Studies of a Powerful PPM Focused X-band Klystron

P.Avrakhov, V.Balakin, V.Chashurin, V.Ezhov,
V.Ermakov, V.Gordienko, S.Kazakov, G.Kuznetzov, A.Larionov,
A.Lunin, N.Solyak, V.Teryaev, Yu.Valyaev, V.Vogel, Yu.Yakubov
Branch of the Institute of Nuclear Physic, Protvino, Russia
Y.H.Chin, S.Fukuda, T.Higo, S.Matsumoto, S.Michizono,
H.Mizuno, S.Tokomoto, H.Tsutsui
High Energy Accelerator Research Organization (KEK), Japan

Introduction

In 1997 BINP developed and produced PPM klystron for KEK. In the beginning of 1998 klystron was sent to Japan and was installed on the test-bench, where earlier were tested klystrons of $XB72K$ series [2]. In May 1998 the testing of the klystron was carried out. Efficiency, calculated with the help of 1-D DISKLY code, is about 45 %, 2-D simulation, carried out with the help of code MAGIC [2], has shown the efficiency equal to 44 %. The output Traveling Wave (TW) system is close to the output system of klystron $XB72K\#9$ [2]. The electric field strength at 100 MW of the output power achieves 760 kV/cm. Drift tube diameter and cavity shapes did not greatly differ from klystron $XB72K\#9$, where parasitic oscillations were not observed. We also hoped to avoid problems connected with parasitic oscillations. The table of parameters of the klystron is represented.

Table 1. Main parameters of the PPM klystron

	Design	Experiment
Operating Frequency	11424 MHz	11424 MHz
Voltage	550 kV	550 kV
Beam Current	380 A	377 A
Cathode	Oxide type	
Cathode Diameter	120 mm	
Microperveance	0.93	0.92
Band Width	40 MHz	40 MHz
Input Saturation Power	50 W	50-100 W
Saturation Gain	63 dB	63-68 dB
Efficiency	45 %	38 %
Output Power	100 MW	77 MW

1. Electron gun

The electron beam in the gun is carried out by the 120 mm oxide cathode, that allows to have maximum of emission current density $J_{max} < 4A/cm^2$. As high-voltage insulator in this gun is used sectional accelerating tube comprising 10 ceramic rings. Constructive capacities, stationed along the accelerating tube, are designed so that the voltage distribution during the high-voltage pulse must be close to linear. As well as the voltage distribution in the tube, the properties of the generated beam strongly depend on the position of the electrostatic screen - the mobile electrode (pos. 1, Fig. 1). Moving this screen relative to the accelerating tube by means of the special drive, thereby one can vary the voltage distribution in the tube or correct the beam optics. It seems that availability of correction is especially important for guns with high beam convergence because their development and assembly are very demanding from the point of view of precision which is not always attainable in practice.

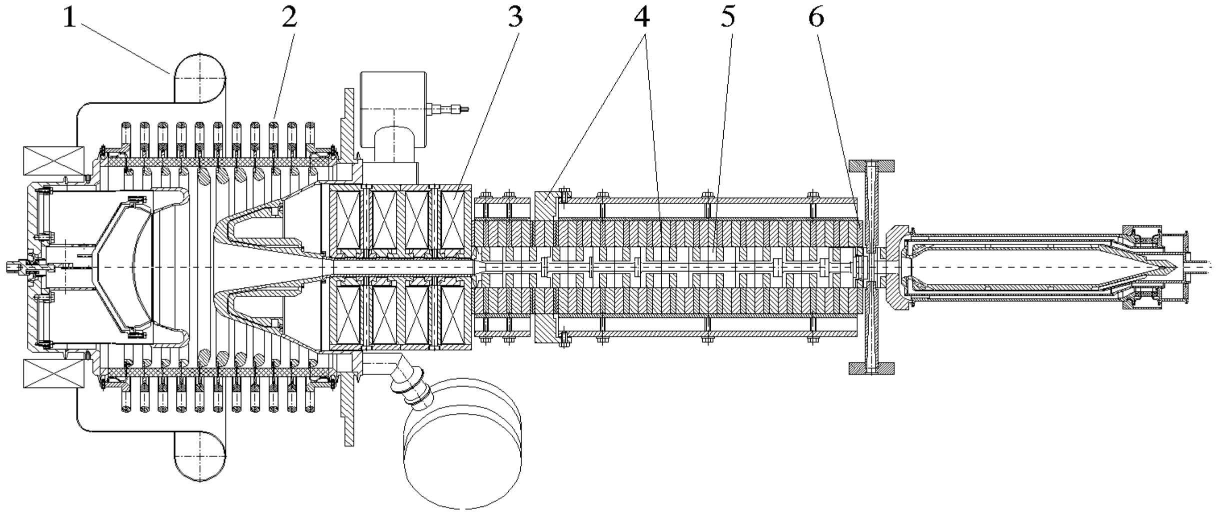

Figure 1: General view of BINP-KEK PPM klystron.

2. PPM Focusing System and Lenses

Two problems arise basically regarding the definition of parameters PPM. It is the choice of a period and the choice of magnetic field magnitude. Mainly the lower bound of Beam Voltage depends on the period, when the beam loses stability (Voltage Stop Band). The equilibrium diameter of the beam depends on the magnitude of magnetic field. The comparison of the root-mean-square field of PPM (*Brms*) with the field of solenoid approaches the comparison of the behaviour of the beam in the solenoid field. The behaviour of the beam in PPM and solenoid is close when the fields of solenoid and Brms of PPM are equal.

We have selected the diameter of the beam equal to 4.5-6 *mm* when the drift tube diameter is 9.6-10 *mm*. It corresponds to Brms equal to 2.6-3.1 *kGs*. The distance choosen between lenses is 26 *mm*. Let's name this distance geometric period. The period of magnetic field is 52 *mm*. The limit of beam stability is about 200 *kV*. We assume that the rise- and fall-pulse time is 200 *ns*, whereas the pulse duration is 1000 *ns*. Then at voltage below 200 *kV* the power value is estimated to be less than 1% of the total beam power. These power losses in the klystron channel can be considered to be quite admissible.

The magnetic system comprises polepieces pos. 5 brazed into the klystron body and removable magnetic blocks 4 (see Fig. 1). The inner part is axial symmetric. Four removable blocks are placed azimuthal symmetrically. The dipole and higher components of the magnetic field near the axis are shielded by the polepieces. The most dangerous for the beam thing is the dipole component of the magnetic field. It does not exceed 20 *Gs* on the axis when the field amplitude is 3.8 *kGs*. The removable blocks are installed on the klystron body by means of the special equipment. The klystron body is water-cooled.

The magnetic material Neodim-Ferrum-Bor is used. It possesses the magnetic energy, which is close to that of Samarium-Cobalt magnets. This material is cheaper, however, it is characterized by lower thermal stability than $Sm - Co$ has. The thermal measurements of the samples have shown that the temperature of magnets should not be higher than $60°C$. To match the beam with PPM, two-lens system is used. One lens can be also used; however in this case it is necessary for matching to change not only the lens current but also the position of the lens concerning the PPM entrance point.

The output section of the PPM channel requires special reviewing. The calculations were done under the static condition when the energy of moving particles remained unchanged. To simulate the RF current and beam energy variations in the output TW system pos. 6, the initial current and initial energy of the beam were varied. These calculations have not revealed any noticeable discrepancy between the beam behavior in the output system with the solenoid type of magnetic field, on the one hand, and the PPM field, on the other. It was decided to extend the PPM field up to the collector. The amplitude of the field in an output part was about 2.5 kGs. Later, 2-D MAGIC calculations showed the necessity of increasing the PPM magnetic field in the output section up to the value equal to 4.5 kGs in order to reach 100 % of beam transmission through the output system. To minimize the risk of destruction caused by the pulse thermal load, the collector was tungsten-covered.

3. Simulation Codes

1-D disk model was used to simulate and analyse the beam dynamics. For klystrons with solenoid type of fields and the output systems as a single cavity, the net results, as well as the experimental results, were close to those obtained by means of 2-D codes. For simulations of the radial dynamics of the stationary beam in the magnetic field, 2-D code was used, which regarded the beam space charge and beam emittance. The magnetic field calculations were carried out using 2-D code. The magnetic fields remained axially symmetric when it was close to the polepieces and the axis. The field value was improved and azimuthal harmonics was established according to the test models. Clearly, that 1-D simulations are not reliable enough for carrying out the analysis of PPM klysrons with the output TW system.

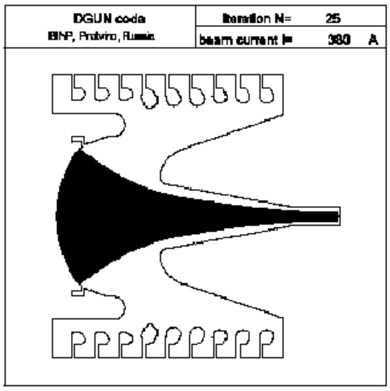

Figure 2: DGUN simulations of the electron gun.

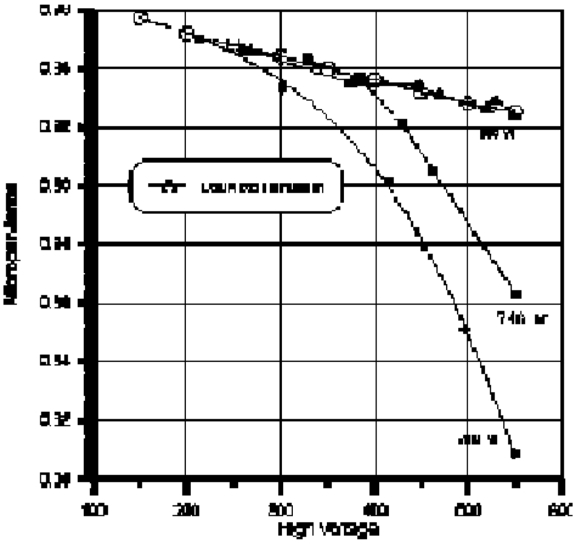

Figure 3: Microperveance vs beam voltage for different heating power of cathode (collector measurement).

Later, with the help of our Japanese colleagues from KEK, the analyses were conducted with the help of 2-D MAGIC code [2]. For simulations of the electron gun the precision code DGUN was used, which was developed by our colleague A.Larionov (Fig. 2). MAGIC [2] and EGUN simulations showed insufficient accuracy for the gun with the high compression of the electron beam. In Fig. 3 we can see that experimental perveance of the electron gun (black points) correspond to calculated perveance. The slope of the performance corresponds to relativity.

4. Experimental and simulation results. Discussion

The current transmission in the klystron channel in static condition (without any input RF power) was close to 100 % (Fig. 4).

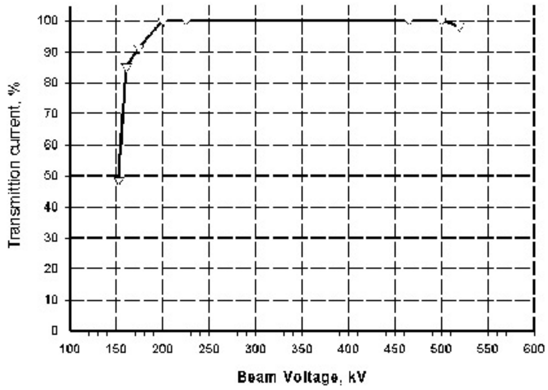

Figure 4: Transmission current through.

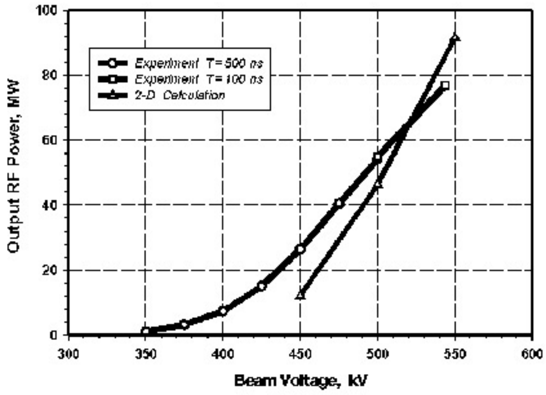

Figure 5: Output RF power vs beam voltage of PPM Klystron # 1.Magic 2-D calculations. Microperveance $P_m = 0.92$ the klystron vs beam voltage.

The lower bound of voltage, where the beam lost stability was equal to 200 kV. It was fast and convinient to tune the match of a beam with a PPM field and to achieve 100 % current transmission by changing the two lenses current. In Fig. 5 the results of the measurement of the output RF power and simulation results are represented. In the experiment with the gun voltage above 500 kV the decrease of the output RF power was observed in relation to simulations. The point of the inflection is especially appreciable in the picture of efficiency. The current interseption in the klystron and the decrease of the collector current are observed in the experiment (Fig. 6).

MAGIC simulations showed that when the beam voltage was higher than 500 kV the noticeable (up to 30 %) current interception arouse during the last cell of the output system (Fig. 7). MAGIC simulations showed also the possibility of 100 % of the beam transmission in the collector which could be achieved by means of the magnetic fields increase in the output part of PPM up to value 4.5 kGs without any essential modifications of the magnetic scheme of PPM. In Fig. 7 the beam dynamics is shown in dependence on the magnetic field value. When the beam voltage is higher than 450 kV parasitic oscillations arose, which could be observed in the spectrum of the output RF signal and signal, reflected from the input cavity. The current transmission in the PPM channel in static condition (without RF) decreased in the moment, appropriate to the time of oscillations beginning with the frequency equal to 21.2 GHz. In the initial part of the current pulse the beam transmission remained close to 100%.

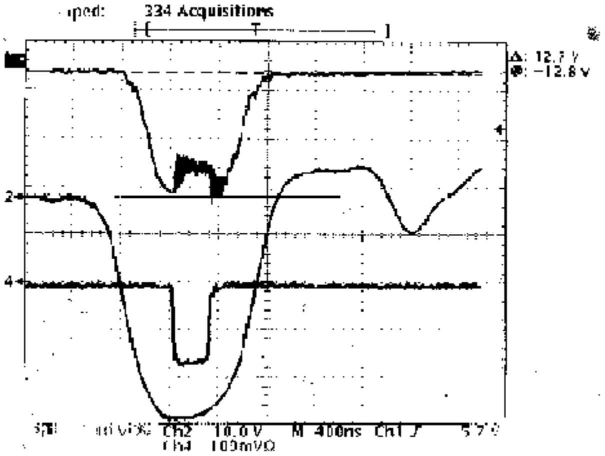

Figure 6: 1 - collector current,
2 - gun voltage, 4 - output RF signal.

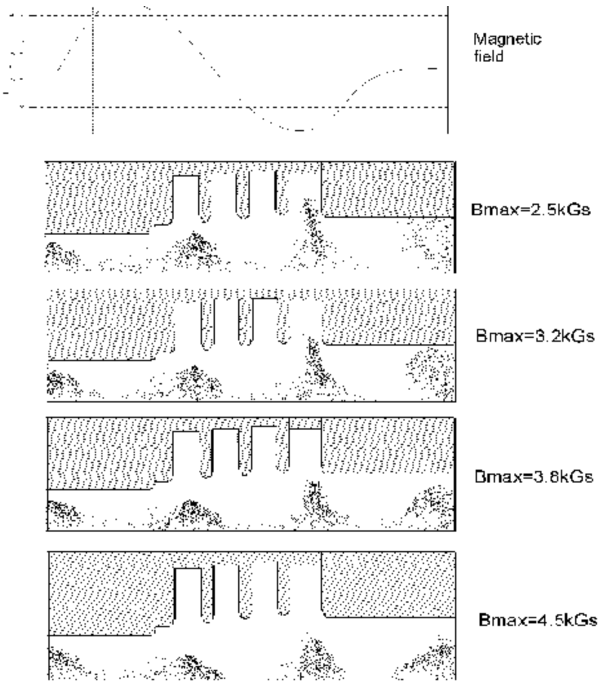

Figure 7: Beam dynamic in
the output TW system.

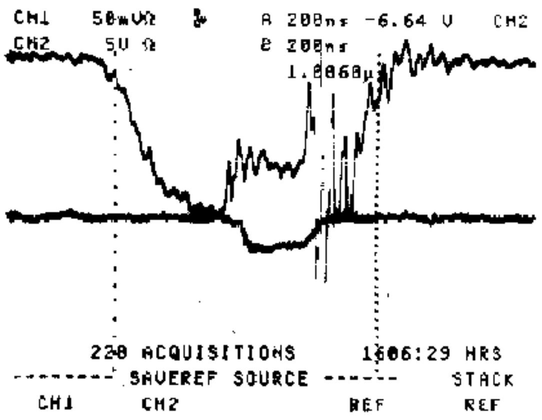

Figure 8: Begining of oscillations.

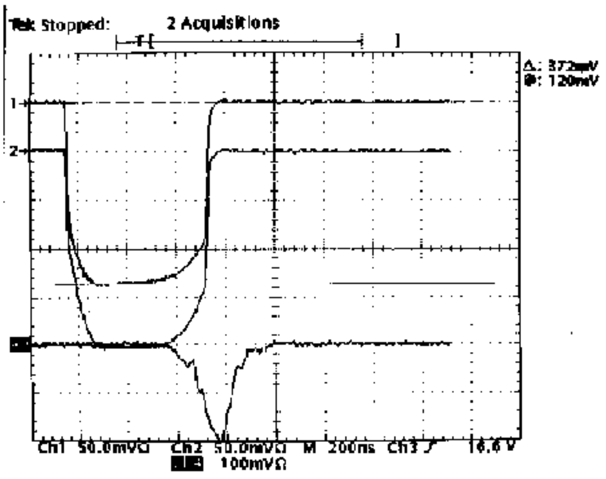

Figure 9: Shift of parasitic oscillations
1 - and 2 - signals of RF loads
remain pure. 3 - signal of parasitic
oscillations, F=21.2 GHz.

In Fig. 8: Above – the collector current, below – the signal of RF load, selected by RF filter of 21.2 GHz. The suppression of parasitic oscillationses during operating RF pulse is observed.

The beginning of parasitic oscillations was shifted in accordance with the increase of the input RF pulse duration (Fig. 9).

When the output power was more than 50 MW the breakdown was observed, characterized by the RF pulse collapse, the miss of RF in one or both RF outputs (Fig. 10).

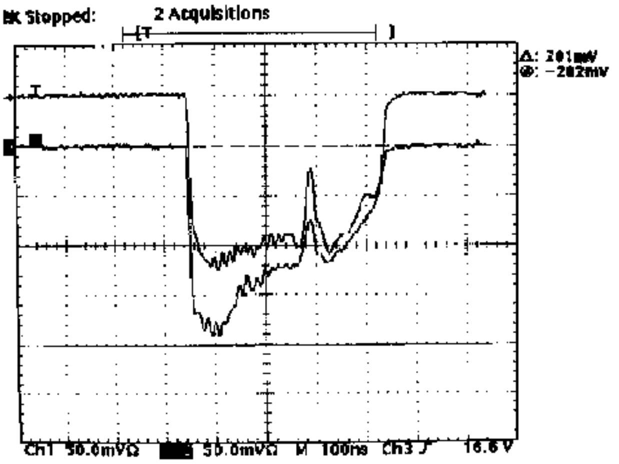

Figure 10: Breakdown phenomena.

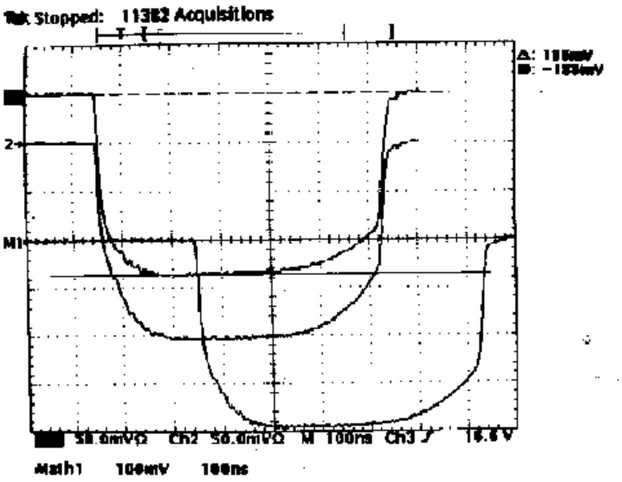

Figure 11: $P_{output} = 50$ MW, $\tau = 600$ ns.
1 -, 2 - signals of RF loads M1 - a total signal.

The breakdown repetition rate increased with the increase of the output power. The long training did not lead to any noticeable decrease of the breakdown repetition rate. The following limiting results are obtained. The output power in RF loads was 50 MW while RF pulse duration was equal to 600 ns and the gun voltage was 500 kV. The RF signals were pure. Parasitic oscillations were absent (Fig. 11). The output power in RF loads was 68 MW while RF pulse duration was equal to 300 ns and the gun voltage was 533 kV. The output power in RF loads was 74 MW while RF pulse duration was 100 ns and the gun voltage was equal to 544 kV. If we take into account the losses of the output wave guides, the output RF power achieves 77 MW, that corresponded to the electron efficiency equal to 38 %.

Conclusion

The results of klystron simulation and testing showed the following.

1. The diminution of efficiency of the klystron in comparison with simulations is caused by the beam interception in the output system.
2. It is possible to avoid the beam interception by means of the magnification of magnetic field magnitude in the output part of PPM.
3. The parasitic oscillations are detected in the klystron, and it is necessary to suppress them.

References

[1] Balakin V. et all. The diode gun with the increased beam convergence for powerful PPM focused X-band klystron. LC97, Zvenigorod, Russia, Okt. 1997.

[2] Chin Y.H. Modeling and Design of Klystron. Proc. LINAC'98, Chicago, 23-28.08.98