HIGH POWER UHF COMPONENTS FOR DESY

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Summary: Data are presented about the design and performance of high power uhf components used at DESY to accelerate electrons up to 6.5 Gev. Provisions and additional requirements for an extension of the beam energy up to 7.5 or 8 Gev are briefly described.

RF Design Parameters

In its original design concept (1958) DESY was planned as a strong focusing synchrotron for an energy of 6 Gev, similar to the Cambridge Electron Accelerator (CEA), but with a basic structure for still higher energies. An eventual increase of the energy up to 7.5 Gev in a later stage of development was provided. The differences in rf equipment cost and operational problems for the two energies were assumed to be considerable due to the rapidly growing energy losses by synchrotron radiation. For the chosen orbit radius r_o = 31,6 m in the 48 magnet sectors, the radiation losses amount to 3.6 Mev per turn at 6 Gev and rise to 8.8 Mev at 7.5 Gev. This corresponds to a ratio of 6 in dissipated rf power for a given number of accelerating units. Therefore, it was expected that some difficult rf problems would exist for beam energies of 6 Gev and above.

In 1964, energies between 6 and 7 Gev were achieved. It is now intended to further increase the power of the rf transmitter to limits which are set by the general parameters and performance of the machine. An ultimate limit will be given by the maximum possible magnet excitation which corresponds to 8 Gev. However, operational experience has shown that the question of maximum beam energy in practice is much more complex and involves many additional problems as, for instance, vacuum pressure stability, lifetime of materials under heavy radiation, mechanical vibration, etc. The rf power amplifier was designed such that the rf power costs may be matched step by step to the momentary requirements of the machine which may vary in a wide range.

Typical rf acceleration pulses for different beam energies are shown in figure 1. With an equilibrium phase angle of 45° the maximum rf accelerating voltage is 5.1 Million volts for 6 Gev and 12.5 Mv for 7.5 Gev operation. The pulse repetition rate is 50 c/s with a design number of 10^{11} accelerated particles per pulse. A 40 Mev-S-band linac is used as injector.

The frequency of the rf system is the sixth subharmonic of the linac frequency or 499,65 Mc/s (λ_o = 60 cm). The frequency range of UHF - TV was attractive since high power amplifier tubes such as triodes, tetrodes, and klystrons were available for long pulse operation. Size and shunt resistance of the accelerating units (the latter being proportional to the square root of frequency for a given length) made the highest possible operation frequency desirable. A high-Q cavity system representing a total shunt resistance of 160 Megohms has been realized, using 16 straight sections of the machine for rf acceleration, each 1.75 m long. The distances between individual accelerating units in the magnet structure correspond to 33 λ_o; the total circumference of the orbit is 528 λ_o = 316.8 m.

Power Amplifier

Instead of several individual rf power sources a single common power amplifier was preferred, placed outside the accelerator tunnel. The main reasons for this solution were lower cost, ease of operation and maintenance, as well as simplicity of a later extension to higher energies.

For the first stage of operation 2 Eimac X 602 K klystrons were provided, with the possibility to use them individually or in parallel. Each klystron can produce 200 kw peak pulse and 75 kw average rf power. The maximum applied beam voltage is 50 kilovolts, beam pulse current 9.5 A, efficiency 40 - 45 percent. After a short section of 6 1/8" coaxial waveguide, the rf output signal is transferred to 18" x 9" rectangular waveguide which is used throughout the cavity feeding system.

For lower energy operation of the synchrotron only one klystron is used and the second serves as standby amplifier. At small beam intensity a beam energy up to 6 Gev can thus be achieved. If parallel operation is required, a waveguide diplexer combines the rf output signals of the two klystrons without affecting the individual tuning. The rf input signal of one klystron amplifier is fed through a variable coaxial phase shifter which is set in a position leading to minimum rf power (nearly zero) at the balance resistor of the diplexer. The same resistor is used as dummy load for power tests on individual klystrons. Quick waveguide switching for a number of different operation modes is provided by means of 3 double-way waveguide switches which are interconnected and support the "magic T"-diplexer. This is illustrated in figure 2. Switches and aluminum waveguides were designed and fabricated by C.H. Jucho

Comp., Dortmund, in cooperation with DESY. A simplified block diagram of the whole rf transmitter in its present stage is shown in figure 3.

A ferrite isolator was installed in the waveguide run to the accelerator in order to protect the klystron output circuits against excessive reflexion. Such reflexions have to be considered as regular operation conditions in the following cases: (a) if the beam loading ratio of the high-Q accelerating units is high, (b) if a small frequency modulation is applied to reduce beam losses by beam loading effects. Reflexion also occurs during cavity tuning or if bad vacuum pressure leads to ionization inside the cavities. The isolator, designed and manufactured by Raytheon Comp., was specified and tested for 400 kw peak, 100 kw average rf input power, and 20 kw total average dissipated power. 12 db isolation and .35 db insertion loss were achieved.

For 7.5 Gev operation and high beam intensity a circulator would be advantageous to handle the reverse flow of rf energy; this device should be capable to transmit 1 to 2 Mw peak and about 300 kw average rf power.

Alternatively, as protection against undesired undercoupled operation of the klystrons, the electrical length of the feeding line can be adjusted by phase shifters to an integral number of half wavelengths. If, in this case, the load impedance at the end is lowered by the particle beam or by detuning, the klystron gap also sees a lower impedance and will work at a lower voltage. Approximate short-circuit operation occurs if the cavity voltage has to be kept small at the beginning of the acceleration cycle under high beam loading conditions, i.e. if the transformed current of the generator practically equals the beam current. If no other beam instabilities are dominant, the generator current sets a static limit to beam intensity. This limit is rather high if the rf power amplifier is capable to run at nearly the same dc input power during the whole acceleration cycle (see ref.1).

Considerations on beam loading effects determined the dimensioning of the rf power amplifier and its dc power supply with respect to average rf output and maximum anode dissipation. A regulated, continuously controllable high-voltage dc supply was installed which can deliver up to 800 kw average dc input power at 50 kv or 25 kv. This unit already provides the maximum dc input power for 7.5 Gev operation and was designed to feed either klystrons or super power triodes. Klystrons for a higher beam energy of DESY should have a microperveance of 2.3, 500 kw peak and 150 to 250 kw average rf output power, 400 kw average collector dissipation; 3 db bandwidth of 3 Mc/s and power gain of about 35 db.

RF Modulation and Drive

At present, the synchrotron still operates without automatic beam control. Slow AM and FM are applied, programmed by function generators. As shown in figure 3, the AM signal is amplified to the high voltage level required by the klystron modulating anodes. A rise- (or fall-) time of 30 (or 5) microseconds is typical for this modulator circuit.

Faster amplitude modulation (and phase modulation) of the rf output signal will be necessary if one wants to increase the beam intensity by suppressing transients in cavity excitation (see ref. 2 and 3). In this case the rf drive signal can be modulated. A slightly modified 2 kw-TV-video transmitter was provided for this purpose. Its relatively high output power can also be used to drive several bigger klystrons or triode stages for 7.5 Gev operation. As linear amplifiers, klystrons generally have lower efficiency than triodes at small signal ratio α, but they do not need additional intermediate amplifiers. They work in class A and have an efficiency $\eta = \alpha^2\eta_0$, whereas triodes in class B have $\eta = \alpha\,\eta_0$. Here, η_0 is the optimum efficiency for $\alpha = 1$. In order to improve the klystron efficiency, the beam current can be pulsed such that enough peak power is available during the acceleration cycle.

The overall bandwidth of the present 400 kw transmitter is about 3 Mc/s (3 db-points) for fast amplitude modulation and about 1 Mc/s for fast phase modulation. A rise time below .3 microsecond can be realized. For stable feedback against coherent phase oscillations, a more serious limit will be the time delay of about 1 microsecond in the control loop due to the distance between beam and rf power amplifier. Stable feedback will be possible if no coherent phase oscillations faster than 150 kc/s occur.

Accelerating Cavities

The rf accelerating units of DESY are short linear accelerator sections operating with standing waves. Their structure and electrical performance is illustrated in figures 4 and 5. 3 TM_{010}-copper resonators, each half a wavelength or 30 cm long, are strongly coupled together and excited in π-mode. The inner diameter is 46.5 cm. Drift tubes have been avoided in order to get a structure of greater technological simplicity and more effective cooling. 12 cm irises are used for capacitive coupling; this diameter corresponds roughly to the radial aperture of the vacuum chamber and gives a coupling coefficient of about 270 relative bandwidths. The unloaded Q, theoretically 43000, was measured between 38000 and 40000.

The rf power is fed into the central section through a 13 cm coupling hole which transforms the shunt resistance of the unit ($\approx$10 MΩ) to the characteristic impedance of the feeding waveguide. A ceramic window of 99.5 percent alumina, 8 mm thick and 16 cm in diameter, serves as vacuum window. At a distance of a quarter wavelength the waveguide is shortened, thus producing a current maximum across the coupling hole.

Remotely controlled water-cooled plungers in each cavity section permit precise tuning in a range of 300 kc/s corresponding to 24 bandwidths. Directional couplers in the feeding waveguides provide information about forward and reflected power on each accelerating unit. For high-power operation, automatic tuning is possible by means of phase discriminators. These units, which are combined with remote manual control, have been installed in the transmitter room and connected with accelerating units by coaxial cables of equal electrical length. In this way voltage and phase of each cavity section can be monitored if necessary.

An extensive development work was carried out for design and fabrication of the accelerating cavities and control devices. A short description of the manufacturing process is given in ref. 4). The vacuum-tight OFHC-copper structure was produced by electroforming and brazing. Stainless-steel flanges were provided for the use with aluminum gaskets, thus high bake-out temperatures are possible. A leakage rate below 10^{-6} torr l/s was achieved. Under normal operation conditions the pumping speed of a 125 l/s ion getter pump is sufficient to keep the vacuum pressure at 10^{-6} torr or below. High-power tests were carried out with 300 kw peak and 28 kw average rf power dissipation in a single unit. This corresponds to about twice the accelerating voltage which will be necessary for 7.5 Gev operation. It was found that a low partial pressure of heavy hydro-carbons is essential to avoid ionization in the electric field.

As shown in figure 5, discs and outer walls of the cavities are directly water cooled. Equal distribution of longitudinal and transverse water flow is accomplished by mutually connected channels.

Waveguide Ring System

A resonant waveguide ring (as proposed by K.W. Robinson for CEA, see ref.5) is applied to feed all cavities with an equal voltage and phase. The equivalent circuit is shown in figure 6. Each of the 16 waveguide sections is electrically 24 wavelengths long and can be tuned within ± 10° by variable phase shifters. The ring is fed at one single point and connected to the rf generator by a 80 m long waveguide run.

16 tee junctions incorporating exchangeable iris diaphragms are used to extract rf power from the ring by means of short waveguide branches which feed the individual cavities. These branches are matched if the cavities are in resonance. Their electrical length can be adjusted to an integral number of half wavelengths such that the extracted power from the ring increases rapidly if individual cavities are detuned. Thus cavity voltage and phase is kept constant over a wide range of tuning errors as shown in fig.7.

The mutual coupling of the cavities in amplitude and phase depends on the loading parameter $1/k = Z/R'$. Standing wave ratios and power losses in the ring are proportional to k (if $k \gg 1$). For the chosen value $k = 20$, 8% of the rf power is lost in the ring.

A dangerous condition for the waveguide branch is complete detuning of individual cavities, for instance by ionization. In this case the incident and reflected power may rise by several orders of magnitude and may damage waveguide walls and cavity windows by arcing. Individual accelerating units can be taken off from the ring if necessary. For this purpose shorting walls are introduced in the waveguide branches at points which give small power losses.

Application to Storage Rings

Similar accelerating units and uhf power sources are of interest for the eventual construction of an electron-positron storage ring at DESY. Stored beams of 2 x 1 amp. at 3 Gev require a CW power of the order of 1 Mw. 4 accelerating units operated at a vacuum pressure of 10^{-9} torr, will be necessary to transfer this power to the circulating beams.

Acknowledgment

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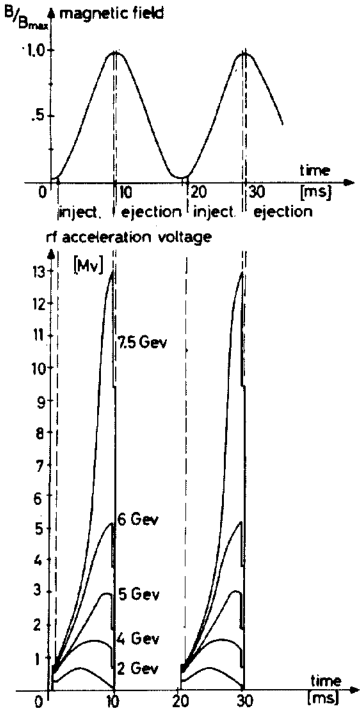

Fig. 1. Typical shape of rf pulses at different energies.

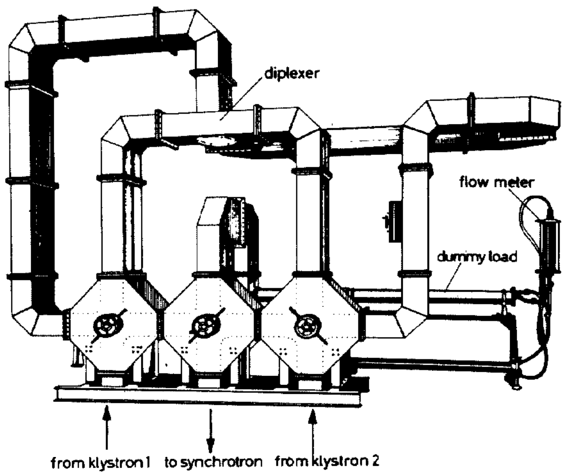

Fig. 2. Waveguide switching and diplexing unit.

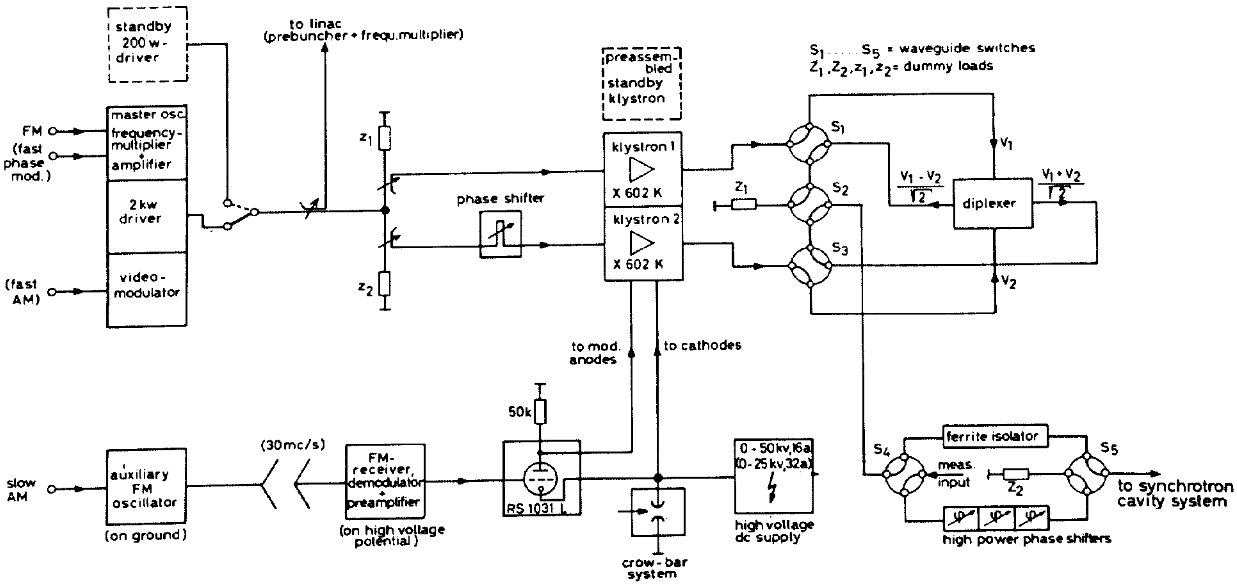

Fig. 3. Simplified block diagram of 400 kw uhf transmitter.

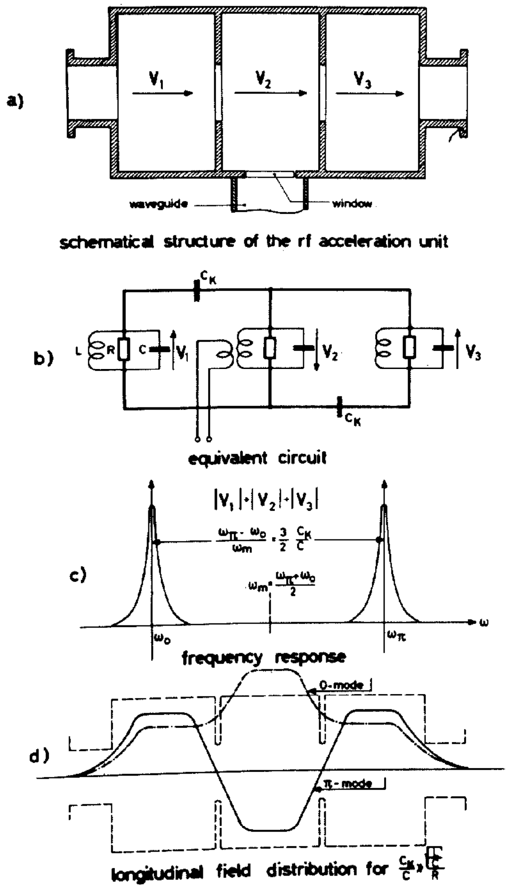

Fig. 4. (a) Schematical structure of the rf acceleration unit. (b) Equivalent circuit. (c) Frequency response. (d) Longitudinal field distribution for $\frac{C_K}{C} \gg \frac{\frac{L}{C}}{R}$

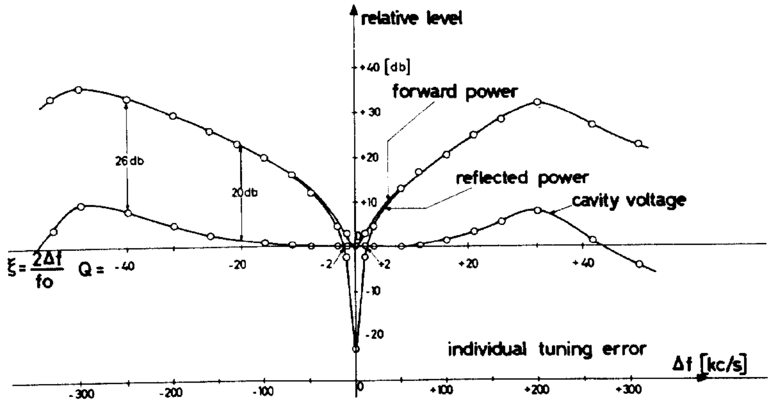

Fig. 7. Effect of individual tuning errors in strongly coupled ring system.

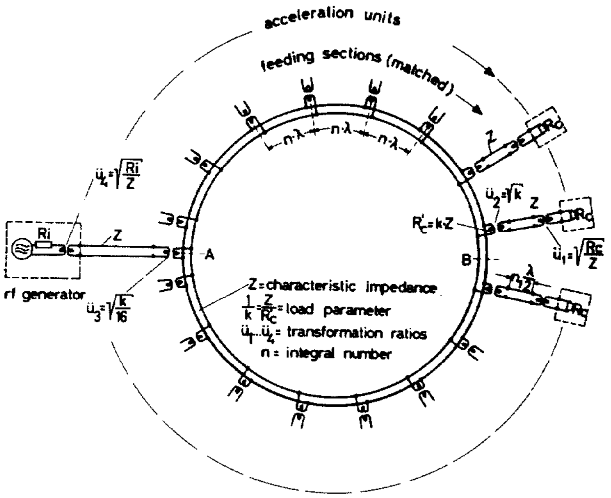

Fig. 6. Equivalent Circuit of RF ring system.

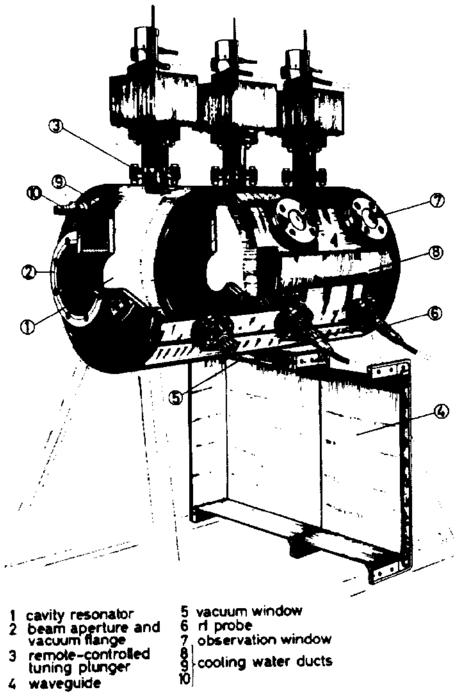

Fig. 5. RF acceleration unit.