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THE RF POWER PLANT OF THE SPS

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ABSTRACT

The four travelling wave accelerating cavities of the CERN SPS are fed by a network of 200 MHz power generators capable of delivering a total RF power of 4 MW (maximum). High power coaxial switches equip three of these cavities for power flow reversal during antiproton operation. Each cavity is fed through a long coaxial line (up to 180 m) by two generators whose outputs are combined in a 1 MW coaxial hybrid. Two types of generators are used: they combine either 4 × 125 kW or 16 × 35 kW tetrode amplifiers to produce 500 kW power in a matched load. Two additional 800 MHz structures are installed in the SPS ring for beam stabilization, one of them being also reversible for antiproton operation. Two 225 kW generators using 60 kW klystrons drive them via 150 m of wave guide. A description of the power plant of the RF system, including associated power supplies, interlock and controls will be given.

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1. Introduction

Originally two 200 MHz accelerating cavities, each driven by a 500 kW amplifier, were installed in the SPS. Power amplifier configurations utilizing 2, 4, 8 and 16 tetrodes or one 500 kW klystron were investigated. At the time four 125 kW tetrode amplifiers, operating in parallel, proved the least costly solution. During the years that followed increasing beam intensities and faster acceleration rates necessitated the installation of a third and finally a fourth accelerating cavity each driven by the same amplifier type. To permit still higher intensities without significant loss of accelerating voltage due to beam loading, it was decided to double the power per cavity by combining two 500 kW amplifiers. This required the installation of four more 500 kW amplifiers. A new price enquiry was made resulting this time in the selection of an amplifier combining 16 × 35 kW tetrodes in the final stage.

A fourth harmonic of the accelerating frequency is used to damp beam instabilities. Two 800 MHz cavities have been installed each driven by a 225 kW amplifier. Since no single klystron was available at this power level and frequency, a solution combining four modified TV klystrons operating at 60 kW was adopted.

2. Configuration of the 200 MHz power plant

The general configuration of the 200 MHz accelerating system is shown in Fig. 1. The combined power of two 500 kW amplifiers is fed via the coaxial line to the accelerating cavity which is installed 60 m underground. The cavity is a travelling wave structure using drift tubes supported by horizontal bars and has a backward wave characteristic. RF power flow and particle movement therefore must be in opposite directions. For operation of the SPS as a proton-antiproton collider the RF power flow in the cavities used for antiprotons must be opposite to that in the cavities used for protons. Three of the four accelerating cavities are equipped with high power coaxial switches which enables RF power flow reversal. In the collider mode two cavities are used for proton and two for antiproton acceleration. For high intensity fixed target physics all four cavities are required for proton acceleration.

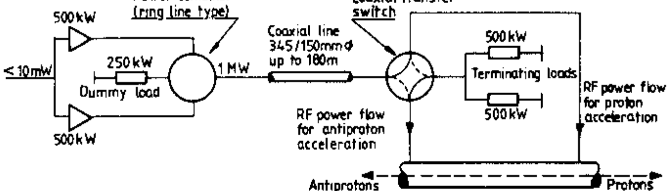

Fig. 1 Configuration of the 200 MHz power plant

RF power not delivered to the beam must be absorbed by a terminating load, capable of dissipating up to 1 MW of RF power.

In the following the main components of the power plant will be described briefly, with the exception of the accelerating cavity, which has been treated in detail in Ref. 1.

1 MW terminating load

Developed for the original 500 kW operation, the RF power load is a 6 m long 6 1/8" stainless steel coaxial line, short circuited at one end and using water treated with sodium nitrite as both the power absorbing and cooling medium. An alumina input window is used and matching of the approximately 6 Ohm water line to the 230 mm 50 Ohm RF input is via a $\lambda/4$ air-cooled conical transformer. Since these loads have proved reliable in operation it was decided to combine two of them in order to up-rate the power dissipation to 1 MW. To avoid power imbalance between the two loads due to thermal run away, the parallel connection has been designed in such a way that a temperature rise in one load transforms its input impedance to a higher impedance at the combining point, resulting in less power input to that load.

High power transmission line

The 50 Ohm coaxial feeder lines are rated for 750 kW CW power without auxiliary cooling. As there is an airflow in the tunnel and access pit, required for tunnel ventilation, even higher power levels can be reached, and the lines have in fact been tested up to 1 MW CW. Their main characteristics are: copper inner conductor 150 mm Ø; aluminium outer conductor 345 mm Ø; line section length 5.55 m; short interconnecting rings mounted between each line section, with triangular ceramic support for inner connector; inner connector made up of a ring of 36 sliding contacts, individually adjusted to give equal contact pressure; attenuation < 0.2 dB/100 m; VSWR < 1.05.

The line lengths vary between 90 and 180 m, all four having a vertical section of some 60 m. To allow for thermal expansion the lines are suspended in flexible hangers.

The transmission lines and most of the high power coaxial and waveguide components have been manufactured by Spinner, Germany.

1 MW coaxial switch

The coaxial switch is of the transfer type. It can be operated locally by hand or remotely via a motor drive. The switching time under remote control is less than 8 seconds. The switch can handle up to 1 MW CW power. The measured input VSWR at any port and in any position is less than 1.04 and the isolation greater than 100 dB.

1 MW hybrid and dummy load

Each pair of 500 kW amplifiers is combined by a coaxial power hybrid of the ring line type using three $\lambda/4$ coax lines and one $\lambda/4$ crossover line. The inner conductor of the ring line is supported by $\lambda/4$ stubs, so that no dielectric supports are required. The hybrid has been tested to 1 MW CW. In the frequency range 199.5 to 200.4 MHz (required for normal proton acceleration) input VSWR values < 1.03, directivity > 40 dB and coupling 3 dB ± 0.05 dB have been measured.

The connections to the amplifiers and feeder line are made by 345 mm Ø coaxial U-links, allowing a relatively quick connection of either of the two amplifiers to the feeder line in the event of a major breakdown of hybrid, dummy load, or one of the amplifiers.

Originally 80 kW loads, cooled by the amplifier cooling water system, were used as dummy loads on the 1 MW hybrid. This very economical solution works well under normal operating conditions, permitting a considerable tolerance in power balance and phasing, but has the disadvantage that if one 500 kW amplifier trips the RF drive-to both must be cut to avoid excessive power in the 80 kW load. By replacing the 80 kW load with a 250 kW load the second amplifier can still deliver 500 kW. Half of that power is absorbed in the dummy load, the remaining 250 kW still providing half of the accelerating voltage normally available in the cavity. This solution is more expensive than the original version since, in addition to the bigger loads, (the already described 500 kW loads are used), larger coaxial components and a new cooling water system, including pumps, interlocks and controls were required. However, this solution has considerably increased the reliability of the RF system, since now the loss of one 500 kW amplifier hardly affects the beam acceleration or the beam storage.

<u>500 kW power amplifiers</u>

The four original 500 kW power amplifier chains comprise predrivers built by CERN and driver and final stage built by Siemens, Germany. The predriver consists of a 30 W transistorized amplifier and 1 kW and 10 kW amplifiers using Philips tetrodes, types YL 1440 and YL 1520, respectively, in modified TV cavities. Driver and final stage use identical coaxial-cavity amplifier units with Siemens RS 2004 J tetrodes.

The RF output power from the driver, approximately 50 kW, is divided via 3 dB hybrids and fed to the four parallel final amplifier units, each capable of delivering up to 140 kW RF output power (see Fig. 2). Outputs from the final amplifiers are combined in a second group of 3 dB hybrids. All hybrids are of the $\lambda/4$ crossover type.

In the event of a major fault in a final amplifier unit, it can be switched completely off line and the three remaining units can continue in operation, delivering up to 310 kW RF power at the amplifier output. Each final amplifier unit is equipped with a coaxial transfer switch and 15 kW RF load in the input line and two RF short circuit plungers in the output line. The terminating load is required to absorb the corresponding drive power and the short circuit to decouple the switched-off unit from power reflected at the accelerating cavity and from power due to imperfect hybrid isolation. Nevertheless, enough voltage was coupled into the off-line unit to excite a resonance in conjunction with the open input circuit. This effect could be easily damped by terminating the input with a 50 Ohm load, which was achieved by interconnecting the transfer switches of pairs of amplifier units, as shown in Fig. 2.

The Siemens RS 2004 J tetrode is water cooled and rated at 120 kW anode dissipation. The tube is operated in class AB in the grounded screen grid mode. To allow for quick tube replacement, all electrical, RF and water connections are made automatically as the tube is lowered into the amplifier. The anode circuit is a $3\lambda/4$ coaxial line, surrounding the likewise coaxial screen and input circuits. Extensive use is made of galvanically deposited copper-on-teflon cylindrical blocking capacitors.

Spurious oscillations are damped using Siemens Siferit U 17 and Emerson and Cuming Eccosorb ZN ferrite materials. Tuned coupling loops terminated in 50 Ohm loads damp an 835 MHz TE11 mode in the anode circuit. The loops are orientated so that they couple to the axial magnetic field of this mode, but not to the circumferential magnetic field of the TEM fundamental.

The second generation of 500 kW amplifiers (see Fig. 3) uses a CERN made 500 W solid-state predriver and driver and final stage built by Philips, Netherlands. Seventeen identical 35 kW amplifier units are employed, using Philips YL 1530 air-cooled tetrodes. The driver power output, approximately 20 kW, is divided by eight in a two $\lambda/4$ section transformer to match the output impedance of 50/8 Ohms to 50 Ohms. Each of the eight outputs feeds two final amplifier units via an 180° hybrid. All sixteen finals have coaxial transfer switches with 1.5 kW loads and phase shifters in the inputs and short circuit devices in the outputs. The outputs from pairs of finals are combined by the same type of 180° hybrid used in the inputs. All following hybrids are of the 3 dB $\lambda/4$ crossover type and from the 140 kW level they are identical to those used in the Siemens plant. The configuration provides a high level of redundancy in that up to five final amplifier units can be switched off line without exceeding power limits in the hybrid dummy loads.

The anode circuit of the grounded screen amplifier unit employs a $\lambda/4$ resonator tuned by a movable

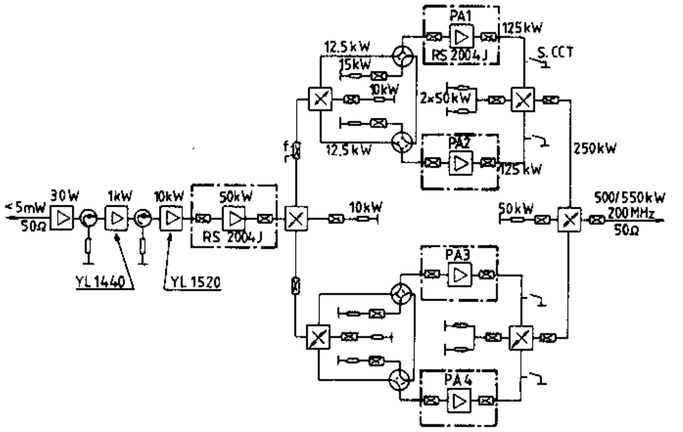

Fig. 2 Layout of 200 MHz, 500 kW amplifier (4 tetrode final stage)

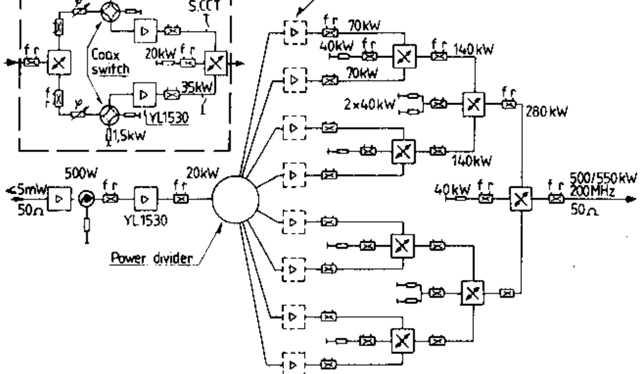

Fig. 3 Layout of 200 MHz, 500 kW amplifier (16 tetrode final stage)

short circuit end plane. The ouput loop is galvanically coupled to the inner conductor of the anode circuit. Loading is adjusted by means of a variable series inductance. Screen decoupling is obtained by using a ferrite loaded (Eccosorb MF 124) short-circuited line. The low input impedance of the tube is transformed by a $\lambda/4$ coaxial line, which has two symmetrically disposed input connectors. A coaxial T transformation brings the input impedance to 50 Ohm.

For both plants anode efficiency is > 55% and overall efficiency > 45%.

Power supplies

Driver and final stage of the Siemens plant have separate anode power supplies. The driver anode supply is a conventional 3-phase full wave rectifier with LC filter, rated for 21 A at 7 kV d.c.. The supply is equipped with an ignitron crowbar to divert the energy in the event of a tube arc. The common anode power supply for the four final tubes delivers 120 A at 8.5 kV d.c. Vacuum contactors in the 18 kV, 3-phase incoming line provide fast ON-OFF switching. As for the driver an LC filter and an ignitron crowbar are used. Motor driven isolating and grounding switches are included in the anode and cathode lines to the four tubes to allow operation of the plant with any final amplifier unit off line. Since the final tubes have a common anode supply and the screen grids are physically grounded, a common screen grid power supply is also used. To measure individual screen grid currents, differential d.c. current transformers are required to obtain $I_{G_2} = (I_K - I_{G_1}) - I_A$. Both driver and final anode power supplies are housed in air-tight cubicles, and are cooled by closed loop forced air circulation through air/water heat exchangers. Individual regulated control grid power supplies are used. They can be remotely switched to "class C", biasing off the power tubes as an energy saving measure if the accelerator is in standby status.

For the Philips plant common anode (10 kV, 120 A) and screen grid (900 V, 5 A) power supplies are employed for all 17 tubes. ON-OFF control of the anode supply is by means of two triple-pole vacuum contactors in the supply lines between HV transformer and rectifier bridges. An LC filter attenuates the already very low 600 Hz ripple. During a current transient, a damping resistor is connected in parallel with the smoothing choke by means of a saturable switching reactor. An ignitron crowbar is incorporated in the supply. The seventeen outputs are connected to the tubes via isolating and grounding switches mounted on a common shaft. Magnetic clutches control the switching of the individual tubes. A second motor operated grounding switch is used at the cable ends near the amplifier units, thus ensuring that the cables are earthed at both ends and the off-line tube is completely isolated from the HV system. Wideband d.c. current transformers monitor I_A and I_{G_2}. The anode supply is forced air cooled by a closed loop system incorporating an air/water heat exchanger.

The screen grid power supply comprises a double secondary transformer feeding thyristor rectifiers in three-phase bridge connection. Standby operation is made by decreasing the screen grid voltage to a level resulting in anode current cut-off. Each tube has its own control grid bias supply, equipped with an active bleeder, using power transistors.

Interlock and control

Both types of 500 kW amplifiers are equipped with a hardwired interlock system to protect the equipment in the event of a failure in cooling systems, power supplies or amplifiers. Local control racks are provided for switching, monitoring and interlock indication. Switching is made in three stages. Stage 1: cooling, filament and bias; Stage 2: high voltage (anode and screen); Stage 3: RF drive permitted. Monitoring includes voltage and current measurement of anode, screen grid, control grid and filament and measurement of forward and reflected RF power at the output of each amplifier unit and at the outputs of each hybrid. A front panel LED display provides general fault information and system status.

The Siemens amplifiers employ discrete transistor industrial logic operating at 24 V for high noise immunity. The Philips plant uses CMOS logic cards mounted in Europe crates. Because of the large amount of fault and status information to be displayed (371 LEDS) the d.c. tube controllers and RF power monitors are connected to a LED matrix, wherein rows and columns are scanned in a time multiplex mode. This technique simplifies the wiring and reduces the power consumption of the control system.

Remote control

The RF power plant is controlled and monitored by the SPS computer control system. This implies that by means of software programs all actions which may be carried out locally, such as switching the amplifier on and off, reading the values of currents, voltages, and power levels, detecting faults and warning levels and resetting faults can be implemented from any console of the RF computer or from the SPS main control room. The hardwired control-interlock system is therefore provided with an interface through which all commands from the computer and all status monitoring and analog signals to the computer pass.

3. 800 MHz damping system

There are two identical 225 kW amplifiers, each comprising four modified TV-type 60 kW CW klystrons combined via waveguide hybrids. Power transfer to the disc-loaded forward wave cavities is by R8 copper waveguide of about 150 m length.

The klystrons are of the external cavity type, having four cavities to achieve the required gain (> 42 dB) and beam efficiency (> 42%). The focusing electromagnets, electron gun, third and final cavities and output coaxial line, incorporating a harmonic filter, are forced air cooled. The collector and body are water cooled. The overall efficiency of the plant is > 37%.

Individual beam supplies employ thyristor primary regulation so that beam voltage, normally 27 kV, can be set to any value and be quickly inhibited in the event of a breakdown in the power supply or klystron.

As in the 200 MHz amplifiers hardwired interlocks, comprehensive analog and RF monitoring and remote control via the accelerator computer system are included.

Acknowledgements
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Reference
1. G. Dôme, The SPS acceleration system. Travelling wave drift tube structure for the CERN SPS, Proc. 1976 Proton Linac Conf., Chalk River, Canada.