DEVELOPMENTS OF HIGH POWER RF COMPONENTS

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Abstract

A summary is given for recent development of high power RF components to be used at high-energy or high-intensity accelerators planned for near future. Stress is put on such passive waveguide components as RF-power boosters, dummy loads and ceramic windows. Of most concern are the thermal stresses for low-frequency components, whereas high surface electric fields are for high frequency ones.

Introduction

Ever larger RF powers with their frequency ranging from UHF to X-band and higher are being required for near-future high-energy or high-intensity accelerators. Therefore R&D work for high power RF components would be vital for realization of those plans.

This article deals mainly with key waveguide components used between the output window of RF power sources and the input of accelerating structures. They include: RF pulse compression systems, dummy loads, mode converters and ceramic windows.

RF pulse compressors are a passive system to boost peak of RF powers by compressing their width. There are such devices of this kind as resonant rings, SLED or open cavities and SLED II systems.

Dummy loads are very important not only for waveguide systems but also for accelerating cavities where a lot of higher order mode (HOM) power should be absorbed since beam currents are becoming larger and larger at recent accelerators.

Output windows are a vital component of high power klystrons. They limit output power levels and tube life. Studies should cover RF field distributions. ceramic materials and coating films.

First a summary is given for RF power requirements for typical large-scale accelerator programs. Then discussions about the above issues are described on the basis of results obtained at large accelerator R&D programs, mainly carried on at BINP, SLAC and KEK, which are based on conventional klystron technologies.

RF Power Requirements in Large Accelerators

Both designed and presently achieved output power ratings of klystrons for typical large-scale accelerator programs are summarized in Table 1. At UHF- and L-bands, powers are around 1 MW for CW operation or a few MW for millisecond long pulse operation with duty factors on the order of 10 %. At S- and X-bands, pulsed powers on the order of 100 MW are obtained with the length ranging from sub-micro to a few micro seconds. Most of the programs listed in Table 1 are in an R&D phase except for the TRISTAN ring. Output powers achieved are, however, not very far from design goals. Those RF power ratings require relevant RF components at a low frequency range to clear thermal problems while at a high frequency range to withstand high RF fields.

For convenience in later discussions, Table 2 summarizes typical RF characteristics of standard waveguides corresponding to each program listed in Table 1. The maximum transverse electric field would be of particular interest for high power operation. For a rectangular waveguide with width a and height b, transmitting average power P in the fundamental TE_{10} mode, the maximum electric field is given by

$$E = \sqrt{(4\zeta_0 \lambda P)/(ab\lambda_g)} \qquad (1)$$

where ζ_0 is the free space impedance (377 ohms), λ the free space wavelength and λ_g the guide wavelength. For example, in a WR 90 waveguide (a=22.86 mm, b=10.16 mm) which is usually used for 11.4 GHz X-band components, 100 MW power transmission generates an electric field E of 23.1 kV/mm. For the standard S-band waveguide WR 284 (a=72.14 mm, b=34.04 mm), E=6.5 kV/mm at 2856 MHz at the same power level.

For circular waveguides, the formula is rather complicated and only results are given for typical examples. For 2856 MHz S-band pill-box windows, a cylinder of 42 mm radius has typically been used with a TE_{11} mode being excited therein. The maximum electric field is then 4.6 kV/mm for 100 MW transmission. For an overmoded 11.4 GHz circular guide of 60 mm radius, E is 2.6 kV/mm for the TE_{11} mode and 3.7 kV/mm for the TE_{01} mode when 100 MW is transmitted.

Passive RF Power Booster

Resonant Ring

Resonant rings are a popular instrument to test high power components, especially windows, at frequencies ranging from L-band to X-band. They are operated not only in pulse mode but also in CW mode.

A resonant ring made of WR 650 waveguides was used in order to test an L-band window for the NPC 1248 MHz klystron. It boosted the input power up by 40 times to 1.2 MW CW. In a 4 ms-pulse mode, 4.5 MW at a repetition rate of 50 Hz[1]. S-band resonant rings are most commonly used for window tests. Their resonating power levels are on the order of 400 MW or more. An X-band resonant ring also for window tests multiplied 14.5 MW 300 ns long input pulses to 102 MW peak and 8.6 MW 700 ns pulses to 72 MW peak.

SLED

The SLED cavity system is now widely used for many S-band electron linacs. At the KEK ATF 1.5 GeV linac, for example, 2856 MHz, 80 MW, 4.5 μs klystron output pulses are compressed to 400 MW peak, 1 μs long pulses with this method. A 11.4 GHz system was also constructed by simply

TABLE 1
Klystron Power Requirements for Large Accelerator Programs

Accelerator	Freq.	Design Goal		Present Status		Klystron
	MHz	MW	DUTY	MW	DUTY	TYPE
JHP(RFQ, DTL)	432	2.0	0.6ms. 50Hz	2.0	0.6ms. 20Hz	TH2134
TRISTAN	509	1.2 1.0	CW CW	1.25 1.1	CW CW	E3786 YK1303
PNC CW LINAC	1,248	4.1 1.2	4ms, 50Hz CW	1.2 0.33	4ms CW	E3718 E3718
JHP(CCL)	1,296	6.0	0.6ms, 50Hz	5.0	0.4ms, 50Hz	TH2104
ATF LINAC	2,856	80 100	4.5μs, 50Hz 1μs, 50Hz	85 120	4.5μs, 50Hz 1μs, 50Hz	E3712 E3712
NLC LINAC	11,424	≥100	1.5μs, 180Hz	51 87	1.5μs, 180Hz 0.2μs, 180Hz	XL1 XC6
JLC LINAC	11424	≥100	0.5μs, 150Hz	90	50ns, 4Hz	XB72K
VLEPP LINAC	14,000	150	0.7μs, 300Hz	60	0.7μs, 1Hz	VLEPP

TABLE 2
Basic Waveguide Types for the Above Accelerator Programs

Accelerator	MHz	Basic Type	Size(mm)	Group Velocity(c)
JHP(RFQ, DTL)	432	WX152D(coaxial)	ϕ152/ϕ66	1.0
TRISTAN	509	WR1500(rectangular)	381/190.5	0.63
PNC CW LINAC	1,248	WR650(rectangular)	165.1/82.55	0.69
JHP(CCL)	1,296	WR650(rectangular)	165.1/82.55	0.71
ATF LINAC	2,856	WR284(rectangular)	72.14/34.04	0.67
NLC/JLC LINAC	11,424	WR90(rectangular)	22.86/10.16	0.82

scaling the S-band cavity dimensions down to one fourth[2]. Its peak output reached 60 MW with a pulse duration of 100 ns for 460 ns 16.2 MW peak input powers. High gradient tests of 20 cm long structures were carried out with this system and gradients over 100 MV/m were obtained[3].

Open Cavity

The open cavity system is a modification of the SLED. It uses a single open spherical cavity instead of two at the SLED. A waveguide is attached to its equator with many coupling irises which function as the 3 dB coupler of the SLED. The electromagnetic energy is resonantly piled up near the equator in a traveling wave mode of a very high Q value.

The first high power test of an open cavity system was recently carried out at 11.4 GHz[4]. It was smoothly conditioned up to a peak power level of 134 MW with a pulse duration of about 110 ns. The corresponding input power was 31.3 MW at peak, the maximum available from a klystron, with a duration of about 500 ns. The actual power gain was hence 4.2, while a theoretical one is 5.0.

SLED II

In the SLED II system, transmission lines are used instead of SLED cavities. Then we can expect a square-shaped output pulse as long as attenuation in the line can be neglected, while only ramping pulses are available in the SLED or open cavity systems.

A prototype system was recently tested at 11.4 GHz[5]. With 32 MW of 900 ns input power, 154 MW of approximately square output power was obtained with a duration of 75 ns, as shown in Fig. 1. The experimental gain was hence 4.8, while a theoretical one is 5.4. An overmoded cylindrical waveguide with a diameter of 7.14 cm was used in order to reduce the attenuation. A system for a much longer pulse length is under preparation, where a guide with a larger diameter of 12.1 cm will be used[6].

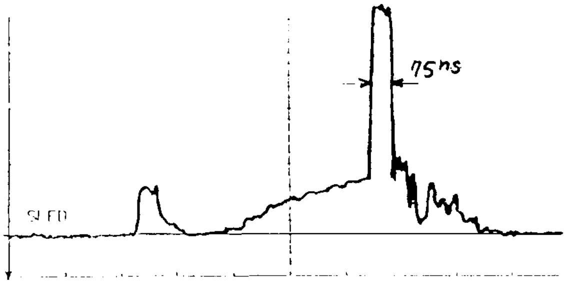

Fig. 1 Output pulse of the SLED II RF pulse compression system at the SLAC Accelerator Structure Test Area

Waveguide Components

Several waveguide components have been newly developed in connection with the pulse compression systems mentioned above. The most basic component would be a flange with a copper gasket to connect waveguides. They should be vacuum tight, be baked up to at least 150 °C and furthermore be capable of transmitting hundreds of MW of RF power. A fairly thin gasket is used for some design in order to constrain surface currents to a narrow region at the junction[7].

For X-band and higher frequencies, overmoded waveguides are indispensable to transmit power a long distance, since the attenuation increases as $f^{3/2}$ when the waveguide size is scaled as f^{-1}. For a copper waveguide of WR 90 type in Table 2, for example, the power attenuation constant of the TE_{10} mode is 2.2×10^{-2} m^{-1} at 11.4 GHz. The cylindrical waveguide 71.4 mm in diameter used for the SLED II test, on the other hand, has a power attenuation constant of only about 1.0×10^{-3} m^{-1} for the TE_{01} mode. If the diameter is enlarged to 12.1 cm as planned, the attenuation will be further reduced to $1.7\times10^{-4} m^{-1}$. For overmoded waveguides, however, mode mixing due to waveguide deformations should be carefully avoided, since the other modes have much larger attenuation constants.

A mode-converter is a key component in order to transform the TE_{01} mode of a standard rectangular waveguide to the TE_{01} mode of an overmoded circular waveguide. A very compact converter with "flower petal" slots have been developed and used successfully at high power levels[5]. It also becomes very easy to bend circular waveguides by 90° or 180° by using this converter.

Dummy Loads

In modern accelerators, high power dummy loads are indispensable components in order not only to match waveguides but also to absorb high-order-mode power from accelerating cavities. They as well as other waveguide components have to be vacuum tight. Water is anyway the most popular absorbing material. But for fear of damages caused by leakage, use of other new absorbing materials is being seriously considered.

Water

Water loads have long and widely been used for high power systems in a wide frequency range from UHF to X-band. This type of loads have been used for the 100 MW X-band klystron output system at KEK. It is simply a waveguide section with an alumina partition wall. With a wall thickness of about a quarter guide-wavelength, the matching of the load can be achieved, since the dielectric constant of alumina is approximately a square root of that of water($\varepsilon \sim 90$).

Ceramics

Dry loads with lossy AlN ceramics are being developed for absorbing multi-kilowatt powers of UHF to S-band frequencies[8]. In order to avoid cooling water channels, AlN is a good choice, since its heat conductivity is almost the same as that of aluminum. Its resistivity is, however, intrinsically very low. Therefore it is mixed with glassy carbon of several per cents by weight. A key issue here is to find a reliable technique to braze it to copper walls since the both materials have fairly different coefficients of thermal expansion.

Metal

For X-band and higher frequencies, metals themselves also are useful materials and indeed a few m long waveguide section would have an enough absorption coefficient. The attenuation constant in a waveguide is proportional to the metal surface-resistance given by

$$\zeta_m = \sqrt{(\omega\mu)/(2\sigma)} \qquad (2)$$

where μ is the permeability and σ the conductivity of the metal. A compact X-band load was fabricated by milling a folded WR 90 waveguide section with a reduced height of 4 mm and a length of 2 m out of a stainless steel block of ferritic type SUS 430. Its reflection coefficient was measured to be -44 dB. It was used for the open cavity pulse compression test to absorb 134 MW 110 ns pulsed powers at 11.4 GHz[9]. The dc conductivity of SUS 430 is about 1/35 times smaller than that for copper, while the measured surface-resistance was about 20 times larger than that for copper at this frequency[10]. Therefore an effective permeability μ of about 11 for this frequency can be deduced from eq. (2).

Ferrite

Ferrite absorbers are also under development for superconducting cavities which may be used in high-current storage rings such as the KEKB accelerators. They are placed on a beam pipe wall adjacent to the cavity to absorb HOM powers excited by beams in the cavity. A load developed at KEK is made of a 150 mm long, 3 mm thick cylinder of 109 mm in diameter made of a Mn-Zn ferrite. The ferrite is inserted inside a copper cylinder. They were bonded together by a HIP(hot isostatic pressing) process. High power tests were carried out up to a total absorption of 2.6 kW CW or an average absorption of 6.7 W/cm^2 at 2.45 GHz[11].

SiC

Silicon carbide is a semiconductor and has a relatively low conductivity, while its heat-conductivity is very high, being on the order of that of aluminum for specially processed samples. Therefore it might be very useful for high power microwave absorbers. In fact, hundreds of SiC absorbers, 2.4 cm in diameter and 30 cm long, have been used up to 10 MW peak, 1.75 kW average powers over 12 years without a failure at the KEK 2.5 GeV S-band linac[12][13]. It has a bullet-like shape with an inner cooling-water channel and is inserted into a high-vacuum S-band waveguide. A similar bullet absorbers are being developed as a HOM damper for normal-conducting cavities of the KEKB rings[14]. Prototypes, 4 cm in diameter and 40 cm long, were tested to an average power of ~2 kW at an L-band frequency. An outgassing rate of 3×10^{-12} Torr l/sec was achieved after baking. A key issue has been to obtain a good bonding with copper base. But it seems promising to use a silver alloy together with titanium which acts as an activating agent.

Window Technologies

Electric fields on ceramic disc surfaces

Electric fields on the ceramic surface of an output window are of most concern for high power klystrons. There are three important issues: 1) field directions, 2) reduction of field intensities and 3) surface breakdown due to parallel field components.

A typical configuration of conventional windows is a pillbox cavity, operating on the TE_{11} mode, with a thin alumina disk therein and waveguides on the both side-walls. Detailed computational analyses of multipacting phenomena were carried out for an S-band pillbox window with a diameter of 92 mm, a length of 28 mm and with a 3.5 mm thick ceramic disk. Windows of this type have been used for 30 MW klystrons of the KEK Photon Factory. Trajectories of both primary and secondary electrons were calculated by assuming typical secondary electron yields for alumina and using a traveling field pattern synthesized from standing wave patterns calculated with the MAFIA code. The field pattern has a noticeable TM_{11} component also, since the window diameter is large compared with the length. Then intense electric field lines terminate normally on the ceramic surface in the parts close to the waveguide openings. Calculations show that most electrons move along these normal electric field lines and bombard the ceramic disk, losing their kinetic energies therein. The simulated distribution of the energy loss agrees well with a color pattern usually observed on the ceramic disk surface after hours of high power operation.

Those results led to development of a longer pillbox window where the TM_{11} space-harmonics component is sufficiently reduced and the tangential TE_{11} field component then becomes dominant on the ceramic surface. For instance, a pillbox window, 402 mm long and 190.5 mm in diameter, with a 6.6 mm thick beryllia disk was developed in order to apply for the PNC L-band klystron. Power levels of 1.7 MW CW and 4.5 MW for 4 ms 50 Hz pulses were successfully reached in a 1248 MHz resonant ring test. Figure 2 shows a TE_{11} mode window with long taper sections developed for the JLC X-band klystron. It transmitted 50 Hz, 70 MW pulses with a flat top of about 200 ns in a resonant ring[16]. Another way of killing TM fields is to excite a TE_{01} mode, although it is necessary to employ such a converter as the flower petal type described above[17].

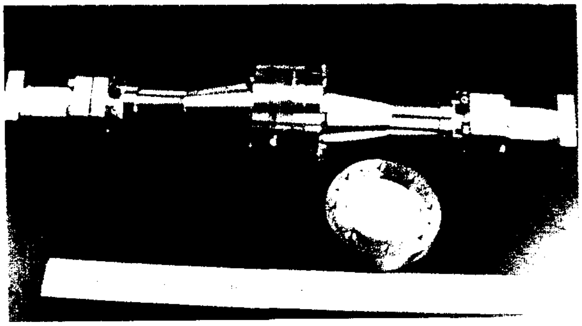

Fig. 2 TE_{11} mode window with a tapered transition developed for the JLC X-band klystron

Another effective way would be to use a ceramic disk in a traveling wave mode regime[18]. Electric fields on the ceramic disk surface are then reduced by a factor of about $\varepsilon^{1/4}$, where ε is the relative dielectric constant of a ceramic (about 9.5 for aluminas), compared with those for a matched waveguide of the same cross section. A preliminary test was carried out for a long pillbox S-band window with traveling wave in the ceramic. A 7.6 mm thick alumina disk was placed at the middle of a pillbox 127 mm long and 84 mm in diameter. Inserted in a resonant ring, it transmitted up to 400 MW of 2 μs, 50 Hz pulsed RF powers[19]. The disk thickness is approximately equal to $\lambda_g/4$ in order to make dimensional tolerances as loose as possible. Since the S-band result seems promising, a window of similar type is under development for the JLC X-band klystron, although the bandwidth becomes fairly smaller compared with a conventional window.

Properties of Alumina

Properties of typical aluminas under high RF powers were surveyed by using a conventional S-band window inserted in a resonant ring[20]. Of most concern was to compare dielectric losses and also to analyze change of physical properties when high voltage breakdowns occur.

In order to reduce the dielectric loss, it was found that an alumina must be as less porous as possible at any rate. An alumina with a purity of 99.9% had a loss tangent of 1.33×10^{-4}, while another with a purity of 99.0% had a loss tangent of 9.4×10^{-5}. The reason would be that the former had been sintered without binding additives in order to get a purer material but actually had a larger porosity. It was also found very effective to particularly reduce MgO contents among commonly used additives such as SiO_2, MgO, CaO, Fe_2O_3, Na_2O_3, etc.[21]. In fact a 99.9% alumina sintered with binders containing no MgO showed a loss tangent as low as 2.7×10^{-5}.

Another interesting phenomena is a correlation between oxygen vacancies in alumina and high voltage breakdowns. Every alumina including sapphire has 2-valence oxygen vacancies behaving as an F^+ center which traps one electron and has a 300 nm absorption peak. But aluminas which suffered from breakdown exhibit a second absorption peak at 410 nm which can be considered as an F center trapping two electrons. They may be generated by primary- and secondary-electron bombardment. The trapped electrons, however, are easily excited to a conduction band [22] and produce large joule losses resulting eventually in local melting of aluminas. Very few F centers were detectable for those materials which endured highest peak power ratings. Coating the alumina surface with TiN films was also effective to suppress production of F centers, since the secondary electron emission is sufficiently reduced. Sapphire has already F centers even without any high power processing. Indeed sapphire broke down at lowest power levels among the materials tested.

Coating technologies

Secondary electrons not only produce harmful F centers in alumina as stated above, but they also bring about a temperature rise in alumina by losing their kinetic energies. Therefore, for high power windows, it is crucial to properly coat the alumina surface with materials of low secondary-electron emissions.

Among several coating materials TiN films are most commonly used ones. They fall into two categories: pure titanium nitride and titanium-nitrogen oxide.

The former is more common because titanium is sputtered usually in a high vacuum chamber and hence in an oxygen-free ambience. This type of coating was used for the alumina test described just in the preceding section. It was indeed very effective in suppressing multipacting phenomena. However, TiN is intrinsically a metal and has a conductivity as high as $5.6 \times 10^4\ \Omega^{-1}\ \text{cm}^{-1}$. Therefore the film thickness should be less than 1 nm. Otherwise joule losses become serious with an overall surface conductivity being increased. But secondary electrons would have a typical energy of the order of 1 keV. Their range in TiN then would be about 0.5 μm, far larger than 1 nm. Operation time at the resonant ring test has not yet been long enough compared with an expected life of practical tubes. Therefore further investigations are necessary to conclude that such a thin film is really effective for a long life operation at extremely high power levels.

The latter type of coating, on the other hand, has solely been applied for output windows of the TRISTAN 508 MHz 1.2 MW CW klystrons and also the JLC ATF 85 MW S-band klystrons. This type of film is composed of Ti, N and O with the ratio 1 : ~0.5: ~0.5. It is processed by a dc sputtering method in a relatively oxygen-rich ambience. It has a columnar structure as shown in Fig. 3. Because of this unique polycrystalline structure, it behaves as a good insulator contrary to TiN. The resistivity is actually much higher than that of alumina. It can be grown as thick as 20 nm or more with its overall resistivity being almost unchanged. A recommended coating thickness was found to be in a range of 3 to 15 nm in bench tests by using high intensity UHF fields[23]. A thickness around 3 nm to 5 nm has been chosen for the windows of the above mentioned tubes. It is not yet clear that this type of coating can be used at extremely high field conditions as encountered in case of X-band high power windows.

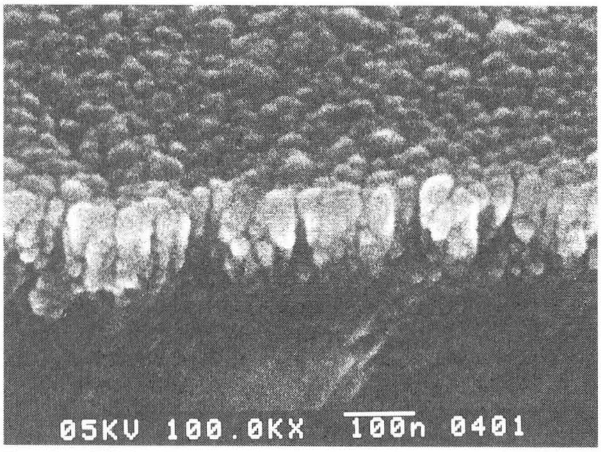

Fig. 3 SEM photograph of a cleaved layer of a titanium-nitrogen oxide grown up on an alumina substrate. The scale in the picture is 100 nm.

Conclusions

Passive components such as metal waveguides seem capable of handling high RF powers required at various accelerator projects. Regarding new ceramics and ferrites, future development is very promising, but a key issue is to establish reliable technologies to bond them to base metals. Window technologies would be most important in developing high power RF systems. More detailed studies of properties of aluminas including those of coatings are necessitated for future accelerator applications.

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