup>	252.042	1	778.172	6.58515 × 10 <sup>21</sup>	= 75 kgf·m/s		
1.35582	0.138255	3.76616 × 10 <sup>-7</sup>	0.323890	1.28506 × 10 <sup>-3</sup>	1	8.46233 × 10 <sup>18</sup>	= 735.499 W		
1.60218 × 10 <sup>-19</sup>	1.63377 × 10 <sup>-20</sup>	4.45050 × 10 <sup>-26</sup>	3.82743 × 10 <sup>-20</sup>	1.51857 × 10 <sup>-22</sup>	1.18171 × 10 <sup>-19</sup>	1			

放射能	Bq	Ci
	1	2.70270 × 10 <sup>-11</sup>
	3.7 × 10 <sup>10</sup>	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58 × 10 <sup>-4</sup>	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)

DESIGN OF NEUTRAL BEAM INJECTION POWER SUPPLIES FOR ITER