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RF POWER AMPLIFIER FOR THE CERN SPS OPERATING AS LEP INJECTOR

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Summary

To permit electron-positron acceleration in the SPS, a new 200 MHz RF system will be installed. The system consists of 32 single-cell, high Q accelerating cavities, providing a total peak accelerating voltage of 30 MV. Each cavity will be equipped with an RF power amplifier, capable of delivering 60 kW CW or 110 kW pulsed power (pulse length up to 1 second, duty cycle up to 20 %). The power amplifier will be mounted directly on top of the cavity. Since the space in the existing SPS tunnel is very limited, a compact amplifier is needed, requiring special RF circuitry design. Also the choice of material is restricted due to the presence of ionizing radiation in the tunnel. This paper describes the design of the amplifier and presents the test results, obtained on a prototype version.

Introduction

A total peak accelerating voltage of 30 MV at 200 MHz is required to accelerate electrons and positrons in the SPS up to the LEP injection energy of 20 GeV [1]. Since 32 accelerating cavities will be installed, approximately 1 MV per cavity is required, taking into consideration a bit of redundancy. To achieve this voltage a power of about 60 kW must be delivered to each cavity. Disregarding the costs, there is not enough space available in the SPS access pit and tunnel (60 m underground) to install 32 high power transmission lines. The power amplifier will therefore be mounted directly on top of the cavity.

For the SPS working as LEP injector, only pulsed RF operation is needed. However, the new RF system will also be used in the proton-antiproton collider mode, where CW operation is required. The power amplifier is therefore rated for CW or pulsed output power of 60 kW. Since the RF power tetrode is capable of delivering higher output power under pulse condition, the amplifier is designed in addition for 110 kW output power with a pulse length of up to 1 second and a duty factor of up to 20 %.

The amplifier will be mounted on the cavity via a short coaxial transmission line. This line transforms the cavity input impedance to a parallel resonance circuit at the amplifier output and permits the installation of directional couplers for measuring forward and reflected power. A coaxial ceramic window with a coupling loop is installed between cavity and transmission line. A characteristic impedance of 10 Ω has been chosen for this window, resulting in a minimum electrical field strength under matched condition (a characteristic impedance of 30 Ω in air corresponds to 10 Ω with a dielectric constant of 9). The cavity resonance impedance of about 9 MΩ is transformed via the coupling loop to the low values required, i.e. 16 Ω for 60 kW and 8 Ω for 110 kW operation. These low impedances keep the electrical field strength at the window small and allow a compact amplifier design.

Since the drive system will be installed on the surface, i.e. up to 300 m away from the final amplifiers, low drive power is appreciated to minimize size and losses of the RF drive cables.

Amplifier design

The design of the amplifier is mainly determined by space limitations, reliability and fast exchange in case of a breakdown.

To get a compact amplifier the RF output circuit is positioned around the tube socket. In this arrangement, the RF input line together with the DC bias, the filament and cathode cables and the hoses for the control grid - screen grid circuit water cooling pass through the RF output circuit and are decoupled via folded $\lambda/4$ stubs. Neither the output coupling nor the input matching are adjustable. Only tuning of the amplifier is foreseen.

To permit reliable operation in the radioactive environment of the SPS tunnel, care must be taken in the choice of materials of the amplifier. Teflon must be avoided. Where organic materials are required, only Polyimide (Kapton, Vespel), Polystyrene, Polyamide-imide (Torlon), Polyphenylene oxide and Silicone are employed, whenever possible.

Fast exchange of a faulty amplifier is made feasible by using connectors for all electrical connections (RF drive, HV anode, bias, cathode, filament, interlock), quick disconnect type couplings for water and air cooling hoses and a quick flange RF connection between amplifier and cavity. A small fork lift is used to transport the amplifier and to place it onto the cavity flange. The time needed by one man to exchange an amplifier completely is less than five minutes.

A photo of the amplifier, mounted on a coaxial line, is shown in Fig. 1. One can recognize three of the four output circuit feed-throughs, i.e. RF input on the right, filament in the middle and control grid - screen grid circuit cooling on the left. The cathode feed-through is identical to the one of the filament, but placed opposite to it (hidden by the tube housing). The tube housing contains the tetrode, the anode blocking capacitor, the anode cooling hoses and the anode filter. The housing is simply lowered into the socket and kept in place by its own weight and a number of RF and high current contacts. Water inlet and outlet for the anode water cooling and HV anode connector are mounted on top of the tube housing, whereas the cooling air inlets are installed on a manifold at the bottom of the amplifier. The bias connector cannot be seen on the photo, since it is mounted behind the RF input. The total height of the amplifier is 75 cm and its maximum diameter 45 cm.

A water-cooled, metal-ceramic tetrode (Siemens RS 2058 CJ) is employed, rated at 90 kW anode dissipation and capable of delivering a peak cathode current of 100 A. The tube is operated in the grounded screen grid mode and in class AB as a compromise between high efficiency and low drive power.

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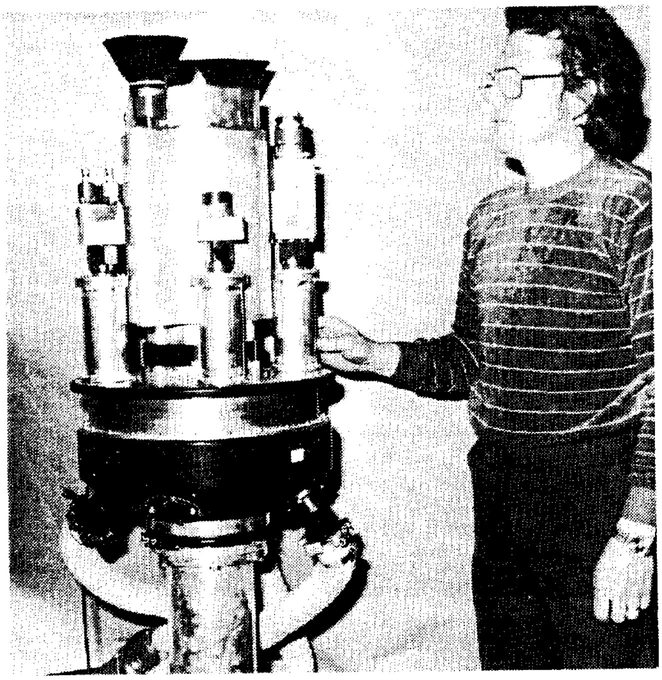

Fig. 1 60/110 kW 200 MHz power amplifier

In the following the main parts of the power amplifier will be described briefly.

RF output circuit

The load impedance seen by the amplifier, i.e. 16 Ω and 8 Ω, respectively, must be transformed to the optimum anode impedance of the tetrode for high efficient operation. At a DC anode voltage of 10 kV the optimum anode impedance is about 600 Ω for 60 kW and about 300 Ω for 110 kW output power. In principle, two λ/4 transformations are used to achieve this task (see Fig. 2).

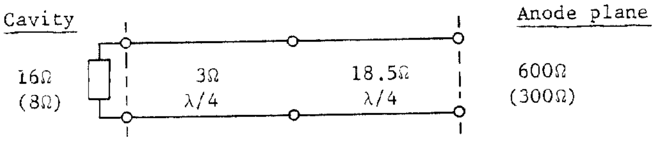

Fig.2 Principle of amplifier output circuit

In practice a more complicated transformation is obtained as can be seen in Fig. 3. The 3 Ω line is made of a 170 mm φ coaxial line, followed by a conical line and a 390 mm φ coaxial line. The 18.5 Ω line is approximated by a combination of coaxial and radial lines, followed by the transformation inside the tube. The approximation is not valid for all output impedances, but works very well in the 8 to 16 Ω range. The main advantages of this type of output circuit are a compact layout, since no special output coupling is needed and consequently a homogeneous field distribution.

Higher order modes are suppressed by coupling loops terminated in 50 Ω. The loops are orientated in such a way that they couple to the axial magnetic field of the spurious mode, but not to the circumferential magnetic field of the fundamental and its harmonics. Tuning of these loops to the frequency of a special mode is not required.

The anode blocking capacitor consists of a low impedance coaxial line, using 5 layers of 50 μ Kapton film as dielectric, an aluminium inner conductor and a brass outer conductor, both silver-plated. Assembly of the capacitor is made by winding the Kapton foil around the inner conductor and by sliding the outer conductor, after being heated to about 200°C, over the inner conductor. At room temperature a force of about 1.5 tons is required to separate the two conductors again. When during high power operation the capacitor warms up, this force is even higher, since due to the higher dilatation of aluminium compared to brass, the inner conductor will be pressed against the outer conductor. The capacitor has a low frequency capacitance of about 10 nF. At 200 MHz it is approximately an open-ended λ/4 transmission line, representing a very low impedance to the output circuit current.

The tuning of the amplifier can be adjusted by four tuning nuts, placed on the four output circuit feed-throughs. By tuning these nuts, the screen grid base plate together with the tetrode and its housing can be moved.

RF input circuit

The low input impedance of the tetrode in grounded grid operation is transformed via a 15 Ω coaxial line, a radial line and a 25 Ω coaxial line to an impedance approaching 50 Ω (Fig. 3). Then a T-junction, terminated on one side with an open-ended 25 Ω coaxial stub, is used to compensate the reactive part of the admittance. The real part is transformed via a λ/4 coaxial line into 50 Ω. Since the inner conductor of the input line is on cathode potential and the outer conductor on control grid potential, a ceramic coupling capacitor of 3.3 nF and four ceramic blocking capacitors of 3 nF, each, are employed to permit DC decoupled RF feeding. A Kapton foil is inserted between outer conductor and ground to avoid DC voltage breakdown. The mounting of coupling and blocking capacitors is designed in such a way, that matching is realized when the 50 Ω coaxial input line is terminated with 50 Ω.

Control grid - screen grid circuit

The impedance of the control grid - screen grid circuit should be low for the fundamental and its harmonics at the plane of the active system of the tetrode. A lossy radial line (Fig. 3), terminated with a ring of capacitors (32 capacitors of 2 nF, each) provides this performance. Eccosorb MF 124 (Emerson + Cuming) has been choosen as dielectric for the radial line. This material is machinable and has adequate electric and magnetic properties over a wide frequency range. Again, a Kapton foil is inserted between Eccosorb and control grid and screen grid plate, respectively, to reduce the risk of a voltage breakdown.

DC and filament feeding

The anode DC voltage is fed via an anode filter and a feed-through to the tube (Fig. 3). The filter consists of an LC network and a lossy cable to suppress the fundamental and its harmonics.

The control grid bias voltage is connected to the outer conductor of the RF input line. This connection is not shown in Fig. 3, since it is mounted behind the RF input part. Also here an LC-filter and a lossy cable are employed to suppress RF on the DC line.

No separate input is needed for the screen grid, because it is grounded. The cathode connection is made via one of the two filament cables.

The filament conductors pass through the RF input circuit near to the socket of the tube. Decoupling from RF is achieved by mounting each conductor in a λ/4 line configuration, short-circuited via a ring of ceramic capacitors (6 capacitors of 3 nF, each).

Amplifier cooling

The water hoses for the anode cooling are placed around the anode blocking capacitor (Fig. 3). They have a length of 3.5 m, each, to keep electrolytic effects small. Screen grid and control grid bases are also water-cooled to maintain the Eccosorb in the radial line at low temperature and to minimize the amount of warm air in the SPS tunnel. Air cooling is required for the electrode rings and the ceramics of the tube and for the other components of the amplifier. A manifold is placed around the 3 Ω output circuit line. The air passes through holes in the separating wall into this line and is then directed partly via the RF output to the tube socket and partly via the upper part of the output circuit to the anode ceramic. A "Vespel" disc (glass fiber reinforced Kapton) guides the air to the lower part of the ceramic, near to the screen grid electrode ring, where good cooling is needed. The main air outlet is through the RF contacts of the anode blocking capacitor and through holes in the cylinder around these contacts. A small fraction of the air passes through the four output circuit feed-throughs and through the tube housing, cooling RF input and filament lines and coupling and blocking capacitors.
To avoid overheating at the inside of the filament ring at the bottom of the tetrode, additional air flow is required at this spot, which is achieved by two small hoses, connected directly to the cooling air manifold.

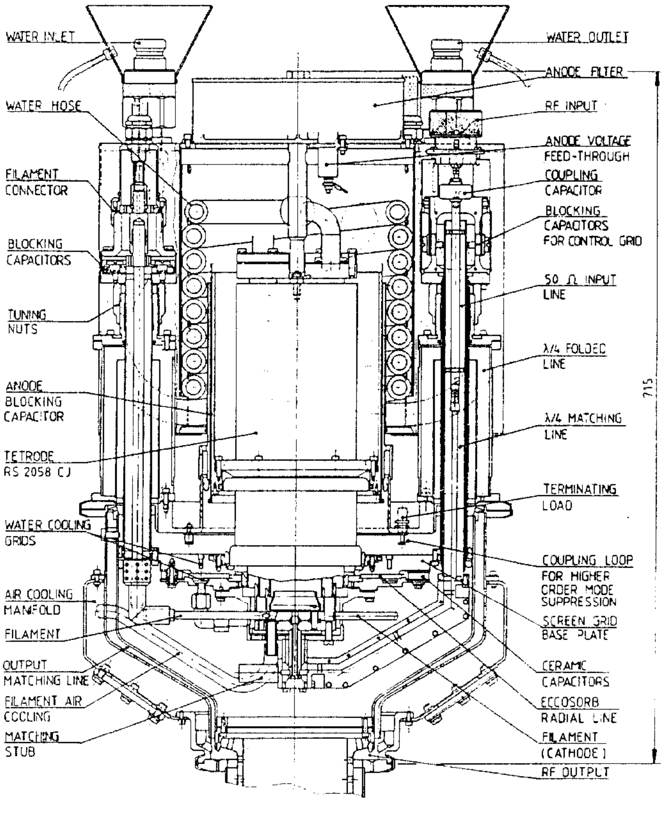

Fig. 3 Cross section of the 60/110 kW 200 MHz power amplifier

Test results

A prototype amplifier was first tested on a terminating load. The 50 Ω load is transformed via λ/4 coaxial lines to 16 Ω for CW and 8 Ω for pulsed operation. The following results have been obtained at 200 MHz:

	CW operation	pulsed operation pulse length 1s duty cycle 20%
anode voltage	10 kV	10 kV
anode quiescent current	0.5 A	0.5 A
anode current	9.4 A	17.0 A
screen grid voltage	900 V	900 V
screen grid curent	320 m A	405 m A
control grid voltage	-200 V	-200 V
control grid current	105 mA	780 mA
filament voltage	12 V	12 V
filament current	180 A	180 A
RF output power	62 kW	114 kW
RF drive power	1.8 kW	5.2 kW
gain	15.4 dB	13.4 dB
anode efficiency	64%	64%

The amplifier proved to be stable at all possible RF and DC power levels. No higher order modes or other spurious oscillations were observed.

RF input matching has been checked for CW operation with five different tetrodes RS 2058 CJ from the series production. The reflection coefficient was less than 5% in all five cases.

After these tests on a terminating load, the amplifier was mounted on the cavity. Only CW operation, with the coupling loop adjusted to 16 Ω cavity input impedance, has been tried so far. Also under these conditions, higher order modes were not observed; however, a spurious oscillation occured at about 198 MHz. At this frequency, the low off-resonance cavity input impedance is transformed to a very high impedance at the anode plane of the tetrode. To suppress the oscillation good screening of the driver system is required, to avoid external feedback. If necessary, an optimisation of the coupling loop - transmission line configuration could be envisaged to shift the frequency of the spurious oscillation further away from the operating frequency. In the present test set-up configuration the transmission line is shorter than required to transform the cavity input impedance to a parallel resonance circuit at the amplifier output plane. This results in a compact layout, but as a consequence, within the cavity bandwidth the anode impedance reaches its maximum not at cavity resonance, but at a higher frequency and the spurious frequency appears near the operating frequency. On the other hand the system will in the definitive installation be less sensitive to this type of spurious mode due to the long distance between driver and final amplifier and the RF drive cable attenuation.

After suppression of the spurious mode in the test set-up, full CW cavity power of 60 kW was reached.

Acknowledgements

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Reference

[1] LEP Design Report, Vol. 1, CERN, Geneva. 1983.