Technical Developments at the KIT Gyrotron Test Facility

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Parasitic beam tunnel oscillations have been discovered on all gyrotrons currently being developed and tested at KIT (1MW/140 GHz tube for W7-X, 2 MW/170 GHz coaxial gyrotron and 105-143 GHz frequency step tunable gyrotron). In the case of the W7-X gyrotrons these problems have been observed only on some of the series production tubes. A modified beam tunnel design, technologically close to the old design, has successfully been tested on both the coaxial and f-step-tunable gyrotrons and has subsequently been implemented on one of the W7-X series-production-tubes presently undergoing factory acceptance tests in Karlsruhe.

The ECRH test loads at KIT are operated under normal atmospheric conditions. Several loads have eventually failed in 1 MW long pulse experiments and KIT has therefore started to design its own loads. The first KIT-load is based on a fixed conical mirror and a cylindrical aluminum absorber coated with a lossy material. The new load was very economical to manufacture and has so far successfully been used during the acceptance tests of two 1-MW CW gyrotrons. Nevertheless a new load based on (uncoated) stainless steel absorbers is being developed as a backup solution for the ongoing high priority gyrotron testing.

A superconducting magnet capable of rapid field changes between 4.15 and 5.67 Tesla for frequency step-tunable gyrotrons has been procured, has achieved its specified maximum (static) field of 7.2 Tesla and has also demonstrated its capability of rapid field-changes. Final acceptance however has been delayed pending rectification of problems with the magnetic field alignment.

Keywords: ECRH; gyrotron; beam tunnel; test load; superconducting magnet

1. Parasitic Oscillations in W7-X gyrotrons

During the ongoing series production of the W7-X gyrotrons problems with parasitic oscillations have been encountered, which prevented operation at nominal power. This led to acceptance test failures of a number (but not all) of the tubes [1]. Similar problems with beam tunnel oscillations have been identified on both the frequency step tunable gyrotron [2] and the European coaxial pre-prototype 170 GHz gyrotron [3]. It is fair to say that quite an odyssey had to be gone through before the nature of the problem was recognized. It emerged eventually that parasitic oscillations in the electron-beam tunnel prevented operation at full power. Only with the development of a more sophisticated frequency measurement diagnostic system [4] a fair degree of confidence in the localization of the parasitic oscillations has become possible, together with an understanding of the nature of these parasitic oscillations.

The original Beam Tunnel consisted of a sandwiched structure of ceramic (BeO)-rings interleaved with copper rings (Fig.1). The first 3 gyrotrons worked well with output power in excess of 900 kWs. A forced ceramics-supplier-change seems to have been sufficient to alter the damping properties of this beam tunnel so much that that under otherwise identical operating conditions unwanted parasitic oscillations would be exited, particularly when approaching the designed gyrotron output power.

Several solutions were considered to suppress the unwanted parasitic oscillations, which were identified as backward waves being exited in the beam tunnel below the cavity. In follow-up inspections of rejected gyrotrons damage to the ceramics has been observed in the shaded region indicated in Fig.1
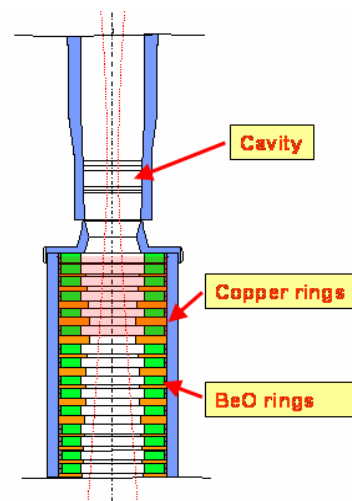

Fig.1 Original Beam Tunnel of the W7-X gyrotron

The considered solutions were:

a)   implementation of a lossy ceramic beam tunnel (a solution employed for example in Japanese gyrotrons)

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b) breaking the azimuthal symmetry by introducing corrugated copper rings, avoiding symmetric $TE_{0,p}$-modes

c) using a monotonously conical shaped beam-tunnel, thus avoiding cavity-like structures

All 3 solutions were prepared and a new beam tunnel combining solution b) and c) was designed (see Fig. 2) and tested in a one-to-one comparison on the frequency step tunable gyrotron and also on the coaxial pre-prototype gyrotron. This choice was involving least technological changes and avoided difficult quality control issues on the loss-properties of a ceramic beam tunnel. The solution worked very well and parasitic oscillations in the beam tunnel ceased completely in both gyrotrons.
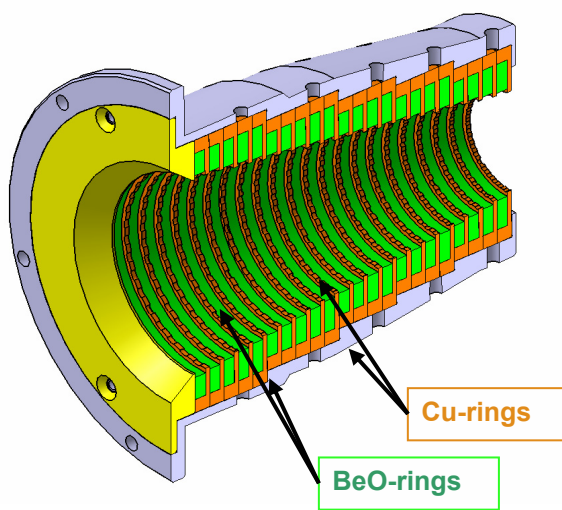

Cu-rings

BeO-rings

Fig.2 Improved Beam tunnel with corrugated copper rings and a conical contour

However, this may not yet be the end of all parasitic oscillations. While on the coaxial pre-prototype gyrotron no more parasitic modes could be seen and a record power of 2.2 MW with 96% Gaussian content has been achieved [3], there was one remaining parasitic mode observed on the f-step-tunable tube, at around 135 GHz. Careful analysis showed that this parasitic mode is not emanating from the beam tunnel, but is actually a forward wave in the launcher, having the same indices (namely $TE_{22,8}$) as the proper (wanted) cavity mode. It is thought that this parasitic mode may feed itself from the spent electron beam, without its own re-bunching process. First experiments on the W7-X series tube 004R (the first one equipped with the new beam tunnel) have also shown the presence of a parasitic oscillation at around 130.5 GHz when operating at a power level above 800 kW. While it is already clear that this mode is not exited in the beam tunnel, it has not yet been possible to define its precise origin. It could be either an After Cavity Interaction (ACI, see [5]) in the launcher or also a backward-wave interaction in the area of the connection between beam-tunnel and resonator (including down taper). The answer depends very critically on the precise

magnetic field distribution in this area and detailed analysis is still ongoing.

2. ECRH Test loads developed at KIT

The KIT ECRH testbed is using a quasi optical transmission line in order to transfer the power from the gyrotron to the load, where the power can be measured calorimetrically (see fig. 3). The load is operated under normal atmospheric conditions and with a circularly polarized beam, which is important for homogenous absorption inside the lossy surface coating of the load. Operation under vacuum would be an advantage, but would necessitate an additional vacuum window or the use of closed waveguide between gyrotron and load. The former is expensive and the latter is likely to cause problems with the gyrotron operation, since all the reflected power from the load (some 3 % on a good load) would be reflected back into the gyrotron, which can be extremely harmful to its proper functioning.
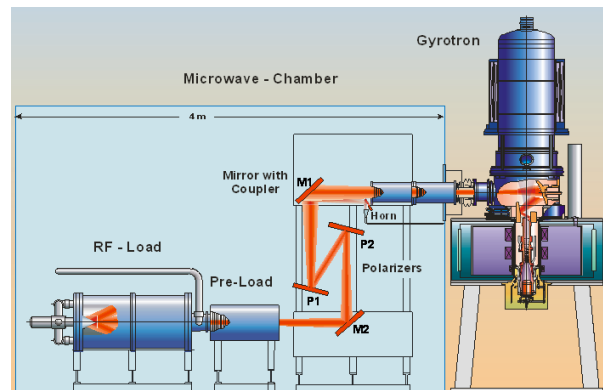

Fig.3 Transmission of gyrotron-beam to testload

Fig.4 is showing the basic principle of the load. The ECRH beam enters from the right through a narrow entrance (near the beam waste). It is then defocused by a fixed conical mirror on the opposite side and is gradually being absorbed in multiple reflections on the lossy surface of the inner cylinder wall of the load.
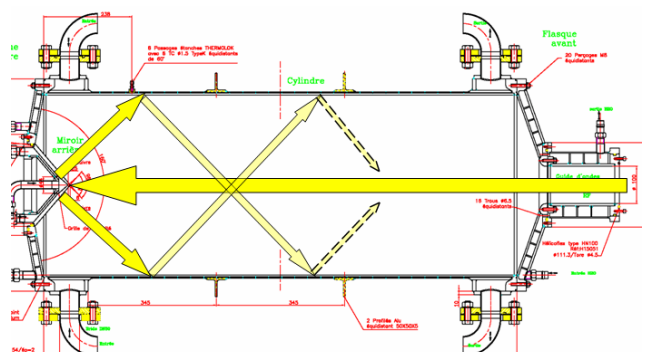

Fig.4 Early design of load with TiO-Al_2O_3-coating (on a layer of NiCrAlY) and a conical defocusing mirror (left)

The coating thickness is carefully controlled along the wall surface in order to obtain constant wall loading along the axis of the load. Fig.5 is showing a plot of the

ray-tracing simulation of the power density on the inner cylinder of the load.

All parts of the load are double walled and a water flow rate of approx. 550 l/min is required to remove the dissipated power of 1 MW in long-pulse and CW operation. The early design of the load shown in Fig.4 actually failed after a while with water leaks caused by thermal fatigue-cracks, because the double-wall structure used for the outer cylinder could not handle the differential expansion which occurred between the inner cylinder (heated by the RF) and the outer cylinder (which remains cool due to the heavy water flow). Based on the knowledge that the microwave design of the load is sound, a new load has been designed, using the same RF-design, but with a new concept for a separate inner
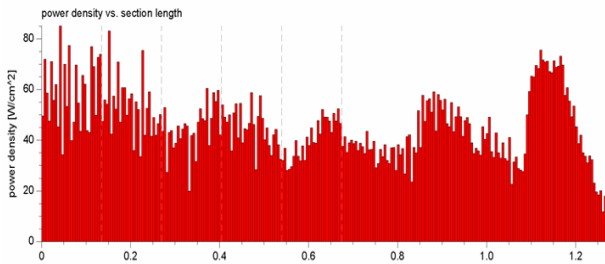

Fig.5 Power density along outer cylinder wall (simulated). The peak on the right is the first bounce of the beam reflecting off the conical mirror.

and outer cylinder, which can expand differentially against each other without causing undue stresses. Fig.6 shows a cross-section through the new load. The inner cylinder (aluminium-alloy) is castellated on the water side and has a wall-thickness of 12 / 16 mm, so required to sustain the forces resulting from the water cooling circuit pressure of up to 6 bar. The differential movement between inner and outer cylinder against each other is taken up by Schnorr disks (visible on the right side of fig.6), which press the input plate against the inner cylinder with a near constant pressure. A sliding O-ring preserves the tightness of the cooling circuit. This new load, designed and built very economically at KIT, is now successfully in use on the acceptance tests of its second 1 MW gyrotron.
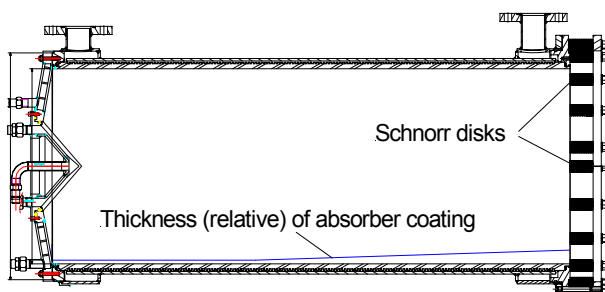

Fig.6 KIT version of 1 MW load with TiO-Al$_2$O$_3$-coating

A faultlessly working load is essential for long-pulse-testing of gyrotrons. The loss-coating is clearly one weakness in these loads, as for example misalignment

could lead to excessive power densities and therefore coating-damage. Also, arcs which can not be avoided all the time, have the potential to damage the coating. Previous experience with the coating employed on these loads has shown that such damage can not be repaired easily (other types of coatings on other loads could just locally be removed and the load could be used again, all be it with lower absorption, but with TiO-Al$_2$O$_3$-coating on a NiCrAlY layer this technique did not work, there was persistent arcing along the edge where the coating had been removed).

A load without coating may be more robust and easier to repair if damaged. In order to have a backup-load and also encouraged by good reports of such loads used elsewhere, KIT has started the development of an all stainless steel load. A first such load with a novel internal structure but without active cooling has been tested and has shown unexpected low levels of reflection (<2%) and could be used with pulses up to 2 seconds at power levels of up to 700 kW. Wall temperatures in excess of 250°C were reached (in successive pulses) before arcing developed. Arc damage in the form of very small pitting was minimal, but nevertheless had to be polished off in order to regain maximum power levels. Access to the internal structure therefore appears to be essential. Work is underway now to design a fully watercooled version of this load. In a first step, only the inner structure has been equipped with cooling. Such a load (Fig.6) is ready for testing with a 1 MW CW gyrotron. If tests are successful, a completely cooled load will be manufactured as a back-up for the KIT gyrotron testbed.
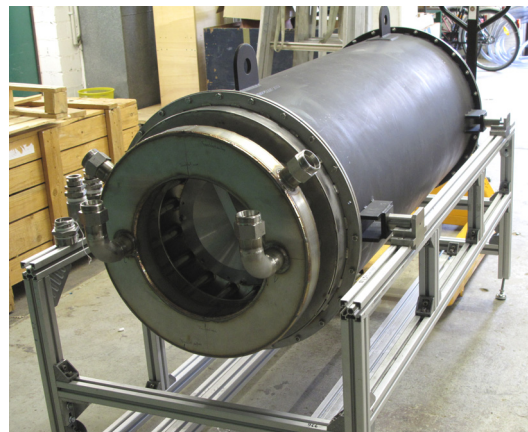

Fig.6 KIT-Prototype of an all stainless steel load

3. Cryomagnet for frequency step tunable gyrotron

Parallel to the development of a frequency step tunable gyrotron [6] the procurement of a superconducting magnet had been started at KIT, together with the corresponding power supplies. The aim is to achieve a

quick frequency change at a rate of 6.6 GHz/s, with a repetition-rate of 1 every 10 seconds.

The magnet is specified to be used up to 7.2 Tesla (corresponding to an electron cyclotron frequency of 174.2 GHz), for gyrotrons operating up to 180 GHz. Table 1 summarizes the main parameters for the magnet.

Table 1: Main parameters of fast tunable superconducting magnet.

Max. Field		7.2 Tesla
rate of Field change (up to 5.665 T)		≥ 0.264 T/s
Warm Borehole Diameter	everywhere	≥ 220 mm
	top 135 mm	≥ 275 mm
max. horizontal displacement of field axis referred to geometrical axis		≤ 0.1 mm
L-He volume and boil off rate requirements without refill	operation at 6.86 T	≥ 120 h
	hold time (0T)	≥ 190 h

Figure 7 gives the coil arrangement chosen by the supplier of this magnet. The letters indicate to which group a coil belongs (see column 1 of table 2). The desired fast field change is obtained by acting on the AC mode coils (AC). The direction of the field in the emitter region (z = 28 mm) can be modified by acting on the Gun Taper coils (G) and the Gun Trim Coils (T). The structure inside the r = 0.1 m radius indicates the gyrotrons gun (up to the cavity).
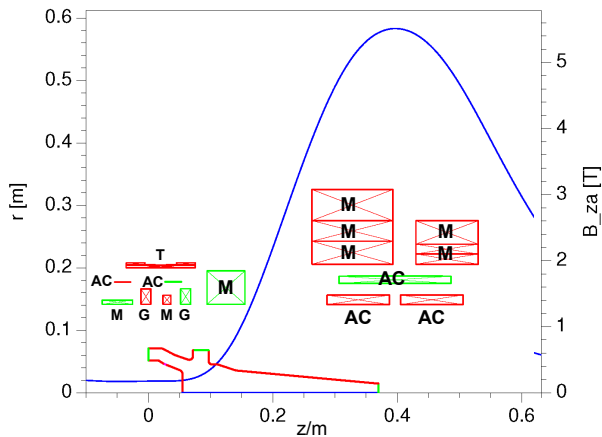

Fig.7 Coil configuration and Field-profile of the cryo-magnet for the fast frequency step tunable gyrotron

The magnet has demonstrated its maximum field capability of 7.2 Tesla and has sustained without problems the magnetic-field sweeps as specified. The helium boil-off rate was also within the specifications, which allow for an excellent stand-alone time in excess of 1 week for the magnet. Final acceptance however is delayed due to problems with the accuracy of the magnetic field alignment.

Table 2 gives the relevant power supply data for the 4 different coil systems. The power supply for the AC-coils is the most complex and powerful one; it operates in 4 quadrants and is capable of changing the current in the AC coil by 20 A in 0.5 seconds with a repetition rate of once every 10 seconds.

Table 2: Coil systems and required Power Supplies

Power Supply	Inductance	Voltage	Current
Main Coil (**M**)	574 Hy	± 10 V	+ 100 A
AC-Coil (Mode) (**AC**)	2.3 Hy	± 100 V	± 125 A
Gun Taper Coil (**G**)	3.3 Hy	± 5 V	± 20 A
Gun Trim Coil (**T**)	1.3 Hy	± 20 V	± 10 A
Dipole Coils (transverse field)	-	5 V	84 A

Acknowledgments

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