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ABSTRACT.
An ECRH (electron-cyclotron resonance heating) system has been designed for JET in the framework of the JET-Enhanced Performance project (JET-EP) under the European Fusion Development Agreement (EFDA). Due to financial constraints it has recently been decided not to implement this project. Nevertheless the design work conducted from April 2000 to January 2002 shows a number of features which can be relevant in preparation of future ECRH systems such as the ITER one. The system was foreseen to comprise 6 gyrotrons, 1 MW each, in order to deliver 5 MW of mm-wave power into the tokamak plasma [1]

1. SYSTEM DESCRIPTION

The main components of the ECRH system are:

- Gyrotrons with depressed collector, each delivering 1 MW of mm-wave power, 10 s pulse duration at a frequency of 113 GHz.
- Main power supplies rated for 60 kV DC at 100 A, thyristor controlled.
- Solid-state crowbars to short-circuit the power supplies in case of a fault.
- Fast IGBT switches, connected in series with the gyrotrons, to disconnect the gyrotron from the power supply within 2 μs to limit the energy deposit in case of an internal arc.
- Fast high-voltage amplifiers with a voltage swing of 30 kV to stabilise the accelerating voltage and to modulate the mm-wave power up to 10 kHz.

2. GYROTRON

To increase the efficiency and simplify the cooling requirements, most high power/long pulse gyrotrons are equipped with a depressed collector. A sketch of a depressed collector gyrotron is given in Figure 1.

3. POWER SUPPLY ARRANGEMENT

Besides the collector power supply, which is the main power supply of the system, an accelerating power supply is necessary. In conventional system architectures the accelerating power supply is connected between cathode and anode (so called body) and the collector is at ground potential. As a result of this, the body supply is floating with respect to ground and needs an output voltage according to the acceleration voltage of about 80 kV. To simplify the design, the body supply will be connected between ground and the body of the gyrotron, thus the acceleration voltage is the sum of the voltages of collector and body power supply. This arrangement is given in Figure 2.

With this arrangement, regulation of the acceleration voltage must be performed by controlling the body supply in dependence of collector voltage as well as of body voltage. The advantage of this design is a lower voltage for the body power supply (about 30 kV) in conjunction with simpler techniques, so no need for an insulation transformer. Fast modulation of the mm-wave output power could be in principle achieved by controlling the body voltage only, at least for low modulation amplitudes, as used for heat wave experiments. For large-amplitude modulation of the power, a synchronous modulation of the collector and body voltage is recommended to prevent collector overloading. [2]

4. POWER SUPPLY REQUIREMENTS

The requirements of the depressed collector power supplies are:

Output voltage:	–40 to –60 kV DC
Output current:	45 A DC
Voltage stability:	1%
Pulse duration:	10 s.
Duty cycle:	1/100

Requirements of the body power supplies are:

Output voltage:	0 to +30 kV
Output current DC:	<20 mA
Output current AC:	+ and – 300 mA
Slew rate:	300 V/µs
Switch-off time:	<10 µs

Due to the high power at moderate stability of the collector voltage, a star point controlled power/rectifier is sufficient.

In the reference design, two gyrotrons are connected to one collector power supply unit. A circuit diagram of a unit is given in Figure 3.

The power supplies are fed from the 33kV distribution network. One 33 kV circuit breaker feeds a matching transformer which in turn feeds 3 thyristor controlled rectifiers.

The matching transformer has two secondary windings, phase displaced to minimize harmonic distortion of the AC supply and the ripple on the DC output voltage. Each matching transformer secondary winding feeds one of two thyristor star point controllers for each of the three units. The outputs of the rectifier transformers are connected to diode bridges. The bridges are then connected in series to give a 12 pulse rectifying system. The output of the diode bridges is smoothed by a 21µF capacitor.

5. IGBT SERIES SWITCHES

The gyrotron is very sensitive to arcs inside the beam tunnel. Energy deposits must be limited as low as 10 Joules. To limit this energy, fast IGBT switches are connected in series with the gyrotrons. These switches can disconnect the gyrotron from the power supply within a few microseconds. If the IGBT switch fails to switch-off, a crowbar will be triggered to short-circuit the output of the power supply.

A circuit diagram of the whole power supply system for one gyrotron is given in Figure 4.

5.1 SPECIFICATIONS

Design parameters of the IGBT switches are:

Continuous DC blocking voltage:	75 kV
Peak blocking voltage:	90 kV
DC current:	45 A
Breaking current (max):	300 A
Breaking time:	<5µs

IGBT switches which can fulfill these specifications are already designed and commercially available in the US [3] and Japan. [4].

The Japanese switch has been developed under the direction of the Japan Atomic Energy Research Institute JAERI and build by the Japanese IDX Company.

The switch consists of 100 water-cooled IGBTs in series and is rated for 100 kV DC, 100 A continuous.

6. MODULATION OF RF POWER

As described in Section 3, the mm-wave output power of the gyrotron can be modulated either by the body voltage or the collector voltage. Decreasing the body voltage by about 15 kV, the mm-wave power will be decreased from 1 MW to 100 kW.

For high modulation frequencies (up to 10 kHz) the body power supply has to act as a high-voltage amplifier with an output-voltage swing of at least 15 kV and a bandwidth of 10 kHz. Due to the capacitive load of about 1 nF, the output current has to be in the order of 300 mA.

A solution is found with a set of commercially available high-voltage solid-state amplifiers wired in a master/slave configuration.

The specifications of the HV amplifier model P6021 from the TREK company in the US [6] are:

Output voltage range:	0–30 kV DC or ACpk
Output current range:	0–20 mA DC
Output current peak:	40 mA
Bandwidth (small signal):	25 kHz
Slew rate:	>350 V/µs

A body supply, composed of 1 master and 6 slave units has been tested at the TREK Company under real load conditions. The required specifications were easily achieved. [6]. For deep power modulation, simultaneous modulation of the collector voltage is necessary. This can be achieved by switching on and off the collector voltage completely by means of the series IGBT switch.

A test of the IGBT switch from IDX was executed at JAERI. With a voltage of 70 kV and a load resistor of 2 kΩ a 10 kHz square wave modulation during a pulse train of 1 ms was achieved. The test-circuit is shown in Figure 5.

The test results are given in Figure 6.

SUMMARY

In this paper the design of a high voltage power supply system for powering 6 high power/long pulse gyrotrons is described. The design is based on the most up to date solid state components and circuits such as: fast breaking IGBT switches and fast high voltage solid state amplifiers.

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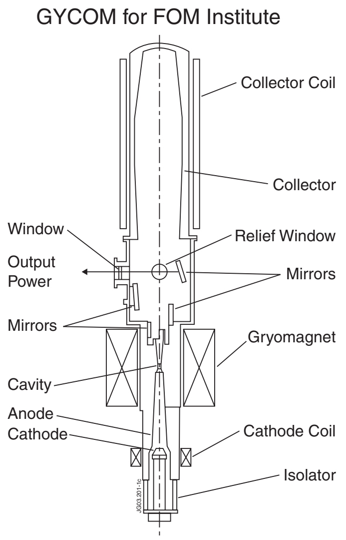


Figure 1: Schematic diagram of a GYCOM 140 GHz, 0.8 MW, 10 s pulse gyrotron.

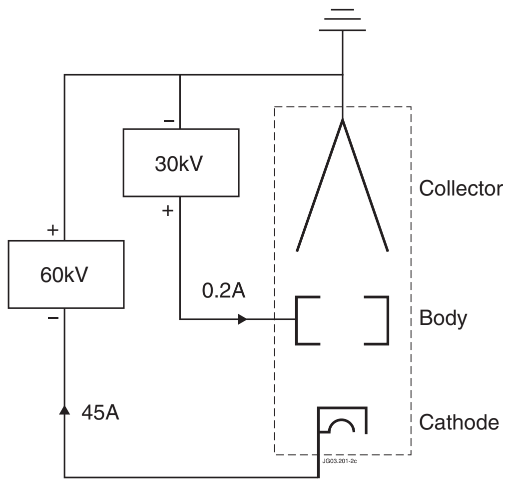


Figure 2: Arrangement of collector and body power supplies.

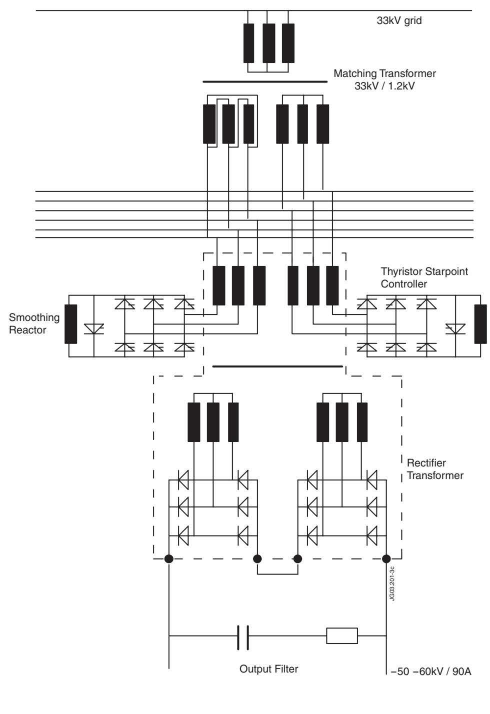


Figure 3: Star point controlled transformer/rectifier unit.

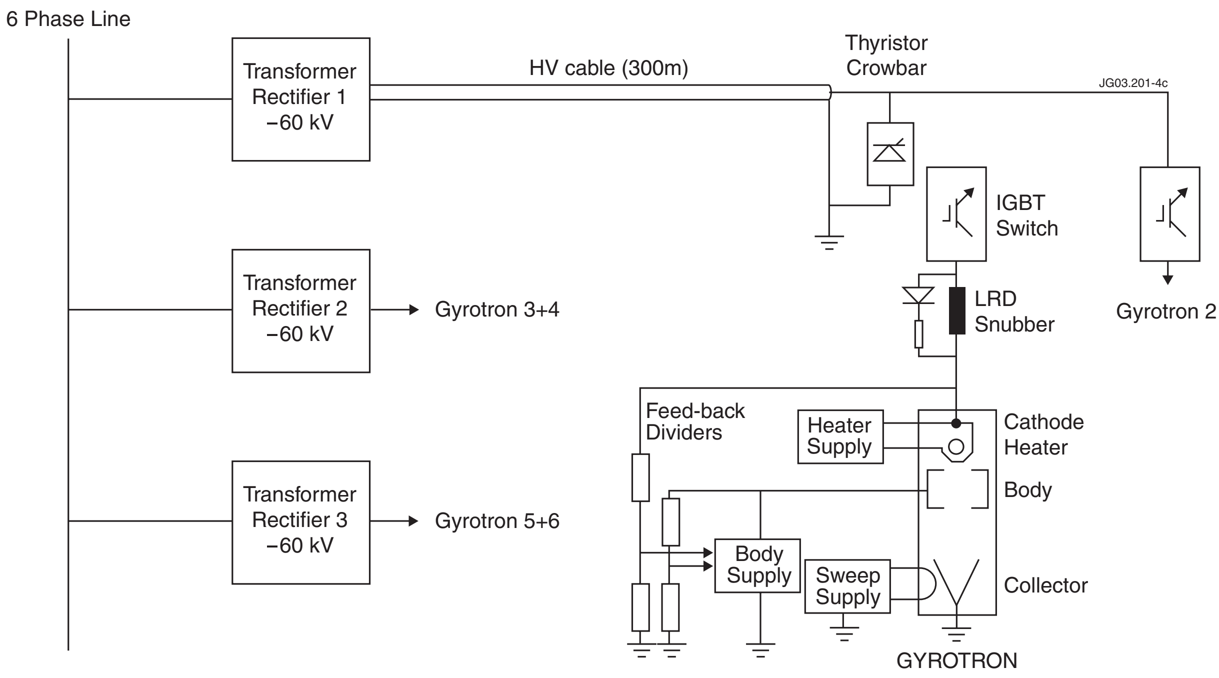


Figure 4: The high voltage power supply system for one gyrotron.

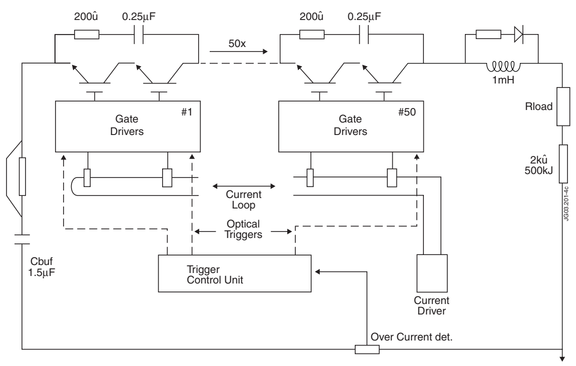
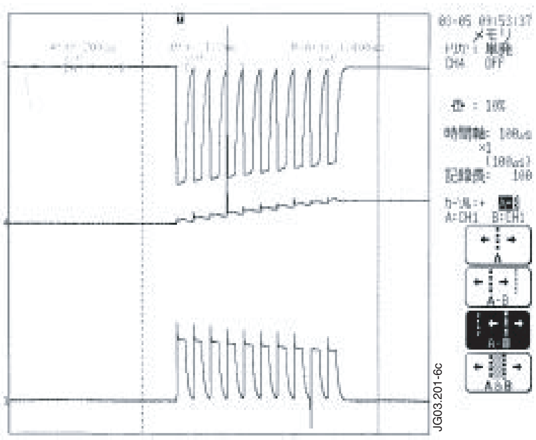


Figure 5: Test-circuit for modulation test.



Upper: Voltage across load resistor with 70kV ampl.
Lower: load current with 35A amplitude at 10kHz.

Figure 6: Modulation test results.